PROCEEDINGS OF SCIENCE

Heavy Flavor Measurements at the STAR Experiment

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Selected new measurements of open and hidden heavy flavor hadrons from the STAR experiment are reported, especially those made possible by the new Heavy Flavor Tracker (HFT) and Muon Telescope Detector (MTD). An improved D^0 R_{AA} measurement shows significant suppression at high p_T in central Au+Au collisions. The first measured D^0 v_2 in Au+Au collisions at top RHIC energy favors charm quark diffusion in the medium, when comparing with model calculations. D_s R_{AA} in Au+Au collisions at top RHIC energy is also reported. Stronger-than-linear growth for relative J/ψ yield vs. event multiplicity is observed in p+p collisions. J/ψ R_{AA} and ratio of yields of different Υ states in Au+Au collisions are also presented and compared with LHC results.

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1. Introduction

Heavy flavor quarks have intrinsic masses that are significantly higher than the critical temperature, Λ_{QCD} and masses of u, d, s quarks. As a result, heavy quarks are produced mostly during early processes of the collision at RHIC energies. They go through the entire system evolution including the Quark Gluon Plasma (QGP) state that we are interested in, and are less influenced by later hadronic stage due to their large masses. These features make heavy quarks ideal probes for studying the QGP properties at RHIC. In the following sections, we will first present some open charm hadron measurements with the new Heavy Flavor Tracker (HFT) [1, 2], including D^0 R_{AA}, v_2, and D_s R_{AA}. Then we will show heavy quarkonium measurements including J/ψ yield vs. event multiplicity in p+p collisions, J/ψ R_{AA} and ratio of yields of different Υ states in Au+Au collisions. Many of them are done with the new Muon Telescope Detector (MTD) [3].

2. Open heavy flavor hadron measurements

Open heavy flavor hadron measurements at the STAR experiment are greatly improved with the new HFT. HFT is a silicon vertex detector with good position resolution, which enables reconstruction of secondary vertices displaced from the collision point, greatly reducing the combinatorial background for open heavy flavor particles.

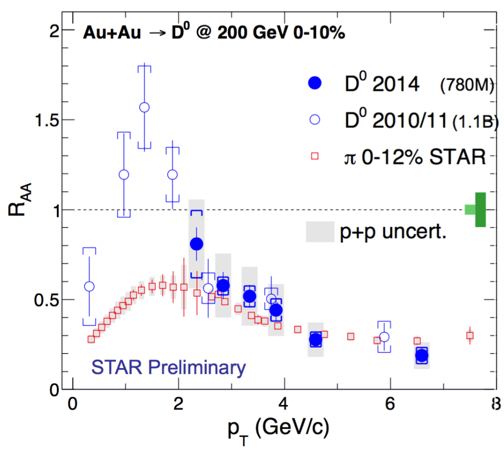

Figure 1: D^0 R_{AA} vs. p_T for 0-10% central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The solid circles are new results with HFT while the open circles are published results [4]. The open squares show π R_{AA} [5] for comparison.

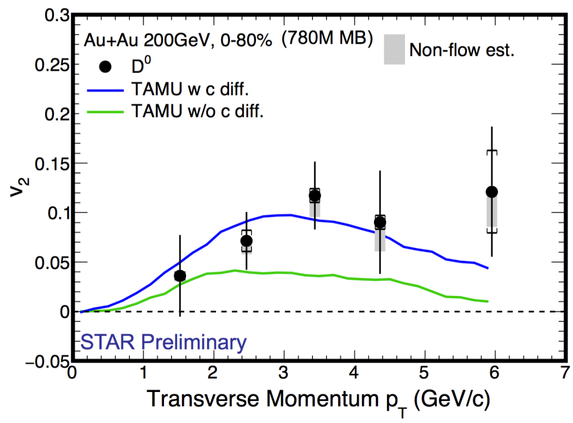

Figure 2: D^0 v_2 vs. p_T for 0-80% central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The brackets show systematic uncertainties of the measurement while the gray bands show an estimation of the maximum non-flow contribution to the measured v_2. The two curves show theoretical predictions with and without charm diffusion in the medium [6, 7]

