

The Physics of EPOS

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Abstract. We discuss recent developments of the EPOS hadronic interaction model, in particular concerning collective phenomena as implemented in EPOS 2.17, relevant for proton-proton, proton-nucleus, and nucleus-nucleus collisions at very high energies.

To start with some historical remarks: in the late nineties of the last century, the authors of the VENUS model (essentially for soft scatterings) and the QGSJET model (with emphasis on hard scatterings) decided to work together to create a “realistic” approach which should be reliable to be extrapolated to high energies, in view of applications as interaction model in air shower simulation. The results was called NEXUS, where the aim of a consistent treatment of soft and hard scatterings has been achieved, as well as a proper treatment of energy sharing among the multiple scatterings. However, it was immediately clear that the scheme is incomplete, higher order effects (or non-linear effects) should be considered to make the approach consistent. Since there was no unique solution to the problem, two ways were pursued, leading to the EPOS and the QGSJETII project.

In EPOS, the energy conserving multiple scattering scheme was considered to be “not negotiable”, however it was believed that the non-linear effects can be “effectively” treated in a simple manner. More details will be discussed later. But first some general remarks about the EPOS project: the aim is a general understanding of particle production in pp, pA, and AA scatterings at ultra-relativistic energies, with possible applications to cosmic ray air shower simulations, but we do not restrict ourselves to observables usually considered “air shower relevant”. In EPOS 2 we are studying collective effects, in particular the hydrodynamic evolution of matter and the consequences for particle production.

It is clear that heavy ion collisions show “fluid-like” behavior, demonstrated in a spectacular manner via the observation of azimuthal anisotropies of particle production at the RHIC collider, and more recently at the LHC. Very detailed data exist about the centrality and species dependence of elliptical flows and even higher harmonics. Also the energy loss of high pt partons (observed as jets) or heavy mesons point towards the creation of “matter”.

The situation in proton-proton scattering is less clear for the moment, but there are at least hints pointing to similar phenomena as observed in heavy ion collisions. Also in pp one observes azimuthal anisotropies, but weaker compared to the heavy ion results. This is enough motivation to continue studying collective effects in AA and pp collisions.

The starting point of EPOS is a multiple scattering approach corresponding to a marriage of Gribov-Regge theory and perturbative QCD (pQCD). An elementary scattering corresponds to a parton ladder, containing a hard scattering calculable based on pQCD, including initial and final state radiation (for details see [1]). 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. One should note that here multiple scattering does not mean just a rescattering of hard partons, it rather means a multiple exchange of complete parton ladders, leading to many flux tubes. In this case, the energy sharing between the different scatterings will be very important, to be discussed later. 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 [2].

As said before, the final state partonic system corresponding to elementary parton ladders are identified with flux tubes. The relativistic string picture [3–5] is very attractive, because its dynamics is essentially derived from general principles as covariance and gauge invariance. The simplest possible string is a surface $X(\alpha, \beta)$ in 3+1 dimensional space-time, with piecewise constant initial velocities $\partial X/\partial \beta$. These velocities are identified with parton velocities, which provides a one to one mapping from partons to strings. For details see [1, 2]. The high transverse momentum (p_t) partons will show up as transversely mov-

ing string pieces. Despite the fact that in the TeV energy range most processes are hard, and despite the theoretical importance of very high p_t partons, it should not be forgotten that the latter processes are rare, most kinks carry only few GeV of transverse momentum, and the energy is nevertheless essentially longitudinal. In case of elementary reactions, the strings will break via the production of quark-antiquark pairs according to the so-called area law [1, 2, 6, 7]. The string segments are identified with final hadrons and resonances. This picture has been very successful to describe particle production in electron-positron annihilation or in proton-proton scattering at very high energies.

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 in the following (see 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. A more quantitative discussion will follow.

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 loose 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”).

Let us discuss how the above ideas are realized. 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. Strictly speaking, energy loss concerns partons, modifying eventually the kink momenta in our picture, and the momenta of the string segments after breaking will be reduced. We will therefore base our discussion on energy loss on string segments.

