PHENIX EXPERIMENT: STUDY OF THE JET QUENCHING EFFECT IN THE ULTRARELATIVISTIC U+U COLLISIONS

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Extensive study of heavy ion collisions at RHIC has resulted in discovery of a new state of matter – strongly interacting quark-gluon plasma (sQGP). Measurements of high-p_T particles contribute to systematic study of sQGP properties. Yields of leading particle such as π^0 can be measured with high precision at high transverse momenta. Study of π^0 in different collision systems allows investigation of the path length dependence of energy loss in the medium. U+U presents an opportunity to research non-spherical heavy ion collision system with highest energy density in central collisions. This paper presents the most recent PHENIX results on π^0 production in U+U collision system. Results are presented as functions of p_T and centrality.

Key words: quark gluon plasma; nuclear modification factor; jet quenching heavy ion collision

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Introduction

The 2005 collaboration at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory [1] announced the discovery of strongly interacting quark-gluon plasma [2] formed in central collisions of ultra-relativistic heavy nuclei. Strongly interacting quark-gluon plasma (sQGP) is a state of nuclear matter existing under extreme conditions (at energy densities of the order of 1 GeV/fm^3 and temperatures of about 170 MeV) where quarks and gluons possessing a color charge are no longer confined inside hadrons and move freely within a volume of the order of 10 fm^3. It is believed that the Universe was in this state a few microseconds after the Big Bang.

The current goal of the PHENIX experiment [3] is detailed study of the properties of the sQGP, its dynamics and the specifics of production and interaction of different particles.

One of the key indicators pointing to the formation of sQGP is the effect of quenching of hadronic jets, which manifests itself as the suppression of the yield of high-energy hadrons in central ultra-relativistic collisions of heavy nuclei. The production of hadrons in the region of high transverse momenta ($p_T > 5$ GeV/c) is governed by fragmentation processes where high-energy partons escape from the collision region and form hadronic jets [4 – 6]. Thus, studying the degree of suppression of the hadron yield in the region of high transverse momenta is considered to be one of the best ways to study the properties of sQGP.

Using π^0 mesons is the most popular method for studying the degree of hadron suppression in the region of high transverse momenta. This is convenient because the spectra of π^0 mesons can be measured over a wide range of transverse momenta with a small error.

The system of ultra-relativistic uranium nuclei (U + U) is particularly interesting. Uranium nuclei have a pronounced non-spherical shape, and as a result, the U + U system has a peculiar collision geometry compared to symmetric (Au + Au, Cu + Cu, Pb + Pb) and asymmetric (Cu + Au) systems. In addition, the central (U + U) collisions are characterized by the highest energy density available at the RHIC. Studying the specifics of production of neutral mesons (in particular, π^0 mesons) allows to better discriminate between different theoretical models describing the properties of sQGP.

Problem statement and description

The main goal of this paper was to study the production of π^0 mesons in (U + U) collisions at an energy $\sqrt{s_{NN}} = 192\text{GeV}$. The following data were obtained and analyzed for this purpose:

invariant spectra of π^0 meson production as a function of their transverse momentum p_T and centrality of (U + U) collisions;

nuclear modification factors of π^0 mesons as a function of p_T and centrality.

The transverse momentum p_T characterizes the interaction energy in the system of colliding nuclei. Centrality serves as one of the basic characteristics of interaction; it indicates the degree of overlap of the colliding nuclei with a fixed impact parameter. The maximum degree of overlap corresponds to central collisions (0 – 20%), and the minimum overlap corresponds to peripheral ones (60 – 80%).

Experimental procedure

The results of the study were obtained using the PHENIX spectrometer (RHIC, BNL) [7]. The measuring system of the PHENIX experiment consists of four spectrometer arms. Two muon arms (the north and the south) cover the rapidity range $1.2 < |\eta| < 2.4$, detecting muon radiation. The east and west central arms (Fig. 1) detect electrons, photons and charged hadrons. The central arms consist of two drift chambers *5*, three layers of pad chambers *7*, eight sectors of electromagnetic calorimeter *2* and *3*, RICH detector *4*, time-of-flight chambers *6*, nucleus-nucleus collision counter *1*, and other elements.

