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Charged-hadron pseudorapidity distributions in PbPb collisions at LHC energies in the RDM

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The energy and centrality dependence of charged-hadron production in relativistic heavy-ion collisions is investigated in a nonequilibrium-statistical relativistic diffusion model (RDM) with three sources. Theoretical pseudorapidity distributions are compared with preliminary PbPb ALICE data at LHC energies of 2.76 TeV. Predictions for 5.52 TeV are presented. The nearly equilibrated source at midrapidity arising from gluon-gluon collisions becomes the major origin of particle production at LHC energies. The midrapidity dip is determined by the Jacobian, plus the interplay of the three sources.

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1. Introduction

First results of charged-hadron production in central PbPb collisions at LHC energies of $\sqrt{s_{NN}}$ = 2.76 TeV [1, 2] have recently been analyzed in a nonequilibrium-statistical relativistic diffusion model (RDM) [3]. So far, the RDM calculations have been compared to central collision data. Now, preliminary ALICE results from the 2010 LHC run at different centralities, and for a large range of pseudorapidities $-3.7 < \eta < 5.1$ have become available [4] which are used here for a comparison with our RDM calculations, and for a determination of the corresponding parameters, which had in [3] only been extrapolated to LHC energies.

In the RDM, the underlying three sources for particle production can be traced back to a midrapidity source resulting from gluon-gluon collisions, and two forward-centered sources arising from valence quark-gluon collisions. The particle production sources are broadenend in time through nonequilibrium-statistical processes such as collisions and particle creations, which are described based on a Fokker-Planck type transport equation [5, 6, 7, 8, 9, 10, 11, 12]. The additional broadening of the distribution functions due to collective expansion then leads to an effective diffusion coefficient [12].

An incoherent superposition of the three sources at the interaction time – where the integration of the transport equation stops – yields good agreement with charged-particle pseudorapidity distributions at RHIC energies. It has been shown in [13, 14, 15] within the RDM that at RHIC energies of 0.13 TeV (0.2 TeV) the midrapidity source generates about 13 % (26 %) of the produced particles in a 0–6% central AuAu collision, whereas the bulk of the particles is still produced in the two fragmentation sources. At SPS, and low RHIC energies of 19.6 GeV the effect of the midrapidity source is negligible [15].

The model is also suited for asymmetric systems such as d + Au, which are more sensitive to the details of the distribution functions. At 0.2 TeV we found that the midrapidity source contains 19 % of the produced particles for 0–20% central collisions [16].

Within the RDM, we investigate here the centrality and energy dependence of the three sources for particle production in collisions of symmetric systems at RHIC and LHC energies in direct comparison with data, and provide a prediction for central collisions at maximum LHC energies.

Ingredients of the model are briefly reconsidered in the following section, the calculations of pseudorapidity distributions of charged hadrons at RHIC and LHC energies and the determination of the RDM parameters are discussed in the third section, and conclusions are drawn in the fourth section.

2. Relativistic Diffusion Model

In the Relativistic Diffusion Model, the time evolution of the distribution functions is governed by a Fokker-Planck equation (FPE) in rapidity space [7] (and references therein) with the rapidity $y = 0.5 \cdot \ln((E+p)/(E-p))$. The beam rapidity can also be written as $y_{beam} = \mp y_{max} = \mp \ln(\sqrt{s_{NN}}/m_p)$. The rapidity diffusion coefficient D_y that contains the microscopic physics accounts for the broadening of the rapidity distributions. The drift $J(y)$ determines the shift of the mean rapidities towards the central value, and linear and nonlinear forms have been discussed [8, 10, 7].

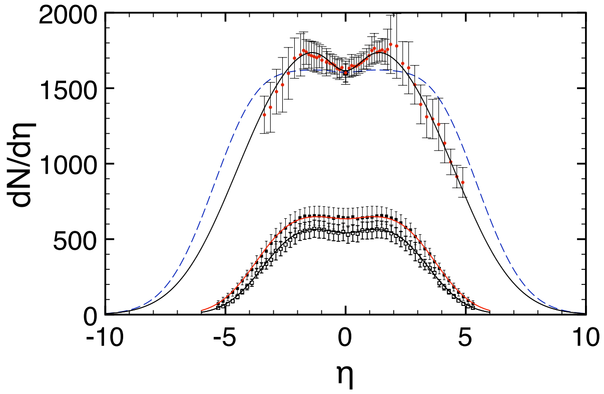

Figure 1: The predicted (dashed [3]) RDM pseudorapidity distribution function for charged hadrons in 0–5% central PbPb collisions at LHC energies of 2.76 TeV is shown in the upper part of the figure, with RDM parameters as in [3]. The solid curve is a χ^2-minimization based on the three-sources RDM with respect to the preliminary ALICE data [4] that takes into account the limiting fragmentation hypothesis in the large rapidity region where no LHC data are available, see [17] for details, and Table 1 for parameters. In the lower part, results for AuAu collisions at $\sqrt{s_{NN}}$ = 0.13 and 0.2 TeV with PHOBOS data [18] are shown.

