Centrality Dependence of Direct Photon Production in $\sqrt{s_{NN}} = 200$ GeV Au + Au Collisions

The first measurement of direct photons in Au + Au collisions at √sNN = 200 GeV is presented. The direct photon signal is extracted as a function of the Au + Au collision centrality and compared to next-to-leading order perturbative quantum chromodynamics calculations. The direct photon yield is shown to scale with the number of nucleon-nucleon collisions for all centralities.

One of the most exciting observations from experiments at the Relativistic Heavy Ion Collider (RHIC) is the strong suppression of the yield of hadrons at large transverse momenta (p_T > 2 GeV/c) in central Au + Au collisions, as compared to measured yields in p + p collisions scaled by the number of binary nucleon-nucleon collisions [1–4].

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Such quenching was predicted to result from the energy loss of hard-scattered partons propagating through the high density matter created in heavy ion collisions [5]. It was later proposed that the observed hadron suppression could be an initial-state effect due to saturation of the initial parton distributions in large nuclei [6]. The high-$p_T$ hadron suppression was not observed in $d + Au$ collisions [7,8]. This indicates that the suppression in $Au + Au$ collisions is due to the extended dense matter in the final state that is absent in $d + Au$ collisions.

Measurement of direct photon production allows more definitive discrimination between initial- and final-state suppression due to the fact that photons, once produced, are essentially unaffected by the surrounding matter. Hence photons produced directly in initial parton scatterings are not quenched unless the initial parton distributions are suppressed in the nucleus. In fact, there may be additional direct photon yield in $AA$ collisions [9] due to various processes such as momentum broadening of the incoming partons, additional fragmentation contributions [10,11], or additional scatterings in the thermalizing dense matter of the final state.

This Letter reports on direct photon production in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV with data taken by the PHENIX experiment [12] during the second RHIC run (2001–2002). This analysis used the beam-beam counters (BBC, 3.0 < $|\eta|$ < 3.9) and the zero degree calorimeter (ZDC) for trigger and event characterization, the electromagnetic calorimeter (EMCal) in the two central arms ($|\eta| \approx 0.35$) to measure the inclusive $\gamma$, $\pi^0$, and $\eta$ yields, and the tracking system of the central arms to estimate the charged particle contamination. The EMCal consists of two subsystems: six sectors of lead-scintillator sandwich calorimeter (PbSc) and two sectors of lead-glass Čerenkov calorimeter (PbGl). Located at a radial distance of about 5 m, each sector covers an azimuthal interval of $\Delta \phi = 22.5^\circ$. The fine segmentation of the EMCal ($\Delta \phi \times \Delta \eta \sim 0.01 \times 0.01$) ensures that the two photons from a decayed $\pi^0$ are well resolved up to transverse momenta of 15–20 GeV/c.

The event centrality was selected by cuts on the correlated distribution of charged particles detected in the BBCs versus energy measured in the ZDC detectors. A Glauber model Monte Carlo combined with a simulation of the BBC and ZDC responses gave an estimate of the associated number of binary collisions ($N_{coll}$) and participating nucleons ($N_{part}$) for each centrality bin (values tabulated in Ref. [3]).

For this analysis a minimum bias trigger sample of $30 \times 10^6$ events, also used for the previously published $\pi^0$ analysis [3], was combined with a level-2 trigger event sample equivalent to additional $55 \times 10^6$ minimum bias events. The level-2 trigger sample was obtained by the use of an EMCal software trigger on highly energetic showers equivalent to the level-1 hardware trigger used in Ref. [13].

The threshold energy of the trigger was set at 3.5 GeV with a resulting trigger efficiency plateau at 100% for single photons above $p_T = 5$ GeV/c (6.5 GeV/c) for the PbSc (PbGl). The normalization of the level-2 data sample relative to the minimum bias data sample is accurate to 2%. In the following, the minimum bias result refers to the combined level-2 and minimum bias trigger samples without selection on centrality.

The direct photon yield is extracted on a statistical basis, without isolation cuts, by a comparison of the inclusive photon spectra to the expected background from hadronic decays [14,15] (mainly $\pi^0 \rightarrow 2 \gamma$). Photodilepton clusters are identified in the EMCal by applying appropriate particle identification (PID) cuts based on time of flight and the shower profile. The consistency of the final results obtained independently with the PbSc and PbGl, and with different PID cuts, including no PID cut, is used to check the systematic error estimates. The $\pi^0$ and $\eta$ yields are determined as described in [3,16] by an invariant mass analysis of photon pairs, with the combinatorial background established by combining uncorrelated photon pairs from different events.

