Evolution of π^0 Suppression in Au + Au Collisions from $\sqrt{s_{NN}} = 39$ to 200 GeV

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Neutral-pion π^0 spectra were measured at midrapidity ($|y| < 0.35$) in Au + Au collisions at $\sqrt{s_{NN}} = 39$ and 62.4 GeV and compared with earlier measurements at 200 GeV in a transverse-momentum range of $1 < p_T < 10$ GeV/c. The high-p_T tail is well described by a power law in all cases, and the powers decrease significantly with decreasing center-of-mass energy. The change of powers is very similar to that observed in the corresponding spectra for $p + p$ collisions. The nuclear modification factors (R_{AA}) show significant suppression, with a distinct energy, centrality, and p_T dependence. Above $p_T = 7$ GeV/c, R_{AA} is similar for $\sqrt{s_{NN}} = 62.4$ and 200 GeV at all centralities. Perturbative-quantum-chromodynamics calculations that describe R_{AA} well at 200 GeV fail to describe the 39 GeV data, raising the possibility that, for the same p_T region, the relative importance of initial-state effects and soft processes increases at lower energies. The p_T range where π^0 spectra in central Au + Au collisions have the same power as in $p + p$ collisions is ≈ 5 and 7 GeV/c for $\sqrt{s_{NN}} = 200$ and 62.4 GeV, respectively. For the $\sqrt{s_{NN}} =$ 39 GeV data, it is not clear whether such a region is reached, and the x_T dependence of the x_T-scaling power-law exponent is very different from that observed in the $\sqrt{s_{NN}} = 62$ and 200 GeV data, providing further evidence that initial-state effects and soft processes mask the in-medium suppression of hard-scattered partons to higher p_T as the collision energy decreases.

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Large transverse-momentum (p_T) particles produced in high-energy nucleus-nucleus (AB) collisions play a crucial role in studying the properties of the medium created in relativistic heavy-ion collisions. Most hadrons at sufficiently high p_T are fragmentation products of hard-scattered partons, and their production rate in vacuum, as measured in $p + p$ collisions, is well described by perturbative quantum chromodynamics (pQCD) [1]. In the absence of any nuclear effects, the production rate in relativistic heavy-ion collisions in the pQCD regime, i.e., at sufficiently high p_T, would scale with the increased probability that a hard scattering occurs, due to the large number of nucleons. This probability is characterized by the nuclear overlap function T_{AB} [2]. However, such scaling has been violated to various degrees depending both on collision energy, $\sqrt{s_{NN}}$, and hadron p_T. At lower collision energies, the hadron yield is enhanced above the expected scaling. This was first observed in $p + A$, and this enhancement is generally attributed to multiple soft scattering (the "Cronin effect" [3]) and is presumed to occur in ion-ion collisions, as well. Initial parton distribution functions in nuclei are different from those in protons [4].

Finally, if a dense, colored medium is formed in the AB collision, the hard-scattered parton may traverse some of it, losing energy in the process. Therefore, the observed yield at a given (high) p_T will be lower than that expected from T_{AB} scaling, exhibiting "suppression" or "jet quenching," described in terms of the nuclear modification factor, R_{AA} [see Eq. (1)]. Alternatively, other studies divide the yields for heavy-ion collisions at one energy with those for the same colliding species at a lower energy Au + Au, rather than scaled $p + p$ reference data, to study energy and centrality scaling [5].

One of the first discoveries at the Relativistic Heavy-Ion Collider (RHIC) was a very large hadron suppression at high p_T (above ≈ 3 GeV/c) in $\sqrt{s_{NN}} = 130$ and 200 GeV Au + Au collisions [6–9]. This suppression was attributed to the dominance of parton energy loss in the medium, i.e., to final-state effects. To test this hypothesis, the same measurements were performed in d + Au collisions [10], where the formation of the hot, dense partonic medium is not expected and initial-state effects (if any) prevail. No suppression in d + Au data was observed, leaving little (if any) room for the initial-state effects as the origin of the large jet quenching observed in Au + Au. Studies with the lighter Cu + Cu system at three energies ($\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV [11]) have revealed that at $\sqrt{s_{NN}} =$ 22.4 GeV mechanisms that enhance R_{AA} (> 1) dominate at all centralities. Note, however, that this data set had a very limited p_T range ($p_T < 4$ GeV/c). At 62.4 GeV, jet quenching overwhelms any enhancement and leads to a suppression ($R_{AA} < 1$) in more central collisions.

