Heavy Flavor Results from STAR

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Abstract. Heavy flavor quarks are considered to be unique probes of the medium created in high energy heavy ion collisions. These proceedings report selected STAR results from various measurements of heavy flavor production, including $J/\psi$ suppression and collectivity, $\Upsilon$ suppression, ratio of bottom-decay electrons to charm-decay electrons, $D$ meson spectra and charm cross section.

1. Introduction

The mass of heavy flavor quarks is significantly higher than the critical temperature at RHIC energies, $\Lambda_{QCD}$ or the mass of u, d, and s quarks. As a consequence, heavy quarks are produced by hard processes early in the collision. Because heavy quarks decay weakly to light quarks within a much longer time than the collision, they can be treated as conserved in total number. Additionally, they are less influenced by the later hadronic stage due to their large mass. These features make heavy quarks an ideal probe for studying the QGP medium properties at RHIC.

In the following, the $J/\psi$ nuclear modification factor $R_{AA}$ and elliptic flow $v_2$, the $\Upsilon$ nuclear modification factor, the ratio of bottom-decay electrons to charm-decay electrons in $p+p$ collisions, $p_T$ spectra of $D^0$ and $D^*$ mesons, and the charm cross section deduced from them will be presented.

2. $J/\psi$ nuclear modification factor and elliptic flow

In relativistic heavy-ion collisions, the $c\bar{c}$ bound state is subject to dissociation due to the color screening of the binding potential in the deconfined medium. As a consequence, the $J/\psi$ production is expected to be suppressed, and such suppression has been proposed as a signature of QGP formation [1]. However, the $J/\psi$ yield in heavy ion collisions can also be affected by other hot and cold nuclear effects [2, 3, 4, 5]. Precise measurements of $J/\psi$ $R_{AA}$ as well as $v_2$ as a function of $p_T$ and centrality will help to understand $J/\psi$ production and whether $J/\psi$ is suppressed by the color screening effect.

Figure 1 shows $J/\psi$ $R_{AA}$ vs. $N_{part}$ for different sets of data and for different model calculations at $\sqrt{s_{NN}} = 200$ GeV [6, 7]. We observe more suppression in central than in peripheral collisions, and $R_{AA}$ is larger for $p_T > 5$ GeV/c than without $p_T$ cut. In peripheral collisions, $R_{AA}$ is consistent with unity at high $p_T$, while in central collisions, the results show a significant suppression even in the high $p_T$ region. The lines in the plot represent predictions from two models that consider $J/\psi$ from both initial pQCD production and coalescence production in transport model calculations [8, 9]. The green lines are for the case where no $p_T$ cut is applied,
while the blue lines are for high $p_T$ ranges. The models, which include color screening effects, can describe the general trend of the data points.

Figure 1. $J/\psi R_{AA}$ as a function of $N_{\text{part}}$.

Elliptic flow ($v_2$) constrains the $J/\psi$ production mechanism from another dimension. $J/\psi$ produced from direct pQCD processes should have little azimuthal preference, while $J/\psi$ produced from recombination of thermalized charm quarks will inherit the flow of charm quarks, exhibiting sizable flow [10]. Flow of $J/\psi$ from recombination can also be used to probe the charm quark flow, which provides a unique tool to test thermalization of the medium.

In Figure 2 $J/\psi$ $v_2$ for the 20 - 60 % most central Au+Au collisions at 200 GeV is presented as a function of $p_T$ [11]. For reference, $v_2$ of charged hadrons and of $\phi$ mesons is also shown. The $J/\psi$ $v_2$ at $p_T > 2$ GeV/$c$ is consistent with zero within errors, in contrast to the results for light quark hadrons. This result disfavors the scenario that $J/\psi$ at large $p_T$ are produced dominantly by coalescence from thermalized charm and anti-charm quarks, and is consistent with predictions from models in Figure 1, which consider both initial and coalescence production.

