Analysis of the first RHIC results in the String Fusion Model

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Abstract

First results from RHIC on charged multiplicities, evolution of multiplicities with centrality, particle ratios and transverse momentum distributions in central and minimum bias collisions, are analyzed in a string model which includes hard collisions, collectivity in the initial state considered as string fusion, and rescattering of the produced secondaries. Multiplicities and their evolution with centrality are successfully reproduced. Transverse momentum distributions in the model show a larger $p_T$-tail than experimental data, disagreement which grows with increasing centrality. Discrepancies with particle ratios appear and are examined comparing with previous features of the model at SPS.
With the first collisions at the Relativistic Heavy Ion Collider (RHIC) at BNL in June 2000, the study of nuclear collisions has entered the truly ultrarelativistic domain. While there exist predictions from many models [1], now experiments have presented results [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13] on several aspects of data, most of them corresponding to AuAu collisions at 130 GeV per nucleon in the center of mass. So it comes the time to examine the ability of models for ultrarelativistic heavy ion collisions, fitted to describe nuclear data at the much lower energies of the Super Proton Synchrotron (SPS) at CERN and nucleon data in the range of energies going from SPS to TeVatron at FNAL, to describe the new situation, and whether the evidences of Quark Gluon Plasma (QGP) already obtained at SPS are verified or not [14]. The aim of this letter is to compare the results of the String Fusion Model (SFM) [15, 16] with some of the first RHIC data. Other comparisons can be found in [17, 18].

After a very brief model description, charged multiplicities at midpseudorapidity in central collisions, evolution of charged multiplicities at midpseudorapidity with centrality, transverse momentum distributions of charged particles at different centralities and ratios of different particles will be compared with available data coming from the experiments. Finally some conclusions will be summarized.

An exhaustive description of the model can be found in [16]. Its main features are the following: Elementary inelastic collisions (binary nucleon-nucleon collisions) are considered as collisions between partons from nucleons of the projectile and the target, distributed in the transverse plane of the global collision. Some of these elementary collisions are taken as hard ones, and proceed as gluon-gluon → gluon-gluon through PYTHIA [19] with GRV 94 LO parton density functions (pdf’s) [20] and EKS98 modification of pdf’s inside nuclei [21], with subsequent radiation and fragmentation performed by ARIADNE [22] and JETSET [19]. Those collisions not being considered hard produce soft strings in pairs. These strings are allowed to fuse if their parent partons are close enough in impact parameter [15]; as the number of strings increases with increasing energy, atomic number and centrality, this mechanism accordingly grows in importance. Fragmentation of soft strings is performed using the tunneling mechanism for mass and transverse momentum distributions, while longitudinal momenta are simulated by an invariant area law. The main consequences of string fusion are a

\[\text{In [18] a model which, like ours, contains multipomeron exchange, a hard component and rescattering of secondaries, but no string fusion, is shown to be able to reproduce the experimental data on elliptic flow.}\]
reduction of multiplicities in the central rapidity region and an increase in heavy particle production. The produced particles are allowed to rescatter (between themselves and with spectators nucleons) using a very naive model with no proper space-time evolution, whose consequences are a small multiplicity reduction, an increase in strange and multistrange baryons and nucleon annihilation. Some comments are in order at this point: First, partons which generate both soft and hard strings can be valence quarks and diquarks, and sea quarks and antiquarks, so the number of soft strings is not simply proportional to the number of wounded nucleons but has some proportionality, increasing with increasing energy, centrality and nuclear size, on the number of binary nucleon-nucleon collisions. Besides, only fusion of two strings in considered in the actual version of the model, and hard strings are not fused. Finally, the rescattering model is simplistic and has been included just to estimate the effects that such kind of physics could have and to tune the parameters of the model as an initial condition for a more sophisticated evolution; thus, results depending strongly on it should be taken with great caution. All these aspects will be commented more extensively when the comparison with experimental data is performed.

