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

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The results of midrapidity ($0 < y < 0.8$) neutral pion spectra over an extended transverse momentum range ($1 < p_T < 12$ GeV/ c) in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions, measured by the STAR experiment, are presented. The neutral pions are reconstructed from photons measured either by the STAR Barrel Electro-Magnetic Calorimeter or by the Time Projection Chamber via tracking of conversion electron-positron pairs. Our measurements are compared to previously published π^\pm and π^0 results. The nuclear modification factors R_{CP} and R_{AA} of π^0 are also presented as a function of p_T . In the most central Au + Au collisions, the binary collision scaled π^0 yield at high p_T is suppressed by a factor of about 5 compared to the expectation from the yield of $p + p$ collisions. Such a large suppression is in agreement with previous observations for light quark mesons and is consistent with the scenario that partons suffer considerable energy loss in the dense medium formed in central nucleus-nucleus collisions at the Relativistic Heavy Ion Collider.

I. INTRODUCTION

The observation of “jet quenching” [1,2] in central Au + Au collisions is one of the most exciting experimental discoveries at the Relativistic Heavy Ion Collider (RHIC). Experimental signature of this observation includes the suppression of inclusive hadron yields at high transverse momentum (p_T) [3,4] and of associated $p_T > 2$ GeV/ c particles on the away side of a high- p_T trigger hadron [5]. These measurements indicate that RHIC has produced high-energy-density matter that is opaque to high- p_T quarks and gluons [1]. Theoretical calculations based on energy loss of high- p_T partons through gluon radiation can explain the suppression of light quark mesons [6]. Measurements of π^0 at high p_T provide a fundamental tool for probing the parton energy loss in the medium created in central nucleus-nucleus collisions at RHIC. However, this medium appears to be transparent to direct photons, of which the nuclear modification factor R_{AA} is found to be approximately unity at high p_T [7]. Measurement of the π^0 spectrum over an extended p_T range is a prerequisite to understand the decay photon background of the direct photon analysis. This measurement also provides an important cross-check for other pion measurements at RHIC using different detectors.

In this article we present the first results for the π^0 spectra and nuclear modification factors at midrapidity over a broad p_T region ($1 < p_T < 12$ GeV/ c) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR experiment. Neutral pions are reconstructed via the diphoton decay channel. Only the west half of the STAR Barrel Electro-Magnetic Calorimeter (BEMC) [8] was completed and commissioned to take heavy-ion collision data in 2004. Measurement of a π^0 spectrum under the high-multiplicity environment in central Au + Au collisions is challenging due to the large transverse size of the STAR BEMC towers (0.05×0.05 in $\Delta\eta \times \Delta\phi$), resulting in high occupancy and appreciable background contamination. The BEMC provides STAR with a trigger capability on high- p_T photons based on large energy deposition in a single BEMC tower or a tower patch. These triggered BEMC photons can be used to reliably construct π^0 mesons in the high- p_T region. However, this is not possible in the low- p_T region as the energy resolution of the BEMC is not sufficiently good. The STAR Time Projection Chamber (TPC) [9] has been used to reconstruct photons that convert to electron-positron pairs [10]. Excellent detection resolution on π^0 invariant masses has been achieved from TPC conversion photons. However, the small photon conversion probability in the STAR detector system restricts the p_T reach. By combining BEMC photons from high- p_T triggers and conversion photons from the TPC, we have been able to achieve good invariant mass resolution on π^0 reconstruction and measure its spectrum over a broad range of p_T .

II. DATA ANALYSIS

A. Data set

The data used in this analysis were taken during the 2004 RHIC run for Au + Au collisions at the energy $\sqrt{s_{NN}} = 200$ GeV. The primary STAR detectors used for this analysis are the TPC and BEMC. A Barrel Shower Maximum Detector

(BSMD) [8] at a depth of 5 radiation lengths (X_0) inside the BEMC measures transverse shower shape and position with higher precision than the BEMC tower. Three Au + Au data sets were used: 11×10^6 events selected by a minimum-bias trigger (MB), 17×10^6 events selected by a central trigger, and 2.4×10^6 events selected by a high tower trigger (HT). The central trigger corresponds to the highest 12% charged particle multiplicity events as determined by the coincidence of the central trigger barrel and the zero degree calorimeters [11]. The HT trigger, which depends on pseudorapidity, requires that at least one BEMC tower has deposited transverse energy greater than the HT energy threshold of 3–4 GeV. The HT trigger enhances selection of events containing high- p_T photons and thus helps to extend our measurement to higher p_T . More details about the STAR trigger system and trigger configuration can be found in Ref. [11]. In this analysis, the position of the primary vertex is required to be within ± 20 cm of the center of the STAR TPC along the beam line. This requirement restricts our conversion photon candidates to midrapidity, where the detector geometry is relatively simple and the material is well studied for reconstructing conversion photons.

B. Photon identification

There are two ways to identify photons in STAR: The STAR BEMC and BSMD measure photons directly from the electromagnetic shower (EMC photon) or the STAR TPC reconstructs photon conversion to e^+/e^- pairs (TPC photon) in materials such as the beam pipe, the Silicon Vertex Tracker (SVT), the Silicon Strip Detector (SSD), and TPC walls and gas. In total these materials are estimated to be equivalent to about $0.1X_0$, with a 10% uncertainty based on studies of conversion probability correction. The photon conversion probability will be discussed in Sec. II D and II E.

