Particle production sources in heavy ion collisions at RHIC and LHC

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A nonequilibrium statistical relativistic diffusion model (RDM) with three sources is applied to the analysis of charged-hadron distributions in Au–Au collisions at RHIC energies, in Pb–Pb collisions at the current LHC energy of 2.76 TeV, and in p–Pb at 5.02 TeV. The relative sizes of the particle production sources at RHIC and LHC energies are investigated in pseudorapidity space as functions of incident energy. The midrapidity source that arises mostly from gluon-gluon collisions becomes more important than the fragmentation sources as the energy increases from RHIC to LHC.

1. Introduction

Charged-hadron production in relativistic heavy ion collisions has been investigated in great detail at the Relativistic Heavy Ion Collider RHIC in Au–Au collisions, and more recently at the Large Hadron Collider LHC in Pb–Pb collisions. In particular, high-precision pseudorapidity distributions $dN_{ch}/d\eta$ of produced charged particles including their centrality dependence are now available in an energy range from $\sqrt{s_{NN}} = 0.019$ to 2.76 TeV [1, 2]. At RHIC energies these data include the fragmentation regions up to the values of the beam rapidities, whereas at the current LHC energy of 2.76 TeV corresponding to a beam rapidity of $y_{beam} = 7.99$ very precise ALICE data are available at $-5 < \eta < 5.5$ [2].

Theoretical descriptions of the underlying partonic processes often focus on gluon-gluon production, such as in many approaches based on the color glass condensate (see [3] as an example). Based on this mechanism particle and antiparticle distributions would, however, be identical – which is not the case experimentally, as found for example in π^+ and π^- distribution functions [4].

The relevance of the fragmentation sources from quark-gluon interactions has been investigated in a recent QCD-based study of net-baryon distributions (baryons minus antibaryons). There the gluon-gluon source that is peaked at midrapidity cancels out such that only the fragmentation sources remain [5, 6], giving rise to two fragmentation peaks that are clearly seen in the data at high SPS and RHIC energies, and in the theoretical predictions at LHC energies. At low SPS energies the fragmentation peaks overlap in rapidity space and hence, are not directly visible in the data, but can still be extracted quite reliably [7].

For produced particles (rather than net baryons), the effect of the fragmentation sources is less obvious, but clearly has to be considered. In this note I propose to investigate the relative importance of gluon-gluon vs. fragmentation sources as a function of c.m. energy in collisions of heavy systems (Au–Au, Pb–Pb) using a phenomenological nonequilibrium-statistical model. This relativistic diffusion model (RDM) [8] has proven to be useful in the analysis of data and in predictions for asymmetric [9] and symmetric [10] systems. Its three sources correspond to the gluon-gluon and fragmentation sources of the available microscopic theories. In direct comparisons with data the RDM can be used to infer the relative sizes of these underlying components as functions of the incident energy.

In charged-hadron production at SPS and low RHIC energies up to $\sqrt{s_{NN}} \simeq 20$ GeV, the gluon-gluon source centered at midrapidity is expected – and has turned out – to be unimportant [11], and the measured pseudorapidity distributions are well reproduced from the fragmentation sources only. At these relatively low energies, the fragmentation sources are peaked close to midrapidity and hence, are influenced considerably by the Jacobian transformation from rapidity to pseudorapidity space. At higher energies, the fragmentation peaks move apart, and the central gluon-gluon source emerges. Then the Jacobian increasingly affects only the central source. Also, its overall effect becomes smaller with rising energy since it depends on $(\langle m\rangle/p_T)^2$. Still, a precise determination of the Jacobian is essential for the modeling of pseudorapidity distributions at LHC energies. The pronounced midrapidity dip that is seen in the recent ALICE Pb–Pb charged-hadron data is due to the interplay of fragmentation and central sources, plus the effect of the Jacobian on the central source.

A brief outline of the method used to determine the relative size and extent of the sources in $\eta-$space is given in the next section. Results for heavy systems at RHIC and LHC energies are presented in Sec. 3. The energy dependence of central and fragmentation sources is discussed in Sec. 4. A brief outlook on single-particle observables in p–Pb at 5.02 TeV is also given. The conclusions are drawn in Sec. 5.

