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PARTON SATURATION AND HYDRODYNAMICS IN EPOS 3*

Tanguy Pierog

KIT, IKP, Karlsruhe, Germany

Klaus Werner

SUBATECH, University of Nantes, Nantes, France

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One of the most surprising results of the first run of the Large Hadron Collider (LHC) are the similarities between events with the same multiplicity but coming from proton–proton (pp), proton–lead (pPb) or lead–lead (PbPb) collisions at different energies. A consistent treatment of the various stages of a high energy hadronic interaction is possible and realized in the EPOS 3 event generator. Using this model, a possible origin of the v2 and v3 flow coefficient observed in pPb and PbPb can be explained. In this paper, we will focus on the new treatment of the saturation scale in this model which is a key aspect to get proper initial conditions for the hydrodynamical calculation.

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1. Introduction

Before the LHC run, it was usually accepted that hydrodynamical phase expansion due to the formation of a quark–gluon plasma (QGP), for instance, was possible only in central heavy ion (HI) collisions. Proton–nucleus (pA) collisions were then used as a reference to probe the effect of such collective behavior (final state effect) but with some nuclear effect at the initial state level, while proton–proton (pp) interactions were free of any nuclear effect. With the LHC run in pp, pPb and PbPb mode, it is now possible to compare high multiplicity pp or pPb events with low multiplicity PbPb

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events (which correspond to the same number of particles) and, surprisingly, the very same phenomena are observed and are very close to what was observed in more central collisions at lower energy at RHIC or SPS accelerators.

One of the most striking features observed in all systems is the long-range two-particle correlations and the evolution of the particle flow as described in [1]. In [2], the author demonstrates how these data from the CMS Collaboration can be reproduced and explained using an approach combining the standard perturbative calculation for initial conditions and hydrodynamical calculation for the final state interactions. This study is based on the EPOS model version 3.111 in which a parametrized saturation scale is used. In this paper, we will present a new approach to calculate the saturation scale in EPOS. In Section 2, the basic principles of the initial condition calculation will be presented. In Section 3, a new way of calculating the saturation scale on an event-by-event basis will be introduced. Finally, in the summary, we will conclude on the difference between light and heavy system as explained in [2].

2. Initial conditions: EPOS 3

In order to make a hydrodynamical evolution calculation, proper initial conditions are needed. In our approach, the EPOS 3 [3] model is used to determine the energy density tensor and flavor content of the thermalized matter and to solve the differential equations of the hydrodynamical calculation.

EPOS 3 is a minimum bias Monte Carlo hadronic generator used for heavy ion interactions. It is the last generation of a long development of the EPOS model [4–7]. It is the only hadronic model which has a consistent treatment of cross section calculation and particle production taking into account energy conservation in both cases thanks to the parton-based Gribov–Regge theory [8]. In this approach, the basic ingredient is the purely imaginary amplitude of a single Pomeron exchange which is the sum of a (parametrized) soft contribution (Regge-like after Fourier transformation from t space to impact parameter b space) $G_0(\hat{s}, b) = \alpha_0(b)\hat{s}^{\beta_0}$ and a semi-hard contribution based on the convolution of a soft pre-evolution, a DGLAP [9] based hard evolution and a standard leading order QCD $2 \to 2$ cross section (mini-jet). The latter (called $\hat{G}$) needs complex calculations but can be fitted to a simple Regge-like term: $G_1(\hat{s}, b) = \alpha_1(b)\hat{s}^{\beta_1}$. $\hat{s} = sx^+x^-$ is the fraction of the center-of-mass energy squared (mass) carried by the Pomeron and b the impact parameter of the nucleon–nucleon collision. Details can be found in [8].

Both cross sections and particle production are based on the total amplitude $G = \sum_i G_i$ via a complex Markov-chain Monte Carlo. The particle production has two main components: the strings composed from the Pomerons (2 strings per Pomeron (Initial State Radiation and Final State Radiation and the soft contribution from the non-perturbative pre-evolution, below the fixed scale Q_0^2, are included) and at high energy, many Pomerons can happen in parallel for each event — multiple parton interaction) which cover the mid-rapidity part and the remnants which carry the remaining energy and quarks, and cover mostly the fragmentation region. A remnant can be as simple as a resonance or a string elongated along beam axis if its mass is too high and is treated in the same way for both diffractive and non-diffractive events.

The string fragments are then used to compute the energy density tensor on an event-by-event basis. If the energy density is higher than some threshold, string segments are merged locally into the so-called "core" to solve hydrodynamical differential equation with an equation of state based on lattice QCD. Details can be found in [5].

