HP13: Near-term Opportunity with W-bosons at RHIC

Purpose: This short write-up collects recent developments for transverse-momentum-dependent (TMD) distribution functions and their evolutions, in particular for the Sivers asymmetry A_N for W^+ and W^- production in transversely polarized proton-proton collisions at RHIC top-energy. It is prepared following the BNL-NPP PAC meeting in June 2014 and the recommendations for RHIC Run 16.

For Run 16 the PAC considered a 22 cryo-week scenario and recommends 10 physics weeks of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as the highest priority. The second priority in this scenario is 7 physics weeks of *either* Au+Au and p+p collisions at $\sqrt{s_{NN}} = 62$ GeV, *or* 7 physics weeks of polarized p+p collisions at $\sqrt{s} = 510$ GeV. In the recommendations, the PAC asks the collaborations to present (updated) physics goals for both second priority scenarios at the next meeting and encourages continued interactions between theory and experiment on TMD evolution. This write-up summarizes the status on the latter as of January 2015. It does not concern $\sqrt{s} = 62$ GeV, alternative run durations, or even complementary processes.

Science: The primary goal of the proposed future polarized p+p collisions at $\sqrt{s} = 510$ GeV is to *"test unique QCD predictions for relations between single-transverse spin phenomena in p+p scattering and those observed in deep-inelastic lepton scattering"*, NSAC performance measure HP13 (2015).

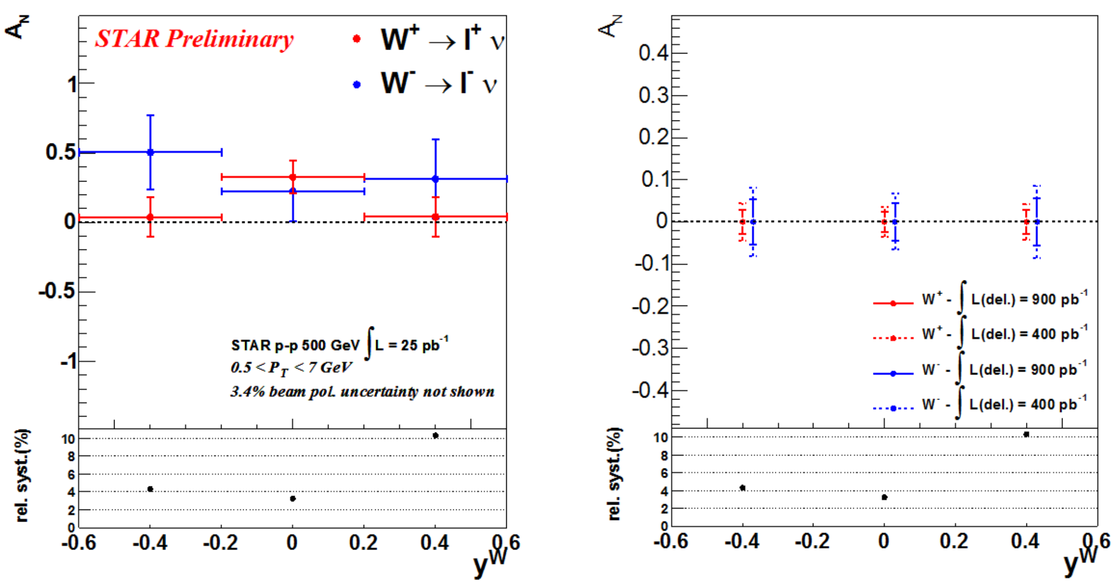
TMD parton-distribution and fragmentation functions extend the parton-model description of nucleon structure and are important to a variety of processes, including Drell-Yan (DY), semi-inclusive deep-inelastic scattering (SIDIS), and electron-positron annihilation into two hadrons/jets at high boson invariant mass. Their theoretical foundation is provided by TMD factorization [1] properties of the cross sections. The Sivers function is an example of a TMD parton distribution and is of particular interest. It describes the correlation between parton transverse-momentum in the proton and the proton spin. The Sivers effect is observed in SIDIS by a characteristic azimuthal modulation of the produced hadron and non-zero values have been observed by the HERMES, COMPASS, and JLab Hall A collaborations.

