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

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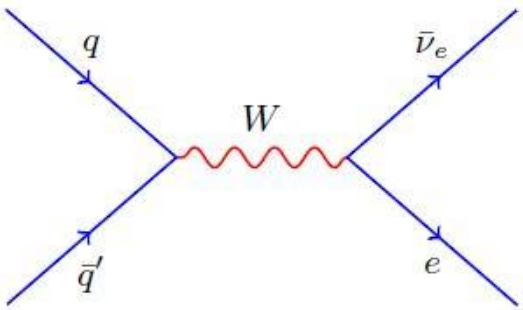
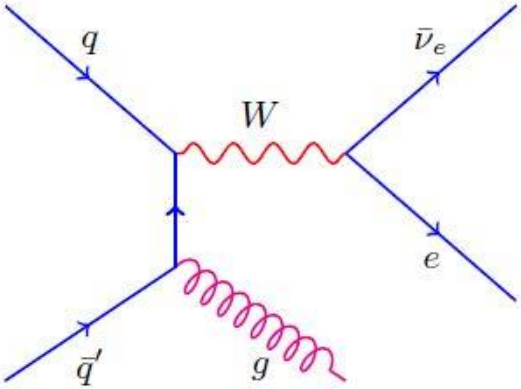
- Motivation
  - $p_T(V)$ is described by QCD calculation





    - 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 ± 0.02 GeV^2
    - Constrain models of non-perturbative approaches
    - Benefit other related electroweak parameter measurements such as m_W

CSS: Nucl. Phys. B250, 199 (1985)
BLNY: Phys. Rev. D 67, 073016 (2003)

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

Iterative Bayesian Unfolding Method: Nucl.Instrum.Meth.,A362,1995
Previous m_W measurement: Phys. Rev. Lett. 108, 151804 (2012)
Phys. Rev. D 89, 012005 (2014)

