Studying the mechanisms of the hadron jets production in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV

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Abstract. Studying the properties and evolution of the quark-gluon plasma (QGP) is one of the main directions in modern nuclear physics. The leading direction in the QGP studies is the research of the particle production originating from hard scattering of partons produced in the ultra-relativistic heavy nuclei collision. Light mesons ($\pi^0$, $\eta$ and $K_S$) invariant spectra and nuclear modification factors measurements at high transverse momenta are used for the parton energy loss models free parameters estimate in large systems and to examine various scaling behaviours. Spherically asymmetric uranium nuclei at $\sqrt{s_{NN}} = 192$ GeV are used to determine the influence of geometrical parameters of the colliding system on the fragmentation of hard partons produced in high energy collision of heavy nuclei. This paper presents differential transverse momentum spectra and nuclear modification factors of $K_S$ mesons in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV measured in a wide transverse momentum range and different centrality intervals with PHENIX experiment at RHIC.

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 for 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 verified at Large Hadron Collider (LHC) [5–7]. Hadron production at high transverse momenta ($p_T > 4$–6 GeV/c) is connected with 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]. In A+A collisions, the interaction of hard-scattered partons with created QGP medium results in a 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 $K_S$ meson production spectra allows to study jet-quenching effect with respect to final-state particle flavor, because $K_S$ meson is a strange pseudoscalar. Collision system of uranium nuclei (U+U) provides the largest energy density available at RHIC and gives a useful possibility to obtain additional restrictions on the parameters for various parton energy loss models [11]. Hadron production is studied as a function of the particle $p_T$ and the collision centrality, which is quantified in percent and represents the geometry of the A+A collision. For example, centrality 0-20% corresponds to central collisions with large created particle multiplicity and energy density; centrality 40-80% corresponds to peripheral collisions with...
low particle multiplicity and created energy density. Jet quenching is probed with a nuclear modification factor ($R_{AA}$). Nuclear modification factor is used for a detailed study of the qualitative properties of the medium:

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N}{d p_T dy} \bigg|_{AA} \frac{d^2 N}{d p_T dy} \bigg|_{pp}$$

where $\frac{d^2 N}{d p_T dy} \bigg|_{AA}$ ( $\frac{d^2 N}{d p_T dy} \bigg|_{pp}$) – the particle yield measured in A+A ($p+p$), $\langle N_{\text{coll}} \rangle$ – average number of binary inelastic nucleon-nucleon collisions.

Spherically asymmetric U+U system at $\sqrt{s_{NN}} = 192$ GeV provides different collision geometry when compared to collisions of spherically symmetric nuclei such as Au+Au and Cu+Cu [11]. Light meson suppression measurements in U+U collisions are especially interesting for the jet quenching systematic studies and can provide an additional free parameters discrimination for various phenomenological parton energy loss models.

2. Data Analysis

This paper present differential transverse momentum spectra and nuclear modification factors of $K_S^0$ meson in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV at RHIC. The analyzed U+U data sample has $9 \times 10^8$ events taken by the PHENIX experiment [12]. Centrality of collisions is measured using the Beam-Beam Counters (BBC) covering $3.0 < |\eta| < 3.9$ region in pseudo-rapidity. Glauber model is used to estimate the average numbers of participating nucleons ($(N_{\text{part}}))$ and

![Figure 1. Invariant transverse momentum spectra measured for $K_S^0$ mesons in U+U collisions at 192 GeV in minimum bias (●), 0-20 % (■), 20-40% (○), 40-80% (□) centrality intervals. Statistical uncertainties are smaller than the marker size. Open boxes correspond to systematic uncertainties.](image-url)
binary inelastic nucleon-nucleon collisions ($\langle N_{\text{coll}} \rangle$) for each centrality classes. $K_S$ meson is
reconstructed in a $\pi^0 \pi^0$ decay channel using the electro-magnetic calorimeter (EMCal) [13]. The 
EMCal detailed description is described in [14].

