Centrality Dependence of $\pi^0$ and $\eta$ Production at Large Transverse Momentum in $\sqrt{s_{_{NN}}} = 200$ GeV $d+Au$ Collisions

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The dependence of transverse momentum spectra of neutral pions and $\eta$ mesons with $p_T < 16$ GeV/c and $p_T < 12$ GeV/c, respectively, on the centrality of the collision has been measured at mid-rapidity by the PHENIX experiment at RHIC in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The measured yields are compared to those in $p+p$ collisions at the same $\sqrt{s_{NN}}$ scaled by the number of underlying nucleon-nucleon collisions in $d+Au$. At all centralities the yield ratios show no suppression, in contrast to the strong suppression seen for central Au+Au collisions at RHIC. Only a weak $p_T$ and centrality dependence can be observed.

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High-energy nucleus-nucleus collisions provide the opportunity to study strongly interacting matter at very high energy densities where Quantum Chromodynamics (QCD) predicts a transition from normal nuclear matter to a deconfined system of quarks and gluons, the Quark-Gluon Plasma (QGP) \[1\]. At the Relativistic Heavy Ion Collider (RHIC) so far is the suppression of hadrons with high transverse momentum \(p_T\) in central (head-on) \(Au+Au\) collisions. The hadron yield at high \(p_T\) is a factor of 5 less than expected from \(p+p\) collisions scaled by the number of corresponding nucleon-nucleon collisions \[2]\). Such suppression was predicted as an effect of parton energy loss in the medium generated in the collisions \[3]\). A control experiment of \(d+Au\) collisions, where no medium is produced in the final state of the collision, showed no indication of hadron suppression at mid-rapidity \[4\], ruling out strong initial-state effects (final-state energy loss in the cold nucleus is generally expected to be small) as the cause for the suppression in \(Au+Au\). For a better understanding of the medium effects at work in \(Au+Au\), however, it is crucial to explore the exact role initial-state effects play in the modification of high-\(p_T\) particle production at RHIC.

Initial-state nuclear effects include the Cronin effect, shadowing, and gluon saturation. The Cronin effect \[5\], an enhancement of the particle yield at intermediate \(p_T\), is usually attributed to multiple soft parton scatterings before a hard interaction of the parton (\(p_T\) broadening). The shadowing of the structure function \[6\] modifies the particle yield depending on the parton momentum fraction, \(x_{\text{Bj}}\), probed in the partonic scattering. An alternative model of the initial state of a nucleus is the gluon saturation or color glass condensate (CGC) in which the gluon population at low \(x_{\text{Bj}}\) is limited by non-linear gluon-gluon dynamics. In this picture, particle production at moderate \(p_T\) originally was predicted to be suppressed in central \(d+Au\) collisions at RHIC \[7\]. In recent CGC models, a Cronin enhancement can also be reproduced with a suitable choice of initial-state parameters \[8\].

One established way to test the contribution of different initial- and final-state nuclear effects is the study of the centrality dependence of particle production at high \(p_T\). Initial state and medium effects are strongest in central collisions. In \(Au+Au\) collisions a strong dependence of the suppression of high-\(p_T\) hadrons on the centrality of the collision has been observed \[9\]--\[12\]: the suppression weakens going to peripheral collisions and finally disappears. This can be compared to the centrality dependence of (initial-state) hadron production in \(d+Au\). The yield of non-identified charged hadrons in \(d+Au\) collisions with \(p_T < 6\) GeV/c was found to be increasingly enhanced going from peripheral to central collisions \[14\], mainly attributed to the influence of (anti)protons \[15\]. At high \(p_T\) the baryon contribution to the yield of unidentified charged hadrons is expected to become small and instead the yield is dominated by charged pions \[12\]. All this sparks paramount interest in the centrality dependence of neutral pion \(\pi^0\) production especially as it can be measured up to very high \(p_T\) where particle production is truly perturbative. Furthermore, the high-\(p_T\) measurement of an additional identified particle like the eta meson \(\eta\), with four times the mass of the pion, may shed light on the question to what extent the particle-species dependence of the suppression (enhancement) observed in \(Au+Au\) \((d+Au)\) depends on the number of constituent quarks rather than on the mass of the particle \[16\].

