PROCEEDINGS OF SCIENCE

Transverse single-spin asymmetries in $W^{\pm}$ and Z^0 boson production in p+p collisions at RHIC

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The Sivers function $f_{1T}^{\perp}$ 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 measurements. In SIDIS, the quark Sivers function is associated with a final state effect. On the other hand, for the virtual photon production in the Drell-Yan process, the Sivers asymmetry appears as an initial state interaction effect. As a consequence, the quark Sivers functions are of opposite sign in SIDIS and in Drell-Yan 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 a direct verification of TMD factorization. While delivering the luminosity required for a precise measurement of asymmetries in Drell-Yan production in p+p collisions is challenging, $W^{\pm}/Z^0$ production is equally sensitive to the predicted sign change and can be well measured at the STAR experiment at RHIC. The results can also provide essential input to study the evolution effects of the Sivers function, because of the high Q^2 in W/Z^0-production. Here we present the first preliminary measurement of the transverse single spin asymmetry, A_N, of the $W^{\pm}/Z^0$ bosons from the STAR experiment. The W boson kinematics are fully reconstructed from the decay lepton and the recoil, by employing a MC-based correction, thus avoiding the dilution that an asymmetry reconstructed from the decay lepton only would suffer.

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1. Introduction

Transversely polarized spin effects have been an extremely active topic among experiment and theory in the past years, because of their connection to transverse momentum dependent (TMD) distributions. For a quantitative application of the TMD framework to transverse single-spin asymmetries measured in proton-proton collisions, the required two scales (typically Q^2 and P_T) are not well defined, except for Drell-Yan di-lepton (DY) and $W^{\pm}/Z^0$ boson production. DY production has been at the center of attention for the non-universality test of the so-called Sivers TMD function [1], $f_{1T}^{\perp}$, 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 [2] 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 virtual photon production in the Drell-Yan process, the Sivers asymmetry appears in the initial state of the interaction. As a consequence, the quark Sivers functions are of opposite sign in SIDIS and in Drell-Yan [3]

$$f_{q/h^{\uparrow}}^{\text{SIDIS}}(x,k_{\perp}) = -f_{q/h^{\uparrow}}^{\text{DY}}(x,k_{\perp}), \tag{1.1}$$

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. While delivering the luminosity required for a meaningful measurement of asymmetries in Drell-Yan production in p+p collisions is challenging, $W^{\pm}$ and Z^0 boson production is equally sensitive to the predicted sign change and can be well measured at the STAR experiment. The results can also provide essential input to study the new theoretical concept of evolution effects of transverse momentum dependent distribution functions, because of the high Q^2 in the $W \to e\nu$ production due to the large boson mass. The STAR experiment at RHIC is currently the best place where these effects can be tested.

The transverse single spin asymmetry, A_N, solely calculated from the lepton decay is predicted to be diluted [4] due to smearing, thus a full reconstruction of the produced boson kinematics is crucial for a meaningful measurement. Based on the transversely polarized data sample collected in the year 2011 at $\sqrt{s} = 500$ GeV ($L_{int} = 25$ pb^{-1}), an analysis has been performed at STAR to fully reconstruct the $W^{\pm}$ bosons from the lepton decay and all other particles in the recoil from the initial hard scattering. This analysis also includes a first look at A_N in Z^0 production. A proposed measurement with increased statistics in 2016 will be directly competitive with a Drell-Yan measurement in pion-proton scattering at CERN.

2. The $W^{\pm}$ selection and asymmetry measurement

A data sample characterized by the W signature as in Ref. [5], mostly requires an isolated high $P_T > 25$ GeV electron and a total recoil $P_T > 18$ GeV. In order to fully reconstruct the W kinematics the momenta of all W decay products must be measured. The momentum of the neutrino produced in the leptonically decayed W cannot be measured and can only be indirectly deduced from conservation of the transverse momentum. In the W events produced at $\sqrt{s} = 500$ GeV at STAR we can assume that most of the missing transverse energy, $\vec{\not{E}}_T$ is carried by the neutrino from the W decay. The assumption $P_{\nu,T} \approx \vec{\not{E}}_T$ is based on the fact that only very little energy is left for anything other than W production from the primary hard scattering. We define the missing transverse energy as a vector restoring the balance in the event

$$\vec{\not{E}}_T = -\sum_{\substack{i\in\text{tracks,}\\ \text{clusters}}} \vec{P}_{i,T}. \tag{2.1}$$

In the transverse plane the initial momentum of the system of interacting partons is negligible and therefore must be the vector sum of all final particle momenta.

