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SUPPRESSION OF THE HADRONIC YIELDS IN THE URANIUM NUCLEI COLLISIONS AT THE DIFFERENT QUARK'S COMPOSITION OF THE PRODUCED PARTICLES

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This paper presents invariant spectra, nuclear modification factors and ratio of invariant spectra of light mesons, obtained in collisions of heavy uranium nuclei at 192 GeV. These values are studied with respect to transverse momenta, numbers of nucleon-nucleon collisions, numbers of participants and centrality. Light mesons production measurements are important in the study of heavy ion collisions, serving as hard probes of the quark-gluon plasma (QGP). The research of light mesons in U + U collisions at 192 GeV allows discriminating the effects of hot matter depending on the geometric characteristics of the colliding heavy nuclei. The obtained results showed independence of the fragmentation of hard partons on the mass and composition of quarks and the absence of the influence of the geometric form of the colliding nuclei on the jet-quenching effect.

Keywords: quark-gluon plasma, light meson, nuclear modification factor, collision of heavy nuclei

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ПОДАВЛЕНИЕ ВЫХОДОВ АДРОНОВ В СТОЛКНОВЕНИЯХ ЯДЕР УРАНА ПРИ РАЗЛИЧНОМ КВАРКОВОМ СОСТАВЕ РОЖДАЮЩИХСЯ ЧАСТИЦ

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В статье представлены экспериментальные инвариантные спектры рождения, факторы ядерной модификации и отношения интенсивностей спектров легких мезонов, полученные в столкновении тяжелых ядер урана при энергии 192 ГэВ. Данные характеристики частично отражают свойства кварк-глюонной плазмы (КГП), рождающейся в столкновении тяжелых ядер урана при различном размере взаимодействующей системы и кварковом составе рождающихся частиц. Приведенные данные представлены в зависимости от поперечного импульса, среднего числа нуклон-нуклонных столкновений, среднего числа участников столкновения и класса по центральности. Предполагалось опытным путем дискриминировать эффекты горячей и плотной материи в зависимости от геометрических характеристик сталкивающихся тяжелых ядер из-за сферической несимметричности ядер урана. Анализ полученных данных привел к выводам о независимости фрагментации жестких партонов от массы и состава кварков легких мезонов и об отсутствии влияния геометрической формы сталкивающихся ядер на проявление эффекта гашения адронных струй.

Ключевые слова: кварк-глюонная плазма, легкий мезон, фактор ядерной модификации, столкновение тяжелых ядер

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Introduction

The generally accepted definition of quark-gluon plasma is a state of matter where the degrees of freedom are color-charged quarks and gluons. Systematic observations of quark-gluon plasma forming in collisions of ultrarelativistic heavy nuclei (A + A) were first carried out at the Relativistic Heavy Ions Collider (RHIC) at collision energies $\sqrt{s_{NN}}$ = 130 and 200 GeV (per nucleon) [1–4] and later at the Large Hadron Collider (LHC) in collisions of lead nuclei at $\sqrt{s_{NN}}$ = 2.76 TeV [5].

Production of hadrons in collisions of ultrarelativistic ions for high transverse momenta, p_T > 5 GeV/c is due to fragmentation of hard partons produced in deep inelastic collisions. Cross sections of hadron production in elementary proton collisions (p + p) are adequately described by the next-to-leading order formalism of perturbative quantum chromodynamics (NLO pQCD) [6]. Production of hadrons in A + A collisions is influenced by the quark-gluon medium: hard partons passing through it lose some of their energy, which leads to suppressed hadron yield in fragmentation (compared to their yield in elementary proton-proton collisions). This effect is known as jet quenching [6, 7]. Considering the production of different types of light mesons (for example, π^0, η, K_S) in (A + A) collisions is a step towards systematic study of the effects of quark-gluon plasma and, in particular, the effect of jet quenching depending on the main characteristics, such as mass and quark composition of these particles.

The jet quenching effect is assessed quantitatively by calculating the nuclear modification factor found depending on transverse momentum and centrality according to the expression:

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

where dN_{AA}, dN_{pp} are hadron yields in (A + A) and (p + p) collisions, respectively; $\langle N_{coll} \rangle$ is the average number of inelastic nucleon-nucleon collisions in a given centrality class of (A + A) interactions.

