

A study on invariant mass reconstruction techniques for a boosted tau pair, in the context of boosted Higgs pair searches in the $b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$ channel at the LHC with the ATLAS detector

Pablo Yáñez

January 25, 2024

Abstract

The LHC has proven to be one of the most ambitious and powerful particle colliders to date, being capable to explore the TeV energy scale and to produce a particle compatible with the Higgs boson, such discovery was confirmed in 2012 by the CMS and ATLAS experiments. While exploring possibilities for physics beyond the Standard Model, the ATLAS collaboration further searches for heavy resonances decaying into a Higgs boson pair. The understanding of the final states involving the decays of a pair of Higgs bosons are crucial channels in the search of heavy resonances, which are predicted by theories encompassed in minimal supersymmetric Standard Model extensions or other theories beyond the Standard Model. A pair of highly collimated tau leptons in the final state challenges the reconstruction of Higgs particles due to the partial overlap of the hadronic tau jets in the detector. Particularly, in this work, we studied the boosted topology of the decay chain $X \rightarrow hh \rightarrow b\bar{b}\tau^+\tau^-$ in a fully hadronic final state, implementing a reconstruction technique for the invariant mass of a boosted tau pair, applying the collinear mass approximation method and compare the results with the visible decay system.

Acknowledgements

Contents

1	Introduction	4
2	Standard Model of Particles	6
2.1	Elementary Particles	6
2.1.1	Quarks and Leptons	6
2.1.2	Gauge Bosons	8
2.2	Gauge Theories	8
2.2.1	Quantum Electrodynamics	9
2.2.2	Quantum Chromodynamics	10
2.2.3	Electroweak Theory	12
2.3	Higgs-Brout-Englert Mechanism	13
2.4	The Higgs pair system	15
2.4.1	Tau Decays	17
2.5	Beyond the Standard Model	18
2.5.1	The Two Higgs Doublet Model: 2HDM	20
2.5.2	Complex Singlet Scalar Model	22
2.6	Searches for Heavy Resonances	23
3	The ATLAS Experiment	24
3.1	The Large Hadron Collider	24
3.2	Detector Coordinate System	24
3.3	The ATLAS Detector	26
3.3.1	Inner Detector	27
3.3.2	Calorimeters	28
3.3.3	Muon Spectrometer	30
3.4	Magnet System	31
3.5	The Trigger and Data Acquisition System	32
4	Object Reconstruction & Event Selection	34
4.1	Object reconstruction	34
4.1.1	Boosted tau pair reconstruction	34
4.1.2	Boosted $H \rightarrow b\bar{b}$ reconstruction	37
4.1.3	Missing Transverse Momentum	41
4.2	Event selection	41
5	MC signal samples	43
5.1	Data Processing	43
6	Mass Reconstruction Improvements	45
6.1	The Collinear Mass Approximation	45
6.2	χ^2 Fit and the Method of Least Squares	45

7	Results	47
8	Trigger Studies	56
8.1	Phase-I upgrade for Run-3	56
8.2	Non-resonant Monte Carlo ggF and VBF signal samples	57
8.3	Offline selection	58
8.4	L1 selection	58
8.5	L1 trigger items for electron+tau chains	58
8.6	Trigger efficiency results	59
8.7	Kinematic distributions - ggF non-resonant sample	59
8.8	Kinematic distributions - VBF non-resonant sample	67
9	Conclusions	74
A	Plots	82
A.1	Heavy mass $m_X = 1.0$ TeV kinematics variables	82
A.2	Heavy mass $m_X = 1.0$ TeV kinematics variables (HERWIG)	83
A.3	Heavy mass $m_X = 1.2$ TeV kinematics variables (HERWIG)	84
A.4	Heavy mass $m_X = 1.4$ TeV kinematics variables (HERWIG)	85
A.5	Heavy mass $m_X = 1.6$ TeV kinematics variables (HERWIG)	86
A.6	Heavy mass $m_X = 1.8$ TeV kinematics variables (HERWIG)	87
A.7	Heavy mass $m_X = 2.0$ TeV kinematics variables	88
A.8	Heavy mass $m_X = 2.0$ TeV kinematics variables (HERWIG)	89
A.9	Heavy mass $m_X = 2.5$ TeV kinematics variables (HERWIG)	90
A.10	Heavy mass $m_X = 3.0$ TeV kinematics variables (HERWIG)	91
B	Kinematic distributions - ggF non-resonant sample	91
B.1	ggF 3J20	91
B.2	ggF 4J12	99
B.3	ggF L1Topo	106
C	Kinematic distributions - VBF non-resonant sample	113
C.1	VBF 3J20	113
C.2	VBF 4J12	120
C.3	VBF L1Topo	127
D	Jet Algorithms	132
D.1	Jet algorithms Review	132

1 Introduction

The field of particle physics has been, in the last decades, one of the most successful scientific research endeavors, under the theoretical framework of the Standard Model, the share amount of successful predictions regarding elementary particles and their interactions can't be understated. Combining established theories such as quantum electrodynamics, quantum flavour dynamics and quantum chromodynamics, and incorporating the Higgs-Brout-Englert symmetry breaking mechanism unifying the electro-weak sector, the Standard Model has demonstrated being a solid representation of the fundamental physics operating on the universe.

In tandem to those theoretical descriptions, experimental particle physics has engineered large and complex experiments which push the boundaries of technological research every day, from the highest energy colliders like; the large hadron collider (LHC), the large electron-positron collider (LEP), and the hadron electron ring accelerator (HERA), to the development and implementation of machine learning algorithms and sophisticated data science methods. Accelerators and colliders are key devices that not only help to understand fundamental particles and the forces intertwined on their interaction, they also keeps deepen our capacity to surpass the requirements that such a challenging goal demands.

Despite being currently the best theoretical description of particle physics, the Standard Model is being considered the effective theory of a more fundamental one. The Standard Model leaves many important questions unanswered, and is not, by any means, free of shortcomings both theoretical and experimental. Theoretical extensions of the Standard Model have been elaborated through the years covering a large variety of hypothetical scenarios. Due to the upcoming upgrades of the LHC and advances in particle detectors technology it is now relevant to prepare in advance for the new possibilities and challenges that would accompany them.

In this regard, the development of particle reconstruction techniques is mandatory to progress forward, the observation and eventual measurement of processes involving the Higgs particle are fundamental. In particular, the Higgs could be a portal to beyond the Standard Model physics and could be used as a tool for detecting heavy resonances, for instance, in the case of a resonance decaying to a pair of Higgs bosons. Even if not compatible with a heavy resonance, the Higgs trilinear coupling can be studied from the same final state and by definition, characterizes important features related to the Higgs sector in the Standard Model.

One promising premise to search physics beyond the Standard Model is the proposal to extend the Higgs sector, particularly by the theories which proposes an additional Higgs doublet: the two Higgs-doublet models (2HDM), under this models such a heavy spin-0 resonance would be compatible to a heavier Higgs particle which can decay in a pair of Higgs bosons, thus enhancing its production with respect to the standard model expectations. This thesis aims to give a broad understanding on this subject, investigating the reconstruction of a Higgs pair system, where one of the Higgs decays into a b-jet pair and the other into an hadronically decaying di-tau system, reconstructing such decay using different techniques, and analysing their limitations and behavior.

Combined and individual searches for resonant Higgs pair production have been performed in several final states: $b\bar{b}b\bar{b}$, $b\bar{b}\tau^-\tau^+$, $b\bar{b}\gamma\gamma$, $W^-W^+\gamma\gamma$, $b\bar{b}VV$ and $W^-W^+W^-W^+$ at $\sqrt{s} = 13$ TeV

and $\sqrt{s} = 8$ TeV by the ATLAS [1] [2] and CMS collaborations [3] [4] [5] respectively. The ATLAS collaboration has previously set limits for the $b\bar{b}\tau^-\tau^+$ final state [6] in a resonant mass range between 260 and 1000 GeV.

This thesis is organized in three main sections: First, a general introduction to particle physics and the ATLAS detector comprised of the present Chapter 1 which serves as a general introduction to the subject and aims to exhibit the motivations behind the study, then Chapter 2 gives away a brief Standard Model physics summary and the needed theoretical outlook to have a better grasp at the aspects covered on this study, Chapter 3 describes the ATLAS experiment including the detector itself and its components. The second section is related to the Higgs pair resonant analysis and includes Chapter 5 which focuses on the MC simulations and generated samples to be considered, Chapter 4 delvesflavour flavour dynamicsdynamics on the event selection and its reasoning including a deep know-how in the different selection and algorithms implemented in the ATLAS $b\bar{b}\tau\tau$ analysis, Chapter 6 goes full on the collinear approximation technique, the personal contribution of the author Chapter 7 presents the results of such approximation on the $hh \rightarrow b\bar{b}\tau\tau$ channel. Then the third section is another brief study on tau trigger efficiencies on the $b\bar{b}\tau\tau$ semileptonic decay in the Run-3, which the author contributed as part of the CERN Summer Student Programme is presented in Chapter 8. Finally Chapter 9 presents the conclusion of both the Higgs pair reconstruction and trigger studies and goes further on future implementations and studies.

2 Standard Model of Particles

The Standard Model (SM) of particle physics is the theoretical framework that explains a plethora of physical phenomena, examples of such features are the prediction of properties of the electroweak currents, this theory includes a description of the electromagnetic, strong and weak interactions, including the Brout-Englert-Higgs mechanism [7], the combined observed particles are in highly accordance to their theoretical constraints and directives, with the Higgs boson being the last fundamental particle given experimental confirmation in 2012 by the ATLAS and CMS collaborations [8, 9].

Regardless of being currently the best theoretical description of particle physics, it is a matter of concern the level of accordance with experimental evidence, a numerous quantity of unanswered questions still challenges our understanding of the universe such as the matter-antimatter asymmetry, the incorporation of a quantum-gravitational interaction or the existence of a dark matter particle which are some of the motivations for physics beyond the Standard Model.

2.1 Elementary Particles

The SM of elementary particles is comprised of twelve matter fermions which follows a Fermi-Dirac statistics: six quarks and six leptons organized in three generations, which all share their charge and spin quantum numbers but differ on rest mass. Along with these fermions, there is four gauge bosons obeying a Bose-Einstein statistics, these bosons carry/mediate three of the four known interactions (Electromagnetic, Weak and Strong nuclear), and a singular scalar boson namely the Higgs boson product of the spontaneous electro-weak symmetry breaking, all of these depicted in Figure 1. All particles are known to have a corresponding antiparticle as a direct consequence of the relativistic invariant description of particles interactions, antiparticles share mass and spin but deviate from their counterpart having opposite quantum charge numbers, this has as a consequence that some particles happens to be their own antiparticles.

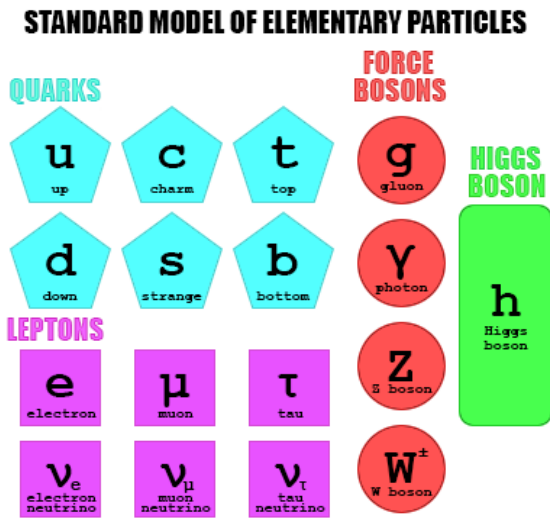


Figure 1: SM of elementary particles.

Governed by quantum field theory, the particles manifest themselves as excitations of their respective fields and inherits the quantum particle-wave behaviour. The Higgs boson lies as the fundamental piece from which all other elementary particles receive their characteristic masses due to their interaction with the all-encompassing Higgs field, via the Brout-Englert-Higgs mechanism.

2.1.1 Quarks and Leptons

There are six quarks, namely the *up*, *down*, *charm*, *strange*, *top* and *bottom* quarks classified by their flavour quantum number resembling the different flavours: isospin (I) which characterize up and down quarks, charm (C), strangeness (S), topness (T) and

bottomness (B) correspondingly, all carry fractional electric charge, either $-1/3$ or $2/3$ and color charge which can take three different values: red (r), green (g) or blue (b); this make them interact via the three interactions described by the Standard Model and mainly by the strong force which held them together as composite particles named hadrons, composed by baryons (tri-quark states) and mesons (di-quark states) as proposed by the quark model [10], due to quantum chromodynamics color confinement, they cannot be observed as free particles and have to be reconstructed from the colorless states generated by hadronization and fragmentation, and manifest themselves as a set of those colorless objects having roughly the same direction than the struck quark, forming a narrow cone of particles named jet. Quark quantum numbers, charges and masses are specified on Table 1

generation	quark	charge [e]	mass [MeV/c ²]	spin	I	C	S	T	B
I	u	$\frac{2}{3}$	~ 2.2	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
	d	$-\frac{1}{3}$	~ 4.7		$-\frac{1}{2}$	0	0	0	0
II	c	$\frac{2}{3}$	~ 1280		0	1	0	0	0
	s	$-\frac{1}{3}$	~ 96		0	0	-1	0	0
III	t	$\frac{2}{3}$	~ 173100		0	0	0	1	0
	b	$-\frac{1}{3}$	~ 4180		0	0	0	0	-1

Table 1: The quarks characteristics present in the Standard Model. Charges, masses, spin and quantum numbers I (isospin), C (*charm*), S (*strangeness*), T (*topness*) and B (*bottomness*)

Leptonic particles (Leptons) encompass three electrically charged flavours, the *electron*, *muon* and *tau* (denoted e , μ , τ respectively) all having a negative unitary electric charge, between such particles only the electron is stable, in contrast to muons and taus which are unstable with a lifetime of $2.2 \mu s$ and $2.9 \times 10^{-7} \mu s$ respectively [11]. The three of them are subject to the electroweak interaction, along these, there are three corresponding electric neutral flavors (*electron*, *muon* and *tau neutrino*), having zero mass but sharing the flavour quantum numbers; L_e , L_μ and L_τ with their electrically charged counterparts, neutrinos interact only through the weak force, leptons being colorless particles do not interact due to the strong force. Lepton quantum numbers, electric charge and mass are specified on Table 2

generation	lepton	charge [e]	mass [MeV/c ²]	spin	L_e	L_μ	L_τ
I	e	-1	0.511	$\frac{1}{2}$	1	0	0
	ν_e	0	< 0.0000022		1	0	0
II	μ	-1	105.66		0	1	0
	ν_μ	0	< 0.17		0	1	0
III	τ	-1	1766.8		0	0	1
	ν_τ	0	< 18.2		0	0	1

Table 2: The leptons characteristics present in the Standard Model. Charges, masses, spin and quantum numbers: L_e (*electron number*), L_μ (*muon number*) and L_τ (*tau number*)

2.1.2 Gauge Bosons

The Standard Model is a gauge theory, this means that the lagrangian of the theory must remain invariant under a local or gauge transformation, having as direct consequence a conserved charge associated to said symmetry. It manifests itself by four gauge bosons as intermediary of the three interactions described by the model. The photon acts as the responsible for the electromagnetic interaction between charged particles, the gluon mediates the strong interaction between quarks and the $W^\pm$ and Z bosons are the electroweak interaction force carriers. The aforementioned fermions and bosons plus the Higgs boson gives a consistent and coherent explanation to most of the observed fundamental particles associated phenomena.

The existence of gauge bosons and their respective interactions with fermionic particles, are explained as a local gauge invariance of the Lagrangian of said particle kinetic energy, and thus describing the dynamics of the system, this is linked by an internal symmetry described by group theory, specifically via the family of operations described by Lie groups. For symmetries to be exact, the gauge particles are assumed to be initially massless so the Higgs mechanism is invoked to generate particle masses via coupling with the Higgs field. This gives a framework that describes the electroweak interaction by the action of the special unitary group $SU(2)_L$ (L indicative that the symmetry applies only to left handed particles) and the unitary group $U(1)_Y$, and the strong interaction characterized by the special unitary group $SU(3)_C$, where the conserved quantum numbers are I the weak isospin, Y the weak hyper-charge and C the colour charge. The combination of said local gauge symmetry groups $SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$, the left-handiness of the fermionic fields, plus the symmetry breaking mechanism and its residual invariance:

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q,$$

defines the interactions contained in the SM.

2.2 Gauge Theories

As stated, a gauge theory is a field theory where all the physics described by the Lagrangian are invariant, as an example let's take a non-Abelian Yang-Mills theory coupled with fermionic matter, to describe such theory we start from the Dirac field Lagrangian:

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \quad (2.1)$$

Symmetry can be incorporated in a Lagrangian if it is invariant under a local transformation, for instance that described by a Lie group $SU(N)$. Such a gauge transformation can be written as:

$$\psi(x) \rightarrow \psi'(x) = e^{iT^a\theta^a(x)}\psi(x) \quad (2.2)$$

The locality of the transformation lies within the spatial dependence of the parameters $\theta^a(x)$, a is related to the dimension of the Lie group in particular $SU(N)$ can take the values between $a = 1, \dots, N^2 - 1$. An internal symmetry is linked to a continuous field variation $\delta\psi(x)$ and the

146 conserved current $J^\mu = \frac{\delta \mathcal{L}}{\delta(\partial_\mu \psi_i)} \delta \psi_i$. And the T^a are the SU(N) group generators of the compact Lie
 147 group whose underlying Lie algebra satisfies:

$$[T^a, T^b] = if^{abc} T^c \quad (2.3)$$

148 The invariance of the Lagrangian gives as a consequence the definition of the covariant derivative
 149 as a covariant transformation derivative operator which reduces to $\partial_\mu \psi$ in the weak field limit by
 150 introducing the gauge boson field A_μ

$$D_\mu = \partial_\mu - ig A_\mu \quad (2.4)$$

151 The insertion of the boson field on the covariant derivative causes an interaction between the
 152 Dirac field ψ and the boson field A_μ . This covariant derivative must transform in the same way as
 153 the Dirac field to ensure the Lagrangian invariance:

$$(D_\mu \psi)' = e^{iT^a \theta^a(x)} D_\mu \psi \quad (2.5)$$

154 Expanding the exponential into a truncated power series and applying equations 2.2, 2.3 and 2.4
 155 the condition on equation 2.5 implies the following gauge field transformation to A_μ

$$A_\mu^a \rightarrow A_\mu'^a = A_\mu^a + f^{abc} A_\mu^b \theta^c + \frac{1}{g} \partial_\mu \theta^a \quad (2.6)$$

156 Adding a kinetic term to the gauge field A_μ to the Dirac Lagrangian on equation 2.1 gives

$$\mathcal{L} = -\frac{1}{2} \text{Tr}\{F_{\mu\nu} F^{\mu\nu}\} + i\bar{\psi} \gamma^\mu D_\mu \psi - m\bar{\psi} \psi \quad (2.7)$$

157 The Lagrangian on equation 2.7 contains a kinetic term for the field on the trace of the energy
 158 momentum tensor $F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - ig f^{abc} A_\mu^b A_\nu^c$, at this point a mass term for the Lagrangian
 159 would have a $\text{Tr}\{A_\mu A^\mu\}$ expression which is not gauge invariant according to a Yang-Mills theory all
 160 gauge boson are massless, this is where the Higgs mechanism explained in Section 2.3 is required.

161 2.2.1 Quantum Electrodynamics

162 The simplest application of a gauge theory, quantum electrodynamics or QED is based on the quan-
 163 tization of a gauge theory with a unitary abelian symmetry group U(1), the gauge transformation
 164 from Equation 2.2 reduces to the phase shift to the state function of the system as:

$$\psi(x) \rightarrow \psi'(x) = e^{i\theta(x)} \psi(x) \quad (2.8)$$

165 The demand on transformation locality makes the phase a space-time function of $x = \{t, \vec{x}\}$, extra
 166 terms appear upon derivation which breaks the invariance, this transformation introduce to the free
 167 Lagrangian a $i\partial_\mu \theta \psi$ component so in accordance to equation 2.5 the covariant derivative relative to
 168 U(1) is:

$$D_\mu \psi = \partial_\mu \psi - ie A_\mu \psi \quad (2.9)$$

And the gauge boson transformation:

$$A'_\mu = A_\mu - \frac{1}{e} \partial_\mu \theta \quad (2.10)$$

To maintain a Lorentz invariant Lagrangian and the gauge invariant expression $D_\mu \psi$ in combination to giving the QED Lagrangian a free massless expression to the gauge field A_μ :

$$\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{Dirac} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \gamma^\mu D_\mu \psi - m\bar{\psi} \psi \quad (2.11)$$

The covariant derivative maintains the local symmetry but introduces the field A_μ , to our U(1) QED gauge theory, interacting through the expression $e\bar{\psi} \gamma^\mu A_\mu \psi$ to the Dirac fermion.

2.2.2 Quantum Chromodynamics

The strong interaction is explained by the interactions between colour charged particles like quarks and gluons, quarks are comprise inside bound states called hadrons (which are SU(3) singlets) and composed by quarks and anti-quarks either by forming tightly bound mesons (quark-antiquark pair) or baryons (triquark) combinations. QCD is described by an $SU(3)_C$ gauge theory associated to the 3-state colour charge, having in consequence 8 generators, where in the defining representation can be expressed as $T^a = (1/2)\lambda^a$, λ^a being the Gell-mann matrices and thus, having as a consequence 8 massless bosonic particles named gluons, carrying the color and anticolor charge between strong interacting particles. The Dirac field lagrangian for each quark field is done in a similar fashion as the one in Equation 2.1 and yet again applying the gauge invariance to this lagrangian would introduce the gluon field. In accordance to Equation 2.5 the covariant derivative is:

$$D_\mu = \partial_\mu - ig_s G_\mu^a \frac{\lambda^a}{2} \quad (2.12)$$

where the g_s is the QCD coupling constant and G_μ the gluon field as mediator of the strong interaction, the non-abelian nature of QCD leads to significantly different behaviours that those founded in abelian theories. As recalled from Equation 2.7 the QCD lagrangian will have a boson kinematics term which, because of the non-commutative nature of the field strength tensor will lead to gluon self-interactions which can be seen explicitly from:

$$\begin{aligned} -\frac{1}{2} \text{Tr}\{G_{\mu\nu} G^{\mu\nu}\} = & -\frac{1}{4} ((\partial_\mu G_\nu^a - \partial_\nu G_\mu^a)(\partial^\mu G^{\nu,a} - \partial^\nu G^{\mu,a}) \\ & + 2gf^{abc}(\partial_\mu G_\nu^a - \partial_\nu G_\mu^a)G^{\mu,b}G^{\nu,c} + g^2 f^{abc} f^{cde} G_\mu^a G_\nu^b G^{\mu,c} G^{\nu,d}) \end{aligned} \quad (2.13)$$

this has as consequence three-gluon and four-gluon vertex interactions from the last two terms in the previous equation. The coupling constant is characteristic of the interaction strength and is dependent on the momentum exchanged between charged particles, therefore giving it a running with a p effective coupling.

The presence of new vertices have as a consequence a whole set of Feynman diagrams which are exclusive of this theory, as the momentum exchanged is carried away by the gluon line, the contribution of these diagrams to the interaction between color charges at one loop can be seen in

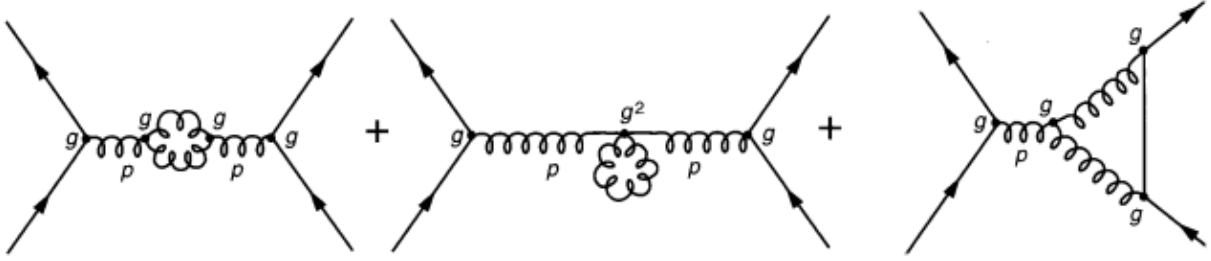


Figure 2: Leading loop chains which contribute to the $Y(p^2)$ calculation

197 Figure 2, if the effective mass of the virtual gluon is large enough to produce real gluon particle pairs,
 198 they will enhance the color charge, this is the so called anti-shadowing. Defining the effective coupling
 199 strength as $\alpha_s \equiv g_s^2$, this running coupling strength is characterized by the expression:

$$\begin{aligned}\alpha_s(p^2) &= \alpha_s(\mu^2)(1 + Y(p^2) + Y^2(p^2) + \dots) \\ &= \alpha_s(\mu^2) \frac{1}{1 - Y(p^2)}\end{aligned}\tag{2.14}$$

200 Where μ^2 is a convenient momentum measure introduced due to the perturbative nature of the
 201 result, $Y(p^2)$ is the contribution at 1-loop to the invariant amplitude

$$\mathcal{M}_{1 \text{ loop} + \text{extra virtual VB}} = Y(p^2)\tag{2.15}$$

202 so for quarks (which have charge and color) is calculated considering the effect of either shadowing
 203 by the gluon or the anti-shadowing of electroweak vector bosons (explaining the opposite behavior
 204 contributions), both at one-loop, thus how affects the coupling:

$$Y(p^2) = \frac{\alpha_s(\mu^2)}{12\pi} (2n_f - 11n_c) \ln \left(\frac{|p^2|}{\mu^2} \right)\tag{2.16}$$

205 When $|p^2|$ is greater than μ^2 , n_f the number of
 206 quark flavours with masses less than $\frac{1}{2}\sqrt{|p^2|}$ and n_c is
 207 the number of colors. In the context of energy scale of
 208 the interactions Q^2 , the strong coupling scale, Λ_{QCD}
 209 ($\Lambda_{QCD} \approx 200\text{GeV}$), $\beta_0 = (11n_c - 2n_f)/12\pi$
 210 the first order perturbative constant and the quarks
 211 flavour that can appear in the loop when the mo-
 212 mentum transferred is greater than the top mass
 213 ($Q^2 > m_t^2$), then $n_f = 6$, and $n_c = 3$.

214 this has as a consequence that, the further apart
 215 these charges are to one another the coupling con-
 216 stant approaches to zero, this phenomenon is known

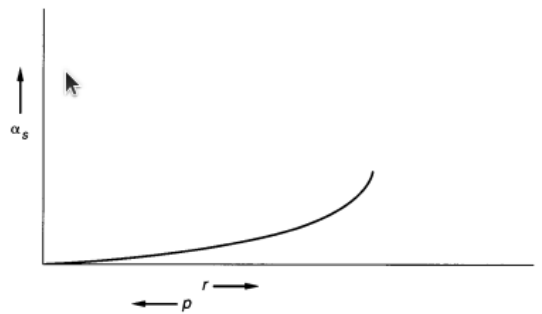


Figure 3: Behaviour of α_s regarding the distance between quarks r , what is referred as QCD running coupling constant

as asymptotic freedom, it means that when one approaches asymptotically to zero distance, the quarks behave more like free particles. But, when these quarks goes further apart their interacting field energy grows larger to the point to create a new pair via virtual gluons creating colorless objects, this is what is referred to as hadronization and the cause of the production of jets of hadrons in a hard-scattering event, the variation of α_s as a function of the distance r is shown in Figure 3. The existence and behaviour of jets confirm the quark and gluon interactions even if they cannot be observed as free particles. That is the nature of the strong interaction, which follows a Yang-Mills non-abelian gauge theory.

2.2.3 Electroweak Theory

Combining QED and the weak interaction [12,13], the electroweak sector is based on the combination of the $U(1)_Y$ and $SU(2)_L$ gauge symmetry groups, it is described by the conservation of both quantum numbers the weak isospin I and the weak hypercharge Y , the later related to the charge of the particle by:

$$Q = I_3 + \frac{Y}{2} \quad (2.17)$$

Under this scheme, fermion fields can be classified between left-handed doublets (grouping either the left-handed leptons and neutrinos or up-type and down-type quarks) and right handed singlets (for the right-handed fermions), this can be achieved applying projection operators to the fields:

$$\psi_L = \frac{1}{2}(1 - \gamma^5)\psi \quad \psi_R = \frac{1}{2}(1 + \gamma^5)\psi \quad \gamma^5 = \begin{pmatrix} \mathbb{I}_{2 \times 2} & 0 \\ 0 & -\mathbb{I}_{2 \times 2} \end{pmatrix} \quad (2.18)$$

the local transformation to the fields that assures the preservation of the weak interaction chirality (acting only on left-handed fermions) under the group $SU(2)_L \otimes U(1)_Y$ is:

$$\psi'_L = e^{iY\beta(x) + iT^a\alpha^a(x)}\psi_L \quad \psi'_R = e^{iY\beta(x)}\psi_R \quad (2.19)$$

being a gauge theory of the symmetry group $SU(2)_L \otimes U(1)_Y$ the amount of gauge fields describing the theory is up to 4: the field B_μ associated with the $U(1)_Y$ group and three W_μ^a fields associated to the $SU(2)_L$ symmetry under the condition that these fields would only couple to left-handed fermions, the lagrangian describing this theory then according to Equation 2.7 is:

$$\mathcal{L}_{EW} = i\bar{\psi}\gamma^\mu D_\mu\psi - \frac{1}{2}\text{Tr}\{W_{\mu\nu}W^{\mu\nu}\} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad (2.20)$$

Where the covariant derivative which guarantee that only left-handed particles interact weakly is:

$$D_\mu = \partial_\mu - ig'\frac{Y}{2}B_\mu - igT^aW_\mu^a \quad (2.21)$$

for the left-handed doublet eigenvalues $T^a = \sigma^a/2$ and $Y = -1$, or $T^a = 0$ and $Y = -2$ for the right-handed singlet, σ^a are the Pauli matrices as the group $SU(2)$ generators, the presence of

two coupling constants is due to the combination of g' the coupling regarding the $U(1)$ group and g associated to the $SU(2)$ group. An analysis of the EW currents $i\bar{\psi}\gamma^\mu D_\mu\psi$ interactions coupled with a fermionic field, shows a pair of charged currents mixing the W_μ^1 and $W_{\mu+}^2$ fields, and a neutral current, as follows:

$$W_\mu^\pm = (W_\mu^1 \mp iW_\mu^2)/\sqrt{2} \quad (2.22)$$

$$Z_\mu = W_\mu^3 \cos(\theta_W) - B_\mu \sin(\theta_W) \quad (2.23)$$

This neutral current weakly interacts with the neutrino, so to include the electromagnetic interaction, an orthogonal linear combination to the field Z_μ which assures no interaction with neutrinos must also be present:

$$A_\mu = W_\mu^3 \sin(\theta_W) + B_\mu \cos(\theta_W) \quad (2.24)$$

These fields A_μ , Z_μ and $W_\mu^\pm$ are the gauge boson fields of the photon, Z^0 and $W^\pm$ respectively, where θ_W is the Weinberg angle defined by

$$\cos \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad (2.25)$$

$$\sin \theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad (2.26)$$

Still, the combination of these gauge theories doesn't explain the massiveness of the weak bosons Z^0 and $W^\pm$, forcing in the lagrangian a mass term would only spoil the gauge invariance which is a fundamental component of the renormalization of the theory, so it is not a solution, the generation of mass is explained by the breaking of the EW symmetry present in the Higgs mechanism.

2.3 Higgs-Brout-Englert Mechanism

The Higgs mechanism was incorporated in the SM as a way to include a mass term contribution to the Lagrangian 2.20 in a gauge invariant way. mechanism [7, 14–16] Its foundation lays on the introduction of an isodoublet scalar field ϕ :

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (2.27)$$

where the superscript indicates the electric charge of those fields. Formulating the lagrangian for the Higgs doublet:

$$\mathcal{L}_H = (D^\mu \phi)^\dagger (D_\mu \phi) - \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2 \quad (2.28)$$

The potential $V(\phi) = \mu^2 \phi^\dagger \phi + \frac{\lambda}{2} (\phi^\dagger \phi)^2$ is symmetric under $SU(2) \otimes U(1)$ transformations so one can link the EW sector to this lagrangian via the covariant derivative defined in Equation 2.21, , a pictorial representation of the Higgs potential with the free parameters $\mu^2 < 0$ and $\lambda > 0$ Figure 4

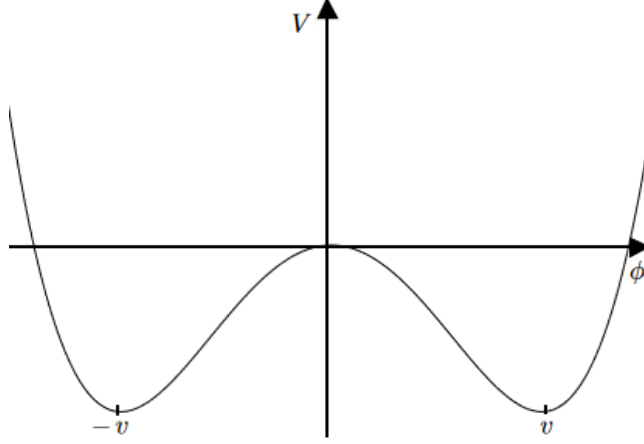


Figure 4: Potential $V(\phi)$ as the symmetry of the system has spontaneously broke

265 The symmetry breaking happens when the Higgs field acquire its vacuum expectation value by
 266 sitting spontaneously in a non-symmetric minimum of the potential, normally it is chosen as $\phi_{(v)}^0 =$
 267 $v = \sqrt{-2\mu^2/\lambda}$ and $\phi_{(v)}^+ = 0$, to preserve the charge current, this state is taken as the reference for the
 268 global symmetry break. An expansion on the vicinity of the expectation value can be parameterized
 269 as:

$$\phi = e^{\frac{i}{v}\sigma^a\pi^a} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix} \quad (2.29)$$

270 where σ^a are the $SU(2)$ transformation broken generators, $h(x)$ and π^a a set of real fields. The
 271 nonphysical fields π^a (one for each broken generator) are massless Nambu-Goldstone fields, when
 272 replaced on the lagrangian 2.28 these fields are absorbed by the gauge vector fields which acquires
 273 new degrees of freedom, $h(x)$ is the Higgs field of the spontaneous symmetry breaking mechanism,
 274 this new phase for the field ϕ is possible due to the non-zero vacuum expectation value. For simplicity
 275 the representation 2.29 will be studied on its unitary gauge equivalent:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.30)$$

276 When replacing the expressions of the physical fields $Z_\mu, W_\mu^\pm$ on the Higgs field Lagrangian kinetic
 277 term directly linked to the covariant derivative operator, gives this result for the vector bosons kinetic
 278 term:

$$(D^\mu\phi)^\dagger(D_\mu\phi) = \frac{1}{2}\partial^\mu h\partial_\mu h + \left(\frac{gv}{2}\right)^2 W^{+\mu}W_\mu^- + \frac{1}{2}\left(\frac{v\sqrt{g^2+g'^2}}{2}\right)^2 Z^\mu Z_\mu + \mathcal{L}_{\text{int}} \quad (2.31)$$

279 Where $\mathcal{L}_{\text{int}}$ are the higher order interaction terms, as it can be seen the vector bosons have
 280 acquired a mass term via the Higgs-Brout-Englert mechanism where the W boson mass terms arise
 281 from $m_W = gv/2$ and the Z^0 mass is $m_Z = gv/2\cos\theta_W$. When one relates this result to the low

energy approximation and the weak coupling given by the Fermi model, the value of the vacuum
can be evaluated as: $v = 1/\sqrt{2^{1/2}G_F} \approx 246$ GeV. The scalar potential, when expressed replacing
Equation 2.30:

$$V(h) = \frac{\lambda v^2}{2}h^2 + \frac{\lambda v}{2}h^3 + \frac{\lambda}{8}h^4 - \frac{v^4\lambda}{8}, \quad (2.32)$$

already gave away the Higgs mass $m_H = \sqrt{\lambda v^2}$, the higher order Higgs field expressions are of
special interest as they characterize the Higgs three-point coupling and four-point coupling, when
expressed proportionally to the Higgs mass one finds the relation: $\lambda_{hhh} = m_h^2/2v^2 = 4\lambda_{hhhh}$. The
 $SU(2)$ symmetry will be broken if a explicit mass for fundamental fermions is explicitly added, as
this would be neither invariant nor hypercharge neutral, condition that is satisfied by the Yukawa
coupling, the Yukawa lagrangian when expanded in the vicinity of the SSB vacuum value v :

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= -g_f \bar{\psi}_L \phi \psi_R + \text{h.c.} \\ &= -\frac{g_f}{\sqrt{2}} \bar{\psi}(v+h)\psi, \end{aligned} \quad (2.33)$$

so all fermions acquire mass via their Yukawa interactions with the Higgs field, yielding the result
 $m_f = g_f v/2^{1/2}$, the only exception is the neutrino, this is because of the null vacuum charged Higgs
field $\phi^+ = 0$ choice. This concludes the well-known theoretical framework of the Standard Model, a
far elaborated and enriching description of gauge theories, electroweak theory and the spontaneous
symmetry breaking mechanism can be reviewed on the literature [17,18].

2.4 The Higgs pair system

The Higgs boson is a very interesting and peculiar particle. It is the only known fundamental particle
that has spin zero, also due to the electro-weak symmetry breaking, it gives masses to the $W^\pm$
and Z gauge bosons, and to the fundamental fermions via the Yukawa coupling, neutrinos being
the exception. The aforementioned is in agreement with the observed properties of the $W^\pm$ and Z
particles [19,20]. The Higgs boson couples proportionally to the mass of the particle with which it
interacts, doing it strongly with high mass particles like the $W^\pm$, Z bosons and the *top* quark, all of
which posses masses in the order of the hundred GeVs, and to a lesser extent to the *bottom* quark
and the tau lepton. It does not couples directly to massless particles like photons, gluons or the SM
description of neutrinos. But, those couplings are induced indirectly due to quantum fluctuations,
like triangular and rectangular loops involving the top quark.

Higgs boson pair production in the SM occurs predominantly via gluon fusion produced by in-
teractions as shown in Figure 5, it has a cross section of $\sigma_{HH}^{ggF} = 31.05_{-23.0\%}^{+6.05\%}$ (scale+m_{top} scheme)
 $\pm 3.0\%$ (PDF+ α_s) fb [21] at $\sqrt{s} = 13$ TeV. This process covers up to 90% of the total Higgs pair
production. To a lesser extent vector boson fusion illustrated on Figure 6 provides a cross section of
 $\sigma_{HH}^{VBF} = 1.76_{-0.04\%}^{+0.03\%}$ (scale) $\pm 2.1\%$ (PDF+ α_s) fb at $\sqrt{s} = 13$ TeV [22]

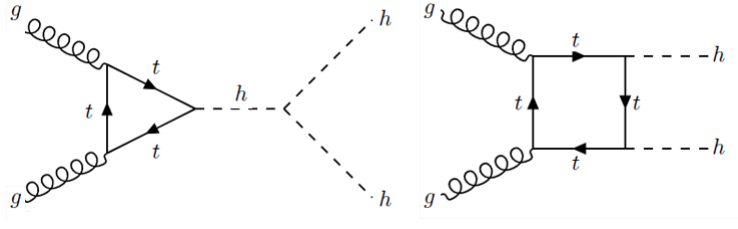


Figure 5: Two diagrams for the Higgs pair production via gluon-gluon fusion, a triangle diagram (left) and a square one (right) via top quark loops

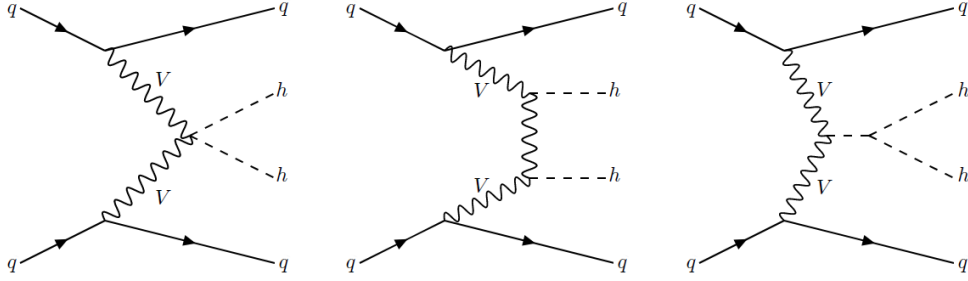


Figure 6: Three diagrams contributing to the Higgs pair production via vector boson fusion (VBF) at three level. From the left to the right: A diagram involving the direct coupling between two vector bosons and two Higgses (c_{2V}), a diagram involving two VH couplings (c_V^2), and a diagram involving one VH coupling and a trilinear Higgs coupling ($c_V \lambda$)

The Higgs boson also has self-interactions, residual of those of the original field appearing in the potential. The trilinear self-coupling (λ_{hhh}), which is directly related to the shape of the Higgs potential and essential for probing the exact nature of the Higgs mechanism can be assessed through Higgs pair production (hh). Thus, possible deviations characterized by the quantity $\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{(SM)}$ can probe new physics.

In the SM, three different types of couplings are involved in HH production via VBF as depicted in Figure 6: the Higgs boson self-coupling (κ_λ), the Higgs-vector-boson coupling (κ_V) and the 4-point (di-vector-boson di-Higgs-boson, or $VVhh$) coupling κ_{2V} . A deviation from these couplings from their SM expectation could also lead to enhanced production of this final state.

The combined searches for Higgs pair production account for the gathering of a plethora of final states channels, as stated the Higgs couples heavily with heavy particles, these final states result from the combination of all possible single Higgs decays: $h \rightarrow b\bar{b}$, $h \rightarrow W^+W^-$, $h \rightarrow \tau^+\tau^-$, $h \rightarrow Z\bar{Z}$ and $h \rightarrow \gamma\gamma$ as shown on Table 3, there are other possible decays into soft-jets or lighter leptons. The combined searches aim to obtain upper limits on the Higgs pair production on the effective cross section and to find deviations with respect to the SM prediction.

As it can be appreciated on Table 3, the Higgs pair predominantly decays to $b\bar{b}b\bar{b}$ or $b\bar{b}W^-W^+$ channel, the $b\bar{b}\tau^-\tau^+$ channel follows with a 7.4% branching ratio, although having a comparatively

$h \rightarrow$	$b\bar{b}$	W^-W^+	$\tau\tau$	ZZ	$\gamma\gamma$
$b\bar{b}$	33%	25%	7.4%	3.1%	0.26%
W^-W^+		4.6%	2.5%	1.2%	0.10%
$\tau\tau$			0.39%	0.34%	0.029%
ZZ				0.076%	0.013%
$\gamma\gamma$					0.0005%

Table 3: Branching ratios of a Higgs pair decays in the SM

small branching fraction this particular final state has a relatively cleaner signal as advantage.

2.4.1 Tau Decays

The $hh \rightarrow b\bar{b}\tau^+\tau^-$ channel has a branching ratio of 7.4% of the hh decays to be experimentally assessed, it is the third most probable decay mode. Since τ leptons are the heaviest leptons they can decay either leptonically (to electrons, e , or muons, μ) or hadronically (mostly to one or three charged pions, plus neutral pions) as the examples seen on Figure 7, several different decay channels can be considered, with different combinations of $\tau\tau$ decays: $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$.

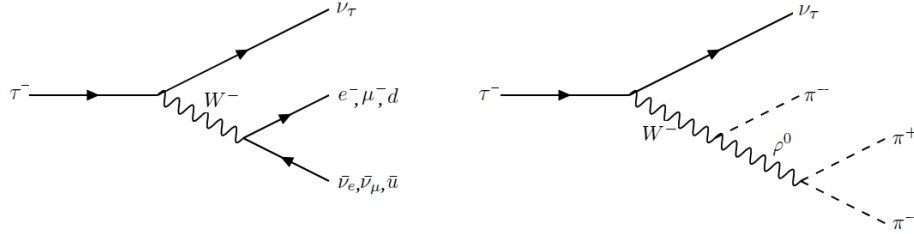


Figure 7: Example of tau decays leptonical/one prong hadronically (left), three prong (right)

The Feynman diagrams depicted on Figure 7 exposes a key factor on the single tau decay analysis: the presence of at least one (undetectable) neutrino that will carry a fraction of the tau energy, thus as a direct consequence, the tau pair system will always show comparatively lower visible mass compared to their expected Higgs resonant invariant mass. On the fully hadronic channel the number of neutrinos is reduced to two so their 4-momenta can be (a priori) fully reconstructed from the missing transverse momentum, if the decay is semi-leptonic then the neutrinos are three and finally, in the fully leptonic decay there are four neutrinos present.

As stated a tau lepton can decay either hadronically 64.79% of the time or leptonically with a branching ratio of 35.21%. The most frequent hadronic tau decay is the 1-prong decay, characterized by the process $\tau \rightarrow \nu_\tau \pi^\pm$ plus neutral pions. The largest branching ratio is the decay into a tau neutrino, a charged pion and a neutral pion with $25.52 \pm 0.09\%$, followed by the case were there is no neutral pion having a probability $10.63 \pm 0.06\%$ then the decay into a tau neutrino, a charged pion and two neutral pions with $9.30 \pm 0.11\%$, finally the least probable 1-prong decay is the decay into a tau neutrino, a charged pion and three neutral pions having a branching ratio of $1.05 \pm 0.07\%$. The

3-prong case has a lower contribution characterized by the process $\tau \rightarrow \nu_\tau 2\pi^\pm \pi^\mp$ plus neutral pions, when there is no neutral pions the branching ratio is $8.99 \pm 0.06\%$ contrasted to the less probable final state where there is one neutral pion with a $2.79 \pm 0.008\%$, other hadronic decays are also possible, but heavily suppressed. Finally for the tau pair system the purely leptonic channel has a 12.3% branching fraction, the semi-leptonic 45.8% and the fully hadronic represents 41.9% branching ratio.

2.5 Beyond the Standard Model

The Standard Model success at describing the particle physics phenomenology thus far has constrained the model parameters and search windows for new physics. Successful as it is, still is an effective theory valid at the accessible energy ranges at collider experiments, it doesn't account for some challenges to particle physics to describe certain phenomena and observations, which lingers outside the scope of the Standard Model. Examples of such motivations for beyond the Standard Model physics are the description of the quantum-gravitational formulation, the neutrino oscillations which indicates that neutrinos are not massless, the hierarchy problem or fine-tuning, the inclusion of dark matter or neither the CP violation relating the matter-antimatter asymmetry. Searches beyond the Standard Model has been formulated to account for all these unanswered question proposing that the model can be extended on higher energy scales that encompass the inclusion of an unification theory of fundamental forces. Let's dive in each of the Standard Model shortcomings:

Gravitation

A quantum description of gravity cannot be encompassed under the considerations of the Standard Model, mainly because such formulations escapes renormalization, predicting infinite values for observables. At a subatomic scale, gravity is several orders of magnitude weaker than any of the other fundamental forces, this issue has no major observable effect.

Neutrino masses

The Standard Model does not account for massive neutrinos, because they are described as left-handed particles they require to permanently manifest such chirality and in consequence be massless. This can not be the case as the observation of neutrino flavour oscillation require a massive neutrino, starting from a neutrino with a definitive flavour eigenstate, because one can not measure the mass of a neutrino, a flavour neutrino can be expressed as a linear combination of resolved states of definite mass:

$$|\nu_\alpha\rangle = \sum_l U_{\alpha l} |\nu_l\rangle, \quad (2.34)$$

where U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and it has the same interpretation for the neutrino sector as the CKM matrix for the quark sector, mixing observable states. It can be prove that the time evolution for the neutrino wave-function when said neutrino travel a distance L , can be expressed as:

$$|\psi_\beta(L)\rangle = \sum_\alpha \sum_k U_{\beta k} U_{\alpha k}^* e^{-i \frac{m_k^2 L}{2E_k}} |\nu_\alpha\rangle, \quad (2.35)$$

385 So the probability amplitude to find a neutrino flavoured β which initial state was a neutrino
386 flavoured α is:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 &= \delta_{\alpha\beta} - 4 \sum_{\ell > k} \Re(U_{\alpha\ell}^* U_{\beta\ell} U_{\alpha k} U_{\beta k}^*) \sin^2 \left(\frac{\Delta m_{\ell k}^2 L}{4E} \right) \\ &+ 2 \sum_{\ell > k} \Im(U_{\alpha\ell}^* U_{\beta\ell} U_{\alpha k} U_{\beta k}^*) \sin \left(\frac{\Delta m_{\ell k}^2 L}{2E} \right), \end{aligned} \quad (2.36)$$

387 The imaginary part introduces CP-violation, so it can be arrange to zero when formulating the
388 PMNS matrix. This result shows a non-vanishing probability that the original neutrino will change
389 flavour depending on the square difference of the masses, the oscillation of neutrinos and their mas-
390 siveness leads to the conjecture that either there do exist right-handed neutrinos to form the Dirac
391 spinor, or that neutrinos are Majorana particles (being their own antiparticle). Any of the aforemen-
392 tioned paths points to new physics.