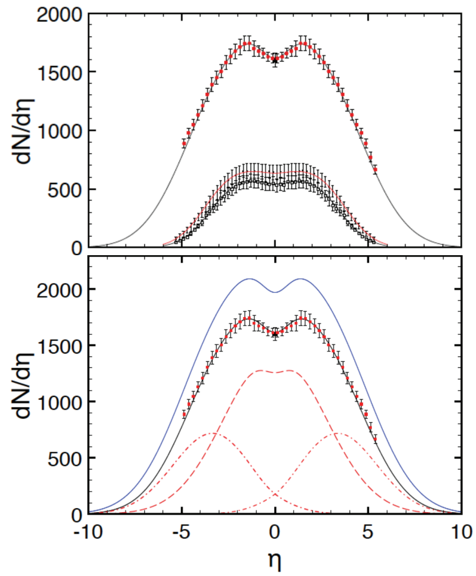

Fig. 1. (Color online) The RDM pseudorapidity distribution function for charged hadrons in central Pb–Pb collisions at LHC energies of 2.76 TeV, and central Au–Au at RHIC energies of 130 and 200 GeV with RDM parameters (Tab. 1) adjusted to the ALICE [12, 2] and PHOBOS [1] data, upper frame. In the bottom frame, the underlying theoretical distributions are shown for 2.76 TeV Pb–Pb. The shape of the midrapidity source is modified by the Jacobian. At LHC energies, the midrapidity value is mostly determined by particle production from gluon–gluon collisions. The upper curve is the RDM-prediction for 5.52 TeV. From Ref. [13].

2. Three sources model

In the three-sources version of the relativistic diffusion model, rapidity distributions of produced particles are calculated from an incoherent superposition of the fragmentation sources $R_{1,2}(y, t = \tau_{int})$ with charged-particle content N_{ch}^1 (projectile-like), N_{ch}^2 (target-like) and the midrapidity gluon-gluon source $R_{gg}(y, t = \tau_{int})$ with charged-particle content N_{ch}^{gg} as

$$\frac{dN_{ch}(y, t = \tau_{int})}{dy} = N_{ch}^1 R_1(y, \tau_{int}) + N_{ch}^2 R_2(y, \tau_{int}) + N_{ch}^{gg} R_{gg}(y, \tau_{int}) \; , \quad (1)$$

with the rapidity $y = 0.5 \cdot \ln((E + p)/(E - p))$, and the interaction time τ_{int} (total integration time of the underlying partial differential equation). In the linear version of the RDM [8], the macroscopic distribution functions are solutions of the Fokker-Planck equation ($k = 1, 2, 3$)

$$\frac{\partial}{\partial t} R_k(y,t) = -\frac{1}{\tau_y}\frac{\partial}{\partial y}\Big[(y_{eq} - y)\cdot R_k(y,t)\Big] + D_y^k \frac{\partial^2}{\partial y^2} R_k(y,t). \tag{2}$$

The consideration of the additive variable rapidity in the nonequilibrium-statistical Fokker-Planck framework has proven to be a useful approach in calculations and predictions of macroscopic distribution functions for produced particles. Integrating the equation with the initial conditions $R_{1,2}(y, t = 0) = \delta(y \pm y_{max})$, the absolute value of the beam rapidities y_{max}, and $R_{3=gg}(y, t = 0) = \delta(y - y_{eq})$ yields the exact solution as described in [13], and references therein.

Since the theoretical model is formulated in rapidity space, one has to transform the calculated distribution functions to pseudorapidity space, $\eta = -\ln[\tan(\theta/2)]$, in order to be able to compare with the available data, and perform χ^2-minimizations. The well-known Jacobian transformation

$$\frac{dN}{d\eta} = \frac{dN}{dy}\frac{dy}{d\eta} = J(\eta, m/p_T)\frac{dN}{dy}, \tag{3}$$

$$J(\eta, m/p_T) = \cosh(\eta)\cdot[1 + (m/p_T)^2 + \sinh^2(\eta)]^{-1/2} \tag{4}$$

depends on the squared ratio of the mass and the transverse momentum of the produced particles. Hence, its effect increases with the mass of the particles, and it is most pronounced at small transverse momenta. For reliable results one has to consider the full p_T-distribution, however. In [10, 13] it is outlined how this can be done approximately.

However, LHC data are still missing in the fragmentation region. We have therefore proposed in [10] to use the well-known limiting fragmentation scaling hypothesis [14] as an additional constraint: At sufficiently high energy, particle production in the fragmentation region becomes almost independent of the collision energy. Hence we use 0.2 TeV Au–Au results at RHIC – where data in the fragmentation region are available – to supplement the LHC 2.76 TeV Pb–Pb data in analogous centrality classes at large values of pseudorapidity as described in [10].

