Transverse-Spin Drell-Yan Physics at RHIC

April 29, 2007 (Draft)

Abstract

We describe the science case and opportunities for future dedicated studies on the single-transverse spin asymmetry in the Drell-Yan process at RHIC. Our goal is to bring this exciting opportunity for the RHIC spin program to the attention of the Long Range Plan process, and to initiate preparations toward developing a proposal.

Authors

Les Bland, Gerry Bunce, Ming Liu, Matthias Grosse-Perdekamp, Akio Ogawa, Werner Vogelsang, Feng Yuan

1 Introduction

A fundamental property of Quantum Chromodynamics (QCD) is its asymptotic freedom at short distances. This is the regime where QCD has been subjected to the most stringent tests, and where it has been established as our theory of the strong interactions. Thanks to asymptotic freedom, it is often possible to use QCD perturbation theory in treating the interactions of quarks and gluons that occur in high-energy hadronic processes. For many QCD observables at large momentum transfer, short-distance and long-distance phenomena may be separated to leading power in the momentum transfer. This is known as *factorization*. Hadronic cross sections become products of parton (quark and gluon) distribution functions and partonic hard-scattering cross sections. The former contain long-distance information on the structure of the proton, while the latter only depend on the large momentum transfer and are hence amenable to QCD perturbation theory. Measurements of the cross sections, when combined with perturbative calculations of the partonic hard-scattering cross sections, will therefore give insights into the structure of the proton. Usually, the parton distribution functions are universal, in the sense that for example the same parton distributions of a proton will appear in any hard-scattering process in which a proton participates. Much of what we know today about the inner structure of the nucleon is based on this approach, which is a cornerstone for the ongoing and future programs in high-energy nuclear and hadronic physics.

Over the past few years, theorists have studied a class of parton distribution functions that may be accessed in spin asymmetries for hard-scattering reactions involving a transversely polarized proton. These distributions, known as “Sivers functions” [1], express a correlation between a parton’s transverse momentum inside the proton, and the proton spin vector. As such they contain information on orbital motion of partons in the proton. It was found that the Sivers functions are not universal in hard-scattering reactions. This by itself is nothing spectacular; however, closer theoretical studies have shown that the non-universality has a clear physical origin that may broadly be described as a rescattering of the struck parton in the color field of the remnant of the polarized proton [2, 3, 4, 5]. Depending on the process, the associated color Lorentz forces will act in different ways on the parton. In deep-inelastic scattering (DIS), the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it becomes an initial-state interaction and is repulsive. As a result, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes [2, 3, 4, 5]. This is a fundamental QCD prediction, directly rooted in the quantum nature of the interactions. It tests *all* concepts for analyzing hard-scattering reactions that we know of. Its verification will be a milestone for the field of hadronic physics and is the motivation for this paper.

Sivers-type single-spin asymmetries have been observed in semi-inclusive DIS at HERMES [6] and COMPASS [7]. Equipped with the resulting information on the Sivers functions, it is now crucial to investigate the spin asymmetry in the Drell-Yan process. This has become a top priority for the world-wide hadronic physics community for the coming decade. The present paper will show that RHIC offers extremely favorable possibilities for studies of Drell-Yan transverse-spin asymmetries.

2 Physics Case

Studies of single-transverse spin asymmetries A_N have a long history, starting from the 1970s and 1980s when large "left-right" asymmetries were observed in hadronic reactions like $p^{\uparrow}p \to \pi X$ at forward angles of the produced pion [8]. Measurements at RHIC [9, 10] have shown over the past few years that large asymmetries in forward single-inclusive hadron production also persist to very high energies. It was known early on [11] that in single-inclusive processes, A_N is suppressed by an inverse power of the pion's transverse momentum, so that simple parton-model estimates would predict nearly vanishing asymmetries. The large size of the observed asymmetries therefore posed a challenge for theorists. Among various possible explanations that were subsequently proposed and investigated, were correlations between the transverse momentum of a struck quark in the proton and the transverse proton spin, represented by novel parton distribution functions, the "Sivers functions" [1]. The spin asymmetries were suggested to arise from the directional preference expressed by this correlation. The Sivers functions thus extend the set of "ordinary" Feynman parton distributions which only depend on a parton's light-cone momentum fraction. While the precise role of the Sivers functions for hadronic hard processes and their factorization remained yet to be understood, it was clear that the functions would contain valuable information about the nucleon, because the correlations they represent would be closely related to orbital angular momenta of partons in the proton.

Significant theoretical progress on single-spin asymmetries and the Sivers functions has been made in recent years. A breakthrough was the realization [2, 12, 13] that there is a class of single-spin observables in QCD that are not suppressed by an inverse power of the hard scale. These asymmetries are characterized by a large momentum scale Q (for example, the virtuality of the photon in DIS) and by a much smaller, and also measured, transverse momentum $q_{\perp}$. This allows a direct probe of the partons' transverse momenta in the nucleon. For some observables, rigorous QCD factorization theorems have been established [14, 15, 16] which relate the spin-dependent cross sections to parton distribution functions not integrated over the transverse momenta of the partons, among them the Sivers functions. This opened the door to clean experimental access to the Sivers functions. The "leading-twist" Sivers single-spin asymmetries emerging in this way have been studied experimentally over the past few years in DIS [6, 7], and there are now quite solid indications that the Sivers effect indeed exists.