393

394 **Hierarchy problem**

395 The hierarchy problem in physics or the naturalness problem has two aspects. First there is no
396 physical reason to explain the discrepancy between the strength between the weak and gravitational
397 force, both quantified by the Fermi constant and Newton gravitational constant respectively. As the
398 Standard Model is implemented to calculate quantum corrections to the Fermi constant, its value
399 shouldn't be several orders of magnitude larger than the gravitational constant, unless there is some
400 cancellation when calculating the quantum corrections. Another example of such higher order correc-
401 tions is the one loop radiative corrections to the Higgs mass, this one loop corrections can be fermionic
402 or bosonic in nature, cutting the loop integral momenta at a scale Λ , the cut-off value where the Stan-
403 dard Model is valid, corrections to the Higgs mass will have the following contributions by fermions
404 and bosons respectively:

$$\Delta m_h^2 = -\frac{g_f^2 \Lambda^2}{16\pi^2}, \quad \Delta m_h^2 = \frac{\lambda_s^2 \Lambda^2}{16\pi^2}, \quad (2.37)$$

405 here, λ_s is the boson coupling strength, the highest energy at which the theory is valid is the
406 Planck scale $\Lambda \sim 10^{19}$, so to maintain the observable Higgs mass $m_h^2 = (m_h^2)_0 - \Lambda^2$, the square bare
407 mass should cancel one part in $\sim 10^{34}$, another example of fine-tuning which for some can be quite
408 unnatural.

409

410 **Dark matter**

411 Based on studies on the cosmic microwave background, estimations says that ordinary matter can
412 only account for near 5% of the energy-mass content in the universe by the *Lambda-CDM* model,

the remaining 95% being either dark matter (26.8%) or dark energy (68.2%). The existence of nearly non-interacting dark particles is backed up by cosmological evidence: the rotation curves of galaxies, gravitational lensing or the universe expansion at an accelerating rate proves that the Standard Model can not be the final word, which motivates beyond the Standard Model physics who can give a dark matter candidate.

Baryon asymmetry

The disparity between matter-antimatter content in the universe is a concern since, there is no explanation nor special treatment between particles and antiparticles in the Standard Model. In early stages of the universe, the equilibrium between its constituents points to similar rates of production and annihilation of matter and antimatter. The main argument why this is inconsistent to the later stages of the universe where there is no such equilibrium is that, the rate of creation of matter and energy is predominant over that of antimatter, and the necessary amount of near 10^{19} cannot be matched by the observed CP violation present in the Standard Model. A symmetric universe which gives over time an asymmetric one requires the action of baryogenesis which: neither satisfies baryon number conservation or conserve C and CP symmetries according to the Sakharov conditions.

Depending on the BSM model, the expected curve describing κ_λ and the Higgs potential associated with such parameter differs from one another, being a motivation to search for the Higgs triple coupling and the Higgs pair production process.

2.5.1 The Two Higgs Doublet Model: 2HDM

One of the simplest extensions to the SM, the Type-II 2HDM [23, 24] is realized in supersymmetry where scalars are part of chiral multiplets, the motivation behind the 2HDM extension of the Higgs sector lies in the philosophy of the Minimal Supersymmetric Standard Model (MSSM), where only the bare minimum of new elements are added which are consistent with the Standard Model phenomenology. The pair of Higgs doublets are unable to couple with their opposite chirality complex conjugate supermultiplets and thus, a single Higgs doublet is not capable to give mass to up-type and down-type quarks at the same time. As the name of the model implies, one way to solve the aforementioned fermion coupling problem, is to introduce an additional complex doublet scalar field, with hypercharge $Y = 1$:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \quad (2.38)$$

other motivations include a CP violation fix for the QCD lagrangian from axion models predictions, this fix consist in rotating the lagrangian under a global U(1) symmetry, but such symmetry could be only be admissible if there are present two Higgs doublets, these models are ruled out at the TeV energy scale, there exists variations with singlets that are still compatible and exhibits an effective low energy 2HDM. Explaining the baryon asymmetry is another motivation for the 2HDM, this thanks

to the allowed mass range that such models can provide and the various sources of CP violation. The scalar potential for two doublets ϕ_1 and ϕ_2 is:

$$V(\phi_1, \phi_2) = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2 + \lambda_3 \phi_1^\dagger \phi_1 \phi_2^\dagger \phi_2 + \lambda_4 \phi_1^\dagger \phi_2 \phi_2^\dagger \phi_1 + \frac{\lambda_5}{2} [(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2] \quad (2.39)$$

where every parameter is real. In order to avoid the introduction of flavour changing neutral currents (FCNCs) it is required that either up-type or down-type quark couple to exactly one doublet. The minimization of the potential 2.39 gives the two Higgs doublets minima $\langle \phi_1 \rangle_0$ and $\langle \phi_2 \rangle_0$ which can be written in term of the two vacuum expectation values v_1 and v_2 :

$$\langle \phi_1 \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \phi_2 \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}. \quad (2.40)$$

Replicating the spontaneous symmetry breaking mechanism around such vacuum expectation minima, eight independent degrees of freedom arise, three of them must become the electroweak bosons longitudinal components:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}, \quad (2.41)$$

the spontaneous symmetry breaking mechanism introduces additional 5 physical scalar fields: the neutral Higgs bosons h and H (where h is usually taken to be the Higgs field from the SM and H presumed to be heavier than h), a pseudoscalar field A and two charged Higgs bosons $H^\pm$. This gives a rich phenomenology as there are six free parameters on this model, the four Higgs masses $m_h, m_H, m_A, m_{H^\pm}$, the ratio of the two expectation values $\tan \beta = v_2/v_1$, which also diagonalizes the charged scalar mass matrix:

$$\mathcal{L}_{\phi^\pm \text{ mass}} = [m_{12}^2 - (\lambda_4 + \lambda_5)v_1 v_2] \begin{pmatrix} \phi_1^- & \phi_2^- \end{pmatrix} \begin{pmatrix} \frac{v_2}{v_1} & -1 \\ -1 & \frac{v_1}{v_2} \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} \quad (2.42)$$

and the mixing angle α which diagonalizes the mass matrix of the neutral Higgs sector:

$$\mathcal{L}_{\rho \text{ mass}} = - \begin{pmatrix} \rho_1 & \rho_2 \end{pmatrix} \begin{pmatrix} m_{12}^2 \frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2 \frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} \quad (2.43)$$

$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. Finally the combinations which gives the physical fields:

$$\begin{aligned}
A &= \eta_1 \sin \beta - \eta_2 \cos \beta \\
h &= \rho_1 \sin \alpha - \rho_2 \cos \alpha \\
H &= -\rho_1 \cos \alpha - \rho_2 \sin \alpha \\
H^\pm &= \phi_1^\pm \sin \beta - \phi_2^\pm \cos \beta
\end{aligned}$$

465 This thesis aims to reconstruct a resonant produced heavy neutral scalar Higgs boson compatible
466 with the 2HDM via gluon-gluon fusion, which are expected to enhance the Higgs pair production.

467 2.5.2 Complex Singlet Scalar Model

468 Another extension of the Standard Model, again motivated by the MSSM as this extension greatly
469 enhances the production of di-Higgs, this model consist in the introduction of a complex scalar singlet,
470 this singlet can be motivated by a MSSM, and it can be formulated taking dark matter candidates in
471 mind, three neutral scalar fields mixed to form massive fields where one of them can be accommodated
472 to be the SM Higgs field, relevant for this study is that the new scalars couplings with the SM particles
473 are heavily suppressed, except resonantly to another pair of massive scalar particles i.e. the Higgs
474 pair. The model [25] as stated propose a complex scalar singlet S_c in conjunction with the doublet
475 scalar field ϕ described in Equation 2.27, to describe the renormalizable scalar potential without
476 adding new symmetries is:

$$\begin{aligned}
V(\phi, S_c) &= \frac{\mu^2}{2} \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2 + \left(\frac{1}{4} \delta_1 \phi^\dagger \phi S_c + \frac{1}{4} \delta_3 \phi^\dagger \phi S_c^2 + a_1 S_c \right. \\
&\quad \left. + \frac{1}{4} b_1 S_c^2 + \frac{1}{6} e_1 S_c^3 + \frac{1}{6} e_2 S_c |S_c|^2 + \frac{1}{8} d_1 S_c^4 + \frac{1}{8} d_3 S_c^2 |S_c|^2 + \text{h.c.} \right) \\
&\quad + \frac{1}{4} d_2 (|S_c|^2)^2 + \frac{1}{2} \delta_2 \phi^\dagger \phi |S_c|^2 + \frac{1}{2} b_2 |S_c|^2.
\end{aligned} \tag{2.44}$$

477 Parameters $a_1, b_1, e_1, e_2, d_1, d_3, \delta_1$ and δ_3 are complex, parameters d_2, δ_2 and b_2 are real, the
478 rest of the potential behaves as the Standard Model Higgs potential. The model has a new vacuum
479 expectation value $\langle S_c \rangle_0 = v_S / \sqrt{2}$, implementing a spontaneous symmetry breaking mechanism in the
480 unitary gauge:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad S_c = \frac{1}{\sqrt{2}} (S(x) + v_S + i(A(x) + v_a)) \tag{2.45}$$

481 creates 3 massive Higgs-like fields with mass eigenstates which can be found from the linear
482 combination of h, S and A rotations:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 \cos \theta_2 & \cos \theta_1 \cos \theta_2 & \sin \theta_2 \\ \sin \theta_1 \sin \theta_2 & \cos \theta_1 \sin \theta_2 & -\cos \theta_2 \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix} \tag{2.46}$$

483 ,by convention h_1 is taken as the Standard Model Higgs field. The 3-point Higgs coupling λ_{211}
 484 leads to a decay width for $h_2 \rightarrow h_1 h_1$:

$$\Gamma(h_2 \rightarrow h_1 h_1) = \frac{\lambda_{211}^2}{32\pi m_2} \sqrt{1 - \frac{4m_1^2}{m_2^2}} \quad (2.47)$$

485 thus, enhancing the Standard Model Higgs pair production.

486 2.6 Searches for Heavy Resonances

487 The search for physics beyond the Standard Model between many possibilities, demands the search
 488 of possible bosonic heavy resonances decaying into a Higgs pair production, which is compatible with
 489 the description of the Two Higgs Doublet Model (2HDM) described on Section 2.5.1 or the Complex
 490 Singlet Scalar Model in Section 2.5.2, the increase on luminosity and center-of-mass energy ($\sqrt{s}$) on
 491 the LHC of the current Run-3 and the HL-LHC would lead to an increase on the production of Higgs
 492 pair events. Regarding the searches for a heavier Higgs boson or other scalar particles predicted by
 493 MSSM compatible extensions, limits were set using the data collected in the LHC Run 1 [26].

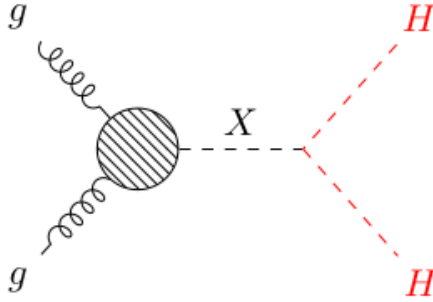


Figure 8: A heavy resonance produced via gluon fusion decaying into a di-Higgs system

494 The case in study were a heavy particle of spin-0, gluon fused, which decays into a Higgs pair
 495 as schematized on Figure 8. In a boosted topology a high momenta Higgs particle decaying into
 496 either the b-pair or tau pairs will be very collimated, so when reconstructed, their decay products
 497 will partially overlap on the detector and will not be possible to resolve and identify it with the
 498 standard reconstruction techniques. One of the goals of this study is to fully delve into the dedicated
 499 reconstruction and identification of such objects as explained in Section 4.

3 The ATLAS Experiment

3.1 The Large Hadron Collider

The LHC [27] short-hand for Large Hadron Collider, is the world's largest, highest-energy, synchrotron. Constructed and operated by the European Organization for Nuclear Research (CERN), it is a 27 kilometer subterranean ring composed of nearly 9300 magnets, operating at a temperature of 1.9 K, plus accelerating sub-structures. The LHC is a discovery machine, designed to collide bunches of $\sim 10^{11}$ protons at a collision rate of 40 MHz, the proton-proton collision to date has reached an instantaneous luminosity that doubles the designed value of $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and center-of-mass energy of 13 TeV, these proton bunches travel at 99.9999991% the speed of light on a high-vacuum with a pressure of 10^{-13} atm. Up to 2808 proton bunches are separated on two opposed circulating beams where every bunch has a 25 ns travel time separation with the next, they maintain their circular trajectory thanks to the magnetic field of 8.3 T produced by a set of near 1200 superconducting dipole magnets and collide between them focused by approximately 400 quadrupole magnets on four interaction points where the detectors (ATLAS, CMS, LHCb and ALICE) are set up. The amount of energy that is necessary to obtain said proton speed is possible due to a complex of smaller pre-accelerators operating in the following fashion: The protons starts its journey as hydrogen gas, an electric field is applied to the gas in order to take away the electron from the hydrogen atom and then is injected in LINAC 4 to accelerate them linearly to a 50 MeV energy. This protons are injected in the proton synchrotron booster to further accelerate them to a 1.4 GeV energy, then the proton synchrotron (PS) has the task not only to accelerate the protons to the energy of 25 GeV but also, via the radio frequency cavities present in this accelerator, the beam is splitted into their characteristic proton bunches temporarily spaced by 25ns. Finally the final destination to the protons before the injection in the LHC ring itself, is the super proton synchrotron (SPS), where protons bunches are accelerated to the 450 GeV LHC injection energy, this whole accelerator complex and the proton beam preparation can be seen schematically on Figure 9.

3.2 Detector Coordinate System

Before explaining the components and characteristics of the ATLAS detector, it is important to well-define the coordinate system used to describe the detector [29], that will be used as a further reference during this thesis. The most basic three dimensional coordinate system defined for describing particles position and 4-momenta inside the detector are the positive z -axis direction pointing towards the counter clockwise beam travelling through the beam pipe, the transversal plane related to this choice of coordinates is the $x - y$ plane where the positive x axis is directed to the center of the LHC, positive y axis is perpendicular and upwards. The transversal plane is treated in cylindrical coordinates, defined by the polar angle ϕ . Symmetry on the transversal plane can be expected on the particles produced by the collision and this can be easily checked when events are displayed on this plane, and is better illustrated on fig 10.

Another angle that can be constructed is θ , the azimuthal angle respect to the z axis, but one problem arise from this formulation and it is that the quantities associated to the z axis are not

The CERN accelerator complex

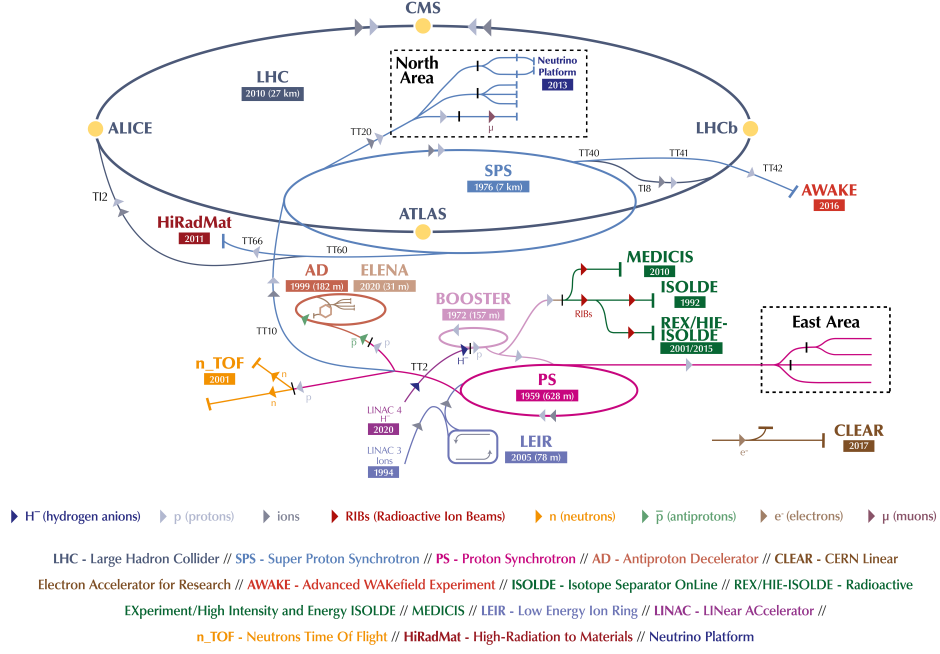


Figure 9: CERN accelerator complex. Source: ref. [28]

© 2008-2022 CERN

Lorentz invariant, mixing up what can be considered forward and backward due to the longitudinal boost and spatial distance differences important to the analysis can be misleading, hence to solve this, a new Lorentz invariant spatial coordinate is defined: the pseudorapidity η expressed as:

$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right) = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) \quad (3.1)$$

On the high energy regime where $m \ll |\mathbf{p}|$, is expected that the particle energy is mostly due to its energy-momentum thus the pseudorapidity can be approximate to the rapidity y which is Lorentz invariant. The pseudorapidity is specially important to define a Lorentz invariant angular difference between objects defined as:

$$\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \quad (3.2)$$

Finally, due to the fact that a high-energy $p - p$ collision on the z axis would produce limited transverse momentum final states, the transverse momentum p_T is a convenient variable to express momentum as the particle momentum can be expressed in Cartesian coordinates as:

$$\mathbf{p} = (p_T \cos \phi, p_T \sin \phi, p_T \sinh \eta). \quad (3.3)$$

Also if the detector were completely hermetic, there will be no need to further expand on the

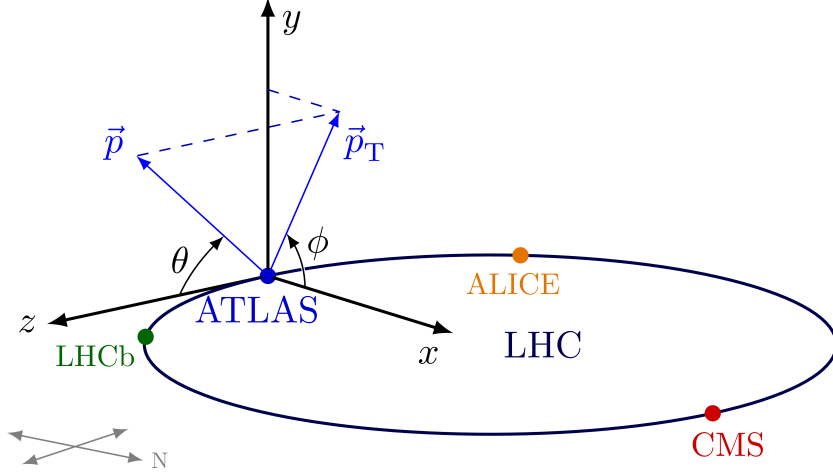


Figure 10: Detector coordinate system. Source: ref. [30]

transversal momentum as the sum of the final states $\mathbf{p}_T$ should be zero, but due to the presence of neutrinos and other detector layout factors this cannot be achieved completely and the transverse momentum of a process takes special significance to reconstruct another important measurement: the missing energy.

3.3 The ATLAS Detector

The ATLAS (A Toroidal LHC ApparatuS) detector [31] depicted in Figure 11 is located at one of the four collision points at the LHC where opposing proton beams packed in bunches scatter. It is one of the two general-purpose particle detectors and the largest ever constructed. The goal of the ATLAS detector is to characterize different particle types properties produced in proton-proton hard scattering and record them for further analysis, the wide range of physics that the ATLAS detector can cover makes it possible to conduct precise measures and search new possibilities beyond the Standard Model. As the physical observables are functions of the momentum and energy of the particles produced, ideally, one would like to measure the 4-momentum of every particle in the event, but this is not quite possible in practice. The ATLAS detector being as hermetic and precise as possible can measure the energy of all the stable particles on detector timescales, through energy deposits to the various calorimeters, and their positions (η, φ) . Energy and tracks are enough to reconstruct the momentum in most cases, with particles deposits of energy within the central calorimetry system. The two exceptions are neutrinos, which leave the detector rarely having interacted at all, being "reconstructed" taking the whole event missing energy, and muons who are not stopped and rarely deposit energy in the calorimeter as they do not ionize enough material to leave a clear signal.

Nevertheless, the momentum of muons can be measured by using the curvature of their trajectories through the muon spectrometer matched with coherent tracks in the inner detector. To do so requires strong magnetic fields to bend their trajectories, and lots of space to see the small curvature of the energetic tracks. The muon system is much of the reason why ATLAS is so big. Curvature of tracks is also used in the inner detector, to distinguish charged particles like electrons, positrons and pions, and together with the calorimeters, help measure their 4-momentum.

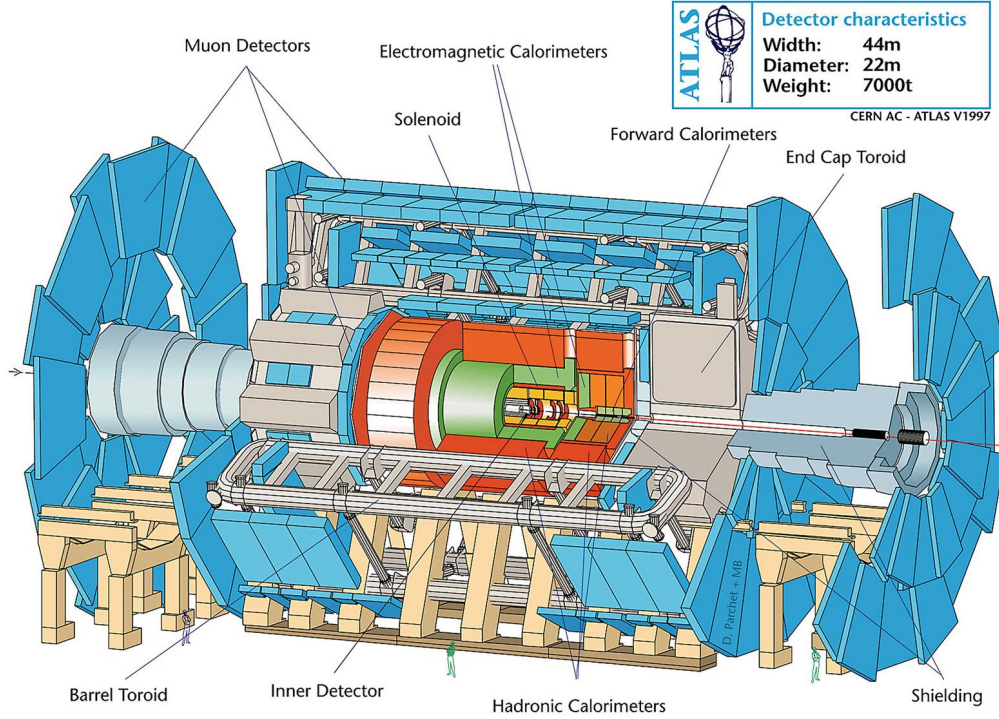


Figure 11: Layout of the ATLAS detector. Source: ref. [32]

© 1998-2022 CERN / License: CC-BY-4.0

The ATLAS detector sub-systems comprise four main components, each of them with complementary capabilities to characterize different particle properties: the Inner Detector (ID), the Hadronic and Electromagnetic calorimeters, the Muon Spectrometer (MS) and the Magnet System.

3.3.1 Inner Detector

The **Inner Detector** is composed of four sub-detector systems, the Insertable B-Layer (IBL) and the Pixel Detector, with high granularity and based on silicon pixel technology, are located near the interaction point and its objective is to determine the origin and momentum of charged particles, where the IBL has improved tracking and vertex detection capabilities due to the challenging environment near the beamline. The Pixel detector is surrounded by the next layer: the Semi-Conductor Tracker (SCT) which is built with silicon microstrips, the SCT is prepared to accurately measure particle tracks and is followed by the outer layer, the Transition Radiation Tracker (TRT) using straw-tubes technology, its main goal is to give particle type information due to their transition radiation as the name implies. The ID has two main sections: the barrel, parallel to the beam pipe and the two end-caps, perpendicular to the beam pipe, this configuration assures its capability to measure charged particle tracks with wide coverage ($|\eta| < 2.5$). To accomplish the correct reconstruction of charged particles the Inner Detector is under a 2 T magnetic field produced by a solenoid magnet located between the Inner Detector and the electromagnetic calorimeter. A pictorial representation of the Inner Detector and its different components can be seen on Figure 12.

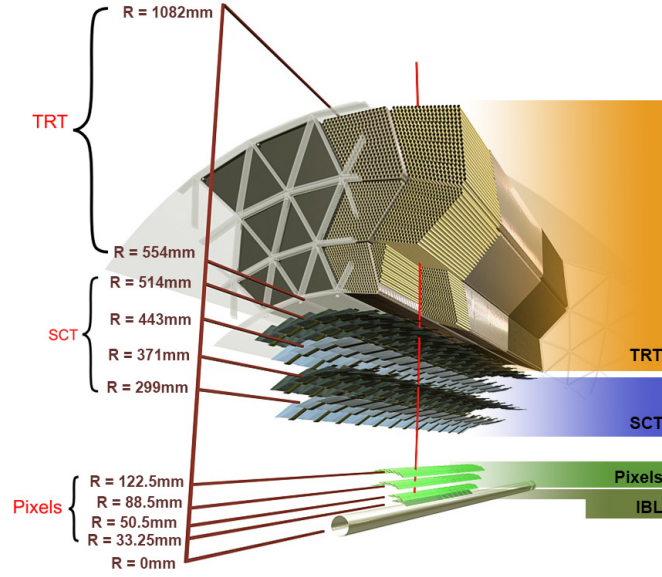


Figure 12: A 3D visualisation of the structure of the barrel of the ID. The beam pipe, the IBL, the Pixel layers, the four cylindrical layers of the SCT and the three layers of TRT barrel modules are shown. Source: ref. [33]

© 1998-2022 CERN / License: CC-BY-4.0

An insertable b-layer (IBL) was added to improve b-jet tagging and position at the beginning of Run 2. In order to identify with precision the interaction vertices, the mechanism designed in the Pixel Detector consist on the ionization of the detector material, inducing mirror charges in the pixels where the length of the electric pulse generated determines the initial ionization position where the charged particle traveled through, it is distributed between three concentric cylinders around the beam axis. The SCT consists of 4088 silicon strip sensor modules distributed on 4 barrel strip layers covering the region $|\eta| < 2.5$ and 9 layers in each endcap, consisting on p -on- n silicon sensors, the charge created in the sensor is digitised and stored before been sent to the DAQ system. Finally, the TRT consists of a set of straws tubes with a tungsten wire in their center which are filled with a mixture of Xe and CO₂ gas, which is ionized when a charged particle travels trough the gas, producing a current.

3.3.2 Calorimeters

The ATLAS calorimeter system measure the energy and position of electromagnetic objects like electrons and photons in the Electromagnetic Calorimeter or long-lived hadrons in the Hadronic Calorimeter. Covering the $|\eta| < 4.9$ region considering both types of calorimeters, most particles besides muons and neutrinos deposit almost entirety their energy in layers divided on small cells of absorbing material designed to completely stop the particles they interact with and to characterize their transverse and longitudinal energy deposits. The calorimeters are composed by alternating

passive and active material layers, passive material absorbs the incoming particle energy and the active material interacts with the particles produced in the event, creating secondary particles in electromagnetic or hadronic showers depending on the calorimeter type. Since muons do not produce electromagnetic showers they require a dedicated section of the detector.

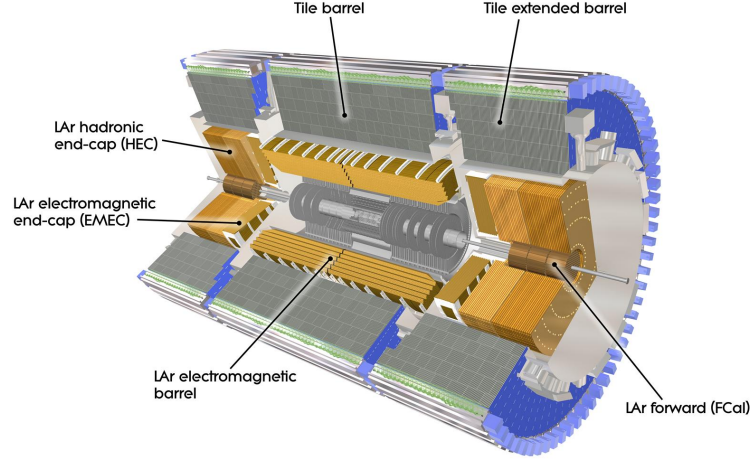


Figure 13: Computer Generated image of the ATLAS calorimeter. Source: ref. [34]

© 1998-2022 CERN / License: CC-BY-4.0

The **Electromagnetic Calorimeter** (ECal) has a coverage of $|\eta| < 3.2$ and measures the energy loss characterized by the radiation length X_0 which is the mean path length where electron/photon energy is absorbed due to Bremsstrahlung deceleration radiation. It consists on lead as its absorbing material which initialize the EM showers and Liquid Argon as its sampling material which is ionized generating a current collected by electrodes. The ECal is divided into a central barrel region covering $|\eta| < 1.475$ and two endcaps that covers the region between $1.375 < |\eta| < 3.2$, it is worth mentioning that the region encompassing the transition between the barrel and endcaps (the crack region), between $1.37 < |\eta| < 1.52$ suffers from a reduced resolution, The barrel has 16 modules covering the ϕ transversal plane subdivided on three sections and the endcaps two wheels, the outermost one for precise measurement in the region $1.375 < |\eta| < 2.5$ and the inner wheel with lower resolution $2.5 < |\eta| < 3.2$. The total length of the ECal is near $22.4X_0$ on the barrel and $24X_0$ on the endcaps.

The **Hadronic Calorimeter** (HCal) covers the region $|\eta| < 4.9$ and is dense enough so hadrons can interact strongly with the nuclei of the material, creating hadron showers of lower energy particles. The HCal is subdivided in three calorimeters having two different detection technologies applied: The barrel region is composed of a steel-scintillator-sampling calorimeter (the TileCal) which is also composed of three sub-regions, a main barrel which covers $|\eta| < 1.0$ and two extended barrels between $0.8 < |\eta| < 1.7$, here the steel act as absorbing material producing the lower energies hadrons, electrons and photons which produces scintillation light, and is registered by photo-multiplier tubes. The two hadronic end-cap calorimeter HEC covering the region between $1.5 < |\eta| < 3.2$ is composed of liquid argon as its active material and copper/tungsten as the passive material.

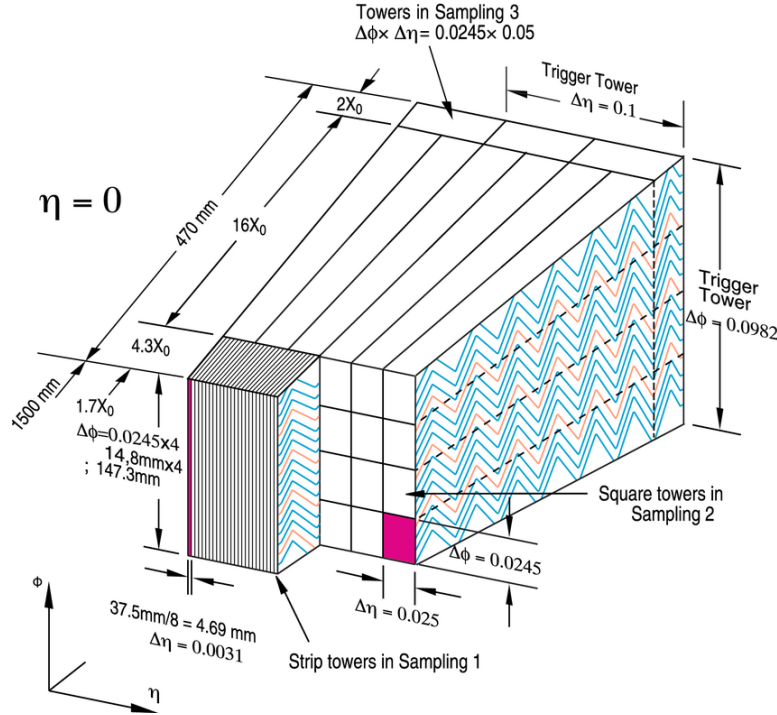


Figure 14: Granularity of the electromagnetic barrel LAr calorimeters. Source: ref. [35]

© 1996-2022 CERN / License: CC-BY-3.0

Finally, the forward calorimeter (FCal) which encompass the pseudorapidity region $3.1 < |\eta| < 4.9$ has one electromagnetic calorimeter and two hadronic ones, it is very similar to the ECal and HCal using liquid argon as its active material but differentiating with their inner counterparts by its passive material being copper and tungsten respectively. This ensures that neither hadrons, electrons or photons reach the muon spectrometer.

3.3.3 Muon Spectrometer

The **Muon Spectrometer** is the outermost layer of the ATLAS detector covering the region within $|\eta| < 2.7$, as muons are minimal ionising particles, they travel through the calorimeters almost undetected rarely interacting, the goal of the Muon Spectrometer is to measure muon momenta with high precision and to provide fast detection for triggers. The trajectories of muon candidates are measured in large wire chambers and matched to high transverse momentum charged particles from the Inner Detector. Close to the barrel wheels lays the Cathode Strip Chamber (CSC) a set of radial anode wires and transversal cathode strips registering hits interpolating the ionisation charge on subjacent cathode strips, followed by the Monitored Drift Tube (MDT) filled with an argon-CO₂ mixture which is ionized by muons and collected by a tungsten wire registering their p_T .

The measurement principle for the muon chamber is based on the muon track deflection produced by the strong magnetic field produced by the superconducting toroid magnet, the magnetic field provided by the magnet configuration is orthogonal to muon tracks in nearly on its entire trajectory

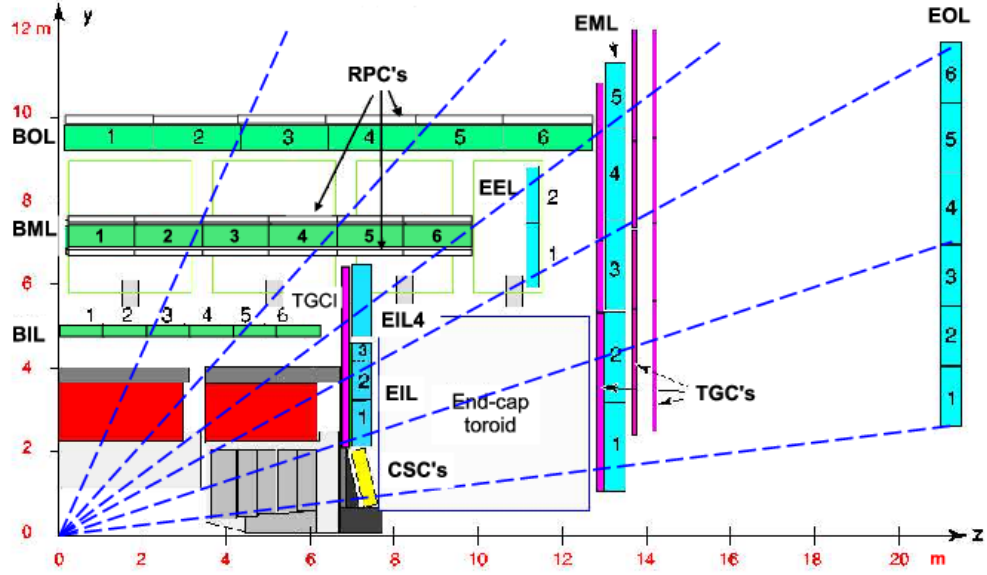


Figure 15: Cross-sectional view of ATLAS. The barrel MDT chambers are shown in green, the endcap MDT chambers are depicted cyan. In the barrel (endcaps), the RPC (TGC) chambers are shown outlined in black (solid purple). Source: ref. [31]

© 1998-2022 CERN / License: CC-BY-4.0

inside the Muon Spectrometer, suppressing the degradation of resolution.

3.4 Magnet System

The **Magnet System** consists of three superconducting magnets: the Central Solenoid (CS) providing magnetic field in the inner tracker, the Barrel Toroid (BT) and two End-Cap Toroids (ECT) which gives a toroidal field configuration for the Muon Spectrometer as depicted in Figure 16. The Magnet System is designed to grant the bending power required for momentum measurements of charged particles.

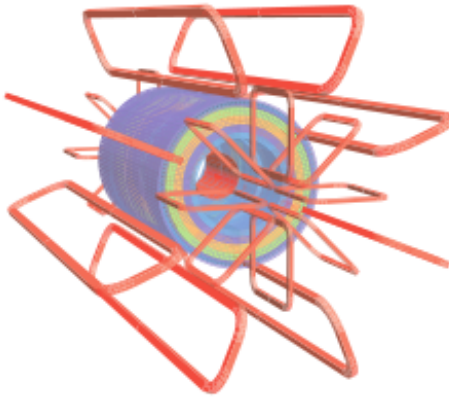


Figure 16: Magnet system of the ATLAS detector. The eight barrel toroid coils and end-cap coils (red) and the four layer tile calorimeter followed by the central solenoid. Source: ref. [31]

© 2008-2022 CERN / License: CC-BY-3.0

The central solenoid is designed to generate a 2 T axial field in the Inner Detector via niobium-titanium superconductor wires into pure aluminium strips, on the muon detector region the symmetrically installed barrel toroid plus end-caps toroids provides a toroidal magnetic field of near 0.5 T an 1 T respectively, the Magnet System being a superconducting system has a 4.7 K working point temperature.

3.5 The Trigger and Data Acquisition System

The LHC is designed to produce high energy proton-proton collisions, to achieve this protons are packed in bunches shaping the beam traveling through the beam pipe, each beam can have near 2800 bunches, and each bunch have around 10^{11} protons. The bunches collide at time intervals of 25 ns, so the LHC nominal full event rate is around 40 MHz, this humongous amount of data cannot be fully recorded as there is no data storage space capacity to keep all that information. Nevertheless, most of the events produced match low energy well-known physics, the role of the Trigger and Data Acquisition system (TDAQ) is to process the input generated in the detector and record in real time the possible interesting events in a convenient output. To understand the magnitude of such event filter, the trigger system reduces the original 40 MHz event rate to a merely 1 kHz record frequency.

The LHC Run 2 had an increased centre-of-mass energy of 13 TeV compared to the Run 1, a higher luminosity and increased number of proton-proton interactions per bunch-crossing or pile-up demanded upgrades to the trigger system, as if not intervened the trigger rates would have surpasses the maximum allowed rates designed for Run 1 and would deem unfit to accomplish the physics program of the experiment. Because of this during the first long shutdown LS1 between Run 1 and Run 2 operations, the trigger system was upgraded and most of its components modified in some capacity. Now the LHC Run 3 challenges the Trigger and Data Acquisition system technical performance anew as the upcoming Phase-I upgrades in preparation for the higher luminosities expected, this report aims to explore the behaviour of such enhancement.

During Run 2 ATLAS used a two-level trigger system: the hardware-based Level 1 (L1) trigger, that lowers the 40 MHz event rate to 100 (kHz) and the software-based High Level Trigger (HLT) which reduces to the final sustainable rate of approximately 1 (kHz). The ATLAS TDAQ system work-flow during Run-2 [36] is shown in Figure 17. The L1 trigger decision is formed by the Central Trigger Processor (CTP), which receives inputs from the L1 calorimeter (L1Calo) and L1 muon (L1Muon) triggers as well as several other subsystems such as the Minimum Bias Trigger Scintillators (MBTS), the LUCID Cherenkov counter and the Zero-Degree Calorimeter (ZDC). After the L1 trigger acceptance, the events are buffered in the Read-Out System (ROS) and processed by the HLT. The HLT receives Region-of-Interest (RoI) information from L1, which can be used for regional reconstruction in the trigger algorithms. After the events are accepted by the HLT, they are transferred to local storage at the experimental site and exported to the Tier-0 facility at CERN's computing centre for offline reconstruction.

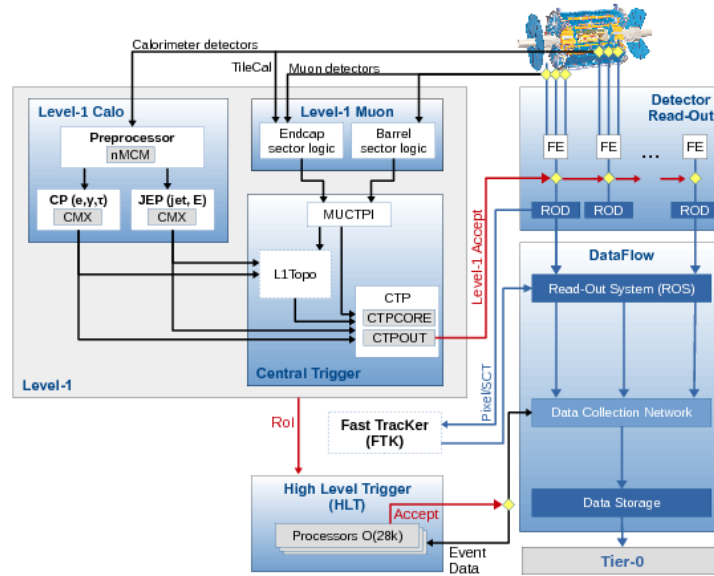


Figure 17: ATLAS Run 2 TDAQ system scheme. Source: ref. [36].

© 2017-2022 The Author(s) / License: CC-BY-4.0, sponsored by SCOAP

The L1 Trigger look out for clusters of localized energy deposits in the calorimeters in tandem with angular matching signals in the muon spectrometer, it selects 1 event every 400 as the nearly 40 million events per second are a quantity immense to be processed in conjunction with track information. Narrow energy deposits on the calorimeter defined by $\Delta\eta \times \Delta\phi$ cones are selected as RoIs correlated with a particle candidate, L1 applies thresholds aiming to reduce pile-up and low momenta non-interesting events. In a case-by-case scenario the L1 Trigger applies cuts on the energy near the main energy deposit to reject the quark and gluons jets background, this along topological cuts and overlap removal between objects. The rate is split evenly between the muon, electromagnetic and hadronic or combined event. After all this hardware-based job the processed events are streamed to the High Level Trigger.

4 Object Reconstruction & Event Selection

4.1 Object reconstruction

On highly boosted topologies like the ones searched in this work, the reconstruction of individual jets for the $H \rightarrow \tau_{had}^- \tau_{had}^+$ or $H \rightarrow b\bar{b}$ has proven to be infructuous as the highly boosted Higgs cause severe overlapping between the objects produced by their decays. The cause of the individual mis-reconstruction of the tau subjets is that the anti- k_t seed jets have an angular distance parameter of $\Delta R = 0.4$ due to the maximum distance between seed jet axes, having as a result a drop on reconstruction efficiency, it has been proved that a larger R ($\Delta R = 1.0$) jet reconstruction for both boosted Higgs decays vastly improves the reconstruction efficiency of these new redefined objects pairs, either tau pairs or large R b-jets, this can be achieved due to the further examination of the region covered by it, the subsequent reconstruction of the individual subjets shows a significant improvement in comparison to the individual reconstruction.

4.1.1 Boosted tau pair reconstruction

The standard hadronic tau particle reconstruction procedure [37] shows a significant drop on efficiency as one approaches a highly boosted regime due to collimation between their seed jets, so another reconstruction technique [38] has been implemented in searches where jet overlapping is characteristic, constructing a pair of tau seed jets as a single object for further analysis. The tau pair reconstruction method for hadronically decaying taus which has small ΔR consists on reconstructing a single large anti- k_t calorimeter seed jet with untrimmed radius $R = 1.0$ with $p_T > 300$ GeV, then hadronic tau decays are resolved on small anti- k_t calorimeter subjets ($R = 0.2$) candidates, selecting the two tau subjets candidates with the highest p_{Ts} , this information can be seen schematically on Figure 18. These subjets are correlated to a track if they are inside the region defined by the cone $\Delta R < 0.2$ within the subjet axis, the subjets, composed by neutral and charged hadrons, have a cut at $p_T > 10$ GeV and their track must satisfy having a $p_T > 1$ GeV, 2 or more pixel hits, 7 or more pixel + SCT hits, a $|d_0| \leq 1.0$ mm and $|z_0 \sin \theta| \leq 1.5$ mm as standard for single tau reconstruction, being d_0 the closest distance between track and primary vertex on the transversal plane and z_0 the longitudinal impact parameter.

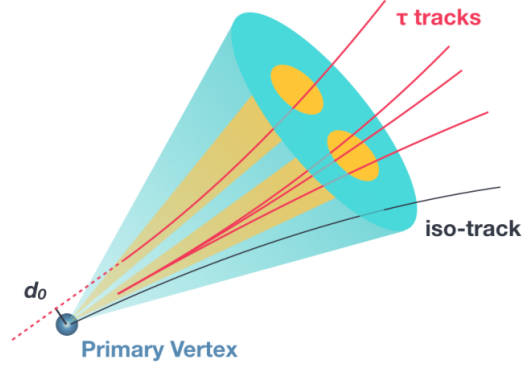


Figure 18: Representation of the elements used for a large-R boosted tau pair reconstruction: the blue cone is the large-R seeding jet, the two smaller yellow ones are the leading and subleading jets. Source: ref. [39]

© 1998-2022 CERN / License: CC-BY-4.0

As the probability of assigning a pile-up vertex as a primary vertex increases proportionally to the number of pile up collisions, the vertex association is performed by the Tau Jet Vertex Association [39] method (TJVA), finding the primary vertex as the one with higher track p_T fraction, this fraction is defined as the sum of tau tracks p_T associated to a candidate vertex divided by the sum of the transversal momentum of all tau tracks:

$$f_{\text{TJVF}}(\text{jet}|\text{vtx}) = \frac{\sum p_T^{\text{trk}|\text{vtx}}}{\sum p_T^{\text{trk}}} \quad (4.1)$$

The calculation of f_{TJVF} is performed with the same criteria for hadronic tau track selection without the impact parameters, this algorithm ensures a reduction on track degradation due to the pile-up. Figure 19 illustrates the association between jets and vertexes in the momentum fraction calculation.

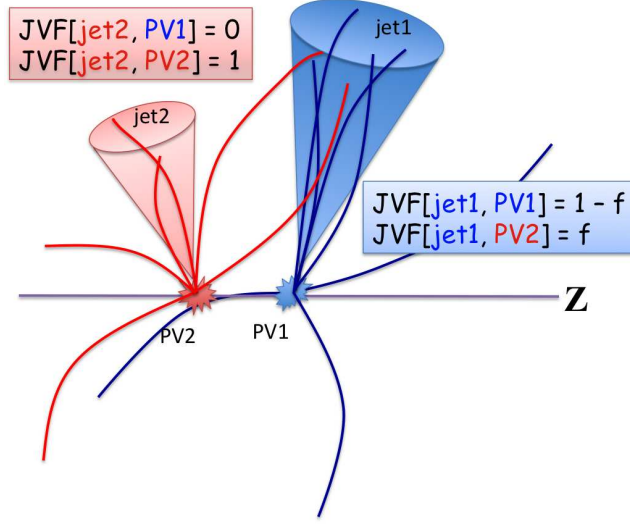


Figure 19: A pictorial example of the jet vertex discriminant. Source: ref. [39]

© 1998-2022 CERN / License: CC-BY-4.0

742 Defined the two subjets, the boosted tau pair 4-momentum and axis are calculated by the sum of
 743 these sub-jets 4-momentum. Finally the tau pair is confirmed as such if the angular difference between
 744 a tau subjet and its particular truth visible tau is $\Delta R < 0.2$. Additionally, as a large fraction of
 745 hadronic tau decays involve one or three charged pions, they are further cut on the number of tracks,
 746 this are referred to as the 1 or 3 prong taus. The efficiency of the reconstruction, cuts and selection
 747 criteria present in the event selection Section 4.2 are better illustrated by Figures 20 and 21.

