A summary of the heavy flavor results from the STAR experiment is presented. Both open heavy flavor as well as quarkonia measurements are presented. A strong suppression of heavy flavor non-photonic electrons is observed in central Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV. Relative contribution of bottom contribution to non-photonic electron spectra in p+p collisions is extracted from data. Nuclear modification factor of $J/\Psi$ mesons at high-$p_T$ is found to be consistent with one in central Cu+Cu collisions at $\sqrt{s_{NN}} = 200$GeV. Strong signal of $\Upsilon(1S+2S+3S)$ state is observed in d+Au collisions at $\sqrt{s_{NN}} = 200$GeV.

1 Introduction

The calculation of Quantum Chromodynamics (QCD) on lattice showed that under conditions of high energy density or high temperature nuclear matter undergoes a phase transition from state of confined quarks and gluons to deconfined state the Quark-Gluon Plasma (QGP). Such conditions were present in first moments after the Big Bang in the early universe and can be created in laboratory by colliding of heavy ions with sufficient energy. The results from experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory provided plenty of information about this state of nuclear matter during recent years [1]. STAR measured a suppression of production of inclusive and also identified hadrons with high transverse momentum ($p_T$) in central Au+Au collisions at $\sqrt{s_{NN}} = 200$GeV [3]. This is generally understood as a result of energy loss of energetic light partons in nuclear matter. Heavy quarks are believed to be mostly created through gluon fusion in the initial phase of the collision and therefore they are well suited to provide and additional information about the parton energy loss and properties of QGP. Due to mass dependent suppression of gluon radiation under small angles, the dead-cone effect, it is expected that energy loss of heavy quarks when compared with light partons should be significantly reduced [4].

In following the STAR open heavy flavor and quarkonia measurements are discussed.

2 Open heavy flavor

Open heavy flavor can be measured either directly by reconstruction of heavy flavor mesons (open charm D, open beauty B) or indirectly by measurement of non-photonic electrons or muons from its semileptonic decays. Direct reconstruction of heavy flavor mesons at RHIC is challenging due to secondary vertex measurement limitation of current experiments. STAR [5] is able to reconstruct directly $D^0$ mesons in the hadronic channel $D^0 \rightarrow K^-\pi^+$ using the information from Time Projection Chamber (TPC). This has been performed in several

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collision systems at $\sqrt{s_{NN}}=200$ GeV: d+Au [6], Cu+Cu [8] and Au+Au [7]. The transverse momentum spectrum of $D^0$ mesons was extracted up to $p_T$ of 3 GeV/c. The charm cross sections were extracted by a combined fit of $D^0$ and non-photonic electron and muon spectra. A binary scaling of charm cross section was observed in agreement with expectation due to dominant charm production in hard scatterings [9]. STAR reported measurements of high-$p_T$ non-photonic electron production in p+p, d+Au, Au+Au [10] and Cu+Cu collisions [11] at $\sqrt{s_{NN}}=200$ GeV. For these measurements information from the TPC and the Electro-Magnetic Calorimeter (EMC) were used. The background contributions to the non-photonic electron spectrum from photonic sources, such as gamma conversions or $\pi^0$ Dalitz decays, are statistically subtracted. The EMC is also used in a trigger scheme during data taking to enhance the high-$p_T$ part of the electron spectrum. FONLL pQCD calculation predicts that from $p_T$ of 5 GeV/c, bottom decays contribute significantly to the non-photonic electron spectrum.

In Figure 1 the nuclear modification factor ($R_{AA}$) of non-photonic electrons is shown for d+Au and 5% most central Au+Au collisions. The $R_{AA}$ is the ratio of the yield measured in Au+Au to the yield from p+p collisions - each scaled by the mean number of binary collisions in the collision system. In a case of d+Au collisions, observed $R_{AA}$ is close to one with a possible small enhancement. However in the case of central Au+Au collisions a strong suppression by a factor of $\sim 5$ is observed. Note, that this is as strong as suppression of inclusive charged hadrons with $p_T > 6$ GeV/c (shaded area). The measured $R_{AA}$ is predicted in several models (see lines in Figure 1) [12-16]. In general, the models over-predict the observed suppression of non-photonic electrons when the parameters of models (e.g. $dN/dy$) are constrained by the suppression of light hadrons. Only if the contribution of bottom quarks is not taken into account, then the suppression is described well.
For further interpretation of the observed suppression it is crucial to address the contribution of bottom semileptonic electrons to measured non-photonic electrons spectra. A study of the azimuthal correlation functions between non-photonic electrons and hadrons was used to extract this information from data. Due to decay kinematics, there is a correlation between electrons and hadrons from semileptonic decays of charm and bottom mesons. Since the mass difference between charm and bottom mesons is large, there is also a large difference between the kinetic energy that mesons can give to the decay daughters. \( e_b/(e_b + e_d) \), the fraction of the total non-photonic electrons due to B-meson decay, is plotted in Figure 2. The measured value of the relative contribution of \( e_b/(e_b + e_d) \) is consistent with the FONLL predictions. This is an indication that the b-quark contribution should be taken into account in describing and interpreting the suppression of non-photonic electrons already at moderate \( p_T \).