In this Letter we present measurements by the PHENIX experiment \[18\] on the production of \(\pi^0\) and \(\eta\) in \(p+p\) and \(d+Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV. The data provides the first measurement of neutral mesons in \(d+Au\) collisions at mid-rapidity as a function of the centrality of the collision. The \(\pi^0\) measurements described in this paper are similar to the analysis of minimum bias \(d+Au\) data in \[6\] but are based on an improved data set that allows the study of the particle production for different selections of the centrality of the collision.

\(\pi^0\) and \(\eta\) are measured by the PHENIX electromagnetic calorimeter (EMCal) via the \(\pi^0 \rightarrow \gamma\gamma\) and \(\eta \rightarrow \gamma\gamma\) decay. The EMCal consists of six lead scintillator (PbSc) and two lead glass (PbGl) sectors, each located at a radial distance of \(\sim 5\) m from the beam axis. The detector covers a pseudorapidity range of \(|\eta| \leq 0.35\) and an azimuthal angle of \(\Delta\phi = \pi\). The EMCal granularity is \(\Delta\eta \times \Delta\phi \approx 0.011 \times 0.011\) for the PbSc and \(0.008 \times 0.008\) for the PbGl. The data sets from PbSc and PbGl are analyzed separately and combined for the final results. The energy calibration for the EMCal is obtained from beam tests, cosmic rays, and minimum ionizing energy peaks of charged hadrons. In a recent improvement of the calibration, the EMCal is calibrated by the invariant mass distribution of neutral pions for each of the 24768 read-out channels separately. The uncertainty on the energy scale is 1.2%.

The data used in this analysis was recorded in 2002-2003 (RHIC Run-3) under two different trigger conditions. 25.2 \(\times 10^6\) and 58.3 \(\times 10^6\) minimum bias events were analyzed for \(p+p\) and \(d+Au\) collisions, respectively. Minimum bias (MB) events are triggered by the Beam-Beam Counters (BBC) \[19\] \((|\eta| = 3.0-3.9)\) and require a vertex position along the beam axis within \(|z| < 30\) cm. The minimum bias trigger accepts \((88 \pm 4)\%\) of all inelastic \(d+Au\) collisions that satisfy the vertex condition. This corresponds to \(1.99 \pm 5.2\)%, the measured fraction of the total \(d+Au\) inelastic cross section, determined using photo-dissociation of the deuteron \[15\]. In \(p+p\) this trigger measures 23.0 mb \(\pm 9.7\%\) of the \(p+p\) inelastic cross section. The measured particle yields are
corrected for the $p + p$ MB trigger bias $^{20}$: the MB trigger measures only $(79 \pm 2\%)$ of high-$p_T$ particles. In $d$+Au collisions this fraction varies from 85% to 100% from peripheral to central collisions; here the uncertainty is $\sim 3\%$. The second data sample was collected with a high-$p_T$ photon trigger in the EMCal in addition to the MB trigger requirement in order to extend the measurement to higher $p_T$. This trigger requires a photon of $p_T > 1.4(1.4)$ and $p_T > 2.5(3.5)$ for PbSc (PbGl) and for $p + p$ and $d + Au$ collisions, respectively. We analyzed $45.1 \times 10^6$ (19.5 $\times 10^6$) events in $p + p$ ($d + Au)$ under this trigger condition. The sampled integrated luminosity was 216 nb$^{-1}$ for $p + p$ and 1.5 nb$^{-1}$ for $d + Au$. (In $d + Au$ that corresponds to an integrated nucleon-nucleon luminosity of 590 nb$^{-1}$).

The division of $d$+Au collisions in different centrality classes is based on the charge deposited in the backward BBC ($-3.9 < \eta < -3.0$), i.e. in the Au beam direction. For each centrality class the corresponding average nuclear overlap function ($T_{AB}$) is calculated using a Glauber Monte Carlo model and simulations of the BBC, taking into account its limited efficiency for peripheral collisions. For the four centrality classes ($0 - 20\%$, $20 - 40\%$, $40 - 60\%$ and $60 - 88\%$) used in this analysis, $\langle T_{AB} \rangle$ translates into an average number of nucleon-nucleon collisions per A+B collision, $\langle N_{coll} \rangle = \sigma_{pp}^{inel} \times \langle T_{AB} \rangle$, of $(15.4 \pm 1.0)$, $(10.6 \pm 0.7)$, $(7.0 \pm 0.6)$ and $(3.1 \pm 0.3)$, respectively.

