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# System size dependence of particle production in EPOS

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**Abstract.** The aim of this paper is to understand particle production for different collision systems, namely proton-proton (pp), proton-nucleus (pA), and nucleus-nucleus (AA) scattering at the LHC. We will investigate in particular particle yields and ratios versus multiplicity, using the same multiplicity definition for the three different systems, in order to analyse in a compact way the evolution of particle production with the system size and the origin of a very different system size dependence of the different particles.

The main goal of heavy ion physics at very high energies is the proof of existence of the creation of a quark-gluon plasma, and the study of the properties of this exotic state, by analyzing the final state of many thousands of produced hadrons. We will investigate particle production in pp, pA, and AA collisions, our analysis tool being the EPOS model. EPOS3 [1] is a universal model in the sense that for pp, pA, and AA collisions, the same procedure applies, based on several elements:

**Initial state.** A Gribov-Regge multiple scattering approach is employed (“Parton-Based Gribov-Regge Theory” PBGRT [2]), where the elementary object (by definition called Pomeron) is a DGLAP parton ladder. Starting from a multi-Pomeron structure for the elastic scattering S-matrix, one then uses cutting rules to obtain (partial) cross sections of inelastic processes, by employing Markov chain techniques.

**Non-linear effects.** High parton density effects like gluon fusion during the parton evolution (see fig. 1(a)) are taken into account by using a dynamical saturation scale for each Pomeron, of the form  $Q_s = Q_s(N_{\text{Pom}}, \hat{s})$ , depending on the number of Pomerons  $N_{\text{Pom}}$  connected the Pomeron in question (see





**Figure 1.** (Color online) (a) Non-linear effect: ladder fusion. (b) Pomerons connected to a given (red) Pomeron

fig. 1(b)), and its energy  $\hat{s}$ . The functional form of  $Q_s$  is obtained from fitting to the energy dependence of basic cross sections and the multiplicity dependence of particle production in pp at very high transverse momenta.

**Core-corona approach.** The parton ladders corresponding to Pomerons are treated as classical relativistic (kinky) strings. So in general, we have a large number of (partly overlapping) strings. Based on the momenta and the density of string segments, one separates at some early proper time  $\tau_0$  the core (going to be treated as fluid) from the corona (escaping hadrons, including jet hadrons). The core-corona procedure has been first described in [3], a more recent discussion is found in [1]. The corresponding energy-momentum tensor of the core part is transformed into an equilibrium one, needed to start the hydrodynamical evolution. This is based on the hypothesis that equilibration happens rapidly and affects essentially the space components of the energy-momentum tensor.

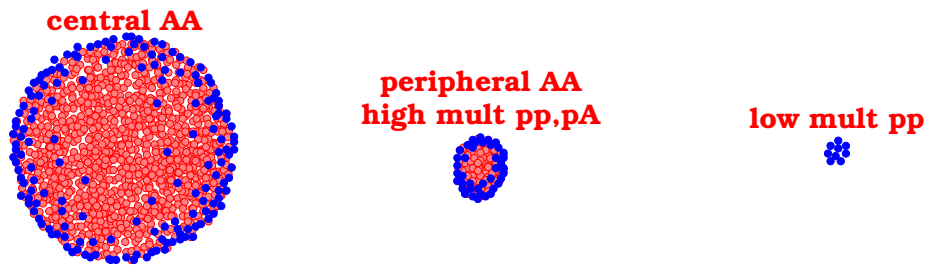
**Viscous hydrodynamic expansion.** Starting from the initial proper time  $\tau_0$ , the core part of the system evolves according to the equations of relativistic viscous hydrodynamics [1, 4], where we use presently  $\eta/s = 0.08$ . A cross-over equation-of-state is used, compatible with lattice QCD [5, 6]. The “core-matter” hadronizes on some hyper-surface defined by a constant temperature  $T_H$ , where a so-called Cooper-Frye procedure is employed, using equilibrium hadron distributions, see [6].

**Final state hadronic cascade.** After hadronization, there occur still hadron-hadron rescatterings, realized via UrQMD [7].

