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PRODUCTION OF K^*-MESONS IN THE COPPER-GOLD NUCLEI COLLISIONS AT $\sqrt{s_{NN}}$ = 200 GEV

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This paper presents invariant transverse momentum spectra and nuclear modification factors of $K^*(892)$-mesons measured in the Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The measurements were performed in five centrality bins in the range of transverse momentum from 2.00 to 5.75 GeV/c in the PHENIX experiment at the RHIC. Nuclear modification factors were compared with previously obtained PHENIX data in Cu + Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV. The nuclear modification factors of K^*-mesons in Cu + Cu and Cu + Au collisions at the same values of a number of participants N_{part} were found to have similar values (within uncertainties).

Keywords: quark gluon plasma, jet quenching, heavy ion collision, strangeness, nuclear modification factor

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РОЖДЕНИЕ K^*-МЕЗОНОВ В СТОЛКНОВЕНИЯХ ЯДЕР МЕДИ И ЗОЛОТА ПРИ ЭНЕРГИИ $\sqrt{s_{NN}}$ = 200 ГЭВ

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В статье приведены результаты измерений инвариантных спектров рождения и факторов ядерной модификации $K^*(892)$-мезонов в столкновениях ядер меди и золота (Cu + Au) при энергии $\sqrt{s_{NN}}$ = 200 ГэВ. Измерения выполнены в пяти классах событий по центральности в диапазоне поперечных импульсов от 2,00 до 5,75 ГэВ/с в эксперименте PHENIX на коллайдере RHIC. Значения факторов ядерной модификации сравнивались с ранее полученными данными на PHENIX в (Cu + Cu)-столкновениях при такой же энергии (200 ГэВ). Установлено, что факторы ядерной модификации K^*-мезонов в столкновениях Cu + Cu и Cu + Au, при одинаковом числе участников N_{part}, имеют одинаковые значения (в пределах неопределенностей).

Ключевые слова: кварк-глюонная плазма, эффект гашения струй, странность, фактор ядерной модификации

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Introduction

Studies on the properties of nuclear matter under extreme conditions, where quarks and gluons become deconfined, are aimed at solving an important problem in high energy physics. It is hypothesized that deconfinement existed in the early Universe [1].

Quantum chromodynamics (QCD) predicts for high energy densities of approximately 1 GeV/fm^3 that a phase transition occurs from ordinary hadronic matter, described in terms of color-neutral hadrons, to a new state of matter called the quark-gluon plasma (QGP), where the degrees of freedom are quarks and gluons leaving the confinement region about 1 fm in radius [2]. Matter with extremely high energy density can be produced in the laboratory by colliding heavy ions at ultrarelativistic energies.

One of the key signatures for QGP production is jet quenching, which consists in strong suppression of particle yields in central collisions of heavy nuclei due to energy losses of quarks and gluons in the medium [3, 4].

An intriguing effect observed in collisions of heavy nuclei is an increased yield of strange hadrons. Since quark-antiquark pairs $s\bar{s}$ are mainly produced in gluon-gluon interactions ($gg \rightarrow s\bar{s}$), the probability of the process in QGP increases for the following reason. Restoration of chiral symmetry in QGP results in decreasing the strange quark mass, which in turn reduces the energy threshold for strangeness production, making the production of an $s\bar{s}$ pair energetically more favorable than that of $u\bar{u}$ and $d\bar{d}$ pairs [5]. Therefore, extracting the yields of vector K^*(892) mesons (whose rest mass is equal to 0.8916 GeV/c^2 ≈ 892 MeV/c^2) with open strangeness ($d\bar{s}$) is an effective method for studying the properties of QGP [6].

Our study presents the data on the yields of K^* mesons, their invariant spectra depending on transverse momentum (pT), and the nuclear modification factors R_{AB}. The observables were measured experimentally in collisions of copper and gold nuclei (denoted as Cu + Au) at $\sqrt{s_{NN}}$ = 200 GeV at midrapidity in the transverse momentum range from 2.00 to 5.75 GeV/c using the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, USA [7–9].

