Energy scan of $\pi^0$ Suppression and Flow in Au+Au Collisions at PHENIX

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Abstract. The neutral pion spectra were measured by the PHENIX detector in $|y| < 0.35$ in Au+Au system at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV. The nuclear modification factor ($R_{AA}$) shows significant suppression and strong centrality dependence in Au+Au collisions. The azimuthal anisotropy is measured with respect to the reaction plane, determined at large rapidity. Here we present both $R_{AA}$ and azimuthal anisotropy of the $\pi^0$ in Au+Au for three different energies.

1. Introduction
A large suppression of the inclusive $\pi^0$ production, up to a factor of 5, observed for the first time in Au+Au at $\sqrt{s_{NN}} = 130$ GeV collisions [1] and $\sqrt{s_{NN}} = 200$ GeV collisions [2], is one of the most significant manifestations of the opaque QCD medium produced in heavy ion collisions. Absence of this suppression in d+Au at $\sqrt{s_{NN}} = 200$ GeV collisions [3] indicates that this phenomenon cannot be attributed to initial state effects or suppression by the cold nuclear matter [4].

Event anisotropy is expected to be sensitive to the early stages of heavy ion collisions. A possible formation of the quark-gluon plasma (QGP) could affect the way how the initial anisotropy in coordinate space is transferred into momentum space in the final state. At high-$p_T$, where the hard scattering processes are dominant over the soft processes, the event anisotropy provides us deeper understanding of the energy loss mechanism.

We show the new results from the latest RHIC low energy program from 2010, namely Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 39 GeV. The aim of the low energy scan is to search for the critical point of the phase transition and to see how the suppression of high-$p_T$ particles evolves. We present the $\pi^0$ elliptical flow and the nuclear modification factor.

2. Nuclear Modification Factor $R_{AA}$
The suppression of high-$p_T$ particles in medium is studied in terms of the nuclear modification factor:

$$R_{AA}(p_T) = \frac{(1/N_{\text{evt}}^{AA})d^2N_{\text{AA}}^{AA}/dydp_T}{\langle N_{\text{coll}} \rangle (1/N_{\text{evt}}^{pp})d^2N_{\text{pp}}/dydp_T},$$

where $d^2N/dydp_T$ is the yield in the corresponding system (p+p or Au+Au ) and $\langle N_{\text{coll}} \rangle$ is the average number of binary collisions obtained from the Glauber model Monte-Carlo [5]. The
observed suppression in Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) [2] \( (R_{AA} \approx 0.2) \) was interpreted to be caused by the energy loss of partons traversing the medium created in Au+Au collisions.

There are four main classes of theoretical models describing the energy-loss mechanism: opacity expansion (GLV) [6], multiple soft scattering (BDMPS-Z-ASW) [7], higher-twist (HT) [8], thermal field theory (AMY) [9]. Although all models provided quite accurate description of the measured \( \phi \)-integrated nuclear modification factor of \( \pi^0 \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) [2], we are still lacking a detailed understanding of the jet quenching phenomena [10].

3. Azimuthal Anisotropy \( v_2 \)

The elliptic flow \( v_2 \) is the second Fourier coefficient of the azimuthal distribution of selected particles. Neglecting the higher harmonics, the azimuthal yield can be written as

\[
\frac{dN}{d\phi} \propto 1 + 2 \cdot v_2 \cos (\phi - \psi_{RP}),
\]

where \( \phi \) is the azimuthal angle of an outgoing particle and \( \psi_{RP} \) is the reaction plane angle. In the optical Glauber model \( \psi_{RP} \) coincides with the direction of the nuclear impact parameter. However, in the real collision the \( \psi_{RP} \) does not necessarily coincide with the impact parameter due to the event-by-event nuclear density fluctuations. The measurements of the parameter \( v_2 \) in PHENIX at RHIC were performed for charged particles [11, 12] as well as for identified particles [13, 14].

