Measurement of the $W^+W^-$ Production Cross Section and Differential Cross Sections with Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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on behalf of the CDF Collaboration

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### Motivation

- $WW$ production is a test of the electroweak sector
- Never before extended to include associated jet properties
- First differential measurement of the $WW$ cross section
- Uniquely possible at the Tevatron due to lesser $t\bar{t}$ background
Motivation

- Precision measurement of Higgs boson production and decay rates
  - Requires understanding of $WW$ background in jet bins
- Vector Boson Scattering - sensitive to new physics in electroweak symmetry breaking
  - Requires understanding of $VV + 2$ jets QCD production

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ATLAS Vector Boson Scattering ($W^\pm W^\pm jj$)
## WW Measurements

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Experiment</th>
<th>Luminosity</th>
<th>Cross Section</th>
<th>Prediction</th>
<th>Jet Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.96 TeV</td>
<td>D0$^1$</td>
<td>1.1fb$^{-1}$</td>
<td>11.5 ± 2.2 pb</td>
<td>12.7 ± 0.7 pb</td>
<td>Inclusive</td>
</tr>
<tr>
<td></td>
<td>CDF$^2$</td>
<td>3.6fb$^{-1}$</td>
<td>12.1$^{+1.8}_{-1.6}$ pb</td>
<td>11.7 ± 0.7 pb</td>
<td>Veto $E_T &gt; 15$ GeV</td>
</tr>
<tr>
<td>7 TeV</td>
<td>ATLAS$^3$</td>
<td>4.6fb$^{-1}$</td>
<td>51.9 ± 4.8 pb</td>
<td>44.4 ± 2.8 pb</td>
<td>Veto $p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>CMS$^4$</td>
<td>4.9fb$^{-1}$</td>
<td>52.4 ± 5.1 pb</td>
<td>47.0 ± 2.0 pb</td>
<td>Veto $E_T &gt; 30$ GeV</td>
</tr>
<tr>
<td>8 TeV</td>
<td>CMS$^5$</td>
<td>3.5fb$^{-1}$</td>
<td>69.9 ± 7.0 pb</td>
<td>57.3$^{+2.3}_{-1.6}$ pb</td>
<td>Veto $p_T &gt; 30$ GeV</td>
</tr>
<tr>
<td></td>
<td>ATLAS(new)$^6$</td>
<td>20.3fb$^{-1}$</td>
<td>71.4$^{+5.6}_{-5.0}$ pb</td>
<td>58.7$^{+3.0}_{-2.7}$ pb</td>
<td>Veto $p_T &gt; 25$ GeV</td>
</tr>
</tbody>
</table>

- Previous $W^+W^-$ measurements
- Inclusive or jet veto
- Consistent with predictions at the $\sim 2\sigma$ level

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$^1$PRL 103 191801 (2009)
$^2$PRL 104 201801 (2010)
$^3$PRD 87 112001 (2013)
$^6$ATLAS-CONF-2014-033
Event Selection

- Leptonic W’s, loose kinematic selection
- Two oppositely charged leptons
  - Single high $E_T(p_T)$ electron or muon trigger
  - Multiple non-overlapping lepton categories
  - Isolation requirement to reduce misidentified objects
  - Additional requirements to reduce Drell-Yan and $W \gamma$
- Two neutrinos

$$E_{T,rel} \equiv \begin{cases} 
E_T & \text{if } \Delta \phi(\vec{E}_T, \text{lepton, jet}) > \frac{\pi}{2} \\
E_T \sin(\Delta \phi(\vec{E}_T, \text{lepton, jet})) & \text{if } \Delta \phi(\vec{E}_T, \text{lepton, jet}) < \frac{\pi}{2}
\end{cases}$$

- Reduces significance of $E_T$ aligned with mismeasured object
- Jets ($E_T > 15$ GeV, $|\eta| < 2.5$)
  - 0 Jet
  - 1 Jet - further separated:
    - $15 < E_T < 25$ GeV
    - $25 < E_T < 45$ GeV
    - $E_T > 45$ GeV
  - 2 or more jets: b-tag veto
Signal and Background Modeling

- Irreducible
  - $WZ$, $ZZ$, $t\bar{t}$
  - Simulated with Pythia

- False $E_T$
  - Drell-Yan
  - Simulated with Pythia and Alpgen

- Misidentified particle
  - $W\gamma$ - simulated with Baur MC, data driven scaling
  - $W^+\text{+jets}$ - data driven method

- $WW$ Signal simulated with Alpgen, verified with MC@NLO

CDF Run II Preliminary

\[ \int L = 9.7 \text{ fb}^{-1} \]

Best fit to data
Control Region - Drell-Yan

- Invariant mass of lepton pair near $Z$ mass
- No $e\mu$ events
  - Unlikely to be $Z$
- Relax $E_T,\text{rel}$ requirement
  - No neutrinos
Control Region - $t\bar{t}$

- Two or more jets
- One or more jets b-tagged
- Identical kinematic selection to two or more jets signal region
Control Region - Same Charge

- Same charge leptons
- Tests modeling of misidentified objects
  - Enhances $W^+\text{jets}$, $W\gamma$
- Identical kinematic selection to signal region
Leading kinematic inputs:

- Scalar sum $E_T$: $WW$ energetic
- $p_T(l_2)$: lower for $j/\gamma$ misidentification
Same leading kinematic inputs

Separate template by jet $E_T$
Leading kinematic inputs

- Scalar sum $E_T$: $t\bar{t}$ even more energetic
- $p_T(j_1j_2)$: higher for $t\bar{t}$
## Systematics