Measurement procedure

Extracting K^* meson yields, we used two procedures to generate independent sources of systematic uncertainties. Experimental data from different detectors were combined to cover different p_T bins, providing the widest range of transverse momenta possible in this collision system. The procedures have different sources of systematic uncertainties; importantly, both procedures were used in the range of intermediate transverse momenta, making it possible to check the validity of the results obtained.

K^* and $\overline{K^*}$ meson yields were extracted using the following subsystems of the PHENIX experiment: drift chamber (DC), third-layer pad chamber (PC3) [10] and time-of-flight (TOF) detector [11].

The transverse momenta of K and π mesons are measured in DC and PC. The TOF detector is used to reconstruct K and π mesons, as well as protons. K^* and $\overline{K^*}$ meson yields are reconstructed from hadronic decays into $K^+\pi^-$ and $K^-\pi^+$ pairs. Unlike-sign particles detected in one collision are combined into pairs for this purpose. Only particles with transverse momenta exceeding 0.3 GeV/c are extracted. A charged particle is assumed to be either a K or a π meson, and, depending on the given decay channel and the particle's charge, it is assigned the mass of a charged K or π meson. Two procedures described below are used to reconstruct the invariant mass spectra of ($K\pi$) meson pairs, increasing the statistical significance of the experimental data in a wide range of transverse momenta.

The first procedure, ToF-PC3, assumes that the transverse momenta of K mesons are measured in DC, and K mesons are reconstructed in the TOF detector, while the transverse momenta of π mesons are measured in DC and in PC3. This procedure allows to detect and calculate the kinematic characteristics of K^* mesons at low p_T (1.9–2.9 GeV/c).

The second procedure, PC3-PC3, assumes that the transverse momenta of K and π mesons are measured in DC and in PC3. This procedure allows to extract K^* meson yields at intermediate and high p_T (2.6–6.5 GeV/c). The drawback of the second procedure is that the combinatorial background is much larger compared with that for the first procedure, which means that K^* meson yields cannot be extracted at transverse momenta below p_T = 2.0 GeV/c in Cu + Au interactions.

Fig. 1 shows examples of approximated invariant mass distributions for ($K\pi$) meson pairs in central collisions; the results were obtained using both procedures.

