Nuclear modification factors of light mesons in Cu+Au collisions

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Abstract. Strongly interacting quark-gluon plasma (sQGP) is a state of nuclear matter at extremely high values of temperature with quarks and gluons as degrees of freedom. Jet-quenching is one of the evidences for sQGP formation in relativistic heavy ion collisions (A+A) and is manifested by suppression of particle yields at high transverse momentum relative to yields of the same particles measured at elementary proton-proton collisions at the same collision energy. Systematic experimental research of jet-quenching is provided by the measurement of nuclear modification factors of light mesons ($\pi^0$, $\eta$, $K^0_s$, $\omega$ etc.) in different A+A systems.

Asymmetric system of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is characterised by similar energy density but different collision geometry when compared to symmetric systems (Au+Au or Cu+Cu). This paper presents measurements of $\pi^0$ and $\eta$ mesons nuclear modification factors in Cu+Au collisions. Results are compared with ones measured in Au+Au and Cu+Cu collisions at the same collision energy.

1. Introduction

Strongly interacting quark-gluon plasma (sQGP) presents a liquid-like state of quasi-free quarks and gluons (partons) at extremely high values of temperature ($T \approx 170$ MeV, $\sim 10^{12}$ K). First theoretical predictions of quark-gluon plasma were carried out by E. Shuryak [1], and first statements of the sQGP formation were made by experiments [2–5] in central collisions of relativistic heavy ions (A+A) at the Relativistic Heavy Ion Collider, RHIC (BNL, USA) [6].

Jet-quenching [7, 8] is the one of the effects, which indicates the sQGP formation. It is manifested by suppression of yields of jets and leading hadrons in A+A relative to binary scaled yields measured in elementary proton-proton ($p+p$) collisions. This effect suggests that high energy partons produced in hard scattering processes lose their energy in the quark-gluon medium, which results in the production of hadrons with the reduced transverse momentum ($p_T$) values.

Nuclear modification factor ($R_{AA}$) is the main observable of jet-quenching and other collective effects in heavy ion collisions:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}(p_T)}{dN_{pp}(p_T)},$$

(1)

where $dN_{AA}$ ($dN_{pp}$) – particle invariant differential yields measured in A+A ($p+p$) collisions, $\langle N_{coll} \rangle$ – average number of binary inelastic nucleon-nucleon collisions. Values of $R_{AA}$ are calculated in different intervals of the collision centrality, which represents the magnitude of
the nuclei overlap. Centrality of 0–20% corresponds to central collisions with a large nuclear overlap region, and centrality of 60–90% corresponds to the most peripheral collisions, where only few nucleons participate in the nuclei interactions.

Systematic study of jet-quenching includes measurement of $p_T$-spectra and $R_{AA}$ of different particles in different systems of colliding nuclei. The PHENIX spectrometer provides excellent capabilities for measurement of light neutral mesons ($\pi^0$, $\eta$, $K^0_s$, $\omega$ etc.). Pions are copiously produced in the nuclei interactions thus $\pi^0$ yields can be measured in a wide $p_T$-range with relatively small uncertainties. $\eta$ mesons have a four-times larger mass and a hidden strangeness thus the measurement and comparison of $R_{AA}$ of $\pi^0$ and $\eta$ provide an opportunity to study the dependence of jet-quenching on particles mass and quark content of the fragmented particles. Study of the particle yield ratios ($\eta/\pi^0$, $K^0_s/\pi^0$ etc.) can help to obtain more detailed information about fragmentation mechanisms of particles with different properties.

The data for Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been delivered by RHIC in 2012. It is the first asymmetric collision system of heavy relativistic ions characterised by similar energy density but different collision geometry when compared to symmetric systems (Au+Au or Cu+Cu). Measurement of light neutral mesons $R_{AA}$ in Cu+Au collisions provides an opportunity to discriminate between parameters of various theoretical models of parton energy loss in the sQGP medium.

2. Data Analysis
All results presented in this paper are carried out with the PHENIX spectrometer central arms, each covers $\pi/2$ of azimuth and $\pm 0.35$ interval of pseudo-rapidity ($\eta$). Subsystems of the PHENIX spectrometer are described in detail elsewhere [9]. In the analysis $\pi^0$ and $\eta$ mesons are reconstructed in their main decay channel ($\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$) with the electromagnetic calorimeter (EMCal) [10].