The low-energy scan at the RHIC provides an opportunity to study the transition from enhancement ($R_{AA} > 1$) to suppression ($R_{AA} < 1$) and the evolution of R_{AA} with collision energy, centrality, and p_T. The results put constraints on energy-loss models (see [12] and references therein). Here, we present new measurements by the PHENIX experiment at the RHIC of π^0 invariant yields and R_{AA} in Au + Au collisions at $\sqrt{s_{NN}} = 39$ and 62.4 GeV. The data were taken during the 2010 run, and the p_T limits (statistics) were 8 and 10 GeV/c, respectively. Reference $p + p$-collision data for $\sqrt{s_{NN}} = 62.4$ GeV were taken in the same experiment in the 2006 run [13], while, for $\sqrt{s_{NN}} =$ 39 GeV, data measured in the Fermilab experiment E706 were used [14].

TABLE I. Sources of systematic uncertainties and their relative effect (in %) on the invariant yields for $\sqrt{s_{NN}} = 39$ GeV (62.4 GeV).

p_T:	2 GeV/c		5 GeV/c		Type
Yield extraction	3%	(3%)	3%	(3%)	A
Particle-identification efficiency	4.5%	(4.5%)	4.5%	(4.5%)	B
Energy scale	10.5%	(8.0%)	14.5%	(10.0%)	B
Acceptance	2%	(2%)	2%	(2%)	B
Conversion	4%	(4%)	4%	(4%)	B
Off vertex	1.5%	(1.5%)	1.5%	(1.5%)	C
Total yields for π^0	12.7%	(10.7%)	16.2%	(12.3%)	

Neutral pions were measured on a statistical basis via their $\pi^0 \rightarrow \gamma\gamma$ decay branch with the electromagnetic calorimeter [15]. The electromagnetic calorimeter comprises two calorimeter types: 6 sectors of lead scintillator sampling calorimeter (PbSc) and 2 sectors of lead glass Čerenkov calorimeter (PbGl). Each sector is located ≈ 5 m from the beam line and subtends $|\eta| < 0.35$ in pseudorapidity and $\Delta\phi = 22.5°$ in azimuth. This Letter presents results obtained with the PbSc sectors only. The segmentation of the PbSc ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$) ensures that the two photons from the $\pi^0 \rightarrow \gamma\gamma$ decays are very well resolved up to $p_T < 12$ GeV/c, i.e., across the entire p_T range of this measurement.

The results are based on data sets of 3.5×10^8 and 7.0×10^8 minimum-bias Au + Au events at 39 and 62.4 GeV, respectively. The minimum-bias trigger for both $\sqrt{s_{NN}} = 39$ and 62.4 GeV was provided by the beam-beam counters (BBC) [16], located close to the beam axis in both directions and covering $3.0 \leq |\eta| \leq 3.9$. In order to reduce background, at least two hits were required in both BBCs. This condition selects ~86% of the total inelastic cross section. The centrality selection in Au + Au collisions at both energies was based on the charged signal sum of the BBCs, which is proportional to the charged particle multiplicity. For each centrality, the average number of binary collisions ($\langle N_{coll}\rangle$) and the number of participants ($\langle N_{part}\rangle$) were calculated using a Glauber model [2] based Monte Carlo code.

The PHENIX analysis of neutral pions is described in detail elsewhere [9]. Table I lists the sources of systematic uncertainties on the extracted-π^0 invariant yields in this analysis. They can be divided into three different categories: (1) type-A, p_T-uncorrelated; (2) type-B, p_T-correlated, where the correlation may be an arbitrary smooth function; and (3) type-C, p_T-correlated, where all points move up or down by the same fraction. The main sources of systematic uncertainties in the π^0 measurement are the energy scale, yield extraction, and particle-identification efficiency correction.

Figure 1 shows the invariant yields of the π^0's for all centralities and also in minimum-bias collisions. From fitting the $\sqrt{s_{NN}} = 39$ and 62.4 GeV minimum-bias spectra with a power-law function ($\propto p_T^n$) for $p_T > 4$ GeV/c, we obtained the powers $n_{39} = -12.07 \pm 0.18$ and $n_{62.4} = -10.60 \pm 0.09$, respectively, significantly steeper than at $\sqrt{s_{NN}} = 200$ GeV, where $n_{200} = -8.06 \pm 0.08$ for minimum-bias collisions [9]. The slopes of the corresponding $p + p$-collision spectra are somewhat different, but comparable: $n_{39}^{pp} = -12.02 \pm 0.31$, $n_{62.4}^{pp} = -9.82 \pm 0.18$, and $n_{200}^{pp} = -8.22 \pm 0.09$, respectively.

