Multiple scattering in EPOS

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Abstract
We discuss the multiple scattering approach in EPOS and its consequences in particular for proton-proton scattering at the LHC.

1 Introduction

It has been known since a long time that very high energy hadrons experience multiple scatterings when they hit protons or neutrons. Concerning inclusive cross sections, the situation becomes quite simple due to the fact that different multiple scattering contributions cancel due to destructive interference (AGK cancellations). The corresponding formulas are simple and can be expressed in terms of parton distributions functions, based on evolutions equations (DGLAP, BFKL, BK).

To get more detailed information, one needs partial cross sections, since individual hadronic interactions are of a particular multiple scattering type (single, or double, or triple...) and contribute differently to certain observables. Even if the inclusive cross sections were perfectly known, one still would need addition information concerning the treatment of multiple scattering. Here, Gribov-Regge theory provides a solution, in particular when energy sharing is properly taken into accound, as in the EPOS approach.

An important issue is the concept of remnants, based on the hypothesis that in a hadron-hadron collision there are three sources of particle production: (1) hadrons from partons which are due to the parton evolution, (2) hadrons from projectile remant excitations, and (3) hadrons from target remnants. Remnants are meant to be the spectator partons from the incident hadrons, representing hadron excitations. In the language of cut diagrams such contributions must exist. There is not much guidance from theory, how to define a "remnant model". However, we expect the remants to be rather energy independent, so one may rely on the wealth of data at relatively low energies ($\sqrt{s} \approx 20 - 1800$GeV) to test the model assumptions.

Concerning the partons from the parton evolution (source (1) in the previous paragraph), we expect that low momentum fraction (low x) partons do not simply evolve following linear evolution equations (like DGLAP or BFKL). There are nonlinear effect becoming more and more important (with decreasing x and increasing nuclear mass number in case of collisions with nuclei), finally leading to saturation. Apart of the theoretical reasoning discussed earlier, one needs such "nonlinear effects" to tame the hadron-hadron cross sections at very high energies (which would otherwise "explode"). So any realistic model needs to deal with saturation, in a more or less sophisticated way.

Finally, if one wants to make precise predictions concerning the hadron chemistry, a crucial ingredient is the fragmentation procedure. Concerning the low transverse momentum hadrons (representing the overwhelming majority of all particles), the preferred procedure is the string approach. Using fragmentation functions is certainly a useful concept for jet fragmentation, but not necessarily for soft particle production.

2 Parton evolution in EPOS

An elementary scattering in EPOS [1] is given by a so-called "parton ladder", see fig. 1, representing

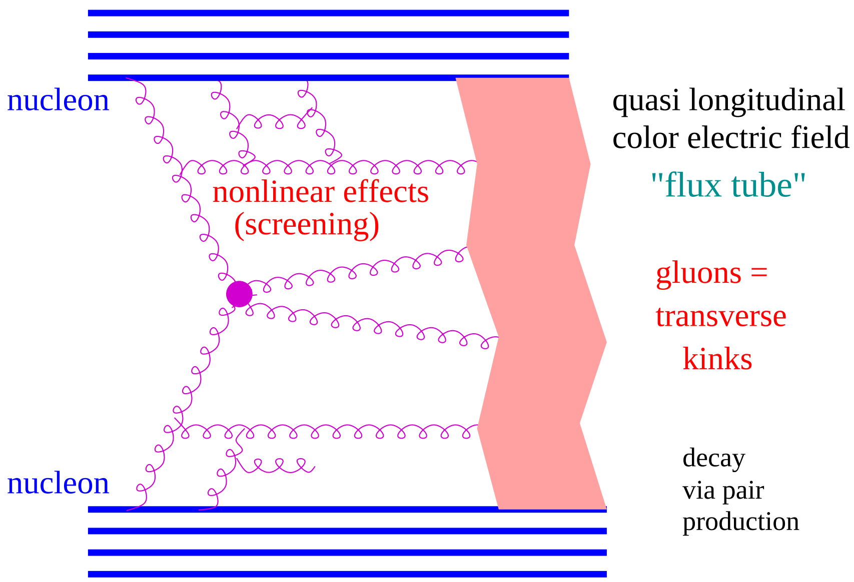

Fig. 1: Elementary interaction in the EPOS model.

parton evolutions from the projectile and the target side towards the center (small x). The evolution is gouverned by an evolution equation, in the simplest case according to DGLAP. In the following we will refer to these partons as "ladder partons", to be distinguished from "spectator partons" to be discussed later. It has been realized more than 20 years ago that such a parton ladder may be considered as a longitudinal color field, conveniently treated as a relativistic string when it comes to hadronization. The intermediate gluons are treated as kink singularities in the language of relativistic strings. A string decays via the production of quark-antiquark pairs, creating in this way string fragments – which are identified with hadrons. Such a picture is also in qualitative agreement with recent developments concerning the CGC.

