Electroweak Physics at the Tevatron

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for the CDF and D0 Collaborations
Aspen, 13 February 2011
CDF $Z \rightarrow ee$ (from Stirling, ICHEP04)

$W$ Tevatron (Run 2) $Z(x10)$

$\sigma \cdot B_i$ (nb)

CDF $D^0(e)$ $D^0(\mu)$

CDF $D^0(e)$ $D^0(\mu)$

NNLO evolution: Moch, Vermaseren, Vogt
NNLO $W, Z$ corrections: van Neerven et al. with Harlander, Kilgore corrections

2004, using < 100 pb$^{-1}$

Electroweak Physics at the Tevatron
Electroweak Physics at the Tevatron
♦ Motivation

♦ High-statistics precision measurements

♦ Diboson physics

♦ Outlook

Electroweak Physics at the Tevatron
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CDF

D0

Muon chambers

θ

θ

η = 0.6

η = 1.0

η = 2.0

Pre-radiator

Shower max

Hadronic cal

EM cal

Solenoid

Tracker

EM cal

Had cal

Silicon

1

2

3

m

η = 1

η = 2

η = 3

Fibre tracker to |η|<1.8
Calorimeter to |η|<4
Muon system to |η|<2
Drift chamber to |η|<1
Further tracking from Si
Calorimeter to |η|<3
Muon system to |η|<1.5

Tevatron

η = 2

η = 3

0

1

2

3

m

η = 0

η = 1

η = 2

η = 3

η = 0

η = 1
**W and Z selection**

**Electrons:**
- good EM shower shape
- small hadronic energy
- isolated in calorimeter
- well-matching good track
  (except far forward)

**Muons:**
- MIP in calorimeter
- isolated
- hits in muon chamber
- well-matching good track

**Z selection:**
- 2 oppositely-charged electrons or muons
- invariant mass consistent with $m_Z$

**W selection:**
- exactly one electron or muon
- energy imbalance in reconstructed event, associated with neutrino
\[
p_T(Z) \quad \text{antiproton} \quad \text{CDF} \quad \text{proton}
\]

\[
y \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z}
\]

\[
d\sigma/dp_T(0<|y|<1) \quad d\sigma/dp_T(1<|y|<2) \quad d\sigma/dp_T(2<|y|<3)
\]

distribution different for different \(y\)?

Event generator tuning

resummation / parton shower with non-perturbative model

pQCD reliable

multiple soft gluon radiation

resummation required
Earlier $p_T(Z)$

Electron channel:

- **DØ 0.98 fb$^{-1}$**
  - ResBos
  - ResBos+KF
  - NNLO
  - Rescaled NNLO
  - DØ data

Compare 4 models:
- Resbos with default parameters
- Resbos with additional NLO–NNLO K-factor
- NNLO (Melnikov and Petriello)
- NNLO rescaled at data at 30GeV/c

RESBOS event generator implements NLO QCD and CSS resummation.
$p_T(Z)$

New measurement in muon channel
Presented at the level of particles entering the detector to avoid model-dependent corrections

However for comparison with previous measurement, correct to $4\pi$ and for mass window:

$$\frac{1}{\sigma_Z} \frac{d\sigma}{dp_T}$$

Phys. Lett. B 693 522
$p_T(Z)$

At particle level:

$1/\sigma_Z \times d\sigma_Z/dp_T$ (1/GeV)

$D\O$, $L=0.97$ fb$^{-1}$
- NLO pQCD + corr.
- PYTHIA Perugia 6

$65 < M_{\mu\mu} < 115$ GeV
muon $|\eta| < 1.7$, muon $p_T > 15$ GeV

Ratio to PYTHIA Perugia 6

$D\O$, $L=0.97$ fb$^{-1}$
- HERWIG+JIMMY
- PYTHIA scale unc.
- PYTHIA Tune D6

$D\O$, $L=0.97$ fb$^{-1}$
- ALP+HERWIG
- SHERPA
- ALP+PY Tune D6
- ALP+PY Perugia 6
- PYTHIA scale unc.

