Study of Diboson Physics with the ATLAS Detector at LHC

Hai-Jun Yang
University of Michigan
(for the ATLAS Collaboration)

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The Large Hadron Collider at CERN
CM = 14 GeV, Lumi = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}

27 km Tunnel in Switzerland & France

First Collision: Summer 2008
04/14/2008

CMS

pp, general purpose; HI

ALICE

pp, general purpose; HI

Atlas

LHCb: B-physics
Physics Motivations - Diboson

• It’s related to some fundamental questions:
  – Why massive bosons?
  – What is the source of the EWSB?

• There should have some new physics leading to EWSB through searching for
  – Direct evidence of new particles (Higgs, SUSY etc.)
  – Indirect evidence of observing anomalous TGCs
  – SM diboson are important control samples for new physics
New Physics with Diboson

- $WW$ – Higgs, $Z'$, $G$, TGCs
- $WZ$ – SUSY, technicolor, $W'$, TGCs
- $ZZ$ – Higgs, TGCs
- $W\gamma$ – TGCs
- $Z\gamma$ – TGCs
Cross Sections of Diboson

<table>
<thead>
<tr>
<th>Diboson mode</th>
<th>Conditions</th>
<th>$\sqrt{s} = 1.96$ TeV $\sigma [pb]$</th>
<th>$\sqrt{s} = 14$ TeV $\sigma [pb]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^- [14]$</td>
<td>$W$-boson width included</td>
<td>12.4</td>
<td>111.6</td>
</tr>
<tr>
<td>$W^\pm Z^0 [14]$</td>
<td>$Z$ and $W$ on mass shell</td>
<td>3.7</td>
<td>47.8</td>
</tr>
<tr>
<td>$Z^0 Z^0 [14]$</td>
<td>$Z$'s on mass shell</td>
<td>1.43</td>
<td>14.8</td>
</tr>
<tr>
<td>$W^\pm \gamma [15]$</td>
<td>$E_T^\gamma &gt; 7$ GeV, $\Delta R(\ell, \gamma) &gt; 0.7$</td>
<td>19.3</td>
<td>451</td>
</tr>
<tr>
<td>$Z^0 \gamma [16]$</td>
<td>$E_T^\gamma &gt; 7$ GeV, $\Delta R(\ell, \gamma) &gt; 0.7$</td>
<td>4.74</td>
<td>219</td>
</tr>
</tbody>
</table>

Production rate at LHC will be at least 100x higher at Tevatron. 10x higher cross section and 10-100x higher luminosity.

Probes much higher energy region, so sensitive to anomalous TGCs.
# ATLAS diboson Event Selection

<table>
<thead>
<tr>
<th>Process</th>
<th>Selection Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$</td>
<td>2 isolated leptons with $P_T &gt; 25$ GeV, opposite charges, $\Delta R(\ell)&gt;0.2$, \n Missing transverse energy $&gt; 30$ GeV, $</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell\nu \ell^+\ell^-$</td>
<td>3 isolated leptons with $P_T(\text{max}) &gt; 25$ GeV, $\Delta R(\ell)&gt;0.2$ \n vertex cut for each lepton pair: $\Delta Z&lt;1$ mm, $\Delta A&lt;0.1$ mm \n MET $&gt; 30$ GeV, $</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+\ell^- \ell^+\ell^-$</td>
<td>4 isolated leptons with at least one $P_T &gt; 20$ GeV \n Separation between each lepton pair $\Delta R(\ell)&gt;0.2$ \n All the lepton come from the same vertex, no hadron jets</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+\ell^- \nu\nu$</td>
<td>2 lepton with $P_T &gt; 20$ GeV, and $</td>
</tr>
<tr>
<td>$W\gamma \rightarrow \ell\nu\gamma$</td>
<td>1 isolated lepton with $P_T &gt; 20$ GeV \n 1 isolated photon with $E_T &gt; 20$ GeV \n MET $&gt; 30$ GeV, $40$ GeV $&lt; M_{\ell} &lt; 250$ GeV, Jet veto, $\Delta R(\ell\gamma)&gt;0.7$</td>
</tr>
<tr>
<td>$Z\gamma \rightarrow \ell^+\ell^-\gamma$</td>
<td>2 isolated leptons with $P_T &gt; 20$ GeV, opposite charges, $\Delta R(\ell)&gt;0.2$, \n $</td>
</tr>
</tbody>
</table>