Important in particular at moderate energies (RHIC): our "parton ladder" is meant to contain two parts [2]: the hard one, as discussed above (following an evolution equation), and a soft one, which is a purely phenomenological object, parametrized in Regge pole fashion. The soft part essentially compensates for the infrared cutoffs, which have to be employed in the perturbative calculations.

As discussed earlier, at high energies one needs to worry about non-linear effects, due to the fact that the gluon densities get so high that gluon fusion becomes important. In our language this means that two partons ladders fuse (or split, if we look from inside to outside [1]). Nonlinear effects could be taken into account by using BK instead of DGLAP evolution. What we try to realize here is a phenomenological approach, which (hopefully) grasps the main features of these non-linear phenomena, and still remains technically doable (we should nor forget that we finally have to generalize the treatment in order to take into accound multiple scatterings, as discussed earlier).

Our phenomenological treatment is based on the fact that there are two types of nonlinear effects: a simple elastic rescattering of a ladder parton on a projectile or target nucleon (elastic ladder splitting), or an inelastic rescattering (inelastic ladder splitting), see fig. 2. The elastic process provides screening, therefore a reduction of total and inelastic cross sections. The importance of this effect should first increase with mass number (in case of nuclei being involved), but finally saturate. The inelastic process will affect particle production, in particular transverse momentum spectra, strange over nonstrange particle ratios, etc. Both, elastic and inelastic rescattering must be taken into account in order to obtain a realistic picture.

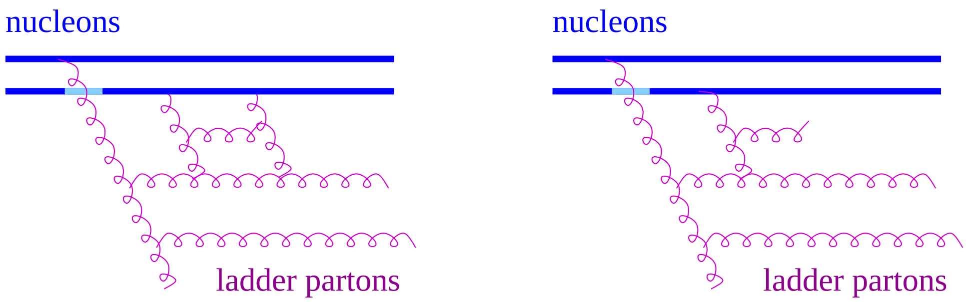

Fig. 2: Elastic (left) and inelastic (right) "rescattering" of a ladder parton. We refer to (elastic and inelastic) parton ladder splitting.

To include the effects of elastic rescattering, we first parameterize a parton ladder (to be more precise: the imaginary part of the corresponding amplitude in impact parameter space) computed on the basis of DGLAP. We obtain an excellent fit of the form $\alpha(x^+x^-)^\beta$, where x^+ and x^- are the momentum fractions of the "first" ladder partons on respectively projectile and target side (which initiate the parton evolutions). The parameters α and β depend on the cms energy $\sqrt{s}$ of the hadron-hadron collision. To mimick the reduction of the increase of the expressions $\alpha(x^+x^-)^\beta$ with enegy, we simply replace them by $\alpha(x^+)^{\beta+\varepsilon_P}(x^-)^{\beta+\varepsilon_T}$, where the values of the positive numbers $\varepsilon_{P/T}$ will increase with the nuclear mass number and $\log s$.

The inelastic rescatterings (ladder splittings, looking from insider to outside) amount to providing several ladders close to projectile (or target) side, which are close to each other in space. They cannot be consider as independend color fields (strings), we should rather think of a common color field built from several partons ladders. In the string language one used the term "string fusion", where the fused string is still an one-dimensional longitudinal object, but with a modified string tension κ. Also this string tension is expected to increase with the nuclear mass number and $\log s$ (for more details see [1]). This affects hadronization, since the flavor dependence of $q-\bar{q}$ string breaking is given by the probabilities $\exp(-\pi m_q^2/\kappa)$, with m_q being the quark masses. Also mean transverse momenta are affected, since they are proportional to $\sqrt{\kappa}$.

