Sea Asymmetry from Polarized W Boson Production

C. Cocuzza[1*], A. Metz [1] and N. Sato [2]

1 Department of Physics, SERC, Temple University, Philadelphia, PA 19122, USA
2 Jefferson Lab, Newport News, Virginia 23606, USA

Jefferson Lab Angular Momentum (JAM) Collaboration

* tug83224@temple.edu

August 11, 2021

Proceedings for the XXVIII International Workshop
on Deep-Inelastic Scattering and Related Subjects,
Stony Brook University, New York, USA, 12-16 April 2021
doi:10.21468/SciPostPhysProc.?

Abstract

We present the results of a global QCD analysis of helicity parton distribution functions (PDFs) that includes the latest polarized W-lepton production data from the STAR collaboration at the Relativistic Heavy-Ion Collider (RHIC). This data allows the first extraction of a nonzero helicity light-quark sea asymmetry within a simultaneous global QCD analysis of unpolarized and helicity PDFs.

1 Introduction

While the valence quark contribution to the proton's spin is constrained by polarized inclusive deep-inelastic scattering (DIS) data, far less is known about the helicity PDFs of gluons and antiquarks [1,2]. For the unpolarized PDFs, an asymmetry between the up and down antiquarks, $\bar{u}-\bar{d}$, has been well established through experiments [3,4] and global analyses. Semi-inclusive DIS (SIDIS) experiments have searched for evidence of an analogous sea asymmetry in helicity PDFs, $\Delta\bar{u}-\Delta\bar{d}$ [5–7], but only recently has evidence emerged for the asymmetry from W-lepton production in polarized pp collisions; see [8] and references therein.

The STAR collaboration at RHIC has measured at center-of-mass energy $\sqrt{s}=510$ GeV the longitudinal single-spin asymmetry $A_L \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where σ_+ (σ_-) is the cross section for positive (negative) proton helicity, for the leptonic decay channels $W^+ \to e^+\nu$ and $W^- \to e^-\bar{\nu}$. At leading order in the strong coupling α_S, these observables can be written as

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

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

where f (Δf) represents an unpolarized (helicity) PDF, x_1 (x_2) is the momentum fraction carried by the parton in the polarized (unpolarized) proton and y_W is the rapidity of the intermediate W boson. Combined with observables from DIS, these asymmetries provide an extra handle that allows the extraction of the helicity antiquark PDFs $\Delta\bar{u}$ and $\Delta\bar{d}$.

For the first time we include this data in a full global QCD analysis using the JAM Monte Carlo framework, along with data on polarized lepton-nucleon DIS and polarized jet production [9]. We also perform a *simultaneous* fit of unpolarized and helicity PDFs in order to properly quantify the errors on both distributions.

2 Methodology

Our theoretical framework is based on the JAM iterative Monte Carlo approach to QCD global analysis [11], which utilizes Bayesian inference sampling methodology that allows thorough exploration of the parameter space and robust error quantification. In this analysis, we parameterize both the unpolarized and helicity PDFs at the input scale $\mu_0^2 = m_c^2$, with m_c the mass of the charm quark, using the standard form,

$$f(x, \mu_0^2) = N x^{\alpha}(1-x)^{\beta}(1+\eta x) \tag{2}$$

where N, α, β, and η are the parameters to be fit. For the helicity PDFs, we discriminate the valence and sea components through parameterizations for the quantities

$$\begin{aligned} \Delta u &= \Delta u_v + \Delta\bar{u}, & \Delta d &= \Delta d_v + \Delta\bar{d}, \\ \Delta\bar{u} &= \Delta S + \Delta\bar{u}_0, & \Delta\bar{d} &= \Delta S + \Delta\bar{d}_0, \\ \Delta s &= \Delta S + \Delta s_0, & \Delta\bar{s} &= \Delta s, \end{aligned} \tag{3}$$

where the dependence on x and μ_0^2 has been suppressed. The input distributions Δu_v, Δd_v, $\Delta\bar{u}_0$, $\Delta\bar{d}_0$, and Δs_0, characterizing the quark distributions in the valence region, and the gluon helicity PDF Δg are parameterized individually as in Eq. (2). We assume that $\Delta\bar{s} = \Delta s$ as no data in this analysis is capable of distinguishing the two distributions. The ΔS distribution, which is shared between all sea quarks, also uses the template function and is designed to describe the small-x region by restricting the α in Eq. (2) so that the resulting distribution is more divergent compared to the valence PDFs. The parameter η is fitted for the gluon distribution to allow the flexibility of a zero crossing at the input scale. A similar, but more flexible, parameterization is used for the unpolarized PDFs [10].

