NUCLEAR PHYSICS

Original article
DOI: https://doi.org/10.18721/JPM.19213

AZIMUTHAL DEPENDENCES OF THE NUCLEAR MODIFICATION FACTORS OF π^0 MESONS IN CU+AU COLLISIONS AT AN ENERGY OF 200 GEV AND U+U COLLISIONS AT 193 GEV

E. V. Bannikov✉, *Ya. A. Berdnikov*, *D. M. Larionova*, *D. O. Kotov*, *K. N. Basirov*, *I. I. Borisov*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ bannikov.ev.21@gmail.com

Abstract. The paper presents the results of calculating the nuclear modification factors of π^0 mesons as a function of their transverse momentum and azimuthal angle at different collision centralities of Cu+Au at an energy of 200 GeV and U+U at 193 GeV. As a result of the analysis of the obtained data, it was established that the azimuthal dependence of the nuclear modification factors of π^0 mesons in both collision systems demonstrated universality in the considered range of transverse momentum and could be explained by the dependence of parton energy losses on the length of their path in the quark-gluon plasma (QGP). It is advisable to use these azimuthal dependences of nuclear modification factors for clarification of the parameters in theoretical models describing the energy losses of partons in the QGP formed in collisions of deformed nuclei or in asymmetric collision systems.

Keywords: quark-gluon plasma, azimuthal anisotropy, nuclear modification factors, π^0 meson

Citation: Bannikov E. V., Berdnikov Ya. A., Larionova D. M., Kotov D. O., Basirov K. N., Borisov I. I., Azimuthal dependences of the nuclear modification factors of π^0 mesons in Cu+Au collisions at an energy of 200 GeV and U+U collisions at 193 GeV, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (2) (2026) 160–170. DOI: https://doi.org/10.18721/JPM.19213

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/licenses/by-nc/4.0/)

© Bannikov E. V., Berdnikov Ya. A., Larionova D. M., Kotov D. O., Basirov K. N., Borisov I. I., 2026. Published by Peter the Great St. Petersburg Polytechnic University.

Научная статья
УДК 539.12
DOI: https://doi.org/10.18721/JPM.19213

АЗИМУТАЛЬНЫЕ ЗАВИСИМОСТИ ФАКТОРОВ ЯДЕРНОЙ МОДИФИКАЦИИ π^0-МЕЗОНОВ В СТОЛКНОВЕНИЯХ РЕЛЯТИВИСТСКИХ ЯДЕР МЕДИ И ЗОЛОТА ПРИ ЭНЕРГИИ 200 ГЭВ И ЯДЕР УРАНА ПРИ 193 ГЭВ

Е. В. Банников✉, *Я. А. Бердников*, *Д. М. Ларионова*, *Д. О. Котов*, *К. Н. Басиров*, *И. И. Борисов*

Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия

✉ bannikov.ev.21@gmail.com

Аннотация. В работе представлены результаты расчета факторов ядерной модификации π^0-мезонов как функции от их поперечного импульса и азимутального угла в различных центральностях столкновений релятивистских ядер Cu+Au при энергии 200 ГэВ и U+U при 193 ГэВ. В результате анализа полученных данных было установлено, что характер азимутальной зависимости факторов ядерной модификации π^0-мезонов в обеих системах столкновений универсален в рассматриваемом диапазоне по поперечному импульсу и может быть объяснен зависимостью потерь энергии партонов от длины их пути в кварк-глюонной плазме (КГП). Азимутальные зависимости факторов ядерной модификации π^0-мезонов, рассчитанные в данной работе, целесообразно использовать для уточнения параметров теоретических моделей, описывающих потери энергии партонов в КГП, образующейся в столкновениях деформированных ядер или в асимметричных системах столкновений.

Ключевые слова: кварк-глюонная плазма, азимутальная анизотропия, фактор ядерной модификации, π^0-мезон

Ссылка для цитирования: Банников Е. В., Бердников Я. А., Ларионова Д. М., Котов Д. О., Басиров К. Н., Борисов И. И. Азимутальные зависимости факторов ядерной модификации π^0-мезонов в столкновениях релятивистских ядер меди и золота при энергии 200 ГэВ и ядер урана при 193 ГэВ // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 2 № .19. С. 160–170. DOI: https://doi.org/10.18721/JPM.19213

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/)

Introduction

In the late 20th century, quantum chromodynamics predicted that matter could transition into a special state at extreme energy densities and/or temperatures, where its fundamental constituents, i.e., partons (quarks and gluons), become asymptotically free [1]. This state of matter was named the quark-gluon plasma (QGP). Subsequently, collider experiments showed that QGP can form in collisions of relativistic heavy ions [2].