In Fig. 1 results of the model (unless otherwise stated, results of the model correspond to its default version with the mentioned pdf’s and string fusion and rescattering, see [16]) for the pseudorapidity distribution of charged particles in central collisions at SPS and RHIC are compared with experimental data. For central AuAu collisions at 130 and 200 GeV per nucleon in the center of mass, the model successfully reproduce the data (the ratio of multiplicities at 200 and 130 GeV is 1.08 in the model, slightly smaller than the experimental value 1.14±0.05 measured by PHOBOS [13]), while at 56 GeV it overestimates the PHOBOS results [3]. Nevertheless, the situation at these energies is not clear: WA98 results [22] at SPS lie above the PHOBOS data at 56 GeV, and far above NA49 data [23] (as extracted in [3]) at SPS; NA49 results on multiplicities in central PbPb collisions at SPS are in agreement with those from WA97 [24]. So it is difficult to conclude anything definitive on the evolution from SPS to RHIC, of multiplicities with increasing energy in the model.

2Usually the soft contribution is taken as proportional to the number of wounded nucleons, while the contribution proportional to the number of binary nucleon-nucleon collisions is considered hard. Let us stress that this is a misleading (model dependent) statement: some proportionality with the number of binary nucleon-nucleon collisions is demanded by a basic requirement of the theory as unitarity, and has nothing to do with the soft or hard origin of these binary nucleon-nucleon collisions.

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Recently it has been proposed [26] that the evolution of multiplicities with centrality can be used as a tool to discriminate among several models for multiparticle production in high-energy nuclear collisions. In this way, models which consider saturation [27] of either the number of partons in the wave function of the projectile and target or in the number of partons produced in the collision [28], show a constant or slightly decreasing behavior of the multiplicity per participant (wounded) nucleon with increasing number of participants. On the other hand, models which consider some proportionality with the number of binary nucleon-nucleon collisions based on the AGK cancellation [30], being this proportionality already present in the soft component [16, 31, 32, 33] or only in the hard component [34], show a behavior, with the multiplicity per participant increasing with increasing number of participants, qualitatively or quantitatively compatible with data. The results of our model for the 75% more central collisions at SPS and RHIC are shown in Fig. 2 and compared with experimental data. It can be seen that the model underestimates WA98 data at SPS, while it overestimates those from NA49, as could be expected from the discussion about Fig. 1, but the qualitative behavior seems correct. At RHIC the agreement with data is quite satisfactory. It can be seen that the inclusion of rescattering results in a slight decrease of multiplicities, while the influence of string fusion is relatively small at SPS but very important at RHIC and crucial for the agreement with experimental data. In our model it is this latter mechanism the one which plays the rôle of shadowing corrections in [31, 32, 34], parton saturation in [28, 29] or string percolation [35] in [33]. Concerning the limitation of fusion of just soft strings in groups of two, let us point out that it seems to be compensated at RHIC with the choice of the fusion strength, while the non-inclusion of fusion of hard strings is unimportant, as they amount for just 1% of the total number of elementary inelastic collisions. This is no longer the case for the future Large Hadron Collider (LHC) at CERN, situation for which we present the results of the model in Fig. 3 (results with rescattering are not presented because this mechanism is too CPU-time consuming at LHC energies for large nuclei): Here, the fusion of just two strings has reached its limit, so multiplicities are not so strongly damped as at RHIC, and fusion of more than two strings (and of hard strings, which now amount for 32% of the total number of elementary inelastic collisions), or even a phase transition like percolation [36], have to be introduced in the model.\footnote{Other proposals which include saturation [29] show an increasing behavior compatible with data.}
Let us now turn to the transverse momentum spectrum. Preliminary measurements \[7, 9\] show that the spectrum in AuAu collisions at 130 GeV per nucleon in the center of mass falls with increasing \( p_T \) faster than predictions from models \[34\] which reproduce the \( p_T \)-distributions in pp collisions at 200 GeV in the center of mass; this discrepancy grows with increasing centrality. A possible explanation is jet quenching \[37\], i.e. the energy loss of high energy partons in a hot medium containing free color charges. So, there has been a great debate on the explanation of the absence of jet quenching at SPS and its presence at RHIC \[38\], and its interpretation as a QGP signature. In our model we find quite the same feature as in \[34\], namely an excess of particles with high \( p_T \) compared with experimental data, excess which becomes less pronounced when going from central to minimum bias collisions. Our model correctly reproduces multiplicities and their evolution with centrality at this energy (as seen in Figs. 1 and 2), and the \( p_T \)-spectrum in pp collisions at SPS and in pp collisions at S\(p\bar{p}\)S at CERN and TeVatron, and the increase of \( \langle p_T \rangle \) with energy and multiplicity (see \[13\]); we have also checked that this is neither an effect of pdf’s or of their nuclear modifications, nor of rescattering, whose influence on the \( p_T \)-spectrum is tiny, see \[16\] and Fig. 4; in fact, from the studies in \[16\] it can be concluded that the transverse momentum enhancement in collisions between nucleons compared to those between nucleons is due in the model both to the hard contribution which becomes more important with an increasing number of elementary collisions, and, above all, to the transverse momentum broadening of the partons at the ends of the strings introduced in the model and responsible of the increase of \( \langle p_T \rangle \) with increasing multiplicity, while string fusion has a very small effect. It is also remarkable that the discrepancy with the experimental data appears in a model like ours, which for the collisions studied at RHIC produces only 1% of hard elementary collisions, and in a model like that of \[34\], in which most of particle production at RHIC energies comes from the hard contribution. So it really looks like an effect which diminishes the number of high \( p_T \) partons, leading them to the low \( p_T \) region. Jet quenching \[37, 38\] seems a good candidate to explain this experimental finding, but it should be taken into account that it also leads to the appearance of more particles at low \( p_T \) and \( \eta \); thus, the simultaneous comparison of the