The raw inclusive photon-candidate spectra must be corrected for charged and neutral hadron contaminations not removed by the PID cuts, as well as for photon conversions. Charged contaminants are identified by associating photon candidates in the EMCal with charged hits in the pad chamber (PC3) positioned directly in front of the EMCal. The charged contaminant spectra are subtracted from the photon-candidate spectra. The charged hadron contamination depends strongly on the PID cut and increases significantly for $p_T < 3$ GeV/c with a contribution of 4% above 3 GeV/c for the tightest PID cut. The contamination of neutral hadrons (mainly antineutrons) is determined with a full GEANT simulation of the detector response to neutrons and antineutrons with input spectra based on the proton and antiproton yields measured by PHENIX [4]. The neutral hadron contamination is found to be negligible above $p_T = 5$ GeV/c ($< 1\%$). The neutral photon-candidate spectra are corrected for conversions removed by the charged contaminant subtraction with a $p_T$-independent factor (5.9%–7.3% for different sectors based on simulation).

The raw spectra are normalized to one unit of rapidity and full azimuth (the purely geometrical acceptance correction is $\sim 1/0.35$). The spectra are further corrected for (i) the detector response (energy resolution, dead areas), (ii) the reconstruction efficiency (PID cuts), and (iii) occupancy effects (cluster overlaps). These corrections are quantified by embedding simulated single $\gamma$’s, $\pi^0$’s, or $\eta$’s from a full PHENIX GEANT simulation into real events and by analyzing the merged events with the same analysis cuts used to obtain the real yields. The overall $\pi^0$ yield correction was $\sim 2.5$ with a centrality dependence of $\lesssim 25\%$. The losses were dominated by fiducial and asym-
metry cuts. The nominal energy resolution was adjusted in the simulation by smearing the energies with a constant term of ~5% for PbSc and ~7% for PbGl to reproduce the measured width of the \( \pi^0 \) peak observed at each \( p_T \). The shape, position, and width of the \( \pi^0 \) peak measured for all centralities were confirmed to be well reproduced by the embedded data.

The energy calibration of the EMCal was corroborated by the position of the \( \pi^0 \) invariant mass peak, by the energy deposit from minimum ionizing charged particles traversing the EMCal (PbSc), and by the correlation between the measured momentum of electron and positron tracks identified by the ring-imaging Čerenkov detector and the associated energy deposit in the EMCal. From these studies it is determined that the accuracy of the energy measurement was better than 1.5%.

The main sources of systematic errors in the PbSc and PbGl measurements are the uncertainties in (i) the yield extraction, (ii) the yield correction, and (iii) the energy calibration. The yield correction has the largest error contribution in the most peripheral reactions. The yields extracted independently using the PbGl and PbSc electromagnetic calorimeters are quoted for the most peripheral and most central reactions. The error on the yield extraction is smaller for PbSc than for PbGl. The yield extraction error is significant for all centralities and is the largest source of systematic error in the most central reactions.

### TABLE I. Summary of the dominant sources of systematic errors on the \( \pi^0 \) and inclusive \( \gamma \) yields extracted independently with the PbGl and PbSc electromagnetic calorimeters. The error estimates are quoted at two \( p_T \) values in central events for the PbGl and PbSc. For the combined \( \pi^0 \) and inclusive \( \gamma \) spectra and \( \gamma/\pi^0 \) ratios, the approximate statistical and systematical errors are quoted for the most peripheral and most central reactions.

<table>
<thead>
<tr>
<th>Error source</th>
<th>PbGl (Central)</th>
<th>PbSc (Central)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^0 ) 3 GeV/c</td>
<td>8.7% 7.0%</td>
<td>9.8% 7.2%</td>
</tr>
<tr>
<td>( \pi^0 ) 8.5 GeV/c</td>
<td>10.3% 10.5%</td>
<td>11.4% 11.8%</td>
</tr>
<tr>
<td>Yield extraction</td>
<td>12.1% 12.0%</td>
<td>10.5% 10.8%</td>
</tr>
<tr>
<td>Yield correction</td>
<td>13.8% 14.1%</td>
<td>10.5% 11.4%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>20.3% 19.8%</td>
<td>17.7% 18.4%</td>
</tr>
<tr>
<td>Total systematic</td>
<td>10.6% 32.5%</td>
<td>2.1% 10.5%</td>
</tr>
<tr>
<td>Statistical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive ( \gamma ) error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-( \gamma ) correction</td>
<td>2.4% 2.4%</td>
<td>3.2% 3.2%</td>
</tr>
<tr>
<td>Yield correction</td>
<td>10.2% 12.0%</td>
<td>9.1% 12.5%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>15.7% 13.7%</td>
<td>12.4% 10.8%</td>
</tr>
<tr>
<td>Total systematic</td>
<td>18.9% 18.4%</td>
<td>15.7% 16.8%</td>
</tr>
<tr>
<td>Statistical</td>
<td>1.2% 14.1%</td>
<td>0.6% 4.1%</td>
</tr>
<tr>
<td>( \gamma/\pi^0 ) syst.</td>
<td>13.6% 12.6%</td>
<td>14.0% 13.4%</td>
</tr>
<tr>
<td>( \gamma/\pi^0 ) stat.</td>
<td>10.7% 35.4%</td>
<td>2.2% 11.3%</td>
</tr>
</tbody>
</table>