The nuclear modification factor with respect to the reaction plane \( (\Delta \phi = \phi - \psi_{RP}) \) [15] allows to study an effect of the initial geometry on the observed suppression:

\[
R_{AA}(\Delta \phi_i, p_T) = R_{AA}^{incl}(p_T) \times \frac{N(\Delta \phi_i, p_T)}{(1/N_{bin}) \sum_{i=1}^{N_{bin}} N(\Delta \phi_i, p_T)},
\]

where \( R_{AA}^{incl}(p_T) \) is the nuclear modification factor as defined in Eq. (1), \( N(\Delta \phi_i, p_T) \) is the number of particles observed in the given \( (\Delta \phi_i, p_T) \) bin and \( N_{bin} \) is the number of the reaction plane bins. However, up to the contribution from higher harmonics, the high-\( p_T \) \( v_2 \) and the corresponding inclusive \( R_{AA} \) contain the same information as \( R_{AA}(\Delta \phi, p_T) \). This can be seen from:

\[
R_{AA}(\Delta \phi, p_T) = \frac{d^2N^{AuAu}/d\Delta \phi dydp_T}{(N_{coll}) d^2N^{pp}/d\Delta \phi dydp_T} \approx \frac{d^2N^{AuAu}/dydp_T (1 + 2 \cdot v_2 \cos (2\Delta \phi))}{(N_{coll}) d^2N^{pp}/dydp_T} = R_{AA}^{incl}(p_T) (1 + 2 \cdot v_2 \cos (2\Delta \phi)).
\]

Figure 1. The integrated \( v_2 \) and the in- and out-of-plane difference of the nuclear modification factor defined on the left hand side of the Eq. (5). The data are from the \( \pi^0 \) measurement in Au+Au at \( \sqrt{s_{NN}}=200 \text{ GeV} \) [14, 15].
Note that contributions from the higher harmonics ($v_3$, $v_4$, ...) are negligible at high-$p_T$ [16]. From Eq. (4) it follows that the often shown difference between the in- and the out-of-plane $R_{AA}$ is simply

$$R_{AA}(0,p_T) - R_{AA}(\pi/2,p_T) \approx 4 \cdot v_2(p_T).$$

PHENIX data [15] for $R_{AA}(\Delta \phi, p_T)$ and high-$p_T$ $v_2$ are shown in Fig. 1 to check how well Eq. (5) holds for the measured data. The different $p_T$ regions of the particle spectra are dominated by different physics processes, while the low-$p_T$ is considered for flow and hydrodynamical behavior, the production of high-$p_T$ particles are dominated by hard processes.

4. Energy Scan

In 2005 RHIC provided Cu+Cu collisions at three different center-of-mass energies, namely $\sqrt{s_{NN}} = 22.4, 62.4$ and 200 GeV [17]. The large suppression of $\pi^0$ at high-$p_T$ was observed at $\sqrt{s_{NN}} = 62.4$ and 200 GeV and moderate enhancement at $\sqrt{s_{NN}} = 22.4$ GeV, see Fig. 2 left. The $p_T$ averaged $R_{AA}$ showed a clear centrality dependence at $\sqrt{s_{NN}} = 62.4$ and 200 GeV and no centrality dependence at $\sqrt{s_{NN}} = 22.4$ GeV, see Fig. 2 right.

![Figure 2](image-url)
mass energies, \( \sqrt{s_{NN}} = 39-200 \) GeV, the data suggest either no or a rather week dependence of the measured \( v_2 \) on \( \sqrt{s_{NN}} \).

**Figure 3.** \( \pi^0 \) invariant yield spectra in Au+Au collisions at \( \sqrt{s_{NN}} = 39 \) GeV (left) and 62.4 GeV (right) in different centrality bins. The minimum bias data are shown as the open squares. Only the statistical uncertainties are shown.

**Figure 4.** The \( v_2 \) of \( \pi^0 \) as a function of \( p_T \) in \( \sqrt{s_{NN}} = 39, 62.4 \) and 200 GeV. Left panel shows the most central collisions (0-20%), right panel corresponds to more peripheral collisions (20-40%).

Evaluation of \( R_{AA} \) requires knowledge of the corresponding p+p reference. A p+p reference with the same experimental set-up as the heavy ion data reduces a significant part of the systematic uncertainties.

In the case of \( \sqrt{s} = 62.4 \) GeV p+p reference, PHENIX measured \( \pi^0 \) cross-section up to \( p_T < 7 \) GeV/c (see Fig 1. in [17]). However, the corresponding Au+Au data reach up to \( p_T < 10 \) GeV/c (see Fig. 3 right). In the range \( 7 < p_T < 10 \) GeV/c, the reference data were estimated by means of a power-law extrapolation of the existing data points. The systematic uncertainties resulting from the extrapolation are assessed based on varying the fit range used for the power-law fit. The extrapolated reference is compatible with the data points measured by the CCOR [20] experiment at ISR in the range \( 7 < p_T < 10 \) GeV/c within the systematic uncertainties (see Fig. 5).