An EMC photon is reconstructed from a single tower. The photon energy is determined by the tower energy. In MB and central events, towers with energy greater than 500 MeV and at least 250 MeV higher than any of their eight surrounding towers are required. The BSMD hit information is not used due to its expected inefficiency for low-energy photons. The photon position is assumed to be at the center of the tower. Charged particle contamination is greatly reduced by projecting TPC tracks into the BEMC and vetoing the first two towers intersected by the track.

In HT triggered events, BSMD hits are used to separate the two close decay photons from a single π^0 decay. The photon positions are determined from the BSMD hits. If multiple photons are found in the same tower, the tower energy is split according to the individual BSMD hit energies. For a photon with energy below the HT threshold, we require that no TPC track is projected into an area of ± 0.05 in $\Delta\eta$ and ± 0.05 in $\Delta\phi$ around the photon candidate. For a photon above the HT threshold, we require that the sum of momenta of all charged particle tracks projected to the surrounding $\Delta\eta - \Delta\phi$ area should be less than 1 GeV/ c .

For TPC photons, we select e^+/e^- candidates via ionization energy loss dE/dx in the TPC. A number of geometrical cuts are applied to each e^+/e^- pair to have a topological signature of a photon conversion. These cuts require that the two tracks originate from a common secondary vertex within or before

entering the TPC with a small opening angle and a small invariant mass and that the reconstructed photon candidate originates from the primary vertex. The photon momentum is taken as the sum of two daughter track momenta at the conversion point. This technique has been used in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV, and more details can be found in Ref. [10].

C. π^0 Reconstruction

In MB and central events an EMC photon is paired with a TPC photon (EMC-TPC), and in HT events pairs of two EMC photons (EMC-EMC) are also used to reconstruct π^0 's. Due to the relatively large tower size of the STAR BEMC, energy determinations for low- p_T photons can be contaminated due to the presence of other nearby photons, neutral particles, and residual charged particles in high multiplicity Au + Au events. The limited energy resolution of BEMC towers at low energy (nominal resolution of BEMC towers has been estimated to be $16\%/\sqrt{E} \oplus 1.5\%$) [8] also hinders the accurate measurement of photon energy. As a result, it is difficult to obtain a clear π^0 signal at low p_T by exclusively pairing EMC photons. However, the relatively tight geometrical cuts for TPC photon reconstruction select very clean conversion photon samples. They significantly reduce the combinatoric background and improve the π^0 mass resolution. The EMC-TPC method yields a clear π^0 signal from 1 GeV/c to intermediate p_T (~ 5 GeV/c) in central Au + Au collisions. At higher p_T above the HT threshold, the EMC photons are less affected by backgrounds and the EMC-EMC method produces clear π^0 signals. Due to its greater efficiency for high- p_T photons, the EMC-EMC method is able to extend the measurement to higher p_T .

The mixed-event technique is used to reproduce a combinatoric background. For the mixed-event distribution, photons from the event being analyzed are paired with photons from events in an event pool, in which events are required to have similar multiplicity and primary vertex position as the one being analyzed. The diphoton invariant mass distribution after mixed-event background subtraction is fit to extract the raw π^0 yield.

Figures 1 and 2 show examples of the diphoton invariant mass distributions before and after mixed-event background subtraction for different π^0 reconstruction methods. In Fig. 1 we show the invariant mass distributions in the p_T regions 1.2–1.5 and 7.0–9.0 GeV/c from the EMC-TPC method, and Fig. 2 shows the invariant mass distributions in the p_T region 9.0–12.0 GeV/c from the EMC-EMC method. All invariant mass distributions are for the 0–20% collision centrality bin. These distributions are fit using a Gaussian plus a polynomial background function. At high p_T , the background is small and can be easily subtracted by fitting a linear dependence on M_{inv} . At low p_T , the signal-to-background ratio is rather small. After mixed-event background subtraction, a larger residual background is observed and a third-order polynomial function is used to fit the background shape. Here the normalization factor between same-event and mixed-event is adjusted for each p_T bin so the residual background has a shape roughly linearly increasing with mass and can be described by a polynomial fit. The residual background may come from correlated photons that are not combinatoric and cannot be reproduced by the mixed-event technique. Such correlations may arise from contaminations to EMC photons or from

