Measurement of Longitudinal Spin Asymmetries for Weak Boson Production in Polarized Proton-Proton Collisions at STAR

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The production of $W^\pm$ bosons in longitudinally polarized $p + p$ collisions is a powerful tool to study the spin-flavor structure of the proton. We report measurements of single- and double-spin asymmetries for W and Z/γ^* production in longitudinally polarized proton-proton collisions at $\sqrt{s} = 510$ GeV at RHIC. The single-spin asymmetry results for $W^\pm$ from data sets collected by STAR experiment in 2011 and 2012 provided new constraints on proton's polarized sea quark distributions and prefer a sizable value for $\bar{u}$ polarization. The status for the analysis of a much larger data set collected by STAR in 2013 will also be given.

Keywords: Weak boson; quark polarization.

1. Introduction

Understanding the spin structure of proton is a fundamental and longstanding challenge in nuclear physics. The total quark contribution has been well measured from polarized inclusive deep-inelastic scattering (DIS) experiments, and was found to contribute only $\sim 30\%$ of the proton spin.¹ The flavor separated contribution can be accessed through semi-inclusive DIS experiments, but they have to rely on the use of fragmentation functions to relate the measurements of the final state hadrons to the quark and anti-quark distributions. The extracted anti-quark helicity-dependent parton distribution functions (PDFs) have relatively large uncertainty^{2,3}.

The production of $W^\pm$ bosons in polarized proton-proton collisions at RHIC, the Relativistic Heavy-Ion Collider, is a powerful tool to study the spin-flavor structure of the proton. The coupling of $W^\pm$ bosons to left-handed quarks and right-handed

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anti-quarks determines the helicity of the incident quarks. This provides a theoretically clean probe of the helicity-dependent PDFs through a parity-violating longitudinal single-spin asymmetry, which is defined as $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where $\sigma_{+(-)}$ is the cross section when the polarized beam has positive (negative) helicity. At leading order, the A_L of $W^\pm$ can be directly sensitive to $\Delta\bar{u}$ and $\Delta\bar{d}$, the helicity-dependent PDFs of $\bar{u}$ and $\bar{d}$ quarks, expressed by:

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}, \quad (1)$$

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}, \quad (2)$$

where x_1 and x_2 are the momentum fractions carried by the incident partons. We can directly measure the flavor separated quark and anti-quark polarizations, by identifying the rapidity of W , y_W . The $A_L^{W^+}$ ($A_L^{W^-}$) approaches $\Delta u/u$ ($\Delta d/d$) in the very forward region ($y_W \gg 0$), or $-\Delta\bar{d}/\bar{d}$ ($-\Delta\bar{u}/\bar{u}$) in the very backward region ($y_W \ll 0$).⁴

First measurements of the single-spin asymmetry, A_L , for W production at RHIC were reported by the STAR⁵ and PHENIX⁶ collaborations from a data set collected in 2009, the successful commission run at $\sqrt{s}=500\text{GeV}$. In this contribution, we report the results for the single- and double-spin asymmetries for $W^\pm$ and Z/γ^* production measured from data sets collected in 2011 and 2012 by STAR experiment, with integrated luminosity of 9 and 77 pb^{-1} , and average beam polarization of 49% and 56%, respectively.

2. Analysis

At STAR, $W^\pm$ bosons are detected via their $W^\pm \rightarrow e^\pm\nu$ decay channels. The charge separation and p_T of the lepton tracks are measured by the Time Projection Chamber (TPC), and the lepton energy is measured by the Barrel and Endcap Electromagnetic Calorimeters (BEMC, EEMC). The candidate $W^\pm \rightarrow e^\pm\nu$ events are characterized by an isolated $e^\pm$ with a E_e^T , transverse energy, that peaks near half the $W^\pm$ mass. Due to the large missing energy in the opposite azimuth of the $e^\pm$ candidates caused by the undetected neutrinos decayed from $W^\pm$, there should be a large imbalance in the vector p_T sum of all reconstructed final-state objects for $W^\pm$ events in contrast to $Z/\gamma^* \rightarrow e^+e^-$ and QCD di-jet background events. The main W selection cuts used to suppress the background and enhance the W signals are based on the isolation and p_T imbalance requirements.

Firstly, we match reconstructed TPC tracks with $p_T > 10$ GeV with the 2×2 EMC tower clusters with $E_T > 14$ GeV. The E_T fraction of the 2×2 EMC cluster over the 4×4 EMC cluster in which it is centered is required to be greater than 95%. Additionally, in the near-cone around the candidate lepton with a radius of

0.7 in $\eta - \phi$ space, the excess E_T fraction is required to be less than 12%. To implement the p_T imbalance requirement, we reconstruct a p_T -balance variable $\vec{p}_T^{bal}$ by summing the $\vec{p}_T^e$ vector of candidate $e^\pm$ and all jets, reconstructed using an anti- k_T algorithm,⁸ outside the near-cone mentioned above. Finally, we require the scalar variable signed p_T -balance, $(\vec{p}_T^{bal} \cdot \vec{p}_T^e)/|\vec{p}_T^e|$, to be larger than 14 GeV.

The charge separated $W^\pm$ yields from 2011 and 2012 data sets as a function of E_e^T in different η -bins are shown at Fig. 1, along with the estimated residual background contributions from $W^\pm \rightarrow \tau^\pm \nu_\tau$, $Z/\gamma^* \rightarrow e^+e^-$ electroweak processes and QCD processes. The electroweak backgrounds were estimated from Monte-Carlo (MC) simulation, with PYTHIA events passing the STAR GEANT model and embedding into STAR zero-bias triggered events. The QCD backgrounds were estimated through two procedures, referred to “Second EEMC” and “Data-driven QCD”, to account for QCD events which passed the W selection criteria due to missing detected jets in range $-2 < \eta < -1.09$, the mirror range of EEMC^a, and range $|\eta| > 2$, respectively.