The EMCal of the PHENIX consists of the two technologically-different subsystems. Lead-scintillator (PbSc) and lead-glass (PbGl) subsystems have different energy resolution ($\delta E/E = 2.1\% \oplus 8.1%/\sqrt{E}$ for PbSc and $0.8\% \oplus 5.9%/\sqrt{E}$ for PbGl), granularity ($\delta \eta \times \delta \phi \approx 0.01 \times 0.01$ for PbSc and $0.008 \times 0.008$ for PbGl), linearity and respect to hadronic background, thus simultaneous use of both types provides an important cross-check of the results in the framework of the one experiment.

The centrality of analysed events is determined by two beam-beam counters (BBC) [11] located along the beam axis in the $3.0 < |\eta| < 3.9$ interval of pseudo-rapidity. A set of geometric parameters including $N_{coll}$, number of participating nucleons ($N_{part}$), impact parameter ($b$) for each centrality interval is calculated using the response of BBC along with the Glauber-model based Monte-Carlo simulation [12].

Invariant mass distributions for $\gamma\gamma$ pairs were accumulated in different intervals of the meson $p_T$ and event centrality. Considered $\gamma$ clusters are required to satisfy several analysis cuts: $\gamma$ energy is equal to 0.4 GeV to reduce charged hadrons contamination. To reduce the combinatorial background an asymmetry cut was applied for each $\gamma\gamma$ pair: $\alpha < 0.8$, where $\alpha = (E_{\gamma1} - E_{\gamma2})/(E_{\gamma1} + E_{\gamma2})$, $E_{\gamma1}$ and $E_{\gamma2}$ are energies of $\gamma$ clusters in the pair.

Peaks of reconstructed $\pi^0$ and $\eta$ seat on a large combinatorial background. The shape of the uncorrelated part of the background is estimated with so-called event-mixing technique, when $\gamma\gamma$ pairs are formed from two different events with similar values of the collision centrality. Estimated shape is normalized to foreground integral in the mass range 0.3–0.4 GeV/$c^2$ and then subtracted. Resulting distributions are fitted to a sum of the Gaussian and second order polynomial to estimate meson yield and remaining background, respectively.

Derived yields are corrected for the detector effects and limited acceptance with the reconstruction efficiency, which is obtained from GEANT 3 based Monte-Carlo simulation. The influence of high occupancy effects in the detector is accounted with embedding simulated $\pi^0$ and
\( \eta \) mesons into real Cu+Au events. Besides that all analysis cuts are applied in the simulation in the same way as in the analysis of real data. Full procedure of \( \pi^0 \) and \( \eta \) reconstruction is carried out separately for PbSc and PbGl subsystems. Final results are obtained by averaging PbSc and PbGl with weights defined by uncertainties uncorrelated between PbSc and PbGl subsystems.

To estimate systematic uncertainties we varied detector performance in simulation and analysis cuts. Among them there are uncertainties from meson raw yield extraction approach, possible mismatch in absolute energy scale, resolution and acceptance of the EMCal between real data and simulations, imperfect reproduction of photon reconstruction algorithms and conversion in detector subsystems in simulation. The main uncertainty at intermediate \( p_T \) is the mismatch in absolute energy scale: the mismatch in \( \sim 1\% \) of the meson masses in data and simulation results in \( \sim 8\% \) uncertainty in yield measurement.

Yields of \( \pi^0 \) are suffered from so-called cluster merging effect at highest \( p_T \) (\( p_T > 12–15 \text{ GeV/}c \)). Two \( \gamma \)s from the decay of high-\( p_T \) \( \pi^0 \) have rather small opening angle and cannot be reconstructed as two individual cluster in the EMCal due to its finite granularity. Thus such \( \pi^0 \)s couldn’t be reconstructed. The mismatch in the reproduction of this effect in the simulation is visible in the data.

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\frac{\text{Figure } 1}{\text{Ratios of } \eta \text{ and } \pi^0 \text{ yields measured in } 0–93\% \text{ (}), 0–20\% \text{ ()}, 20–40\% \text{ (}), 40–60\% \text{ (}) \text{ and } 60–90\% \text{ (}) \text{ centrality intervals of Cu+Au collisions. Dashed curve shows } m_T \text{-scaling function. Error bars and open boxes show statistical and systematic uncertainties, respectively.}}\]
Figure 3. Comparison of $\pi^0$ meson nuclear modification factors measured as a function of $p_T$ in Cu+Au (●), Au+Au (▲) [16] and Cu+Cu (▼) [17] 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 $N_{\text{part}} = 80.4$, 40-50% Au+Au with $N_{\text{part}} = 74.4$ and 0-10% Cu+Cu with $N_{\text{part}} = 98.2$. Error bars and open boxes show statistical and systematic uncertainties, respectively. Boxes at unity show scaling uncertainty.

followed by $\sim$15% uncertainty. For $\eta$ mesons this effect can be observed only at $p_T > 60$ GeV/c, which far exceeds the limit of $\eta$ yield measurements.