Understanding the properties of the QGP is a pressing problem in high-energy physics; however, a major challenge in research is that the QGP lifetime is very short (~10 fm/c [3]), making direct experimental observation impossible. Experimental approaches to studying the formation and properties of the QGP in relativistic ion collisions are based on measuring the yields of produced particles and their angular characteristics.

The goal of this study was to measure the azimuthal dependences of hadron suppression at high transverse momenta ($p_T > 5$ GeV/c) [4].

© Банников Е. В., Бердников Я. А., Ларионова Д. М., Котов Д. О., Басиров К. Н., Борисов И. И., 2026. Издатель: Санкт-Петербургский политехнический университет Петра Великого.

Problem statement

One of the main facilities used for collisions of relativistic heavy ions is the Relativistic Heavy Ion Collider (RHIC). The PHENIX experiment [3] at RHIC discovered that the production of hadrons with high transverse momenta p_T in heavy-ion collisions (e.g., Au+Au) is suppressed compared to their production in proton–proton (p+p) collisions [5]. Hadron production at high p_T occurs predominantly through fragmentation of jets formed by high-energy partons [6]. As these high-energy partons traverse the dense QGP medium formed in heavy-ion collisions, they interact with it and lose energy, mainly via gluon bremsstrahlung [6]. The energy loss of the parent partons leads to a weakening of the hadronic jets, consequently reducing the transverse momentum of the hadrons in these jets (the jet quenching effect).

Thus, the observed suppression of hadron production at high p_T was interpreted as evidence for QGP formation in heavy-ion collisions [3].

The suppression of hadron production at high p_T is typically quantified using the nuclear modification factors R_{AB} (NMFs), defined as the ratio of hadron yields in nucleus–nucleus collisions to those in p+p collisions:

$$R_{AB}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AB}/dp_T dy}{d^2N_{pp}/dp_T dy},$$

where $\langle N_{coll} \rangle$ is the average number of binary inelastic nucleon–nucleon collisions; $d^2N_{AB}/dp_T dy$ is the p_T differential yield of the particles considered in (A+B) collisions; $d^2N_{pp}/dp_T dy$ is the p_T differential yield in p+p collisions; y is the rapidity.

The suppression of hadron production in nucleus–nucleus collisions due to the energy loss of high-energy partons causes the $R_{AB}(p_T)$ values to fall below unity at $p_T > 5$ GeV/c.

Previously measured $R_{AB}(p_T)$ of hadrons at $p_T > 5$ GeV/c in relativistic heavy-ion collisions were described by theoretical models that account for parton energy loss in the QGP medium [6–8]. One of the key parameters in these models is the transport coefficient $\hat{q}$, which characterizes the average squared transverse momentum exchanged between a high-energy parton and the QGP medium per unit path length.

The main difficulty with the theoretical models used to describe parton energy loss in the QGP is that different models yield different values of the transport coefficient $\hat{q}$ and different estimates of the path-length dependence of the energy loss [6]. Such differences make it impossible to unambiguously and accurately describe the measured $R_{AB}(p_T)$ dependences of hadrons and their azimuthal anisotropy (experimentally quantified by the elliptic flow v_2).

While existing models accurately describe the $R_{AB}(p_T)$ dependence of hadrons at $p_T >$ 5 GeV/c, they systematically underestimate v_2 [9]. A simultaneous description of $R_{AB}(p_T)$ and v_2 requires both accounting for the more complex initial collision geometry (which increases v_2 in model calculations) and adopting more sophisticated approaches, such as AdS/CFT [6]. However, these approaches require further separate investigation [9, 10]. Despite recent advances in modeling the interactions of hadronic jets with the QGP medium [11], this problem remains unresolved.

Thus, to gain a clearer understanding of parton energy loss processes, it is necessary to experimentally measure quantities that are more sensitive to the path length of partons in the QGP medium.

