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First Measurement of W Bosons and their Parity Violating Spin Asymmetry A_L in 500 GeV/c^2 Polarized $\vec{p}$+p Collisions at PHENIX

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In the 2009 Run of the Relativistic Heavy Ion Collider, PHENIX has observed W bosons for the very first time in polarized p+p collisions at $\sqrt{s}$ = 500 GeV/c^2 through the $W^{\pm} \rightarrow e^{\pm}$ decay channel. The parity violating spin asymmetry $A_L(W^{\pm} \rightarrow e^{\pm})$ can be used to extract the flavor-identified polarized quark parton distributions. PHENIX measured $A_L(e^{+})$ = -0.83 ± 0.31 ± (11% syst), consistent within errors to a variety of current polarized pdf's.

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1. Introduction to W Bosons in Polarized Proton Collisions to Extract Polarized Quark pdf's

There has been considerable effort over the past few decades to measure the composition of the quark and gluon spin content of the proton. Starting in 2009, the Relativistic Heavy Ion Collider (RHIC) has started colliding longitudinally polarized protons at center of mass energies of 500 GeV/c^2, an energy high enough to produce W bosons. In polarized proton collisions W bosons become a very elegant tool to measure the flavor identified polarized pdf's[2, 3]. W bosons are ideal for this purpose since the analyzing power for W's is as high as possible since W's maximally violate parity. In addition, W's are created at a very large scale where theoretical uncertainties are well under control, and do not suffer from the ambiguities of fragmentation, a weakness of SIDIS measurements of the polarized pdf's. Since the W couples only to left-handed quarks and right-handed anti-quarks, in polarized proton collisions one can compute the parity violating single spin asymmetry A_L for the W^+, which at LO and ignoring any strange or charm contribution is

$$A_L^{W^+}(y) = \frac{1}{P}\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\bar{d}(x_1, M_W^2)u(x_2, M_W^2) - \Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2)}{u(x_1, M_W^2)d(x_2, M_W^2) + d(x_1, M_W^2)u(x_2, M_W^2)} \tag{1.1}$$

(1.2)

Since the PHENIX detector is far from hermetic, one can only measure the leptons from the decay of the W, so that the simple relations above between the W and the polarized quark pdf's cannot be used since $A_L(e^\pm)$ is measured and not $A_L(W^\pm)$. However, one can show at LO that the momentum fraction x of the quarks in the W production can be calculated from the rapidity y_e and p_T of just the decay lepton,

$$x_1 = \frac{M_W}{\sqrt{s}}\exp(y_e \mp \cosh^{-1}\frac{M_w}{2p_T}), \quad x_2 = M_W^2/x_1 s \tag{1.3}$$

The one uncertainty comes from a degeneracy in the W rapidity, since there are two possible rapidities which can produce the same lepton y and p_T; this is the reason for the sign ambiguity in the above relations. This sign ambiguity is small for leptons at large rapidities, and not as important at mid-rapidities, so that the net result is that the lepton carries much of the basic kinematic information about the initial state quarks and is a good carrier of information about the quark polarization in the proton. Theorists have tested this hypothesis in a more sophisticated NLO framework and have a similar conclusion[5, 6, 7]. The NLO based framework will ultimately provide the most sensitive extraction of the flavor identified polarized quark pdf's from the measured $A_L(e^\pm)$.

2. Measurement

2.1 RHIC and the PHENIX Detector

This data was collected with the PHENIX detector during the 2009 500 GeV/c^2 $\vec{p}+p$ run at RHIC. A total integrated luminosity of 8.6 pb^{-1} was collected after a 30 cm z-vertex cut with a proton beam polarization of 39%. The luminosity is determined from coincidences in beam-beam counters (BBC) covering $3.1 < |\eta| < 3.9$. A van der Meer scan was used to determine the percentage of the total luminosity seen by the BBC. At the luminosities during this run the BBC coincidence rate is lower than the true luminosity rate since there can be more than one collision event in a bunch crossing, and the BBC counts at most one event per bunch crossing. The multi-collision crossings also affect the online vertex reconstruction of the BBC. Corrections for both of these effects were taken into account.

