Parity-Odd Asymmetries in W-Jet Events at the Fermilab Tevatron

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Parity-odd asymmetries in the decay angular distribution of a W boson produced with a hard jet in $p\bar{p}$ collisions arise only from QCD rescattering effects. If observed, these asymmetries will provide a first demonstration that perturbative QCD calculation is valid for the absorptive part of scattering amplitudes. We propose a simple observable to measure these asymmetries and perform realistic Monte Carlo simulations at energies reached at the Fermilab Tevatron. It is shown that the Tevatron run II should provide sufficient statistics to test the prediction.

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Weak boson production at hadron colliders has become a high statistics process which allows for detailed studies of the underlying dynamics. A substantial fraction of the weak bosons have a large transverse momentum (high-q_T) with recoiling jets [1–4]. The data are reproduced well by QCD calculations [5,6] based on the factorization of long-distance and short-distance physics. Recently, azimuthal angle distributions of charged leptons arising from these W bosons were measured by the CDF Collaboration [7] using the run-I data at the Tevatron $p\bar{p}$ collider. The results are in good agreement with the predictions [8] including higher-order corrections up to $\mathcal{O}(\alpha_s^2)$ [9]. The decay polar angle distributions have been also measured by D0 [10] and CDF [11] Collaborations. These lepton distributions can provide extra information on the production mechanism because the angular distributions of the decay leptons reflect the polarization of the produced weak boson, and especially the interference between different polarization states.

Parity-nonconserving (P odd) asymmetries in the lepton distributions merit particular attention, even though the run-I luminosity was too small to measure them. As is well known, P-odd asymmetries without a spin measurement are also naïve-T-odd observables, because both P and T transformations change the sign of any three-momentum [12]. In T-conserving theories such asymmetries can arise from the scattering phase, or the absorptive part of the amplitudes [13]. Although one may argue that perturbative QCD calculations of the absorptive part of scattering amplitudes were validated in deep inelastic scattering and e^+e^- annihilation processes, it is limited to the *forward* scattering amplitudes and no experimental test has been made for the absorptive part of *nonforward* amplitudes. Measurements of such P-odd quantities thus would test perturbative QCD in a new regime and give support to the calculations of strong interaction phases, e.g., in B decays, where the interplay of strong and weak phases produces CP violating asymmetries.

The one-loop absorptive part of the high-q_T W plus jet amplitudes were calculated in Ref. [14] more than two decades ago. The P-odd asymmetries in the decay lepton angular distributions were found to arise at $\mathcal{O}(\alpha_s)$ and their q_T dependence was presented. In realistic experiments, however, the asymmetries calculated in Ref. [14] suffer from a cancellation problem arising from the ambiguity in kinematic reconstruction of the W momentum with unknown neutrino longitudinal momentum. In this Letter, we propose new observables corresponding to the P-odd asymmetries which can be measured without kinematical ambiguity, and perform realistic Monte Carlo simulation including the effects of QCD higher-order corrections and appropriate kinematical cuts for detector acceptance and event selection. The predictions made in Ref. [14] were for the Sp$\bar{\text{p}}$S collider at the center-of-mass (c.m.) energy of 540 GeV. We here reevaluate the asymmetries at the Tevatron energy of 1.96 TeV.

We consider production of a high-q_T W boson associated by a recoiling jet in $p\bar{p}$ collisions:

$$p(p_p) + \bar{p}(p_{\bar{p}}) \to W^-(q) + \text{jet}(p_j) + X;\qquad W^-(q) \to \ell^-(p_\ell) + \bar{\nu}(p_{\bar{\nu}}). \tag{1}$$

The spin-averaged differential cross section can be cast in the following form in which the dependence on W decay angles are made explicit:

$$\frac{d\sigma}{dq_T^2 d\cos\hat{\theta} d\cos\theta d\phi} = F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi + F_5\cos\theta + F_6\sin\theta\cos\phi + F_7\sin\theta\sin\phi + F_8\sin 2\theta\sin\phi + F_9\sin^2\theta\sin 2\phi. \tag{2}$$

