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Hadron production and bottomia suppression at the LHC

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Abstract. Hadron production in relativistic heavy-ion collisions at LHC energies is investigated. After a brief consideration of stopping, particle production is accounted for in a relativistic diffusion model with two fragmentation sources, and a central source that is mostly due to gluon-gluon collisions. The particle content and energy dependence of the sources is discussed. The suppression of Υ-mesons in the hot quark-gluon medium in PbPb collisions as compared to pp at $\sqrt{s_{NN}} = 2.76$ TeV is accounted for in a model that encompasses gluodissociation, collisional damping, screening, and reduced feed-down. Model results are compared with CMS and ALICE data.

1 Introduction

A brief survey of several features of hadron production in relativistic heavy-ion collisions at LHC energies is given in this article, which is essentially based on results published in [1] and [2].

The stopping process in the very first phase of the collision is mostly characterized by the interaction of fast valence quarks with low-x gluons in the respective other nucleus. A QCD-based model that allows to calculate the two fragmentation peaks occurring at large values of the rapidity in net-baryon, or net-proton (proton minus antiproton) rapidity density distributions at and above SPS energies had been developed in [3], and subsequent works. It is found to be in good agreement with net-proton data from AuAu collisions at RHIC energies, but the position and magnitude of the predicted fragmentation peaks in PbPb collisions at LHC energies are presently beyond experimental reach due to the lack of particle identifcation beyond rapidities of about $|y| > 2$. At the LHC design energy of 5.52 TeV PbPb with $y_{beam} = \mp 8.68$ the peaks are expected to occur at rapidities $|y| \simeq 6-7$.

When considering rapidity or pseudorapidity distributions of produced charged particles, the fragmentation distributions also play a significant role, but since they shift to large values of rapidity at LHC, particle production near mid rapidity is almost exclusively determined by the central gluon-gluon source. This source cancels out in net-proton distributions, but in charged-hadron distributions its importance rises strongly with incident energy. In this note a previously developed [4] nonequilibrium-statistical relativistic diffusion model (RDM) is applied to determine the relative importance of the three sources as function of energy from a direct comparison of the analytical solutions of the phenomenological model with PHOBOS [5] and recent ALICE data [6] data. This allows also for predictions at the LHC design energy, and for an analysis of the asymmetric pPb system at the current LHC energy of 5.02 TeV.

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The heavier the hadron that is produced in the collision, the shorter its formation time. Very heavy mesons such as the J/ψ, or the Υ meson with a rest mass of about 9.46 GeV/c^2 in its $1S$ spin-triplet ground state are produced in hard collisions at very short times, typically at $\tau_F \simeq 0.1 - 0.5$ fm/c. Since the $\Upsilon(1S)$ state is particularly stable, it has a sizeable probability to survive in the hot quark-gluon medium that is produced in the fireball of a heavy-ion collision at LHC energies. We have accordingly devised a model that accounts for the dissociation of the various bottomium states in the hot medium (gluodissociation), the damping of the quark-antiquark binding due to the presence of the hot medium, which generates an imaginary part of the temperature-dependent potential, and the screening of the real part of the potential due to the hot medium. The latter turns out to be unimportant for the $\Upsilon(1S)$ ground state, but it is relevant for the less strongly bound excited states. Once the bottomia states have survived the quark-gluon plasma environment, the feed-down cascade from the excited states to the ground state has to be considered in detail. Due to the rapid depopulation of the excited states caused by the various mechanisms, the feed-down to the ground state is reduced accordingly, causing additional suppression as compared to the situation in pp collisions at the same energy. We then compare the calculated centrality-dependent $\Upsilon(nS)$-suppression [2, 7] to recent CMS data [8], and predict the suppression at the LHC design energy.

2 Hadron production sources

The relativistic diffusion model (RDM) for the investigation of the time evolution of particle production sources in relativistic heavy-ion collisions has been applied in [1] to charged-hadron production in AuAu collisions at RHIC energies, and to PbPb collisions at LHC energies of 2.76 TeV. The size of the fragmentation sources, and of the mid rapidity gluon-gluon source has been identified as functions of centrality and energy. The result for a 0–5% central PbPb collision is shown in fig.1.

