Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02324-8

THE EUROPEAN
PHYSICAL JOURNAL C

Medium effects on high p_T particle production measured with the PHENIX experiment

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[b] Research supported by U.S. Department of Energy DE-AC02-98CH1-886

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Received: 14 March 2005 / Revised version: 20 May 2005 /
Published online: 8 July 2005 –

Abstract. Transverse momentum (p_T) spectra measured by the PHENIX experiment at RHIC in Au+Au, d+Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV and in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV are presented. A suppression of the yield of high p_T hadrons in central Au+Au collisions by a factor 4–5 at $p_T > 5$ GeV/c is found relative to the pp reference scaled by the nuclear overlap function $\langle T_{AB} \rangle$. In contrast, direct photons are not suppressed in central Au+Au collisions and no suppression of high p_T particles can be seen in d+Au collisions. This leads to the conclusion that the dense medium formed in central Au+Au collisions is responsible for the suppression.

PACS. 25.75.Dw

1 Introduction

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is exploring the fundamental theory of strong interactions, QCD, at extremely high temperatures and densities. An important goal is the creation and study of a deconfined and thermalized state of strongly interacting matter, the quark-gluon plasma (QGP), in heavy ion collisions. The majority of particles in central Au+Au collisions at RHIC is created with rather low transverse momenta ($p_T < 2$ GeV/c). However, the small fraction of particles with high p_T originating from parton-parton interactions with high momentum transfer are of particular importance for the understanding of nucleus-nucleus (A+A) collisions. In pp collisions the scattered partons propagate through the normal QCD vacuum where they finally fragment into the observed, colorless hadrons. In A+A collisions the hard parton-parton scatterings happen in the early stage of the collision, before a possible QGP has formed. Therefore the high-energetic scattered partons traverse the subsequently produced excited nuclear matter. As a consequence, particle production at high p_T is sensitive to the properties of the hot and dense matter created in A+A collisions.

Here we study high-p_T photons, neutral pions and η mesons as well as charged particles which are measured at mid-rapidity with the two central spectrometer arms of the PHENIX experiment [1]. Each arm covers $|\eta| \leq 0.35$ in pseudorapidity and $\Delta\phi = \pi/2$ in azimuth. Photons, π^0 and η mesons were measured by the PHENIX electromagnetic calorimeters (EMCal). The mesons were reconstructed via their $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decay channels. The EMCal consists of six lead-scintillator and two lead-glass sectors, each located at a radial distance of about 5 m from the interaction region [2]. The systematic uncertainty of the absolute energy scale of the EMCal is 1.5% in this measurement. The charged-particle spectrometer consists of tracking detectors and of a magnetic field axially symmetric around the beam axis. Charged-particle tracks are reconstructed with a drift chamber followed by two layers of multiwire proportional chambers with pad readout. Particle momenta are measured with a resolution $\delta p/p = 0.7\% \oplus 1.0\% p$ (GeV/c) in Au+Au and $\delta p/p = 0.7\% \oplus 1.1\% p$ (GeV/c) in d+Au and pp.

2 Initial conditions: particle production in pp collisions at $\sqrt{s} = 200$ GeV

For the interpretation of the complicated dynamics in a heavy-ion collision a good, well understood, reference measurement of high p_T particle production in proton-proton collisions is needed. Then, by comparing the particle production in heavy-ion collisions to this baseline reference at the same $\sqrt{s_{NN}}$, it is possible to study certain properties of the QCD medium, as discussed in Sect. 3. Experimentally, for the comparison it is an advantage to measure both the heavy-ion spectra and the proton reference spectra together in the same experiment, preferably in the same data-taking period, to reduce the systematic uncertainties in the comparison. Apart from the importance as a reference for heavy-ion reactions, the measurement of

