Heavy Flavor Physics in STAR

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Abstract. In relativistic heavy–ion collisions at RHIC, heavy quarks are primarily created from initial hard scatterings. Since their large masses are not easily affected by the strong interaction with QCD medium they may carry information from the system at early stage. The interaction between heavy quarks and the medium is sensitive to the medium dynamics; therefore heavy quarks are suggested as an ideal probe to quantify the properties of the strongly interacting QCD matter. The STAR Collaboration should complete the Heavy Flavor Tracker (HFT) and the Muon Telescope Detector (MTD) upgrades by 2014. These detectors will greatly enhance the STAR physics capability to measure heavy quark collectivity and correlations using topologically reconstructed charmed hadrons and heavy quark decay electron-muon correlations. In addition, measurements of the quarkonium muon decay channels will enable us to separate Upsilon 1S from 2S and 3S states in \( p + p \) and A+A collisions. Selected STAR results on open charm and quarkonia production in \( p + p \) and Au+Au collisions at 200 GeV are presented. An overview of the upgrades, their expected performance and current status is presented.

1. Introduction
In high–energy collisions at RHIC, heavy quarks (c, b) are expected to be created from initial hard scatterings [1] and the relative changes in their masses are small by the strong interactions with the QCD medium. Thus they carry clean information from the system at the early stage. The interaction between heavy quarks and the medium is sensitive to the medium dynamics, therefore heavy quarks are suggested as an ideal probe to quantify the properties of the strongly interacting QCD matter [2]. STAR has embarked on a Heavy Flavor program in \( p + p \), \( d + Au \) and A+A collisions at RHIC using existing detectors systems. In order to fully exploit this physics sector upgrades are needed. In this paper I will present selected results obtained so far, and will give an overview of the two upgrades that addresses heavy flavor physics, and their expected performance.

2. STAR Experiment
The data presented in this proceeding were collected with the Solenoidal Tracker at RHIC (STAR) detector[3]. The main detector subsystems used for these analyses are the large cylindrical time projection chamber (TPC), which is able to track charged particles in the pseudo-rapidity range \( |\eta| < 1.1 \) with full azimuthal coverage, time of flight (TOF) which significantly provides charged hadrons identification over a wide \( p_T \) range, and barrel electromagnetic calorimeter (BEMC) being able to trigger on high-\( p_T \) particles and improving electron-hadron separation. Both TOF and BEMC subsystems provide full azimuthal coverage as TPC, but slightly reduced pseudo-rapidity range. The Solenoid has a uniform magnetic field of 0.5 T along the beamline.
3. Open heavy flavor

STAR has begun measurements of open heavy flavor though the decay channel of $D^0 \to \pi K$ and $D^* \to D^0 \pi$ in both $p+p$ and $Au+Au$ collisions. The $p+p$ results have been submitted[4], and the $Au+Au$ has been reported in [5, 6]. Here we report on a few selected results from STAR.

![Figure 1.](image1.png) **Figure 1.** $D^0$ signal in $p+p$ 200 GeV collisions after background subtraction using two different methods. Background estimated from track rotation is used in the left panel, and unlike sign subtraction in the right panel. The red line is the background fit to the residual background. The signal after a residual background is subtracted is shown by the red points.

![Figure 2.](image2.png) **Figure 2.** $D^*$ signal in $p+p$ 200 GeV collisions. Combinatorial background is reproduced by the distributions from the wrong-sign (black dotted) and side-band (blue solid) methods.