To form a $\pi^0$-candidate each $\gamma \gamma$ pair is required to have its invariant mass in a $1.5\sigma$ range 
from the $\pi^0$ meson mass parametrisation and be in one of two central arms of the spectrometer. All selected $\pi^0$-candidates are required to have their transverse momentum in the range $2 < p_T(\pi^0) < 11 \text{ GeV}/c$ ($2 < p_T(\pi^0) < 14 \text{ GeV}/c$) in PbSc (PbGl) sectors [14]. The lower reach of 
the limitation is selected to reduce the contribution of the combinatorial background, the upper 
reach is selected to avoid the merging of $\gamma$ clusters due to small opening angle. An additional 
energy calibration is applied for all selected $\pi^0$-candidates to bring the reconstructed $\pi^0$ masses 
to the Particle Data Group value $m(\pi^0) = 134.977 \text{ MeV}/c^2$, which helps to improve $K_S$ signal-
to-background ratios (S/B) [15]. $K_S$ yields are obtained from the $\pi^0$-candidate pairs invariant 
mass ($M_{\text{inv}}$) distributions analysis. The distributions are produced in different $K_S p_T$ and event 
centrality classes and fitted to a sum of the Gaussian and the second order polynomial, which 
describe the signal and the background, respectively. $K_S$ yields are obtained as the integral under 
the Gaussian. Estimated $K_S$ meson yields are then corrected for the limited acceptance and 
detector effects with the reconstruction efficiency. The $K_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ decay reconstruction 
efficiency is obtained from the Monte-Carlo simulation based on GEANT 3 [16]. Simulated $K_S$ 
mesons are embedded into the real events to consider high occupancy effects in the EMCal.

The detector performance in the simulation and the analysis cuts are varied to estimate 
systematic uncertainties of the $K_S$ meson results. Main systematic uncertainty comes from 
the raw yield extraction parameters selection (approximation range, polynomial order) and is 
estimated to be 15-19% depending from $p_T$ and centrality.

**Figure 2.** Comparison of $R_{AA}$ values in U+U ($\bullet$) ($\sqrt{s_{NN}} = 192 \text{ GeV}$), Au+Au ($\blacksquare$) 
($\sqrt{s_{NN}} = 200 \text{ GeV}$) and Cu+Cu ($\circ$) [17] ($\sqrt{s_{NN}} = 200 \text{ GeV}$) collisions at similar $\langle N_{\text{coll}} \rangle$ for 
different centrality bins in 0-20% (a), 20-40% (b), 40-80% (c). Error bars and open boxes show 
statistical and systematic uncertainties, respectively. Boxes at unity show scaling uncertainty.
3. Results

Fig. 1 shows the $K_S$ meson invariant $p_T$-spectra obtained for three different centrality classes and minimum bias collisions. Invariant $p_T$-spectra measured in a transverse momentum range: up to 11 GeV/$c$ in minimum bias, and up to 9 GeV/$c$ in central and semi central U+U collisions.

Fig. 2 compares $K_S$ meson nuclear modification factors measured as a function of $p_T$ in U+U at $\sqrt{s_{NN}} = 192$ GeV, Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, respectively, with similar $\langle N_{coll}\rangle$ numbers. Production of $K_S$ mesons is strongly suppressed in central, semi-central and semi-peripheral collision for both colliding systems. The suppression level of $K_S$ meson production in U+U collisions looks similar to one obtained in Au+Au and Cu+Cu [17] collisions in all centrality bins within large uncertainty.

Fig. 3 presents the ratio of $K_S$ and $\pi^0$ yields ($K_S/\pi^0$) measured as a function of $p_T$ in different U+U centrality intervals. 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 [17] within uncertainties.

4. Summary

PHENIX has measured $K_S$ meson production in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV at mid rapidity in the transverse momentum range of $1 < p_T < 11$ GeV/$c$, using RHIC Run-12 data. In central collisions the nuclear modification factor is suppressed by a factor of 4 at $p_T > 5$ GeV/$c$. Suppression of $K_S$ meson in U+U is the same as in Au+Au and Cu+Cu at similar energy and the numbers of binary collisions in all centrality bins within uncertainties which indicates the absence of the jet quenching effect dependence on the geometric shape of colliding nuclei. Obtained $K_S/\pi^0$ show $p_T$ or centrality independence within uncertainties and consistent with results previously obtained in d+Au and Cu+Cu collisions at the similar collision energy and suggesting fragmentation of partons is independent from the centrality or nuclear overlap of colliding systems.

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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] Owens J F 1987 Rev. Mod. Phys. 59 465
[9] Baier R, Schiff D, and Zakharov B G 2000 Ann. Rev. Nucl. Part. Sci. 50 37-69
[10] Wang X-N, Gyulassy M, and Plumer M 1995 Phys. Rev. D 51 3436-46
[11] Iordanova A 2013 Journal of Physics: Conference Series 458 012004
[12] Adcox K et al 2003 Nucl. Inst. Meth. A 499 469-07
[13] Aphecetche L et al 2003 Nucl. Inst. Meth. A 499 521-36
[14] Berdnikov A et al 2018 Bulletin of the Russian Academy of Sciences: Physics 82 1262-1265
[15] Beringer J et al 2012 Phys. Rev. D 86 010001
[16] Adler S et al 2003 Nucl. Inst. Meth. A 499 593-602
[17] Adare A et al 2014 Phys. Rev. C 90 054905