A more detailed analysis of the path-length dependence of parton energy loss in the QGP can be performed by varying the collision systems and measuring the $R_{AB}(p_T)$ function of hadrons at $p_T > 5$ GeV/c for different centrality classes. It is convenient to use π^0 mesons as probe hadrons, since they can be identified over a wide range of transverse momenta with relatively small measurement uncertainties.

This approach made it possible to measure the $R_{AB}(p_T)$ dependences for π^0 mesons up to about 20 GeV/c for different centrality bins in Au+Au [12], Cu+Au [13], and U+U [14] collisions. In particular, the measurements showed that the suppression pattern of π^0 mesons at $p_T > 5$ GeV/c does not depend on the initial collision geometry for similar values of N_{part} (the

number of participants characterizing the collision centrality and the volume of the QGP produced) [13, 14].

The overlap region of heavy nuclei generally has an ellipsoidal shape; therefore, the average path length traversed by a parent parton in the QGP depends on the azimuthal angle of its emission relative to the reaction plane $\Delta\varphi$ (the plane formed by the beam axis and the impact parameter vector). The degree of hadron suppression depends on the average path length of the parent partons in the QGP, so the suppression of hadron production is azimuthally anisotropic within a given centrality bin. This azimuthal anisotropy in momentum space is quantified by the elliptic flow.

The relationship between hadron suppression and the path length of parent partons in the QGP cannot be studied directly from the $R_{AB}(p_T)$ dependences, as the $R_{AB}(p_T)$ function is integrated over the azimuthal angle $\Delta\varphi$. However, the azimuthal functions $R_{AB}(p_T,\Delta\varphi)$, which have high sensitivity to the parton path length in the QGP, can be estimated by simultaneously using the measured NMFs and elliptic flows of hadrons as a function of p_T.

Such R_{AB} dependences on the two kinematic variables p_T and $\Delta\varphi$ have already been studied for π^0 mesons in different centrality bins of Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in [10, 12], where it was found that the degree of π^0 meson suppression for the same value of N_{part} (or in the same centrality bin) can differ by nearly a factor of two depending on the azimuthal angle relative to the reaction plane.

In this work, we consider two heavy-ion collision systems: copper–gold (Cu+Au) and uranium–uranium (U+U). Unlike collisions of symmetric gold nuclei, these collision systems have additional anisotropy of the nuclear overlap region relative to the reaction plane. Such anisotropy in Cu+Au collisions arises from the difference in the sizes of the copper and gold nuclei, leading to complete overlap of the copper nucleus in central collisions. Uranium nuclei are prolate-deformed; therefore, depending on their spatial orientation, the shape of the nuclear overlap region can differ even within the same centrality bin.

Thus, our paper is aimed at measuring the azimuthally dependent $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV.

The results are expected to clarify the role of the initial collision geometry in the path-length dependence of parton energy loss in the QGP, and provide new bounds on the parameter values in theoretical models describing parton energy loss.

Methodology

The azimuthal anisotropy of the π^0 meson suppression can be calculated directly from the NMFs [10]:

$$R_{AB}\left(p_T,\Delta\varphi_i\right)=R_{AB}\left(p_T\right)\frac{\Delta N\left(p_T,\Delta\varphi_i\right)}{\frac{1}{k}\sum_{i=1}^{k}\Delta N\left(p_T,\Delta\varphi_i\right)},$$

where $\Delta N(p_T,\Delta\varphi_i)$ is the yield of π^0 mesons in the ith azimuthal bin $\Delta\varphi_i$ at transverse momentum p_T.

Summation in the denominator is performed over all ith angular bins (their number is k). For the calculations, we used the $R_{AB}(p_T)$ values for π^0 mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV from [13, 14]. The second factor in this expression characterizes the azimuthal dependence of the π^0 meson yields: it is the ratio of the yield in the $\Delta\varphi_i$ bin to the average yield over all bins at a given p_T. However, the measured $\Delta N(p_T,\Delta\varphi_i)$ values for π^0 mesons in different azimuthal bins in Cu+Au and U+U collisions have not been previously published, so we had to use an alternative approach to estimate the azimuthal anisotropy of particle production.