It should be noted that the data in pseudorapidity space appear to extend beyond the value of the beam rapidity, $y = 1/2 \cdot \ln(1 + \beta_{||})/(1 - \beta_{||})$ with $\beta_{||} \equiv \beta_{beam} = v_{beam}/c = (\exp{(2y_{beam})} - 1)/(\exp{(2y_{beam})} + 1)$ as seen clearly for 130 GeV Au–Au in Fig. 2. Although it is not excluded that this is to some extent a physical effect, it is most likely due to the transformation from pseudorapidity $\eta = -\ln{(\tan(\theta/2))}$ to rapidity y,

$$y = \frac{1}{2}\ln\frac{\sqrt{(m/p_T)^2 + \cosh^2 y} + \sinh\eta}{\sqrt{(m/p_T)^2 + \cosh^2 y} - \sinh\eta}, \tag{5}$$

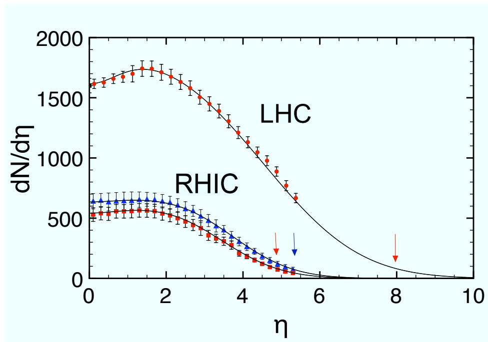

Fig. 2. (Color online) Pseudorapidity distributions for produced charged hadrons in central 130 and 200 GeV Au–Au, and 2.76 TeV Pb–Pb collisions. Calculated RDM distributions (solid curves) have been optimized in χ^2-fits with respect to the PHOBOS data from Ref. [1], and the ALICE data from [2]. The data tend to extend beyond the values of the beam rapidities (arrows).

where $y \to \eta - \ln(m/p_T)$ for $m \ll p_T$, and $y \to \eta$ for $p_T \ll m$.

In Pb–Pb at LHC energies, about 83% of the produced charged hadrons are pions, and for pions the limit $\eta \simeq y$ is reached at larger η values than for protons. Hence, the pion-dominated $dN/d\eta-$distribution extends beyond y_{beam} that is defined for protons.

3. Results

The result of the three-sources RDM calculation for the pseudorapidity distribution of produced charged hadrons 2.76 TeV Pb–Pb is shown in figure 1 together with recent ALICE data [2] for $0-5\%$ centrality in a χ^2 optimization. Parameters are given in Tab. 1. A prediction for the LHC design energy of 5.52 TeV Pb–Pb is also shown.

The relative size of the three sources in central 2.76 TeV Pb–Pb is displayed in the lower frame of figure 1. At this LHC energy, the midrapidity source already contains the largest fraction of produced charged hadrons. Its shape is significantly deformed by the Jacobian transformation from rapidity to pseudorapidity space, whereas the fragmentation sources are not much influenced by the transformation.

In the full distribution that arises from the incoherent superposition of the three sources, it is evident that the midrapidity dip is more pronounced at LHC energies as compared to RHIC energies, although the effect of the Jacobian tends to be smaller at the higher incident energy. This clearly indicates that there has to be a physical origin of the midrapidity dip in

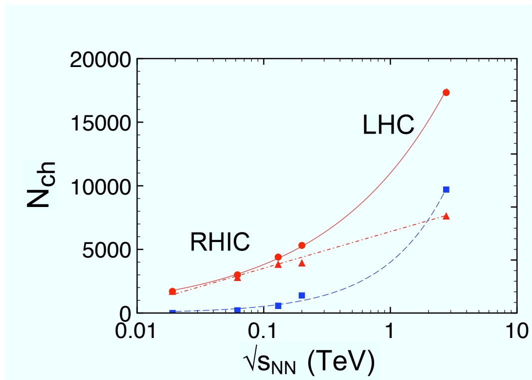

Fig. 3. (Color online) Number of produced charged hadrons as function of the c.m. energy $\sqrt{s_{NN}}$ from RDM-fits of the available data for central heavy ion collisions at 0.019, 0.062, 0.13, 0.2 TeV (RHIC, Au–Au), and 2.76 TeV (LHC, Pb–Pb). Circles are the total numbers, squares are hadrons produced from the midrapidity source, and triangles are particles from the fragmentation sources. The gluon-gluon source (dashed) becomes the main source of particle production between RHIC and LHC energies. From Ref. [13].

addition to the effect of the Jacobian.

