Neutral meson production in Cu+Au collisions at 200 GeV

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Abstract. Strongly interacting quark-gluon plasma (sQGP) was discovered in central heavy ion collisions at RHIC energies. Jet quenching is one of the sQGP evidence observed in particle yields suppression related to yields measured in elementary nucleon-nucleon collisions. System of Cu+Au collisions is characterized by special nuclear overlap geometry different to other large systems (such as Au+Au). Study of such collision systems will help to estimate sQGP properties with higher accuracy. Neutral mesons such as $\pi^0$ give a good opportunity for studying sQGP effects especially jet quenching due to their large production rate. This paper presents results on neutral pion invariant differential spectra and nuclear modification factors measured with PHENIX experiment.

1. Introduction

In 2005 all experiments at Relativistic Heavy Ion Collider, RHIC (BNL, USA) [1] made a statement that strongly interacting Quark-Gluon Plasma (sQGP) had been found in central heavy nuclei collisions (A+A). It is a deconfined and liquid-like state of nuclear matter under extreme conditions of temperature and pressure [2–5].

Jet quenching is one of the evidences for sQGP formation, which manifests itself in suppressed production of high energy hadrons in A+A collisions relative to ones measured in elementary p+p collisions. Partons lose their energy interacting with hot and dense medium, which results in production of hadrons with softened spectra comparing to p+p collisions while direct photons do not interact with the medium, thus their production is not suppressed [6].

In relativistic heavy nuclei collision physics observables are usually measured as a function of collision centrality, which characterize relative geometry of colliding nuclei. In most central collisions with large overlap region centrality is taken equal to 0%. In peripheral collisions where only few nucleons take part in nuclei interactions centrality is about 50-60% (different for different colliding nuclei systems).

Particle suppression in A+A collisions is often studied with so-called nuclear modification factors ($R_{AA}$) calculated as a function of particle transverse momentum in different centrality A+A collisions:

$$ R_{AA} (p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} (p_T)}{dN_{pp} (p_T)}, $$ (1)
where $dN_{AA} (dN_{pp})$ – hadron invariant differential yields measured in A+A (p+p) collisions \( \langle N_{coll} \rangle \) – average number of binary inelastic nucleon-nucleon collisions calculated as a function of centrality by Glauber Monte-Carlo modelling \[7\]. If nuclear modification factor for hadrons emitted from the medium is equal to unity a collision of two nuclei could be described as a superposition of binary scaled elementary nucleon-nucleon collisions. Otherwise, different from unity $R_{AA}$ suggests that medium effects in nuclei interactions are presented.

Measurements of neutral pion($\pi^0$) yields provide excellent opportunity to probe sQGP formed in A+A collisions and study jet quenching effect. Neutral pions are light mesons consisting of first generation quark (u, d) combinations thus $\pi^0$ mesons are a significant part of particles produced in heavy nuclei collisions and their yields could be measured in a wide transverse momentum range with good signal to background ratio.

In 2012 RHIC successfully delivered Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This is a first asymmetric heavy nuclear collision system and differs from symmetric ones (Cu+Cu, Au+Au) by special form of nuclear overlap region. The study of particle suppression in such collision system will help to better discriminate between input parameters of various theoretical models and describe partonic energy loss mechanisms more precisely.

2. Experimental setup

PHENIX spectrometer consists of central and forward arms. Forward arms cover 1.2 < $|\eta|$ < 2.2 range in pseudo-rapidity and full azimuthal angle and provide capabilities for muon measurements \[8\]. Each central arm (Fig. 1), western and eastern, covers 90 degrees in azimuthal angle and $|\eta|$ < 0.35 region in pseudo-rapidity and provides detection of photons, electrons and charged hadrons originating from nuclei collision region \[9, 10\]. All results shown in the paper were obtained using central arms of the PHENIX detector.

Two beam-beam counters (BBC) \[11\] are used for z-vertex measurement and centrality classification of nuclei collision events. Also BBC provides the minimum bias (MinBias) trigger. Electromagnetic calorimeter \[12\] at PHENIX consists of six lead-scintillator sectors (PbSc) and two lead-glass sectors (PbGl) and provides measurements of photon kinematic properties and serves as an effective tool for neutral meson reconstruction. Usage of two different calorimeter types provide independent cross-check of final results within the same experiment. Calorimeter nominal energy resolution is $\delta E/E = 8.1\% / \sqrt{E(GeV)} \pm 2.1\%$ for PbSc and $\delta E/E = 5.9\% / \sqrt{E(GeV)} \pm 0.8\%$ for PbGl. Also electromagnetic calorimeter provides a ERT trigger, which is used for rare high energy events selection.

Figure 1. Layout of PHENIX detector central arms for RHIC Run-12 data taking period. Following detectors are presented in the layout: beam-beam counters (BBC), drift chambers (DC), ring-image Cherenkov detectors (RICH), electromagnetic calorimeter sectors(PbSc, PbGl), three layers of pad chambers (PC1, PC2, PC3), time-of-flight system (TOF).
3. Data analysis

Neutral pion yields were measured with EMCal by analysing transverse momentum dependent invariant mass distributions of daughter photons in $\pi^0 \rightarrow \gamma\gamma$ decay channel in different nuclei collision centrality bins. Two data samples are used in the analysis: MinBias ($6 \cdot 10^9$ events) and ERT ($1.8 \cdot 10^{10}$ events). MinBias and ERT data samples were used to measure $\pi^0$ meson yields at $p_T < 8$ GeV/$c$ and $p_T > 8$ GeV/$c$ ranges respectively.