The analysis is based on 105 million $p+p$ minimum bias events collected at STAR in the year 2009 and 280 million $Au+Au$ minimum bias events from year 2010. This analysis used TPC, which provides the information of particle momentum and ionization energy loss (dE/dx) covering the full $2\pi$ azimuthal angle at $|\eta|<1$, and TOF, which covered 72% in 2009 and 100% in 2010 in azimuth. The decay daughter ($K\pi$) identification was greatly improved by a combination of TPC dE/dx and TOF measured particle velocity. The $D^0$ was reconstructed via $K\pi$ invariant mass. The same-sign and mix-event background subtraction in $p+p$ and $Au+Au$ collisions, respectively, followed the same analysis techniques as previous analysis [7]. In Fig. 1 examples of $D^0$ signals are shown as open circles in $p+p$ for 0.6 < $p_T$ < 2.0 GeV/c collisions in two different background subtraction methods. The signal and the residual backgrounds shown as the filled circles are described by a Gaussian plus second-order polynomial function. $D^*$ ($2.0 < p_T < 6.0$ GeV/c) was reconstructed via a mass difference between $D^0\pi$ and $D^0$ in $p+p$ collisions based on the analysis techniques in [7]. The combinatorial background is reproduced by the distributions from the wrong-sign and side-band methods (see Fig. 2).

The full efficiency and acceptance corrected charm pair differential production cross section at mid-rapidity in 200 GeV $p+p$ collisions is shown in the left panel of Fig. 3 and compared with fixed-order next-to-leading Logarithm (FONLL) calculations (dashed curve) [9]. The data agree with the FONLL upper bound. $D^0$ (triangles) and $D^*$ (circles) are scaled by the charm fragmentation ratios. The charm production cross section at mid-rapidity in 200 GeV $p+p$ collisions was extracted from a power-law function fit (solid curve), as $170 \pm 45$ (stat.) $+38/-59$ (sys.) $\mu$b. The dominant systematic uncertainties are from $D^0$ background subtraction and the raw yield extraction.

A similar technique[8] was applied to obtain the $D^0$ invariant $p_T$ distributions in 0-80% minimum–bias $Au+Au$ collisions. The charm production cross section per nucleon-nucleon
collision at mid-rapidity in 200 GeV Au+Au collisions was extracted from the average of a power-law fit, as $186 \pm 22$ (stat.) $\pm 30$ (sys.) $\pm 18$ (normalization) $\mu b$, assuming that the ratio of $D^0$ to the number of $c\bar{c}$ pair does not change from $p+p$ to Au+Au collisions. The charm cross section for three centrality bins, 0-20%, 20-50% and 50-80% is obtained according to the integrated yields. The charm production cross section per nucleon–nucleon collision at mid-rapidity as a function of $N_{bin}$ is shown in the right panel of Fig. 4. The results for $p+p$, d+Au [8] and Au+Au 0-80% minimum bias collisions are shown as a circle, a triangle and a star, respectively. The squares show the results from the three centrality bins. Within errors, the results are in agreement and follow the number of binary collision scalings, which indicates that the charm quark is produced via initial hard scatterings at early stage of the collisions at RHIC. The FONLL (orange band) and NLO (solid lines) $1\sigma$ uncertainties are also shown here for comparison. The PHENIX result for $p+P$ is consistent with the STAR measurements.

![Figure 3](image1.png)

**Figure 3.** Invariant cross section of charm production vs. $p_T$ at mid–rapidity in $p+p$ collisions at 200 GeV.

![Figure 4](image2.png)

**Figure 4.** Charm cross production per nucleon–nucleon collision at mid-rapidity as function of $N_{bin}$

4. Heavy Quarkonium

STAR has measured Upsilon production in the $e^+e^-$ channel in $p+p$, d+Au, and Au+Au at $\sqrt{s_{NN}} = 200$GeV. For details on the analysis see [10]. We reconstruct Upsilon candidates by measurements of unlike–sign pairs of identified electrons. The total unlike–sign signal is composed of four main parts: a combinatorial background, Drell–Yan production, correlated $b\bar{b}$ pairs, and $T(1S + 2S + 3S) \rightarrow e^+e^-$. The combinatorial background is modeled by looking at like-sign (same charge) pairs of identified electrons. The shape of the Drell–Yan signal is obtained from PYTHIA simulations. The $b\bar{b}$ background is obtained from pQCD calculation by R. Vogt [11]. The shape of the Upsilon signal comes mainly from detector effects such as bremsstrahlung radiation, momentum resolution and trigger bias. It is obtained via embedding PYTHIA simulations into our detector model and real data. In Fig. 5 the invariant spectrum for electron pairs is shown for $p+p$ at 200 GeV. The yield is extracted from a combined fit using the combinatorial background and the knowledge of the Drell–Yan signal shape.

