Measurement of the $p_T(W)$ Distribution in $p\bar{p}$ Collisions at D0

Chen Wang
University of Science and Technology of China
On Behalf of the D0 Collaboration

EPS-HEP2019
July. 12th, Ghent
Motivation

- $p_T(V)$ is described by QCD calculation

- Leading Order (LO): $p_T(V) = 0$
- Including higher order: $p_T(V)$ arise from the initial state parton emission
- Test QCD predictions

- In $p\bar{p}$ collisions, the production dominated by valence quark
  - In the LHC experiments, it involves sea quarks

- Low $p_T(V)$ region dominated by multiple soft gluon emissions
  - QCD predictions from a soft-gluon resummation formalism (CSS)
  - Using a form factor with 3 non-perturbative parameters, $g_1, g_2$ and $g_3$ (BLNY)
  - Insensitive to $g_1$ and $g_3$, $g_2$ fixed to previous measurement $0.68 \pm 0.02\text{ GeV}^2$
  - Constrain models of non-perturbative approaches
  - Benefit other related electroweak parameter measurements such as $m_W$

Introduction

➢ First Tevatron Run II $p_T(W)$ measurement
  ➢ First measurement unfolded to particle level

➢ Based on previous $m_W$ measurement
  ➢ Same data sample, 4.35 fb$^{-1}$ Run II Data
  ➢ Same background estimation strategy
  ➢ Same detector calibration methodologies
  ➢ Same parametrized MC simulation (PMCS)

➢ Focus on low $p_T(W)$ region (<15 GeV)
  ➢ Sensitive to QCD non-perturbative parameter $g_2$

➢ Provide unfolded-level results
  ➢ Iterative Bayesian Unfolding Method

➢ D0 Detector

➢ Central tracking system
  ➢ Silicon Microstrip Tracker (SMT)
  ➢ Scintillating Central Fiber Tracker (CFT)
  ➢ 1.9 T Solenoid

➢ Calorimeter
  ➢ Liquid argon and uranium $|\eta| < 4.2$
  ➢ Electron energy measurement
  ➢ Hadronic recoil reconstruction
Samples and selections

- Data: Run II, $4.35 fb^{-1}$, $\sqrt{s} = 1.96 TeV$
- Trigger requirement:
  - At least one electromagnetic (EM) cluster
  - Transverse energy threshold: 25~27 GeV depend on instant luminosity

- Offline selections:
  - Electron candidate:
    $p_T^e > 25 \text{ GeV}, |\eta^e| < 1.05$
    Pass shower shape and isolation requirements
  - W candidate:
    At least one electron candidate
    $50 < m_T < 200 \text{ GeV}, p_T^{\text{Missing}} > 25 \text{ GeV}, u_T < 15 \text{ GeV}$

- Hadronic Recoil $\vec{u}_T = \sum \vec{p}_T^{\text{calo}}$, represents $p_T(W)$
  - The vector sum of reconstructed energy clusters in the calorimeters excluding deposits from the lepton

- $\vec{p}_T^\nu = \vec{p}_T^{\text{Missing}} = - (\vec{u}_T + \vec{p}_T^e)$, represents $p_T^\nu$

$$m_T = \sqrt{2p_T^e p_T^\nu (1 - cos\Delta\phi)}$$
➢ Detector Calibration

➢ Electron energy calibrated using Z mass
  ➢ Two parameters: \( E_{corr} = \alpha E_{obs} + \beta \)

➢ Hadronic Recoil calibrated with Z candidates
  ➢ \( \hat{\eta} \): the direction bisecting the two electrons
  ➢ Tuned by the imbalance in \( \hat{\eta} \) direction, \( \eta_{imb} \)

\[
\eta_{imb} = (\vec{u}_T + \vec{p}_T^{ee}) \cdot \hat{\eta}
\]

➢ In W candidates, only one charged lepton detected
  ➢ \( u_\parallel \): the parallel component of the hadronic recoil to the direction of the electron
  ➢ Tests the modeling of the hadronic recoil

➢ Good agreement between many data distributions and the prediction
Background Estimation

Three backgrounds: $W \rightarrow \tau \nu \rightarrow e\nu\nu\nu$, $Z \rightarrow e\nu$, Multi-Jet

- $W \rightarrow \tau \nu \rightarrow e\nu\nu\nu$: Estimated from MC simulation (PMCS)
- $Z \rightarrow e\nu$: one electron escapes detection
- Multi-Jet: one jet misidentified as one electron

Estimated from data

<table>
<thead>
<tr>
<th>Background</th>
<th>$W \rightarrow \tau \nu$</th>
<th>$Z \rightarrow e\nu$</th>
<th>$MJ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction</td>
<td>1.668% ± 0.0001%</td>
<td>1.08% ± 0.02%</td>
<td>1.018% ± 0.065%</td>
</tr>
</tbody>
</table>

Background less than 4%, uncertainty due to the background estimation is negligible

Good agreement between data and prediction at the reconstruction level
Unfolding procedure

Fiducial selections:

\[ p_T^e > 25 \text{ GeV}, \, |\eta^e| < 1.05 \]
\[ p_T^\nu > 25 \text{ GeV}, \, 50 < m_T < 200 \text{ GeV} \]

Basic inputs estimated from MC simulations

- Fiducial Correction: \( u_T \) distribution within fiducial volume
- Response Matrix: correct detector effects and migration
- Efficiency Correction

Response Matrix \( R \):

