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Neutral meson production at high p_T with the PHENIX experiment at RHIC

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Abstract. Over the first five years of operation the PHENIX experiment at RHIC has collected a wealth of data for various systems and collision energies that is providing valuable information for the understanding of the suppression pattern observed in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. An overview on transverse-momentum (p_T) spectra of π^0 and η in different collision energies and systems is presented.

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 extremly 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.

One of the most interesting results of the early RHIC program was the observation that in central Au + Au collisions hadrons with high transverse momentum (p_T) are suppressed by a factor of five compared to their yield in $p+p$ collisions scaled by the number of corresponding nucleon–nucleon collisions [1]. This effect was predicted to be a consequence of parton energy loss in the medium that is generated in the collisions [2, 3]. Furthermore, a control experiment of $d+$Au collisions showed no indication of hadron suppression at mid-rapidity [4]. As no medium is produced in the final state of $d+$Au collision, strong cold-nuclear-matter (*i.e.* initial-state) effects as the cause for the suppression observed in Au + Au were ruled out.

To better understand the medium effects at work, however, more detailed studies are necessary. Recently, new studies of two- and multi-particle correlations and of single particle production at high p_T relative to the reaction plane of the collision have started to provide additional information. A complementary way to challenge our understanding of the suppression mechanism is a systematic comparison of single particle production at high p_T for different reaction systems and energies.

Here we study high-p_T neutral pions (π^0) and eta mesons (η) at mid-rapidity, measured with the two central spectrometer arms of the PHENIX experiment. Each arm covers $|\eta| \leq 0.35$ in pseudorapidity and $\Delta\varphi = \pi/2$ in azimuth. The π^0 and η were identified by the PHENIX electromagnetic calorimeters (EMCal) via the $\pi^0 \to \gamma\gamma$ decay. The EMCal consists of six lead-scintillator (PbSc) and two lead-glass sectors (PbGl), each located at a radial distance of about 5 m to the interaction region [5]. In addition, the PHENIX zero-degree calorimeters and the two beam–beam counters (BBC's) were used for triggering, vertex and centrality determination. The energy calibration for the EMCal is obtained from beam tests, cosmic rays, and minimum ionizing energy peaks of charged hadrons. The systematic uncertainty of the absolute energy scale of the EMCal is 1.2–1.5% in these measurements.

π^0 and η are reconstructed with an invariant mass analysis of photon pairs in the EMCal. Photon candidates in the EMCal are selected by applying particle identification (PID) cuts based on the shower profile in the detector. After subtraction of the combinatorial background the invariant mass distribution is integrated around the particle mass peak. The combinatorial background is determined by pairing photons from different events with similar centrality and vertex. The raw spectra are finally corrected for trigger efficiency, acceptance, and reconstruction efficiency.

2 The $p+p$ reference

Hadron production mechanisms in heavy-ion collisions are usually studied via their scaling behavior with respect to $p+p$ collisions. In order to come to significant conclusions about the production mechanism at play, a good, well understood reference measurement of high p_T particle production in proton–proton ($p+p$) collisions is needed. 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

