Particle production beyond the thermal model

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1. INTRODUCTION

The statistical hadronization or thermal model [1] has consistently provided good descriptions of relative or absolute particle production yields in e^+e^-, *pp* and relativistic heavy-ion collisions, e.g. [2]. However, a necessary and sufficient condition for statistical equilibrium in the systems under investigation is provided by the *distribution functions* of the relevant observables rather than the particle yields. An example for a purely thermal distribution may be found in the cosmic microwave background radiation.

In relativistic heavy-ion collisions, the distributions of both transverse momentum p_T (Fig.1) as well as rapidity y or pseudorapidity η of produced charged hadrons (Figs. 2, 3) clearly deviate from thermal distributions. At RHIC and LHC energies, the deviations in a p_T-region of $0.5 < p_T < 8$ GeV/*c* and the ensuing transition from exponential to power-law p_T-distributions are usually attributed to collective expansion. This transition is conveniently parametrized by the distribution functions shown in Fig.1. Above ≈ 8 GeV/*c*, however, hard processes become visible which require a pQCD treatment. When integrated over p_T to obtain particle yields, their contribution is negligible, but decisive as an indicator for nonequilibrium processes.

Indications for nonequilibrium behaviour can also be found in (pseudo)rapidity distributions of produced charged hadrons as measured by ALICE in PbPb [4], and both ATLAS and ALICE in *p*Pb collisions [5]. Here the distribution functions have important contributions from the fragmentation regions that are clearly visible in net-proton rapidity distributions at RHIC energies [6], increase in particle content with $\log(s_{NN})$ for produced particles, and are not in equilibrium with particles produced in the midrapidity source.

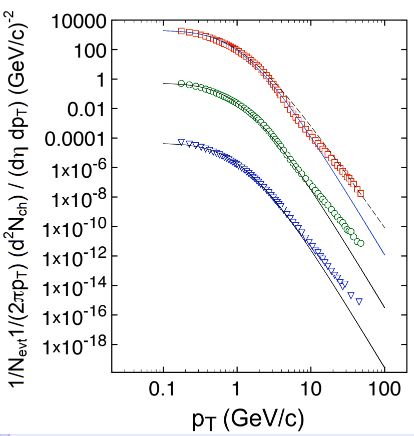

Fig. 1: Transverse momentum distributions of produced charged hadrons in 2.76 TeV PbPb as measured by ALICE [3] for 0-5%, 30-40% and 70-80% centralities compared with distribution functions ~ $[1 + (q-1)m_T/T]^{-q/(q+1)}$ for q = 1.2 that implicitly account for thermal emission and collective expansion, but not for hard (pQCD) processes beyond $p_T \approx 8$ GeV/*c* (GW, unpublished).

Table 1: RDM parameters for AuAu and PbPb collisions at RHIC and LHC energies for the dN/dη distributions in Fig.3 [11]

$\sqrt{s_{NN}}$ (TeV)	y_{beam}	τ_{int}/τ_y	$\langle y_{1,2}\rangle$	$\Gamma_{1,2}$	Γ_{gg}	N_{ch}^{tot}
0.019	∓3.04	0.97	∓1.16	2.83	0	1704
0.062	∓4.20	0.89	∓1.72	3.24	2.05	3003
0.13	∓4.93	0.89	∓2.02	3.43	2.46	4398
0.20	∓5.36	0.82	∓2.40	3.48	3.28	5315
2.76	∓7.99	0.87	∓3.34	4.99	6.24	17327
5.52	∓8.68	0.85*	∓3.70	5.16*	7.21*	22792*

2. RELATIVISTIC DIFFUSION MODEL

In the Relativistic Diffusion Model [7,8], the (pseudo-)rapidity distribution of produced particles emerges from an incoherent superposition of the beam-like fragmentation components at larger rapidities arising from valence quark-gluon interactions, and a component centered at midrapidity due to gluon-gluon collisions. All three distributions are broadened in rapidity space as a consequence of diffusion-like processes governed by a Fokker-Planck equation

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

Since the equation is linear, a superposition of the distribution functions using the initial conditions $R_{1,2}(y,t=0) = \delta(y \pm y_{max})$ with the absolute value of the beam rapidities $y_{max} = \ln(\sqrt{s_{NN}}/m_p)$ and $R_{eq}(y,t=0) = \delta(y-y_{eq})$ yields the solution

$$\frac{dN_{ch}(y,t=\tau_{int})}{dy} = N^1_{ch}R_1(y,\tau_{int}) + N^2_{ch}R_2(y,\tau_{int}) + N^{eq}_{ch}R_{eq}(y,\tau_{int}).$$

In the solution, the mean values and variances are obtained analytically from the moments equations. Relaxation time and diffusion coefficient are related through a dissipation-fluctuation theorem (Einstein relation). Due to the collective expansion of the system, however, the effective diffusion coefficient is substantially larger. Hence the partial widths Γ_k (FWHM) are treated here as independent variables, which are related to the standard deviations through $\Gamma_k = \sqrt{8\ln 2}\cdot\sigma_k$. For symmetric systems, the RDM then has 4 parameters, Tab.1. This nonequilibrium-statistical model goes beyond the thermal model: Only for t -> ∞ a thermal distribution would be attained.