$\sigma_{WW} = 113.3$ pb

$\sigma_{WZ} = 29.4$ pb

$\sigma_{ZZ} = 18.8$ pb

$\sigma_{WW} = (51.8+38.8)\times 1.4$ pb

$\sigma_{ZZ} = 18.8$ pb

$\sigma_{Z\gamma} = 20.2\times 1.4$ pb
**Boosted Decision Trees**

- Relative new in HEP – MiniBooNE, BaBar, D0 (single top discovery), ATLAS
- Advantages: robust, understand ‘powerful’ variables, relatively transparent, ...

“A procedure that combines many weak classifiers to form a powerful committee”

- Split data recursively based on input variables until a stopping criterion is reached (e.g. purity, too few events)
- Every event ends up in a “signal” or a “background” leaf
- Misclassified events will be given larger weight in the next decision tree (boosting)
- Build a set of decisions trees (~100 – 1000)

Analysis with Boosted Decision Trees

PP $\rightarrow$ WW $\rightarrow$ $e\nu\mu\nu$ analysis using ATLAS fully simulated MC datasets (~ 30 Million events).

ATLAS (1 fb$^{-1}$)

- MC Data
- Signal+Background
- Signal($ww\rightarrow e\nu\mu\nu$)
- Background

ATLAS

$pp \rightarrow WW \rightarrow e\nu\mu\nu$

Uncertainty of $\sigma_{ww\rightarrow e\nu\mu\nu}$

Integrated Luminosity (fb$^{-1}$)
### Diboson Results with 1fb⁻¹ Int. Lumi

<table>
<thead>
<tr>
<th>Diboson mode</th>
<th>Signal</th>
<th>Background</th>
<th>$N_\sigma$</th>
<th>Analysis (signal eff.)</th>
<th>$\sigma_{\text{stat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+W^- \rightarrow e^\pm \nu \mu^\mp \nu$</td>
<td>419.9 ± 3.5</td>
<td>80.8 ± 8.0</td>
<td>47</td>
<td>BDT (eff=15.2%)</td>
<td>4.9%</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow \mu + \nu \mu^- \nu$</td>
<td>90.3 ± 1.6</td>
<td>20.2 ± 2.8</td>
<td>20</td>
<td>BDT (eff=6.6%)</td>
<td>10.5%</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow e^+ \nu e^- \nu$</td>
<td>78.0 ± 1.6</td>
<td>35.4 ± 3.6</td>
<td>13</td>
<td>BDT (eff=5.7%)</td>
<td>11.3%</td>
</tr>
<tr>
<td>$W^+W^- \rightarrow \ell^+ \nu \ell^- \nu$</td>
<td>103.1 ± 2.6</td>
<td>16.6 ± 2.0</td>
<td>25</td>
<td>Cut based (eff=2.0%)</td>
<td>9.9%</td>
</tr>
<tr>
<td>$W^\pm Z \rightarrow \ell^\pm \nu \ell^+ \ell^-$</td>
<td>152.6 ± 1.7</td>
<td>16.1 ± 2.5</td>
<td>38</td>
<td>BDT (eff=17.9%)</td>
<td>8.1%</td>
</tr>
<tr>
<td>$Z \rightarrow 4\ell$</td>
<td>53.4 ± 1.6</td>
<td>8.0 ± 1.1</td>
<td>19</td>
<td>Cut based (6.3%)</td>
<td>13.7%</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$</td>
<td>16.5 ± 0.1</td>
<td>1.9 ± 0.2</td>
<td>7.2</td>
<td>Cut based (eff=7.7%)</td>
<td>24.6%</td>
</tr>
<tr>
<td>$W \gamma \rightarrow e\nu \gamma$</td>
<td>1901 ± 77</td>
<td>1474 ± 147</td>
<td>50</td>
<td>BDT (eff=6.7%)</td>
<td>2.3%</td>
</tr>
<tr>
<td>$W \gamma \rightarrow \mu \nu \gamma$</td>
<td>2976 ± 121</td>
<td>2318 ± 232</td>
<td>62</td>
<td>BDT (eff=10.5%)</td>
<td>1.8%</td>
</tr>
<tr>
<td>$Z \gamma \rightarrow e^+ e^- \gamma$</td>
<td>337.4 ± 12</td>
<td>187.2 ± 19</td>
<td>25</td>
<td>BDT (eff=5.5%)</td>
<td>5.4%</td>
</tr>
<tr>
<td>$Z \gamma \rightarrow \mu^+ \mu^- \gamma$</td>
<td>774.8 ± 25</td>
<td>466.7 ± 47</td>
<td>36</td>
<td>BDT (eff=12%)</td>
<td>3.6%</td>
</tr>
</tbody>
</table>
SM Diboson Production at LHC

