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Open heavy flavor production at STAR

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Relativistic heavy ion collisions provide a unique opportunity for studying Quark-Gluon Plasma (QGP), a new state of nuclear matter with properties determined by quark and gluon degrees of freedom. Such a nuclear matter existed in the early Universe, a few microseconds after the Big Bang. Heavy quarks are unique probes of the QGP properties because they are produced very early in heavy ion collisions and are expected to interact differently from light quarks with the QGP. Moreover, their production is sensitive to the dynamics of the medium; such measurements could be used to determine the fundamental properties of the QGP, for instance transport coefficients.

In this paper we present recent STAR results on open heavy flavor production at mid-rapidity in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. We report on measurements of open charm mesons (reconstructed directly via hadronic decay channels) and electrons from semileptonic decays of heavy flavor hadrons (so called non-photonic electrons, NPE). Production of D^0 and NPE as a function of transverse momentum and collision centrality is presented. We also report on measurements of azimuthal momentum anisotropy of NPE at 39, 62 and 200 GeV. STAR data are compared to theoretical model calculations and physics implications are discussed.

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1. Introduction

Heavy quarks are unique probes of the QGP properties because they are produced very early in the heavy ion collisions and they are expected to interact with the QGP differently from light quarks. In heavy ion collisions, we use an approach analogous to tomography for studying the QGP: An external, penetrating probe, whose properties (like production mechanism) are under experimental and theoretical control, propagates through the medium. Then we can infer properties of the analyzed system from modification of the probe. Heavy quarks serve as such external-to-QGP probes. Because of their large mass, they are produced very early in the collision, in the initial interactions with large momentum transfer, before the QGP phase. Their production, both total and differential cross-section, are well described by perturbative QCD (pQCD).

Experimentally, we study heavy quark production via decay products of charmed and beauty mesons. At the moment, there are two feasible techniques for such studies: using electrons from semi-leptonic decay of open heavy flavor mesons (so called non-photonic electrons, NPE), or through hadronic decays of charmed mesons. In the first case, the yields are larger and a specialized trigger can be used, although the information about the parent meson kinematics is incomplete and such electron sample is a mixture of electrons from charmed and beauty hadron decays. In the latter, we identify charmed mesons via hadronic decays (e.g. $D^0 \rightarrow K^-\pi^+$) which give access to the kinematic of parent meson, but it suffers from large combinatorial background if a vertex detector is not available.

Azimuthal anisotropy is another important tool for studying the QGP properties. An azimuthal anisotropy of final state particles reflects the collective behavior of nuclear matter called anisotropic flow. It is usually quantified by Fourier series of the particle azimuthal distribution with respect to the reaction plane (a plane defined by a beam and impact parameter between two colliding nuclei), where the second coefficient (v_2) is called elliptic flow. Simultaneous measurements of the c and b quark production and azimuthal momentum anisotropy are crucial for understanding the nature of surprisingly strong interactions of heavy quarks with the surrounding partonic medium, and the parton energy loss mechanism in general. They also could be used to determine the transport coefficients of the QGP, like momentum broadening transport coefficient $\hat{q}$, which are fundamental properties of the QGP. Heavy quark azimuthal anisotropy (v_2) is of particular interest because it provides insights into thermalization of heavy quarks and additional means to discriminate between models which describe heavy quark in-medium interactions.

2. Data analysis

STAR [1] is a large acceptance ($|\eta| <1$, full coverage in ϕ) multipurpose detector composed of several subsystems, which is well suited for measurement of the heavy quark production. In the analyses reported here, STAR Time Projection Chamber (TPC), Barrel Electromagnetic Calorimeter (BEMC) and Time-Of-Flight (TOF) detectors are used. The TPC is used for charged track reconstruction and particle identification via specific ionization energy loss (dE/dx). In the case of NPE measurement, BEMC is used at high p_T for electron selection and also for a high-p_T electron trigger, while TOF provides electron identification at low p_T. For a direct reconstruction of open charm mesons, TOF informations together with the dE/dx are combined to select daughter pion and koan candidates. In this article, we present results obtained with $p+p$ data taken in 2009, and Au+Au data collected in 2010 and 2011 at $\sqrt{s_{\rm NN}} = 200$, 62 and 39 GeV. More details about NPE and charmed meson measurements at STAR can be found in Refs. [2, 3, 4].