The measurements in Au+Au were divided into into three centrality bins: 0–10%, 10–30%, and 30–60%. Using the 2009 $p+p$ measurement as the baseline, we calculate $R_{AA}$ for the three
centrality bins (see Fig. 6). The results are compared to a model by Strickland et al. [12], which incorporates lattice-based QCD calculations with a hydrodynamic model of expansion and cooling. Two different forms of the potential are shown. The data show better agreement with the Internal Energy-based potential. In this model, in central collisions, the Υ(3S) is almost completely suppressed, \( R_{AA}(2S) \approx 0.2 \), and \( R_{AA}(1S) \approx 0.4 - 0.7 \). The incomplete suppression is due to differential temperatures in the plasma between the hot core and cooler corona.

5. The Muon Telescope Detector upgrade

The MTD upgrade is aimed at addressing properties of the QGP through measurements of quarkonia, and by di-lepton measurements in the intermediate mass range. Measurements of \( c\bar{c} \) correlations will still be challenging if not impossible, but can be approached through \( \mu-e \) correlations, to measure the contribution from heavy flavor correlations to the di-electron or di-muon continuum.

The MTD, based on Multi-gap Resistive Plate Chamber with long read-out strips (LMRPC), covers 45% in azimuth and \(|\eta| < 0.5 \) in pseudo-rapidity behind the return iron bars for the STAR magnet. Figure 7 shows the location of a single MTD tray behind the magnet iron bars. The full proposal with physics motivation and technical description can be found in [13]. The MTD is based on the same detector and electronics technologies as the recently installed TOF system in STAR [14]. Several prototypes have been tested successfully over the years [15].

The LMRPC module has five gas gaps arranged in a single stack as shown schematically in Fig. 8. The thickness of each gap is 250 µm and is defined using nylon monofilament fishing line. Float glass sheets of 0.7 mm thickness and a volume resistivity of \( \sim 10^{13} \text{Ω-cm} \) are used as the resistive plates. The active area of each LMRPC, defined by the inner glass stack, is
Figure 7. Position of a MTD tray outside the STAR magnet back legs. All the trays will be at this position at 400 cm radius.

Figure 8. End view of a LMRPC module.

87 × 52 cm². The read-out pads are segmented into 12 double-ended strips which are 3.8 cm wide. There is a 6 mm gap between each strip. Twisted-pair cables bring the differential signals from each end of each strip to the front-end electronics. The LMRPC modules are enclosed in a gas-tight aluminum box that is filled with a mixture of 95% Freon R–134a and 5% isobutane.

The primary mechanical structure of the MTD system is a “tray”. Each is a simple aluminum box built using off-the-shelf raw materials. Each tray holds the detectors in three dimensions at a specific position in STAR, provides the mount points for the on-detector electronics, and forms the leakless gas volume.

The expected performance of the MTD is presented. The projected invariant mass spectrum for $J/\Psi$ and $\Upsilon(1S+2S+3S)$ are shown in Fig. 9 as it can be achieved in RHIC d+Au run at 200 GeV. Figure 10 shows the precision projections for $\mu-e$ invariant mass distribution and azimuthal angular correlation from charm correlation contribution from simulation in d+Au.
Figure 9. The expected di-muon invariant mass distribution from $J/\psi$ and background in d+Au collisions (top panel); the invariant mass distribution of di-muon decayed from $\Upsilon$ at $0<p_T<5$ GeV/c (bottom panel). The different $\Upsilon$ states can be separated. The equivalent $p+p$ luminosity is also shown in the figure.

Figure 10. The expected electron-muon correlation from charm pair production and from random background in d+Au collisions. The statistics shown are equivalent to 2 billion minimum bias d+Au collisions.

collisions at $\sqrt{s_{NN}} = 200$ GeV. The black curve is from combinatorical random background, which can be further reduced by additional cuts (dashed curve).