The electromagnetic calorimeter measures the energy and positions of photons, electrons and hadrons emitted into its acceptance. The PHENIX detector uses two types of calorimeters:

scintillation sampling calorimeter PbSc (4 sectors in the west arm and 2 sectors in the east arm);

lead-glass Cherenkov calorimeter Pb*Gl* (2 sectors in the east arm).

Each of these calorimeters has both advantages and disadvantages, and using them simultaneously allows to carry out measurements with the required accuracy and to assess the systematic effects. Each sector of the calorimeter is divided into identical towers determining its segmentation.

The π^0 meson yields are measured in the $\pi^0 \to \gamma\gamma$ channel. The photon energies and momenta are measured in the electromagnetic calorimeter. However, hadrons may lose energy and form hadronic showers upon falling into the active volume of the detector. Electron showers produced by photons can be binned in many ways, and in this paper we have chosen the discrimination method based on determining the shape of the shower for this purpose.

Different types of quantitative methods are used for different types of detectors. Analysis of the shape of the showers produced in the PbSc electromagnetic calorimeter consists of comparing the energy release within the towers with the data obtained by the Monte Carlo simulation. The comparison is carried out by the χ^2-fitting procedure correlating the energies deposited in the towers of the same cluster with the data obtained by Monte Carlo simulation. The electromagnetic nature of the clusters reconstructed with the PbSc calorimeter is established using the inequality $\chi^2 < 3$. Analysis of the shape of the showers produced in the Pb*Gl* calorimeter is carried out using cluster dispersion analysis. The electromagnetic nature of the clusters reconstructed with the Pb*Gl* calorimeter is established using the discrimination inequality.

Additional energy constraints are used to discriminate between hadron clusters. A lower threshold is established for the energy of the reconstructed clusters:

$$E\gamma > 400 \text{ MeV},$$

since the mean energy deposited in the calorimeter by charged hadrons $E \approx 300$ MeV.

The criteria for selecting events include the following conditions:

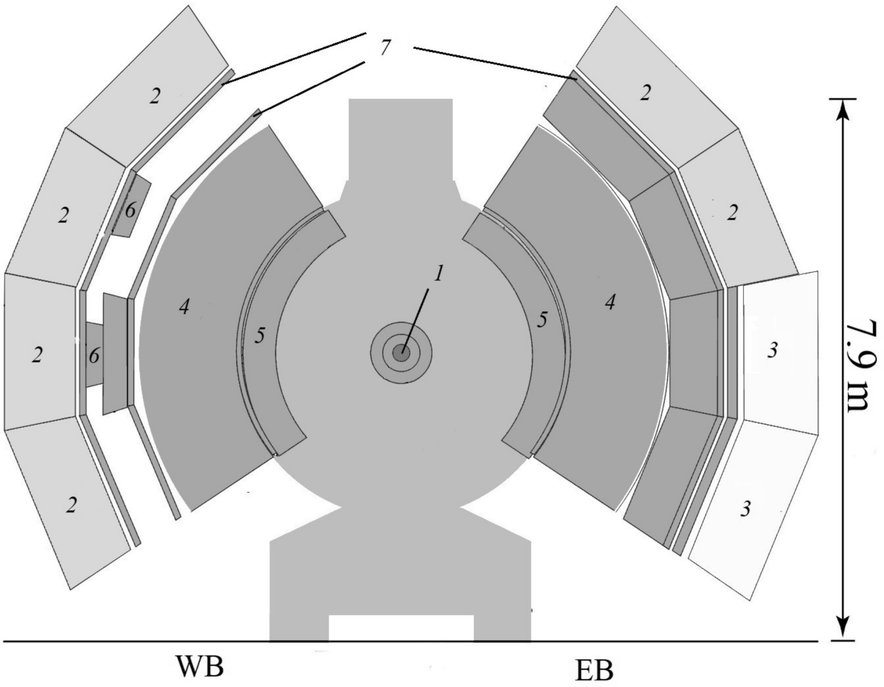

Fig. 1. Schematic of the central part of the PHENIX detector:
nucleus–nucleus collision counter *1*, electromagnetic calorimeter *2*, *3* (8 sectors), RICH detector *4*, drift chambers *5*, time-of-flight chambers *6*, three layers of pad chambers *7*, WB and EB are the west and east branches of the detector

data segments that have not passed the calorimeter’s quality control are excluded;

in this paper, the constraint of the interaction vertex was determined by the inequality

$$-20 < z_v < +20.$$

The efficiency of the trigger in this interval was constant in the cycle of (U + U) collisions.