In a typical collider detector like STAR the problem with measuring the missing momentum from the hadronic recoil is that particles with very high rapidities escape the detector. At the same time, the beam remnants with high longitudinal momentum carry away only a little portion of the total transverse momentum. We accounted for the unmeasured tracks and clusters by using an event-by-event Monte Carlo correction to the data. Knowing its transverse momentum, the longitudinal component of the neutrino's momentum can be reconstructed solving the quadratic equation for the invariant mass of the produced boson

$$M_W^2 = (E_e + E_\nu)^2 - (\vec{P}_e + \vec{P}_\nu)^2, \tag{2.2}$$

where we assumed the nominal value of the W-mass. Eq. 2.2 leads to two possible solutions for P_L^ν, and we chose the smaller one in magnitude which, as shown by a Monte Carlo study, leads to a much smaller fraction of mis-reconstructed events in our kinematic domain.

Background sources coming from $W^\pm \to \tau^\pm \nu_\tau$, $Z^0 \to e^+e^-$ and QCD events have been estimated to be at most a few percent of the selected sample, as shown in table 1.

Process	$W^\pm \to \tau^\pm \nu_\tau$	$Z^0 \to e^+e^-$	QCD
B/S	1.88% (W^+); 1.39% (W^-)	0.88% (W^+); 2.94% (W^-)	1.59% (W^+); 3.40% (W^-)

Table 1: Background over signal in the W^+ and W^- samples respectively.

The single spin asymmetry A_N is expressed as:

$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}. \tag{2.3}$$

We bin our data sample in three observables: the rapidity y, the azimuthal angle ϕ, and the P_T of the produced boson. Thus, we calculate A_N using the square root formula [6], which helps to cancel out unwanted effects due to geometry and luminosity.

$$A_N \sin(\phi) = \frac{1}{<P>} \frac{\sqrt{N_\uparrow(\phi_i)N_\downarrow(\phi_i+\pi)} - \sqrt{N_\uparrow(\phi_i+\pi)N_\downarrow(\phi_i)}}{\sqrt{N_\uparrow(\phi_i)N_\downarrow(\phi_i+\pi)} + \sqrt{N_\uparrow(\phi_i+\pi)N_\downarrow(\phi_i)}}, \tag{2.4}$$

where N is the number of recorded events in the $i-th$ bin with a certain spin ($\uparrow\downarrow$) configuration in the "left" (ϕ_i) or in the "right" ($\phi_i+\pi$) side of the detector and $<P>\simeq 53\%$ is the average RHIC beam polarization for 2011 transverse p+p run.

The STAR preliminary 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 challenge using a theoretical prediction for the asymmetry from [7]. The 3.4% systematic uncertainty on beam polarization measurement is not shown in the plots.

3. The Z^0 selection and asymmetry measurement

The $Z^0 \to e^+e^-$ process has many advantages: it is experimentally very clean and the boson kinematics are easy to reconstruct since there is no neutrino in the final decay (thus it carries only the overall systematics coming from the polarization measurement), it is background free and the asymmetry is expected to be the same size as the $W^{\pm}$ one. The only big disadvantage is the much lower cross section which makes the measurement very statistics hungry.

A data sample characterized by the Z^0 signature has been selected, requiring two isolated high $P_T > 25$ GeV electrons, of opposite charge and with an invariant mass within $\pm 20\%$ of the nominal value. The STAR preliminary 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.

