Recent Heavy-Flavor results at STAR

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Abstract. We present the recent results on non-photonic electron (NPE) yields from RHIC run8 p+p collisions. The $e/\pi$ ratio as a function of $p_T$ in run8 with a factor of 10 reduction of the inner detector material at STAR is found to be consistent with those results from run3 taking into account the NPE from charm leptonic decay and the difference of photonic electron yield from photon conversion in detector material. $J/\Psi$ spectra in $p+p$ and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV with high sampled luminosity $J/\Psi$ spectrum at high-$p_T$ follows $x_T$ scaling, but the scaling is violated at low $p_T$. $J/\Psi$-hadron correlations in $p+p$ collisions are studied to understand the $J/\Psi$ production mechanism at high $p_T$. We observed an absence of charged hadrons accompanying $J/\Psi$ on the near-side, in contrast to the strong correlation peak in the di-hadron correlations. This constrains the $B$-meson contribution and jet fragmentation to inclusive $J/\Psi$ to be $\lesssim 17\%$. Yields in minimum-bias Cu+Cu collisions are consistent with those in $p+p$ collisions scaled by the underlying binary nucleon-nucleon collisions in the measured $p_T$ range. Other measurements and future projects related to heavy-flavors are discussed.

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Productions of open and hidden heavy-flavor hadron states in relativistic heavy-ion collisions are related to several fundamental properties of QCD [1, 2, 3, 4, 5]. Energetic open charm and bottom quarks are expected to lose less energy than the light quark or gluon jets when traversing the QGP. The heavy quarks at low $p_T$ can serve as a probe of the degree of a QGP thermalization analogy to classic Brownian Motion. The dissociation of $J/\Psi$ and $\Upsilon$ due to color-screening in a Quark-Gluon Plasma (QGP) created in relativistic heavy-ion collisions [2] is a classic signature of de-confinement of the fundamental theory of Quantum Chromodynamics (QCD). Recently, techniques based on the AdS/CFT duality have been utilized to study the dissociation of quark-antiquark pairs with high velocities relative to the QGP. Calculations in this framework show that bound states of heavy fermion pairs (an analog of quarkonium in QCD) have an effective dissociation temperature that decreases with $p_T$ (or velocity) as $1/\sqrt{\gamma}$ [3]. To test this conjecture, measurements of $J/\Psi$ $R_{AA}$ to $p_T > 5$ GeV/c are needed where the effective $J/\Psi$ dissociation temperature is expected to be below the temperature reached at RHIC collisions ($\sim 1.5 T_c$). $J/\Psi$ in hadron-hadron collisions can be produced from the following processes: (i) gluon and heavy-quark fragmentation, (ii) decay feed-down from B mesons and $\Xi_c$ states, and (iii) direct production either through charm quark and anti-quark pair in a color-octet or color-singlet state. Therefore it is important to identify the $J/\Psi$ production before $J/\Psi$ can be used as a probe of the color dissociation in QGP.

We report the recent results on non-photonic electron (NPE) yields from RHIC run8 p+p collisions and the $J/\Psi$ spectra at high transverse momentum ($5 < p_T < 14$ GeV/c) from EMC triggered events and at low transverse momentum from minbias events in $p + p$ and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR experiment at RHIC/BNL. The $e/\pi$ ratio as a function of $p_T$ in run8 with a factor of 10 reduced inner detector material at STAR is used to compare step-by-step with those results from run3 [6, 7, 8] to assess if large amount of the electrons from the photon-conversion in detector material in run3 has produced an artificially high NPE yield. The electron and $\pi$ identification is provided by a combination of dE/dx in the STAR Time Projection Charmber (TPC) [9] and velocity from Time-of-Flight (TOF). This technique results in a small systematic error ($\lesssim 5\%$) on $e/\pi$ ratio since most of the detector acceptance and efficiency cancels. The large acceptance of TPC and the Barrel ElectroMagnetic Calorimeter (BEMC) [10] with $|\eta| < 1$ and full azimuthal coverage are well suited for an analysis of $J/\psi$-hadron correlations in $p + p$ collisions to understand the $J/\Psi$ production mechanism at high $p_T$.