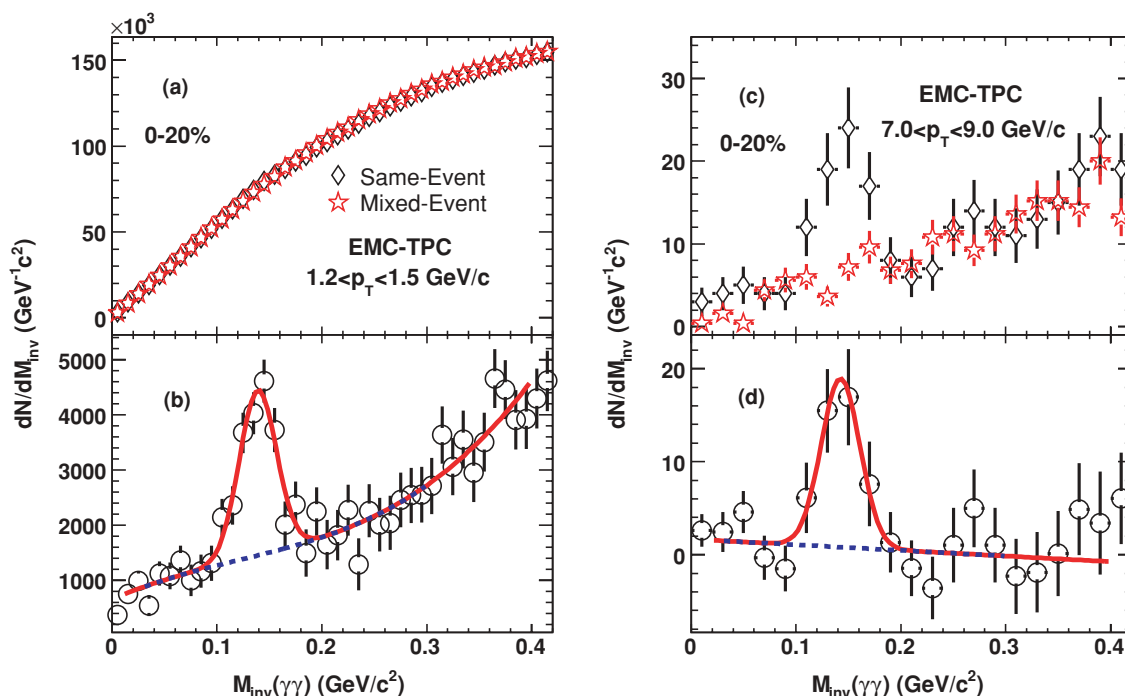


FIG. 1. (Color online) The diphoton invariant mass distributions using the EMC-TPC method in 0–20% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The solid line is a fit result of a Gaussian peak plus a background function. The residual background is shown as a dotted line. Panels (a) and (b) are from a low- p_T bin in MB events; panels (c) and (d) are from a high- p_T bin in HT events. Panels (b) and (d) are distributions after mixed-event background subtraction from panels (a) and (c).

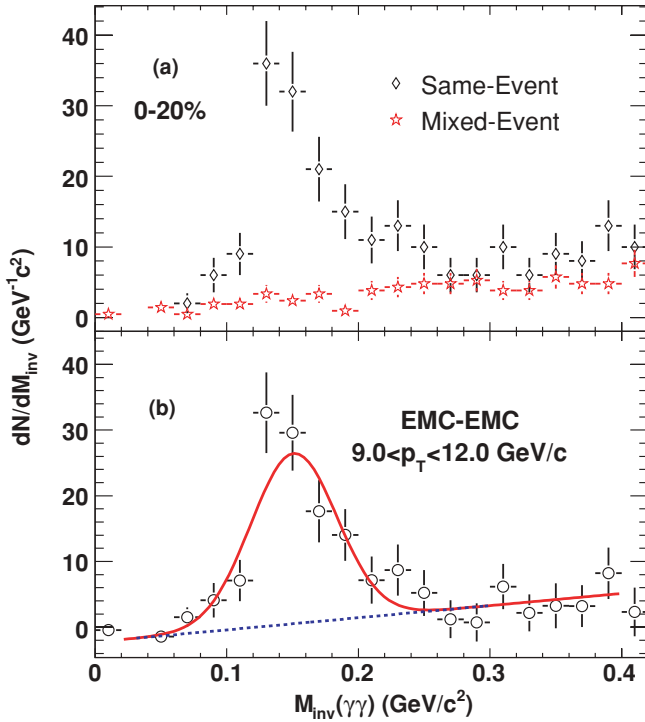


FIG. 2. (Color online) The diphoton invariant mass distributions using the EMC-EMC method in 0–20% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The solid line is a fit result of a Gaussian peak plus a background function. The residual background is shown as a dotted line. Panel (b) is the distribution after mixed-event background subtraction from panel (a).

resonance decays to multiple photons in the final state. The amount of residual background is strongly centrality and p_T dependent, more pronounced in the most central events and at lower p_T . Figure 1(a) shows the situation where both combinatoric and residual backgrounds are most severe; nevertheless the π^0 signal can still be observed above the residual background [Fig. 1(b)].

Several systematic checks have been performed. First, a track rotation technique was used to generate combinatoric background for comparison. It rotates the EMC photons by 180° in the azimuthal plane and mixes them with the photons reconstructed in the TPC. Second, the normalization factor was adjusted and the invariant mass distribution was refit to extract π^0 yield. Although these two procedures may significantly change the shape of residual background, yields extracted using the same function are consistent with each other. We have also changed the order of polynomial used for background fitting, as well as the fit range, and have included the variance in the overall systematic errors.