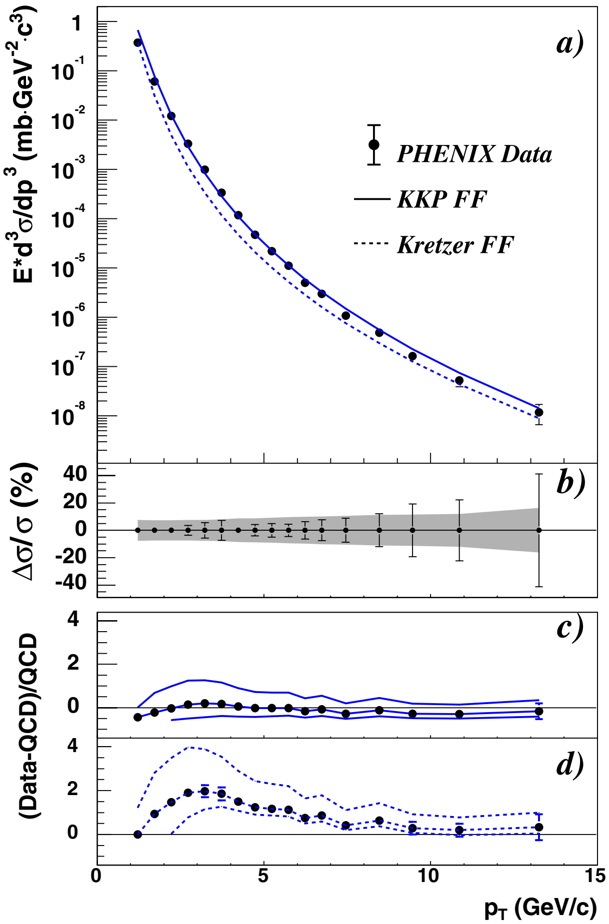

Fig. 1. π^0 invariant cross section at mid-rapidity from pp collisions at $\sqrt{s_{NN}} = 200$ GeV, together with NLO pQCD predictions

particle production in proton-proton collisions is of value by itself, providing, e.g., the possibility to constrain the gluon distribution function.

The differential cross-section for π^0 production in pp collisions at $\sqrt{s_{NN}} = 200$ GeV [3] is shown in Fig. 1. At high p_T the data shows the characteristic power-law behavior due to hard scattering. The π^0 measurement is well reproduced by standard next-to-leading-order (NLO) pQCD calculations [5,6] over the range $2 \leq p_T \leq 15$ GeV/c. Therefore, this measurement can provide a good baseline for π^0 spectra measured in Au+Au collisions as will be discussed in Sect. 3.

The comparison of π^0 production in pp to pQCD calculations relies on the choice of the parton-to-pion fragmentation function. A more direct test of pQCD and a constraint of the gluon distribution function is the measurement in pp of the production of direct photons, i.e. photons which are not produced in electromagnetic decays. The PHENIX experiment measured direct photon production in pp collisions at $\sqrt{s_{NN}} = 200$ GeV. The final result from RHIC Run-2 [7], and preliminary results from Run-3 show good agreement with NLO pQCD calculations. This is shown in Fig. 2 for the preliminary Run-3 result in comparison to [8]. So, with the understanding of