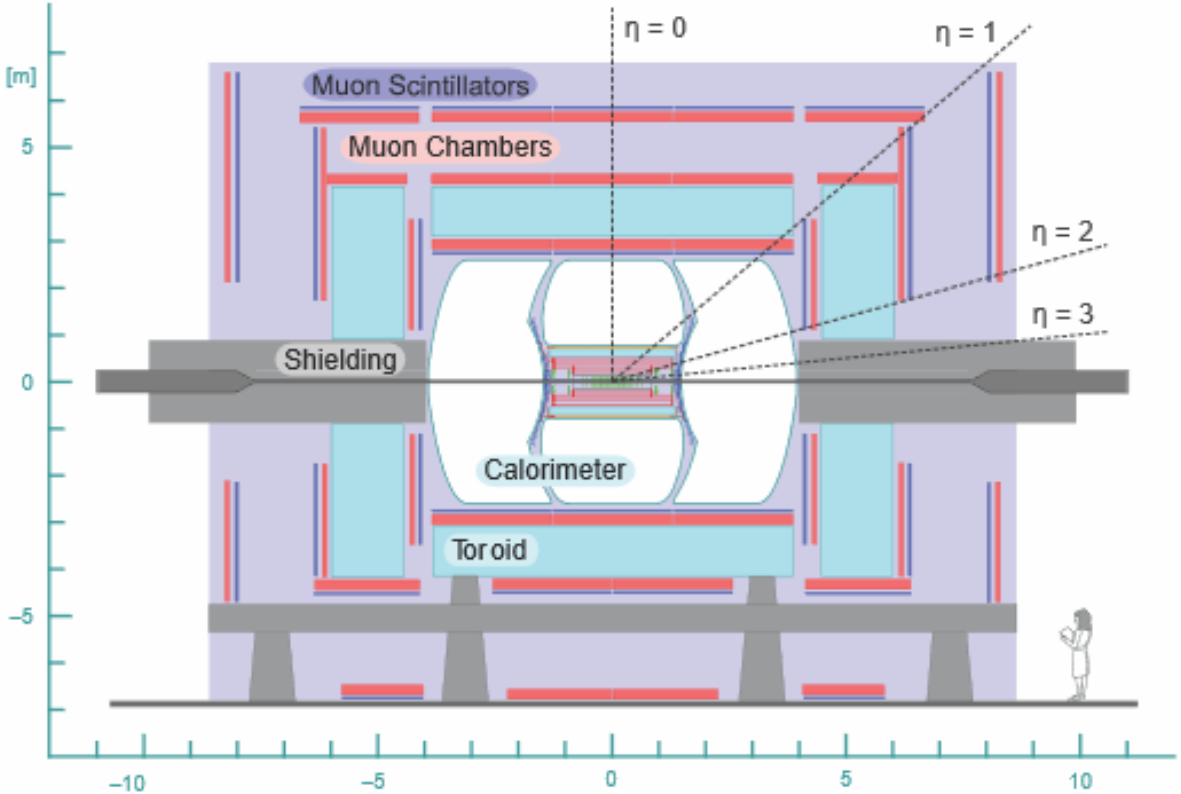
D0 Detector

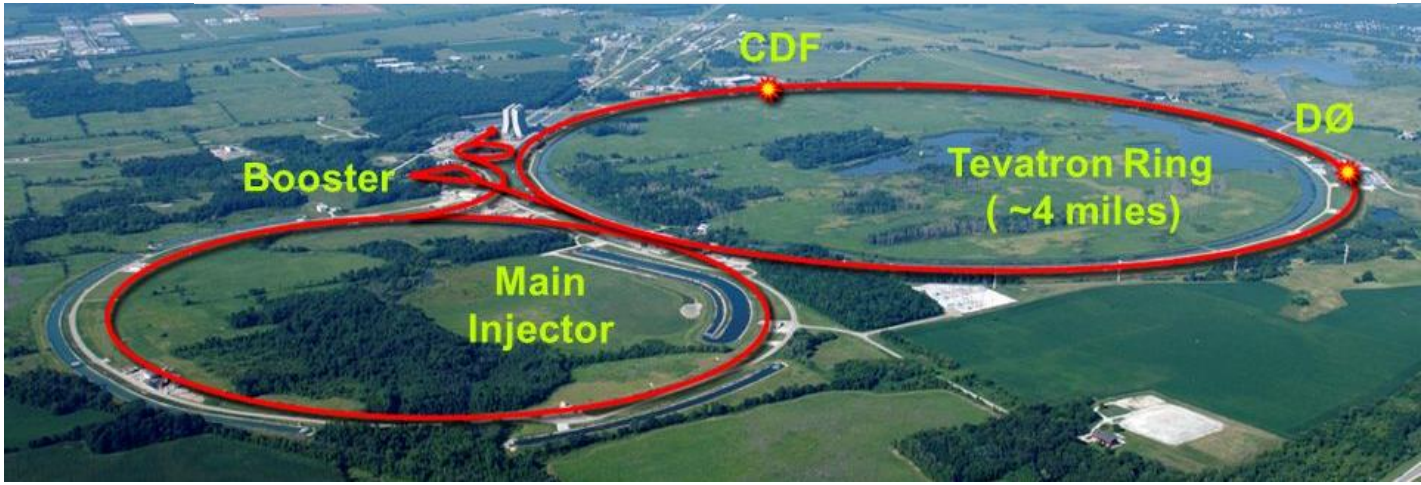
Central tracking system

- 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:

    $p_T^e > 25$ GeV, $|\eta^e| < 1.05$

    Pass shower shape and isolation requirements
  - W candidate:

    At least one electron candidate

    $50 < m_T < 200$ GeV, $p_T^{Missing} > 25$ GeV, $u_T < 15$ GeV

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

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

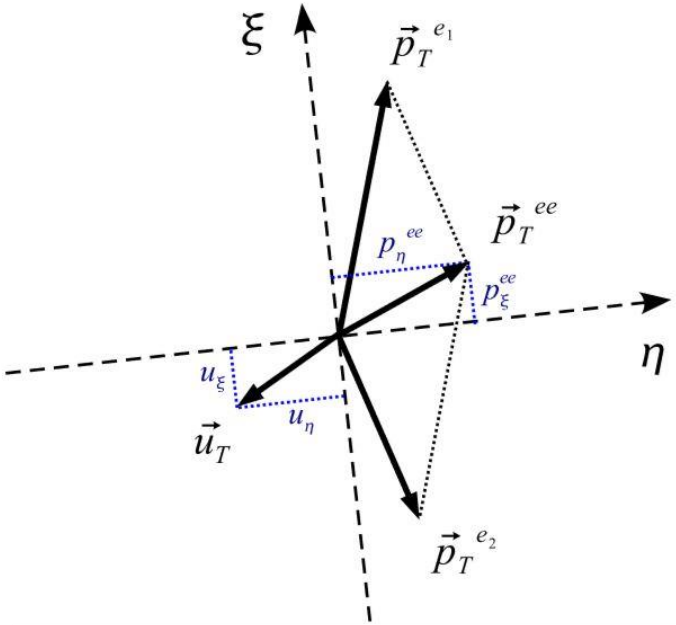
$$m_T = \sqrt{2p_T^e p_T^{\upsilon}(1 - cos\Delta\phi)}$$

Detector Calibration

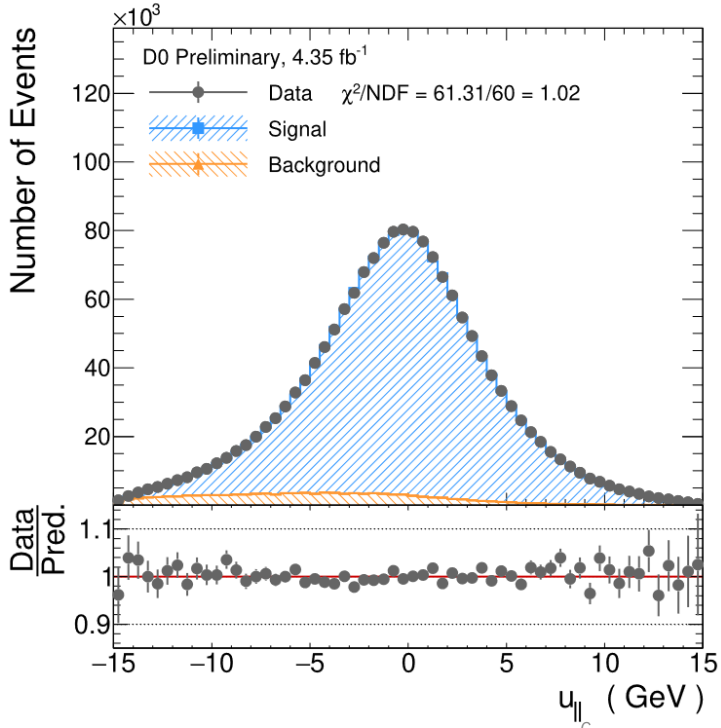
- Electron energy calibrated using Z mass
  - Two parameters: $E_{corr} = \alpha E_{obs} + \beta$

- Hadronic Recoil calibrated with Z candidates
  - $\hat{\eta}$: the direction bisecting the two electrons
  - Tuned by the imbalance in $\hat{\eta}$ direction, η_{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

