PHENIX MEASUREMENTS OF HEAVY FLAVOR PRODUCTION AND SPIN ASYMMETRIES IN $p+p$ COLLISIONS AT RHIC

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Transverse single-spin asymmetries observed in $p+p$ collisions give valuable information on the spin structure of the nucleon. At RHIC energies, heavy flavor production is dominated by gluon-gluon fusion and the transverse single-spin asymmetry is sensitive to the twist-3, tri-gluon correlations in the collinear QCD factorization scheme. The PHENIX experiment has performed measurements of the cross section and transverse single-spin asymmetries of μ^- and μ^+ production from semi-leptonic decays of heavy mesons in transversely polarized $p+p$ collisions at $\sqrt{s} = 200$ GeV during the 2012 RHIC run. Results of these measurements will be compared to model calculations for D meson production.

1 Motivation

The topic of Transverse Single Spin Asymmetries (TSSAs) have generated substantial interest due to the observation of large asymmetries in the production of light mesons at forward rapidity in transversely polarized $p+p$ collisions at a wide range of energies from the Zero Gradient Synchrotron up to the Relativistic Heavy Ion Collider (RHIC). To explain the origin of large TSSAs at forward rapidity, two formalisms have been proposed within perturbative QCD framework. Both formalisms connect the transverse motion of the parton inside the nucleon and/or to the spin-dependent quark fragmentation. The transverse-momentum-dependent framework requires two momentum scales, and so is applicable to W, DY, and Z production in $p+p$ collisions at RHIC. On the other hand, the collinear factorization framework needs only one scale (Q^2 or p_T), and is applicable to many observables, such as π^0, γ, jet, heavy flavor in $p+p$ collisions at RHIC [1,2]. Heavy flavor production is a great tool for investigating the gluon distribution in the proton; especially the effect of pure gluonic correlation functions on D meson production in transversely polarized $p+p$ is studied extensively as a twist-3 observable in the collinear factorization framework [3]. It has been difficult to constrain the tri-gluon correlation functions for lack of experimental results.

2 Experimental Setup

RHIC at Brookhaven National Laboratory is unique, as the only polarized p+p collider. As many as 120 bunches are accelerated up to an energy of 255 GeV per proton in two countercirculating storage rings with a 106 ns separation. The beam injected into each ring in the 2012 run typically comprises 109 filled bunches. During the $\sqrt{s} = 200$ GeV run in 2012, two transversely polarized bunches are collided with average polarization $P = 0.64 \pm 0.03$ for the counterclockwise-beam and $P = 0.59 \pm 0.03$ for the clockwise-beam. The integrated luminosity is 9.2 pb^{-1}. The PHENIX experiment has two muon arms at forward and backward rapiditiy as shown in Figure 1. Full azimuthal angles are covered in the pseudorapidity range $-2.2 < \eta < -1.2$ (south arm) and $1.2 < \eta < 2.4$ (north arm). Copper-and-iron and steel absorbers in front of the muon arm help to suppress charged pions and kaons. Each muon arm has a muon tracker (MuTr) which consists of three stations of cathode strip chamber to measure momentum, and muon identifier (MuID) which is composed of 5 layers of proportional tube planes and absorber for muon identification.

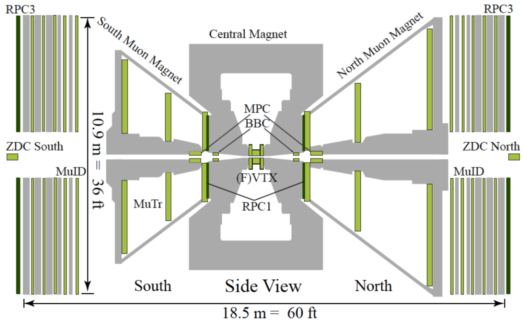

Figure 1 – Side view of the PHENIX muon ams in the 2012 run

3 Data Analysis and Results

The same method as in previous studies of muons from open heavy-flavor decays in the PHENIX experiment is used in this analysis [5,6]. A track is chosen as a good muon candidate when it penetrates through all the MuID gaps with track quality cuts. Charged pions and charged kaons are the primary sources of background. Initial particle distributions for the hadron-cocktail simulation are estimated from measurements of charged pions and kaons at midrapidity [8,9] and the PYTHIA event generator. Muons from $\pi^{\pm}$, $K^{\pm}$ decays in front of the absorber are dominant at $p_T < 5$ GeV/c. The normalized z_{vtx} distribution of tracks (dN_{μ}/dz_{vtx}) gives constraints on decay muon background. The number of produced decay muons is proportional to the flight length before reaching the absorber. Tracks stopped at MuID Gap3, providing a light hadron sample with proper p_z cut are used for punch-through hadron estimation. Muons from J/ψ decays are estimated from the invariant cross section in the forward region [7]. The left side of Figure 2 [4] shows the p_T spectra of inclusive muon candidates and background sources. The cross section and comparison to FONLL calculation are shown on the right side of Figure 2 [4]. The agreement between the data and the FONLL prediction becomes better with increasing p_T.

