Nuclear modification factors of $K_S$ and $\omega$ mesons in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. Jet quenching is an important evidence of the quark-gluon plasma (QGP) formation. The effect of jet quenching is emerged in ultra-relativistic heavy-ion collisions (A+A) by suppressed production of hadron yields at high transverse momenta ($p_T > 5$ GeV/c) when compared to one measured in elementary proton-proton collisions ($p+p$). Cu+Au collisions are characterised by the unique asymmetric nuclei overlap geometry different from one presented in symmetric collisions (Au+Au, Cu+Cu). It makes the Cu+Au collision system especially interesting for jet quenching studies. In this paper we present results of the $K_S$ meson production measurement in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with respect to the meson $p_T$ and collision centrality obtained using the electromagnetic calorimeter of PHENIX experiment. $K_S$ mesons are reconstructed via the $K_S \rightarrow \pi^0 (\rightarrow \gamma \gamma) \pi^0 (\rightarrow \gamma \gamma)$ decay channel. Obtained $K_S$ meson nuclear modification factors are consistent with ones measured for $\pi^0$ and $\eta$ mesons and reconstructed jets in the same collision system and ones measured in Cu+Cu and Au+Au collisions at the same collision energy.

1. Introduction

Quark-gluon plasma (QGP) is a deconfined state of nuclear matter with color-charged quarks and gluons (partons) as degrees of freedom. First evidences of the QGP formation in central ultra-relativistic heavy ion collisions (A+A) were established at Relativistic Heavy Ion Collider (RHIC) experiments [1–4]. Later, the fact of the QGP production was confirmed at Large Hadron Collider (LHC) [5–7].

Hadron production at high transverse momenta ($p_T > 5$ GeV/c) is governed by the fragmentation of hard-scattered partons. Parton hard scattering and fragmentation processes in elementary proton-proton ($p+p$) collisions are well described by perturbative Quantum Chromodynamics (pQCD) [8]. When A+A collisions are considered, the interaction of hard-scattered partons with created QGP medium leads to the modification of fragmented hadron yields. In particular, hard-scattered partons traverse in the medium and lose a part of their energy which results in suppressed production of hadron yields (jet quenching effect) [9,10].

Measurements of the different high-$p_T$ hadron species ($\pi^0$, $\eta$, $K_S$, $\omega$) production provide a systematic study of in-medium effects with respect to the fragmentation function and quantum numbers (mass, flavour, spin) of the final-state hadrons. For example, a $K_S$ meson is a strange pseudoscalar, thus measurements of its production help to study the flavour dependence of the parton energy loss. In the same way as a $\pi^0$ meson, an $\omega$ meson contains only the first generation quarks ($u$, $d$) but as a vector has a different spin. Thus, measurements of $\omega$ meson production...
in A+A collisions allows to explore fragmentation properties as a function of final hadrons spin states.

Usually, the hadron production is studied with respect to the particle $p_T$ and the collision centrality. The collision centrality is quantified in percent and represents the geometry of the A+A collision. For example, centrality 0-20% corresponds to central collisions with large particle multiplicity and created energy density; centrality 60-90% corresponds to peripheral collisions, where only few nucleons part in the nuclei interaction.

Quantitatively, jet quenching is probed with a nuclear modification factor ($R_{AA}$):

$$R_{AA}^{cent}(p_T) = \frac{1}{N_{coll}^{cent}} \frac{dN_{AA}^{cent}(p_T)/dp_T}{dN_{pp}(p_T)/dp_T},$$

(1)

where $dN_{AA}^{cent}(p_T)/dp_T$ ($dN_{pp}(p_T)/dp_T$) – the particle yield measured in A+A ($p+p$), $N_{coll}^{cent}$ – the number of binary inelastic nucleon-nucleon collisions. The $dN_{AA}^{cent}(p_T)/dp_T$ and $N_{coll}^{cent}$ are determined for the selected centrality interval.

Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is an asymmetric system of ultra-relativistic heavy colliding nuclei and has different collision geometry when compared to symmetric systems such as Au+Au and Cu+Cu. Opposite to Au+Au, in Cu+Au a nuclear overlap region has an additional asymmetry along the axis connecting the interacting nuclei centres (Fig.1). Thus, light meson suppression measurements in Cu+Au collisions are especially interesting for the jet quenching systematic studies and can provide an additional input parameters discrimination for various phenomenological parton energy loss models.

2. Data Analysis

All results presented in the paper are obtained with the PHENIX spectrometer [11] in data collected in RHIC Year-2012 run. The centrality categorization and determination of the collision vertex along the beam axis ($z_{vertex}$) are provided with two beam-beam counters (BBC) [12].
BBCs are located in the $3.0 < |\eta| < 3.9$ region in pseudorapidity towards North and South beam directions. The mean numbers of the nucleons participating in nuclei interactions ($\langle N_{\text{part}} \rangle$) and binary collisions ($\langle N_{\text{coll}} \rangle$) for selected centrality intervals are estimated with the Glauber-model Monte-Carlo simulation [13] considering the BBC response.