The theoretical studies have revealed an even more striking property of the Sivers functions [2, 3, 4, 5]. Let us give a simple QED example that captures the essential physics. In Fig. 1(a) we consider a "toy" DIS process. A transversely polarized charge-less "hadron", consisting of particles with electric charges $+1$ and -1, is probed by a highly virtual photon. In order not to be forced to vanish by time-reversal invariance, a single-spin asymmetry for the process requires the presence of an interaction phase. Such a phase may be generated by a rescattering of the struck "parton" in the field of the "hadron remnant", by exchange of a photon as shown in the figure. The amplitude with the additional exchanged photon interferes with that without the photon. As the electric charges of the two interacting particles are opposite, this final-state interaction is *attractive*.

Now consider a similar model for the Drell-Yan process in Fig. 1(b). "Partons" of opposite charge annihilate to produce a highly virtual photon. The interaction generating the phase in this case is "initial-state" and is between the remnant of the transversely polarized "hadron" and the

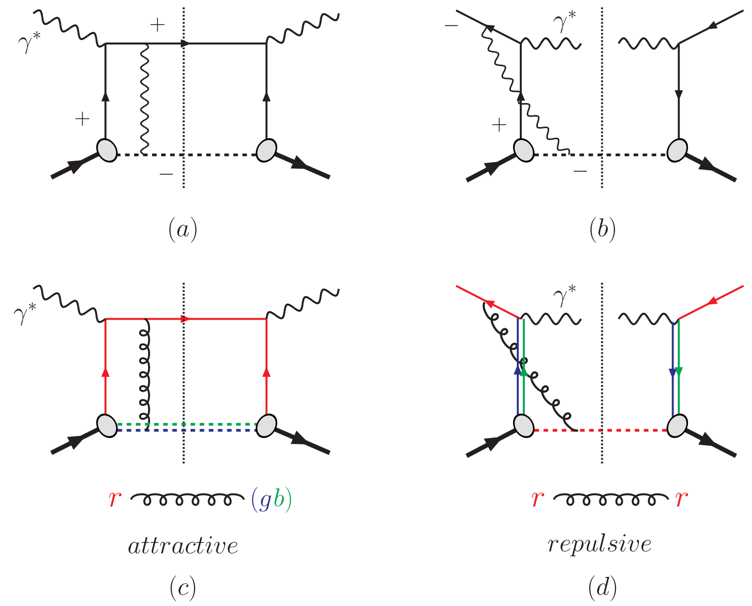

Figure 1: *(a),(b) Simple QED example for process-dependence of the Sivers functions in DIS and the Drell-Yan process. (c),(d) Same for QCD.*

initial parton from the other, unpolarized, "hadron". These necessarily have opposite charges, and the interaction is *repulsive*. As a result, the spin-effect in this case needs to be of opposite sign as that in DIS.

These simple models are readily generalized to true hadronic scattering in QCD. In DIS, the final-state interaction is through a gluon exchanged between the $\mathbf{3}$ and $\bar{\mathbf{3}}$ states of the struck quark and the nucleon remnant, which is attractive, as indicated in Fig. 1(c). In the Drell-Yan process, the interaction is between the $\mathbf{3}$ and $\mathbf{3}$ states (or $\bar{\mathbf{3}}$ and $\bar{\mathbf{3}}$) and therefore repulsive, as shown in Fig. 1(d). This is the essence of the – by now widely quoted – result that the Sivers functions contributing to DIS and to the Drell-Yan process have opposite sign [2, 3, 4, 5]:

$$f^{\rm Sivers}(x,k_\perp)\Big|_{\rm DY} = -f^{\rm Sivers}(x,k_\perp)\Big|_{\rm DIS} \; . \tag{1}$$

In the full gauge theory, the phases generated by the additional (final-state or initial-state) interactions can be summed to all orders into a "gauge-link", which is a path-ordered exponential of the gluon field and makes the Sivers functions gauge-invariant. The non-universality of the Sivers functions is then reflected in a process-dependence of the space-time direction of the gauge-link. The crucial role played by the gauge link has given rise to intuitive model interpretations of single-spin asymmetries in terms of spatial deformations of parton distributions in a transversely polarized nucleon [17]. The process-dependence of the Sivers functions will also manifest itself in more complicated QCD hard-scattering, albeit in a more intricate way [18]. An example is the single-spin asymmetry in di-jet angular correlations [19, 20, 21], which is now under investigation at RHIC [22]. The verification of the predicted non-universality of the Sivers functions is an outstanding challenge in strong-interaction physics. It is most cleanly possible in the Drell-Yan process, which provides the motivation for this proposal.

We consider the single-transverse-spin asymmetry (SSA) for the Drell-Yan process in pp scattering at RHIC: $p(S_\perp) + p \to \gamma^* + X$, where the virtual photon decays into the lepton pair.

