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Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at $\sqrt{s} = 510$ GeV

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We report new STAR measurements of the single-spin asymmetries $A_L$ for $W^+\rightarrow W^+\rightarrow e^+\nu$ and $W^-\rightarrow W^-\rightarrow e^-\bar{\nu}$ decay channels. Provide sensitivity to the helicity distributions of the quarks, $\Delta u$ and $\Delta d$, and antiquarks, $\Delta \bar{u}$ and $\Delta \bar{d}$, that is free of uncertainties associated with nonperturbative fragmentation. The cross sections are well described [1]. The primary observable is the longitudinal single-spin asymmetry $A_L \equiv (\sigma_+ - \sigma_-)/\sigma_+\sigma_-$ where $\sigma_+(-)$ is the cross section when the helicity of the polarized proton beam is positive (negative). At leading order,

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

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

where $x_1(x_2)$ is the momentum fraction carried by the colliding quark or antiquark in the polarized (unpolarized) beam. $A_L^{W^+}(y_W)$ approaches $-\Delta u/\bar{u}$ in the very forward region of $W$ rapidity, $y_W \gg 0$, and $\Delta d/\bar{u}$ in the very backward region of $W$ rapidity, $y_W \ll 0$. The observed positron and electron pseudorapidities, $\eta$, are related to $y_W$ and to the decay angle of the positron and electron in the $W$ rest frame [19]. Higher-order corrections to $A_L(\eta)$ are known [20–22] and have been incorporated into the aforementioned global analyses.

In this article, we report new measurements of the single-spin asymmetries for decay positrons and electrons from $W^\pm$ bosons produced in longitudinally polarized proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 510$ GeV. In addition, we report new results for the double-spin asymmetries $A_{LL}$ for $W^\pm$ and $A_L$ for $Z/\gamma^\ast$ production and subsequent decay into electron-positron pairs.

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Understanding the spin structure of the proton in terms of its quark, antiquark, and gluon constituents is of fundamental interest. This description is commonly done using polarized parton distribution functions (PDFs), which can be determined using perturbative QCD techniques and global analyses of data from polarized deep-inelastic lepton-nucleon scattering (DIS) experiments and from high-energy polarized proton-proton scattering experiments at the Relativistic Heavy Ion Collider (RHIC). Recent examples of such PDFs are given in Refs. [1,2]. The data from leptonic $W$-decays in polarized proton-proton collisions at RHIC [3–7] provide constraints in these global analyses, which now show a strong asymmetry in the light sea-quark polarizations for parton momentum fractions, $0.05 < x < 0.25$, at hard perturbative scales. The existence of such an asymmetry in the polarized PDFs has been searched for directly in semi-inclusive DIS experiments [8–10] but has thus far been established only in the case of the unpolarized PDFs. There, Drell-Yan measurements [11,12] and DIS measurements [13,14], in particular, have reported large enhancements in the ratio $\bar{d}$ over $\bar{u}$ antiquark distributions. This has provided a strong impetus for theoretical modeling [15] and renewed measurement [16]. Considerable progress is being made also in lattice-QCD [17].

The leptonic $W^+ \rightarrow e^+\nu$ and $W^- \rightarrow e^-\bar{\nu}$ decay channels provide sensitivity to the helicity distributions of the quarks, $\Delta u$ and $\Delta d$, and antiquarks, $\Delta \bar{u}$ and $\Delta \bar{d}$, that is free of uncertainties associated with nonperturbative fragmentation. The cross sections are well described [18]. The primary observable is the longitudinal single-spin asymmetry $A_L \equiv (\sigma_+ - \sigma_-)/\sigma_+\sigma_-$ where $\sigma_+(-)$ is the cross section when the helicity of the polarized proton beam is positive (negative). At leading order,
Electron sum events are characterized by an isolated topological feature that allows discrimination against jets, the ratio of the number of positrons or electrons, and discriminate against jets, the ratio of the number of positrons or electrons to the transverse momentum, $p_T$, imposed on the transverse momentum of the particle from the curvature of the TPC tracks in the solenoidal magnetic field. Figure 1(a) and 1(b) show the distribution of the reconstructed charge-sign, $Q = \pm 1$, multiplied by