Photon candidates in the EMCal are selected by applying particle identification (PID) cuts based on the shower profile in the detector. To determine the yields of $\pi^0$ and $\eta$, the invariant mass of all photon pairs with an energy asymmetry $|E_1 - E_2|/(E_1 + E_2) < 0.7$ in a given $p_T$ bin is calculated. After subtraction of the combinatorial background the invariant mass distribution is integrated around the particle mass peak $^{11}$. The integration window reflects thereby the $p_T$ dependence of the mass peak position and width. The combinatorial background is determined by pairing photons from different events with similar centrality (for $d + Au$) and vertex. In this analysis the signal-to-background ratio for high-$p_T$ $\pi^0$ is about 25 and 13 at $p_T = 4$ GeV/c in $p + p$ and central $d + Au$ collisions, respectively. It decreases to 7 and 2 at $p_T = 2$ GeV/c. For $\eta$, this ratio is about 2 at $p_T = 8$ GeV/c, decreasing to 0.3 ($p + p$) and 0.2 (central $d + Au$) at $p_T = 3$ GeV/c. The raw spectra are corrected for trigger efficiency, acceptance, and reconstruction efficiency. This includes dead areas, the influence of energy resolution, analysis cuts, the peak extraction window, and photon conversion. The corrections are determined using Monte Carlo simulations. Due to the fine granularity of the calorimeter, occupancy effects are negligible. Furthermore, the $\pi^0$ spectra are corrected at $p_T > 10$ GeV/c (15 GeV/c) for two-photon merging effects in the PbSc (PbGl), studied in Monte Carlo simulations and confirmed with test beam data. Finally a correction in the $\pi^0$ and $\eta$ yields to account for the true mean value of each $p_T$ bin is applied to the steeply falling spectra. For $p_T < 3.5$ (3.0) GeV/c the $p + p$ $\pi^0$ ($\eta$) spectrum is calculated from the minimum bias data sample, above this threshold the high-$p_T$ triggered sample is used. In $d + Au$, this transition is made at $p_T = 4.5$ and 3.5 GeV/c for $\pi^0$ and $\eta$, respectively.

The main contributions to the systematic uncertainty on the $p + p$ and $d + Au$ spectra are given in Table I for $\pi^0$ and $\eta$. Most uncertainties are identical for $p + p$ and $d + Au$, only the uncertainty on the peak extraction is slightly larger in $d + Au$. Category (d) includes uncertainties on the EMCal global energy scale and non-linearity. The uncertainties in (d) and (e) are partially correlated. All others are uncorrelated.

The fully corrected $p_T$ distributions of $\pi^0$ and $\eta$ are shown in Fig. 1. The top panels show the invariant yield in $d + Au$ collisions for four centrality bins scaled for clarity by the factors indicated. The bottom panels show the invariant cross section in $p + p$ and $d + Au$ collisions. The improved dataset allows the study of $\pi^0$ ($\eta$) production up to 18 (12) GeV/c, the highest $p_T$ values measured for identified particles in $p(d)+A$ collisions. For the first time, the invariant cross section for $\pi^0$ and $\eta$ in $d + Au$ collisions has been measured at this energy. The $\pi^0$ result in $p + p$ agrees with the previous measurement at $\sqrt{s_{NN}} = 200$ GeV $^{27}$ within statistical uncertainties, and confirms the agreement with pQCD within the uncertainty of the calculation. Therefore the $p + p$ cross section can be used as a well-understood reference for the production in $d$+A and Au+Au collisions.

To quantify nuclear medium effects at high $p_T$ it is customary to use the nuclear modification factor which is given by the ratio of the $d + Au$ yield to the $p + p$ cross section $^{11}$ scaled by $\langle T_{AB} \rangle$:

$$R_{AB}(p_T) = \frac{d^2N_{d+Au}/dydp_T}{\langle T_{AB} \rangle} \times \frac{d^2\sigma_{pp}^{\pi^0}/dydp_T}{d^2\sigma_{pp}^{\eta}/dydp_T}. \quad (1)$$