3 Remnants in EPOS

Still the picture is not complete, since so far we just considered two interacting partons, one from the projectile and one from the target. These partons leave behind a projectile and target remnant, colored, so it is more complicated than simply projectile/target deceleration. One may simply consider the remnants to be diquarks, providing a string end, but this simple picture seems to be excluded from strange antibaryon results at the SPS [3]. We therefore adopt the following picture: not only a quark, but a two-fold object takes directly part in the interaction, namely a quark-antiquark or a quark-diquark pair, leaving behind a colorless remnant, which is, however, in general excited (off-shell). If the first ladder parton is a gluon or a seaquark, we assume that there is an intermediate object between this gluon and the projectile (target), referred to as soft Pomeron. And the "initiator" of the latter on is again the above-mentionned two-fold object.

So we have finally three "objects", all of them being white: the two off-shell remnants, and the parton ladder in between. Whereas the remnants contribute mainly to particle production in the fragmentation regions, the ladders contribute preferentially at central rapidities.

We showed in ref. [4] that this "three object picture" can solve the "multi-strange baryon problem" of ref. [3]. In addition, we assembled all available data on particle production in pp and pA collisions between 100 GeV (lab) up to Tevatron, in order to test our approach. Large rapidity (fragmentation region) data are mainly accessible at lower energies, but we believe that the remnant properties do not change much with energy, apart of the fact that projectile and target fragmentation regions are more or less separated in rapidity. But even at RHIC, there are remnant contribution at rapidity zero, for example the baryon/antibaryon ratios are significantly different from unity, in agreement with our remnant implementation. So even central rapidity RHIC data allow to confirm out remnant picture.

4 Factorization and Multiple Scattering

An inclusive cross section is one of the simplest quantities to characterize particle production. Often one need much more information, for example when trigger conditions play a role. Also in case of shower simulations one needs information about exclusive cross sections (the widely used pQCD generators are not event generators in this sense, they are generators of inclusive spectra, and a Monte Carlo event is not a physical event). As discussed earlier, inclusive cross section are particulary simple, quantum interference helps to provide simple formulas referred to a "factorization". Although factorization is widely used, strict mathematical profs exist only in very special cases, and certainly not for hadron production in pp scattering.

To go beyond factorization and to formulate a consistent multiple scattering theory is difficult. A possible solution is Gribov's Pomeron calculus, which can be adapted to our language by identifying Pomeron and parton ladder. Multiple scattering means that one has contributions with several parton ladders in parallel. This formulation is equivalent to using the eikonal formula to obtain total cross sections from the knowledge of the inclusive one.

We indicated several years ago inconsistencies in this approach, proposing an "energy conserving multiple scattering treatment" [2]. The main idea is simple: in case of multiple scattering, when it comes to calculating partial cross sections for double, triple ... scattering, one has to explicitly care about the fact that the total energy has to be shared among the individual elementary interactions. In other words, the partons ladders which happen to be parallel to each

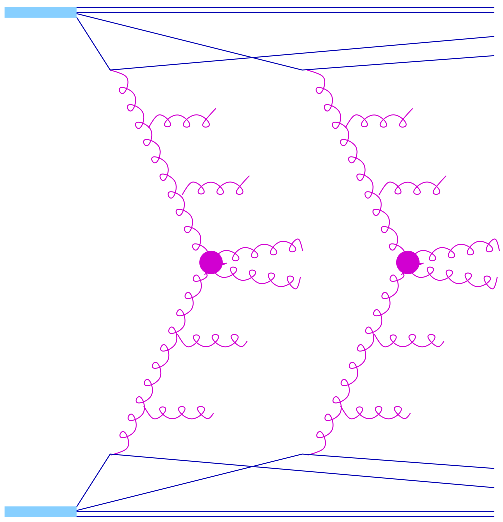

Fig. 3: Multiple scattering with energy sharing.

other share the collision energy, see fig. 3.

A consistent quantum mechanical formulation of the multiple scattering requires not only the consideration of the usual (open) parton ladders, discussed so far, but also of closed ladders, representing elastic scattering. These are the same closed ladders which we introduced earlier in connection with elastic rescatterings. The closed ladders do not contribute to particle production, but they are crucial since they affect substantially the calculations of partial cross sections. Actually, the closed ladders simply lead to large numbers of interfering contributions for the same final state, all of which have to be summed up to obtain the corresponding partial cross sections. It is a unique feature of our approach to consider explicitly energy-momentum sharing at this level (the "E" in the name EPOS). For more details see [2].

5 Hadronization

As mentionned already, the fragmentation procedure is a crucial ingredient of our model. Here, we employ the string approach. Using fragmentation functions is certainly a useful concept for jet fragmentation, but not necessarily for soft particle production.