The PHENIX detector consists of two almost back-to-back central arms covering $\Delta\phi = 90^\circ$ each and $|\eta| < 0.35$, as well as two forward muon arms covering $1.2 < |\eta| < 2.2$, and is described in more detail in reference[1]. For this analysis, which concerns itself with the $W^\pm \to e^\pm$ measurement, only the central arm was used. The events were triggered using 4×4 tower sums in the electromagnetic calorimeter, and reached full efficiency at 12 GeV/c^2. The energy of the electron candidates were measured using the EmCal, with an energy scale set using π^0 and η mass distributions. Drift Chambers (DC) and Pad Chambers (PC) were used to track and determine the charge sign of the $e^\pm$ candidates and associate them to EmCal clusters. Frequent checks of the tracking and beam position were done using straight tracks taken during zero-field runs to ensure against any bias to the charge sign determination.

2.2 W Boson Signal

For this analysis, with the relatively low integrated luminosity, only about a hundred W candidates were expected, so the approach was to make the cuts as loose as possible to ensure good efficiency. To find good $e^\pm$ candidates, an association between tracks and clusters of 10 mrad in azimuthal angle is made, with a 30 ns wide timing cut in the EmCal to select the region of good collison time and reduce cosmic background, and an $E/p < 2$ cut to reduce hadronic backgrounds. In figure 2.2 the p_T spectrum for the positively and negatively charged candidates is shown. The estimated background (black histogram) as well as the expected signal plus estimated background (red histogram) is shown. The expected signal comes from from the lepton decays of $W^\pm$ and γ^*/Z calculated in PYTHIA. The main contributions to the background come from QCD and consist of charged hadron clusters and photons. The photons come from the decays of hadrons such as π^0 or are directly produced, and they pass the track matching cut because they either convert before the tracking detectors or are accidentally matched to a track in the high multiplicity environment of a jet. The backgrounds from charm, bottom, and $W \to \tau$ was also studied and found to be small below p_T = 20 GeV/c. The background estimation comes from a hybrid data-driven

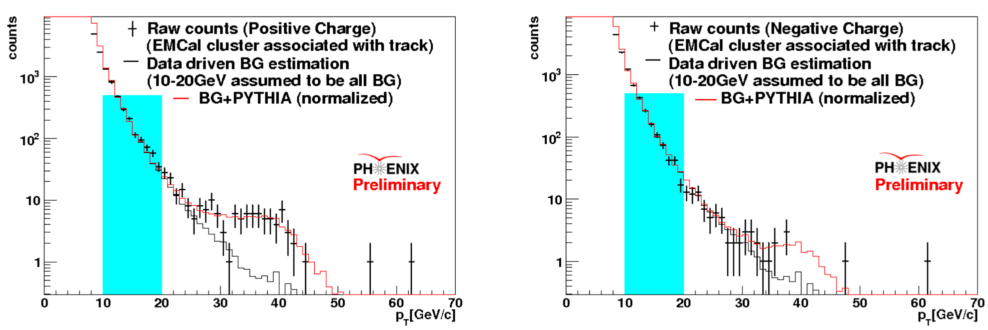

Figure 1: Spectrum of positron (left) and electron (right) candidates in the PHENIX detector.

and monte carlo approach. For the charged hadron background, a spectrum of NLO pQCD π^+

and π^- were generated and run through the GEANT based monte carlo of PHENIX. For the other backgrounds, the spectrum of clusters in the EmCal was measured, and then multiplied both by the estimated conversion rate of the inner part of PHENIX and the probability of track association. This produces an absolute spectrum of the background from the photonic contribution. Since the charged hadron response in the PHENIX monte carlo has some uncertainty, the charged hadron background was added with a free normalization to the photonic background, and fit to the region between $12 < p_T < 20$ GeV/c. From the figure one can see good agreement between the background estimate and the data. Note that the background is relatively small since PHENIX was designed specifically to measure electrons, and thus the low inner material and thin calorimeter are very effective at reducing conversion and hadronic backgrounds, justifying the loose cuts used.

