Probing the sea contribution to the protons’ spin

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Abstract. Longitudinal single-spin asymmetries ($A_L$) of parity-violating $W$ bosons are measured with PHENIX via the decay daughter muons in $\sqrt{s} = 500$ GeV $p + p$ collisions at RHIC. These proceedings report on the latest $W^\pm \rightarrow \mu^\pm \nu$ asymmetry results obtained during the 2011 RHIC run using the forward muon-arm detector in PHENIX.

1. Introduction

Over twenty years ago, a naive picture of the protons’ spin would have expected that the constituent quark spin would form a large contribution to the total proton spin. Upon the first measurements of the protons’ spin this picture was found not to be true and has since sparked much theoretical and experimental interest as to the make-up of this fundamental property of the proton [1].

Several components have been theorized to be necessary in the spin formation with all pieces summing to precisely $\frac{1}{2}\hbar$. The sum rule (Eqn. 1) includes quark components (quark and anti-quark), a gluon component, and an orbital angular momentum component. The relative contributions at different $x$ – the fraction of the momentum carried by the individual quark or gluon – are the quantities we wish to measure. These are expressed as spin-dependent parton distribution functions (see Ref. [2] for theoretical work).

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_Z
\] (Eqn. 1)

Investigation over the succeeding years using (semi-inclusive) deep inelastic scattering ((SI)DIS) have lead to a precise understanding of the spin-dependence of the parton-distribution functions for quarks, but to a lesser degree for the contribution of the anti-quark [2]. To investigate this at RHIC, $W$ bosons provide an almost ideal probe as they directly probe the sea quark contribution to the proton’s spin via their leading order production in hard scattered $u + d \rightarrow W^+$ ($\bar{u} + \bar{d} \rightarrow W^-$) interactions. RHIC collisions of polarized protons at $\sqrt{s} = 500$ GeV are energetic enough for $W$ production. Underlying the parity-violating $W$ production, the weak decay $W^\pm \rightarrow l^\pm + \nu(\bar{\nu})$ preserves the asymmetries for which the resultant $l^+(\bar{l}^-)$ which are expected to be large in magnitude at high-rapidity, yet opposite in sign.

In these proceedings, we report on the most recent result on the work to elucidate the sea quark contribution to the protons’ spin using the PHENIX detector at RHIC. The necessary upgrades to the forward muon arms, the analysis to reduce the backgrounds and the current preliminary results will be discussed in the context of the published central-arm results and theoretical expectations.
2. The PHENIX Detector towards a $W$ measurement

The $W$ production cross-section at RHIC energies is very small compared to the inelastic or the lepton production cross-section. For the central arms ($W \to e\nu$, where the $\nu$ is not apparent in the apparatus) measurement, this small cross-section is aided by several factors. Firstly, in the decay of $W$’s at mid-rapidity the energy distribution peaks close to half the mass of the $W$. Such a Jacobian peak has a shape which is distinct from the background continuum of electrons. Secondly, in a related way, the dominating contribution to the energy spectrum at high energy (around $20 < E < 30$ GeV) is the $W \to e$ process. The $W \to e$ contribution can be relatively enhanced by imposing an isolation requirement in a close-proximity region to reduce the background $e$ candidates. At high energy such electron candidates are dominantly from photon conversions and mis-identified hadrons. For a further description of the $W \to e$ signal extraction see Ref. [3].

By measuring electrons with high precision and the ability to efficiently trigger on them, the central arms provide the basis for the $W$ measurements. However, the amplitude of the asymmetry at mid-rapidity is expected to be small for $W$ bosons, presenting a significant challenge with that measurement. A larger asymmetry for $W$’s is expected to be observed at forward rapidity, where different experimental challenges exist. The underlying Jacobian peak observed in the central region is diminished at forward rapidity, in fact completely washed out with the resolution of the forward muon arms at high momentum. At all momenta, a large background exists from mis-identified low momentum hadrons, which has to be reduced by a factor of 100 or more to be able to extract the true $W$ signal muons. Finally, prior to Run 11, the ability to trigger on forward muons was limited to a low-momentum ($p > 1.5$ GeV/$c$) threshold, which does not provide enough rejection to effectively trigger on the $W$ muons. As the $\mu$s from the $W$ decay appear at high momenta, an online selectivity of momenta is highly desirable, in fact necessary if one wishes to record all such muons. Thus, an upgrade to the electronics in the Muon-tracker was made to allow essentially straight-line trajectories to be triggered online. A further upgrade saw a new detector implemented at the furthest $z$ position in the Muon-Tracker/Identifier system. The Resistive plate chambers, RPCs, have sufficient timing to allow for a definite beam-clock association to the candidate $\mu$s. An additional iron absorber was also added into the front of the muon tracker to help reduce sources of hadronic background which decay within the muon track volume and could mimic a high-momentum signal muon.