Phys. Lett. B 693 522
$a_T$ : component of $p_T^{(ll)}$ transverse to dilepton thrust axis.
Less susceptible than $p_T^{(ll)}$ to detector effects

Best variable: $\phi^*_\eta = \tan(\phi_{acop}/2) \sin(\theta^*_\eta)$ – highly correlated with $a_T/m_{ll}$

$(\theta^*_\eta$ measures scattering angle of leptons wrt beam, in rest frame of dilepton system)
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\[ \phi^* \eta \]

DØ 7.3 fb\(^{-1}\)

- \(\mu\mu\) data
- ee data

- Red: ResBos
- Black: ResBos (small-\(x\))

arXiv:1010.0262
Drell-Yan angular coefficients

$q\bar{q} \rightarrow Z/\gamma* \rightarrow \ell^+\ell^-$

Rest frame of dilepton system

\[
\frac{d\sigma}{dP_T^2 dy d\cos \theta d\phi} \propto (1 + \cos^2 \theta)
\]

LO term

\[
+ \frac{1}{2} A_0 (1 - 3 \cos^2 \theta)
\]

higher order term

\[
+ A_1 \sin 2\theta \cos \phi + \frac{1}{2} A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi
\]

(\theta, \phi) terms

\[
+ A_4 \cos \theta
\]

LO term : determine $A_{fb}$

\[
+ A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi
\]

very small terms

Integrate over all $\phi$, measure as function of $p_T$

Integrate over all $\cos \theta$,
Drell-Yan angular coefficients

**CDF Preliminary Result with \( \int L = 2.1 \text{ fb}^{-1} \)**

- \( A_0 \)
- \( A_2 \)

**CDF Preliminary Result with \( \int L = 2.1 \text{ fb}^{-1} \)**

- \( q\bar{q} : P_T^2/(P_T^2+M_Z^2) \)
- \( qg : 5P_T^2/(5P_T^2+M_Z^2) \)
- VBP Resummation
- ResBos Resummation
- Pythia
- Pythia Z+1jet
- Madgraph
- Dyad
- FEWZ(NNLO)
- Powheg
- Data

\( 66 < M(e^+e^-) < 116 \)

**CDF Preliminary Result with \( \int L = 2.1 \text{ fb}^{-1} \)**

- \( A_0 \sim A_2 \) at LO
- 'Lam-Tung' relation
- True only for spin-1 gluons,
  strongly broken for scalar gluons
Drell-Yan angular coefficients

CDF Preliminary Result with $\int L = 2.1 \text{ fb}^{-1}$

66 < $M(e^+e^-)$ < 116

$A_3$

$\sin^2 \theta_W = 0.2329^{+0.0013}_{-0.0012}$

$A_4$ sensitive to Weinberg angle
$A_4$ using 2.1 fb$^{-1}$ data = 0.1098 ± 0.0079

Translated to $\sin^2 \theta_W$ in FEWZ:
$\sin^2 \theta_W = 0.2331 \pm 0.0008$

Translated $\sin^2 \theta_W$ in POWHEG:
$\sin^2 \theta_W = 0.2328 \pm 0.0008$

CDF Run II Preliminary
W charge asymmetry

\[ A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \]

\[ A_\ell(\eta) = \frac{d\sigma(\ell^+)/d\eta - d\sigma(\ell^-)/d\eta}{d\sigma(\ell^+)/d\eta + d\sigma(\ell^-)/d\eta} = A(y_W) \otimes (V-A) \sim \frac{d(x)}{u(x)} \]

Run 1 measurement resulted in d quark increased by 30% at \( Q^2 = (20\text{GeV})^2 \)
W charge asymmetry

- $E_T > 25$ GeV
- $25$ GeV $< E_T < 35$ GeV
- $E_T > 35$ GeV

- CDF Run II Preliminary 1 fb$^{-1}$ data (e) (no systematic uncertainties)
- DØ 0.75 fb$^{-1}$ data (e)
- DØ Run II Preliminary 5 fb$^{-1}$ data ($\mu$)
- RESBOS with CTEQ6.6

he Tevatron
$m_W$:  
DO:  $m_W = 80402 \pm 43$ MeV/$c^2$  
CDF:  $m_W = 80413 \pm 48$ MeV/$c^2$  
Tev:  $m_W = 80420 \pm 31$ MeV/$c^2$  (includes Run 1)  
LEP:  $m_W = 80376 \pm 33$ MeV/$c^2$  

Heading to CDF 25MeV/$c^2$ measurement

**CDF**  
$\Delta m_Z$ (stat)  
published (200/pb)  43 MeV  
expected (2.3/fb)  13 MeV

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$\Gamma_W$ predicted in Standard Model: 
$\Gamma_W^{SM} = 2091 \pm 2$ MeV (PDG)