Particle yield in (A + A) collisions is typically measured as a function of transverse momentum and collision centrality. Centrality is measured as a percentage and determines the impact parameter and the degree of overlap of colliding nuclei [8]. Collisions with small impact parameter and centrality in the range of 0–20% are characterized by high multiplicity of particles and are called central collisions. Only a small fraction of interacting nucleons participate in peripheral collisions with centrality in the range of 60–80%.

Yields of K_S mesons are measured in the $K_S \to \pi^0\pi^0$ channel. Daughter particles of K_S meson decay (π^0 mesons) were measured earlier in [9]. K_S mesons consist of strange quarks, which makes it possible to study the production of light mesons depending on the quark composition of the given particles in comparing the nuclear modification factors of K_S, π^0 and η mesons [9]. The difference in the masses of K_S, π^0 and η mesons [9] allows to study the effect of jet quenching depending on the mass component of the given particles.

The system of colliding nuclei of uranium-238 (U + U) at $\sqrt{s_{NN}}$ = 192 GeV is of particular interest for studying the jet quenching effect. Uranium nuclei have a pronounced spherical asymmetry, so collisions of these nuclei have a peculiar collision geometry, different from that of symmetric nuclei (for example, gold or copper). Besides, uranium nuclei are the heaviest used in collider experiments: their collisions have the highest energy density and, as a result, the highest multiplicity of particles among all (A + A) systems in this energy range [10]. Thus, analyzing the characteristics of production of neutral light mesons in (U + U) collisions at $\sqrt{s_{NN}}$ = 192 GeV is an important part of systematic studies on the jet quenching effect that should make it possible to additionally discriminate between free parameters of different models describing the energy losses of hard partons in quark-gluon plasma.

This paper reports on jet quenching in production of π^0, η and K_S mesons in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV.

Study procedure

Raw data on collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV were collected using the PHENIX spectrometer at RHIC (Brookhaven National Laboratory, USA) in 2012. The centralities and coordinates of the vertex along the beam axis (z_{vert}) for each interaction of uranium nuclei were found using a system of beam-beam counters (BBC) [11]. The BBC counters determine the Minimum Bias trigger, selecting all the events of nucleus-nucleus collisions where at least one inelastic nucleon-nucleon interaction has occurred. The coordinate z_{vert} lies in the range $|z_{vert}|$ < 20 cm in this case. The BBC response together with the spectrometer response simulated by the Monte Carlo method based on the Glauber theory [12] is used to determine the average number of collisions N_{coll} and the average number $\langle N_{part} \rangle$ of nucleons participating in the nucleus-nucleus interaction.

Light K_S, π^0 and η mesons are detected in the $K_S \to \pi^0\pi^0$ (BR = 30.69±0.05%), $\pi^0 \to \gamma\gamma$ (BR = 98.82±0.03%) and $\eta \to \gamma\gamma$ (BR = 72.12±0.34%) channels [10] in the system of electromagnetic calorimeters of the PHENIX spectrometer. Geometry and characteristics of the calorimeters were described in [13]. Some kinematic constraints are imposed to improve the signal-to-background ratio. In particular, the constraints imposed on the minimum energy E_γ and the photon energy asymmetry are, respectively,

$$E_\gamma > 400 \text{ MeV and } \frac{|E_{\gamma 1} - E_{\gamma 2}|}{E_{\gamma 1} - E_{\gamma 2}} < 0.8.$$

The procedure for measuring the π^0 and η meson yields in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV was described in [8, 14].

To produce candidates for the role of π^0 mesons (referred to as π^0 candidates from now on) in $K_S \to \pi^0\pi^0$ decay, the invariant mass of a pair of γ quanta should be in the range of 1.5σ (σ is the standard deviation) of the measured masses of π^0 mesons, depending on their transverse momenta, and in the same arm of the PHENIX spectrometer. A pair of γ quanta should have a total momentum in the ranges

$$2 < p_T < 11 \text{ and } 2 < p_T < 14 \text{ GeV}/c$$

in the PbSc and PbGl subsystems [13] of the electromagnetic calorimeter, respectively. An additional adjustment is introduced for all γ pairs selected as π^0 candidates to re-