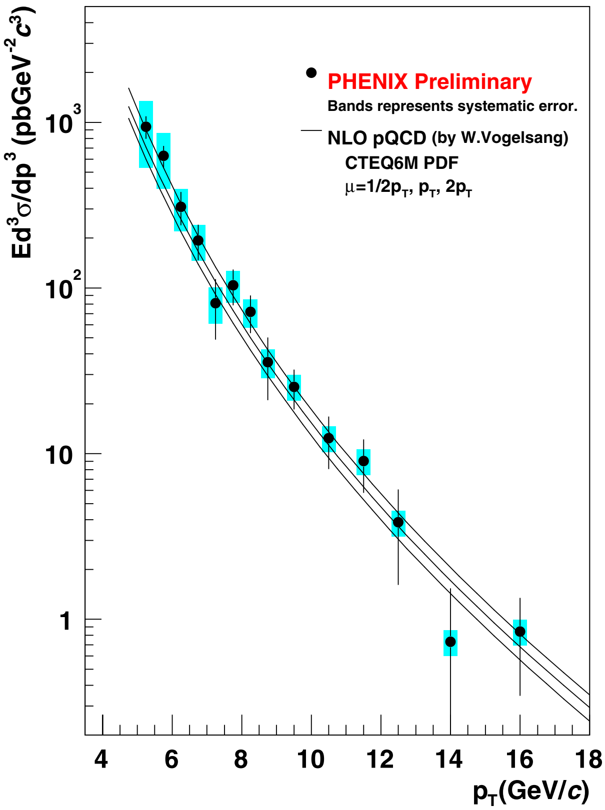

Fig. 2. Invariant cross section of direct photon production at mid-rapidity from pp collisions at $\sqrt{s_{NN}} = 200$ GeV (PHENIX Run-3) together with a NLO pQCD calculation

direct photon production in pp collisions, a good baseline for direct photon spectra in Au+Au collisions is available as well.

Further measurements of the differential cross-section in pp collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX experiment currently include charged hadrons [4], electrons, and η-mesons.

3 Particle production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

In heavy ion collisions, the transition region from "soft" to "hard" processes dominating the hadron production at a given p_T is strongly affected by flow phenomena [9, 10] and possible parton coalescence [11–14]. This complicates the understanding of particle production in the p_T region up to 4 GeV/c. At larger transverse momenta, however, the underlying hard parton-parton interactions can be considered as an incoherent superposition of individual nucleon-nucleon collisions. Therefore, a common way to understand the hadron production mechanisms in A+A collisions is to study their scaling behavior with respect to pp collisions. It is expected that soft processes ($p_T < 1$ GeV/c) scale with the number of participating nucleons N_{part}. In the absence of any medium effects the production of high-p_T particles should be comparable to

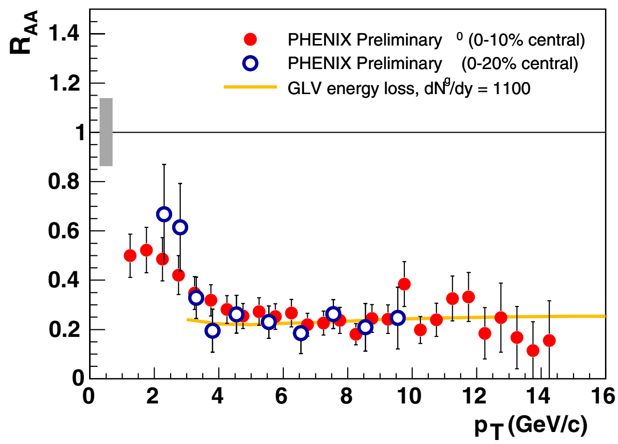

Fig. 3. R_{AA} for π^0 and η mesons in central (π^0: 0–10%, η: 0–20%) Au+Au collisions at mid-rapidity. The shaded box on the left shows the systematic error resulting from an overall normalization of the spectra and uncertainties in $\langle T_{\mathrm{AB}}\rangle$

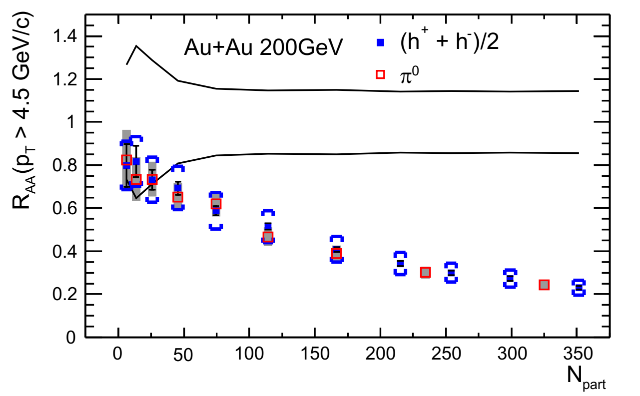

Fig. 4. R_{AA} vs N_{part} for p_{T}-integrated ($p_{\mathrm{T}} > 4.5$ GeV/c) Au+Au π^0 and charged hadron spectra. The band indicates the systematic error on a hypothetical T_{AB} scaling of the pp p_{T}-integrated cross section

the production in pp after scaling with a geometrical factor which reflects the increased number of binary nucleon collisions.