4. Outlook

This preliminary study is a proof-of-principle which shows that STAR is able to measure the transverse single spin asymmetries A_N for fully reconstructed $W^{\pm}$, Z^0 bosons based on a pilot run of transverse polarized p+p collisions at $\sqrt{s} = 500$ GeV with a recorded integrated luminosity of 25 pb^{-1}. The preliminary results from Fig. 1 can be compared with the most up-to-date theoretical A_N predictions for $W^{\pm}$, Z^0 boson production including TMD-evolution from reference [7], shown in Fig. 2, where the error bands have been updated accounting for the current almost complete uncertainty on see-quark functions in the fits [8]. Measuring the production of $W^{\pm}$ bosons at $\sqrt{s} = 500$ GeV can lead to the first experimental test of the sign change of the Sivers function. Furthermore, it provides an ideal tool to study the spin-flavor structure of sea quarks inside the proton. The left-handed W boson only couples to (anti)quarks of a certain helicity, giving rise to large parity-violating single spin asymmetries. In addition, the coupling of the W to the weak charge correlates directly to quark flavor. Ignoring quark mixing, $W^{\pm}$ bosons are produced through $u + \bar{d}(d + \bar{u})$ interactions. A measurement of the transverse single spin asymmetry will provide the worldwide first constraint on the sea quark Sivers function in an x-range, where the measured asymmetry in the $\bar{u}$ and $\bar{d}$ unpolarized sea quark distribution functions, as measured by E866 [9], can only be explained by strong non-pQCD contributions. Figure 3 shows the projected uncertainties for transverse single spin asymmetries of $W^{\pm}$, Z^0 bosons as functions of rapidity and P_T for a delivered integrated luminosity of 900 pb^{-1} compared to 400 pb^{-1} , at an average beam polarization of $\sim 55\%$. RHIC is capable of delivering 900 pb^{-1} in 14 weeks running using a dynamic $\beta*$ squeeze [10] through the fill. The dynamic $\beta*$ squeeze provides a factor 2 increase of the luminosity in a fill as the luminosity profile through the fill is kept flat.

STAR is the only experiment capable of measuring A_N for direct photons, for $W^{\pm}$ and Z^0 bosons, and possibly for DY. It can provide a world-wide unique opportunity to simultaneously test TMD evolution, access the Sivers function for sea quarks, and test the predicted sign-change for the Sivers function.

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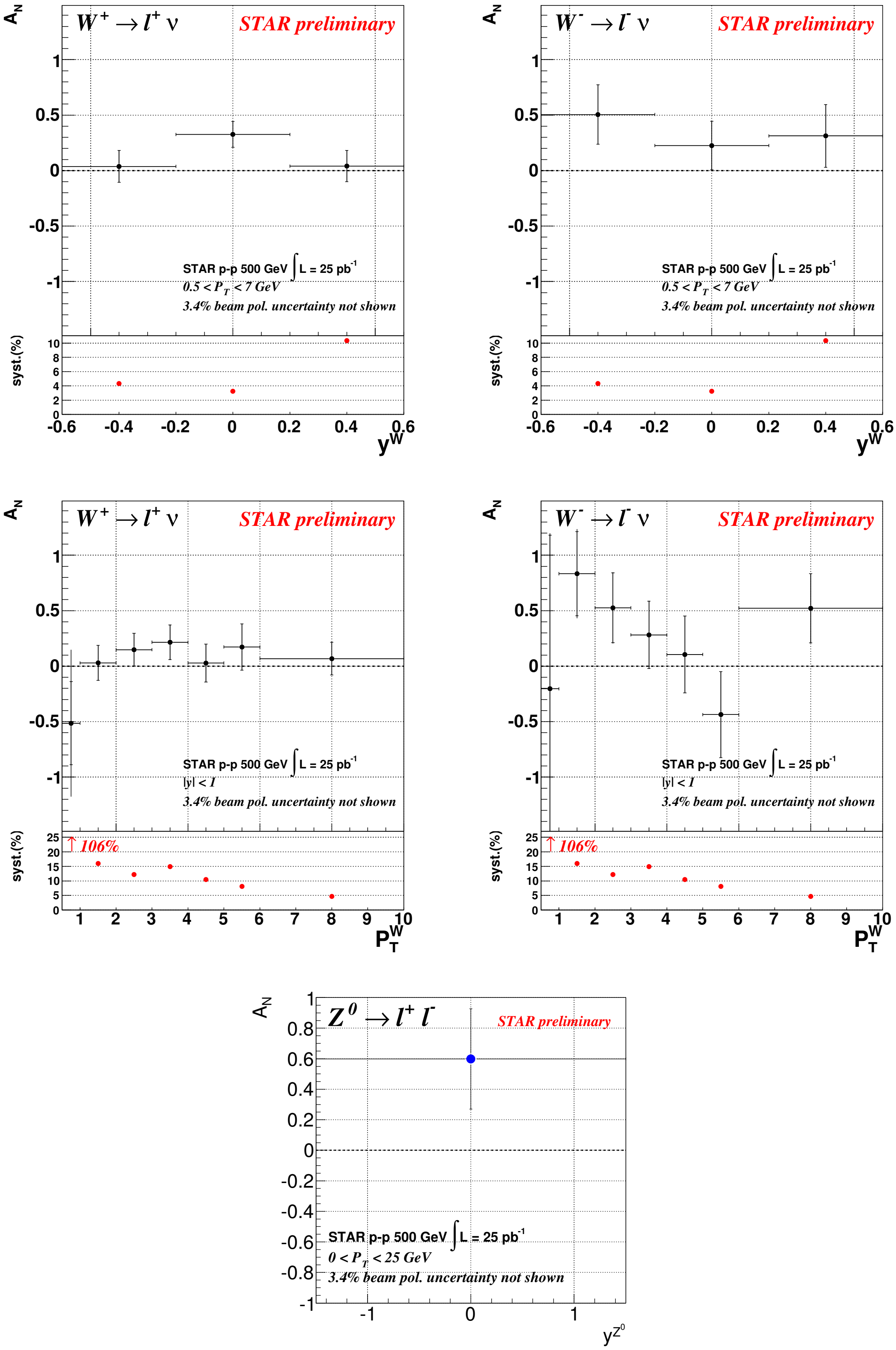