There are nine independent functions reflecting the spin-1 nature of the W. In Eq. (2), q_T and $\hat{\theta}$ are the transverse momentum and the scattering angle of the W boson in the W-jet c.m. frame. The polar and azimuthal angles θ and ϕ of the charged lepton is defined in the Collins-Soper frame [15] in this Letter. The Collins-Soper frame is a rest frame of the W boson in which the z axis is taken to bisect the opening angle between $\vec{p}_p$ and $-\vec{p}_{\bar{p}}$, and the y axis is along the direction of $\vec{p}_p \times (-\vec{p}_{\bar{p}})$ [16]. The azimuthal angle is measured from the x axis which lies in the scattering plane.

The F_1 term gives the total rate of the high-q_T W production after integration over the lepton angles: $d\sigma/dq_T^2 d\cos\hat{\theta} = 16\pi/3F_1$. The terms F_1 through F_6 are P even, and the rest are P odd. The nine invariant functions F_i are written as a convolution of the parton distribution functions and the hard scattering part:

$$F_i = \sum_{a,b} \int dY f_{a/p}(x_+, \mu_F^2) f_{b/\bar{p}}(x_-, \mu_F^2) \hat{F}_i^{ab\to W^- j}, \quad (3)$$

where the momentum fractions $x_\pm$ are

$$x_\pm = \frac{q_T + (q_T^2 + m_W^2 \sin^2\hat{\theta})^{1/2}}{s^{1/2}\sin\hat{\theta}} e^{\pm Y}. \quad (4)$$

The scale of the distribution functions μ_F, as well as the scale of the running strong coupling constant μ_R, should be set to the relevant scale of the collisions. The hard part functions $\hat{F}_i$ are expressed as

$$\hat{F}_i^{ab\to W^- j} = \frac{3BG_F m_W^2}{4\sqrt{2}s(\hat{s} + m_W^2)\sin^2\hat{\theta}} f_i^{ab\to W^- j}(x_a, x_b), \quad (5)$$

where $\hat{s} = x_+ x_- s$, $B = B(W^- \to \ell^- \bar{\nu}_\ell)$, and G_F the Fermi constant. $f_i^{ab\to W^- j}$ are the functions of the dimensionless variables $x_a = m_W^2/2q \cdot p_a$ and $x_b = m_W^2/2q \cdot p_b$. p_a (p_b) is momentum of a parton a (b) inside the proton (antiproton).

In the leading order, the annihilation subprocess $q\bar{q}' \to W^- g$ and the Compton subprocess $qg \to W^- q'$ ($\bar{q}g \to W^- \bar{q}'$) contribute. For both processes, the leading contribution to $i = 1$–6 comes from the tree level diagrams [17], and the remainings ($i = 7, 8, 9$) receive leading contribution from the one-loop diagrams [14]. In our notation, f_i with $i = 1$ to 6 are $\mathcal{O}(\alpha_s)$, while $f_{7,8,9}$ are $\mathcal{O}(\alpha_s^2)$, at the leading order. Complete analytic forms in our notation can be found, e.g., in Refs. [14,18], where in the latter reference the Z boson vertices are found.

Higher-order corrections are important for quantitative predictions. In particular, recoil logs dominate the higher-order corrections at small q_T [19–21], so that all-order resummation is needed to gain a reliable prediction [22–24]. For the total rate of W-jet events, the next-to-leading order (NLO) correction is known to give an enhancement of $K \sim 1.3$ [5,6] relatively independent of q_T at $q_T > 30$ GeV. The higher-order effects are known to be well approximated by setting $\mu_F = \mu_R = q_T/2$ in the LO expression [25]. Moreover, threshold resummation studies indicate rather modest next-to-next-to-leading order corrections [26]. The NLO correction to the P-even parts of the angular distribution are found to be small [9,27], while those to the P-odd parts have not been calculated to our knowledge. Later we will limit ourselves to W bosons with $q_T > 30$ GeV because of large higher-order corrections for $q_T \lesssim 20$ GeV [28].

