

W^\pm production and single-spin asymmetries in polarized $\vec{p} + p$ collisions at $\sqrt{s} = 500$ GeV at STAR

Scott W. Wissink, for the STAR Collaboration

Indiana University, Bloomington, IN 47408, USA

E-mail: wissink@indiana.edu

Abstract. W boson production in longitudinally polarized p+p collisions provides a clean and novel probe of the flavor dependence of (sea) light anti-quark polarization distributions in the nucleon. The $W^{+(-)}$ are produced in leading order via $u + \bar{d}(d + \bar{u})$ fusion, and can be studied through detection of their decay charged leptons. The STAR Time Projection Chamber (TPC) provides excellent charged particle tracking at mid-rapidity, and allowed for robust e^+/e^- separation for p_T up to ~ 50 GeV/ c in this measurement. Electromagnetic calorimeters (EMCs) determine the precise lepton energy. The large acceptances of the STAR TPC and EMC systems cover most of the decay lepton (e^\pm) phase space, and allow for strict isolation conditions to be imposed on the lepton, while also enabling a veto on substantial away-side energy. These two requirements reduce the ‘QCD’ background by several orders of magnitude, resulting in clean yield extraction. Preliminary results for the W^+ and W^- production cross sections and parity-violating single-spin asymmetries A_L , obtained from the 2009 data set at $\sqrt{s} = 500$ GeV, are presented.

1. Introduction

Collisions of high energy polarized proton beams ($\sqrt{s} = 200$ -500 GeV) at the RHIC facility at Brookhaven National Laboratory provide a unique opportunity to gain insight into one of the fundamental challenges facing modern nuclear physics: obtaining a quantitative description of the spin structure of the nucleon. Two decades of polarized lepton deep-inelastic scattering experiments (pDIS) have revealed that the integrated contribution of quark and anti-quark spins to that of the proton is surprisingly small, on the order of $\sim 33\%$ [1]. While semi-inclusive measurements allow one, in principle, to disentangle the flavor-dependence of the $q + \bar{q}$ contributions [2, 3, 4], doing so relies on having a detailed understanding of how u and d quarks and anti-quarks fragment into observable hadrons. On the theoretical front, it has become feasible in recent years to carry out so-called ‘global’ analyses that fit both pDIS (inclusive and semi-inclusive) data and recent RHIC $\vec{p} + \vec{p}$ scattering data simultaneously and on an equal footing [5]. This new generation of analyses is more complete than previous versions, in that they not only incorporate larger data sets, but are carried out to next-to-leading order (NLO) in QCD for the hard processes, and treat the soft processes self-consistently [5]. Even working within such a framework, however, the uncertainties obtained for the anti-quark polarized parton distribution functions (pPDF’s) remain large, suggesting that \bar{q} helicity preferences in the nucleon are relatively unconstrained by current data sets.

To date, much of the RHIC spin physics effort has been focused on constraining gluonic spin contributions to the proton through measurements of the longitudinal double-spin asymmetry

A_{LL} in inclusive jet [6, 7] and neutral hadron [8] production. In this report, we present preliminary results on a major new thrust in the RHIC program: probing the spin and flavor structure of the \bar{q} sea in the nucleon via measurements of the parity-violating longitudinal *single*-spin asymmetry A_L in inclusive W boson production, studied at $\sqrt{s} = 500$ GeV. The dominant mechanism for producing a $W^{+(-)}$ in high-energy $p + p$ collisions is through $u + \bar{d}$ ($d + \bar{u}$) interactions, an s -channel process between a (typically) high- x quark in one proton and a lower- x anti-quark in the other. The $\sim 11\%$ decay branch for $W^\pm \rightarrow e^\pm + X$ provides a clean experimental signature of reasonably high efficiency. Interpretation of these leptonic W decay events is also fairly ‘clean,’ in that one is probing the q and \bar{q} pPDF’s at high scales set by the W mass ($M_W^2 > 6000$ GeV²), where perturbative approaches are well justified. Ambiguities due to uncertainties in fragmentation functions are absent. Moreover, the maximal parity-violating nature of the weak interaction ensures a robust connection between the measured A_L ’s and the helicities of the interacting q and \bar{q} in the polarized protons. Finally, we note that the simplicity of the actual detection scheme (determining the direction and energy of the decay e) facilitates the development of a theoretical framework for inclusive lepton production in which realistic experimental constraints (*e.g.*, on the detected lepton’s transverse momentum p_T and pseudo-rapidity η) can be easily treated [9, 10].