Figure 3 shows the extracted π^0 peak positions and widths as a function of p_T using different π^0 reconstruction methods. Results from real data are compared to Monte Carlo (MC) simulation of π^0 embedded in real data. The π^0 peak position shows some p_T dependence at low p_T for the EMC-TPC method and at higher p_T for the EMC-EMC method. At low p_T the drop is understood as the effect of energy loss of e^+/e^- tracks due to bremsstrahlung. At high p_T the rise of peak

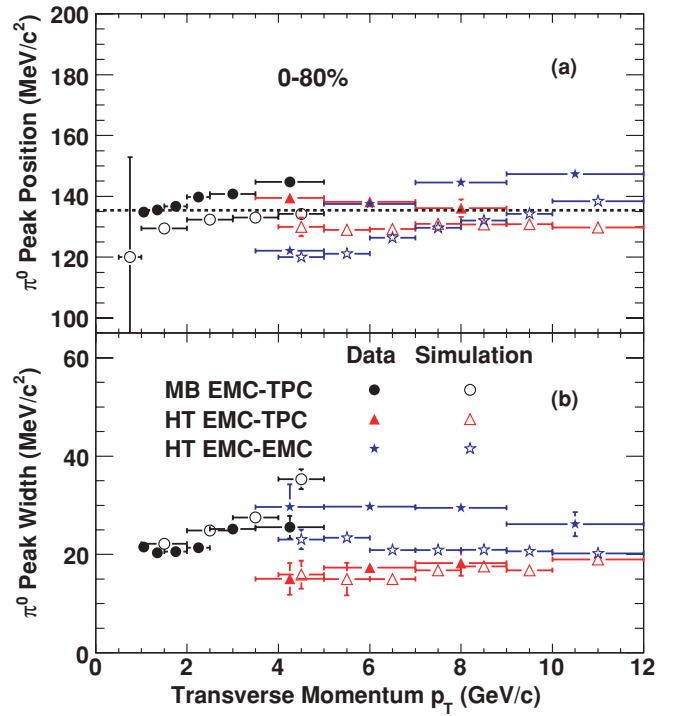


FIG. 3. (Color online) The π^0 invariant mass peak positions (a) and peak widths (b) as a function of p_T in 0–80% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Corresponding results from π^0 embedded simulation are shown for comparison.

position as a function of p_T is due to the saturation of dynamic range for energy measurement from the BSMD in this data set. The BSMD read-out saturated when the deposited energy exceeds about 6 GeV, leading to more evenly distributed energies of two spatially close photons when they hit the same BEMC tower and therefore produces a larger invariant mass. This effect is more pronounced at higher p_T . The saturation scale was lower than anticipated due to electronics signal termination issues in 2004. The effect has been included in the simulation. The trend of p_T dependence is well reproduced by the simulation but the simulation underestimates the mass peak position by 4–8%. The use of TPC photons significantly improves the π^0 peak resolution. For the same HT data sample the EMC-TPC method yields peak widths narrower than those from the EMC-EMC method, which is consistent with the MC simulation. Comparing the MB and HT data samples, the requirement of BSMD hits improves the spatial resolution of EMC photons and thus measures a narrower π^0 peak width.

D. π^0 detection efficiency

The raw yield of π^0 is corrected for an overall centrality dependent detection efficiency calculated from a full MC simulation, embedding π^0 's into real events. The efficiency is calculated as the ratio of the reconstructed $\pi^0 p_T$ spectrum over the input spectrum, using the same cuts as the real data analysis. The input π^0 spectrum for the embedding analysis is weighted so that it reproduces the previously measured charged [12] or neutral pion spectrum [13]. The calculated

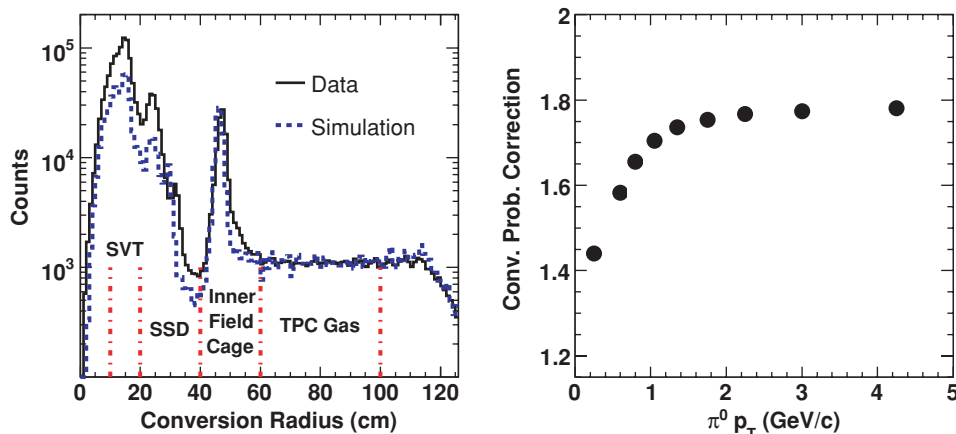


FIG. 4. (Color online) (Left) Photon conversion point radius distributions from real data and MC simulation in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The two distributions are normalized in the radius region of the TPC gas at $60 < r < 100$ cm. (Right) Conversion probability correction factor for π^0 as a function of p_T .

efficiency takes into account the losses due to acceptance, photon conversion probability, tracking inefficiency, track energy loss, and track quality cuts.