Further constraints on the helicity PDFs are provided by fitting

$$\begin{aligned} &\int_0^1 \mathrm{d}x\big[\Delta u^+(x,Q^2) - \Delta d^+(x,Q^2)\big] = g_A, \\ &\int_0^1 \mathrm{d}x\big[\Delta u^+(x,Q^2) + \Delta d^+(x,Q^2) - 2\Delta s^+(x,Q^2)\big] = a_8, \end{aligned} \tag{4}$$

where $\Delta f^+ = \Delta f + \Delta\bar{f}$, while $g_A = 1.269(3)$ and $a_8 = 0.586(31)$ are the triplet and octet axial-vector charges, respectively, obtained from neutron and hyperon β-decays [12]. Further constraints on the PDFs can be imposed through the use of positivity for PDFs, which, at leading order, requires that the relation $|\Delta f(x,Q^2)| \leq f(x,Q^2)$ holds for all quarks, antiquarks, and the gluon at all values of x and Q^2. Results will be shown both without these constraints (referred to as "JAM") and with these constraints (referred to as "+Pos").

The PDFs are evolved using the DGLAP evolution equation, and the renormalization group equation (RGE) is solved numerically for α_S at two loops making use of the boundary condition $\alpha_S(M_Z) = 0.118$. The boundary conditions for the RGE are parameterized at the scale μ_0^2 and inferred from data. The evolution equations are solved using the zero-mass variable-flavor-number scheme with splitting kernels evaluated at $\mathcal{O}(\alpha_S^2)$. The values of the heavy-quark mass thresholds for the evolution of the PDFs and α_S are taken from the PDG values $m_c = 1.28$ GeV and $m_b = 4.18$ GeV in the $\overline{\mathrm{MS}}$ scheme [13]. All hard-scattering kernels are expanded to NLO in the strong coupling, with the NLO expressions for W-lepton production taken from [14].

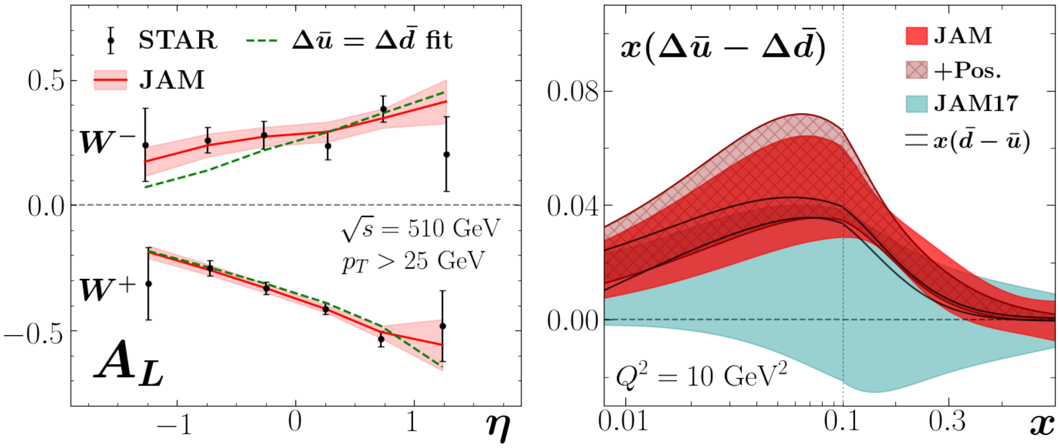

Figure 1: **Left panel**: Single-spin asymmetries $A_L^{W^\pm}$ from STAR [8] (black circles) compared with the full JAM fit (red solid lines and bands) and with a fit where $\Delta\bar{u}$ is set equal to $\Delta\bar{d}$ (green dashed lines). **Right panel**: Result from this analysis (JAM) for the helicity sea asymmetry $x(\Delta\bar{u}-\Delta\bar{d})$ (red bands) at $Q^2 = 10$ GeV^2. The result is also shown with positivity constraints (red hatched bands) and is compared to the results from JAM17 [11] (cyan band) and the unpolarized asymmetry $x(\bar{d}-\bar{u})$ (black lines) (note the reversed sign). All bands and doubled lines represent 1σ uncertainty.