3. $\Upsilon$ nuclear suppression factor

Compared to $J/\psi$, $\Upsilon$ states are much cleaner probes to test suppression due to the screening effect because recombination can be neglected at RHIC [12] and there are negligible weak decay feed-down. Figure 3 shows $\Upsilon$ (1S+2S+3S) $R_{AA}$ as a function of $N_{\text{part}}$. We observe an increase of suppression with larger $N_{\text{part}}$. And the measured $R_{AA}$ in the most central collisions is consistent with the prediction from the internal energy potential model requiring strong 2S and complete 3S suppression [13].

4. Non-photonic Electrons (NPE) from bottom and charm

Open heavy flavor particles are also important in studying the medium created in heavy ion collisions. Open charm can be used to measure the total charm yield, which is an important base line for understanding charmonia coalescence production. Furthermore, the $R_{CP}$ and $R_{AA}$ of charm and bottom as a function of $p_T$ can be used to study heavy quark energy loss in QGP. Open heavy flavor particles decay before reaching the detectors. One way to study them is to measure their decay electrons. Heavy flavor, photon conversion and Dalitz decays are the major sources of electron production at RHIC. By reconstructing and subtracting the latter two sources, STAR can measure NPE from bottom and charm decays [14, 15].
The ratio of bottom-decay electrons to total NPE in p+p 200 GeV collisions can be obtained by fitting the NPE-hadron azimuthal correlation data with correlation line shapes of charm and bottom decay electrons from PYTHIA. The result as a function of $p_T$ is shown in Figure 4 [16]. We can see that the contribution of $B$ meson decay increases with $p_T$. The result is consistent with FONLL prediction. A similar measurement of NPE-$D_0$ correlation gets consistent result.

5. $D^0$ and $D^*$ $p_T$ spectra and charm cross section
Measuring only the decay electrons does not constrain the heavy flavor kinematics due to momentum smearing. STAR also measured fully reconstructed $D^0$ and $D^*$ mesons directly. Since the $D$ mesons have a very short decay length, STAR can not distinguish their decay vertices from the primary vertex right now. A statistics cumulant method is used instead to beat the small signal to background (s/b) ratio. Figure 5 shows $D^0$ and $D^*$ $p_T$ spectra in p+p 200 GeV collisions divided by their predicted portion of total charm yield, 0.56 and 0.22 respectively [17, 18]. The result is consistent with the FONLL [19] upper limit.

From $p_T$ spectra of $D$ mesons we can deduce the charm cross section. This is also done for d+Au and Au+Au collisions with different centralities. Figure 6 shows the charm cross section per nucleon-nucleon collision as a function of number of binary collisions ($N_{bin}$) [18, 20]. We can see that the charm cross section follows $N_{bin}$ scaling, which confirms that charm quarks are produced mostly via initial hard scatterings.

6. Conclusion and outlook
In summary, by using various heavy flavor probes, we gain a better understanding of the medium created in relativistic heavy ion collisions. $J/\psi$ suppression pattern and elliptic flow results are consistent with models with both suppressed initial $J/\psi$ and coalescence production in transport model. $\Upsilon$ $R_{AA}$ shows more suppression in central collisions, and is consistent with a model requiring strong 2S and complete 3S suppression in central collisions. By measuring the azimuthal correlation between NPE and hadrons, an increasing ratio of NPE from bottom to total NPE as a function of $p_T$ is observed in p+p collisions. The charm cross section measured through $D$ mesons follows number of binary collisions scaling, which confirms that charm quarks are produced mostly via initial hard processes.

In the near future, STAR will have two major detector updates targeting precise heavy flavor
measurements: the Heavy Flavor Tracker (HFT) and the Muon Telescope Detector (MTD). The HFT is a silicon vertex detector which will greatly reduce background for open heavy flavor particles by reconstructing secondary vertices. It will significantly enhance the s/b ratio of $D$ and $\Lambda_C$ measurements, and will be able to distinguish between prompt and $B$ feed down $J/\psi$. It will also enable the measurement of the ratio of NPE from $B$ to NPE from charm in Au+Au collisions. The MTD uses the magnet yoke as an absorber for other charged particles and detects muons, which can enhance $J/\psi$ and $\Upsilon$ measurements with its fast trigger ability, and distinguish different $\Upsilon$ states in the di-muon decay channel with good mass resolution.

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