Measurement of WW Cross Section at 7 TeV with the ATLAS Detector at LHC

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Outline

- WW Production at LHC
- WW Event Selection
- Background Estimations
- Sources of Systematic Uncertainties
- WW Fiducial and Total Cross Sections
- Summary
**WW Production at LHC**

\[ qq' \rightarrow WW \text{ production } \sigma_{\text{NLO}} = (44.92 \pm 2.25) \text{ pb at 7 TeV} \]

- Major background to SM Higgs \( \rightarrow \) WW search
- Sensitive to new physics through anomalous TGC
- Experimental signature: two isolated leptons with large MET
- Major backgrounds: W/Z + jets, ttbar, single top

\[ gg \rightarrow WW \text{ contributes additional } \sim 3\% \text{ of WW event rate : } 1.3 \text{ pb} \]
WW Analysis using 2010 Data

- Based on 34 pb\(^{-1}\) integrated luminosity at 7 TeV
- Observed 8 WW candidates (1 ee, 2 μμ, 5 eμ)
- Expected signal: 6.85 ± 0.07 ± 0.66
- Expected background: 1.68 ± 0.37 ± 0.42
- WW: \(\sigma_{W^+W^-} = 41^{+20}_{-16} \text{(stat.)} \pm 5 \text{(syst.)} \pm 1 \text{(lumi.) pb}\)

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Major Challenges in 2011 Data

- Higher luminosity \((\sim 1.75 \times 10^{33}\text{cm}^{-2}\text{s}^{-1})\)
- higher pileup, more backgrounds from Drell-Yan, Top etc.
- Corrections on JES, MET, lepton isolation
- Needs better understanding of systematic uncertainties
Major $\ell^+\ell^- + \mathbf{E}_T^{\text{miss}}$ Backgrounds

- **W+jets**
  - $W$ leptonic decay produces a charged lepton and large missing $E_T$.
  - Associated jets can fake a second charged lepton.
    - **Suppressed by lepton identification.**

- **Drell-Yan**
  - High $P_T$ charged lepton pairs produced from leptonic decays of Drell-Yan bosons.
  - Missing $E_T$ either from mis-measurement of leptons or of associated jets, or from $Z \rightarrow \tau\tau$.
    - **Reduced by Z mass veto and missing $E_T$ cut.**

- **Top**
  - $WW$ pairs produced in $tt$ or single top processes.
    - **Rejected by vetoing on high-$P_T$ jets.**

- **Di-boson ($WZ, ZZ, W/Z+\gamma$)**
  - Leptons from boson decays or faked by photons.
  - Missing $E_T$ from neutrino production or $e/\mu$ escape.
    - **Suppressed by the criteria mentioned above plus the requirement of exactly two high $P_T$ charged leptons.**
WW Event Selection

- **Remove Drell-Yan Background:**
  - Exact two leptons with opposite sign charge, $p_{\ell_T} > 20$ GeV
  - $|M_{ll} - M_Z| > 15$ GeV for ee and $\mu\mu$ channels
  - $M_{ll} > 15$ GeV for ee and $\mu\mu$, and $M_{ll} > 10$ GeV for $e\mu$ channel
Further remove Drell-Yan and Wjets/QCD:

- $\text{MET}^{\text{Rel}} > 25 \text{ GeV}$ (for $e\mu$)
- $\text{MET}^{\text{Rel}} > 45 \text{ GeV}$ (for $\mu\mu$)
- $\text{MET}^{\text{Rel}} > 40 \text{ GeV}$ (for $ee$

$$E_{T, \text{Rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \times \sin(\Delta \phi_{\ell,j}) & \text{if } \Delta \phi < \pi/2 \\ E_T^{\text{miss}} & \text{if } \Delta \phi \geq \pi/2 \end{cases}$$

$\text{MET}^{\text{Rel}}$ distributions after Z mass veto cut
Jet Veto to Remove Top Background

no jet with $E_T > 30$ GeV and $|\eta| < 4.5$

WW Cross Section - H. Yang
W+Jets Background Estimation

- Data driven method to estimate W + Jets
  - Define a fake factor $f$:
    $$ f_l \equiv \frac{N_{\text{lepton ID}}}{N_{\text{Jet-Rich ID}}} $$
    using di-jet samples in data
  