3. Results

Figure 1 presents $\eta/\pi^0$ ratios measured as a function of meson $p_T$ in different centrality intervals of Cu+Au collisions. Values of the ratios are the same for all centrality intervals within uncertainties and consistent with $m_T$-scaling curve [13], normalized to 0.5 at highest $p_T$. Obtained results are consistent with previous measurements in lepton-lepton, hadron-hadron, hadron-nucleus and nucleus-nucleus collisions in a wide interval of collision energies [14], which suggests that $\eta$ meson fragmentation processes are independent from presence of the sQGP medium.

Comparison of $\pi^0$ and $\eta$ $R_{AA}$ measured as a function of meson $p_T$ in different centrality intervals of Cu+Au collisions is presented in the Figure 2. Values of $R_{AA}$ are the same within uncertainties in all centrality intervals. Meson yields are suppressed twice in central Cu+Au collisions. A hint of enhancement of $\pi^0$ and $\eta$ yields is observed in peripheral Cu+Au collisions. A similar pattern of $R_{AA}$ is observed for reconstructed jets in the same collision system [15].

Figure 3 shows comparison of $\pi^0$ $R_{AA}$ measured in Cu+Au, Au+Au [16] and Cu+Cu [17] collisions at $\sqrt{s_{NN}} = 200$ GeV and similar values of $N_{\text{part}}$. For all collision systems $\pi^0$ $R_{AA}$ values are the same within uncertainties in the whole $p_T$ range, which suggests that $\pi^0$ suppression level depends on the size of the nuclear overlap region but not on its shape. $R_{AA}$ of $\eta$ mesons are also the same within uncertainties in Cu+Au and Au+Au [14, 18] collisions as presented in the Figure 4.

4. Summary

PHENIX has measured $\pi^0$ and $\eta$ nuclear modification factors in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as a function of meson $p_T$ and event centrality. Production of $\pi^0$ and $\eta$ mesons shows similar suppression in all centrality intervals, which suggests that suppression occurs on the parton level before fragmentation processes, i.e. the suppression is the result of the energy loss of partons in the QGP medium. This effect could not be reproduced with the Perturbative QCD calculations yet, but with different semi-phenomenological models, for example [7,8]. Production of $\pi^0$ and $\eta$ is suppressed twice in central Cu+Au collisions, a hint of enhancement of $\pi^0$ and $\eta$
Figure 4. Comparison of $\eta$ meson nuclear modification factors measured as a function of $p_T$ in Cu+Au (●), Au+Au (published in 2007, ▲) [14] and Au+Au (published in 2010, ★) [18] collisions at 200 GeV. Panel (a) is for 0-20% Cu+Au with $N_{\text{part}}$ = 154, 20-60% Au+Au (published in 2007) with $N_{\text{part}}$ = 100 and 20-40% Au+Au (published in 2010) with $N_{\text{part}}$ = 140. Panel (b) is for 60-90% Cu+Au with $N_{\text{part}}$ = 8.85, 60-92% Au+Au (published in 2007 and 2010) with $N_{\text{part}}$ = 14.5 and 0-10% Cu+Cu with $N_{\text{part}}$ = 14.5. Error bars and open boxes show statistical and systematic uncertainties, respectively. Boxes at unity show scaling uncertainty.

yields is observed in peripheral Cu+Au collisions. A similar suppression pattern is observed for reconstructed jets in the same collision systems. $R_{AA}$ values of $\pi^0$ and $\eta$ are the same within uncertainties in different collision systems at the same collision energy and similar values of $N_{\text{part}}$, which suggests that suppression level mostly depends on the nuclei overlap size but not on its geometry. Measured values of $\eta/\pi^0$ ratios are consistent with previously measured in different systems, which suggests that $\eta$ meson fragmentation processes are independent from presence of the quark-gluon medium.

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