The Sivers functions in SIDIS and DY processes are predicted to differ by a sign, because of the difference between the interactions in the final and initial state [2,3]. This is a fundamental prediction rooted in the gauge invariance of QCD. Specifically,

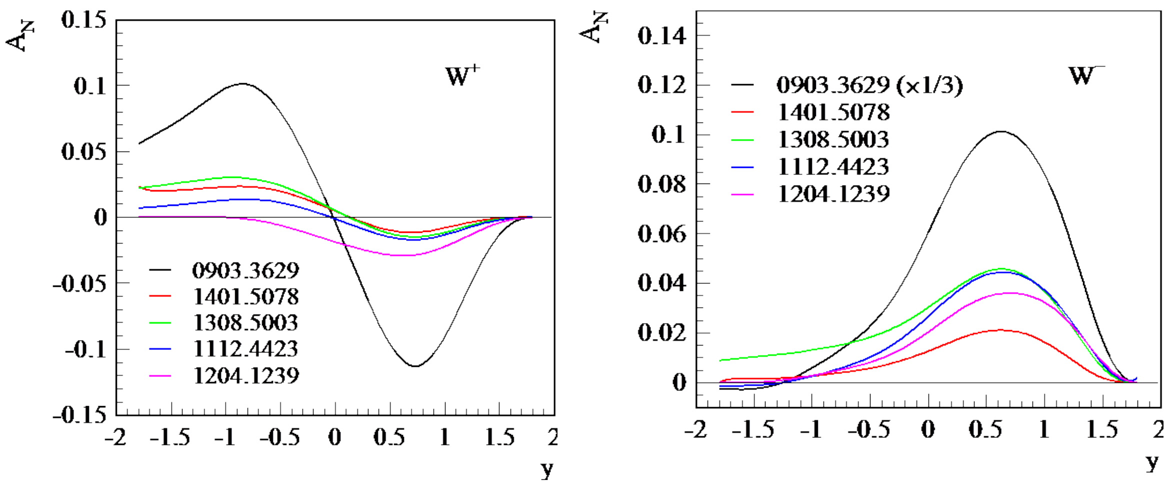
$$f_{1T}^{\perp,SIDIS}(x,k_\perp;Q) = -\, f_{1T}^{\perp,DY}(x,k_\perp;Q),$$

at identical hard scale, Q, and separately for each (anti-)quark flavor. To test the sign change, it is imperative to measure the righthand side with DY(-like) processes determine the Sivers functions for quarks and anti-quarks by flavor, and relate measurements at different scales through TMD evolution.

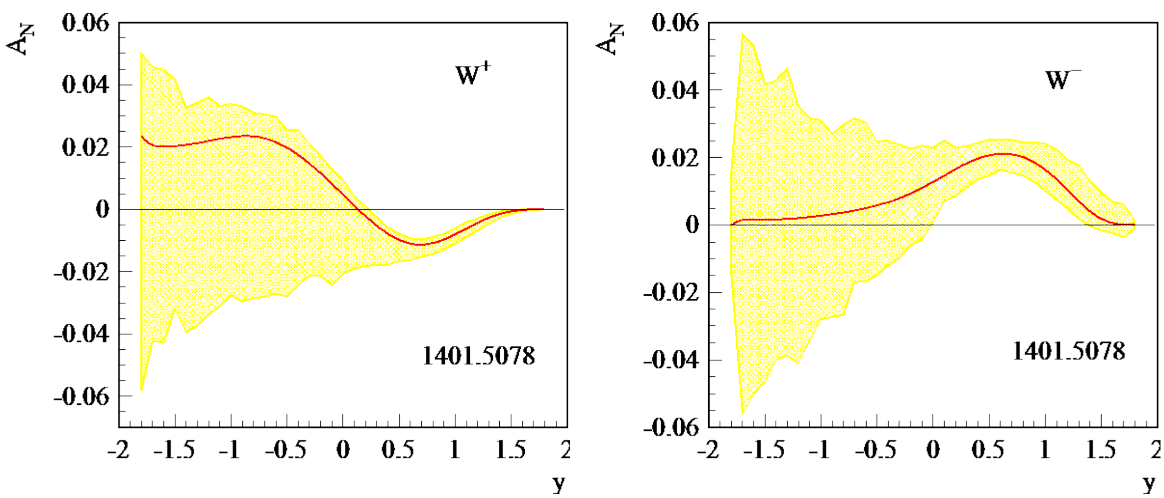
Near-term opportunity at RHIC: Top-energy RHIC polarized p+p beam operations in recent years have proven highly successful. Among their primary aims was to "*measure flavor-identified quark and anti-quark contributions to the spin of the proton via the longitudinal-spin asymmetries of W production*", NSAC performance measure HP8 (2013). During these beam periods, STAR has collected also a modest sample corresponding to an integrated luminosity of 25 pb^{-1} with average transverse beam polarizations of 53%. STAR has analyzed this sample and released preliminary results on the Sivers asymmetry A_N for W^+, W^-, and Z^0 production as a function of boson rapidity and transverse momentum at DIS-2014 [4]. A publication is in preparation. The transverse W analysis is markedly different from the longitudinal W analysis and utilizes the large STAR acceptance and techniques developed at the Tevatron and LHC to reconstruct the W-boson kinematics from the recoil jet. The STAR proof-of-concept analysis provides a sound basis for projections of statistical and systematic uncertainties for the instantaneous and integrated luminosities of the proposed scenario for Run 16 (400 pb^{-1} delivered, 55% polarization). The proof-of-concept results and the projected uncertainties for future measurements are given below. Precision from Run 16 at the level of 0.04 can be achieved in three bins in rapidity in the case of W^+ and 0.07 in the case of W^-. The difference between the precision for W^+ and W^- is primarily due to the difference in the production cross section.