  - W+jet background contributes to WW selection:
    $$ N_{W+jet\ Bkg} = f_l \times N_{\text{lepton ID}} + N_{\text{Jet-Rich ID}} $$
    $$ N_{\mu\mu-\text{ch}}^{W+jet\ Bkg} = f_e \times N_{\mu\mu ID} + N_{\text{Jet-Rich e}} + f_{\mu} \times N_{\text{elec. ID}} + N_{\text{Jet-Rich \(\mu\)}} $$

- Checked with an independent data driven matrix method

<table>
<thead>
<tr>
<th>Channel</th>
<th>Estimated W+jets background from Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee-channel</td>
<td>5.3±0.4(stat)±1.7(syst)</td>
</tr>
<tr>
<td>$e\mu$-channel (e fake)</td>
<td>8.1±0.5(stat)±2.9(syst)</td>
</tr>
<tr>
<td>Sum of $e$ fake background</td>
<td>13.4±0.6(stat)±4.6(syst)</td>
</tr>
<tr>
<td>$\mu\mu$-channel</td>
<td>12.4±2.9(stat)±5.2(syst)</td>
</tr>
<tr>
<td>$e\mu$-channel ($\mu$ fake)</td>
<td>24.7±3.8(stat)±8.7(syst)</td>
</tr>
<tr>
<td>Sum of $\mu$ fake background</td>
<td>37.1±4.8(stat)±14.0(syst)</td>
</tr>
<tr>
<td>Sum of $e\mu$-channel</td>
<td>32.9±3.8(stat)±9.2(syst)</td>
</tr>
<tr>
<td>$ee + \mu\mu + e\mu$-channel</td>
<td>50.5±4.8(stat)±14.7(syst)</td>
</tr>
</tbody>
</table>
Drell-Yan Background Estimation

- **Data-Driven Method (DDM):**

\[
N_{DY}^{\text{out}}(\text{estimated}) = N_{DY}^{\text{in,DATA}} \times R_{\text{out/in}}; \quad \text{here} \quad R_{\text{out/in}} = \frac{N_{DY}^{\text{out,MC}}}{N_{DY}^{\text{in,MC}}}
\]

- **MC closure test:** good agreement between input and estimated DY background has been observed

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>18.7 ± 1.9 ± 1.9</td>
<td>19.2 ± 1.7 ± 2.1</td>
<td>16.0 ± 2.8 ± 1.7</td>
</tr>
<tr>
<td>DDM</td>
<td>18.2 ± 3.4</td>
<td>20.1 ± 3.6</td>
<td>-</td>
</tr>
</tbody>
</table>

- Drell-Yan is estimated from Alpgen MC prediction. Systematic uncertainty (~10.4%) is determined by comparing \( \text{MET}_{\text{rel}} \) distributions from Data and MC using Z control sample
Top Background Estimation

- Top background is estimated using a *semi-data-driven method*:
  - $N_{\text{jet}} \geq 2$: Control region is dominated by Top background
  - Assuming fraction of Top events with $N_{\text{jet}} = 0$ and $N_{\text{jet}} \geq 2$ are similar in MC and data
  - Advantage: uncertainties on luminosity and the top cross sections are cancelled out in the MC ratio

\[
N_{\text{Top}}^{\text{Estimated}}(N_{\text{jet}} = 0) = N_{\text{Top}}^{\text{MC}}(N_{\text{jet}} = 0) \times \frac{N_{\text{data}}(\text{control region})}{N_{\text{MC}}^{\text{Top}}(\text{control region})}
\]

- Estimated Top in signal region ($N_{\text{jet}} = 0$)
  - $58.6 \pm 2.1 \text{ (stat)} \pm 22.3 \text{ (syst, from JES)}$
  - Cross-checked with b-tagged Top control sample to estimate Top background
- MC Expectation: 56.7
# WW Selected Events (1.02 fb\(^{-1}\))