\[4\] Possible differences in the \( p_T \)-spectrum in nucleon-nucleon collisions between our model and those based on hard scatterings like HIJING \[34\] should become visible at LHC, where the results are not so tightly constrained by the existing experimental data at SPS, S\(p\bar{p}\)S and TeVatron: In our model the contribution from hard scatterings will be smaller and thus we expect less high-\( p_T \) particles.
evolution of both multiplicities and transverse momentum distributions with centrality should be a crucial test for this mechanism\textsuperscript{5}. One would think that the presence of saturation of low transverse momentum partons \textsuperscript{27, 28} would make the comparison with experimental data even worse: the low \(p_T\) region of the spectrum, populated of poorly resolved partons, would be damped due to parton fusion and the spectrum become flatter than without saturation. Quite the same would occur in percolation of strings \textsuperscript{36}: soft strings have a larger transverse dimension than hard partons and would fuse more easily, and fused strings with higher string tension would produce particles with higher \(p_T\) than ordinary strings, so the mean \(p_T\) would increase with atomic size or centrality \textsuperscript{40}, contrary to what data apparently show\textsuperscript{6}.

Finally, in Table \textsuperscript{1} model results for different particle ratios are shown and compared with published experimental data \textsuperscript{12, 22, 33, 42, 4, 5, 6, 11}. For completeness, let us indicate the results in the model for the ratios \(\bar{\Lambda}/\Lambda, \bar{\Xi^+}/\Xi^-, K^+/K^-, \bar{p}/\pi^-\) and \(K^-/\pi^-\) at \(\eta \sim 0\), for which we get 0.85|0.87|0.87, 0.60|0.92|0.88, 1.08|1.03|1.04, 0.02|0.07|0.04 and 0.08|0.12|0.16 respectively without string fusion or rescattering|with string fusion|with string fusion and rescattering\textsuperscript{7}. The results in the model have been obtained in the corresponding pseudorapidity regions, for AuAu collisions at 130 GeV per nucleon in the center of mass with a centrality of 10 % and for particles with \(p_T > 0.2\) GeV/c. Each experiment applies different centrality and kinematical cuts for the different ratios, but a common conclusion of all of them is that ratios are very weakly dependent on centrality of the collision and \(p_T\) of the particles, so this should not seriously affect the comparison. From these results it can be seen that the model overestimates antibaryon production, a feature already present at SPS, see \textsuperscript{16}, but string fusion is needed to increase the strangeness and antibaryon yield, which is badly underestimated, see the comparison with SPS data in \textsuperscript{16}, if this mechanism is not

