David Waters
University College London
on behalf of the CDF & DØ Collaborations

• What are we Measuring & Why?
• WW and WZ Production
• Anomalous Couplings
• First Measurement of ZZ Production
• Summary
Heavy Diboson Production at the Tevatron

Leading order diagrams:

- **t-channel**
- **s-channel**

(QCD) production: PDF’s, (NLO/LO) k-factors, diboson-$p_T$ spectrum.

(EWK) production: Triple Gauge Couplings predicted by $\text{SU(2)}_L \otimes \text{U(1)}_Y$.

- Measuring the production cross sections and kinematics provide a verification of all these production model ingredients.
Heavy Diboson Production at the Tevatron

• Heavy diboson production as a signature of new physics:

Indeed, heavy diboson production is intimately related to Higgs searches:

► $WW$ production is a (quasi-) irreducible background to $H \rightarrow WW$
► $WZ$ and $ZZ$ production are critical backgrounds to $WH \& ZH$ assoc. prod.
► Technically many of the techniques developed for diboson measurements have applications in Higgs searches.
► Heavy diboson measurements provide a “standard-candle” for the measurement of very small cross sections.
Overview of Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events/Experiment in 1fb⁻¹</th>
<th>Signal/Background</th>
<th>Significance of Observation (Gaussian σ equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW → lvlv</td>
<td>580</td>
<td>~2</td>
<td>&gt;&gt; 5</td>
</tr>
<tr>
<td>WW /WZ → lvjj</td>
<td>4100</td>
<td>~0.01</td>
<td>~1.7</td>
</tr>
<tr>
<td>WZ → lvll</td>
<td>50</td>
<td>~2-4</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>ZZ → llll</td>
<td>6</td>
<td>~10-20</td>
<td>4.4</td>
</tr>
<tr>
<td>ZZ → llvv</td>
<td>40</td>
<td>~0.05-0.25</td>
<td></td>
</tr>
</tbody>
</table>
CDF Detector

Drift chamber outer tracker:
\[ \delta p_T / p_T \approx 0.0005 \times p_T \quad [\text{GeV/c; beam constrained}] ; \quad |\eta| < 1 \]

Silicon vertex detector:
tracking coverage out to \(|\eta| < 2.8\)

Central calorimeter:
\[ \delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\% \quad |\eta| < 1.1 \]

Plug calorimeter: coverage out to \(|\eta| < 3.0\)

Muon chambers: coverage out to \(|\eta| < 1.0\)

DØ detector: previous talk
Optimising Sensitivity

• Major technical advance: maximise single-lepton acceptance.

CDF Electron Coverage
forward leptons, track only leptons

CDF Muon Coverage
WW

- First observed by DØ and CDF in 2004 in ~200 pb⁻¹ samples.
  - **DØ (240 pb⁻¹)**: 25 candidates, expected background ~8
    
    \[ \sigma(WW) = 13.8^{+4.3}_{-3.8} \text{ (stat.)}^{+1.2}_{-0.9} \text{ (syst.)} \pm 0.9 \text{ (lumi.) pb} \]
    
    \[ [\sigma_{\text{NLO}}(WW) = 12.4 \pm 0.8 \text{ pb}] \]
  
  - **CDF (update using 825 pb⁻¹)**: 95 candidates, expected background ~38
    
    \[ \sigma(WW) = 13.6 \pm 2.3 \text{ (stat.)} \pm 1.6 \text{ (syst.)} \pm 1.2 \text{ (lumi.) pb} \]

- Well understood samples.
- Starting point for H→WW searches.
WZ

• First observed in 2006 in ~1 fb\(^{-1}\) samples.
• Recent updates in tri-lepton channel:
  
  ▶ **DØ (1 fb\(^{-1}\))**: 13 candidates against expected background of 4.5 ± 0.6

\[ \sigma(WZ) = 2.7^{+1.7}_{-1.3} \text{ (stat. + syst.) pb} \quad [\sigma_{\text{NLO}}(WZ) = 3.7 \pm 0.3 \text{ pb}] \]

  ▶ **CDF (1.9 fb\(^{-1}\))**: 25 candidates against expected background of 4.7 ± 0.8:

\[ \sigma(WZ) = 4.4^{+1.3}_{-1.0} \text{ (stat.) ± 0.2 (syst.) ± 0.3 (lumi.) pb} \]

7-11 April 2008

DIS’08 : Heavy Diboson Production at the Tevatron
**WWZ Anomalous Couplings**

- WZ production probes WWZ vertex independent of WWγ (cf. LEP2).

