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

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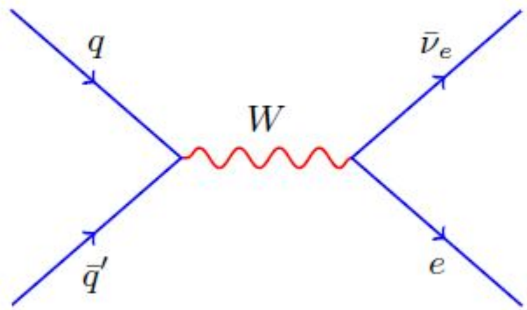
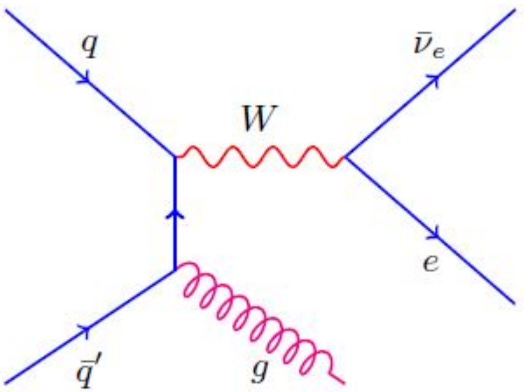
➢ Motivation

- ➢ $p_T(V)$ 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

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)
  - ➢ Compare to predictions from measured $g_2 = 0.68 \pm 0.02$ GeV^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)