At forward rapidity ($\eta_e > 1$), in addition to the isolation and signed p_T -balance requirement described above, the EEMC Shower Maximum Detector (ESMD) is used to suppress the backgrounds. More details are described in Ref. 9.

Fig. 1. E_T^e distribution of W^- (top) and W^+ (bottom) candidate events (black), background contributions, and sum of backgrounds and $W \rightarrow e\nu$ MC signal (red-dashed).⁹

^aSTAR detector has only one Endcap EMC in the west side, covering $1.09 < \eta < 2$.

3. Results

A likelihood method was used to extract the spin asymmetry results with 2011 and 2012 data sets, to treat the low statistics of 2011 sample. We defined the likelihood function L_{year} for 2011 and 2012 data sets independently, $year=2011, 2012$,

$$L_{year} = \prod_i^4 \mathcal{P}(M_i^a | \mu_i^a) \mathcal{P}(M_i^b | \mu_i^b) g(\beta^a) g(\beta^b). \quad (3)$$

It is the product of two Poisson probabilities, $\mathcal{P}(M_i | \mu_i)$, for measuring M_i events in an expected value μ_i and two Gaussian probabilities $g(\beta)$ for the estimated background dilution. The superscripts a and b respectively stand for the positive side and negative side of a pair of symmetric detector η regions. The expected value μ_i is the function of spin asymmetries, collision helicity configuration, beam polarization, and spin average yield. β is the unpolarized background dilution factor defined as $\beta = S/(S+B)$, where S and B are the numbers of signal and background events as shown in Fig. 1. The asymmetry results, central values and confidence intervals, are extracted from the product of likelihood functions, $L_{2011} \times L_{2012}$. The $W^\pm$ single-spin asymmetry results measured for $e^\pm$ with $25 < E_T^e < 50$ GeV are shown in Fig. 2, as the function of decayed $e^\pm$ pseudorapidity, with comparison to the theoretical predictions based on DSSV08² and LSS10³ helicity-dependent PDF

Fig. 2. Longitudinal single-spin asymmetries for $W^\pm$ production as a function of lepton pseudorapidity magnitude, $|\eta_e|$, in comparison with theory predictions.⁹

Fig. 3. Longitudinal double-spin asymmetries for $W^\pm$ production as a function of lepton pseudorapidity magnitude, $|\eta_e|$, in comparison with theory predictions.⁹

sets, using both CHE¹⁰(next-to-leading order) and RHICBOS¹¹(fully resummed), as indicated by the Legends.

In Fig. 2, the measured $A_L^{W^+}$ is negative, consistent with the theoretical predictions. For $A_L^{W^-}$ however, the measured asymmetry is larger than the central value of the theoretical predictions for $\eta_e < 0$. This region is most sensitive to the up antiquark polarization $\Delta\bar{u}$, which is not currently well constrained as can be seen by the large uncertainty in the theoretical prediction there. The large, positive values for $A_L^{W^-}$ indicate a preference for a sizable, positive $\Delta\bar{u}$ in the range $x > 0.05$.

The double-spin asymmetry, A_{LL} for $W^\pm$ was also measured and is shown in Fig. 3, which is sensitive to the product of quark and antiquark polarizations, and has also been proposed to test positivity constraints using a combination of A_L and A_{LL} .¹² The measured double-spin asymmetries are consistent with the theoretical predictions and in conjunction with $A_L^{W^\pm}$ satisfy the positivity bounds within the current uncertainties.

The sample of $Z/\gamma^* \rightarrow e^+e^-$ was also reconstructed from a pair of isolated and oppositely charged $e^\pm$ candidates from the 2011 and 2012 data sets. The single-spin asymmetry A_L^{Z/γ^*} for Z/γ^* production with $|\eta| < 1.1$, $E_T^e > 14$ GeV, and $70 < m_{e^+e^-} < 110$ GeV/ c^2 was extracted through a similar likelihood method described above. The measured asymmetry is $A_L^{Z/\gamma^*} = -0.07^{+0.14}_{-0.14}$, which is consistent with theoretical predictions using the different helicity-dependent PDFs, A_L^{Z/γ^*} (DSSV08) = -0.07 and A_L^{Z/γ^*} (LSS10) = -0.02.

4. Outlook

In 2013, the STAR experiment collected a much larger $p + p$ data sample, with an integrated luminosity of ~ 300 pb⁻¹ at $\sqrt{s} = 510$ GeV with an average beam polarization of $\sim 54\%$, which is more than 3 times larger than the total integrated luminosity of previous years. And, with the Forward Gem Tracker (FGT) installed for 2013 running, the acceptance can be enlarged by a factor of 2 in pseudorapidity.

Fig. 4. Projected uncertainties for the longitudinal single-spin asymmetries as a function of lepton pseudorapidity for $W^\pm$ production measurements from 2013 data set.

This will enhance the sensitivity to $\bar{u}$ and $\bar{d}$ quark polarization. Currently, the analysis on 2013 data set is ongoing and the expected precision for $W^\pm$ A_L are shown in Fig. 4. The new measurements are expected to provide further important constraints on the sea quarks helicity-dependent PDFs.

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