$$Q \cdot E_T/p_T$$

where $E_T$ is the transverse energy and $p_T$ is the transverse momentum of the particle. The positron (red) and electron (blue) candidate events have been excluded in the BEMC (a) and EEMC (b) regions. Star of STAR 2013 is marked by a hatched shade.
the ratio of $E_T^e$ observed in the BEMC and EEMC to $p_T^\tau$ determined with the TPC for events in the signal region, $25 < E_T^e < 50$ GeV. The relative yields of the $W^+$ and $W^-$ follow the pseudorapidity dependence of the cross-section ratio. The distributions were each fitted with two double-Gaussian template shapes, determined from a Monte Carlo simulation in each of the templates. The remaining $p_T$-balance values were fixed by studies in which simulated $W^+ \rightarrow e^+\nu$ and $W^- \rightarrow e^-\bar{\nu}$ events were embedded (c.f. the paragraph below) in zero-bias data. The hatched regions, $|Q \cdot E_T/p_T| < 0.4$ and $|Q \cdot E_T/p_T| > 1.8$, were excluded to remove tracks with poorly reconstructed $p_T$ and to reduce contamination from events with opposite charge-sign. This contamination is negligible at midrapidity, but increases to 9.6% and 12.0% for $W^+$ and $W^-$ candidate events, respectively, in the EEMC region. The forward $A_t$ values were corrected for this contamination using the asymmetries observed in the data.

Figure 2 shows the distributions of $W^+$ and $W^-$ yields as a function of $E_T^e$ for the four central $\eta_e$ intervals considered in this analysis, along with the estimated residual background contributions from electroweak and QCD processes. The residual electroweak backgrounds are predominantly due to $W^\pm \rightarrow \tau^\pm \nu_\tau$ and $Z/\gamma^* \rightarrow e^+e^-$. These contributions were estimated from Monte Carlo simulations, using events generated with PYTHIA 6.4.28 [29] and the "Perugia 0" tune [30] that passed through a GEANT 3 [31] model of the STAR detector, and were subsequently embedded into STAR zero-bias data. The simulated samples were normalized to the $W$ data using the known integrated luminosity. The TAUOLA package was used for the polarized $\tau^\pm$ decay [32]. Residual QCD dijet background in which one of the jets pointed to uninstrumented pseudorapidity regions was estimated using two separate procedures. The contribution from $e^\pm$ candidate events with an opposite-side jet fragment in the uninstrumented region $2 < \eta < -1.1$ was estimated by studying such data in the EEMC, which instruments the region $1.1 < \eta < 2$. This is referred to as the “Second EEMC” procedure. Residual background from the uninstrumented region $|\eta| > 2$ was estimated by studying events that satisfy all isolation criteria, but do not satisfy the cuts on the scalar signed $p_T$-balance variable. This is referred to as the “Data-driven QCD” procedure. To assess the background remaining in the signal region, the $E_T$ distribution of this background-dominated sample was normalized to the signal candidate distribution that remained after all other background contributions had been removed for $E_T$ values between 14 and 18 GeV. Additional aspects of both procedures are described in Refs. [3, 18].

Figure 3 shows the charge-separated distributions in the EEMC region as a function of the signed $p_T$-balance variable, together with the estimated residual background contributions. Residual electroweak backgrounds for these regions were estimated in the same way as for the midrapidity data. Residual QCD backgrounds were estimated using the ESMD, where the isolation parameter $R_{ESMD}$ was required to be less than 0.6 for QCD background events. The shape was determined for each charge-sign separately and normalized to the measured yield in the region where the signed $p_T$-balance variable was between $-8$ and $8$ GeV/$c$. This region is dominated by QCD backgrounds.