In run8, STAR has removed the inner silicon tracker (SVT and SSD). This reduces the detector material close to the beam pipe by a factor of 10. STAR has also installed one sector (out of 24 in total) of new TPC electronics, which increases the TPC Data Acquisition rate by a factor of 10 and at the same time provides a buffered readout scheme to reduce the deadtime [11] to few percent at 1KHz readout rate. The old TPC electronics provides a maximum of 100Hz readout at 100% deadtime. Within the same sector, five TOF trays with final detector configuration have been installed as well. This
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Figure 1. (Color online). Inclusive $e/\pi$ ratio (red circles) as a function of $p_T$ from run8 p+p collisions. The dotted dash lines are $e/\pi$ ratio with electrons from $\pi^0 \rightarrow \gamma e^+e^-$ and the dotted line is the $\eta$ Dalitz decay. The solid line is the NPE in d+Au minbias collisions scaled by the binary collisions over the pion yield in p+p collisions as in other $e/\pi$ ratios. The Dashed line is the inclusive $e/\pi$ ratio from the sum of all the electron yields.

special sector took data at 200Hz with a L0 trigger requiring at least a hit in the TOF. We refer the detailed analysis to Ref. [12].

Figure 1 shows the $e/\pi$ ratio as a function of $p_T$ from run8. In the same figure, the $e_{\pi^0\rightarrow\gamma e^+e^-}/\pi$ ratio from $\pi^0 \rightarrow \gamma e^+e^-$ (Dalitz decay) and a similar curve for $e/\pi$ ratio from the $\eta$ Dalitz decay are presented. The pion spectrum was taken from an average of the $\pi^\pm$ spectra measured by STAR in non-singly diffractive p+p collisions. The spectrum was well described by a Levy function with fit function as: $dN/dy(n-1)(n-2)/(2\pi nT(nT + m(n-2)))/(1 + (\sqrt{p_T^2 + m^2 - m})/nT)^n$ where $dN/dy=1.38$, $n=9.7$ and $T=0.131$. The red line is the ratio of NPE over the pion spectrum where NPE is the non-photonic electron yields obtained from a fit to the combined results of NPE and D0 yields in d+Au minbias collisions scaled by its binary collisions [6]. The inclusive electron yields consist of photonic electrons from $\pi^0$ and $\eta$ Dalitz decays, photon conversions at the detector material and non-photonic electrons from heavy-flavor semileptonic decays. Other sources ($\phi \rightarrow e^+e^-$, direct photon) are at few percent level and have very similar spectrum shape as those of photonic sources from Dalitz and photon conversions. To match the low-$p_T$ ($\lesssim 0.5$ GeV/c) inclusive electron yields where photonic background dominates, we need an electron spectrum from photon conversion about 90% of what the electron spectrum from $\pi^0$ Dalitz decay. We denote this detector dependent electron background as $e_{\text{run8bg}}/\pi$. This means that $e_{\text{run8bg}}/\pi = 0.9 \times e_{\pi^0\rightarrow\gamma e^+e^-}/\pi$. Since the Branching Ratio of $\pi^0$ Dalitz decay is 1.2%, the equivalent detector material for a photon conversion from $\pi^0 \rightarrow \gamma \gamma$ or $\eta \rightarrow \gamma \gamma$ decays at the 90% of the $e/\pi$ ratio from $\pi^0$ Dalitz decay is $0.9 \times 0.012/2 = 0.54\%$ conversion probability or $0.54\% \times 9/7 = 0.69\%$ radiation length ($X_0$). The total sum
of all the contributions (Dalitz decays, NPE inferred from d+Au data, and photon conversion in detector material) to inclusive electron yields is shown as pink dashed line, which agrees with the inclusive electron to pion ratio. The inclusive $e/\pi$ ratios from run3 and an early PHENIX result (the only published inclusive electron yields) [13] are presented for comparison. To reproduce run3 data [6], we need a factor of 10 more conversion background ($10 \times e_{\text{run3bg}}$), consistent with the different amounts of material existing in run3 and run8. PHENIX inclusive electron spectrum is similar to our current inclusive electron spectrum. This provides an opportunity to compare the inclusive electron yields, the background subtraction and NPE step-by-step between two experiments [13, 14, 8].