3. Results

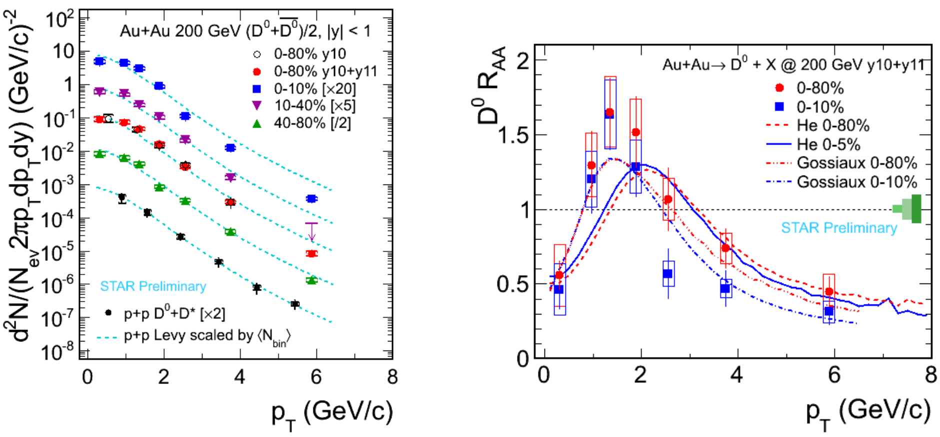

Figure 1: Left panel: D^0 invariant yield as a function of p_T in $p+p$ and Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The dashed lines represent a Levi fit to $p+p$ data scaled by number of binary collisions in a given centrality bin. Right panel: D^0 nuclear modification factor as a function of p_T in central (0-10%) and min-bias (0-80%) Au+Au collisions. The lines represent model calculations by He et al. [5] and Gossiaux et al. [6].

Figure 1 (left panel) shows D^0 p_T spectrum in $p+p$ and Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The dashed lines represent a Levi fit to $p+p$ data scaled by number of binary collisions ($N_{\rm bin}$) in a given centrality bin. The Levi fit describes the $p+p$ data well; however, there are clear discrepancies when the fit is compared to Au+Au data. To quantify a modification of the D^0 production in Au+Au collisions, we calculate the nuclear modification factor R_{AA}:

$$R_{AA} = \frac{{\rm d}^2 N_{Au+Au}/dydp_T}{N_{\rm bin} \times {\rm d}^2 N_{p+p}/dydp_T} \tag{3.1}$$

where ${\rm d}^2 N_{Au+Au}/dydp_T$ and ${\rm d}^2 N_{p+p}/dydp_T$ are invariant yield is Au+Au and $p+p$ collisions, respectively, and $N_{\rm bin}$ is number of binary collisions in a given Au+Au centrality class. Figure 1 (right panel) shows the D^0 R_{AA} for 0-10% most central and min-bias Au+Au collusions. At hight p_T, the D^0 production is significantly suppressed. The suppression decreases from central to peripheral collisions and is not observed in the most peripheral bin (40-80%). Moreover, D^0 production is enhanced at intermediate p_T (a "bump" at $p_T \sim 1.5$ GeV/c). The STAR data are compared to model predictions by He et al. [5] and Gossiaux et al. [6]. Both models assume that heavy quarks are strongly coupled with the surrounding partonic medium and predicts a large suppression at high p_T. The models qualitatively reproduce the shape of R_{AA} as a function of p_T, the enhancement at $p_T \sim 1.5$ GeV/c in that calculations is mostly due to radial flow of a light