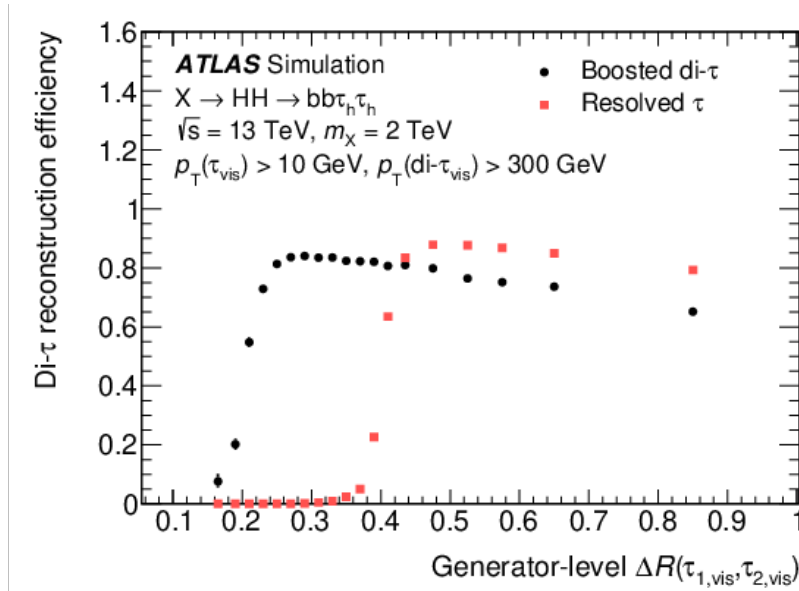


Figure 20: Efficiency versus ΔR illustrating the merging of boosted taus

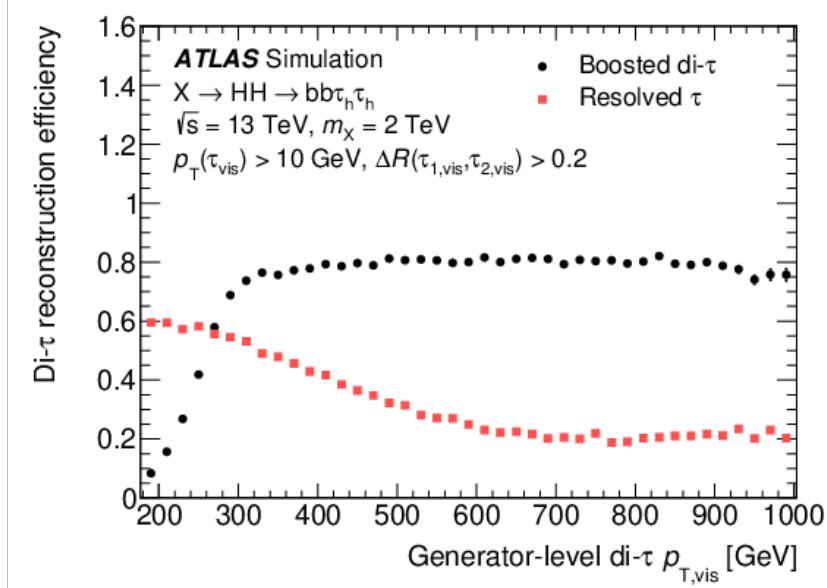


Figure 21: Efficiency versus p_T illustrating the boosted regime efficiency drop for single taus

Reconstruction efficiency of resolved taus (squares) and tau pair objects (circles) for a simulated resonance mass of $m_X = 2$ TeV. Source: ref. [40]

© 1998-2022 CERN / License: CC-BY-4.0

Pursuing the purpose of reducing the background from quark and gluon-initiated jets, a Boosted Decision Tree (BDT) identification algorithm is implemented to improve the separation between signal and background based on the BDT-score of a particular event, using the feedback information on the calorimeter clusters, tracks and vertices. The background events would typically be characterized by low p_T subjets, fewer collimated tracks and higher track multiplicity. The BDT training is implemented using adaptive boost algorithm [41] (AdaBoost) and a 0.5 boosting parameter in the Toolkit for Multivariate Analysis [42] (TMVA). The training of the signal is a combination of five simulated signal samples for a spin 2 graviton $G \rightarrow hh \rightarrow \tau^+\tau^-\tau^+\tau^-$ with resonance masses in the range 1.5, 1.75, 2.0, 2.25 and 2.5 TeV. The background sample incorporate the 3.2 fb^{-1} of data recorded by the ATLAS experiment in 2015, multijet events selected by combined jet triggers with transverse energy cuts between 100 and 400 GeV.

4.1.2 Boosted $H \rightarrow b\bar{b}$ reconstruction

The b pair is reconstructed firstly by clustering its hadronic decays enclosed in a large-R calo-jet using the anti- k_t algorithm with a radii parameter of $R = 1.0$. Calorimeter jets are reconstructed from noise suppressed topo-clusters of calorimeter cells which are calibrated to the hadronic energy scale using the local calibration weighting method [43] (LCW). It is mandatory to consider the effect of initial state radiation (ISR), multiple parton interaction (MI) and pile-up events on the final state radiation, the Jet Trimming [44] approach can be generally outlined as seen in Figure22, its objective is to subtract the contamination from radiation taking advantage on its softness.

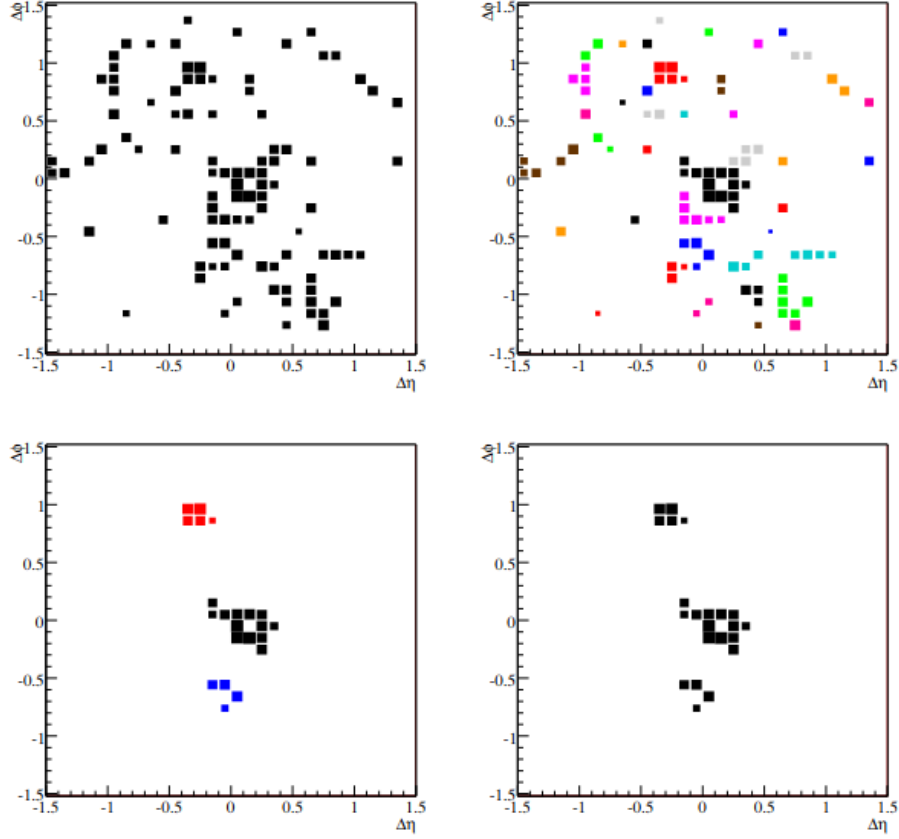


Figure 22: In order from left to right, top to bottom this sequence of images exemplify the steps to trim an initial clustered jet, then its constituents subjets $\Delta R < 0.2$ and the p_T fraction cut. The area of each cell is proportional to the log of the cell p_T . Source: ref. [44]

Author: David Krohn, Jesse Thaler, Lian-Tao Wang / License: CC BY-NC 2.0

767 Jet Trimming for the Higgs reconstruction is achieved following these steps: first use the Large-
768 R jets as a seed jet, recluster their constituents with k_t subjets contained within an $R = 0.2$ radii
769 parameter, the subjet is discarded if $p_T^{subjet}/p_T^{J_0} < 0.05$ where $p_T^{J_0}$ is the full seed jet transverse
770 momentum, the remaining subjets are merged into the desired trimmed jet. The calibration to be
771 applied is the one involving energy and mass scales namely the jet energy scale [45] (JES), MC factors
772 are derived as a correction relating calorimeter response to the true jet energy. The dependence of
773 the jet response on: number of primary vertices (N_{PV}) and average number of interactions ($\langle\mu\rangle$) is
774 removed applying a pile-up offset correction. The mass response is determined from the mean of a
775 Gaussian fit to the core of the distribution of the reconstructed jet mass divided by the corresponding
776 generator-level jet mass, procedure depicted on Figures 23 and 24.

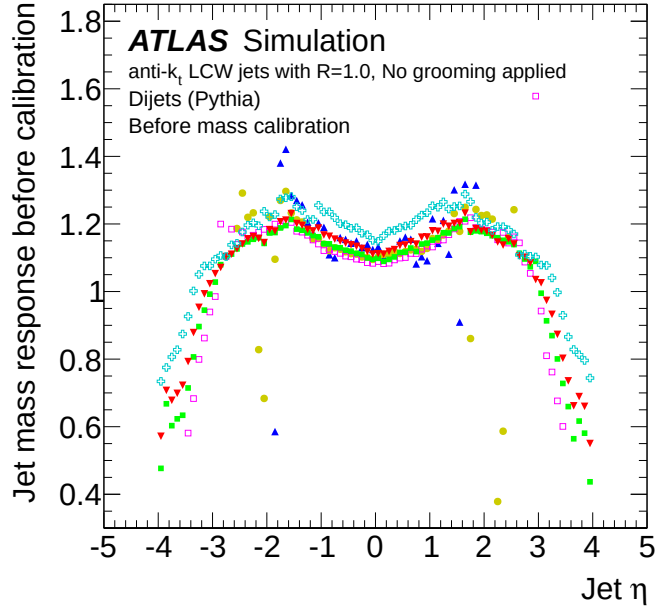


Figure 23: anti- k_T , $\Delta R = 1.0$ before calibration

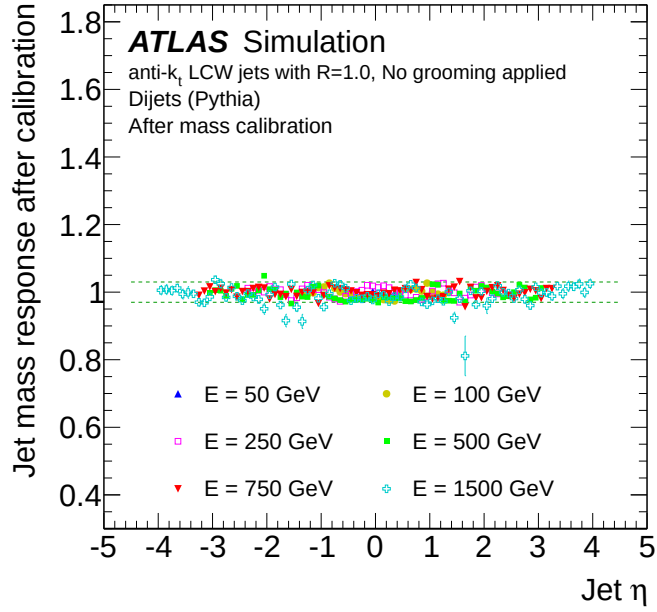


Figure 24: anti- k_T , $\Delta R = 1.0$ after calibration

Distribution mass response $m_{\text{jet}}^{\text{reco}}/m_{\text{jet}}^{\text{true}}$ before and after JES, the dotted line are a $\pm 3\%$ calibration precision envelope. Source: ref. [45]

After trimming and calibration the large- R jet reconstructed is required to have p_T higher than 300 GeV and $|\eta| < 2.0$, its mass is calculated using the combined mass technique [46] mixing tracking and calorimeter information:

$$m_{\text{comb}} = am_{\text{calo}} + bm_{\text{TA}} \quad a = \frac{\sigma_{\text{calo}}^{-2}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}} \quad b = \frac{\sigma_{\text{TA}}^{-2}}{\sigma_{\text{calo}}^{-2} + \sigma_{\text{TA}}^{-2}} \quad (4.2)$$

where the calorimeter-based jet mass m_{calo} is obtained from the dispersion relation and the energy deposit on the calorimeter:

$$m_{\text{calo}} = \sqrt{\left(\sum_{i \in \text{Jet}} E_i\right)^2 - \left(\sum_{i \in \text{Jet}} \mathbf{p}_i\right)^2} \quad (4.3)$$

and the track-assisted jet mass m_{TA} are calculated as follows:

$$m_{\text{TA}} = \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} m^{\text{track}} \quad (4.4)$$

As the calorimeter jet mass is not involved in the calculation of the track-assisted jet mass, it is possible to improve the mass resolution combining both mass definitions as stated by Equation 4.2, the low correlation at high p_T and the Gaussian behaviour of the p_T and mass distributions ensures that the combination implemented is linear. If both mass definitions are calibrated then the combined mass is calibrated if $a + b = 1$, the weights a and b are thus the ones that minimize resolution and implements the constrain for a combined calibrated mass.

The identification of b-hadrons require the reconstruction of b-tagged track jets, these were initially fixed radii jets but for multi-TeV energy requirements it was necessary to modify these methods. Implementing the Variable Radius algorithm [47] fixes the main issue the fixed radii anti- k_T algorithm posses, it overlaps the hadronization of b quarks due to the Higgs high p_T . The Variable Radius method parameterize the ΔR cone change in size as:

$$\Delta R = \frac{\rho}{p_T} \quad (4.5)$$

The free parameter ρ tells how fast the jet effective size is narrowed respect to its p_T , it is required also cuts to R , namely R_{min} and R_{max} to prevent jets too large for low p_T or undetectable in the high p_T regime, the optimum value for the set of free parameters: ρ , R_{min} and R_{max} is chosen based on the combination that maximizes double subjet b-labeling efficiency [48], particularly in boosted $h \rightarrow b\bar{b}$ the combination $\rho = 30$ GeV, $R_{\text{min}} = 0.02$ and $R_{\text{max}} = 0.4$ is implemented. The following step for these track jets is to subtract the pileup matching the reconstructed track jets with their respective untrimmed large- R jet counterpart, this is achieved through the Ghost Association Method [49], an infrared safe, jet-by-jet and event-by-event pile-up subtraction. The method consists in the introduction of ghost soft-particles which cluster to a jet on the y - ϕ plane, the area A measured on the rapidity (y) - polar (ϕ) plane reflects the susceptibility to diffusive noise (pile-up and underlying events), The correction $p_T^{(\text{sub})}$ for a particular jet j is $p_{T,j}^{(\text{sub})} = p_{T,j} - A_j \rho$, where ρ measure the level of diffusive noise, ρ can be estimated by the quantity $p_{T,j}/A_j$, this fraction values are distributed around

the main value of ρ , so $\rho = \text{median}[p_{Tj}/A_j]$, only track jets which has $p_T > 10$ GeV, $|\eta| < 2.5$ and at least two tracks are considered for the next algorithm.

Finally this track information is used by the three b-tagging algorithms, which results are the inputs for the final BDT algorithm MV2c20 used to discriminate between the aforementioned b-jets from light jets and c-jets so the Large-R jet b hadron multiplicity can be determined, these algorithms are the impact parameter based algorithm (IP2D, IP3D), the inclusive secondary vertex reconstruction algorithm and the decay chain multi-vertex reconstruction algorithm [50, 51]. The track selection need to satisfy the fact that tracks are associated to a calo-jet, depending on their angular separation $\Delta R(\text{track}, \text{jet})$, this separation is p_T -dependant (cones are narrower at higher p_T) and if a track satisfies the association criteria for more than one jet, the jet with lower ΔR is selected. Besides this selection, is also worth mentioning that the track selection for each algorithm is different and specific, the variables obtained by these 3 algorithms are combined in a BDT whose function is to discriminate b-jets from light and c-jets [52] taking into account b-jets as signal, and as background light-flavour jets and c-jets in a 90/10 proportion at a 0.7 efficiency working point, the BDT is trained from a background sample composed of 93% light-flavour jets and 7% c-jets. This results on trimmed large-R jets tagged either as 0, 1 or 2-tagged b-jets

4.1.3 Missing Transverse Momentum

The missing transverse momentum E_{miss}^T is defined as the negative vector sum of the transverse momenta of the fully reconstructed and calibrated objects [53], combining two contributions: the hard-objects, namely, reconstructed particles like electrons, photons, taus, muons and jets and the soft terms which are reconstructed charged tracks associated to the primary vertex but with no hard object affiliation. Soft terms from topo clusters are taken in consideration by the track-based soft term (TST) algorithm [54] and their momentum calculated via the measurements on the Inner Detector.

4.2 Event selection

Events must satisfy pre-selection cuts and requirements [40] on their reconstructed objects:

- There must be one di-tau object successfully reconstructed, if there is 2 or more the highest p_T di-tau is selected.
- The di-tau candidate must be inside the pseudorapidity region $|\eta| < 1.37$ or $1.52 < |\eta| < 2.0$ rejecting the transition region between barrel and endcap calorimeters, both tau subjects must have a $p_T > 50$ GeV threshold to reduce multi-jet background events.
- No more than three subjects present, and they require to satisfy an angular difference of $\Delta R_{\text{lead,sublead}} < 0.8$ so they are within the original large-R jet cone.
- The product of the charges between subjects is $Q = q^{\text{lead}} \times q^{\text{sublead}} = \pm 1$ where the charge can be obtained as the sum of the charges of the associated tracks.

- Selection of $H \rightarrow b\bar{b}$: at least one large-R jet with $p_T > 300$ GeV and $m > 50$ GeV, $|\eta| < 2.0$ and angular difference $\Delta R > 1$ between the jet and the tau pair object. Again if multiple large-R jets fulfill this conditions, the highest p_T jet is selected.
- Events are vetoed if there are more large-R jets with at least one b-tagged VR track jet. If there is more than two b-tagged large-R jets, these events are vetoed so the search is orthogonal to $X \rightarrow hh \rightarrow b\bar{b}b\bar{b}$. Additionally if two VR track jets are extremely collimated they are removed.
- The missing transverse energy must satisfy a 10 GeV cut to clearly define a direction of missing transverse momentum.

Finally, regions are constructed applying cuts to different variables, for this analysis only Signal Region events are considered, a SR event is considered if the tau pair BDT score is higher than 0.72, has opposite charge sign between the leading and subleading tau subjects charge product, exactly 2 b-tagged track jets are present in the large-R jet, a polar angle difference between the tau pair and the missing transverse momentum of $|\Delta\phi| < 1$ so they point roughly in the same direction and the mass of the large-R jet must reside between the 60-160 GeV window.

5 MC signal samples

Simulated MC signals produced by the ATLAS simulation infrastructure for a heavy spin-0 resonance produced via gluon-gluon fusion and decaying into a Higgs boson pair, reproducing the detector conditions for the Run-2 data taken periods: 2015+2016, 2017 and 2018 with integrated luminosities of 36.2 fb^{-1} , 44.3 fb^{-1} and 58.45 fb^{-1} respectively, for a total integrated luminosity of $\mathcal{L} = 139 \text{ fb}^{-1}$ and a center of mass energy of $\sqrt{s} = 13 \text{ TeV}$ are the necessary input to calculate other quantities. Simulated resonant Higgs pair for the 2 Higgs Doublet Model 2DHM were produced for different values of heavy resonant mass values of: 1.0, 1.1, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5 and 3.0 TeV, this samples are simulated using an effective field theory model (EFG) implemented in MG5_aMC@NLO v2.6.1 [55] at leading order, interfaced with the Herwig 7.1.3 [56] parton shower generator, using parton distribution functions from NNPDF23_lo_as.0130_qed [57] [58] for the matrix element calculations in conjunction with the MMHT2014lo68cl [59] adding multiple parton interactions, this heavy scalar width has a fixed resolution of $\sigma = 10 \text{ MeV}$. The decays of b-mesons are manipulated with EVTGEN v.1.6.0 [60] and the detector response simulated using GEANT4 [61].

For this analysis, the dedicated Higgs derivation format **HIGG4D6**, requiring at least one tau pair object reconstructed, satisfying the requirement $p_T > 300 \text{ GeV}$ and two large-R jets with $p_T > 300 \text{ GeV}$, they must fire any of the following triggers depending on the period:

- 2015+2016:
HLT_j360_a10r_L1J100 (2015) or HLT_j360_a10r_L1J100, HLT_j400_a10r_L1J100,
HLT_j420_a10r_L1J100, HLT_j440_a10r_L1J100 (2016)
- 2017:
HLT_j420_a10r_L1J100, HLT_j440_a10r_L1J100, HLT_j460_a10r_L1J100
- 2018:
HLT_j460_a10r_L1J100

5.1 Data Processing

AOD stands for Analysis Object Data, it is a ROOT-readable format which contains the reconstructed physics object information i.e. the contents of the AOD (xAOD). AODs files are central to the analysis workflow for the ATLAS collaboration, these contain all the necessary information required to do a full physics analysis. The lifetime of an AOD file is already eventful before its creation as is one of the outputs from the raw data reconstruction and data preparation. The AOD is the common analysis format so its size is in the order of the PB , but they are too large to be analyzed directly, so specific physic groups analysis Derivation frameworks creates the Derived AODs (DAODs) refining data either by skimming, slimming, thinning or enhancing the content of the original xAOD, as the analysis gains specificity.

After the simulation and trigger selection combinatory efforts, the CxAOD framework is used to produce lightweight CxAODs files from these DAODs. The CxAODMaker framework is used to produce CxAODs, it stands for Calibrated xAODs, and its contents are the product of applying the

corresponding object overlap removal, event selection and according CP tools, the build of scale factors and systematic uncertainties. The further study is performed within the CxAODReader framework which takes the CxAODs and can perform the final selection or event categorization as well as producing Histograms or dumping Ntuples for training Machine Learning methods or performing further optimization studies. The framework was compiled using AnalysisBase release v.21.2.83 for the CxAOD v.10 production.

Further analysis on these CxAOD were performed using a modified [CxAODReader_HH_bbtatau boosted v.10](#) to create the final Ntuples containing the desired Higgs pair decay products information necessary to reconstruct them and perform the studies that will be shown in the next sections.

6 Mass Reconstruction Improvements

6.1 The Collinear Mass Approximation

The collinear mass approximation technique [62] is a frequently implemented method for the reconstruction of $H \rightarrow \tau^- \tau^+$ based on the assumption that the neutrinos related to each tau decay are almost parallel respect to their corresponding tau visible decay products, namely the angles between them are almost the same: $\theta_\nu \sim \theta_{vis}$ and $\phi_\nu \sim \phi_{vis}$ and that the missing energy in the event is only due to the presence of the neutrinos. Taking these considerations into account the invisible momentum that those neutrinos carry in each tau decay can be estimated balancing out the missing energy of the event to the projection on the transversal plane of the missing objects:

$$\not{E}_x^T = p_{miss,1} \sin \theta_{vis,1} \cos \phi_{vis,1} + p_{miss,2} \sin \theta_{vis,2} \cos \phi_{vis,2} \quad (6.1)$$

$$\not{E}_y^T = p_{miss,1} \sin \theta_{vis,1} \sin \phi_{vis,1} + p_{miss,2} \sin \theta_{vis,2} \sin \phi_{vis,2} \quad (6.2)$$

where $\not{E}_x^T$ and $\not{E}_y^T$ are the x and y components of the missing transverse energy vector $\not{E}^T$, $p_{miss,1}$ and $p_{miss,2}$ are the invisible momentum carried by each neutrino of each tau decay, θ_{vis} and ϕ_{vis} correspond to the visible angular kinematic variables of the tau leptons. Solving Equations 6.1 and 6.2 one can find the $p_{miss,1}$ and $p_{miss,2}$ four-vectors and either reconstruct the di-tau mass adding up its constituents or rescaling the visible di-tau mass:

$$M_{\tau\tau} = \frac{m_{\tau\tau}^{vis}}{\sqrt{x_1 x_2}} \quad (6.3)$$

here x_1 and x_2 stands for the visible momentum fraction $x_{1,2} = p_{vis1,2} / (p_{vis1,2} + p_{miss1,2})$ carried by the visible taus. The advantage of such simple method is a fully reconstructed tau pair mass but comes at expenses of many shortcomings, first the method require a large missing transversal momentum and second the solution for Equations 6.1 and 6.2 diverges as the angles $\phi_{vis,1}$ and $\phi_{vis,2}$ are integer multiples of π as the solution is inversely proportional to the quantity $\sin(\phi_{vis,1} - \phi_{vis,2})$ thus giving unreasonable solutions for the invisible momenta. Even if solved the method is sensitive to $\not{E}_T$ resolution and over-estimate the di-tau mass producing long tails in the reconstructed invariant di-tau mass distribution.

6.2 χ^2 Fit and the Method of Least Squares

To further improve the results for the collinear mass approximation, kinematics constrains can be implemented on a χ^2 fit [63] to reconstruct the tau pair mass and invisible 4-momenta by using the method of least squares for parameter estimation, to achieve this one starts from the χ^2 distribution between a measurement y and a predictive function f :

$$\chi^2 = \sum_{i=1}^N \left[\frac{y_i - f(x_i; \boldsymbol{\theta})}{\sigma_i} \right]^2 \quad (6.4)$$

Where θ is the parameter vector which values one wants to estimate, σ_i is the uncertainty on the measured variable and N the number of events/measurements. As the missing momenta per event are independent between each other (i.e. the free parameters $p_{miss,1}$ and $p_{miss,2}$ are not global parameters) and thus they are different and independent event by event, minimizing χ_i^2 for each event is enough to find the unknown missing momenta, finally taking in consideration that minimizing the combined χ^2 function of the measurements of $E_{miss,x}^T$ and $E_{miss,y}^T$ and fixing the Higgs invariant mass at the 125 GeV value, the χ_i^2 distribution to minimize is:

$$\chi_i^2 = \left(\frac{m_{\tau\tau}^{fit} - 125}{\sigma_{\tau\tau}} \right)^2 + \left(\frac{m_{bb}^{fit} - 125}{\sigma_{bb}} \right)^2 + \left(\frac{E_{miss,x}^{fit} - E_{miss,x}}{\sigma_{miss,x}} \right)^2 + \left(\frac{E_{miss,y}^{fit} - E_{miss,y}}{\sigma_{miss,y}} \right)^2 \quad (6.5)$$

implementing as free parameters the missing invisible momenta of each tau decay, the tau pair resolution is set to 10% of the Higgs mass and 20% on the large-R jet resolution. The minimization of the combined χ^2 formulae for each event i.e.

$$\frac{\partial \chi_i^2}{\partial p_{miss,j}} = 0 \quad (6.6)$$

were $j = 1, 2$, gives as result the free parameters which minimise both χ^2 and Log-Likelihood distributions, this is achieved replacing Equations 6.1, 6.2 and 6.3 on the combined χ_i^2 expression 6.5 and obtaining the free parameters vector $\hat{\mathbf{p}}^{(i)} = \{p_{miss,1}^{(i)}, p_{miss,2}^{(i)}\}$ that gave a local minimum for the combined χ^2 per event thus having the necessary constituents to calculate the tau pair object 4-momentum once again.

7 Results

Based on Equations 6.1 and 6.2, the invisible momenta projection on the transversal plane can be formulated as a linear combination were the transformation matrix $\mathbf{M}$, that relates the MET and p_{miss} vector can be expressed as:

$$\begin{pmatrix} MET_x \\ MET_y \end{pmatrix} = \underbrace{\begin{bmatrix} \sin \theta_1 \cos \phi_1 & \sin \theta_2 \cos \phi_2 \\ \sin \theta_1 \sin \phi_1 & \sin \theta_2 \sin \phi_2 \end{bmatrix}}_{\mathbf{M}} \begin{pmatrix} p_{miss,1} \\ p_{miss,2} \end{pmatrix} \quad (7.1)$$

The behaviour of the solutions $p_{miss,j}$ $j = 1, 2$ is directly related to the determinant of $\mathbf{M}$ and to the matrices $\mathbf{M}_1$ and $\mathbf{M}_2$:

$$\mathbf{M}_1 = \begin{bmatrix} MET_x & \sin \theta_2 \cos \phi_2 \\ MET_y & \sin \theta_2 \sin \phi_2 \end{bmatrix}; \quad \mathbf{M}_2 = \begin{bmatrix} \sin \theta_1 \cos \phi_1 & MET_x \\ \sin \theta_1 \sin \phi_1 & MET_y \end{bmatrix}$$

So the solutions are $p_{miss,1} = |\mathbf{M}_1|/|\mathbf{M}|$ and $p_{miss,2} = |\mathbf{M}_2|/|\mathbf{M}|$, both solutions has the denominator $|\mathbf{M}| = \sin \theta_1 \sin \theta_2 \sin(\phi_2 - \phi_1)$ so momentum could not converge at the limits $\phi_2 - \phi_1 \rightarrow n\pi$, also is worth noting that, if not restricted explicitly, the values $|\mathbf{M}|$, $|\mathbf{M}_1|$ and $|\mathbf{M}_2|$ can take negative values displaying non-physical negative solutions for $p_{miss,1}$ and $p_{miss,2}$ as can be seen on Figure 25:

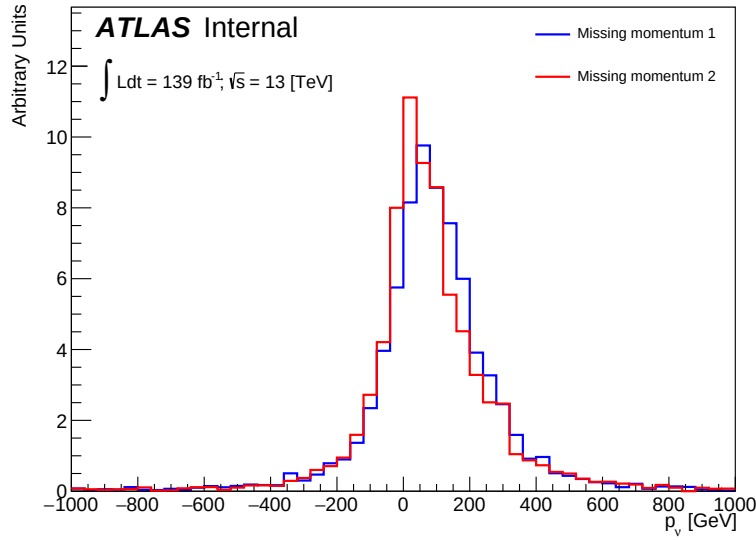


Figure 25: p_{miss} distribution, produced for a resonant mass $m_X = 1.2$ TeV

here the angles ϕ_1 , ϕ_2 and θ_1 , θ_2 are assumed to be the angles of the leading and subleading visible taus. as stated by the collinear approximation, searching the cause of these nonphysical solutions, the analysis on the E_{miss}^T vector direction and the subjects direction is a pivotal point for understanding the underlying difficulties reconstructing $p_{miss,1}$ and $p_{miss,2}$

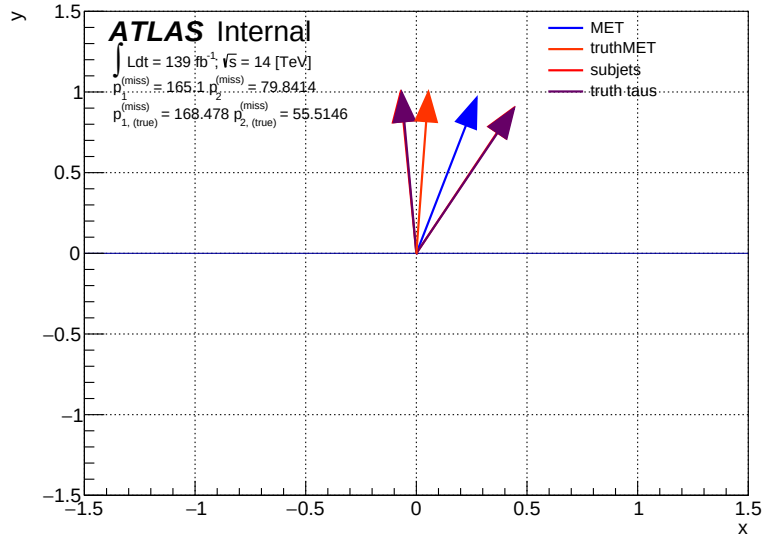


Figure 26: Positive $p_{\text{miss},1}$ and $p_{\text{miss},2}$ example

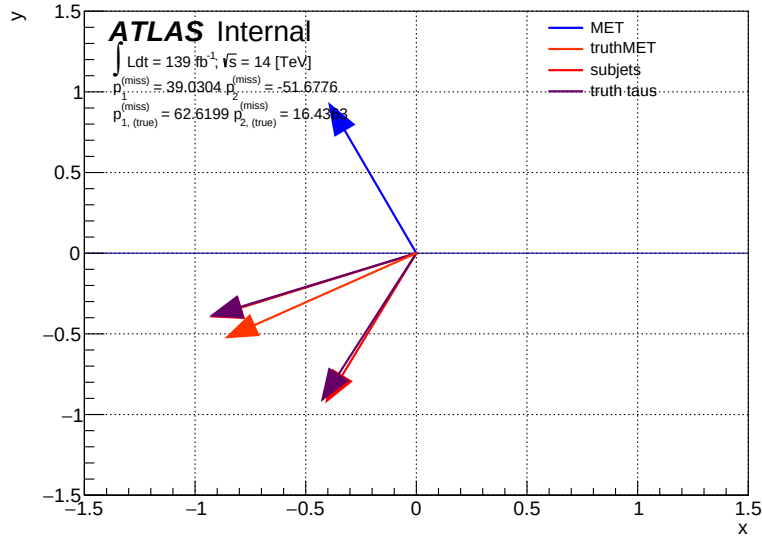


Figure 27: MET vector misaligned example

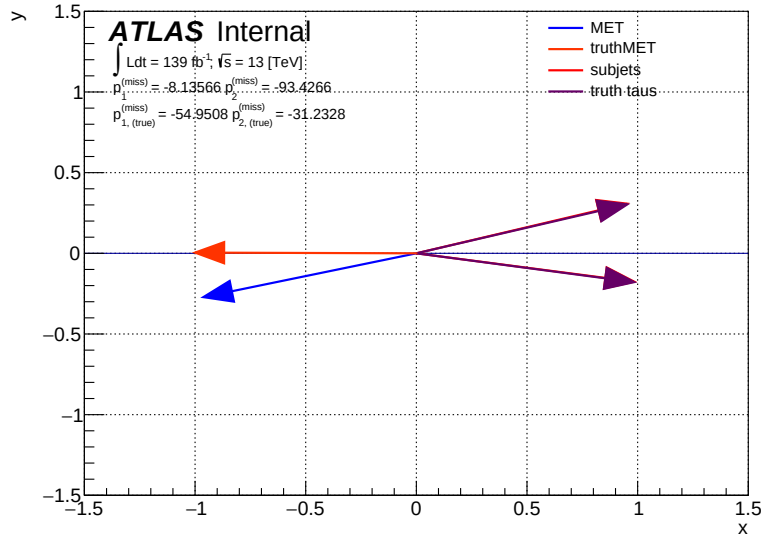


Figure 28: MET vector and truthMET misaligned example

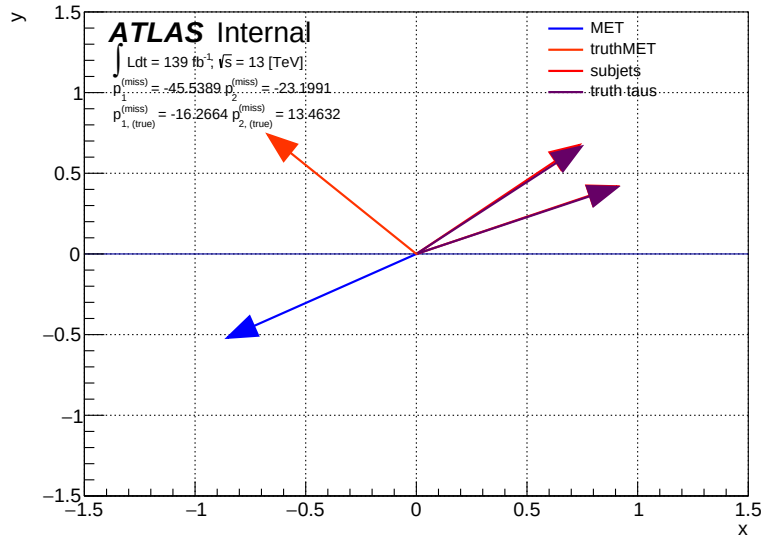


Figure 29: MET vector and truthMET misaligned example

Transversal plane MET direction (blue), tau subjects/truth taus (red/purple), truth MET (orange) for a simulated resonance mass $m_X = 1 \text{ TeV}$

As can be seen in the examples on Figures 26 to 29, non-aligned MET vectors lying outside the angle difference $\Delta\phi$ lead to pathological projections when trying to apply Equations 6.1 and 6.2, this is the reasoning behind the Signal Regions cuts relating the transversal direction between the tau pairs and the missing transversal energy $|\Delta\phi| < 1$. All reconstructions are characterized by their observed invariant mass and their resolution, reconstructing the collinear missing objects, taking the

962 p_{miss} positive solutions and comparing both di-tau visible and invariant mass on Figure 30 and 31,
 963 although the tau pair invariant mass is correctly reconstructed at the Higgs mass value 125 GeV and
 964 one can make a reconstruction of the invisible objects 4-momenta as a noteworthy achievement, the
 965 events unsuccessfully reconstructed greatly impact the resolution and number of events as a drawback.

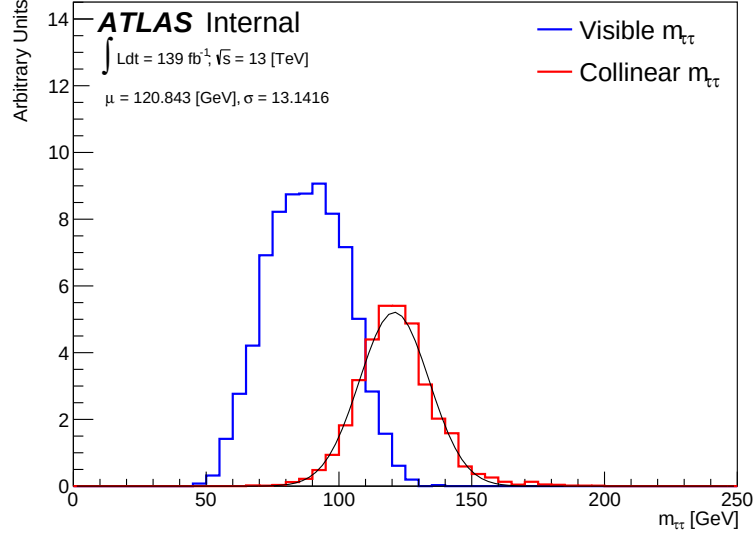


Figure 30: $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.2$ TeV

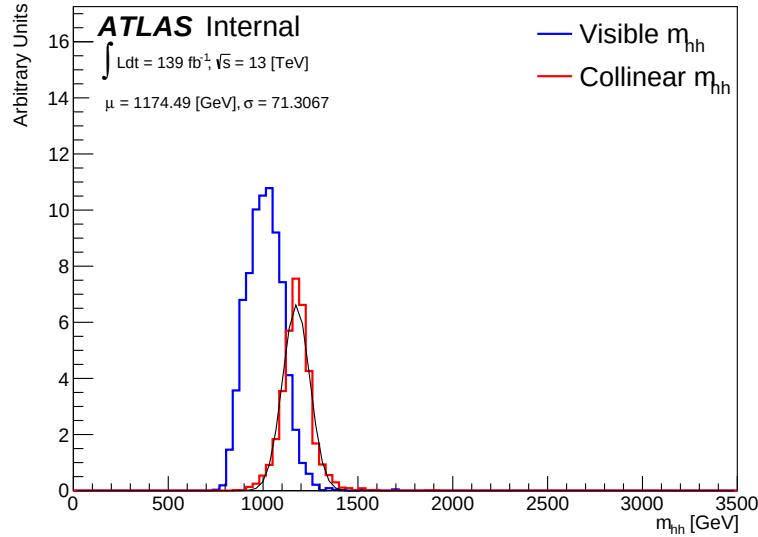


Figure 31: m_{hh} distribution, produced for a resonant mass $m_X = 1.2$ TeV

The invariant mass reconstruction for the tau pair object when implementing the collinear approximation solving the E_{miss}^T projection. For comparison the visible mass (blue) is exhibit in tandem with the full tau pair object (red)

966 Instead of solving Equations 6.1 and 6.2 directly, implementing a χ^2 parameter estimation as
 967 described in Section 6.2, based on the ranges exhibit by the p_{miss} reconstructed directly one restrains
 968 the values of the missing momentum between the values $30 [\text{GeV}] < p_{miss,i} < 1000 [\text{GeV}]$, the low
 969 cut is to avoid accumulation of low momentum solutions and reproduce the behaviour of the physical
 970 solutions that can be seen in Figure 25, the results can be seen in Figure 32 and is noteworthy that the
 971 kinematics constraints on the tau pair mass fixed at $125 [\text{GeV}]$ cause a drop on the missing momentum
 972 reconstruction on the vicinity of said energy value.

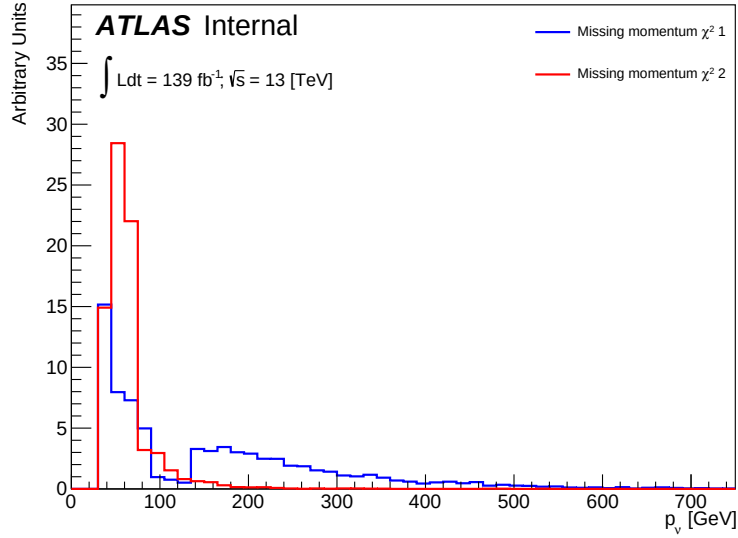


Figure 32: p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.2$ TeV

973 With this information one can again reconstruct the fully tau pair mass and compare this approach,
 974 to solving the transversal projection of the missing energy and missing momenta as can be seen in
 975 Figure 33, the number of events successfully reconstructed is greatly enhanced, reconstructing all the
 976 events in the sample, and the $\chi^2 m_{\tau\tau}$ distribution has the same benefits as solving the system of
 977 equations directly, the distribution exhibits the long tailed higher momentum entries as part of the
 978 sensibility to the missing transversal energy resolution

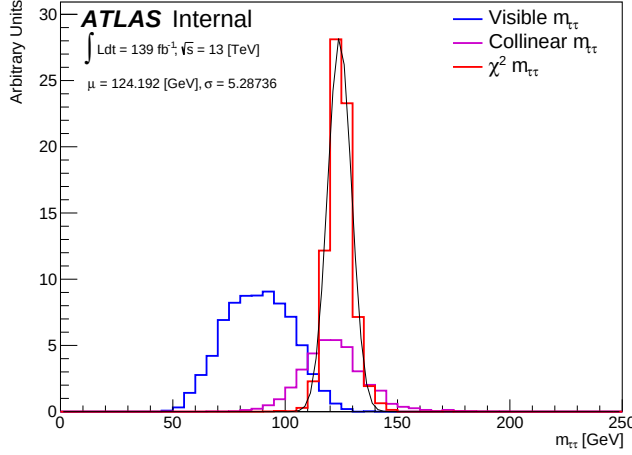


Figure 33: $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.2$ TeV

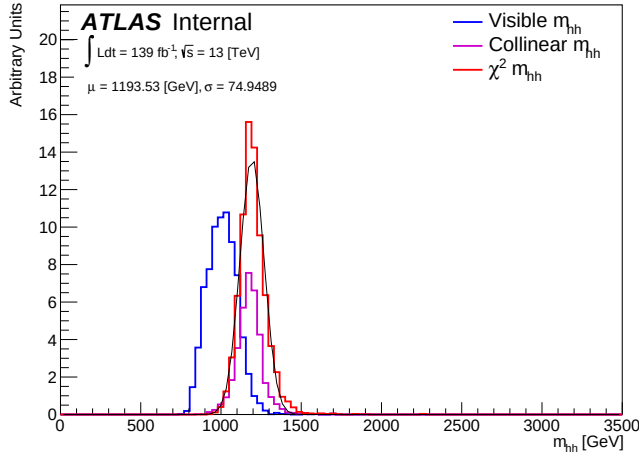


Figure 34: m_{hh} distribution, produced for a resonant mass $m_X = 1.2$ TeV

The invariant mass reconstruction for the tau pair object when implementing the collinear approximation minimizing the χ^2 function using the E_{miss}^T projection as kinematics constrains.

Finally the reconstructed Higgs pair inherits the benefits and drawbacks of the tau pair reconstruction as can be seen in Figure 34, the Higgs pair exhibits peaks closer to the mass of the original heavy resonance as verification, this behaviour is shown without the need to impose directly its kinematics constrains on the parameter estimation.

This analysis was performed on every heavy resonance signal sample and its results summarized on Table 4. A Gaussian fit is performed on the tau pair reconstruction for each method to obtain the expected value and variance for each mass distribution, in the sake of comparison. The full set of plots for all mass values can be found in the appendix A. Finally the numerical results are shown plotted in Figures 35 and 36, they broadly speaking show a better invariant mass value and a narrower

988 resolution, so it is considered an improvement.

m_X [TeV]	Events	Col. DT	Fraction	$m_{\tau\tau}$	$m_{\tau\tau}^{(col)}$	$m_{\tau\tau}^{\chi^2}$ [GeV]	m_{hh}	$m_{hh}^{(col)}$	$m_{hh}^{\chi^2}$ [GeV]
1	1638	653	39.86%	96.14	125.45	125.61	896.76	1010.3	1009.73
1.1	4734	2046	43.6%	90.81	122.68	124.43	949.57	1089.5	1097.18
1.2	4438	2033	45.81%	88.32	120.84	124.25	1011.18	1174.49	1194.74
1.4	6833	3144	46.01%	83.34	119.93	124.09	1132.27	1354.89	1394.35
1.6	8021	3730	46.5%	81.19	120.43	123.79	1267.23	1550.16	1596.65
1.8	8448	3877	47.08%	79.27	119.93	123.66	1405.11	1746.49	1801.48
2	8388	3961	47.22%	76.65	120.07	123.43	1544.32	1932.11	1993.89
2.5	6557	3058	46.43%	77.51	121.8	123.42	1890.13	2418.03	2471.71
3	3871	1749	45.18%	77.58	125.18	123.61	2249.52	2091.08	2912.3

Table 4: Collinear tau pairs comparison, depending on the resonance mass, the number of SR events, the accurately reconstructed number of events, the fraction between them and the tau/Higgs pairs correctly reconstructed solving the collinear mass equation. Finally the masses of the tau/Higgs pairs, the visible value, solving the system of equations (col) and applying the χ^2 parameter estimation respectively.

m_X [TeV]	$\sigma_{\tau\tau}$	$\sigma_{\tau\tau}^{(col)}$	$\sigma_{\tau\tau}^{\chi^2}$ [GeV]	σ_{hh}	$\sigma_{hh}^{(col)}$	$\sigma_{hh}^{\chi^2}$ [GeV]
1	13	11.71	6.85	59.87	57.13	49.89
1.1	13.02	12.36	5.637	70.3	61.25	60.85
1.2	14.7	13.14	5.252	86.79	71.31	75.69
1.4	15.32	13.9	4.65	117.17	88.628	100.18
1.6	16.82	14.96	4.886	148.49	99.664	123.56
1.8	16.79	15.54	5.002	182.17	108.79	143.99
2	15.86	15.89	5.186	208.96	119.89	160.05
2.5	18.2	16.96	5.101	279.91	140.3	207.63
3	18.89	19.61	6.04	344.94	169.69	248.17

Table 5: Collinear tau pairs comparison, depending on the resonance mass. the $\sigma_{\tau\tau}/\sigma_{hh}$ visible value, solving the system of equations (col) and applying the χ^2 parameter estimation respectively.

