A unified description of the reaction dynamics: Comparing pPb and PbPb collisions at the LHC

Klaus Werner
SUBATECH, University of Nantes – IN2P3/CNRS– EMN, Nantes, France

Abstract. There is little doubt that in heavy ion collisions at the LHC, we observe a hydrodynamically expanding system, providing strong evidence for the formation of a Quark Gluon Plasma (QGP) in the early stage of such collisions. These observations are to a large extent based on results on azimuthal anisotropies, perfectly compatible with a hydrodynamic evolution. Surprisingly, in p-Pb collisions one observes a very similar behavior. Motivated by the experimentally observed similarities of $v_n$ results in pPb and PbPb collisions at similar multiplicities at the LHC [1], we analyze these findings using the EPOS3 approach.

1. Introduction
Collective hydrodynamic flow seems to be well established in heavy ion (HI) collisions at energies between 200 and 2760 AGeV, whereas p-p and p-A collisions are often considered to be simple reference systems, showing “normal” behavior, such that deviations of HI results with respect to p-p or p-A reveal “new physics”. Surprisingly, recent results from p-Pb at 5 TeV on the transverse momentum dependence of azimuthal anisotropies are very similar to the observations in HI scattering at comparable multiplicities.

In fig. 1, we show results from the CMS collaboration[1] on the $p_t$ dependence of $v_2$ of charged particles for two different multiplicity ranges, for pPb (a) and PbPb (b). The results for the two systems are quite similar, although the shapes in pPb and PbPb are somewhat different. We

Figure 1. (Color online) $p_t$ dependence of $v_2$ of charged particles from the CMS collaboration[1].

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
observe for both systems little change with multiplicity. Remarkable is the fact that $v_2$ at large $p_t$ (where hard physics is expected to dominate) remains large.

In fig. 2, we show results from the CMS collaboration[1] on the $p_t$ dependence of $v_3$ of charged particles for the two different multiplicity ranges, for pPb (a) and PbPb (b). Here, the

Figure 2. (Color online) $p_t$ dependence of $v_3$ of charged particles from the CMS collaboration[1].

Figure 3. (Color online) (a) Pomeron number distribution in pPb and PbPb collisions (the PbPb distribution extends up to about 2000). (b) Average charged particle multiplicity density at central pseudorapidity $dn/d\eta(0)$ as a function of the Pomeron number. (c) Radial flow at freeze-out in pPb and PbPb for a given $N_{\text{track}}$ range at space-time rapidity $\eta = 0$. 
two systems are almost perfectly identical. The curves increase slightly with Ntrack. For large values of \( p_t \), in all cases, \( v_3 \) becomes small.

In [1] they study as well the mass splitting in the \( p_t \) dependence of \( v_2 \) and \( v_3 \) for kaons compared to lamdbdas. Again, pPb and PbPb show the same effect.

In EPOS 3 [2], the basic quantity to characterize the geometry of a collision is the number \( N_{\text{Pom}} \) of Pomerons. In fig. 3(a), we plot the \( N_{\text{Pom}} \) distributions in pPb and PbPb. The overlap area amounts to around 60 or less Pomerons. The Pomeron number is very closely related to multiplicity, but in a different way for pPb and PbPb, as shown in fig.3(b), where we plot the average charged particle multiplicity density at central pseudorapidity \( dn/d\eta(0) \) as a function of the Pomeron number. We also indicate the intervals corresponding to the \( N_{\text{track}} \) ranges used by CMS. The corresponding Pomeron numbers are systematically higher for pPb compared to PbPb. The reason is that the radial flow at freeze-out is much bigger in pPb, as shown in fig.3(c), where we plot the radial flow at freeze-out in pPb and PbPb for a given \( N_{\text{track}} \) range. This is due to the fact that in pPb the initial radial size is very small leading to a fast radial expansion. This strong flow in pPb has visible consequences.

2. Unified description of the reaction dynamics

To analyze the \( p_t \) dependence of \( v_2 \) and \( v_3 \) in given given multiplicity ranges for pPb and PbPb collisions, we employ EPOS3 [2], a unified description of the dynamics of ALL reactions, from p-p to AA. EPOS3 [2] is based on several stages:

**Initial conditions.** A Gribov-Regge multiple scattering approach is employed [3], where the elementary object (by definition called Pomeron) is a DGLAP parton ladder, using in addition a CGC motivated saturation scale [5] for each Pomeron, of the form \( Q_s \propto N_{\text{part}} \tilde{s}^\lambda \), where \( N_{\text{part}} \) is the number of nucleons connected the Pomeron in question, and \( \tilde{s} \) its energy. The parton ladders are treated as classical relativistic (kinky) strings. Our formalism is referred to as “Parton-Based Gribov-Regge Theory” (PBGRT).

**Core-corona approach.** At some early proper time \( \tau_0 \), one separates fluid (core) and escaping hadrons, including jet hadrons (corona), based on the momenta and the density of string segments [4, 2]. 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 [2, 6], where we use presently \( \eta/s = 0.08 \). A cross-over equation-of-state is used, compatible with lattice QCD [7, 8].

**Statistical hadronization** The “core-matter” hadronizes on some hypersurface defined by a constant temperature \( T_H \), where a so-called Cooper-Frye procedure is employed, using equilibrium hadron distributions, see [8].

**Final state hadronic cascade** After hadronization, the hadron density is still big enough to allow hadron-hadron rescatterings. For this purpose, we use the UrQMD model [9].