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>$WW$</th>
<th>$WZ$</th>
<th>$ZZ$</th>
<th>$t\bar{t}$</th>
<th>$DY$</th>
<th>$W\gamma$</th>
<th>$W$+jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section</td>
<td>6.0%</td>
<td>6.0%</td>
<td>6.0%</td>
<td>4.3%*</td>
<td></td>
<td></td>
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<tr>
<td>Acceptance</td>
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<tr>
<td>$E_T$ Modeling</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(19.0-26.0%*)</td>
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<tr>
<td>Higher-order Diagrams</td>
<td>10.0%</td>
<td>10.0%</td>
<td></td>
<td>10.0%*</td>
<td></td>
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<tr>
<td>$t\bar{t}$ QCD</td>
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<td></td>
<td></td>
<td></td>
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<td>2.7%</td>
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<td>Conversion Modeling</td>
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<td></td>
<td></td>
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<td>6.8%</td>
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<tr>
<td>Scale</td>
<td>(23.7†-3.8%)</td>
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<tr>
<td>PDF Modeling</td>
<td>(0.8-1.8%)</td>
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</tr>
<tr>
<td>Jet Energy Scale</td>
<td>(21.5†-4.7%)</td>
<td>(13.2†-6.4%)</td>
<td>(13.3†-3.5%)</td>
<td>(12.9†-26.8%)</td>
<td>(28.7†-10.2%)</td>
<td>(22.0†-3.5%)</td>
<td></td>
</tr>
<tr>
<td>$b$–tag veto</td>
<td>(0.0-3.9%)</td>
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<tr>
<td>Lepton ID Efficiencies</td>
<td>3.8%</td>
<td>3.8%</td>
<td>3.8%</td>
<td>3.8%</td>
<td>3.8%</td>
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<tr>
<td>Trigger Efficiencies</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
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<tr>
<td>JetFake Rate</td>
<td></td>
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<td></td>
<td>(17.2-19.0%)</td>
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<tr>
<td>Luminosity</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
<td></td>
</tr>
</tbody>
</table>

* indicates uncorrelated systematic. † indicates anticorrelated systematic.

**Dominant systematics**

- Fake Rate
- $E_T$ Modeling
- Parton Showering Scale
- Jet Energy Scale
Determination of the Cross Section

- Neural net output templates separated by jet multiplicity and $E_T$
- Each bin fit simultaneously
  - Maximum likelihood method
  - Systematics - nuisance parameters with Gaussian constraint
  - Signal normalization - freely floating
- Cross section extracted from normalization
- Result unfolded
  - Jet distributions affected by detection/reconstruction
  - Cluster jets at hadronic level and compare to fully reconstructed
  - Correct via iterative Bayesian method
- Compared to Alpgen (LO with N hard jets) and MC@NLO (NLO)
## Results

### WW(\ell\nu\nu) Cross Section

<table>
<thead>
<tr>
<th>Jet Bin</th>
<th>σ(pb)</th>
<th>Uncertainty(pb)</th>
<th>CDF Run II Preliminary</th>
<th>∫L = 9.7 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>14.0</td>
<td>±0.6</td>
<td>+1.6 -1.3</td>
<td>11.3 ± 1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.7 ± 0.9</td>
</tr>
<tr>
<td>0 Jets</td>
<td>9.6</td>
<td>±0.4</td>
<td>+1.1 -0.9</td>
<td>8.2 ± 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.6 ± 0.6</td>
</tr>
<tr>
<td>1 Jet Inclusive</td>
<td>3.05</td>
<td>±0.46</td>
<td>+0.48 -0.32</td>
<td>2.43 ± 0.31</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.47 ± 0.18</td>
</tr>
<tr>
<td>1 jet, 15 &lt; E_T &lt; 25 GeV</td>
<td>1.47</td>
<td>±0.17</td>
<td>+0.15 -0.11</td>
<td>1.26 ± 0.16</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>1.18 ± 0.09</td>
</tr>
<tr>
<td>1 jet, 25 &lt; E_T &lt; 45 GeV</td>
<td>1.09</td>
<td>±0.18</td>
<td>+0.17 -0.12</td>
<td>0.77 ± 0.10</td>
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<tr>
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<td></td>
<td>0.79 ± 0.06</td>
</tr>
<tr>
<td>1 jet, E_T &gt; 45 GeV</td>
<td>0.49</td>
<td>±0.15</td>
<td>+0.20 -0.11</td>
<td>0.40 ± 0.05</td>
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<td></td>
<td></td>
<td>0.46 ± 0.03</td>
</tr>
<tr>
<td>2 or More jets</td>
<td>1.36</td>
<td>±0.30</td>
<td>+0.46 -0.29</td>
<td>0.64 ± 0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.61 ± 0.05</td>
</tr>
</tbody>
</table>

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**Will Parker, UW Madison**  
**ICHEP2014, Valencia, July 5th, 2014**  
**W^+W^- Production with Jets**  
**15/16**
Conclusion

- Measurement of the differential cross section for $WW$ production as a function of jet energy and multiplicity
  - Loose kinematic selection
  - Multivariate discriminant
  - Binned maximum likelihood fit

- Unfolded result found to be consistent with the Standard Model prediction

- Lesser $t\bar{t}$ background makes this uniquely possible at the Tevatron

- This is the most precise measurement of the $WW$ cross section at a $p\bar{p}$ collider, and the first jet-differential cross section measurement in a massive diboson state