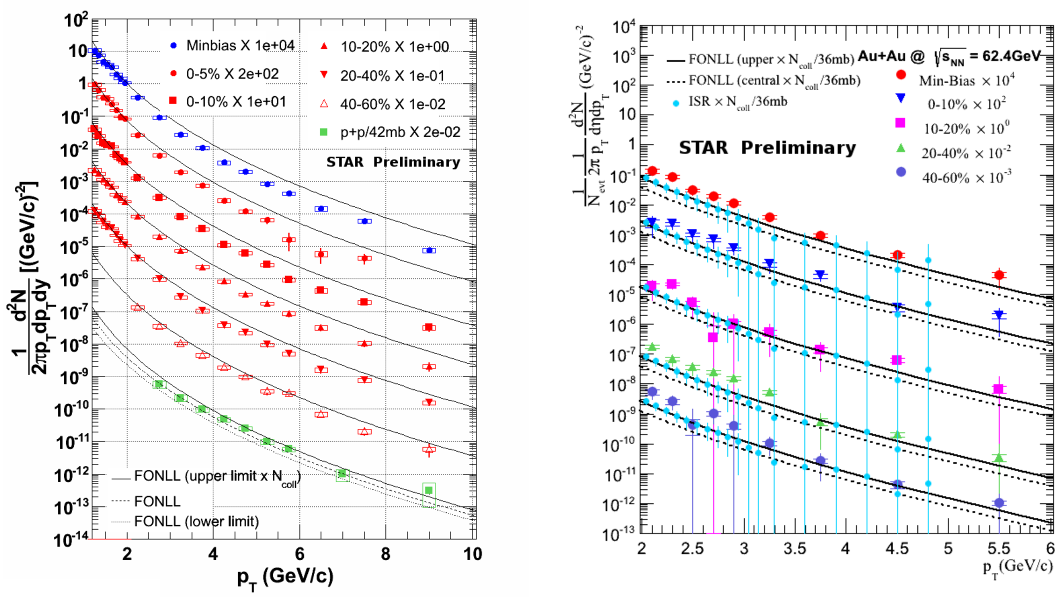

Figure 2: Invariant yield of non-photonic electrons as a function of p_T in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (left panel) and at $\sqrt{s_{NN}} = 62$ GeV (right panel). Solid lines represent an upper limit on FONLL predictions for NPE production scaled by number of binary collisions (N_{bin}) in a given centrality. For 62 GeV, ISR results for NPE p_T spectrum [7], scaled by N_{bin}, are also presented.

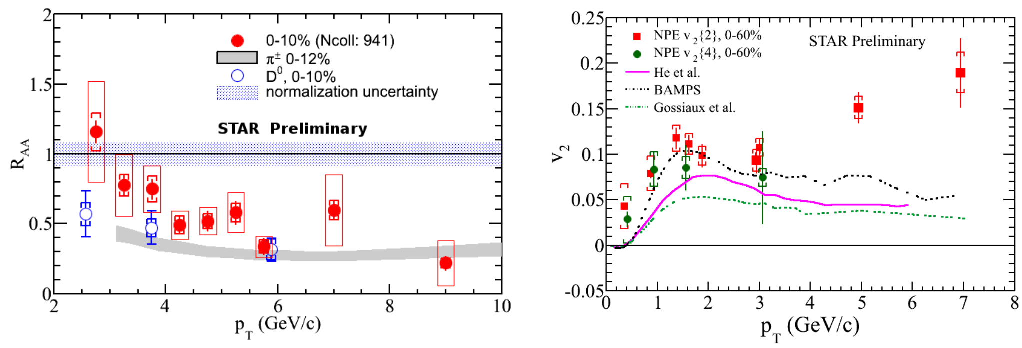

Figure 3: Non-photonic electron nuclear modification factor (left panel) and azimuthal anisotropy at $\sqrt{s_{NN}} = 200$ GeV.

quark which coalesces with a charm quark to produce a D meson. However, similar effect for other particles (proton, pions) is observed at intermediate p_T in d+Au collisions [8] and it is interpreted as so-called Cronin enhancement. Thus the "bump" could originate from a Cronin effect combined with a suppression at high p_T.