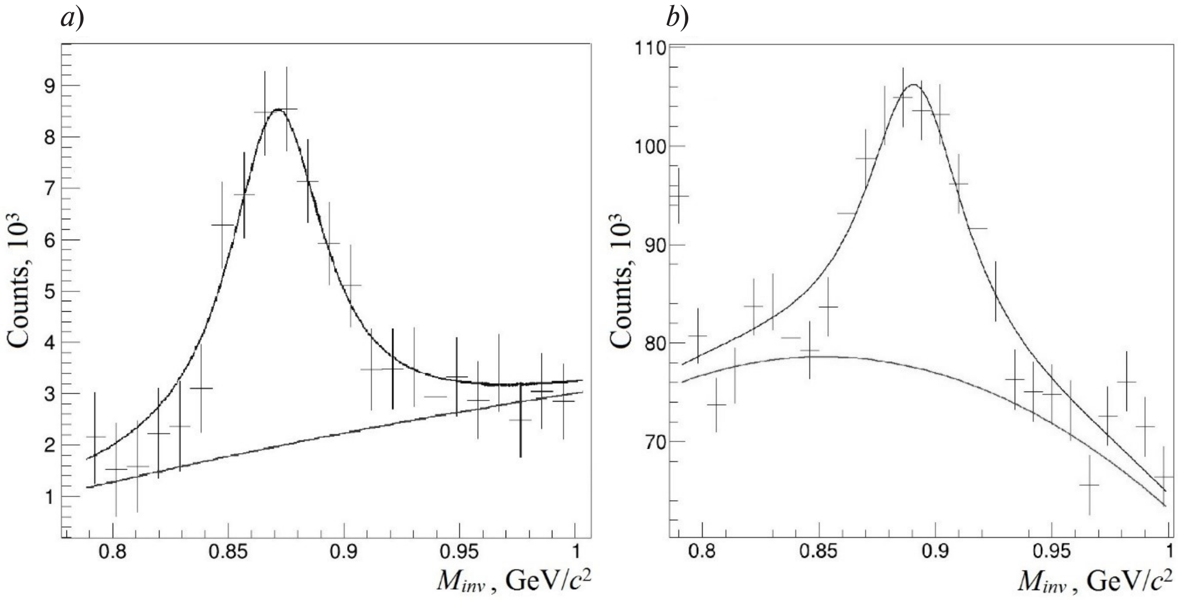

Fig. 1. Invariant mass distributions of K and π meson production in central Cu + Au collisions, obtained by two procedures: ToF-PC3 (*a*) and PC3-PC3 (*b*) in p_T ranges of 2.3–2.6 and 2.9–3.4 GeV/*c*, respectively

Because K and π mesons produced in K^* meson decays cannot be distinguished from other particles of the same kind, all tracks of these particles from each event satisfying the acceptance criteria are combined into like-sign or unlike-sign pairs. The components of the three-momentum vector **p** for each track are measured using DC:

$$p_y = p \sin \theta_0 \sin \varphi_0,$$

$$p_z = p \cos \theta_0.$$

The invariant mass and transverse momentum are then calculated for a pair of (Kπ) mesons based on two-body decay kinematics.

$$m^2_{K\pi} = \left(E_K + E_\pi\right)^2 - \left(\mathbf{p}_K + \mathbf{p}_\pi\right)^2,$$

$$p^2_{T_{K\pi}} = \left(p_{x_K} + p_{x_\pi}\right)^2 + \left(p_{y_K} + p_{y_\pi}\right)^2,$$

where $E_K = \sqrt{\mathbf{p}^2_K + m^2_K}$ and $m_K = 0.43667$ GeV; $E_\pi = \sqrt{\mathbf{p}^2_\pi + m^2_\pi}$ and $m_\pi = 0.13957$ GeV.

The invariant mass spectrum for a pair of unlike-sign mesons contains both the K^* meson signal and the combinatorial background. The latter includes two components: the correlated and the uncorrelated background. Event mixing is used to estimate the combinatorial background. Analysis is aimed at extracting the yields of K^* mesons from the yields of inclusive $(K\pi)^\pm$ pairs. K^* meson yields were obtained in all reconstructions by integrating the invariant mass distribution within ±100 MeV/c^2 of the K^* meson mass (892 MeV/c^2) after subtracting the combinatorial background.

The experimental data are reconstructed as two-dimensional distributions of K^* meson yields as functions of invariant mass and transverse momentum, divided into transverse momentum bins and fitted with a relativistic Breit–Wigner distribution (RBW) convoluted with a Gaussian plus a second-order polynomial accounting for the residual background:

$$RBW = \frac{1}{2\pi} \cdot \frac{M M_0 \Gamma}{(M^2 - M_0^2)^2 + M_0^2 \Gamma^2},$$

where M_0, GeV/c^2 and Γ, GeV/c^2, are the mass and the decay width of K^* mesons, respectively, according to the data from PDG (Particle Data Group); M, GeV/c^2, is the experimental value of particle mass.

The residual background is mostly generated by decay of other types of mesons.

The invariant production spectrum of K^* mesons is calculated as follows for each transverse momentum bin:

$$\frac{1}{2\pi p_T}\cdot\frac{d^2N}{dp_T dy}=\frac{1}{2\pi p_T}\times$$
$$\times\frac{1}{2}\cdot\frac{1}{N_{events}Br}\cdot\frac{1}{\varepsilon_{eff}(p_T)}\cdot\frac{N(\Delta p_T)}{\Delta p_T \Delta y},$$

where p_T and Δp_T, GeV/c, are the meson transverse momentum and its bin width; y and Δy are the rapidity and its bin width; $N(\Delta p_T)$ is the number of mesons reconstructed by the detector (meson yields); N_{events} is the total number of events reconstructed for a given centrality bin; $\varepsilon_{eff}(p_T)$ is the K^* meson reconstruction efficiency, obtained by Monte Carlo simulation of decay, passage, and regeneration of mesons in the PHENIX detector; Br = 0.666 is the probability of meson decay in the given channel. The coefficient 1/2 is taken in the formula for averaging the invariant K^* and $\overline{K}^*$ meson yields.

