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Measurement of heavy-flavor electron production in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV at STAR

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Studying heavy-flavor production in heavy-ion collisions (HIC) can enhance our comprehension of parton interactions with the Quark-Gluon Plasma (QGP) created in these collisions. Due to their significant mass, heavy quarks (charm and bottom) are mainly generated during the initial phase of high-energy HIC when hard scatterings are prevalent, and experience the entire evolution of the QGP. One way to study heavy quarks is through the measurement of electrons from heavy flavor hadron decay, Heavy Flavor Electrons (HFE). In this contribution, we present analysis of HFE at low transverse momentum (p_{T}) in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV using data taken in 2017 by the STAR experiment. The strong HFE suppression was already observed in the central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Measuring heavy-flavor quark nuclear modification factors below the RHIC top energy offers new insights on the the in-medium energy loss, especially the collisional energy loss which is dominant at low p_{T}.

Keywords: Quark-Gluon Plasma; Heavy-flavor; STAR

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1. Introduction

Quantum Chromodynamics (QCD) is the underlying theory of strong interaction. At a very high temperature or and low baryon chemical potential, models inspired by QCD predict a phase transition from the hadron gas to a deconfined medium called Quark-Gluon Plasma (QGP). This state of matter existing under extreme conditions of high temperature and density is of fundamental interest. By colliding heavy ions at ultra-relativistic energies, it is possible to explore the QCD phase diagram and properties of the QGP.

One of the tools to study QGP properties is to use heavy quarks. Given that the masses of heavy quarks are considerably larger than the QCD scale parameter, Λ_{QCD}, and the QGP temperature, they are dominantly produced in the initial hard scatterings and thus participate in whole medium evolution. Moreover, such partonic processes can be calculated by perturbative QCD. These factors make heavy quarks the ideal probes of QGP. With heavy quarks one can study the nature of energy loss (collisional or radiative) by using nuclear modification factor.

One of the proxies for measuring heavy quarks is to use heavy-flavor electrons (HFE), electrons coming from the semileptonic decays of open heavy-flavor hadrons (D and B). The relative contributions of D and B hadron decays depend on electron p_{T}: at low momenta D mesons are dominant. The branching ratio of semileptonic decays is higher than that of hadronic decays, which makes HFE a valuable tool for studying heavy quarks production.

Fig. 1 depicts recent STAR results for the nuclear modification factor, R_{AA}, as a function of p_{T} for various centrality classes in Au+Au collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV.[1] A suppression by a factor of two is observed in central collisions indicating a significant energy loss of heavy quarks in QGP. A larger suppression is observed in central collisions than in peripheral collisions, which is consistent with expectations. It is now of interest to examine the energy loss at lower energies, such as 54.4 GeV, following up on a recent STAR publication of elliptic flow of HFE at this energy.[2]

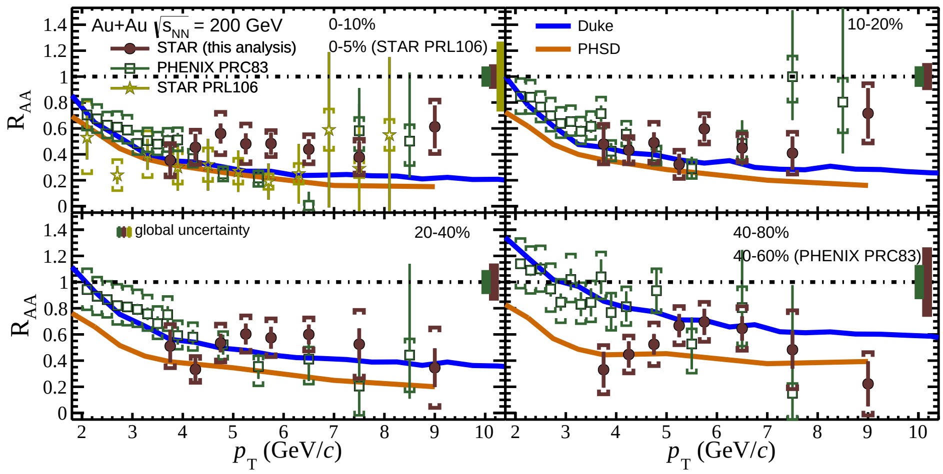

Fig. 1. HFE R_{AA} (full circles) as a function of p_{T} in different centrality intervals in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV[1] compared with STAR[3] (stars) and PHENIX[4] (empty squares) published results and Duke (blue line) and PHSD (orange line) model calculations.