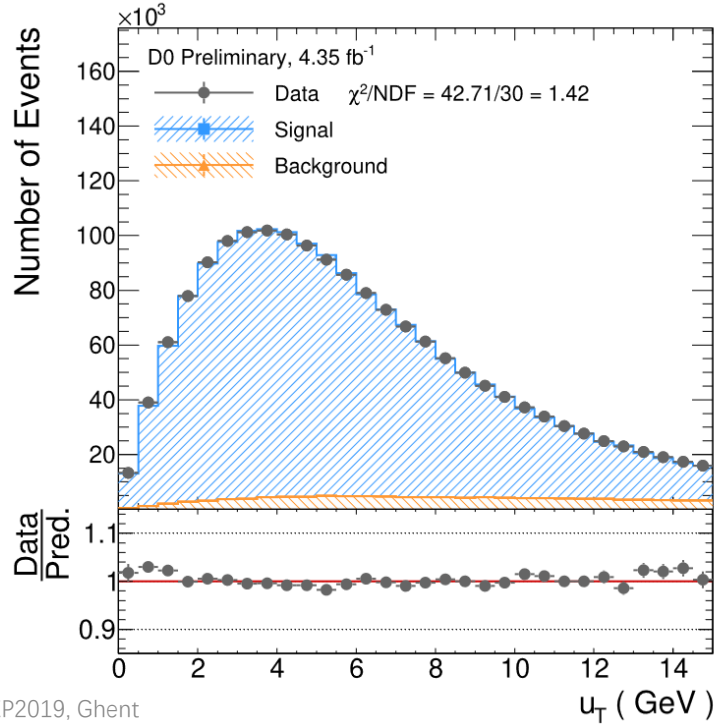
- Three backgrounds: $W \to \tau\upsilon \to e\upsilon\upsilon\upsilon$, $Z \to ee$, Multi-Jet
  - $W \to \tau\upsilon \to e\upsilon\upsilon\upsilon$: Estimated from MC simulation (PMCS)
  - $Z \to ee$: one electron escapes detection
  - Multi-Jet: one jet misidentified as one electron

  } Estimated from data

Background	$W \to \tau\upsilon$	$Z \to ee$	MJ
Fraction	$1.668\% \pm 0.0001\%$	$1.08\% \pm 0.02\%$	$1.018\% + 0.065\%$

- 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:

$$p_T^e > 25 \text{ GeV}, |\eta^e| < 1.05$$
$$p_T^\upsilon > 25 \text{ GeV}, 50 < m_T < 200 \text{ GeV}$$