**Total errors PbGl and PbSc combined**

<table>
<thead>
<tr>
<th>Error source</th>
<th>Peripheral</th>
<th>Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^0 ) syst.</td>
<td>13.2% 17.0%</td>
<td>13.9% 16.1%</td>
</tr>
<tr>
<td>( \pi^0 ) stat.</td>
<td>3.0% 35.3%</td>
<td>1.8%  9.6%</td>
</tr>
<tr>
<td>( \gamma ) syst.</td>
<td>11.4% 15.6%</td>
<td>11.5% 15.9%</td>
</tr>
<tr>
<td>( \gamma ) stat.</td>
<td>3.0% 28.8%</td>
<td>0.6%  3.8%</td>
</tr>
<tr>
<td>( \gamma/\pi^0 ) syst.</td>
<td>9.9% 13.1%</td>
<td>9.7%  11.2%</td>
</tr>
<tr>
<td>( \gamma/\pi^0 ) stat.</td>
<td>4.2% 45.6%</td>
<td>1.9%  10.3%</td>
</tr>
<tr>
<td>( \gamma ) bkg calc.</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

The ratio of measured (inclusive) \( \gamma/\pi^0 \) and calculated background \( \gamma/\pi^0 \) since this has the advantage that many uncertainties, such as the energy scale, cancel to a varying extent in the ratio. Since the \( \pi^0 \) spectra of the background calculations are taken to be the same as the measured spectra, we have

\[
R_\gamma = \frac{<\gamma/\pi^0>_{\text{measured}}}{<\gamma/\pi^0>_{\text{background}}} = \frac{\gamma_{\text{measured}}}{\gamma_{\text{background}}},
\]

and any significant deviation of the double ratio above unity indicates a direct photon excess. In Fig. 1 an excess

![Picture](232301-4)

**FIG. 1 (color online).** Double ratio of measured (inclusive) \( \gamma/\pi^0 \) and calculated background \( \gamma/\pi^0 \) as a function of \( p_T \) for minimum bias and for five centralities of Au + Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) (0%–10% is the most central). Statistical and total errors are indicated separately on each data point by the vertical bar and shaded region, respectively. The solid curves are the ratio of pQCD predictions described in the text to the background photon invariant yield based on the measured \( \pi^0 \) yield for each centrality class. The shaded regions around the curves indicate the variation of the pQCD calculation for scale changes from \( p_T/2 \) to \( 2p_T \), plus the \( \langle N_{\text{coll}} \rangle \) uncertainty.
is observed at high \( p_T \) with a magnitude that increases with increasing centrality of the collision.

The measured results are compared to NLO perturbative QCD (pQCD) predictions [17], scaled by the number of binary nucleon collisions for each centrality selection. The same calculations are in agreement with the PHENIX direct photon measurement [15] for \( p + p \) collisions at the same \( \sqrt{s} \), and similar NLO pQCD calculations provide a good description of the measured \( \pi^0 \) production in \( p + p \) collisions [13]. The calculations were performed [15,17] with normalization and factorization scales set equal to \( p_T \), and using the CTEQ6 [18] set of parton distribution functions and the GRV set of fragmentation functions [19]. The direct photon spectra extracted as \( \gamma_{\text{Direct}} = (1 - R_{\gamma}^{-1}) \).

\( \gamma_{\text{Measured}} \) are shown in Fig. 2 for all nine centrality selections as well as minimum bias, and compared to the same NLO calculations. The binary collision scaled predictions are seen to provide a good description of the measured direct photon spectra (Fig. 2). The increasing ratio with centrality seen in Fig. 1 is therefore attributed to the decreasing decay background due to \( \pi^0 \) suppression [3].