2. Analysis

The experimentally identified electrons, named inclusive electrons e^{incl}, include the following components:

(i) Photonic electrons, e^{PE}:

(a) Dalitz decays: $\eta \to \gamma e^+ e^-$, $\pi^0 \to \gamma e^+ e^-$,

(b) Gamma conversion: $\gamma \to e^+e^-$, $\eta \to \gamma\gamma$, $\pi^0 \to \gamma\gamma$.

(ii) Hadron-decayed electrons, e^{HDE}, from ρ, ω, ϕ, J/ψ, Drell-Yan and K_{e3}.

The HFE yield can be then calculated as:

$$N^{\mathrm{HFE}} = \frac{N^{\mathrm{incl}} \cdot purity - N^{\mathrm{PE}}/\varepsilon^{\mathrm{PE}}}{\varepsilon^{\mathrm{total}}} - N^{\mathrm{HDE}}, \tag{1}$$

where N^{incl} is the inclusive electron yield, N^{PE} is the photonic electron yield,*purity* is the purity of the inclusive electrons, $\varepsilon^{\mathrm{PE}}$ is the photonic electron identification efficiency, $\varepsilon^{\mathrm{total}}$ is the total efficiency of electron identification and reconstruction, N^{HDE} are hadron-decayed electrons.[2] The fraction in Eq. 1 is also referred to as the non-photonic electron yield. The photonic electron identification efficiency is calculated by propagating γ conversions, π^0 and η decays through the GEANT simulation of the STAR detector[2] before embedding them into real events.

2.1. *Inclusive electron identification*

Inclusive electrons are identified using information from the Time Projection Chamber (TPC),[5] Time Of Flight (TOF),[6] and Barrel ElectroMagnetic Calorimeter (BEMC).[7] The TPC is employed to reconstruct the particle momentum and identify it using the energy loss, dE/dx, and momenta, $\mathbf{p}$. For this we use an $n\sigma_x$ parameter which is derived from the particle energy loss according to the formula:

$$n\sigma_e = \frac{1}{R} \ln \frac{< dE/dx >_{\mathrm{measured},x}}{< dE/dx >_x}, \tag{2}$$

where R is STAR TPC $\ln dE/dx$ resolution. It relates the measured and the expected energy loss in the TPC for a given particle species (x). The nσ_e cut for the TPC electron identification is following:

- p $\leqslant$ 0.8 GeV/c^2: (2.25p - 3) < nσ_e < 2
- p > 0.8 GeV/c^2: -1.2 < nσ_e < 2

The TOF detector information is used to identify electrons in the low p_{T} region. The $1/\beta$ cut has been set to $|1 - 1/\beta| < 0.025$ for all tracks with TOF information. To get more statistics in the higher p_{T} region, for $p_{\mathrm{T}} \geqslant 1.5$ GeV/c^2, tracks without TOF information were not excluded. The identification in the high p_{T} region, $p_{\mathrm{T}} >$ 1.25 GeV/c^2, was done using the information from the BEMC. Since the mass of the electron is almost equal to its energy, it is worth using the E/p ratio for electron selection. The applied E/p cut is defined as 0.6 < E/p < 1.6. Tracks that pass all the aforementioned cuts are classified as inclusive electrons.

2.2. *Photonic electron identification*

Once the inclusive electron selection is done, one can identify photonic electrons. As it is not possible to determine whether a single electron is a photonic electron or not, it can be done statistically using the so-called photonic electron tagging method.[8] Tagged electrons, which are identical to inclusive electrons, are paired with partner electrons. In order to enhance the efficiency of photonic electron reconstruction, partner electrons have more loose selection criteria, which include track cuts and $|\mathrm{n}\sigma_e| < 3$. Then, the Distance of the Closest Approach (DCA) cut, $|\mathrm{DCA}| < 1$ cm, and the invariant mass cut, $M_{ee} < 0.1$ GeV/c, are applied to the pair. In the event that the pair comprises either an electron or a positron, it is designated as an unlike-sign (UL) pair, which is indicative of real PE. In the event that the pair comprises either two electrons or two positrons, it is designated as a like-sign (LS) pair, which describes the background. The background is calculated as a geometrical mean of LS pairs:

$$N^{\mathrm{LS}} = 2\sqrt{N^{e^+e^+}N^{e^-e^-}} \tag{3}$$

and is subsequently subtracted from the UL to obtain the photonic electron yield. Fig.2 shows the invariant mass selection of photonic electrons in central (left) and peripheral (right) collisions in one of the measured p_{T} intervals. Red circles and black squares show the LS and UL pairs, respectively. The UL signal with background subtracted is shown by blue triangles. Purple dashed line represents used invariant mass cut.

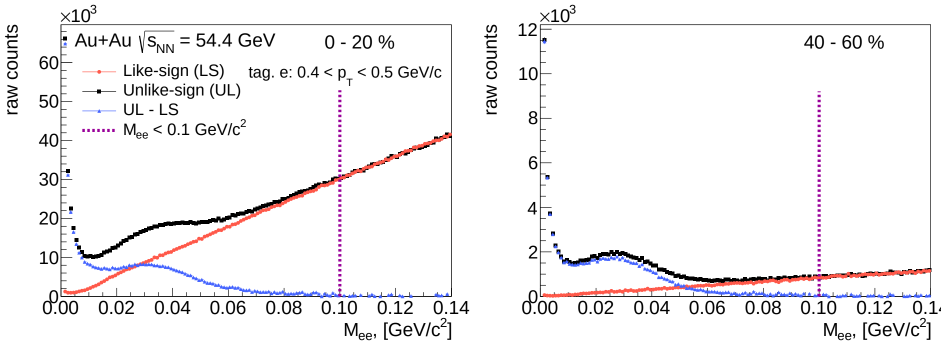

Fig. 2. Invariant mass selection of photonic electrons in central (left) and peripheral (right) collisions.

2.3. *Purity and $n\sigma_e$ cut efficiency*

It is important to estimate the purity of inclusive electrons. First, the pure hadron and photonic electron samples are identified using the cuts listed in the Table 1. Afterwards, pure samples are fitted with the Gaussian function in different p_{T} intervals, and the mean and sigma values extracted from the fits for each p_{T} interval. Next, these values are used for fitting the $\mathrm{n}\sigma_e$ distributions after applying TOF and BEMC electron identification with a multi-Gaussian function. An example of such fits for different p_{T} intervals in 0 - 20 % centrality is shown in Fig. 3. Different colors correspond to different particle species, while the dashed light-blue line represents the total fit. As it can be seen, there are momentum regions where the electron dE/dx overlaps with that of other hadrons: kaons (Fig. 3 left), protons and merged pions (Fig. 3 right). These regions will have lower purity.

Table 1. Selection cuts for pure hadron and electron samples.

Particle	Mass cut, (GeV/c^2)	nσ_e cut
proton	$\lvert m_p^2$ - 0.879$\rvert < 0.02$	$\lvert n\sigma_p \rvert < 4$
kaon	$\lvert m_K^2$ - 0.243$\rvert > 0.05$	$\lvert n\sigma_K \rvert < 4$
merged π	$\lvert m^2_{\mathrm{merged}\pi}$ - 0.019$\rvert > 0.03$	$\lvert n\sigma_{\mathrm{merged}\pi} \rvert < 5$
electron	$m_e^2 < 0.04$	$\lvert n\sigma_e \rvert < 3$

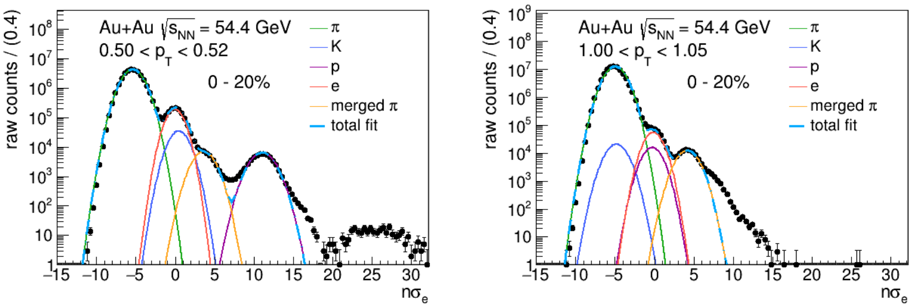

Fig. 3. An example of nσ_e fits for 0 - 20 % centrality.

