

Transverse single-spin asymmetry of weak bosons and Drell-Yan production in p+p collisions at STAR: present and future

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Accessing the Sivers TMD function in proton+proton collisions through the measurement of transverse single spin asymmetries (TSSAs) in Drell-Yan and weak boson production is an effective path to test the fundamental QCD prediction of the non-universality of the Sivers function. Furthermore, it provides data to study the spin-flavor structure of valence and sea quarks inside the proton and to test the evolution of parton distributions. The TSSA amplitude, A_N , has been measured at STAR in proton+proton collisions at $\sqrt{s} = 500$ GeV, with a recorded integrated luminosity of 25 pb^{-1} . Within relatively large statistical uncertainties, the current data favor theoretical models that include a change of sign for the Sivers function relative to observations in SIDIS measurements, if TMD evolution effects are small. RHIC plans to run proton+proton collisions of transversely polarized beams at $\sqrt{s} = 510$ GeV in 2017, delivering an integrated luminosity of 400 pb^{-1} . This will allow STAR to perform a precise measurement of TSSAs in both Drell-Yan and weak boson production. The present status and future plans for the Sivers function program at STAR will be discussed as well as other observables sensitive to the non-universality of the Sivers function in the Twist-3 framework, e.g. the TSSA of direct photons.

XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects

11-15 April, 2016

DESY Hamburg, Germany

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1. Introduction

Understanding the partonic structure of the proton in multi-dimensions has become a hot topic in the past decade [1]. Transversely polarized spin effects can be used to access transverse momentum dependent (TMD) [2] parton distribution functions (PDFs), which contain information on the intrinsic transverse momentum of a parton, together with the fraction that the same parton carries of the longitudinal momentum of the parent nucleon, leading to a 2+1 dimensional picture of the proton. Drell-Yan and W^\pm/Z^0 boson production in p-p collisions are observables which provide the two scales typically required to apply the TMD framework to transverse single-spin asymmetries. One hard scale is given by the invariant mass, while a soft scale is given by the transverse momentum. A particularly interesting TMD is the so-called Sivers function [3], f_{1T}^\perp , which describes the correlation of parton transverse momentum with the transverse spin of the nucleon.

There is evidence of a quark Sivers effect in semi-inclusive DIS (SIDIS) measurements [4] where the quark Sivers function is associated with a final state effect from the gluon exchange between the struck quark and the target nucleon remnants. On the other hand, for the DY process or the W^\pm/Z^0 production in p-p collisions, the Sivers asymmetry originates from the initial state of the interaction. As a consequence, the different color flow leads to the fundamental prediction that the quark Sivers functions are of opposite sign in SIDIS and in $DY/W^\pm/Z^0$ [5]

$$f_{1T}^{\perp SIDIS}(x, k_\perp) = -f_{1T}^{\perp DY/W^\pm/Z^0}(x, k_\perp), \quad (1.1)$$

and this non-universality is a fundamental prediction from the gauge invariance of QCD.

The experimental test of this sign change is one of the open questions in hadronic physics, and can provide insights on the TMD factorization [5]. While luminosity and experimental requirements for a meaningful measurement of asymmetries in Drell-Yan production are challenging, weak boson production is also sensitive [6] to the predicted sign change and can be measured at STAR.

Thanks to the high $Q^2 \simeq M_{W^\pm/Z^0}^2$ scale, the weak boson production provides also a stringent test of the TMD evolution [6]. Furthermore, the $W^+(W^-)$ boson, which is produced through $u + \bar{d}(d + \bar{u})$ annihilation, can provide essential input to disentangle the contribution to the Sivers function of light-sea quarks, which is essentially unconstrained by fits to SIDIS data [6]. The STAR experiment at RHIC is currently the only place in the world where all these effects can be tested simultaneously.

The transverse single-spin asymmetry, A_N , solely calculated from the decay lepton is a very strong function of the lepton kinematics [7] and therefore its measurement is experimentally challenging. Therefore a full reconstruction of the produced boson kinematics is crucial for a meaningful measurement.

2. Recent results

Based on the transversely polarized data sample corresponding to a luminosity of $L = 25 \text{ pb}^{-1}$ collected in the year 2011 at $\sqrt{s} = 500 \text{ GeV}$, the STAR Collaboration has recently published [8] the world's first measurement of A_N in weak boson production. The W^\pm boson momentum has been

fully reconstructed from the decay lepton and all other particles in the recoil from the initial hard scattering.

