Onset of π^0 Suppression Studied in Cu + Cu Collisions at $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV

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Neutral pion transverse momentum (p_T) spectra at midrapidity ($|y| \lesssim 0.35$) were measured in Cu + Cu collisions at $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV. Relative to π^0 yields in $p + p$ collisions scaled by the number of inelastic nucleon-nucleon collisions ($N_{\rm coll}$) the π^0 yields for $p_T \gtrsim 2$ GeV/c in central Cu + Cu collisions are suppressed at 62.4 and 200 GeV whereas an enhancement is observed at 22.4 GeV. A comparison with a jet-quenching model suggests that final state parton energy loss dominates in central Cu + Cu collisions at 62.4 and 200 GeV, while the enhancement at 22.4 GeV is consistent with nuclear modifications in the initial state alone.

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The measurement of particle yields at high transverse momentum ($p_T \gtrsim 2$ GeV/c) has played a key role in characterizing the medium created in nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) [1,2]. Hadrons produced at sufficiently high p_T result from the interaction of quarks and gluons with high momentum transfer (“hard scattering”) which can be described by perturbative quantum chromodynamics (pQCD). These hadrons are produced as particle jets in the fragmentation of the scattered partons. A scattered parton propagating through a medium with high color-charge density such as a quark-gluon plasma loses energy (“jet quenching”) resulting in hadron yields at high p_T being suppressed [3]. Such a suppression was indeed observed in central Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV at RHIC, providing evidence for large color-charge densities in these systems [4–6]. This Letter presents results on the onset of π^0 suppression in Cu + Cu collisions as a function of $\sqrt{s_{NN}}$.

Characteristic properties of the suppression of hadrons at high p_T, e.g., the dependence on p_T and centrality, were studied in detail in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]. However, the energy dependence of hadron production in $A + A$ collisions as predicted by jet-quenching models [7–9] is not well constrained by measurements. Work in this direction was presented in [10–13]. To study the energy dependence of jet quenching it is desirable to measure identified particles in the same colliding system over a large $\sqrt{s_{NN}}$ range and to compare to $p + p$ reference data measured in the same experimental setup. Identified particles provide an advantage over unidentified hadrons in that the interpretation is not complicated by the different contributions from baryons and mesons. The study of Cu + Cu collisions is particularly useful because hadron suppression in Au + Au collisions is observed for rather peripheral collisions with a number of participating nucleons of $N_{\rm part} \sim 50$–100 [5]. This $N_{\rm part}$ range can be studied with reduced uncertainties in $N_{\rm coll}$ with the smaller ^{63}Cu nucleus.

A critical parameter in jet-quenching models is the initial color-charge density of the medium. By studying Cu + Cu collisions in the range $\sqrt{s_{NN}} \sim 20$–200 GeV this parameter can be varied with essentially no change in transverse size and shape of the reaction zone. Moreover, the enhancement of hadron yields due to multiple soft scattering of the incoming partons (“nuclear k_T” or “Cronin enhancement”) is expected to increase towards smaller $\sqrt{s_{NN}}$ [8], thus the interplay between this enhancement and the suppression due to parton energy loss can be studied.

In this Letter we present π^0 yields for Cu + Cu collisions at $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV. Reference data for $p + p$ collisions at $\sqrt{s} = 62.4$ and 200 GeV were taken with the same experiment [14,15]. At $\sqrt{s_{NN}} = 22.4$ GeV a $p + p$ reference was obtained from a parametrization of the world's data on pion production [16].

Neutral pions were measured via their $\pi^0 \to \gamma\gamma$ decay branch with the electromagnetic calorimeter (EMCal) of the PHENIX experiment [17]. The EMCal comprises two calorimeter types: 6 sectors of a lead scintillator sampling calorimeter (PbSc) and 2 sectors of a lead glass Cherenkov calorimeter (PbGl). Each sector is located ~5 m from the beam line and subtends $|\eta| < 0.35$ in pseudorapidity and

$\Delta\varphi = 22.5°$ in azimuth. Owing to the PbSc (PbGl) granularity of $\Delta\eta \times \Delta\varphi = 0.011 \times 0.011$ (0.008×0.008) the probability that the two photon showers from a π^0 decay result in partially overlapping clusters is negligible up to a π^0 p_T of 12 GeV/c (15 GeV/c). The energy calibration of the EMCal was corroborated by the position of the π^0 invariant mass peak, the energy deposited by minimum ionizing charged particles traversing the EMCal (PbSc), and the correlation between the measured momenta of electron and positron tracks identified by the ring-imaging Cherenkov detector and the associated energy deposited in the EMCal. These studies showed that the accuracy of the energy measurement was better than 1.5%.