The π^0 meson yields were measured by combining photonic clusters reconstructed in the sectors of the calorimeter, by reconstructing the effective masses of these mesons as a function of their transverse momentum and by constructing phase distributions of the decay products of these particles.

Data processing was performed using the ROOT CERN 5.34 mathematical library. Monte Carlo simulations of meson production were carried out in the Geant 3 package.

The collective effects of the nucleon interaction in colliding ($A + A$) nuclei can be conveniently described using the nuclear modification factor R_{AA}, equal to the ratio of invariant hadron yields in the collisions of ($A + A$) nuclei to the invariant yields of the same hadrons in proton-proton interactions ($p + p$) This ratio is normalized to the number of inelastic nucleon-nucleon pair collisions $\langle N_{\text{coll}} \rangle$:

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

where dN_{AA}, dN_{pp} are the respective hadron yields in the collisions of ($A + A$) nuclei and ($p + p$) protons in a given range of transverse momenta.

The number of inelastic nucleon-nucleon pair collisions is determined through calculation by the Monte Carlo method according to the Glauber theory which takes into account the geometry of the colliding nuclei. Normalization to this number is based on the assumption that hadrons are produced in elementary parton-parton interactions (the interactions are described by perturbative quantum chromodynamics). If the value of the nuclear modification factor is equal to unity, collective interaction effects are not observed in the system of colliding nuclei. If the nuclear modification factor differs from unity, it indicates either a suppression or an excess of the particle yield.

The data that satisfy the constraints on photon clusters reconstructed in the electromagnetic calorimeter and constraints on nuclear collision events are used to measure the π^0 meson yields. The neutral pion yields are measured separately in the PbSc and Pb*Gl* subsystems in the $\pi^0 \to \gamma\gamma$ channel

The first step in measuring meson yields is the construction of the effective mass distribution of two gamma quanta depending on the centrality of the colliding U + U nuclei and on the total transverse momentum of the two γ quanta. The effective mass distributions contain a useful meson signal and a combinatorial background (uncorrelated and correlated). The correlated background contains the decay channels of other particles whose final state is accompanied by production of gamma quanta, and the uncorrelated background consists of random combinations of γ pairs.

The form of the uncorrelated background can be reconstructed using the event-mixing technique that involves combining gamma pairs with similar characteristics (vertex and centrality) taken from two different events.

Next, effective mass distributions with event mixing (background) are constructed for each centrality class and normalized to the effective mass distribution for real events (background + signal) and subtracted from it.

Results and discussion

The neutral π^0 meson yields in uranium nuclei collisions (U + U) at $\sqrt{s_{NN}}$ = 192GeV were measured in five centrality classes (0 – 20 %, 20 –40 %, 40 – 60 %, 60 – 80 %, 0 – 80 %) and different transverse momentum ranges. The effective mass distribution $M_{\gamma\gamma}$ with event mixing was normalized to the effective mass distribution for real events in the intervals

$$0.080 < M_{\gamma\gamma} < 0.085\ (\mathrm{GeV}/c^2),$$

$$0.036 < M_{\gamma\gamma} < 0.040\ (\mathrm{GeV}/c^2).$$

The combinatorial background decreases sharply with an increase in the transverse momentum, allowing to subtract the distribution over the effective mass of two γ quanta of the signal + background and background types in the interval

$$1 < p_T < 10\ \mathrm{GeV}/c$$

with respect to the transverse momentum, and the uncorrelated background in the remaining interval is described well along with the residual correlated background.

The result of subtraction of two distributions is approximated by a Gaussian function for describing the signal from reconstructed π^0 mesons and a linear function for describing the residual correlated background, in the interval

$$0.07 < M_{\gamma\gamma} < 0.25\ \mathrm{GeV}/c^2.$$

The π^0 meson yield is measured by counting the number of samples and subtracting the integral under the linear function; this integral describes the residual correlated background. The region of counting the number of samples under the Gaussian function and integrating the linear function lies in the interval

$0.10 < M_{\gamma\gamma} < 0.17\ \mathrm{GeV}/c^2$.