2. Experimental and analysis details for mid-rapidity W ’s

The data used for the W production analysis presented here were collected in 2009, from collisions of RHIC polarized proton beams, each at 250 GeV. The beam polarizations were measured using proton-carbon polarimeters that operated in the Coulomb-nuclear interference region [11], and had been calibrated against a polarized hydrogen gas-jet target [12]. Longitudinal polarization of the proton beams in the STAR interaction region (IR) was achieved using pairs of spin rotator magnets installed upstream and downstream of the IR, taking the proton spin orientation from vertical to longitudinal and back to vertical during each pass. The longitudinal polarizations achieved, averaged over all runs, were 0.38 and 0.40, with a common scale uncertainty of 9.2%.

The primary STAR detector subsystems used in this work are the Time Projection Chamber (TPC), which provides tracking of charged particles in a uniform 0.5 T solenoidal field for pseudorapidities $|\eta| < 1.3$, and the Barrel and Endcap Electromagnetic Calorimeters (BEMC, EEMC), which are lead-scintillator sampling calorimeters that extend over the ranges $|\eta| < 1.0$ and $1.1 < \eta < 2.0$, respectively, and provide full azimuthal coverage in ϕ . Potential W candidate events were selected online via a two-step trigger condition imposed on the BEMC tower energies. Kinematically, leptons emitted at mid-rapidity from W decay have a large transverse energy, E_T , with a maximum at roughly $M_W/2$ and a distribution characteristic of a ‘Jacobian peak.’ The first-level hardware trigger requirement was that the E_T for a single BEMC tower ($\Delta\eta \times \Delta\phi = 0.05 \times 0.05$) exceed 7.3 GeV. A higher-level trigger required that at least one 2×2 ‘patch’ of towers, that included a trigger tower, had a summed $E_T > 13.0$ GeV. A total of 1.4×10^6 events were collected that satisfied this latter condition, from a data sample of approximately 14 pb^{-1} , as determined using a Vernier scanning technique [13].

Offline, W candidate events were selected based on established kinematic and topological differences between leptonic W decays and background QCD-driven processes. Events from $W \rightarrow e + \nu$ will contain a nearly isolated e^\pm and an (undetected) neutrino opposite in azimuth, resulting in a large missing E_T . Such events will exhibit a substantial imbalance in the vector sum of the transverse momenta, \vec{p}_T , when evaluated for all final-state particles. Background QCD events, however, which are dominated by di-jets and other $2 \rightarrow 2$ processes, would typically have a much smaller magnitude for \vec{p}_T when summed over particles detected at all azimuthal angles.

For this analysis, a W -decay e^\pm candidate was defined to be any TPC track with $p_T > 10$ GeV/ c that originated from a primary vertex along the beam direction(s) that was within