In heavy-ion collisions, high p_T heavy flavor quarks may lose energy due to interaction with the medium. This effect can be quantitatively represented by the Nuclear Modification Factor R_{AA}, the ratio between production yields in heavy-ion collisions and p+p collisions, normalized by the number of binary collisons. Interaction with the medium will shift high p_T heavy quarks to lower p_T in heavy-ion collisions, and make open heavy flavor hadron R_{AA} smaller than unity at high

p_T. Figure 1 shows D^0 R_{AA} vs. p_T for 0-10% central collisions at $\sqrt{s_{NN}}$=200 GeV. Significant suppression at high p_T can be observed, comparable with π for $p_T > 4$ GeV/c, indicating strong charm-medium interaction. At p_T around 1.5 GeV/c, the R_{AA} is larger than 1. This is consistent with the scenario that charm quarks coalesce with a radially flowing bulk medium [4].

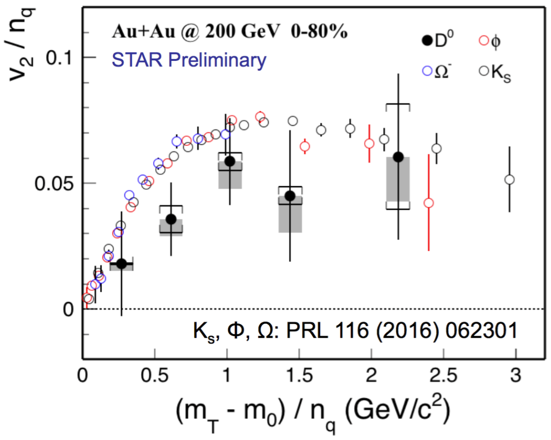

Figure 3: v_2/n_q vs. $(m_T - m_0)/n_q$ for D^0 in 0-80% central events compared with K_s^0, ϕ and Ω [8]. m_0 is the rest mass of the particle, and $m_T = \sqrt{p_T^2 + m_0^2}$. n_q is number of constituent quarks.

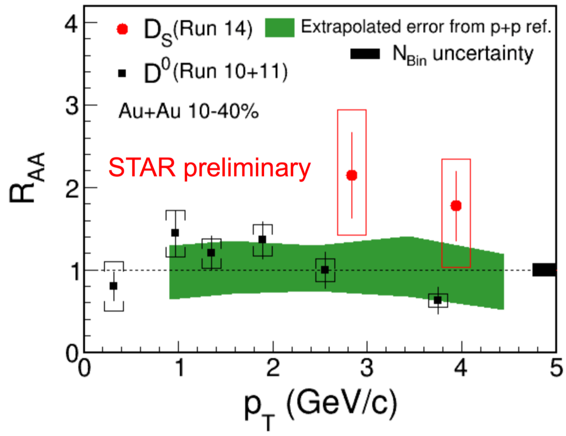

Figure 4: R_{AA} vs. p_T of D_s (solid circle) comparing with D^0 (solid square) [4] in 10-40% central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The green band shows uncertainty from p+p reference.

The medium effects on heavy quarks can also be studied with the azimuthal anisotropy of open heavy flavor hadrons, especailly the second-order Fourier coefficient v_2. Positive v_2 has been observed for light flavor particles, which is considered as an evidence for strong interaction among light quarks and gluons in the medium. This is because non-central heavy-ion collisions create an initial interacting medium with an elliptic shape. The different pressure gradients along different directions of this elliptic medium will lead to different expanding velocities and particle momentum distributions at the final state, and thus positive final v_2. Figure 2 shows D^0 v_2 as a function of p_T for central 0-80% Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV, comparing with theoretical predictions. The predicted D^0 v_2 with charm diffusion is higher than that without charm diffusion, and agrees better with the data. Figure 3 compares normalized v_2 of D^0 with light flavor particles K_s^0, ϕ and Ω. The light flavor mesons and bayons fall in a common trend after transforming p_T to $(m_T - m_0)$ and being normalized by number of constituent quarks n_q, which indicates complete collective motion of light quarks. D^0 v_2 is slightly lower than the common trend, which may indicate that charm quarks are not fully thermalized with the medium at RHIC energies. But more precise measurements in finer centrality bins are needed to make firm conclusions.