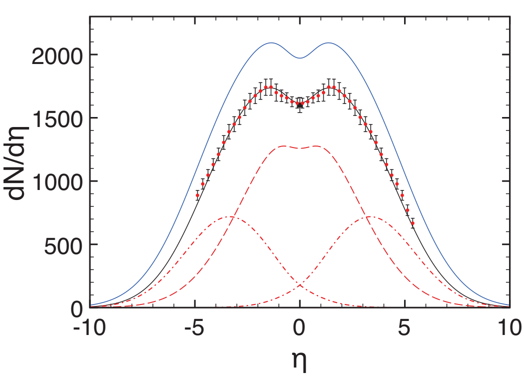

Figure 1. Calculated pseudorapidity distributions of produced charged hadrons in 2.76 TeV PbPb [1] are compared with ALICE data [6] in a χ^2-minimization. The underlying theoretical distributions are shown as dashed and dash-dotted curves. Only the shape of the midrapidity source is significantly modified 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 [1].

The Jacobian transformation from rapidity y to pseudorapidity η causes a dip in the mid rapidity source, but has a rather negligeable effect on the fragmentation sources at larger values of rapidity. The incoherent superposition of the sources gives a good representation of the ALICE data [6], and the five RDM parameters can be determined in a χ^2-minimization with respect to these data [1]. A prediction to the design energy of 5.52 TeV based on an extrapolation of these parameters is also shown. The minimum near mid rapidity occurs due to both, the effect of the Jacobian plus the interplay of fragmentation and central sources.

Using similar RDM-investigations of central charged-hadron distributions at RHIC energies, the particle content of the sources can be investigated as function of the c.m. energy, see fig.2. Whereas

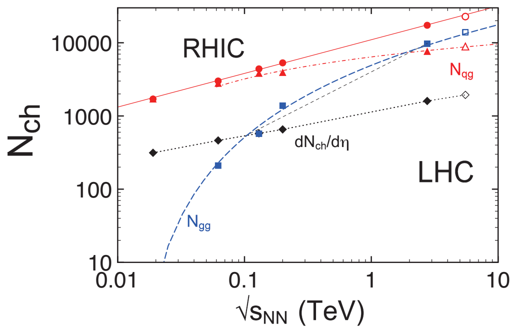

Figure 2. The total charged-hadron production in central AuAu and PbPb collision is following a power law $N_{tot} \propto (s_{NN}/s_0)^{0.23}$ (solid line), whereas the particle content in the fragmentation sources is $Nqg \propto \ln(s_{NN}/s_0)$, dash-dotted curve. The particle content in the mid-rapidity source obeys $N_{gg} \propto \ln^3(s_{NN}/s_0)$, dashed curve, not too far from a power law (short-dashed line) in the intermediate energy range 0.1–2.76 TeV, see [1].

the total particle production obeys a power law (upper straight line in the log-log plot), the fragmentation sources have a weaker trend according to $Nqg \propto \ln(s_{NN}/s_0)$, but the gluon-gluon source rises strongly with c.m. energy according to $N_{gg} \propto \ln^3(s_{NN}/s_0)$. It remains as a challenge to derive such a behaviour from basic theory.

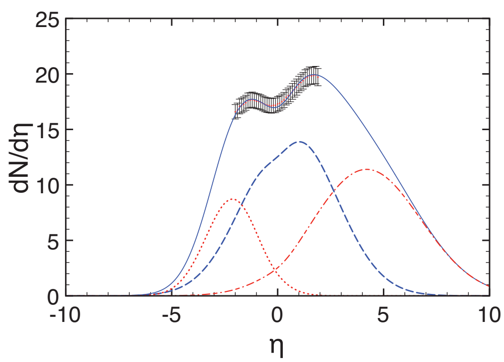

Figure 3. The predicted RDM pseudorapidity distribution function for charged hadrons in minimum-bias pPb collisions at LHC c.m. energy of 5.02 TeV shown here is adjusted in the mid-rapidity region to the preliminary ALICE data [9] (systematic error bars only). The underlying distributions in the three–sources RDM are also shown, with the dashed curve arising from gluon-gluon collisions, the dash-dotted curve from valence quark-gluon events in the Pb-like region, and the dotted curve correspondingly in the proton-like region. From [1].

With the same approach, also asymmetric systems such as pPb at LHC energies can be investigated. Here the fragmentation sources have unequal particle content, and the midrapidity source is not centered at $\langle\eta\rangle = 0$, but at a centrality- and transverse momentum-dependent equilibrium value of the rapidity. The result for minimum-bias pPb collisions at the LHC energy of 5.02 TeV is shown [1] in fig.3 in a χ^2-minimization with respect to ALICE data [9].