The inclusive (azimuthally integrated) $R_{AB}(p_T)$ dependences for π^0 mesons are measured experimentally as the ratio (normalized by $\langle N_{coll}\rangle$) of the pT differential yields of π^0 mesons in nuclear collisions to those in proton–proton collisions. To determine the azimuthal dependence of particle production, $R_{AB}(p_T,\Delta\varphi)$, the total invariant differential yield $E\cdot d^3N/d^3p$ can be expanded into a Fourier series in the azimuthal angle relative to the reaction plane [15]:

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\Psi^{RP})]\right),$$

where φ is the particle azimuthal angle, y is the rapidity, v_n are the Fourier coefficients (anisotropic flow), Ψ^{RP} is the azimuthal angle of the reaction plane.

Thus, the azimuthal anisotropy of the transverse momentum distribution is characterized by the coefficients of anisotropic flow, where the elliptic flow v_2 (the second Fourier coefficient) dominates. The analytical representation of the expression for calculating $R_{AB}(p_T,\Delta\varphi)$ as a continuous function (for $k \to \infty$, $\Delta N(p_T,\Delta\varphi_i) \to dN/d\Delta\varphi$) then takes the following form:

$$R_{AB}(p_T,\Delta\varphi)=R_{AB}(p_T)\left[1+2v_2(p_T)\cos(2\Delta\varphi)\right],$$

where the azimuthal dependence of the π^0 meson yields is parameterized by the $v_2(p_T)$ values, and the angle $\Delta\varphi$ can take arbitrary values in the range $0 < \Delta\varphi < \pi/2$.

We took the $v_2(p_T)$ values from [16]. With these, all quantities necessary for calculating $R_{AB}(p_T,\Delta\varphi)$ are available.

We calculated the $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in four (or three) p_T bins in the range $5 < p_T < 10$ GeV/c and in four (or three) centrality bins for Cu+Au (or U+U) collisions. The choice of the p_T bins and centrality bins was guided by the previously measured $R_{AB}(p_T)$ and $v_2(p_T)$ values. We considered the azimuthal dependence of π^0 meson NMFs in six $\Delta\varphi$ bins in the range $0 < \Delta\varphi < \pi/2$.

Measurement results

Fig. 1 shows the calculated $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in four transverse momentum bins within $5 < p_T < 10$ GeV/c and in four centrality bins of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The calculated $R_{AB}(p_T,\Delta\varphi)$ values are shown in Fig. 1,*d* only for three centrality bins of Cu+Au collisions, because the $v_2(p_T)$ values for π^0 mesons in the range $8 < p_T < 10$ GeV/c for the 40–60% centrality bin are not available.

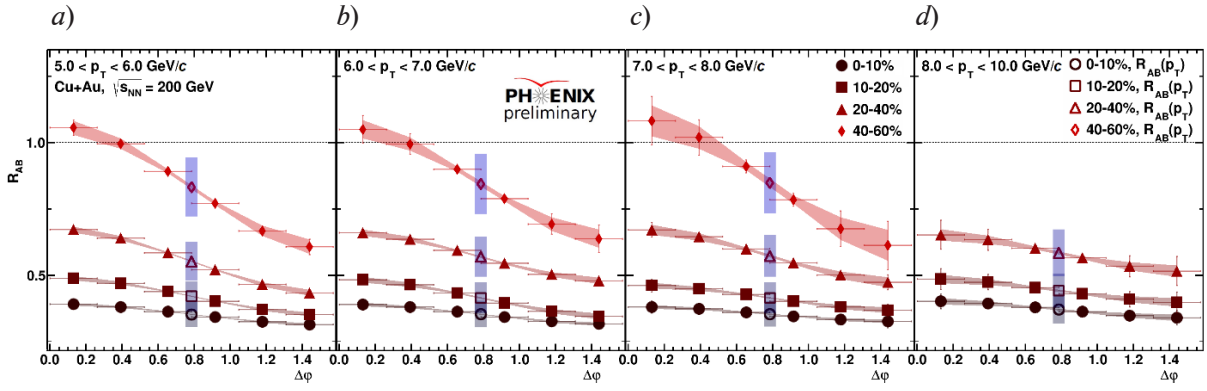


Fig. 1. $R_{AB}(p_T,\Delta\varphi)$ dependences for π^0 mesons calculated for four p_T bins (*a*–*d*) in the range $5 < p_T < 10$ GeV/c and for four centrality bins of Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Centrality bins, %: 0–10, 10–20, 20–40 and 40–60. Inclusive $R_{AB}(p_T)$ values are shown by points at $\Delta\varphi = \pi/4$ (0.785 rad)

