Jet-Quenching Studies Using Leading Mesons in Cu+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract. Quark-gluon plasma (QGP) is a hot and dense color-charged medium, created in ultra-relativistic heavy nuclei collisions. Jet-quenching is one of the evidence for QGP formation and manifests itself in suppressed hadron production at high transverse momenta when compared to proton-proton collisions. We present results of jet-quenching studies in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using production of leading mesons ($\pi^0$, $\eta$, $K_S$, $\omega$). Measurements are performed with PHENIX spectrometer at RHIC. Yields of $\pi^0$, $\eta$, $K_S$, and $\omega$ mesons and reconstructed jets show the same suppression level at high transverse momenta region within uncertainties when compared to $p+p$ results. The suppression level of $\pi^0$, $\eta$, $K_S$, and $\omega$ mesons in Cu+Au collisions is equal within uncertainties to one measured in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV at similar participant nucleon numbers.

1. Introduction

Ultra-relativistic heavy-ion collisions (A+A) at RHIC and LHC are used to produce hot and dense color-charged medium – quark-gluon plasma (QGP) [1–7]. The created quark-gluon medium rapidly cools down and transits into hadronic phase, nevertheless its properties can be probed by daughter-particles production measurements. Jet-quenching [8, 9] is one of the main evidences for QGP formation and is manifested by suppressed hadron production in a large transverse momenta region ($p_T > 4–6$ GeV/c), when compared to the binary-scaled yields measured in elementary proton-proton interactions ($p+p$) at the same energy. Hadron production at this region is due to fragmentation of partons originating from hard scattering processes.

In a heavy-ion collision hard-scattered parton loses a part of its energy via elastic collisions or bremsstrahlung in a quark-gluon medium, which results in fragmented hadrons $p_T$-spectra softening. Parton energy-loss mechanisms cannot be described from the first principles: a variety of phenomenological models is used instead [10–16]. Parton traverse in QGP is usually quantified by a transport coefficient $\hat{q}$ [10, 11], which represents the squared four-momentum exchange between the hard parton and the medium divided by the mean free path-length. The relation between temperature ($T$), shear viscosity ($\eta$), entropy ($s$), and $\hat{q}$ defines the coupling intensity of the QGP color-charged constituents: if $T^3/\hat{q} \approx \eta/s$, quark-gluon medium is a weakly-coupled gas and in case of $T^3/\hat{q} \ll \eta/s$ quark-gluon plasma acts as a near-perfect liquid [11]. Systematic study of this relation can provide an information about mechanisms of transition between quark-gluon gas inside hadrons and liquid quark-gluon plasma produced in A+A.
Different hadron production systematic measurements at high transverse momenta in different heavy-ion collision systems are important for precise extraction of free parameters for jet-quenching models. Probes of different leading neutral mesons ($\pi^0$, $\eta$, $K_S$, $\omega$) allow studying of jet-quenching effect with respect to the final hadron fragmentation function and properties (mass, flavour, spin, etc.). A copious production of $\pi^0$ mesons provides their yield measurement in a wide $p_T$-range with relatively small uncertainties. $K_S$ mesons are strange particles and $\eta$ mesons contain hidden strangeness in their wave-function, therefore data analysis for these particles provides an examination of strangeness influence on the jet-quenching. Both $\pi^0$ and $\omega$ mesons consist from first-generation quarks and anti-quarks ($u$, $d$), but $\pi^0$ mesons are pseudoscalars with zero spin while $\omega$ mesons are vectors and their spin is equal to one, thus $\omega$ production research allow us to study jet-quenching with respect to final state spin.

Jet-quenching effect for a given particle type is usually expressed in terms of nuclear modification factor ($R_{AA}$):

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{AA}}{dp_T} / \frac{d\sigma_{pp}}{dp_T},$$

where $dN_{AA}/dp_T$ – the particle yield measured in $A+A$, $d\sigma_{pp}/dp_T$ – an inclusive differential cross-section of the particle in $p+p$ at the same energy, $T_{AA}$ – the nuclear overlap thickness, which is defined as a convolution of colliding nuclei thickness in the beam direction over their overlap region [17]. Values of $dN_{AA}(p_T)/dp_T$ and $T_{AA}$ are obtained with respect to a collision centrality. Centrality is quantified in percent and represents a size of the nuclear overlap. For example, centrality 0-20% corresponds to central collisions with large particle multiplicity and created energy density; centrality 60-90% corresponds to peripheral collisions with only few nucleons participating in the nuclei interaction.