Figure 2 shows the NPE p_T spectrum for Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV. The data are compared with FONLL calculations scaled by N_{bin} corresponding to a given centrality bin. At 200 GeV, NPE production in central and mid-central collisions is suppressed compared to

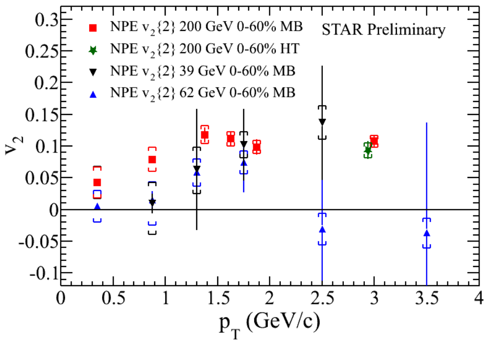

Figure 4: Non-photonic electron azimuthal anisotropy $v_2\{2\}$ at $\sqrt{s_{\rm NN}} = 200$, 62.4 and 39 GeV.

FONLL; however, the suppression is not observed at 62.4 GeV. Note, that results for 62.4 GeV are not corrected for $J/\psi \to e^+e^-$ contribution, which is as large as 20% at high p_T at 200 GeV. Figures 3 and 4 show the $R_{\rm AA}$ and elliptic flow of non-photonic electrons. We observe a strong NPE suppression at high p_T in central collisions, similar as for D^0 and light hadrons ($\pi^\pm$). Figure 3 (right panel) shows v_2 results obtained using two- and four-particle correlations ($v_2\{2\}$ and $v_2\{4\}$, respectively). $v_2\{2\}$ and $v_2\{4\}$ have different sensitivity to the flow fluctuations and so called nonflow (correlations not related to the reaction plane) - there is a positive contribution of fluctuation and nonflow to the $v_2\{2\}$ while, in the case of $v_2\{4\}$, nonflow is negligible and the effect of fluctuations is negative[9]. Therefore $v_2\{2\}$ and $v_2\{4\}$ provide an upper and lower limit on the average azimuthal anisotropy of non-photonic electrons. We compare our data to a few model calculations. Note, that models calculate the elliptic flow of NPE and heavy quarks with respect to the reaction plane. The flow fluctuations and "nonflow" are not included there, therefore the predicted v_2 values should be between $v_2\{2\}$ and $v_2\{4\}$. In a partonic transport model, BAMPS [10, 11], (black dashed line) heavy quarks lose energy due to elastic collisions with the rest of the medium. To account for radiative energy loss, the heavy quarks scattering cross-section is scaled up by a phenomenological factor K = 3.5. The dashed-dotted green line shows the implementation of radiative and collisional energy loss from Gossiaux et al. [12, 6]. It is a QCD inspired model with pQCD description of heavy quark quenching and additional non-perturbative corrections, with the hadronization implemented as coalescence at low-p_T and pure fragmentation for high momentum quarks. He et al. employ the TMatrix interactions model [5] which is a non-perturbative approach to heavy quark energy loss. In this framework, heavy quark interaction with the medium is simulated with relativistic Fokker-Planck-Langevin dynamics for elastic scattering in a strongly coupled QGP (modeled by relativistic hydrodynamics). Each of these models predicts a non-zero v_2 of charm quarks, thus observed finite NPE v_2 suggest a finite elliptic flow of charm quarks which is acquired due to interactions with quarks and gluons in the QGP phase. On the other hand, v_2 at $\sqrt{s_{\rm NN}} = 62.4$ and 39 GeV (Fig. 4) is consisted with zero at $p_T < 1$ GeV, although the errors are sizable and the difference compared to 200 GeV is not statistically significant. At 200 GeV, v_2 increases with p_T for $p_T > 3$ GeV which is due to jet-like correlations unrelated to the reaction plane or resonance decays ("nonflow").

4. Summary

D^0 and non-photonic electron production is suppressed at high p_T in Au+Au collision at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. On the other hand, NPE spectra at $\sqrt{s_{\mathrm{NN}}} = 62.4$ GeV is not suppressed compared to the pQCD calculations. We also observe a finite elliptic flow of non-photonic electrons $\sqrt{s_{\mathrm{NN}}} = 200$ GeV and comparison with models suggests a finite elliptic flow of charm quarks. Finite v_2 and a large suppression at high p_T at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV indicate that heavy quarks interact strongly with the surrounding partonic medium.

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