The conversion probability is crucial for the π^0 efficiency calculation when TPC photons are used. A comparison of distributions for the photon conversion radii between data and MC simulation is shown in the left panel of Fig. 4. The two distributions are normalized to the data in the inner radius region of the TPC gas where geometry is simple and well understood. The comparison indicates that the photon conversion probability can be well reproduced in the regions of TPC gas and the inner field cage but is underestimated in the regions of SVT and SSD where structures are complex. Similar observation has been reported in earlier publications [10]. The results for TPC photons are corrected for this effect, using the conversion rates in the TPC gas as a reference. A correction factor $F_{\text{geo}} = (n_{\text{det}}/n_{\text{gas}})_{\text{data}}/(n_{\text{det}}/n_{\text{gas}})_{\text{MC}}$ is calculated as a function of the conversion photon p_T , where n_{det} and n_{gas} are numbers of conversion points in the whole detector and in the TPC gas only. In the embedding analysis a reconstructed TPC photon associated with a MC photon is weighted by the factor F_{geo} corresponding to its p_T , which folds the correction in the efficiency calculation. The final correction factor for π^0 as a function of p_T is shown in the right panel of Fig. 4.

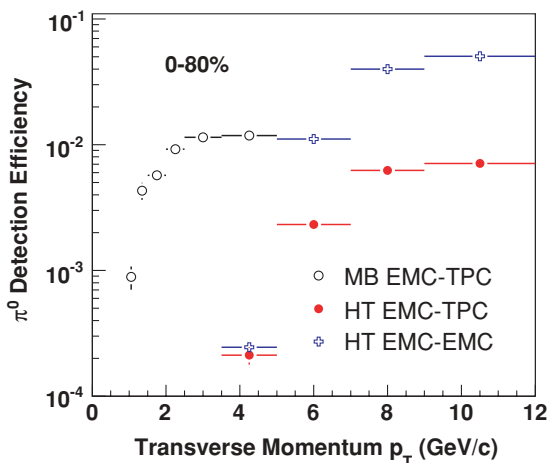


FIG. 5. (Color online) The overall detection efficiency of π^0 from embedding study in 0–80% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

Figure 5 shows the overall detection efficiency as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The use of TPC photons is statistically challenging due to the relatively low conversion probability. Using EMC photons enhances the efficiency significantly and is preferable in studying the π^0 spectrum at high p_T . The efficiencies shown here have taken the conversion probability correction into account.

E. Systematic errors

Major sources of systematic errors for the π^0 measurement in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are listed in Table I. Systematic errors are calculated for each p_T bin, and systematic errors from different sources are added in quadrature. The systematic errors are estimated by using several methods. First, we have varied photon reconstruction cuts and compared the fully corrected spectra. By changing the geometrical cuts applied to the TPC photon reconstruction, a systematic error of 10–20% in the final spectra is obtained. For the EMC photons in MB events, different energy cuts are used to select EMC photon samples with different levels of purity. In HT events, instead of a single tower, a cluster with up to 2×2 towers is used to reconstruct an EMC photon. These various photon reconstruction methods give a systematic error of 10–20% to the final π^0 spectra. Next, we have also included the uncertainties in the absolute energy scale of the BEMC, which could affect the overall shape of the π^0 spectra. An offset in the BEMC energy scale would contribute to the small deviations

TABLE I. Summary of main sources of systematic uncertainties on the π^0 yields in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Systematic uncertainties from varying photon cuts and yield extraction techniques are p_T uncorrelated, and systematic uncertainties from the BEMC energy scale and conversion probability correction are p_T correlated.

	MB		HT	
	EMC-TPC	EMC-TPC	EMC-TPC	EMC-EMC
Photon cuts	10–20%	20–30%	10–20%	10–20%
BEMC energy scale ($\pm 5\%$)	20–30%	25–35%	20–35%	20–35%
Yield extraction	10%	15%	10%	10%
Conversion probability correction	10%	10%	–	–

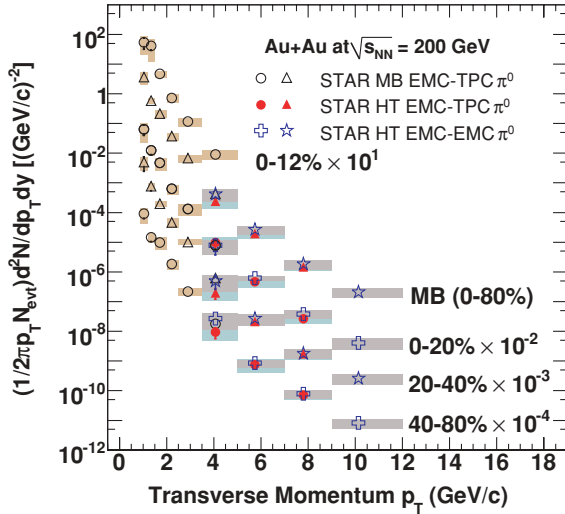


FIG. 6. (Color online) Invariant yield of STAR π^0 as a function of p_T at midrapidity for different collision centrality bins in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Spectra for different collision centralities are scaled for clarity. Statistical errors are shown as vertical lines and point-to-point systematic errors are shown as bars.

in the π^0 mass peaks between real data and simulations. We have included a uncertainty of $\pm 5\%$ [14] in the BEMC energy scale in our Monte Carlo simulations. We estimated systematic errors of 20–35% throughout the p_T range. Third, we have varied the fitting procedure used to extract the raw π^0 yield. The raw yield of π^0 depends on the background fitting function, fit range, and the normalization of same- and mixed-event invariant mass distributions. Results using different fitting parameters indicate a systematic error of 10–15%. We have also cross-checked the uncertainty due to the conversion

probability correction by applying the correction factor as a function of conversion point position. The result agrees with the original within 10%. As a result, a 10% systematic error is assigned for the conversion probability correction factor.