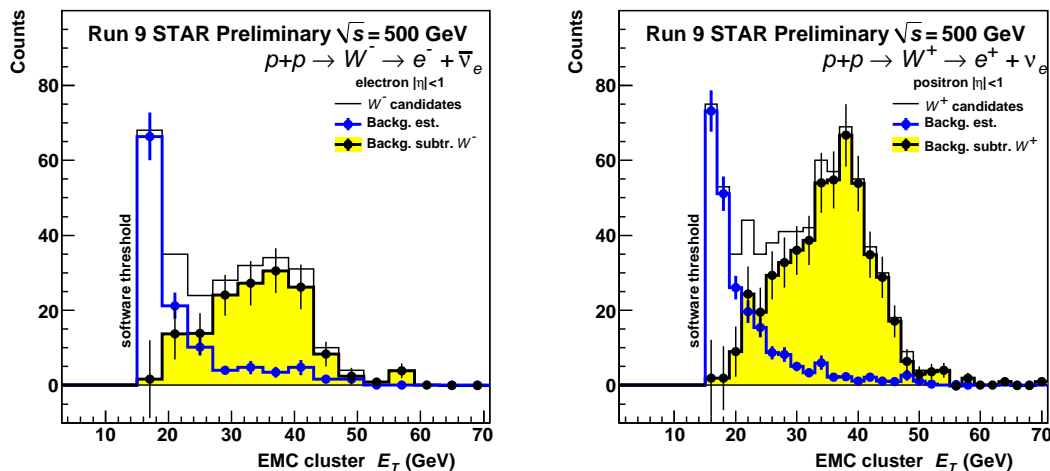


Figure 1. BEMC transverse energy (E_T) distributions for W^- (left) and W^+ (right) candidates. Background estimates are shown in blue, and the signal distributions in filled yellow.

100 cm of the center of STAR ($z=0$). The candidate track was required to ‘point’ to a 2×2 BEMC tower cluster with an E_T sum, E_T^e , greater than 15 GeV, and whose energy-weighted centroid was less than 7 cm from the extrapolated track trajectory. To select isolated leptons only, the additional summed E_T in the surrounding 4×4 tower cluster was required to be less than 5% of E_T^e , and *all* the excess energy (summed BEMC and EEMC E_T plus TPC track p_T) within a radius $R = 0.7$ in η - ϕ space of the candidate was required to be less than 12% of E_T^e . Finally, to suppress most QCD contributions, candidate events were rejected if they had either substantial ‘away-side’ E_T or no imbalance in total p_T . The away-side E_T was taken to be the EMC and TPC E_T sum over the full η range covered by STAR detectors, and over all ϕ within ± 0.7 radians of being opposite to ϕ_e . The total p_T was calculated as the vector sum of the lepton candidate p_T , plus that of any jets reconstructed with thrust axes more than $R = 0.7$ from the candidate. In this analysis, all W candidates were required to have an away-side $E_T < 30$ GeV, and total $p_T > 15$ GeV.

3. Raw yields and background concerns

Figure 1 shows the charge-separated yields obtained, as a function of E_T^e (the BEMC 2×2 tower cluster E_T), for all events that satisfied the full set of selection criteria outlined above. The $W^\pm \rightarrow e^\pm$ candidates exhibit the expected Jacobian peak shape, with maxima at $E_T^e \sim M_W/2$. Our efficiency for detecting and reconstructing such events was estimated using PYTHIA-based Monte-Carlo, with full GEANT simulation of the STAR detector responses. Within the kinematic acceptance of the e^\pm imposed in this analysis ($|\eta_e| < 1$ and $E_T^e > 25$ GeV), the overall reconstruction efficiency was estimated to be 56%.

To extract final yields, it was necessary to account for the remaining background that underlies the Jacobian peak of interest. The background was assumed to arise from three sources. The first contribution is from the process $W^\pm \rightarrow \tau^\pm + \nu$, followed by the decay $\tau^\pm \rightarrow e^\pm + 2\nu$. The size and shape (in E_T^e) of this background was determined using a Monte-Carlo simulation similar to the one used to estimate the reconstruction efficiency. A second source of background is due to QCD di-jet events in which the away-side jet fell largely outside the STAR detector acceptance. This is dominated by jets heading into the region $-2 < \eta < -1$, *i.e.*, towards the