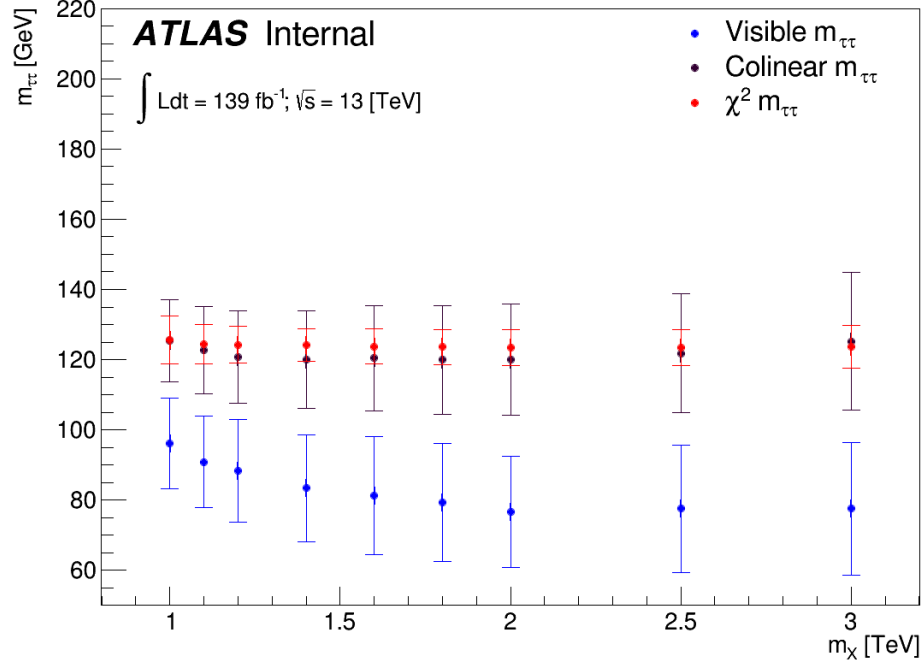


Figure 35: $m_{\tau\tau}$ resonance value depending on m_X

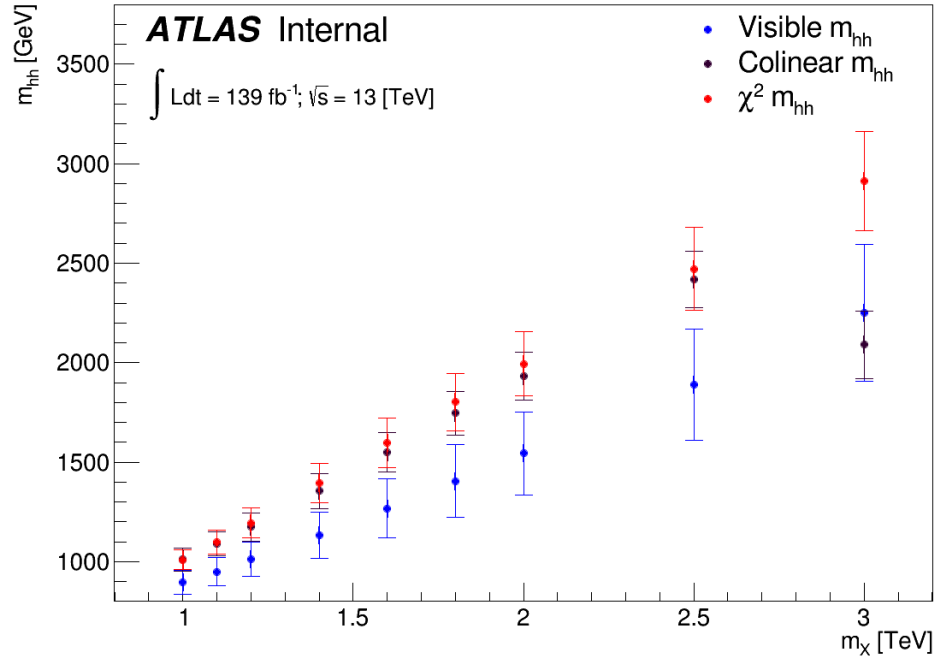


Figure 36: m_{hh} resonance value depending on m_X

The invariant mass reconstruction mean value for the tau pair/Higgs pair object in regards to the parent particle m_X

8 Trigger Studies

8.1 Phase-I upgrade for Run-3¹

In order to carry the LHC physics program and extend the reach of the different experiments. The LHC complex were and will be improved during three stages in preparation for Run 3 and the upcoming High Luminosity Large Hadron Collider (HL-LHC). Nowadays the LHC is still undergoing through its second large shutdown (LS2), the ATLAS detector is currently being monitored and calibrated as the detector upgrades are tested, the upgraded detector performance for the next data taking period Run 3 [64,65] are relevant for this study.

In accordance to the LHC planned upgrade, the objective of the Phase-I upgrade is to supply higher-granularity, higher resolution and longitudinal shower information from the calorimeter to the Level-1 trigger processors. To achieve this goal newly developed Super Cells will increase the segmentation layers and granularity as can be seen in Figure 37, which compares the energy deposition of an electron in the trigger readout system and the proposed upgraded Super Cell system. The upgrade will improve the trigger energy resolution and efficiency for selecting trigger objects like electrons, photons, tau leptons, jets and missing transverse momentum E_T^{miss} , all while enhancing the discrimination variables against background and fake events that will be present in a high instantaneous luminosity and high pile-up environment.

The calorimeter cells and the L1Calo trigger system as implemented in Run 2 is too coarse and the reconstruction of objects from the trigger level is demanding as the high pile-up levels, nearly at the order of $\langle\mu\rangle = 80$ interactions, degrade the calorimeter resolution and the isolation requirements for particles, this leads to a drop in trigger performance. Such degradation in performance can be relieved transferring the offline algorithms to the trigger level.

The Phase-I upgrades contribute digital optical signals to the L1Calo system, this digitization is the key feature that grant the trigger towers Super Cells to have their characteristic three layer segmentation in accordance to the clustering requirements. The Super Cells inputs to the L1Calo system in Run-3, are created from the analog summation of the three layer calorimeter cells across the longitudinal layers in a region $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, the contribution of the high-granularity layers shapes the final calorimeter read-out. The Phase-I upgrade increases the granularity of the LAr trigger inputs to ten Super Cells per trigger tower.

These Super Cells provides enhancements to the elec-

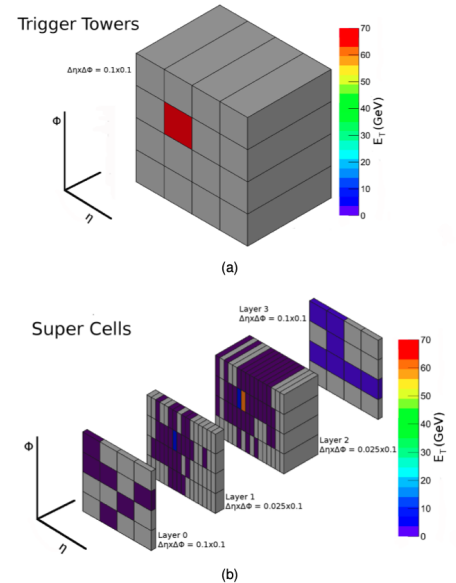


Figure 37: Level-1 Calorimeter trigger electronics with Trigger Towers (a) and by the proposed upgraded trigger electronics with Super Cells in Run-3 (b) Source: ref. [64].

© 2013-2022 CERN / License: CC-BY-3.0

¹The work shown in this section took place before the start of the Run 3 as the writing of this section tries to reflect.

tron, photon and tau lepton L1 Calo algorithms. Three new feature extractor (FEX) sub-systems will be added to the L1Calo: the electromagnetic (eFEX), jet (jFEX), and global (gFEX) feature extractors, they will progressively assume the functions of the Run-2 processing sub-systems. The three FEX systems process different input information and have different algorithmic trigger requirements. An overview of the upgraded system is shown in Figure 38 [65].

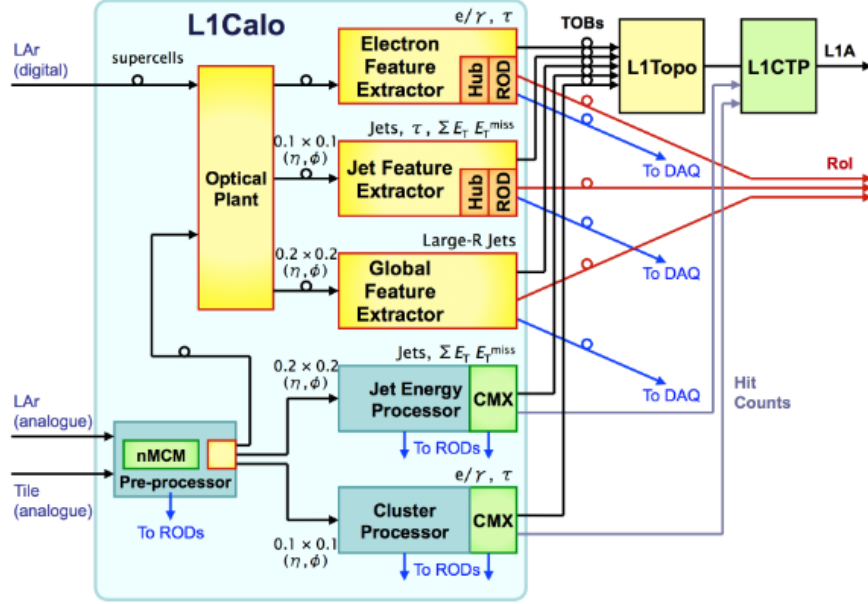


Figure 38: L1Calo system architecture for Run-3 [65].

© 2013-2022 CERN / Licenses: CC-BY-3.0

8.2 Non-resonant Monte Carlo ggF and VBF signal samples

SM di-Higgs process via gluon-gluon fusion was simulated with Powheg-Box v2 generator [66–68] at next-to-leading order (NLO), with full NLO corrections with finite top mass, using the PDF4LHC parton distribution function (PDF) set. Parton showers and hadronization were simulated with Pythia 8 version 8.244 parton shower model [69], with the A14 set of tuned parameters [70, 71] and the NNPDF23LO PDF set [72]. The EvtGen v1.6.0 program [60] is used to model the properties of the bottom and charm hadron decays.

SM di-Higgs process via vector boson fusion (VBF) was generated at leading-order (LO) using MadGraph version 2.7.3 [73], with the NNPDF30NLO PDF set [74]. Parton showering and hadronization are performed using Pythia 8 version 8.244 [69] with the A14 set of tuned parameters and the NNPDF23LO PDF set [72]. The EvtGen v1.7.0 program [60] is used for the bottom and charm hadron decays. Below, the non-resonant signal samples with the corresponding reconstruction tags used in this study:

ggF: mc16_13TeV.600029.PH7EG.PDF4LHC15_HHbbtauLepHad.cHHH01d0.recon.ESD.e8269_e7400_s3126_r12406;

VBF: mc16_13TeV.502993.MGPy8EG.hh.bbtt.vbf.novhh.lh.l1cvv1cv1.recon.ESD.e8273.e7400.s3126.r12406.

These samples are processed within the L1Calo group framework named **NtupleDumper** in order to obtain L1 objects, offline and truth particles information. Afterwards, the event selection is applied by using a modified version of the $b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$ trigger **Inventor analysis**. The main task in this project consisted of adapting this analysis package to the $b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ channel by implementing L1 electron objects, methods and triggers.

8.3 Offline selection

In this study the following offline event selection is implemented: offline taus are required to have a $p_T > 20$ GeV and have 1 or 3 tracks satisfying a 'loose' working point in a RNN identification algorithm [75], an overlap removal procedure between offline taus and electrons removes the taus if $\Delta R < 0.2$ between them and each one is required to be truth-matched within $\Delta R < 0.3$ cone. In a similar way, an overlap removal between offline jets and taus discards the jet if it is within $\Delta R < 0.3$. Offline electrons must have $p_T < 7$ GeV and pass a 'LHMedium' identification criteria [76]. At least 2 offline jets are required with $p_T > 20$ GeV and $|\eta| < 2.5$.

8.4 L1 selection

Level 1 selection is emulated by the following requirements: L1 taus with $E_T < 60$ GeV are required to be isolated, satisfying $\tau_{\text{iso}} < E_T/10 + 2$ GeV, L1 electrons cuts are applied depending on the EM and hadronic isolation cuts:

- when E_T is at least 10 GeV the hadronic isolation is required to satisfy $e_{\text{iso}}^{(\text{had})} < (E_T/23 - 0.2)$ GeV;
- when E_T is at least 20 GeV the EM isolation is required to satisfy $e_{\text{iso}}^{(\text{EM})} < (E_T/8 - 1.8)$ GeV.

The overlap removal between L1 objects are defined as follows:

- between a tau and an electron, removing the tau if $\Delta R < 0.2$;
- between jets and taus, removing the jet if $\Delta R < 0.3$ for Run-3 or $\Delta R < 0.4$ for Run-2. Smaller tau RoIs in Run-3 explain the different choice of values.

8.5 L1 trigger items for electron+tau chains

In Run-2 the rate of electromagnetic triggers (EM) can be controlled by raising thresholds, adding hadronic core isolation (H), adding electromagnetic isolation (I) and varying thresholds with η to account for energy loss (V). Both hadronic core isolation and electromagnetic isolation (HI) is applied to preserve thresholds as long as possible. The following electron+tau trigger chains are investigated in this study for Run-2 and Run-3:

- L1_EM15VHL2TAU12IM_J25_3J12 (3J12);

- L1_EM20VHL_2TAU20IM_2TAU20_J25_3J20 (3J20);
- L1_EM15VHL_2TAU12IM_4J12 (4J12);
- L1DR-EM15TAU12I-J25 (L1Topo).

8.6 Trigger efficiency results

Trigger efficiency is defined as the ratio between the number of accepted to the total number of produced events. The overall purpose of any trigger is to maximize the physics acceptance keeping the vast majority of interesting events.

$$\varepsilon \equiv \frac{N(\text{events accepted})}{N(\text{events produced})}$$

Following the object reconstruction and the event selection described in Sections 4.1 and 4.2 respectively, the efficiency results for each electron+tau trigger chain are summarized in Tables 6 and 7:

Table 6: $hh \rightarrow b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ trigger efficiency (ggF sample)

(a) Run 2 Efficiencies		(b) Run 3 Efficiencies	
Trigger Chain	Efficiency	Trigger Chain	Efficiency
3J12	0.850546840654	3J12	0.45230936852
3J20	0.781995814348	3J20	0.43046898043
4J12	0.753864367373	4J12	0.388347461425
L1Topo	0.860017106289	L1Topo	0.458631228009

Table 7: $hh \rightarrow b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ trigger efficiency (VBF sample)

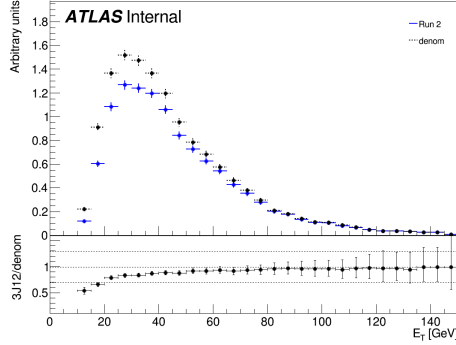
(a) Run 2 Efficiencies		(b) Run 3 Efficiencies	
Trigger Chain	Efficiency	Trigger Chain	Efficiency
3J12	0.83235916086	3J12	0.382052697108
3J20	0.718044411983	3J20	0.355033810568
4J12	0.817809091266	4J12	0.366463711319
L1Topo	0.838593409567	L1Topo	0.38170588117

It is not fully understood yet why Run-3 efficiency results show a significant drop when compared to Run-2. The impact of this drop in some of the kinematic distributions of the reconstructed objects is presented in Sections 8.7 and 8.8.

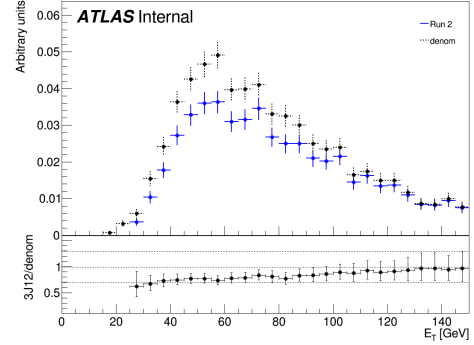
8.7 Kinematic distributions - ggF non-resonant sample

The overall effect of the triggers considering Run-2 and Run-3 can be directly appreciated from the kinematic variables distributions, when one compares the L1 reconstructed objects with their

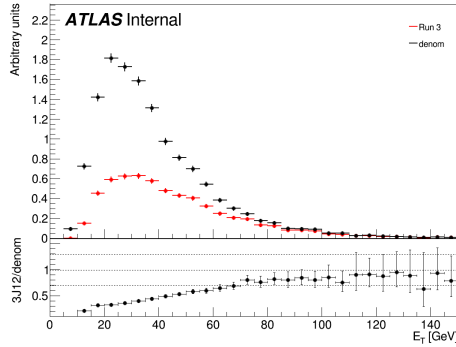
1095 counterpart after the trigger that keeps the events of interest, particularly with the softer shape of
 1096 the E_T distributions. In each of the following plots, the **denom** distribution represents the events
 1097 when no triggers are applied, providing a trigger efficiency visualization for the different reconstructed
 1098 objects.



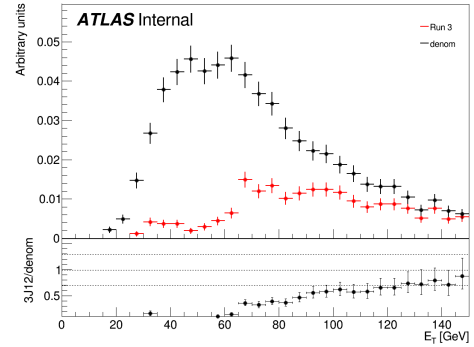
(a) Run 2 Leading L1 Jet E_T Distribution



(b) Run 2 Leading Jet Passing Trigger E_T Distribution



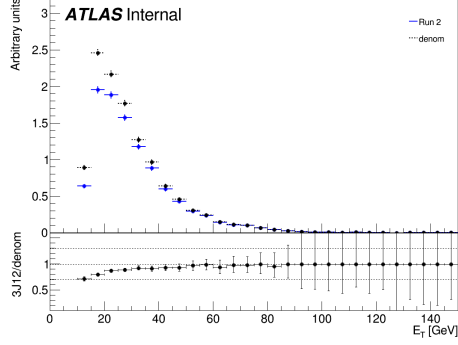
(c) Run 3 Leading L1 Jet E_T Distribution



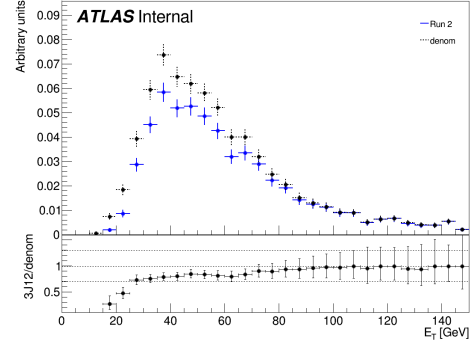
(d) Run 3 Leading Jet Passing Trigger E_T Distribution

Figure 39: Side-by-side leading jet E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section).

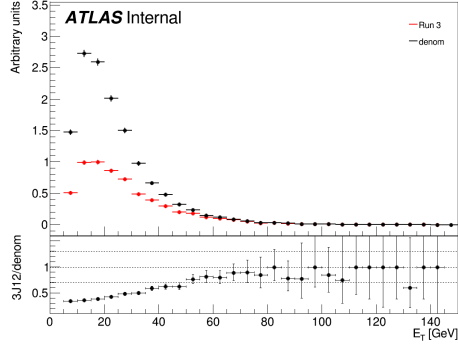
1099 Anomalies in the shape/behavior of the Run 3 simulated events passing the triggers can be ap-
 1100 preciated for $E_T < 60$ GeV which can be seen in Fig. 39d with heavily suppressed events. The rest
 1101 of the objects composing the Higgs pairs system show the following distributions:



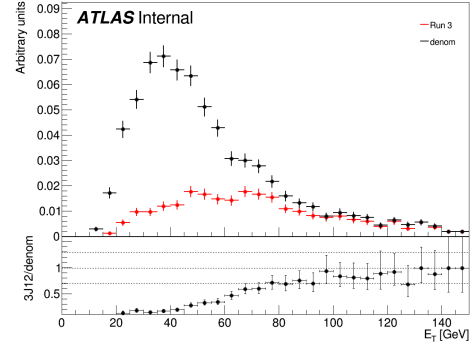
(a) Run 2 Sub-leading L1 Jet E_T Distribution



(b) Run 2 Sub-leading Jet Passing Trigger E_T Distribution

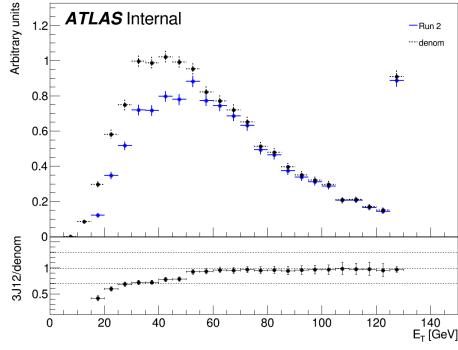


(c) Run 3 Sub-leading L1 Jet E_T Distribution

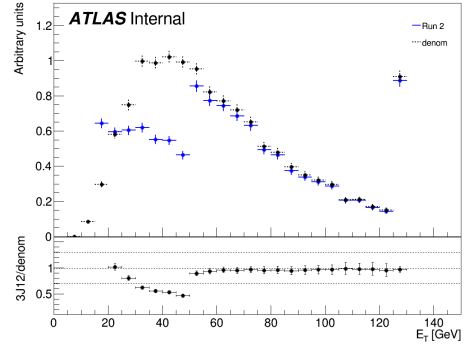


(d) Run 3 Sub-leading Jet Passing Trigger E_T Distribution

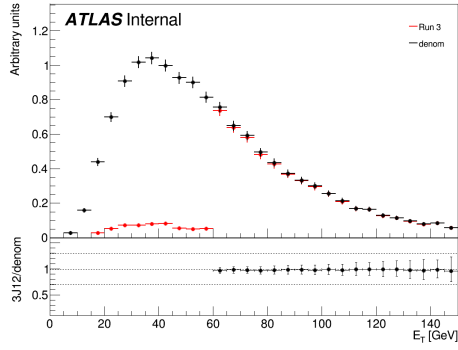
Figure 40: Side-by-side sub-leading jet E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)



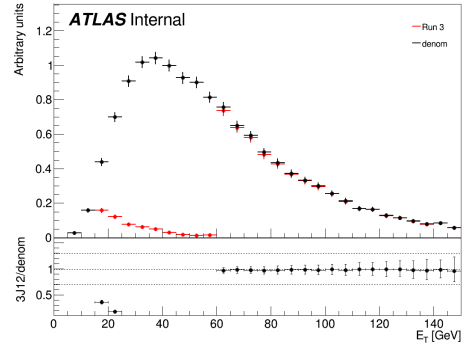
(a) Run 2 L1 Electron E_T Distribution



(b) Run 2 Electron Passing Trigger E_T Distribution



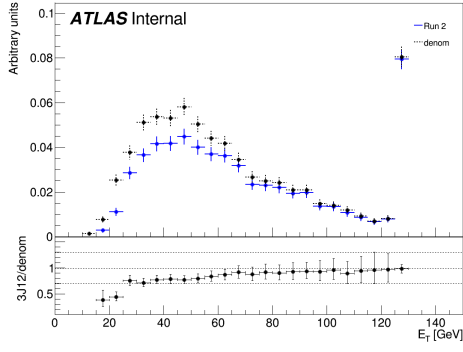
(c) Run 3 L1 Electron E_T Distribution



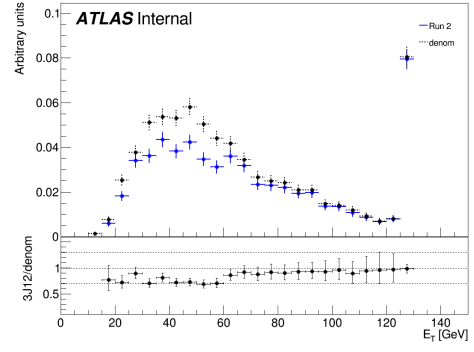
(d) Run 3 Electron Passing Trigger E_T Distribution

Figure 41: Side-by-side electron E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section).

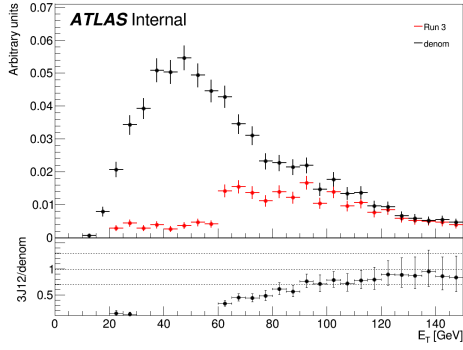
1102 For Fig 41b the electrons distributions show that for $E_T < 50$ GeV there is a significant drop and
 1103 shape modification, not yet fully understood.



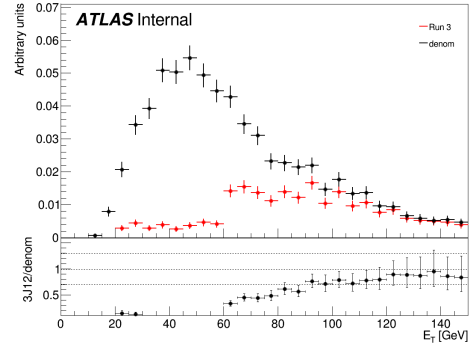
(a) Run 2 L1 Tau-1 E_T Distribution



(b) Run 2 Tau-1 Passing Trigger E_T Distribution

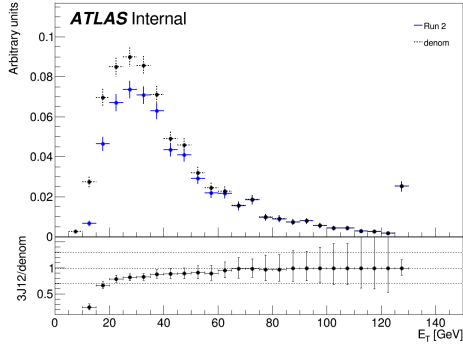


(c) Run 3 L1 Tau-1 E_T Distribution

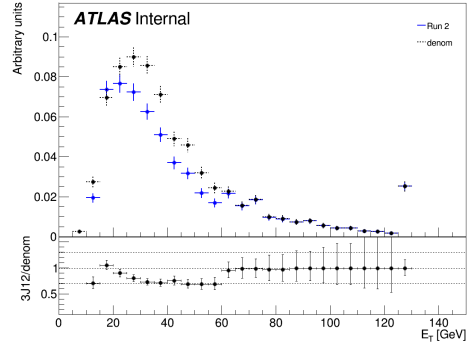


(d) Run 3 Tau-1 Passing Trigger E_T Distribution

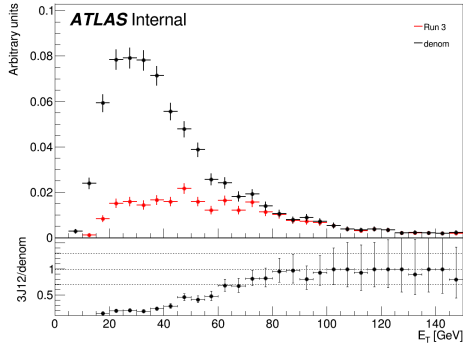
Figure 42: Side-by-side tau-1 E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)



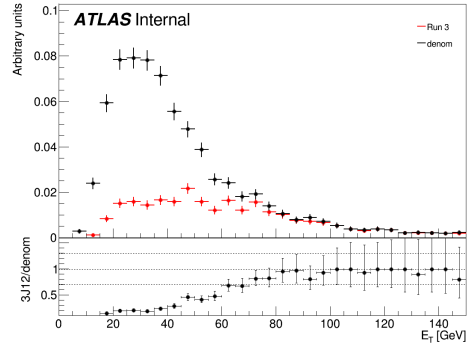
(a) Run 2 L1 Tau-2 E_T Distribution



(b) Run 2 Tau-2 Passing Trigger E_T Distribution



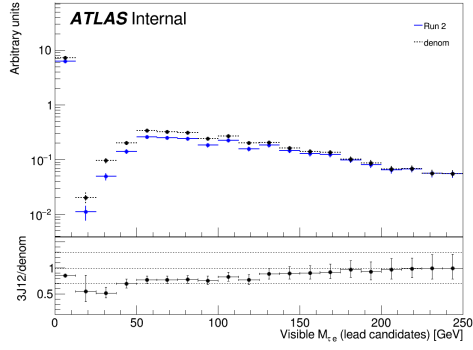
(c) Run 3 L1 Tau-2 E_T Distribution



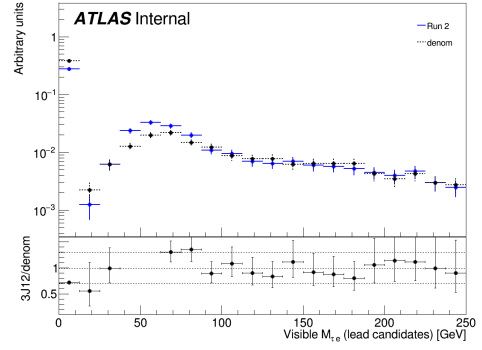
(d) Run 3 Tau-2 Passing Trigger E_T Distribution

Figure 43: Side-by-side tau-2 E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)

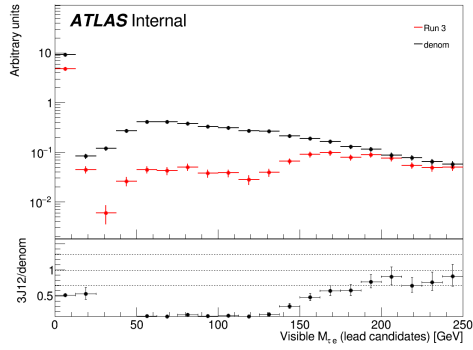
Finally for the reconstructed masses:



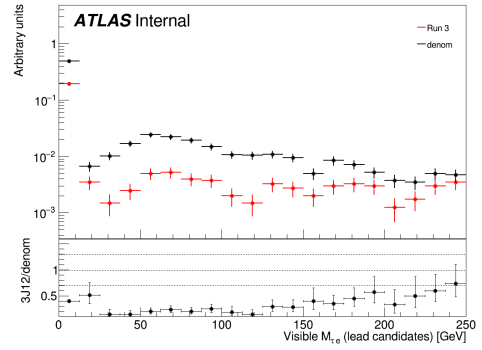
(a) Run 2 L1 di-Tau Mass



(b) Run 2 passing di-Tau Mass

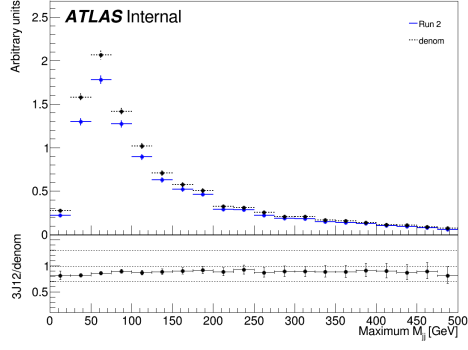


(c) Run 3 L1 di-Tau Mass

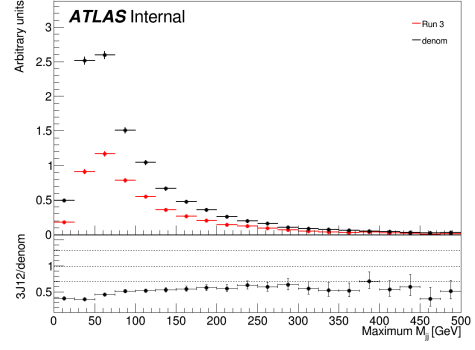


(d) Run 3 passing di-Tau Mass

Figure 44: Log scaled passing di-tau mass distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)

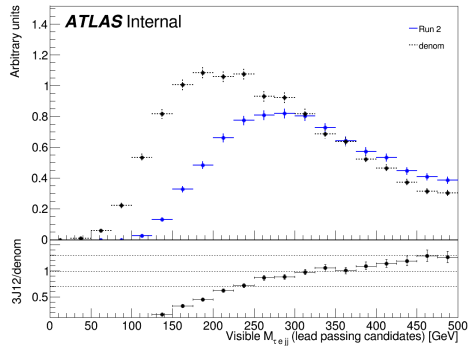


(a) Run 2 passing di-jet Mass

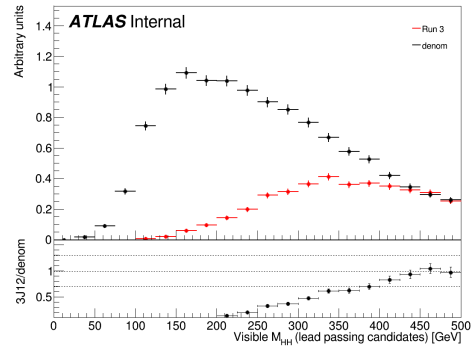


(b) Run 3 passing di-jet Mass

Figure 45: Di-jet system reconstructed mass passing trigger (scaled properly with the cross-section)



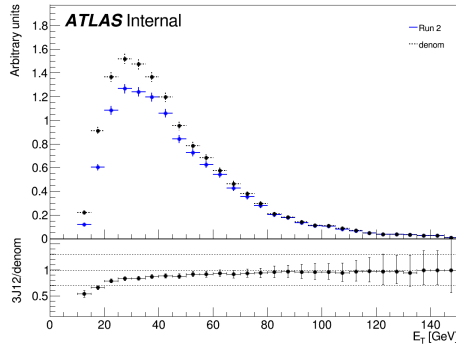
(a) Run 2 di-Higgs mass



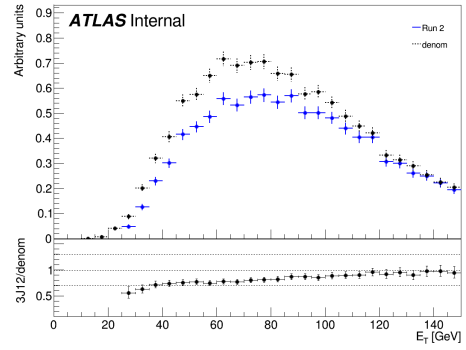
(b) Run 3 di-Higgs mass

Figure 46: Di-Higgs reconstructed mass (scaled properly with the cross-section)

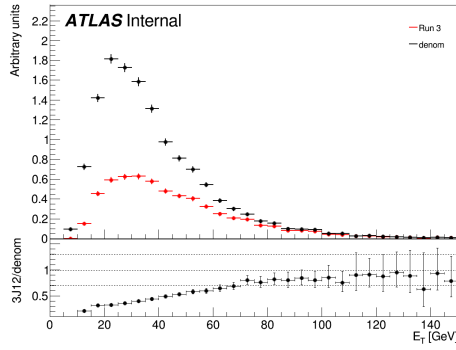
1105 **8.8 Kinematic distributions - VBF non-resonant sample**



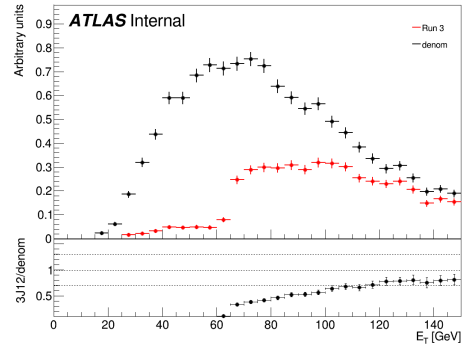
(a) Run 2 Leading L1 Jet E_T Distribution



(b) Run 2 Leading Jet Passing Trigger E_T Distribution

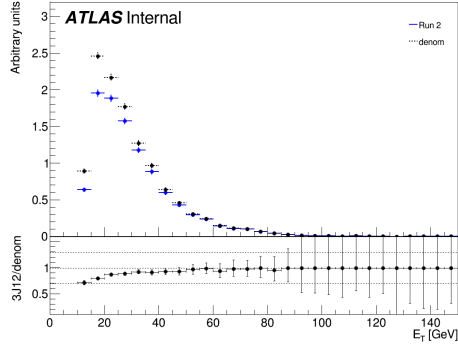


(c) Run 3 Leading L1 Jet E_T Distribution

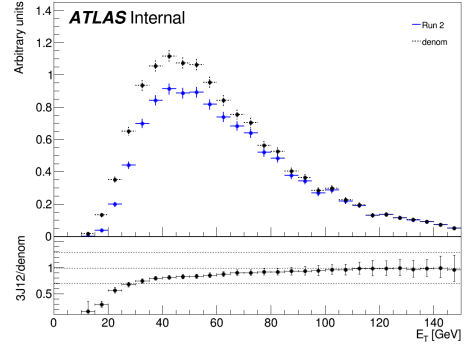


(d) Run 3 Leading Jet Passing Trigger E_T Distribution

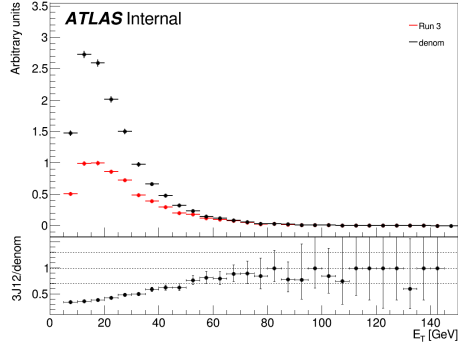
Figure 47: Side-by-side leading jet E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section).



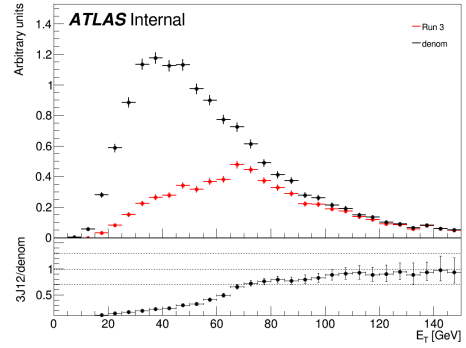
(a) Run 2 Sub-leading L1 Jet E_T Distribution



(b) Run 2 Sub-leading Jet Passing Trigger E_T Distribution

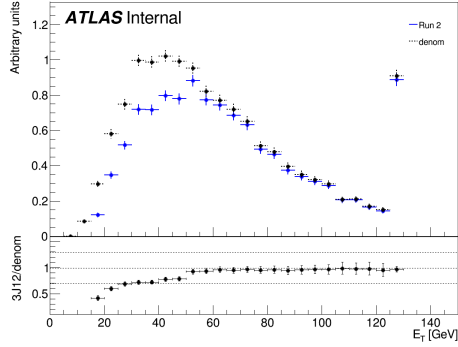


(c) Run 3 Sub-leading L1 Jet E_T Distribution

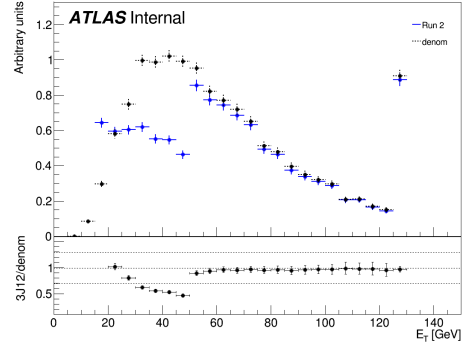


(d) Run 3 Sub-leading Jet Passing Trigger E_T Distribution

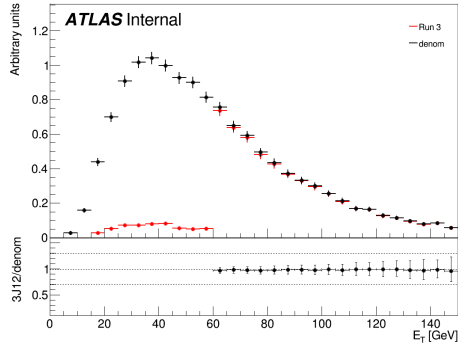
Figure 48: Side-by-side sub-leading jet E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)



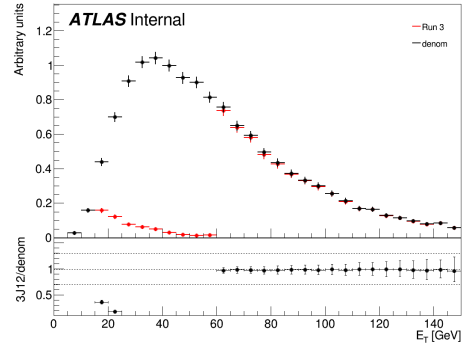
(a) Run 2 L1 Electron E_T Distribution



(b) Run 2 Electron Passing Trigger E_T Distribution

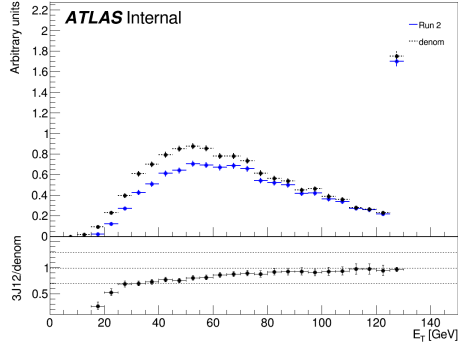


(c) Run 3 L1 Electron E_T Distribution

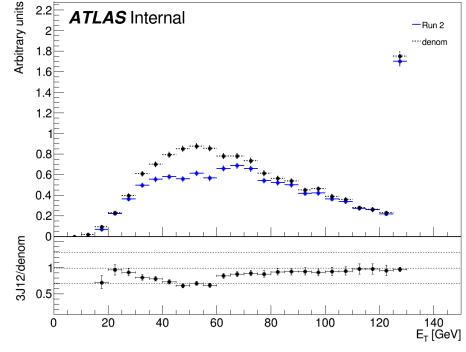


(d) Run 3 Electron Passing Trigger E_T Distribution

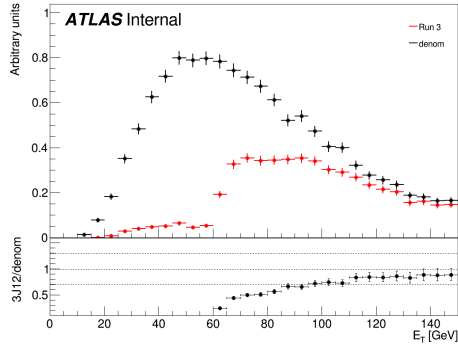
Figure 49: Side-by-side electron E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section).



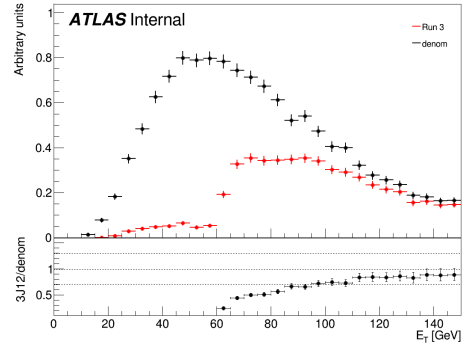
(a) Run 2 L1 Tau-1 E_T Distribution



(b) Run 2 Tau-1 Passing Trigger E_T Distribution

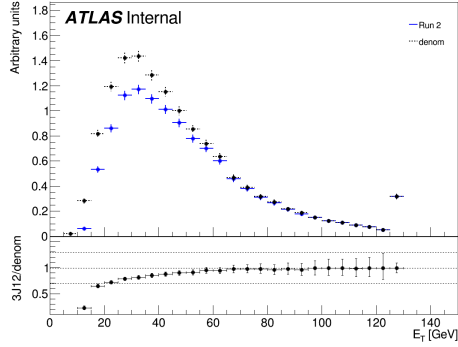


(c) Run 3 L1 Tau-1 E_T Distribution

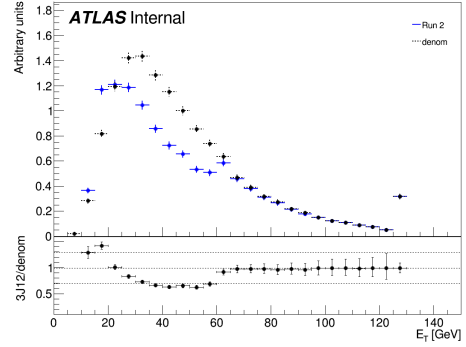


(d) Run 3 Tau-1 Passing Trigger E_T Distribution

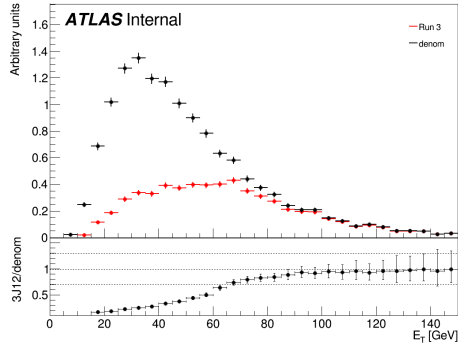
Figure 50: Side-by-side tau-1 E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)



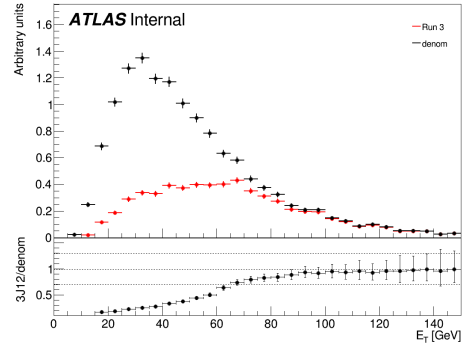
(a) Run 2 L1 Tau-2 E_T Distribution



(b) Run 2 Tau-2 Passing Trigger E_T Distribution



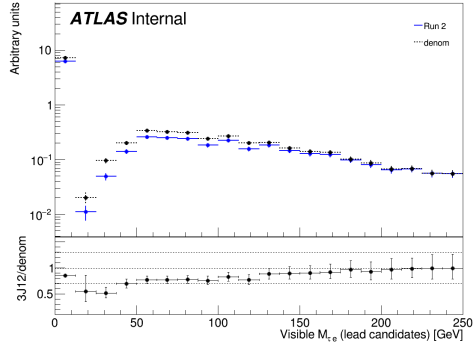
(c) Run 3 L1 Tau-2 E_T Distribution



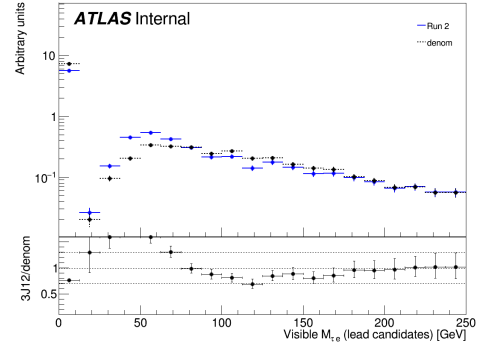
(d) Run 3 Tau-2 Passing Trigger E_T Distribution

Figure 51: Side-by-side tau-2 E_T distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)

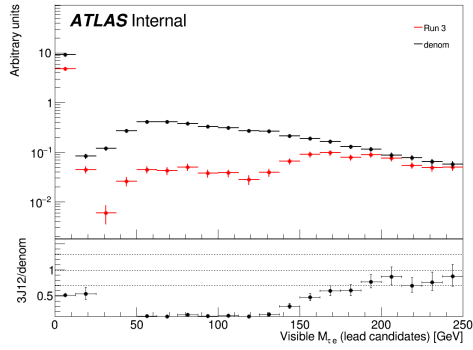
Finally for the reconstructed masses:



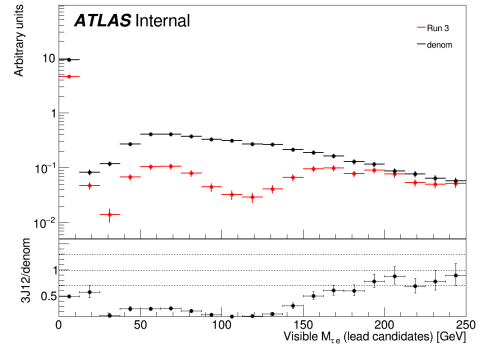
(a) Run 2 L1 di-Tau Mass



(b) Run 2 passing di-Tau Mass

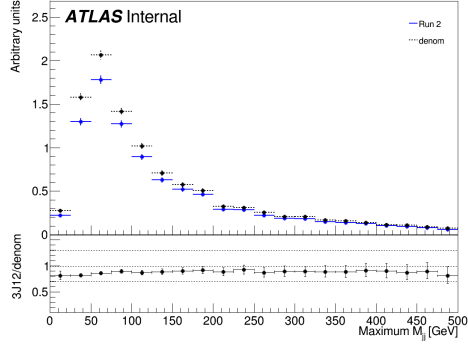


(c) Run 3 L1 di-Tau Mass

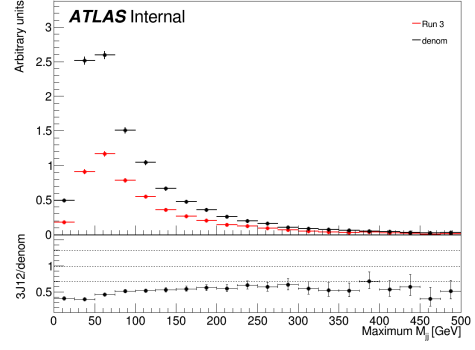


(d) Run 3 passing di-Tau Mass

Figure 52: Log scaled di-tau mass distribution before (left) and after (right) the combined trigger chain **3J12** (scaled properly with the cross-section)

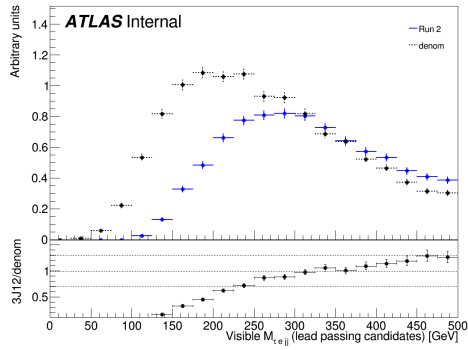


(a) Run 2 passing di-jet Mass

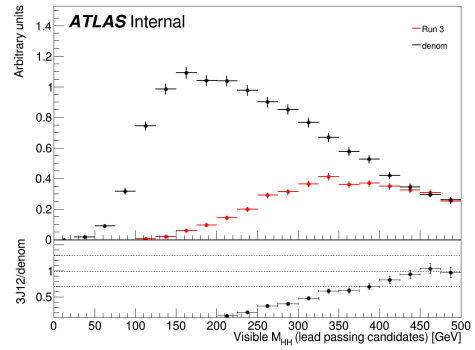


(b) Run 3 passing di-jet Mass

Figure 53: Di-jet system reconstructed mass passing trigger (scaled properly with the cross-section)



(a) Run 2 di-Higgs mass



(b) Run 3 di-Higgs mass

Figure 54: Di-Higgs reconstructed mass (scaled properly with the cross-section)

9 Conclusions

A study on the reconstruction of simulated heavy resonances $X \rightarrow hh$, in the energy range 1-3 TeV using the collinear mass method approximation technique, combined with a χ^2 fit to reconstruct tau pair objects on the $b\bar{b}\tau^+\tau^-$ fully hadronic channel was presented. The collinear mass approximation was found unsuited for the tau pair reconstruction under these conditions, an extremely boosted topology produces tau subjets too collimated to apply the approximation as the reconstructed tau pair mass present non-physical solutions to their missing momentum due to their near negligible angular distance with respect to the subjets. The χ^2 fit with kinematics constraints related to the collinear mass approximation proven to show a significant improvement on the invariant mass reconstruction. Regardless, the approximation (when could be applied) shows better results as the tau pair and Higgs pair objects 4-momenta can be fully reconstructed from the analysis of the missing objects, this objects can be further analysed but as the result is highly sensitive to the Missing Transverse Energy measure, such analysis should be done with awareness. The Higgs pairs masses reconstructed using these methods show propagation of the long-tailed ends characterized by the collinear mass reconstruction and suppression to the missing transversal energy is advised as processes like $Z \rightarrow \tau^-\tau^+$ are very disruptive for the Higgs reconstruction. Nonetheless such techniques are low-cost in terms of complexity and can be used as an advantageous first iteration for more sophisticated reconstruction methods.