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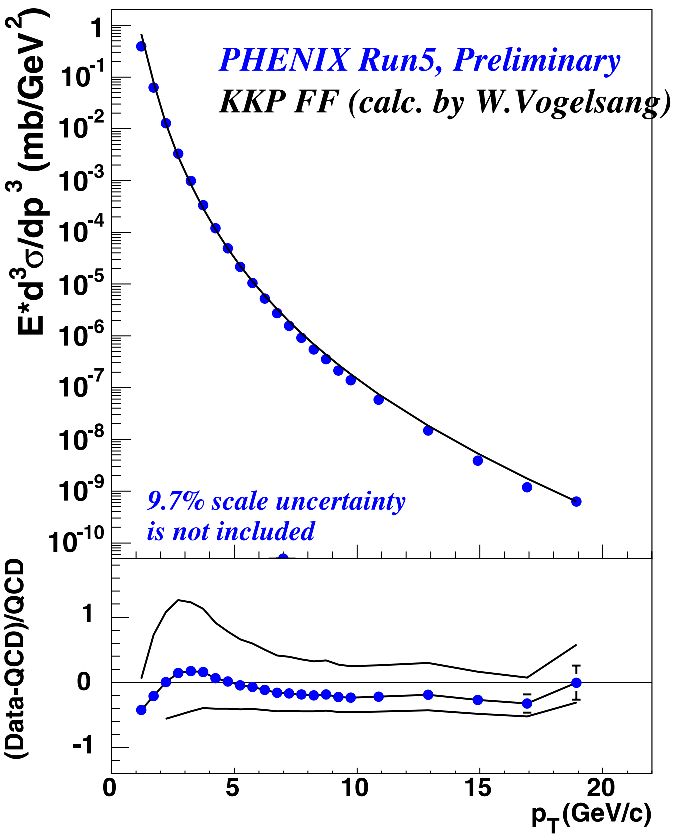

Fig. 1. Invariant cross section of π^0 production at mid-rapidity from $p+p$ collisions at $\sqrt{s} = 200$ GeV (PHENIX Run 5) together with a NLO pQCD calculation [7, 8]

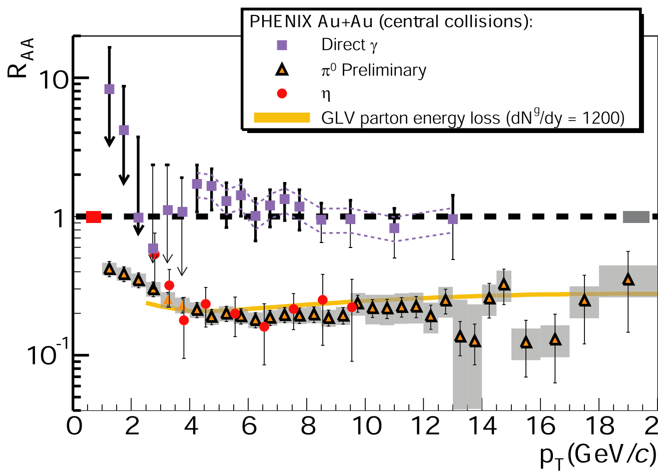

Fig. 2. Nuclear modification factor in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for direct photons, π^0 and η [14]. The *bands* around the π^0 data points show systematic errors which can vary with $p_{\rm T}$. The *shaded band* around unity on the left (right) indicates the $\langle T_{\rm AB}\rangle$ uncertainty (normalization uncertainty due to the $p+p$ reference). For the direct γ $p+p$ reference a pQCD calculation was used. The *dotted lines* around the direct γ data points indicate the theoretical scale uncertainty of the calculation

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

PHENIX has measured $p+p$ reference data for π^0 [6], direct γ and η in $\sqrt{s} = 200$ GeV. The preliminary differential cross-section for π^0 production in $p+p$ collisions at $\sqrt{s} = 200$ GeV from Run-5 is shown in Fig. 1. At high $p_{\rm T}$ the data show 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 [7, 8] over the range $2.0 \le p_{\rm T} \le 20$ GeV$/c$. It can provide a good baseline for π^0 spectra measured in Au + Au collisions.