The average nuclear overlap function $\langle T_{AB} \rangle$, averaged

| TABLE I: Main systematic uncertainties in % on $\pi^0$ and $\eta$ spectra. The uncertainties are given for PbSc (PbGl). The normalization uncertainties of 9.7% for the $p + p$ and 5.2% for the $d + Au$ cross section as well as the MB-trigger-bias uncertainty of $\sim 3\%$ for the centrality-selected yields are not listed. |
| --- |
| meson | $\pi^0$ | $\pi^0$ | $\eta$ | $\eta$ |
| $p_T$ (GeV/c) | 2 | 15 | 3 | 10 |
| a) peak extraction | 2.7(2.7) | 2.0(2.0) | 14(14) | 6.0(6.0) |
| b) geom. accept. | 3.5(3.5) | 3.5(3.5) | 4.5(4.5) | 4.5(4.5) |
| c) $\pi^0$ reconstr. eff. | 0.7(0.7) | 4.0(4.0) | 0.7(0.7) | 3.6(3.6) |
| d) energy scale | 5.0(5.0) | 11.4(11.4) | 5.0(5.0) | 9.4(9.4) |
| e) merging corr. | - | 5.9(2.1) | - | - |
| Total | 6.7(6.7) | 17.0(12.9) | 15.5(15.5) | 12.6(12.6) |
over the respective impact parameter range, is determined solely by the density distribution of the nucleons in the nuclei A and B and the impact parameter.

Figure 1 shows the nuclear modification factor $R_{dA}(p_T)$ for $\pi^0$ and $\eta$ in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV for four different centrality selections and for minimum bias events. As the $p+p$ and $d+Au$ measurements were both made in the same year, many of the systematic errors associated with detector performance were nearly identical and the corresponding systematic errors in the comparison are negligible. Within systematic errors $R_{dA}(p_T)$ for $\pi^0$ and $\eta$ is $\approx 1$ in all centrality bins, and only a weak $p_T$ dependence can be seen. In order to check the absolute normalization systematics we can also calculate $R_{dA}(p_T)$ using the inelastic cross section measured through photo-dissociation of the deuteron. This constitutes an important cross check. It replaces the systematic uncertainties of the BBC efficiency and $\langle T_{AB}\rangle$, which are determined by model calculations, by the uncertainty of the cross section measurement of similar size. The resulting $R_{dA}(p_T)$ is 9.8 % larger than that obtained from the minimum bias yield, consistent within 1.5 $\sigma$.

Though very different in mass, $\eta$ and $\pi^0$ show a similar, weak centrality dependence of $R_{dA}(p_T)$ over the measured $p_T$ range. These results do not show the significant enhancement seen for protons where the proton $R_{AA}$ is substantially larger than that of pions in the intermediate $p_T$ ($2 < p_T < 4$ GeV/$c$) region. The $\pi^0$ data exhibit small shape variations with centrality that may be due to initial-state effects including shadowing and multiple scattering. Possible Cronin enhancements in the intermediate $p_T$ region due to initial-state multiple scattering or anti-shadowing are not more than 10% around 4 GeV/$c$. At low $p_T$ ($p_T < 3$ GeV/$c$) the drop towards smaller $R_{dA}$ is consistent with analogous measurements for charged pions and is usually attributed to a change to a regime of soft physics ($N_{part}$ scaling) at the smallest $p_T$ values. At the largest $p_T$ values measured ($p_T > 9$ GeV/$c$) the most central $\pi^0$ result hints at a small suppression, though this is only a $\sim 1.7$ sigma effect.

In conclusion, we have presented the first study of the centrality dependence of $\pi^0$ and $\eta$ production at mid-rapidity in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Transverse momentum spectra up to $p_T = 18$ and 12 GeV/$c$
have been measured for $\pi^0$ and $\eta$, respectively. The invariant yield per nucleon-nucleon collision is compared to that in $p+p$ collisions measured at the same $\sqrt{s_{NN}}$. The strong suppression observed for $\pi^0$ production at high $p_T$ in central Au-Au collisions cannot be seen for $d+Au$ in any centrality: Within systematic errors $R_{dA}(p_T)$ is $\approx 1$ in all centrality bins. A weak centrality dependence of the shape of $R_{dA}$ versus $p_T$ is seen, presumably due to initial-state effects. A possible Cronin enhancement is substantially smaller than the $R_{dA} > 1.9$ that corresponds to results from lower energy measurements. Within systematic errors $R_{dA}$ for $\pi^0$ and $\eta$ agrees well, giving no indication for cold nuclear matter effects having a mass dependence. Since nuclear modifications in $d+Au$ are small even in the most central collisions where initial state effects are expected to be largest, we conclude that initial state effects in Au+Au must be small as well, so the large suppression seen in Au+Au must be mostly due to medium effects.

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