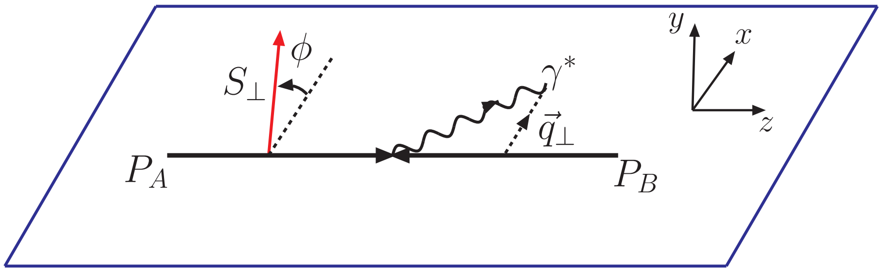

Figure 2: *Definition of momenta and angles for the Drell-Yan process.*

The three momenta P_A, P_B and q form the so-called reaction plane, see Fig. 2. After integrating out the lepton angles in the rest frame of the virtual photon, we obtain the following differential cross section for the Drell-Yan process:

$$\frac{d\sigma}{dM^2 dy d^2 q_\perp} = \frac{4\alpha^2\pi}{3sM^2}\left[W_{UU}(x_1, x_2, M^2, q_\perp) + \sin\phi W_{TU}(x_1, x_2, M^2, q_\perp)\right] \ , \tag{2}$$

where M is the invariant mass of the lepton pair, $q_\perp$ the virtual photon's transverse momentum, and y its rapidity. ϕ is the azimuthal angle between the virtual photon and the transverse polarization vector in a frame where the polarized hadron is moving in the $+z$ direction as shown in Fig. 2. At low transverse momentum, x_1 and x_2 are related to the mass and rapidity through $x_1 = M/\sqrt{s}\, e^y$ and $x_2 = M/\sqrt{s}\, e^{-y}$, where s is the hadronic center-of-mass energy squared. The hadronic tensors W_{UU} and W_{TU} depend on the unpolarized quark and anti-quark distributions and the Sivers functions, respectively. An azimuthal asymmetry can for example be calculated from the above equation by integrating over the transverse momentum of the virtual photon, $|q_\perp|$, but keeping the $\sin\phi$-azimuthal angle dependence. This asymmetry depends on the "$1/2$-moment" of the Sivers functions [20]:

$$f_T^{(1/2)}(x) = \int d^2k_\perp \frac{|\vec{k}_\perp|}{M} f^{\rm Sivers}(x, k_\perp) \tag{3}$$

(defined for each flavor). As we discussed above, the nontrivial universality property for the Sivers function allows us to predict the SSA for the Drell-Yan process at RHIC by using the constraints from the SIDIS process studied by the HERMES and COMPASS collaborations. In Ref. [20], the valence quark Sivers functions were fitted to the HERMES data, and the following parameterizations were obtained:

$$u_T^{(1/2)}(x)|_{\rm DIS} = -0.75x(1-x)u(x), \quad d_T^{(1/2)}(x)|_{\rm DIS} = 2.76x(1-x)d(x) \ , \tag{4}$$

where $u(x), d(x)$ denote the unpolarized quark distributions. We notice that the $(1-x)$ suppression for the Sivers function relative to the unpolarized quark distribution is consistent with a power counting analysis for the quark distribution at large-x [23]. To predict the SSA for the Drell-Yan process, we reverse the signs for the Sivers functions in (4). With these results, we show in Fig. 3 the prediction at RHIC as function of the pair rapidity, for $\sqrt{s} = 200$ GeV, integrated over the lepton pair mass range $4 < M < 10$ GeV. The asymmetry is found to be sizable over a wide range of rapidities.

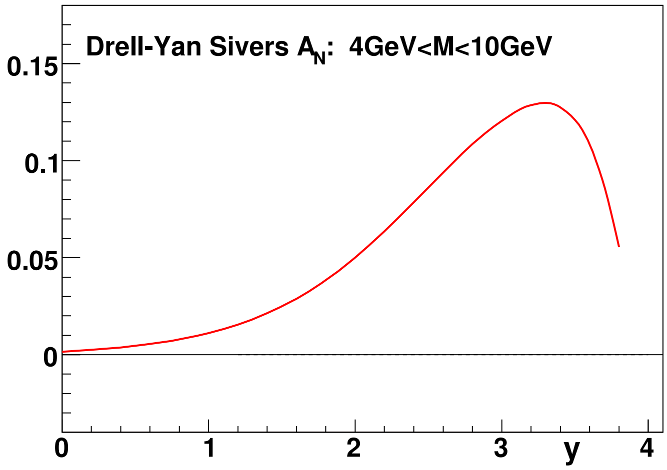

Figure 3: *Sivers asymmetry for the Drell-Yan process at RHIC, as function of virtual-photon rapidity y.*

3 Experimental Issues

The Drell-Yan (DY) process is the production of di-lepton pairs (e^+e^- or $\mu^+\mu^-$) in the collisions of two hadrons. The DY process has been extensively studied in fixed target experiments (as reviewed in [24]), where energetic pion or proton beams interact with proton (or deuterium [25]) targets with total center-of-mass energy $\sqrt{s} < 40$ GeV. There are plans for future fixed-target DY measurements at FermiLab, CERN, JPARC and GSI. The DY process has also been studied in $p + \overline{p}$ and $p + p$ interactions at collider energies with $\sqrt{s} > 40$ GeV. Of most relevance here are results from the ISR for both low-mass ($M > 4$ GeV) e^+e^- [26] and $\mu^+\mu^-$ [27] pairs. A robust QCD description of DY production is available and views the process at leading order as a quark, with momentum fraction x_1 from one hadron, annihilating an anti-quark of momentum fraction x_2 from the other hadron, having exactly the opposite color charge. A virtual photon is produced in this $q + \overline{q}$ annihilation and subsequently decays into a di-lepton pair, either e^+e^- or $\mu^+\mu^-$, observed by the experimental apparatus. The momentum fractions of the initial-state q and $\overline{q}$ can be determined from the measured invariant mass of the di-lepton pair (M) and the measured rapidity (y) of the di-lepton via $x_1 = \sqrt{\tau}e^y$ and $x_2 = \sqrt{\tau}e^{-y}$, where $\sqrt{\tau} = M/\sqrt{s}$.