\textsuperscript{5}In \textsuperscript{33} the evolution of \(\langle \bar{p}/\pi^- \rangle\) versus \(p_T\) with centrality is proposed as a test of jet quenching; the increase of this ratio with increasing \(p_T\) observed by PHENIX \textsuperscript{33} is reproduced with a soft exponential component proportional to the number of participants plus a quenched perturbative distribution proportional to the number of binary collisions. In our model, the corresponding increase due to the soft part would be stronger than in \textsuperscript{33} due to string fusion and to the fact that this component is, in our case, proportional to the number of both wounded nucleons and binary collisions.

\textsuperscript{6}A recent analysis \textsuperscript{16} shows that nevertheless it is possible to simultaneously explain the evolution with centrality of both multiplicity distributions and transverse momentum spectra in a very crude realization of the percolating string approach.

\textsuperscript{7}These results can be compared with preliminary, not yet published results: 0.73±0.03, 0.82±0.08, 1.12±0.01±0.06, 0.08 and 0.15 respectively, presented by STAR at QM2001 \textsuperscript{9}. 
included (in the ratios at central rapidities and due to the lack of stopping at RHIC energies, see below, and to the fact that string fusion creates on average the same amount of baryons and antibaryons, this feature is mainly visible in those involving multistrange baryons or in $\bar{p}/\pi^-$). This discrepancy is less pronounced for $\Xi$’s than for $\Lambda$’s, and for $\Lambda$’s than for nucleons, and is more pronounced in the central region of (pseudo)rapidity. As stated in the brief model description, our rescattering model is simplistic, and cannot be expected to produce correct quantitative results, only the trend which it shows should be considered. So all that we can conclude is that for the ratios at RHIC, similar problems appear than those already present at SPS\footnote{Apparently, the antibaryon-to-baryon ratios measured at RHIC favor a coalescence model, see \cite{16} for a comparison of our results at full RHIC energy and those coming from other models.}. As a last comment, a preliminary, non-corrected for hyperon decay, measurement of the $p$-$\bar{p}$ yield at midpseudorapidity by BRAHMS \cite{3}, gives $8\div10$ for a centrality of 6 \% (a value $4\div6$ has been extracted \cite{12} from preliminary STAR data for the same centrality), while in our model we get a lower value $\sim2$; this may suggest that the problem in the $\bar{p}/p$ ratio lies not only in a $\bar{p}$ excess, but also in some lack of stopping in the model. 

In conclusion, we have compared the results of the SFM with some of the first RHIC data. At RHIC, charged multiplicities in the central region for central collisions and their evolution with centrality are successfully reproduced, suggesting the presence of some mechanism, like string fusion, which moderates the increase of multiplicities with increasing centrality; On the other hand and in view of the SPS data, it is difficult to obtain clear conclusions from the behavior of multiplicities in the transition from SPS to RHIC. Results on particle ratios show, when compared to experimental data, similar problems of antibarion excess previously found at SPS, and are probably related to the oversimplification of the model of rescattering and to problems with data at SPS, see \cite{16}. Finally, in the SFM the $p_T$-spectrum at RHIC is flatter than in data and this problem gets worse with increasing centrality, a feature which also appears in other models \cite{34, 38} in which the contribution of hard elementary collisions is much larger than in ours. At first sight, it looks improbable that parton saturation or percolation of strings could improve the comparison with the $p_T$-distributions (but see \cite{41}). So, from our point of view these data are most striking and, if confirmed, maybe a good candidate for a signature of non-conventional physics appearing in heavy ion collisions at RHIC. Although the results of the model on features which should depend strongly
on the evolution of the system (particle ratios and $p_T$-spectrum if jet quenching is present) cannot be considered satisfactory, the agreement with multiplicities and their evolution with centrality, which are usually assumed not to vary too much during evolution [28, 29], gives us some confidence in the ability of the model to describe the initial condition, to be used for further evolution, in a collision between heavy ions at high energies.