Medium effects in AA collisions are often presented using the nuclear modification factor given as the ratio of the measured AA invariant yields to the NN-collision-scaled \( p + p \) invariant yields:

\[
R_{AA}(p_T) = \frac{\langle N_{coll}\rangle / \sigma_{pp}^{\text{inel}} \times \frac{1}{2\pi} d^2\sigma_{AA}/dp_Tdy}{\langle N_{coll}\rangle / \sigma_{pp}^{\text{inel}} \times \frac{1}{2\pi} d^2\sigma_{pp}/dp_Tdy}, \tag{2}
\]

where the \( \langle N_{coll}\rangle / \sigma_{pp}^{\text{inel}} \) is the average nuclear thickness function, \( \langle T_{AA} \rangle \), in the centrality bin under consideration (Ref. [3]). \( R_{AA}(p_T) \) measures the deviation of AA data from an incoherent superposition of NN collisions.

The centrality dependence of the high \( p_T \) \( \gamma \) production represented as a function of the number of participating nucleons, \( N_{\text{part}} \), is shown by the closed circles in Fig. 3. The production in \( Au + Au \) collisions relative to \( p + p \) is characterized by the \( R_{AA}(p_T > 6 \text{ GeV/c}) \) ratio of Eq. (2) as the ratio of Au + Au over the \( \langle N_{coll}\rangle \) scaled \( p + p \) yields each integrated above 6 GeV/c. The direct photon \( p + p \) yields are taken as the NLO pQCD predictions described above. As noted above, the high \( p_T \) direct \( \gamma \) production is well described by the \( p + p \) direct \( \gamma \) yield prediction scaled by \( \langle N_{coll}\rangle \) for all centralities. This is in sharp contrast [3] to the centrality dependence of the \( \pi^0 \) \( R_{AA}(p_T > 6 \text{ GeV/c}) \) shown by open circles in Fig. 3 where the measured \( \pi^0 \) yield [13] is used as the \( p + p \) reference in Eq. (2).

The observed close agreement between the measured yields and NLO calculations is in contrast to observations for central \( Pb + Pb \) collisions at \( \sqrt{s_{NN}} = 17.3 \text{ GeV} \) [14] where the measured photon yield exceeds the scaled NN photon yield by about a factor of 2. The present result constrains modifications of the initial parton distributions, or of the fragmentation contributions [10,11] (in these

![FIG. 2 (color online). Direct \( \gamma \) invariant yields as a function of transverse momentum for 9 centrality selections and minimum bias \( Au + Au \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The vertical error bar on each point indicates the total error. Arrows indicate measurements consistent with zero yield with the tail of the arrow indicating the 90% confidence level upper limit. The solid curves are pQCD predictions described in the text.](image-url)

![FIG. 3 (color online). Ratio of \( Au + Au \) yield to \( p + p \) yield normalized by the number of binary nucleon collisions as a function of centrality given by \( N_{\text{part}} \) for direct \( \gamma \) (closed circles) and \( \pi^0 \) (open circles) yields integrated above 6 GeV/c. The \( p + p \) direct photon yield is taken as the NLO pQCD prediction described in the text. The error bars indicate the total error excluding the error on \( \langle N_{coll}\rangle \) shown by the dashed lines and the scale uncertainty of the NLO calculation shown by the shaded region at the right.](image-url)
NLO calculations the contribution is significant: \(-50\%\) at 3.5 GeV/\(c\) and \(-35\%\) at 10 GeV/\(c\), or additional photon yield from thermal radiation to levels comparable to the present measurement uncertainty.

In summary, the transverse momentum spectra of direct photons have been measured at midrapidity up to \(p_T = 13\) GeV/\(c\) for nine centrality bins of Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. The significance of the direct photon signal increases with collision centrality due to the increasingly suppressed \(\pi^0\) production and associated decrease in the photon background from hadron decays. The direct photon spectral shapes and invariant yields are consistent with NLO pQCD predictions for \(p + p\) reactions scaled by the average number of inelastic NN collisions for each centrality class. The close agreement between measurement and the binary scaled pQCD predictions of the direct photon yield suggests that nuclear modifications of the quark and gluon distribution functions in the relevant region of momentum fraction \(x\) are minor. The result provides strong confirmation that the observed large suppression of high \(p_T\) hadron production in central Au + Au collisions is dominantly a final-state effect due to parton energy loss in the dense produced medium, rather than an initial-state effect.

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[16] S.S. Adler et al. (to be published). An \(\eta/\pi^0\) ratio of \(R_{\eta/\pi^0}(p_T \rightarrow \infty) = 0.45 \pm 0.05\) has been used.