Study of Electroweak and Higgs Physics with ZZ Production with ATLAS at the LHC

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PhD Thesis Research

Study of Electroweak and Higgs Physics with ZZ Productions at the LHC

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Yanwen Liu (USTC, Chair)
Ziping Zhang (USTC)
My contributions to ATLAS

• Detector work:
  – Commissioning of the new EE MDT chambers at CERN
  – R & D of thin gap Resistive Plate Chamber for ATLAS new Small Wheel upgrade
  – Operation and maintenance of ATLAS Monitored Drift Tube (MDT) Gas System
  – Operation and maintenance of Gas Monitor for MDT

• Physics analyses:
  – SM ZZ cross section measurement at 7 TeV [JHEP03(2013)128] (8 TeV analysis is under review)
  – Heavy Higgs search in $H \rightarrow ZZ \rightarrow ll\nu\nu$ (to be published soon)
  – mono-Z dark matter search [PhysRevD.90.012004]
  – Invisible Higgs search in $ZH \rightarrow ll+$invisible channel [PhysRevLett.112.201802]
  – Higgs off-shell couplings measurement in $H^{*} \rightarrow ZZ \rightarrow ll\nu\nu$ [arXiv:1503.01060]
  – Single resonance $Z \rightarrow 4\ell$ measurement [PhysRevLett.112.231806]
  – Higgs spin and parity measurement [PhysLettB726(2013)120]
  – SM WW at 8 TeV (paper under review), ssWW [PhysRevLett.113.141803]
Outline

• Introduction

• Electroweak physics study with ZZ production in final state of $Z(\rightarrow ll) + E_T^{\text{miss}}$
  – SM ZZ production cross section measurement in $ZZ\rightarrow ll\nu\nu$
  – Probing anomalous triple gauge couplings

• Higgs physics studies with ZZ channel [$Z(\rightarrow ll) + E_T^{\text{miss}}$]:
  – Higgs off-shell signal strength measurement with $H^* \rightarrow ZZ \rightarrow ll\nu\nu$
  – Heavy Higgs search with $H \rightarrow ZZ \rightarrow ll\nu\nu$

• Summary
Introduction
Standard Model of Particle Physics

A theory to describe the elementary particles and their interactions based on
- Gauge invariance
- Higgs mechanism

Gauge invariance is well tested before the LHC

A breakthrough of the Particle Physics is the discovery of the Higgs boson at the LHC
ZZ production in pp collisions at the LHC

- In SM:
  - $qq \rightarrow ZZ$
  - $gg \rightarrow ZZ$
  - $gg \rightarrow H \rightarrow ZZ$

- Beyond the SM:
  - Non-SM Higgs decay width
  - Additional Higgs bosons, new resonance in high mass

forbidden in SM ($V, V'$ are neutral gauge boson)
Higgs Physics at the LHC

- Higgs production modes at the LHC
- Higgs decay branching ratio

Measured Higgs boson mass:
- ATLAS: $125.02^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$ (syst) GeV
- CMS: $125.36^{±0.37}_{±0.18}$ (stat) $±0.18$ (syst) GeV

Higgs mass is not specified in SM

Combined by ATLAS and CMS

$m_H = 125.09^{±0.21}_{±0.11}$ (stat) $±0.11$ (scale) $±0.02$ (other) $±0.01$ (th)

reach the precision of $≈0.2\%$!
The Large Hadron Collider at CERN

26.7 km ring, proton-proton collisions $\sqrt{s} = 7/8$ TeV (design $\sqrt{s} = 14$ TeV)

Peak lumi 7x10$^{33}$ cm$^{-2}$ s$^{-1}$ (design lumi. 10$^{34}$ cm$^{-2}$ s$^{-1}$)

$Z \rightarrow \mu \mu$ event with 25 reconstructed vertices

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Excellent performance of the LHC and of the ATLAS: 5 fb$^{-1}$@ 7 TeV and 21 fb$^{-1}$@ 8 TeV of pp data recorded in Run 1
How Particles are Identified in ATLAS

Basic principle: Different types of particles interacting with the detector have different responses.