Nuclear effects on the π^0 production are quantified using the nuclear modification factor

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{\rm evt})d^2N_{AA}^{\pi^0}/dp_T dy}{\langle T_{AB}\rangle d^2\sigma_{pp}^{\pi^0}/dp_T dy}, \quad (1)$$

where $\sigma_{pp}^{\pi^0}$ is the production cross section of π^0 in $p + p$ collisions and $\langle T_{AB}\rangle = \langle N_{coll}\rangle/\sigma_{pp}^{\rm inel}$ is the nuclear overlap function averaged over the range of impact parameters contributing to the given centrality class according to the Glauber model. Thus, R_{AA} compares the yield observed in $A + A$ collisions to the yield expected from the superposition of N_{coll} independent $p + p$ interactions. In the absence of nuclear effects, R_{AA} should be equal to unity. However, $R_{AA} \approx 1$ does not necessarily imply the absence of suppression; it may also indicate a balance between enhancing and depleting mechanisms.

In order to calculate R_{AA}, a reference p_T distribution in $p + p$ collisions is needed. Preferably, this is measured with the same detector, in which case many systematic uncertainties cancel in the ratio. The PHENIX experiment has measured the π^0 cross section in $p + p$ collisions at

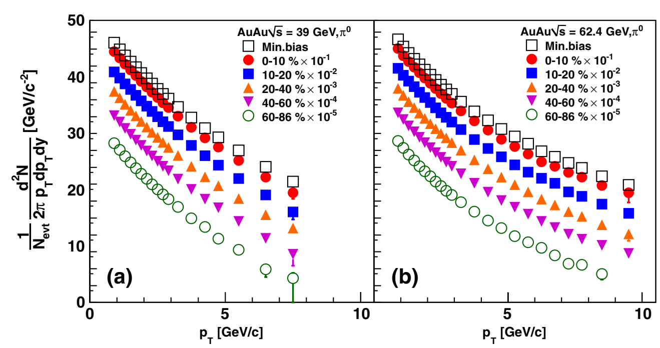

FIG. 1 (color online). Invariant yields of π^0 in Au + Au at (a) $\sqrt{s_{NN}} = 39$ GeV and (b) 62.4 GeV in all centralities and minimum bias. Only statistical uncertainties are shown.

$\sqrt{s_{NN}} = 62.4$ GeV [13], but only up to $p_T = 7$ GeV/c, while the current Au + Au measurement reaches up to 10 GeV/c. Hence, the $p + p$ data were fitted with a power-law function between $4.5 < p_T < 7$ GeV/c and then extrapolated. The systematic uncertainty resulting from this extrapolation reaches 20% at 10 GeV/c, estimated from a series of fits, where each time one or more randomly selected points are omitted and the remaining points are refitted.

Because PHENIX has not measured the $p + p$ spectrum of π^0 at $\sqrt{s_{NN}} = 39$ GeV, data from the Fermilab experiment E706 [14] were used. However, the E706 acceptance $(-1.0 < \eta < 0.5)$ is different from that of PHENIX $(|\eta| < 0.35)$, and, since $dN/d\eta$ is not flat and narrows for high-p_T particles, a p_T-dependent correction was applied to the E706 data. This correction factor was determined from a PYTHIA simulation by means of the ratio of yields (normalized per unit rapidity) when calculated from the observed yield in the PHENIX and E706 acceptance windows. The systematic uncertainty of the correction is 1–2% at 3 GeV/c but reaches 20% at 8 GeV/c.

Figure 2 shows the nuclear modification factor of π^0's measured in Au + Au collisions at $\sqrt{s_{NN}} = 39$, 62.4, and 200 GeV (data from [9]) as a function of p_T for (a) most central collisions and (b) 40–60% centrality. In the most central collisions (0–10%), there is a significant suppression for all three energies, while, in midperipheral collisions (40–60%) at $\sqrt{s_{NN}} = 39$ GeV, R_{AA} is consistent with unity above $p_T > 3$ GeV/c.

