W and Z Production at the Tevatron:
Recent Results and Prospects

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on behalf of the CDF and DØ collaborations
Overview

• Introduction:
  – Tevatron, detectors and integrated luminosity
  – Z and W production and detection
  – Motivation for precise measurements

• Recent results
  – Z transverse momentum
    • $Z \rightarrow \mu \mu$, 1 fb$^{-1}$, DØ
  – Z transverse momentum using $\phi^{*}_{\eta}$
    • $Z \rightarrow ee$ & $Z \rightarrow \mu \mu$, 7.3 fb$^{-1}$, DØ
  – Z cross section and rapidity
    • $Z \rightarrow ee$, 2.2 fb$^{-1}$, CDF
  – W charge asymmetry
    • $W \rightarrow e\nu$, 1 fb$^{-1}$, CDF
      – re-analysis in terms of lepton $A_{FB}$ allowing direct comparison with
    • $W \rightarrow \mu\nu$, 4.9 fb$^{-1}$, DØ
  – Z forward-backward asymmetry
    • $Z \rightarrow ee$, 4.1 fb$^{-1}$, CDF

  ➢ New for this conference
  ➢ New for winter 2010 conferences

• Prospects

N.B. W mass measurements covered elsewhere
The Fermilab Tevatron Collider

1992-95 Run I:
\[ \int L dt \sim 0.1 \text{ fb}^{-1}, \ 1.8 \text{ TeV} \]

Major accelerator/detector upgrades
2002-11 Run II:
\[ \int L dt \sim 9 \text{ fb}^{-1} \text{ delivered, } 1.96 \text{ TeV} \]
\[ \int L dt \sim 12 \text{ fb}^{-1} \text{ expected by 2011} \]

Further running 2012-2014? - being considered
Integrated Luminosity History

Average data taking efficiency since 2002 is 84% (CDF) and 89% (DØ)
CDF

CDF detector highlight

- Large volume, high precision, charged particle tracker
  - 9-layer silicon tracker
  - 96-layer drift chamber
  - 1.4 m outer radius

DØ

DØ detector highlight

- High acceptance, low background, muon system
  - 0.5 m outer radius for DØ central tracker!
Producing $W$ and $Z$ in $\bar{p}p$

*Proton is a composite object*

- PDFs (Parton Distribution Functions)
  \[ m^2_{\ell\ell} = x_1 x_2 s \]
- Gluon bremsstrahlung
  \[ x_{1,2} = e^{\pm y} m_{\ell\ell}/\sqrt{s} \]

Select $\sim 10^6$ tagged $W \rightarrow \ell\nu$ and $\sim 10^5$ $Z \rightarrow \ell^+\ell^-$ events per fb$^{-1}$
Signatures of W and Z Production at the Tevatron

- $Z \rightarrow \ell^+\ell^-$: pair of charged leptons:
  - high $p_T$
  - isolated
  - opposite-charge
- peak in $\ell^+\ell^-$ invariant mass
Signatures of W and Z Production at the Tevatron

- \( Z \rightarrow \ell^+\ell^- \): pair of charged leptons:
  - high \( p_T \)
  - isolated
  - opposite-charge
- peak in \( \ell^+\ell^- \) invariant mass

- \( W \rightarrow \ell \nu \): single charged lepton:
  - high \( p_T \)
  - isolated
- \( E_T^{\text{miss}} \) (from \( \nu \))
  - cannot measure longitudinal \( \nu \)
- peak in “transverse mass”

\[
\text{transverse mass: } m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos \phi_{\nu})}
\]
Signatures of W and Z Production at the Tevatron

- $W \rightarrow l \nu$: single charged lepton:
  - high $p_T$
  - isolated
- $E_T^{\text{miss}}$ (from $\nu$)
  - cannot measure longitudinal $\nu$
- peak in “transverse mass”

$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \phi_{lv})}$$
Why bother?

• Electroweak production
• Leptonic final states
• High statistics samples
• Low backgrounds

➢ Precise measurements!

• Clean probe of QCD and EW interactions
• Essential to tie standard processes down before claiming discoveries
  – either at the Tevatron or the LHC
\( Z \rightarrow \mu\mu \) transverse momentum

- \( Z \rightarrow \mu\mu, \) 1 fb\(^{-1}\), DØ
- Unfold \( p_T^Z \) resolution
- For \( p_T^Z < 30 \) GeV
  - \( \sigma_{\text{syst}} \sim 5\% \)
  - dominated by \( p_T^\mu \) resolution systematics
  - cf. \( \sigma_{\text{stat}} \sim 1\% \)
  - Restricts choice of bin widths
- Have such measurements reached the end of the road?

Data-MC agreement
Study of $p_T^Z$ using a novel method

- $a_T$ less susceptible to detector resolution and efficiency variations than $p_T^Z$
- $a_T/m_\tilde{\chi}$ even less susceptible to detector resolution
- $\Phi^*_\eta \approx a_T/m_\tilde{\chi}$
- measured using only the directions of the leptons and thus very well measured.

\[ \phi^*_\eta = \tan\left(\frac{\phi_{acop}}{2}\right) \sin(\theta^*_\eta) \]

\[ \cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right) \]
Study of $p_T^Z$ using a novel method

- $Z \rightarrow ee, Z \rightarrow \mu\mu; 7.3 \text{ fb}^{-1}, \text{DØ}$
- 966,000 events with $70 < m_\mu < 110 \text{ GeV}$
  - Compare corrected data to ResBos
    - with and without small-$x$ broadening [Nadolsky, et al, Phys. Rev. D 64, 114011 (2001)]