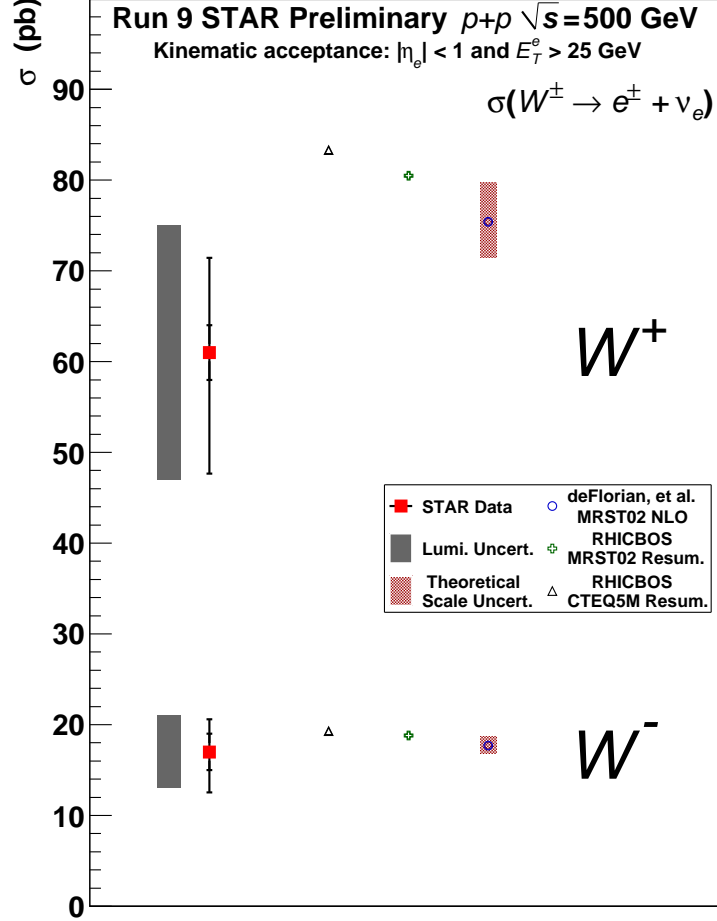


Figure 2. Measured cross sections for W^+ and W^- production, compared to full resummed and NLO predictions. See text for details.

‘missing’ Endcap EMC. By isolating the background events vetoed by use of the EEMC, one can measure this contribution and correct for it, by subtracting the endcap-vetoed events twice. The final contribution – essentially everything that is left – was estimated by normalizing a data-driven background shape (see below) to the remaining W candidate signal in the E_T^e range below 19 GeV, after the first two background sources had been subtracted. This shape was obtained by using the inverse of the last two requirements for the W candidate selection; that is, we required that either the away-side E_T exceeded 30 GeV, or the total vector-summed p_T be less than 15 GeV.

The full background (all contributions) and the background-subtracted spectra (final W candidates) are shown in Figure 1 as the blue histograms and the filled yellow histograms, respectively. The systematic uncertainty associated with the background subtraction scheme was determined by varying thresholds for the inverse cuts used in obtaining the data-driven background component, and by varying the range over which this background shape was normalized to the accepted W signal.