Copper and gold nuclei collision (Cu+Au) at $\sqrt{s_{NN}} = 200$ GeV is a first asymmetric ultra-relativistic heavy-ion collision system with different nuclear overlap geometry when compared to symmetric systems such as Au+Au and Cu+Cu. In Cu+Au collisions a nuclear overlap region has an additional asymmetry along the axis connecting the interacting nuclei centers. Such an asymmetry of nuclear overlap is followed by an asymmetry of the created medium making Cu+Au collisions an important part of jet-quenching systematic research.

This paper shows results of $\pi^0$, $\eta$, $K_S$, and $\omega$ mesons nuclear modification factor measurements in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

2. Data Analysis

Results in the paper were obtained with the PHENIX spectrometer [18] at RHIC in data of year 2012. Collisions were categorized by centrality with two beam-beam counters (BBC) [19] located in the $3.0 < |\eta| < 3.9$ region in pseudorapidity towards North and South beam directions. The mean numbers of $T_{AA}$ and nucleons participating in a nuclei-nuclei interaction ($N_{part}$) in selected centrality classes were estimated with the BBC response Monte-Carlo simulation based on Glauber model [17].

Yields of $\pi^0$, $\eta$, $K_S$, and $\omega$ mesons were measured with PHENIX electromagnetic calorimeter (EMCal) consisting of six lead-scintillator sectors ( PbSc) and two Cherenkov-sampling sectors ( PbGl). Each sector covers $|\eta| < 0.35$ region in pseudorapidity and $\pi/8$ in azimuth. The EMCal construction and performance details can be found elsewhere in [20]. Details of $\pi^0$ and $\eta$ mesons reconstruction are given in [21]. Reconstruction of $K_S$ and $\omega$ mesons is performed in $K_S \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ ($BR = 30.69 \pm 0.05\%$ [22]) and $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ ($BR = 8.40 \pm 0.22\%$ [22]) decays, respectively. In the analysis, a minimum photon energy ($E_\gamma$) cut of 0.4 GeV and a standard shower shape cut [20] for $\gamma$-candidates are used for reduction of the hadron showers contribution in the EMCal. For each $\gamma\gamma$ pair forming a $\pi^0$-candidate an asymmetry cut of $|E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2}) < 0.8$ is introduced to reduce the background from combinatorial pairs. In addition, both $\gamma$-candidates are required to be in the same calorimeter sector.
\(\pi^0\)-candidate each \(\gamma\gamma\) pair is required to have its invariant mass in a 2\(\sigma\) range from the \(\pi^0\) meson mass parameterisation 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 combinatorial background. The higher reaches correspond to the point where cluster merging effect significantly affects \(\pi^0\)-candidates reconstruction [21]. 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 [22], which helps to significantly improve \(K_S\) and \(\omega\) signal-to-background ratios \((S/B)\). For \(\pi^0\gamma\) pairs selection in the \(\omega\) meson production analysis, an angle cut of \(|\cos \theta^*| < 0.6\) is used, where \(\theta^*\) – is an angle between the \(\pi^0\) motion direction in the \(\pi^0\) rest frame and the \(\pi^0\gamma\) direction in the laboratory frame. This cut is similar to asymmetry cut for \(\gamma\gamma\) pairs and helps to significantly improve \(\omega\) meson signal.

\(K_S\) and \(\omega\) meson yields are respectively determined from \(\pi^0\pi^0\) and \(\pi^0\gamma\) invariant mass \((m_{inv})\) distributions accumulated in the selected \(K_S\) transverse momentum and centrality intervals. Examples of these distributions are shown in figure 1. The \(m_{inv}\) distributions are fitted to a sum of the Gauss function and the second order polynomial describing the signal and the background, respectively. \(K_S\) yields are obtained as the difference between the sum of the \(m_{inv}\) distribution bin content in a 2\(\sigma\) vicinity around the peak position and the polynomial fit integral in the same region; \(\omega\) yields are obtained as a Gaussian integral. Obtained yields are corrected for the limited acceptance, detector performance, and applied analysis cuts with the reconstruction efficiency derived from the GEANT [23] Monte-Carlo simulation representing a full detecting tract from particle production in a collision vertex to the yield extraction from the invariant mass distributions. The influence of high multiplicities is accounted by embedding simulated \(K_S\) or \(\omega\) mesons into real Cu+Au collision events.