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Study of $p_T^Z$ using a novel method

- At low $\phi^*_\eta$: narrow bins, $\sigma_{\text{stat}} \sim 5$ per mille and $\sigma_{\text{syst}} \sim 1$ per mille
- Compare $Z\rightarrow ee$, $Z\rightarrow \mu\mu$ corrected data
  - ratio to ResBos
- Small-$x$ broadening option clearly disfavoured
Z→ee total cross section and rapidity

- Z→ee, 2.2 fb⁻¹, CDF
- Electron coverage out to |η|<2.8
- Select 168000 candidate events in range |y|<2.9

Acceptance x Efficiency
- using central (C) and forward (pluq, P) electrons

\[ \sigma = 256.6 \pm 0.7 \text{ (stat.)} \pm 2.0 \text{ (syst.)} \pm 15.4 \text{ (lumi)} \text{ pb} \]

cf.  \[ \sigma = 238.7 \pm 7.1 -7.0 \text{ pb (CTEQ6.6M NLO)} \]
\[ \sigma = 248.7 \pm 5.1 -4.0 \text{ pb (MSTW2008E NNLO)} \]
$d\sigma^Z/dy$

- $d\sigma^Z/dy$ sensitive to PDFs
- Total cross section and $d\sigma^Z/dy$ in good agreement with theory
W Charge Asymmetry and PDFs

- u quark PDF is harder than d quark PDF
- $W^+$ ($W^-$) tends to be boosted along proton (antiproton) direction
- asymmetry = $(N^+ - N^-)/(N^+ + N^-)$
- We actually observe the charged lepton
- $W$ decay partially washes out asymmetry
W Charge Asymmetry and PDFs

- Experiments published measurement in different form
  - Inclusive W boson charge $A_{FB}^{C}$ (CDF)
  - Charged lepton $A_{FB}^{C}$ in lepton $p_T$ bins (DØ)

MSTW and CTEQ have problems to incorporate both CDF and DØ data into their global PDF fits.
W Charge Asymmetry and PDFs

- CDF have re-analyzed their data (stat. uncertainties only) to allow a direct comparison with DØ
- The experiments agree!
- The problem looks to be in the theory!
Forward-backward asymmetry in $Z \rightarrow ee$

4.1 fb$^{-1}$, CDF 218000 candidate events

In the rest frame of the dilepton system:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

where:

- $N_F$ ($N_B$) is the number of $e^-$ scattered in the same hemisphere as the outgoing proton (antiproton) beam.
Prospects with 10-20 fb$^{-1}$

- It would be good to see measurements of each important quantity
  - transverse momentum, rapidity, asymmetry
  - as function of $m_{ll}$
- Using full data set
  - from both CDF and DØ
  - in both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$
- Many of these measurements have the potential to remain statistics limited
  - scope for clever ideas!
- Potential impact on EW couplings, QCD models, PDFs
Example: Forward-backward asymmetry in $Z \rightarrow \ell \ell$

In the *rest frame* of the dilepton system:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Could achieve a high statistical precision

$$\Delta \sin^2 \theta^\text{eff}_W \approx \pm 0.0002 \text{ (stat.)} \pm 0.0005 \text{ (PDF)} \quad \Rightarrow \quad \text{Needs work!}$$

In addition, can extract world's best $a, \nu$ couplings for light quarks
Backup Slides
$x = \begin{align*}
Q_T & \quad \text{solid red line} \\
Q_T/Q \times M_2 & \quad \text{dotted red line} \\
a_T \times \sqrt{2} & \quad \text{solid magenta line} \\
a_T/Q \times \sqrt{2} & \quad \text{dotted magenta line} \\
a_L \times \sqrt{2} & \quad \text{solid blue line} \\
a_L/Q \times \sqrt{2} & \quad \text{dotted blue line} \\
\phi_{CS} \times \sqrt{2} & \quad \text{solid green line} \\
\phi_t & \quad \text{dotted green line} \\
\tan(\phi_{acop}/2) \times 0.85 \times \sqrt{2} M_2 & \quad \text{dotted black line}
\end{align*}$
EW Cross Sections at the Tevatron

First Observed by DØ: summer 2008
At the level of simple “tree level” diagrams the EW interactions are determined by three “input” parameters.
Masses of W and Z also given in terms of coupling constants

$$m_W^2 = m_Z^2 \cos^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F \sin^2 \theta_W}$$

For practical purposes we use as inputs the three most precisely known EW experimental observables:
- The fine structure constant: $\alpha = e^2 / 2 \varepsilon \hbar c$
- Fermi constant (measured in muon decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$): $G_F$
- Z mass: $m_Z$

Adding QCD requires an additional constant:
- The strong coupling constant: $\alpha_s$
Loops

- Loops cause running of coupling constants
  - $\alpha \rightarrow \alpha(Q^2)$
  - $\sin^2\theta_W \rightarrow \sin^2\theta_W^{\text{eff}}$
- EW observables then depend on:
  - $\alpha, G_F, m_Z, m_t, m_H$
- Basic programme:
  - Measure precisely L and R couplings of each fermion to $\gamma, Z, W$
  - Measure precisely boson self-interactions
  - Measure precisely $\alpha_s, \alpha, G_F, m_Z, m_t$
  - Test consistency of measurements with Standard Model predictions
  - Find the Higgs!
    - (or other new particles beyond the Standard Model)
• a
W Charge Asymmetry and PDFs

- CDF have re-analyzed their data (stat. uncertainties only) to allow a direct comparison with DØ