Figure 1: Transverse single spin asymmetry amplitude for $W^{\pm}$ and Z^0 boson production measured at STAR in a pilot run at $\sqrt{s} = 500$ GeV with a recorded luminosity of 25 pb^{-1}.

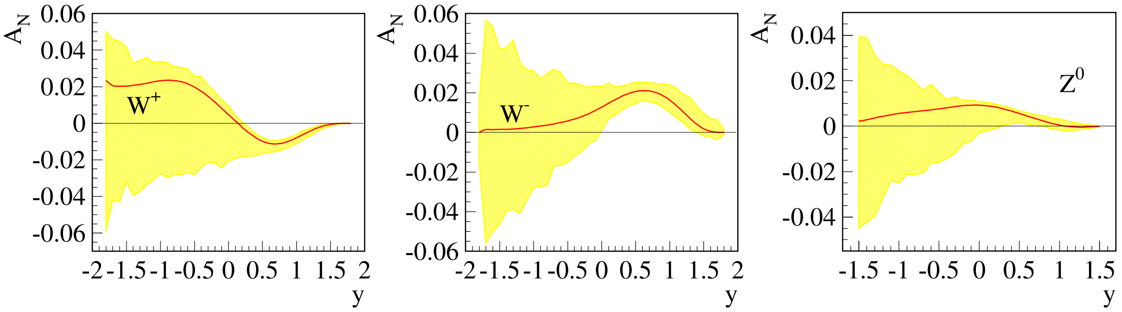

Figure 2: Theoretical prediction of A_N for $W^{\pm}$ and Z^0 boson production in p+p collisions at $\sqrt{s} = 500$ GeV including TMD-evolution [7].

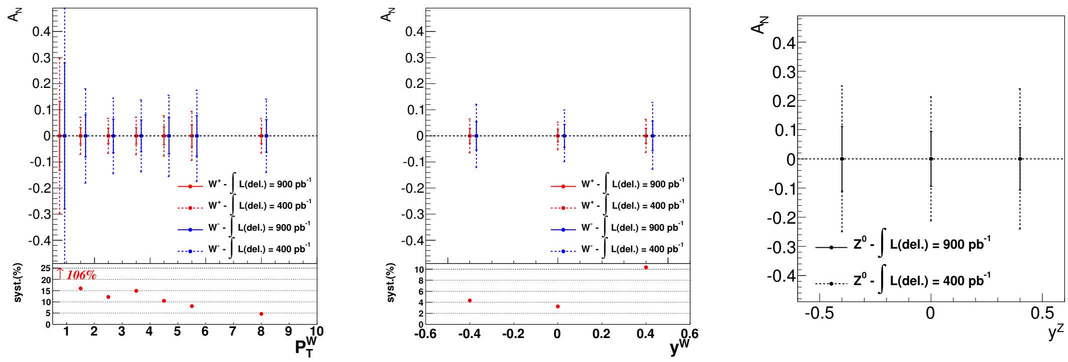

Figure 3: Projections of statistical uncertainties of an A_N measurement for $W^{\pm}$ and Z^0 boson production at STAR assuming a delivered luminosity of 900 pb^{-1}, the 400 pb^{-1} case is also shown for comparison.

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