We estimate the energy loss ΔE of string segments along their trajectory to be

$$\Delta E = k_{\text{Eloss}} E_0 \int (\rho V_0)^{3/8} \max(1, \sqrt{E/E_0}) dL/L_0, \quad (1)$$

inspired by [9], where ρ is the density of string segments at initial proper time τ_0 , V_0 is an elementary volume cell size (technical parameter, taken to be 0.147 fm^3), L_0 is a (technical) length scale (taken to be 1 fm), E the energy of the segment in the “Bjorken frame” moving with a rapidity y equal to the space-time rapidity η_s , dL is a length element, and k_{Eloss} and E_0 are parameters. We introduce an energy cutoff E_0 to have sufficient energy loss for slowly moving segments.

A string segment will contribute to the bulk (type A segment), when its energy loss is bigger than its energy, i.e.

$$\Delta E \geq E. \quad (2)$$

All the other segments are allowed to leave the bulk (type B or C segments). 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 [10], already discussed in [1].

After having performed the hydrodynamic expansion, we have to come back to the string segments which escape the bulk because their energy is bigger than the energy loss. We employ a formation time: the string segments are formed at times t distributed as $\exp(-t/\gamma\tau_{\text{form}})$, with some parameter τ_{form} which is taken to be $1\text{fm}/c$. If the formation time is such that the segment is produced outside the “hadronization surface” defined by T_H , the segment will escape as it is (type B segment).

Most interesting are the segments which are formed inside but still escape, because they have $E > \Delta E$. 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

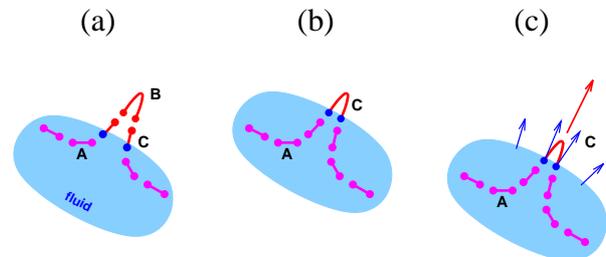


Figure 1. (Color online) Flux tube in matter (from other flux tubes, blue colored area). One distinguishes three types of behavior for string segments, noted as A, B, C (see text). The highest p_t string segment may be of type B (a) or of type C (b). A type C segment picks up quark and antiquark from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

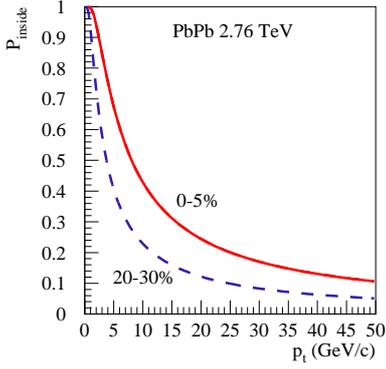


Figure 2. (Color online) The estimate P_{inside} to form (pre)hadrons inside the fluid, as a function of p_t , for Pb-Pb collisions at 2.76 TeV. We show the curves for the 0-5% and the 20-30% most central events.

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(c).

In any case, due to the fluid-jet interaction, the properties of this segment change drastically compared to the normal fragmentation:

- The quark and antiquark (or diquark) from the fluid provide a push in the direction of the moving fluid.
- The quark (antiquark) flavors are determined from Bose-Einstein statistics, with more strangeness production compared to the Schwinger mechanism.
- The probability p_{diq} to have a diquark rather than an antiquark will be bigger compared to a highly suppressed diquark-antidiquark breakup in the Schwinger picture (p_{diq} is a parameter).

Our procedure has 4 parameters: $k_{\text{Eloss}} (=0.042)$, $E_0 (=6 \text{ GeV})$, $\tau_{\text{form}} (=1 \text{ fm}/c)$, $p_{\text{diq}} (=0.22)$. It allows to cover in a single scheme the production of jets, of bulk, and the interaction between the two.