Background contributions coming from $W^\pm \rightarrow \tau^\pm \nu_\tau$, $Z^0 \rightarrow e^+ e^-$ have been studied using PYTHIA 6.4 [9], whereas background from QCD events has been studied using a data driven procedure reversing our signed- P_T -balance selection cut. All background sources have been estimated to be at most a few percent of the selected sample.

The novel STAR results for the A_N measurement of the W^+ and W^- boson production are shown separately in Fig. 1 as a function of y^W and P_T^W . The systematic uncertainties, added in quadrature, have been evaluated via a Monte Carlo test using a theoretical prediction for the asymmetry from [6]. The 3.4% overall systematic uncertainty on beam polarization measurement is not shown in the plots.

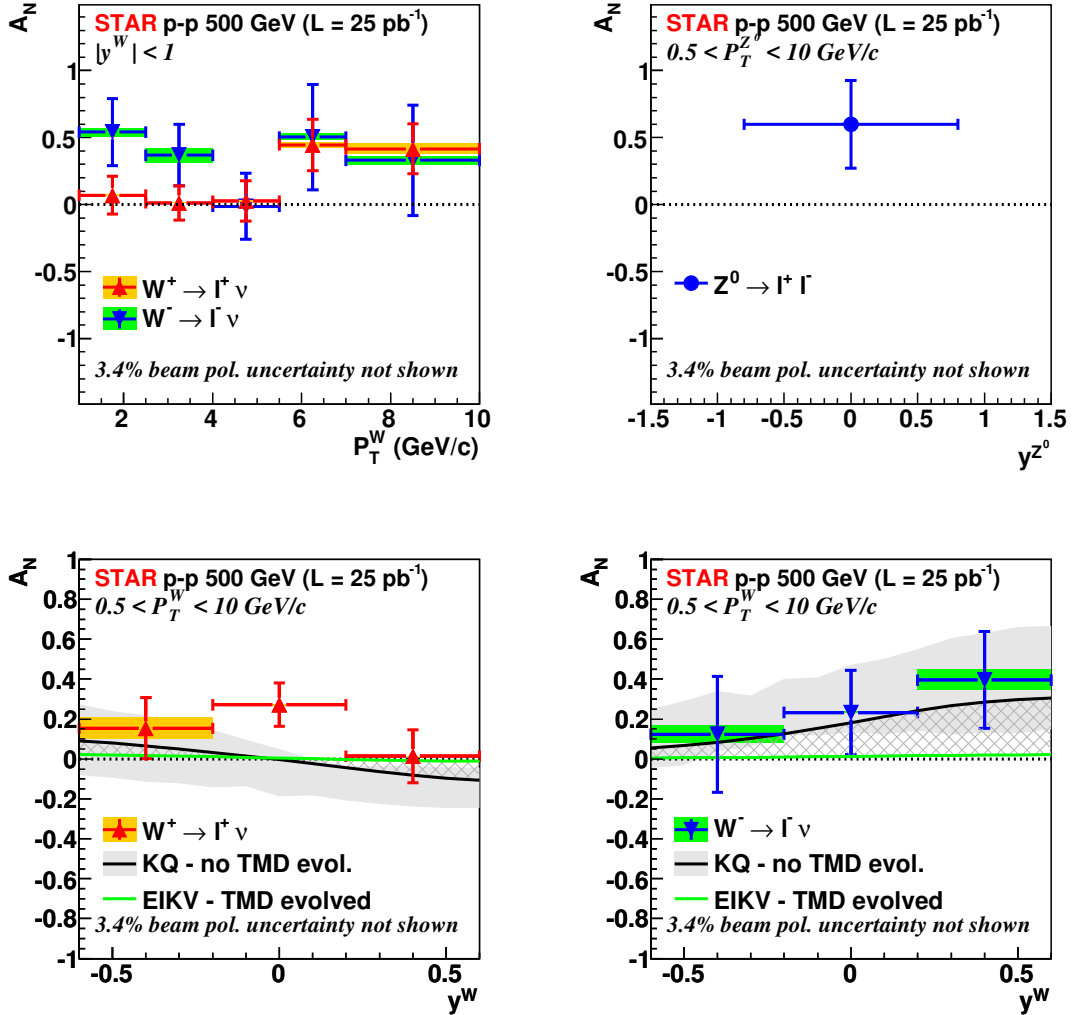


Figure 1: Transverse single-spin asymmetry amplitude for W^\pm and Z^0 boson production measured at STAR in a pilot run at $\sqrt{s} = 500 \text{ GeV}$ with a recorded luminosity of 25 pb^{-1} .