6. The Heavy Flavor Tracker upgrade

The Heavy Flavor Tracker (HFT) is a state-of-the-art micro-vertex detector utilizing active pixel sensors and silicon strip technology. The HFT will significantly extend the physics reach of the STAR experiment for precision measurements of the yields and spectra of particles containing heavy quarks. This will be accomplished through topological identification of mesons and baryons containing charm quarks, such as $D^0$ and $\Lambda_c$, by the reconstruction of their displaced decay vertices with a precision of better than 20 $\mu$m at high $p_T$ in $p+p$, d+Au, and A+A collisions. The combined measurements of directly identified charm hadrons and of the total non-photonic electrons will enable the measurement of bottom production at RHIC, including the bottom production cross section, the nuclear modification factor and the collectivity of the decay electrons.

The HFT consists of 4 layers of silicon detectors grouped into three subsystems with different technologies, guaranteeing increasing resolution when tracking from the TPC towards the vertex of the collision. The Silicon Strip Detector (SSD) is an existing detector in double-sided strip technology. It forms the outermost layer of the HFT. The Intermediate Silicon Tracker (IST), consisting of a layer of single-sided strip-pixel detectors, is located inside the SSD. Two layers of silicon pixel detector (PXL) are inside the IST. A cutout of the arrangement within STAR is shown in Fig. 11. The pixel detectors have the resolution necessary for a precision measurement
Figure 11. Cutout view of the inside of the STAR detector and TPC. The position of the 3 detector systems are indicated.

Figure 12. Expanded view of one half of the PXL sub-system. The active sensors are indicated by blue. The 5 supporting sectors are made of thin carbon fiber. The sector are mounted on the D–tubes, and can be retracted and inserted during a one day opening.

of the displaced vertex.

The PXL detector is a low mass detector that will be located very close to the beam pipe. It consists of two layers of silicon pixel detectors, one layer at 2.5 cm average radius and the other at 8.0 cm average radius. The PXL has a total of 40 ladders, 10 in the inner layer and 30 in the outer layer. Each ladder contains a row of 10 monolithic CMOS detector chips and each ladder has an active area of $\sim 20 \text{ cm} \times \sim 1.92 \text{ cm}$. The CMOS chips contain a $\sim 1000 \times \sim 1000$ array of 18 µm square pixels and will be thinned down to a thickness of 50 µm to minimize multiple coulomb scattering in the detector. The effective thickness of each ladder is 0.4% of a radiation length. A blowup of the PXL sectors for half the detector is shown in Fig. 12. It is supported by an innovative insertion mechanism that allows for rapid access to the PXL layers (order 8 hours) during RHIC runs. The IST consists of a barrel of approximately 0.4 m$^2$ of silicon pad sensors at a radius of 14 cm and a length of 58 cm and is $\sim 1.2\%$ of an radiation length. The sensors are supported by 24 carbon fiber ladders, which are tiled for maximum hermiticity. It is read out using the APV25-S1 chips. The outermost layer consist of the existing SSD detector with upgraded read-out electronics. The high resolution of the PXL layers coupled with the small radiation length should result in very good DCA resolution for low-momentum particles. For the low $p_T$ $D^0$ the typical kaon momentum in the decay is 750 MeV/c and we expect 45µm DCA resolution in both $r\phi$ and $z$ for that momentum.

Since flow is a hydrodynamic phenomenon, the low $p_T$ region is most relevant for studies of collectivity. Generally, data and hydro predictions agree up to about 1.5 GeV/c $p_T$, beyond which point data deviate from the hydro prediction. In Fig. 13 we present the precision of a $v_2$ measurement for $D^0$ that can be achieved within the first year of Au+Au data taking with the HFT by analyzing 500 million minimum bias events. The red and green lines represent the results from model calculations based on a coalescence assumption. The red line assumes that charm quarks have the same flow strength as the light quarks, whereas the green line assumes that charm quarks do not flow. The error bars of the data points on the red and green lines represent the statistical errors the HFT measurement will have, assuming that the production...
follows either line. The blue (dotted) line shows the low \( p_T \) hydro prediction for the \( D^0 \) mass and the purple line represents the charged hadron \( v_2 \) measured by STAR.