3. PSEUDORAPIDITY DISTRIBUTIONS

If particle identification is not available, one has to convert the results to pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$ with the scattering angle θ. For the conversion an approximate Jacobian is used,

$$\frac{dy}{d\eta} \simeq J(\eta, \langle m\rangle/\langle p_T\rangle) = \cosh(\eta)\cdot[1+(\langle m\rangle/\langle p_T\rangle)^2+\sinh^2(\eta)]^{-1/2}$$

with the mean mass $<m> \approx <m_\pi>$, and an effective mean transverse momentum [9] $<p_T> = <p_{T,eff}> = m_\pi J_{y=0}/(1-J_{y=0}^2)^{1/2}$ with the Jacobian $J_{y=0}$ at midrapidity taken from experiment (for pions, kaons and protons) as discussed in [9].

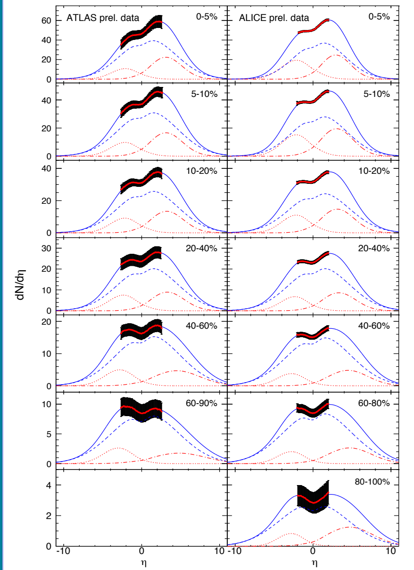

Fig. 2: Calculated RDM charged-hadron pseudorapidity distributions for centrality dependent 5.02 TeV *p*Pb collisions compared with ALICE and ATLAS data [5] in χ^2-minimizations [12].

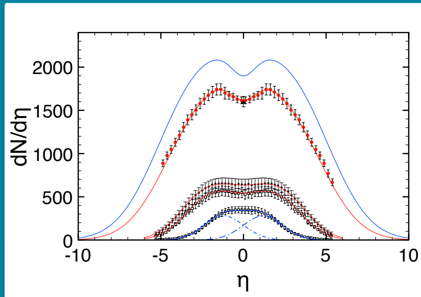

Fig. 3: Calculated RDM pseudorapidity distributions of produced charged particles from central AuAu collisions (bottom) at 0.02, 0.13 and 0.2 TeV [11] in comparison with PHOBOS data [10]. Distribution functions for 0-5% central PbPb collisions at LHC energy of 2.76 TeV are shown in the upper part of the figure, with an RDM-fit (solid) to the ALICE data [4] and a prediction for 5.52 TeV. The corresponding parameter values are given in Tab. 1. From [11].

4. RESULTS

With parameter values for central collisions given in the Tab.1 , the 3-sources RDM results for PbPb at 2.76 TeV TeV energy are shown in Fig. 3 [11].

Corresponding centrality-dependent results for pPb collisions at 5.02 TeV are shown in Fig. 2 [12]. Here the asymmetric shapes of the distributions are much more sensitive to the details of the model, enhancing the credibility of the nonequilibrium 3-sources approach. The model had previously also been compared with dAu data at RHIC energies in [8].

The total hadron-production yield integrated over η follows $\ln(s_{NN})$ for the fragmentation sources in both *p*Pb and PbPb at LHC energies, whereas the midrapidy gluonic source has a cubic log dependence ~ $\ln^3(s_{NN})$, see Fig. 4 and the discussion in [11].

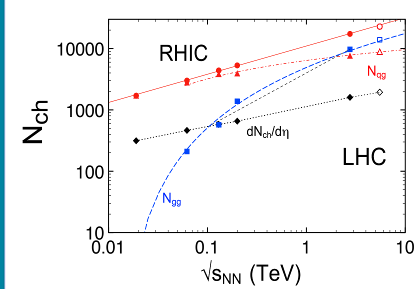

Fig. 4: The total charged-hadron production in central AuAu and PbPb collision in the energy region 19.6 GeV to 5.52 TeV is following a power law (solid line), whereas the particle content in the fragmentation sources is Nqg ~ $\ln(s_{NN}/s_0)$, dash-dotted curve. The particle content in the mid-rapidity source rises rapidly, Ngg ~ $\ln^3(s_{NN}/s_0)$ [11].

5. CONCLUSION

Deviations from thermal distribution functions for produced particles in relativistic heavy-ion collisions are sensitive indicators for nonequilibrium processes. These are discussed for both transverse momentum and pseudorapidity distributions of produced charged hadrons.

A three-sources nonequilibrium-statistical relativistic diffusion model (RDM) is used for the description and prediction of pseudorapidity distributions. Two fragmentation sources and a midrapidity gluonic source evolve as functions of time according to a Fokker-Planck equation, but they remain far from the thermal equilibrium distribution due to the short interaction times of about 10^{-23} s at RHIC and LHC energies.

The particle content integrated over pseudorapidity is proportional to $\ln(s_{NN})$ only in the fragmentation sources. In the midrapidity source that arises from gluon-gluon collisions, a dependence ~$\ln^3(s_{NN})$ is found and discussed in [11].

ACKNOWLEDGEMENT

This work is supported by DFG through the Transregional Research Center TRR33 at the Universities of Bonn, Heidelberg and LMU Munich.

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