The solid symbols in Fig. 1 correspond to $R_{AB}(p_T,\Delta\varphi)$ values, the open symbols correspond to $R_{AB}(p_T)$ values. The uncertainties of the $R_{AB}(p_T,\Delta\varphi)$ values were obtained by propagating the uncertainties from the $v_2(p_T)$ values. The systematic uncertainties of the $R_{AB}(p_T,\Delta\varphi)$ values are shown in Fig. 1 as shaded bands whose width represents the magnitude of the systematic uncertainty. The systematic uncertainties from the inclusive $R_{AB}(p_T)$ values are shown in Fig. 1 as solid boxes $\Delta\varphi = \pi/4$ and apply to all $R_{AB}(p_T,\Delta\varphi)$ values of the corresponding series.

The azimuthal anisotropy of NMFs for π^0 mesons increases with increasing centrality, leading to a difference of about a factor of 1.7 between the $R_{AB}(p_T,\Delta\varphi)$ values in the reaction plane ($0 < \Delta\varphi < \pi/12$) and perpendicular to it ($5\pi/12 < \Delta\varphi < \pi/2$) in peripheral Cu+Au collisions (40–60%). The observed azimuthal anisotropy of the $R_{AB}(p_T,\Delta\varphi)$ values indicates that the degree of π^0 meson suppression depends on the emission angle. A high-energy parent parton emitted in the direction of the reaction plane traverses, on average, a shorter path in the QGP than a parton emitted perpendicular to it. The shorter path length in the QGP leads, on average, to weaker interactions of the parton with the strongly interacting medium and, consequently, to smaller energy losses. As a result, the hadronic jet formed by the high-energy parton is quenched to a lesser extent, and the transverse momentum of the π^0 mesons produced by its fragmentation is larger.

Thus, the observed azimuthal dependence of the π^0 meson suppression can be explained by the path-length dependence of the parent parton energy loss in the QGP before fragmentation.

Fig. 1 also shows that the inclusive and azimuthally dependent NMFs of π^0 mesons decrease from peripheral (40–60%) to central (0–10%) collisions. This observation indicates that the degree of π^0 meson suppression increases with the size of the QGP formed in Cu+Au collisions, as previously noted in [13].

The observed trends in the $R_{AB}(p_T,\Delta\varphi)$ dependence for π^0 mesons in Cu+Au collisions are universal across all four transverse momentum bins in the range $5 < p_T < 10$ GeV/c. This suggests that the mechanism of parton energy loss in the QGP is similar over the entire transverse momentum range considered.

Fig. 2 shows the calculated $R_{AA}(p_T,\Delta\varphi)$ values for π^0 mesons in three transverse momentum bins in the range $5 < p_T < 10$ GeV/c and in three centrality bins of U+U collisions at $\sqrt{s_{NN}} = 193$ GeV. Fig. 2,*c* shows the calculated $R_{AA}(p_T,\Delta\varphi)$ values only for two centrality bins of U+U collisions, because the $v_2(p_T)$ values for π^0 mesons in the range $8 < p_T < 10$ GeV/c for the 40–60% centrality bin are not available. The notations for the NMFs differ between the two collision systems: (A+B, R_{AB}) is used for collisions of different nuclei (Cu+Au), while (A + A, R_{AA}) is used for collisions of identical nuclei (U+U). The uncertainties of the $R_{AA}(p_T,\Delta\varphi)$ and $R_{AA}(p_T)$ values in Fig. 2 are shown similarly to Fig. 1.