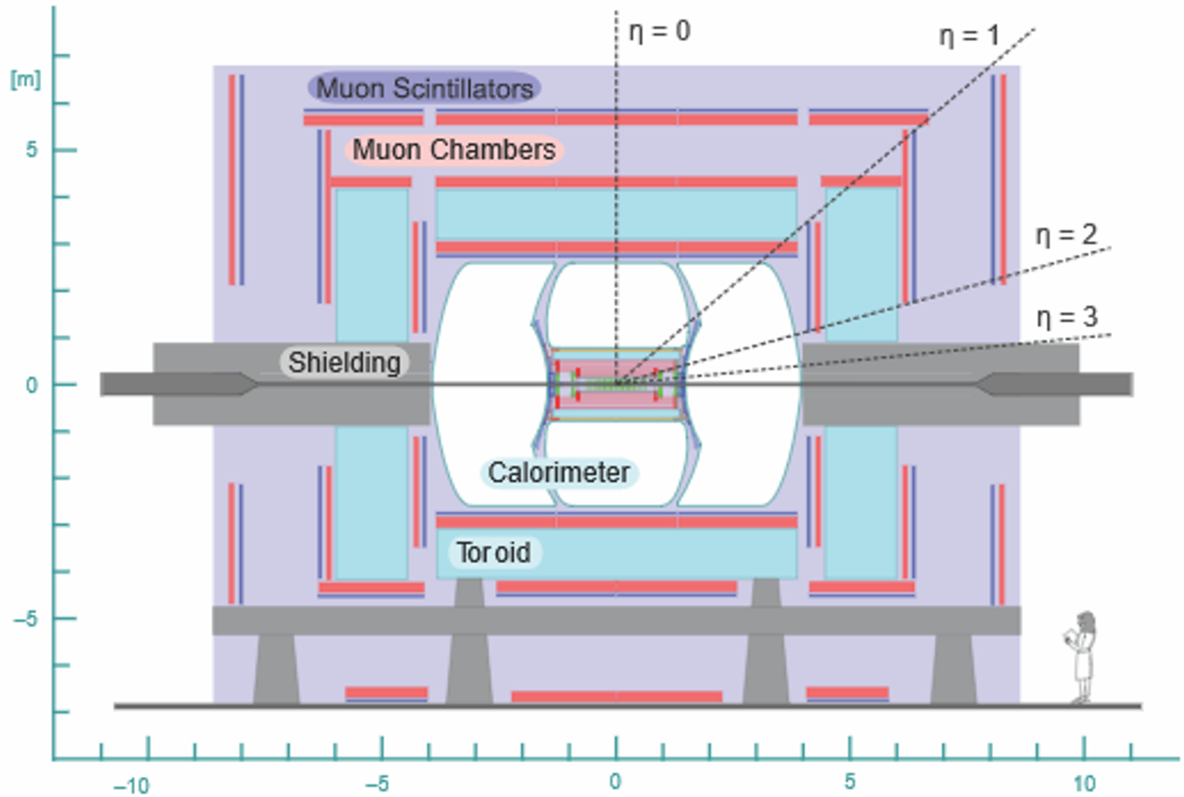
➢ D0 Detector

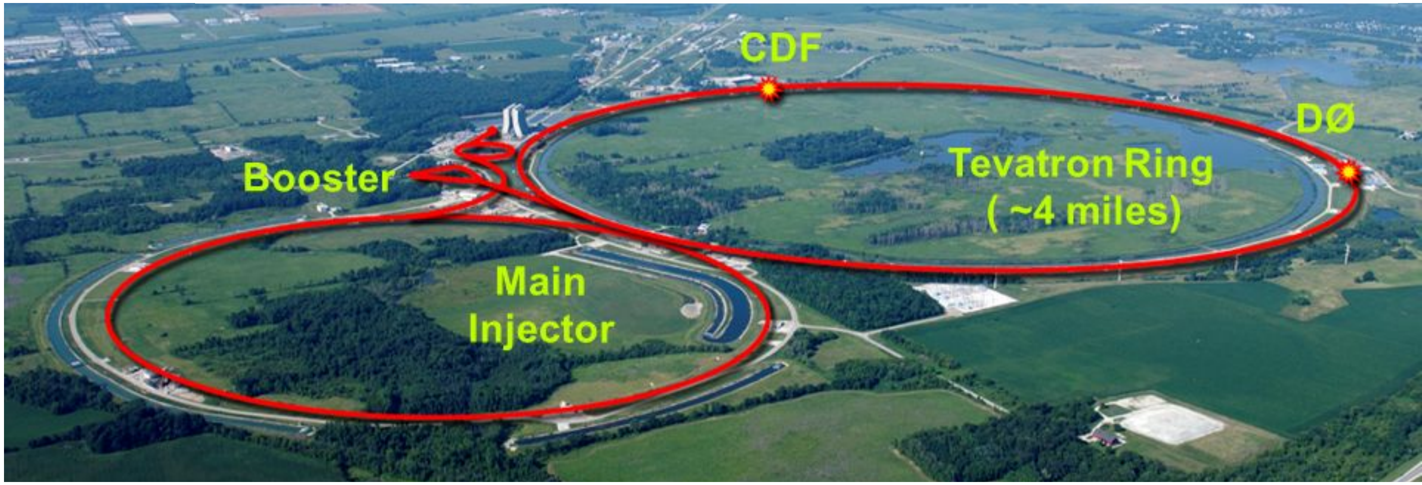
➢ Central tracking system

- ➢ 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
- ➢ 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:

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

    Pass shower shape and isolation requirements
  - W candidate:

    At least one electron candidate

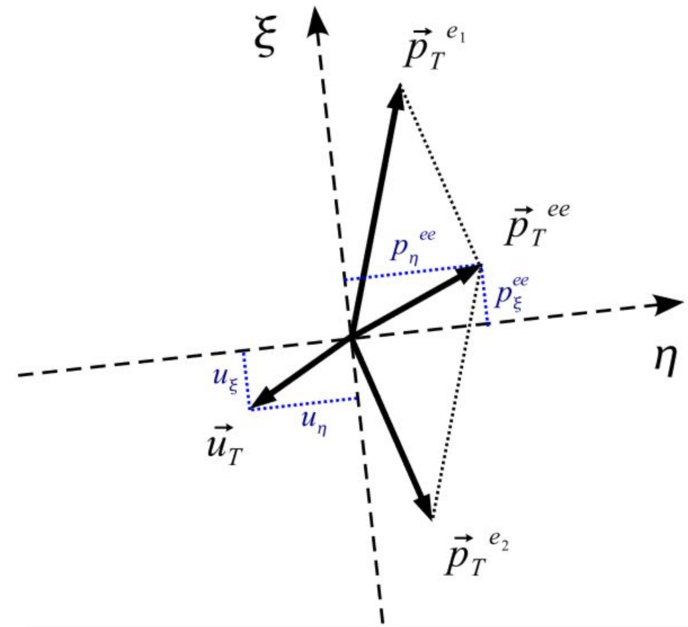
    $u_T < 15$ GeV, $p_T^{Missing} > 25$ GeV, $50 < m_T < 200$ GeV

- 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
- $\vec{p}_T^{\,Missing} = -(\vec{u}_T + \vec{p}_T^{\,e})$ represents neutrino momentum
- $m_T = \sqrt{2p_T^e p_T^\upsilon(1 - \cos\Delta\phi)}$

