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

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Parity-odd asymmetries in the decay angular distribution of a W boson produced with a hard jet in pp 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 Tevatron energies. 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 large transverse momentum (high-qt) with recoiling jets [1,2,3,4,5,6,7]. The data are reproduced well by QCD calculations [5,6] based on the factorization of long- 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 pp collider. The results are in good agreement with the predictions [8] including higher order corrections up to O(α2s) [9]. The decay polar angle distributions have also been 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 naive-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 non-forward 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-qt 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 O(αs) and their qt dependence was presented. In realistic experiments, however, the asymmetries calculated in Ref. [14] suffer from cancellation problems arising from the ambiguity in kinematic reconstruction of the W momentum with unknown neutrino longitudinal momentum. In this paper, 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 SpS 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-qt W boson associated by a recoiling jet in pp collisions:

\[ p (p_p) + \bar{p} (p_{\bar{p}}) \rightarrow W^- (q) + j (p_j) + X; \quad (1) \]

\[ W^- (q) \rightarrow \ell^- (p_{\ell^-}) + \nu (p_{\nu}) . \]

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

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

There are nine independent functions reflecting the spin-1 nature of the W. In Eq. (2), q_T and \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...
\( \theta \) and \( \phi \) of the charged lepton is defined in the Collins-Soper frame in this paper. Collins-Soper frame is a rest frame of the \( W \) boson in which the \( z \)-axis is taken to bisect the opening angle between \( \vec{p}_f \) and \( -\vec{p}_i \), and the \( y \)-axis is along the direction of \( \vec{p}_f \times (-\vec{p}_i) \). The azimuthal angle is measured from the \( x \)-axis which lies in the scattering plane.

The \( F_i \) term gives the total rate of the high-\( q_T \) \( W \) production after integration over the lepton angles: \( d\sigma / d q_T^2 d \cos \theta = 16\tau / 3 F_1 \). 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:

\[
F_i = \sum_{a,b} \int dY f_{a/P}(x_+, \mu_F^2) f_{b/P}(x_-, \mu_F^2) \hat{F}_i^{ab \rightarrow W^-j},
\]

where the momentum fractions \( x_\pm \) are

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

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

\[
\hat{F}_i^{ab \rightarrow W^-j} = \frac{3 B G_F m_W^3}{4 \sqrt{2} s (s + m_W^2) \sin^2 \hat{\theta}} f_i^{ab \rightarrow W^-j}(x_a, x_b)
\]

where \( s = x_+ x_- \), \( B = B(W^- \rightarrow \ell^- \nu_\ell) \), and \( G_F \) the Fermi constant. \( f_i^{ab \rightarrow W^-j} \) 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 \( q \bar{q} \rightarrow W^- g \) and the Compton subprocess \( qg \rightarrow W^- q' \) (\( \bar{q} g \rightarrow W^- \bar{q}' \)) contribute. For both processes, the leading contribution to \( i = 1 \sim 6 \) comes from the tree level diagrams, and the remainings \((i = 7, 8, 9)\) receive leading contribution from the one-loop diagrams. In our notation, \( f_i \) with \( i = 1 \sim 6 \) 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] and [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 \( q_T \) [13, 20, 21], so that all-order resummation is needed to gain a reliable prediction [22, 23, 24]. For the total rate of \( W \)-jet events, the NLO correction is known to give an enhancement of \( K \sim 1.3 \) [1]. 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 [23]. Moreover, threshold resummation studies indicate rather modest NNLO corrections [24]. 

The NLO correction to the \( P \)-even parts of the angular distribution are found to be small [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

\[
A_i(q_T, \cos \hat{\theta}) = F_i / F_1
\]

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 \( A_7,8,9 \) are nearly anti-symmetric (symmetric) under the reflection of the sign of \( \cos \hat{\theta} \). Interestingly, the individual asymmetries are not obtained from the annihilation subprocess and the Compton subprocess are very similar. The largest asymmetry is expected for \( A_7 \) where the magnitude of the asymmetry exceeds 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 \( (\hat{\theta} \rightarrow \pi - \hat{\theta}, \theta \rightarrow \pi - \theta, \phi \rightarrow -\phi) \). As we cannot measure the neutrino longitudinal momentum at hadron colliders, there is a two-fold ambiguity on the sign of \( \cos \hat{\theta} \) in determining the Collins-Soper frame. This ambiguity affects \( A_8 \), but \( A_7 \) and \( A_9 \) are independent of the sign of \( \cos \hat{\theta} \). However, we have another two-fold ambiguity in determining \( \cos \hat{\theta} \) and the asymmetries of Eq. [9] 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 $W \to \ell \bar{v}_\ell$ event selection, we apply the following cuts: $|\eta^{ab}| < 1$, $E_T^\ell > 20$ GeV, $E_T > 20$ GeV and $M_T^W > 40$ GeV, where $E_T$ is the missing transverse energy and $M_T^W = \sqrt{\left(|p_T^\ell| + |p_T^\nu\ell|\right)^2 - (\hat{p}_T^\nu + \hat{p}_T^\ell)^2}$ the transverse mass of the $W$. For jet detection and identification, we demand; $|\eta^{ab}| < 2.4$, $E_T^j > 15$ GeV and $\Delta R > 0.7$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, with $\Delta\phi$ the difference between the azimuthal angles of the charged lepton and the jet in the laboratory frame.

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 $\mu$), 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 $30 < q_T(\text{GeV}) < 50$ and $(2, 5, 5, 3) \times 10^3$ for $q_T(\text{GeV}) > 50$, 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 [30].

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:

$$A_{LR}(\Delta\eta, q_T) \equiv \frac{N(\hat{p}_\ell \cdot \hat{n}_y > 0) - N(\hat{p}_\ell \cdot \hat{n}_y < 0)}{N_{\text{sum}}}, \quad (7)$$

where $\hat{n}_y = \hat{p}_\nu \times \hat{q}_T / |\hat{p}_\nu \times \hat{q}_T|$ 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 $N(0 < \phi < \pi) - N(\pi < \phi < 2\pi))/N_{\text{sum}}$ 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 $A_T$.

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 $\delta A = \sqrt{(1 - A^2)/N_{\text{sum}}}$ for each bin. The asymmetry is negative for $\Delta\eta > 0$ and positive for $\Delta\eta < 0$, which agrees with the shape of $A_T$ 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 $A_T$ at large $|\cos\hat{\theta}|$.

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 non-zero asymmetry at the Tevatron. To define the significance, we simply combine the eight bins of Fig. 2 as $\chi^2 = \sum_{\text{bins}} A^2 / (\delta A)^2$. By using the asymmetry values listed in Table I, we find that the integrated luminosity needed to establish the non-zero asymmetry at the 3$\sigma$ 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.

![FIG. 2: Left-right asymmetries defined in Eq. (7) for 30 < $q_T$(GeV) < 50 (upper), and for $q_T$(GeV) > 50 (lower). $\Delta\eta = \eta_t - \eta_j$ is the difference of the $\ell^-$ 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.]

| $\Delta\eta = \eta_t - \eta_j$ | < -1 | [-1, 0] | [0, 1] | > 1 |
|-----------------------------|------|--------|--------|-------|
| 30 < $q_T$ (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   |       |
| $q_T$ (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   |       |

TABLE I: Table of the scale ambiguities of the left-right asymmetries $A_{LR}$ (%). 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.
Another asymmetry may be defined as

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

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 \(A_0\). \(A_0\) is expected to have the same sign for any \(\cos \theta\), therefore we may combine all data regardless of \(\Delta \eta\). For this reason and the smallness of the expected magnitude of \(A_0\), 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.

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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