Figure 2 also shows pQCD calculations [17,18] for 0–10% centrality. The solid curves are obtained with a

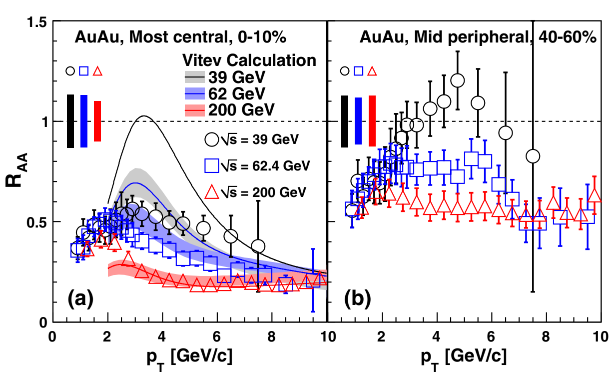

FIG. 2 (color online). Nuclear modification factor (R_{AA}) of π^0 in Au + Au collisions in (a) most central 0–10% and (b) midperipheral 40–60%. Error bars are the quadratic sum of statistical and p_T-correlated systematic uncertainties (including systematic uncertainties from the $p + p$-collision reference). Boxes around 1 are the quadratic sum of the C-type uncertainties combined with the N_{coll} uncertainties. These are fully correlated between different energies. Also shown for central collisions are pQCD calculations [18] with the Cronin effect, as implemented in [17] (solid lines), and with the Cronin effect corresponding to 30% larger initial-state parton mean free paths for all three energies (shaded bands).

parametrization of initial-state multiple scattering [17] that overestimates the Cronin effect. At high p_T, the theoretical result is compatible with the 200 GeV Au + Au data (and also the 200 GeV Cu + Cu data [11]). Neither the 62.4 nor the 39 GeV data are consistent with the predictions. The only qualitative agreement is that the turnover point of the R_{AA} curves moves to higher p_T with lower collision energy, as observed in the data. The bands are calculated within the same framework but with 30% larger initial-state parton mean free paths and the energy loss varied by ±10%. The Cronin effect is then compatible with lower energy $p + A$ data and earlier calculations [19]. The 200 GeV data are still well described, and the 62.4 GeV data are consistent within uncertainties, but the 39 GeV R_{AA}, particularly the shape, is inconsistent with the corresponding band.

Coupled with the observations that the slopes at high p_T become much steeper but the bulk properties (like elliptic flow, energy density, apparent temperature) change only slowly in the collision-energy range in question, it is quite conceivable that hard scattering as a source of particles at a given p_T becomes completely dominant only at higher transverse momentum; i.e., jet quenching will be "masked" up to higher p_T. Note that, while the shapes at lower p_T are different, at $p_T > \approx 7$ GeV/c R_{AA} is essentially the same for the 62.4 and 200 GeV data, irrespective of centrality (see also Fig. 3). The simultaneous description of results spanning such a wide range in $\sqrt{s_{NN}}$ is a challenge for energy-loss models that must incorporate multiple effects beyond radiative-energy-loss effects that may each have a different dependence on $\sqrt{s_{NN}}$.

Figure 3 shows p_T-averaged R_{AA} as a function of the number of participants. The averaging was done above $p_T > 6$ GeV/c. Our first observation is that R_{AA} decreases with increasing centrality even for the lowest-energy system. Similarly, as already discussed in the context of Fig. 2, at high enough p_T the suppression is the same at 62.4 and 200 GeV, at all centralities. This is remarkable because the power n of the fit to the spectra changes approximately by

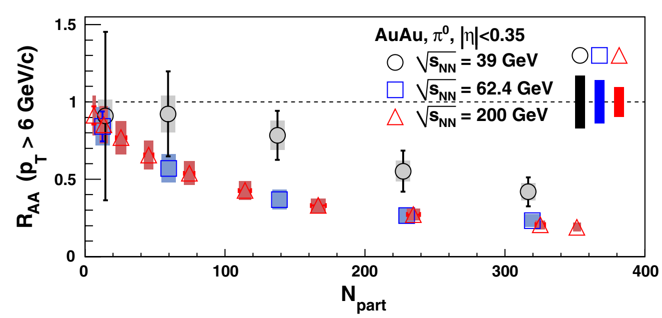

FIG. 3 (color online). Nuclear modification factor averaged for $p_T > 6$ GeV/c. Uncertainties are shown as error bars (statistical), boxes (sum of p_T-uncorrelated and N_{coll}), boxes around one (types B and C and uncertainties from the $p + p$-collision reference).

two units from 200 to 62.4 GeV, so the average momentum loss of the partons also has to be different in order to compensate the effect of the changing slope. The average momentum loss is usually defined by the fractional momentum shift $\delta p_T/p_T$ between the corresponding Au + Au and T_{AB}-scaled $p + p$ spectra as follows. Since the power-law tails of the $p + p$ and Au + Au spectra are similar, they can be fitted simultaneously with the same function and same power n

$$f(p_T) = \frac{A}{[p_T(1 + \delta p_T/p_T)]^n}, \quad (2)$$

with δp_T being the horizontal shift between the scaled $p + p$ and the Au + Au spectra. In panel (a) of Fig. 4, the observed fractional momentum shifts are shown for central collisions, as a function of the Au + Au p_T. This shows that partons in 200 GeV collisions suffer the largest average momentum loss compared to the lower energies.