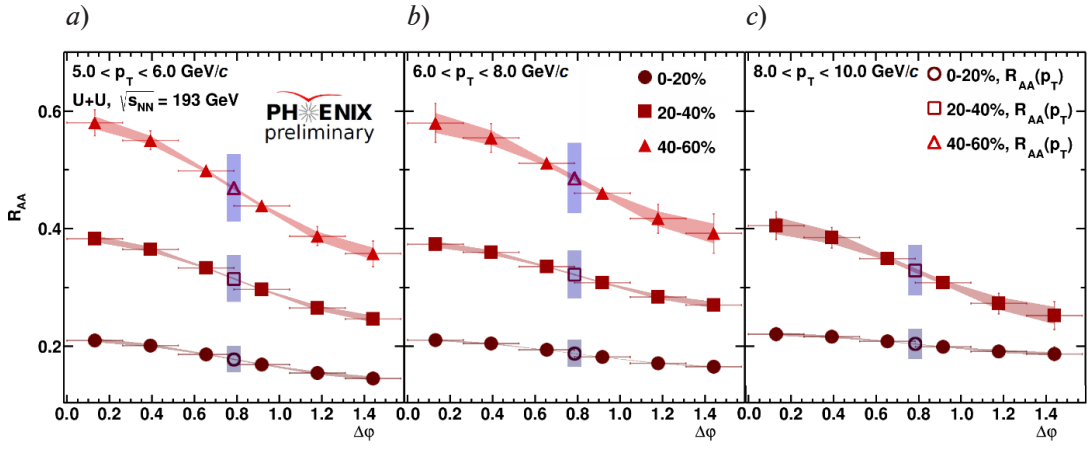


Fig. 2. $R_{AA}(p_T,\Delta\varphi)$ dependences for π^0 mesons, similar to those shown in Fig. 1, but for U+U collisions at $\sqrt{s_{NN}} = 193$ GeV, calculated for three p_T bins (*a*–*c*) in the same range and for three centrality bins: 0–20%, 20–40%, and 40–60% The inclusive $R_{AA}(p_T)$ values are shown by points at $\Delta\varphi = \pi/4$

The observations made for the $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in Cu+Au collisions also apply to the similar values in U+U collisions. It is worth noting that the ratio of the $R_{AA}(p_T,\Delta\varphi)$ values for π^0 mesons in the reaction plane and perpendicular to it reaches about 1.5 in the U+U system, which is smaller than in Cu+Au collisions. This difference is most likely due to non-flow effects (e.g., jet correlations [17, 18]). Such effects can bias the measured $v_2(p_T)$ values for π^0 mesons in peripheral Cu+Au collisions [16], leading to an overestimation of elliptic flow.

Conclusion

We calculated the azimuthally dependent nuclear modification factors of π^0 mesons for different transverse momentum bins within $5 < p_T < 10$ GeV/c and for different centrality bins in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U collisions at $\sqrt{s_{NN}} = 193$ GeV.

It was found that the azimuthally dependent nuclear modification factors of π^0 mesons in Cu+Au collisions are systematically larger than those in U+U collisions. This is explained by the larger volume of the QGP produced in U+U collisions. The trends observed in the $R_{AB}(p_T,\Delta\varphi)$ dependence of π^0 mesons in these collisions are universal across all transverse momentum ranges within $5 < p_T < 10$ GeV/c: the azimuthal anisotropy of the π^0 meson nuclear modification factors is larger in peripheral collisions than in central collisions, while the degree of hadron suppression is smaller. The observed behavior of the calculated $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in Cu+Au and U+U collisions is consistent with the path-length dependence of parton energy loss in the QGP.

The ratio of $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons in the reaction plane and perpendicular to it reaches about 1.5 in the U+U system and 1.7 in Cu+Au collisions One possible reason for this difference could be non-flow effects, whose influence on the measured $v_2(p_T)$ values for π^0 mesons in peripheral Cu+Au collisions [16] leads to an overestimation of elliptic flow values.

The calculated $R_{AB}(p_T,\Delta\varphi)$ values for π^0 mesons can be used to refine the parameters of theoretical models describing parton energy loss in the quark-gluon plasma produced in collisions of deformed nuclei or in asymmetric collision systems.

REFERENCES

1. **Shuryak E.,** Quantum chromodynamics and the theory of superdense matter, Phys. Rept. 61 (2) (1980) 71–158.

2. **Matsui T., Satz H.,** J/ψ suppression by quark-gluon plasma formation, Phys. Lett. B. 178 (4) (1986) 416–422.

3. **Adcox K., Adler S., Afanasiev S., et al.** (PHENIX Collaboration), Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration, Nucl. Phys. A. 757 (1–2) (2005) 184–283.