There is a clear Jacobian distribution in the data, which is a well known signature of W production. One expects a Jacobian distribution in the lepton p_T since for a W decaying at rest, one can calculate the lepton p_T distribution from the solid angle distribution via

$$\frac{d\sigma}{dp_T} = \frac{d\sigma}{dcos\theta}\frac{dcos\theta}{dp_T} = \frac{d\sigma}{dcos\theta}(\frac{2p_T}{M_W})(\frac{1}{4}M_W^2 - p_T^2)^{-\frac{1}{2}} \tag{2.1}$$

The distribution is independent of phi, and the angle θ is relative to the beam-axis. The Jacobian factor comes from the last term, which produces a peak at $p_T = M_W/2$. There will be a natural smearing of this spectrum from the width of the W of ~ 2 GeV/c^2 and the fact that the W is not produced at rest (this spectrum is also not corrected for the detector resolution).

2.3 Parity Violating Single Spin Asymmetry A_L

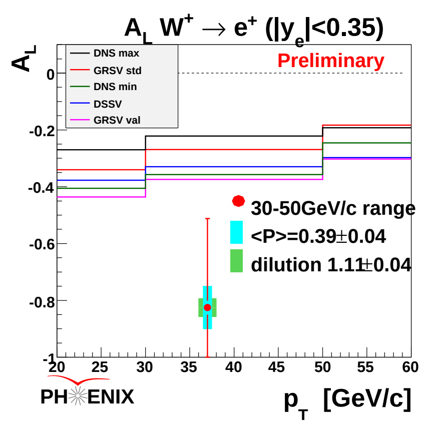

Figure 2: Parity violating Single Spin Asymmetry $A_L(W^+ \to e^+)$ for $|y_e| < 0.35$. The curves are calculated using the RHICBOS[5, 6] generator using different polarized pdf's. See text for details on the PDF's used and explanation of the measurement.

Since both beams are polarized, one has four possible spin patterns, ++, +-, - -, -+, with corresponding cross-sections $\sigma^{++} = N^{++}/L^{++}$, etc. For a single spin asymmetry measurement one beam is averaged over so that it is net unpolarized, and then the other beam is averaged over producing double the statistics, ie,

$$A_L^{LU} = \frac{1}{P}\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{1}{P}\frac{(\sigma^{++}+\sigma^{+-}) - (\sigma^{--}+\sigma^{-+})}{(\sigma^{++}+\sigma^{+-}) + (\sigma^{--}+\sigma^{-+})} \tag{2.2}$$

and vice versa for A_L^{UL}. Due to the low statistics, instead of the direct calculation as shown in the equation above, a fit of the four spin separated cross-sections was done to extract the value for $A_L(e^+)$ so that the poisson fluctuations could be taken properly into account. Also, to increase the signal-to-noise ratio in the asymmetry measurement an isolation cut of 2 GeV/c^2 was imposed around the positron candidate. This cut reduces the p_T spectrum of fig 2.2 by a factor of 4 below 25 GeV/c, but leaves the W signal region above 25 GeV largely unchanged, which demonstrates that our W candidates are isolated.

In figure 2.3 the $A_L(e^+)$ for $p_T > 30$ GeV/c is plotted along with calculations by RHICBOS[5, 6] for the expected A_L using the PDF sets DNS[8], GRSV[9], and DSSV[10]. The A_L has been corrected for dilution due to the γ^*/Z contribution and QCD, and the systematic error is due to uncertainties in the amount of QCD background. Here the asymmetry for both the QCD and γ^*/Z has been assumed to be 0. Even though the γ^*/Z asymmetry may not quite be 0, the contribution to A_L should be small since γ^*/Z is only $\sim$ 8% of the W. There is additionally a scale uncertainty to A_L due to the error on the polarization.

3. Summary and Outlook

For the first time a parity violating asymmetry from W bosons has been observed in p+p collisions. This run, which was the first to collide at 500 GeV/c^2, served as an exploratory run for both the collider to learn how to achieve high proton beam polarization at high luminosity, as well as to test the capabilities of PHENIX for measuring the $e^\pm$ decays from W bosons and for handling very high luminosities. Both goals have been successfully demonstrated with this measurement of $A_L(e^+)$. The RHIC Spin Plan[4] calls for a total integrated luminosity of 300 pb^{-1} at 70% beam polarization, and at the completion of this program we will have A_L with an order of magnitude better sensitivity than this first result, placing the strongest constraints available to the flavor identified pdf's in the x region covered by the W production at RHIC, x $\sim$ 0.1.

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