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Cascading in ultrarelativistic nuclear collisions

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ABSTRACT

We sketch the string model VENUS 3 for ultrarelativistic nuclear collisions, which treats the reinteraction of decay products from string fragmentation among themselves or with spectator nucleons. We investigate rapidity and transverse energy distributions in proton-nucleus and nucleus-nucleus collisions. Comparing the spectra with and without interaction we observe almost no increase in the total pion multiplicity; however, there is a backward shift in rapidity. On the other hand we observe considerably more protons in the target fragmentation region around $y = 0$. Transverse energy distributions are significantly broader once the target fragmentation region is covered.

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1. Introduction

It is a commonly accepted picture for the initial stage of an ultrarelativistic heavy ion collisions to cut the nuclei geometrical into spectator and participant regions. A small nucleus colliding centrally with a big one would drill a cylindrical hole through the latter, so that all the nucleons in the cylinder and all projectile nucleons participate in the interaction, whereas all target nucleons outside the cylinder just spectate.

In a string model, the participant region is the zone where strings are formed: so we have a central cylinder with longitudinal oriented strings, surrounded by the spectator nucleons outside the cylinder. The strings expand along their longitudinal axes, and break for the first time after typically 1 fm/c. Whenever a string breaks the resulting two substrings acquire transverse momentum. The transverse momentum component allows the string segments to move outside the participant cylinder and interact with spectator nucleons.

It is the purpose of this letter to introduce the new string model VENUS 3 for ultrarelativistic hadronic collisions, which accounts for reinteractions of string segments (or resonances) among themselves and with spectator matter. It is to our knowledge the only string model so far which treats consistently reinteractions of everything with everything, not just when spectator matter is involved like in [1,2]. In particular concerning the formation of a quark gluon plasma interactions of string pieces among each other are important.

Let us sketch the main ideas of our model. Whenever a projectile and a target nucleon come close to each other, massive strings are formed via string flip [3,4]. Considering projectile and target nucleons as low mass diquark-quark ($qq-q$) strings, string flip provides $qq-q$ strings with diquark and quark from different nucleons (see fig. 1.). Such strings usually have a large mass. The strings evolve in space-time according to classical string theory, concerning expansion as well as string breaking [5]. Since a string breaks typically after 1 fm/c, it never gets considerably longer than 1 fm, so for the purpose of rescattering we consider the segments as pointlike, and correspondingly define tracks (see [6]). We follow the tracks of all objects - strings, string segments (which may or not be hadrons) and also spectator nucleons. Whenever two objects come closer than a universal interaction radius r_0 , they interact. As interaction we assume exclusively fusion, the fused objects living for a while and then decaying again. If in a process $h_1 + h_2 \rightarrow h_3 + h_4$ an intermediate resonance is formed it is most important to consider a finite resonance lifetime. Otherwise the multiplicity at an early time may be artificially increased by having two hadrons instead of the one resonance.

The model of interacting string fragmentation was first applied to neutrino-neon scattering [6], which is essentially the fragmentation of a diquark-quark string inside a nucleus. So this model has been tested already, the parameters have been fixed, and it can therefore without further freedom be applied to the more complicated proton-nucleus and nucleus-nucleus collisions.

Since we have described the building blocks of the model elsewhere [3,4,5,6], we keep the description of the model qualitative and non-technical.

2. String model with cascading

We briefly describe the string model VENUS 3. The mechanism to form strings in a hadron-hadron collision is "string-flip" or "colour-exchange". Consider for example two colliding baryons which have a large relative momentum. These baryons might be regarded as low mass strings, with partons (quarks and diquarks) at the ends. A string-flip interaction means that not the parton momenta are changed, but the string structure (the way the partons are grouped together to form singlets). Instead of linking the partons within each hadron as before the collision, the string flip mechanism provides links (strings) between partons from different nucleons (see fig. 1(b)). In this way partons with large relative momentum are grouped together, providing a string with a large mass. So the effect of such an interaction is essentially to transform low mass strings with large relative momentum into two high mass strings with low relative momentum.

We take into account that the hadron has a more complicated structure than a simple quark-diquark ($q-qq$) string (baryon) or a quark-antiquark ($q-\bar{q}$) string (meson). We also consider additional $q-\bar{q}$ strings (sea quarks). We can set up a consistent multi-string-flip model, which provides the possibility of having more than two strings in a hadron-hadron collision [3,4]. In addition we include consistently diffractive scattering [4]. Having already the concept of multiple-string-flip, it is trivial to generalize to hadron-nucleus or nucleus-nucleus collisions. Assuming straight line trajectories for the nucleons, a string-flip occurs whenever two nucleons come closer than $\sqrt{\sigma_{pp}/\pi}$. There is no additional input, no further parameters to extend the hadron-hadron model.

We want to stress that we consider quarks, antiquarks and strings as basic objects in our model. Taking into account gluons in addition would be double counting, because the strings replace them. String-flip is an effective interaction which takes care of this fact (see [3]), where the string-flip principle is discussed using strong coupling QCD).