In Fig. 1, we show the differential P-odd asymmetries, defined as

$$A_i(q_T, \cos\hat{\theta}) = F_i/F_1 \quad (6)$$

with $i = 7, 8, 9$. This is the Tevatron run-II adaptation of Fig. 2 of Ref. [14], with CTEQ6M parton distribution functions [29]. The asymmetries grow monotonically with increasing q_T. The curves of $A_{7,8}$ (A_9) are nearly antisymmetric (symmetric) under the reflection of the sign of $\cos\hat{\theta}$. Interestingly, the individual asymmetries (not shown) of the annihilation subprocess and the Compton subprocess are very similar. The largest asymmetry is expected for A_7 where the magnitude of the asymmetry exceed 10% at $q_T = 40$ GeV for larger values of $|\cos\hat{\theta}|$. The asymmetries for the W^+ production are obtained from those of W^- by CP transformation ($\hat{\theta} \to \pi - \hat{\theta}$, $\theta \to \pi - \theta$, $\phi \to \phi$).

As we cannot measure the neutrino longitudinal momentum at hadron colliders, there is a twofold ambiguity on the sign of $\cos\theta$ in determining the Collins-Soper frame. This ambiguity affects A_8, but A_7 and A_9 are independent of the sign of $\cos\theta$. However, we have another twofold ambiguity in determining $\cos\hat{\theta}$ and the asymmetries of Eq. (6) cannot be measured directly. Instead of $\cos\hat{\theta}$, we propose to use the difference of the pseudorapidities of the charged lepton and the jet in the laboratory frame, $\Delta\eta \equiv \eta_\ell - \eta_j$, which has a positive correlation with $\cos\hat{\theta}$.

In our analysis, we include kinematical cuts for detecting charged leptons and jets [8,27]. For $W \to \ell\bar{\nu}_\ell$ event

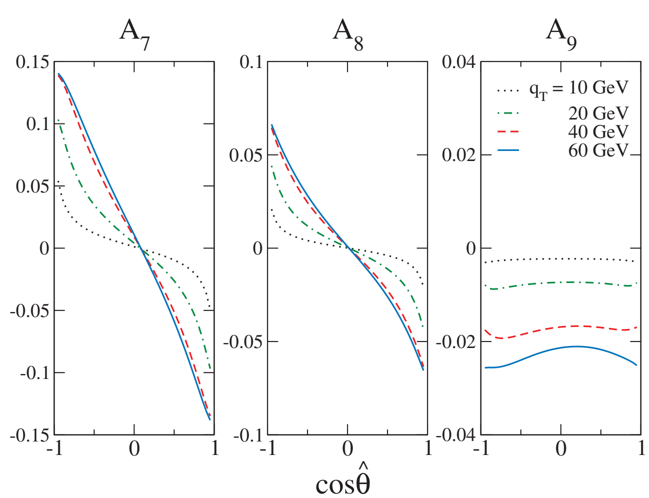

FIG. 1 (color). Differential asymmetries A_7 (left), A_8 (center), and A_9 (right) for W^- production in $p\bar{p}$ collision at $\sqrt{s} = 1.96$ TeV. $\hat{\theta}$ denotes the scattering angle between proton beam and W^- momenta in the W-jet c.m. frame.

selection, we apply the following cuts: $|\eta_\ell^{\rm lab}| < 1$, $E_T^\ell > 20$ GeV, $\not{E}_T > 20$ GeV and $M_T^W > 40$ GeV, where $\not{E}_T$ is the missing transverse energy and $M_T^W = \sqrt{(|p_T^\ell| + |\not{p}_T|)^2 - (\vec{p}_T^\ell + \vec{\not{p}}_T)^2}$ the transverse mass of the W. For jet detection and identification, we demand; $|\eta_j^{\rm lab}| < 2.4$, $E_T^j > 15$ GeV and $\Delta R > 0.7$, where $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, with $\Delta\phi$ the difference between the azimuthal angles of the charged lepton and the jet in the laboratory frame [7].