The expense to paid for the χ^2 is that missing momentum values near the 125[GeV] value are heavily suppressed and the missing momentum obtained from the solution to the missing energy objects projection in the transversal plane could not be replicated morphologically, the χ^2 approach, being a statistical one, requires additional checks, another problem that could arise from this approach is the sculpting of the background if one tries to reconstruct a background sample, these considerations are deemed problematic and requires further study.

Future work regarding these methods is to cross-check the behaviour of the method regarding reconstruction of tau and Higgs pairs using background and data samples to study the effect of the kinematics constraints imposed by the χ^2 minimization. Another continuation to the studies could include the comparison respect to other tau pair mass reconstruction techniques, the study of uncertainties and cross section limits by means of an statistical analysis.

In regards to the trigger studies, a very preliminary set of studies with electron+tau trigger chains were presented. These studies aim to evaluate the impact different Run-2 and Run-3 L1 inputs have in some of the $\tau_{\text{lep}}\tau_{\text{had}}$ triggers currently being used by the Run-2 di-Higgs search in the $HH \rightarrow b\bar{b}\tau\tau$ channel. L1 selections were emulated so that the number of L1 objects passing the corresponding thresholds varies for each combined L1 item considered. One would expect similar efficiencies between Run-2 and Run-3, however, there is a significant drop in Run-3, reflected in the kinematic distributions, not yet fully understood. Some of the electron kinematic distributions indicate possible miss-identification which will be further investigated, reflected in the lack of agreement in the shape between the passing electron E_T distribution when no trigger chain is applied and when the trigger fires like in 41b and 49b.

References

- [1] ATLAS Collaboration,, *Searches for Higgs boson pair production in the $hh \rightarrow b\bar{b}\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma b\bar{b}$, $bbbb$ channels with the ATLAS detector*, Phys. Rev. D **92** (2015) 092004,
<https://link.aps.org/doi/10.1103/PhysRevD.92.092004>.
- [2] ATLAS Collaboration,, *Combination of searches for Higgs boson pairs in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, Physics Letters B **800** (2020) 135103,
<https://www.sciencedirect.com/science/article/pii/S0370269319308251>.
- [3] CMS Collaboration,, *Search for two Higgs bosons in final states containing two photons and two bottom quarks in proton-proton collisions at 8 TeV*, Phys. Rev. D **94** (2016) 052012,
<https://link.aps.org/doi/10.1103/PhysRevD.94.052012>.
- [4] CMS Collaboration,, *Search for Higgs boson pair production in the $b\bar{b}\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 8\text{ TeV}$* , Phys. Rev. D **96** (2017) 072004,
<https://link.aps.org/doi/10.1103/PhysRevD.96.072004>.
- [5] CMS Collaboration,, *Combination of Searches for Higgs Boson Pair Production in Proton-Proton Collisions at $\sqrt{s} = 13\text{ TeV}$* , Phys. Rev. Lett. **122** (2019) 121803,
<https://link.aps.org/doi/10.1103/PhysRevLett.122.121803>.
- [6] ATLAS Collaboration,, *Search for Resonant and Nonresonant Higgs Boson Pair Production in the $b\bar{b}\tau^+\tau^-$ Decay Channel in pp Collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS Detector*, Phys. Rev. Lett. **121** (2018) 191801,
<https://link.aps.org/doi/10.1103/PhysRevLett.121.191801>.
- [7] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett. **13** (1964) 508–509, <https://link.aps.org/doi/10.1103/PhysRevLett.13.508>.
- [8] ATLAS Collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1–29, [arXiv:1207.7214](https://arxiv.org/abs/1207.7214) [hep-ex].
- [9] CMS Collaboration, S. Chatrchyan et al., *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, Phys. Lett. B **716** (2012) 30–61, [arXiv:1207.7235](https://arxiv.org/abs/1207.7235) [hep-ex].
- [10] M. Gell-Mann, *A schematic model of baryons and mesons*, Physics Letters **8** (1964) 214–215,
<https://www.sciencedirect.com/science/article/pii/S0031916364920013>.
- [11] P. D. G. et al, *Review of Particle Physics*, Progress of Theoretical and Experimental Physics **2020** (2020),
<https://academic.oup.com/ptep/article-pdf/2020/8/083C01/34673722/ptaa104.pdf>,
<https://doi.org/10.1093/ptep/ptaa104>, 083C01.

- [12] S. L. Glashow, *Partial-symmetries of weak interactions*, Nuclear Physics **22** (1961) 579–588,
<https://www.sciencedirect.com/science/article/pii/0029558261904692>.
- [13] S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (1967) 1264–1266,
<https://link.aps.org/doi/10.1103/PhysRevLett.19.1264>.
- [14] P. W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. **145**
(1966) 1156–1163, <https://link.aps.org/doi/10.1103/PhysRev.145.1156>.
- [15] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev.
Lett. **13** (1964) 321–323, <https://link.aps.org/doi/10.1103/PhysRevLett.13.321>.
- [16] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global Conservation Laws and Massless
Particles*, Phys. Rev. Lett. **13** (1964) 585–587,
<https://link.aps.org/doi/10.1103/PhysRevLett.13.585>.
- [17] W. B. Rolnick, *The Fundamental Particles and Their Interactions*. Addison-Wesley, 1994.
- [18] V. A. Rubakov and S. S. Wilson, *Classical Theory of Gauge Fields*. Princeton University Press,
2002.
- [19] UA1 Collaboration, G. e. a. Arnison, *Experimental Observation of Isolated Large Transverse
Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV*, Phys. Lett. B **122** (1983)
103–116.
- [20] UA1 Collaboration, G. e. a. Arnison, *Experimental Observation of Lepton Pairs of Invariant
Mass Around 95-GeV/c² at the CERN SPS Collider*, Phys. Lett. B **126** (1983) 398–410.
- [21] M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. M. Lindert, and J. Mazzitelli,
Higgs boson pair production at NNLO with top quark mass effects, JHEP **05** (2018) 059,
arXiv:1803.02463 [hep-ph].
- [22] F. A. Dreyer and A. Karlberg, *Vector-boson fusion Higgs pair production at N³LO*, Phys. Rev.
D **98** (2018) 114016, <https://link.aps.org/doi/10.1103/PhysRevD.98.114016>.
- [23] G. Branco, P. Ferreira, L. Lavoura, M. Rebelo, M. Sher, and J. P. Silva, *Theory and
phenomenology of two-Higgs-doublet models*, Physics Reports **516** (2012) 1–102,
<https://www.sciencedirect.com/science/article/pii/S0370157312000695>, Theory and
phenomenology of two-Higgs-doublet models.
- [24] A. Djouadi, *The anatomy of electroweak symmetry breaking Tome II: The Higgs bosons in the
Minimal Supersymmetric Model*, Physics Reports **459** (2008) 1–241,
<https://doi.org/10.1016%2Fj.physrep.2007.10.005>.
- [25] S. Dawson and M. Sullivan, *Enhanced di-Higgs boson production in the complex Higgs singlet
model*, Physical Review D **97** (2018), <https://doi.org/10.1103%2Fphysrevd.97.015022>.

- [26] ATLAS Collaboration, G. Aad et al., *Search for neutral MSSM Higgs bosons decaying to $\tau^+\tau^-$ pairs in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Physics Letters B **705** (2011) 174–192, <https://www.sciencedirect.com/science/article/pii/S0370269311012330>.
- [27] L. Evans and P. Bryant, *LHC Machine*, Journal of Instrumentation **3** (2008) S08001–S08001, <https://doi.org/10.1088/1748-0221/3/08/s08001>.
- [28] C. Lefèvre, *The CERN accelerator complex. Complexe des accélérateurs du CERN*, 2008. <https://cds.cern.ch/record/1260465>.
- [29] G. Barr, R. Devenish, R. Alczak, and T. Weldberg, *Particle Physics in the LHC era (Oxford Master Series in Physics)*. Oxford University Press, 2016.
- [30] I. Neutelings. https://tikz.net/axis3d_cms/.
- [31] ATLAS Collaboration, G. Aad and et al, *The ATLAS Experiment at the CERN Large Hadron Collider*, Journal of Instrumentation **3** (2008) S08003–S08003, <https://doi.org/10.1088/1748-0221/3/08/s08003>.
- [32] C. AC, *Layout of ATLAS. Dessin representant le detecteur ATLAS*, 1998. <https://cds.cern.ch/record/39038>.
- [33] J. Pequenaio, *Computer generated image of the ATLAS inner detector*, 2008. <https://cds.cern.ch/record/1095926>.
- [34] J. Pequenaio, *Computer Generated image of the ATLAS calorimeter*, 2008. <https://cds.cern.ch/record/1095927>.
- [35] ATLAS Collaboration Collaboration,, *ATLAS calorimeter performance: Technical Design Report*. Technical design report. ATLAS. CERN, Geneva, 1996. <https://cds.cern.ch/record/331059>.
- [36] ATLAS Collaboration, M. Aaboud et al., *Performance of the ATLAS Trigger System in 2015*, Eur. Phys. J. C **77** (2017) 317, [arXiv:1611.09661](https://arxiv.org/abs/1611.09661) [hep-ex].
- [37] ATLAS Collaboration,, *Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV*, <https://inspirehep.net/literature/1597609>.
- [38] D. Kirchmeier, *Reconstruction and Identification of Boosted Tau Pair Topologies at ATLAS*, Master’s thesis, Dresden, Tech. U., 5, 2015. <https://inspirehep.net/literature/1429473>.
- [39] ATLAS Collaboration,, *Performance of the Reconstruction and Identification of Hadronic Tau Decays in ATLAS with 2011 Data*, <https://inspirehep.net/literature/1204341>.

- [40] ATLAS Collaboration,, *Reconstruction and identification of boosted di- τ systems in a search for Higgs boson pairs using 13 TeV protonproton collision data in ATLAS*,
<https://arxiv.org/abs/2007.14811v2>.
- [41] Y. Freund and R. E. Schapire, *A Decision-Theoretic Generalization of On-Line Learning and an Application to Boosting*, Journal of Computer and System Sciences **55** (1997) 119–139,
<https://www.sciencedirect.com/science/article/pii/S002200009791504X>.
- [42] A. Hoecker and et al, *TMVA - Toolkit for Multivariate Data Analysis*, 2007.
<https://arxiv.org/abs/physics/0703039>.
- [43] ATLAS Collaboration,, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, <https://arxiv.org/abs/1603.02934>.
- [44] D. Krohn, J. Thaler, and L.-T. Wang, *Jet trimming*, Journal of High Energy Physics **2010** (2010), <https://doi.org/10.1007/2Fjhep02%282010%29084>.
- [45] ATLAS Collaboration, G. Aad and et al, *Performance of jet substructure techniques for large- R jets in proton-proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, JHEP **09** (2013) 076, [arXiv:1306.4945](https://arxiv.org/abs/1306.4945) [hep-ex].
- [46] ATLAS Collaboration,, *Jet mass reconstruction with the ATLAS Detector in early Run 2 data*,
<https://inspirehep.net/literature/1477266>.
- [47] D. Krohn, J. Thaler, and L.-T. Wang, *Jets with variable R* , Journal of High Energy Physics **2009** (2009) 059–059, <https://doi.org/10.1088/1126-6708/2009/06/059>.
- [48] ATLAS Collaboration,, *Variable Radius, Exclusive- k_T , and Center-of-Mass Subjet Reconstruction for Higgs($\rightarrow b\bar{b}$) Tagging in ATLAS*,
<https://inspirehep.net/literature/1795324>.
- [49] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, Physics Letters B **659** (2008) 119–126, <https://www.sciencedirect.com/science/article/pii/S0370269307011094>.
- [50] ATLAS Collaboration,, *Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run*, <https://inspirehep.net/literature/1795335>.
- [51] ATLAS Collaboration,, *Performance of b -jet identification in the ATLAS experiment*, Journal of Instrumentation **11** (2016) P04008–P04008,
<https://doi.org/10.1088/1748-0221/11/04/P04008>.
- [52] ATLAS Collaboration,, *Expected performance of the ATLAS b-tagging algorithms in Run-2*,
<https://inspirehep.net/literature/1795377>.
- [53] ATLAS Collaboration, M. Aaboud and et al, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, The European Physical Journal C **78** (2018),
<https://doi.org/10.1140/epjc%2Fs10052-018-6288-9>.

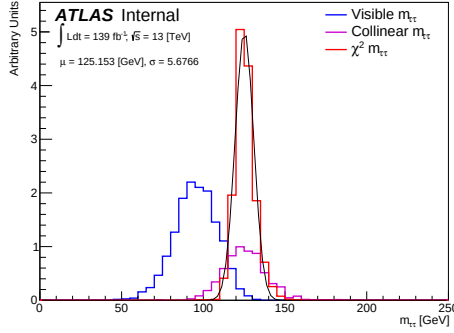
- [54] ATLAS Collaboration,, E_T^{miss} performance in the ATLAS detector using 2015-2016 LHC pp collisions, <https://inspirehep.net/literature/1679132>.
- [55] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5: going beyond*, Journal of High Energy Physics **2011** (2011), <https://doi.org/10.1007%2Fjhep06%282011%29128>.
- [56] J. Bellm, S. Gieseke, and et al, *Herwig 7.0/Herwig 3.0 release note*, The European Physical Journal C **76** (2016), <https://doi.org/10.1140%2Fepjc%2Fs10052-016-4018-8>.
- [57] R. D. Ball, V. Bertone, and et al, *Parton distributions with LHC data*, Nuclear Physics B **867** (2013) 244–289, <https://doi.org/10.1016%2Fj.nuclphysb.2012.10.003>.
- [58] R. D. Ball, , and V. B. et al, *Parton distributions for the LHC run II*, Journal of High Energy Physics **2015** (2015), <https://doi.org/10.1007%2Fjhep04%282015%29040>.
- [59] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, The European Physical Journal C **75** (2015), <https://doi.org/10.1140%2Fepjc%2Fs10052-015-3397-6>.
- [60] D. J. Lange, *The EvtGen particle decay simulation package*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **462** (2001) 152–155, <https://www.sciencedirect.com/science/article/pii/S0168900201000894>, BEAUTY2000, Proceedings of the 7th Int. Conf. on B-Physics at Hadron Machines.
- [61] S. Agostinelli, J. Allison, and et al, *Geant4—a simulation toolkit*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **506** (2003) 250–303, <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [62] R. Ellis, I. Hinchliffe, M. Soldate, and J. Van Der Bij, *Higgs decay to $\tau^+\tau^-$ a possible signature of intermediate mass Higgs bosons at high energy hadron colliders*, Nuclear Physics B **297** (1988) 221–243, <https://www.sciencedirect.com/science/article/pii/0550321388900193>.
- [63] O. Behnke, K. Kroniger, G. Schott, and T. Schorner-Sadenius, eds., *Data Analysis in High Energy Physics: A Practical Guide to Statistical Methods*. Wiley-VCH, 2013.
- [64] M. Aleksa, W. Cleland, Y. Enari, M. Fincke-Keeler, L. Hervas, F. Lanni, S. Majewski, C. Marino, and I. Wingerter-Seez, *ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report*, tech. rep., 9, 2013. <https://inspirehep.net/literature/1614085>.
- [65] ATLAS Collaboration, G. Aad et al., *Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System*, tech. rep., 9, 2013. <https://inspirehep.net/literature/1615722>.

- [66] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004) 040, [arXiv:hep-ph/0409146](#).
- [67] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **11** (2007) 070, [arXiv:0709.2092 \[hep-ph\]](#).
- [68] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043, [arXiv:1002.2581 \[hep-ph\]](#).
- [69] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159–177, [arXiv:1410.3012 \[hep-ph\]](#).
- [70] *ATLAS Pythia 8 tunes to 7 TeV data*, tech. rep., CERN, Geneva, Nov, 2014. <https://cds.cern.ch/record/1966419>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-021>.
- [71] *Summary of ATLAS Pythia 8 tunes*, tech. rep., CERN, Geneva, Aug, 2012. <https://cds.cern.ch/record/1474107>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2012-003>.
- [72] R. D. Ball, V. Bertone, S. Carrazza, C. S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, J. I. Latorre, J. Rojo, and M. Ubiali, *Parton distributions with LHC data*, Nuclear Physics B **867** (2013) 244–289, <https://www.sciencedirect.com/science/article/pii/S0550321312005500>.
- [73] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, JHEP **06** (2011) 128, [arXiv:1106.0522 \[hep-ph\]](#).
- [74] NNPDF Collaboration, R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040, [arXiv:1410.8849 \[hep-ph\]](#).
- [75] ATLAS Collaboration Collaboration, *Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment*, tech. rep., CERN, Geneva, Aug, 2019. <https://cds.cern.ch/record/2688062>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-033>.
- [76] ATLAS Collaboration, G. Aad et al., *Electron reconstruction and identification efficiency measurements with the ATLAS detector using the 2011 LHC proton-proton collision data*, Eur. Phys. J. C **74** (2014) 2941, [arXiv:1404.2240 \[hep-ex\]](#).

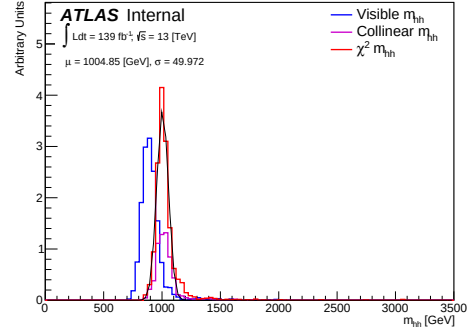
- 1348 [77] S. Catani, Y. Dokshitzer, M. Seymour, and B. Webber, *Longitudinally-invariant k -clustering*
1349 *algorithms for hadron-hadron collisions*, Nuclear Physics B **406** (1993) 187–224,
1350 <https://www.sciencedirect.com/science/article/pii/055032139390166M>.
- 1351 [78] M. Cacciari, G. P. Salam, and G. Soyez, *The anti- k_t jet clustering algorithm*, Journal of High
1352 Energy Physics **2008** (2008) 063, <https://dx.doi.org/10.1088/1126-6708/2008/04/063>.

1353 Appendix A Plots

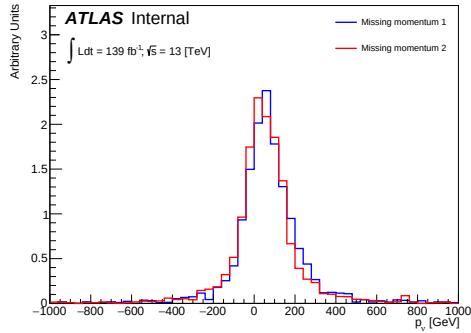
1354 A.1 Heavy mass $m_X = 1.0$ TeV kinematics variables



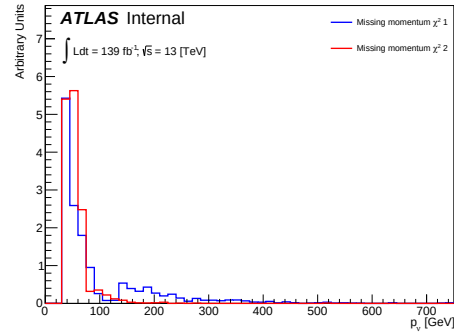
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.0$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.0$ TeV



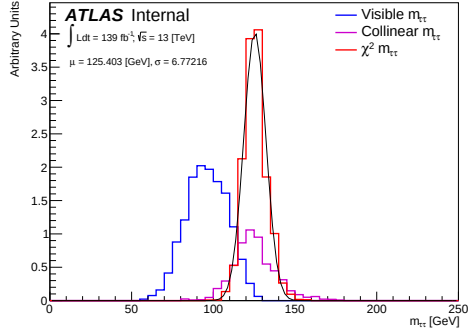
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.0$ TeV



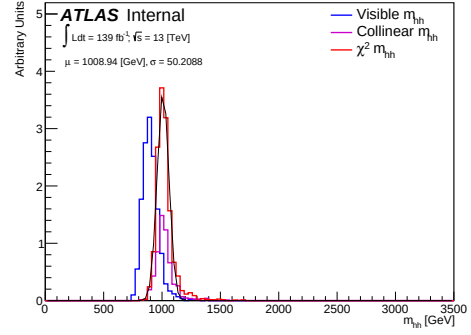
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.0$ TeV

Figure 55: Kinematics distribution for the heavy resonant mass $m_X = 1.0$ TeV

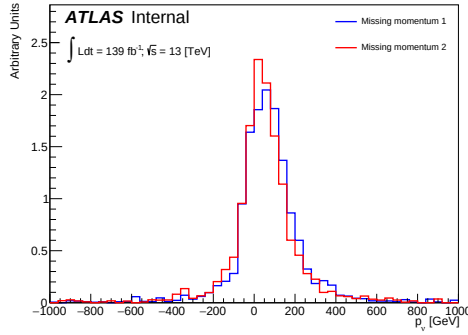
1355 **A.2 Heavy mass $m_X = 1.0$ TeV kinematics variables (HERWIG)**



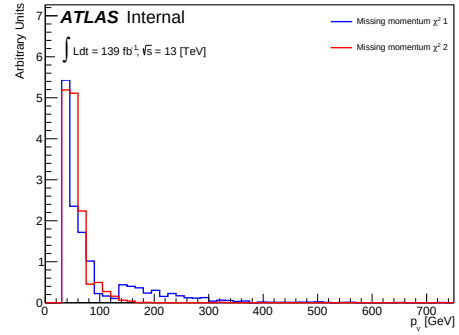
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.0$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.0$ TeV



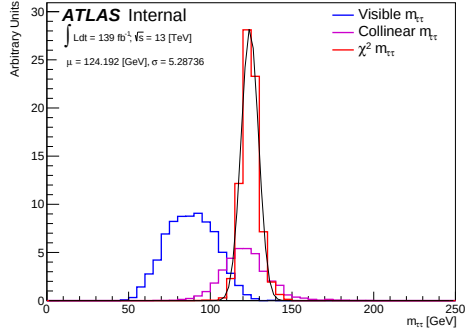
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.0$ TeV



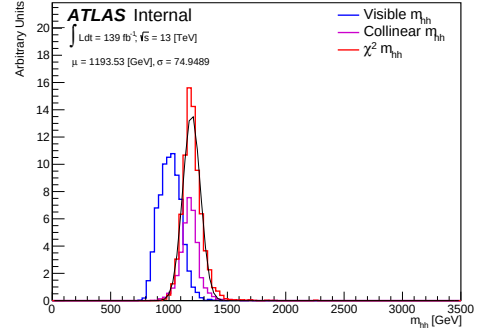
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.0$ TeV

Figure 56: Kinematics distribution for the heavy resonant mass $m_X = 1.0$ TeV

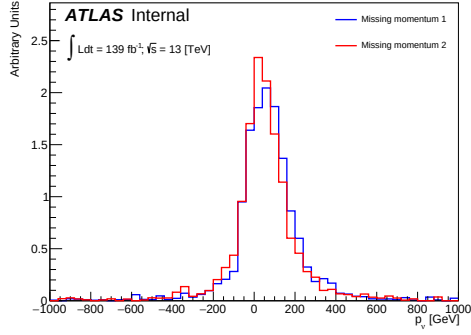
A.3 Heavy mass $m_X = 1.2$ TeV kinematics variables (HERWIG)



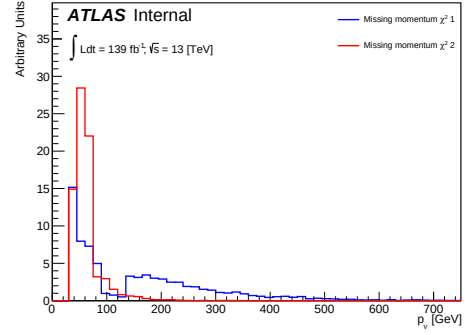
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.2$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.2$ TeV



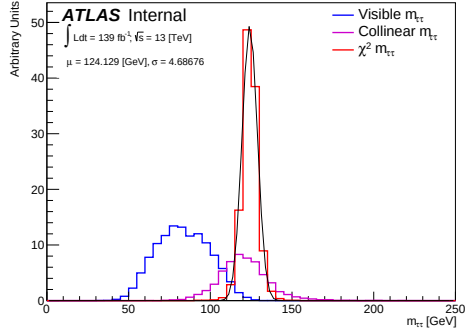
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.2$ TeV



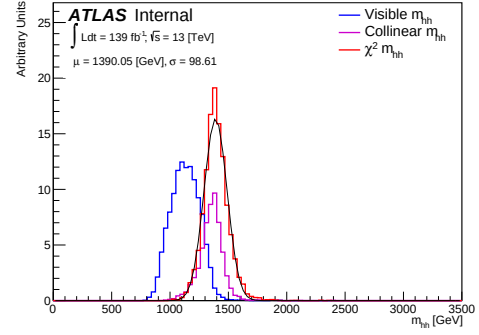
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.2$ TeV

Figure 57: Kinematics distribution for the heavy resonant mass $m_X = 1.2$ TeV

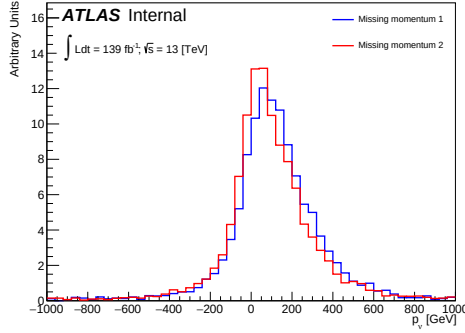
1357 **A.4 Heavy mass $m_X = 1.4$ TeV kinematics variables (HERWIG)**



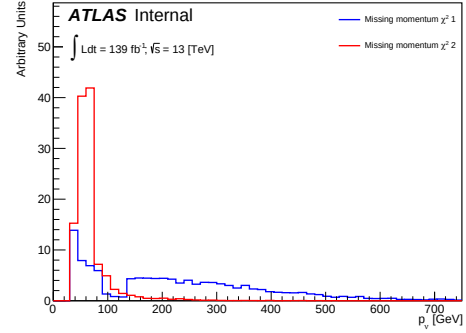
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.4$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.4$ TeV



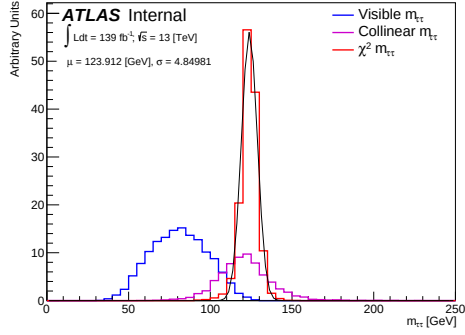
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.4$ TeV



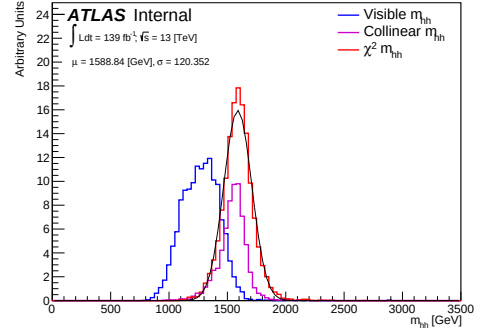
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.4$ TeV

Figure 58: Kinematics distribution for the heavy resonant mass $m_X = 1.4$ TeV

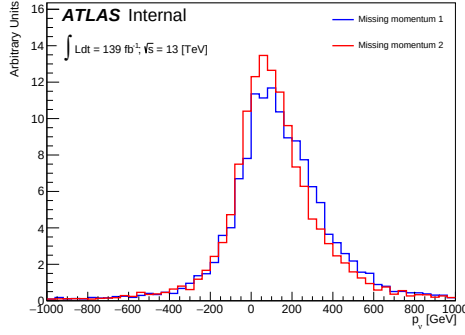
1358 **A.5 Heavy mass $m_X = 1.6$ TeV kinematics variables (HERWIG)**



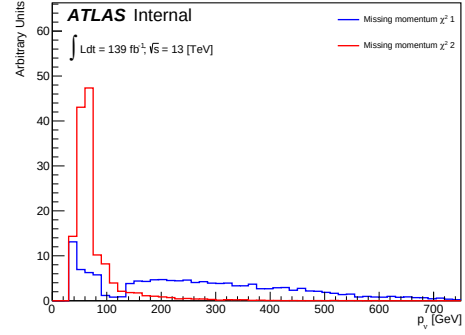
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.6$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.6$ TeV



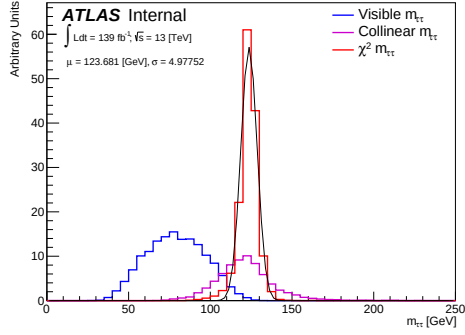
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.6$ TeV



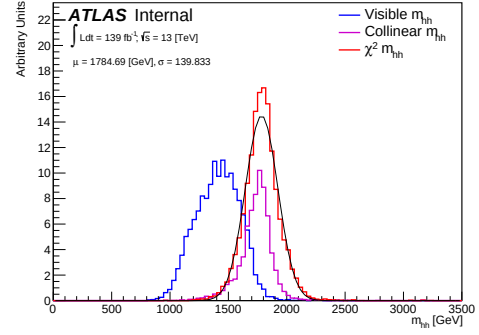
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.6$ TeV

Figure 59: Kinematics distribution for the heavy resonant mass $m_X = 1.6$ TeV

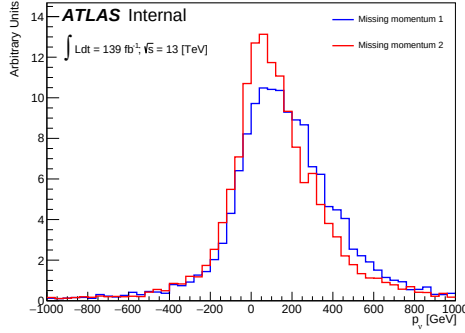
1359 **A.6 Heavy mass $m_X = 1.8$ TeV kinematics variables (HERWIG)**



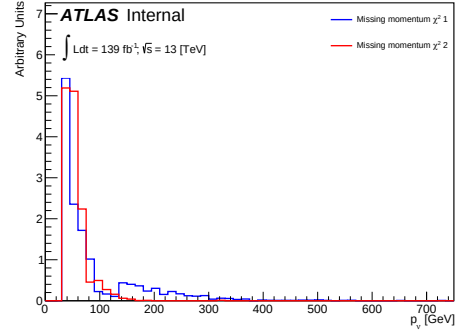
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.8$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 1.8$ TeV



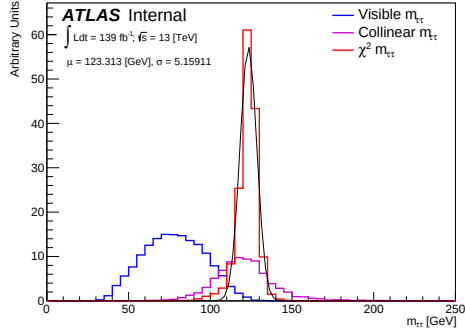
(c) p_{miss} distribution, produced for a resonant mass $m_X = 1.8$ TeV



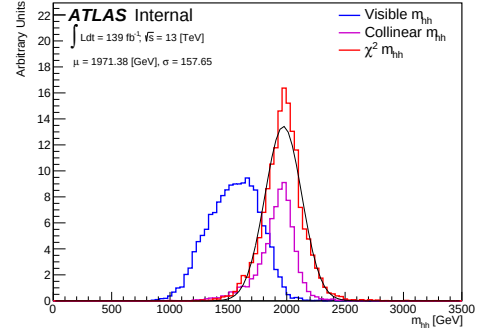
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 1.8$ TeV

Figure 60: Kinematics distribution for the heavy resonant mass $m_X = 1.8$ TeV

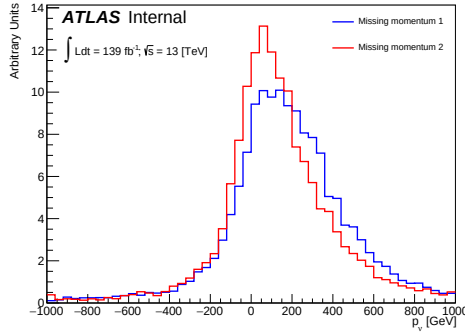
A.7 Heavy mass $m_X = 2.0$ TeV kinematics variables



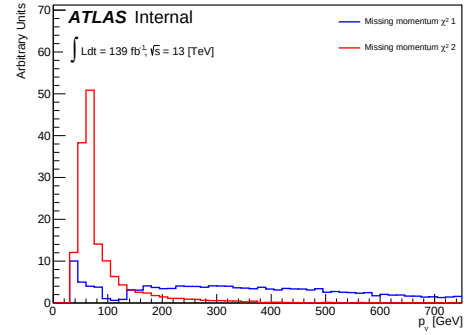
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 2.0$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 2.0$ TeV



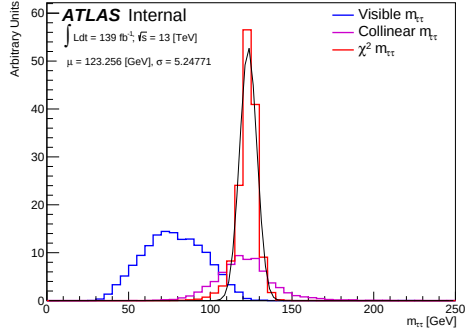
(c) p_{miss} distribution, produced for a resonant mass $m_X = 2.0$ TeV



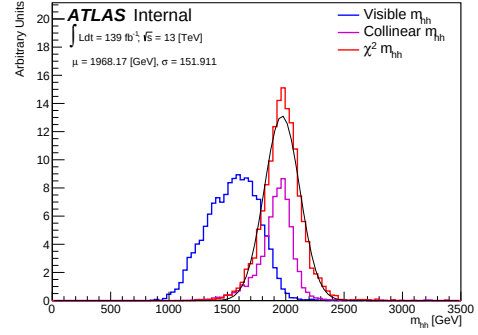
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 2.0$ TeV

Figure 61: Kinematics distribution for the heavy resonant mass $m_X = 2.0$ TeV

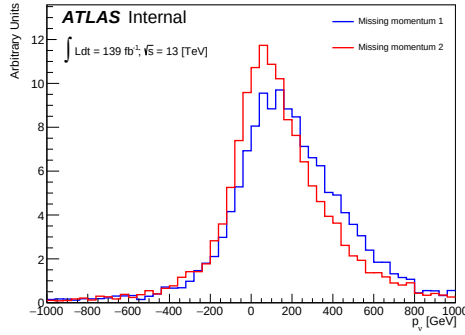
1361 **A.8 Heavy mass $m_X = 2.0$ TeV kinematics variables (HERWIG)**



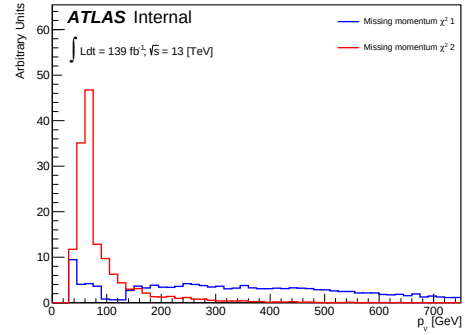
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 2.0$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 2.0$ TeV



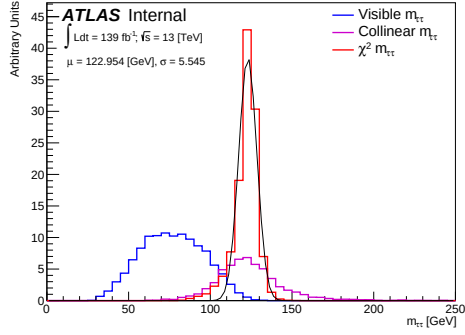
(c) p_{miss} distribution, produced for a resonant mass $m_X = 2.0$ TeV



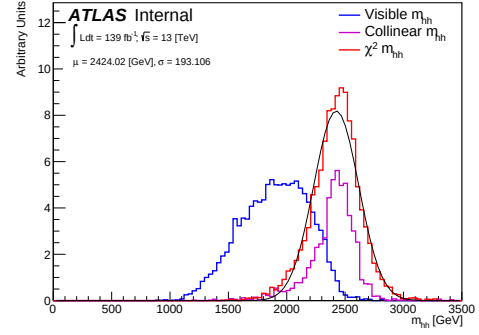
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 2.0$ TeV

Figure 62: Kinematics distribution for the heavy resonant mass $m_X = 2.0$ TeV

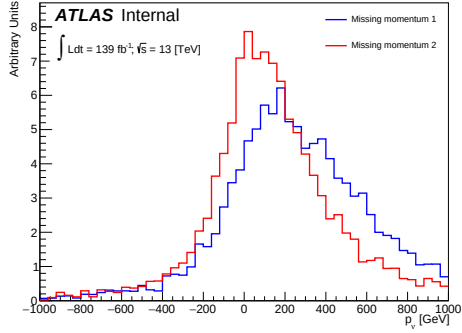
1362 **A.9 Heavy mass $m_X = 2.5$ TeV kinematics variables (HERWIG)**



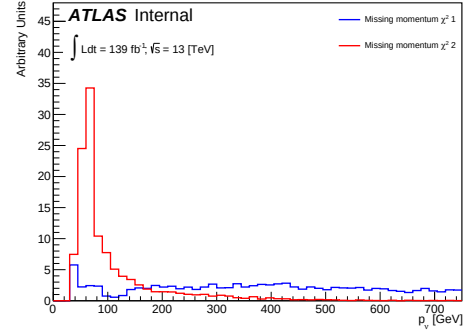
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 2.5$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 2.5$ TeV



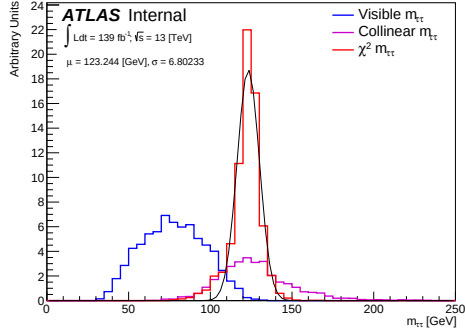
(c) p_{miss} distribution, produced for a resonant mass $m_X = 2.5$ TeV



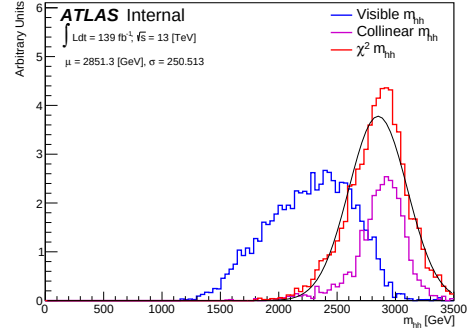
(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 2.5$ TeV

Figure 63: Kinematics distribution for the heavy resonant mass $m_X = 2.5$ TeV

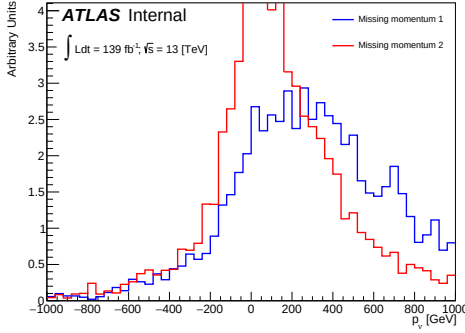
1363 **A.10 Heavy mass $m_X = 3.0$ TeV kinematics variables (HERWIG)**



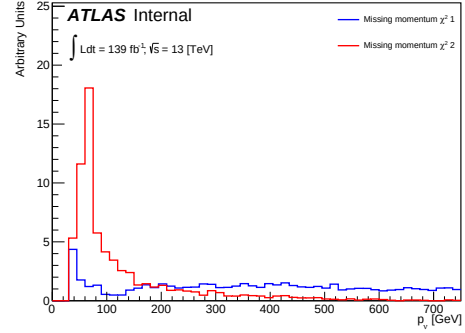
(a) $m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 3.0$ TeV



(b) m_{hh} distribution, produced for a resonant mass $m_X = 3.0$ TeV



(c) p_{miss} distribution, produced for a resonant mass $m_X = 3.0$ TeV

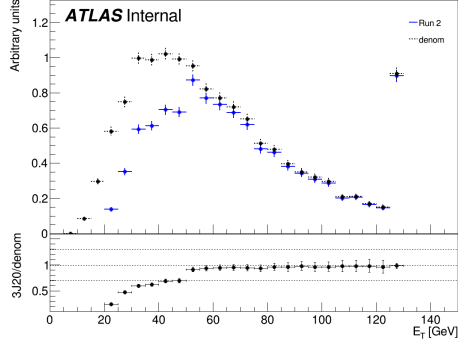


(d) p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X = 3.0$ TeV

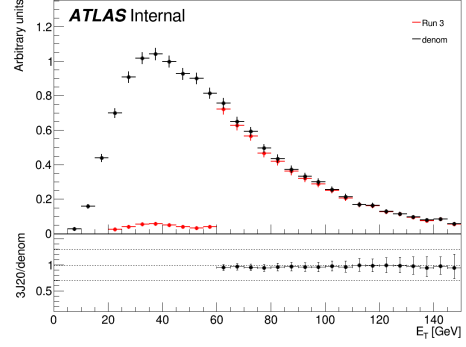
Figure 64: Kinematics distribution for the heavy resonant mass $m_X = 3.0$ TeV