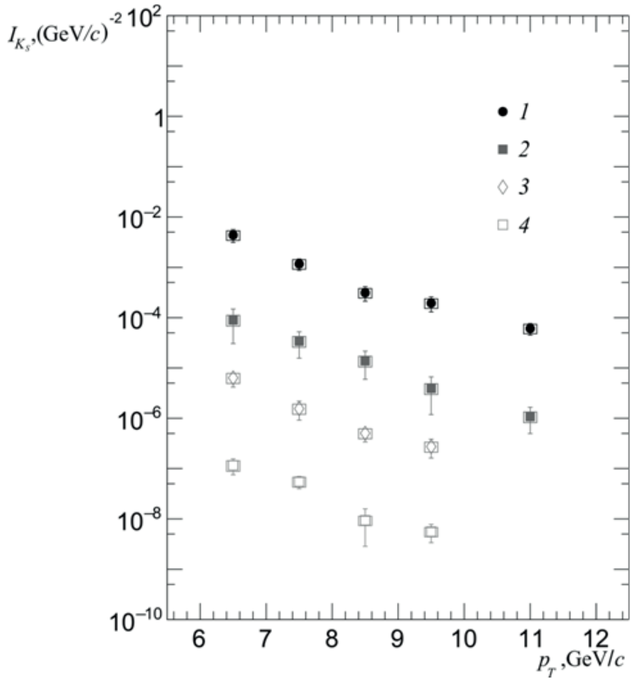

Fig. 1. Invariant spectra of K_S meson production as function of transverse momentum, measured in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV for different centrality classes, % 0–80 (*1*), 0–20 (*2*), 20–40 (*3*), 40–80 (*4*)

The vertical bars and the horizontal grey rectangles on the points here and below correspond to statistical and systematic measurement error, respectively duce the mass of the π^0 candidate to the table value m_{tabl} = 134.977 MeV, which allows to increase the signal-to-background ratio in the distributions over the invariant mass of $\pi^0\pi^0$ pairs.

Distributions over the invariant mass of pairs of π^0 candidates used to determine the yield of K_S mesons are formed in different transverse momentum ranges and centrality classes and are approximated by the sum of a Gaussian function (describing the signal from K_S mesons) and a parabola (describing the background). The yield of K_S mesons is found by the area under the Gaussian function.

Due to limited acceptance of the detector, the effects of its operation, and the kinematic constraints used in analysis, K_S meson yields are corrected using the reconstruction efficiency. This quantity is calculated for K_S mesons by Monte Carlo simulation of the detector's response using the GEANT-3 software package [15].

Invariant yields of K_S mesons in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV in different transverse momentum ranges and centrality classes are measured by the formula used in the study of π^0 meson production [8].

The main systematic error in measuring the yields of K_S mesons produced in collision of U + U nuclei is the error related to selecting the parameters for approximating invariant mass distributions: the approximation range, signal integration range and the polynomial degree during approximation. The error is 15.0–22.5% in different ranges of transverse momenta and in different centrality classes. A substantial contribution to systematic measurement error is also made by conversion of γ quanta in detector materials (10.4%).

Results and discussion

Fig. 1 shows invariant spectra of K_S meson production as function of transverse momentum in collisions of uranium nuclei (U + U) at $\sqrt{s_{NN}}$ = 192 GeV. The spectra were measured in four centrality classes and in a wide range of transverse momenta: up to 11 GeV/c in central collisions.

Fig. 2 shows a comparison of nuclear modification factors for K_S mesons produced in collisions of uranium nuclei (U + U) at $\sqrt{s_{NN}}$ = 192 GeV, gold (Au + Au) [16] and copper (Cu + Cu) nuclei [17] at $\sqrt{s_{NN}}$ = 200 GeV with an equal number of inelastic nucleon-nucleon collisions $\langle N_{coll}\rangle$. The values of $\langle N_{coll}\rangle$ for each system of colliding nuclei and each centrality class are given in Table. The nuclear modification factors of K_S mesons were calculated by formula (1).