3 Central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Hard parton–parton interactions with small cross section can be considered as an incoherent sequence of individual nucleon–nucleon collisions. In the absence of any medium effects the production of high-$p_{\rm T}$ particles should be comparable to the production in $p+p$ after scaling with a geometrical factor which reflects the increased number of scattering centers. It is customary to quantify the medium effects at high p_T using the *nuclear modification factor* which is given by the ratio of the $A+A$ to the $p+p$ invariant yields [9] that are scaled by the *nuclear overlap function* $\langle T_{AA}\rangle$:

$$R_{AA}(p_{\rm T}) = \frac{{\rm d}^2 N^{\pi^0}_{AA}/{\rm d}y\,{\rm d}p_{\rm T}}{\langle T_{AA}\rangle\,{\rm d}^2\sigma^{\pi^0}_{pp}/{\rm d}y\,{\rm d}p_{\rm T}}\,. \qquad (1)$$

The average nuclear overlap function $\langle T_{AB}\rangle$ is determined solely from the geometry of the nuclei A and B. The average number of nucleon–nucleon collisions per $A+B$ collision is given by $\langle N_{\rm coll}\rangle = \sigma^{pp}_{\rm inel}\langle T_{AB}\rangle$. $R_{AA}(p_{\rm T})$ measures the deviation of $A+A$ from an incoherent superposition of NN collisions in terms of suppression ($R_{AA} < 1$) or enhancement ($R_{AA} > 1$).

Recently the PHENIX experiment could extend the $p_{\rm T}$ reach of π^0 in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by a high statistics run (RHIC Run-4). Figure 2 shows R_{AA} for π^0 together with η and direct γ as a function of $p_{\rm T}$ for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The suppression of π^0 is almost constant even up to the highest $p_{\rm T}$ measured. This results is in agreement with expectations of energy loss effects with initial gluon densities in the order of ${\rm d}N^{\rm g}/{\rm d}y \approx 1200$ [10]. The direct γ in contrast is unsuppressed compared to the scaled reference [11]. For $p_{\rm T} > 4$ GeV direct γ is in good agreement with a NLO pQCD calculation scaled by the number of binary nucleon collisions within current experimental errors and theoretical uncertainties. While this suggests that the initial-hard-scattering probability is not reduced, the agreement with pQCD calculations might just be a coincidence caused by mutually counterbalancing effects like energy loss and Compton like scattering of jet partons [12].

4 High p_T η production

An equally strong suppression of π^0 and charged hadrons in Au + Au collisions of the same centrality for $p_T > 5\,\text{GeV}/c$ [13] suggests that the suppression mechanism is independent of the identity of the high-p_T hadron. This furthermore suggests that the suppression takes place at the parton level prior to its fragmentation into the hadron. In this scenario the energy loss of the hadron depends only on the energy lost in the medium by the parent quark or gluon. It is independent of the nature of the final leading hadron, produced with the same universal fragmentation functions which govern hadron production in the vacuum in more elementary systems. A measurement of the yields of the η meson, which has 4 times the mass of the pion, at large enough p_T can test the consistency of the data with medium-induced partonic energy loss prior to vacuum hadronization.

PHENIX has measured the production of η mesons in Au+Au, d+Au and $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV which allows to study the effects of hot and cold nuclear matter with an additional probe of identified high-p_T particles and to compare with the results of neutral pion and direct photon production [14]. Figure 2 shows this comparison for the most central Au + Au collisions. The nuclear modification factor for η mesons shows the same pattern as for π^0, a suppression of a factor of five, and the same constancy at high p_T.

The similarity between π^0 and η at high p_T can be demonstrated clearly by studying the η/π^0 ratio for different collision species and centralities. Since η and π^0 are reconstructed within the same data set via their decay into two photons, many systematic uncertainties cancel. The ratio is shown in Fig. 3 for d + Au and $p+p$ reactions and for three different centralities in Au + Au together with a PYTHIA calculation [15]. The ratios for all colliding species and centralities are consistent within the errors, supporting the assumption that the energy loss occurs at the partonic level.