1364 **Appendix B Kinematic distributions - ggF non-resonant sample**

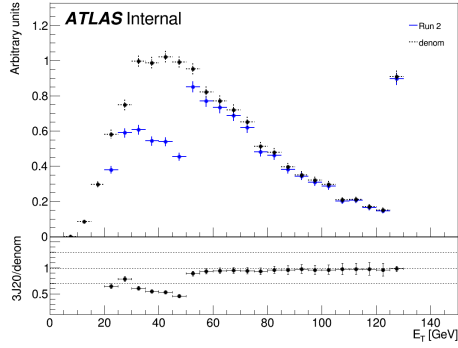
1365 **B.1 ggF 3J20**



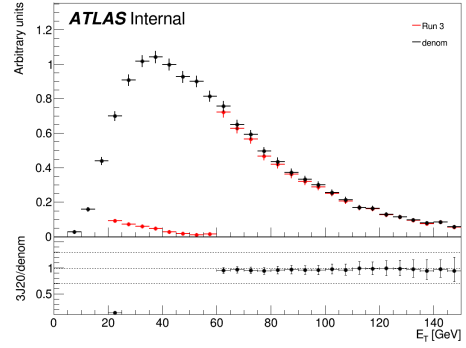
(a) Run-2 L1 electron E_T



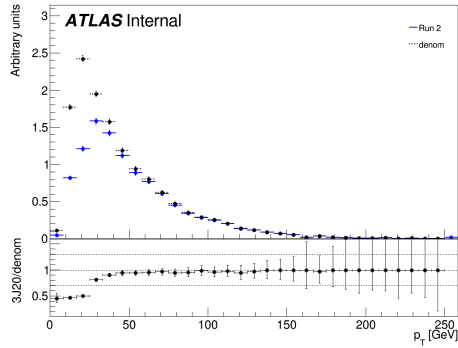
(b) Run-3 L1 electron E_T



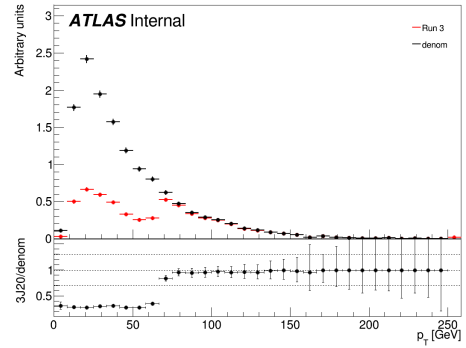
(c) Run-2 passing electron E_T



(d) Run-3 passing electron E_T

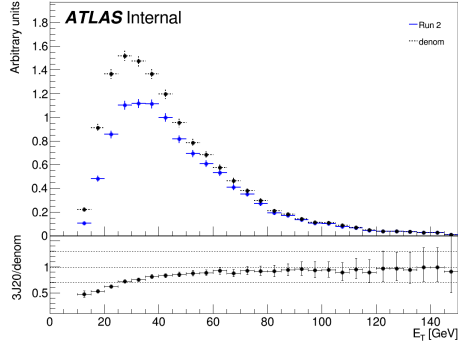


(e) Run-2 offline electron p_T

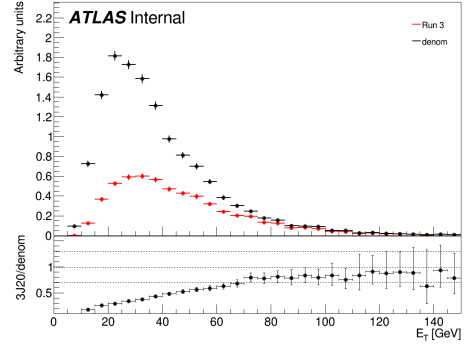


(f) Run-3 offline electron p_T

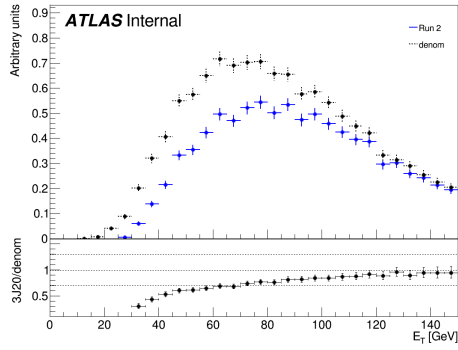
Figure 65: 3J20 electron distributions



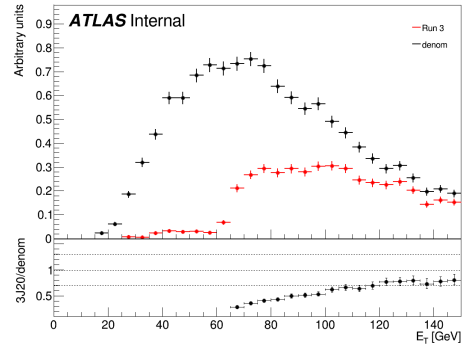
(a) Run-2 L1 leading jet E_T



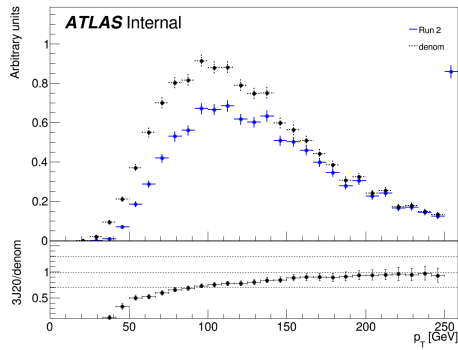
(b) Run-3 L1 leading jet E_T



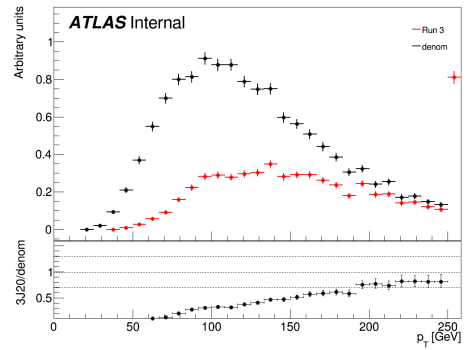
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

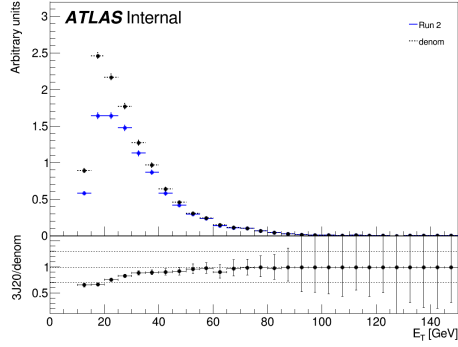


(e) Run-2 offline leading jet p_T

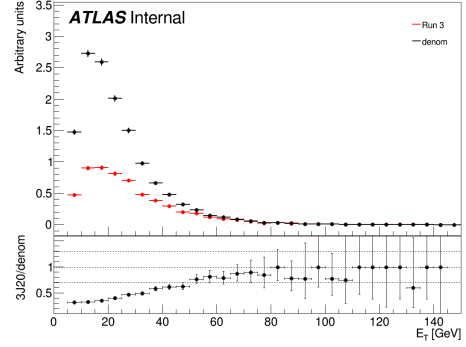


(f) Run-3 offline leading jet p_T

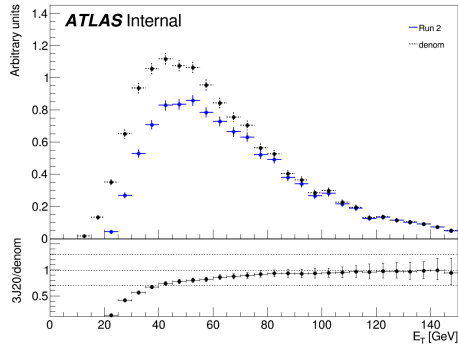
Figure 66: 3J20 leading jet distributions



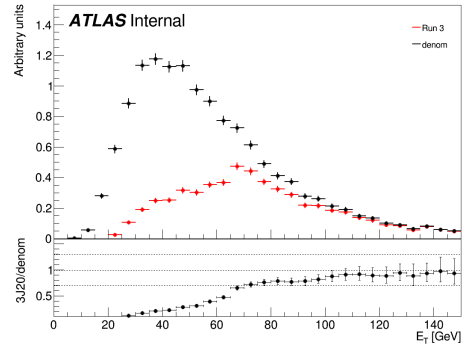
(a) Run-2 L1 sub-leading jet E_T



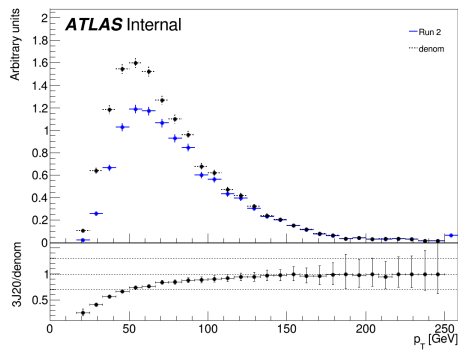
(b) Run-3 L1 sub-leading jet E_T



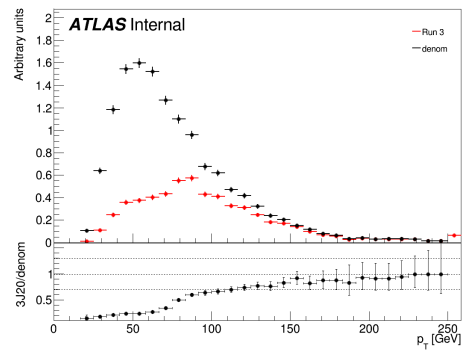
(c) Run-2 passing sub-leading jet E_T



(d) Run-3 passing sub-leading jet E_T

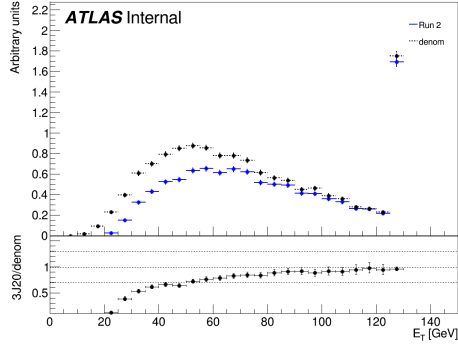


(e) Run-2 offline sub-leading jet p_T

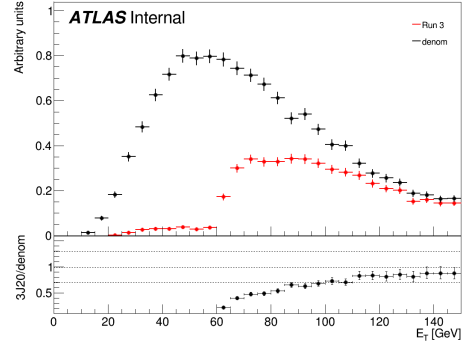


(f) Run-3 offline sub-leading jet p_T

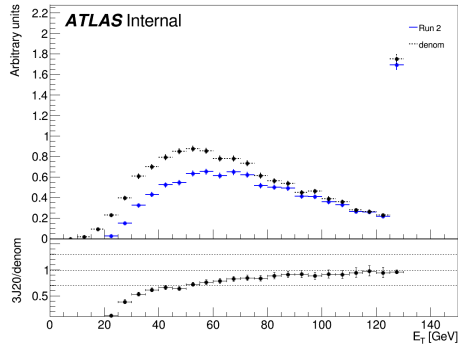
Figure 67: 3J20 sub-leading jet distributions



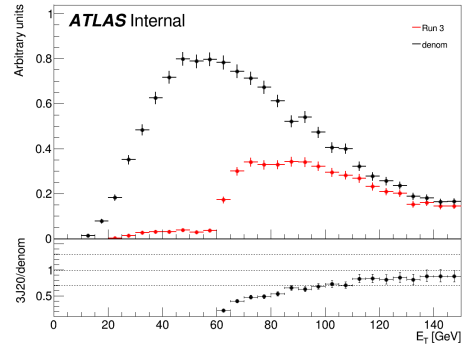
(a) Run-2 L1 tau-1 E_T



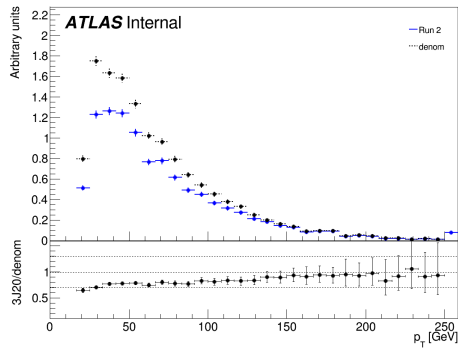
(b) Run-3 L1 tau-1 E_T



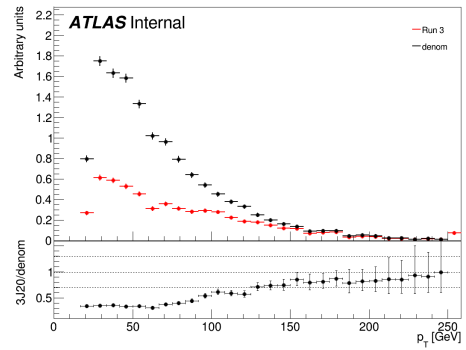
(c) Run-2 passing tau-1 E_T



(d) Run-3 passing tau-1 E_T

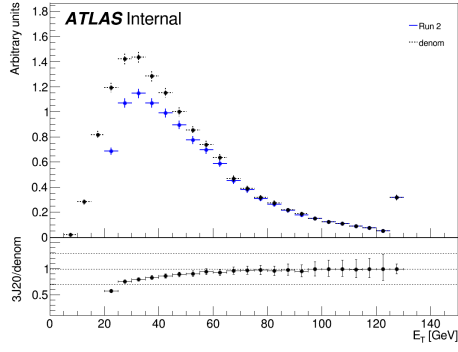


(e) Run-2 offline tau-1 p_T

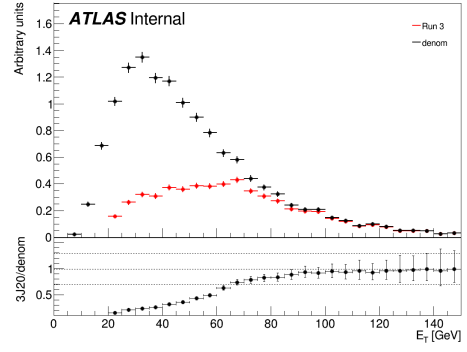


(f) Run-3 offline tau-1 p_T

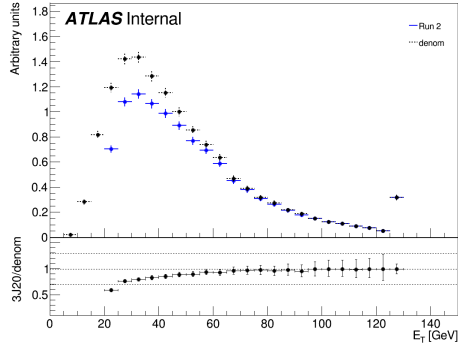
Figure 68: 3J20 tau-1 distributions



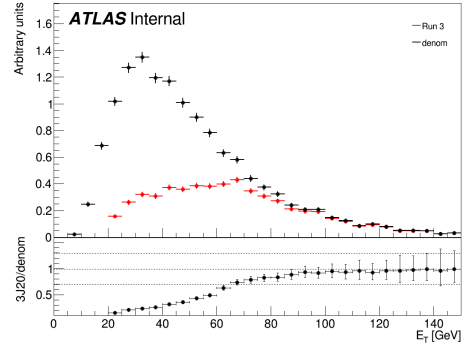
(a) Run-2 L1 tau-2 E_T



(b) Run-3 L1 tau-2 E_T

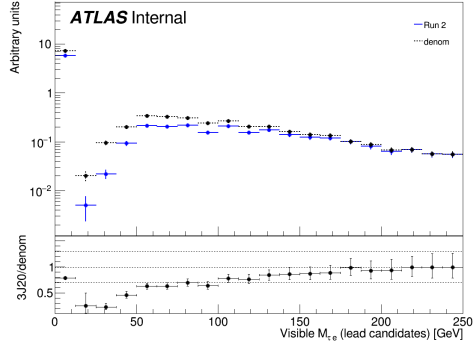


(c) Run-2 passing tau-2 E_T

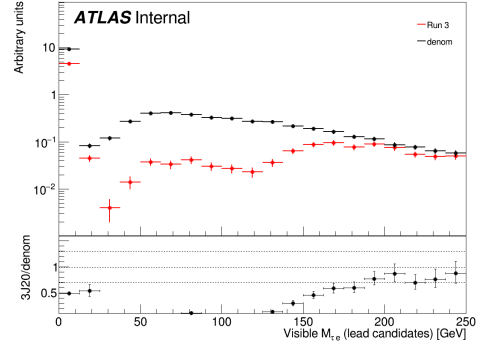


(d) Run-3 passing tau-2 E_T

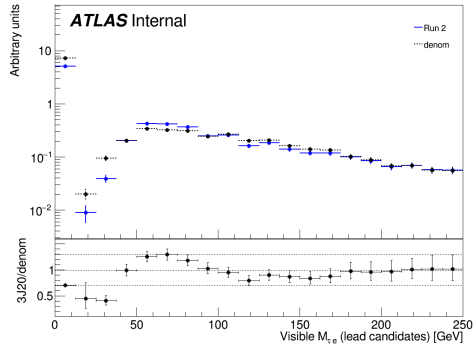
Figure 69: 3J20 tau-2 distributions



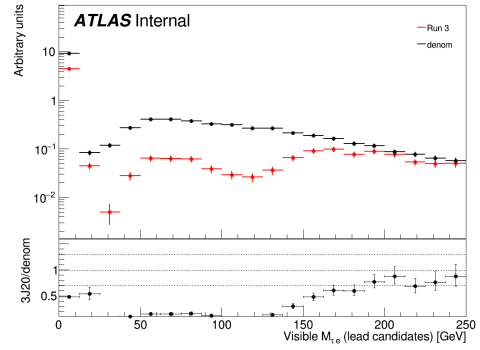
(a) Run-2 L1 $M_{\tau e}$



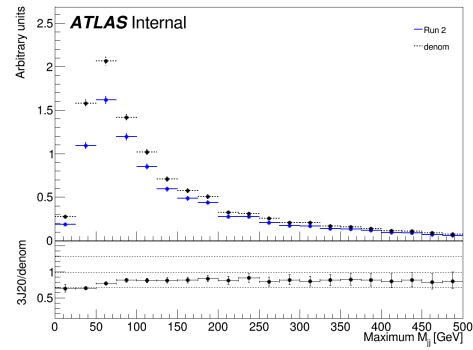
(b) Run-3 L1 $M_{\tau e}$



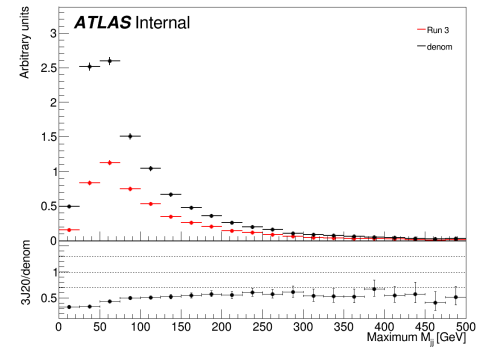
(c) Run-2 passing $M_{\tau e}$



(d) Run-3 passing $M_{\tau e}$

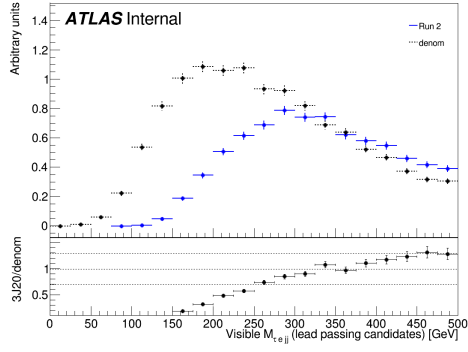


(e) Run-2 max M_{jj}

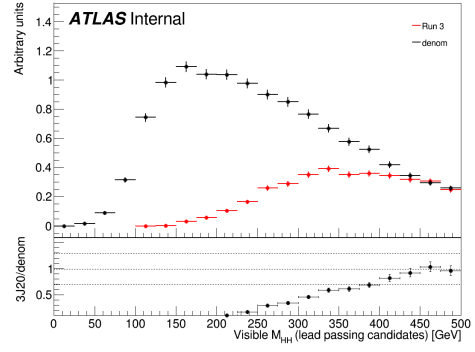


(f) Run-3 max M_{jj}

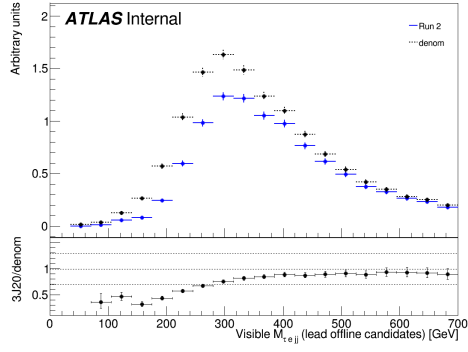
Figure 70: 3J20 reconstructed masses distribution



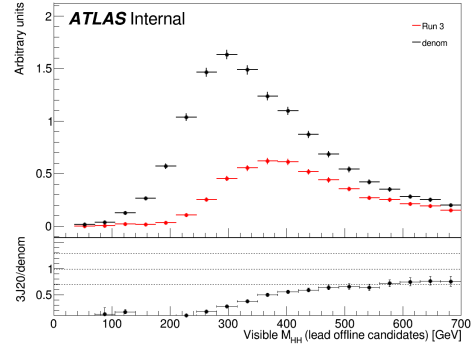
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



(c) Run-2 di-Higgs offline Mass



(d) Run-3 di-Higgs offline Mass

Figure 71: 3J20 di-Higgs Mass distributions

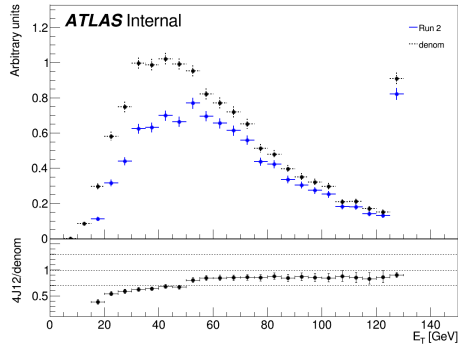
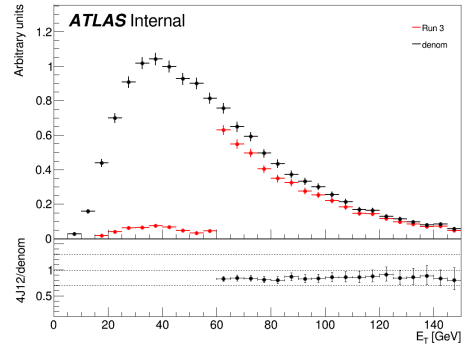
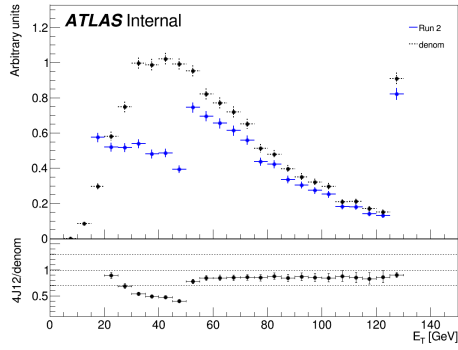
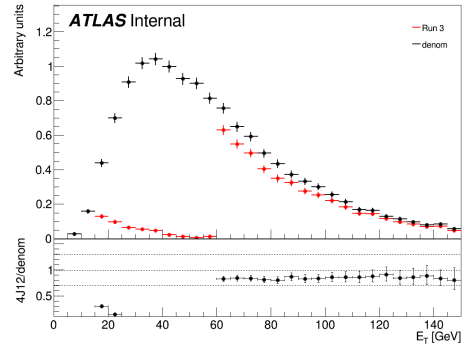
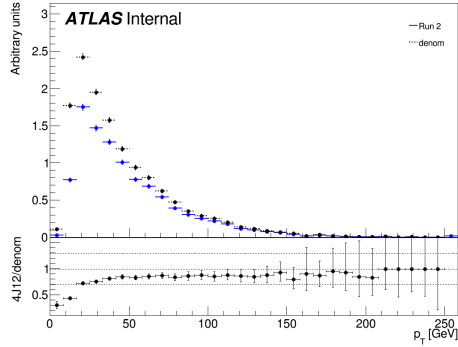
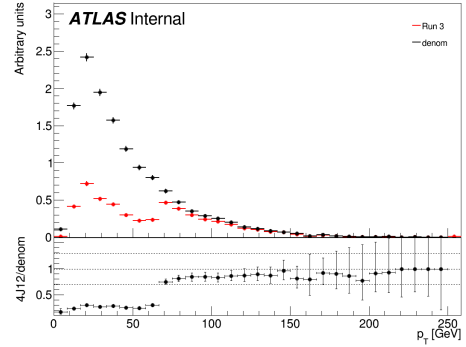
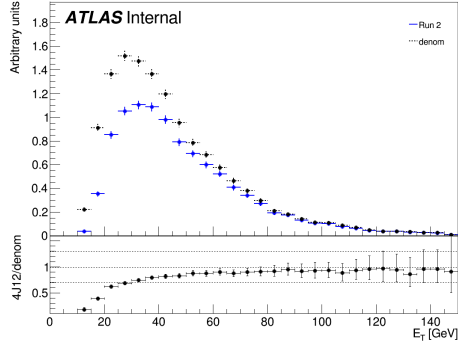
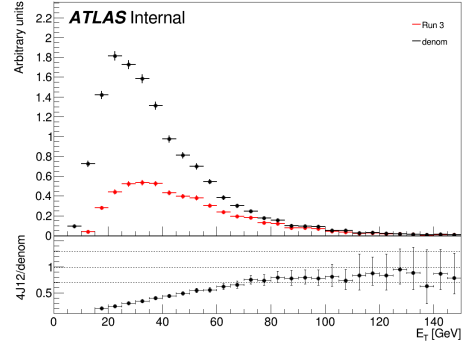
(a) Run-2 L1 electron E_T (b) Run-3 L1 electron E_T (c) Run-2 passing electron E_T (d) Run-3 passing electron E_T (e) Run-2 offline electron p_T (f) Run-3 offline electron p_T

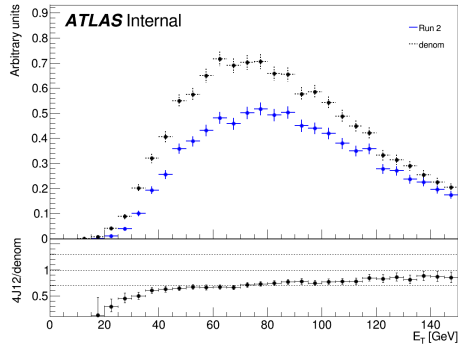
Figure 72: 4J12 electron distributions



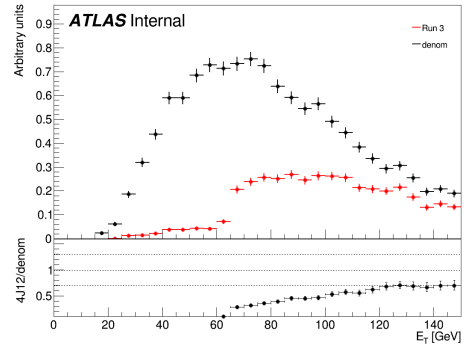
(a) Run-2 L1 leading jet E_T



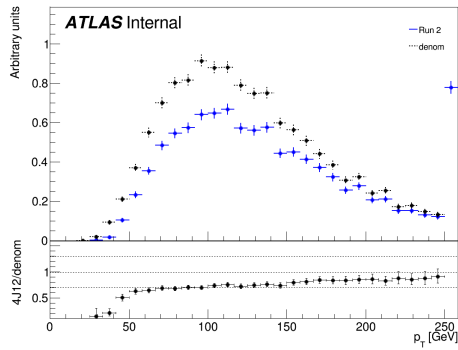
(b) Run-3 L1 leading jet E_T



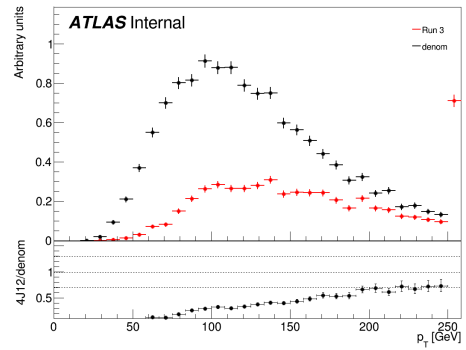
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

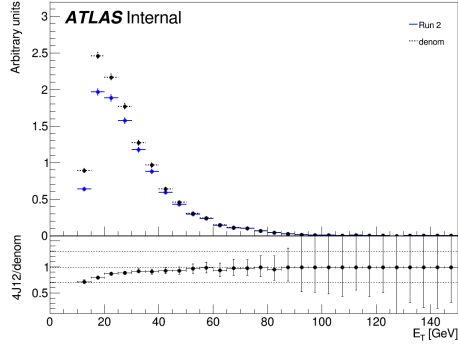


(e) Run-2 offline leading jet p_T

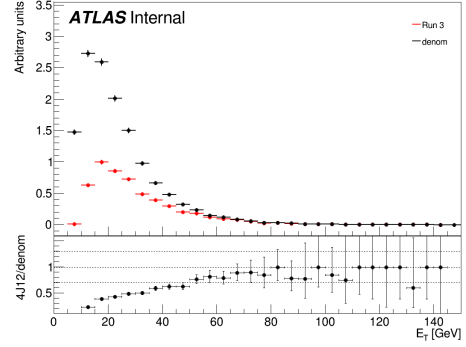


(f) Run-3 offline leading jet p_T

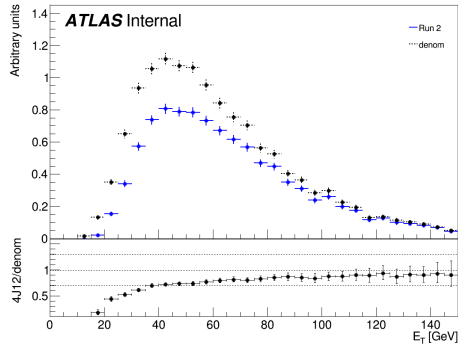
Figure 73: 4J12 leading jet distributions



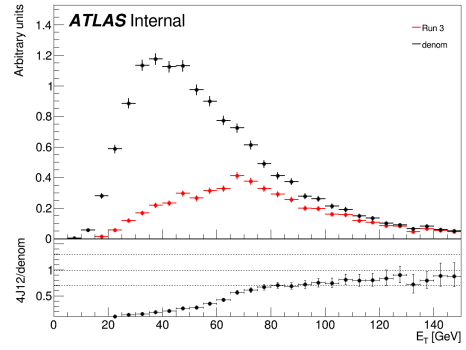
(a) Run-2 L1 sub-leading jet E_T



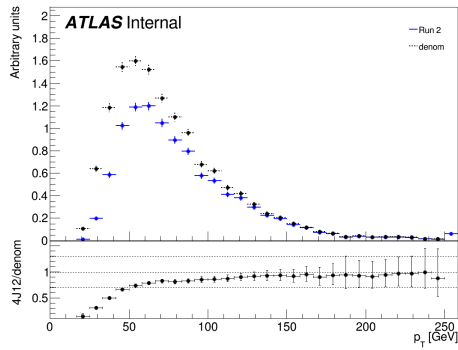
(b) Run-3 L1 sub-leading jet E_T



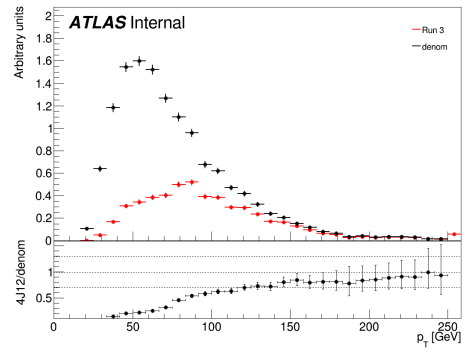
(c) Run-2 passing sub-leading jet E_T



(d) Run-3 passing sub-leading jet E_T

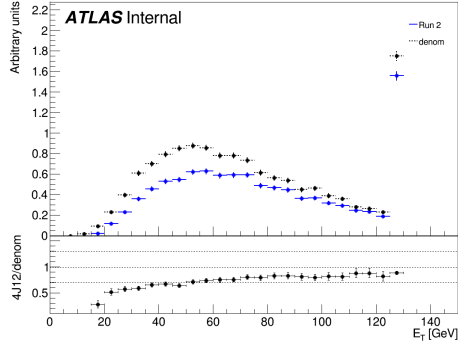


(e) Run-2 offline sub-leading jet p_T

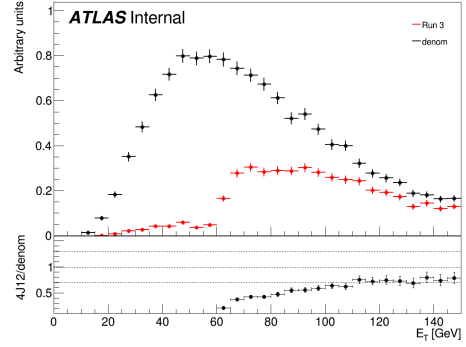


(f) Run-3 offline sub-leading jet p_T

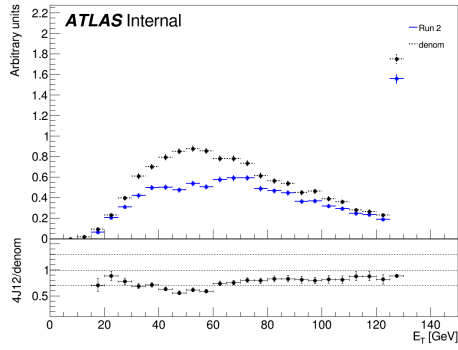
Figure 74: 4J12 sub-leading jet distributions



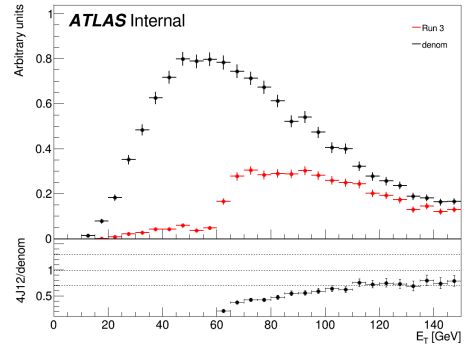
(a) Run-2 L1 tau-1 E_T



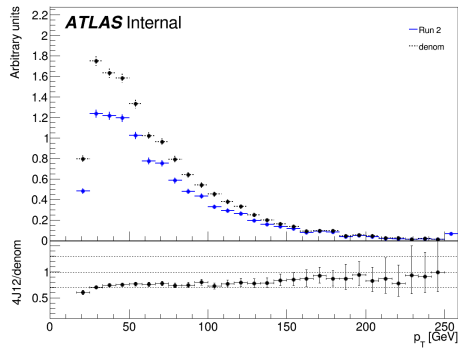
(b) Run-3 L1 tau-1 E_T



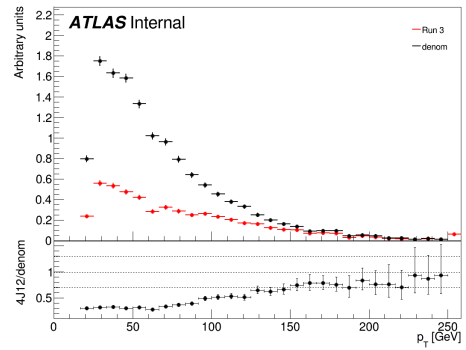
(c) Run-2 passing tau-1 E_T



(d) Run-3 passing tau-1 E_T

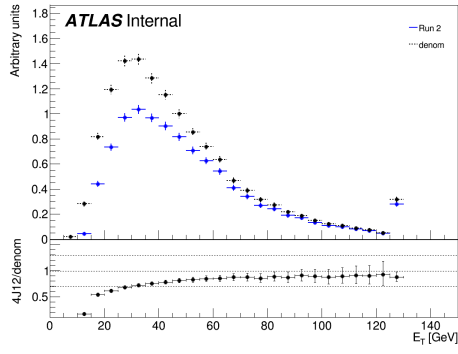


(e) Run-2 offline tau-1 p_T

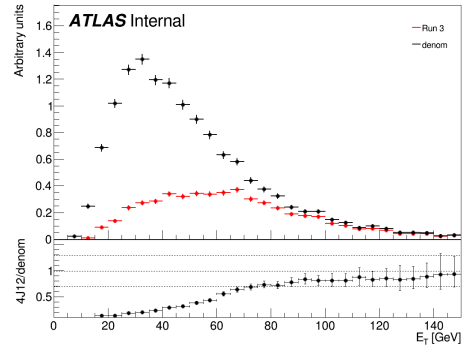


(f) Run-3 offline tau-1 p_T

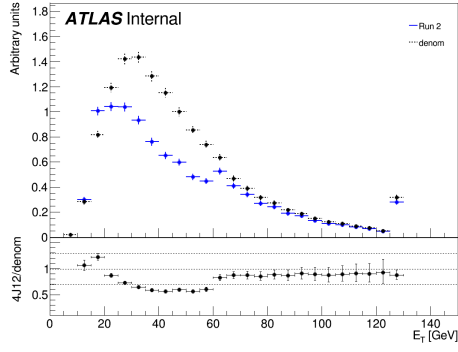
Figure 75: 4J12 Tau-1 distributions



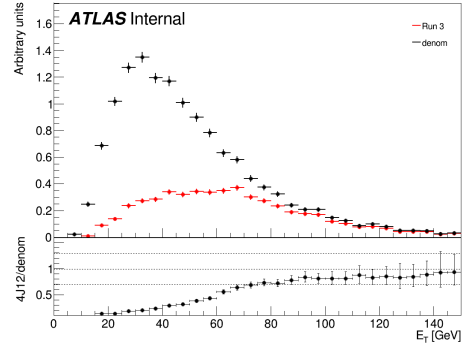
(a) Run-2 L1 tau-2 E_T



(b) Run-3 L1 tau-2 E_T

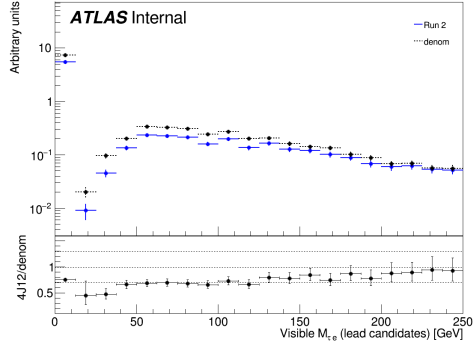


(c) Run-2 passing tau-2 E_T

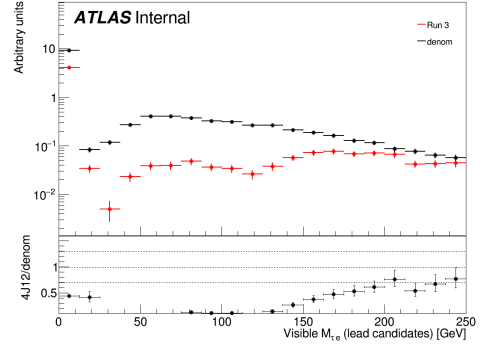


(d) Run-3 passing tau-2 E_T

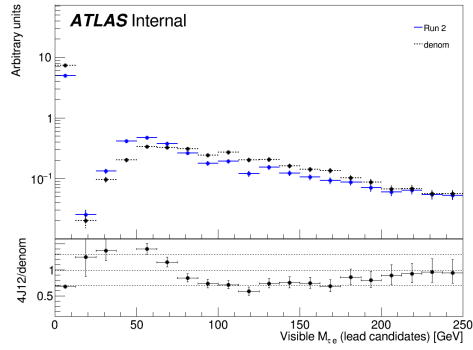
Figure 76: 4J12 tau-2 distributions



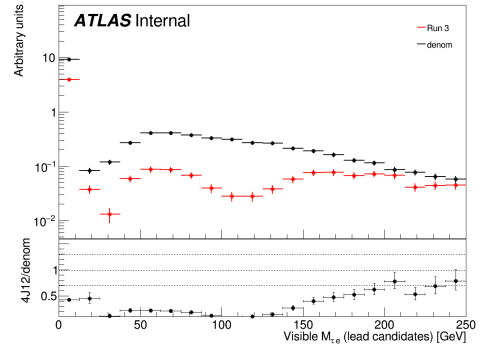
(a) Run-2 L1 $M_{\tau e}$



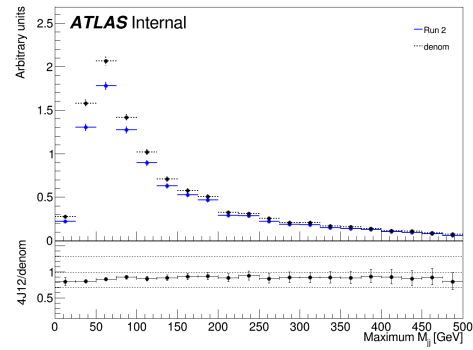
(b) Run-3 L1 $M_{\tau e}$



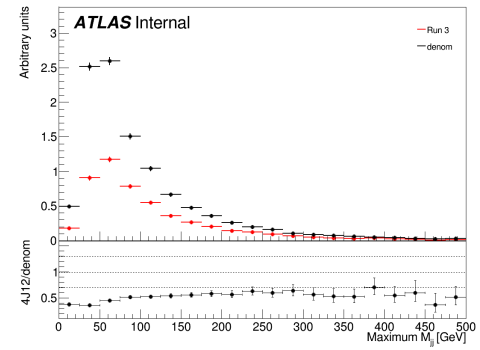
(c) Run-2 passing $M_{\tau e}$



(d) Run-2 passing $M_{\tau e}$

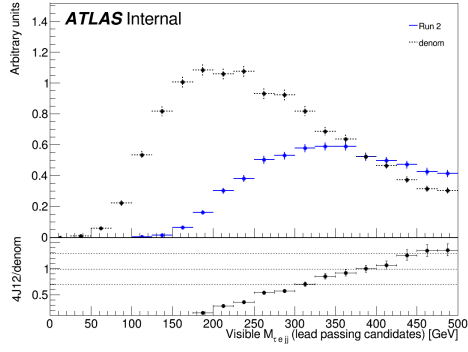


(e) Run-2 max M_{jj}

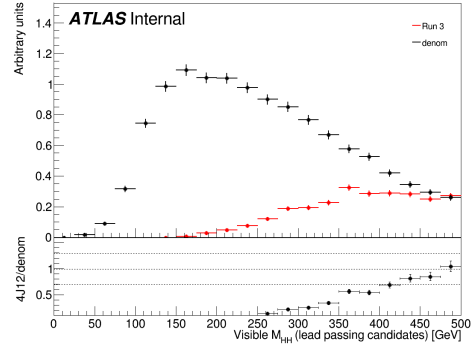


(f) Run-2 max M_{jj}

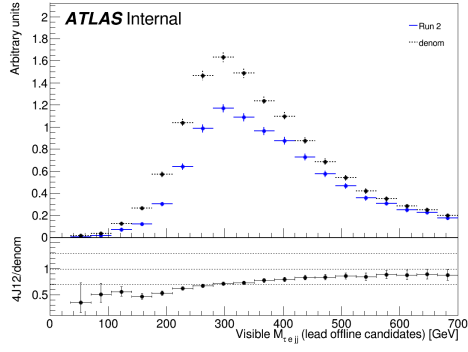
Figure 77: 4J12 reconstructed masses distribution



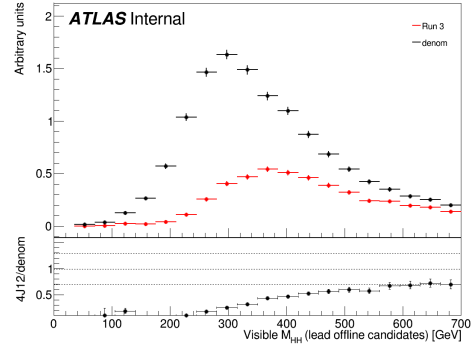
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



(c) Run-2 di-Higgs offline Mass



(d) Run-3 di-Higgs offline Mass

Figure 78: 4J12 di-Higgs Mass distribution

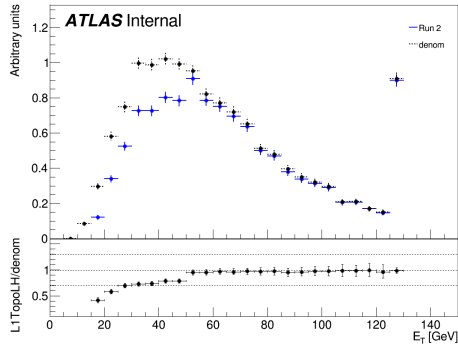
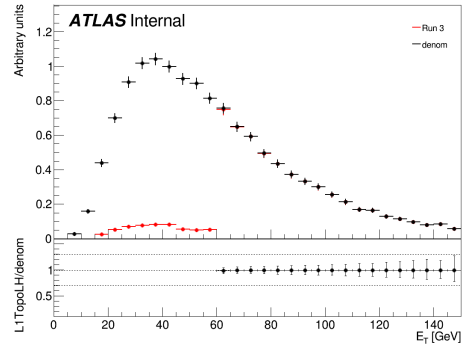
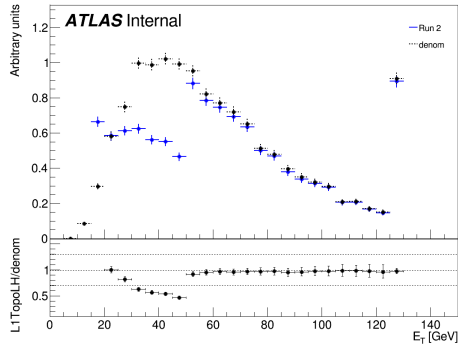
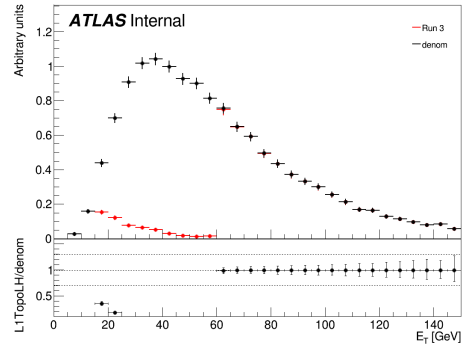
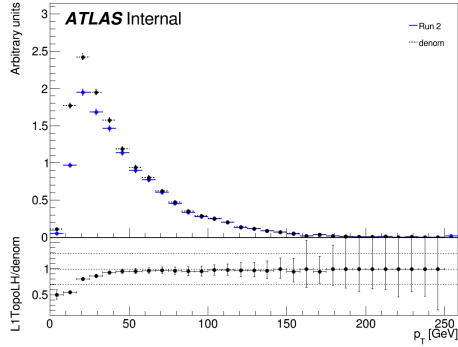
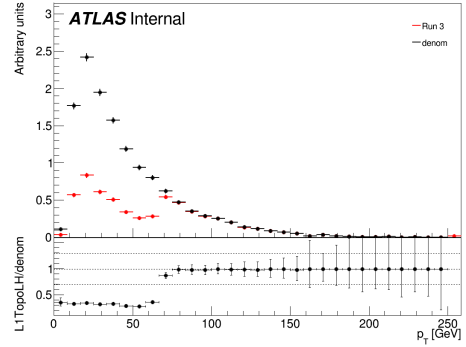
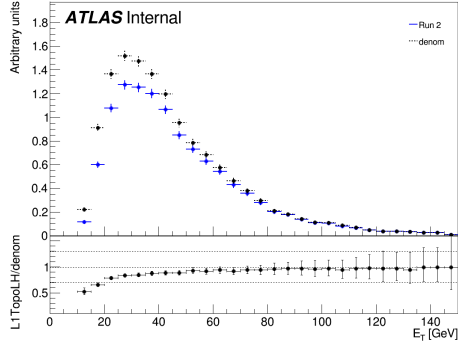
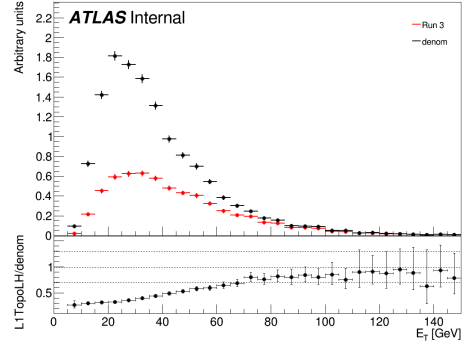
(a) Run-2 L1 electron E_T (b) Run-3 L1 electron E_T (c) Run-2 passing electron E_T (d) Run-3 passing electron E_T (e) Run-2 offline electron p_T (f) Run-3 passing electron p_T

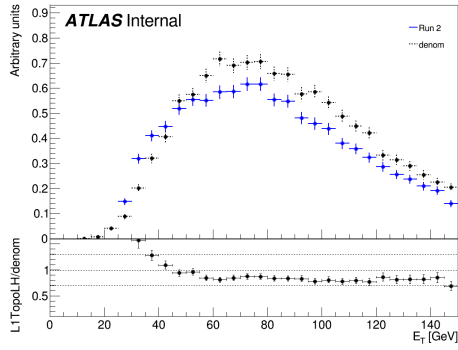
Figure 79: L1Topo electron distributions



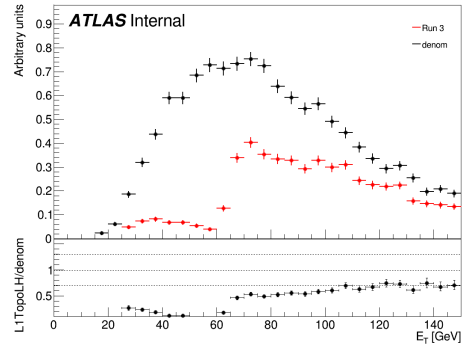
(a) Run-2 L1 leading jet E_T



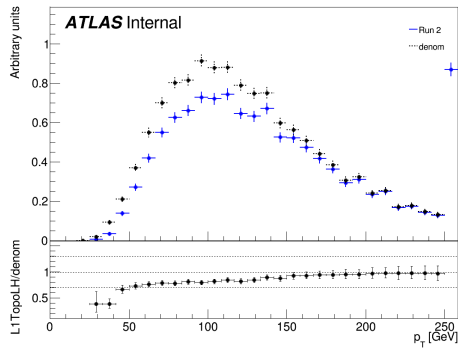
(b) Run-3 L1 leading jet E_T



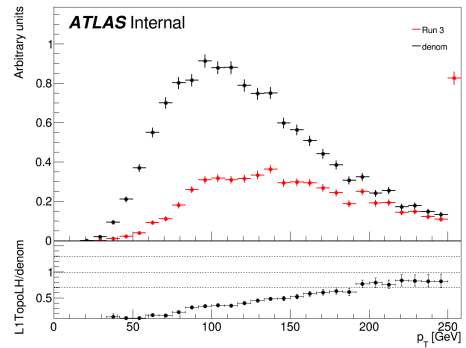
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