We perform Monte Carlo simulation using BASES/SPRING [30] with an integrated luminosity of 1 fb^{-1}. We consider a single flavor of leptonic W decay (either e or μ), and combine W^+ and W^- events by assuming CP invariance [31]. The event yields are found to be $(6, 10, 11, 8) \times 10^3$ for $30 < q_T({\rm GeV}) < 50$ and $(2, 5, 5, 3) \times 10^3$ for $q_T({\rm GeV}) > 50$, respectively, in the $\Delta\eta$ intervals (<-1, $[-1, 0]$, $[0, 1]$, >1). At the Tevatron energy, the contributions of annihilation subprocess and Compton subprocess to the production cross section is about the same [5,6].

We examine two observables related to the P-odd asymmetries, which can be defined without knowing the neutrino longitudinal momentum. One is a left-right asymmetry of the charged lepton momentum with respect to the scattering plane;

$$A_{\rm LR}(\Delta\eta, q_T) \equiv [N(\vec{p}_\ell \cdot \vec{n}_y > 0) - N(\vec{p}_\ell \cdot \vec{n}_y < 0)]/N_{\rm sum}, \quad (7)$$

where $\vec{n}_y = \vec{p}_p \times \vec{q}_T / |\vec{p}_p \times \vec{q}_T|$ in the laboratory frame. It is defined as the asymmetry between the number of events having charged lepton momentum with positive and negative y component, and may be expressed as $[N(0 < \phi < \pi) - N(\pi < \phi < 2\pi)]/N_{\rm sum}$ in the Collins-Soper frame. Since $\sin\theta \sin\phi$ is proportional to the y component of the charged lepton momentum, this asymmetry is expected to reflect the property of A_7. In Fig. 2, we show the left-right asymmetries with expected statistical error-bars obtained by assuming 1 fb^{-1} luminosity and setting the scale as $\mu = q_T/2$. The errors are estimated from $\delta A = \sqrt{(1 - A^2)/N_{\rm sum}}$ for each bin. The asymmetry is negative for $\Delta\eta > 0$ and positive for $\Delta\eta < 0$, which agrees with the shape of A_7 vs $\cos\hat{\theta}$ in Fig. 1 (left) as is expected. The magnitude of the asymmetry increases with q_T, and reaches 5% for $|\Delta\eta| > 1$, which is about 30% of the magnitude of A_7 at large $|\cos\hat{\theta}|$.

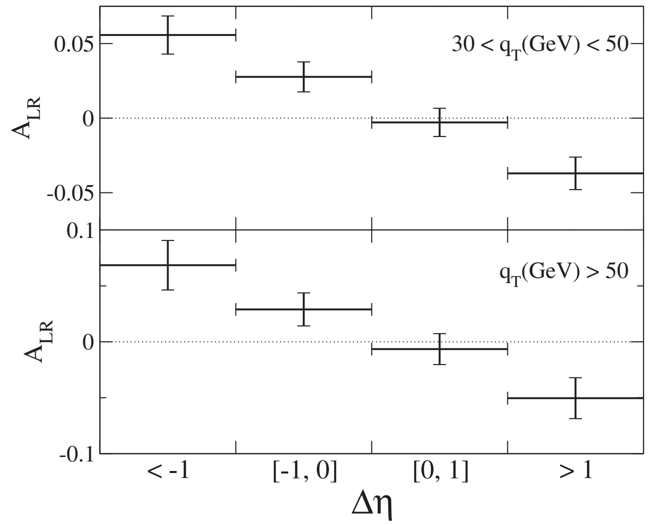

FIG. 2. Left-right asymmetries defined in Eq. (7) for $30 < q_T({\rm GeV}) < 50$ (upper), and for $q_T({\rm GeV}) > 50$ (lower). $\Delta\eta = \eta_\ell - \eta_j$ is the difference of the ℓ^- and jet pseudorapidity in the laboratory frame. In the figure, asymmetries are evaluated by setting the scale as $\mu = q_T/2$, and error bars show the expected statistical errors for the 1 fb^{-1} luminosity at the Tevatron.

