

OPEN ACCESS

Jets, Bulk Matter, and their Interaction in Heavy Ion Collisions at the LHC

To cite this article: K Werner *et al* 2013 *J. Phys.: Conf. Ser.* **422** 012001

View the [article online](#) for updates and enhancements.

You may also like

- [Three-quark potential at finite temperature and chemical potential](#)
Jia-Jie Jiang, , Ya-Zhao Xiao et al.
- [Event-by-event study of space-time dynamics in flux-tube fragmentation](#)
Cheuk-Yin Wong
- [Flux tubes in full QCD at high temperature](#)
S Chagdaa, B Purev and E Galsandorj



ECS The Electrochemical Society
Advancing solid state & electrochemical science & technology

ECS UNITED

247th ECS Meeting
Montréal, Canada
May 18-22, 2025
Palais des Congrès de Montréal

Showcase your science!

Abstracts due December 6th

Jets, Bulk Matter, and their Interaction in Heavy Ion Collisions at the LHC

**K. Werner^(a), B. Guiot^(a), Iu. Karpenko^(b), M. Bleicher^(c), T. Pierog^(d),
S. Porteboeuf-Houssais^(e)**

^(a) SUBATECH, University of Nantes – IN2P3/CNRS– EMN, Nantes, France

^(b) Bogolyubov Institute for Theoretical Physics, Kiev 143, 03680, Ukraine

^(c) FIAS, Johann Wolfgang Goethe Universitaet, Frankfurt am Main, Germany

^(d) Karlsruhe Inst. of Technology, KIT, Campus North, Inst. f. Kernphysik, Germany

^(e) LPC, Universit Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France

E-mail: werner@subatech.in2p3.fr

Abstract. We discuss a theoretical scheme that accounts for bulk matter, jets, and the interaction between the two. The physical picture of our approach is the following: Initial hard scatterings result in mainly longitudinal flux tubes, with transversely moving pieces carrying the p_t of the partons from hard scatterings. These flux tubes constitute eventually both bulk matter (which thermalizes, flows, and finally hadronizes) and jets, according to some criteria based on partonic energy loss. High energy flux tube segments will leave the fluid, providing jet hadrons via the usual Schwinger mechanism of flux-tube breaking caused by quark-antiquark production. But the jets may also be produced at the freeze-out surface. Here we assume that the quark-antiquark needed for the flux tube breaking is provided by the fluid, with properties (momentum, flavor) determined by the fluid rather than the Schwinger mechanism. Considering transverse fluid velocities up to $0.7c$, and thermal parton momentum distributions, one may get a “push” of a couple of GeV to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate p_t jet hadrons.

The starting point is a multiple scattering approach corresponding to a marriage of Gribov-Regge theory and perturbative QCD (pQCD), for details see [1]. An elementary scattering corresponds to a parton ladder, containing a hard scattering calculable based on pQCD, including initial and final state radiation. These ladders are identified with flux tubes, which are mainly longitudinal objects, with transversely moving parts, carrying the transverse momenta of the hard scatterings. These objects are also referred to as kinky strings [2, 3, 4]. The consistent quantum mechanical treatment of the multiple scattering is quite involved, it is based on cutting rule techniques to obtain partial cross sections, which are then simulated with the help of Markov chain techniques [5].

Strings break via the production of quark-antiquark pairs according to the so-called area law [1, 5, 6, 7]. The string segments are identified with final hadrons and resonances. In heavy ion collisions and also in high multiplicity events in proton-proton scattering at very high energies, the density of strings will be so high that the strings cannot decay independently as described above. Here we have to modify the procedure as discussed briefly in the following. All the details can be found in ref. [8].

The starting point are still the flux tubes (kinky strings) originating from elementary collisions. These flux tubes will constitute both, bulk matter which thermalizes and expands

collectively, and jets. The criterion which decides whether a string piece ends up as bulk or jet, will be based on energy loss. In the following we consider a flux tube in matter, where “matter” first means the presence of a high density of other flux tubes, which then thermalize.

Three possibilities should occur, referred to as A, B, C, see Fig. 1(a,b) :

- A** String segments far from the surface and/or being slow will simply constitute matter, they lose their character as individual strings. This matter will evolve hydrodynamically and finally hadronize (“soft hadrons”).
- B** Some string pieces (like those close to transversely moving kinks) will be formed outside the matter, they will escape and constitute jets (“jet hadrons”).
- C** There are finally also string pieces produced inside matter or at the surface, but having enough energy to escape and show up as jets (“jet hadrons”). They are affected by the flowing matter (“fluid-jet interaction”).

The surface is defined by a constant temperature. In principle the formation and expansion of matter and the interaction of partons with matter is a dynamical process. However, the initial distribution of energy density and the knowledge of the initial momenta of partons (or string segments) allows already an estimate about the fate of the string segments. By “initial time” we mean some early proper time τ_0 which is a parameter of the model.