Width of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\Gamma_W$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-Ia</td>
<td>$2,032 \pm 329$</td>
</tr>
<tr>
<td>CDF-Ib</td>
<td>$2,043 \pm 138$</td>
</tr>
<tr>
<td>DØ-I</td>
<td>$2,242 \pm 172$</td>
</tr>
<tr>
<td>CDF-II</td>
<td>$2,033 \pm 72$</td>
</tr>
<tr>
<td>DØ-II</td>
<td>$2,034 \pm 72$</td>
</tr>
<tr>
<td>Tevatron Run-I/II</td>
<td>$2,046 \pm 49$</td>
</tr>
<tr>
<td>LEP-2*</td>
<td>$2,196 \pm 83$</td>
</tr>
</tbody>
</table>

World Av.* = 2,085 ± 42

$\chi^2 / \text{dof} = 1.4 / 4$

$\Gamma_{W}$ error improves from 62 to 49 MeV

February 2010
Dibosons

\[ q \rightarrow W/Z/\gamma \]

\[ q' \rightarrow W/Z/\gamma \]

Production Cross Section [pb]

- \( W\gamma \)
- \( Z\gamma \)
- \( WW \)
- \( t\bar{t} \)
- \( WZ \)
- \( t \)
- \( ZZ \)
- \( H \rightarrow WW \)

Theory
Using \((Z\rightarrow ll)+\gamma\)
and \((Z\rightarrow \nu\nu)+\gamma\)
\[ \sigma(p\bar{p} \rightarrow WZ) \times 10^{-4} = (5.5 \pm 0.9) \times 10^{-4} \]

\[ \sigma(p\bar{p} \rightarrow WZ) = (4.1 \pm 0.7) \text{ pb} \]
σ(pp → WZ) = 3.89^{+1.07}_{-0.90} \text{ pb}

$-0.075 < \lambda_Z < 0.093$

$-0.027 < \Delta \kappa_Z < 0.080$

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ZZ → 4l

ZZ seen in 4 lepton at 5.7σ
All now observed!

CDF

Production Cross Section [pb]

σ(pp → ZZ) / σ(pp → Z)
= (2.3^{+1.5}_{-0.9} \text{ (stat)} ± 0.3 \text{ (syst)}) \times 10^{-4}

σ(pp → ZZ)
= (1.7^{+1.2}_{-0.7} \text{ (stat)} ± 0.2 \text{ (syst)}) pb
$\sigma(p\bar{p} \rightarrow ZZ) = 1.45^{+0.45}_{-0.42} (stat.)^{+0.41}_{-0.30} (syst.) \text{ pb}$
WW/WZ $\rightarrow l\nu jj$

CDF Run II Preliminary $\int L \, dt = 4.30$ fb$^{-1}$

- Data CEM
- Fit Result
- W/Z+jet + Top
- QCD

$\chi^2/\text{ndf} = 192.30/98$
QCD frac = 10.66%

Similar final state to low-mass Higgs:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Electrons</th>
<th>Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC W +jets</td>
<td>18010 $\pm$ 531</td>
<td>16673 $\pm$ 482</td>
</tr>
<tr>
<td>MC Z+jets</td>
<td>353 $\pm$ 42</td>
<td>966 $\pm$ 115</td>
</tr>
<tr>
<td>diboson</td>
<td>750 $\pm$ 68</td>
<td>651 $\pm$ 59</td>
</tr>
<tr>
<td>top</td>
<td>1324 $\pm$ 134</td>
<td>1149 $\pm$ 115</td>
</tr>
<tr>
<td>QCD (from data)</td>
<td>2314 $\pm$ 462</td>
<td>639 $\pm$ 159</td>
</tr>
<tr>
<td>Total MC + QCD data</td>
<td>22751</td>
<td>20078</td>
</tr>
</tbody>
</table>

Electroweak Physics at the Tevatron
\[ \sigma(\text{WW+WZ}) = (18.1 \pm 3.3\text{ (stat)} \pm 2.5\text{ (sys)}) \text{ pb} \]

5.2\sigma significance
WW/WZ → ℓνjj

Use matrix element techniques

σ(WW+WZ )
= (16.5 +3.3 -3.0) pb

5.4σ significance
Tevatron outlook

End: Sep 2011 (?)

Integrated luminosity ($\text{pb}^{-1}$)

On tape: $\sim 8.5 \text{ fb}^{-1}$ per experiment

Results shown today: 1-7 $\text{fb}^{-1}$

* Delivered
* Acquired

2002 now

Electroweak Physics at the Tevatron
Outlook

◆ Completing strong electroweak physics programme

◆ Focusing on high-statistics Tevatron legacy measurements and diboson physics underpinning symmetry-breaking searches