We propose to develop the first measurement of transverse single-spin asymmetries (SSA) for the DY process in a colliding beam facility. Such a measurement is now conceivable given the successful development of high luminosity $p_\uparrow + p$ collisions with demonstrated beam polarization larger than 50% at the Relativistic Heavy Ion Collider (RHIC) facility at Brookhaven National Laboratory. As discussed earlier, measurement of transverse SSA for the DY process provides sensitivity to the expected difference in sign for the spin- and transverse-momentum dependent Sivers distribution function from that observed in semi-inclusive deep inelastic scattering from a transversely polarized target. The transverse SSA measurement for DY is the amplitude of the spin-dependent modulation of the yield as a function of the azimuthal angle between the di-lepton transverse momentum (q_T) and the polarization vector of one proton.

Proposals will be developed to complete transverse SSA measurements for DY at RHIC. The

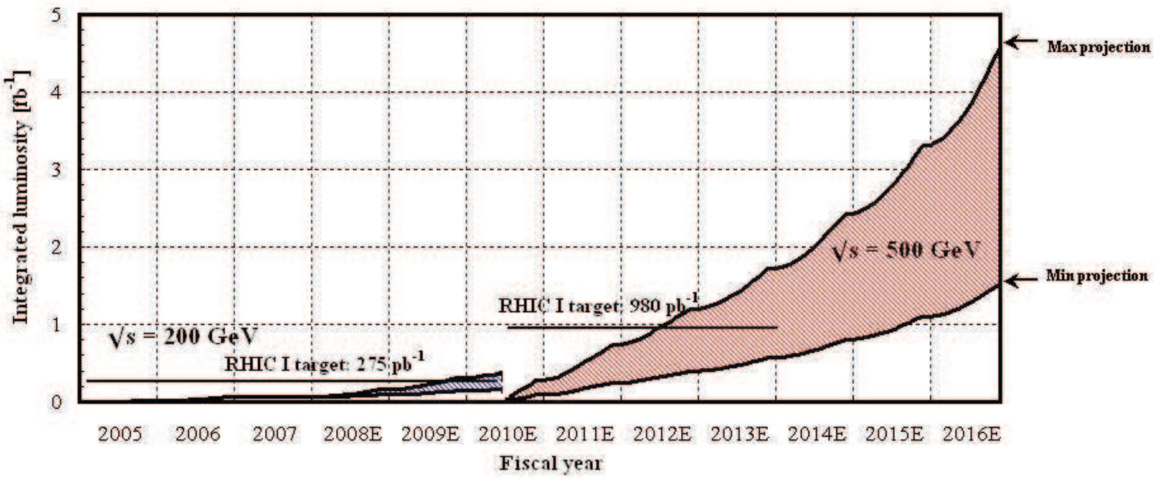

Figure 4: *Projected luminosity for polarized proton collisions at RHIC.*

.

issues these proposals need to address are discussed below.

A basic requirement of detectors that aim to study the DY process is the ability to identify the rare production of di-leptons from much more prolific sources of particle production. The event-by-event determination of the charge of each lepton is expected to be of critical importance for discriminating the DY process from background. Charge-sign determination enables the comparison of the yield of candidate events with the same charge, corresponding to a pure background sample, to the yield of events with opposite charge. Charge sign discrimination requires tracking through a magnetic field. At present, only the PHENIX muon arms have this capability for acceptance in the forward direction, whose importance is discussed below. Given that the DY process leads to a continuous and steeply falling invariant mass distribution, and represents typically 10^{-6} of the interaction cross section, it is important to benchmark simulations of background sources against data before embarking on a spin asymmetry measurement. The most important background that can mimic DY is from the decays of heavy quarks (charm or beauty) leading to oppositely charged leptons. This background can be suppressed by requiring large enough pair mass and/or by employing isolation, requiring that each lepton of a pair is not accompanied by other particles.

The development of high luminosity for polarized proton collisions, concurrent with the development of highly polarized beams, at the RHIC facility enables future measurements of the transverse SSA for the DY process. Projections for polarized proton collisions (Fig. 4) at RHIC suggest that delivered integrated luminosities of ≈ 0.8 (0.3) fb^{-1} per run are possible in the future for $\sqrt{s} = 500(200)$ GeV $p_\uparrow + p$ collisions with beam polarization of 70%. The sensitivity of measurements depends on the luminosity recorded by the experiments. The ratio of recorded to delivered integrated luminosity depends on many variables. Reduction of the bunch length is one