The total number of analyzed Cu + Cu events for the three energies is shown in Table I. The minimum bias (MB) trigger for all reaction systems was provided by beam-beam counters (BBCs) located at $3.0 \lesssim |\eta| \lesssim 3.9$. The reaction vertex along the beam axis, determined from the arrival time differences in the BBCs, was required to be in the range $|z| \leq 30$ cm. An additional high-p_T trigger was employed in Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV. This trigger was based on the analog energy signal measured in overlapping 4×4 towers of the EMCal in coincidence with the MB trigger condition. It reached an efficiency plateau for photon energies $E \gtrsim 4$ GeV.

The centrality selection in Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 62$ GeV was based on the charge signal of the BBCs which is proportional to the charged-particle multiplicity. The BBC trigger efficiency ($\varepsilon_{\text{trig}}$) for these systems was determined with the aid of the HIJING event generator and a full GEANT simulation of the BBC response (see Table I). At $\sqrt{s_{NN}} = 22.4$ GeV centrality classes were defined based on the charged-particle multiplicity N_{PC1} measured with the pad chamber (PC1) detector ($|\eta| < 0.35$). The measured N_{PC1} distribution was accurately reproduced in a Glauber Monte Carlo calculation [18] and centrality classes were determined by identical cuts on the measured and simulated PC1 multiplicities. In the Glauber calculation N_{PC1} was assumed to scale with N_{part}^{α} and multiplicity fluctuations were described with a negative binomial distribution. Varying α and the negative binomial distribution parameters, the measured N_{PC1} distribution could be reproduced with $\varepsilon_{\text{trig}}$ values between 0.75 and 0.90. Possible autocorrelations between N_{PC1} and the π^0 yield resulting from measuring these quantities in the same pseudorapidity range were studied with HIJING and found to be negligible. Results of the Glauber calculations for $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV are shown in Table II.

Neutral pion yields were measured on a statistical basis by calculating the invariant mass of all photon pairs in a given event and counting those within the π^0 mass range. The background of combinatorial pairs was calculated by pairing photon hits from different events. Only photon pairs with an energy asymmetry $|E_1 - E_2|/(E_1 + E_2) < 0.7$ were accepted. The raw π^0 yields were corrected for the geometrical acceptance and reconstruction efficiency. The latter takes into account the loss of π^0's due to photon identification cuts, the energy asymmetry cut, inactive detector areas, and photon conversions. Moreover, it corrects the distortion of the π^0 spectrum which results from the finite energy resolution in conjunction with the steeply falling spectra and shower overlap effects. The reconstruction efficiency was determined in a Monte Carlo simulation and is typically on the order of $\varepsilon_{\pi^0} \approx 0.7$–0.8. For Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV the transition between the minimum bias and the high-p_T sample occurs at $p_T = 8$ GeV/c. The final spectra were calculated as the weighted average of the PbSc and PbGl results, which agree within 15%, a deviation well covered by the uncertainties.

The main systematic uncertainties of the π^0 spectra result from the π^0 peak extraction, the reconstruction efficiency, and the EMCal energy calibration. For $p_T \gtrsim 2$ GeV/c the peak extraction uncertainty is ~4% for all systems, approximately independent of p_T. The uncertainty in the reconstruction efficiency was estimated to be ~15% for the three Cu + Cu analyses. The uncertainty in the EMCal energy scale of 1.5% translates into an uncer-

TABLE I. Cu + Cu data sets presented with the number of analyzed events. For the data taken with the high-p_T trigger, the number of equivalent minimum bias events is given. At 22.4 GeV the given $\varepsilon_{\text{trig}}$ range indicates the uncertainty.