The nuclear modification factors of particles in heavy ion collisions, used to analyze the collective effects governing the particle spectra depending on transverse momentum, are calculated by the formula:

$$R_{CuAu}=\frac{d^2N_{CuAu}(p_T)/dydp_T}{N_{coll}/\sigma_{pp}^{inel}\cdot d^2\sigma_{pp}/dydp_T},$$

where the numerator is the quantity characterizing the invariant spectrum of meson production in collisions of heavy copper and gold nuclei; $d^2\sigma_{pp}/dydp_T$ is the invariant differential cross section for production of these particles in collisions of the given nuclei at the same center-of-mass energy; N_{coll} is the average number of binary collisions per event in Cu + Au collisions; σ_{pp}^{inel} is the inelastic cross section for proton-proton scattering (here σ_{pp}^{inel} = 42.2 mb).

Measurement results and discussion

The reconstructed invariant spectra for the production of K^* mesons as a function of transverse momentum are shown in Fig. 2. The measurements were performed in five centrality bins with the transverse momenta ranging from 2.00 to 5.75 GeV/c. The given spectra were approximated by the Levy function for K^* mesons [12].

Fig. 3 shows the measured nuclear modification factors R_{AB} with systematic uncertainties, depending on transverse momentum, obtained for K^* mesons in Cu + Au interactions at $\sqrt{s_{NN}}$ = 200 GeV for different centrality bins. The results were obtained using two procedures: ToF-PC3 and PC3-PC3. We found that the results for the same transverse momenta are in good agreement.

The nuclear modification factors R_{AB} for K^* mesons in central Cu + Au collisions take values less than unity at high transverse momenta (R_{AB} values for pT = 5–6 GeV/c lie in the range from 0.4 to 0.7). As collision centrality increases, there is less suppression of K^* meson yields, and R_{AB} values approach unity.

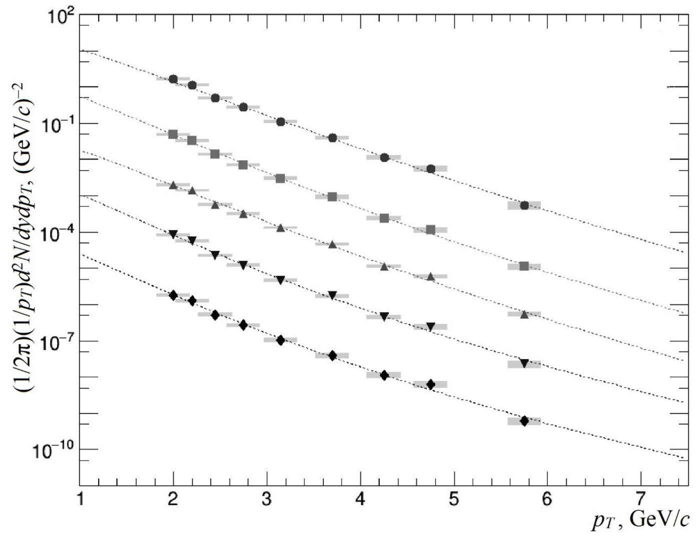

Fig. 2. Invariant spectra for production of K^* mesons in Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for five centrality bins, %:
0–80 (●); 0–20 (■); 20–40 (▲); 40–60 (▼); 60–80 (♦).
The statistical uncertainties of the measurements are no larger than the symbols.
The boxes correspond to systematic uncertainties.