The dashed tracks are invisible to the detector.
SM ZZ production cross section measurement
Motivation

- Precision test of SM predictions in the EWK sector at high energy
- Probe for new physics by searching for deviations from the SM
  - anomalous triple gauge couplings (aTGC)
  - heavy resonances decaying to a pair of Z bosons
- Irreducible background to Higgs studies and new physics searches
- Previous measurements:
  - Measured at 7 TeV with $\text{ZZ} \rightarrow 4l$ and $\text{ZZ} \rightarrow llvv$: $5 \text{ fb}^{-1}$ [JHEP03(2013)128]
  - Measured at 8 TeV with $\text{ZZ} \rightarrow 4l$:
    - $5 \text{ fb}^{-1}$: ATLAS-CONF-2012-090
    - $20 \text{ fb}^{-1}$: ATLAS-CONF-2013-020
- Physics measurements:
  - Cross section measurement with $\text{ZZ} \rightarrow llvv$ at 8 TeV
  - Probe aTGC

$\text{phase space: } 66 < m_{Z1}, m_{Z2} < 116 \text{ GeV}$
Theoretical calculation

- **qq → ZZ**
  - Full NLO QCD calculation available with MC generators MCFM and PowhegBox
  - High order corrections:
    - NLO EWK correction
    - NNLO QCD k-factors as function of \( m_{ZZ} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>( \sigma ) [pb]</th>
<th>NLO EWK</th>
<th>NLO EWK + NNLO QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q\bar{q} \rightarrow ZZ )</td>
<td>6.56</td>
<td>6.26</td>
<td>6.82</td>
</tr>
<tr>
<td>( gg \rightarrow H \rightarrow ZZ )</td>
<td>0.32</td>
<td>-</td>
<td>0.92</td>
</tr>
<tr>
<td>combined</td>
<td>6.88</td>
<td>6.58</td>
<td>7.74</td>
</tr>
</tbody>
</table>

- **gg → ZZ**
  - Box diagram (continuum): calculation available only at LO: MCFM, gg2VV
  - \( gg \rightarrow H \rightarrow ZZ \): NNLO QCD k-factors as function of \( m_{ZZ} \)
Cross section measurement

• Total cross section measurement procedure:
  – Define a signal region (fiducial volume)
  – Count the observed events $N_{\text{obs}}$, estimate the background contribution $N_{\text{bkg}}$
  – Calculate the signal acceptance ($A_{ZZ}$), efficiency correction factor ($C_{ZZ}$) using MC simulation

$$\sigma_{ZZ}^{\text{tot}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times \text{BR}\{ZZ \rightarrow \ell\ell\nu\bar{\nu}\} \times A_{ZZ} \times C_{ZZ}}$$

$A_{ZZ} = \frac{N_{\text{MC Fiducial Volume Generated ZZ}}}{N_{\text{MC All Generated ZZ}}}$

$C_{ZZ}$: Efficiency correction factor in FV

• Fiducial cross section:

$$\sigma_{ZZ \rightarrow \ell\ell\nu\bar{\nu}}^{\text{fid}} = \frac{N_{\ell^+\ell^-\nu\bar{\nu}}^{\text{obs}} - N_{\ell^+\ell^-\nu\bar{\nu}}^{\text{bkg}}}{\mathcal{L} \times C_{ZZ \rightarrow \ell\ell\nu\bar{\nu}}}$$

- $76 < m(Z/\gamma^* \rightarrow \ell^+\ell^-) < 106 \text{ GeV}$;
- $\text{axial-}E_{T}^{\text{miss}} = -p_{T}^{\nu+\bar{\nu}} \times \cos(\Delta\phi(p_{T}^{\nu+\bar{\nu}},p_{T}^{Z})) > 90 \text{ GeV}$;
- $\frac{|p_{T}^{\nu+\bar{\nu}} - p_{T}^{Z}|}{p_{T}^{Z}} < 0.4$;
- $p_{T}^{\ell} > 25 \text{ GeV}$;
- $|\eta^{\ell}| < 2.5$;
- No (particle-level) jets with $p_{T} > 25 \text{ GeV}$ and $|\eta| < 4.5$.
SM ZZ: signal and background