The above procedure is employed for each event (event-by-event procedure).

We will discuss particle production as a function of the average multiplicity per eta interval  $\langle dn/d\eta(0) \rangle$  at central pseudorapidity ( $\eta = 0$ ), whereas forward pseudorapidity intervals are used to define the different multiplicity classes. This is the same procedure as used by the ALICE experiment. In the following  $\langle dn/d\eta(0) \rangle$  is simply referred to as “multiplicity”.

Crucial for the following discussion is the fact that the core-corona separation behaves quite differently for small and big systems (although we employ the same procedure), see fig. 2. Whereas for very large multiplicity (central AA) most of the matter is core, with small corona contributions at



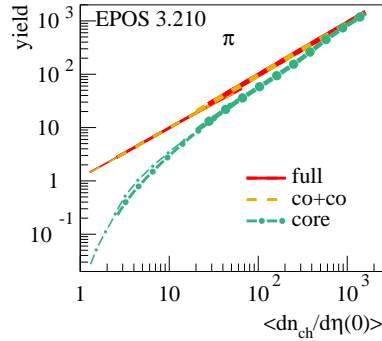
**Figure 2.** (Color online) Core (red) and corona (blue) in a plane perpendicular to the beam axis, for big (left), small (right) and intermediate (middle) systems.

the surface (or some high pt segments further inside), we get at very low multiplicity (in pp) only corona : the system is not dense enough to form a core. High multiplicity pp and pA, or peripheral AA collisions are in between, both core and corona being important.

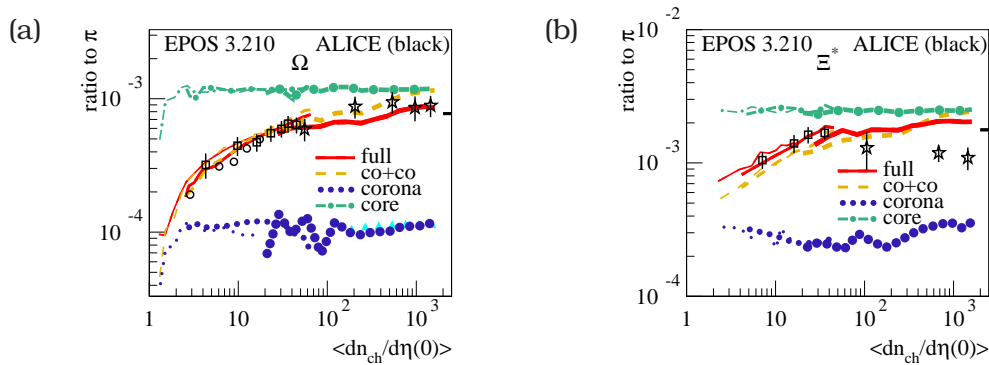
core	green dashed-dotted	particle from the core only	no hadronic cascade
corona	blue dotted	particles from corona only	no hadronic cascade
co-co	yellow dashed	particles from core and corona	no hadronic cascade
full	red full	all particles	with hadronic cascade
	blue triangles	particles from pure string decay	no cascade, no hydro
	thin lines	pp simulation	
	intermediate lines	pA (pPb) simulation	
	thick lines	AA (PbPb) simulation	
	open circles	pp data	
	open squares	pA (pPb) data	
	open stars	AA (PbPb) data	

**Table 1.** Color, line, and symbol codes used for the plots in this paper, to accommodate the different contributions and the different systems.

Another way of seeing the multiplicity dependence of the core-corona separation is shown in fig. 3, where we plot the pion yield versus multiplicity, for only core particles (“core”, green dashed-dotted), the contribution from core + corona (“co-co”, particles from core and corona, yellow dashed), both contributions from EPOS simulation without hadronic cascade. The ratio “core” over “co-co” would be the relative core fraction, which increases continuously from zero (at small multiplicity) to unity (at large multiplicity). We also plot the “full” contribution, referring to all particles, for a simulation with hadronic cascade (A summary of color, line, and symbol codes is found in table 1). In all cases we plot curves for the three systems: pp, pA, and AA. There are substantial overlap regions, where different systems contribute, but we observe unique curves, no system size dependence. We also observe that the