To quantify the medium effects at high p_{T} it is customary to use the *nuclear modification factor* which is given by the ratio of the A+A to the pp invariant yields [3] scaled by the *nuclear overlap function* $\langle T_{\mathrm{AB}}\rangle$:

$$R_{AA}(p_T) = \frac{d^2N^{\pi^0}_{AA}/dydp_{\mathrm{T}}}{\langle T_{\mathrm{AB}}\rangle \times d^2\sigma^{\pi^0}_{pp}/dydp_{\mathrm{T}}}. \qquad (1)$$

The average nuclear overlap function $\langle T_{\mathrm{AB}}\rangle$, averaged over the respective impact parameter range, is determined solely by the density distribution of the nucleons in the nuclei A and B, and by the impact parameter. The average number of nucleon-nucleon collisions per A+B collision is given by $\langle N_{\mathrm{coll}}\rangle = \sigma^{\mathrm{pp}}_{\mathrm{inel}} \times \langle T_{\mathrm{AB}}\rangle$.

$R_{\mathrm{AA}}(p_{\mathrm{T}})$ measures the deviation of A+A from an incoherent superposition of NN collisions in terms of suppression (R_{AA} <1) or enhancement (R_{AA} >1). At low p_{T}, in the soft regime, scaling with the number of participating nucleons N_{part} would result in $R_{\mathrm{AA}} < 1$. At intermediate p_{T} an enhancement in the yields relative to binary scaling, the "Cronin" effect, was reported [15]. This effect was attributed to k_T broadening due to initial state multiple parton scatterings.

One of the most interesting results at RHIC so far is the break-down of binary scaling in the nuclear modification factor [16,18] in central Au+Au collisions at mid-rapidity and high p_{T}. In contrast to the expectation neglecting in-medium modifications, it was found that R_{AA} is suppressed by up to a factor of five. Figure 3 shows R_{AA} for π^0 and η mesons in central Au+Au collisions at mid-rapidity. The suppression is approximately p_{T}-independent for $p_{\mathrm{T}} > 4.5$ GeV/c. Both π^0 and η mesons show the same amount of suppression. This is noteworthy as the charged particle production in the moderate p_{T} region of $2 < p_{\mathrm{T}} < 5$ GeV/c is suppressed less than pion production [16] while at higher p_{T} R_{AA} for π^0's and charged particles becomes equal (Fig. 4). This evolution in the charged particle suppression is related to contributions from (anti)protons [16,17].

In comparison to the published Run-2 result [18] the preliminary R_{AA} in Fig. 3 is using an extended data set of Run-2 (level-2)-triggered data [19] and the preliminary result on Run-3 π^0 production in pp now allowing a π^0 measurement reaching out to $p_{\mathrm{T}} > 14$ GeV/c. This is an especially interesting result addressing the question of how the suppression strength behaves for higher p_{T}.

The suppression of high-p_{T} hadrons in heavy ion collisions at RHIC had been predicted [20–22] and it has been suggested that the observed suppression is the result of parton energy loss in a medium of high color-charge density (mainly gluons) like the quark-gluon plasma [23,24]. A number of model predictions which were made prior to the release of the data can describe the suppression qualitatively if they take into account constant [25] or energy-dependent [22,26] parton energy loss effects. By comparing to the data, the p_{T} independence of the π^0 R_{AA}, however, rules out the possibility of a constant energy loss. The only model that predicted the flat p_{T} dependence was the GLV prescription [26]. It is compared to the data in Fig. 3 for an initial gluon density of $dN^g/dy \approx 1100$.