At RHIC, there are four helicity configurations for the two longitudinally-polarized proton beams: $++$, $+-$, $-+$, $--$.
and $--$. The data from these four configurations can be combined such that the net polarization for one beam effectively averages to zero, while maintaining high polarization in the other. The longitudinal single-spin asymmetry $A_L$ for the combination in which the first beam is polarized and the second carries no net polarization was determined from

$$A_L = \frac{1}{\beta P} \frac{R_{++}N_{++} + R_{+-}N_{+-} - R_{--}N_{--} - R_{-+}N_{-+}}{R_{++}N_{++} + R_{+-}N_{+-} + R_{-+}N_{-+} + R_{--}N_{--}},$$

where $\beta$ is the signal purity, $P$ is the average beam polarization, and $R$ and $N$ are the normalizations for relative luminosity and the raw $W^\pm$ yields, respectively, for the helicity configurations indicated by the subscripts. The relative luminosities were obtained from a large QCD sample that exhibits no significant single-spin asymmetry. Typical values were between 0.993 and 1.009. The purity was evaluated from the aforementioned signal and background contributions and was found to be between 83% and 98%. $A_L$ was determined in a similar way for the combination in which the second beam is polarized and the first carries no net polarization, and the values for the two combinations were then combined.

The $A_L$ results for $W^+$ and $W^-$ from the data sample recorded by STAR in 2013 are shown in Fig. 4 as a function of $\eta_e$. The vertical error bars show the size of the statistical uncertainties, including those associated with the correction for the wrong charge-sign in the case of the points at $|\eta_e| \approx 1.2$. The previously published STAR data [4] are shown for comparison. Shown also are the $A_L$ results on high-energy forward decay muons and midrapidity positrons or electrons from combined $W$ and $Z/\gamma^*$ production by the PHENIX experiment with their statistical and systematic uncertainties as a function of $\eta_e$ and $\eta_\mu$, respectively [6,7].

The size of systematic uncertainties associated with BEMC and EEMC gain calibrations (5% variation) and the data-driven QCD background are indicated by the boxes.
TABLE I. Longitudinal single- and double-spin asymmetries, $A_L$ and $A_{LL}$, for $W^\pm$ production obtained from the STAR 2013 data sample, as well as the combination of 2013 with 2011 + 2012 results. The longitudinal single-spin asymmetry is measured for six decay positron or electron pseudorapidity intervals. The longitudinal double-spin asymmetry was determined in the same intervals and the results for the same absolute pseudorapidity value were combined. The systematic uncertainties include all contributions and thus also include the point-by-point correlated uncertainties from the relative luminosity and beam polarization measurements that are broken out separately in Figs. 4 and 5.

| $\langle \eta_e \rangle$ | $A_L \pm \sigma_{stat} \pm \sigma_{syst}$ | $A_L \pm \sigma_{stat} \pm \sigma_{syst}$ | $A_{LL} \pm \sigma_{stat} \pm \sigma_{syst}$ | $A_{LL} \pm \sigma_{stat} \pm \sigma_{syst}$ |
|----------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
|                      | 2013                                             | 2011–2013                                        | 2013                                             | 2011–2013                                        |
| $W^+$                | $-1.24 \pm 0.94 \pm 0.18 \pm 0.022$             | $-0.312 \pm 0.145 \pm 0.017$                   | $0.039 \pm 0.049 \pm 0.014$                     | $0.016 \pm 0.042 \pm 0.011$                     |
|                      | $-0.72 \pm 0.25 \pm 0.035 \pm 0.016$            | $-0.251 \pm 0.030 \pm 0.014$                   | $0.049 \pm 0.063 \pm 0.014$                     | $0.072 \pm 0.054 \pm 0.011$                     |
|                      | $-0.25 \pm 0.32 \pm 0.027 \pm 0.014$            | $-0.331 \pm 0.023 \pm 0.014$                   | $-0.052 \pm 0.331 \pm 0.044$                    | $0.000 \pm 0.262 \pm 0.028$                     |
| $W^-$                | $0.25 \pm 0.40 \pm 0.027 \pm 0.016$             | $-0.412 \pm 0.023 \pm 0.016$                   | $0.067 \pm 0.120 \pm 0.025$                     | $-0.012 \pm 0.101 \pm 0.019$                    |
|                      | $0.72 \pm 0.55 \pm 0.034 \pm 0.024$             | $-0.534 \pm 0.029 \pm 0.022$                   | $-0.096 \pm 0.107 \pm 0.026$                    | $-0.028 \pm 0.092 \pm 0.020$                    |
|                      | $1.24 \pm 0.36 \pm 0.18 \pm 0.023$             | $-0.482 \pm 0.140 \pm 0.020$                   | $0.038 \pm 0.501 \pm 0.014$                     | $-0.133 \pm 0.331 \pm 0.061$                    |
|                      | $1.27 \pm 0.26 \pm 0.18 \pm 0.010$             | $0.241 \pm 0.146 \pm 0.010$                    | $0.205 \pm 0.148 \pm 0.009$                     | $-0.147 \pm 0.260 \pm 0.038$                    |