- Dataset: full 8 TeV data, 20.3 fb\(^{-1}\)
- Experimental signatures: two isolated high \(p_T\) leptons with high \(E_T^{\text{miss}}\)
- Signal modeling: \(qq \rightarrow ZZ\) (PowhegBox) + \(gg \rightarrow ZZ\) (gg2VV)
  - Depending on the choice of PDF set, QCD scales, and parton shower model
- Backgrounds:
  - \(WZ \rightarrow l\nu l\nu\): MC based, validated using trilepton control region
  - \(WW/\text{top}/Z\tau\tau\): real \(E_T^{\text{miss}}\), data driven, flavor symmetry
  - \(Z+\text{jets}\): fake \(E_T^{\text{miss}}\), ABCD method
  - \(W+\text{jets}\): fake lepton, fake-factor method
  - Others: triboson, tt+V

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Event selection

- Two same flavor opposite sign leptons
  - electron: $E_T > 25$ GeV, isolated
  - muon: $p_T > 25$ GeV, isolated
  - 3rd electron (muon): $E_T (p_T) > 7 \ (6)$ GeV, relaxed isolation requirement
- Z mass cut: $76 < m_{ll} < 106$ GeV

To suppress $Z+\text{jets}$ background
Event selection (2)

- Z $p_T$ balance cut: fractional $p_T$ difference ($|E_{T\text{miss}} - p_T^{ll}| / p_T^{ll} < 0.4$) → to remove fake $E_{T\text{miss}}$ background
- Jet veto: jet $p_T > 25$ GeV, $|\eta| < 4.5$ → to remove top background
- Third lepton veto: remove events with “3rd” leptons → to suppress WZ background
Background estimation: WZ

- WZ background is estimated with MC simulation: **PowhegBox + Pythia NLO QCD + NLO EWK correction**
- Validate the normalization in trilepton control region

### Observed and expected events from MC in WZ control region:

<table>
<thead>
<tr>
<th>Channel</th>
<th>observed</th>
<th>MC (total)</th>
<th>MC (WZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eee</td>
<td>40.0</td>
<td>32.0 ± 1.3</td>
<td>26.7 ± 1.0</td>
</tr>
<tr>
<td>eeμ</td>
<td>44.0</td>
<td>37.3 ± 1.1</td>
<td>31.6 ± 1.0</td>
</tr>
<tr>
<td>μμν</td>
<td>44.0</td>
<td>35.7 ± 1.4</td>
<td>29.8 ± 0.9</td>
</tr>
<tr>
<td>μμμ</td>
<td>50.0</td>
<td>41.8 ± 1.4</td>
<td>35.4 ± 1.2</td>
</tr>
</tbody>
</table>

### WZ background in the signal region:

<table>
<thead>
<tr>
<th>Channel</th>
<th>estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>15.2 ± 0.7 ± 1.8</td>
</tr>
<tr>
<td>μμ</td>
<td>16.9 ± 0.7 ± 2.2</td>
</tr>
</tbody>
</table>

**Systematics:**
- Experimental (7~9%)
- PDF (6%), QCD scale (8%)
Background estimation: $WW/\text{top}/Z \rightarrow \tau\tau$

- Use the **flavor symmetry** in $WW/\text{ttbar} \& Wt/Z(\rightarrow\tau\tau)$ leptoic decays: $ee : \mu\mu : e\mu = 1 : 1 : 2$

- A data-driven method which **inclusively estimates those BGs** from the $e\mu$ control region

\[ N_{ee}^{\text{bkg}} = \frac{1}{2} \times N_{e\mu}^{\text{data,sub}} \times k \]

\[ N_{\mu\mu}^{\text{bkg}} = \frac{1}{2} \times N_{e\mu}^{\text{data,sub}} \times \frac{1}{k} \]

\[ k = \sqrt{\frac{N_{ee}^{\text{data}}}{N_{\mu\mu}^{\text{data}}}} \]

$k$: correct for differences between the efficiencies of electrons and muons

Data-driven estimates are consistent with the MC predictions within uncertainty, but with smaller uncertainty

<table>
<thead>
<tr>
<th></th>
<th>$ee$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data driven estimation</td>
<td>$13.3 \pm 2.8 \pm 0.7$</td>
<td>$14.0 \pm 2.9 \pm 0.7$</td>
</tr>
<tr>
<td>MC prediction</td>
<td>$10.7 \pm 0.9 \pm 2.3$</td>
<td>$14.8 \pm 1.3 \pm 3.2$</td>
</tr>
</tbody>
</table>
Background estimation: Z+jets