Besides the NPE measurements, STAR excels in other heavy-flavor related measurements: minbias $D^0$ measurements and $D^*$ in a jet without secondary vertex, e-h, e-D0 correlations. These results are presented in Ref. [15]. We have measured the fraction of $B/(B+D)$ from e-h correlation in p+p collisions and NPE $R_{AA}$. This means that we can infer the $B$ and $D$ $R_{AA}$ in a model dependent analysis. Reference [15] shows our preliminary result of $B$ $R_{AA}$ vs $D$ $R_{AA}$. It suggests that the bottom hadrons are as suppressed as charm hadrons. To directly reconstruct bottom and charm hadrons, the current STAR upgrade plans include Time-of-Flight for particle identification, Heavy-Flavor Tracker for secondary vertex, DAQ1000 faster readout rate and future muon telescope detector.

Both the TPC and the BEMC at STAR can provide electron identification [16, 17]. BEMC has been used as a fast online trigger to enrich the data sample with high-$p_T$ electrons. The combination of shower energy deposit in BEMC towers and shower shape from Shower-Maximum Detector (SMD) provides powerful hadron rejection. At moderate $p_T$, the TPC can identify electrons efficiently with reasonable hadron rejection. This allows a study of $J/\Psi$ at high-$p_T$. In this analysis, the high $p_T$ $J/\Psi$ was reconstructed through the dielectron decay channel with a decay branch ratio of 5.9%. The electron at high $p_T$ was identified by combining the energy and shower shape measured in the BEMC and ionization energy loss ($dE/dx$) measured by the TPC; the other electron at lower $p_T$ was identified by the $dE/dx$ only with better efficiency but lower purity. The data were from $p + p$ and Cu+Cu runs in 2005 and $p + p$ run in 2006 at RHIC. An online BEMC trigger that requires only the transverse energy ($E_T$) deposit in one BEMC tower to be above certain threshold [18]. In addition, this trigger was in coincidence with a minimum bias trigger requiring a coincidence between the two Zero Degree Calorimeters (ZDCs). The integrated luminosity is $\sim 2.8 (11.3) \, pb^{-1}$ for $p + p$ collisions collected in year 2005 (2006) with $E_T > 3.5 (5.4) \, GeV$, and $\sim 860 \, \mu b^{-1}$ for Cu+Cu collisions with $E_T > 3.75 \, GeV$. In Cu+Cu data, the most central 0-60% of the total hadronic cross section was selected by using the uncorrected charged particle multiplicity at mid-rapidity ($|\eta| < 0.5$).

The invariant cross section of inclusive pion and proton production in high energy $p + p$ collisions have been presented in Ref. [18, 27] and found to follow the $x_T$ scaling law [28, 29, 30]: $E \frac{d^3 \sigma}{dp^3} = \frac{g(x_T)}{\sqrt{s}}$, where $x_T = 2p_T/\sqrt{s}$. The value of the power $n$ depends
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Figure 2. (Color online). (a): $J/\psi$ invariant cross section times the dielectron branching ratio as a function of $p_T$ in $p + p$ collisions from year 2005 data (stars) and year 2006 data (circles) and in Cu+Cu collisions (squares) at $\sqrt{s_{NN}} = 200$ GeV. The Cu+Cu results are scaled by 1/100 for clarity. (b): $x_T$ scaling of pions, protons and $J/\psi$s. The pion and proton results are from Ref. [19, 20, 21, 22]. The $J/\psi$ results from other measurements are from the following references, CDFII [23], CDF [24], UA1 [25], and ISR [26].

