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

Ken Bloom (with thanks to Chen Wang)
University of Nebraska-Lincoln
On behalf of the D0 Collaboration

DPF 2019
1 August 2019
➢ **Motivation**

➢ $p_T(V)$ is described by QCD calculations

➢ Leading Order (LO): $p_T(V) = 0$

➢ Including higher order: $p_T(V)$ arises from initial state parton emission

➢ Test QCD predictions

➢ In $p\bar{p}$ collisions, the production dominated by valence quarks

➢ 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 $g_3$, but sensitive to $g_2$

➢ Constrain models of non-perturbative approaches

➢ Benefits 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)
  ➢ Compare to predictions from measured \( g_2 = 0.68 \pm 0.02 \) GeV\(^2\)

➢ 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
- Missing energy reconstruction
Samples and selections

Data: Run II, 4.35 fb\(^{-1}\), \(\sqrt{s} = 1.96\) TeV

Trigger requirement:
- At least one electromagnetic cluster
- Transverse energy threshold: 25-27 GeV depending on instantaneous 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
  \[ u_T < 15 \text{ GeV}, \ p_T^{\text{Missing}} > 25 \text{ GeV}, \ 50 < m_T < 200 \text{ GeV} \]

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

\(\vec{p}_T^{\text{Missing}} = -(\vec{u}_T + \vec{p}_T^e)\) represents neutrino momentum

\[ m_T = \sqrt{2p_T^e p_T^\nu(1 - \cos\Delta\phi)} \]
➢ 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
  ➢ \( \vec{u}_\parallel \): the component of the hadronic recoil parallel to the direction of the electron
  ➢ Tests the modeling of the hadronic recoil

➢ Good agreement between many data distributions and predictions
Background Estimation

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

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

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

\[
p^e_T > 25 \text{ GeV}, \quad |\eta^e| < 1.05
\]
\[
p^\nu_T > 25 \text{ GeV}, \quad 50 < m_T < 200 \text{ GeV}
\]

- 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

\[
R_{ij} = P(N_i | \mathcal{X}_j)
\]

\( N_i \): the number of events in the \( i^{th} \) \( u_T \) bin
\( \mathcal{X}_i \): the case that \( p_T(W) \) is in the \( i^{th} \) bin

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

\( X_i \): the number of events in the \( i^{th} p_T(W) \) bin
Unfolding procedure

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

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

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:

$$M_{ij} = P\left(\mathcal{X}_i \mid \mathcal{N}_j\right) = \frac{P(\mathcal{N}_j \mid \mathcal{X}_i)P(\mathcal{X}_i)}{\sum_k P(\mathcal{N}_j \mid \mathcal{X}_k)P(\mathcal{X}_k)} = \frac{R_{ji}X_i}{\sum_k R_{jk}X_k}$$

Use MC values for initial $X_i$ and then iterate by updating $X_i$ and $M_{ij}$ at each step.

Model dependence is reduced after iterations.

Number of iterations is optimized at 16.

Dominant uncertainties due to unfolding method and residual model dependence.

<table>
<thead>
<tr>
<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>$\frac{1}{\sigma} \frac{d\sigma}{dp_T(W)}$ central value</td>
<td>0.107</td>
<td>0.293</td>
<td>0.189</td>
<td>0.117</td>
<td>0.094</td>
<td>0.199</td>
</tr>
<tr>
<td>Total uncertainty</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>&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>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><strong>MC model for unfolding</strong></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><strong>MC model for $\bar{u}_T &gt; 15$ GeV</strong></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>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>&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>
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>ResBos (Version CP 020811) + CTEQ6.6</td>
<td>2.55</td>
<td>1.24</td>
</tr>
<tr>
<td>ResBos (Version CP 112216) + CT14HERA2NNLO</td>
<td>1.17</td>
<td>0.97</td>
</tr>
<tr>
<td>Pythia 8 + CT14HERA2NNLO</td>
<td>2.95</td>
<td>0.84</td>
</tr>
<tr>
<td><strong>Pythia 8 + ATLAS MB A2Tune + CTEQ6L1</strong></td>
<td><strong>9.77</strong></td>
<td><strong>3.39</strong></td>
</tr>
<tr>
<td><strong>Pythia 8 + ATLAS MB A2Tune + MSTW2008LO</strong></td>
<td><strong>7.26</strong></td>
<td><strong>2.38</strong></td>
</tr>
<tr>
<td><strong>Pythia 8 + ATLAS AZTune + CT14HERA2NNLO</strong></td>
<td><strong>0.55</strong></td>
<td><strong>0.16</strong></td>
</tr>
</tbody>
</table>
➢ Summary

➢ First Tevatron measurement of the unfolded $p_T(W)$ distribution
➢ Focus on low $p_T(W)$ region to study soft gluon radiation effects
➢ Better precision than the Run I measurement
➢ Unfolded-level results provided with the iterative Bayesian method

➢ Further study

➢ Correlation of systematic uncertainties 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

\[
\frac{d\sigma(h_1h_2 \rightarrow VX)}{dQ^2dQ_T^2dy} = \frac{1}{(2\pi)^2} \delta(Q^2 - M_V^2) \int d^2b \ e^{i\tilde{Q}_T \cdot \tilde{b}} \tilde{W}_{jk}(b, Q, x_1, x_2) + Y(Q_T, Q, x_1, x_2)
\]

\(b\): 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

\[
\tilde{W}_{jk}^{NP}(b, Q, x_1, x_2) = \exp \left( -g_1 - g_2 \ln \left( \frac{Q}{2Q_0} \right) - g_1 g_3 \ln (100x_1x_2) \right) b^2
\]