- The probability for the events in one \( p_T(W) \) bin to be reconstructed into different \( u_T \) bins

\[ R_{ij} = P(N_i|X_j) \]

\( N_i \): the case that \( p_T(W) \) is in the \( i^{th} \) bin
\( X_i \): the case that \( u_T \) is in the \( i^{th} \) bin

\[ N_i = \sum_j R_{ij} X_j \]
Unfolding procedure

A simple solution for $X_i$ is to use $R^{-1}$ as the unfolding matrix

$$X_i = \sum_j R^{-1}_{ij} N_j$$

Purity $R_{ii}$:
- The probability for the events in one $p_T(W)$ bin to be reconstructed into the same $u_T$ bin

Low purity caused by limited resolution
- Maximum Purity: $\max(R_{ii}) \sim 45$
- Minimum Purity: $\min(R_{ii}) \sim 16$

Low purity leads to large fluctuations in simple unfolding method
Unfolding procedure

In the iterative Bayesian unfolding method, another matrix $M$ is used instead of $R^{-1}$

- Defined by the Bayes' theorem, the probability of an event in one $u_T$ bin from different $p_T(W)$ bins

\[
M_{ij} = P(X_i | N_j) = \frac{P(N_j | X_i)P(X_i)}{\sum_k P(N_j | X_k)P(X_k)} = \frac{R_{ji}X_i}{\sum_k R_{jk}X_k}
\]

- Use MC values for initial $X_i$, iterate by updating $X_i$ and $M_{ij}$ at each step
  - Model dependence is suppressed after iterations
  - Number of iterations: 16

- Dominant uncertainties due to unfolding method and residual model dependence

<table>
<thead>
<tr>
<th>$\frac{1}{\sigma} \frac{d\sigma}{dp_T(W)}$ central value</th>
<th>Binning</th>
<th>0-2 GeV</th>
<th>2-5 GeV</th>
<th>5-8 GeV</th>
<th>8-11 GeV</th>
<th>11-15 GeV</th>
<th>15-600 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
<td></td>
<td>0.015</td>
<td>0.015</td>
<td>0.010</td>
<td>0.006</td>
<td>0.007</td>
<td>0.012</td>
</tr>
<tr>
<td>Data statistics</td>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>MC statistics</td>
<td></td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>MC model for unfolding</td>
<td></td>
<td>0.015</td>
<td>0.014</td>
<td>0.010</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>MC model for $u_T &gt; 15$ GeV</td>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.004</td>
<td>0.005</td>
<td>0.011</td>
</tr>
<tr>
<td>Hadronic recoil</td>
<td></td>
<td>0.002</td>
<td>0.005</td>
<td>0.001</td>
<td>0.003</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>Electron energy</td>
<td></td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

12.07.2019

EPS-HEP2019, Ghent
Result and chi-square calculation

<table>
<thead>
<tr>
<th>Generator/Model</th>
<th>Reconstruction level $\chi^2$/ndf</th>
<th>Unfolded level $\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ResBos (Version CP 020811)</strong>+CTEQ6.6</td>
<td>2.55</td>
<td>1.24</td>
</tr>
<tr>
<td><strong>ResBos (Version CP 112216)</strong>+CT14HERA2NNLO</td>
<td>1.17</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Pythia 8+CT14HERA2NNLO</strong></td>
<td>2.95</td>
<td>0.84</td>
</tr>
<tr>
<td><strong>Pythia 8+ATLAS MB A2Tune+CTEQ6L1</strong></td>
<td>9.77</td>
<td>3.39</td>
</tr>
<tr>
<td><strong>Pythia 8+ATLAS MB A2Tune+MSTW2008LO</strong></td>
<td>7.26</td>
<td>2.38</td>
</tr>
<tr>
<td><strong>Pythia 8+ATLAS AZTune+CT14HERA2NNLO</strong></td>
<td>0.55</td>
<td>0.16</td>
</tr>
</tbody>
</table>
➢ Summary

➢ First Tevatron Run II $p_T(W)$ measurement
➢ Focus on low $p_T(W)$ region
➢ Better precision than the previous Run I measurement
➢ Unfolded-level results provided with the iterative Bayesian method

➢ Further study

➢ Correlation of the systematic uncertainty due to the MC modeling
  ➢ Leading systematic uncertainty caused by low purity

➢ Further $g_2$ fitting with the unfolded level $p_T(W)$ distribution
Backup
Collins-Soper-Sterman (CSS) resummation formalism

Production of a vector boson in the collision of two hadrons

$$\frac{d\sigma(h_1 h_2 \rightarrow VX)}{dQ^2 dQ_T^2 dy} = \frac{1}{(2\pi)^2} \delta(Q^2 - M_V^2) \int d^2b \ e^{i\vec{Q}_T \cdot \vec{b}} \tilde{W}_{jk}(b, Q, x_1, x_2) + Y(Q_T, Q, x_1, x_2)$$

$b$: impact parameter

the nonperturbative terms in the form of an additional factor $\tilde{W}_{jk}^{NP}(b, Q, x_1, x_2)$

$$\tilde{W}_{jk} = \tilde{W}_{jk}^{pert} \tilde{W}_{jk}^{NP}$$

Brock-Landry-Nadolsky-Yuan form

$$\tilde{W}_{jk}^{NP}(b, Q, x_1, x_2) = \exp\left(-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right) - g_1g_3 \ln(100x_1x_2)\right)b^2$$