Eight sectors of the electromagnetic calorimeter (EMCal): six sectors of lead-scintillator (PbSc) and two sectors of Cherenkov sampling (PbGl) are used to reconstruct $K_S$ meson yields. Each sector covers 22.5 degree in azimuthal angle and $|\eta| < 0.35$ region in pseudorapidity. The EMCal construction and performance details can be found elsewhere in [14].

Two hardware triggers are used in the analysis for the data sample formation. The Minimum Bias trigger (MB) is fired if both BBCs simultaneously detect charged particles. The MB trigger is used to measure $K_S$ meson yields at $p_T < 10$ GeV/c. The ERT-A trigger is fired if at least one high-energy electromagnetic shower is induced in the EMCal. The ERT-A trigger is used at higher transverse momenta. With the $|z_{\text{vertex}}| < 20$ cm cut MB and ERT-A data samples contain $6.9 \times 10^9$ and $1.8 \times 10^{10}$ collision events, respectively.

$K_S$ mesons are reconstructed via $K_S \rightarrow \pi^0 \pi^0$ decay channel with a branching ratio $BR = 30.69 \pm 0.05\%$ [15]. In turn, $\pi^0$ mesons are reconstructed via $\pi^0 \rightarrow \gamma \gamma$ decay channel with $BR = 98.82 \pm 0.03\%$ [15]. A minimum photon energy ($E_\gamma$) cut of 0.4 GeV and a standard shower shape cut [14] for $\gamma$-candidates are introduced to reduce the contribution of hadron showers in the EMCal. An asymmetry cut of $|E_\gamma - E_\gamma'|(E_\gamma + E_\gamma') < 0.8$ is applied to each $\gamma \gamma$ pair to reduce the background from combinatorial pairs. In addition, both $\gamma$-candidates are required to be in the same EMCal sector.

To form a $\pi^0$-candidate each $\gamma \gamma$ pair is required to have its invariant mass in a $2 \sigma$ range from the $\pi^0$ meson mass parametrisation and be in the same East or West central arm of the spectrometer. Also, $\pi^0$-candidates are required to have its transverse momentum ($p_T^{\pi^0}$) in the range $2 < p_T^{\pi^0} < 11$ GeV/c ($2 < p_T^{\pi^0} < 14$ GeV/c) for the candidates reconstructed in PbSc (PbGl) sectors. The lower reach is limited to reduce the contribution of the

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** $K_S$ meson invariant $p_T$-spectra measured in 0-93% (●, multiplied by $10^3$), 0-20% (■, multiplied by $10^4$), 20-40% (◇, multiplied by $10^4$), 40-60% (□, multiplied by $10^{-1}$), and 60-90% (● multiplied by $10^{-2}$) centrality intervals of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Error bars and open boxes show statistical and systematic uncertainties, respectively.

**Figure 4.** Ratios of $K_S$ and $\pi^0$ meson yields measured as a function of transverse momentum in 0-93% (●), 0-20% (■), 20-40% (◇), 40-60% (□), and 60-90% (●) centrality intervals of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Error bars and open boxes show statistical and systematic uncertainties, respectively.
combinatorial background. The higher reaches correspond to the point where cluster merging effect significantly affects $\pi^0$-candidates reconstruction \cite{16}. For all selected $\pi^0$-candidates an additional energy correction is applied to bring the reconstructed $\pi^0$ masses to the Particle Data Group value, which helps to significantly improve $K^0_S$ signal-to-background ratios ($S/B$).

$K^0_S$ yields are determined from $\pi^0$-candidate pair invariant mass ($M_{\text{inv}}$) distributions accumulated in the selected $K^0_S$ transverse momentum and event centrality intervals. The distributions are fitted to a sum of the Gauss function and the second order polynomial, which describe the signal and the background, respectively. Examples of the $M_{\text{inv}}$ distributions are shown in Fig.2. $K^0_S$ yields are obtained as the difference between the sum of the distribution bin content in a $2\sigma$ vicinity around the peak position and the polynomial fit integral in the same region.

Obtained $K^0_S$ yields are corrected for the limited acceptance and detector effects with the reconstruction efficiency. The $K^0_S\rightarrow\pi^0\pi^0$ decay reconstruction efficiency is derived from the Monte-Carlo simulation based on GEANT 3.61 \cite{17}. The high multiplicity effects influence is accounted by embedding simulated $K^0_S$ mesons into real Cu+Au collision events end then analysed in the same way as in real data.