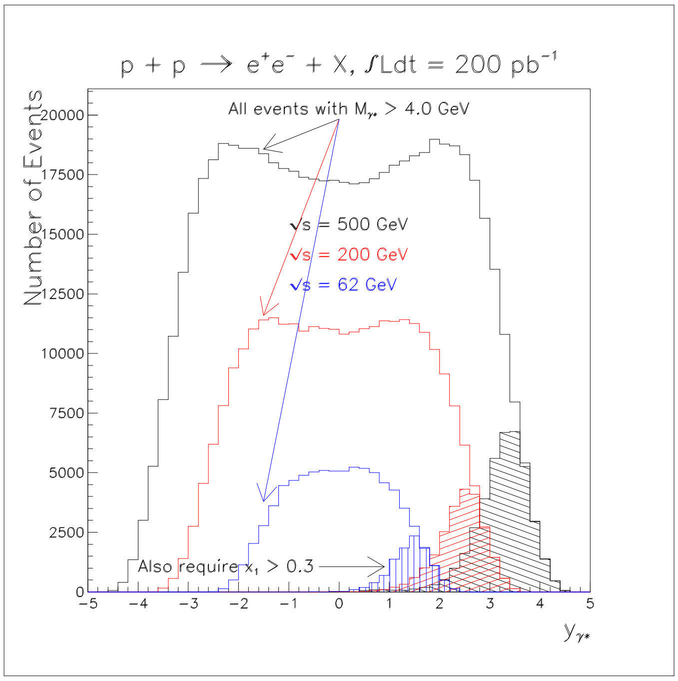

Figure 5: *PYTHIA simulation of the rapidity distribution of* e^+e^- *dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with* $x_1 > 0.3$.

.

method to significantly improve this ratio. Another is to ensure that limitations are not present in the recording of data sensitive to the di-lepton process, either by having sufficiently fast data acquisition or by being able to identify the rare di-lepton process in real time in a trigger system.

Predictions [20, 28] for transverse SSA for the DY process are based on phenomenological fits to the Sivers function deduced from transverse SSA measured in semi-inclusive deep inelastic scattering. These predictions provide a guide regarding the magnitude of the analyzing power and its variation with the di-lepton rapidity. But, these predictions do not necessarily accommodate the most recent RHIC results for transverse SSA for inclusive pion [29] and di-jet production [22]. A striking feature of the RHIC results, is a strong favoring of valence-like x values, as evidenced by non-zero A_N only for Feynman $x > 0.25$ for inclusive pion production and a null result for A_N in di-jet production for $\eta_1 + \eta_2 < 4$, where η_i represents the pseudo-rapidity of each jet. The theoretical description of transverse SSA for inclusive pion and di-jet production is not expected to be as robust as for the DY process because multiple partonic processes contribute to the yields. It remains an important issue to assure a future DY transverse SSA experiment at RHIC has sufficient sensitivity to events initiated by valence quarks from the polarized proton.

An issue related to rapidity acceptance is the optimal choice of the $p_\uparrow + p$ collision energy.

The cross section for DY production when differential in both x_1 and x_2 is proportional to $1/s$ thereby suggesting that lower collision energies might be most favorable. But, it is expected that transverse SSA for DY depends only on x_1 of the quark from the polarized proton, rather than on both x_1 and the x_2 of the anti-quark from the unpolarized proton. More anti-quarks are found at low x_2, and the lowest x_2 values can be reached by higher $\sqrt{s}$ collisions. This is illustrated by PYTHIA simulations of the dilepton yield from DY production in Fig. 5. The importance of acceptance at larger rapidity to emphasize valence-like x_1 values is also evident. At present, it appears that $\sqrt{s} = 200$ GeV polarized proton collisions would be the best choice for a future transverse spin DY measurement. But, optimization of the collision energy should be revisited after the rapidity acceptance of experiments is fully established.

4 Drell-Yan Experimental Benchmarking

We have not yet identified the Drell-Yan continuum in the interesting mass range of $M > 4$ GeV at RHIC. J/Ψ events have been measured by PHENIX [30]. Results were reported at both forward (dimuons) and mid-rapidity (dielectrons). We concentrate on the forward region, where the A_N Drell-Yan signal is expected to be large (Fig. 3), due to the large valence quark content at this rapidity (Fig. 5). In this region we have only the published result for $p + p \to J/\Psi + X$ for $\sqrt{s}$=200 GeV [30], where we show the dimuon mass spectrum in Fig. 6.

The PHENIX muon spectrometers detect high energy muons at large forward/backward rapidities $1.2 < |\eta| < 2.4$ and cover 2π in azimuth. As seen in Fig. 6, the J/Ψ mass region is well described. The interesting mass region for Drell-Yan is $M > 4$ GeV, where the published data (presented in a linear plot) have about 10 events/bin, down a factor of 100 from the J/Ψ peak.

In Drell-Yan dimuon production, the experimentally accessible kinematic region is $4 < M < 10$ GeV and the expected main backgrounds are from heavy flavor semileptonic decays $p + p \to Q + \bar{Q}$ and $Q \to \mu^{\pm} + X$, and heavy quarkonium decays, such as $J/\Psi \to \mu^+\mu^-$. Fig. 7 shows the dimuon mass cocktail distributions ($dN^{\mu^+\mu^-}/dM$) from PYTHIA (v6.205) plus full PHENIX muon spectrometer simulations. The simulation is for pp collisions at $\sqrt{s} = 200$ GeV. The CTEQ5M1 parton distribution functions have been used. The detector responses and smearing effects are included in the dimuon invariant mass distributions.