3 Quality of Fit

In this analysis we include 365 data points of the DIS asymmetries $A_\parallel$ and A_1 from fixed-target experiments on proton, deuterium, and ^{3}He with cuts on the four-momentum transfer Q and the hadronic final state masses W of $Q^2 > m_c^2$ and $W^2 > 10$ GeV^2. We also include 61 data points on polarized jet production and 18 data points on W-lepton single-spin asymmetries, in particular those from the recent measurement at STAR [8]. We obtain the main constraints for the unpolarized PDFs from (unpolarized) data on DIS, jet production, W/Z boson production, and Drell-Yan.

The quality of our analysis is summarized by the global average $\chi^2/N_{\text{dat}} = 0.90$ for a total of 444 data points, with a χ^2/N_{dat} of 0.93 for DIS, 1.00 for jet production, and 0.46 for W-lepton production. The addition of positivity constraints slightly increases the χ^2/N_{dat} but the amount is negligible for all datasets. However, when $\Delta\bar{u} = \Delta\bar{d}$ is enforced there is a large increase in the χ^2/N_{dat} for the STAR data, from 0.45 without this constraint to 1.53. The STAR measurement on $A_L^{W^\pm}$ is shown in Fig. 1 (left panel) compared to the JAM theory. When the asymmetry is forced to be zero, the quality of the fit suffers the most for $A_L^{W^-}$ at low rapidity. This can be understood from Eq. (1), where it is seen that the asymmetries are most sensitive to $\Delta\bar{u}$ and $\Delta\bar{d}$ at backwards rapidity.

4 Result for sea asymmetry of helicity PDFs

The result of our global analysis based on over 150 Monte Carlo samples for the helicity light-quark sea asymmetry is shown in Fig. 1 (right panel). We find a clear nonzero sea asymmetry in the range $0.01 < x < 0.3$ at $Q^2 = 10$ GeV^2. The inclusion of positivity constraints makes little difference below $x \simeq 0.1$, but significantly reduces the errors above that as the helicity sea-quark PDFs are restricted by the size of the unpolarized sea-quark PDFs. The unpolarized asymmetry is shown for comparison, and it is seen that the helicity asymmetry is opposite in sign but similar in magnitude.

The results are compared to those from the JAM17 analysis [11], which analyzed both DIS and SIDIS data. The SIDIS data provides flavor separation for the light sea quarks but the extracted sea asymmetry of JAM17 is consistent with zero. Despite this, the results from JAM17 are still consistent with the results from this analysis within 1σ, indicating that the SIDIS data is consistent with the latest W-lepton data in this analysis.

5 Conclusions

We have presented the helicity sea asymmetry from a global QCD analysis using the latest W-lepton production data from RHIC. We find that the STAR data is crucial for extracting a nonzero asymmetry and that the resulting asymmetry is positive between $0.01 < x < 0.3$ at $Q^2 = 10$ GeV^2. In the future, high-x DIS data from Jefferson Lab will be added to this analysis to further reduce PDF uncertainties and extract nuclear and higher-twist effects. With the Jefferson Lab 12-GeV upgrade and the Electron-Ion Collider (EIC) under construction, future experiments will be able to provide new information on the spin structure of the proton [15, 16]. The EIC, being the first polarized electron-ion collider, will be able to provide new information on all helicity PDFs while also extending the kinematic coverage of polarized DIS experiments.