- Z+jets: fake $E_T^{\text{miss}}$, low MC statistics
- Used a so-called ABCD method
- Two uncorrelated variables: fractional $p_T$ difference ($|E_T^{\text{miss}} - p_T^{ll}| / p_T^{ll}$) and axial- $E_T^{\text{miss}}$

$N_B = \frac{N_A}{N_C} \times N_D \times \alpha$

$\alpha$: correction factor for the correlation between the two variables

Main systematic is from the $\alpha$ factor

<table>
<thead>
<tr>
<th>Channel</th>
<th>estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>$4.29 \pm 1.77 \pm 2.25$</td>
</tr>
<tr>
<td>$\mu\mu\mu$</td>
<td>$5.56 \pm 2.08 \pm 3.98$</td>
</tr>
</tbody>
</table>
Background Estimation: fake lepton

- Lepton faked from jets: W+jets, multijet, semi-leptonic decay of top events
- Using fake factor method

\[
\begin{array}{c|c|c}
\text{W+jets/QCD events} & \text{pass (signal region-SR)} & \text{fail (control region-CR)} \\
\hline
\text{Jet enriched sample} & \text{pass} & \text{fail}
\end{array}
\]

\[\frac{N_{W+jets}^{pass}}{N_{W+jets}^{fail}} = \frac{N_{Z+jets}^{pass}}{N_{Z+jets}^{fail}}\]

\[N_{W+jets}^{pass} = \sum N_{W+jets}^{fail} * FF\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>W+jets/Multijets</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>0.41 ± 0.16 ± 0.14</td>
</tr>
<tr>
<td>(\mu \mu)</td>
<td>0.54 ± 0.29 ± 0.17</td>
</tr>
</tbody>
</table>
Systematic uncertainties: experimental

- The experimental uncertainties on cross section measurements mainly come from the determination of $C_{ZZ}$

<table>
<thead>
<tr>
<th>$C_{ZZ}$ uncertainties</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$ energy smearing</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>$e$ energy scale</td>
<td>1.73</td>
<td>0.06</td>
</tr>
<tr>
<td>$e$ identification efficiency</td>
<td>0.68</td>
<td>0.00</td>
</tr>
<tr>
<td>$e$ reconstruction efficiency</td>
<td>1.58</td>
<td>0.00</td>
</tr>
<tr>
<td>$e$ isolation efficiency</td>
<td>0.28</td>
<td>0.00</td>
</tr>
<tr>
<td>$\mu$ momentum scale</td>
<td>0.00</td>
<td>0.11</td>
</tr>
<tr>
<td>$\mu$ momentum smearing (ID)</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>$\mu$ momentum smearing (MS)</td>
<td>0.00</td>
<td>0.08</td>
</tr>
<tr>
<td>$\mu$ reconstruction efficiency</td>
<td>0.00</td>
<td>0.67</td>
</tr>
<tr>
<td>$\mu$ isolation efficiency</td>
<td>0.00</td>
<td>2.99</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.08</td>
<td>0.51</td>
</tr>
<tr>
<td>JES</td>
<td>3.68</td>
<td>3.63</td>
</tr>
<tr>
<td>JER</td>
<td>1.41</td>
<td>2.64</td>
</tr>
<tr>
<td>JVF</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td>MET soft-term resolution</td>
<td>1.17</td>
<td>0.77</td>
</tr>
<tr>
<td>MET soft-term scale</td>
<td>0.23</td>
<td>0.57</td>
</tr>
<tr>
<td>pile-up</td>
<td>0.62</td>
<td>0.54</td>
</tr>
<tr>
<td>PDF</td>
<td>0.35</td>
<td>0.44</td>
</tr>
<tr>
<td>PS</td>
<td>2.46</td>
<td>1.25</td>
</tr>
<tr>
<td>EWK correction</td>
<td>0.32</td>
<td>0.34</td>
</tr>
<tr>
<td>$\Delta C_{ZZ}/C_{ZZ}$</td>
<td>5.45</td>
<td>5.74</td>
</tr>
</tbody>
</table>
Systematic uncertainties: theory

- The theoretical uncertainties on cross section measurements contain uncertainties on both $A_{ZZ}$ and $C_{ZZ}$

- Theory uncertainties:
  - PDF: varying the PDF sets
  - QCD scale: varying the renormalization scale ($\mu_R$) and factorization scale ($\mu_F$)
  - Parton showering (Pythia vs. Herwig)
  - Electroweak correction