The $K^0_S$ meson invariant $p_T$-spectra are accumulated as follows:

$$\frac{1}{N_{\text{event}}} \frac{d^2N}{2\pi p_T dp_T dy} = \frac{1}{2\pi p_T \Delta p_T \Delta y} \times \frac{N_{K^0_S}}{N_{\text{event}} \epsilon_{\text{rec}} BR},$$

(2)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Nuclear modification factors of $\pi^0$ ($\bullet$), $\eta$ ($\bullet$), and $K^0_S$ ($\Phi$) mesons measured as a function of $p_T$ in 0-20\% (a), 20-40\% (b), 40-60\% (c), and 60-90\% (d) centrality intervals of Cu+Au collisions at $s_{NN} = 200$ GeV. Error bars and boxes around points shows statistical and $p_T$-dependent systematic uncertainties. Boxes at unity shows $p_T$-independent systematic uncertainties.}
\end{figure}
where $N_{K_S}$ – the $K_S$ meson extracted yield, $\epsilon_{rec}$ – the $K_S$ meson reconstruction efficiency, $N_{event}$ – the number of analysed events, $BR$ – the $K_S \rightarrow \pi^0\pi^0$ decay branching ratio.

The detector performance in the simulation and the analysis cuts are varied to estimate systematic uncertainties of the $K_S$ meson results. Main systematic uncertainties come from the $K_S$ yield extraction parameters selection and a photon conversion in the detector materials. The corresponding uncertainty is estimated by variations of the fitting range, peak integration region and the fit polynomial order and is assigned to be 10-15%, 8-12%, and 18-25% in the low, intermediate, and high $p_T$ regions, respectively, depending on the centrality interval.

A part of daughter photons from $\pi^0$ meson decays experiences a conversion into $e^-e^+$ pairs when passing through detector materials. In the presence of magnetic field electrons and positrons are bended to the opposite directions, thus the original photon can not be reconstructed in the EMCal. It leads to the lose of about 25% $\pi^0$ mesons. The uncertainty of the photon conversion from this effect reproduction mismatches in simulations and real data and was estimated to be 5.2% for $\pi^0$ meson production [16]. For $K_S$ meson production the uncertainty from photon conversion is assigned as a double uncertainty from $\pi^0$ meson measurements and is estimated to be 10.4% independently on the meson $p_T$ and collision centrality.

3. Results

Fig. 3 shows $K_S$ meson invariant $p_T$-spectra measured in different centrality intervals of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $p_T$ range of measurements is limited by rapidly decreasing $S/B$ at low $p_T$ and decreasing statistics at high momenta.

Fig. 4 presents the ratio of $K_S$ and $\pi^0$ yields ($K_S/\pi^0$) measured as a function of $p_T$ in different Cu+Au centrality intervals. Yields of $\pi^0$ were previously published in [16]. The ratios are $p_T$-independent and consistent for all centrality intervals within large uncertainties. Also, obtained ratios are consistent with ones measured in $d$+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV [18].

Fig. 5 shows a comparison of $\pi^0$ [16], $\eta$ [16], and $K_S$ mesons nuclear modification factors, measured as a function of transverse momentum in different centrality intervals of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The reference $K_S$ spectra obtained in $p+p$ collisions were

$$
R_{AA} = \frac{N_{p+p}}{N_{Au+Au}}
$$

Figure 6. Nuclear modification factors of $K_S$ mesons measured as a function of $p_T$ in Au+Au (∙), Cu+Cu (○), and Cu+Au (●) collisions at $\sqrt{s_{NN}} = 200$ GeV at similar $N_{part}$. Uncertainties are the same as in Fig. 5. Panel (a) is for 20-60% Au+Au with $\langle N_{part} \rangle = 102 \pm 6$, 0-20% Cu+Cu with $\langle N_{part} \rangle = 86 \pm 2$, and 20-40% Cu+Au with $\langle N_{part} \rangle = 80 \pm 3$. Panel (b) is for 60-93% Au+Au with $\langle N_{part} \rangle = 14 \pm 2$, 60-94% Cu+Cu with $\langle N_{part} \rangle = 6.4 \pm 0.4$, and 60-90% Cu+Au with $\langle N_{part} \rangle = 8.9 \pm 1.4$. 

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published in [19]. Nuclear modification factors obtained for different meson species are consistent within uncertainties in the whole $p_T$ range for all selected centrality intervals. Also, the $R_{AA}$ are consistent with ones measured for reconstructed jets in the same collision system [20] suggesting that the meson suppression pattern does not depend of the fragmented parton flavor. Fig. 6 compares $K_S$ meson nuclear modification factors, obtained in Au+Au, Cu+Cu [18], and Cu+Au at $\sqrt{s_{NN}} = 200$ GeV and similar $N_{part}$. $K_S$ meson yields are similarly suppressed in different heavy-ion systems suggesting that the meson production suppression mostly depends on the energy density created in nuclei interactions and do not depend on the collision geometry (or the dependence is weak).

4. Summary

In summary, PHENIX has measured $K_S$ meson invariant $p_T$-spectra and nuclear modification factors as a function of $p_T$ in different centrality intervals of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Obtained $K_S/\pi^0$ do not show $p_T$ or centrality dependence within uncertainties and are consistent with results previously obtained in $d+Au$ and Cu+Cu collisions at the same collision energy. In Cu+Au collisions $K_S$ meson production shows similar suppression pattern as one for $\pi^0$ and $\eta$ mesons and for reconstructed jets. Also, the observed $K_S$ meson suppression pattern is the same as in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV within uncertainties of measurements.

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