Recent WW, WZ and ZZ Results from the Tevatron

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Diboson introduction

- Important test of EW sector of standard model.
- Significant backgrounds in searches for the SM Higgs.
- $W W, W Z,$ and $Z Z$ have all been observed at the Tevatron.
  - Start to explore more challenging final states...
- Following analyses will be presented:
  - $W Z \rightarrow l \nu l l$
  - $W V \rightarrow l \nu j j$ ($V = W$ or $Z$)
  - $V Z$ with heavy flavour jets.
The Tevatron, CDF and D0

Results presented today using up to 9.5 fb\(^{-1}\) of data!

12 fb\(^{-1}\) delivered per experiment!

\[ \sqrt{s} = 1.96 \text{ TeV} \]
WZ → lνll (D0)

- Select events with three high $p_T$ isolated electrons/muons and missing transverse energy.
- Measure cross section as ratio of WZ relative to Z
  - Significant cancellation in systematic uncertainties (e.g. lepton reconstruction efficiencies)
  - Use NNLO prediction* of Z cross section. Known to $\approx 3\%$, compared to $\approx 6\%$ for measured luminosity.

\[
\sigma_{WZ} = 4.5^{+0.6}_{-0.7} \text{ pb}
\]
\[
\sigma_{NLO}^{WZ} = 3.2 \pm 0.2 \text{ pb}
\]

Measured cross section in agreement with but a little less than 2 $\sigma$ higher than the SM prediction.

WZ → lνll (CDF)

- Use neural network to extract signal cross section.
- Use measured luminosity.

$$\sigma_{WZ} = 3.9^{+0.8}_{-0.7} \text{ pb}$$

CDF 7.1 fb^{-1}

95% C.L.

<table>
<thead>
<tr>
<th>$\Lambda$ (TeV)</th>
<th>$\lambda_Z$</th>
<th>$\Delta g_1^Z$</th>
<th>$\Delta \kappa_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1.5</td>
<td>$(-0.12, 0.23)$</td>
<td>$(-0.58, 0.94)$</td>
</tr>
<tr>
<td>Observed</td>
<td>1.5</td>
<td>$(-0.09, 0.22)$</td>
<td>$(-0.42, 0.99)$</td>
</tr>
<tr>
<td>Expected</td>
<td>2.0</td>
<td>$(-0.11, 0.20)$</td>
<td>$(-0.53, 0.86)$</td>
</tr>
<tr>
<td>Observed</td>
<td>2.0</td>
<td>$(-0.08, 0.20)$</td>
<td>$(-0.39, 0.90)$</td>
</tr>
</tbody>
</table>

*different $Z/\gamma$ mass window to D0

$\mathbb{W}/WZ \rightarrow l\nu jj$ (D0)

- High $p_T$ electron or muon, missing $E_T$, and 2 or 3 jets
- Cannot resolve $WW$ from $WZ$ based on the dijet mass
- Measure the combined cross section (assuming the SM ratio of $WW$ vs $WZ$).

$$\sigma(WW + WZ) = 19.6 \pm 3.2 \text{ pb}$$

$$\sigma_{NLO}^{WW} = 11.7 \pm 0.8 \text{ pb} \quad \sigma_{NLO}^{WZ} = 3.5 \pm 0.3 \text{ pb}$$

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**Mass resolution**

$\approx 18\%$

**arXiv:1112.0536v1**, Dec 2012, Accepted by PRL.
WW/WZ → lνjj (D0)

- Cannot resolve $Z \rightarrow jj$ from $W \rightarrow jj$?
- **B-tagging** enhances the fraction of $WZ$ (i.e., due to $Z \rightarrow bb$, $Z \rightarrow cc$ decays).

![Graphs showing $M_{jj}$ distributions for different channels with and without b-tagging.](image)

$arXiv:1112.0536v1$, Dec 2012, Accepted by PRL.
**WW/WZ → lνjj (D0)**

- With the addition of B-tagging information, we can resolve WW and WZ.

![Graph showing WW/WZ cross sections](graph.png)

**Standard Model**

- $\sigma(WW) = 15.9^{+3.7}_{-3.2}$ pb
- $\sigma(WZ) = 3.3^{+4.1}_{-3.3}$ pb

**NLO**

- $\sigma_{WZ}^{\text{NLO}} = 3.5 \pm 0.3$ pb
- $\sigma_{WW}^{\text{NLO}} = 11.7 \pm 0.8$ pb

- Also extract $\sigma(WZ)$ after constraining $\sigma(WW)$ to the SM value.
  - $\sigma(WZ) = 6.5 \pm 0.9\text{(stat)} \pm 3.0\text{(syst)}$ pb, with $2.2\sigma(1.2\sigma)$ observed(expected) significance.
Dibosons with heavy flavour jets

- Main low mass Higgs search channels involve VH with $H \rightarrow bb$.
  - Three main final states: $\nu\nu bb$, $l\nu bb$, $llbb$.
- Significant background from VZ with $Z \rightarrow HF$.
- Recast the Higgs searches as VZ cross section measurements.
  - Validation of the methods used in the Higgs searches (e.g. background modeling).
  - Demonstrate sensitivity to processes with cross sections at the same order of magnitude, and in the same final states.