4. **Cao. S., Wang X.-N.,** Jet quenching and medium response in high-energy heavy-ion collisions: a review, Rept. Prog. Phys. 84 (2) (2021) 024301.

5. **Adcox K., Adler S., Ajitanand N., et al.** (PHENIX Collaboration), Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV, Phys. Rev. Lett. 88 (2) (2001) 022301.

6. **d'Enterria D.,** Jet quenching, Section 6.4. in book: Landolt – Börnstein – Group I: "Elementary Particles, Nuclei and Atoms", Vol. 23 (2010) 471–520.

7. **Cunqueiro L., Sickles A.,** Studying the QGP with jets at the LHC and RHIC, Prog. Part. Nucl. Phys. 124 (May) (2022) 103940.

8. **Harris J. W., Müller B.** "QGP signatures" revisited, Eur. Phys. J. C. 84 (3) (2024) 247.

9. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration), Azimuthal anisotropy of π^0 production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV: Path-length dependence of jet quenching and the role of initial geometry, Phys. Rev. Lett. 105 (2) (2010) 142301.

10. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration), Neutral pion production with respect to centrality and reaction plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, Phys. Rev. C. 87 (3) (2013) 034911.

11. **Acharya S., Adamová D., Adler A., et al.** (ALICE Collaboration), The ALICE experiment: A journey through QCD, Eur. Phys. J. C. 84 (14 Aug) (2024) 813.

12. **Afanasiev S., Aidala C., Ajitanand N., et al.** (PHENIX Collaboration), High-p_T π^0 production with respect to the reaction plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, Phys. Rev. C. 80 (5) (2009) 054907.

13. **Aidala C., Ajitanand N., Akiba Y., et al.** (PHENIX Collaboration), Production of π^0 and η mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, Phys. Rev. C. 98 (5) (2018) 054903.

14. **Acharya U., Aidala C., Ajitanand N., et al.** (PHENIX Collaboration), Production of π^0 and η mesons in U+U collisions at $\sqrt{s_{NN}}$ = 192 GeV, Phys. Rev. C. 102 (6) (2020) 064905.

15. **Voloshin S., Zhang Y.,** Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions, Z. Phys C. 70 (4) (1996) 665–671.

16. **Bannikov E. V., Berdnikov Ya. A., Larionova D. M., Kotov D. O.,** Comparison of π^0 meson elliptic flow in Cu+Au collisions at the energy of 200 GeV and U+U collisions at 193 GeV, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (1) (2026) 144–157.

17. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration), Azimuthal anisotropy of π^0 and η mesons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV // Phys. Rev. C. 88 (6) (2013) 064910.

18. **Jia, J.,** Ways to constrain the away-side jet in Au+Au collisions in PHENIX, Nucl. Phys. A. 783 (1–4) (2007) 501–506.

СПИСОК ЛИТЕРАТУРЫ

1. **Shuryak E.** Quantum chromodynamics and the theory of superdense matter // Physics Reports. 1980. Vol. 61. No. 2. Pp. 71–158.

2. **Matsui T., Satz H.** J/ψ suppression by quark-gluon plasma formation // Physics Letters B. 1986. Vol.178. No. 4. Pp. 416 –422.

3. **Adcox K., Adler S., Afanasiev S., et al.** (PHENIX Collaboration). Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration // Nuclear Physics A. 2005. Vol. 757. No. 1–2. Pp. 184–283.

4. **Cao. S., Wang X.-N.** Jet quenching and medium response in high-energy heavy-ion collisions: A review // Reports on Progress in Physics. 2021. Vol. 84. No. 2. P. 024301.

5. **Adcox K., Adler S., Ajitanand N., et al.** (PHENIX Collaboration). Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV // Physical Review Letters. 2001. Vol. 88. No. 2. P. 022301.

6. **d'Enterria D.** Jet quenching (Section 6.4) // Landolt – Börnstein – Group I: "Elementary Particles, Nuclei and Atoms". 2010. Vol. 23. Pp. 471–520.

7. **Cunqueiro L., Sickles A.** Studying the QGP with jets at the LHC and RHIC // Progress in Particle and Nuclear Physics. 2022. Vol. 124. May. P. 103940.

