ZZ production cross-section measurements and neutral Trilinear Gauge Coupling limits in ATLAS

Shih-Chieh Hsu (LBNL)
On Behalf of the ATLAS Collaboration
Lawrence Berkeley National Lab

2011 Meeting of the Division of Particles and Fields of the American Physical Society
August 12, 2011 in Providence, RI

Motivation

Signature
Four isolated charged leptons with small backgrounds.

Foundation for later work
- The only significant background for $H \rightarrow ZZ$ searches
- Probe anomalous triple gauge (TGC) coupling (in this talk)
- Search for new physics (e.g. $G \rightarrow ZZ$)

Footnote: $Z$ in this talk refers to $Z/\gamma^*$
ATLAS Detector and a $2e2\mu$ Candidate
Object and Event Selections

**Objects Selections:**

**Trigger:** Offline selection on plateau of trigger efficiency, at least one electron $E_T > 25$ GeV or muon $p_T > 20$ GeV

**Electron:** $E_T > 15$ GeV, $|\eta| < 2.47$

**Muon:** $p_T > 15$ GeV, $|\eta| < 2.5$

**Track Isolation:** $\sum p_{T,trk}(\Delta R(trk,lep)<0.2)/p_{T,lep} < 0.15$

Insensitive to pile-up effects

**Event Selections:**

- 4 and only 4 leptons
  - Tau leptonic decay contribution is $0.3\%$
- $\min (|m_{01} - 91.25| + |m_{23} - 91.25|)$
- $66$-$116$ GeV mass requirement on both Z candidates
Signal Yield and Selection Efficiency

<table>
<thead>
<tr>
<th>Channels</th>
<th>$e^+e^−e^+e^−$</th>
<th>$μ^+μ^−μ^+μ^−$</th>
<th>$e^+e^−μ^+μ^−$</th>
<th>$μ^+μ^−μ^+μ^−$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuts</td>
<td>$N_{ZZ}/C_{ZZ}$ (%)</td>
<td>$N_{ZZ}/C_{ZZ}$ (%)</td>
<td>$N_{ZZ}/C_{ZZ}$ (%)</td>
<td>$N_{ZZ}/C_{ZZ}$ (%)</td>
</tr>
<tr>
<td>Four leptons</td>
<td>1.84 / 49</td>
<td>3.61 / 94</td>
<td>5.3 / 67</td>
<td>11 / 69</td>
</tr>
<tr>
<td>Trigger Match</td>
<td>1.83 / 49</td>
<td>3.60 / 94</td>
<td>5.3 / 67</td>
<td>11 / 69</td>
</tr>
<tr>
<td>Two pairs</td>
<td>1.78 / 47</td>
<td>3.60 / 94</td>
<td>5.1 / 66</td>
<td>11 / 68</td>
</tr>
<tr>
<td>Mass cut on leading Z</td>
<td>1.68 / 45</td>
<td>3.33 / 87</td>
<td>4.8 / 61</td>
<td>9.8 / 64</td>
</tr>
<tr>
<td>Mass cut on subleading Z</td>
<td>1.57 / 41</td>
<td>3.09 / 81</td>
<td>4.5 / 57</td>
<td>9.1 / 59</td>
</tr>
</tbody>
</table>

- Yields predictions $N_{zz}$ at 1.02 fb$^{-1}$
- Event reconstruction efficiency $C_{zz}$ is defined with respect to truth fiducial volume

**Truth Fiducial Volume:**

- $(Z/γ^*)(Z/γ^*) → ℓ^+ℓ^−ℓ^+ℓ^−$, $ℓ = e, μ$;
- $|m(Z/γ^*) - m_{PDG}(Z)| < 25$ GeV;
- $p_T^ℓ > 15$ GeV;
- SF: MC efficiency scale factor correction
## Systematics on Acceptance

Systematics uncertainty is dominated by the lepton reconstruction and ID efficiency determined from data-driven method.

<table>
<thead>
<tr>
<th>Source</th>
<th>$eeee$</th>
<th>$\mu\mu\mu\mu$</th>
<th>$ee\mu\mu$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ reconstruction efficiency</td>
<td>-</td>
<td>2.0</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$\mu$ $p_T$ smearing</td>
<td>-</td>
<td>0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$\mu$ trk isolation</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\mu$ d0Sig</td>
<td>-</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu$ z0</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$e$ reconstruction efficiency</td>
<td>2.8</td>
<td>-</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>$e$ identification efficiency</td>
<td>6.0</td>
<td>-</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>$e$ energy scale</td>
<td>0.6</td>
<td>-</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>$e$ energy smearing</td>
<td>&lt; 0.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e$ trk isolation</td>
<td>0.3</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$e$ d0Sig</td>
<td>0.5</td>
<td>-</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$e$ z0</td>
<td>0.2</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>trigger</td>
<td>&lt; 0.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZZ \rightarrow \tau$</td>
<td></td>
<td></td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.7</td>
<td>2.0</td>
<td>3.3</td>
<td>3.0</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td></td>
<td>3.7</td>
</tr>
</tbody>
</table>
Data-Driven Fake Estimate