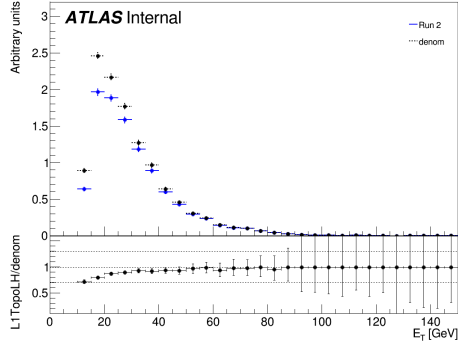


(e) Run-2 offline leading jet p_T

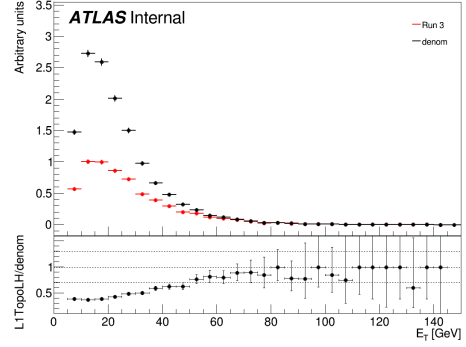


(f) Run-3 offline leading jet p_T

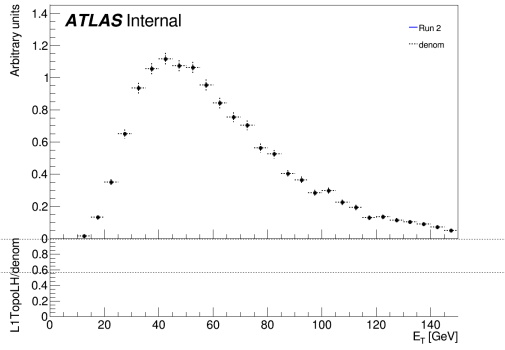
Figure 80: L1Topo leading jet distributions



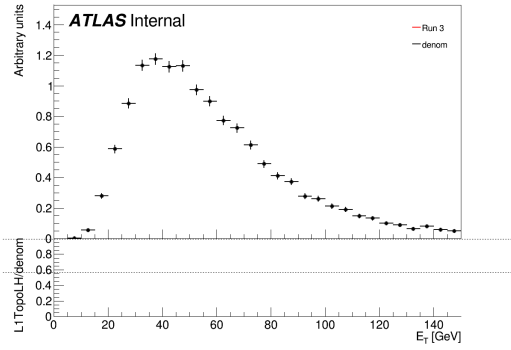
(a) Run-2 L1 sub-leading jet E_T



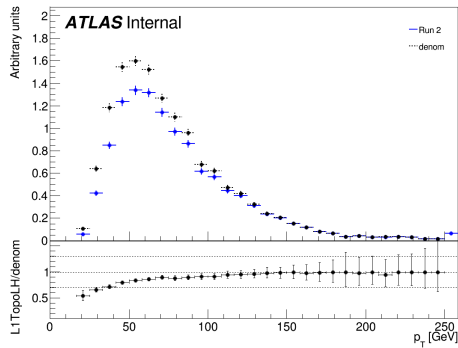
(b) Run-3 L1 sub-leading jet E_T



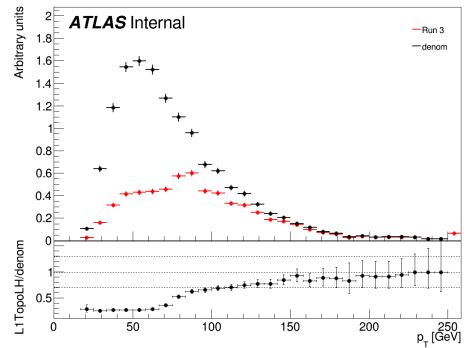
(c) Run-2 passing sub-leading jet E_T



(d) Run-3 passing sub-leading jet E_T

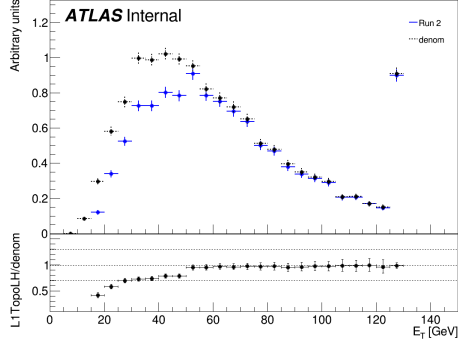


(e) Run-2 offline sub-leading jet p_T

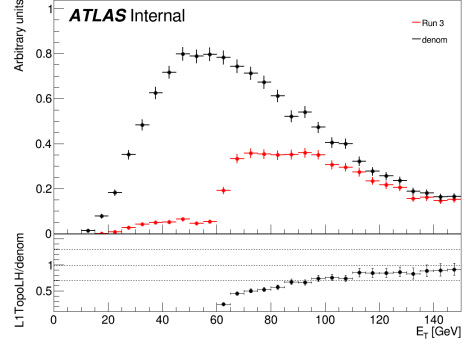


(f) Run-3 offline sub-leading jet p_T

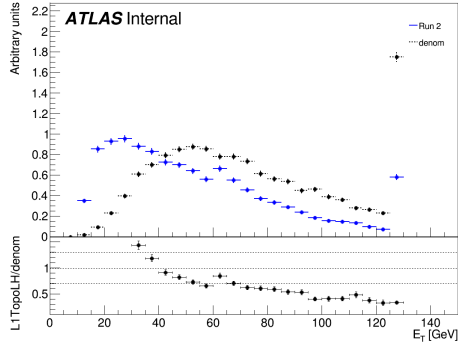
Figure 81: L1Topo sub-leading jet distributions



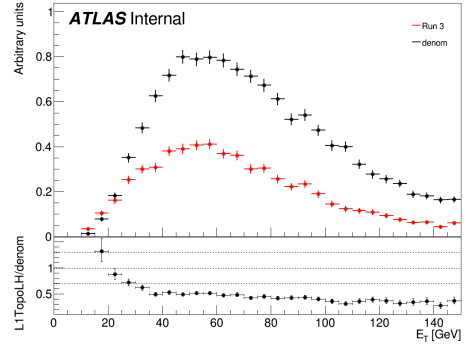
(a) Run-2 L1 tau-1 E_T



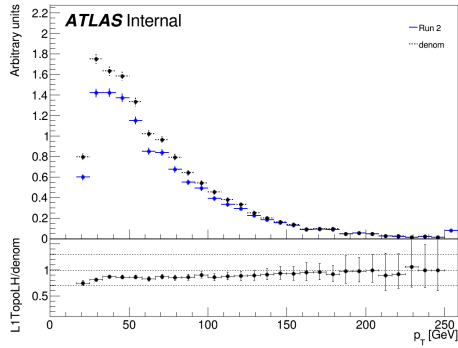
(b) Run-3 L1 tau-1 E_T



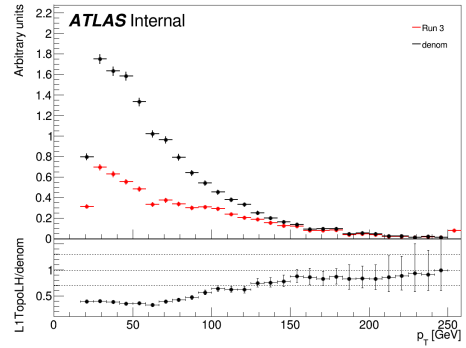
(c) Run-2 passing tau-1 E_T



(d) Run-2 passing tau-1 E_T

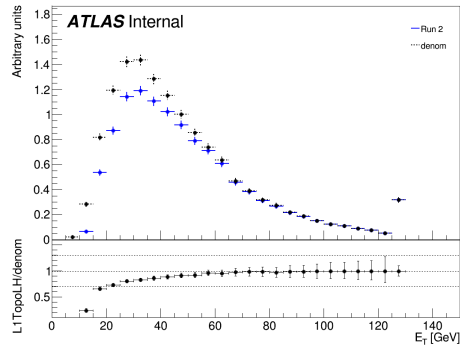


(e) Run-2 offline tau-1 p_T

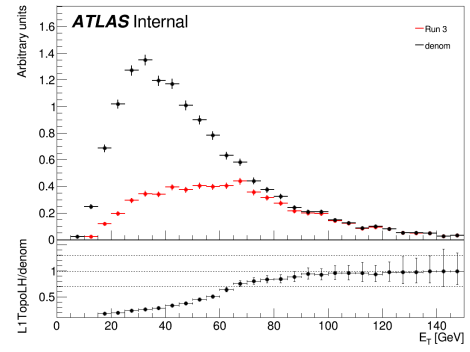


(f) Run-3 offline tau-1 p_T

Figure 82: L1Topo tau-1 distributions

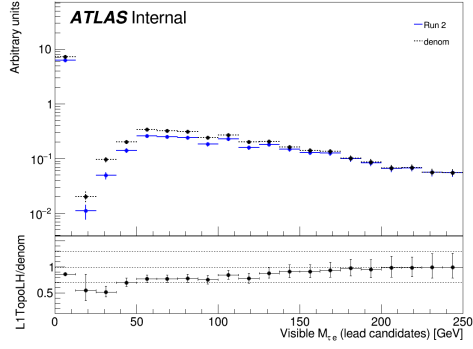


(a) Run-2 L1 tau-2 E_T

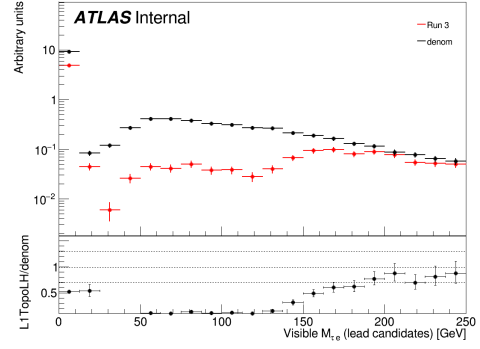


(b) Run-3 L1 tau-2 E_T

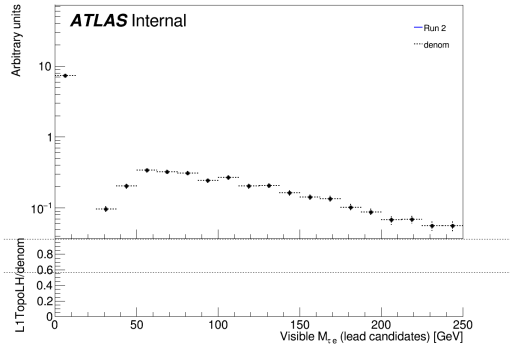
Figure 83: L1Topo tau-2 distributions



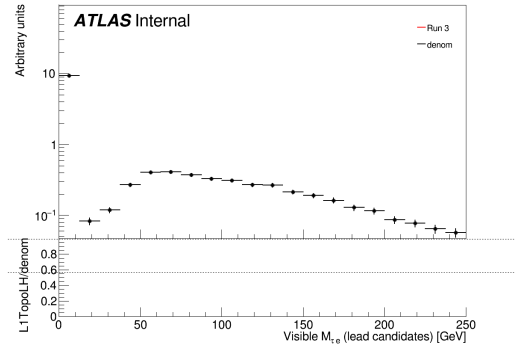
(a) Run-2 L1 $M_{\tau e}$



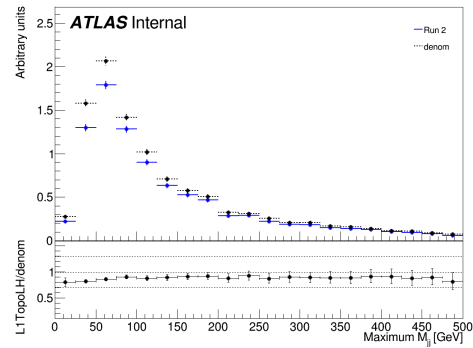
(b) Run-3 L1 $M_{\tau e}$



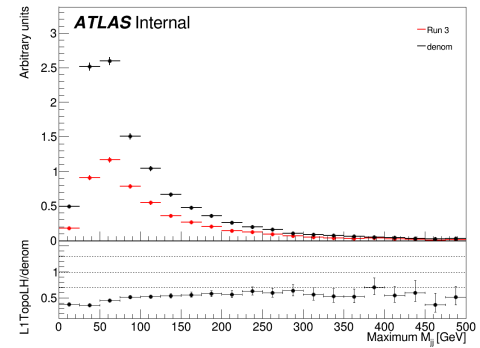
(c) Run-2 passing $M_{\tau e}$



(d) Run-3 passing $M_{\tau e}$

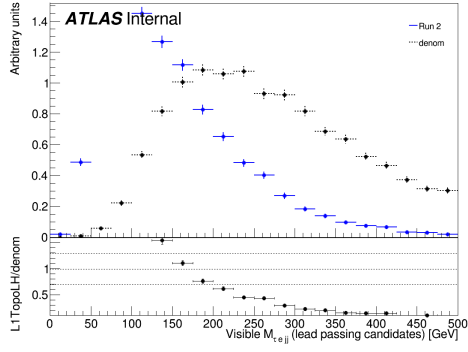


(e) Run-2 max M_{jj}

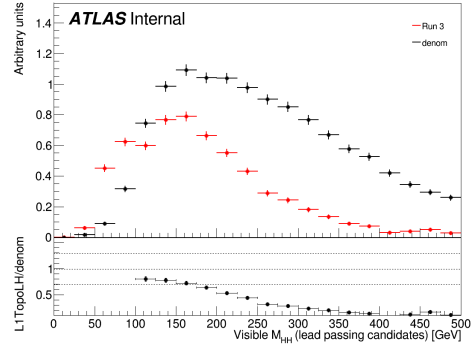


(f) Run-3 max M_{jj}

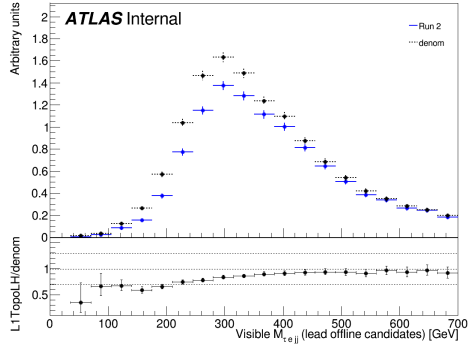
Figure 84: L1Topo reconstructed masses distribution



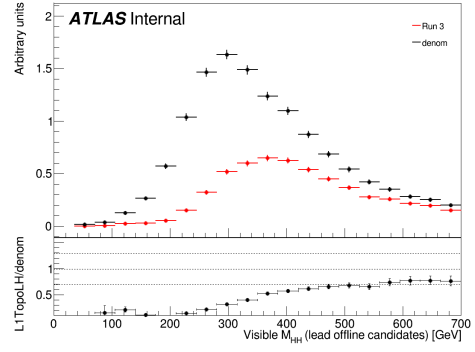
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



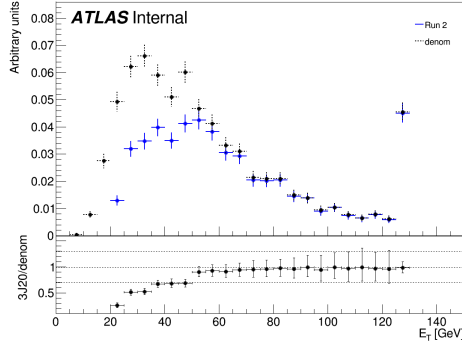
(c) Run-2 di-Higgs offline Mass



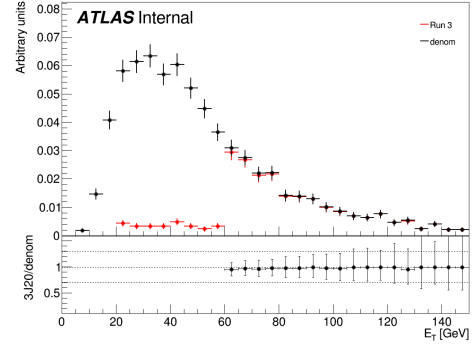
(d) Run-2 di-Higgs offline Mass

Figure 85: L1Topo di-Higgs Mass distributions

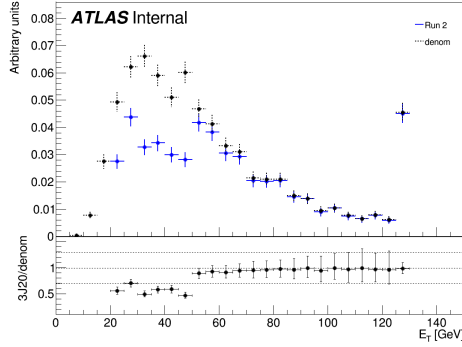
1369 **C.1 VBF 3J20**



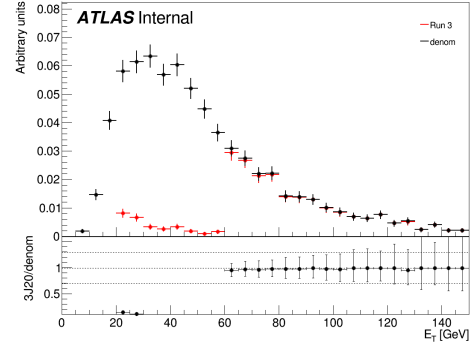
(a) Run-2 L1 electron E_T



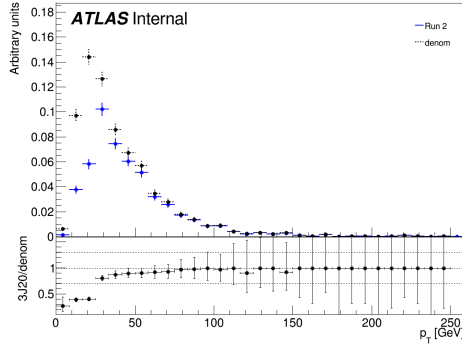
(b) Run-3 L1 electron E_T



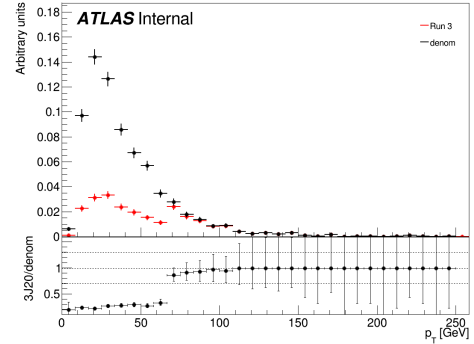
(c) Run-2 passing electron E_T



(d) Run-3 passing electron E_T

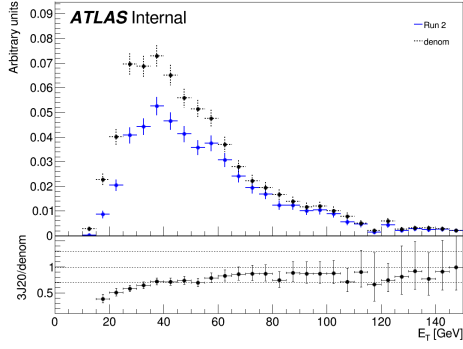


(e) Run-2 offline electron p_T

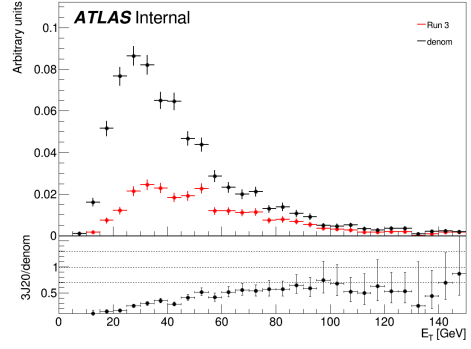


(f) Run-3 offline electron p_T

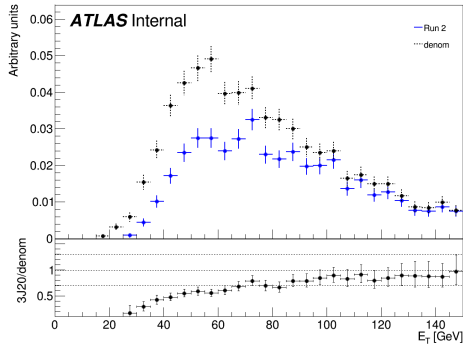
Figure 86: 3J20 electron distributions



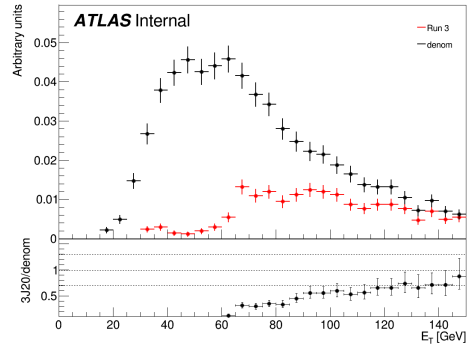
(a) Run-2 L1 leading jet E_T



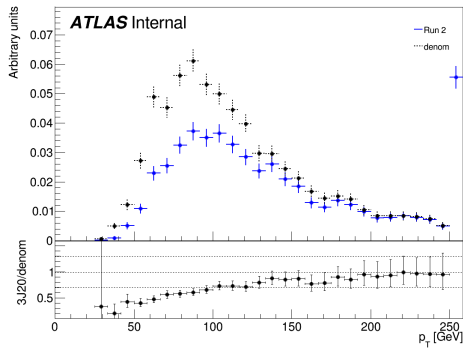
(b) Run-3 L1 leading jet E_T



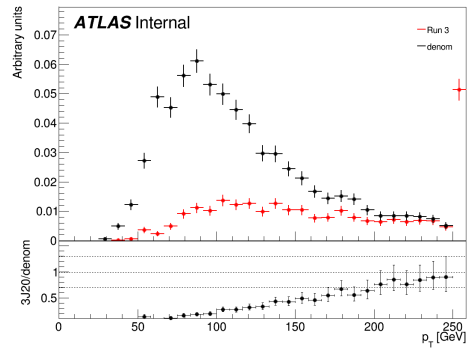
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

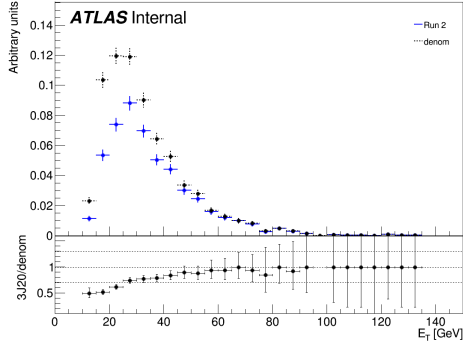


(e) Run-2 offline leading jet p_T

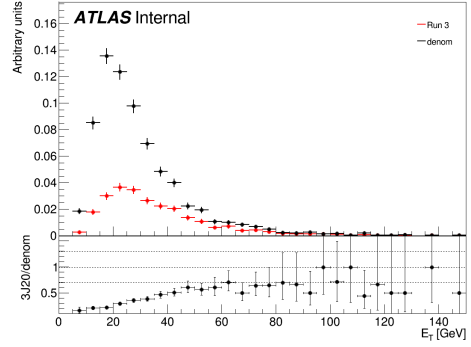


(f) Run-3 offline leading jet p_T

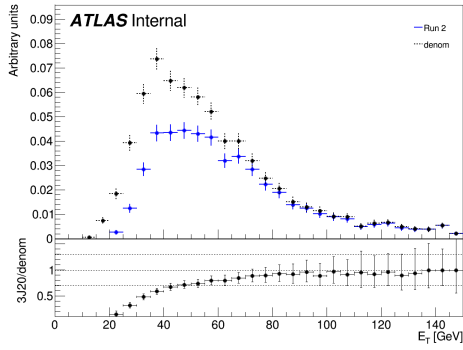
Figure 87: 3J20 leading jet distributions



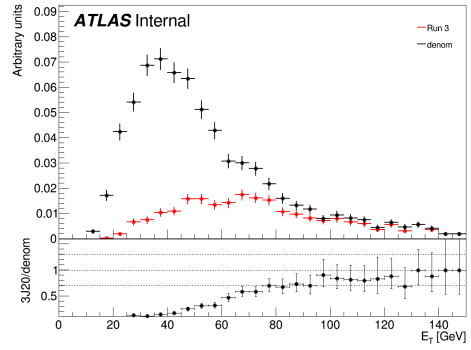
(a) Run-2 L1 sub-leading jet E_T



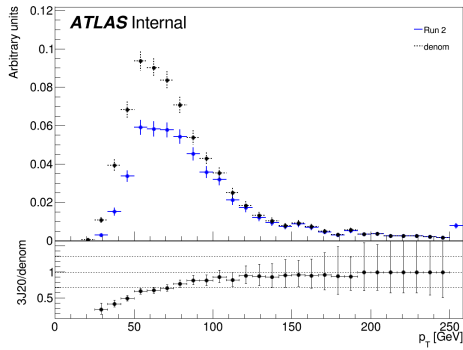
(b) Run-3 L1 sub-leading jet E_T



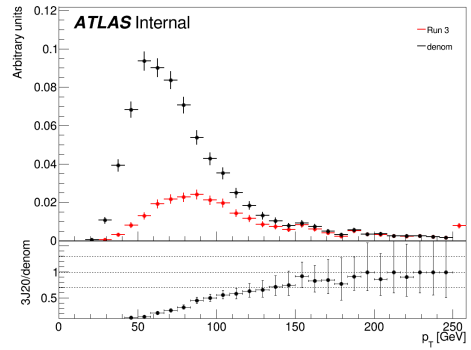
(c) Run-2 passing sub-leading jet E_T



(d) Run-3 passing sub-leading jet E_T

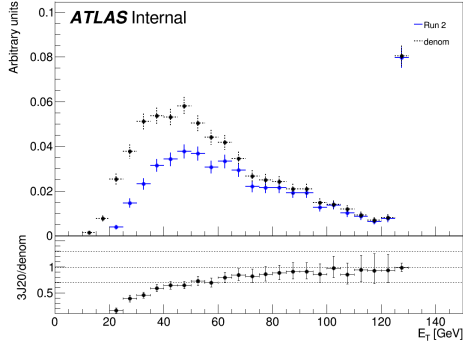


(e) Run-2 offline sub-leading jet p_T

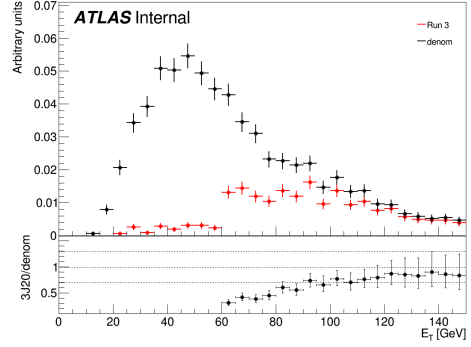


(f) Run-3 offline sub-leading jet p_T

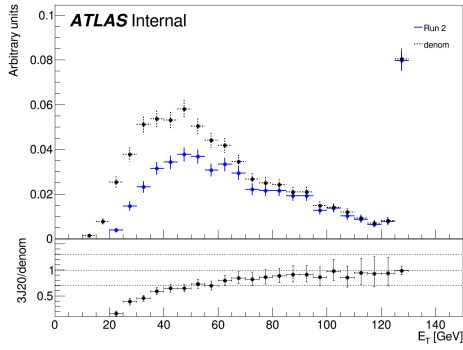
Figure 88: 3J20 sub-leading jet distributions



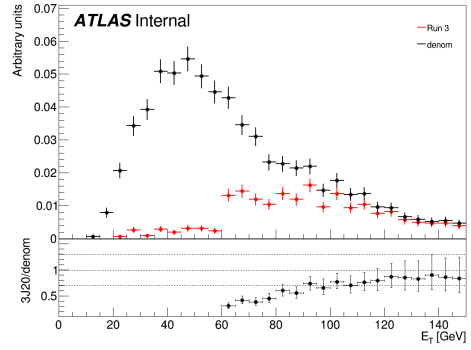
(a) Run-2 L1 tau-1 E_T



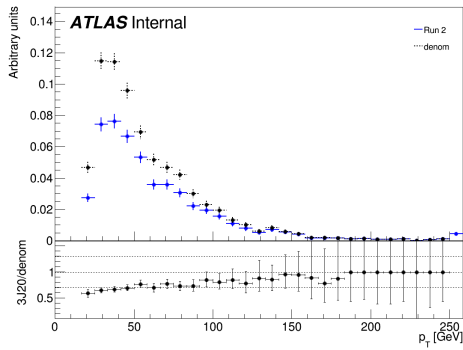
(b) Run-3 L1 tau-1 E_T



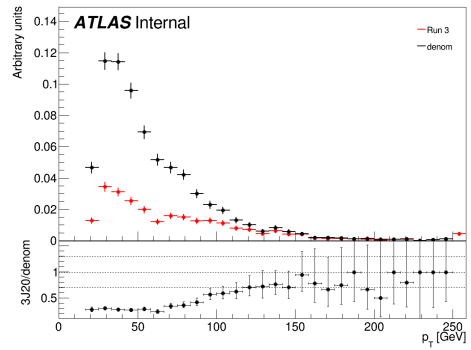
(c) Run-2 passing tau-1 E_T



(d) Run-3 passing tau-1 E_T

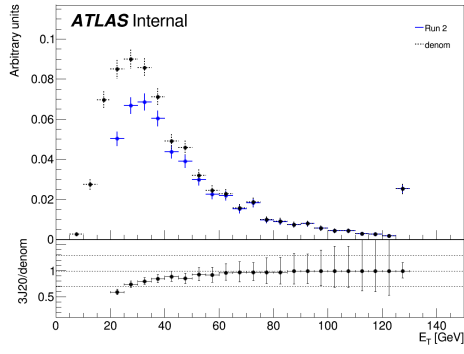


(e) Run-2 offline tau-1 p_T

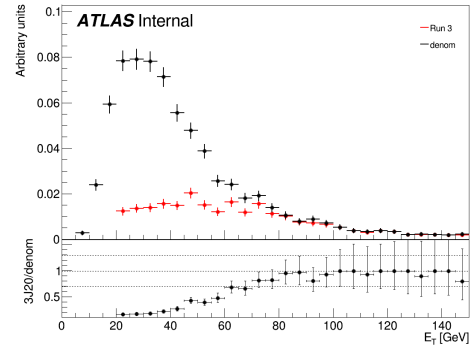


(f) Run-3 offline tau-1 p_T

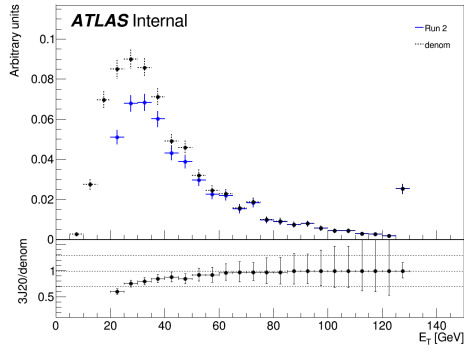
Figure 89: 3J20 tau-1 distributions



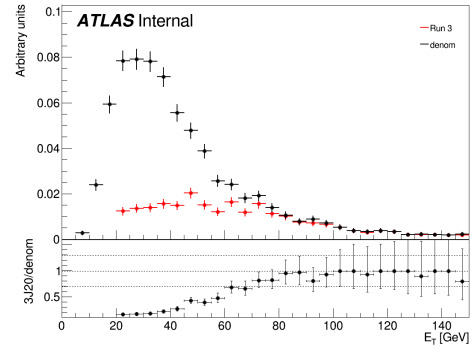
(a) Run-2 L1 tau-2 E_T



(b) Run-3 L1 tau-2 E_T

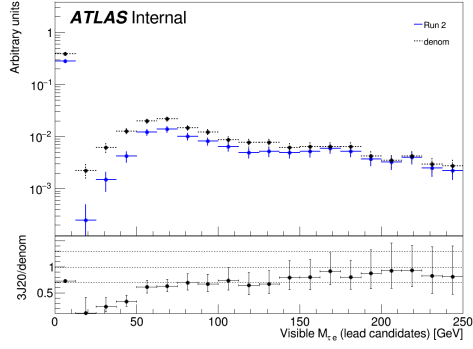


(c) Run-2 passing tau-2 E_T

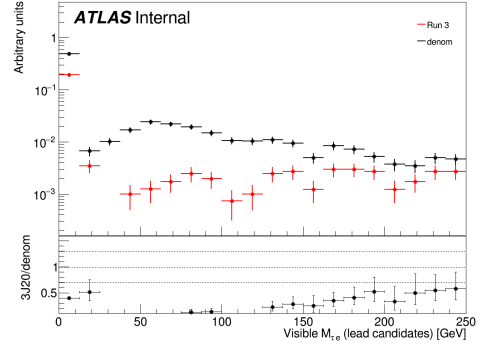


(d) Run-3 passing tau-2 E_T

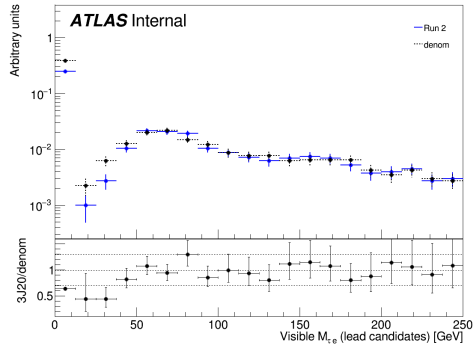
Figure 90: 3J20 tau-2 distributions



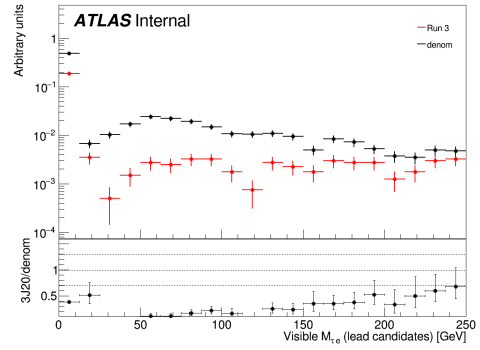
(a) Run-2 L1 $M_{\tau e}$



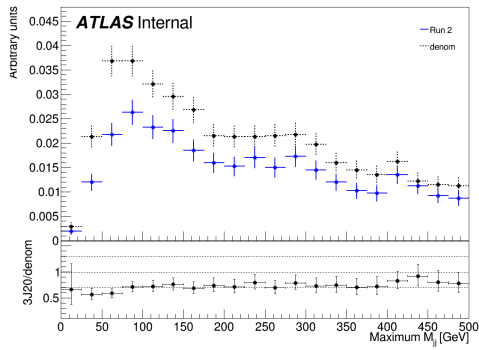
(b) Run-3 L1 $M_{\tau e}$



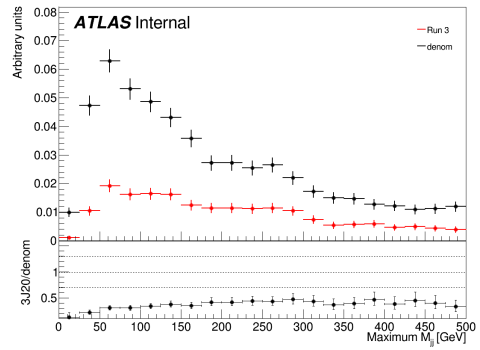
(c) Run-2 passing $M_{\tau e}$



(d) Run-3 passing $M_{\tau e}$

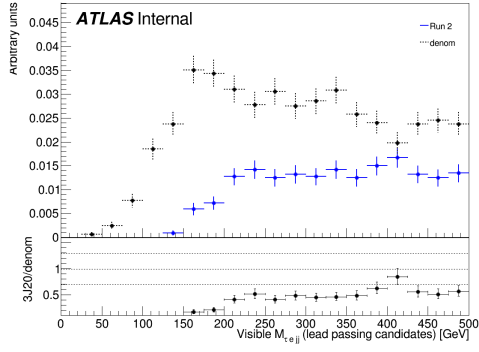


(e) Run-2 max M_{jj}

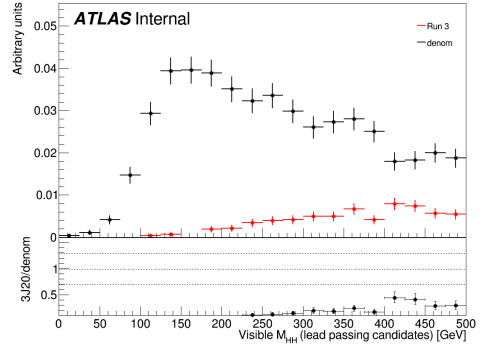


(f) Run-3 max M_{jj}

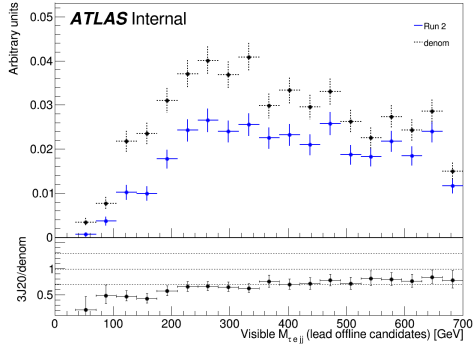
Figure 91: 3J20 reconstructed masses distribution



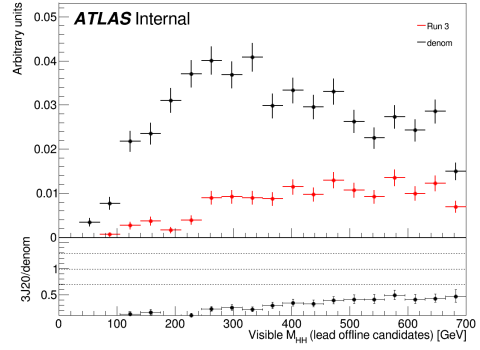
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



(c) Run-2 di-Higgs offline Mass



(d) Run-3 di-Higgs offline Mass

Figure 92: 3J20 di-Higgs Mass distributions

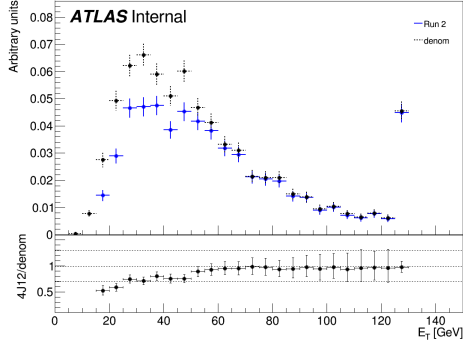
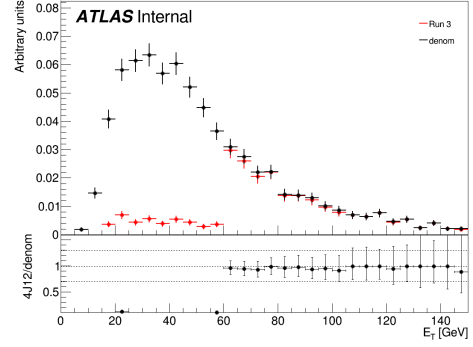
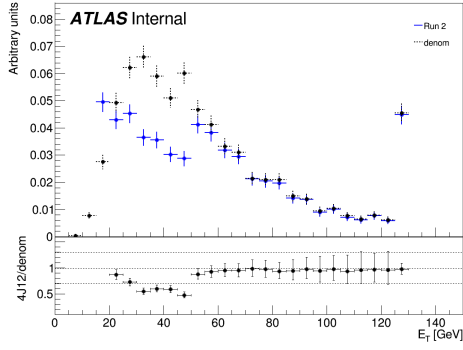
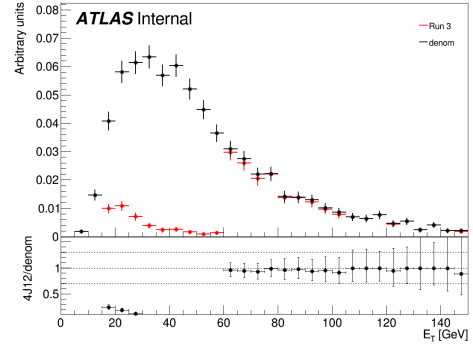
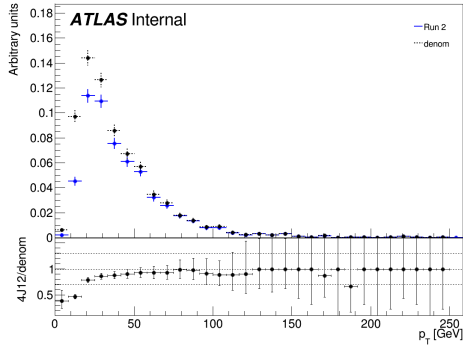
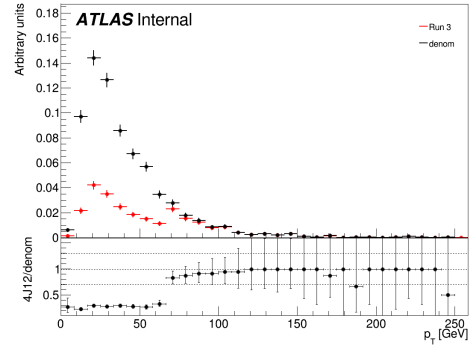
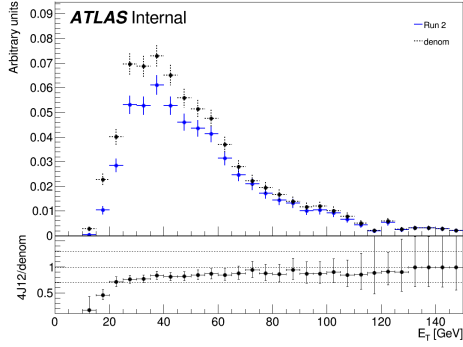
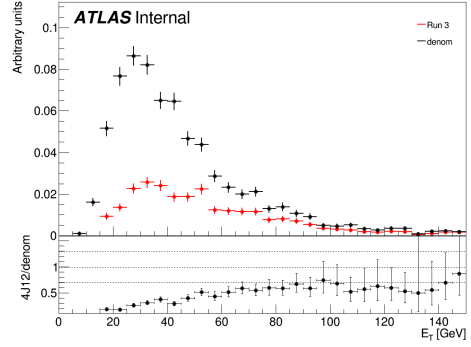
(a) Run-2 L1 electron E_T (b) Run-3 L1 electron E_T (c) Run-2 passing electron E_T (d) Run-3 passing electron E_T (e) Run-2 offline electron p_T (f) Run-3 offline electron p_T

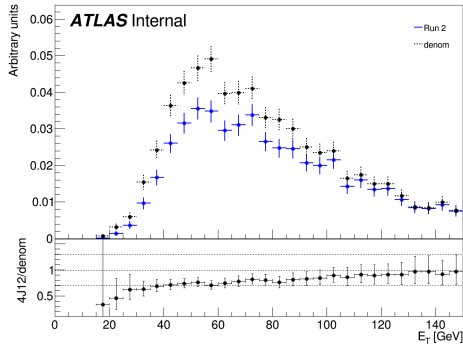
Figure 93: 4J12 electron distributions



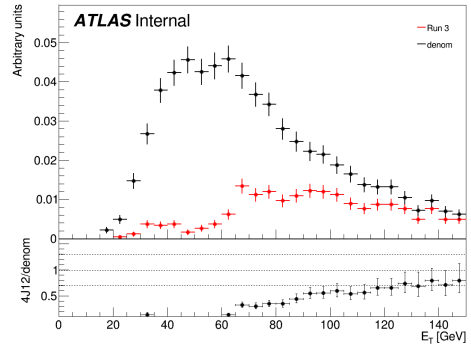
(a) Run-2 L1 leading jet E_T



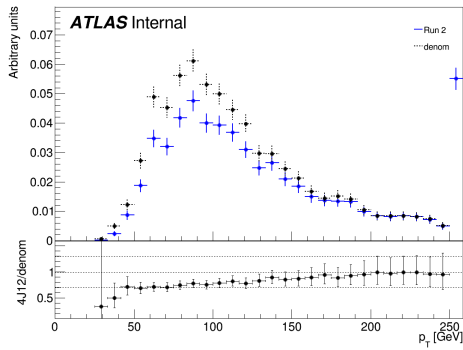
(b) Run-3 L1 leading jet E_T



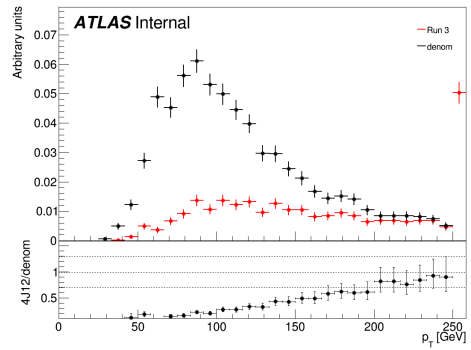
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

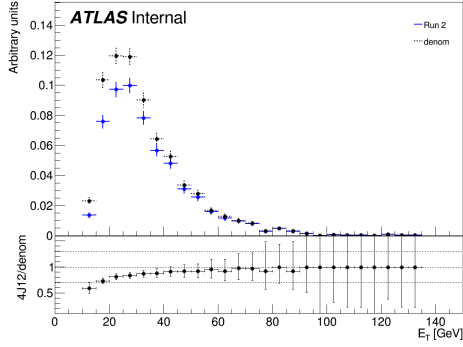


(e) Run-2 offline leading jet p_T

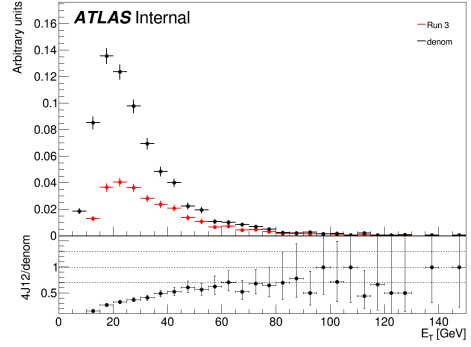


(f) Run-3 offline leading jet p_T

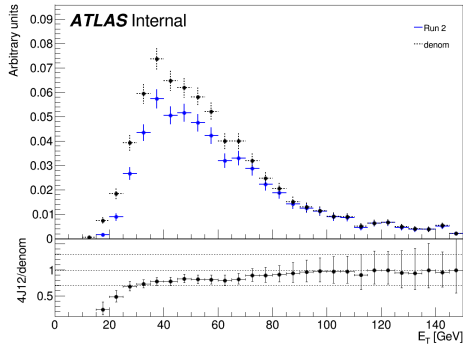
Figure 94: 4J12 leading jet distributions



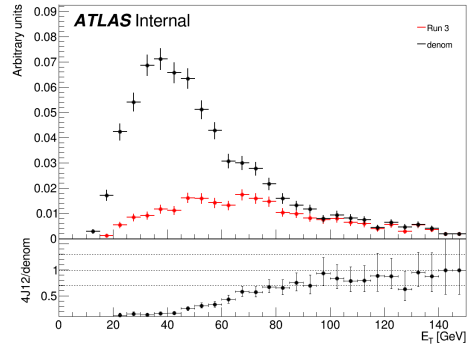
(a) Run-2 L1 sub-leading jet E_T



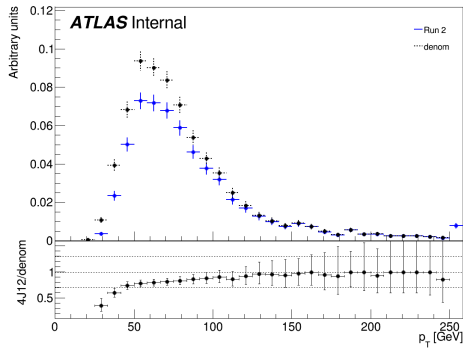
(b) Run-3 L1 sub-leading jet E_T



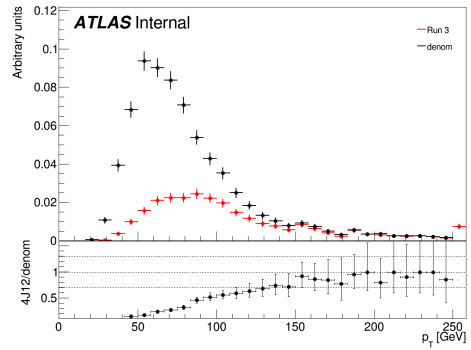
(c) Run-2 passing sub-leading jet E_T



(d) Run-3 passing sub-leading jet E_T

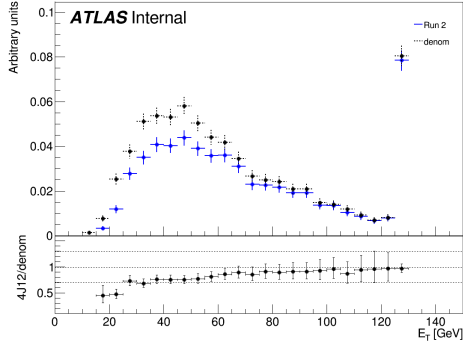


(e) Run-2 offline sub-leading jet p_T

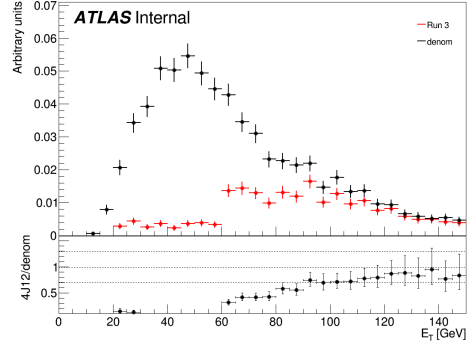


(f) Run-3 offline sub-leading jet p_T

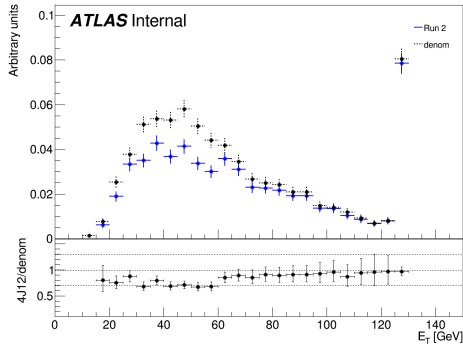
Figure 95: 4J12 sub-leading jet distributions