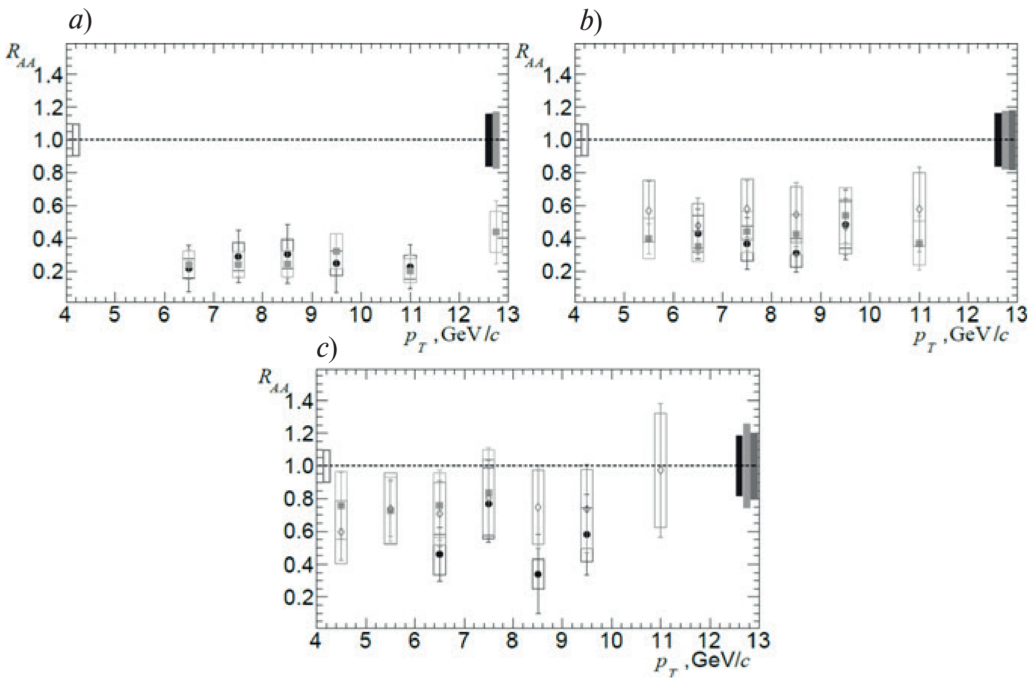

Fig. 2. Nuclear modification factors R_{AA} as function of transverse momentum p_T for K_S mesons in (U + U) interactions (solid circles), (Au + Au) interactions (solid squares) and (Cu + Cu) interactions (diamonds) [16, 17] at energies of 192 and 200 GeV, respectively (see Table)

Rectangles over the dashed lines indicate the systematic error for N_{coll}

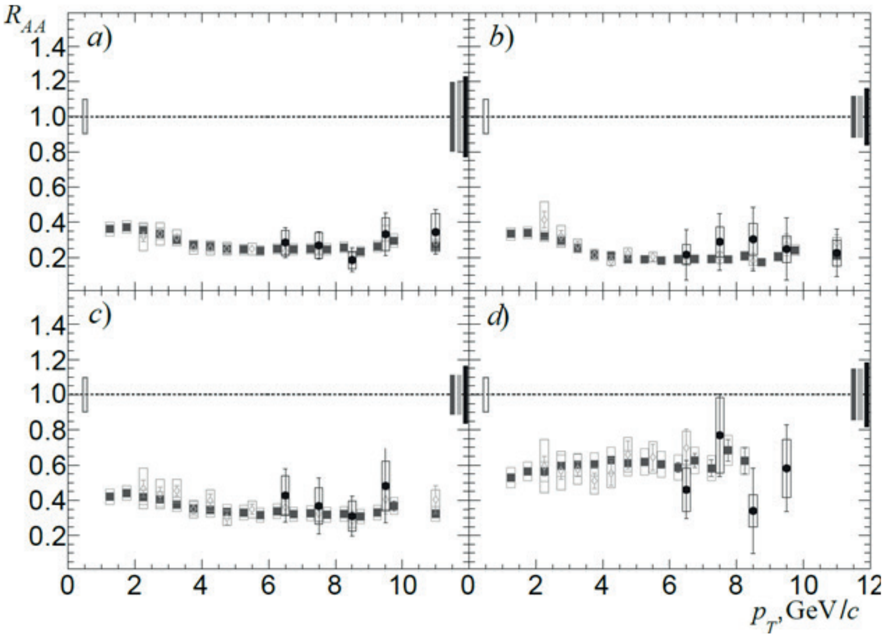

Fig. 3. Nuclear modification factor R_{AA} as function of transverse momentum p_T for π^0 mesons (squares), η mesons (diamonds) and K_S mesons (circles) in (U + U) interactions at $\sqrt{s_{NN}}$ = 192 GeV for different centrality classes, %: 0–80 (*a*), 0–20 (*b*), 20–40 (*c*), 60–80 for π^0 and η mesons, and 40–80 for K_S mesons (*d*). Rectangles over the dashed lines indicate the systematic error for N_{coll}