5 Energy dependence

To study the dependence of particle production on the beam energy the RHIC program has started to add further data sets to the $\sqrt{s_{NN}} = 130$ GeV and 200 GeV Au + Au data from the early years. In Run 4 Au + Au data at $\sqrt{s_{NN}} = 62.4$ GeV were taken and in Run 5 Cu + Cu data sets were added at $\sqrt{s_{NN}} = 22.4$, 62.4 and 200 GeV. The lower-energy data provide important information on the particle production at an energy between CERN SPS ($\sqrt{s_{NN}} = 17.3$ GeV) and full RHIC energy. An interesting question in this context is the study of the onset of the π^0 suppression at high-p_T observed in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. A re-evaluation of the existing SPS data [16] with an improved $p+p$ reference [17], suggests that weak jet-quenching effects may already be present in central heavy-ion collisions at $\sqrt{s_{NN}} = 17.3$ GeV.

The PHENIX experiment measured π^0 production in Cu + Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV up to $p_T \approx 5\,\text{GeV}/c$. The measurement of a corresponding $p+p$ reference from RHIC is currently not available but a wealth of data exists for $p+p \to \pi^0/\pi^\pm + X$ in the range $\sqrt{s} = 21.7$–23 GeV which allows to construct a $p+p$ reference with a systematic uncertainty of $\approx 20\%$. The nuclear modification factor $R_{AA}(p_T)$ is shown in Fig. 4 in comparison to the WA98 result of π^0 production in Pb + Pb collisions.

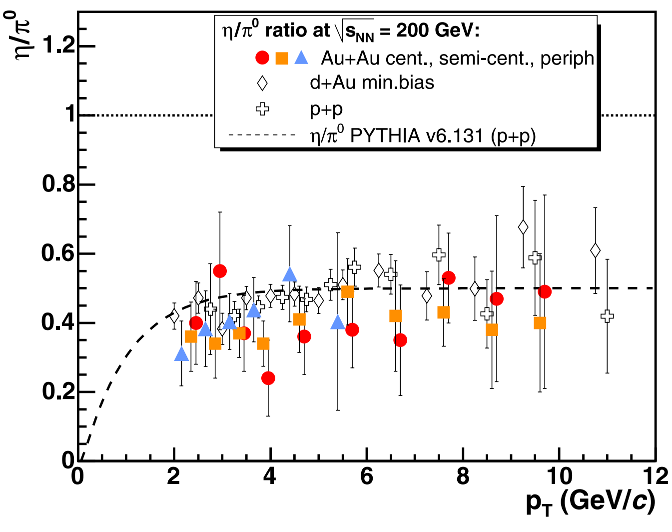

Fig. 3. Ratio of η and π^0 spectra measured for different colliding species and centralities at $\sqrt{s_{NN}} = 200$ GeV [14] together with a PYTHIA calculation [15]

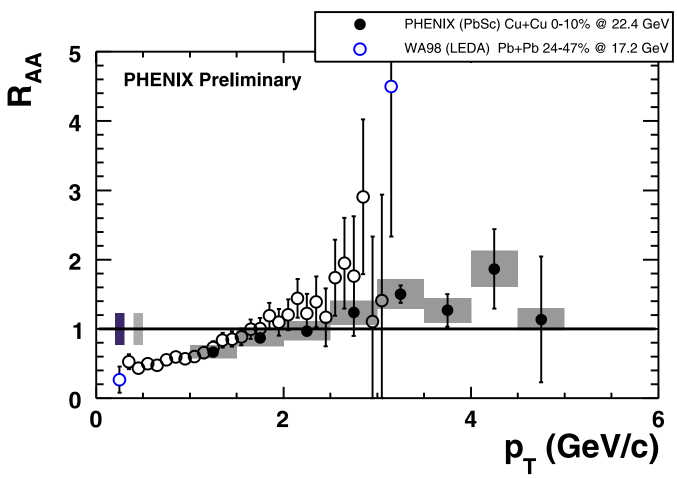

Fig. 4. Nuclear modification factor for mid-central Pb + Pb collisions ($N_{\text{part}} = 132$, $\sqrt{s_{NN}} = 17.3$ GeV) measured by WA98 at CERN-SPS and for central Cu + Cu collisions ($N_{\text{part}} = 140$, $\sqrt{s_{NN}} = 22.4$ GeV) measured by PHENIX at RHIC