An example of the effective mass distribution of two gamma quanta after subtracting the combinatorial background and approximation is shown in Fig. 2.

Analysis of the experimental data obtained provides information only on the π^0 mesons whose decay products have fallen into the detector acceptance. To determine the true spectra of the particles produced in nucleus-nucleus collisions, the efficiency of reconstruction of these particles in the detector has to be estimated. This is achieved through Monte Carlo simulation of the meson flux through the detector system and recording the meson decay products. In this case, the reconstruction efficiency is the ratio of the number of particles reconstructed in the detector during the simulation to the number of the initial particles.

The efficiencies of reconstructing neutral pions in the sectors of the electromagnetic calorimeter that we have estimated for different centralities of copper and gold nuclei collisions are shown in Fig. 3.

The dependence of invariant differential yields of π^0 mesons on the transverse momentum is calculated using the following formula:

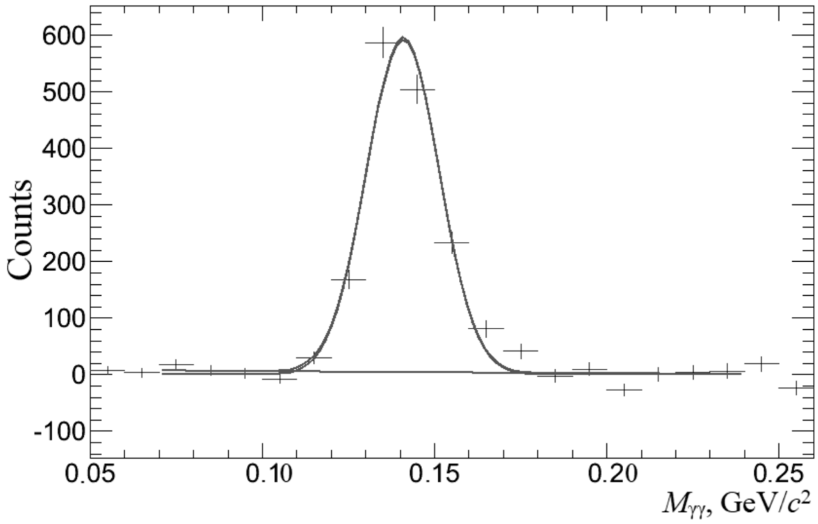

Fig. 2. Effective mass distribution of two gammas after subtraction of the combinatorial background and approximation; the distribution was measured in the range from 9.5 to 10.0 GeV/*c* (in central collisions) in the Pb*Gl* subsystem

$$dN_{AA}(p_T) = \frac{1}{2\pi p_T}\frac{N_{\pi^0}(p_T)}{N_{event}\Delta p_T \varepsilon_{rec}(p_T)}, \quad (2)$$

where N_{π^0} is the yield of neutral π mesons (π^0), ε_{rec} is the recording efficiency, N_{event} is the number of analyzed events.

The invariant spectra of π^0 mesons as a function of the transverse momentum are shown in Fig. 4 for different centrality classes. Because it is impossible to discriminate the signal at the background level in the region of low transverse momenta, the neutral pion (π^0) spectrum starts at 2 GeV/*c*. Due to limited amount of statistical data available, the π^0 meson spectra could be measured only up to 16 GeV/*c*.

The nuclear modification factors of neutral π^0 mesons were calculated by formula (1) using two different sets of the number N_{coll} of the nucleons participating in the interaction in different centrality ranges of (U + U) collisions in a wide range of transverse momenta, up to 16