<table>
<thead>
<tr>
<th>Final State</th>
<th>(e^+e^-E_T^{\text{miss}})</th>
<th>(\mu^+\mu^-E_T^{\text{miss}})</th>
<th>(e^\pm\mu^\mp E_T^{\text{miss}})</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Events</td>
<td>74</td>
<td>97</td>
<td>243</td>
<td>414</td>
</tr>
<tr>
<td>Background estimations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top(data-driven)</td>
<td>9.5±0.3±3.6</td>
<td>12.3±0.4±4.7</td>
<td>36.8±1.3±14.0</td>
<td>58.6±2.1±22.3</td>
</tr>
<tr>
<td>W+jets (data-driven)</td>
<td>5.3±0.4±1.7</td>
<td>12.4±2.9±5.2</td>
<td>32.9±3.8±9.2</td>
<td>50.5±4.8±14.7</td>
</tr>
<tr>
<td>Drell-Yan (MC/data-driven)</td>
<td>18.7±1.9±1.9</td>
<td>19.2±1.7±2.1</td>
<td>16.0±2.8±1.7</td>
<td>54.0±3.7±4.5</td>
</tr>
<tr>
<td>Other dibosons (MC)</td>
<td>0.9±0.1±0.1</td>
<td>2.4±0.2±0.3</td>
<td>3.4±0.3±0.4</td>
<td>6.8±0.4±0.8</td>
</tr>
<tr>
<td>Total Background</td>
<td>34.4±2.0±4.4</td>
<td>46.3±3.4±7.3</td>
<td>89.1±4.9±16.8</td>
<td>169.8±6.4±27.1</td>
</tr>
</tbody>
</table>

| Expected WW Signal    | 29.5±0.3±3.0                  | 52.5±0.4±4.9                  | 150.5±0.7±13.4                  | 232.4±0.9±21.5  |

| Significance (\(S/\sqrt{B}\)) | 5.0 | 7.7 | 15.9 | 17.8 |

**ATLAS Preliminary**

- **Leading Lepton \(P_T^\ell\)**
- **Subleading Lepton \(P_T^\ell\)**

**Events / 10 GeV**

**Ldt = 1.02 fb\(^{-1}\) \(\sqrt{s} = 7\) TeV**
Kinematic Distributions of WW Candidates

**ATLAS Preliminary**

- **$p_T(\ell^+\ell^-)$**
- **$\Delta\phi(\ell^+\ell^-)$**
- **$M_T(\ell^+\ell^-, \text{MET})$**
- **$P_T(\ell^+\ell^-, \text{MET})$**

$L_d = 1.02 fb^{-1} \quad \sqrt{s} = 7 \text{TeV}$

**WW Cross Section - H. Yang**
## Sources of Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>$e^+e^- E_T^{\text{miss}}$</th>
<th>$\mu^+\mu^- E_T^{\text{miss}}$</th>
<th>$e^\pm\mu^\mp E_T^{\text{miss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.7%</td>
<td>3.7%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Cross-section (theory)</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>PDF</td>
<td>1.2%</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Trigger</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Lepton $p_T$ smearing</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Reco eff. scale factors</td>
<td>1.4%</td>
<td>0.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$E_T/p_T$ scale correction</td>
<td>0.9%</td>
<td>0.0%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Particle ID eff. scale factors</td>
<td>3.3%</td>
<td>1.4%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Isolation</td>
<td>4.0%</td>
<td>2.0%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ in-time contribution</td>
<td>3.5%</td>
<td>3.9%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ out-of-time contribution</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Jet-veto</td>
<td>4.8%</td>
<td>4.8%</td>
<td>4.8%</td>
</tr>
<tr>
<td>Total experimental uncertainty</td>
<td>8.1%</td>
<td>6.7%</td>
<td>6.2%</td>
</tr>
<tr>
<td>Overall uncertainty</td>
<td>10.3%</td>
<td>9.2%</td>
<td>8.9%</td>
</tr>
</tbody>
</table>

**Dominant Syst. Uncertainties**

- Particle ID eff. scale factors
- Jet-veto
- Total experimental uncertainty

**Lepton recon. Eff**
- E/P scale / smearing

**Lepton ID and Isolation Eff.**
- Isolation
- $E_T^{\text{miss}}$ in-time contribution
- Jet-veto

**Missing Transverse Energy uncertainty**
- $E_T^{\text{miss}}$ out-of-time contribution

**WW Cross Section - H. Yang**
WW Fiducial Phase Space

- Measure “fiducial” cross section to minimize the dependence on theoretical prediction. The WW fiducial phase space requirements:

  - muon cuts: $p_T > 20 \text{ GeV}, |\eta| < 2.4$
  - electron cuts: $p_T > 20 \text{ GeV}, |\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
    - leading electron in $ee$ channel and electron in $e\mu$ channel: $p_T > 25 \text{ GeV}$
  - jet cuts: $p_T > 30 \text{ GeV}, |y| < 4.5, \Delta R(e,\text{jet}) > 0.3$
  - event cuts:
    - $\mu\mu$ channel: $p_T^{\nu+\bar{\nu}}> 45 \text{ GeV}, m_{\mu\mu} > 15 \text{ GeV}$ and $|m_{\mu\mu} - m_Z| > 15 \text{ GeV}$
    - $ee$ channel: $p_T^{\nu+\bar{\nu}}> 40 \text{ GeV}, m_{ee} > 15 \text{ GeV}$ and $|m_{ee} - m_Z| > 15 \text{ GeV}$
    - $e\mu$ channel: $p_T^{\nu+\bar{\nu}}> 25 \text{ GeV}, m_{e\mu} > 10 \text{ GeV}$

\[
A_{WW} = \frac{N_{\text{fiducial}}}{N_{\text{total}}} \\
C_{WW} = \frac{N_{\text{selected}}}{N_{\text{fiducial}}} \\
\epsilon_{WW} = A_{WW} \times C_{WW}
\]

<table>
<thead>
<tr>
<th>Channels</th>
<th>$A_{WW} \times C_{WW}$</th>
<th>$A_{WW}$</th>
<th>$C_{WW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\nu e\nu$</td>
<td>$0.039 \pm 0.001 \pm 0.004$</td>
<td>$0.090 \pm 0.001 \pm 0.007$</td>
<td>$0.432 \pm 0.006 \pm 0.035$</td>
</tr>
<tr>
<td>$\mu\nu \mu\nu$</td>
<td>$0.069 \pm 0.001 \pm 0.006$</td>
<td>$0.086 \pm 0.001 \pm 0.005$</td>
<td>$0.802 \pm 0.006 \pm 0.066$</td>
</tr>
<tr>
<td>$e\nu \mu\nu$</td>
<td>$0.100 \pm 0.001 \pm 0.008$</td>
<td>$0.167 \pm 0.001 \pm 0.011$</td>
<td>$0.596 \pm 0.005 \pm 0.040$</td>
</tr>
</tbody>
</table>

Stat. error  Syst. error
The WW fiducial phase space acceptance $A_{WW}$ and correction factor $C_{WW}$

- Systematic uncertainties of $A_{WW}$ include:
  - PDF uncertainty (~1.2% - 1.4%)
  - Renormalization and factorization scales uncertainty (~1.5% – 5.3%)
  - Parton shower/fragmentation modeling uncertainty (~4.8%)

- Systematic uncertainties of $C_{WW}$ include (slide p17)
  - Uncertainty associated with jet veto cut is replaced by JES uncertainty (~4.5%)
  - Renormalization and factorization scales uncertainty (~2.0%)

The measured WW fiducial cross sections in three dilepton channels.

$$L\left(\sigma_{WW}^{i,fid}\right) = \ln \left[ \frac{e^{-\left(N_S^i+N_b^i\right)} \times \left(N_S^i + N_b^i\right)^{N_{obs}^i}}{N_{obs}^i!} \right], \quad N_S^i = \sigma_{WW \rightarrow \ell\nu\ell\nu}^{i} \times \mathcal{L} \times C_{WW}^{i}$$