$\sqrt{s_{NN}}$ (GeV)	$\varepsilon_{\text{trig}}$	$N_{\text{evt}}^{\text{MB}}$	$N_{\text{evt}}^{\text{high}-p_T}$ ($N_{\text{evt}}^{\text{sampled}}$)
22.4	75%–90%	5.8×10^6	⋯
62.4	(88 ± 4)%	192×10^6	⋯
200	(94 ± 2)%	794×10^6	15.5×10^6 (4720×10^6)

TABLE II. Glauber Monte Carlo calculations for Cu + Cu collisions at 22.4, 62.4, and 200 GeV using inelastic cross sections of 32.3, 35.6, and 42 mb, respectively. The N_{coll} systematic uncertainty at 62.4 and 200 GeV is ~12%, almost independent of N_{coll}. At 22.4 GeV the relative uncertainty of N_{coll} can be parametrized as $0.094 + 0.173e^{-0.0272N_{\text{coll}}}$.

	22.4 GeV		62.4 GeV		200 GeV	
	$\langle N_{\text{part}}\rangle$	$\langle N_{\text{coll}}\rangle$	$\langle N_{\text{part}}\rangle$	$\langle N_{\text{coll}}\rangle$	$\langle N_{\text{part}}\rangle$	$\langle N_{\text{coll}}\rangle$
0%–10%	92.2	140.7	93.3	152.3	98.2	182.7
10%–20%	67.8	93.3	71.1	105.5	73.6	121.1
20%–30%	48.3	59.7	51.3	67.8	53.0	76.1
30%–40%	34.1	38.0	36.2	42.6	37.3	47.1
40%–50%	23.1	22.9	24.9	26.2	25.4	28.1
50%–60%	15.5	13.9	16.1	15.0	16.7	16.2
60%–70%	⋯	⋯	⋯	⋯	10.4	9.0
70%–80%	⋯	⋯	⋯	⋯	6.4	4.9
80%–94%	⋯	⋯	⋯	⋯	3.6	2.4
60%–88%	⋯	⋯	7.0	5.5	⋯	⋯

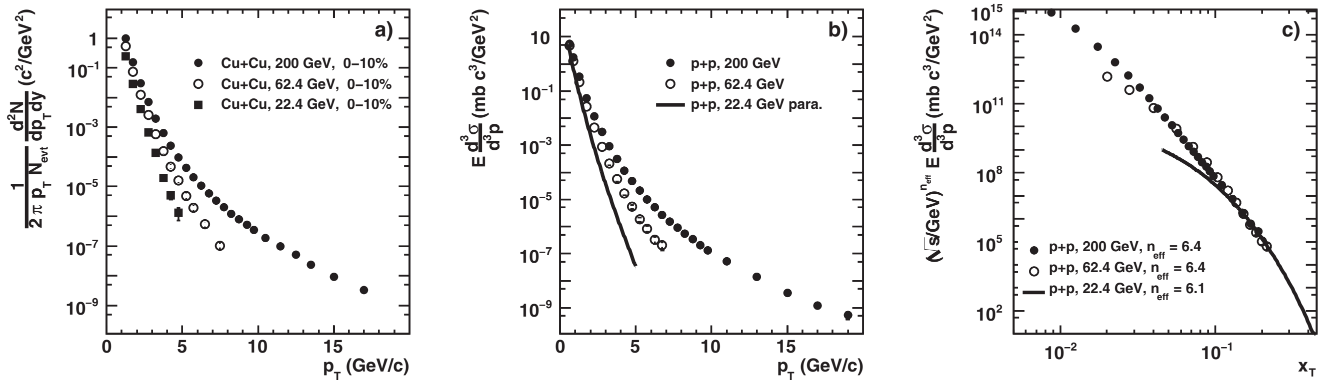

FIG. 1. For $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV are plotted (a) invariant π^0 yields in central Cu + Cu collisions, (b) invariant π^0 cross sections in $p + p$ collisions [14–16], and (c) the $p + p$ data plotted as a function of $x_T = 2p_T/\sqrt{s}$, which exhibit an approximate x_T scaling. The error bars represent the quadratic sum of the statistical and total systematic uncertainties.

tainty in the yields that increases from $\sim 8\%$ at $p_T = 3$ GeV/c to 15% at $p_T = 6$ GeV/c. The part of the spectra in Cu + Cu at 200 GeV measured with the high-p_T trigger is subject to an additional uncertainty of 10% related to the trigger efficiency.