III. RESULTS

The π^0 invariant yield per collision at midrapidity ($0 < y < 0.8$) as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 6. Statistical and systematic errors are shown as vertical lines and bars, respectively. The horizontal size of the vertical bars also indicates the range of the p_T bin. In addition to the overall MB 0–80% result, the data sample is also divided into three collision centrality bins, 0–20%, 20–40%, and 40–80%, based on measured charged particle multiplicity at midrapidity from the TPC [15], with 0–20% the most central collisions. The π^0 spectra are measured over an extended p_T range from 1 to 12 GeV/c. Results from different π^0 reconstruction algorithms and different data samples were compared in overlapping p_T ranges and were found to be in good agreement. Therefore, in the following figures only a combined data point using statistical weighted average of data from various algorithms will be shown in the overlapping p_T bins.

Our π^0 spectra are compared to the previously published π^\pm and π^0 results. The ratios of our measured π^0 spectra to the STAR π^\pm [12] and the PHENIX π^0 [13] in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 7. Parametrized results of the π^0 and π^\pm spectra from power law functions are used to match the p_T binning of our π^0 data. The error bars are propagated using the averaged error of two neighboring data points. The spectrum ratio is slightly larger in peripheral collisions than in central and midcentral collisions. With the best statistics in MB 0–80% collision centrality, the STAR π^0 yields are consistent with the PHENIX π^0 yields, and about

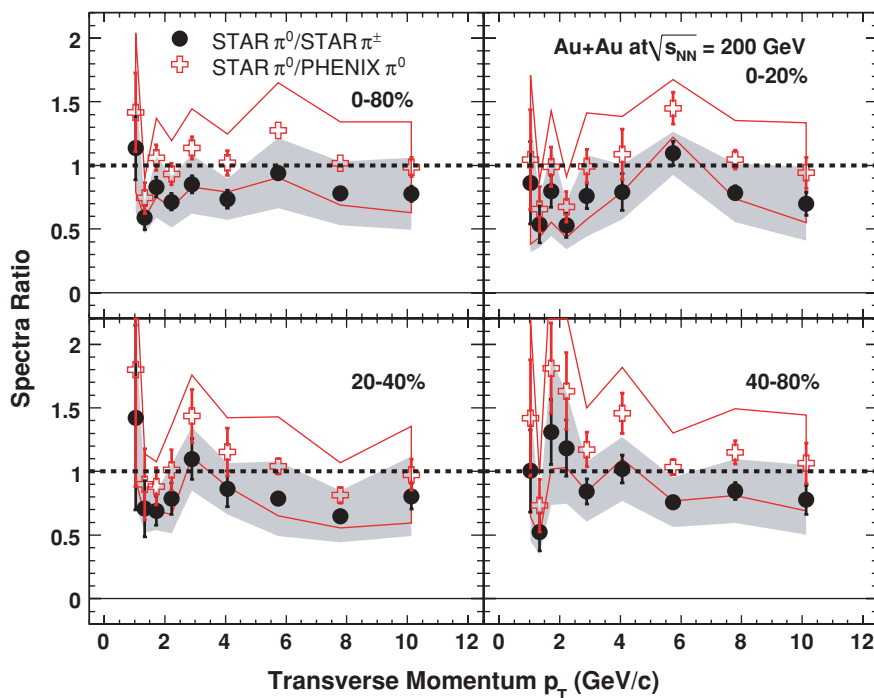


FIG. 7. (Color online) The ratios of STAR π^0 spectra over π^\pm from STAR [12] (solid symbol) and π^0 from PHENIX [13] (open symbol) as a function of p_T for different collision centrality bins in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Statistical errors are shown as vertical lines and point-to-point systematic errors are shown as bands.

15% smaller than the STAR π^\pm yields over the p_T range. Considering that the systematic uncertainties in the STAR π^0 and π^\pm analyses are mostly independent, the two yields are consistent within systematic uncertainties.

The nuclear modification factors can be calculated using peripheral collisions as a reference (R_{CP}) or using nucleon-nucleon collisions as a reference (R_{AA}):

$$R_{CP}(p_T) = \frac{[d^2N/p_T dy dp_T / \langle N_{bin} \rangle]^{central}}{[d^2N/p_T dy dp_T / \langle N_{bin} \rangle]^{peripheral}},$$

and

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dy dp_T / \langle N_{bin} \rangle}{d^2\sigma_{pp}/dy dp_T / \sigma_{pp}^{inel}},$$

where $\langle N_{bin} \rangle$ is the average number of binary nucleon-nucleon collisions per nucleus-nucleus collision. The σ_{pp}^{inel} is taken to be 42 mb for $\sqrt{s_{NN}} = 200$ GeV [16]. The measurements of suppression for high- p_T charged hadrons from STAR [1] and neutral pions from PHENIX [2] (R_{CP} and $R_{AA} < 1$) in most central Au + Au collisions at RHIC provided the first experimental evidence that partons suffer energy loss in the dense matter created in these collisions.