Strangeness enhancement is predicted to be a signal of QGP, and is expected to affect the yield of D_s [7]. In Fig. 4, R_{AA} of D_s is compared with D^0 for 10-40% central Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. In this measurement, the D_s p_T spectrum in p+p collisions is deduced from the charm quark p_T spectrum measured through D^0 and D^* [9], multiplied by the charm fragmentation ratio $f(c \rightarrow D_s)$. The measurement of D_s is difficult, and in 10-40% centrality the best signal is obtained. The measured R_{AA} of D_s is higher than unity as well as R_{AA} of D^0, which is consistent with strangeness enhancement. But it is statistically not significant.

3. Heavy quarkonium measurements

Heavy quarkonia can be measured through di-electron and di-muon channels at the STAR experiment. Electrons can be identified by combining information from the Time Projecton Chamber, Time Of Flight detector and Barrel ElectroMagnetic Calorimeter. The new MTD can be used to identify and trigger on muons, and improve measurements of low p_T J/ψ and Υ. The MTD is made of multi-gap resistive plate chambers with good timing resolution placed at the outermost layer of STAR, and uses the magnet yoke as an absorber for other charged particles.

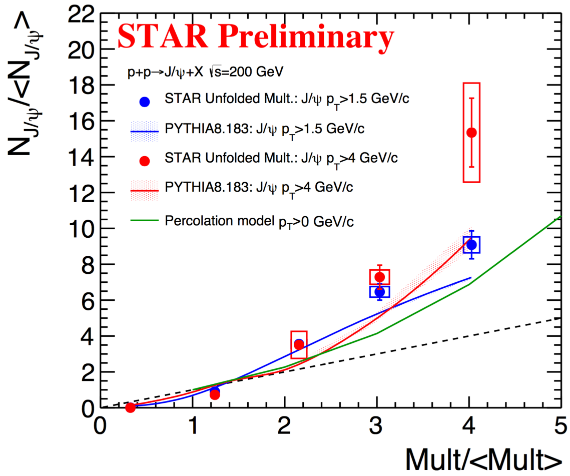

Figure 5: Relative J/ψ production yield vs. relative event multiplicity in p+p collisions at $\sqrt{s}$=200 GeV. The blue and red solid circles show results for J/ψ with p_T > 1.5 and 4 GeV/c respectively. The lines show different model predictions [10].

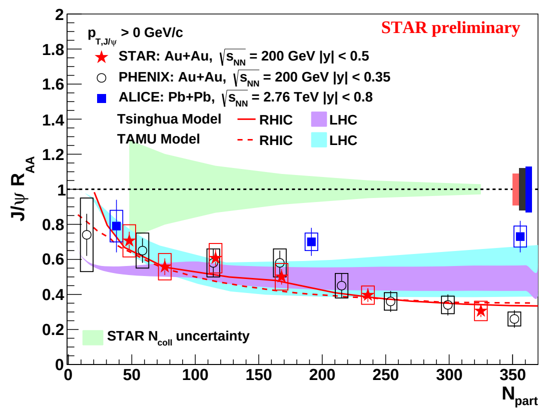

Figure 6: J/ψ R_{AA} vs. N_{part}, comparing with results from PHENIX and ALICE experiments [11, 12], and different model predictions [13, 14, 15, 16].

The relative J/ψ production yield is measured as a function of relative event multiplicity in p+p collisions at $\sqrt{s}$=200 GeV. The result is shown in Fig. 5. A stronger-than-linear growth of relative J/ψ yield is observed as event multiplicity increases, indicating correlation between soft and hard processes. Both PYTHIA8 and Percolation model reproduce trends in data qualitatively. There is a hint of different trends for low and high p_T J/ψ.