The \(K_S\) and \(\omega\) meson invariant \(p_T\)-spectra are accumulated as follows:

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

where \(N\) – the \(K_S(\omega)\) meson extracted yield, \(\epsilon_{\text{rec}}\) – the \(K_S(\omega)\) meson reconstruction efficiency, \(N_{\text{event}}\) – the number of analyzed events, \(BR\) – the \(K_S(\omega)\) meson decay branching ratio.

Systematic uncertainties of \(K_S\) and \(\omega\) meson invariant yields are estimated by the detector performance in the simulation and variation of the analysis cuts. For \(K_S\) mesons main systematic uncertainties come from the invariant mass distribution analysis and a photon conversion in the detector materials. For \(\omega\) mesons main uncertainties come from the invariant mass distribution analysis and application of photon shower shape cuts. The uncertainty from invariant mass

\textbf{Figure 1.} Invariant mass distribution examples for \(\pi^0\pi^0\) pairs in \(6.0 < p_T < 6.5\) GeV/c \((a)\) and for \(\pi^0\gamma\) pairs in \(7 < p_T < 8\) GeV/c \((b)\). Red solid curves show a ”signal + background” approximation, red dashed curves show a ”background” approximation.

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Figure 2. Ratios $K_S/\pi^0$ (a) and $\omega/\pi^0$ (b) 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 absolute values of statistical and systematic uncertainties, respectively.

distribution analysis 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 for $K_S$ meson. For $\omega$ mesons this uncertainty is assigned to be 7–15% depending on $p_T$ and centrality. Uncertainty from photon conversion in detector materials is assigned to be 10.4% for $K_S$ meson yields and 7.8% for $\omega$ meson yields. Uncertainty from application of shower shape cuts in the $\omega$ meson production analysis is assigned to be 9.2%.

Figure 3. Nuclear modification factors of $\pi^0$ (●) [21], $\eta$ (◆) [21], $K_S$ (•) and $\omega$ (■) 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 $\sqrt{s_{NN}} = 200$ GeV. Error bars and open boxes around points show statistical and $p_T$-dependent systematic uncertainties. Boxes at unity shows $p_T$-independent systematic uncertainties.
Figure 4. Integrated nuclear modification factors of different meson species in heavy nuclei collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. Cu+Au: $\pi^0$ (○, $p_T > 5$ GeV/c) [21], $K_S$ (■, $p_T > 5$ GeV/c), $\omega$ (□, $p_T > 7$ GeV/c); Au+Au: $\pi^0$ (◇, $p_T > 5$ GeV/c) [28], $K_S$ (◇, $p_T > 6$ GeV/c), $\omega$ (◇, $p_T > 7$ GeV/c) [25]; Cu+Cu: $K_S$ (◇, $p_T > 6$ GeV/c) [24], $\omega$ (◇, $p_T > 7$ GeV/c) [25]. Error bars and open boxes show statistical and $p_T$-dependent systematic uncertainties.

3. Results

Figure 2 presents the ratios of $K_S$ or $\omega$ meson yield to $\pi^0$ ones ($K_S/\pi^0$, $\omega/\pi^0$) as function of $p_T$ in different Cu+Au centrality intervals. The $p_T$ range of $K_S$ and $\omega$ meson yield measurements is limited by rapidly decreasing $S/B$ at low $p_T$ and decreasing statistics at high $p_T$. The $\pi^0$ reference is obtained by rebinning $\pi^0$ meson yields, which are published in [21]. The ratios are assigned to be $p_T$- and centrality-independent within large uncertainties. Also, obtained $K_S/\pi^0$ are consistent with ones measured in $d+Au$ and Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [24], and $\omega/\pi^0$ ratios are similar to ones measured earlier in $p+p$, $d+Au$, Cu+Cu, and Au+Au at the same collision energy [25]. The ratios of $\eta$ and $\pi^0$ mesons show similar independence [21].