3 Υ suppression in PbPb collisions at LHC energies

The production of heavy mesons and in particular, of bottomia in initial hard partonic interactions in relativistic PbPb collisions at LHC energies is of special interest, because quarkonia in the hot fireball can act as a probe to test the properties of the hot medium. In our model [2, 7] we investigate the suppression of the $\Upsilon(nS)$ states in PbPb as compared to the expectation from scaled pp collisions at the same energy, and compare with centrality-dependent CMS data [8] for the $1S$ and $2S$ states. In the hot medium, the three most important dissociation mechanisms are taken to be gluodissociation, damping, and screening of the real part of the quark-antiquark potential. The calculated gludissociation cross section for the $1S$ and $2S$ states together with the thermal gluon distribution function are shown as functions of the gluon energy at two different temperatures in fig.4.

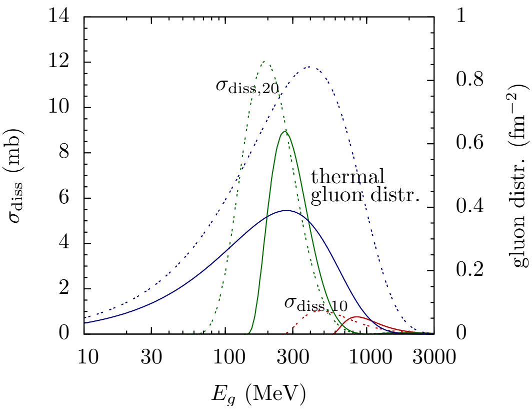

Figure 4. Gluodissociation cross section $\sigma_{\rm diss}$ (left scale) of the $\Upsilon(1S)$ and $\Upsilon(2S)$ states and the thermal gluon distribution (right scale) plotted for temperature T = 170 (solid curves) and 250 MeV (dotted curves) as functions of the gluon energy E_g. From Nendzig and Wolschin [2].

Since the matrix elements that characterize gludissociation (see formulae in [2]) have a finite extent in the gluon energy space, the corresponding cross sections exhibit maxima. Still, when averaged over the temperature-dependent gluon-energy distribution, and considering the momentum-dependent running of the strong-coupling constant [2], the average gludissociation cross section rises monotonically as function of temperature in the region of interest – that is, for initial temperatures of $T \simeq 550$ MeV at the Υ formation time $\tau_F \simeq 0.1 - 0.5$ fm/c.

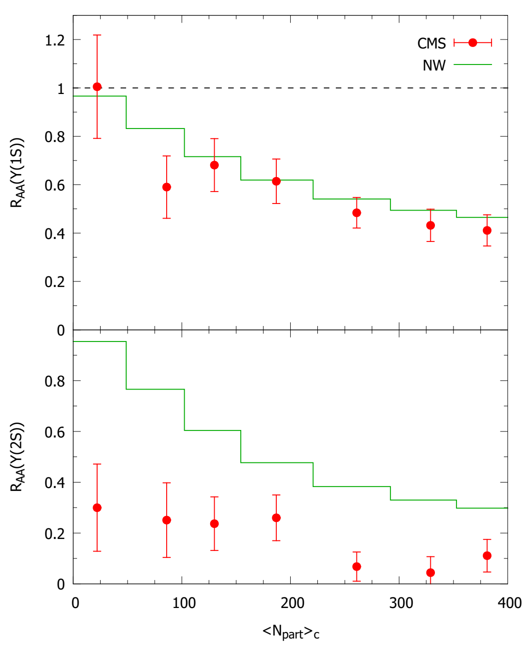

Figure 5. $\Upsilon(nS)$ suppression factors in 2.76 TeV PbPb measured by CMS [8] (circles) and calculated with the model of Nendzig and Wolschin [2] (solid lines) for τ_{init} = 0.1 fm/c, τ_F = 0.5 fm/c, T_i = 550 MeV and T_c = 170 MeV, averaged over transverse momentum, 4 GeV/c < p_T < 24 GeV/c. From [10].

In addition to gludissociation in the hot medium, we have also considered the damping widths due to the imaginary parts of the quark-antiquark potential, and the screening of the real parts. Gludissociation and damping widths add up incoherently to total bottomia widths for the six states considered in the hot fireball, namely, $\Upsilon(1S, 2S, 3S)$ and $\chi_b(1P, 2P, 3P)$; other spin-triplet states are above the $B\bar{B}$ threshold and hence, are not relevant for a comparison with the measured $\Upsilon(nS)$ suppression.

The time and centrality dependence of the suppression of these six states in the hot medium is then calculated based on an ideal hydrodynamic expansion of the medium that includes transverse expansion, as well as the relativistic Doppler effect whenever the mean transverse momenta of the produced bottomia states and the p_T of the expanding medium are different from each other. At the end of the QGP phase – when the temperature has dropped below the critical temperature – we calculate the centrality-dependent QGP suppression factors R_{AA}^{QGP}.