3. Results

In this section some components needed for the HFE yield calculation (Eq. 1) are presented. The uncorrected raw inclusive and photonic electron yields for different centralities are shown in Fig. 4. The bumped structure is a consequence of the utilization of BEMC, TOF, and TPC for electron identification, with the BEMC energy over momentum ratio employed from $p_{\mathrm{T}} > 1.25$ GeV/c.

The total efficiency of electron identification and reconstruction consists of the following components: TPC tracking, TOF and BEMC matching efficiencies, $1/\beta$, E/p and nσ_e cut efficiencies. The efficiencies for TPC tracking, BEMC matching, and the E/p cut are obtained from STAR detector simulations. In contrast, the other efficiencies are calculated using a pure electron sample in the data. Fig. 5 depicts the $1/\beta$ (left) efficiency which is approximately 0.98 throughout the whole p_{T} range. The BEMC matching and E/p cut efficiencies are shown in Fig. 5 (right) and are approximately 85% for $p_{\mathrm{T}} > 1.25$ GeV/c.

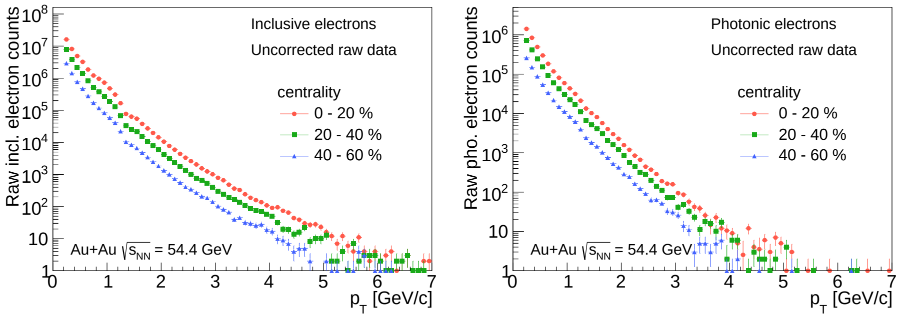

Fig. 4. Raw inclusive (left) and photonic (right) electron yields for different centrality ranges.

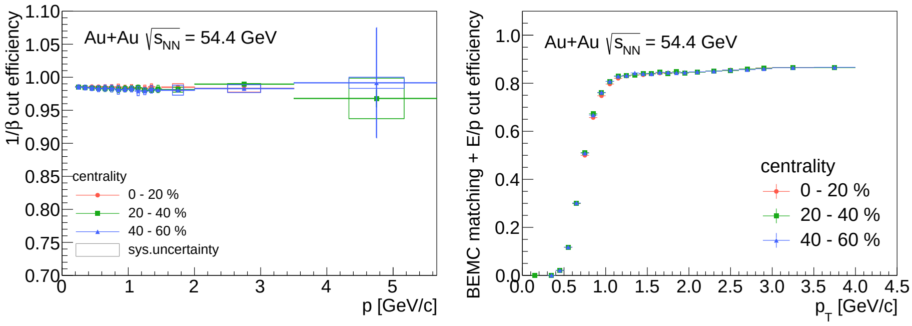

Fig. 5. $1/\beta$ (left) and BEMC matching + E/p cut (right) efficiencies for different centralities.

4. Conclusion and outlook

These proceedings present an ongoing analysis of the heavy-flavor electron production measurement in Au+Au collisions at 54.4 GeV/c. The various components of Eq. 1, including the raw inclusive and photonic electron yields, the $1/\beta$ cut efficiency, the BEMC matching efficiency, and the E/p cut efficiency, were presented. The subsequent step is to calculate the non-photonic electron yield and subtract the hadron contribution in accordance with Eq. 1. It is planned to measure central-to-peripheral nuclear modification factors as functions of p_{T}. This will provide further insight into the interaction of charm quarks with the QGP medium and, thereby complementing the existing results at $\sqrt{s_{NN}} = 200$ GeV and the recent HFE v_2 measurement at $\sqrt{s_{NN}} = 54.4$ GeV.

Acknowledgments

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