- Model independent effective Lagrangian for charged triple gauge boson interactions with anomalous couplings (C & P Conservation)

\[ L/g_{WWV} = i g_1^V (W_{\mu\nu}^* W_{\mu\nu}^V - W_{\mu\nu} W_{\mu\nu}^* V_{\mu\nu}) + i \kappa^V W_{\mu\nu}^* V_{\mu\nu} + \frac{\lambda^V}{M_W^2} W_{\rho\mu}^* W_{\nu}^\mu V_{\nu\rho} \]

where \( V = Z, \gamma \).

- In the Standard Model: \( g_1^V = \kappa_V = 1 \) and \( \lambda_V = 0 \).

- Five anomalous coupling parameters: \( \Delta g_1^Z, \Delta \kappa_Z, \lambda_Z, \Delta \kappa_\gamma, \) and \( \lambda_\gamma \)
Probing Anomalous TGCs in ATLAS

• To probe the anomalous couplings we need a model of the kinematic distributions for various couplings. We use:
  – NLO generators
    • MC@NLO produces events that are fully simulated in ATLAS
    • BHO MC generates events with anomalous couplings
  – Reweighting
    • Using kinematic distributions from BHO we reweight the fully simulated MC@NLO events to produce expected distributions for a range of anomalous couplings.
Anomalous spectra and reweighting ratio

- The $M_T(WW)$ spectrum for $W^+W^-$ events with anomalous coupling parameters using the BHO Monte Carlo.
- At right are the ‘weights = $d\sigma$(non-SM)/$d\sigma$(SM)’ used to reweight fully simulated events.
$M_T(WW)$ sensitive to WWZ & WWγ couplings

- Binned likelihood comparing mock SM observations to a SM profile & two reweighted anomalous profiles
- Using 10 bins from 0-500GeV and one overflow bin.
- In addition, the three decay channels, ee, eμ, and μμ, are binned separately for a total of 33 bins.
2D anomalous TGC sensitivity using $M_T(WW)$

95% confidence contours for 0.1, 1, 10, and 30 fb$^{-1}$ integrated luminosity

**Right:** HISZ assumption (2 parameters)

**Bottom:** “Standard” assumption, $Z$ param. $= \gamma$ param. (3 parameters)
## ATLAS TGC sensitivity for 1.0 fb$^{-1}$