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1. Results of the model for the pseudorapidity distribution of charged particles for central (5 %) PbPb collisions at 17.3 GeV per nucleon in the center of mass (dashed-dotted line), and central (6 %) AuAu collisions at 56 (dotted line), 130 (dashed line) and 200 (solid line) GeV per nucleon in the center of mass, compared with experimental data at SPS from NA49 [23, 24] (black square) and WA98 [24] (black, upward pointing triangle), and at RHIC from PHOBOS [2, 13] (black, downward pointing triangle for 56 GeV, open circle for 130 GeV and black circle for 200 GeV), BRAHMS [6] (open square) and PHENIX [4] (open triangle).

2. Pseudorapidity density of charged particles at $\eta = 0$ divided by one half the number of participant nucleons, versus the number of participant nucleons, in PbPb collisions at 17.3 GeV per nucleon in the center of mass (multiplied by 1/2, lower curves and symbols) and in AuAu collisions at 130 GeV per nucleon in the center of mass (upper curves and symbols); also the experimental number for pp collisions at 130 GeV per nucleon is given [33], filled square. Experimental data are from PHENIX [4] (filled triangles), PHOBOS [2] (open triangle), WA98 [24] (filled circles) and NA49 [23, 24] (open circle).
(open circle). Curves are results of the model for the 75% more central events, without fusion or rescattering (dotted lines), with fusion (dashed lines) and with fusion and rescattering (solid lines).

3. The same as in Fig. 2, but for PbPb collisions at 5.5 TeV per nucleon in the center of mass.

4. Transverse momentum spectrum \( \frac{1}{2\pi p_T} \frac{dN}{d\eta dp_T}|_{\eta=0} \) versus \( p_T \) of charged particles at \( \eta = 0 \) in AuAu collisions at 130 GeV per nucleon in the center of mass, for central collisions (5%, solid and dashed lines and filled circles) and for minimum bias collisions (92%, multiplied by 0.01, dotted and dashed-dotted lines and open circles). Data are from PHENIX [7]; solid and dotted lines are results of the model with string fusion, dashed and dashed-dotted lines with string fusion and rescattering.

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1. Different particle ratios in central (10%) AuAu collisions at 130 GeV per nucleon in the center of mass in the model without string fusion or rescattering (NF), with string fusion (F) and with string fusion and rescattering (FR) for particles with \( p_T > 0.2 \) GeV/c, compared with experimental data [12, 12, 8, 9, 10, 11]. For the centrality criteria and kinematical cuts in the different experiments and ratios, see the experimental references and comments in the text.
Figures:

Figure 1:
Figure 2:
Figure 3:
### Table 1:

| Ratio       | NF | F  | FR | BRAHMS | PHENIX | PHOBOS | STAR |
|-------------|----|----|----|--------|--------|--------|------|
| $\bar{p}/p$ | 0.81 | 0.85 | 0.80 | 0.64±0.04 | 0.64±0.01 | 0.60±0.04 | 0.65±0.01 |
| ($\eta \sim 0$) | ±0.06 ($y \sim 0$) | ±0.07 | ±0.06 | ±0.07 |
| $\bar{p}/p$ | 0.38 | 0.50 | 0.38 | 0.41±0.04 |
| ($y \sim 2$) | ±0.06 |
| $K^-/K^+$ | 0.92 | 0.97 | 0.96 | 0.91±0.07 |
| ($\eta \sim 0$) | ±0.06 |
| $\pi^-/\pi^+$ | 1.02 | 1.02 | 1.01 | 1.00±0.01 |
| ($\eta \sim 0$) | ±0.02 |