In relativistic heavy-ion collisions, heavy quarkonia are subject to dissociation due to the color screening of their binding potential in the deconfined medium [19]. As a consequence, their production is expected to be suppressed, which is different for different quarkonium states depending on their binding energies and the medium temperature. Thus the suppression pattern of heavy quarkonium states has been proposed as a QGP thermometer [20].

Figures 6 and 7 show J/ψ R_{AA} vs. number of participating nucleons N_{part}, for p_T integrated and high p_T J/ψ respectively. Stronger suppression is observed in more central collisions, where N_{part} is larger and the dissociation effect in the medium is stronger. For p_T integrated J/ψ, the R_{AA} at RHIC is smaller than LHC. The reason may be that at LHC, the collision energy is so high that more than one pair of charm and anti-charm quarks can be produced, and J/ψ can be generated from recombination of random charm and anti-charm quark pairs that are not originally produced as a pair through an initial hard scattering. This recombination effect is less significant

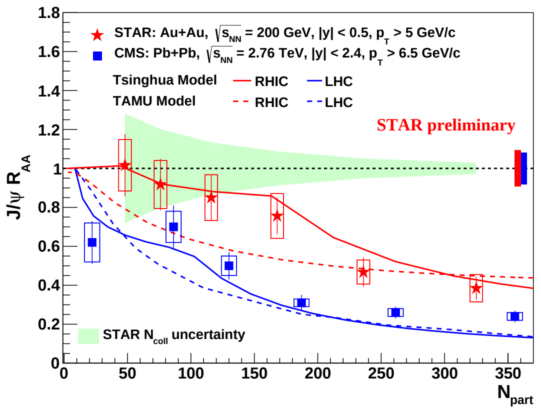

Figure 7: High p_T J/ψ R_{AA} vs. N_{part}, comparing with results from CMS experiment [17], and different model predictions [13, 14, 15, 16].

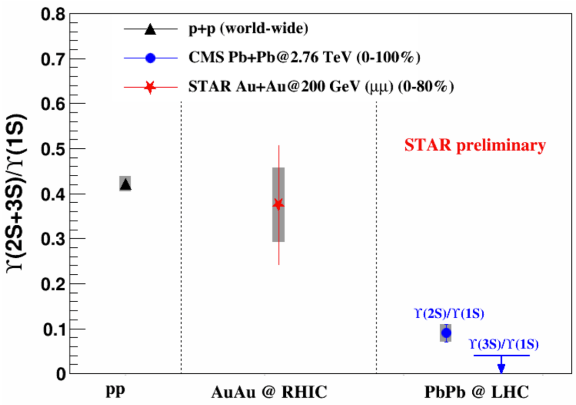

Figure 8: Yield ratio of $\Upsilon(2S+3S)$ to $\Upsilon(1S)$ in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV, comparing with world data for p+p collisions and LHC results [18].

at lower RHIC energies. It's also much less important at high p_T. The high p_T J/ψ R_{AA} is smaller at LHC than RHIC, indicating stronger dissociation effect in the medium at LHC due to higher temperature and longer evolution time. The transport models with dissociation and recombination can qualitatively describe data from both RHIC and LHC.

Different Υ states have different binding energies corresponding to different melting temperatures. The MTD enables STAR to measure Υ through the di-muon channel, and distinguish different Υ states with sufficient mass resolution, because the muon doesn't suffer strong Bremsstrahlung energy loss like the electron. Figure 8 shows the yield ratio of $\Upsilon(2S+3S)$ to $\Upsilon(1S)$ in Au+Au collisions, compared with world data for p+p collisions and LHC results. We observe a hint of less melting of $\Upsilon(2S+3S)$ at RHIC than at LHC, consistent with lower medium temperature at RHIC.

4. Conclusion

The new HFT and MTD detectors have greatly improved open and hidden heavy flavor measurements at the STAR experiment. D^0 R_{AA} and v_2 measurements indicate strong interactions between charm quarks and the medium created in heavy-ion collisions. D_s R_{AA} is consistent with strangeness enhancement. Relative J/ψ yield vs. event multiplicity shows correlation between soft and hard processes. J/ψ R_{AA} and ratio of yields of different Υ states both indicate a lower medium temperature reached at RHIC than at LHC.

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