- 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

$$R_{ij} = P(\mathcal{N}_i|\mathcal{X}_j)$$

$\mathcal{N}_i$: the case that $p_T(W)$ is in the ith bin

$\mathcal{X}_i$: the case that u_T is in the ith bin

N_i: the number of events in the ith $p_T(W)$ bin

X_i: the number of events in the ith u_T bin

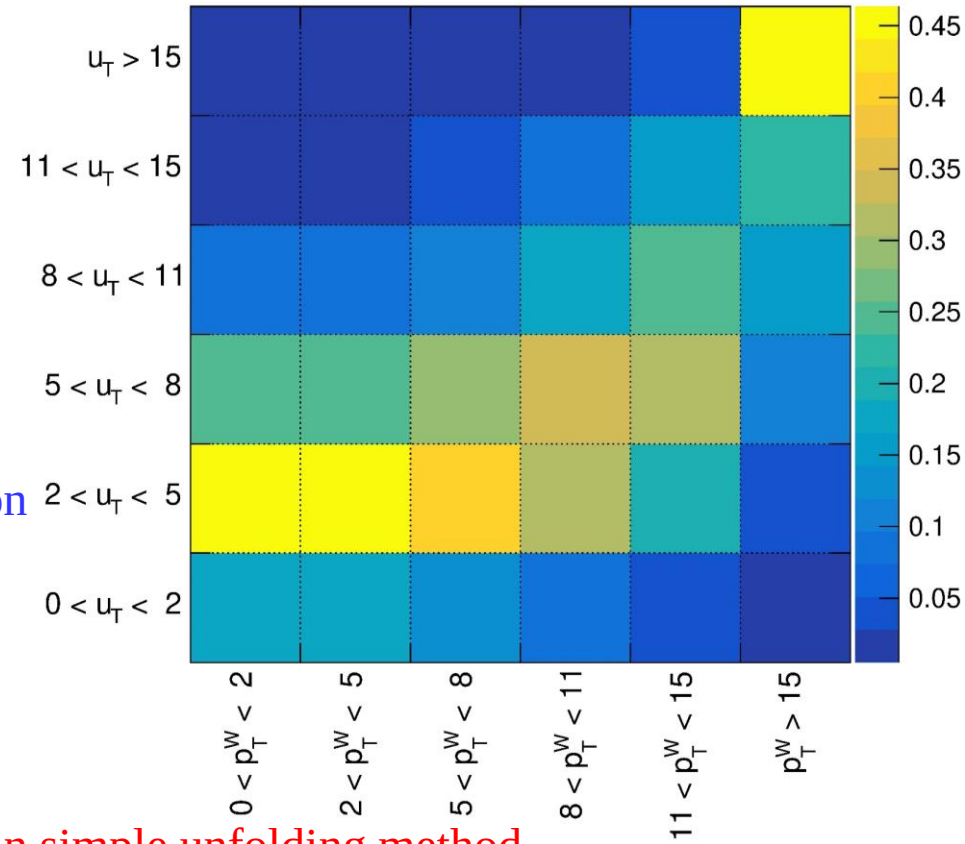
$$N_i = \sum_j R_{ij} X_j$$

Unfolding procedure

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

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

- 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

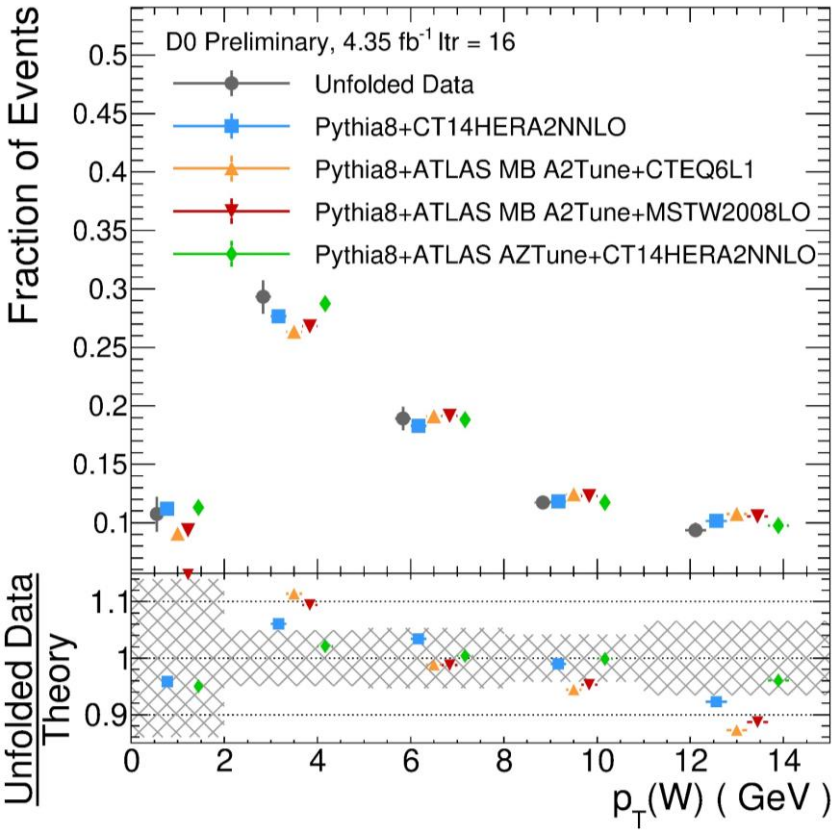
$$M_{ij} = P(\mathcal{X}_i|\mathcal{N}_j) = \frac{P(\mathcal{N}_j|\mathcal{X}_i)P(\mathcal{X}_i)}{\sum_k P(\mathcal{N}_j|\mathcal{X}_k)P(\mathcal{X}_k)} = \frac{R_{ji}X_i}{\sum_k R_{jk}X_k}$$