Significant progress has been made also in TMD evolution, required to relate the existing SIDIS Sivers measurements to those in W production and, more generally, to all DY processes. The initial predictions [5] for W-boson A_N, developed just as the RHIC top-energy p+p program came online, had no evolution. Subsequent work [6,7] provided assessments of the importance of TMD evolution and the possible size of its effect. Over the past year, two independent groups [8,9] have published results that use TMD evolution in their fits to extract the Sivers functions from SIDIS data and provide predictions for W-boson A_N and complementary processes. The compilation of W-boson A_N below (courtesy Z.B. Kang) demonstrates that the effects from TMD evolution are a) potentially quite sizable and b) highly uncertain. The black curves are the initial predictions [5] without evolution, whereas the colored curves [6-9] show W-boson A_N including TMD evolution versus W-rapidity. Detailed reviews/critiques may be found in [10-12]. Here, we simply note that key differences originate from the treatment of the non-perturbative part that is intrinsic to TMD evolution and is to be constrained by measurements with sensitivity to scales well beyond those accessed by the existing SIDIS data.



A second type of sensitivity of W-boson A_N is to the sea-quark Sivers functions, which are left essentially unconstrained in any of the SIDIS fits other than through positivity bounds. Positivity bounds for the sea-quark Sivers functions have been propagated in the framework of [9] and are visualized as the yellow bands below,



They demonstrate the characteristic sensitivity of W measurements to anti-quark distributions at negative rapidity and quantify the size in A_N.

At the time of writing, we do not have a single impact measure that quantifies the probability of a Sivers sign-change by propagating the body of generated pseudo-data through phenomenological frameworks that fit for the Sivers functions and quantify the effects of TMD evolution for existing SIDIS and prospective measurements of W-boson A_N.

Summary: Two independent groups have evaluated and published W-boson A_N with differing approaches for the non-perturbative part of TMD evolution. Evaluations based on the work by other groups are now available as well. A_N is reduced in absolute size in these predictions by a factor 3-10 compared to the prediction without TMD evolution. The differences arise, predominantly, from differences in the treatment of the non-perturbative part of TMD evolution. Observation of W-boson A_N at the proposed precision forms an identified and timely path to meaningful observation of, and hence constraints on, this evolution with existing instrumentation and established methods. The understanding of TMD evolution is integral to HP13 and affects proposals for DY measurements as well as parts of the eRHIC science program, including for example determinations of quark-transversity using Collins fragmentation. The proposed W-boson A_N measurements are anticipated also to constrain the Sivers functions of the light sea-quarks. The "discovery potential" of the sign-change for these and other measurements remains to be quantified.

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