A crucial ingredient to the mechanism of fluid-jet interaction is the formation time of jet hadrons (the hadrons which leave the fluid). An estimate of the probability distribution of the formation times t of jet hadrons with gamma factors γ is given as [8]

$$P_{\text{inside}} = 1 - \exp\left(-\frac{(r_{\text{Pb}} - b/2)m}{p_t \tau_{\text{form}}}\right). \quad (3)$$

In Fig. 2, we show the result for the 0-5% and the 20-30% most central events in Pb-Pb collisions at 2.76 TeV, using $c\tau_{\text{form}} = 1 \text{ fm}$, $mc^2 = 1 \text{ GeV}$, $r_{\text{Pb}} = 6.5 \text{ fm}$, and for the average impact parameters $b = 1.8 \text{ fm}$ (0-5%) and $b = 7.8 \text{ fm}$ (20-30%).

By construction, the probability $P_{\text{fluid-jet}}$ of having a fluid-jet interaction is equal to the probability of forming

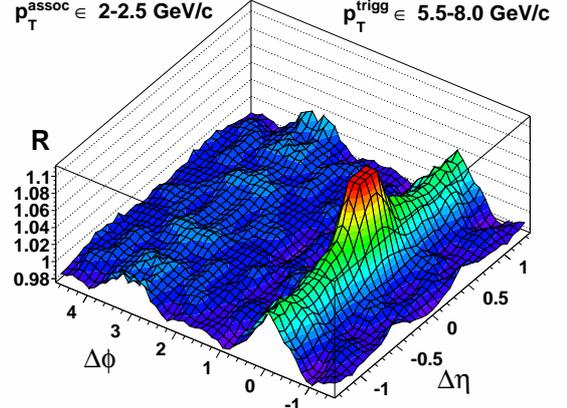


Figure 3. (Color online) Calculated dihadron correlation function for p_t^{trigg} in the interval 5.5-8.0 GeV/c and p_t^{assoc} in the range 2-2.5 GeV/c in the 0–10% most central Pb-Pb collisions at 2.76 TeV.

(pre)hadrons inside the fluid, so its estimate is given by P_{inside} . From Fig. 2, we see that the probability is quite large for intermediate values of p_t , but even large values (50 GeV/c) are significantly affected. Whether the effect of the interaction can be seen in some observable is a different question and will be discussed later.

The bulk matter extracted as described above provides the initial condition for a hydrodynamic evolution. As explained in [1], we compute the energy momentum tensor and the flavor flow vector at some position x (at $\tau = \tau_0$) from the four-momenta of the bulk string segments. The time $\tau = \tau_0$ is as well taken to be the initial time for the hydrodynamic evolution. We employ three-dimensional ideal hydrodynamics as described in [8]. We try to mimic viscous effects by taking artificially large values of the flux tube radii (we take 1 fm), in order to get smoother initial conditions. This has the effect of reducing the elliptical flow by 20-30%, as needed

Our prescription for bulk-jet separation and interaction should strongly affect dihadron correlations, which provide much more information than simple spectra. With all parameters (k_{Eloss} , E_0 , τ_{seg} , p_{diq}) being fixed from the considerations in the last section, we now compute dihadron correlation functions defined as

$$R(\Delta\eta, \Delta\phi) = \frac{M}{S} \times \frac{S(\Delta\eta, \Delta\phi)}{M(\Delta\eta, \Delta\phi)}, \quad (4)$$

where S is the number of pairs in real events, and M the number of pairs for mixed events.