FIG. 5. Longitudinal single-spin asymmetries, $A_L$, for $W^\pm$ production as a function of the positron or electron pseudorapidity, $\eta_e$, for the combined STAR 2011 + 2012 and 2013 data samples for $25 < E_T < 50$ GeV (points) in comparison to theory expectations (curves and bands) described in the text.

FIG. 6. The difference of the light sea-quark polarizations as a function of $x$ at a scale of $Q^2 = 10$ (GeV/c)$^2$. The data confirm the existence of a sizeable, positive $\Delta u$ in the range $0.05 < x < 0.25$ [4] and the existence of a flavor asymmetry in the polarized quark sea.

In addition, $A_L$ was determined for $Z/\gamma^*$ production from a sample of 274 electron-positron pairs with $70 < m_{e^+e^-} < 110$ GeV/c$^2$. The $e^+$ and $e^-$ were each required to be isolated, have $|\eta_e| < 1.1$, and $E_T > 14$ GeV. The result, $A_L^{Z/\gamma^*} = -0.04 \pm 0.07$, is consistent with that in Ref. [4] but with half the statistical uncertainty.

Reweighting procedure of Refs. [36,37] with the 100 publicly available NNPDFpol1.1 PDFs. The results from this reweighting, taking into account the total uncertainties of the STAR 2013 data and their correlations [38], are shown in Fig. 5 as the blue hatched bands. The NNPDFpol1.1 uncertainties [1] are shown as the green bands for comparison. Figure 6 shows the corresponding differences of the light sea-quark polarizations versus $x$ at a scale of $Q^2 = 10$ (GeV/c)$^2$. The data confirm the existence of a sizeable, positive $\Delta u$ in the range $0.05 < x < 0.25$ [4] and the existence of a flavor asymmetry in the polarized quark sea.
The systematic uncertainty is negligible compared to the statistical uncertainty. This result is also consistent with theoretical expectations, $A_L^{Z/γ} = -0.08$ from DSSV14 [2] and $A_L^{γ/γ} = -0.04$ from NNPDFpol1.1 [1].

In summary, we report new STAR measurements of longitudinal single-spin and double-spin asymmetries for $W^±$ and single-spin asymmetry for $Z/γ$ bosons produced in polarized proton-proton collisions at $\sqrt{s} = 510$ GeV. The production of weak bosons in these collisions and their subsequent leptonic decay is a unique process to delineate the quark and antiquark polarizations in the proton by flavor. The $A_L$ data for $W^+$ and $W^-$, combined with previously published STAR results, show a significant preference for $\Delta u(x, Q^2) > \Delta d(x, Q^2)$ in the fractional momentum range $0.05 < x < 0.25$ at a scale of $Q^2 = 10$ (GeV/c)$^2$. This is opposite to the flavor asymmetry observed in the spin-averaged quark-sea distributions.

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