We will identify parton ladders with classical strings. Here, we consider only strings x with piecewise constant intial conditions $v(\sigma) \equiv \partial x/\partial\tau(\sigma, \tau = 0)$, which are called kinky strings. So the string is characterized by a sequence of σ intervals $[\sigma_k, \sigma_{k+1}]$, and the corresponding velocities v_k. Such an interval with the corresponding constant value of v is referred to as "kink". Now we are in a position to map partons onto strings: we identify the ladder partons with the kinks of a kinky string, such that the length of the σ-interval is given by the parton energies, and the kink velocities are just the parton velocities. The string evolution is then completely given by these initial conditions, expressed in terms of parton momenta. Hadron production is finally realized via string breaking, such that string fragments are identified with hadrons. Here, we employ the so-called area law hypothesis: the string breaks within an infinitesimal area dA on its surface with a probability which is proportional to this area, $dP = p_B\,dA$,where p_B is the fundamental parameter of the procedure.

6 Collective expansion

Recent developments in EPOS concern the hydrodynamic expansion of matter in case of heavy ion collisions – or high multiplicity events in very high energy proton-proton scattering, for example at the LHC.

The elementary scatterings as discussed above lead to the formation of strings, which break into segments, which are usually identified with hadrons. When it comes to high multiplicity events in very high energy proton-proton scattering, the procedure is modified: one considers the situation at an early proper time τ_0, long before the hadrons are formed: one distinguishes between string segments in dense areas (more than some critical density ρ_0 of segments per unit volume), from those in low density areas. The high density areas are referred to as core, the low density areas as corona [5]. Let us consider the core part. It is important to note that initial conditions from EPOS are based on strings, not on partons. Based on the four-momenta of the string segments which constitute the core, we compute the energy density $\varepsilon(\tau_0, \vec{x})$ and the flow velocity $\vec{v}(\tau_0, \vec{x})$.

Having fixed the initial conditions, the system evolves according the equations of ideal hydrodynamics, see fig. 4, until the energy density reaches some critical value (usually expressed in terms of a critical temperature). In the simplest case, particles freeze out immediately at this freeze out hypersurface, based on the Cooper-Frye prescription.

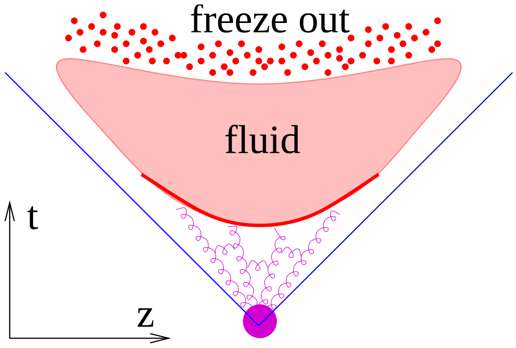

Fig. 4: Sketch of a hydrodynamic evolution in space time, starting from the hyperbola representing the initial proper time.

The interesting question arises whether such “collective expansion effects” matter for pp. There are several signs which suggest this, for example the increase of the mean transverse

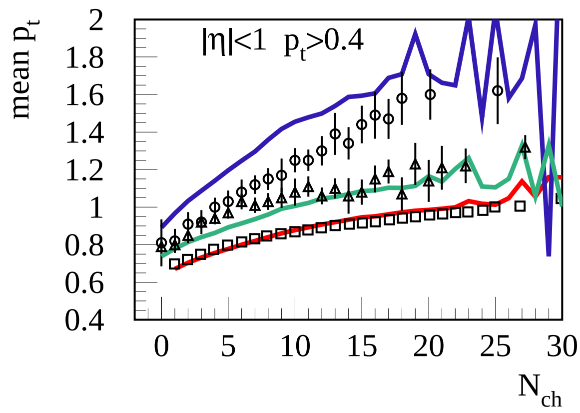

Fig. 5: The mean transverse momentum of (from top to bottom) lambdas, kaons, and pions, in pp collisions at 1800 GeV. A "hydro-inspired" EPOS simulation is compared to data from CDF.

momentum of hadrons in pp collisons observed at the Tevatron collider [6], see fig. 5. Here, one sees the typical "flow pattern", namely a considerably larger increase of the mean pt's in case of heavier hadrons. The EPOS calculations are, however, not (yet) based on a hydrodynamical evolution, they are based on a statistical hadronization with imposed collective flow, the latter one introduced by hand. Real hydrodynamical calculations will be performed soon.

7 Summary

To summarize: we have discussed multiple scattering as realized by the EPOS model, which is expected to be a very important issue for proton-proton scattering at the LHC.

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