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Onset of $\pi(0)$ Suppression Studied in Cu plus Cu Collisions at root $s(\text{NN})=22.4, 62.4, \text{ and } 200 \text{ GeV}$

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Onset of $\pi(0)$ Suppression Studied in Cu plus Cu Collisions at root $s(\text{NN})=22.4$, 62.4, and 200 GeV

Abstract
Neutral pion transverse momentum ($p(T)$) spectra at midrapidity ($|y|$ less than or similar to 0.35) were measured in Cu + Cu collisions at root $s(\text{NN}) = 22.4$, 62.4, and 200 GeV. Relative to $\pi(0)$ yields in $p + p$ collisions scaled by the number of inelastic nucleon-nucleon collisions ($N_{\text{coll}}$) the $\pi(0)$ yields for $p(T)$ greater than or similar to 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.

Disciplines
Elementary Particles and Fields and String Theory | Physics

Comments

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Neutral pion transverse momentum ($p_T$) spectra at midrapidity ($|y| \approx 0.35$) were measured in Cu + Cu collisions at $\sqrt{s_{NN}} = 22.4$, 62.4, and 200 GeV. Relative to $\pi^0$ yields in $p + p$ collisions scaled by the number of inelastic nucleon-nucleon collisions ($N_{\text{coll}}$) the $\pi^0$ yields for $p_T \approx 2$ 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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\[ \Delta \varphi = 22.5^\circ \] in azimuth. Owing to the PbSc (PbGl) granularity of \( \Delta \eta \times \Delta \varphi = 0.011 \times 0.011 \) (0.008 \times 0.008) the probability that the two photon showers from a \( \pi^0 \) decay result in partially overlapping clusters is negligible up to a \( \pi^0 p_T \) of 12 GeV/c (15 GeV/c). The energy calibration of the EMCal was corroborated by the position of the \( \pi^0 \) 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 \( 3.0 \leq |\eta| \leq 3.9 \). 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 \times 4 towers of the EMCal in coincidence with the MB trigger condition. It reached an efficiency plateau for photon energies \( E \geq 4 \) 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 \( N_{\text{PC1}} \) measured with the pad chamber (PC1) detector \( (|\eta| < 0.35) \). The measured \( N_{\text{PC1}} \) 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 \( N_{\text{PC1}} \) was assumed to scale with \( N_{\text{part}} \) and multiplicity fluctuations were described with a negative binomial distribution. Varying \( \alpha \) and the negative binomial distribution parameters, the measured \( N_{\text{PC1}} \) distribution could be reproduced with \( \varepsilon_{\text{trig}} \) values between 0.75 and 0.90. Possible autocorrelations between \( N_{\text{PC1}} \) and the \( \pi^0 \) 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 \( \pi^0 \) 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 \( \pi^0 \) yields were corrected for the geometrical acceptance and reconstruction efficiency. The latter takes into account the loss of \( \pi^0 \)’s due to photon identification cuts, the energy asymmetry cut, inactive detector areas, and photon conversions. Moreover, it corrects the distortion of the \( \pi^0 \) 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 \( \varepsilon_{\pi^0} \simeq 0.7–0.8 \). 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 \( \pi^0 \) spectra result from the \( \pi^0 \) peak extraction, the reconstruction efficiency, and the EMCal energy calibration. For \( p_T \geq 2 \) GeV/c the peak extraction uncertainty is \( \sim 4\% \) for all systems, approximately independent of \( p_T \). The uncertainty in the reconstruction efficiency was estimated to be \( \sim 15\% \) 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. |

<table>
<thead>
<tr>
<th>( \sqrt{s_{NN}} ) (GeV)</th>
<th>( \varepsilon_{\text{trig}} )</th>
<th>( N_{\text{MB}} )</th>
<th>( N_{\text{high-}\ p_T} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.4</td>
<td>75%–90%</td>
<td>5.8 \times 10^6</td>
<td>\cdots</td>
</tr>
<tr>
<td>62.4</td>
<td>(88 \pm 4)%</td>
<td>192 \times 10^6</td>
<td>\cdots</td>
</tr>
<tr>
<td>200</td>
<td>(94 \pm 2)%</td>
<td>794 \times 10^6</td>
<td>15.5 \times 10^6 (4720 \times 10^6)</td>
</tr>
</tbody>
</table>

| 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 \( N_{\text{coll}} \) systematic uncertainty at 62.4 and 200 GeV is \( \sim 12\% \), almost independent of \( N_{\text{coll}} \). At 22.4 GeV the relative uncertainty of \( N_{\text{coll}} \) can be parametrized as \( 0.094 + 0.173e^{-0.0272N_{\text{coll}}} \). |