In Fig. 3, we show a correlation function for p_t^{trigg} in the interval 5.5-8.0 GeV/c and p_t^{assoc} in the range 2-2.5 GeV/c, in the 0–10% most central Pb-Pb collisions at 2.76 TeV. Although the trigger p_t is too large to originate from freeze-out (from the flowing fluid), one observes a ridge structure, which is due to the fluid-jet interaction. Let us consider the situation of an initial azimuthal anisotropy in

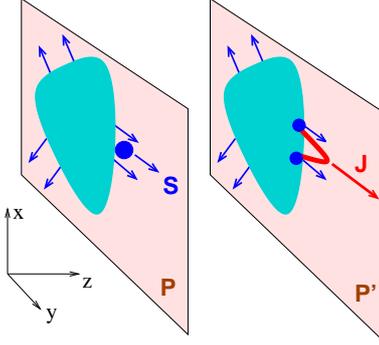


Figure 4. (Color online) Sketch of two cuts of the fluid volume corresponding to the space-time rapidities η_s and η'_s , the two corresponding transverse planes being \mathbf{P} and \mathbf{P}' . We show the example of a triangular flow pattern – the same at η_s and η'_s .

the energy density which is transported into a corresponding anisotropy in the flow. We sketch in Fig. 4 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 the dihadron correlation at $\Delta\phi = 0$, the “ridge”. The correlation remains visible, even when the flow contribution to the jet hadron is only 10%, this is why the correlation is still present even for trigger transverse momenta beyond 10 GeV/c.

In semi-peripheral Pb-Pb collisions at 2.76 GeV/c, one observes for example for p_t^{trigg} in the interval 5.5-8.0 GeV/c and p_t^{assoc} in the range 2-2.5 GeV/c a clear elliptical flow structure, again due to the mechanism of fig. 4.

The correlation functions are essentially flat as a function of $\Delta\eta$, for large $\Delta\eta$. One therefore gets complete information about the long range correlations by integrating over $\Delta\eta$,

$$R(\Delta\phi) = \frac{1}{2(B-A)} \int_{A < |\Delta\eta| < B} R(\Delta\eta, \Delta\phi) d\Delta\eta, \quad (5)$$

where we use $A = 0.8$ and the maximum $B = 2$. This function agrees perfectly with its Fourier decomposition,

$$R(\Delta\phi) = 1 + \sum_{n=1}^5 2V_{n\Delta} \cos(n\Delta\phi), \quad (6)$$

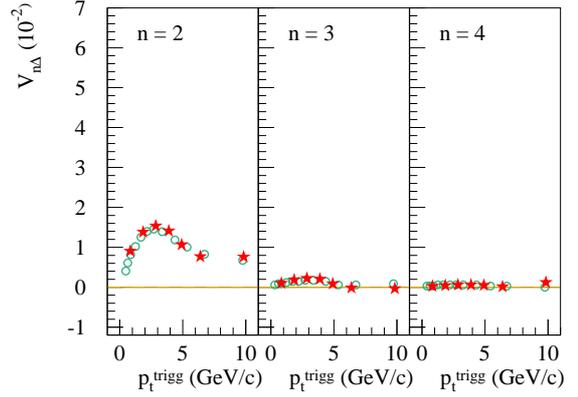


Figure 5. (Color online) The Fourier coefficients $V_{n\Delta}$ as a function of p_t^{trigg} for p_t^{assoc} within 0.25-0.5 GeV/c in the 40-50% most central Pb-Pb collisions at 2.76 TeV. We compare the ALICE data [11] (circles) with calculations (red stars).

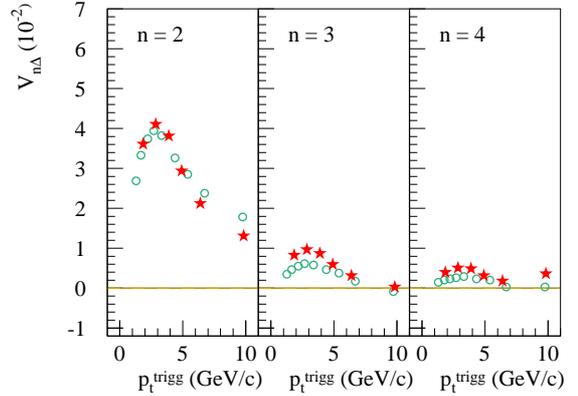


Figure 6. (Color online) The Fourier coefficients $V_{n\Delta}$ as a function of p_t^{trigg} for p_t^{assoc} within 1-1.5 GeV/c in the 40-50% most central Pb-Pb collisions at 2.76 TeV. We compare the ALICE data [11] (circles) with calculations (red stars).

using the first five terms. This is very convenient, because it allows to discuss the features of the correlation functions for different options for p_t^{trigg} and p_t^{assoc} by simply considering the Fourier coefficients.