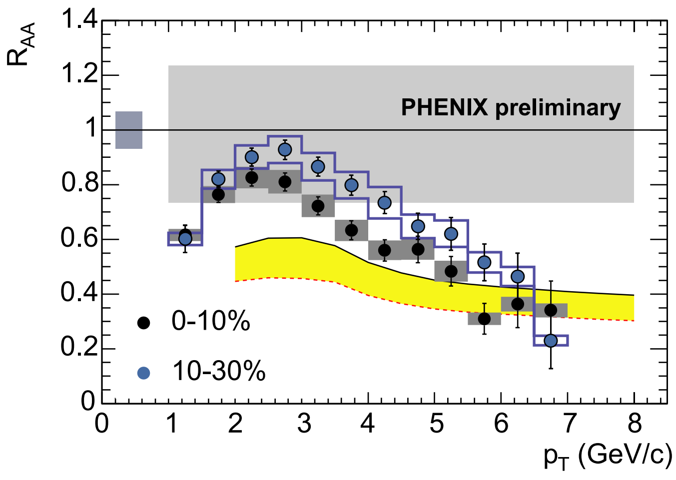

Fig. 5. Nuclear modification factor $R_{AA}(p_T)$ for neutral pions in Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV for two different centrality selections in comparison to a model prediction [19]. The *bands* around the data points show systematic errors which can vary with p_T. The *small shaded band* around unity on the left indicates the $\langle T_{AB} \rangle$ uncertainty, the *large band* indicates the normalization uncertainty due to the $p+p$ reference

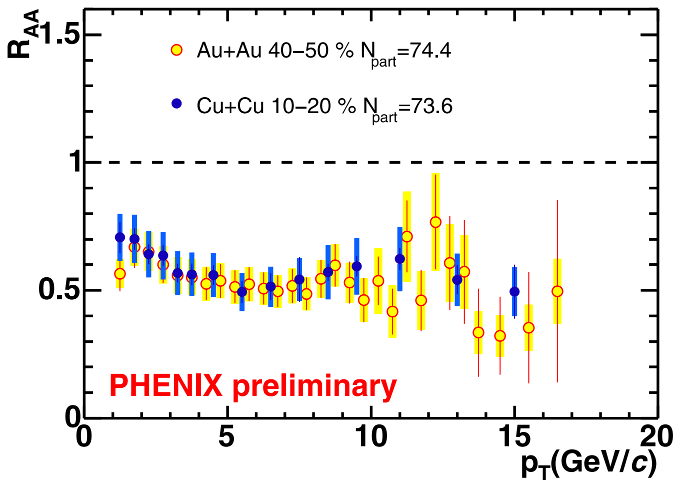

Fig. 6. Comparison of the nuclear modification factor in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for $N_{\text{part}} \approx 74$

The data indicate a Cronin-type enhancement, no strong variation with centrality can be observed (not shown). Both measurements agree well in their overlap region with the PHENIX measurement extending to higher p_T. A future measurement of the $p+p$ reference with PHENIX could improve the significance of the result with a smaller systematic uncertainty.

The limited significance due to the lack of a good baseline measurement becomes apparent for the current result on $R_{AA}(p_T)$ for π^0 production in Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Figure 5 shows $R_{AA}(p_T)$ for two different centrality selections. Note the huge systematic uncertainty on the normalization due to large uncertainties in the $p+p$ reference [18] as indicated by the shaded grey band at unity.

The π^0 data show a suppression of up to a factor 5 at high p_T with a strong p_T dependence. A model prediction [19] incorporating the final-state energy loss with a gluon rapidity density of $\mathrm{d}N_g/\mathrm{d}y = 650$–$800$ and initial-state Cronin scattering is shown in Fig. 5 as well.