3. Saturation scale

To correct the limitation observed for instance in EPOS LHC [10] for high transverse momentum (p_t) particles, in particular, in pA, a new saturation scale has been introduced which can be different for each Pomeron. In EPOS LHC and previous versions, non-linear effects due to Pomeron–Pomeron interactions were treated by a simple correction on the β_i exponent of the G_i contributions of the Pomeron amplitude [7]. But this approach was changing both soft (multiplicity) and hard component (high p_t) in the same way. Since strong nuclear effects are needed to reproduce both cross section and multiplicity of pA interactions leading to a strong correction on β, a strong suppression of high p_t particles was observed in EPOS simulations. The number of particles as a function of the pseudorapidity and $R_{p\mathrm{Pb}}$ (p_t distribution normalized to pp distribution rescaled with the number of binary collisions) are shown in Fig. 1 for the EPOS LHC model (dashed line). The pseudorapidity distribution is well reproduced, while $R_{p\mathrm{Pb}}$ is too small at large p_t.

Instead of applying the correction on β to the real Pomeron amplitude $\hat{G}$, it is possible to change $\hat{G}$ itself to reproduce the modified G (called $\tilde{G}$) simply by changing the scale at which the perturbative calculation is done: Q_0^2. Q_0^2 is replaced by $Q_\mathrm{s}^2(x^+, x^-, s, b)$ to calculate each Pomeron amplitude. In EPOS 3.1 [3], the functional shape of Q_s^2 was fixed, leading to real complications for the future use of the model in air shower simulations, for instance. To have more flexibility and to improve the consistency of the model, it is,

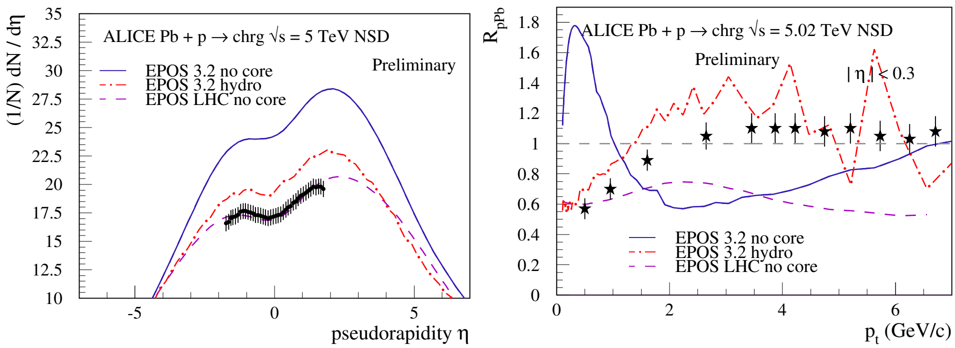

Fig. 1. Pseudorapidity distribution (left panel) and $R_{p\mathrm{Pb}}$ (right panel) of charged particles from pPb collisions at 5.02 TeV. Simulations are done with EPOS LHC without core (dashed line), EPOS 3.2 without core (full line) and EPOS 3.2 with core and hydro simulations (dash-dotted line) Points are data from the ALICE experiment.

in fact, possible to calculate Q_{s}^2 by the generation of Pomeron using the effective $\tilde{G}$ which reproduce the cross section and the multiplicity observed in the data. Since, by definition, we want to recover a perfect binary scaling at high p_{t}, we can use $N_{\mathrm{bin}}\hat{G}(Q_{\mathrm{s}}^2) = N_{\mathrm{col}}\tilde{G}(x^+, x^-, s, b)$ to compute Q_{s}^2 Pomeron-by-Pomeron. N_{bin} is the number of binary collisions based on the Glauber model for a particular event, while N_{col} is the real number of colliding pairs of nucleon in the model (using $\tilde{G}$). The result is shown in Fig. 2 for pPb simulations at 5 TeV. The solid line is the value of Q_{s}^2 on the lead side and the dashed line on the proton side. Left panel is for central collisions and right panel for peripheral collisions. The light dash-dotted lines are the