<table>
<thead>
<tr>
<th>Channels</th>
<th>expected $\sigma^{fid}_{WW}$ (fb)</th>
<th>measured $\sigma^{fid}_{WW}$ (fb)</th>
<th>$\Delta\sigma_{stat}$ (fb)</th>
<th>$\Delta\sigma_{syst}$ (fb)</th>
<th>$\Delta\sigma_{lumi}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\nu\nu\nu$</td>
<td>66.8</td>
<td>90.1</td>
<td>$\pm$ 18.9</td>
<td>$\pm$ 11.3</td>
<td>$\pm$ 3.3</td>
</tr>
<tr>
<td>$\mu\nu\mu\nu$</td>
<td>63.8</td>
<td>62.0</td>
<td>$\pm$ 12.1</td>
<td>$\pm$ 10.7</td>
<td>$\pm$ 2.3</td>
</tr>
<tr>
<td>$e\nu\mu\nu$</td>
<td>245.1</td>
<td>252.0</td>
<td>$\pm$ 24.6</td>
<td>$\pm$ 29.4</td>
<td>$\pm$ 9.3</td>
</tr>
</tbody>
</table>

WW Cross Section - H. Yang
The total WW production cross section is determined from three dilepton channels (e^+e^-, μ^+μ^-, eμ + E_T^{miss}) by maximizing the log-likelihood function using 1.02 fb^{-1} data.

\[ L(σ_{WW}^{tot}) = \ln \prod_{i=1}^{3} \frac{e^{-(N^i_s+N^i_b)} \times (N^i_s+N^i_b)^{N^i_{obs}}}{N^i_{obs}!}, \quad N^i_s = σ_{WW}^{tot} \times Br^i \times \mathcal{L} \times ε^i_{WW} \]

<table>
<thead>
<tr>
<th>Channels</th>
<th>Total cross-section (pb)</th>
<th>Δσ_{stat}(pb)</th>
<th>Δσ_{syst}(pb)</th>
<th>Δσ_{lumi}(pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eνeν</td>
<td>62.1</td>
<td>± 13.5</td>
<td>± 9.1</td>
<td>± 2.3</td>
</tr>
<tr>
<td>μνμν</td>
<td>44.7</td>
<td>± 8.7</td>
<td>± 7.7</td>
<td>± 1.7</td>
</tr>
<tr>
<td>eνμν</td>
<td>47.3</td>
<td>± 4.8</td>
<td>± 6.2</td>
<td>± 1.8</td>
</tr>
<tr>
<td>Combined</td>
<td>48.2</td>
<td>± 4.0</td>
<td>± 6.4</td>
<td>± 1.8</td>
</tr>
</tbody>
</table>

- **Fitted σ_{WW} = 48.2 ± 4.0 (stat) ± 6.4 (syst) ± 1.8 (lumi) pb**
  - Dominated by systematic uncertainties, mainly come from uncertainties of data driven background estimations

- **NLO SM prediction: σ_{WW} (SM) = 46 ±3 (theory) pb**

Summary

- The WW production cross section and fiducial cross section are measured using three dilepton channels ($e^+e^-, \mu^+\mu^-, e\mu + E_T^{miss}$).
- Total integrated luminosity of 1.02 fb$^{-1}$ data collected by the ATLAS detector in 2011 are used for this analysis. 414 WW candidates are observed, 232 WW signal and 170 backgrounds events are expected.
- The measured WW cross section is consistent with NLO SM prediction ($46 \pm 3$ pb):
  \[
  \sigma_{WW} = 48.2 \pm 4.0 \text{ (stat)} \pm 6.4 \text{ (syst)} \pm 1.8 \text{ (lumi)} \text{ pb}
  \]
- We expect to extract limits on anomalous TGC ($WW\gamma$, $WWZ$) based on 1.02 fb$^{-1}$ data soon.
Backup Slides
The numbers are normalized to the data integrated luminosity of 1.02 fb⁻¹ using the SM $W^+W^-$ cross sections.