The transverse single spin asymmetry (A_N) is defined as

$$A_N(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}. \quad (1)$$

In this measurement, the unbinned maximum likelihood method is used to prevent bias by low statistics bins. The logarithmic form of likelihood function is

$$\log \mathcal{L} = \sum \log(1 + P \cdot A_N \sin(\phi_{\rm pol} - \phi_i)), \quad (2)$$

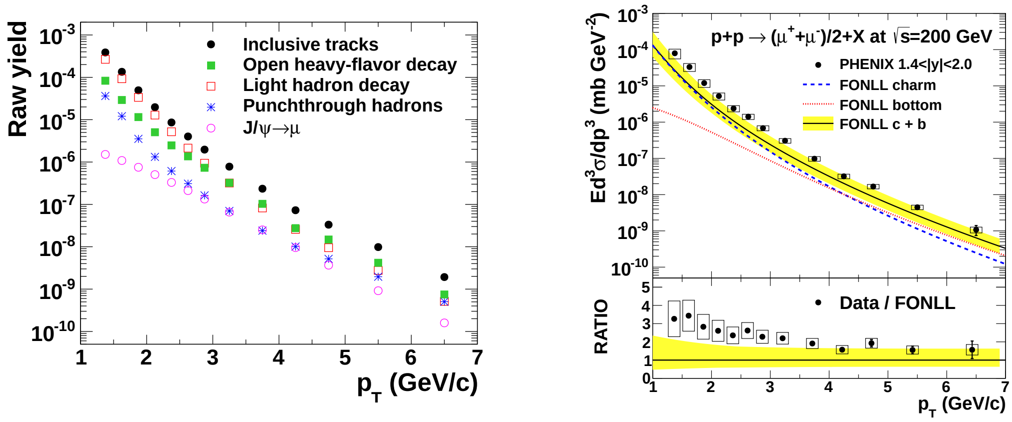

Figure 2 – p_T spectra of inclusive muon candidates and background sources from the hadron-cocktail simulation (left) and charge-combined, invariant cross section of muons from open heavy-flavor decays as a function of p_T in $p+p$ collisions at $\sqrt{s} = 200$ GeV at forward rapidity (right) [4]. The solid line and band are the FONLL calculation for charm and bottom and systematic uncertainty. Contributions from charm and bottom are shown separately by dashed and dotted curves. The ratio between the data and the FONLL calculation is shown (right bottom). Vertical lines (boxes) represent statistical (systematic) uncertainties of the data.

where P is the polarization, $\phi_{\rm pol}$ is the direction of beam polarization ($+\frac{\pi}{2}$ or $-\frac{\pi}{2}$), and ϕ_i is the azimuthal angle of each track in the PHENIX lab frame. The statistical uncertainty of the log-likelihood estimator is related to its second derivative,

$$\sigma^2(A_N) = (-\frac{\partial^2 \mathcal{L}}{\partial A_N^2})^{-1}. \tag{3}$$

The A_N of muons from open heavy-flavor decays and uncertainty are obtained as

$$A_N^{\rm HF} = \frac{A_N^{\rm incl} - f_{\rm h} \cdot A_N^{\rm h} - f_{J/\psi} \cdot A_N^{J/\psi \to \mu}}{1 - f_{\rm h} - f_{J/\psi}}, \tag{4}$$

$$\delta A_N^{\rm HF} = \frac{\sqrt{(\delta A_N^{\rm incl})^2 + f_{\rm h}^2 \cdot (\delta A_N^{\rm h})^2 + f_{J/\psi}^2 \cdot (\delta A_N^{J/\psi \to \mu})^2}}{1 - f_{\rm h} - f_{J/\psi}}. \tag{5}$$

where the $A_N^{\rm incl}$ is measured A_N of inclusive muon candidates at MuID Gap4. The $A_N^{\rm h}$ from MuID Gap3 tracks is the A_N of light hadron background. $A_N^{J/\psi \to \mu}$ is calculated by decay simulation combined with previous $A_N^{J/\psi}$ measurement in PHENIX [10]. $f_{\rm h} = (N_{\rm DM} + N_{\rm PH})/N_{\rm incl}$ is the fraction of the light-hadron background, and $f_{J/\psi} = N_{J/\psi \to \mu}/N_{\rm incl}$ is the fraction of muons from J/ψ. Both fractions ($f_{\rm h}$ and $f_{J/\psi}$) are determined from the background estimation described above.

