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

Hiroshi Yokoya (U. of Toyama)

and
R.Frederix(CERN), K.Hagiwara, T.Yamada(NCU,Taiwan), HY, in progress

BURI2014, Toyama, 2/13-14 (2014)
Outline: W-jet production at hadron colliders,
Parity-odd and naïve-T-odd observables,
Simulation study

Summary
• High-\(q_T\) W-boson production at Hadron Colliders

\[
p + p(\bar{p}) \rightarrow W^\pm + X; \quad W^\pm \rightarrow \ell^\pm \nu
\]
Lepton Angular Distributions

- Information of the polarization of $W$-boson → details of production mechanism

- Distributions can be expressed by 9 structure functions.

$$\frac{d^4 \sigma}{dq_T^2 d \cos \hat{\theta} d \cos \theta d \phi} = F_1(1 + \cos^2 \theta) + F_2(1 - 3 \cos \theta^2)$$

\[
\begin{align*}
F_3 \sin 2\theta \cos \phi & \quad + F_4 \sin^2 \theta \cos 2\phi \\
F_5 \cos \theta & \quad + F_6 \sin \theta \cos \phi \\
F_7 \sin \theta \sin \phi & \quad + F_8 \sin 2\theta \sin \phi \\
F_9 \sin^2 \theta \sin 2\phi & \quad + \quad \quad \quad (P\text{-odd})
\end{align*}
\]

$P : \phi \rightarrow -\phi$

- $p$QCD prediction : $F_i(q_T^2, \cos \hat{\theta}) = \sum_{a,b} \int dY f_{a/p}(x_+, \mu_F^2)f_{\bar{b}/\bar{p}}(x_-, \mu_F^2) F_i^{ab} \rightarrow W^- j$

$\cos \hat{\theta}$: scattering angle
$\theta, \phi$: lepton angles in $W$-rest frame
• Some of P-even distributions have been measured by CDF collaboration. → agree with pQCD (NLO) calc.

• However, P-odd distributions have not been measured yet.

Our work: revisit the P-odd effects and study the method to measure the P-odd distributions experimentally.
Parity-odd asymmetry

General arguments of parity-odd asymmetry

• Parity transformation: \((\vec{p}, \vec{s}) \rightarrow (-\vec{p}, \vec{s})\)

• Parity-odd observables:
  - with spin: \(\langle \vec{p}_\ell \cdot \vec{s} \rangle \rightarrow -\langle \vec{p}_\ell \cdot \vec{s} \rangle\)
  - without spin: \(\langle \vec{p}_p \times \vec{q} \cdot \vec{p}_\ell \rangle \rightarrow -\langle \vec{p}_p \times \vec{q} \cdot \vec{p}_\ell \rangle\)

(need a source of parity-violation, e.g. weak int.)
Parity-odd and Naïve-T (\(\tilde{T}\))-odd

- P-odd observables without spins are interesting, because these are naïve-T (\(\tilde{T}\))-odd at the same time.

\[
\begin{align*}
\text{\(\tilde{T}\)-transformation:} & \quad (\vec{p}, \vec{s}) \rightarrow (-\vec{p}, -\vec{s}) \\
\text{(unitary)} & \\
\tilde{T} | i(\vec{p}, \vec{s}) \rangle = | i(-\vec{p}, -\vec{s}) \rangle
\end{align*}
\]

\[
\begin{align*}
\text{T-transformation:} & \quad (\vec{p}, \vec{s}) \rightarrow (-\vec{p}, -\vec{s}) \\
\text{(anti-unitary)} & \\
T | i(\vec{p}, \vec{s}) \rangle = \langle i(-\vec{p}, -\vec{s}) |
\end{align*}
\]
Unitarity and $\tilde{T}$-odd quantity

- **Unitarity of S-matrix**

  \[ S_{fi} = \delta_{fi} + i(2\pi)^4 \delta^4(P_f - P_i)T_{fi} \]

  \[ T_{fi} - T_{if}^* = iA_{fi} \quad \text{where} \quad A_{fi} = \sum_n T_{nf}^* T_{ni}(2\pi)^4 \delta^4(P_n - P_i) \]

  gives

  \[ |T_{fi}|^2 = |T_{if}|^2 - 2\text{Im}(T_{if}^* A_{fi}) + |A_{fi}|^2 \]

- **$\tilde{T}$-odd quantity**

  subtract $|T_{\tilde{f}\tilde{i}}|^2$

  \[ |T_{fi}|^2 - |T_{\tilde{f}\tilde{i}}|^2 = (|T_{if}|^2 - |T_{\tilde{f}\tilde{i}}|^2) - 2\text{Im}(T_{fi}^* A_{fi}) - |A_{fi}|^2 \]