The new triggering system currently matches hit combinations in the muon tracker, which are consistent with straight lines, to a predefined map. To determine the map, straight line

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1 As the rate of interactions is greater than the rate at which PHENIX can record data to tape, minimum bias (or high-frequency type) triggers must be prescaled to prevent the recording rate to slow down – known as dead-time.
trajectories are passed through a geometrical description of the muon tracker and RPC. All possible combinations are stored in a look-up table. To further restrict the trigger to accept only signal muons the time recorded in the RPCs must be consistent with a particle originating from the collision region. This requirement specifically rejects beam-related backgrounds which come from outside the PHENIX detector volume.

3. Background and Signal Extraction
The expected rate for $W$ production is only a few hundred lepton tracks are expected in a given year’s running at RHIC are to be measured in the acceptance of the central or muon arms. As such, the number of other tracks in these detectors is much larger in comparison and must be significantly reduced (by several orders of magnitude) in order to extract the desired signal.

As discussed, for the central-arm measurement the Jacobian peak helps to distinguish the signal $e^+$’s from the background spectrum, see Figure 2. The background spectrum folds in the estimated cross-section of electrons from heavy flavor decays and photon conversion. The uncertainty in the background accounts for photon conversion probability uncertainties, overall background normalization, and the uncertainty associated with extrapolating to high momenta.

![Figure 2. Measured positron (upper) and electron (lower) spectrum from the PHENIX central-arm electromagnetic calorimeter, from Ref.[3]. The red/blue lines represent the data without/with an isolation cut. The estimated background is shown as the bands. The charge-sign is determined from the Drift Chamber bend prior to the calorimeter.](image)

There are two broad types of backgrounds concerning the muon arms: *irreducible* – real muons from charm and bottom decays, and *reducible* – muons which originate from light hadrons. The latter are the largest source of background, but through their decay topology, can be reduced. The former cannot be removed directly, but their contribution can be estimated from the data itself.

To minimize the contamination from the reducible backgrounds, one must first understand how they come about. Hadrons generally lose all their energy in the absorber and do not impinge the muon tracker active elements. However, a small fraction (sub-percent) can punch-through and form a track in the muon tracker. As the time of flight is quite long into the muon arms, charged pions and kaons can decay within the muon-tracker elements into a real muon (and neutrino). Such a decay has two features: a kink in the apparent track of the particle (as seen by the muon tracker) and a “deep” road through the muon-identifier (which is only likely for real muons). Although rare, the first feature can occur such that a low momentum track may appear as a high-momentum track after the decay. This contaminates the high-momentum sample. The deep road means that this “high-momentum” track also has a valid muon-identifier road. This combination does cause a significant problem as the number of hadrons produced in $p + p$ collisions is large compared to the $W$ muons. Fortunately, these new tracks are not perfect
and have subtle differences from the true high-momentum tracks. The fit-$\chi^2$ to the muon-tracker portion of the track is typically larger for hadronic backgrounds. The matching between the muon-tracker track and the muon-identifier road is worse owing to the former being reconstituted from two different trajectories. The residual distributions, then, from these elements are used to cut finely on true signal and to reduce the effect from backgrounds. See the right panel of Figure 3 for an example of the matching residual differences between muons and decay-hadrons in the muon tracker.

Billions of Monte-Carlo simulations of single hadrons, as well as Pythia events, were used to determine the optimal cut positions on the residual distributions. Several cut levels (to retain between 90% and 99% of signal muons from each cut) were chosen, where the lowest cut values (at 90%) represent the most stringent cuts. As a cross-check, these distributions were formed from samples of real data muons to ensure that the detector behaves the same in both simulation and data. Hundreds of hours of cosmic-ray triggered events were reconstructed to allow for a study of the cut position in that environment. Tracks which pass through both muon arms provide a crucial test of these residual distributions, as well as of the momentum resolution of the high-momentum tracks (discussed below). In a collision environment, muons resultant from $J/\psi$ decays also provide a zeroth-order cross-check of the simulations, albeit at much lower transverse momentum.

For the irreducible backgrounds, removal is not possible as these are true muons, and look just like the $W$-originating muons, except that the spectral shapes (in $p_T$) are distinct. For this, samples of Pythia events for various sources of real muons were generated, simulated through a Geant description of the detector setup and reconstructed as though this was a real data sample. The final reconstructed simulation was scaled to the sampled data luminosity and compared to the recorded data at high momentum. The cross-section for these muons are dominantly at a lower momentum than that of the $W$ muons, the only way that these can impact the signal is by being smeared out to higher momenta. As the resolution of the muon tracker degrades rapidly for high-momentum tracks, some of these other muons are pushed to higher momenta and appear as our $W$ signal. The amount of smearing which is present in the data is modeled in the simulation and thus the impact can be studied. To check that the smearing is accurately described, the momentum of the cosmic-muon pairs, which are reconstructed in opposite arms, are compared. As both originate from the same muon (with the same momentum) the smearing in the tracker can be derived from this sample and compared to the simulations. They were found to be in agreement, even at the highest momentum, see the left panel of Figure 3. Finally, to check the overall scale of the backgrounds, the dimuon spectrum in data was compared to that from the Pythia simulations, scaled to the measured cross-section. This provides an estimate as to the overall scale in the simulation. The sum of all background muon sources agrees reasonably well with the data, after the application of the residual cuts.