It is very relevant to include at all impact parameters the corona zone where the temperature never rises above the critical value so that none of the QGP dissociation mechanisms play a role there, leading to an occupation of the excited states even in more central collisions where the excited states melt in the high-temperature region due to screening. In the corona, additional hadronic suppression that is mostly due to collisions with pions – which we have investigated separately – may occur.

Once the centrality-dependent suppression in the hot fireball and in the corona is established, the bottomia states de-excite in a feed-down cascade before being detected through the emission of $\mu^+\mu^-$ pairs, with a branching ratio of approximately 2.48% for the $1S$ state, 1.93% for the $2S$ state, and 2.18% for the $3S$ state. The calculation of the feed-down cascade including the newly detected $\chi_b(3P)$ state is described in [11]. It yields the final centrality-dependent suppression factors R_{AA} [2] as shown in fig.5 in comparison with the CMS data [8] for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states for a parameter set indicated in the caption.

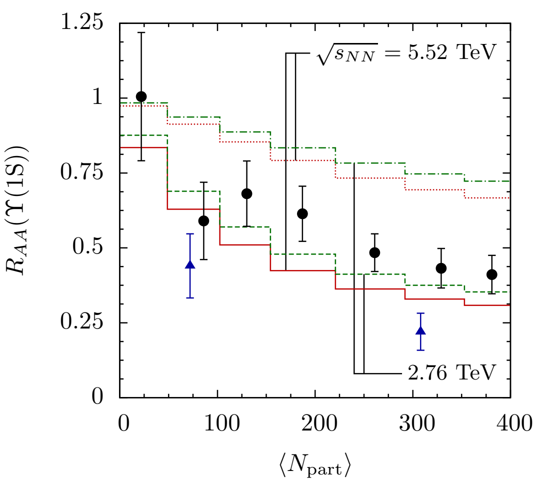

Figure 6. Predictions for $R_{AA}(1S)$ and $R_{AA}^{QGP}(1S)$ for PbPb collisions at $\sqrt{s_{NN}} = 5.52$ TeV (solid and dotted lines, respectively) and the previous results for $\sqrt{s_{NN}} = 2.76$ TeV (dashed and dash-dotted lines, respectively) as a function of centrality, averaged over p_T, plotted for an Υ formation time of $\tau_F = 0.3$ fm/c, together with data from CMS [8] and ALICE [12] for $\sqrt{s_{NN}} = 2.76$ TeV. From [2].

The suppression of the spin-triplet ground state and its centrality dependence is in good agreement with the data for all centralities except for the 40-50% bin. For the first excited $2S$ state, however, the calculated centrality dependence is too steep. Although the overall amount of suppression would be enhanced through a shorter formation time τ_F with ensuing larger QGP lifetime, such that the central bins are better accounted for, the problem of missing suppression in the three peripheral bins 50-100%, 40-50% and 30-40% remains to be solved. We have checked the influence of hadron-induced dissociation in the corona region, with the result that the centrality-dependence of pion-induced dissociation is probably not strong enough to account for the difference. Another interesting possibility may be the dissociation through the transient magnetic fields, which is expected to be more pronounced for peripheral collisions.

Since the results for the ground-state suppression are in agreement with experiment, we have also calculated the $\Upsilon(1S)$ suppression in PbPb at the LHC design energy of 5.52 TeV. solid line in fig.6. The central initial temperature is increased by 6.6% to 586 MeV using the scaling relation between the initial entropy density and the charged-particle multiplicity density $s_0 \propto dN_{ch}/d\eta \propto T_0^3$. The ground state is found to be slightly more suppressed in the medium at the higher energy and hence, the total suppression in PbPb as compared to pp is stronger. However, the effect is less than 10% when doubling the c.m. energy.

4 Conclusion

Particle production sources in relativistic heavy-ion collisions at RHIC and LHC energies have been investigated. The relevance and effect of the fragmentation sources not only in stopping, but also in particle production has been outlined, and discussed as function of incident energy. The particle content in the mid-rapidity gluon-gluon source increases rapidly (stronger than a power law) with incident c.m. energy. Charged-hadron production in the asymmetric pPb system at 5.02 TeV is investigated accordingly.

The suppression of the strongly bound $\Upsilon(1S)$ spin-triplet ground state in PbPb collisions at LHC energies as compared to scaled pp collisions at the same energy is a sensitive indicator for the properties of the quark-gluon plasma that causes gluodissociation and damping. The feed-down cascade from the excited bottomia states to the ground state produces additional suppression, since the excited states melt through screening, or depopulate through dissociation processes. Our model results [2] for the ground state are in good agreement for the CMS data [8], but the suppression of the first excited state calls for additional centrality-dependent dissociation mechanisms.

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