Acknowledgements

We thank Jake Ethier and Wally Melnitchouk for the fruitful collaboration on the work in [9, 10], which forms the basis for this contribution. We thank Felix Ringer and Werner Vogelsang for the code used for calculating the W-lepton cross sections. We thank P. C. Barry and Y. Zhou for helpful discussions. This work was supported by the U.S. Department of Energy Contract No. DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates Jefferson Lab, and the National Science Foundation under grant number PHY-1516088. The work of C.C. and A.M. was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, within the framework of the TMD Topical Collaboration, and by Temple University (C.C.). The work of N.S. was supported by the DOE, Office of Science, Office of Nuclear Physics in the Early Career Program. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education (ORISE) for the DOE. ORISE is managed by ORAU under contract number DE-SC0014664. All opinions expressed in this paper are the author's and do not necessarily reflect the policies and views of DOE, ORAU, or ORISE.

References

[1] C. A. Aidala, S. D. Bass, D. Hasch and G. K. Mallot, *The spin structure of the nucleon*, Rev. Mod. Phys. **85**, 655 (2013), doi:10.1103/RevModPhys.85.655.

[2] P. Jimenez-Delgado, W. Melnitchouk and J. F. Owens, *Parton momentum and helicity distributions in the nucleon*, J. Phys. G **40**, 093102 (2013), doi:10.1088/0954-3899/40/9/093102.

[3] M. Arneodo et al., *Re-evaluation of the Gottfried sum*, Phys. Rev. D **50**, R1(R) (1994), doi:10.1103/PhysRevD.50.R1.

[4] J. Dove et al. [SeaQuest], *The asymmetry of antimatter in the proton*, Nature **590**, 561 (2021), doi:10.1038/s41586-021-03282-z.

[5] B. Adeva et al. (Spin Muon Collaboration), *Polarised quark distributions in the nucleon from semi-inclusive spin asymmetries*, Phys. Lett. B **420**, 180 (1998), doi:10.1016/S0370-2693(97)01546-3.

[6] A. Airapetian et al. (HERMES Collaboration), *Quark helicity distributions in the nucleon for up, down, and strange quarks from semi-inclusive deep-inelastic scattering*, Phys. Rev. D **71**, 012003 (2005), doi:10.1103/PhysRevD.71.012003.

[7] M. G. Alekseev et al. (COMPASS Collaboration), *The spin-dependent structure function of the proton g_1^p and a test of the Bjorken sum rule*, Phys. Lett. B **693**, 227 (2010), doi:10.1016/j.physletb.2010.05.069.

[8] J. Adam et al. (STAR Collaboration), *Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at $\sqrt{s} = 510$ GeV*, Phys. Rev. D **99**, 051102 (2019), doi:10.1103/PhysRevD.99.051102.

[9] C. Cocuzza, J. J. Ethier, W. Melnitchouk, A. Metz, and N. Sato, in preparation (2021).

[10] C. Cocuzza, J. J. Ethier, W. Melnitchouk, A. Metz, and N. Sato, in preparation (2021).

[11] J. J. Ethier, N. Sato and W. Melnitchouk, *First simultaneous extraction of spin-dependent parton distributions and fragmentation functions from a global QCD analysis*, Phys. Rev. Lett. **119**, 132001 (2017), doi:10.1103/PhysRevLett.119.132001.

[12] P. Jimenez-Delgado, A. Accardi and W. Melnitchouk, *Impact of hadronic and nuclear corrections on global analysis of spin-dependent parton distributions*, Phys. Rev. D **89**, 034025 (2014), doi:10.1103/PhysRevD.89.034025.

[13] M. Tanabashi et al. (Particle Data Group), *Review of Particle Physics*, Phys. Rev. D **98**, 030001 (2018) and 2019 update, doi:10.1103/PhysRevD.98.030001.

[14] F. Ringer, W. Vogelsang, *Single-spin asymmetries in W boson production at next-to-leading order*, Phys. Rev. D **91**, 094033 (2015), doi:10.1103/PhysRevD.91.094033.

[15] W. C. Chang and J. C. Peng, *Flavor structure of the nucleon sea*, Prog. Part. Nucl. Phys. **79**, 95 (2014), doi:10.1016/j.ppnp.2014.08.002.

[16] D. F. Geesaman and P. E. Reimer, *The sea of quarks and antiquarks in the nucleon*, Rept. Prog. Phys. **82**, 046301 (2019), doi:10.1088/1361-6633/ab05a7.