After string formation we have to deal with the second main building block of the model, namely the evolution and fragmentation of strings, including reinteractions of "string-fragments". Whenever rescattering is concerned, it is most important not just have a parametrization of string-fragmentation data, we rather need a good fragmentation model with proper space-time evolution. Despite all the difficulties of quantization, strings are very attractive at least as effective objects. So we take the classical string theory seriously, which very elegantly provides a string Lagrangian as well as a string breaking law from invariance arguments: we require locality, covariance and invariance under reparametrization of the string surface. This provides the full dynamics in terms of a few fundamental parameters: the string tension κ and the string breaking strength α . A detailed description of the string evolution and fragmentation model in VENUS 3 can be found in [5].

Let us discuss some characteristic features of our fragmentation model by comparing it with the Lund model [7]. In our model strings break successively into two arbitrary substrings, whereas in the Lund model one substring is forced to be a hadron. So in our case it is likely to cut a string somewhere in the middle, leaving two substrings with comparable mass, whereas in the Lund model the string breaks at one edge, with two very different masses (at least for heavy strings). Our model therefore has a tree structure (see

Fig. 1. The string-flip principle to form strings. Incident nucleons are considered as low-mass $qq - q$ strings (a). The interaction does not change parton momenta, however the partons are linked together differently (b). This provides strings with partons of large relative momentum at both ends.

Fig. 2. Tracks of string segments in space-time ("fragmentation-tree"). For the purpose of rescattering, string-segments are considered pointlike, the distance between tracks determines rescattering.

fig. 2) and the Lund model has a ladder structure. The sequence of breaks we are talking about should not be confused with the time sequence, which is of course frame-dependent and always inside-outside, purely from kinematics. The reason for Lund's ladder structure is the fact that hadrons and resonances have discrete mass. We relax this requirement by allowing resonances with continuous mass which decay into on-shell hadrons.

The fragmentation procedure in VENUS 3 is performed in a covariant manner, with the consequence that the first break in our iteration is in general not the earliest breakpoint in real time, in some reference frame. However to treat interactions we need to know a time sequence. So we choose as reference frame the nucleon-nucleon cm system and reconstruct a real time sequence of string decays. With $t_1, t_2, t_3 \dots$ being the time sequence of breaks, we have between the string formation time t_0 and the first break t_1 just one string, between t_1 and t_2 two segments, between t_2 and t_3 three segments and so on. Since string segments usually do not get very long (they break before they get too long) we consider them as pointlike, and construct the tracks of all segments: starting with one track between t_0 and t_1 we have two tracks between t_1 and t_2 and so on (see fig. 2). The final string segments - resonances - decay after an appropriate lifetime, providing a further bifurcation of a track. It is a unique feature of our treatment that we have a complete space-time picture of the collision from the beginning to the end, which we consider a necessary condition to include rescattering.

Let us assume we have a number of strings fragmenting in a nuclear medium (spectator matter). We first construct as described above the "fragmentation-tree" (tracks of segments) of each individual string, ignoring the others and the nuclear medium. We also construct the tracks of the nucleons. We follow the tracks in time, and whenever two tracks $\vec{x}_A(t)$ and $\vec{x}_B(t)$ come close, i.e.

$$|\vec{x}_A(t) - \vec{x}_B(t)| < r_0, \quad (1)$$

then these two objects interact. The interaction radius r_0 is a universal parameter (set to 0.7 fm), being the same for all entrance channels A and B . There are two reasons for such a drastic simplification: first, we want to keep the model simple and transparent (at least for the beginning) and second, most of the cross-sections are not known anyhow, so trying to parametrize all cross-sections would hide our lack of knowledge at too many places. Once two objects fulfil eq. (1), they are most likely close in momentum space, so we have low energy scattering, which is dominated by resonance scattering. So we assume that an interaction always goes via fusion:

$$A + B \rightarrow R \quad (2)$$

For the fused object we determine mass and quark content, check in our resonance table which resonance this corresponds to, and then decay R after an appropriate lifetime:

$$R \rightarrow C + D + \dots \quad (3)$$

The two interacting objects may be two string fragments, or one such fragment and a spectator nucleon. So we consider participant-participant as well as participant-spectator interactions!

3. Results

We made careful investigations to confirm that rescattering effects are essentially only affected by one parameter: the interaction radius r_0 (see eq. (1)). In the following we are comparing two scenarios:

$$\begin{array}{ll} r_0 = 0 & \longleftrightarrow \text{interaction turned off} \\ r_0 = 0.7 \text{ fm} & \longleftrightarrow \text{best guess for interaction radius} \end{array}$$

where our default value of $r_0 = 0.7 \text{ fm}$ may be not the final answer; it is really a best guess rather than an optimized parameter. In the following figures we shall use dashed lines if using $r_0 = 0$ and solid lines if using $r_0 = 0.7 \text{ fm}$ (default value in VENUS 3.00), points represent data.