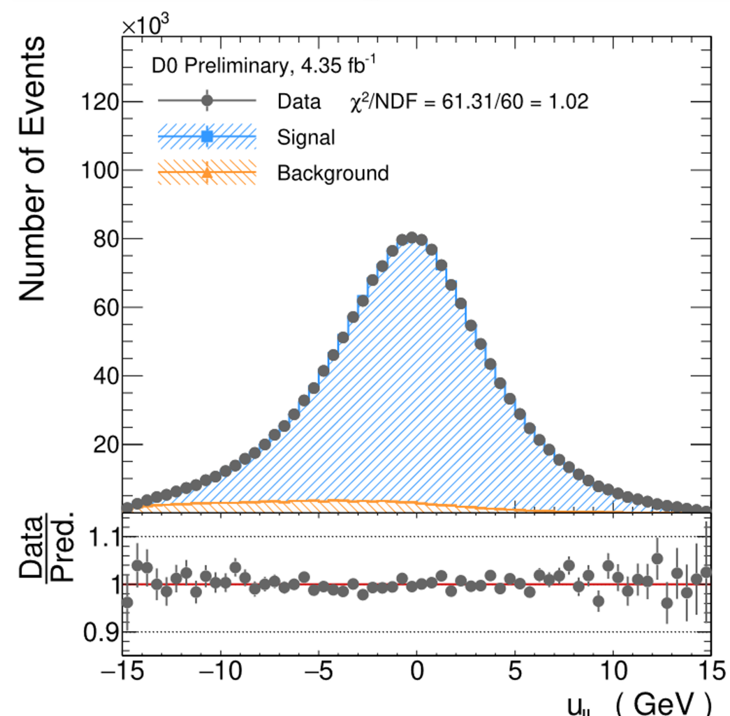
➢ Detector Calibration

- ➢ 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}

$$\eta_{imb} = (\vec{u}_T + \vec{p}_T^{\,ee}) \bullet \hat{\eta}$$



- ➢ In W candidates, only one charged lepton detected
  - ➢ $u_{||}$: 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

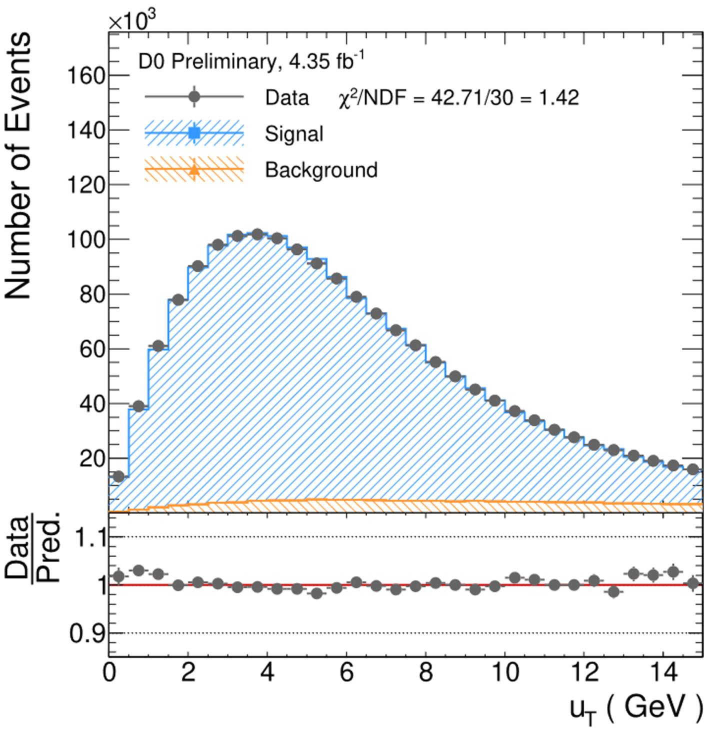
- ➢ Three backgrounds: $W \rightarrow \tau\upsilon \rightarrow e\upsilon\upsilon\upsilon$, $Z \rightarrow ee$, Multi-Jet
  - ➢ $W \rightarrow \tau\upsilon \rightarrow e\upsilon\upsilon\upsilon$: Estimated from MC simulation (PMCS)
  - ➢ $Z \rightarrow ee$: one electron escapes detection
  - ➢ Multi-Jet: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