As the approximate p_{T}-independence of the suppression for $p_{\mathrm{T}} > 4.5$ GeV/c is common for all centralities this can be used to better illustrate the centrality dependence of the suppression. Figure 4 shows R_{AA} versus N_{part} calculated from the integrated Au+Au spectra [18] and pp reference cross section over $p_{\mathrm{T}} > 4.5$ GeV/c for π^0's and charged hadrons. The figure suggests a smoothly increasing suppression with N_{part}; there is no evidence for a sudden onset of the suppression. The charged particles show a similar evolution of the suppression with N_{part}. In the most central collisions R_{AA} values of 0.24 ± 0.04 and 0.23 ± 0.05 for charged particles and π^0's are measured. In peripheral collisions R_{AA} is consistent with unity within the errors, that are large due to the large uncertainty of the peripheral $\langle T_{\mathrm{AB}}\rangle$ values.

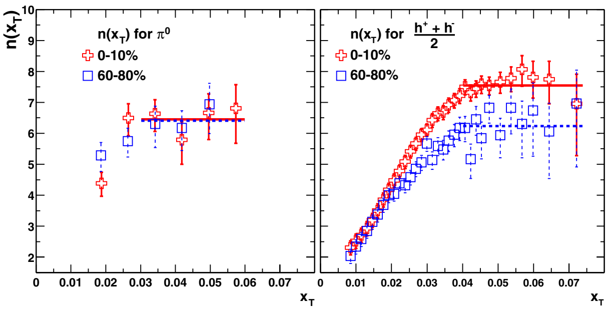

Fig. 5. Power-law exponent $n(x_T)$ for π^0 and h spectra in central and peripheral Au+Au collisions calculated at a given x_T from $\sqrt{s_{NN}} = 130$ and 200 GeV data [16]

3.1 x_T scaling in Au+Au collisions

As discussed in Sect. 2, particle production at high p_{T} in pp collisions is the result of hard scattering processes according to pQCD. It can be shown that in the high p_{T} region the measured pp cross sections follow a general "x_T-scaling" behaviour $Ed^3\sigma/d^3p = 1/\sqrt{s}^n G(x_{\mathrm{T}})$ with $x_{\mathrm{T}} = 2p_{\mathrm{T}}/\sqrt{s}$ [4] This characteristic variation with $\sqrt{s}$ at high p_T is produced by the fundamental power-law and scaling dependence of the pp hard scattering cross section in pQCD. If the production of high-p_{T} particles in Au+Au collisions is the result of hard scattering as well, then x_{T} scaling should be valid and it should yield the same value of the exponent $n(x_{\mathrm{T}}, \sqrt{s})$. The only assumption required is that the structure and fragmentation functions in Au+Au collisions should scale, so just a different $G(x_T)$ will be used. Figure 5 shows $n(x_{\mathrm{T}}, \sqrt{s_{NN}})$ in Au+Au calculated from the ratio of $Ed^3\sigma/dp^3$ at a given x_T for $\sqrt{s_{NN}} = 130$ and 200 GeV for peripheral and central collisions [4]. The π^0's (left) show x_T scaling, with the same value of $n = 6.3$ as in pp collisions, for peripheral and central Au+Au collisions. The non-identified charged hadrons x_{T}-scale with $n = 6.3$ for peripheral collisions only. $h^{\pm}$ in central Au+Au collisions show a significantly larger value of n, indicating different physics by the contribution of (anti)protons. Within the experimental sensitivity of the data it can be concluded that high-p_{T} π^0 production in peripheral and central Au+Au collisions and $h^{\pm}$ production in peripheral Au+Au collisions follow pQCD as in pp collisions, with parton distribution and fragmentation functions that scale with x_{T}.