Table

Number of collisions N_{coll} as function of centrality for different types of interactions (see Fig. 2) [16, 17, 19]

Centrality, %	N_{coll}	Fig. 2
Au + Au, 200 GeV		
0–20	783.2±71.4	*a*)
20–60	300.8±32.6	*b*)
60–93	14.5±2.5	*c*)
Cu + Cu, 200 GeV		
0–20	151.8±16.1	*b*)
20–60	42.0±3.5	*c*)
U + U, 192 GeV		
0–20	934.5±97.5	*a*)
20–40	335.0±33.0	*b*)
40–80	56.7±5.0	*c*)

Note. Different variants possible for collisions of uranium nuclei are due to different degrees of deformation of the uranium nucleus in calculations of the nucleon numbers N_{coll} in the Glauber model [19].

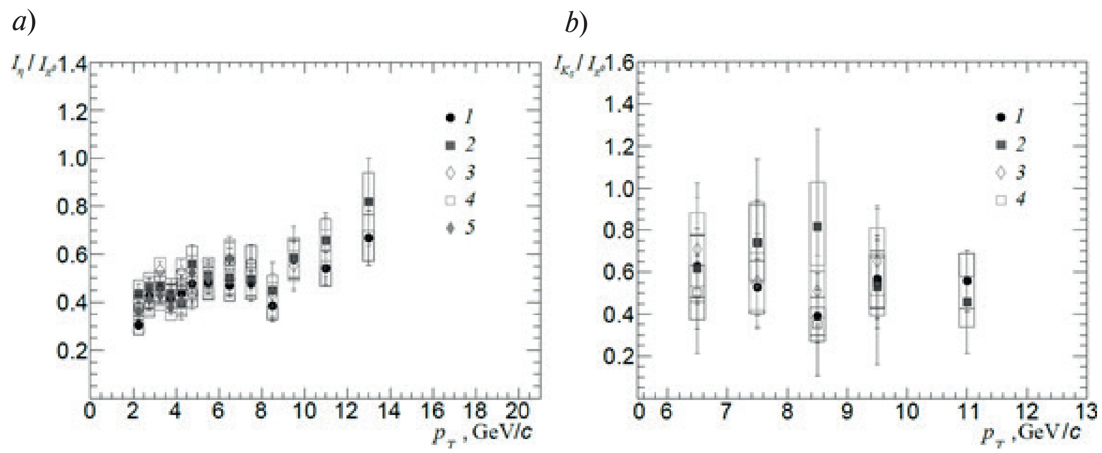

Fig. 4. Ratios of η meson to π^0 meson production spectra *(a)* and K_S meson to π^0 meson production spectra *(b),* measured in U + U collisions at $\sqrt{s_{NN}}$ = 192 GeV, as functions of transverse momentum for different centrality classes, %: 0–80 (*1*), 0–20 (*2*), 20–40 (*3*), 40–60 for η/π^0 and 40–80 for K_S/π^0 (*4*), 60–80 (*5*)