A pure data-driven technique is developed
To estimate all background processes containing at least one lepton-like jet background (Z+jets, Top, WZ, W+jets, QCD)

Extrapolation from QCD enriched regions via fake ratio, $f$
Discrepancy of $f$ in MC/Data is included as systematics

Double counting removal

\[
N(\text{background}) = N(\ell\ell\ell\ell j) \times f - N(\ell\ell j) \times f^2 - N(ZZ \text{ in control region}).
\]
12 ZZ candidates are observed

\[ \int L \, dt = 1.02 \, \text{fb}^{-1} \sqrt{s} = 7 \, \text{TeV} \]

Predicted BG in signal region:
\[ 0.3^{+0.9}_{-0.3} \, \text{(stat)} \, ^{+0.4}_{-0.3} \, \text{(syst)} \]

Signal Region
# Observed ZZ Yields

<table>
<thead>
<tr>
<th>Final State</th>
<th>$e^+e^-e^+e^-$</th>
<th>$\mu^+\mu^-\mu^+\mu^-$</th>
<th>$e^+e^-\mu^+\mu^-$</th>
<th>$\ell^+\ell^-\ell^+\ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Bkg(data-driven)</td>
<td>$0.01^{+0.03+0.05}_{-0.01-0.01}$</td>
<td>$0.3^{+0.9}_{-0.3} \pm 0.3$</td>
<td>$&lt; 0.01^{+0.03}_{-0.01}$</td>
<td>$0.3^{+0.9+0.4}_{-0.3-0.3}$</td>
</tr>
<tr>
<td>Expected ZZ</td>
<td>$1.57 \pm 0.03 \pm 0.11$</td>
<td>$3.09 \pm 0.04 \pm 0.06$</td>
<td>$4.5 \pm 0.1 \pm 0.2$</td>
<td>$9.1 \pm 0.1 \pm 0.3$</td>
</tr>
</tbody>
</table>

\[
-2 \ln Q = -2 \ln \frac{L(s + b)}{L(b)}; \quad L(s + b) = \frac{e^{-(N_s + N_b)} \cdot (N_s + N_b)^{N_{obs}}}{N_{obs}!}, \quad L(b) = \frac{e^{-N_b} \cdot (N_b)^{N_{obs}}}{N_{obs}!},
\]

Number expected background $0.3^{+0.9}_{-0.3}$ (stat.) $+0.4_{-0.3}$ (syst.)

Expected p-value: $4.2 \times 10^{-6}$ significance: 4.2 $\sigma$

Observed p-value: $3.4 \times 10^{-6}$ Observed significance: 4.5 $\sigma$
Z Mass Plots

Nice agreement of the Z mass

\[ \int L \, dt = 1.02 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

ATLAS Preliminary

Events / 10 GeV

Predicted Background:
\[ 0.3^{+0.9}_{-0.3} \text{ (stat)} \pm 0.4 \text{ (syst)} \]

Data 2011

\[ M^{\text{Leading Z}} \text{ [GeV]} \]

\[ M^{\text{Subleading Z}} \text{ [GeV]} \]
ZZ Kinematic Plots

Interesting to watch the tail evolution with more data accumulated in ATLAS
4μ candidate event

Run Number: 183003,
Event Number: 121099951
Date: 2011-06-02, 10:08:24 CET
EtCut>0.3 GeV
PtCut>2.5 GeV
Cells:Tiles, EMC
Cross-section Measurement

**Fiducial cross-section:**
Defined within fiducial volume to minimize theoretical acceptance extrapolation and $L$ is luminosity.

\[
\frac{N_{\text{obs}} - N_{\text{bkg}}}{C_{\text{ZZ}} \cdot BR(\text{ZZ} \rightarrow e, \mu) \cdot L}
\]

**Total cross-section:**
Extrapolation to ZZ zero width approximation calculation

\[
\frac{N_{\text{obs}} - N_{\text{bkg}}}{A_{\text{ZZ}} \cdot C_{\text{ZZ}} \cdot BR(\text{ZZ} \rightarrow e, \mu) \cdot L}
\]

\[
A_{\text{zz}} = \frac{\sigma(\text{ZZ NLO fiducial})}{\sigma(\text{ZZ on-shell})} = 0.501
\]