4. Results
The preliminary results on the single-$\mu$ cross-section for positive (upper panel) and negative (lower) forward $\mu$ are presented in Figure 4. The data were collected at $\sqrt{s} = 500$ GeV $p + p$ collisions during RHIC Run 11. In the figure, the upper green data shows the raw $p_T$ distributions, without any track selectivity. This illustrates the rejection factor ($\mathcal{O}(100)$) which is needed to reduce the backgrounds to the same order of magnitude as the $W$ signal. The red (lower green) show the efficiency corrected final data using the muon-identifier only (muon-tracker) trigger. The statistical reach of the muon-identifier trigger is limited due to the necessary prescale factor applied to allow data to be read out. The filled histograms represent the expected distribution from data. The blue (purple) shades represent the residual irreducible (reducible) backgrounds. The red-filled histogram represents the muons from the signal. The red fill represents the muons from the $W$ signal. Note that this is a logarithmic scale, the true
Figure 3. The left panel shows the comparison between the momentum resolution determined from simulation (red) and cosmic data (blue). The right panel illustrates the residual parameter DG0 (spatial difference between extrapolated muon-tracker track and the muon-identifier road). The blue/purple color-filled histograms illustrate the distribution contribution from hadronic sources, green and orange are real muons (not from W’s), and red represents the $W \rightarrow \mu$ signal. The vertical lines represent cut-levels; the red (green) upper distributions are data with $\mu$-ID (high-$p_T$) triggers.

signal-to-background is 0.21 to 0.42, dependent on the charge sign and rapidity, integrated over the region $p_T > 20\text{ GeV}/c$.

The single-spin asymmetries extracted for single muons are shown in Figure 5. The luminosity sampled to form this measurement was $\mathcal{L} = 25\text{ pb}^{-1}$, with an average polarization of $P \sim 50\%$. The statistical uncertainty is shown as a line, the systematic uncertainty is shown as a box. The largest contribution to the systematic uncertainty is due to the uncertainty in the background sources (both reducible and irreducible). To determine the systematic errors, the backgrounds were varied by a factor of two in calculating the asymmetry. This is only the first measurement of forward W’s with a factor of four more data (from RHIC Run 12 onwards) planned to be recorded over the course of the next few years. Data from Run 12, where more $p + p$ data at $\sqrt{s} = 510\text{ GeV}$ were recorded, includes a new silicon pre-tracker for the muon-tracker which may help to constrain the background contributions in future W measurements.

Published results from the central arm $W \rightarrow e\nu$ measurement [3] are shown in Figure 6. The sampled luminosity in this dataset from Run 9 was approximately $8.6\text{ pb}^{-1}$, with a luminosity of $\sim 40\%$. Analysis is ongoing toward results from Run 11 and 12 which will have a higher statistical significance.

5. Summary
The PHENIX experiment at RHIC has measured longitudinal single-spin asymmetries from the maximally parity violating $W \rightarrow l\nu$ decay at mid- and forward-rapidity. For the forward measurement a series of detector upgrades were necessary to enable an effective online high-momentum selectivity of such candidates. From the Run 9 data, the first W cross-section and asymmetry measurements were made at mid-rapidity. This was followed by forward measurements using data collected in Run 11. The next few years of RHIC running, with fully commissioned PHENIX upgrades will provide a further factor of four in statistics, coupled with better constraints on the background contributions from muons and light hadrons.
Figure 4. Preliminary positive (upper panel) and negative (lower) forward $\mu$ cross-section measured in $\sqrt{s} = 500$ GeV $p + p$ collisions during RHIC Run 11. The upper green histogram shows the raw data, without any track selectivity, the red (lower green) show the efficiency corrected final data using the muon-identifier only (muon-tracker) trigger. The red-filled histogram represents the muons from the signal. The blue (purple) represent the residual irreducible (reducible) backgrounds.

[1] J. Ashman et al. Nucl. Phys. B328 (1989) 1.
[2] D. de Florian et al. Phys. Rev. D80 (2009) 034030.
[3] A. Adare et al. Phys. Rev. Lett 106 (2011) 062001.
Figure 5. Preliminary positive (upper panel) and negative (lower) forward W single-spin asymmetries measured in $\sqrt{s} = 500$ GeV $p + p$ collisions during RHIC Run 11. The data and associated statistical (line) and systematic (box) errors are measured in the forward ($\eta > 0$) and backward ($\eta < 0$) regions. The lines depict different model expectations.

Figure 6. Measured positron (upper) and electron (lower) asymmetries from the PHENIX central-arm electromagnetic calorimeter, from Ref. [3]. The error bars represent the combined statistical and systematic uncertainties, the colored lines show model expectations.