The measured amplitudes are compared with theoretical predictions from KQ [7], which does not account for TMD evolution, and from EIKV [6], which depicts the largest evolution effects among all current theoretical calculations. The gray band in Fig. 1 highlights the uncertainty on the EIKV calculation due to the current ignorance of the sea-quark Sivvers function. Despite the large statistical uncertainties, global fits to the current data favor theoretical models that include a change of sign for the Sivvers function relative to observations in SIDIS measurements, if TMD evolution effects are small.

The transverse single-spin asymmetry of the $Z^0 \rightarrow e^+e^-$ process has been also measured because it has many advantages: it is experimentally very clean and the boson kinematics are easily reconstructed from the two decay leptons produced at central rapidities, well within the acceptance of the STAR detector. Thus, the measurement is background free, carries only the overall systematic uncertainty coming from the polarization measurement, and the asymmetry is expected to be of the same size as that of the W^\pm . The only challenge comes from the much lower cross section of the $Z^0 \rightarrow e^+e^-$ process, which requires the collection of a very large data sample for a statistically significant measurement.

The STAR result for the A_N measurement of the Z^0 boson production in a single y^Z, P_T^Z bin is shown in Fig. 1.

3. Future program

This recently published analysis demonstrates the capability of STAR to perform measurements with fully reconstructed W^\pm bosons. A larger data sample is needed for a conclusive test of the change in the sign of the Sivvers function, to decompose the contribution from sea-quarks and to pin down the TMD evolution.

RHIC plans to collect 400 pb^{-1} events of transversely polarized p+p collisions at $\sqrt{s} = 510 \text{ GeV}$ during the 2017 run, using a dynamic β^* squeeze [10] throughout the fill which will reduce the pileup effects in the tracker and increase the boson selection efficiency. This will allow for a precise A_N measurement of weak boson production at STAR (for projections see Fig. 2), and can lead to the first experimental test of the sign change of the Sivvers function if the evolution effects on the A_N prove to be smaller than a factor ~ 5 . Furthermore it will provide an ideal tool to study the spin-flavor structure of sea quarks inside the proton.

STAR will be also pursuing the investigation of TMDs and the experimental test of the Sivvers sign change through measuring A_N in Drell-Yan. This measurement is particularly challenging as it requires a severe suppression of the overwhelming hadronic background, which is of the order of $10^5 \sim 10^6$ larger than the signal. In order to achieve the electron/hadron discrimination, necessary for such background suppression, STAR envisions to install a post-shower detector at the forward rapidity range $2.5 < \eta < 4.0$ behind the Forward Pre-shower Spectrometer (FPS) and the Forward Meson Spectrometer (FMS), to create a three-detector system [11].

Monte Carlo simulation was used to estimate signal-to-background ratio for Drell-Yan to QCD events. For the background simulation, all basic QCD $2 \rightarrow 2$ processes as well as heavy-flavor channels were generated, and events were smeared using the simulated detector resolutions of the forward detector system. The Drell-Yan production through quark-antiquark annihilation and quark-gluon scattering processes were separately generated and scaled to the same luminosity. The

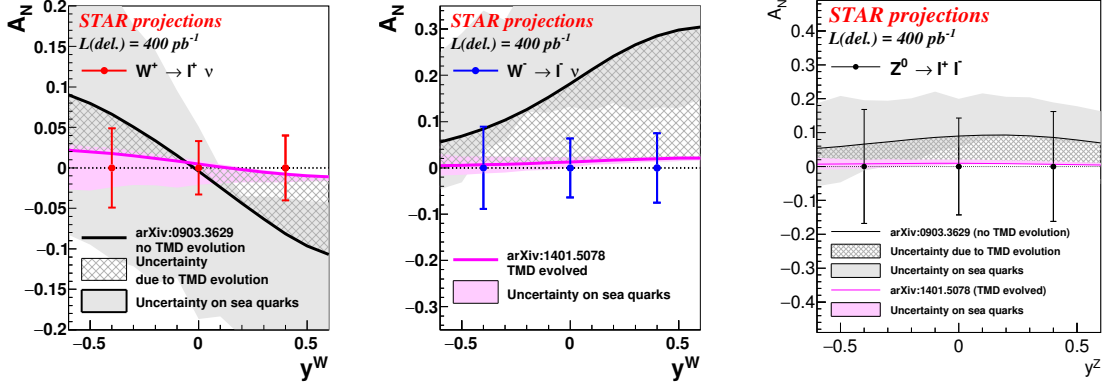


Figure 2: The projected uncertainties for the A_N of W^\pm and Z^0 as a function of the boson rapidity for a delivered integrated luminosity of 400 pb^{-1} , and an average beam polarization of 55%.

final yields of Drell-Yan events (signal) and background events are shown in Fig. 3 (left). Clearly, the proposed forward-detector system upgrade provides the needed rejection factor to allow for a measurement of the TSSA in Drell-Yan. The projected uncertainty is shown in Fig. 3 (right).

