RECENT DEVELOPMENTS IN EPOS

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ABSTRACT

Currently, EPOS-LHC is the public EPOS version, heavily used by experimental groups in high energy and cosmic ray physics. It is based on an S-matrix approach, being the ideal framework for multiple scattering in small systems. However, factorization and binary scaling does not come for free, it is a very complex issue, and in the current model it is simply not properly done. Another topic concerns flow, which is only implemented as "parameterized" which quite limited application. There was substantial progress during the past few year, referred to as "EPOS4 project", to develop a consistent formalism, which accommodates a multiple scattering S-matrix approach, factorization, and saturation, all of these topics being closely related to each other. In addition, secondary interactions are considered, most importantly a full hydrodynamic evolution. In this talk, we will report about the status of the EPOS4 project.

1 INTRODUCTION

Recent experimental findings required considerable changes in the theoretical understanding of hadronic interactions (in particular proton-proton (p-p) and proton-nucleus (p-A) scattering). Collective hydrodynamic flow seemed to be well established in heavy ion (HI) collisions at energies between 200 GEV and several TeV since a long time, whereas p-p and p-A collisions have often been 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, the first results from p-Pb at 5 TeV on the transverse momentum dependence of azimuthal anisotropies and particle yields are very similar to the observations in HI scattering [1, 2]. In the following, we discuss the EPOS approach, where these "new features" are taken care of.

In 2001, we presented "Parton Based Gribov Regge Theory" (PBGRT) [3] (see also [4]) with a rigorous treatment of energy sharing in the GRT multiple scattering framework, where we consider soft and hard Pomerons, the latter ones being parton ladders according to DGLAP parton evolution [5, 6, 7]. This approach (PBGRT) is the the theoretical basis of the EPOS event generator, or more precisely of the "primary interactions", happening (at high energies) instantaneously at $t = 0$. We also consider "secondary interactions", which amounts to a hydrodynamical expansion of a core part of matter (determined from the primary scatterings). The EPOS approach uses precisely the same concepts for proton-proton (pp), proton-nucleus (pA) and nucleus-nucleus (AA) scattering.

All EPOS versions, also the most recent ones, are composed of primary and secondary interactions, also referred to as initial state and final state scatterings. The former ones are based on PBGRT [3], almost unchanged over the years. The only issue which evolved significantly is the way of treating so-called "high density effects", referred nowadays as saturation effects.

Also common to all EPOS versions is a core-corona separation mechanism [8], which defines the initial conditions of the secondary interactions. This mechanism allows to identify a core part which expands collectively, and a corona part of particles escaping from the dense core region. The core part corresponds to a collective evolution of matter. And this collective behavior is present (more or less dominant) in all reactions, from pp to AA. One of the key observations here is the measurement of particle ratios (with respect to pions) as a function of the multiplicity (more precisely $\langle dn_{\mathrm{ch}}/d\eta(0)\rangle$) from ALICE [9, 10, 11, 12, 13, 14, 15, 16, 17]. One can see an impressive increase of for example the Omega over pion yield, and one observes essentially a continuous curve from p-p (different multiplicities) over p-A to nucleus-nucleus (different centralities). The core-corona picture in EPOS provides a simple explanation of such a behavior.

Since core contributions are also important for p-p and p-A collisions, this core-corona picture may even be important in in air-shower simulations, related to the "muon deficit" in simulations compared to data.

2 CORE-CORONA EFFECTS IN AIRSHOWERS?

When studying "new features" for small systems, one looks at observables like "Omega over pion ratio", which is of course irrelevant for air shower simulations. But there are other more relevant quantities, which also depend on the relative core/corona weight [18]. Such a quantity is electromagnetic to hadronic energy of an air shower,

$$R = \frac{E_{\mathrm{EM}}}{E_{\mathrm{hadr}}}, \tag{1}$$

which is strongly correlated with the muon yield: Energy going into EM cascade is lost for muon production. Therefore, a too big value of R will lead to a too small muon yield. It is interesting to see what are the values of R in different scenarios. Considering a simple toy string model (only u-ubar and ddbar break), we get

$$R = R_{\mathrm{toy\,string}} = 0.5\,. \tag{2}$$

Using a realistic string model, calibrated with e^+e^- data, we get

$$R = R_{\mathrm{real\,string}} = 0.41\,. \tag{3}$$

And finally, using statistical hadronization (thermal model), the simplest way to hadronize a quark-gluon fluid, we find

$$R = R_{\mathrm{thermal}} = 0.34\,. \tag{4}$$

The thermal model actually refers to a grand canonical ensemble. So clearly, the "thermal" scenario would help to produce more muons, compared to the string approach. In [18], a core-corona toy model is used to investigate this. In EPOS4, we could go one step further, and use a realistic core-corona approach, and a realistic microcanonical hadronization.