**Fiducial volume:**
with respect to on-shell Z

- $(Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+ \ell^- \ell^+ \ell^-, \ell = e, \mu$;
- $|m(Z/\gamma^*) - m_{\text{PDG}}(Z)| < 25 \text{ GeV}$;
- $p_T^\ell > 15 \text{ GeV}$;
Cross-Section Results

**Fiducial cross-section results**, where lepton is e or mu without tau contribution

\[
\sigma_{ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-}^{\text{fid}} = 19^{+6}_{-5} \text{ (stat)} ^{+1}_{-2} \text{ (syst)} \pm 1 \text{ (lumi)} \text{ fb}
\]

**Total cross-section** is extrapolated to ZZ on-shell Xsec:

\[
\sigma_{ZZ}^{\text{tot}} = 8.4^{+2.7}_{-2.3} \text{ (stat)} ^{+0.4}_{-0.7} \text{ (syst)} \pm 0.3 \text{ (lumi)} \text{ pb}
\]

The results is consistent to NLO Calculation

\[
\text{Xsec (NLO)} = 6.46^{+0.2}_{-0.3} \text{ pb}
\]
ZZ Anomalous Triple Gauge Coupling

Two most generalized ZZV vertex, \( V=Z,\gamma \)

\[ \mathcal{L} = \frac{e}{m_Z^2} \left[ f_A^V (\partial_\mu V^{\mu \beta}) Z_\alpha (\partial_\alpha Z_\beta) + f_5^V (\partial_\sigma V_{\sigma \mu} Z^{\mu \beta} Z_\beta) \right] \]

Form factor is introduced to preserve unitarity at high energy

\[ f_i^V (s) = \frac{f_{i0}^V}{(1 + s/\Lambda_{FF}^2)^n} \]

Benchmark point (Exponent n=3, energy cut-off \( \Lambda=2 \text{ TeV} \)) is chosen from the reference: Baur & Rainwater, PRD62 113011 (2000)
Neutral Trilinear Gauge Coupling Measurement

Total expected yield is parametrized as function of TGC parameter

\[ s(\sigma_{\text{fiducial}}, C_{ZZ}, f_i^V) = (C_{SM} + C_{f_i^V} \cdot f_i^V + C_{f_i^V, f_i^V} \cdot (f_i^V)^2) \cdot L \cdot C_{ZZ}. \]

Profiling likelihood is used to include systematics uncertainty

\[ L(\sigma, C_{ZZ}, b, \Delta_b, \Delta C_{ZZ}, N) = P(\sigma, C'_{ZZ}, b', N) \cdot G(C'_{ZZ}; C_{ZZ}, \Delta C_{ZZ}) \cdot G(b'; b, \Delta_b) \]

\[ \cdot G(C'_{SM}; C_{SM}, \Delta C_{SM}) \cdot G(C'_{f_i^V}; C_{f_i^V}, \Delta C_{f_i^V}) \cdot G(C'_{f_i^V, f_i^V}; C_{f_i^V, f_i^V}, \Delta C_{f_i^V, f_i^V}) \]

Infinite energy-cut off results are also included as a reference

<table>
<thead>
<tr>
<th>Coupling 95% CI</th>
<th>( f_4^V )</th>
<th>( f_4^L )</th>
<th>( f_5^V )</th>
<th>( f_5^L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda = 2 \text{ TeV} )</td>
<td>[−0.15, 0.15]</td>
<td>[−0.12, 0.12]</td>
<td>[−0.15, 0.15]</td>
<td>[−0.13, 0.13]</td>
</tr>
<tr>
<td>( \Lambda = \infty )</td>
<td>[−0.08, 0.08]</td>
<td>[−0.07, 0.07]</td>
<td>[−0.08, 0.08]</td>
<td>[−0.07, 0.07]</td>
</tr>
</tbody>
</table>
First nTGC results in 7 TeV pp collisions. The best limits with higher energy cut-off $\Lambda$
Summary

- The first ZZ production cross-section in 7 TeV pp collisions is reported:
  - Observed 12 candidates with background $0.3^{+0.9}_{-0.3} (\text{stat.}) +0.4^{+0.4}_{-0.3} (\text{syst.})$ gives 4.5 $\sigma$ significance
  - The measured cross-section is consistent with SM predictions 6.5 pb

\[
\sigma_{ZZ}^{\text{tot}} = 8.4^{+2.7}_{-2.3} (\text{stat}) +0.4^{+0.4}_{-0.7} (\text{syst}) \pm 0.3 (\text{lumi}) \text{pb.}
\]

- The first nTGC limits are extracted in 7 TeV pp collision which provides the most stringent limits with higher cut-off

- More details can be found in ATLAS-CONF-2011-107:
Backup
Control Region Plots

Z performance shows reasonable agreement between MC and Data.