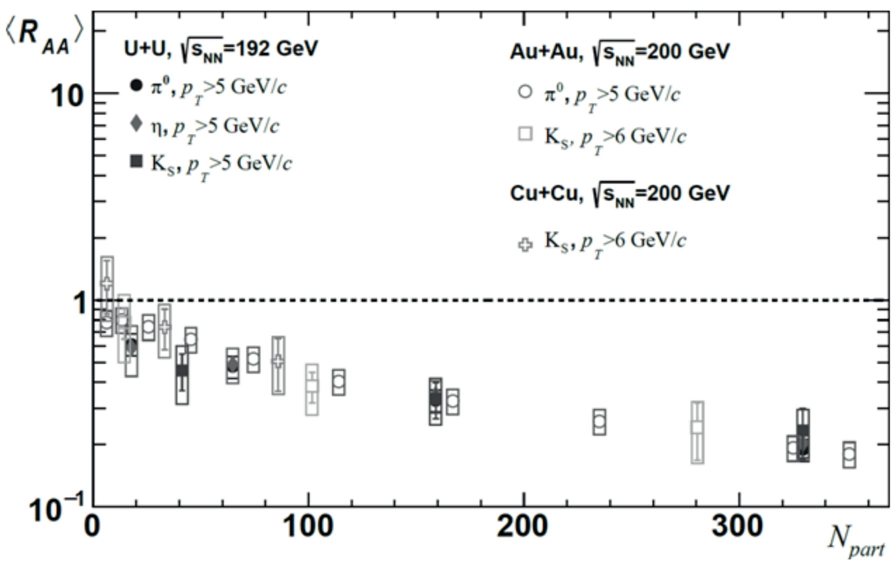

Fig. 5. Integral nuclear modification factors of π^0, η and K_S mesons in collisions of U + U, Au + Au and Cu + Cu nuclei [16, 17, 19] at $\sqrt{s_{NN}}$ = 192 GeV and 200 as functions of average number $\langle N_{part}\rangle$ of collision participants

The nuclear modifications factor of K_S mesons measured in collisions of uranium, gold and copper nuclei (U + U, Au + Au and Cu + Cu) at $\sqrt{s_{NN}}$ = 192 and 200 GeV coincide within the measurement error for all given values of $\langle N_{coll}\rangle$. A similar behavior of nuclear modification factors was observed in the study of yields of particles (π^0 mesons) that did not include the *s* quark [9], which indicates that the jet quenching effect does not depend on the geometric shape of colliding nuclei and the quark composition of the given light mesons in (U + U), (Au + Au) and (Cu + Cu) collisions at $\sqrt{s_{NN}}$ = 192 and 200 GeV.

Fig. 3 shows a comparison of nuclear modification factors of π^0, η and K_S mesons, measured in collisions of U + U nuclei at $\sqrt{s_{NN}}$ = 192 GeV in different centrality classes.

The nuclear modification factors of π^0, η and K_S mesons, measured in collisions of U + U nuclei at $\sqrt{s_{NN}}$ = 192 GeV, coincide within the error in the entire range of transverse momenta and in all centrality classes.

The ratios of η to π^0 meson yields (η/π^0) and of K_S to π^0 meson yields (K_S/π^0), measured in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV, in different centrality classes are shown in Fig. 4.

The behavior of η/π^0 and K_S/π^0 ratios measured in collisions of U + U nuclei at $\sqrt{s_{NN}}$ = 192 GeV does not depend on centrality and transverse momentum within the systematic error. The ratios η/π^0 and K_S/π^0 for the spectra coincide with the previously measured ratios within statistical and systematic error [17, 18]. The fact that the η/π^0 and K_S/π^0 ratios do not depend on the collision system indicates that fragmentation of hard partons does not depend on mass and quark composition of π^0, η and K_S mesons.

Fig. 5 shows the integral nuclear modification factors of π^0, η and K_S mesons produced in collisions of uranium, gold and copper nuclei at $\sqrt{s_{NN}}$ = 192 and 200 GeV [8, 14, 16–18]. The behavior of integral nuclear modification factors of π^0, η, and K_S mesons produced in collisions of U + U nuclei as functions of $\langle N_{part}\rangle$ does not differ, within the systematic error, from the behavior of integral nuclear modification factors of π^0, η and K_S mesons produced in collisions of Cu + Cu and Au + Au nuclei.

Conclusion

We have measured the invariant spectra of K_S meson production as function of transverse momentum in four centrality classes and the nuclear modification factors of K_S mesons in three centrality classes in collisions of uranium nuclei (U + U) at $\sqrt{s_{NN}}$ = 192 GeV.

Coinciding nuclear modification factors for the K_S mesons produced in collisions of uranium nuclei at $\sqrt{s_{NN}}$ = 192 GeV, gold and copper at $\sqrt{s_{NN}}$ = 200 GeV, with an equal average number of inelastic nucleon-nucleon collisions in the entire measured range of transverse momenta in all centrality classes indicates the absence of the jet quenching effect does not depend on the shape of colliding nuclei. A similar behavior of nuclear modification factors is observed in particles with a different quark composition (π^0 and η mesons) [8].

The behavior of the η/π^0 and K_S/π^0 ratios and the integral nuclear modification factors of π^0, η and K_S mesons indicates that fragmentation of hard partons does not depend on mass and composition of quarks of π^0, η and K_S mesons produced in collisions of U + U nuclei at $\sqrt{s_{NN}}$ = 192 GeV.

Measurements performed in (U + U) collisions at $\sqrt{s_{NN}}$ = 192 GeV for π^0, η and K_S mesons confirm that the geometric shape of colliding nuclei has no effect on jet quenching.

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