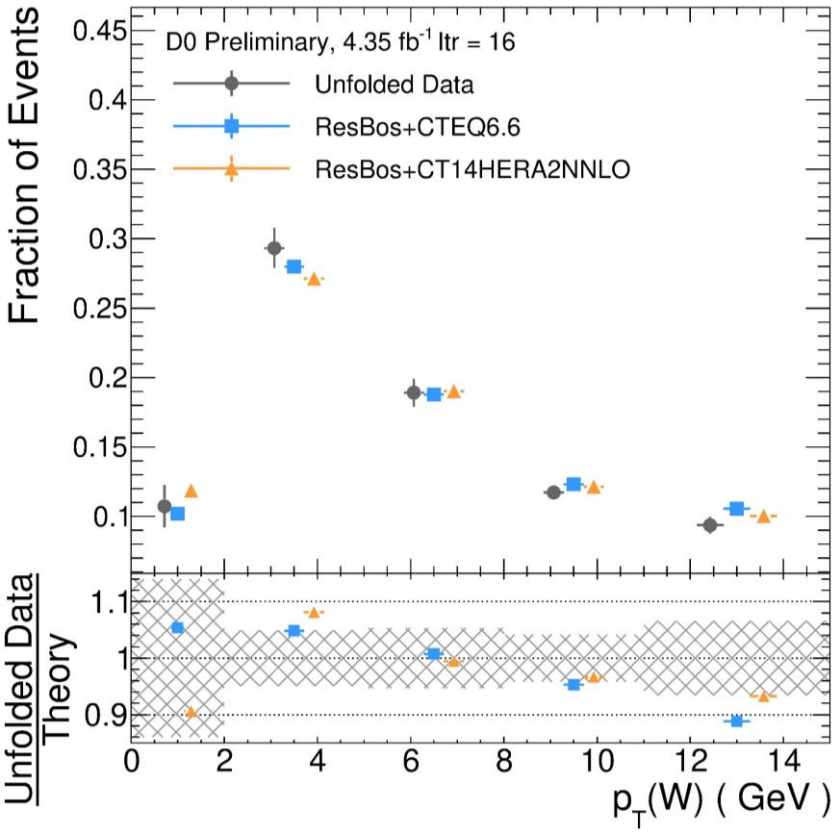
  - Use MC values for initial X_i, iterate by updating X_i and M_{ij} at each step
    - Model dependence is suppressed after iterations
    - Number of iterations: 16

  - Dominant uncertainties due to unfolding method and residual model dependence

Binning	0-2 GeV	2-5 GeV	5-8 GeV	8-11 GeV	11-15 GeV	15-600 GeV
$\frac{1}{\sigma}\frac{d\sigma}{dp_T(W)}$ central value	0.107	0.293	0.189	0.117	0.094	0.199
Total uncertainty	0.015	0.015	0.010	0.006	0.007	0.012
Data statistics	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
MC statistics	0.001	0.002	0.001	0.001	0.002	0.002
MC model for unfolding	0.015	0.014	0.010	0.003	0.002	0.001
MC model for $\vec{u}_T > 15$ GeV	<0.001	<0.001	0.002	0.004	0.005	0.011
Hadronic recoil	0.002	0.005	0.001	0.003	0.004	0.001
Electron energy	<0.001	0.001	<0.001	0.001	0.001	<0.001

➢ Result and chi-square calculation





Generator/Model	Reconstruction level χ^2/ndf	Unfolded level χ^2/ndf
RESBOS (Version CP 020811)+CTEQ6.6	2.55	1.24
RESBOS (Version CP 112216)+CT14HERA2NNLO	1.17	0.97
PYTHIA 8+CT14HERA2NNLO	2.95	0.84
PYTHIA 8+ATLAS MB A2Tune+CTEQ6L1	9.77	3.39
PYTHIA 8+ATLAS MB A2Tune+MSTW2008LO	7.26	2.38
PYTHIA 8+ATLAS AZTune+CT14HERA2NNLO	0.55	0.16

- 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

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

b: impact parameter

➢ the nonperturbative terms in the form of an additional factor $\widetilde{W}_{j\bar{k}}^{NP}(b, Q, x_1, x_2)$

$$\widetilde{W}_{j\bar{k}} = \widetilde{W}_{j\bar{k}}^{pert}\widetilde{W}_{j\bar{k}}^{NP}$$

➢ Brock-Landry-Nadolsky-Yuan form

$$\widetilde{W}_{j\bar{k}}^{NP}(b, Q, x_1, x_2) = \exp\left(-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right) - g_1 g_3 \ln(100 x_1 x_2)\right) b^2$$

CSS: Nucl. Phys. B250, 199 (1985)
BLNY: Phys. Rev. D 67, 073016 (2003)