3 MULTIPLE SCATTERING APPROACH OF PRIMARY INTERACTIONS IN EPOS

All this discussion about a "plasma core" in small systems is very interesting, but the main requirement of having a core is a sufficiently high density of strings after the primary scattering stage, and here multiple scattering pays a crucial role. We will therefore recall basic elements of the multiple scattering approach of primary interactions in EPOS. All details of the PBGRT approach, discussed in the following, can be found in [3] or [4]. The basic assumption of PBGRT is the hypothesis that the T-matrix can be expressed as a sum of products of elementary objects called Pomerons. Then one evaluates its discontinuities ("cuts"), which is done using "cutting rules". In our multiple scattering approach PBGRT, we have for each cut Pomeron an expression $G = \frac{1}{2s\,\mathrm{i}}\mathrm{disc}\,T_{\mathrm{Pom}}$, where T_{Pom} represents a parton ladder, computed using the DGLAP equations, using some soft cutoff Q_0. The functions G can be computed using numerical integration, and their dependence on the light cone momentum fractions x^+ and x^-can be fitted as $G(Q_0\,;\,x^+,x^-) = \alpha\,(x^+x^-)^{\beta}$, with coefficients α and β which depend on s and the impact parameter b, and of course on the cutoff Q_0. To mimic nonlinear effects, our fits are modified (for pp) by adding an exponent ε, which means instead of G we use

$$G_{\mathrm{eff}}(Q_0\,,\,x^+,x^-) = \alpha\,(x^+x^-)^{\beta+\varepsilon}. \tag{5}$$

The exponent $\varepsilon = \varepsilon(s)$ is chosen to reproduce the energy dependence of cross sections. Finally one defines a saturation scale Q_s via

$$G_{\mathrm{eff}}(Q_0\,;\,x^+,x^-) = f \times G(Q_s\,;\,x^+,x^-), \tag{6}$$

(with some coefficient f) and then considers the parton ladder with the cutoff Q_s, changing the internal structure of the Pomeron.

4 SECONDARY INTERACTIONS IN EPOS

In heavy ion collisions and also in high multiplicity events in proton-proton and proton-nucleus 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. The starting point are the flux tubes (kinky strings) representing the cut Pomerons. Some of these flux tubes will constitute bulk matter which thermalizes and expands collectively – this is the so-called "core". Other segments, being close to the surface or having a large transverse momentum, will leave the "bulk matter" and show up as hadrons (including jet-hadrons), this is the so-called "corona".

In principle the core–corona separation is a dynamical process. However, the knowledge of the initial transverse momenta p_t of string segments and their density $\rho(x, y)$ allows already an estimate about the fate of these string segments. By "initial" we mean some early proper time τ_0, which is a parameter of the model. String segments constitute bulk matter or escape, depending on their transverse momenta p_t and the local string density ρ. Also low p_t segments corresponding to a very high p_t jet may escape.

We compute for each string segment

$$p_t^{\text{new}} = p_t - f_{\text{Eloss}} \int_\gamma \rho \, dL, \tag{7}$$

where γ is the trajectory of the segment. If a segment has a positive p_t^{new}, it is allowed to escape – it is a corona particle. Otherwise, the segment contributes to the core. We have a nonzero core contribution not only in central heavy ion collisions, but even in pp. The corona elements will show up as hadrons, whereas the core provides the initial condition of a hydrodynamical evolution, where the particles will be produced later at "freeze-out" from the flowing medium, which occurs at some "hadronization temperature" T_H. After this "hadronization" the hadrons still interact among each other, realized via a hadronic cascade procedure.

The corona contributions dominate completely the high p_t regions. The core becomes important for both pions and protons at intermediate p_t, but the core over corona fraction is much bigger for protons, and the crossing (core=corona) happens at larger p_t. The fact that the core is much more visible in protons compared to pions is a consequence of radial flow: when particles are produced in a radially flowing medium, the heavier particles acquire more transverse momentum than the light ones. It is a mass effect (lambdas look similar to protons, kaons are in between pions and protons).

5 MICROCANONICAL HADRONIZATION

In pp and pA the core (plasma part) may be quite small, so the "thermal model" may not work. Energy and flavor conservation play a role, and therefore we employ in EPOS4 a microcanonical approach (equal to the thermal model (GC) in the limit of infinite volume). New methods, extremely fast, work for small and big systems (faster than the approximate GC method). We discuss here a static droplet, but in reality we treat a flowing object, with hadronization through a space-time hypersurface (covariant framework using $T^{\mu\nu}$ and $d\Sigma_\nu$).