<table>
<thead>
<tr>
<th>( p_T ) (GeV)</th>
<th>( \langle N_{\text{pan}} \rangle )</th>
<th>( \langle N_{\text{coll}} \rangle )</th>
<th>( \langle N_{\text{pan}} \rangle / \langle N_{\text{coll}} \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%–10%</td>
<td>92.2</td>
<td>140.7</td>
<td>93.3</td>
</tr>
<tr>
<td>10%–20%</td>
<td>67.8</td>
<td>93.3</td>
<td>71.1</td>
</tr>
<tr>
<td>20%–30%</td>
<td>48.3</td>
<td>59.7</td>
<td>51.3</td>
</tr>
<tr>
<td>30%–40%</td>
<td>34.1</td>
<td>38.0</td>
<td>36.2</td>
</tr>
<tr>
<td>40%–50%</td>
<td>23.1</td>
<td>22.9</td>
<td>24.9</td>
</tr>
<tr>
<td>50%–60%</td>
<td>15.5</td>
<td>13.9</td>
<td>16.1</td>
</tr>
<tr>
<td>60%–70%</td>
<td>\cdots</td>
<td>\cdots</td>
<td>\cdots</td>
</tr>
<tr>
<td>70%–80%</td>
<td>\cdots</td>
<td>\cdots</td>
<td>\cdots</td>
</tr>
<tr>
<td>80%–94%</td>
<td>\cdots</td>
<td>\cdots</td>
<td>\cdots</td>
</tr>
<tr>
<td>60%–88%</td>
<td>\cdots</td>
<td>7.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>
tainty in the yields that increases from ~8% at \( p_T = 3 \text{ GeV/c} \) to 15% at \( p_T = 6 \text{ GeV/c} \). 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 \( \sqrt{s} = 22.4 \text{ GeV} \). In [16] the world’s data on charged and neutral pion production for 21.7 \( \leq \sqrt{s} \leq 23.8 \text{ GeV} \) were scaled to \( \sqrt{s} = 22.4 \text{ GeV} \) and fit with \( E d^3 \sigma \equiv A(1 + p_T/p_0)^m(1 - 2p_T/\sqrt{s})^n \) where \( A = 174.4 \text{ mb GeV}^{-2} \text{c}^3, p_0 = 2.59 \text{ GeV/c} \), \( n = -17.43, m = 6.15 \). The scaling correction was determined with a next-to-leading-order pQCD calculation. The correction is largest for \( \sqrt{s} = 23.8 \text{ GeV} \) and reduces these spectra by ~30%. The systematic uncertainty of the fit increases from ~12% at \( p_T = 1.5 \text{ GeV/c} \) to ~23% at \( p_T = 4.0 \text{ GeV/c} \) [16].

The \( \pi^0 \) \( p_T \) spectra for \( p+p \) and central Cu + Cu collisions (0%–10% of \( \sigma_{\text{inel}}^{\text{Cu+Cu}} \)) 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 \( \sqrt{s_{\text{coll}}(x_T,\sqrt{s})} E d^3 \sigma \equiv G(x_T) \) 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 \( p_T \geq 2 \text{ GeV/c} \).

Nuclear effects on high-\( p_T \) \( \pi^0 \) production can be quantified with the nuclear modification factor

\[
R_{AA}(p_T) = \frac{1/N_{AA}^{\text{nn}} d^2 N_{AA}/dp_T dy}{(T_{AA}) d^2 \sigma_{pp}/dp_T dy},
\]

where \( \langle T_{AA} \rangle = \langle N_{\text{coll}} \rangle / \sigma_{pp}^{\text{inel}} \). 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 \( p_T \geq 3 \text{ GeV/c} \)) and 200 GeV \( (R_{AA} = 0.5–0.6 \) for \( p_T \geq 3 \text{ GeV/c} \)) is consistent with expectations from parton energy loss. The \( R_{AA} \) in Cu + Cu at 22.4 GeV is similar to the enhancement by a factor ~1.5 (at \( p_T = 3 \text{ GeV/c} \)) observed in \( p + W \) relative to \( p + \text{Be} \) collisions at \( \sqrt{s_{NN}} = 19.4 \) and 23.8 GeV [21]. For similar \( N_{\text{part}} \) 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 \( p_T \approx 3 \text{ GeV/c} \) 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. 1.** For \( \sqrt{s_{NN}} = 22.4, 62.4, \) and 200 GeV are plotted (a) invariant \( \pi^0 \) yields in central Cu + Cu collisions, (b) invariant \( \pi^0 \) 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.

**FIG. 2.** Measured \( \pi^0 \) \( R_{AA} \) 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 \( \sqrt{s_{NN}} = 22.4 \text{ GeV} \) the error bars also include the systematic error of the fit of the \( p + p \) spectra. The boxes around unity indicate uncertainties related to \( (N_{\text{coll}}) \) 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 ($N_{\text{part}} \sim 10, 50, 100$) [22,23]. The boxes around unity represent the normalization and ($N_{\text{coll}}$) uncertainties for a typical $N_{\text{coll}}$ uncertainty of 12%.

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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[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 ($dN_g/dy = \kappa d\eta/dydN_{ch}/d\eta$ with $\kappa = 3/2 \pm 30\%$ and $d\eta/dy = 1.2$ 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 $\pi^0$ 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 $N_{\text{part}}$, 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-$p_T$ $\pi^0$ 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 $\pi^0$ yields for $p_T \approx 2$ GeV/c are not suppressed. The $R_{AA}$