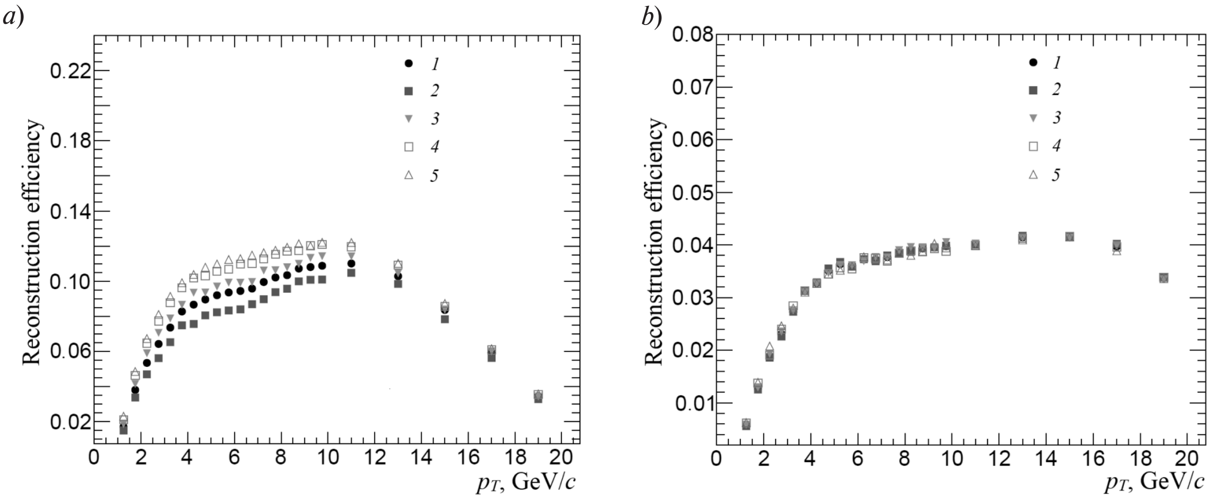

Fig. 3. Reconstruction efficiencies of π^0 mesons in the PbSc (*a*) and Pb*Gl* (*b*) electromagnetic calorimeters as a function of the transverse momentum for different centrality classes, %: 0 – 80 (*1*), 0 – 20 (*2*), 20 – 40 (*3*), 40 – 60 (*4*), 60 – 80 (*5*)

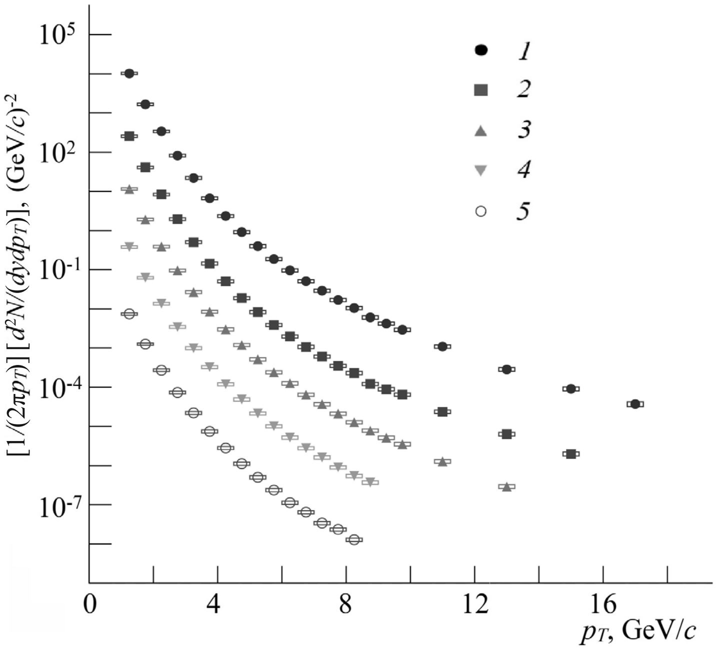

Fig. 4. Invariant spectra of π^0 mesons with respect to the transverse momentum for different centrality classes of (U + U) collisions at an energy $\sqrt{s_{NN}} = 192$ GeV (the curve numbers correspond to those in Fig. 3).

The vertical bars and the horizontal grey rectangles on the points here and below correspond to statistical and systematic measurement errors, respectively