MC efficiency correction factors ($\varepsilon_{\text{data}}/\varepsilon_{\text{MC}}$) have been applied.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>ee Channel</th>
<th>$\mu\mu$ Channel</th>
<th>$e\mu$ Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\nu\nu$</td>
<td>$\tau\nu\nu$</td>
<td>$\mu\nu\nu$</td>
</tr>
<tr>
<td>Total Events</td>
<td>552.3</td>
<td>211.4</td>
<td>552.3</td>
</tr>
<tr>
<td>2 leptons (SS+OS)</td>
<td>116.6</td>
<td>11.8</td>
<td>229.0</td>
</tr>
<tr>
<td>2 leptons (OS)</td>
<td>115.7</td>
<td>11.6</td>
<td>229.0</td>
</tr>
<tr>
<td>leading electron Pt &gt; 25GeV</td>
<td>114.4</td>
<td>11.4</td>
<td>-</td>
</tr>
<tr>
<td>trigger matching</td>
<td>114.2</td>
<td>11.4</td>
<td>231.9</td>
</tr>
<tr>
<td>$M_{\ell\ell} &gt; 15$ GeV, $M_{e\mu} &gt; 10$ GeV</td>
<td>113.5</td>
<td>11.3</td>
<td>229.7</td>
</tr>
<tr>
<td>Z mass veto</td>
<td>88.2</td>
<td>8.4</td>
<td>176.6</td>
</tr>
<tr>
<td>$E_{T,\text{miss}}$ cut</td>
<td>38.6</td>
<td>2.9</td>
<td>69.7</td>
</tr>
<tr>
<td>Jet veto (Num of Jet=0)</td>
<td>27.8</td>
<td>1.7</td>
<td>49.4</td>
</tr>
<tr>
<td>$W^+W^-$ Acceptance</td>
<td>5.0%</td>
<td>0.8%</td>
<td>8.9%</td>
</tr>
</tbody>
</table>
ATLAS Detector

Muon Spectrometer ($|\eta|<2.7$): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

3-level trigger reducing the LVL1 rate to ~300 Hz

EM calorimeter: Pb-LAr Accordion $e/\gamma$ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10%/\sqrt{E} \oplus 0.007$
High granularity

Hadron calorimetry ($|\eta|<4.9$)
Fe/scintillator Tiles (central), Cu-LAr (endcap)
E-resolution: $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$
FWD calorimetry: Cu/W-LAr $\sigma/E \sim 90%/\sqrt{E} \oplus 0.07$

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, TRT
Precise tracking and vertexing,
$\sigma/p_T \sim 3.8 \times 10^{-4} p_T$ (GeV) $\oplus 0.015$

Length: ~46 m
Radius: ~12 m
Weight: ~7000 tons
~$10^8$ electronic channels
3000 km of cables
GRL (35.2 pb\(^{-1}\))

**Trigger:**
Single e with \(E_T > 15\) GeV  
Single m with \(p_T > 13\) GeV  
Efficiency plateau \(E_T(p_T) > 20\) GeV  
Dilepton \(\varepsilon(data)/\varepsilon(MC) = 1.0\) (\(\sigma_{syst} < 0.1\%\))

**Primary vertex:**
Vertex with max. sum track \(p_T^2\)  
\(N_{\text{track}} > = 3\) (with \(p_T > 150\) MeV)  
Two leptons from primary vertex  
MC pile-up reweighted to reproduce data

‘**RobusterTight**’ electron  
\(E_T > 20\) GeV; \(|\eta| < 2.5\), (remove [1.37--1.52])  
Isolation: Sum \(E_T^{\text{Cone}=0.3} < 6\) GeV  
d0/\(\sigma_d0 < 10\); \(|z0| < 10\) mm  
\(\varepsilon(data)/\varepsilon(MC) = 0.97\) (with \(\sigma_{syst} ~ 5.3\%\))

‘**Combined**’ Muon:  
\(p_T > 20\) GeV; \(|\eta| < 2.4\)  
\(p_T^{MS} > 10\) GeV; \(|(p_T^{MS} - p_T^{ID})/ p_T^{ID}| < 0.5\)  
Isolation: \((\text{Sum } p_T^{\text{Cone}=0.2})/ p_T^{\mu} < 0.1\)  
d0/\(\sigma_d0 < 10\); \(|z0| < 10\) mm  
\(\varepsilon(data)/\varepsilon(MC) = 0.98\) (with \(\sigma_{syst} ~ 1.0\%\))

**Jet:**
Anti-Kt, \(R = 0.4\); \(|\eta| < 3.0\); \(p_T > 20\) GeV  
Discarded if \(\Delta R\) (jet, electron) < 0.2  
Jet veto SF = 0.97 (with \(\sigma_{syst} ~ 6.0\%\))