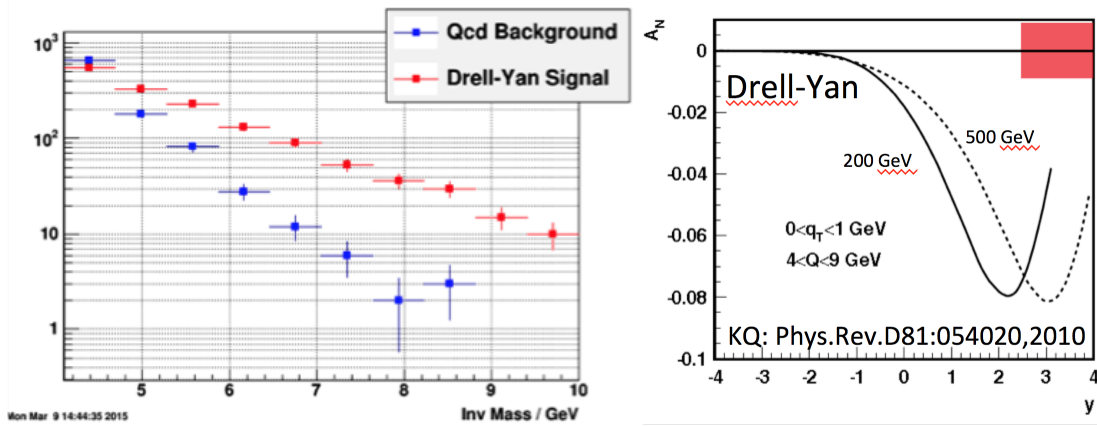


Figure 3: Left: Drell-Yan signal (red) and QCD background (blue) as a function of the invariant mass. Right: the projected uncertainties for the A_N in Drell-Yan in the corresponding rapidity-bin (red area) for a delivered integrated luminosity of 400 pb^{-1} .

Using the same data collected during the 2017 RHIC run, STAR plans also to investigate the Sivers function sign change indirectly by measuring single scale processes like A_N for prompt photons. These observables can be described in the Twist-3 formalism but the relevant functions appearing in this framework can be related to the Sivers function. The assumption is that if the correlation due to different color interactions for initial and final states between the Sivers function and the Twist-3 function would be violated, the asymmetry would be positive but of the same magnitude. The projected uncertainties for the A_N measurement in direct photon, after background subtraction, is shown in Fig. 4 and compared to theoretical predictions [12].

The STAR experiment at RHIC is currently the only experiment capable of investigating the

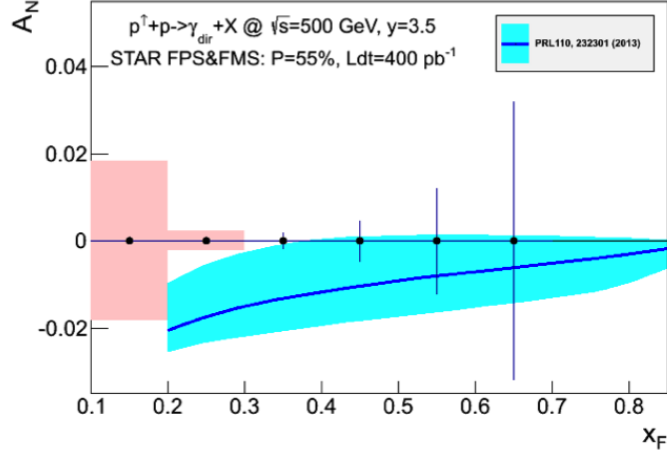


Figure 4: Statistical and systematic uncertainties for the direct photon A_N compared to theoretical prediction [12] for a delivered integrated luminosity of 400 pb^{-1} , and an average beam polarization of 55%.

TMD evolution effects, studying the contribution from sea-quarks to the Sivers function, and providing an ultimate experimental test of the non-universality of the Sivers function. This can be done by measuring the TSSA for a variety of processes - W^\pm , Z^0 , Dell-Yan, prompt- γ - simultaneously at the same experiment.

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