95% CL intervals for anomalous TGCs, cutoff $\Lambda = 2$ TeV

<table>
<thead>
<tr>
<th>Diboson</th>
<th>$\lambda_z$</th>
<th>$\Delta \kappa_z$</th>
<th>$\Delta g_1^z$</th>
<th>$\Delta \kappa_\gamma$</th>
<th>$\lambda_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ(ATLAS) 1.0 fb$^{-1}$</td>
<td>[-0.028, 0.024]</td>
<td>[-0.203, 0.339]</td>
<td>[-0.021, 0.054]</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>WZ(D0) 1.0 fb$^{-1}$</td>
<td>[-0.17, 0.21]</td>
<td>[-0.12, 0.29]</td>
<td>$\Delta g_1^z = \Delta \kappa_z$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>WW(ATLAS) 1.0 fb$^{-1}$</td>
<td>[-0.108, 0.111]</td>
<td>[-0.117, 0.187]</td>
<td>[-0.355, 0.616]</td>
<td>[-0.240, 0.251]</td>
<td>[-0.259, 0.421]</td>
</tr>
<tr>
<td>WW(LEP)</td>
<td>$\lambda_z = \lambda_\gamma$</td>
<td>$\Delta \kappa_z = \Delta g_1^z$</td>
<td>-</td>
<td>[-0.051, 0.034]</td>
<td>[-0.105, 0.069]</td>
</tr>
<tr>
<td>$W_\gamma$(ATLAS) 1.0 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>[-0.43, 0.20]</td>
</tr>
<tr>
<td>$W_\gamma$(D0) 0.16 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>[-0.88, 0.96]</td>
</tr>
</tbody>
</table>
Summary

• The Diboson analyses use ~ 30 M ATLAS fully simulated datasets.

• WW, WZ, Wγ and Zγ signal can be established with statistical sensitivity better than 5σ for the first 0.1 fb⁻¹ integrated luminosity, and ZZ signal can be established with 1.0 fb⁻¹ data.

• The anomalous triple gauge boson coupling sensitivities from LHC/ATLAS can be significant improved over the results from Tevatron and LEP using the first 1.0 fb⁻¹ data.

• SM Diboson productions are important control samples for Higgs, SUSY, Technicolor, G, Z’ particle searches with diboson final states.

LHC will start collisions in 2008, please still tuned!
Backup slides
Systematic Uncertainties

- **Signal systematics ~9%**
  - Luminosity measurement  6.5%
  - PDF assumption  3%
  - NLO scaling  5%
  - Particle ID  3%

- **Background systematics ~18%**
  (in addition to the above)
  - MC sample statistics  15% (may drop to 10%)
  - Calibration on lepton, jet energy  5%

- **The systematic errors start to dominate the cross-section measurement uncertainties after 5-10 fb⁻¹.**
**ATLAS TGC sensitivity for 10 fb\(^{-1}\)**

95% CL intervals for anomalous TGCs compare with Tevatron and LEP, cutoff \( \Lambda = 2 \) TeV

<table>
<thead>
<tr>
<th>Diboson, (fit spectra)</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>( WZ, (M_T) )</td>
<td>[-0.015, 0.013]</td>
<td>[-0.095, 0.222]</td>
<td>[-0.011, 0.035]</td>
<td>[-0.26, 0.07]</td>
<td>[-0.05, 0.02]</td>
</tr>
<tr>
<td>( W\gamma, (p_T^\gamma) )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( WW, (M_T) )</td>
<td>[-0.040, 0.038]</td>
<td>[-0.035, 0.073]</td>
<td>[-0.149, 0.309]</td>
<td>[-0.088, 0.089]</td>
<td>[-0.074, 0.165]</td>
</tr>
<tr>
<td>( WZ, (D_0) )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1.0 fb(^{-1}))</td>
<td>[-0.17, 0.21]</td>
<td>[-0.12, 0.29]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W^\pm \gamma, (D_0) ), (0.16 fb(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( WW, (LEP) )</td>
<td>[-0.051, 0.034]</td>
<td>[-0.105, 0.069]</td>
<td>[-0.059, 0.026]</td>
<td>[-0.88, 0.96]</td>
<td>[-0.2, 0.2]</td>
</tr>
</tbody>
</table>