Since there is no measurement yet of dimuon production in the higher mass range at this energy, we tune the PYTHIA parameters to the best knowledge of our understanding of various physics processes in p+p collisions at RHIC: (1) The PYTHIA DY dimuon invariant mass distribution is checked against the results from next-to-leading order perturbative QCD (NLO pQCD) calculations performed by R. Vogt and is found in good agreement in the high mass region $M > 4$ GeV; (2) for open charm production, the parameters are tuned to best fit the non-photonic single electron spectrum (mostly from open charm decays) measured by the PHENIX experiment [31]; (3) for open beauty production, we used parameters tuned by the ALICE collaboration that best reproduce the NLO pQCD calculations. The cocktail relative yields are determined from the best fit to the PHENIX dimuon measurements with the following constraints:

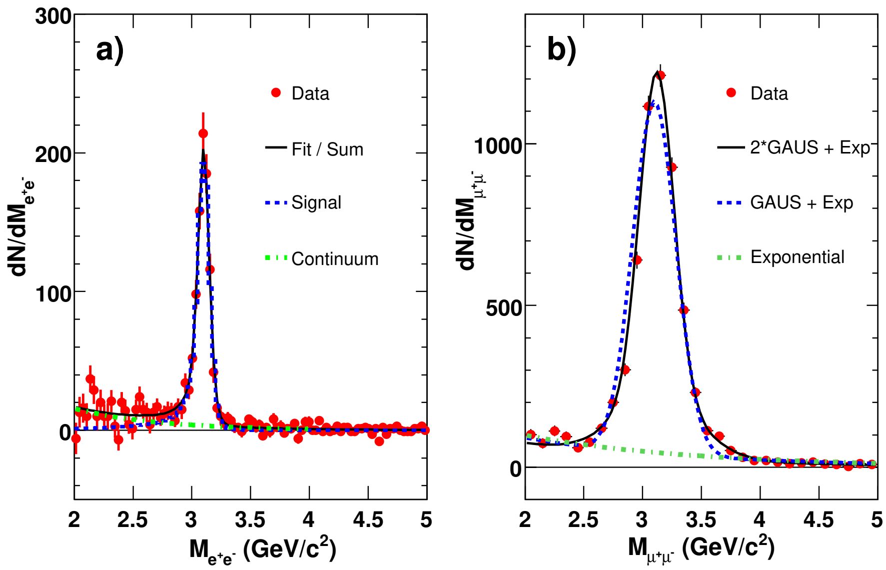

Figure 6: *Dimuon invariant mass spectra from the PHENIX run 5 J/Ψ measurement. The left plot is from the PHENIX central arm di-electron measurement at rapidity $|\eta| < 0.35$ and the right hand plot is from the dimuon measurement for the rapidity range $1.2 < |\eta| < 2.2$. Note there is a significant exponential component for masses above the J/Ψ mass peak which is expected mostly from DY production.*

(1) Relative heavy quarkonium yields [32]:

$$\frac{N^{J/\Psi}}{N^{\Psi'}} = 58\pm^{8}_{7} \, , \quad \frac{N^{\Upsilon}}{N^{\Upsilon'}} \sim 3.6 \, , \quad \frac{N^{\Upsilon}}{N^{\Upsilon''}} \sim 8 \, . \tag{5}$$

(2) Relative yields of open beauty vs. open charm production in the "Fixed-order next-to-leading logarithm (FONLL)" theoretical framework [33]:

$$\sigma^{c\bar{c}} = 256 \pm^{400}_{146} \mu\mathrm{b} \, , \quad \sigma^{b\bar{b}} = 1.87 \pm^{0.99}_{0.67} \mu\mathrm{b} \, . \tag{6}$$

We would measure the asymmetry for the production of unlike sign lepton pairs, after subtraction of like sign lepton pairs. The observed ratio is like/unlike $\simeq$ 50% for the PHENIX muon arms in this mass region. This subtraction must be included in an estimate of sensitivity for the asymmetry measurement.

As discussed above, in the high mass region of $4 < M < 10$ GeV the main background is expected to be dimuons from open b-quark decays. The contribution is expected to be about equal to Drell-Yan. The b-quarks would be from displaced vertices and both b-quark muons would be embedded in jets. We expect to be able to identify an enhanced b-quark background data set through use of planned upgrade detectors: the Forward Silicon Vertex Detector (FVTX)

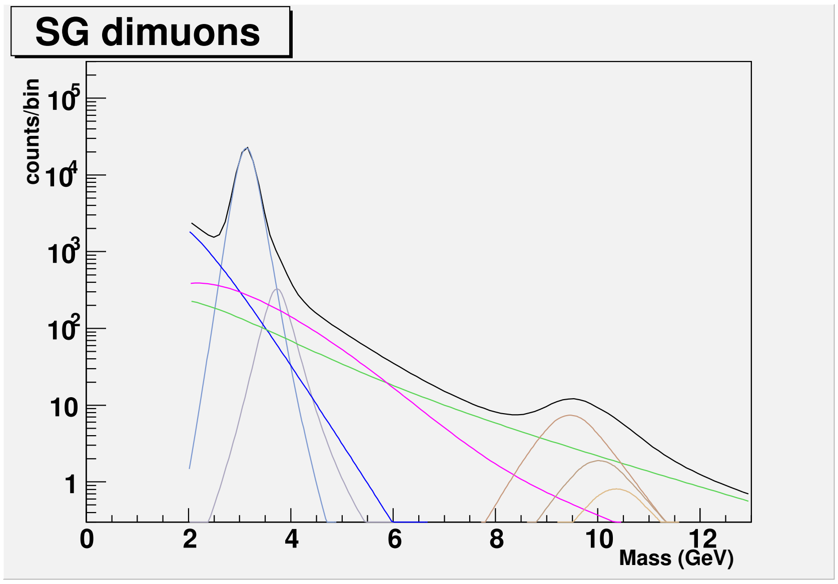

Figure 7: *Dimuon invariant mass $dN^{\mu^+\mu^-}/dM$ cocktail distributions in the PHENIX muon spectrometer acceptance, from full PYTHIA plus PHENIX detector simulations. Black = Total, Light-Blue = J/Ψ, Light-Gray = Ψ', Blue = $c\bar{c}$, Magenta = $b\bar{b}$, Green = Drell-Yan, Light-Brown = three Upsilon states.*