Only the bulk segments are used to determine the initial conditions for hydrodynamics, following the same procedure as explained in [1, 8]. Starting from this initial condition, the bulk matter will evolve according to the equations of ideal hydrodynamics till “hadronization”, which occurs at some “hadronization temperature” T_H [1]. Hadronization means that we change from matter description to particle description, but hadrons still interact among each other, realized via a hadronic cascade procedure [9], already discussed in [1].

Most interesting are the segments which are formed inside but still escape. These are type C segments. They escape, but their properties change. Actually such a segment leaves “matter” at the hadronization surface at a particular space-time point x , which is characterized by some collective flow velocity $\vec{v}(x)$. We assume that the string breaking in this case is modified such that the quark and antiquark (or diquark) necessary for the string breaking are taken from the flowing fluid rather than being produced via the Schwinger mechanism. So the new string segment is composed of a quark and antiquark (diquark) carrying the flow velocity, and the string piece in between, which has not been changed. This string piece may or may not carry large momentum, depending on whether it is close to a kink or not, the former possibility shown in Fig. 1(b).

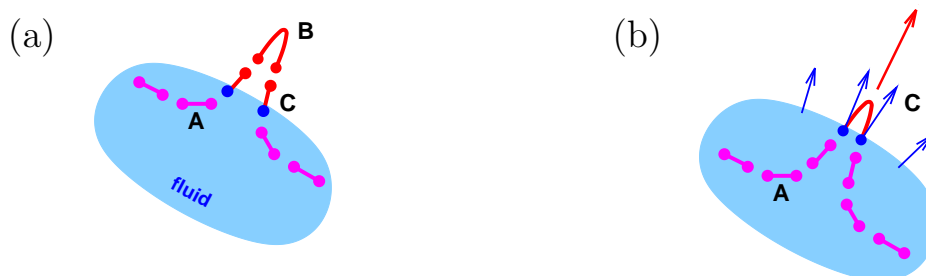


Figure 1. (Color online) Flux tube in matter (from other flux tubes, blue colored area). One distinguishes three types of behavior for string segments, noted as A, B, C (see text). The highest p_t string segment may be of type B (a) or of type C (b). A type C segment picks up quark and antiquark from the fluid, carrying momenta and flavor according to the fluid properties (b).

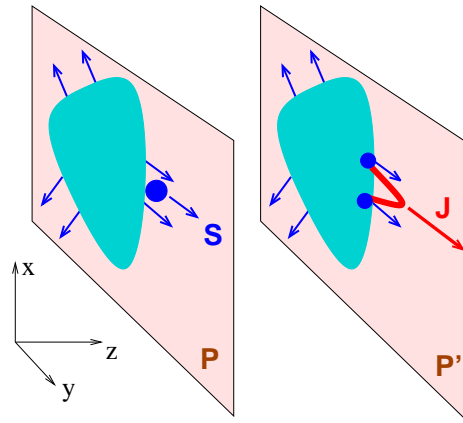


Figure 2. (Color online) Sketch of two cuts of the fluid volume corresponding to the space-time rapidities η_s and η'_s , the two corresponding transverse planes being \mathbf{P} and \mathbf{P}' . We show the example of a triangular flow pattern – the same at η_s and η'_s .

Our prescription for bulk-jet separation and interaction affects strongly dihadron correlations and azimuthal anisotropy results at intermediate p_t , due to the fluid-jet interaction. Let us consider the situation of an initial azimuthal anisotropy in the energy density which is transported into a corresponding anisotropy in the flow. We sketch in Fig. 2 the (somewhat exaggerated) situation of a triangular transverse flow pattern with maximal flow around $\phi = 0^\circ$, 120° , and 240° (with respect to the y -axis). The flow maxima are indicated by blue arrows. Again it is very important that this flow pattern is (not necessarily in magnitude, but in shape) very similar at different longitudinal positions – in the figure indicated by the two transverse planes \mathbf{P} and \mathbf{P}' , corresponding to two different space-time rapidities η_s and η'_s . A soft hadron (\mathbf{S}) produced at η_s at the fluid surface close to the position of maximal flow (for example at $\phi = 0^\circ$), will be boosted by the latter one and therefore carry information about this flow. A jet hadron (\mathbf{J}) produced at η'_s at the same angle ($\phi = 0^\circ$) close to the surface, will pick up a quark and an antiquark, both carrying flow, which adds the corresponding transverse momentum to the p_t of the string segment (red element in the figure). It is the same flow which affects the jet hadron at η'_s and the soft hadron at η_s , which creates dihadron correlations. It also explains anisotropic behavior at quite large p_t . In Fig. 3, we plot v_2 as a function of the transverse momentum for different centralities in Pb-Pb collisions at 2.76 TeV. The magnitude of the elliptical flow coefficients increase at low p_t to reach a maximum around 2-3.5 GeV/c and then drop slowly at large p_t . The behavior at high p_t is the most interesting aspect: even at 10 GeV/c, there is a significant amount of elliptical flow, due to the fluid-jet interaction, which pushes jet particles in the direction of the collective flow at the freeze-out surface.