Since our predictions for the P-odd asymmetries are at the LO level, they can have significant higher-order corrections. We estimate their uncertainties by varying the renormalization and factorization scale by a factor 2 and 1/2. The results listed in Table I, show that our predictions are uncertain by 10%–20%.

It may be useful to estimate the minimum luminosity needed to establish the nonzero asymmetry at the Tevatron. To define the significance, we simply combine the eight bins of Fig. 2 as $\chi^2 = \sum_{\rm bins} A^2/(\delta A)^2$. By using the asymmetry values listed in Table I, we find that the integrated luminosity needed to establish the nonzero asymmetry at the 3σ level ($\chi^2 > 9$) is 250, 180, 150 pb^{-1} when we calculate the LO expression at $\mu = q_T$, $q_T/2$, $q_T/4$, respectively. Although the above numbers are obtained by assuming 100% detection efficiency with no systematic errors, the prospect of observing the predicted asymmetry in the run-II data should be good, since more luminosity will be accumulated and both electron and muon decays can be used at two detectors.

Another asymmetry may be defined as

$$A_Q \equiv [N(0 < \phi < \pi/2) - N(\pi/2 < \phi < \pi) + N(\pi < \phi < 3\pi/2) - N(3\pi/2 < \phi < 2\pi)]/N_{\rm sum}. \quad (8)$$

Since $\sin 2\phi$ is positive for $0 < \phi < \pi/2$ and $\pi < \phi < 3\pi/2$, and negative for $\pi/2 < \phi < \pi$ and $3\pi/2 < \phi < 2\pi$, this quadrant asymmetry reflects the nature of A_9. A_9 is expected to have the same sign for any $\cos\hat{\theta}$; therefore, we may combine all data regardless of $\Delta\eta$. For this reason and the smallness of the expected magnitude of A_9, we calculate this asymmetry from all the events with any $\Delta\eta$ and $q_T > 30$ GeV, and find $A_Q = -0.8\%$ ($\mu = q_T$), -0.8% ($\mu = q_T/2$) and -0.9% ($\mu = q_T/4$). The statistical error is expected to be $\pm 0.5\%$ for the 1 fb^{-1} luminosity at the Tevatron.

TABLE I. Table of the scale ambiguities of the left-right (LR) asymmetries $A_{\rm LR}$ (%). The asymmetries are calculated in LO with setting the scale as $\mu = q_T$ (upper), $q_T/2$ (middle), and $q_T/4$ (lower) for each bins.

$\Delta\eta = \eta_\ell - \eta_j$	< -1	$[-1, 0]$	$[0, 1]$	>1
$30 < q_T(\text{GeV}) < 50$	4.7	2.2	−0.8	−3.3
	5.3	2.4	−0.9	−3.7
	6.2	2.9	−1.0	−4.3
$q_T(\text{GeV}) > 50$	5.1	2.4	−0.6	−4.4
	5.9	2.5	−0.7	−4.2
	6.9	2.9	−1.1	−4.5

Summing up, we have studied the P-odd asymmetries in the decay angular distribution of a W boson produced with a hard jet in $p\bar{p}$ collisions. We have proposed simple observables which are free from the ambiguity in the neutrino longitudinal momentum, and performed a realistic Monte Carlo simulation. It was shown that these asymmetries can be measured at the Tevatron run II, with the recent increase in the luminosity.

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