- $p_T(Z)$ is the kinematic observable most sensitive to anomalous WWZ couplings.

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- **t-channel**

- **s-channel**

  destructive interference in SM (that’s why diboson cross sections are so small!)

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CDF Run II Preliminary

$\int L dt = 1.9 \text{ fb}^{-1}$

- Data
- $WWZ = 0$
- SM WWZ Coupling
- Summed Backgrounds

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- *p$_T$(Z)* is the kinematic observable most sensitive to anomalous WWZ couplings.
WWZ Anomalous Couplings

95% Confidence Level Intervals for $\Lambda=2$ TeV (*)

<table>
<thead>
<tr>
<th>CDF (1.9 fb$^{-1}$)</th>
<th>DØ (1.0 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.13 &lt; \lambda_Z &lt; 0.14$</td>
<td>$-0.17 &lt; \lambda_Z &lt; 0.21$</td>
</tr>
<tr>
<td>$-0.13 &lt; \Delta g_1^Z &lt; 0.23$</td>
<td>$-0.14 &lt; \Delta g_1^Z &lt; 0.34$</td>
</tr>
<tr>
<td>$-0.76 &lt; \Delta \kappa_Z &lt; 1.18$</td>
<td>$-0.12 &lt; \Delta \kappa_Z = \Delta g_1^Z &lt; 0.29$</td>
</tr>
</tbody>
</table>

(*) AC definitions as per Hagiwara et al. 1987
Very challenging experimentally:
- 5-10 × more signal compared to fully leptonic channels
- 1000 × more background (S/B ~ 1%)
- Similar final state to WH→lvjj
- Potentially greater sensitivity to anomalous couplings

(II) Then fit $m_{jj}$ distribution:

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**WW/WZ→lvjj (CDF)**
$\sigma \times \text{BR} = 2.09 \pm 0.14 \text{ pb}$

<table>
<thead>
<tr>
<th>$N_{\text{signal}}$</th>
<th>$410 \pm 212 \text{ (stat)} \pm 107 \text{ (syst) pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>$\sigma \times \text{BR} = 1.47 \pm 0.77 \text{ (stat)} \pm 0.38 \text{ (syst) pb}$</td>
</tr>
<tr>
<td>95% Limit</td>
<td>$\sigma \times \text{BR} &lt; 2.88 \text{ pb}$</td>
</tr>
<tr>
<td>NLO Prediction</td>
<td>$\sigma \times \text{BR} = 2.09 \pm 0.14 \text{ pb}$</td>
</tr>
</tbody>
</table>
4-lepton final state has very low backgrounds (mainly Z+jets).

Wide mass range $m_{ll}>30$ GeV/c$^2$ includes $Z/\gamma^*$. 

<table>
<thead>
<tr>
<th></th>
<th>eeee</th>
<th>ee\mu\mu</th>
<th>\mu\mu\mu</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.44\pm0.03</td>
<td>0.81\pm0.09</td>
<td>0.46\pm0.05</td>
<td>1.71\pm0.15</td>
</tr>
<tr>
<td>Background</td>
<td>0.080\pm0.021</td>
<td>0.013\pm0.004</td>
<td>0.033\pm0.006</td>
<td>0.13\pm0.03</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

$\sigma(ZZ) < 4.4$ pb 

$[\sigma_{\text{NLO}}(ZZ) = 1.6$ pb]$
ZZ → llll (CDF)

Mass range $m_{ll} \in [76, 106]$ and [40, 140] GeV/c$^2$ to include $Z/\gamma^*$. Very small backgrounds from $Z(\gamma)+jets$.

Separate high and low purity samples to extract maximum sensitivity:

<table>
<thead>
<tr>
<th>Category</th>
<th>Candidates without a trackless electron</th>
<th>Candidates with a trackless electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>$1.990 \pm 0.013 \pm 0.210$</td>
<td>$0.278 \pm 0.005 \pm 0.029$</td>
</tr>
<tr>
<td>$Z + jets$</td>
<td>$0.014^{+0.010}_{-0.007} \pm 0.003$</td>
<td>$0.082^{+0.089}_{-0.060} \pm 0.016$</td>
</tr>
<tr>
<td>Total</td>
<td>$2.004^{+0.016}_{-0.015} \pm 0.210$</td>
<td>$0.360^{+0.089}_{-0.060} \pm 0.033$</td>
</tr>
</tbody>
</table>

Observed: 2, 1
Example $ZZ \rightarrow \mu\mu\mu\mu$ event.