on the quantum exchanged in the hard scattering and is related to the number of point-like constituents taking an active role in parton model. It reaches 8 in the case of a diquark scattering and reaches 4 in more basic scattering processes (as in QED). Figure 2 shows the $x_T$ scaling of $J/\psi$, pion and proton in $p + p$ collisions. The $J/\psi$ data [23, 24, 25, 31, 26] covers the $\sqrt{s}$ range from 30 GeV (ISR) to 1960 GeV (CDFII). The high $p_T$ $J/\psi$ cross section at these various center-of-mass energies also follow the $x_T$ scaling law. These data are fitted simultaneously at the high $p_T$ region using the function $(1 - x_T)^m/p_T^n$. The power $n$ is found to be 5.6 ± 0.2 for $J/\psi$, which is lower than that for pion and proton (6.5 ± 0.1 [20]). This suggests that the high $p_T$ $J/\psi$ production mechanism is likely to originate from a $2 \rightarrow 2$ parton-parton hard scattering. On the other hand, the low $p_T$ $J/\psi$ shows clear deviation from the $x_T$ scaling, very similar to the behavior of the pion and proton yields at $p_T < 2$ GeV/c. Although production of low $p_T$ $J/\psi$ must originate from a hard process, the subsequent soft process could determine the $J/\psi$ formation and yields. In this regard, there is no reason to believe/assume the initial $J/\psi$ production at low $p_T$ should follow a binary scaling in a nucleus-nucleus or nucleon-nucleus collision. In fact, there is no experimental evidence that the binary scaling is followed, although the effect is often attributed to the cold nuclear absorption. This may explain why the $J/\psi$ suppression in Au+Au collisions at RHIC is stronger at forward rapidity than at midrapidity. This observation may strengthen the recent theoretical development on $J/\psi$ production mechanisms [32, 33].

The nuclear modification factor $R_{AA}$ is the ratio of the $p_T$ spectra in Cu+Cu and $p + p$ collisions scaled by the number of the underlying binary nucleon-nucleon
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The systematic uncertainty is similar to that on the invariant spectra with the contribution from efficiency partly cancelling out in the ratio. The $R_{AA}$ tends to increase from low to high $p_T$, although the error bars currently do not allow to draw strong conclusions. If we assume the systematic and statistical errors of PHENIX Cu+Cu data points at high $p_T$ are correct and are independent of those from STAR, we can obtain more high $p_T$ data points by combining PHENIX Cu+Cu results with STAR $p+p$ results, the average $R_{AA}$ at $p_T > 5$ GeV/c is $0.96 \pm 0.2(\text{stat.}) \pm 0.13(\text{syst.})$. These results are consistent with unity and two standard-deviation higher than that at low $p_T$ ($R_{AA} \sim 0.6$) measured by PHENIX [34]. This result is also in contrast to the expectation from AdS/CFT-based model (dotted-dashed curve) [3, 35] and from the Two-Component-Approach model (dashed curve) [36], which predict a decreasing $R_{AA}$ with increasing $p_T$. Similar result was also observed by NA60 Collaboration in $In + In$ collisions at $\sqrt{s_{NN}} = 17.3$ GeV [37], although the $R_{AA}$ reaches unity at much smaller $p_T$ than at RHIC and most likely of a different physics origin. These results could indicate that other $J/\Psi$ production mechanisms such as recombination or formation time [38, 39] may play an important role at high $p_T$.