Figure 3 compares $\pi^0$ [21], $\eta$ [21], $K_S$, and $\omega$ nuclear modification factors, measured as a function of transverse momentum and centrality in Cu+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. The $K_S$ meson production cross-section in $p+p$ collisions used for the $R_{AA}$ determination are published in [26]. For the $\omega$ meson nuclear modification factor estimation we used an approximation of $\pi^0$ meson cross-section in $p+p$ collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, multiplied by the $\omega/\pi^0 = 0.81 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.})$ measured in the same $p+p$ data [25]. Nuclear modification factors obtained for different meson species are equal to each other within uncertainties in different $p_T$ and centrality intervals. In central Cu+Au collisions, yields of the mesons are suppressed twice when compared to $p+p$ results. Also, the $R_{AA}$ at $p_T > 10$ GeV/c are equal within uncertainties to ones measured for reconstructed jets in the same collision system [27]. These facts suggest that in Cu+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV the jet-quenching effect occurs at the partonic level.

Figure 4 compares different meson integrated nuclear modification factors as functions of $N_{\text{part}}$ in Au+Au [25, 28], Cu+Cu [24, 25], and Cu+Au [21] collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. Presented nuclear modification factors are equal within uncertainties in these three collision systems, which suggests the jet-quenching independence from nuclear overlap form released in Cu+Au, Au+Au, and Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV.
4. Summary
In summary, PHENIX has measured $\pi^0$, $\eta$, $K_S$, and $\omega$ meson production as a function of $p_T$ and centrality in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Obtained $K_S/\pi^0$, $\omega/\pi^0$, as well as $\eta/\pi^0$ in Cu+Au collisions show no $p_T$ or centrality dependence within uncertainties and are consistent with results previously obtained in $p+p$, $d+Au$, $Cu+Cu$, and $Au+Au$ collisions at the same collision energy. Yields of $\pi^0$, $\eta$, $K_S$, and $\omega$ mesons, as well as reconstructed jets are similarly suppressed with respect to ones in $p+p$ collisions at high transverse momenta suggesting that jet-quenching occurs at the partonic level in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Equality of different meson $R_{AA}$ at similar $N_{part}$ in Cu+Au, Au+Au, and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV suggests the jet-quenching independence from nuclear overlap form released in Cu+Au, Au+Au, and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV.

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References
[1] Arsene I et al 2005 Nucl. Phys. A 757 1-27
[2] Back B et al 2005 Nucl. Phys. A 757 28-101
[3] Adams J et al 2005 Nucl. Phys. A 757 102-83
[4] Adcox K et al 2005 Nucl. Phys. A 757 184-283
[5] Chatrchyan S et al 2012 Eur. Phys. J. C. 72 1945
[6] Abelev B et al 2013 Phys. Lett. B 720 52-62
[7] Aad G et al 2013 Phys. Lett. B 719 220-41
[8] Baier R, Schiff D, and Zakharov B G 2000 Ann. Rev. Nucl. Part. Sci. 50 37-69
[9] Wang X-N, Gyulassy M, and Plumer M 1995 Phys. Rev. D 51 3436-46
[10] Majumder A, Muller B, and Wang X-N 2007 Phys. Rev. Lett. 99 192301
[11] Xu J, Buzatti A, and Gyulassy M 2014 J. High Energy Phys 2014 063
[12] Cao S et al 2016 Phys. Rev. C 94 014909
[13] Chien Y T, Vitev I 2016 J. High Energy Phys. 2016 23
[14] Elayavalli R K, Zapp K C 2017 J. High Energy Phys. 2017 141
[15] Dijiorjevic M, et al 2019 Nucl. Phys. A. 982 699-702
[16] Miller M L, Reygers K, Sanders S J, and Steinberg P 2007 Ann. Rev. Nucl. Part. Sci. 57 205
[17] Adcox K et al 2003 Nucl. Inst. Meth. A 499 469-97
[18] Allen M et al 2003 Nucl. Inst. Meth. A 499 549-59
[19] Aphecetche L et al 2003 Nucl. Inst. Meth. A 499 521-36
[20] Aidala C et al 2018 Phys. Rev. C 98 054903
[21] Tanabashi M et al 2018 Phys. Rev. D 98 030001
[22] Brun R, Hadelberg R, Hansroul M, and Lassale J C 1978 Geant: Simulation program for particle physics experiments. User guide and reference manual CERN-DD-78-2-REV
[23] Adare A et al 2014 Phys. Rev. C 90 054905
[24] Adare A et al 2011 Phys. Rev. C 84 044902
[25] Adare A et al 2011 Phys. Rev. D 83 052004
[26] Timilsina A 2016 Nucl. Phys. A 956 637-40
[27] Adare A et al 2008 Phys. Rev. Lett 101 232301