3 out of 4 muons missed by muon chambers! Smart lepton ID essential.
• Recall: BR(ZZ → llνν) ~ 6 × BR(Z → llll).
• But backgrounds are much worse.
• Define a (signed) missing-\(E_T\) like object:

Most backgrounds removed by requiring missing-\(E_T\) be \textit{large} and \textit{significant}.

The WW background (real missing-\(E_T\)) can only be separated statistically.
**ZZ → llνν (DØ)**

Use kinematic information to form a signal/background likelihood discriminant.

+ leading lepton $p_T$
+ $l^+$ polar angle in $l^+l^-$ rest-frame
+ opening angle between dilepton and leading lepton

- Probability of background alone giving rise to the observed likelihood distribution:

<table>
<thead>
<tr>
<th></th>
<th>eeνν</th>
<th>μμνν</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 fb(^{-1})</td>
<td>0.1140</td>
<td>0.0052</td>
<td>0.0082</td>
</tr>
<tr>
<td>p-value</td>
<td>(0.0753)</td>
<td>(0.1100)</td>
<td>(0.0387)</td>
</tr>
<tr>
<td>(expected)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>significance</td>
<td>1.21</td>
<td>2.57</td>
<td>2.40 σ</td>
</tr>
<tr>
<td>(expected)</td>
<td>(1.44)</td>
<td>(1.23)</td>
<td>(1.77)</td>
</tr>
</tbody>
</table>

$$\sigma(ZZ) = 2.1 \pm 1.1 \text{(stat.)} \pm 0.4 \text{(syst.) \ \text{pb}} \quad [\sigma_{\text{NLO}}(ZZ) = 1.6 \pm 0.1 \ \text{pb}]$$
ZZ→llνν (CDF)

- CDF use full kinematic information to try to dig out S/B~20:

\[ P(x_{obs}) = \frac{1}{\langle \sigma \rangle} \int \frac{d\sigma_{LO}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy \]

- Discrimination against the dominant background is obtained by forming the likelihood ratio:

\[ LR = \frac{P_{ZZ}}{P_{ZZ} + P_{WW}} \]
The data contain high probability ZZ events, e.g. $\text{ZZ} \rightarrow \ell\ell\nu\nu$ shown.

Probability of background alone describing the data is 0.12 (1.2$\sigma$)
ZZ Combination (CDF)

- Extend the likelihood discriminant to include the two (high-purity and lower-purity) 4-lepton measurements:

<table>
<thead>
<tr>
<th>1.9 fb^{-1}</th>
<th>llvν</th>
<th>4-lepton</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.12</td>
<td>1.1 \times 10^{-5}</td>
<td>5.1 \times 10^{-6}</td>
</tr>
<tr>
<td>significance</td>
<td>1.2</td>
<td>4.2</td>
<td>4.4 $\sigma$</td>
</tr>
</tbody>
</table>

- Expected: 50/50 chance of seeing a 5$\sigma$ effect.

$$\sigma(ZZ) = 1.4^{+0.7}_{-0.6} \text{ (stat. + syst.) pb} \quad [\sigma_{NLO}(ZZ) = 1.4 \pm 0.1 \text{ pb}]$$
ZZ Measurement

Tevatron Run II $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

- $1.9 \text{ fb}^{-1}$ \( ll\nu\nu \) and 4-\( l \)
  - $4.4\sigma$

- $2.2 \text{ fb}^{-1}$ \( ll\nu\nu \)
  - $2.4\sigma$

NEW!
Summary

Tevatron Run II $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

- CDF Preliminary
- CDF Published
- D0 Preliminary
- D0 Published
- Theory

$W$, $Z$, $W\gamma$, $Z\gamma$, $WW$, $WZ$, $ZZ$, $H\to WW$

- NEW!

2004
2006
2008
??
The End
Effective Missing-\(E_T\) Definition

- Combines elements of \textit{missing-}\(E_T\) and \textit{missing-}\(E_T\) \textit{significance}:

\[
E_T = \sqrt{E_l^2 + (1.5 \times E_t')^2} - \delta_m - \delta_{\text{track, jets}}
\]

- Gives extra weight to better measured component.
- Maximum correction due to lepton mis-measurement.
- Maximum correction due to recoil mis-measurement (estimated using leptons tracks and jets).

\[
\vec{t} \propto (\vec{p}_{T1} - \vec{p}_{T2})
\]
ZZ→llνν (DØ)

DØ Preliminary 2.2 fb⁻¹

# pseudo-experiments

LLR

S+B
B only
Separate high and low purity samples

ZZ→llll (CDF)