  } Estimated from data (applies to $Z \rightarrow ee$ and Multi-Jet)

Background	W→τυ	Z→ee	MJ
Fraction	1.668%±0.0001%	1.08%±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:

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

➢ 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 u_T is in the i^{th} bin
$\mathcal{X}_i$: the case that $p_T(W)$ is in the i^{th} bin

N_i: the number of events in the i^{th} u_T bin
X_i: the number of events in the i^{th} $p_T(W)$ bin

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

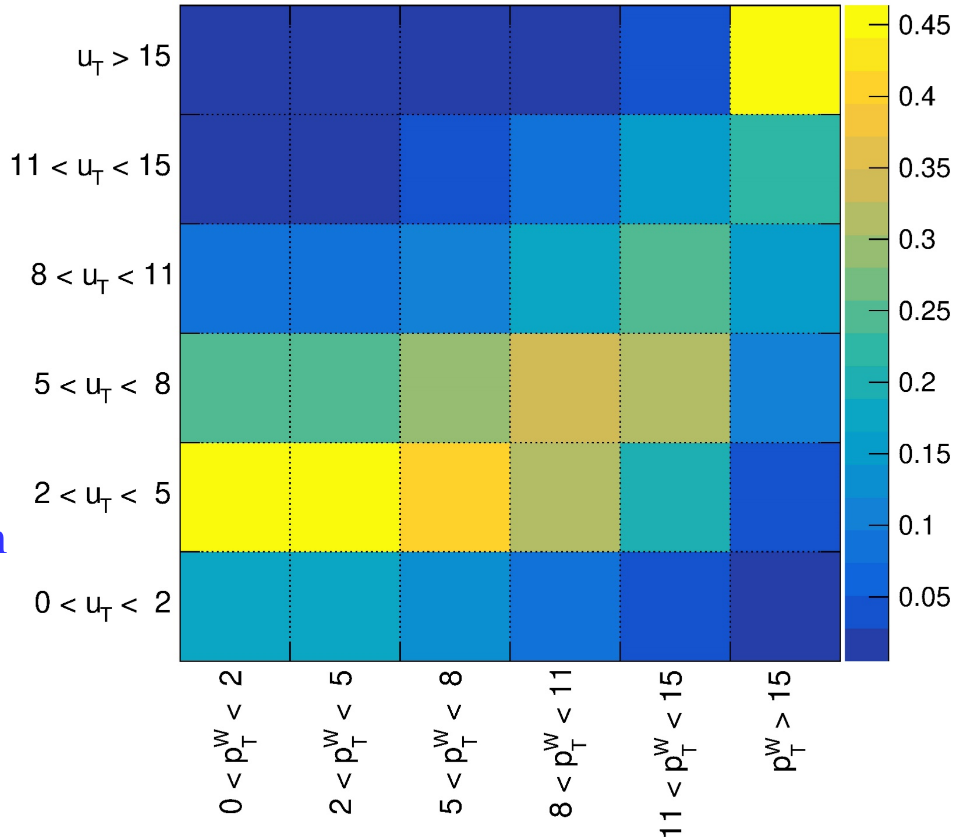
➢ Unfolding procedure

➢ A simple solution for X_i would be 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

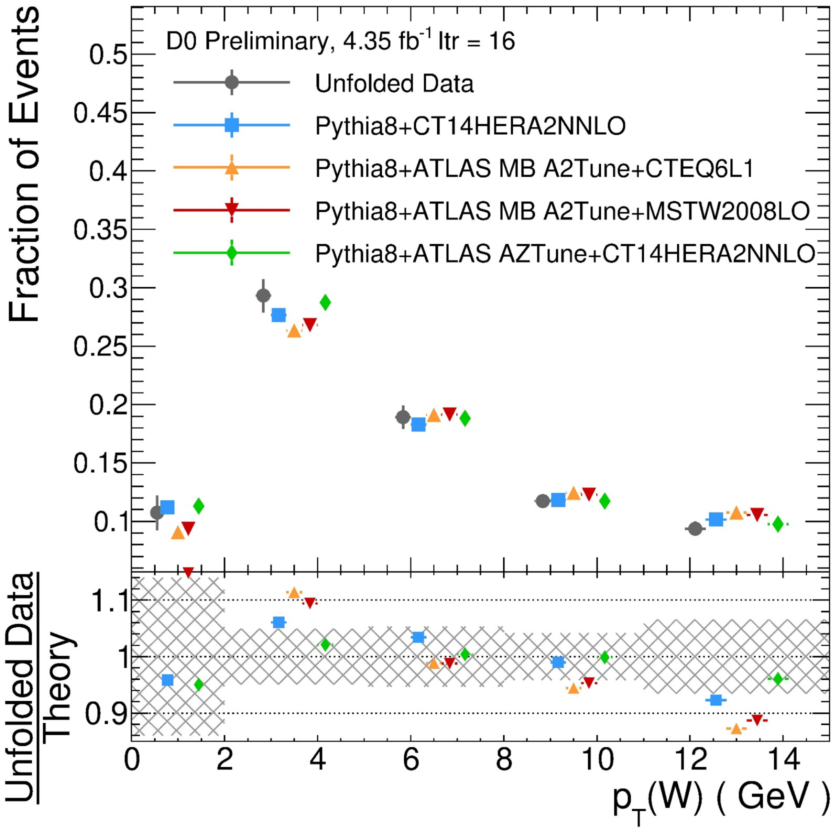
- Unfolding procedure
  - In the iterative Bayesian unfolding method, another matrix M is used instead of R^{-1}
    - Defined by the Bayes theorem, the probability of an event in one u_T bin from different $p_T(W)$ bins