**\(E_T^{\text{miss}}\):**  
\MET_{\text{LocHadTopo}} (\(|\eta|<4.5\)), account for \(\mu\)’s  
\[ E_T^{\text{miss}} \times \sin(\Delta\phi_{\ell,j}) \quad \text{if } \Delta\phi < \pi/2 \]  
\[ E_T^{\text{miss}} \quad \text{if } \Delta\phi \geq \pi/2 \]
### Diboson Production Cross Sections

<table>
<thead>
<tr>
<th>SM cross section</th>
<th>Tevatron (ppbar, 1.96 TeV, pb)</th>
<th>LHC (pp, 7 TeV, pb)</th>
<th>LHC (pp, 14 TeV, pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>12.4</td>
<td>44.9</td>
<td>111.6</td>
</tr>
<tr>
<td>WZ</td>
<td>3.7</td>
<td>18.5</td>
<td>47.8</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.4</td>
<td>6.0</td>
<td>14.8</td>
</tr>
<tr>
<td>Wγ</td>
<td>19.3*</td>
<td>69.0#</td>
<td>120.1#</td>
</tr>
<tr>
<td>Zγ</td>
<td>4.7*</td>
<td>13.8#</td>
<td>28.8#</td>
</tr>
</tbody>
</table>

(*) $E_T^\gamma > 7 \text{ GeV}$ and $\Delta R(\ell, \gamma) > 0.7$, for W/Z e/µ decay channels only

(#) $E_T^\gamma > 10 \text{ GeV}$ and $\Delta R(\ell, \gamma) > 0.7$, for W/Z e/µ decay channels only

→ Diboson production rates at LHC (7 TeV) are ~3-5 times of Tevatron

→ $\sqrt{s}$ at LHC is higher than Tevatron (3.5x-7x) which greatly enhances the detection sensitivity to anomalous triple-gauge-boson couplings
Generic Search for New Particles with Diboson through VBF Process

- Vector-Boson Fusion (VBF) Process: $qq \rightarrow q_{\text{tag}} q_{\text{tag}} V V$ ($V = W, Z$)
  - Two vector bosons with two tagged jets in F/B regions
  - Production rate $\sim 2.5\%$ of $qq \rightarrow WW$ (WHIZARD, PDF MRST2004)

- An example of ATLAS sensitivity to a 850 GeV spin-zero resonance produced in VBF process (at 14 TeV).
Search for **new physics** through Anomalous TGCs with Diboson Events

- Effective Lagrangian with charged/neutral triple-gauge-boson interactions

\[
L/\hat{g}_{WWV} = ig^{\nu}_1 (W^{\ast}_\mu W_\mu V^\nu - W_{\mu\nu} W^{\ast}_\mu V^\nu) + ik^{\nu} W_{\mu} W^\nu V^\mu V^\nu + \frac{i\lambda^V}{M^2_W} W^{\ast}_{\rho\mu} W^{\mu} V^\nu V^\rho
\]

\[
L = -\frac{e}{M^2_Z} [f^V_4 (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^{\alpha} Z_\beta) + f^V_5 (\partial^{\sigma} V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta]
\]

- The anomalous parameters: \(\Delta g_{1Z}, \Delta \kappa_Z, \lambda_Z, \Delta \kappa_\gamma, \lambda_\gamma, f_4^Z, f_5^Z, f_4^\gamma, f_5^\gamma, h_3^Z, h_4^Z, h_3^\gamma, h_4^\gamma\)

- Complementary studies through different Diboson channels (\(\hat{s} = M^2_{WW}\))

<table>
<thead>
<tr>
<th>Production</th>
<th>(\Delta \kappa_Z, \Delta \kappa_\gamma) term</th>
<th>(\Delta g_{1Z}) term</th>
<th>(\lambda_Z, \lambda_\gamma) term</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>grow as (\hat{s})</td>
<td>grow as (\hat{s}^{\frac{1}{2}})</td>
<td>grow as (\hat{s})</td>
</tr>
<tr>
<td>WZ</td>
<td>grow as (\hat{s}^{\frac{1}{2}})</td>
<td>grow as (\hat{s})</td>
<td>grow as (\hat{s})</td>
</tr>
<tr>
<td>W_\gamma</td>
<td>grow as (\hat{s}^{\frac{1}{2}})</td>
<td>---</td>
<td>grow as (\hat{s})</td>
</tr>
</tbody>
</table>
# Limits on Anomalous Couplings