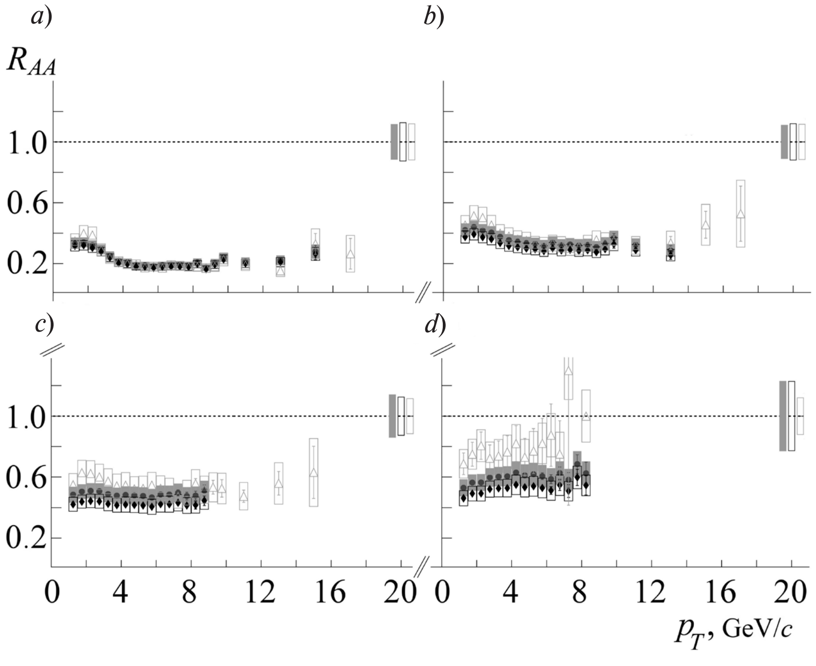

Fig. 5. Dependences of the magnitude of the nuclear modification factor R_{AA} on the transverse momentum p_T for neutral pions in (U + U) interactions (circles and diamonds) and (Au + Au) interactions (triangles) for energies of 192 and 200 GeV, respectively (see the table).

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

GeV/*c*. Two different sets of N_{coll} values are used because uranium nuclei have different degrees of deformation when the nucleon number N_{coll} is calculated in the Glauber model [8 – 10].

Fig. 5 shows the dependences of the nuclear modification factors on the transverse momentum of neutral pions, measured in (U + U) and (Au + Au) collisions [11, 12] at energies $\sqrt{s_{NN}}$ = 192 and 200 GeV, respectively, and at close N_{coll} values. The N_{coll} values corresponding to the centrality classes for which the nuclear modification factors are shown are given in the table.

The nuclear modification factors measured in the (U + U) and (Au + Au) systems coincide within the error at large N_{coll} values, which indicates that the degree of neutral pion suppression does not depend on the geometry of the nuclear overlap region. There is a slight difference in the values of nuclear modification factors obtained in collisions of uranium and gold nuclei at small N_{coll} values.

Conclusion

The PHENIX experiment uncovered the reconstruction efficiencies of π^0 mesons for each type of electromagnetic calorimeter and each centrality range as a function of the transverse momentum. The invariant differential spectra and the nuclear modification factors of π^0 mesons were measured as a function of the transverse momentum in four centrality classes of (U + U) collisions with the energy in the center-of-mass frame equal to 192 GeV. The yields of neutral pions measured in the (U + U) and (Au + Au) collisions at energies of 192 and 200 GeV were equally suppressed with a larger number of nucleon-nucleon collisions ($N_{\text{coll}} > 90$), which indicates that the degree of suppression does not depend on the shape of

Table

Collision numbers N_{coll} as a function of the collision centrality for different types of interactions (see Fig. 5)

Centrality, %	N_{coll}	Fig. 5
Au + Au (200 GeV)		
0 – 5	1065.4 ± 105.3	*a*)
20 – 30	373.8 ± 39.6	*b*)
40 – 50	120.3 ± 13.7	*c*)
60 – 80	20.4 ± 5.9	*d*)
U + U (variant I), 192 GeV		
0 – 20	934.5 ± 97.5	*a*)
20 – 40	335.0 ± 33.0	*b*)
40 – 60	95.9 ± 13.0	*c*)
60 – 80	17.5 ± 3.8	*d*)
U + U (variant II), 192 GeV		
0 – 20	999.0 ± 114.0	*a*)
20 – 40	375.0 ± 45.0	*b*)
40 – 60	110.0 ± 14.6	*c*)
60 – 80	19.7 ± 4.4	*d*)

Note. Different variants possible in the collisions of uranium nuclei are due to different degrees of deformation of the uranium nucleus in calculations of the number N_{coll} of nucleons in the Glauber model [8 – 10].

the overlap region of the colliding nuclei. The yield of π^0 mesons in peripheral ($N_{\text{coll}} \approx 20$) (U + U) collisions may be suppressed more strongly than that in (Au + Au) collisions. Nevertheless, it does not seem possible to reliably discriminate between the results obtained in the peripheral collisions of uranium and gold for the given measurement accuracy.

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