In figs. 3,4 we show rapidity distributions of negative pions and protons in $p\text{-Ag}$ reactions at 100 GeV (data are from [8]). We observe that the total number of pions remains almost unchanged by turning on interactions. However, we observe a shift from central to backward rapidity. We see a much greater effect for protons: the number of observed protons is considerably increased, and we even observe protons at negative rapidity, which is not possible in $p\text{-p}$ collisions. Without rescattering (dashed histogram) the protons have the following origin in the model: for each collision (on the average ~ 3) we have a diquark-quark string, the diquark facing backwards. Each of these diquarks leads after fragmentation to a baryon, so with roughly half of these being protons we expect approximately 1.5 protons in the fragmentation region ($y < 3$), which is more or less the integral of the dashed histogram (fig. 4). Concerning rescattering the most important process is the following: a produced particle (baryon or meson) hits a target spectator, the two hadrons fuse and decay again. This leads to the large increase of baryon number in fig. 4 and the shift in the pion distribution in fig. 3. We observe qualitatively the same behaviour for the reaction $\text{O}+\text{Au}$, see figs. 5,6 (data are from [9, 10]).

Another variable widely used in experiments is the transverse energy E_t which sums up weighted energies of all particles in a given rapidity interval. This quantity is essentially a convolution of multiplicity and single particle transverse momentum distribution. By comparing with the rapidity distributions in figs. 3-6 we try to qualitatively understand the effect of rescattering on E_t -distributions. Fig. 7 shows E_t -spectra for a pseudo rapidity interval $0.6 < \eta < 2.4$ in $p\text{-Pb}$ collisions at 200 GeV (data are from [11]). From our multiplicity studies we conclude that the pion multiplicity should not change much in this interval (compare fig. 3); however, one effect of the rescattering process eq. (2,3) is the transformation of longitudinal momentum into transverse one [12]. Such an increase of the mean transverse momentum leads to a broader E_t -distribution – as observed in fig. 7. Fig. 8 demonstrates that for a central rapidity interval $2.2 < \eta < 3.8$ there is almost no effect. In this interval however the multiplicity in a rescattering scenario is decreased. This is obviously just compensated by an increase of the average p_t [12]. Both histograms (VENUS with and without rescattering) fit the data [13] equally well, although for other observables there is quite a difference between the two scenarios. This shows the limited value of the E_t variable to be used to discriminate between models.

Fig. 3. Rapidity distributions of pions for $p\text{-Ag}$ scattering at 100 GeV. Points are data, the dashed histogram represents VENUS without rescattering, the solid histogram shows VENUS results with rescattering.

Fig. 4. Rapidity distributions of protons for $p\text{-Ag}$ scattering at 100 GeV. Same conventions as in fig. 3.

Fig. 5. Pseudo rapidity distributions of charged particles for O-Au scattering at 200 GeV. Points are data, the dashed histogram represents VENUS without rescattering, the solid histogram shows VENUS results with rescattering.

Fig. 6. Pseudo rapidity distributions of protons for O-Au scattering at 200 GeV. Same conventions as in fig. 5.

Fig. 7. Transverse energy distributions for p-Pb collisions at 200 GeV for a backward rapidity interval. Points are data, the histograms represent VENUS with (solid) and without (dashed) rescattering.

Fig. 8. Transverse energy distributions for p-Pb collisions at 200 GeV for a central rapidity interval. Same conventions as in fig. 7. The data actually represent p-Au scattering.

We now turn to E_T -distributions for nucleus-nucleus collisions. In fig. 9 we show E_T -spectra for a backward rapidity range ($-0.1 < \eta < 2.9$) for O-W scattering at 200 GeV (the data are from [14]). The solid histogram represents as usual full VENUS (with rescattering), we also show VENUS results without rescattering (dashed). We see the same effect as for p-A at backward rapidities: rescattering leads to wider distributions, due to more $< p_t >$ per particle. For central-forward rapidities we see again – as for p-A at central rapidities in fig 8 – almost no effect due to rescattering, see fig 10 (the data are from [15]).

4. Summary

We introduced the new string model VENUS 3 for ultrarelativistic collisions. It differs from older VENUS versions by a completely new fragmentation treatment – based upon classical string theory – and the inclusion of rescattering of string fragments or resonances among themselves and with target spactators. It has been shown that it fulfils the most stringent requirements, like large baryon production in the fragmentation region and wide E_T -distributions for rapidity intervals covering this region. To further test and develop the model we still have to compare with much more sensitive experimental spectra, first of all for example p_t -distributions for different rapidity cuts for different identified particles, for neutrino-nucleus, proton-nucleus, and nucleus-nucleus collisions.

Fig. 9. Transverse energy distributions for O-W collisions at 200 GeV for a backward rapidity interval. Points are data, the histograms represent VENUS with (solid) and without (dashed) rescattering.

Fig. 10. Transverse energy distributions for O-Au collisions at 200 GeV for a central-forward rapidity interval. Same conventions as in fig. 9.

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