To summarize: We presented a theoretical scheme which accounts for bulk matter, jets, and the interaction between the two. The criterion for bulk-jet separation is based on parton energy loss. But in addition to the latter mechanism, there are very important new phenomena which have not been discussed so far: The interaction between jet hadrons and soft ones (from fluid freeze-out), and the interaction between the fluid and jet hadrons at the moment of the creation of the latter ones. Particle production between zero and (at least) 20 GeV/c is affected. We understand quantitatively azimuthal anisotropies in single particle production and dihadron (long range) correlations at large values of p_t .

ACKNOWLEDGMENTS: This research has been carried out within the scope of the ERG (GDRE) “Heavy ions at ultra-relativistic energies”, a European Research Group comprising IN2P3/CNRS, Ecole des Mines de Nantes, Universite de Nantes, Warsaw University of

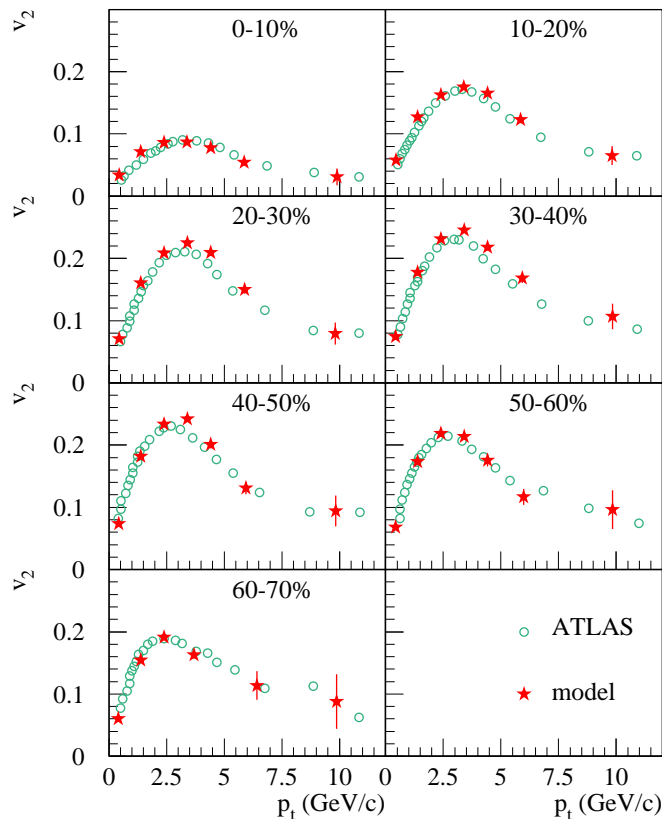


Figure 3. (Color online) p_t dependence of elliptical flow for different centralities in Pb-Pb collisions at 2.76 TeV. We compare the ATLAS data [11] (circles) with calculations (red lines).

Technology, JINR Dubna, ITEP Moscow, and Bogolyubov Institute for Theoretical Physics NAS of Ukraine. Iu.K. acknowledges partial support by the State Fund for Fundamental Researches of Ukraine (Agreement F33/42-2012) and National Academy of Sciences of Ukraine (Agreement F3/2012). . M.B. thanks the Hessian LOEWE initiative for financial support.

- [1] K. Werner, Iu.Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, Phys. Rev. C 82, 044904 (2010)
- [2] Y. Nambu, Proc. Intl. Conf. on Symmetries and Quark Models, Wayne State Univ., 1969
- [3] J. Scherk, Rev. Mod. Phys. 47, 123 (1975)
- [4] C. Rebbi, Phys. Rep. 12 (1974) 1
- [5] H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog and K. Werner, Phys. Rept. 350, 93, 2001
- [6] X. Artru, Phys. Rep. 97, 147 (1983)
- [7] D. A. Morris, Nucl. Phys. B288, 717, 1987
- [8] K.Werner, Iu.Karpenko, M. Bleicher, T.Pierog, S. Porteboeuf-Houssais, arXiv:1203.5704, Phys. Rev. C 85, 064907 (2012)
- [9] M. Bleicher et al., J. Phys. G25 (1999) 1859; H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stoecker, Phys. Rev. C78 (2008) 044901
- [10] ALICE collaboration, K. Aamod et al., Phys.Lett. B708 (2012) 249-264, arXiv:1109.2501
- [11] ATLAS collaboration, G. Aad et al., Phys.Lett. B707 (2012) 330-348, arXiv:1108.6018