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

Whereas our approach is described in detail in [2], referring to older works [3, 4, 8], we confine ourselves here to a couple of remarks, to selected items. The initial conditions are generated in the Gribov-Regge multiple scattering framework. Our formalism is referred to as “Parton-Based Gribov-Regge Theory” (PBGRT) and described in very detail in [3], see also [2] for all the details of the present (EPOS3) implementation. The fundamental assumption of the approach is the hypothesis that the S-matrix is given as a product of elementary objects, referred to
\[ \sigma^{\text{tot}} = \sum_{\text{cut}} \int \sum_{\text{uncut}} \int A - G - d\sigma^{\text{exclusive}} \]

**Figure 4.** (Color online) PBGRT formalism: The total cross section expressed in terms of cut (dashed lines) and uncut (solid lines) Pomerons, for nucleus-nucleus, proton-nucleus, and proton-proton collisions. Partial summations allow to obtain exclusive cross sections, the mathematical formulas can be found in [3], or in a somewhat simplified form in [2].

**Figure 5.** (Color online) Initial condition for QGP as obtained in the PBGRT framework in the year 2000, see ref [10].

as Pomerons. Once the Pomeron is specified (taken as a DGLAP parton ladder, including a saturation scale), everything is completely determined. Employing cutting rule techniques, one may express the total cross section in terms of cut and uncut Pomerons, as sketched in fig. 4. The great advantage of this approach: Doing partial summations, one obtains expressions for partial cross sections \( d\sigma^{\text{exclusive}} \), for particular multiple scattering configurations, based on which the Monte Carlo generation of configurations can be done. No additional approximations are needed. The above multiple scattering picture is used for p-p, p-A, and A-A.

Based on the PBGRT approach, we obtain in A-A collisions a very large number of strings, but the randomness of their transverse positions leads to “bumpy” energy density distributions in the transverse plane at \( \tau_0 \), as published for the first time in the year 2000, see fig. 21 of [10], reproduced as fig. 5 in this paper.

To understand the results later in this paper, we will discuss an example of core-corona separation in a semi-peripheral p-Pb collision, as shown in fig. 6. Shown (in the left figure)
Figure 6. (Color online) Left: Core-corona separation in a semi-peripheral p-Pb collision. Right: the corresponding core and corona contributions to the $p_t$ spectra of pions and protons.

are string segments in the transverse plane, red (core) and green (corona) ones. There are sufficient overlapping core string segments to provide a core of plasma matter, showing a (short) hydrodynamic expansion, quickly building up flow. In the right figure, we plot the contribution from core and corona to the $p_t$ spectra of pions and protons. In particular for protons, the core dominates at intermediate $p_t$ (mass effect).

3. Results for $v_2$

Coming back to the centrality dependence of $v_n$, we plot in fig. 7(a) the $p_t$ dependence of $v_2$ for charged particles from EPOS3 without hydro (red curve) compared to CMS data[1] (points). Amazingly the EPOS curve reproduces the data, although in the model there is no hydrodynamic flow active, the effect is a pure jet effect. To better see this, we check the dihadron correlation function, with $p_t$ between 1 and 2 GeV/c, integrated over $\Delta \eta$ with $|\Delta \eta| > 2$, as shown in fig. 7(b). We plot the two hadron correlation function from EPOS3 without hydro (black points) together with the Fourier series based on three coefficients (plus the zeroth one), which already

Figure 7. (Color online) (a) $p_t$ dependence of $v_2$ for charged particles from EPOS3 without hydro (red curve) compared to CMS data[1] (points). (b) Two hadron correlation function from EPOS3 without hydro (black points) together with the Fourier series based on three coefficients (plus the zeroth one).
reproduces the correlation function quite well. Considering the coefficients, we note that the third one \((v_{3\Delta})\) is negative, in complete disagreement with experimental data! So one can say that the second coefficient agrees “by accident”.

In the following, we employ full EPOS (including hydro and hadronic cascade). In fig. 8, we plot the \(p_t\) dependence of \(v_2\) for charged particles from EPOS3 (lines) compared to CMS data\([1]\) (points), for two different multiplicity ranges, in (a) pPb and (b) PbPb collisions. We observe for the calculation the same trend as seen in the data: Little change with multiplicity, large \(v_2\) at large \(p_t\), similar magnitude in pPb and PbPb, but different shape, understood in the model to be due to the bigger radial flow in pPb compared to PbPb. Why do we nevertheless obtain similar magnitudes? This is due to the fact that the smaller flow in PbPb is compensated by bigger eccentricities \(\epsilon_2\), as shown in fig. 9, where we plot the eccentricities \(\epsilon_n\) from EPOS3,

For three different multiplicity ranges, in (a) pPb and (b) PbPb collisions.

To summarize: Comparing pPb and PbPb, for the same multiplicities, using EPOS 3.111 (optimized to get pt spectra), we find: The \(p_t\) dependence of \(v_2\) for the two systems is quite
similar (as in the data). Microscopic properties are different though: There is more flow in pPb, compensated by bigger eccentricities in PbPb.

[1] CMS collaboration, Phys. Lett. B 742 (2015) 200, arXiv:1409.3392
[2] K. Werner et al., Phys. Rev. C 89 (2014) 064903, arXiv:1312.1233
[3] H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog and K. Werner, Phys. Rept. 350, 93, 2001
[4] K. Werner, Phys. Rev. Lett. 98, 152301 (2007)
[5] L. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233; L. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 3352; L. McLerran, R. Venugopalan, Phys. Rev. D 50 (1994) 2225.
[6] Iu. Karpenko, P. Huovinen, M. Bleicher, arXiv:1312.4160
[7] S. Borsanyi et al., JHEP 1011 (2010) 077, arXiv:1007.2580
[8] K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, arXiv:1010.0400, Phys. Rev. C 83, 044915 (2011)
[9] M. Bleicher et al., J. Phys. G25 (1999) 1859; H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78 (2008) 044901
[10] H.J. Drescher, S. Ostapchenko, T. Pierog, K. Werner, hep-ph/0011219, PhysRevC.65.054902