PHENIX has not yet acquired a $p + p$ data set at $\sqrt{s} = 22.4$ GeV. In [16] the world's data on charged and neutral pion production for $21.7 \leq \sqrt{s} \leq 23.8$ GeV were scaled to $\sqrt{s} = 22.4$ GeV and fit with $Ed^3\sigma/d^3p = A(1 + p_T/p_0)^n(1 - 2p_T/\sqrt{s})^m$ where $A = 174.4$ mb GeV$^{-2}c^3$, $p_0 = 2.59$ GeV/c, $n = -17.43$, $m = 6.15$. The scaling correction was determined with a next-to-leading-order pQCD calculation. The correction is largest for $\sqrt{s} = 23.8$ GeV and reduces these spectra by $\sim 30\%$. The systematic uncertainty of the fit increases from $\sim 12\%$ at $p_T = 1.5$ GeV/c to $\sim 23\%$ at $p_T = 4.0$ GeV/c [16].

The π^0 p_T spectra for $p + p$ and central Cu + Cu collisions (0%–10% of $\sigma_{\mathrm{inel}}^{\mathrm{Cu+Cu}}$) at $\sqrt{s_{NN}} = 22.4, 62.4$ [14], and 200 GeV [6] are shown in Figs. 1(a) and 1(b). At sufficiently high p_T where pion production in $p + p$ collisions is dominated by fragmentation of jets, QCD predicts a scaling law $\sqrt{s}^{n_{\mathrm{eff}}(x_T,\sqrt{s})}\, Ed^3\sigma/d^3p = G(x_T)$ with a universal function $G(x_T)$ where $x_T = 2p_T/\sqrt{s}$ [19]. Figure 1(c) shows that such a scaling in x_T is indeed observed for $p + p$ collisions at 22.4, 62.4, and 200 GeV, consistent with previous observations [20]. The x_T values at which the universal curve $G(x_T)$ is reached indicate that particle production is dominated by hard processes for $p_T \gtrsim 2$ GeV/c.

Nuclear effects on high-p_T π^0 production can be quantified with the nuclear modification factor

$$R_{AA}(p_T) = \frac{(1/N_{AA}^{\mathrm{evt}})d^2N_{AA}/dp_Tdy}{\langle T_{AA}\rangle d^2\sigma_{pp}/dp_Tdy}, \qquad (1)$$

where $\langle T_{AA}\rangle = \langle N_{\mathrm{coll}}\rangle/\sigma_{pp}^{\mathrm{inel}}$. Figure 2 shows $R_{AA}(p_T)$ for the 0%–10% most central Cu + Cu collisions. The suppression at 62.4 GeV ($R_{AA} \approx 0.6$ for $p_T \gtrsim 3$ GeV/c) and 200 GeV ($R_{AA} \approx 0.5$–0.6 for $p_T \gtrsim 3$ GeV/c) is consistent with expectations from parton energy loss. The $R_{AA} > 1$ in Cu + Cu at 22.4 GeV is similar to the enhancement by a factor ~ 1.5 (at $p_T \approx 3$ GeV/c) observed in p + W relative to p + Be collisions at $\sqrt{s_{NN}} = 19.4$ and 23.8 GeV [21]. For similar N_{part} values the R_{AA} in Cu + Cu at 22.4 GeV agrees with the R_{AA} in Pb + Pb collisions at 17.3 GeV [12].

For $p_T \gtrsim 3$ GeV/c the measured R_{AA} values at 62.4 and 200 GeV are consistent with a numerically evaluated parton energy-loss model described in [22,23]; see Fig. 2. This calculation takes into account shadowing from coherent final state interactions in nuclei [24], Cronin enhancement

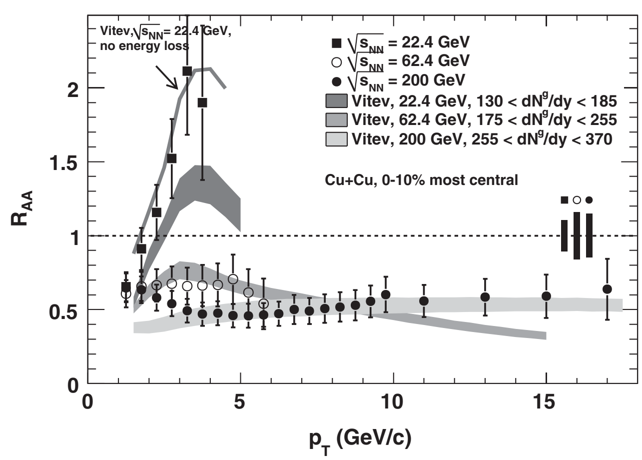

FIG. 2. Measured π^0 R_{AA} are compared to a jet quenching calculation [22,23]. The error bars (here and in Fig. 3) represent the quadratic sum of the statistical and the point-to-point uncorrelated and correlated systematic uncertainties. For $\sqrt{s_{NN}} = 22.4$ GeV the error bars also include the systematic error of the fit of the $p + p$ spectra. The boxes around unity indicate uncertainties related to $\langle N_{\mathrm{coll}}\rangle$ and absolute normalization. The bands for the calculation correspond to the assumed range of the initial gluon density dN^g/dy.