Here I use the standard linear FPE with a drift function $J(y) = (y_{eq} - y)/\tau_y$. The rapidity relaxation time is τ_y, and the equilibrium value of the rapidity y_{eq}. This is the so-called Uhlenbeck-Ornstein [19] process, applied to the relativistic invariant rapidity for the three components $R_k(y,t)$ (k=1,2,3) of the distribution function in rapidity space

$$\frac{\partial}{\partial t}R_k(y,t) = -\frac{1}{\tau_y}\frac{\partial}{\partial y}\Big[(y_{eq}-y)\cdot R_k(y,t)\Big] + \frac{\partial^2}{\partial y^2}\Big[D_y^k \cdot R_k(y,t)\Big]. \tag{2.1}$$

In the linear case, a superposition of the distribution functions [5, 11] using the initial conditions $R_{1,2}(y,t=0) = \delta(y \pm y_{max})$ with the absolute value of the beam rapidities y_{max}, and $R_3(y,t=0) = \delta(y - y_{eq})$ yields the exact solution. The mean values are derived analytically from the moments equations as $< y_{1,2}(t) >= y_{eq}[1-\exp(-t/\tau_y)] \mp y_{max}\exp(-t/\tau_y)$ for the sources (1) and (2) with the absolute value of the beam rapidity y_{max}, and y_{eq} for the local equilibrium source which is equal to zero only for symmetric systems. Hence, both mean values $< y_{1,2} >$ would attain y$_{eq}$ for t→ ∞, whereas for short times they remain between beam and equilibrium values. The variances are $\sigma_k^2(t) = D_y^k\tau_y[1-\exp(-2t/\tau_y)]$, and the corresponding FWHM-values are obtained from $\Gamma_k = \sqrt{8\ln 2}\cdot\sigma_k$ since the partial distribution functions are Gaussians in rapidity space (but not in pseudorapidity space). The charged-particle distribution in rapidity space is obtained as incoherent superposition of nonequilibrium and central (“equilibrium") solutions of

$$\frac{dN_{ch}}{dy}(y,t=\tau_{int}) = N_{ch}^1 R_1(y,\tau_{int}) + N_{ch}^2 R_2(y,\tau_{int}) + N_{ch}^{gg} R_{gg}(y,\tau_{int}) \tag{2.2}$$

with the interaction time τ_{int} (total integration time of the differential equation).

To calculate pseudorapidity distributions which depend only on the scattering angle θ, we convert the results from rapidity to pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$, using a Jacobian $J(\eta, \langle m\rangle/\langle p_T\rangle)$ that now considers pions, kaons and protons explicitly as in [17].

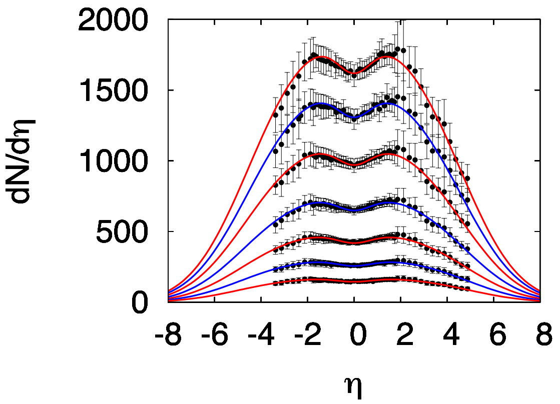

Figure 2: Pseudorapidity distributions for produced charged hadrons in 2.76 TeV PbPb collisions as functions of centrality, from bottom to top: 50–60%, 40–50%, 30–40%, 20–30%, 10–20%, 5–10%, 0–5%. Calculated RDM distributions have been optimized with respect to the prel. ALICE data, using the limiting fragmentation scaling hypothesis in the region of large rapidities where no data are available. From [17].

Table 1: Three-sources RDM-parameters τ_{int}/τ_y, $\Gamma_{1,2}, \Gamma_{gg}$, and n_{gg}. See [3, 17] for details.

$\sqrt{s_{NN}}$ (TeV)	y_{beam}	τ_{int}/τ_y	$< y_{1,2} >$	$\Gamma_{1,2}$	Γ_{gg}	N_{ch}^{tot}	n_{gg}	$\frac{dN}{d\eta}\vert_{\eta\simeq 0}$
0.13	$\mp$4.93	0.89	$\mp$2.02	3.43	2.46	4398	0.13	579±23[18]
0.20	$\mp$5.36	0.82	$\mp$2.40	3.48	3.28	5315	0.26	655±49 [18]
2.76	$\mp$7.99	0.87	$\mp$3.34	4.99	6.24	17327	0.56	1601±60 [2]
5.52	$\mp$8.68	0.85*	$\mp$3.70	5.16*	7.21*	22792*	0.61*	1940*

I had presented a prediction for pseudorapidity distributions in central PbPb at 2.76 TeV with extrapolated RDM parameters in [3], with the midrapidity point adjusted to the ALICE data [2]. It is shown by the dashed curve in Fig. 1. Evidently, the predicted fragmentation-peak position is too far from midrapidity when compared to the preliminary data [4], and the experimental midrapidity dip is more pronounced than in the prediction.