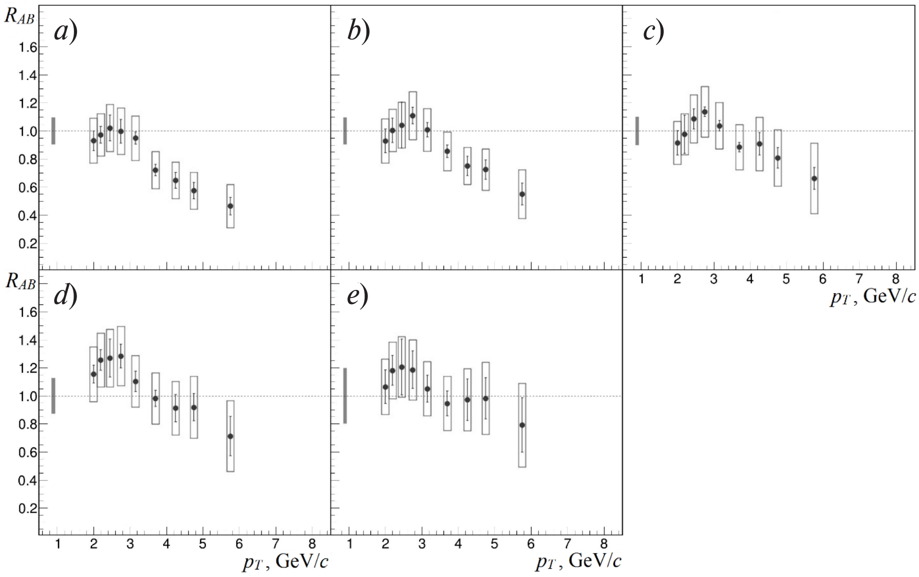

Fig. 3. Distributions of nuclear modification factors as functions of transverse momentum for *K** mesons in Cu + Au collisions at $\sqrt{s_{NN}}$= 200 GeV for five centrality bins, %: 0–20 (*a*), 20–40 (*b*), 0–80 (*c*), 40–60 (*d*), 60–80 (*e*).
Bars and boxes correspond to statistical and systematic uncertainties

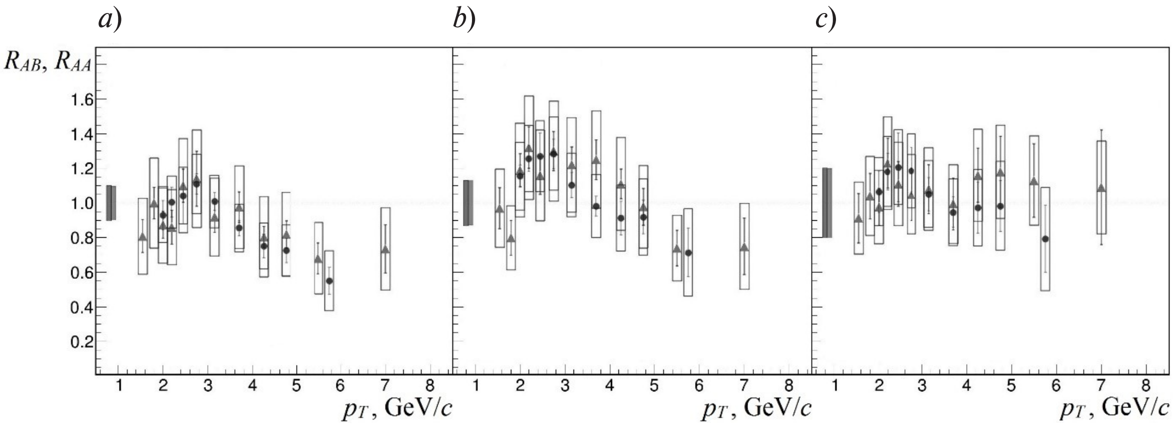

Fig. 4. Comparison of nuclear modification factors R_{AB} for *K** mesons in Cu + Au collisions (circles) with nuclear modification factors R_{AA} for Cu + Cu collisions (triangles) at the same $\sqrt{s_{NN}}$ = 200 GeV and with similar numbers of participants N_{part}: 80.37 (Cu + Au) and 85.9 (Cu + Cu) (*a*); 34.92 and 45.2 (*b*); 11.54 and 6.40 (*c*).
Bars and boxes correspond to statistical and systematic uncertainties

Fig. 4 compares the nuclear modification factors R_{AB} for *K** mesons, measured in collisions of Cu + Au nuclei, with the nuclear modification factors R_{AA}, measured in collisions of identical nuclei (Cu + Cu) at the same energy of 200 GeV. Evidently, the results are in good agreement given a similar number of participants (within the uncertainties).