Figure 8 shows our measurements of the nuclear modification factor R_{CP} for π^0 as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for the 0–20% and 20–40% over 40–80% collision centrality bins. When calculating R_{CP} some systematic uncertainties cancel out, such as the BEMC energy scale and conversion probability correction. Compared to the 40–80% peripheral Au + Au collisions, the more central

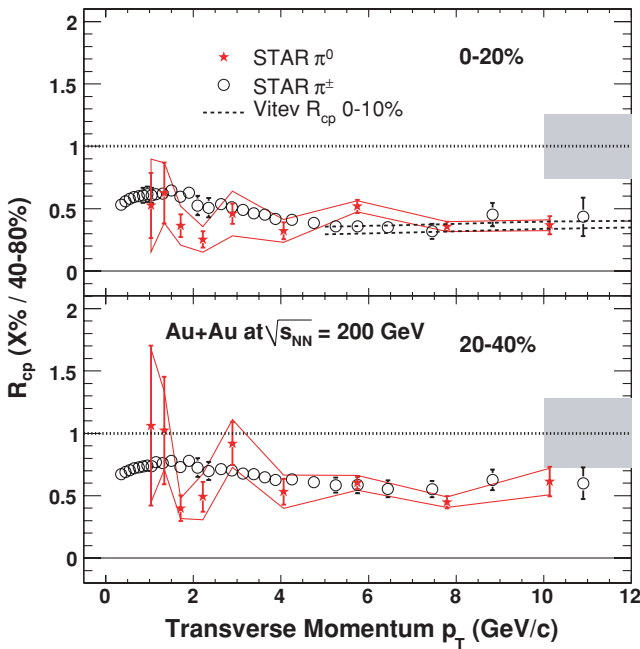


FIG. 8. (Color online) The nuclear modification factor R_{CP} as a function of p_T of STAR π^0 compared to STAR π^\pm [12] in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Statistical errors are shown as vertical lines and point-to-point systematic errors are shown as solid lines. The shaded band on the right demonstrates the uncertainty of N_{bin} . The dashed curves are jet quenching theoretical calculations [18].

collisions show a suppression of the π^0 yield indicated by $R_{CP} < 1$ and the suppression is even stronger for the most central collisions. At high $p_T > 4$ GeV/c the $\pi^0 R_{CP}$ is independent of p_T within uncertainties. Our measured $\pi^0 R_{CP}$ values show the same magnitude of suppression as the STAR π^\pm data [12], which are shown as open circles.

Figure 9 shows our measurements of the nuclear modification factor R_{AA} for π^0 as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for 0–20%, 20–40%, and 40–80% collision centrality bins, where a parameterized description of the π^\pm spectrum in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV from Ref. [17] is used to calculate R_{AA} . The error bars of the $p + p$ result are propagated using the averaged error of two neighboring data points. The $\pi^0 R_{AA}$ shows a similar centrality dependence as the R_{CP} . In the most central Au + Au collisions the π^0 yield is suppressed by a factor of about 5 relative to

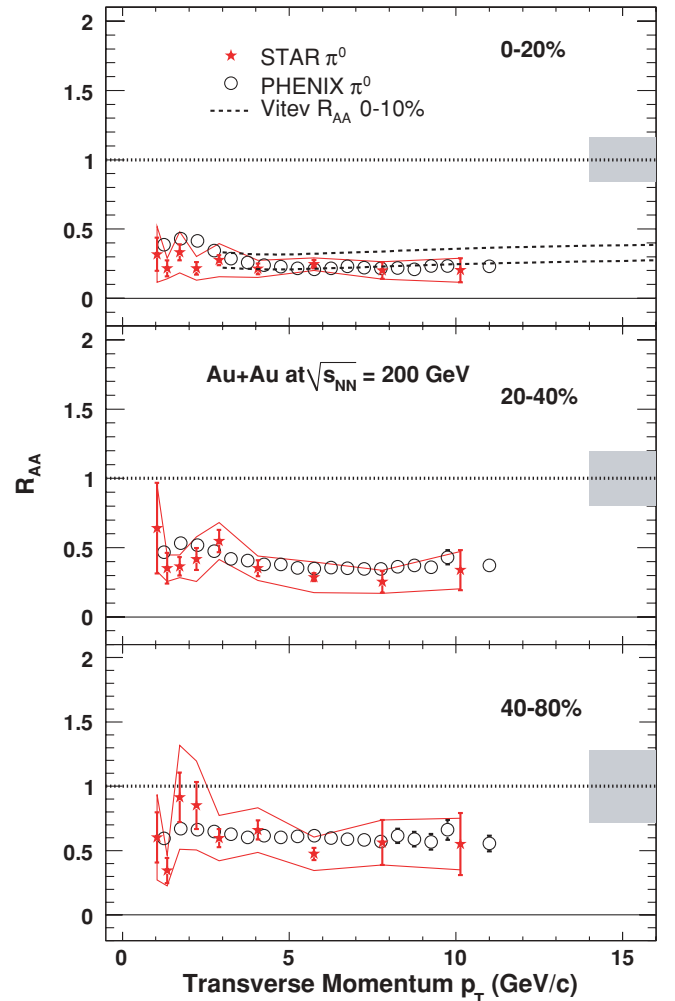


FIG. 9. (Color online) The nuclear modification factor R_{AA} as a function of p_T of STAR π^0 compared to PHENIX π^0 [13] in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Statistical errors are shown as vertical lines and point-to-point systematic errors are shown as solid lines. The shaded band on the right demonstrates the uncertainty of N_{bin} and the normalization uncertainty in $p + p$ collisions of 14% [3]. The dashed curves are theoretical calculations in 0–10% Au + Au collisions [19].

the expectation from scaled nucleon-nucleon collisions. For all the collision centrality bins, our measured R_{AA} values for π^0 at high p_T agree with previously published results from the PHENIX collaboration [13] within systematic uncertainties.