The energy loss of heavy quarks is predicted to be significantly less compared to light quarks because of a suppression of gluon radiation at angles \( \Theta < M_Q / E \), where \( M_Q \) is the heavy quark mass and \( E \) is the heavy quark energy. This kinematic effect is known as the dead cone effect. However, a recent measurement of the nuclear modification factor, \( R_{AA} \), for non–photonic electrons, the products of charm and bottom hadron decay, yielded the surprising result that heavy quarks may also be strongly suppressed in the medium. In order to make progress in understanding the nature of the energy loss mechanism, it is important to measure \( R_{AA} \) or \( R_{CP} \) for topologically reconstructed \( D \) mesons. Figure 14 shows the expected precision for \( R_{CP} \) for \( D^0 \) mesons that can be achieved with 500 M minimum–bias events in STAR with the HFT under the assumption that the suppression for heavy quarks is of the same size as the suppression for the light quarks.

**Figure 13.** Elliptic flow \((v_2)\) as a function of \( p_T \) in Au+Au collisions at 200 GeV. The red and the green curves show calculations for the limiting cases that the charm quark flows like the light quarks and that the charm quark does not flow in a coalescence model. The error bars of the data points represent the statistical errors the HFT measurements will achieve. The purple curve shows the measured \( v_2 \) value for charged hadrons.

**Figure 14.** Expected errors for the \( R_{CP} \) measurement as a function of \( p_T \).

### 7. Status of Upgrades

The MTD construction, to be completed in 2014, has started. In 2012 10% of the MTD was installed at STAR that worked nicely with smooth data taking. In 2013 up to 60% of MTD will be installed and hope to get a few weeks of Au+Au run at 200 GeV for the \( \mu - e \) measurement. The project is a capital detector improvement with significant contributions to the LMRPC construction from University of Science & Technology of China, Hefei, Tsinghua University and Variable Energy Cyclotron Centre, Kolkata.

The Heavy Flavor Tracker was proposed in 2008, and approved as a DOE Nuclear Physics MIE in 2009. It received CD2/3 approval in October 2011 and is fully funded. Significant R&D for the PXL CMOS sensors has taken place at LBL and IPHC, Strasbourg for many years.
Prototype PXL sensors is planned to be installed for an engineering run in 2013, and the full complement of detectors should be in place for the RHIC Run–14.

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References
[1] Lin Z and Gyulassy, M 1995 Phys. Rev. C {51} 2177; Erratum, ibid. C 52, 440 (1995).
[2] Mueller B 2005 Nucl. Phys. A {750} 84
[3] Ackermann K.H. et al [STAR Collaboration] 2003 Nucl. Instrum. Methods A {499} 624
[4] Adamczyk L et al [STAR Collaboration] 2012 arXiv:1204.4244 (nucl-ex)
[5] Zhang Y [for the STAR collaboration] 2011 J.Phys.G {38} 124142
[6] Tlusty D [for the STAR collaboration] 2012 arXiv:1208.0057 (nucl-ex)
[7] Adams J et al [STAR collaboration] 2009 Phys.Rev.D {79} 112006
[8] Abelev B et al [STAR Collaboration] 2005 Phys.Rev.Lett. {94} 062301
[9] Vogt R Eur.Phys.J.ST {155} 213, (2008).
[10] Kesich A [for the STAR collaboration] 2012 arXiv:1207.7166 (nucl-ex)
[11] Vogt R private communication
[12] Strickland M and Bazow D 2012 arXiv:1112.2761
[13] STAR Muon Telescope Detector Proposal: http://www.star.bnl.gov/~ruanj/MTDreview2010/MTD_proposal_v14.pdf.
[14] STAR Time-of-Flight Proposal: http://www.star.bnl.gov/STAR/tof/publications/TOF_20040524.pdf.
[15] Ruan L et al 2009 Journal Phys.G {36} 095001