The hypothesis promoted in this work is that the interplay of the three sources provides the observed effect. In 2.76 TeV Pb–Pb collisions, the fragmentation sources are peaked at large values ($< y_{1,2} >= 3.34$) of rapidity – whereas at 0.2 TeV RHIC energy, the center is at $< y_{1,2} >= 2.4$. Consequently, the midrapidity yield at LHC energies is essentially due to the central source, with only a small contribution from the fragmentation sources. Although the relative particle content in the central source is larger at LHC energies than at RHIC, this produces the observed midrapidity dip, together with the effect of the Jacobian on the central source.

4. Energy dependence of the hadron production sources

There are now sufficiently precise data on charged-hadron production at RHIC [1] and LHC [2] energies available in order to investigate the relative size of the three particle production sources as function of energy in heavy ion collisions (Au–Au at RHIC, Pb–Pb at LHC). I have displayed the energy dependence of the sources in figure 3, with parameters as shown in Tab. 1.

According to these results, the total charged-hadron production (circles) follows a power law $\propto s_{NN}^{0.23}$. The hadrons produced from the central source (squares) have an even stronger dependence on initial energy according to

Table 1. Three-sources RDM-parameters τ_{int}/τ_y, $\Gamma_{1,2}, \Gamma_{gg}$, and N_{gg}. N_{ch}^{1+2} is the total charged-particle number in the fragmentation sources, N_{gg} the number of charged particles produced in the central source. Parameters at 5.52 TeV denoted by * are extrapolated. From Ref. [13].

$\sqrt{s_{NN}}$ (TeV)	y_{beam}	τ_{int}/τ_y	$\Gamma_{1,2}$	Γ_{gg}	N_{ch}^{1+2}	N_{gg}	$\frac{dN}{d\eta}\vert_{\eta\simeq 0}^{exp}$
0.019	∓3.04	0.97	2.83	0	1704	-	314±23[1]
0.062	∓4.20	0.89	3.24	2.05	2793	210	463±34[1]
0.13	∓4.93	0.89	3.43	2.46	3826	572	579±23[1]
0.20	∓5.36	0.82	3.48	3.28	3933	1382	655±49 [1]
2.76	∓7.99	0.87	4.99	6.24	7624	9703	1601±60 [12]
5.52	∓8.68	0.85*	5.16*	7.21*	8889*	13903*	1940*

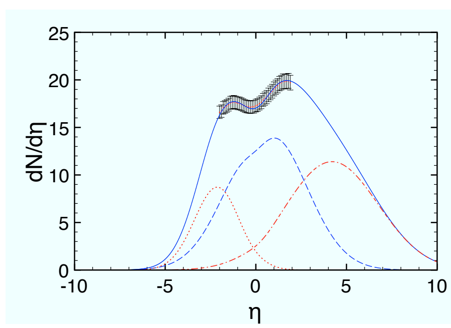

Fig. 4. (Color online) The RDM pseudorapidity distribution function for charged hadrons in minimum bias p–Pb collisions at LHC c.m. energy of 5.02 TeV shown here is adjusted in the mid-rapidity region to the ALICE data [15]. From Ref. [13].

$\propto s_{NN}^{0.44}$, whereas particles produced in the fragmentation sources have a weaker dependence $\propto \log(s_{NN}/s_0)$.

The strong rise of the particle production yield from the central (gluon-gluon induced) source is evidently due to the increasing gluon content of the system at high relativistic energies. In particular, the total particle production rate from the central source becomes larger than that from the two fragmentation sources at an incident energy between the highest RHIC energy (0.2 TeV), and the LHC regime. In view of the lack of data in this intermediate regime, the precise crossing point is, however, difficult to determine.

In central p–Pb collisions at 5.02 TeV, ALICE data [15] have also been used to compare with the analytical RDM-solutions, cf. figure 4. The RDM calculation exhibits a steeper slope on the proton-like side, as compared to the Pb-like side. Forthcoming LHC p–Pb large-η data could confirm this.

5. Conclusions

The particle content of fragmentation (valence quark–gluon) and midrapidity (gluon–gluon) sources for charged-hadron production in heavy ion collisions at high relativistic energies has been determined as function of c.m. energy in a phenomenological approach.

In turns out that particle production from the gluon–gluon source becomes more important than that from the fragmentation sources in the energy range between the maximum RHIC energy of 0.2 TeV, and the current LHC energy of 2.76 TeV.

Acknowledgments

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