E.g. $\nu\nu bb$:

Cross section times branching fractions (to bb):

<table>
<thead>
<tr>
<th>Final state</th>
<th>VH</th>
<th>VZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l\nu bb$</td>
<td>27 fb</td>
<td>105 fb</td>
</tr>
<tr>
<td>$llbb$</td>
<td>5 fb</td>
<td>24 fb</td>
</tr>
<tr>
<td>$\nu\nu bb$</td>
<td>15 fb</td>
<td>73 fb</td>
</tr>
</tbody>
</table>
CDF Inputs

- All channels use $9.5 \text{ fb}^{-1}$ of data.
- Retrain the multivariate discriminants to treat $VZ$ as signal rather than $VH$. 

CDF Run II Preliminary 9.45/ fb

![Graph showing events/bin for different channels](image)

CDF Note 10796

CDF Note 10799

CDF Note 10798
CDF Combination

- Group bins from the different channels according to expected s/b.
- Evidence for VZ signal with $3.2\sigma$ significance.

$\sigma(ZZ + WZ) = 4.1^{+1.4}_{-1.3} \text{ pb}$

$\sigma^{NLO}(ZZ + WZ) = 4.3 \pm 0.3 \text{ pb}$
D0 Inputs

• Individual inputs to D0 analysis (7.5-8.4 fb⁻¹)

DØ Note 6260–CONF, November 2012

Tuesday, March 27, 12
D0 Combination

- Group bins from the different channels according to expected s/b.
- **Evidence** for VZ signal with $3.3\sigma$ significance (2.9\sigma expected).

\[\sigma(ZZ + WZ) = 4.5 \pm 1.6 \text{ pb}\]

\[\sigma^{\text{NLO}}(ZZ + WZ) = 4.3 \pm 0.3 \text{ pb}\]

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**D0 Preliminary, 7.5-8.4 fb**

- Data - Bkgd
- Bkgd Uncert.
- WZ
- ZZ

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**D0 Preliminary, 7.5-8.4 fb**

- Data - Bkgd
- Bkgd Uncert.
- VZ
Tevatron Combination

- **4.6σ evidence** for VZ with heavy flavour

\[ \sigma(ZZ + WZ) = 4.47 \pm 0.64(\text{stat}) \pm 0.73(\text{syst}) \text{ pb} \]

\[ \sigma^{\text{NLO}}(ZZ + WZ) = 4.3 \pm 0.3 \text{ pb} \]

![Data vs Background](image1.png)

![MVA ordered by s/b](image2.png)


Tuesday, March 27, 12
Conclusions

• Many new diboson results, and no deviations from SM predictions.

• Precise cross section measurements with $WZ \rightarrow l\nu l\nu$
  
  • Stringent limits on anomalous triple gauge couplings.

• Precise measurement of $WV$ cross section in $WV \rightarrow l\nu jj$
  
  • Separate measurements of $\sigma(WW)$ and $\sigma(WZ)$.

• $4.6\sigma$ evidence for $VZ$ with heavy flavour jets
  
  • Tevatron combination using the same methods as in the low mass Higgs ($\rightarrow bb$) searches.

  • Good validation of the low mass Higgs searches.
Backup Slides
Tevatron luminosity

- Final delivered luminosity $\approx 12 \text{ fb}^{-1}$ per experiment
B-tagging at D0

- Neural network based B tagger.
Simultaneous $\sigma(WZ)$ and $\sigma(ZZ)$

- Another result extracted from the D0 analysis:

\[ WZ \text{ Cross Section (pb)} \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \]

\[ ZZ \text{ Cross Section (pb)} \quad 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4 \quad 4.5 \]

DØ Preliminary

L = 7.5-8.4 fb$^{-1}$

- Standard Model
- Measurement
- 68% Contour
- 95% Contour

DØ Note 6260–CONF, November 2012
W+2 jet anomaly?

![Graph showing dijet mass and events distribution](image)


DØ, 4.3 fb⁻¹

- Data - Bkgd
- Bkgd ± 1 s.d.
- Diboson
- Gaussian (Fitted)
- Gaussian (4 pb)

\[ M_{jj} = 145 \text{ GeV/c}^2 \]

\[ \chi^2 = 0.464 \]
CDF WWZ aTGGs

- Set limits using shape and normalization of $Z_pT$ distribution in WZ events.
CDF WWZ aTGGs

Unitarity conserved by form factor

Difficult to separate WW/WZ due to dijet mass resolution

- **D0 1.1 fb⁻¹**
- **CDF 4.3 fb⁻¹**
- **CDF 3.5 fb⁻¹**

- WW/WZ → ℓνjj
- WW/WZ → ℓνjj
- WW/WZ/ZZ → vvvjj
- PRL 102, 161801 (2009) evidence
- PRL 104, 101801 (2010) observation
- PRL 103, 091803 (2009) observation
Tevatron Higgs combination

Tevatron Run II Preliminary, $L \leq 10 \text{ fb}^{-1}$

- Expected
- Observed
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

CMS Exclusion

ATLAS+CMS Exclusion

SM=1

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