Fig. 5 compares the data for p_T distributions of nuclear modification factors of *K**, φ, π^0, η, K_S and ω mesons in Cu + Au collisions at 200 GeV. Evidently, the nuclear modification factors R_{AB} of *K** and φ mesons equal unity in central collisions at intermediate p_T values, while the nuclear modification factors R_{AB} of π^0, η, K_S and ω mesons are suppressed in central collisions over the entire range of p_T values. All light mesons exhibit the same level of suppression at high p_T in the most central collisions. The nuclear modification factors

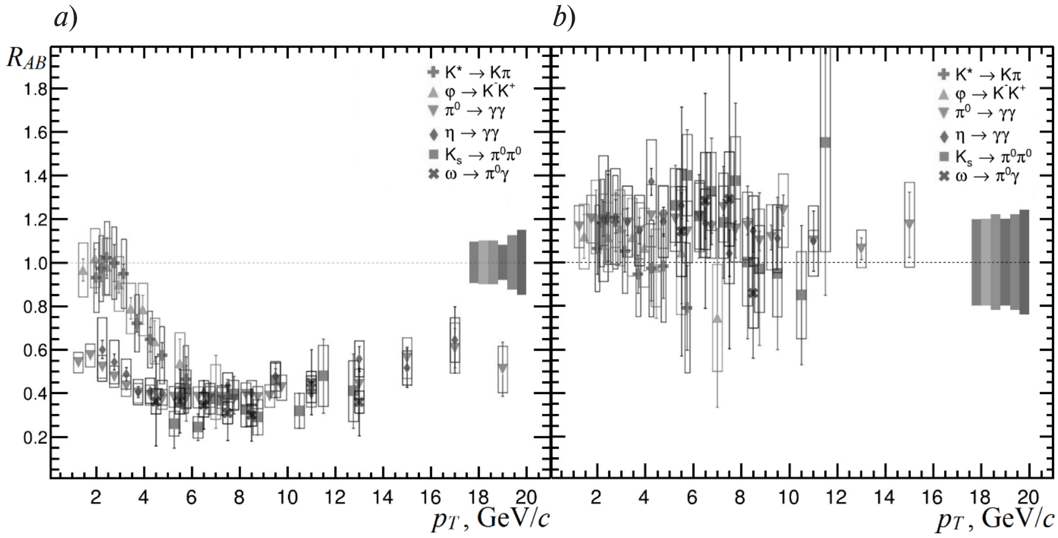

Fig. 5. Collisions of Cu + Au nuclei at $\sqrt{s_{NN}}$ = 200 GeV.
Data are compared for distributions of nuclear modification factors as functions of transverse momentum for different light mesons in central (*a*) and peripheral (*b*) collisions.
Bars and boxes correspond to statistical and systematic uncertainties

R_{AB} equal unity in peripheral collisions for all mesons considered (within uncertainties). The same behavior was also observed for light mesons in Cu + Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV [12].

Conclusion

We have measured the invariant production spectra and nuclear modification factors of *K** mesons in collisions of copper and gold (Cu + Au) nuclei at $\sqrt{s_{NN}}$ = 200 GeV, in the pseudorapidity range $|\eta| < 0.35$, at transverse momenta in the range of $2.00 < p_T < 5.75$ GeV/*c* and for five centrality bins. All data for the measurements were obtained at the PHENIX experiment in 2012.

We have carried out comparative analysis of the nuclear modification factors of *K** mesons in Cu + Cu and Cu + Au interactions at the same energy $\sqrt{s_{NN}}$ = 200 GeV and the nuclear modification factors of *K**, φ, π^0, η, K_S and ω mesons in Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. We have found that *K** meson yields in Cu + Au and Cu + Cu collisions at the same energy $\sqrt{s_{NN}}$ = 200 GeV have the same values over the entire range of transverse momenta given similar numbers of participants.

Thus, suppression of mesons depends on the size of the nuclear overlap region but does not depend on the shape of the nuclei for a large number of participants [13–15].

*K** and φ meson yields in central Cu + Au collisions are less suppressed in the range of intermediate p_T compared to mesons consisting only of first-generation quarks, which points to excessive production of strangeness. The yields of *K** mesons and other light mesons are suppressed in the range of high transverse momenta in central collisions of copper and gold, which confirms the presence of the jet quenching effect.

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