  \(\rightarrow\) emerges from the absorptive parts of the scattering amplitude
In perturbation theory, the absorptive part of scattering amplitudes can be calculated by the imaginary part of the amplitudes.

\[
\int d\Phi_2 \left( \text{diagram 1} \right) \left( \text{diagram 2} \right)^* = \text{diagram 3} = \text{Im} \left( \text{diagram 4} \right)
\]

Cutkosky rule

Therefore, measurement of naïve-T-odd quantities can test the perturbative predictions for the absorptive part of scattering amplitudes, or the scattering phase.
One-loop calculation

- Absorptive part for the W-jet production in one-loop level:

1. Annihilation subprocess: \( q\bar{q}' \rightarrow Wg \)

2. Compton subprocess: \( qg \rightarrow Wq' \) \( (\bar{q}g \rightarrow W\bar{q}') \)
Parity-odd asymmetries

$A_i(q_T^2, \cos \theta) = F_i / F_1$ for $i = 7, 8, 9$

LHC

$pp, \sqrt{S} = 8$ TeV

with CTEQ6M

$A_7 \sim 10$-15%,
$A_8 \sim$ a few %,
$A_9 \sim$ a few %

Hereafter, we focus on $A_7$ measurement
Measurement at collider experiments

- Two-fold ambiguity

- (longitudinal) neutrino momentum cannot be measured, but is solved by using W-boson on-shell condition.

→ Two-fold ambiguity in determining
  - W-jet c.m. frame \( \cos \hat{\theta}, \hat{s}, x_{\pm,\cdot} \)
  - W-rest frame \( \cos \theta, \phi \)

- However, to measure \( A_7 \), we only need to know

\[
\sin \theta \sin \phi \rightarrow \text{y-component of } p_\ell \text{ in the lab. frame}
\]

\[
\cos \hat{\theta} \quad \rightarrow \text{use pseudo-rapidity difference of lepton and jet, instead.} \quad \Delta \eta = \eta_\ell - \eta_{jet}
\]
Event in the transverse plane

$(p^l)_y$ is invariant under the Lorentz Boost from lab. frame to the $W$-rest frame

$$p_y^\ell = \frac{m_W}{2} \sin \theta \sin \phi$$

Missing $E_T$ resolution is crucial for the accuracy of $(p^l)_y$ measurement
• Standard cuts for $W$+jets events:

- One lepton with high-$p_T > 25$ GeV
- Large missing $E_T > 25$ GeV
- Large transverse mass, $M_T > 60$ GeV
- Hard jets with $p_T > 30$ GeV

• For our purpose, we may further require

- Veto on the second leading jet $p_T > 30$ GeV
- $q_T > 20$ GeV
- etc.
MC simulation by aMC@NLO

An automated NLO cross-section calculator + event generator

http://amcatnlo.web.cern.ch/amcatnlo/

• We confirmed that it calculates the absorptive part correctly.
• MC sim. with parton-shower, hadronization and detector effect.
• Able to check the effect of jet smearing, MET resolution etc.

This is very important for experimentalists to handle with such theory prediction in Monte-Carlo simulation

→ We demonstrate the aMC@NLO simulation for the realistic P-odd observables at the LHC.
Check of distributions by MC simulation

- \( \sin \theta \sin \phi \{=p_T^\gamma/(m_W/2)\} \) distribution before/after cuts (LHC 8TeV)

- Small \( \sin \theta \sin \phi \) events are suppressed by cuts → good for \( A_7 \), since smearing effect by MET resolution can be reduced.

MC simulation by aMC@NLO
• Comparison of the Asymmetries at parton-level, particle-level (Herwig) and detector-level (Delphes).

\[ A_7 = \langle 4 \sin \theta \sin \phi \rangle \propto \langle (p_\ell)_y \rangle \]

• We find that asymmetry can be retained after smearing effects.

MC simulation by aMC@NLO

error bar = statistic error in our sim. (~1 fb\(^{-1}\))

(LHC 8 TeV)
Summary

- Naïve-T-odd asymmetry emerges from the absorptive part of the scattering amplitudes. In hard process it can be predicted, and comparison with experiments would be an interesting test.

- We study the naïve-T-odd (P-odd) asymmetry in W-jet production at the LHC at one-loop level with detailed simulation study for the realistic experimental situations.

- It will be a first observation of naïve-T-odd observables in hard process.