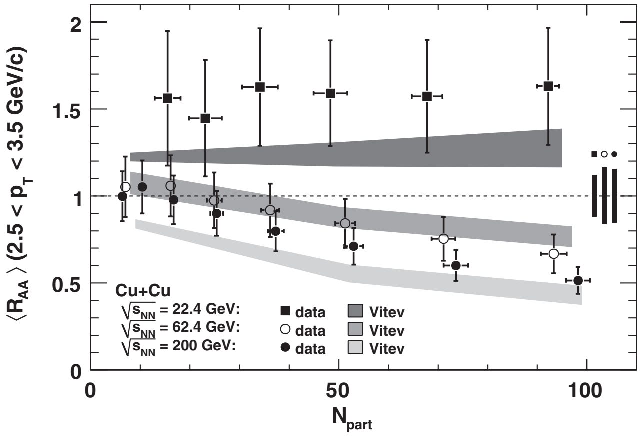

FIG. 3. The average R_{AA} in the interval $2.5 < p_T < 3.5$ GeV/c as a function of centrality for Cu + Cu collisions at $\sqrt{s_{NN}} =$ 22.4, 62.4, and 200 GeV. The shaded bands represent jet-quenching calculations at three discrete centralities ($N_{\rm part} \sim$ 10, 50, 100) [22,23]. The boxes around unity represent the normalization and $\langle N_{\rm coll} \rangle$ uncertainties for a typical $N_{\rm coll}$ uncertainty of 12%.

[25], initial state parton energy loss in cold nuclear matter [26], and final state parton energy loss in dense partonic matter [9,22,23]. The Cronin enhancement measured in $p + A$ collisions is described well by this model [25]. The initial gluon rapidity density dN^g/dy which characterizes the medium was not fit to the R_{AA} values, but instead was constrained by measured charged-particle multiplicities and the assumption of parton-hadron duality ($dN^g/dy = \kappa d\eta/dy dN_{ch}/d\eta$ with $\kappa = 3/2 \pm 30\%$ and $d\eta/dy \equiv 1.2$ at all energies) [22,23]. The average fractional energy losses $\Delta E/E$ for a quark (gluon) with $E =$ 6 GeV corresponding to the dN^g/dy ranges in Fig. 2 are 0.13–0.19 (0.29–0.42), 0.16–0.20 (0.35–0.44), 0.20–0.28 (0.44–0.63) in central Cu + Cu collisions at 22.4, 62.4, and 200 GeV, respectively [23]. For Cu + Cu at $\sqrt{s_{NN}} =$ 22.4 GeV the calculation is also shown without final state parton energy loss. The measurement is consistent with this calculation but does not rule out a scenario with parton energy loss.

Figure 3 shows that the π^0 suppression in the range $2.5 < p_T < 3.5$ GeV/c increases towards more central Cu + Cu collisions for $\sqrt{s_{NN}} =$ 62.4, 200 GeV. On the other hand, R_{AA} at $\sqrt{s_{NN}} =$ 22.4 GeV remains approximately constant as a function of $N_{\rm part}$, suggesting either that the Cronin enhancement depends only weakly on centrality or that in this energy range parton energy loss is offset by the larger effect of Cronin enhancement.

In conclusion, high-p_T π^0 yields in central Cu + Cu collisions at 62.4 and 200 GeV are suppressed, suggesting that parton energy loss is significant, while at 22.4 GeV the π^0 yields for $p_T \gtrsim 2$ GeV/c are not suppressed. The R_{AA} measured in central Cu + Cu at 22.4 GeV is consistent with Cronin enhancement alone but does not rule out parton energy-loss effects. These measurements provide a unique constraint for jet-quenching models and demonstrate that parton energy loss starts to prevail over the Cronin enhancement between $\sqrt{s_{NN}} =$ 22.4 and 62.4 GeV.

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