<table>
<thead>
<tr>
<th>System</th>
<th>$\lambda_Z$</th>
<th>$\Delta \kappa_Z$</th>
<th>$\Delta g^Z_1$</th>
<th>$\Delta \kappa_\gamma$</th>
<th>$\lambda_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW (D0, 1.1 fb$^{-1}$)</td>
<td>$\lambda_Z = \lambda_\gamma$</td>
<td>$\Delta \kappa_Z = \Delta \kappa_\gamma$</td>
<td>[-0.14, 0.30]</td>
<td>[-0.54, 0.83]</td>
<td>[-0.14, 0.18]</td>
</tr>
<tr>
<td>WW (LEP)</td>
<td>$\lambda_Z = \lambda_\gamma$</td>
<td>$\Delta \kappa_Z = \Delta g^Z_1 - \Delta \kappa_\gamma \tan^2 \theta_w$</td>
<td>[-0.051, 0.034]</td>
<td>[-0.105, 0.069]</td>
<td>[-0.059, 0.026]</td>
</tr>
<tr>
<td>WZ (D0, 4.1 fb$^{-1}$)</td>
<td>[-0.075, 0.093]</td>
<td>[-0.376, 0.686]</td>
<td>[-0.053, 0.156]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ (CDF, 1.9 fb$^{-1}$)</td>
<td>[-0.14, 0.15]</td>
<td>[-0.81, 1.29]</td>
<td>[-0.14, 0.25]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_\gamma$ (D0, 0.7 fb$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td>[-0.51, 0.51]</td>
<td>[-0.12, 0.13]</td>
</tr>
</tbody>
</table>

## $\Lambda = 1.2$ TeV

<table>
<thead>
<tr>
<th>System</th>
<th>$f_4^Z$</th>
<th>$f_5^Z$</th>
<th>$f_4^\gamma$</th>
<th>$f_5^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ (CDF, 1.9 fb$^{-1}$)</td>
<td>[-0.12, 0.12]</td>
<td>[-0.13, 0.12]</td>
<td>[-0.10, 0.10]</td>
<td>[-0.11, 0.11]</td>
</tr>
<tr>
<td>ZZ (D0, 1.1 fb$^{-1}$)</td>
<td>[-0.28, 0.28]</td>
<td>[-0.31, 0.29]</td>
<td>[-0.26, 0.26]</td>
<td>[-0.30, 0.28]</td>
</tr>
<tr>
<td>ZZ (LEP combined)</td>
<td>[-0.30, 0.30]</td>
<td>[-0.34, 0.38]</td>
<td>[-0.17, 0.19]</td>
<td>[-0.32, 0.36]</td>
</tr>
</tbody>
</table>

## $\Lambda = 1.5$ TeV

<table>
<thead>
<tr>
<th>System</th>
<th>$h_3^Z$</th>
<th>$h_4^Z$</th>
<th>$h_3^\gamma$</th>
<th>$h_4^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_\gamma$ (CDF, 5.0 fb$^{-1}$)</td>
<td>[-0.017, 0.0167]</td>
<td>[-0.0006, 0.0005]</td>
<td>[-0.017, 0.016]</td>
<td>[-0.0006, 0.0006]</td>
</tr>
<tr>
<td>$Z_\gamma$ (D0, 3.6 fb$^{-1}$)</td>
<td>[-0.033, 0.033]</td>
<td>[-0.0017, 0.0017]</td>
<td>[-0.033, 0.033]</td>
<td>[-0.0017, 0.0017]</td>
</tr>
<tr>
<td>$Z_\gamma$ (LEP combined)</td>
<td>[-0.30, 0.30]</td>
<td>[-0.34, 0.38]</td>
<td>[-0.17, 0.19]</td>
<td>[-0.32, 0.36]</td>
</tr>
</tbody>
</table>