3.2 Energy dependence: comparison to Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV

One way to investigate the onset of suppression in central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV and to map out elastic and inelastic scattering properties of a possibly created quark-gluon plasma, is to study the $\sqrt{s_{\mathrm{NN}}}$ dependence of particle production. To obtain more information in the energy range between the measurements at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV (CERN SPS), $\sqrt{s_{\mathrm{NN}}} = 130$ GeV and 200 GeV (RHIC), in early 2004 the RHIC experiments measured particle production in Au+Au collisions

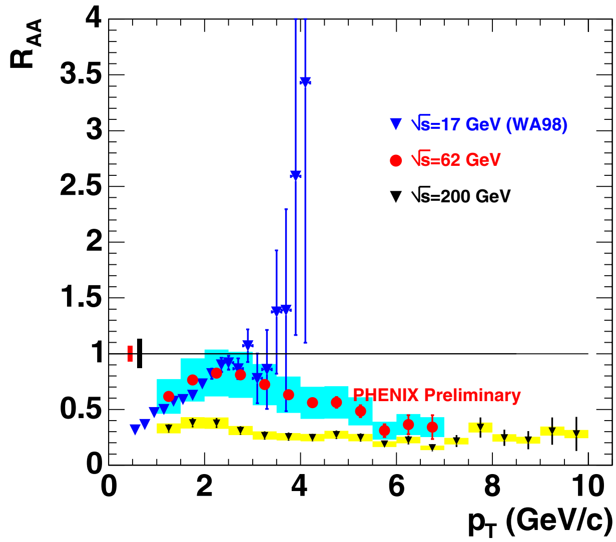

Fig. 6. Nuclear modification factor $R_{AA}(p_{\mathrm{T}})$ for π^0's in central Au+Au collisions at RHIC at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 62.4$ GeV and central Pb+Pb collisions at the SPS at $\sqrt{s_{NN}} = 17$ GeV. The boxes surrounding the data points indicate the systematic errors that are correlated with p_{T}, the black box at 1 shows the percent normalization error on the data for $\sqrt{s_{NN}} = 200$ GeV and the red box for $\sqrt{s_{NN}} = 62.4$ GeV

at $\sqrt{s_{\mathrm{NN}}} = 62.4$ GeV. Figure 6 compares the results on $R_{\mathrm{AA}}(p_{\mathrm{T}})$ for π^0 production at three different $\sqrt{s_{NN}}$. The boxes around the data points indicate the systematic errors correlated in p_{T}, and the shaded grey band at 1 indicates the percent normalization error. At the SPS, in Pb+Pb collisions, no apparent suppression can be observed and a possible energy loss effect is outbalanced by the Cronin enhancement [28] (re-analysis of pp reference [29]). The $\sqrt{s_{\mathrm{NN}}} = 62.4$ GeV data show a similar suppression as in $\sqrt{s_{\mathrm{NN}}} = 200$ GeV for $p_{\mathrm{T}} > 5$ GeV/c. Note the huge systematic error on the normalization due to large uncertainties in the pp reference as there is no π^0 measurement from RHIC available at this energy [30]. A model prediction which was made prior to the release of the $\sqrt{s_{\mathrm{NN}}} = 62.4$ GeV data [31] incorporating the final-state energy loss with a gluon rapidity density of $dN_g/dy = 650$–800 and initial state Cronin scattering is consistent with the data within the large systematic uncertainties. For further interpretations of the data a future measurement of the pp reference at RHIC at this energy is strongly desirable.