The nuclear modification factors for inclusive light quark mesons at high p_T in central heavy-ion collisions have been investigated with several model calculations. The nuclear modification factors R_{CP} and R_{AA} have been calculated in terms of parameters such as the initial gluon density [18,19] and the medium transport coefficient \hat{q} [20], which characterize properties of the dense matter created. Recent theoretical calculations suggest that the collisional energy loss may also play an important role in explaining the large suppression of nonphotonic electrons from heavy quark decays [21]. In Fig. 8, we show an example of a theoretical calculation of R_{CP} with initial gluon density $dN^g/dy = 1150$ in 0–10% Au + Au and between 100 and 150 in 40–80% Au + Au collisions [18]. In Fig. 9, theoretical calculations with $dN^g/dy = 800$ to 1150 for 0–10% Au + Au collision centrality [19] are shown as dashed curves in comparison to measurements from STAR and PHENIX from 0–20% collision centrality. Experimental measurements and theoretical predictions agree reasonably well, indicating that the yield suppression of light quark mesons may be accounted for by the parton energy loss mostly through gluon radiation.

IV. SUMMARY

We have presented the first STAR results for π^0 production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The π^0 spectra are measured over the range of $1 < p_T < 12$ GeV/c using the combination of conversion photons from TPC reconstruction and photons from BEMC energy measurement. Despite the relatively large tower size, the STAR BEMC alone can be used to reconstruct π^0 's for $p_T > 4$ GeV/c. The use of conversion

photons significantly enhances detection capability for π^0 's at low and intermediate p_T and extends our π^0 measurement to a lower- p_T range.

Our measurements of π^0 spectra are consistent with the STAR charged π^\pm and PHENIX π^0 results within statistical and systematic errors. The nuclear modification factors R_{CP} and R_{AA} of the STAR π^0 data confirm the previously published π results and can be described by theoretical calculations based on parton energy loss through gluon radiation in the dense medium created at RHIC. In the most central Au + Au collisions the inclusive π^0 yield shows a factor of about 5 suppression relative to the expectation from scaled $p + p$ collisions for $p_T > 5$ GeV/c. Our measurements confirm the magnitude of light hadron suppression observed in central Au + Au collisions and provide further support for the physical picture of jet quenching in the dense matter created in nucleus-nucleus collisions at RHIC.

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- [1] J. Adams *et al.*, Nucl. Phys. **A757**, 102 (2005).
 - [2] K. Adcox *et al.*, Nucl. Phys. **A757**, 184 (2005).
 - [3] J. Adams *et al.*, Phys. Rev. Lett. **91**, 172302 (2003).
 - [4] S. S. Adler *et al.*, Phys. Rev. Lett. **91**, 072301 (2003); B. B. Back *et al.*, Phys. Lett. **B578**, 297 (2004); I. Arsene *et al.*, Phys. Rev. Lett. **91**, 072305 (2003).
 - [5] C. Adler *et al.*, Phys. Rev. Lett. **90**, 082302 (2003); J. Adams *et al.*, Phys. Rev. Lett. **97**, 162301 (2006).
 - [6] M. Gyulassy, P. Levai, and I. Vitev, Phys. Rev. Lett. **85**, 5535 (2000); M. Gyulassy *et al.*, in *Quark Gluon Plasma 3*, edited by R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2003), p. 123.
 - [7] S. S. Adler *et al.*, Phys. Rev. Lett. **94**, 232301 (2005).
 - [8] M. Beddo *et al.*, Nucl. Instrum. Methods A **499**, 725 (2003).
 - [9] M. Anderson *et al.*, Nucl. Instrum. Methods A **499**, 659 (2003).
 - [10] J. Adams *et al.*, Phys. Rev. C **70**, 044902 (2004).
 - [11] F. S. Bieser *et al.*, Nucl. Instrum. Methods A **499**, 766 (2003).
 - [12] B. I. Abelev *et al.*, Phys. Rev. Lett. **97**, 152301 (2006).
 - [13] A. Adare *et al.*, Phys. Rev. Lett. **101**, 232301 (2008).
 - [14] B. I. Abelev *et al.*, Phys. Rev. Lett. **97**, 252001 (2006).
 - [15] J. Adams *et al.*, Phys. Rev. Lett. **92**, 112301 (2004).
 - [16] C. Amsler *et al.*, Phys. Lett. **B667**, 364 (2008).
 - [17] J. Adams *et al.*, Phys. Lett. **B637**, 161 (2006); J. Adams *et al.*, Phys. Lett. **B616**, 8 (2005).
 - [18] I. Vitev, Phys. Lett. **B639**, 38 (2006).
 - [19] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**, 252301 (2002).
 - [20] A. Dainese, C. Loizides, and G. Paic, Eur. Phys. J. C **38**, 461 (2005); C. Loizides, Eur. Phys. J. C **49**, 339 (2007).
 - [21] B. I. Abelev *et al.*, Phys. Rev. Lett. **98**, 192301 (2007).