The p+p reference at \( \sqrt{s} = 39 \) GeV has not been measured by PHENIX yet and therefore we used the \( \pi^0 \) yield measured by the Tevatron E706 experiment [21]. The acceptance correction coming from the different rapidity coverage was estimated based on the PYTHIA8 simulation [22] (see Fig. 6 right).
Figure 5. Left: The p+p reference at $\sqrt{s} = 62.4$ GeV from PHENIX [19] fitted with a power-law function. The data are compared with the data from the CCOR experiment at ISR [20]. Right: Relative difference between the measured data and the power-law fit which was used as the reference in the range $7 < p_T < 10$ GeV/c. The yellow band gives the estimated systematic uncertainties following from the extrapolation procedure.

Figure 6. Left: An example of the $\pi^0$ rapidity distribution obtained from E706 [21] and PYTHIA8 [22] in p+p collisions at $\sqrt{s_{NN}} = 39$ GeV. The $p_T$ range of selected $\pi^0$'s was $5.0 < p_T < 5.5$ GeV/c. The green and the blue box represent the rapidity coverage of the PHENIX and the E706 experiment respectively. Right: The ratio of PYTHIA8 simulated $\pi^0$ invariant yields in PHENIX and E706 acceptance. The estimated systematic uncertainty of this correction is given by the gray boxes around the data points.

The resulting $\pi^0$ $R_{AA}$ [18] was in Au+Au at $\sqrt{s_{NN}} = 39$ and 62.4 GeV is shown in Fig. 7. The left panel corresponds to the most central collisions where all three energies shows large suppression indicating that an opaque medium is produced even at the $\sqrt{s_{NN}} = 39$ GeV Au+Au collisions. The right panel shows a significant suppression of the $\sqrt{s_{NN}} = 200$ and 62.4 GeV Au+Au collisions for $p_T > 4$ GeV/c and for the same $p_T$ region for $\sqrt{s_{NN}} = 39$ GeV it is close to unity. In both centralities, the $R_{AA}$ for $\sqrt{s_{NN}} = 62.4$ and 200 GeV are comparable for $p_T > 6$ GeV/c.

The $p_T$ averaged $R_{AA}$ was calculated in two ranges, $4 < p_T < 6$ GeV/c and $p_T > 6$ GeV/c (see Fig. 8). In the lower $p_T$ region we observe a suppression of $\pi^0$ at $\sqrt{s_{NN}} = 62.4$ and 200 GeV and for the $\sqrt{s_{NN}} = 39$ GeV data the suppression starts to be pronounced only when $N_{part} > 100$. In the high $p_T$ range, $\sqrt{s_{NN}} = 62.4$ and 200 GeV data seem to have a similar magnitude of $R_{AA}$ at all centralities.
Figure 7. The nuclear modification factor measured in Au+Au collisions at $\sqrt{s_{NN}} = 39$, 62.4 and 200 GeV. The error bars shown represent a quadratic sum of the statistical uncertainties and the point-to-point uncorrelated and correlated systematic uncertainties. The boxes around unity indicate uncertainties related to $\langle N_{\text{coll}} \rangle$ and absolute normalization. Left: The most central collisions 0-10%. Right: The mid-peripheral collisions 40-60%.

Figure 8. The $p_T$ averaged $R_{AA}$ of $\pi^0$ in Au+Au at $\sqrt{s_{NN}} = 39$, 62.4 and 200 GeV as a function of the number of participants ($N_{\text{part}}$). Data corresponding to two $\pi^0$ $p_T$ ranges are shown: 4 < $p_T$ < 6 GeV/c (left) and $p_T$ > 6 GeV/c (right).