Only recently, in Run 6, PHENIX was able to take new data for a $p+p$ reference at $\sqrt{s} = 62.4$ GeV; the analysis is still under way with the expectation to improve the systematic uncertainties on the absolute normalization by a large factor.

6 System size dependence

Comparing the Au + Au and Cu + Cu data sets furthermore allows the study of the influence of the collision system and geometry on the particle production at high p_T. At the same N_{part} the overlap region for the smaller Cu-system is more spherical and the surface/volume ratio is smaller. In addition, smaller colliding systems, like Cu, allow for a more precise discrimination for small values of N_{part}, corresponding to peripheral Au + Au collisions.

Figure 6 shows R_{AA} for π^0 in Cu + Cu and Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for centrality selections with a similar number of participants N_{part}. The N_{part} value is associated with the centrality using a Glauber model calculation. It can be seen that π^0 are suppressed by a similar factor for similar N_{part}, i.e. similar energy density, in the two systems.

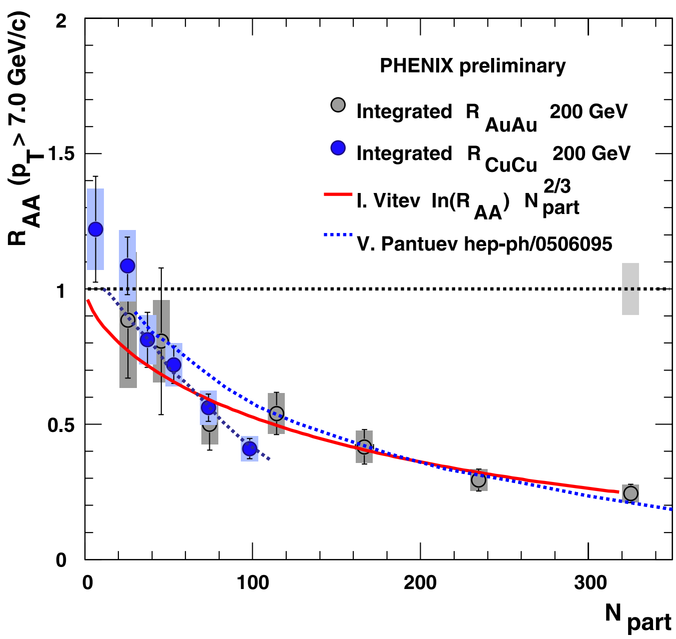

Fig. 7. Integrated nuclear modification factor for Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV compared to a scaling with $\ln R_{AA} \propto N_{\text{part}}^{2/3}$ [20] and to a calculation with surface/volume effects [21]

This is illustrated more generally in Fig. 7. The integrated nuclear modification factor is shown as a function of centrality. It can be seen that R_{AA} is very similar for Au + Au and Cu + Cu and approximately follows a scaling with $\ln R_{AA} \propto N_{part}^{2/3}$ as suggested in [20].

However, the N_{part} dependence shows a slightly different slope for Cu + Cu and Au + Au, suggesting a geometrical effect in the nuclear modification factor. This N_{part} dependence is in very good agreement with a prediction [21] where only jets originating from a certain depth below the surface of the collision region can be observed. For a further interpretation of the data the influence of geometrical effects like a surface bias needs to be better understood.

7 Conclusions

A systematic study of high p_T π^0 and η production in different collision systems and at different center-of-mass energies has been discussed. PHENIX has measured $p+p$ reference data up to $p_T = 19\,\mathrm{GeV}/c$. The π^0 and η yield in central Au + Au at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ collisions show a similar suppression pattern, indicating that the suppression is happening on the partonic level. The first measurement of high-p_T particle production near SPS energies ($\sqrt{s_{NN}} = 22.4\,\mathrm{GeV}$) at RHIC has been presented. The data agree with previous measurements by the WA98 experiment and extends the measurement to higher p_T. Finally R_{AA} for Au + Au and Cu + Cu reactions shows a similar dependence on p_T and N_{part} with small signs of effects of the collision geometry.

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