and the Nose Cone Calorimeter. Both will cover the acceptance of the muon spectrometers. A study of the sensitivity of displaced vertices from the FVTX is encouraging, indicating a possible separation of this background by nearly an order of magnitude. Isolation, not studied yet, is regularly used for example at the Tevatron to reduce background for Drell-Yan production of the W boson. Significant background identification and reduction is expected from isolation. Therefore, we expect to be able to greatly improve the signal to background ratio from about 1 to 1, and to separately identify and measure the asymmetry of the background, for the PHENIX experiment.

For the STAR Forward Meson Spectrometer (FMS) and Endcap calorimeters, which would measure Drell-Yan through dielectrons, we have no benchmarking available. New vertex detectors and forward tracking detectors are planned for the upgrade program. Charge identification would be available for the Endcap events. As presented in Section 3, the FMS would also need charge measurement, through addition of a transverse magnetic field (for example a toroid after the STAR solenoid), and tracking. This is not planned at this time. Both the FMS and Endcap are calorimeters that will provide triggering and offer isolation to reduce backgrounds from heavy quark decays.

We see the benchmarking studies discussed above as indicating that the mass region $4 < M < 10$ GeV will/can be accessible for the PHENIX/STAR experiments at RHIC.

5 New Results from DIS and First Drell Yan Projections

The HERMES collaboration has recently updated its measurement of Sivers amplitudes in semi inclusive deep inelastic scattering. The new HERMES result is based on the data samples taken from 2002 through 2005 with transverse target polarization [34]. Hermes observes a positive Sivers amplitude for positively charged pions with good statistical precision. The effect for negative pions is consistent with zero, see Fig. 8.

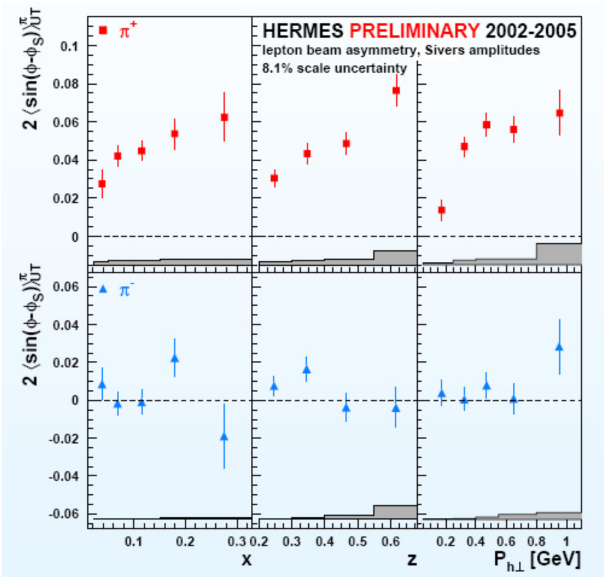

Figure 8: *Sivers amplitudes observed by the HERMES collaboration in semi inclusive DIS [34].*

.

In Fig. 9 we present first projections for statistical errors of future measurements of Sivers asymmetries in Drell Yan at RHIC. We assume a polarization of $P = 0.7$ and a data sample of $\int Ldt = 250$ pb^{-1} at a center of mass energy of $\sqrt{s} = 200$ GeV. Using the duty factor and vertex cuts typical for the PHENIX experiment, this corresponds to the integrated luminosity of 10 weeks of running with RHIC II luminosities each in 2015 and 2016. For comparison the integrated luminosity expected in PHENIX from RHIC I through 2012 with transverse spin will be $\int Ldt = 30\,\mathrm{pb}^{-1}$.

For the data point from the PHENIX muon arms at $y = 1.8$ systematic uncertainties from heavy flavor backgrounds have been estimated and found to be twice the size of the statistical error bars. However, simulation studies show that the forward vertex detector upgrade planned for the PHENIX experiment will significantly reduce this background.

We compare the projected statistical uncertainties to the negative Sivers asymmetries predicted for Drell Yan, see also Fig. 3. A precision test of the universality of the Sivers function appears feasible with large integrated luminosities (RHIC II) and future detector upgrades planned for STAR and PHENIX.

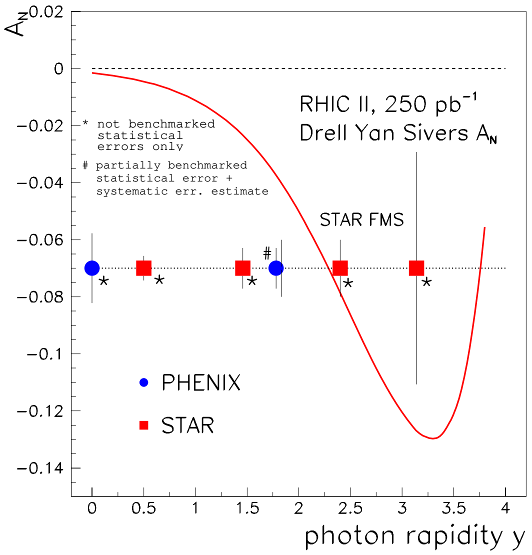

Figure 9: *Projected Drell Yan Sivers asymmetries for the STAR and PHENIX experiments at RHIC. The projections assume a data sample of* $\int Ldt = 250\ pb^{-1}$. *Error bars represent statistical uncertainties only. Systematic errors from heavy flavor backgrounds were estimated for the PHENIX muon arms and the resulting systematic error is shown for the corresponding data point at* $y = 1.8$.