5. $x_T$ Scaling and Fractional Energy Loss
Inclusive single-particle spectra at sufficiently high-$p_T$ and collision energy were predicted to exhibit scaling in $\sqrt{s}$ with the variable $x_T = 2p_T/\sqrt{s}$ such that the production cross section can be written in a form [23, 24]

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

where $G(x_T)$ is a general function and the effective exponent $n(x_T, \sqrt{s})$ characterizes the process [24]. The scaling variable $n_{\text{eff}}(x_T, \sqrt{s})$ is evaluated using the linear variation of the logarithm of the ratio of the invariant cross-section in p+p collisions at different center of mass energies. In case of Au+Au data the total cross-section can be defined via the Glauber model where we observe the difference in collision energy range $\sqrt{s_{NN}} = 39$, 62.4 and 200 GeV is very small. Therefore, we obtain the effective exponent $n_{\text{eff}}(x_T, \sqrt{s})$ in case of Au+Au, from invariant yields instead of cross-section:

$$n_{\text{eff}}^{AA}(x_T) = \log \frac{\text{yield}(x_T, \sqrt{s_1})/\text{yield}(x_T, \sqrt{s_2})}{\log (\sqrt{s_2}/\sqrt{s_1})}.$$
Fig. 9 left panel shows the $x_T$ scaling power $n_{\text{eff}}(x_T)$ for pairing the $\pi^0$ invariant cross-sections in p+p and invariant yields in Au+Au collisions. In case of 62.4 and 200 GeV both for the p+p and Au+Au data show similar shape and they are comparable within the uncertainties. The p+p data for 39 and 200 GeV is comparable with the higher energy results. However, the $n_{\text{eff}}(x_T)$ for 39 and 200 GeV in Au+Au collisions behave differently when compared other data pairs. The rise of the effective exponent in lower $x_T$ values is attributed with the dominance of soft processes [25], while at higher $x_T$ values they deviate strongly from leading-twist scaling predictions [24, 26]. The data on Fig. 9 suggest that the transition from soft processes to hard processes occurs at higher $p_T$ in Au+Au collisions than in p+p collisions at 39 GeV.

![Figure 9](image1)

**Figure 9.** Left: The $x_T$ scaling power $n_{\text{eff}}(x_T)$ for p+p and Au+Au (minimum bias) calculated with different collision energy pairs. Right: Using the $n_{\text{eff}}$ we scaled the Au+Au and the p+p invariant yields. The Au+Au yield have an additional arbitrary scaling.

![Figure 10](image2)

**Figure 10.** Left panel shows the spectra of $\pi^0$ in the Au+Au and $T_{\text{AB}}$ scaled p+p spectra at 200 GeV collisions. The fractional momentum loss $\delta p_T/p_T$ is illustrated as the horizontal shift between the two spectra. Right panel shows the fractional momentum loss result for the most central collisions (0-10%) at 39, 62.4 and 200 GeV collisions.

The parton created from hard scattering is propagating through the medium and looses its energy. Final state fragments of this parton have also decreased magnitude of momentum, $p_T' = p_T - \delta p_T$, where $p_T$ and $p_T'$ are the original and final momentum of the $\pi^0$, respectively. The average momentum loss of the neutral pions can be studied as the momentum shift between
the Au+Au and $T_{AB}$ scaled p+p spectra. On Fig. 10 left panel we show the spectra of $\pi^0$ in Au+Au and scaled p+p collisions. The fractional momentum loss $\delta p_T/p_T$ is defined as a horizontal shift of the spectrum. On Fig. 10 right panel we show the point-by-point fractional momentum loss results for $\pi^0$ at three energies, namely 39, 62.4 and 200 GeV. The data shows the energy loss is the largest at 200 GeV collisions and approximately flat in this range.

6. Summary
The energy scan program at RHIC provides information about the evolution of the high-$p_T$ suppression. The $R_{AA}$ of $\pi^0$ was measured at three different energies in Au+Au at $\sqrt{s_{NN}} = 39$, 62.4 and 200 GeV. The most central collisions (0-10%) shows factor of 2 suppression at $\sqrt{s_{NN}} = 39$ GeV, while in mid-peripheral collision (40-60%) the high-$p_T$ particles are not suppressed. A strong suppression is shown at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV both in the most central and a still significant suppression in mid-peripheral collisions. The results suggest a smooth transition of the energy-loss in $\sqrt{s_{NN}}$ and system size (centrality). The measurement of the flow ($v_2$) of the $\pi^0$ at same colliding energies shows no significant dependence on the $\sqrt{s_{NN}}$, indicating the soft processes vary slowly with the collision energy. The $x_T$ scaling exponent suggest the transition from soft processes to hard processes occurs at higher $p_T$ in Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV than in p+p collisions at same collision energies.

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