3.3 Direct photon production

Like the parton energy loss descriptions, a gluon saturation calculation [32] is able to predict the magnitude of the observed suppression, but it fails to reproduce exactly the flat p_T dependence of the quenching. This model assumes a saturation of gluons at small Bjorken-x in the initial state wavefunction of the Au nuclei, which leads to fewer hard gluon-gluon scatterings and thus to fewer high-p_{T} particles. One way to distinguish between initial-state

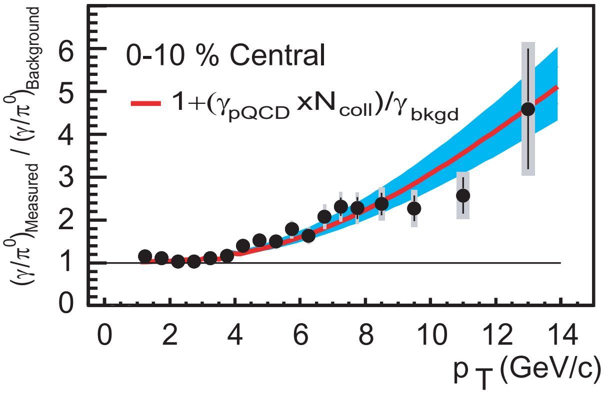

Fig. 7. Ratio of the measured inclusive photon yield and the expected yield of background photons from hadronic decays for central Au+Au collisions, at $\sqrt{s_{NN}} = 200$ GeV, as a function of p_T. Statistical and systematic errors are indicated separately on each data point by the vertical bar and shaded box, respectively. The solid curve indicates the expected photon excess from pQCD calculations assuming a scaling of the direct photon yield with $\langle N_{coll}\rangle$

effects (like gluon saturation) and final-state effects (like parton energy loss) is to study the production of direct photons. Both direct photons and hadrons are sensitive to modifications in the initial state of the incoming partons. Direct photons, however, are basically unaffected by the hot and dense matter created in A+A collisions.

PHENIX measured direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV up to $p_T = 14$ GeV/c by comparing the measured inclusive photon p_T spectrum with the expected spectrum of background photons from hadronic decays [19]. This is shown in Fig. 7 for the 0–10% most central events. A significant direct photon signal can be measured for $p_T > 4$ GeV/c. In addition, it can be shown that the magnitude of the signal increases with increasing centrality, due to the decreasing decay background caused by π^0 suppression.

The direct photon signal is compared to a NLO pQCD prediction [8], scaled by the number of binary nucleon collisions. As it was shown in Sect. 2, the same calculation agrees with the PHENIX direct photon measurement in pp. The good agreement of the measurement in Au+Au and the binary scaled pQCD calculation shows that direct photons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are not suppressed but scale with $\langle N_{coll}\rangle$. Furthermore, it suggests that modifications in the initial state in the relevant region of momentum fraction x_{Bj} are small. This leads to the conclusion that the suppression of high-p_T hadrons is due to final-state effects.

4 Particle production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

As an alternative way to separate between initial state and final-state effects, Phenix studies particle production in d+Au collisions and first results have been published [33]. Models attributing the high-p_T hadron suppression in central Au+Au collisions to final-state effects or initial-state effects make different predictions for d+Au collisions. In a d+Au collision the highly excited matter is not created over a large volume and so high-p_T particle suppression is not expected in the parton energy loss scenario. By contrast, in case of modifications in the initial-state, high-p_T particle production should be suppressed in d+Au as well. In [32] a suppression of $R_{dA} \approx 0.7$ is predicted for central d+Au collisions.

In [33] it was discussed that the nuclear modification factor R_{dA} for high-p_T π^0's and charged particles at mid-rapidity in minimum-bias d+Au collisions shows no suppression. Within uncertainties, R_{dA} for neutral pions is equal to unity, while unidentified charged particles exhibit a clear enhancement when compared to pp collisions. Several models incorporating both the Cronin enhancement and shadowing effects can describe the π^0 data well [34, 35].