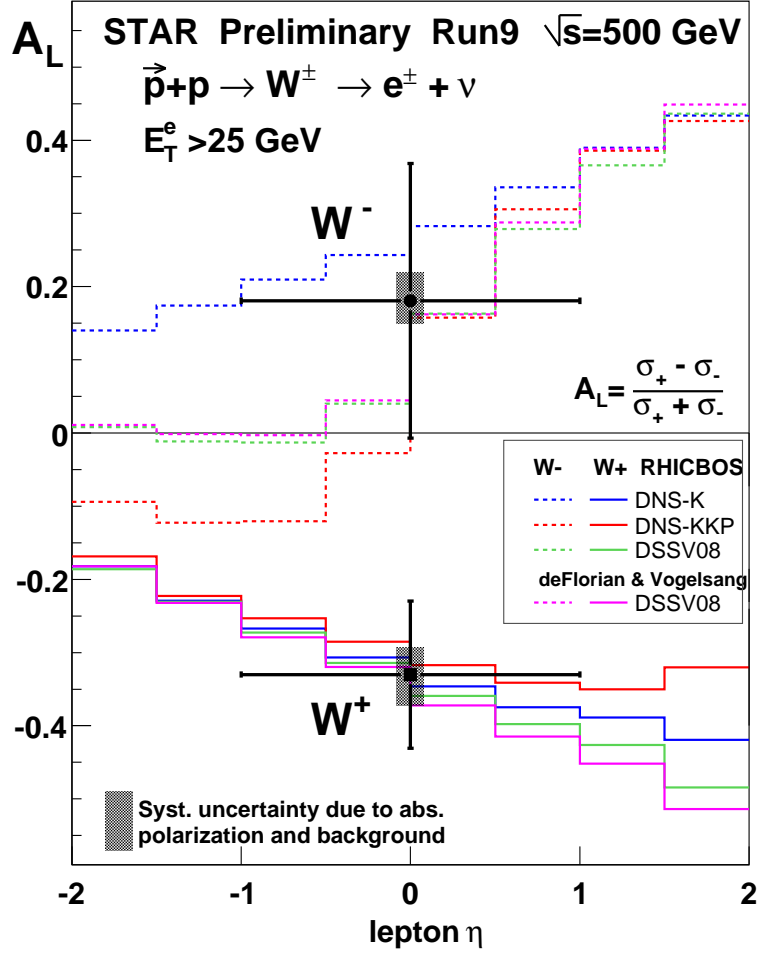


Figure 3. Measured longitudinal single-spin asymmetries, A_L , for W^- (top) and W^+ (bottom) events, integrated over lepton pseudorapidities $|\eta| < 1$, compared to several theoretical predictions. See text for details.

4. Results

Preliminary results for the $W^\pm \rightarrow e^\pm + X$ production cross section, integrated over all candidate events with $|\eta_e| < 1$ and $E_{T_e} > 25$ GeV, are presented in Figure 2. The measured values are $\sigma(W^+) = 61 \pm 3$ (stat.) $^{+10}_{-13}$ (syst.) ± 14 (lumi.) pb, and $\sigma(W^-) = 17 \pm 2$ (stat.) $^{+3}_{-4}$ (syst.) ± 4 (lumi.) pb. The statistical and systematic uncertainties, excluding absolute luminosity contributions, are indicated by the horizontal ticks on the error bars for the (red) data points. Systematic uncertainties due to the measured luminosity, which are shown separately as the gray bands to the left of the data, are dominated by uncertainties in the vernier scan measurement attributed to poorly understood non-Gaussian terms in the beam profile analysis [13]. The measured W^+ and W^- production cross sections are seen to be consistent with predictions based on full resummed (RHICBOS) [9] and NLO (CHE) [14] evaluations, which are also shown in Fig. 2. Theoretical scale uncertainties for the NLO predictions are indicated by brown shaded

bands.

In Figure 3, preliminary values are shown for the measured longitudinal single-spin asymmetries $A_L = (1/P_{\text{avg}})(N_+ - N_-)/(N_+ + N_-)$, where $N_{+(-)}$ are the luminosity-normalized candidate yields obtained with positive (negative) helicity proton beams, and P_{avg} is the magnitude of the beam polarization, averaged over both RHIC beams and over all runs. The asymmetries are $A_L(W^+) = -0.33 \pm 0.10$ (stat.) ± 0.04 (syst.), and $A_L(W^-) = +0.18 \pm 0.19$ (stat.) ± 0.04 (syst.). The systematic uncertainties, shown as the vertical gray bands on Fig. 3, are dominated by errors associated with P_{avg} .

The measured spin asymmetries are again compared to resummed RHICBOS [9] and NLO CHE [10] predictions. The CHE calculations use the DSSV08 pPDF's [5], while RHICBOS calculations are also shown for the older DNS-K and DNS-KPP pPDF's [14]. The calculations are all quite similar, especially at forward η_e for W^- and at backward η_e for W^+ , where the asymmetries are driven by the well-known valence d and u quark pPDF's, respectively. Similarly, the large differences seen among the calculations at the opposite ends of η_e simply reflect how poorly the \bar{u} and \bar{d} pPDF's are constrained by current data. Both spin asymmetries are very consistent with current theoretical expectations. A more detailed discussion of the final spin asymmetry results can be found in Ref. [15]

5. Summary and Outlook

Study of the parity-violating, longitudinal single-spin asymmetry A_L for W boson production, via collisions of high-energy polarized protons, offers a clean and novel approach for probing the flavor and spin structure of the proton. We report here the first measurements of W^+ and W^- production cross sections and single-spin asymmetries at $\sqrt{s} = 500$ GeV, for decay electrons and positrons detected at mid-rapidity ($|\eta_e| < 1$) and with $E_T^e > 25$ GeV. The results presented here, taken with the STAR detector at RHIC, are seen to be consistent with full resummed and NLO calculations. Future measurements of this sort planned for STAR at mid-rapidity, together with new measurements at more forward and backward pseudorapidities, taken with increased luminosity and higher beam polarizations, are expected to provide significant constraints on the helicity properties of the QCD sea.

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