In figs. 5 and 6, we plot some coefficients $V_{n\Delta}$ as a function of p_t^{trigg} .

We compare our simulation (stars) with the results from ALICE [11] (circles). We see clearly the dominance of elliptical flow: the $n = 2$ coefficients are by far the largest. Nevertheless, also the higher harmonics contribute. We see in all cases an increase of the coefficients with p_t^{assoc} and with p_t^{trigg} up to values of around 2-3 GeV/c. At the latter values the hydrodynamic flow contributes the most to the correlation between soft hadrons from the fluid. For higher transverse momenta, the coefficients get smaller, because the correlation between soft particles dies out. But $V_{2\Delta}$ does not at all drop to zero at high p_t because here the correlations between soft and jet particles come into play – the jet particles which suffered

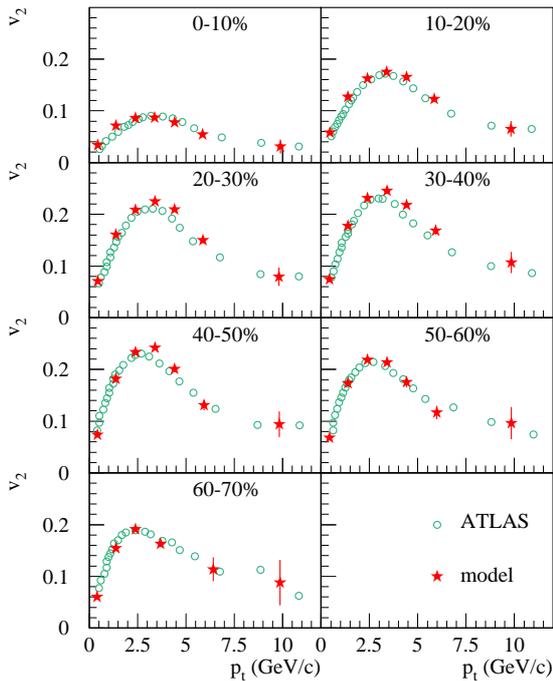


Figure 7. (Color online) p_t dependence of elliptical flow (defined with respect to the opposite hemisphere sub-event plane) for different centralities in Pb-Pb collisions at 2.76 TeV. We compare the ATLAS data [12] (circles) with calculations (red lines).

a push by the fluid, as discussed earlier (fluid-jet interaction). The fluid transfers at maximum few GeV/c of transverse momentum to the jet, but this is easily visible in the correlation (even at 20 GeV/c).

Whereas dihadron correlations provide the most complete information about particle production – in particular concerning the role of the “flowing” fluid, one may get the essential information by considering the elliptical flow coefficient v_2 of single particle production. Here we consider a definition where the reference plane is given by the event plane angle ϕ^{backward} (ϕ^{forward}), obtained from counting all particles in the opposite hemisphere [12]. In Fig. 7, 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 (and this effect will continue up to even

higher p_t , but we are simply running out of statistics). The high p_t behavior is closely related to the formation time discussion we had earlier. The non-vanishing v_2 at high p_t is mainly due to fluid-jet interactions, and the values follow indeed the estimated probability P_{inside} to form the jet hadron inside the fluid, see ref. [8].

To summarize: We discussed about recent progress in EPOS concerning the collective hydrodynamical expansion of matter, and we showed that we get a more and more quantitative understanding of particle production at low and high p_t . As a next step, we will investigate pPb collisions, where first experimental results are becoming available.

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