(\( \lambda_\gamma = \lambda_Z, \Delta \kappa_Z = \Delta g^Z_1 - \Delta \kappa_\gamma \tan^2 \theta_W \))
Neutral TGCs Sensitivity (10 fb$^{-1}$)

$$g_{ZZV} \Gamma_{ZZV}^{\alpha \beta \mu} = e \frac{P^2 - M_V^2}{M_Z^2} \left[ i f_4^V (p^\alpha g^{\mu \beta} + p^\beta g^{\mu \alpha}) + i f_5^V \varepsilon^{\mu \alpha \beta \rho} (q_1 - q_2)_\rho \right]$$

<table>
<thead>
<tr>
<th></th>
<th>$f_4^Z$</th>
<th>$f_5^Z$</th>
<th>$f_4'^Z$</th>
<th>$f_5'^Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ $\rightarrow \ell\ell\ell\ell$</td>
<td>[-0.010, 0.010]</td>
<td>[-0.010, 0.010]</td>
<td>[-0.012, 0.012]</td>
<td>[-0.013, 0.012]</td>
</tr>
<tr>
<td>ZZ $\rightarrow \ell\ell\nu\nu$</td>
<td>[-0.012, 0.012]</td>
<td>[-0.012, 0.012]</td>
<td>[-0.014, 0.014]</td>
<td>[-0.015, 0.014]</td>
</tr>
<tr>
<td>Combined</td>
<td>[-0.009, 0.009]</td>
<td>[-0.009, 0.009]</td>
<td>[-0.010, 0.010]</td>
<td>[-0.011, 0.010]</td>
</tr>
<tr>
<td>LEP Limit</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>
$M_T(WZ)$ spectrum sensitive to WWZ couplings

- Binned likelihood comparing mock SM observations to a SM profile and two reweighted anomalous profiles
- $M_T(WZ)$ was found to be the most sensitive kinematics quantity ($P_T(Z)$, $M(\ell\ell)$, and others are also useful, but not as sensitive).
- Using 10 bins from 0-500GeV and one overflow bin.
TGC sensitivity using $M_T(WZ)$ with 0.1 fb$^{-1}$ integrated luminosity

One parameter limits (assuming other couplings are SM)

-0.4 < $\Delta \kappa_Z$ < 0.6
-0.06 < $\Delta g_1^Z$ < 0.1
-0.06 < $\lambda_Z$ < 0.05

Tevatron results

-0.12 < $\Delta \kappa_Z$ < 0.29  2 TeV  D0 with 1.0 fb$^{-1}$
-0.17 < $\lambda_Z$ < 0.21  2 TeV  CDF with 1.9 fb$^{-1}$
-0.82 < $\Delta \kappa_Z$ < 1.27
-0.13 < $\lambda_Z$ < 0.14
TGC sensitivity using $M_T(WZ)$ with 30fb$^{-1}$ integrated luminosity

One parameter limits (assuming other couplings are SM)

$\Lambda=2$ TeV

- $-0.08 < \Delta \kappa_Z < 0.17$
- $-0.01 < \Delta g_1^Z < 0.008$
- $-0.005 < \lambda_Z < 0.023$

$\Lambda=3$ TeV

- $-0.07 < \Delta \kappa_Z < 0.13$
- $-0.003 < \Delta g_1^Z < 0.018$
- $-0.008 < \lambda_Z < 0.005$
Systematic Error Effect on TGCs
2D Limits, \( \Lambda = 2\text{TeV} \), using \( P_T(Z) \)

No systematic errors

9.2\% signal, 18.3\% background
Experimental Advantages

• W’s and Z’s leptonic decay final states provide experimentally clean signals.
• Identification of W and Z bosons are well established.
• W and Z masses provide a valuable constraint.
• They are good sources of high Pt leptons
  – Efficient observation with low background
  – Trigger at low momentum threshold