8. **Harris J. W., Müller B.** "QGP signatures" revisited // The European Physical Journal C. 2024. Vol. 84. No. 3. P. 247.

9. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration). Azimuthal anisotropy of π^0 production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV: Path-length dependence of jet quenching and the role of initial geometry // Physical Review Letters. 2010. Vol. 105. No. 2. P. 142301.

10. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration). Neutral pion production with respect to centrality and reaction plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV // Physical Review C. 2013. Vol. 87. No. 3. P. 034911.

11. **Acharya S., Adamová D., Adler A., et al.** (ALICE Collaboration). The ALICE experiment: A journey through QCD // The European Physical Journal C. 2024. Vol. 84. 14 August. P. 813.

12. **Afanasiev S., Aidala C., Ajitanand N., et al.** (PHENIX Collaboration). High-p_T π^0 production with respect to the reaction plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV // Physical Review C. 2009. Vol. 80. No. 5. P. 054907.

13. **Aidala C., Ajitanand N., Akiba Y., et al.** (PHENIX Collaboration). Production of π^0 and η mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV // Physical Review C. 2018. Vol. 98. No. 5. P. 054903.

14. **Acharya U., Aidala C., Ajitanand N., et al.** (PHENIX Collaboration). Production of π^0 and η mesons in U+U collisions at $\sqrt{s_{NN}}$ = 192 GeV // Physical Review C. 2020. Vol. 102. No. 6. P. 064905.

15. **Voloshin S., Zhang Y.** Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions // Zeitschrift für Physik C. 1996. Vol. 70. No. 4. Pp. 665–671.

16. **Банников Е. В., Бердников Я. А., Ларионова Д. М., Котов Д. О.** Сравнение эллиптических потоков π^0-мезонов в столкновениях Cu+Au при энергии 200 ГэВ и U+U при 193 ГэВ // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 19. № 1. С. 144–157.

17. **Adare A., Afanasiev S., Aidala C., et al.** (PHENIX Collaboration). Azimuthal anisotropy of π^0 and η mesons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV // Physical Review C. 2013. Vol. 88. No. 6. P. 064910.

18. **Jia J.** Ways to constrain the away-side jet in Au+Au collisions in PHENIX // Nuclear Physics A. 2007. Vol. 783. No. 1–4. Pp. 501–506.

THE AUTHORS

BANNIKOV Egor V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
bannikov.ev.21@gmail.com
ORCID: 0000-0002-9820-062X

BERDNIKOV Yaroslav A.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
berdnikov@spbstu.ru
ORCID: 0000-0003-0309-5917

LARIONOVA Daria M.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
dashalario@gmail.com
ORCID: 0009-0007-7019-5586

KOTOV Dmirty O.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
dmitriy.kotov@gmail.com
ORCID: 0000-0002-3395-0454

BASIROV Kirill N.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
kirill.basirov@mail.ru

BORISOV Ivan I.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
borisov.ii@edu.spbstu.ru

СВЕДЕНИЯ ОБ АВТОРАХ

БАННИКОВ Егор Викторович – *аспирант Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, **г**. Санкт-Петербург, Политехническая **ул., 29**
bannikov.ev.21@gmail.com
ORCID: 0000-0002-9820-062X

БЕРДНИКОВ Ярослав Александрович – *доктор физико-математических наук, профессор Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251*, Россия, г. Санкт-Петербург, Политехническая ул., 29*
berdnikov@spbstu.ru
ORCID: 0000-0003-0309-5917

ЛАРИОНОВА Дарья Максимовна – *кандидат физико-математических наук, доцент Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
dashalario@gmail.com
ORCID: 0009-0007-7019-5586

КОТОВ Дмитрий Олегович – *кандидат физико-математических наук, доцент Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
dmitriy.kotov@gmail.com
ORCID: 0000-0002-3395-0454

БАСИРОВ Кирилл Наилевич – *инженер Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
kirill.basirov@mail.ru

БОРИСОВ Иван Ильич – *студент Физико-механического института Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
borisov.ii@edu.spbstu.ru

Received 11.01.2026. Approved after reviewing 19.01.2026. Accepted 19.01.2026.
Статья поступила в редакцию 11.01.2026. Одобрена после рецензирования 19.01.2026. Принята 19.01.2026.

© Peter the Great St. Petersburg Polytechnic University, 2026