Among the analysis details one of the most important is the requirement for each photon from $\pi^0$ decay to have energy larger than 0.4 GeV. To obtain better signal-to-background ratio an asymmetry cut was applied on combined photons energies: $\alpha < 0.8$, where $\alpha = |E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2})$.

The reconstruction efficiency for neutral pions in acceptance of PHENIX detector was obtained with Geant 3 Monte-Carlo simulation. All event selection cuts were applied into simulation in the same way than in real data. Reconstruction efficiency as a function of transverse momentum was calculated as a ratio of the number of neutral pions reconstructed in simulation to their total number separately for different collision centralities.

Systematic uncertainty of results was obtained by varying different analysis parameters. Main uncertainty comes from possible mismatch of calorimeter absolute energy scale in data and simulation. At high transverse momentum ($p_T > 13$ GeV/$c$) cluster merging effect gives a significant contribution to the total systematic uncertainty: two photons from high energy $\pi^0$ decay have such a narrow opening angle and are reconstructed in electromagnetic calorimeter as one photon, thus $\pi^0$ could not be reconstructed. Cluster merging effect is more significant for PbSc subsystem then for PbGl one due to lower sector granularity. Total systematic uncertainty changes from 8% at low $p_T$ to 25% at high $p_T$ for PbSc sectors and from 8% at low $p_T$ to 15% at high $p_T$ for PbGl sectors.

4. Results

Invariant transverse momentum $\pi^0$ meson yields as a function of transverse momentum and collision centrality were calculated separately for PbSc and PbGl subsystems according to formula:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Invariant differential $\pi^0$ meson spectra measured in Cu+Au collisions at 200 GeV with no centrality selection (a) and for different centrality bins (b). Curves on the plot (b) are shown for 0-10\% (○, multiplied by $10^2$), 10-20\% (□, multiplied by $10^1$), 20-40\% (∆), 40-60\% (●, multiplied by $10^{-1}$), 60-90\% (■, multiplied by $10^{-2}$).}
\end{figure}
\[ dN_{AA}(p_T) = \frac{1}{2p_T \Delta p_T N_{\text{events}} \epsilon_{\text{acc.rec.eff}}(p_T) BR}, \]

where \( N_{\pi^0} \) – extracted raw yields, \( N_{\text{events}} \) – number of analyzed events, \( \epsilon_{\text{acc.rec.eff}} \) – reconstruction efficiency, \( BR = 0.998 \) – branching ratio for \( \pi^0 \to \gamma\gamma \) decay channel.

Resulted yields were obtained by averaging ones measured using PbSc and PbGl subsystems with weights inversely proportional to statistical and systematic uncertainties. Fig. 2 presents invariant differential transverse momentum spectra of neutral pions measured in different centrality Cu+Au collisions. Spectra are measured in a large \( p_T \) range: up to 20 GeV/c in central and semi central collisions.

Neutral pion nuclear modification factors were calculated according to formula (1) in different centrality Cu+Au collisions (Fig. 3). Invariant differential spectrum of \( \pi^0 \) mesons measured in p+p collisions at 200 GeV is published in [13]. In central Cu+Au collisions (0-10%) \( \pi^0 \) production is suppressed two times in comparison with \( \pi^0 \) yields measured in elementary p+p collisions. In peripheral Cu+Au collisions (60-90%) a hint on production of neutral pion yields is observed.

Suppression pattern observed for \( \pi^0 \) in Cu+Au collisions at 200 GeV is similar to one observed for reconstructed jets in same collision system [14].

Comparison of \( \pi^0 \) meson nuclear modification factors vs. \( p_T \) measured in Cu+Au, Au+Au [15] and Cu+Cu [16] collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) and similar numbers of participants is presented.

![Figure 3.](image-url)

Nuclear modification factors as a function of \( \pi^0 \) mesons transverse momentum measured in 0-10% (a), 10-20% (b), 20-40% (c), 40-60% (d), 60-90% (e) centrality bins and with no centrality selection (f) Cu+Au collisions at 200 GeV. Boxes at markers show transverse momentum dependent systematic uncertainty. Open boxes at unity show scaling uncertainty.
Figure 4. Comparison of $\pi^0$ meson nuclear modification factors, measured as a function of transverse momentum in Cu+Au (●), Au+Au (▲) and Cu+Cu (▼) collisions at 200 GeV. Panel (a) is for 0-10% Cu+Au with $N_{\text{part}} = 177$ and 20-30% Au+Au with $N_{\text{part}} = 167$. Panel (b) is for 20-40% Cu+Au with $N_{\text{part}} = 80$, 40-50% Au+Au with $N_{\text{part}} = 74$ and 0-10% Cu+Cu with $N_{\text{part}} = 98$.

in Fig. 4 for central and semi-central Cu+Au collisions. One can see that $\pi^0$ shows a similar suppression in the whole transverse momentum range. This fact suggests that $\pi^0$ suppression level depends on the size of the nuclear overlap region but not on its shape.

5. Conclusion

PHENIX experiment has measured neutral pion invariant differential yields and nuclear modification factors in different centrality Cu+Au collisions at 200 GeV.

In central Cu+Au collisions $\pi^0$ meson yields are suppressed approximately by a factor of 2, while in peripheral collisions a hint on enhancement for neutral pion yields is observed. Reconstructed jets measured in Cu+Au collisions at 200 GeV are suppressed in similar way than neutral pion yields. Suppression level of $\pi^0$ mesons depends on the size of the medium but not on its shape.

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