3 Quarkonia measurements

The main question in quarkonia studies we would like to address is how, possibly formed, QGP influences the quarkonia yields. As result of the color Debye screening of the strong heavy quark interaction in dense nuclear matter, the binding energy of a bound quarkonium state decreases and it could lead to its disassociation. This would be manifested as suppression of quarkonia yields in heavy ion collisions when compared to p+p collisions. Since different quarkonia have different binding energy, they would disassociate at different temperature of QGP and therefore could be used as a thermometer.

The suppression of \( J/\Psi \) production was observed at the CERN SPS experiments. Surprisingly a suppression of similar strength was observed at RHIC for \( J/\Psi \) with \( p_T < 5 \text{ GeV}/c \) at mid-rapidity, although the energy density and temperature reached at RHIC are much higher than at the SPS. The suppression at RHIC at forward rapidity is stronger than at mid-rapidity. This indicated that additional mechanisms influence the observed \( J/\Psi \) yield, such as recombination, feeddown from higher charm states, feeddown from B mesons. The hot wind dissociation model predicts that effective dissociation temperature decreases with increasing \( J/\Psi \) velocity. Therefore the suppression is expected to be stronger at high \( p_T \).

Figure 3 shows the nuclear modification factor of \( J/\Psi \) in Cu+Cu collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). The solid line and band show the average and uncertainty of the two 0-20% data points. The curves are model calculations described in the text.
Figure 4: (Left) Measurement of $\Upsilon \rightarrow e^+e^-$ signal and background in $\sqrt{s_{NN}} = 200$GeV collisions. The solid symbols with statistical error bars are obtained by combining the unlike-sign ($e^+e^-$) pairs. The dashed histogram shows the like-sign background. (Right) The red star shows the measured $BR \times (d\sigma/dy)_{y=0}$ at midrapidity. The cross section is compared with the NLO CEM model prediction (blue solid circles), see text for details. The raw yields vs. $y$ are shown by the red histogram at the bottom with the statistical errors.

predicted $p_T$ dependence is contrary to the measured data. The dotted line represents calculations of the two component model [20]. This model includes $J/\Psi$ dissociation, statistical $c\bar{c}$ coalescence, formation time effects and B-meson feeddown. The model describes the overall trend of the data fairly well. The calculations represented by the solid and dash-dotted lines are based on models WHDG and GLV of charm energy loss. They qualitatively describe the heavy flavor suppression in Au+Au however predict strong $J/\Psi$ suppression for $p_T > 5$GeV/c, contrary to the data. These results may suggest that the high-$p_T$ $J/\Psi$ production is dominated by the color singlet channel.

Another quarkonium system studied in $e^+e^-$ channel in STAR is $\Upsilon$ meson. Lattice QCD calculations predict that $\Upsilon''$ melts at RHIC energies, $\Upsilon$ probably melts, however $\Upsilon$ state survives [21, 22]. STAR has employed two level $\Upsilon$ trigger during data taking and reported measurements in p+p [23] and Au+Au collisions [24].

During the RHIC run 2008 STAR measured d+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Due to removal of inner silicon detectors from the detector setup, lower background from $\gamma$ conversion electrons was present. Two levels of the STAR $\Upsilon$ trigger consist from hardware and software level. Only events with a BEMC tower with deposited energy above the threshold passed Level 0. After clustering of towers in the Level 2 conditions on opening angle, deposited energy and invariant mass of possible $\Upsilon$ candidates were required. Details of the analysis steps are presented in [25]. Figure 4 (left) shows unlike sign and like sign combination of electron-positron pairs. In the region of expected $\Upsilon$ signal (horizontal lines) very small background is populated. Strong signal $\Upsilon + \Upsilon' + \Upsilon''$ states of 8$\sigma$ significance and the integral count of 172 ± 20 (stat.) was obtained. The extracted value of the cross section to $e^+e^-$ channel is found as $BR \times (d\sigma/dy)_{y=0}^{1S+2S+3S} = 35 \pm 4$(stat.) ± 5(sys.)ub. at midrapidity in $\sqrt{s_{NN}} = 200$GeV d+Au collisions. Figure 4 (right) shows a comparison of the measurement with the Color Evaporation Model NLO pQCD calculation [24] including DIS 2009.
the anti-shadowing effect and no absorption. Using the STAR p+p measurement of cross section nuclear modification factor of $R_{dAu}=0.98 \pm 0.32\text{(stat.)} \pm 0.28\text{(sys.)}$ was found.

4 Conclusions

In this paper recent results of heavy flavor physics from the STAR collaboration at RHIC at $\sqrt{s_{NN}} = 200\text{GeV}$ energy were presented. The strong suppression of non-photonic electrons is observed in central Au+Au collisions. The inability of theoretical models to describe this satisfactorily raises the question about the mechanisms of energy loss of heavy quarks in nuclear matter. The relative contribution of bottom decays is an important factor in interpreting the measured data and was found to be consistent with FONLL pQCD predictions. Measurement of $J/\Psi$ production in central Cu+Cu collisions revealed that at high-$p_T$ the spectra are consistent with no suppression. This is in contrary with theoretical expectations. The measurement of $\Upsilon$ production at mid-rapidity in d+Au collisions was reported. The production cross section is consistent with the NLO calculations.

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