3. Results and RDM-parameters

We have performed a χ^2-optimization of the three-sources model solutions [17] with respect to the preliminary ALICE data and using the limiting fragmentation scaling hypothesis in order to determine the modification of the parameters from the prediction [3]. The result for central PbPb at 2.76 TeV is shown by the solid curve in Fig. 1, with parameters given in Table 1. The value of the time parameter τ_{int}/τ_y is decisive for the position of the fragmentation peak in $\eta-$space. It was found to decrease for increasing $\log\sqrt{s_{NN}}$ from AGS to the highest RHIC energies with a functional dependence discussed in [3], and hence, the extrapolation to LHC energies was based on a continued fall, resulting in $\tau_{int}/\tau_y \simeq 0.67$ at 2.76 TeV.

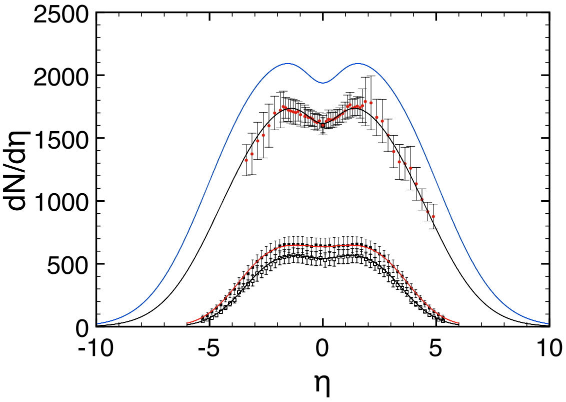

Figure 3: Extrapolation of pseudorapidity distributions of charged hadrons to central 5.52 TeV PbPb (upper curve) with RDM parameters from Table 1. Results for 0.13 and 0.2 TeV central AuAu, and 2.76 TeV central PbPb are shown for comparison (lower curves, as in Fig. 1).

The comparison with the preliminary data, however, reveals that it actually levels off at LHC energies to a value of $\tau_{int}/\tau_y \simeq 0.87$ at 2.76 TeV. This indicates that in the large energy gap between the highest RHIC and the current LHC energy, the rapidity relaxation time τ_y decreases faster than the interaction time τ_{int}. The interaction time is inversely proportional to the Lorentz factor γ, which rises from 107 at 0.2 TeV to 1477 at 2.76 TeV. Hence, the rapidity relaxation time τ_y decreases by about an order of magnitude in this energy region. There is presently no detailed theoretical explanation for this effect.

A discussion of the other RDM parameters and their energy dependence is given in [17]. At 2.76 TeV, the bulk of the midrapidity density is generated in the central source, there is a relatively small overlap of the fragmentation sources (see also [20, 21]) at midrapidity. With extrapolations of the time parameter, the numbers of charged particles in the sources, and the partial widths $\Gamma_{1,2,gg}$ from Table 1 (asterisk), a prediction for central PbPb at 5.52 TeV is shown in Fig. 3.

4. Conclusion

We have analyzed recent preliminary ALICE results for PbPb collisions at LHC energy of $\sqrt{s_{NN}}$ = 2.76 TeV. Charged-hadron pseudorapidity distributions have been calculated analytically in the non-equilibrium statistical relativistic diffusion model RDM. For seven different centralities, the distribution functions have been determined in a χ^2-optimization of the analytical model solutions with respect to the preliminary data, using the limiting fragmentation hypothesis.

A comparison with a previous prediction [3] that was based on an extrapolation of the parameters with $\log\sqrt{s_{NN}}$ reveals that the rapidity relaxation time τ_y decreases substantially in the energy region between RHIC and LHC energies, leading to a larger time parameter τ_{int}/τ_y and hence, to a fragmentation-peak position that is closer to midrapidity than expected from the earlier extrapolation of the time parameter. Based on the RDM fit to the data in the three-sources model, the midrapidity source that is associated with gluon-gluon collisions accounts for about 56% of the total charged-particle multiplicity measured by ALICE in central PbPb collisions at 2.76 TeV. The fragmentation sources that correspond to particles that are mainly generated from valence quark – gluon interactions are centered at pseudorapidity $<\eta_{1,2}>\simeq<y_{1,2}>\simeq\mp3.3$. The total particle content in these sources amounts to about 44% of the total charged hadron production, but contributes only marginally to the midrapidity yield. It is, however, decisive for the occurence of the midrapidity dip together with the Jacobian transformation (which is less pronounced at LHC).

With the results for PbPb at 2.76 TeV LHC energy and previous RDM results for AuAu collisions at RHIC energies, we have extrapolated the three-sources model parameters to the LHC design energy of 5.52 TeV for PbPb, and calculated the corresponding charged-hadron pseudorapidity distribution. Small corrections of the extrapolated values for the diffusion-model parameters may be required once the final measured distributions become available at both LHC energies.

Acknowledgments

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