**Figure 3.** (Color online) Pion yield versus multiplicity. We compare different contributions (core, core plus corona (co-co) and the the full contribution (the latter on including the final state hadronic cascade) for different systems: pp (thin lines), AA (thick lines), and pA (intermediate lines). (A summary of color, line, and symbol codes is found in table 1)



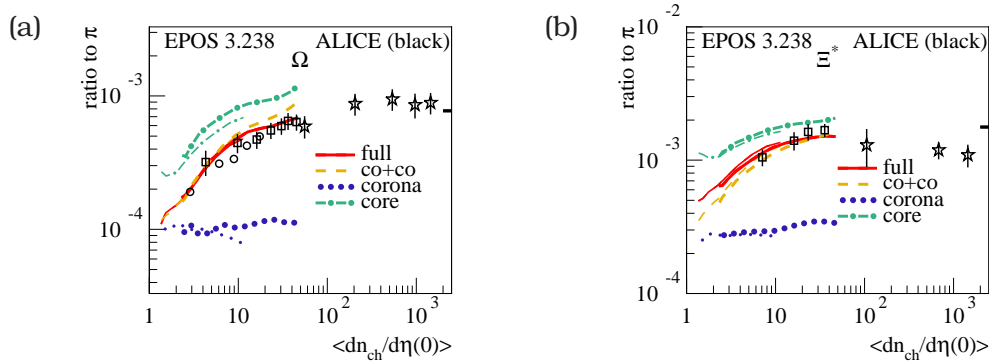
**Figure 4.** (Color online) Particle to pion ratio for different particle species versus multiplicity, for different contributions from the EPOS simulations, for different systems (pp, pA, AA). We also plot ALICE data. These and data for many more hadrons can be found in [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. See table 1 for color, line, and symbol codes.

hadronic cascade has no effect on the pion production (“co-co” and “full” gives identical results).

In the following we will investigate the multiplicity dependence (for pp, pA, AA) of some particle ratios to pions, for the different contributions from EPOS simulations, compared to data from the ALICE collaboration, who measured such ratios for many particle species [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. We always refer to the color, line, and symbol codes of table 1.

In fig. 4(a), we plot the  $\Omega$  to pion ratio versus multiplicity, for different contributions from the EPOS simulations, for different systems (pp, pA, AA), see table 1 for color, line, and symbol codes. Despite a large overlap for





**Figure 5.** (Color online) Sama as figs. 4, but here we consider phase space decay.

the different systems, we observe universal curves, for all contributions. The core contribution is completely flat, as expected since the particle ratios only depend on the properties of the fluid at freeze out, taken to be the same in all systems. Also the corona contribution (from string segments which escape the fluid) is essentially flat, so we have two flat curves, from core and corona, but here core and corona curves are separated by about a factor of 10, leading to a strong increase of the core+corona (co-co) contribution of a factor of 10 with multiplicity. The full curve is slightly reduced at high multiplicity compared to co-co, due to hadronic final state interactions (baryon-antibaryon annihilation). We observe very similar results for the  $\Xi^*$  resonance (lifetime 21.7 fm/c), see fig. 4(b), but some discrepancy compared to the data.

It is not be very realistic to use the (grand canonical) Cooper-Frye prescription for decaying the plasma, in case of very small systems. As a first test, we employ the EPOS LHC model, which uses n-body phase space decay, with complete energy and momentum conservation (but parameterized flow rather than hydrodynamics). The results are shown in fig. 5. Now, the core curves are no longer flat, but they decrease at small multiplicities. But core alone is not enough to describe the data, still core-corona separation is needed, with a slightly bigger core weight compared to the case of Cooper-Frye prescription.

To summarize, we have shown that the study of the multiplicity dependence of particle ratios for different collision systems (pp, pA, AA) provides useful information concerning the production mechanism of particles. Using phase space decay compared to the Cooper-Frye prescription changes their core curves, but still core-corona separation is needed to explain the data.

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