Inclusive single-particle spectra at sufficiently high p_T and collision energy were predicted to exhibit scaling with the variable $x_T = 2p_T/\sqrt{s}$ such that the production cross section can be written in a form [20,21]

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}} G(x_T), \quad (3)$$

where $G(x_T)$ is a universal function and $n(x_T, \sqrt{s})$ characterizes the specific process [21]. The scaling power $n_{\mathrm{eff}}(x_T)$ between any pair of $\sqrt{s_{\mathrm{NN}}}$ energies is then calculated as

$$n_{\mathrm{eff}}(x_T) = \frac{\log[\mathrm{Yield}(x_T, \sqrt{s_1})/\mathrm{Yield}(x_T, \sqrt{s_2})]}{\log(\sqrt{s_2}/\sqrt{s_1})}. \quad (4)$$

In panel (b) of Fig. 4, $n_{\mathrm{eff}}(x_T)$ is shown when comparing invariant-π^0 yields in $p + p$ and Au + Au collisions at different energies. Both the shape and the magnitude of $n_{\mathrm{eff}}(x_T)$ are similar for the 62.4/200 GeV $p + p$ and Au + Au as well as for the 39/200 GeV $p + p$ data. The rise of $n_{\mathrm{eff}}(x_T)$ at lower x_T can be attributed to the dominance of soft processes [22], while at higher x_T they deviate strongly from leading-twist scaling predictions [21,23]. However, for 39/200 GeV, we observe a significant difference for $n_{\mathrm{eff}}(x_T)$ for $p + p$ compared to Au + Au collisions. It may not even reach its maximum in the measured x_T range, and its constant rise is similar to the rise observed in the low-x_T (soft) region of the other data shown. One possible explanation could be that, while present, hard scattering is still not the overwhelming source of high-p_T π^0's in the currently available p_T range in 39 GeV Au + Au collisions.

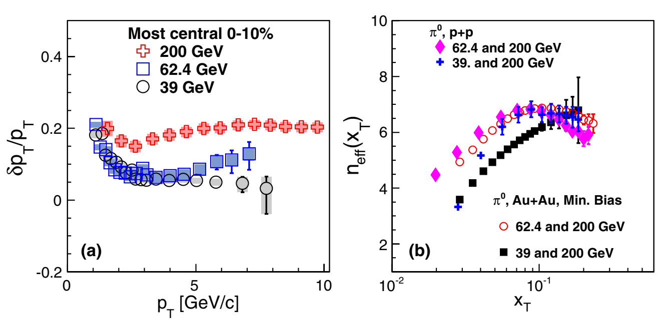

FIG. 4 (color online). (a) Fractional momentum shift $\delta p_T/p_T$ between Au + Au and T_{AB}-scaled $p + p$ data as a function of the Au + Au p_T. (b) Power n_{eff} of x_T scaling for $p + p$ and Au + Au (minimum bias) at various collision energies.

In summary, the π^0 p_T spectra were measured in Au + Au collisions at two different energies, $\sqrt{s_{\mathrm{NN}}} = 39$ and 62.4 GeV, and compared to the earlier result for $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. In all cases, the high p_T part of the invariant yields can be well described with a single power-law function. The powers decrease considerably at lower $\sqrt{s_{\mathrm{NN}}}$, and, since the soft processes change only slowly with collision energy, jet quenching might be masked up to higher transverse momenta. The high-p_T π^0 yields in Au + Au at 62.4 GeV are suppressed, and above $p_T > 6$ GeV/c the data points are comparable with the 200 GeV results at all centralities. The π^0 yields in Au + Au at 39 GeV are suppressed in the most central collisions, but no suppression is apparent in more peripheral collisions. At lower energies, a decreasing momentum shift compensates for the steeper slopes at high p_T, making the R_{AA}'s comparable, in fact, identical in the case of 62.4 and 200 GeV. When related to 200 GeV, $n_{\mathrm{eff}}(x_T)$ is similar for 62.4 and 39 GeV $p + p$ and 62.4 GeV Au + Au but very different for the 39 GeV Au + Au data. Measurements of flow, multiplicity, and other quantities indicate that the soft processes vary slowly with $\sqrt{s_{\mathrm{NN}}}$ [24]. Also, the Cronin effect, which counteracts suppression, is actually increasing with decreasing energy [25]. This, coupled with the rapid decrease of the high-p_T slope with decreasing energy, masks the in-medium suppression of hard-scattered partons up to higher p_T.

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