In addition to the minimum-bias data it is worthwhile to study the centrality dependence of R_{dA}. Figure 8 shows the nuclear modification factor $R_{dA}(p_T)$ for neutral pions in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for four different centrality selections, compared to theoretical calculations. The boxes around the data points indicate the systematic errors correlated in p_T, and the shaded gray band at 1 indicates the percent normalization error. In all centralities no suppression can be seen. Within uncertainties, R_{dA} for neutral pions shows no Cronin-enhancement, $R_{dA}(p_T)$ is equal to unity for all centralities. There is only a hint for a small increase of R_{dA} with centrality. This is different from the behavior of unidentified charged particles where there is a clear increase of R_{dA} with centrality in d+Au, a trend opposite to the Au+Au results. The data can be well described over all centralities by a Glauber-Eikonal approach [36] without considering initial state gluon-saturation effects, shown as the curved band in Fig. 8. The prediction for the gluon-saturation calculation [32] is plotted as well. Even with the systematic uncertainties of the preliminary PHENIX data, the model prediction seems to underestimate the data in the most central data sample. The d+Au results support the conclusion that a final-state nuclear medium effect, such as parton energy loss, is necessary to describe the suppression observed in central Au+Au collisions.

5 Conclusions

One of the most significant observations at RHIC so far has been the suppression of high-p_T hadrons at mid-rapidity in central $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions relative to binary-scaled pp reference spectra. This observation is consistent with predictions in which hard-scattered partons lose energy in a dense medium. A competing theory, the gluon saturation model, appears as an unlikely explanation as it can be shown that direct photons are not suppressed in central Au+Au collisions. PHENIX has improved the measurement of reference spectra in pp for direct photons, π^0 and η mesons in the high p_T region and

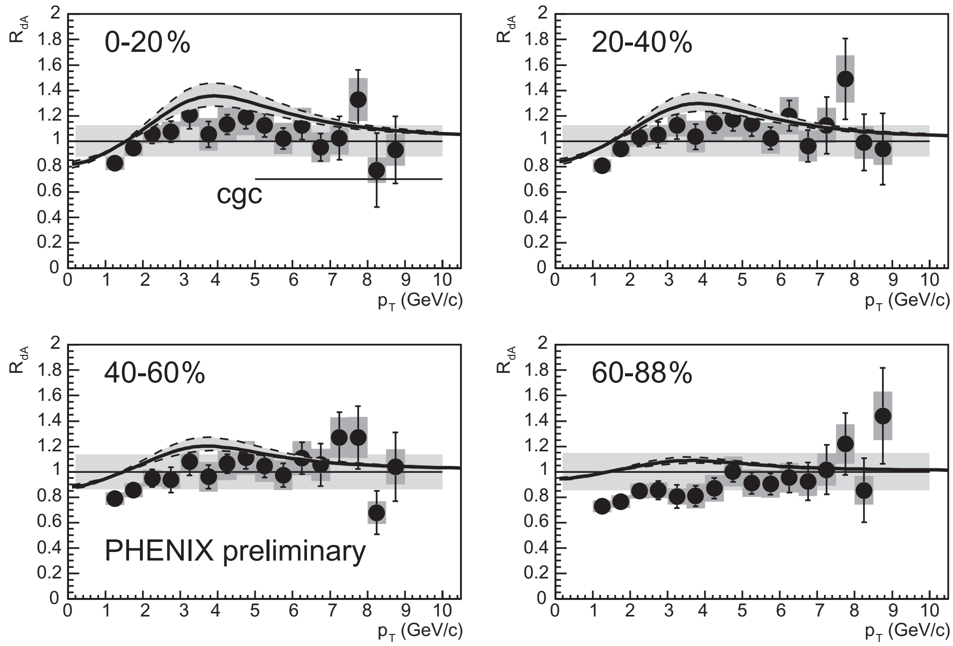

Fig. 8. Nuclear modification factor $R_{dA}(p_T)$ for neutral pions in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for four different centrality selections compared to theoretical calculations [36, 32]

extended the π^0 measurement in Au+Au to higher p_T. A measurement of high-p_T hadron production in d+Au collisions does not show a suppression, supporting the expectation of the parton energy loss scenario but disproving predictions by the gluon saturation model. Very little centrality dependence of $R_{AA}(p_T)$ for neutral pions is observed in d+Au; within uncertainties no Cronin-enhancement can be seen.

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