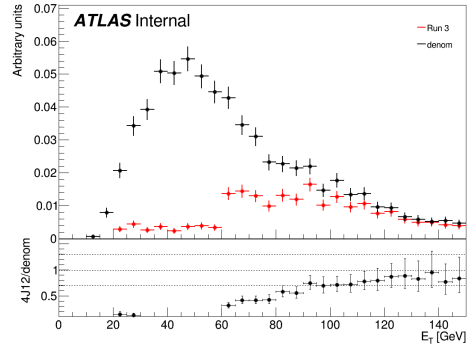
(a) Run-2 L1 tau-1 E_T



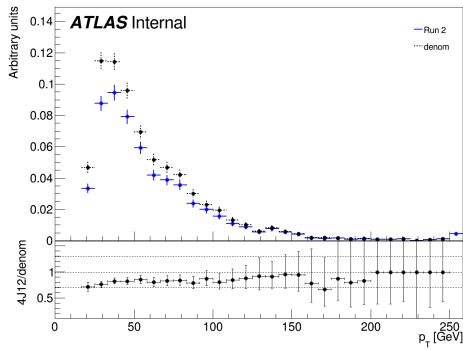
(b) Run-3 L1 tau-1 E_T



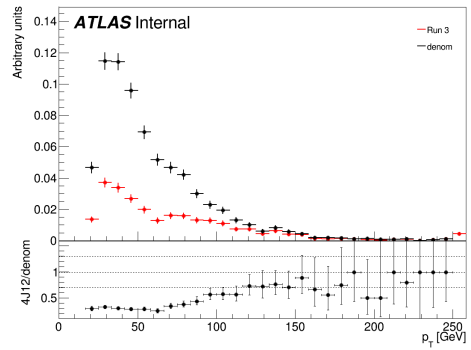
(c) Run-2 passing tau-1 E_T



(d) Run-3 passing tau-1 E_T

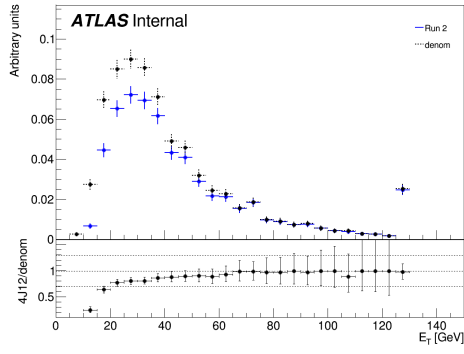


(e) Run-2 offline tau-1 p_T

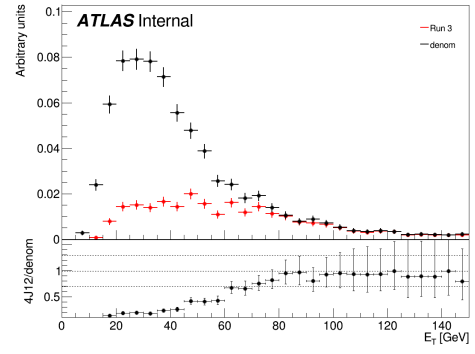


(f) Run-3 offline tau-1 p_T

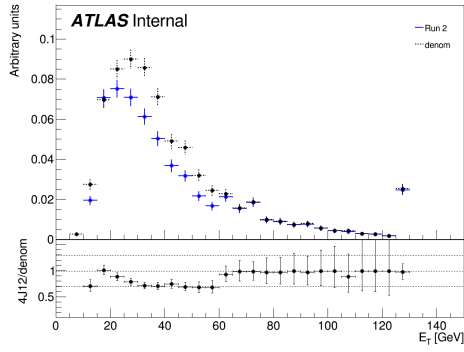
Figure 96: 4J12 Tau-1 distributions



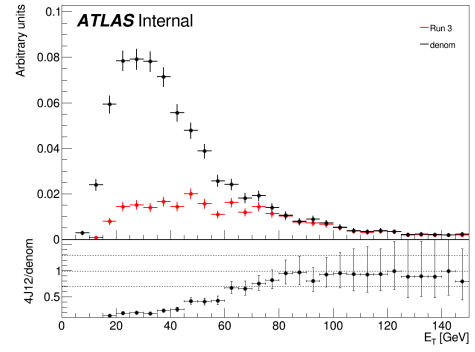
(a) Run-2 L1 tau-2 E_T



(b) Run-3 L1 tau-2 E_T

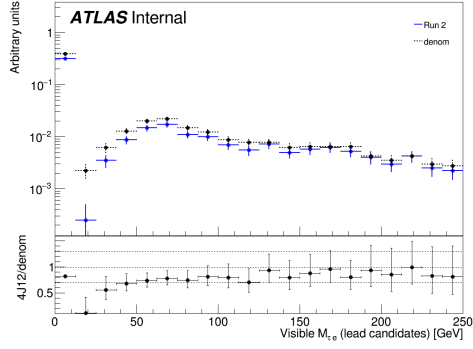


(c) Run-2 passing tau-2 E_T

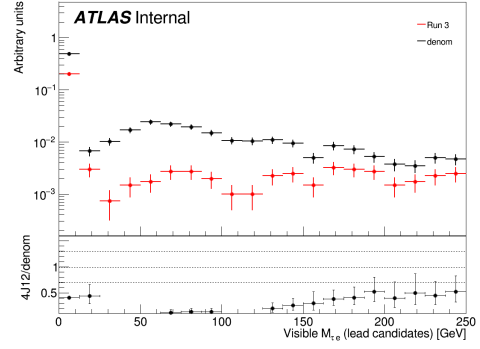


(d) Run-3 passing tau-2 E_T

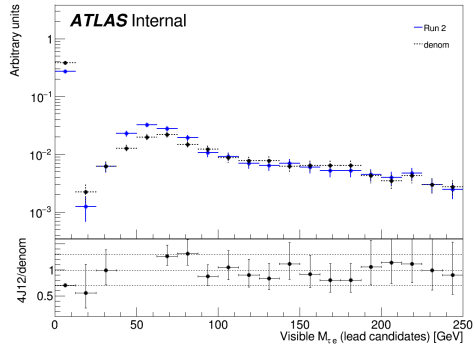
Figure 97: 4J12 tau-2 distributions



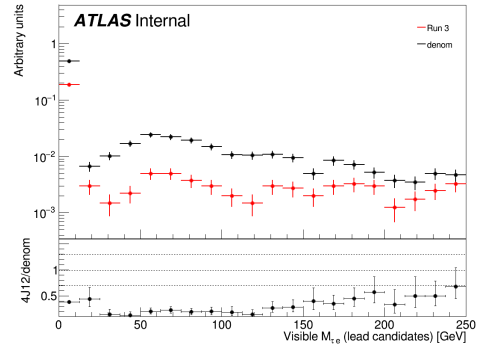
(a) Run-2 L1 $M_{\tau e}$



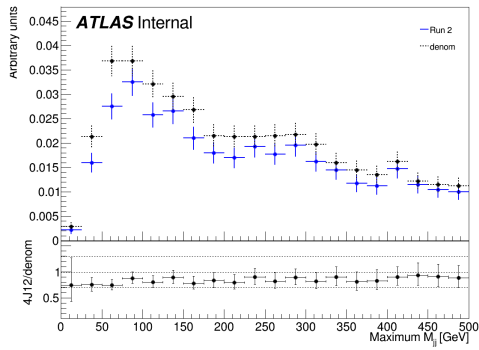
(b) Run-3 L1 $M_{\tau e}$



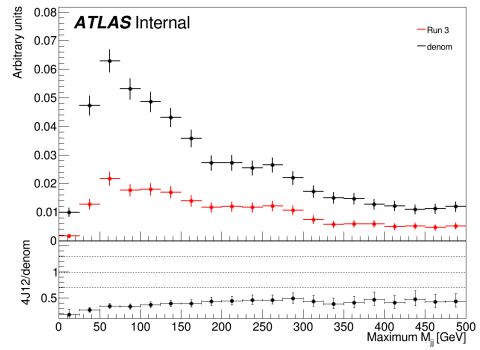
(c) Run-2 passing $M_{\tau e}$



(d) Run-2 passing $M_{\tau e}$

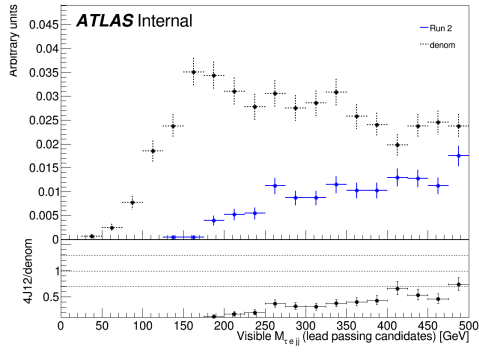


(e) Run-2 max M_{jj}

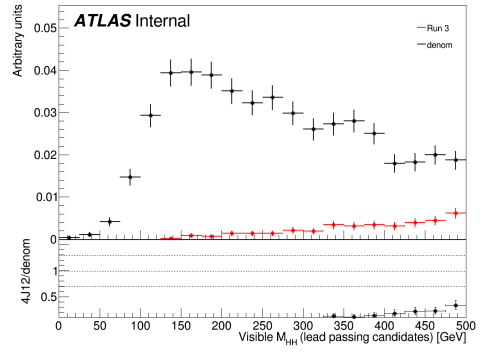


(f) Run-2 max M_{jj}

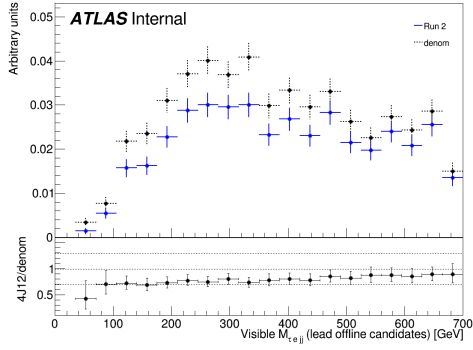
Figure 98: 4J12 reconstructed masses distribution



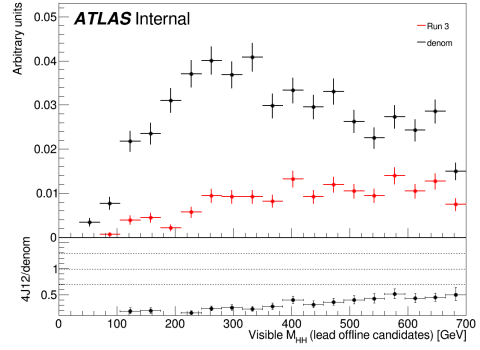
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



(c) Run-2 di-Higgs offline Mass



(d) Run-3 di-Higgs offline Mass

Figure 99: 4J12 di-Higgs Mass distribution

C.3 VBF L1Topo

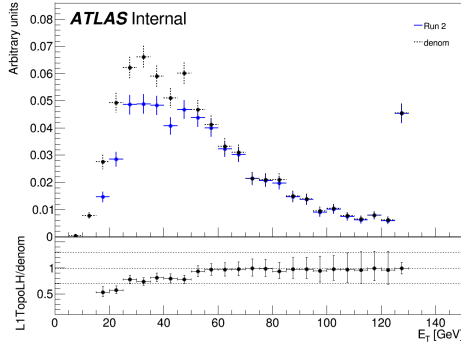
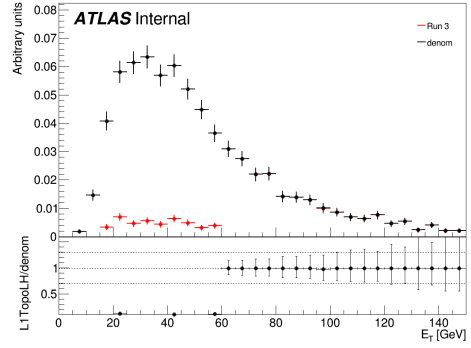
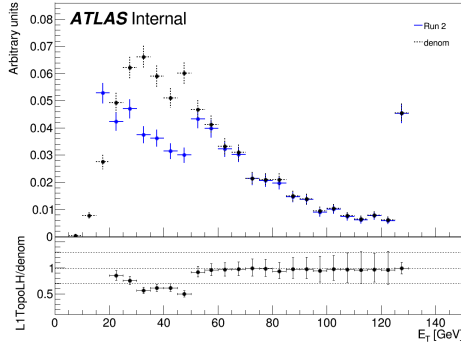
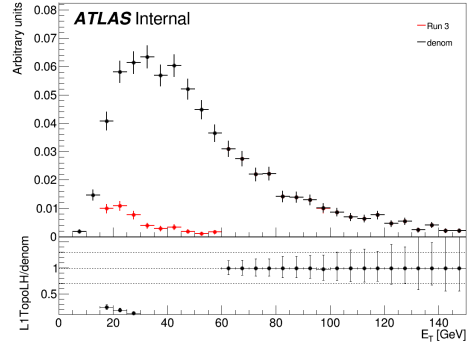
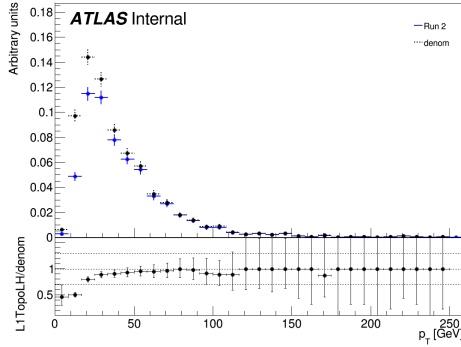
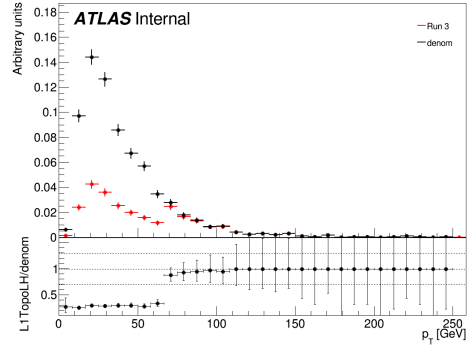
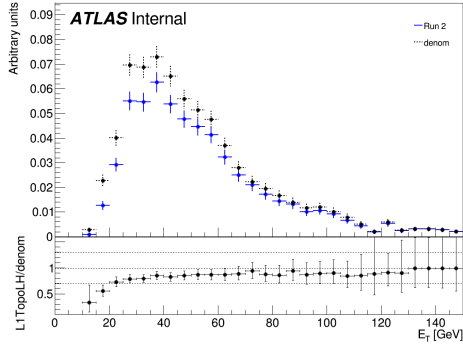
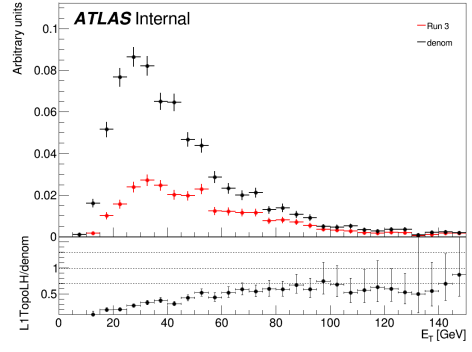
(a) Run-2 L1 electron E_T (b) Run-3 L1 electron E_T (c) Run-2 passing electron E_T (d) Run-3 passing electron E_T (e) Run-2 offline electron p_T (f) Run-3 passing electron p_T

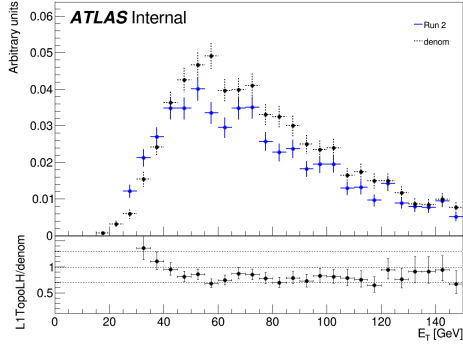
Figure 100: L1Topo electron distributions



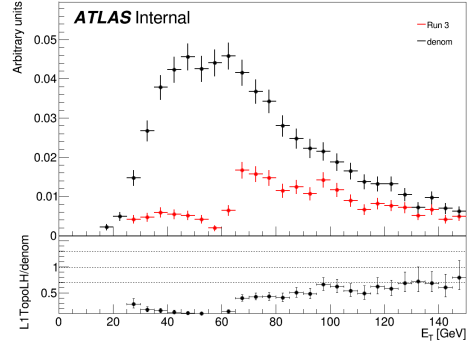
(a) Run-2 L1 leading jet E_T



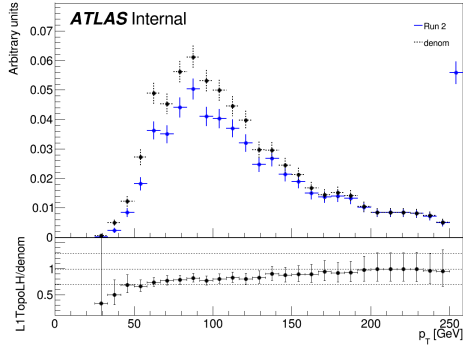
(b) Run-3 L1 leading jet E_T



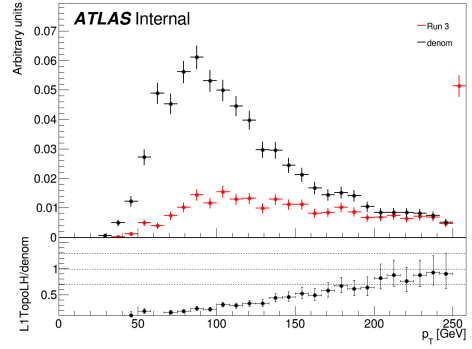
(c) Run-2 passing leading jet E_T



(d) Run-3 passing leading jet E_T

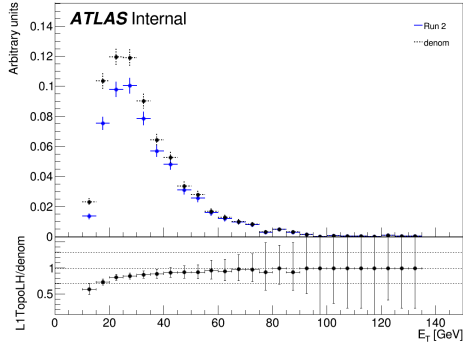


(e) Run-2 offline leading jet p_T

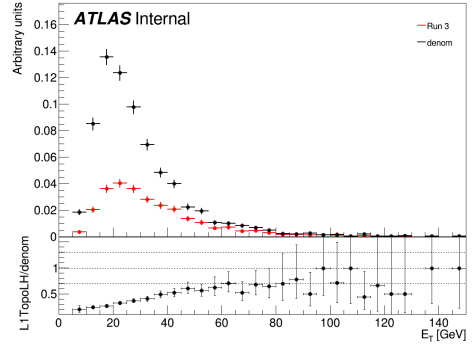


(f) Run-3 offline leading jet p_T

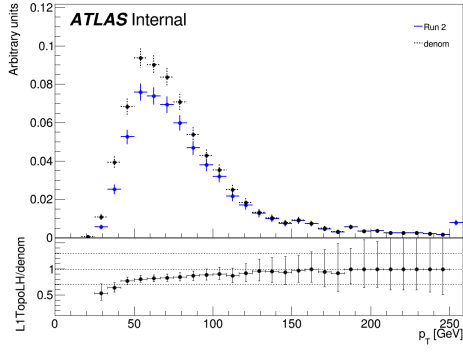
Figure 101: L1Topo leading jet distributions



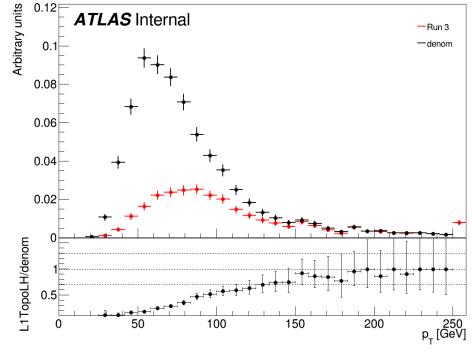
(a) Run-2 L1 sub-leading jet E_T



(b) Run-3 L1 sub-leading jet E_T

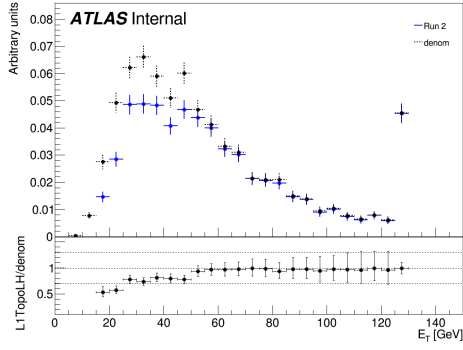


(c) Run-2 offline sub-leading jet p_T

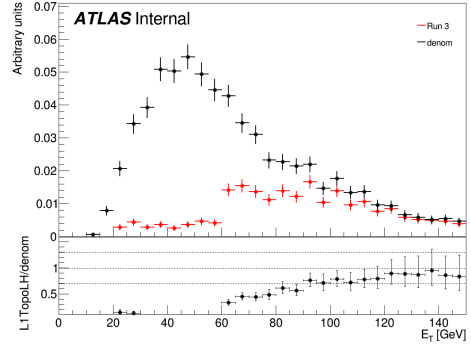


(d) Run-3 offline sub-leading jet p_T

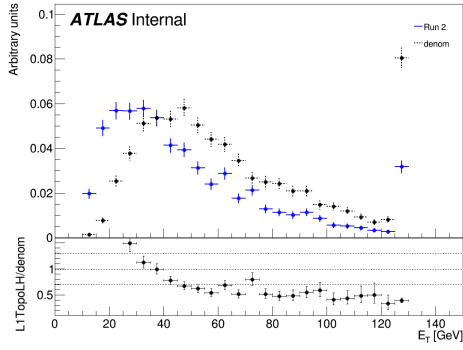
Figure 102: L1Topo sub-leading jet distributions



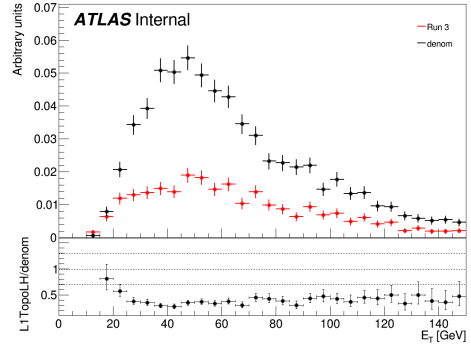
(a) Run-2 L1 tau-1 E_T



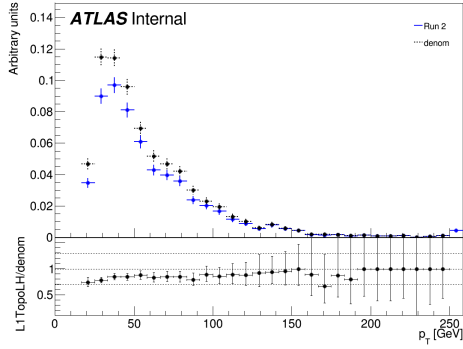
(b) Run-3 L1 tau-1 E_T



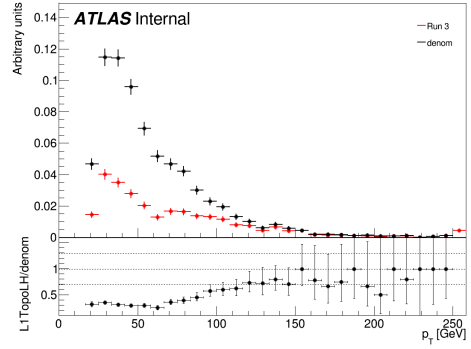
(c) Run-2 passing tau-1 E_T



(d) Run-2 passing tau-1 E_T

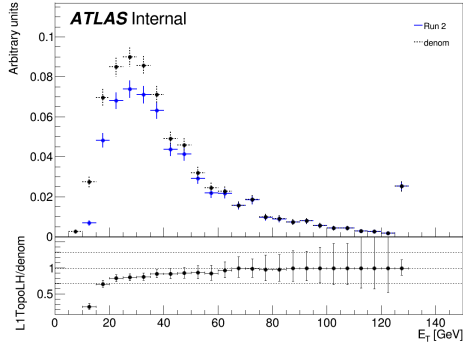


(e) Run-2 offline tau-1 p_T

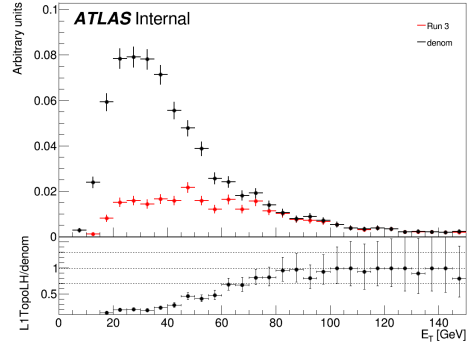


(f) Run-3 offline tau-1 p_T

Figure 103: L1Topo tau-1 distributions

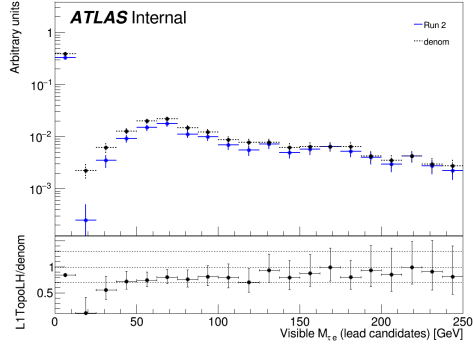


(a) Run-2 L1 tau-2 E_T

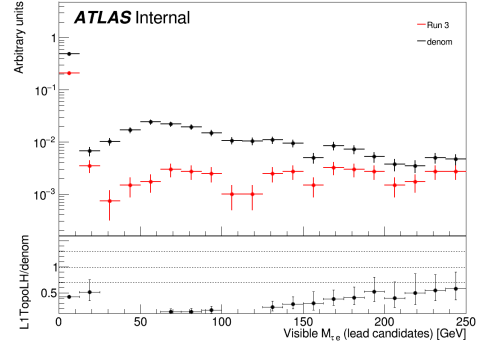


(b) Run-3 L1 tau-2 E_T

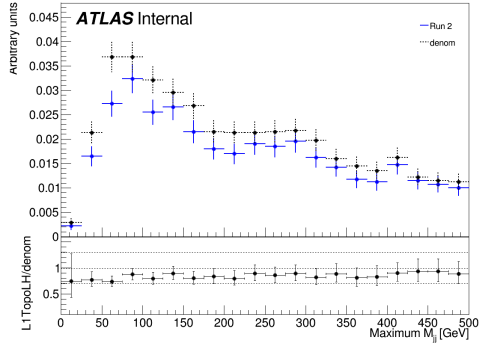
Figure 104: L1Topo tau-2 distributions



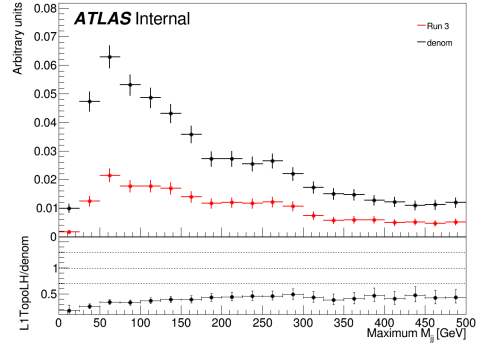
(a) Run-2 L1 $M_{\tau e}$



(b) Run-3 L1 $M_{\tau e}$

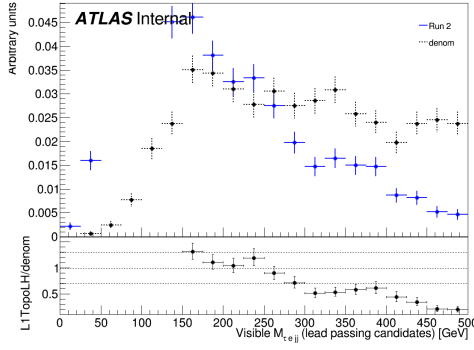


(c) Run-2 max M_{jj}

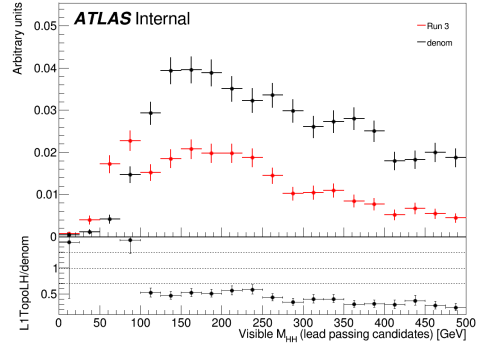


(d) Run-3 max M_{jj}

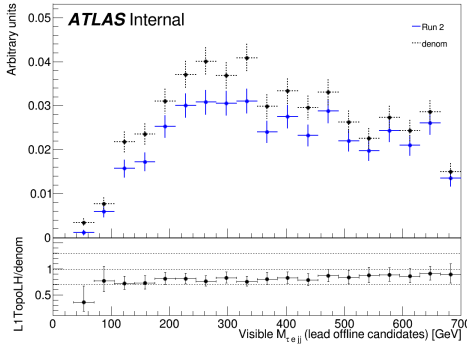
Figure 105: L1Topo reconstructed masses distribution



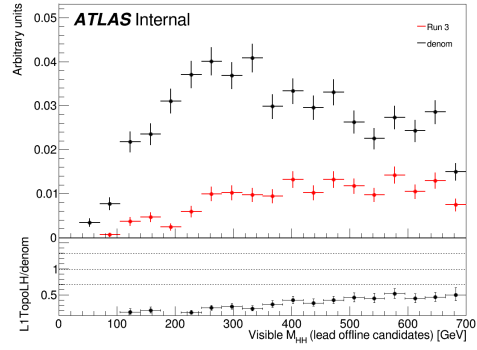
(a) Run-2 di-Higgs reconstructed Mass



(b) Run-3 di-Higgs reconstructed Mass



(c) Run-2 di-Higgs offline Mass



(d) Run-2 di-Higgs offline Mass

Figure 106: L1Topo di-Higgs Mass distributions

Appendix D Jet Algorithms

The hadronic interactions on high energy physics where hard scattered events produces colored partons, said partons would produce colourless objects due to hadronization and hadronic showering explained by colour confinement. Such multiplicity of objects challenges the reconstruction of the scattering, as clustered detector measurements make difficult to reconstruct a particular event. To solve this, cluster of hadrons set in a general direction are related to a jet object which comprises the coloured particles kinematic characteristics.

The procedure to include certain object to the jet is called a jet algorithm, the jet reconstruction study is pivotal to the understanding of the hard scattering events. Jet algorithms are designed to be infrared safe while operating as fast as possible, the algorithms lump together hadrons via either a cone reconstruction or a sequential recombination in a prefix order, that can be by angle, from soft to hard or from hard to soft object.

D.1 Jet algorithms Review

As the ones implemented in the LHC are sequential recombination algorithms, those will be the ones explained. The deciding procedure defined by those algorithms require measured quantities from the detector calorimeter as input, the particle pairs four-momenta is then recursively combined into the

jet. Each iteration identifies the smallest entry on the values $d_{i,j}$ and $d_{i,B}$. If this minimum distance happens to be a jet pair distance then both jets four-momenta are merged together, removing their jet-measure removed, the new combined jet is added as entry and the whole measures set recalculated. Otherwise, if the smallest entry is a jet-to-beam distance, the jet four-momenta is integrated to the beam and its measure removed. An inclusive algorithm will continue until all objects are merged with the beam returning the jets merged with the beam whose p_T is greater than a fixed minimum value. On the other hand, an exclusive one will end when a distance threshold d_{cut} is attained, returning the unmerged jets who satisfies $d_{i,B} < d_{cut}$.

A sequential recombination algorithm parameterized formulation can be expressed as:

$$d_{i,j} = \min[p_{T,i}^{2n}, p_{T,j}^{2n}] R_{i,j}^2, \quad d_{i,B} = p_{T,i}^{2n} R_0^2 \quad (\text{D.1})$$

where $R_{i,j}$ is the separation on the (η, ϕ) plane between the jet i and jet j , R_0 a parameter which specify the jet size. Reminiscing the recombination order, when the parameter n is positive the objects are recombined firstly by the softer ones, $n = 0$ indicates the merging by angle while negative n will recombine the objects starting from the harder ones. The most common sequential recombination algorithms are the k_T algorithm ($n = 1$), the Cambridge-Aachen algorithm ($n = 0$) [77] and the LHC default algorithm is the Anti- k_T algorithm ($n = -1$) [49]. The algorithms who have a parameter $n \leq 0$ are the ones who models a jet as cone shape objects.

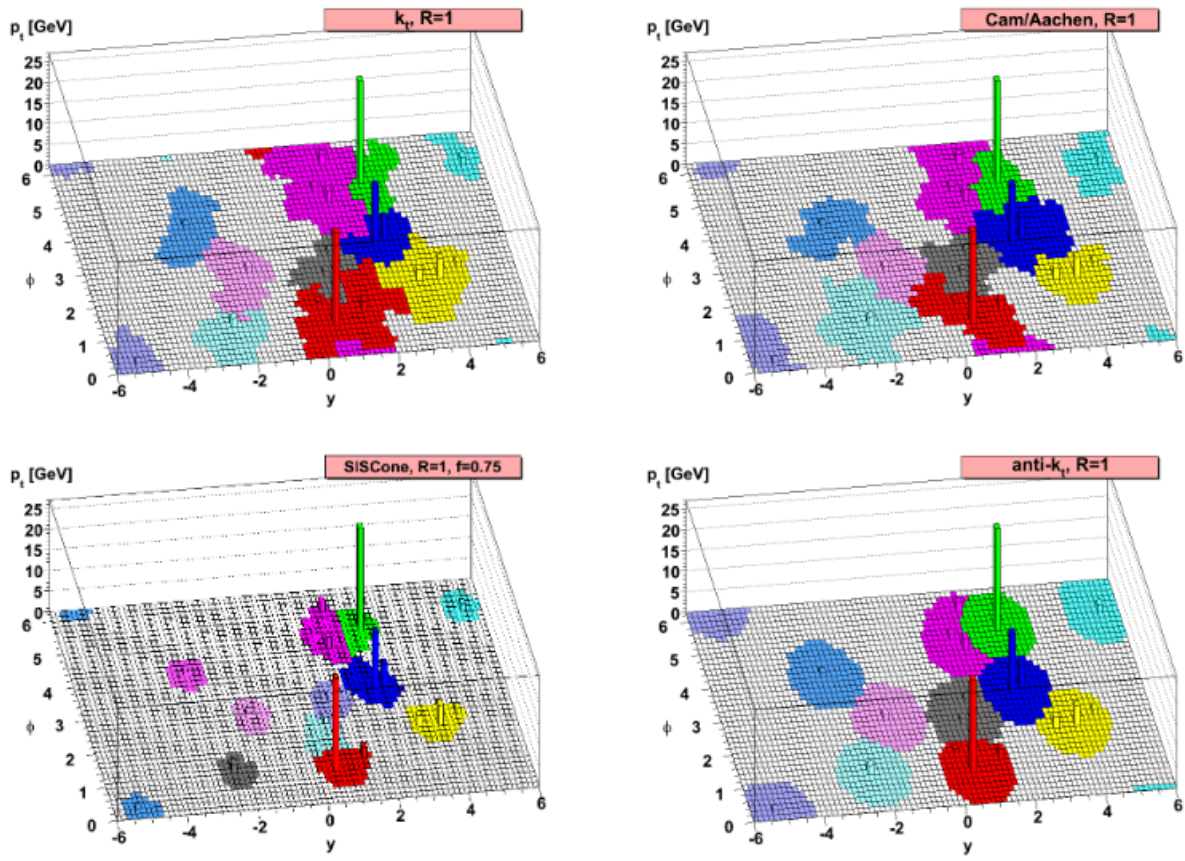


Figure 107: Herwig generated parton-level event sample, clustered soft ghost particles are associated to jets by four jets algorithms, showing the "catch" area of the hard jet. Source: ref. [78]

List of Figures

1404			
1405	1	SM of elementary particles.	6
1406	2	Leading loop chains which contribute to the $Y(p^2)$ calculation	11
1407	3	Behaviour of α_s regarding the distance between quarks r , what is referred as QCD	
1408		running coupling constant	11
1409	4	Potential $V(\phi)$ as the symmetry of the system has spontaneously broke	14
1410	5	Two diagrams for the Higgs pair production via gluon-gluon fusion, a triangle diagram	
1411		(left) and a square one (right) via top quark loops	16
1412	6	Three diagrams contributing to the Higgs pair production via vector boson fusion	
1413		(VBF) at three level. From the left to the right: A diagram involving the direct	
1414		coupling between two vector bosons and two Higgses (c_{2V}), a diagram involving two	
1415		VH couplings (c_V^2), and a diagram involving one VH coupling and a trilinear Higgs	
1416		coupling ($c_V\lambda$)	16
1417	7	Example of tau decays leptonical/one prong hadronically (left), three prong (right) . .	17
1418	8	A heavy resonance produced via gluon fusion decaying into a di-Higgs system	23
1419	9	CERN accelerator complex. Source: ref. [28]	25
1420	10	Detector coordinate system. Source: ref. [30]	26
1421	11	Layout of the ATLAS detector. Source: ref. [32]	27
1422	12	A 3D visualisation of the structure of the barrel of the ID. The beam pipe, the IBL,	
1423		the Pixel layers, the four cylindrical layers of the SCT and the three layers of TRT	
1424		barrel modules are shown. Source: ref. [33]	28
1425	13	Computer Generated image of the ATLAS calorimeter. Source: ref. [34]	29
1426	14	Granularity of the electromagnetic barrel LAr calorimeters. Source: ref. [35]	30
1427	15	Cross-sectional view of ATLAS. The barrel MDT chambers are shown in green, the	
1428		endcap MDT chambers are depicted cyan. In the barrel (endcaps), the RPC (TGC)	
1429		chambers are shown outlined in black (solid purple). Source: ref. [31]	31
1430	16	Magnet system of the ATLAS detector. The eight barrel toroid coils and end-cap coils	
1431		(red) and the four layer tile calorimeter followed by the central solenoid. Source: ref. [31]	32
1432	17	ATLAS Run 2 TDAQ system scheme. Source: ref. [36].	33
1433	18	Representation of the elements used for a large-R boosted tau pair reconstruction: the	
1434		blue cone is the large-R seeding jet, the two smaller yellow ones are the leading and	
1435		subleading jets. Source: ref. [39]	35
1436	19	A pictorial example of the jet vertex discriminant. Source: ref. [39]	36
1437	20	Efficiency versus ΔR illustrating the merging of boosted taus	36
1438	21	Efficiency versus p_T illustrating the boosted regime efficiency drop for single taus . . .	37
1439	22	In order from left to right, top to bottom this sequence of images exemplify the steps to	
1440		trim an initial clustered jet, then its constituents subjets $\Delta R < 0.2$ and the p_T fraction	
1441		cut. The area of each cell is proportional to the log of the cell p_T . Source: ref. [44] . .	38
1442	23	anti- k_T , $\Delta R = 1.0$ before calibration	39
1443	24	anti- k_T , $\Delta R = 1.0$ after calibration	39

1444	25	p_{miss} distribution, produced for a resonant mass $m_X = 1.2$ TeV	47
1445	26	Positive $p_{miss,1}$ and $p_{miss,2}$ example	48
1446	27	MET vector misaligned example	48
1447	28	MET vector and truthMET misaligned example	49
1448	29	MET vector and truthMET misaligned example	49
1449	30	$m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.2$ TeV	50
1450	31	m_{hh} distribution, produced for a resonant mass $m_X = 1.2$ TeV	50
1451	32	p_{miss} distribution implementing a χ^2 minimization, produced for a resonant mass $m_X =$	
1452		1.2 TeV	51
1453	33	$m_{\tau\tau}$ distribution, produced for a resonant mass $m_X = 1.2$ TeV	52
1454	34	m_{hh} distribution, produced for a resonant mass $m_X = 1.2$ TeV	52
1455	35	$m_{\tau\tau}$ resonance value depending on m_X	54
1456	36	m_{hh} resonance value depending on m_X	55
1457	37	Level-1 Calorimeter trigger electronics with Trigger Towers (a) and by the proposed	
1458		upgraded trigger electronics with Super Cells in Run-3 (b) Source: ref. [64].	56
1459	38	L1Calo system architecture for Run-3 [65].	57
1460	39	Side-by-side leading jet E_T distribution before (left) and after (right) the combined	
1461		trigger chain 3J12 (scaled properly with the cross-section).	60
1462	40	Side-by-side sub-leading jet E_T distribution before (left) and after (right) the combined	
1463		trigger chain 3J12 (scaled properly with the cross-section)	61
1464	41	Side-by-side electron E_T distribution before (left) and after (right) the combined trigger	
1465		chain 3J12 (scaled properly with the cross-section).	62
1466	42	Side-by-side tau-1 E_T distribution before (left) and after (right) the combined trigger	
1467		chain 3J12 (scaled properly with the cross-section)	63
1468	43	Side-by-side tau-2 E_T distribution before (left) and after (right) the combined trigger	
1469		chain 3J12 (scaled properly with the cross-section)	64
1470	44	Log scaled passing di-tau mass distribution before (left) and after (right) the combined	
1471		trigger chain 3J12 (scaled properly with the cross-section)	65
1472	45	Di-jet system reconstructed mass passing trigger (scaled properly with the cross-section)	66
1473	46	Di-Higgs reconstructed mass (scaled properly with the cross-section)	66
1474	47	Side-by-side leading jet E_T distribution before (left) and after (right) the combined	
1475		trigger chain 3J12 (scaled properly with the cross-section).	67
1476	48	Side-by-side sub-leading jet E_T distribution before (left) and after (right) the combined	
1477		trigger chain 3J12 (scaled properly with the cross-section)	68
1478	49	Side-by-side electron E_T distribution before (left) and after (right) the combined trigger	
1479		chain 3J12 (scaled properly with the cross-section).	69
1480	50	Side-by-side tau-1 E_T distribution before (left) and after (right) the combined trigger	
1481		chain 3J12 (scaled properly with the cross-section)	70
1482	51	Side-by-side tau-2 E_T distribution before (left) and after (right) the combined trigger	
1483		chain 3J12 (scaled properly with the cross-section)	71

1484	52	Log scaled di-tau mass distribution before (left) and after (right) the combined trigger chain 3J12 (scaled properly with the cross-section)	72
1485			
1486	53	Di-jet system reconstructed mass passing trigger (scaled properly with the cross-section)	73
1487	54	Di-Higgs reconstructed mass (scaled properly with the cross-section)	73
1488	55	Kinematics distribution for the heavy resonant mass $m_X = 1.0$ TeV	82
1489	56	Kinematics distribution for the heavy resonant mass $m_X = 1.0$ TeV	83
1490	57	Kinematics distribution for the heavy resonant mass $m_X = 1.2$ TeV	84
1491	58	Kinematics distribution for the heavy resonant mass $m_X = 1.4$ TeV	85
1492	59	Kinematics distribution for the heavy resonant mass $m_X = 1.6$ TeV	86
1493	60	Kinematics distribution for the heavy resonant mass $m_X = 1.8$ TeV	87
1494	61	Kinematics distribution for the heavy resonant mass $m_X = 2.0$ TeV	88
1495	62	Kinematics distribution for the heavy resonant mass $m_X = 2.0$ TeV	89
1496	63	Kinematics distribution for the heavy resonant mass $m_X = 2.5$ TeV	90
1497	64	Kinematics distribution for the heavy resonant mass $m_X = 3.0$ TeV	91
1498	65	3J20 electron distributions	92
1499	66	3J20 leading jet distributions	93
1500	67	3J20 sub-leading jet distributions	94
1501	68	3J20 tau-1 distributions	95
1502	69	3J20 tau-2 distributions	96
1503	70	3J20 reconstructed masses distribution	97
1504	71	3J20 di-Higgs Mass distributions	98
1505	72	4J12 electron distributions	99
1506	73	4J12 leading jet distributions	100
1507	74	4J12 sub-leading jet distributions	101
1508	75	4J12 Tau-1 distributions	102
1509	76	4J12 tau-2 distributions	103
1510	77	4J12 reconstructed masses distribution	104
1511	78	4J12 di-Higgs Mass distribution	105
1512	79	L1Topo electron distributions	106
1513	80	L1Topo leading jet distributions	107
1514	81	L1Topo sub-leading jet distributions	108
1515	82	L1Topo tau-1 distributions	109
1516	83	L1Topo tau-2 distributions	110
1517	84	L1Topo reconstructed masses distribution	111
1518	85	L1Topo di-Higgs Mass distributions	112
1519	86	3J20 electron distributions	113
1520	87	3J20 leading jet distributions	114
1521	88	3J20 sub-leading jet distributions	115
1522	89	3J20 tau-1 distributions	116
1523	90	3J20 tau-2 distributions	117
1524	91	3J20 reconstructed masses distribution	118

1525	92	3J20 di-Higgs Mass distributions	119
1526	93	4J12 electron distributions	120
1527	94	4J12 leading jet distributions	121
1528	95	4J12 sub-leading jet distributions	122
1529	96	4J12 Tau-1 distributions	123
1530	97	4J12 tau-2 distributions	124
1531	98	4J12 reconstructed masses distribution	125
1532	99	4J12 di-Higgs Mass distribution	126
1533	100	L1Topo electron distributions	127
1534	101	L1Topo leading jet distributions	128
1535	102	L1Topo sub-leading jet distributions	129
1536	103	L1Topo tau-1 distributions	130
1537	104	L1Topo tau-2 distributions	131
1538	105	L1Topo reconstructed masses distribution	131
1539	106	L1Topo di-Higgs Mass distributions	132
1540	107	Herwig generated parton-level event sample, clustered soft ghost particles are associated to jets by four jets algorithms, showing the "catch" area of the hard jet. Source: ref. [78]	134

1543 List of Tables

1544	1	The quarks characteristics present in the Standard Model. Charges, masses, spin and quantum numbers I (isospin), C (<i>charm</i>), S (<i>strangeness</i>), T (<i>topness</i>) and B (<i>bottomness</i>)	7
1545			
1546			
1547	2	The leptons characteristics present in the Standard Model. Charges, masses, spin and quantum numbers: L_e (<i>electron number</i>), L_μ (<i>muon number</i>) and L_τ (<i>tau number</i>) . .	7
1548			
1549	3	Branching ratios of a Higgs pair decays in the SM	17
1550	4	Collinear tau pairs comparison, depending on the resonance mass, the number of SR events, the accurately reconstructed number of events, the fraction between them and the tau/Higgs pairs correctly reconstructed solving the collinear mass equation. Finally the masses of the tau/Higgs pairs, the visible value, solving the system of equations (col) and applying the χ^2 parameter estimation respectively.	53
1551			
1552			
1553			
1554			
1555	5	Collinear tau pairs comparison, depending on the resonance mass. the $\sigma_{\tau\tau}/\sigma_{hh}$ visible value, solving the system of equations (col) and applying the χ^2 parameter estimation respectively.	53
1556			
1557			
1558	6	$hh \rightarrow b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ trigger efficiency (ggF sample)	59
1559	7	$hh \rightarrow b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ trigger efficiency (VBF sample)	59