Microcanonic decay of a given volume in its CMS into n hadrons, is given as

$$\begin{aligned} dP &= C_{\mathrm{vol}}\, C_{\mathrm{deg}}\, C_{\mathrm{ident}} \\ &\quad \times \delta(E-\Sigma E_i)\, \delta(\Sigma \vec{p}_i) \prod_A \delta_{Q_A, \Sigma q_{A\,i}} \prod_{i=1}^{n} d^3 p_i, \end{aligned} \tag{8}$$

with

$$C_{\mathrm{vol}} = \frac{V^n}{(2\pi\hbar)^{3n}}\ ,\quad C_{\mathrm{deg}} = \prod_{i=1}^{n} g_i\ ,\quad C_{\mathrm{ident}} = \prod_{\alpha\in\mathcal{S}} \frac{1}{n_\alpha!}\ , \tag{9}$$

where n_α is the number of particles of species α, $\mathcal{S}$ is the set of particle species. This is different from decay rate of a massive particle (using LIPS), where asymptotic states are defined over an infinitely large volume (see [19]). Having developed very sophisticated techniques to generate multi-particle configuration according to the eq. (8), we are are ably to make extensive test, first for big systems ($E = 200\,\mathrm{GeV}$, $V = 350\,\mathrm{fm}^3$), where we see that the microcanonical results agrees completely with the grand canonical one. Only going down to very small systems (($E = 6.25\,\mathrm{GeV}$, $V = 10.9375\,\mathrm{fm}^3$), we see substantial deviations, with fewer heavy particles being produced.

In the following, we will apply the core-corona approach, with the core decaying via microcanonical hadronization, studying the ratio of Omega over pion yields versus multiplicity. In fig. 1, we show EPOS results for p-Pb scattering (thin lines) as well as Pb-Pb (thick lines), for different contributions. We consider first results without hadronic cascade: From core only (dashed-dotted), from corona only (dotted), and the sum of core and corona "co+co" shown as dashed line. The complete simulation, including hadronic cascade referred to as "full" is plotted as full line. We compare with ALICE data for p-Pb (squares) and Pb-Pb (stars) [9, 10, 11, 12, 13, 14, 15, 16, 17], already mentioned earlier. Both corona and core contributions are universal curves (pPb = PbPb in the overlap region). We know that the relative core contribution increases with multiplicity, we understand that the core+corona curve (co+co, dashed) simply interpolates between the corona level at small multiplicity towards the core level at high multiplicity. The "full" results shows some reduction with respect to the "co+co" case, with increasing multiplicity, due to baryon-antibaryon annihilation. There are two important messages. First, there is a substantial core contribution even in proton-nucleus collisions, so statistical particle production is important. Second, the pure core contribution is essentially flat, and drops only at very small multiplicities. So the "thermal model" is not too bad as approximation.

6 CONCLUSIONS

We presented some new features in the framework of the "EPOS4 project", in particular the microcanonical hadronization procedure, which is a universal approach for big and small systems. We understand well the dependence of particle ratios (like Omega over pion) as a function of the multiplicity: It is essentially a two component picture, where with increasing multiplicity one gets more and more core contribution. We see that even in proton-nucleus collisions there is a substantial core contribution , and secondly, the statistical particle production, done via microcanonical hadronization, is close to the thermal limit.

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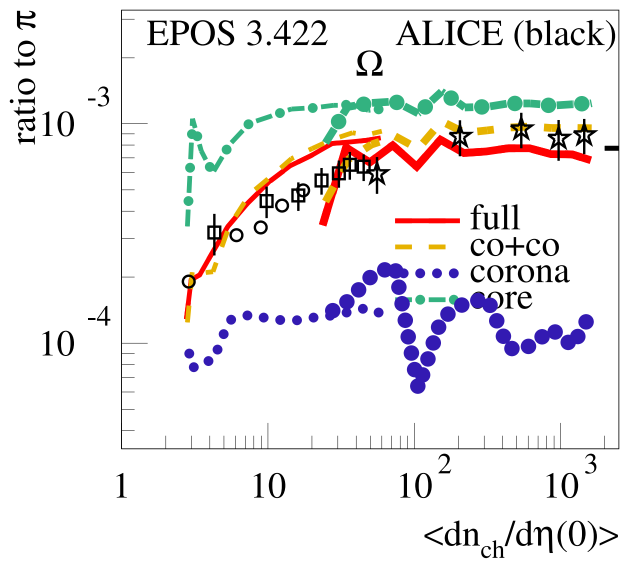

Figure 1: Particle ratios of Omega baryons to pions, as a function of the multiplicity, as obtained from EPOS simulations, for pPb (thin lines) and PbPb (thick lines), for different contributions (as explained in the text). We compare with ALICE data, see text.