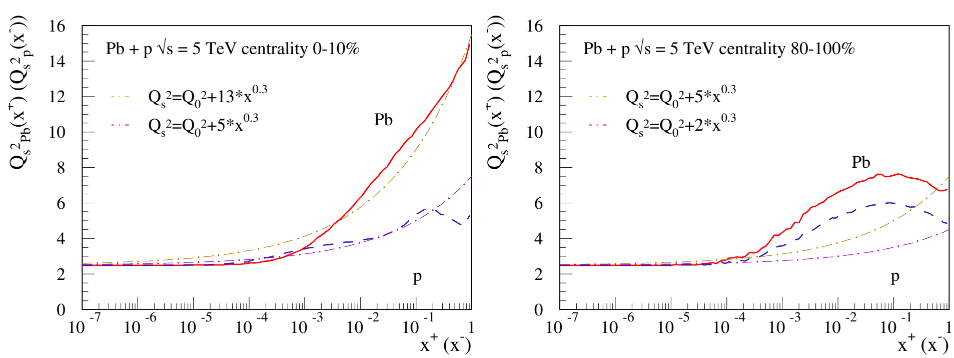

Fig. 2. Value of Q_{s}^2 from pPb collisions at 5.02 TeV for 0–10% centrality bin (left panel) and 80–100% (right panel). A solid line is used for the Pb side and a dashed line for the proton side. The corresponding parametrization is given as dash-dotted line.

value of Q_s^2 as parametrized in [3]. The new approach seems to be in a good agreement with the parametrization used before for central collisions but gives different value at large impact parameter.

To illustrate the fact that a change of Q_s^2 is a way to reduce soft parton production without changing the hard ones (above Q_s^2), the deviation between EPOS 3.2 calculation of the jet transverse momentum distribution rescaled by the number of binary collisions and a pure pQCD calculation using Cteq6 [12] parton distribution functions can be observed in Fig. 3 for two different centrality bin of pPb collisions at 5 TeV. In both cases, the high p_t part is in perfect agreement, while a strong suppression is observed at low p_t in particular for the most central events.

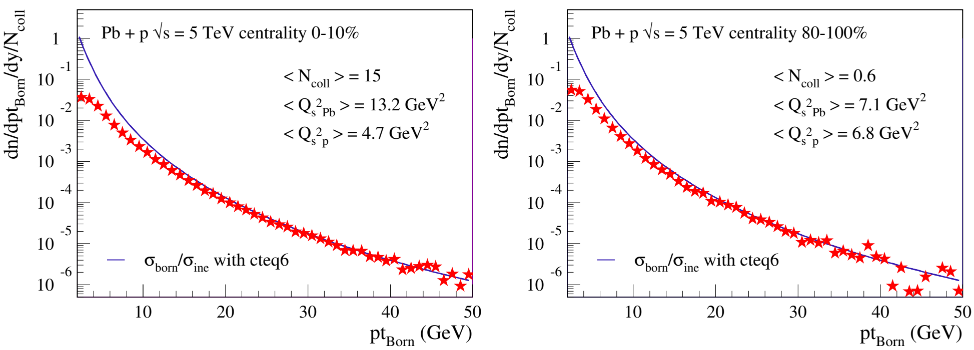

Fig. 3. Born parton p_t distribution normalized by the Glauber number of binary collisions from pPb collisions at 5.02 TeV for 0–10% centrality bin (left panel) and 80–100% (right panel). EPOS 3.2 simulations are shown with stars and compared to the normalized inclusive cross section (solid line).

As a consequence, very preliminary results of EPOS 3.2 without core (solid line) shown in Fig. 1 indicate that $R_{p\mathrm{Pb}}$ is reaching unity for p_t larger than 6 GeV/c but without core formation the multiplicity is still too high and low p_t spectra are not well reproduced. However, using the full calculation including real hydro-calculation in EPOS 3.2 (dash-dotted line), the multiplicity is reduced and the $R_{p\mathrm{Pb}}$ can be completely described thanks to the radial flow. Some studies on the nucleon–nucleon cross section in pPb are still needed to improve the multiplicity.

4. Summary

To properly reproduce data from pp, p–nucleus and nucleus–nucleus events, good initial conditions and hydrodynamical calculation are necessary. For instance, the data published in [1] can be explained using the EPOS 3 model [2]. The flow parameters v2 and v3 which have the same behavior as a function of p_t in pPb and PbPb for a given multiplicity window have, in fact, different origins. On the one hand, in pPb, the system being smaller for a given multiplicity, the higher density creates a higher radial flow than in PbPb. On the other hand, the size of the system in PbPb implies larger asymmetries which create a large eccentricity which compensates the lower value of the radial flow. As a consequence, the asymmetry measurement of the flow which can be quantified using v2 and v3 parameters appears to be similar in pPb and PbPb. This can be quantitatively reproduced by EPOS 3, including the mass splitting observed between Kaon and Lambda strange particles. To obtain such result, it was necessary to improve the description of high p_{t} particles in the EPOS model. As a first step, a parametrized saturation scale Q_{s}^2 was introduced. In this paper, it has been shown that the next step to improve the model is to have a free Q_{s}^2 for each parton scattering with the fundamental constrain to have binary scaling at high p_{t}. Preliminary results are encouraging.

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