The large S/B ratio of the $J/\Psi$ in $p+p$ collisions allows the study of $J/\psi$-hadron correlations to understand the $J/\Psi$ production mechanism at high $p_T$. Figure 3a shows the azimuthal angle correlations between a high $p_T$ $J/\Psi$ ($p_T > 5$ GeV/c) and all charged hadrons with $p_T > 0.5$ GeV/c in the same event. No significant near side correlations were observed, which is in contrast to the dihadron correlation measurements [40] where the height of the near-side correlation at zero degree is no less than that of the away-side correlation at 180 degree. Since the Monte Carlo simulations show a strong near side correlation if the $J/\Psi$ is produced from $B$-meson decay [25, 41], these results can be used to constrain the $B$-meson contribution to $J/\Psi$ production. The contribution to the $J/\psi$-hadron correlation from $B$-meson decay was simulated with the same kinematic acceptance in PYTHIA events. If we attribute all the near-side excess to the $B$-meson feed-down as was done in UA1 [25, 41], we conclude that $B$-meson feed-down contributes
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Figure 4. (Color online) (a) High-\(p_T\) \(J/\psi\) in d+Au collisions from run8 (b) \(\Upsilon\) raw yields in d+Au collisions from run8.

\(\lesssim 17 \pm 3\%\) to the inclusive \(J/\Psi\) yields at \(p_T > 5\) GeV/c. A calculation of \(B\)-meson production based on pQCD [42] with the \(B \rightarrow J/\Psi + X\) decay form factor from CLEO measurements [43] shows that the fraction of \(J/\Psi\) from \(B\)-meson feed-down at high \(p_T\) is sensitive to the \(B\)-meson cross section and should contribute to the \(J/\Psi\) yields at the level of 20-40\%. Apart from a conclusion on the \(B\)-meson contribution of \(\lesssim 17\%\), this also means that \(J/\Psi\) are produced alone most of the time (\(\gtrsim 80\%\)) and is unlikely from jet fragmentation. This provides important information on \(J/\Psi\) production mechanism. Further correlation measurements of \(J/\Psi - \gamma\) with high statistics will provide the fraction of \(J/\Psi\) from \(\Xi_c\) decay. Future measurements of \(J/\Psi\) \(R_{AA}\) from Au+Au and p+p collisions with RHIC luminosity and detector upgrades are anticipated to provide a precision test on the \(p_T\) dependence of \(J/\Psi\) suppression [18, 44].

The STAR experiment already reported on the first RHIC measurement of the \(\Upsilon(1S + 2S + 3S)\) cross section at mid-rapidity in p+p collisions at \(\sqrt{s} = 200\) GeV [45]. The first ever measurements of \(\Upsilon\) mesons in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV are underway. We observe a stable signal, that will allow us to get first information on the nuclear modification factor of the \(\Upsilon\). This will be complemented by measurements in d+Au collisions taken in 2008. A clean signal with negligible background from d+Au collisions in run8 is shown in Fig. 4 together with the \(J/\Psi\) invariant mass distribution from the same run.

In summary, we reported the preliminary non-photonic electron results from run8 p+p collisions taken from a new TOF and TPC readout sector with low inner detector material budget at STAR. We also reported measurements of \(J/\Psi\) spectra in \(p + p\) and minimum bias Cu+Cu collisions from low \(p_T\) to high \(p_T\) at RHIC mid-rapidity through the dielectron channel. The high \(p_T\) \(J/\Psi\) production was found to follow the \(x_T\) scaling with a beam energy dependent factor \(\sim \sqrt{s_{NN}}^{5.6 \pm 0.2}\) while the low \(p_T\) \(J/\Psi\) fails the \(x_T\) scaling test. The average of \(J/\Psi\) nuclear modification factor \(R_{AA}\) at \(p_T > 5\) GeV/c is \(1.2 \pm 0.4\) (stat.) \(\pm 0.2\) (syst.) and is \(0.96 \pm 0.20 \pm 0.13\) when combined from all RHIC data. This is consistent with no \(J/\Psi\) suppression, and is about 2\(\sigma\) above the values at low \(p_T\).
measured by PHENIX [34]. We observed an absence of charged hadrons accompanying high $p_T$ $J/\Psi$ on the near side. The fraction of $J/\Psi$ from $B$-meson decay is found to be less than $17 \pm 3\%$ at $p_T > 5$ GeV/c.

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