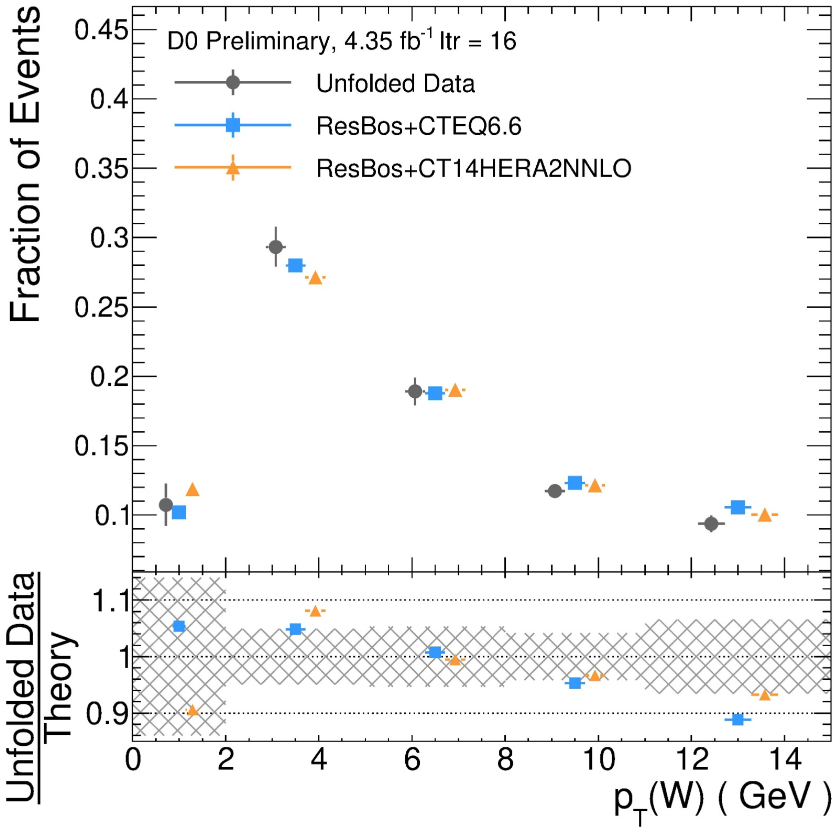
$$M_{ij} = P\left(\mathcal{X}_i \middle| \mathcal{N}_j\right) = \frac{P(\mathcal{N}_j|\mathcal{X}_i)P(\mathcal{X}_i)}{\sum_k P(\mathcal{N}_j|\mathcal{X}_k)P(\mathcal{X}_k)} = \frac{R_{ji}X_i}{\sum_k R_{jk}X_k}$$

  - Use MC values for initial X_i 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

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 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

$$\frac{d\sigma\left(h_1h_2 \to VX\right)}{dQ^2dQ_T^2dy} = \frac{1}{(2\pi)^2}\delta\left(Q^2 - M_V^2\right)\int d^2b\, e^{i\vec{Q}_T\bullet\vec{b}}\widetilde{W}_{j\bar{k}}\left(b, Q, x_1, x_2\right) + Y(Q_T, Q, x_1, x_2)$$

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

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

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