References

[1] D. W. Sivers, Phys. Rev. **D41**, 83 (1990).

[2] S. J. Brodsky, D. S. Hwang and I. Schmidt, Phys. Lett. B **530**, 99 (2002); Nucl. Phys. B **642**, 344 (2002).

[3] J. C. Collins, Phys. Lett. B **536**, 43 (2002).

[4] X. Ji and F. Yuan, Phys. Lett. B **543**, 66 (2002); A. V. Belitsky, X. Ji and F. Yuan, Nucl. Phys. B **656**, 165 (2003).

[5] D. Boer, P. J. Mulders and F. Pijlman, Nucl. Phys. B **667**, 201 (2003).

[6] A. Airapetian *et al.* [HERMES collaboration], Phys. Rev. Lett. **94**, 012002 (2005).

[7] V. Y. Alexakhin *et al.* [COMPASS Collaboration], Phys. Rev. Lett. **94**, 202002 (2005).

[8] see, for example, G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976); D. L. Adams *et al.* [E581 and E704 Collaborations], Phys. Lett. B **261**, 201 (1991); D. L. Adams *et al.* [FNAL-E704 Collaboration], Phys. Lett. B **264**, 462 (1991); K. Krueger *et al.*, Phys. Lett. B **459**, 412 (1999).

[9] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **92**, 171801 (2004); C. A. Gagliardi [STAR Collaboration], talk presented at the "14th International Workshop on Deep Inelastic Scattering (DIS 2006)", Tsukuba, Japan, April 20-24, 2006, arXiv:hep-ex/0607003.

[10] F. Videbaek [BRAHMS Collaboration], AIP Conf. Proc. **792**, 993 (2005); J. H. Lee [BRAHMS Collaboration], talk presented at the "14th International Workshop on Deep Inelastic Scattering (DIS 2006)", Tsukuba, Japan, April 20-24, 2006.

[11] G. L. Kane, J. Pumplin and W. Repko, Phys. Rev. Lett. **41**, 1689 (1978).

[12] J. C. Collins, Nucl. Phys. B **396**, 161 (1993).

[13] P. J. Mulders and R. D. Tangerman, Nucl. Phys. B **461**, 197 (1996) [Erratum-ibid. B **484**, 538 (1997)]; D. Boer and P. J. Mulders, Phys. Rev. D **57**, 5780 (1998).

[14] J. C. Collins and D. E. Soper, Nucl. Phys. B **193**, 381 (1981) [Erratum-ibid. B **213**, 545 (1983)]; Nucl. Phys. B **197**, 446 (1982).

[15] X. Ji, J. P. Ma and F. Yuan, Phys. Rev. D **71**, 034005 (2005); X. Ji, J. P. Ma and F. Yuan, Phys. Lett. B **597**, 299 (2004); JHEP **0507**, 020 (2005).

[16] J. C. Collins and A. Metz, Phys. Rev. Lett. **93**, 252001 (2004).

[17] M. Burkardt, Nucl. Phys. A **735**, 185 (2004).

[18] A. Bacchetta, C. J. Bomhof, P. J. Mulders and F. Pijlman, Phys. Rev. D **72**, 034030 (2005); C. J. Bomhof and P. J. Mulders, JHEP **0702**, 029 (2007); J. W. Qiu, W. Vogelsang and F. Yuan, arXiv:0704.1153 [hep-ph].

[19] D. Boer and W. Vogelsang, Phys. Rev. D **69**, 094025 (2004).

[20] W. Vogelsang and F. Yuan, Phys. Rev. D **72**, 054028 (2005).

[21] C. J. Bomhof, P. J. Mulders, W. Vogelsang and F. Yuan, Phys. Rev. D **75**, 074019 (2007).

[22] J. Balewski, talk presented at the SPIN 2006 Symposium, Kyoto, Japan, October 2-7, 2006, arXiv:hep-ex/0612036.

[23] S. J. Brodsky and F. Yuan, Phys. Rev. D **74**, 094018 (2006).

[24] W J. Stirling and M. R. Whalley, J. Phys. G **19**, D1 (1993).

[25] E. A. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998).

[26] C. Kourkoumelis *et al.*, Phys. Lett. **91B**, 475 (1980).

[27] D. Antreasyan *et al.*, Phys. Rev. Lett **48**, 302 (1982).

[28] J .C. Collins *et al.*, Phys. Rev. D **73**, 094023 (2006).

[29] L. Nogach (STAR), talk presented at the SPIN 2006 Symposium, Kyoto, Japan, October 2-7, 2006, arXiv:hep-ex/0612030.

[30] PHENIX Collaboration, hep-ex/0611020.

[31] A. Adare et al. (PHENIX Collab.), Phys. Rev. Lett. **97**, 252002 (2006).

[32] R. Vogt, Phys. Rept. **310**, 197 (1999).

[33] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005).

[34] M. Diefenthaler et al., HERMES Collaboration, Int. Workshop on DIS 2007, Munich, Germany, April 16-20, 2007.