Figure 3 shows the A_N of negatively- ($A_N^{\mu^-}$) and positively- ($A_N^{\mu^+}$) charged muons from open heavy-flavor decays as a function of p_T in the forward ($x_F > 0$) and backward ($x_F < 0$) regions with respect to the polarized-proton beam direction. Figure 4 shows the A_N versus x_F of muons from open heavy-flavor decays. A recent theoretical calculation [3] in the collinear factorization framework predicts A_N in the production of D-mesons (A_N^D) produced by the gluon-fusion ($gg \to c\bar{c}$) process, so that it is sensitive to the tri-gluon correlation functions which depend on the momentum fraction of the gluon in the proton. Two model calculations, assuming either a linear x-dependence or a $\sqrt{x}$-dependence for the non-perturbative functions in the twist-3 cross section for A_N^D are introduced to compare their behavior in the small-x region, and the overall A_N^D scale is determined with the assumption $|A_N^D| \leq 0.05$ at $|x_F| < 0.1$. To compare the A_N^μ result with A_N^D, a simulation is performed with the decay kinematics and cross section of $D \to \mu$ determined from PYTHIA. The results are consistent with zero within the total uncertainty and generally agree with the asymmetry expected in the twist-3 model calculation.

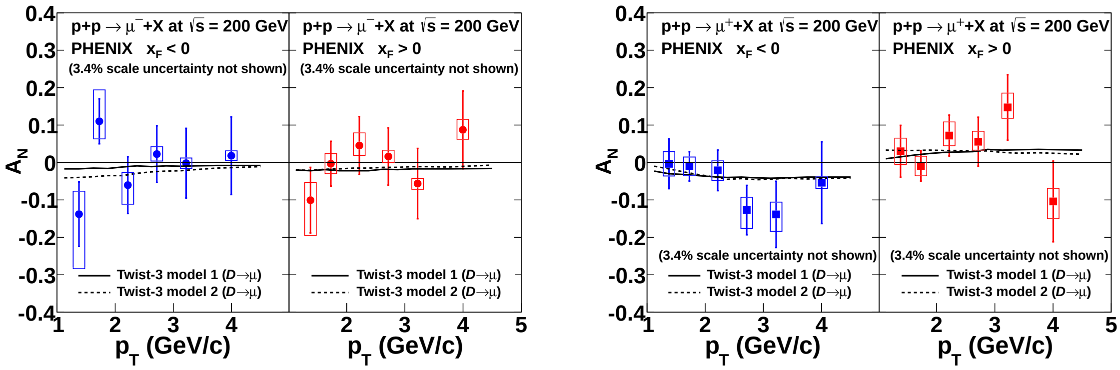

Figure 3 – A_N of negatively-charged (left) and positively-charged (right) muons from open heavy-flavor decays as a function of p_T in the backward ($x_F < 0$) and forward ($x_F > 0$) regions. Vertical bars (boxes) represent statistical (systematic) uncertainties [4]. Solid and dashed lines represent twist-3 model calculations [3]

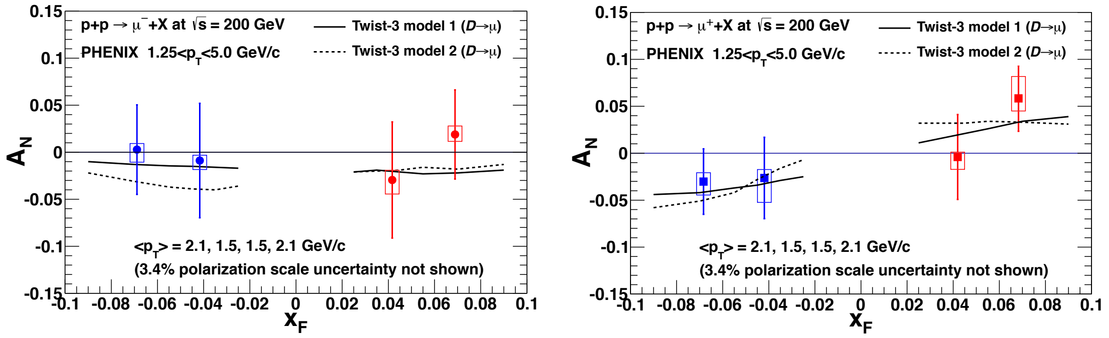

Figure 4 – A_N of negatively-charged (left) and positively-charged (right) muons from open heavy-flavor decays as a function of x_F for 1.25 GeV/c < p_T^{μ} < 5.0 GeV/c. Vertical bars (boxes) represent statistical (systematic) uncertainties [4]. Solid and dashed lines represent twist-3 model calculations [3]

4 Summary

The cross section and transverse single-spin asymmetry of muons from open heavy-flavor decays at $1.4 < |y| < 2.0$ in transversely polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV were measured by PHENIX. The transverse single spin asymmetry results show no clear indication of nonzero asymmetry within uncertainties. Simulation is done to compare A_N of D meson in the twist-3 prediction and the measured A_N of muons from open heavy-flavor decays. The results generally agree with the twist-3 prediction in the collinear factorization framework. Future study using the RHIC 2015 data with improved statistics can provide more constraints on the tri-gluon correlation functions. Also, polarized p+A(Au,Al) data in 2015 will be interesting.

References

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