<table>
<thead>
<tr>
<th>Sources</th>
<th>$A_{ZZ}$</th>
<th>$C_{ZZ}$</th>
<th>$A_{ZZ} \times C_{ZZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ee</td>
<td>$\mu\mu$</td>
<td>combined</td>
</tr>
<tr>
<td>Systematic %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>1.45</td>
<td>1.37</td>
<td>1.40</td>
</tr>
<tr>
<td>QCD scale</td>
<td>2.57</td>
<td>2.89</td>
<td>2.86</td>
</tr>
<tr>
<td>PS</td>
<td>2.57</td>
<td>2.89</td>
<td>2.86</td>
</tr>
<tr>
<td>EWK correction</td>
<td>0.92</td>
<td>1.00</td>
<td>0.96</td>
</tr>
<tr>
<td>Total</td>
<td>3.51</td>
<td>3.82</td>
<td>3.76</td>
</tr>
</tbody>
</table>
The observed number of events is consistent with the expected within uncertainty.
• The $A_{ZZ}$ and $C_{ZZ}$ values are calculated from MC simulation
  – Combined from $qq \rightarrow ZZ$ and $gg \rightarrow ZZ$

<table>
<thead>
<tr>
<th>Sources %</th>
<th>ee</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{ZZ}$</td>
<td>$0.0413 \pm 0.0005 \pm 0.0015$</td>
<td>$0.0400 \pm 0.0005 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta A_{ZZ}/A_{ZZ}$</td>
<td>3.51</td>
<td>3.82</td>
</tr>
<tr>
<td>$C_{ZZ}$</td>
<td>$0.6783 \pm 0.0156 \pm 0.0370$</td>
<td>$0.7566 \pm 0.0173 \pm 0.0434$</td>
</tr>
<tr>
<td>$\Delta C_{ZZ}/C_{ZZ}$</td>
<td>5.45</td>
<td>5.74</td>
</tr>
<tr>
<td>$A_{ZZ} \times C_{ZZ}$</td>
<td>$0.02809 \pm 0.00042 \pm 0.00205$</td>
<td>$0.03032 \pm 0.00044 \pm 0.00218$</td>
</tr>
<tr>
<td>$\Delta A_{ZZ} \times C_{ZZ}$</td>
<td>7.30</td>
<td>7.20</td>
</tr>
<tr>
<td>$A_{ZZ} \times C_{ZZ}$</td>
<td>$0.02809 \pm 0.00042 \pm 0.00205$</td>
<td>$0.03032 \pm 0.00044 \pm 0.00218$</td>
</tr>
</tbody>
</table>
Cross section extraction

- Using maximum likelihood fit to extract the measured cross section:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross-Section [fb]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measured</td>
<td>predicted</td>
</tr>
<tr>
<td>$ee\nu\nu$</td>
<td>$5.07^{+0.52}<em>{-0.45}\text{(stat)}^{+0.74}</em>{-0.70}\text{(syst)}^{+0.19}_{-0.16}\text{(lumi)}$</td>
<td>$3.66 \pm 0.23$</td>
</tr>
<tr>
<td>$\mu\mu\nu\nu$</td>
<td>$4.62^{+0.59}<em>{-0.51}\text{(stat)}^{+0.68}</em>{-0.64}\text{(syst)}^{+0.18}_{-0.14}\text{(lumi)}$</td>
<td>$3.53 \pm 0.20$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured</th>
<th>$8.84^{+1.04}<em>{-0.88}\text{(stat)}^{+0.87}</em>{-0.85}\text{(syst)}^{+0.33}_{-0.28}\text{(lumi)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLO QCD</td>
<td>$6.88^{+0.31}_{-0.27}$</td>
</tr>
<tr>
<td>Predicted</td>
<td>NLO QCD + NLO EWK</td>
</tr>
<tr>
<td></td>
<td>NLO EWK + NNLO QCD</td>
</tr>
</tbody>
</table>
Triple Gauge Couplings

- Gauge boson coupling is the direct consequence of the non-Abelian nature of $SU(2)_L \times U(1)_Y$ in SM
  - Triple gauge boson couplings (TGC):
    - Charged TGC: $WWZ$, $WW\gamma$, allowed in SM
    - Neutral TGC: $ZZZ$, $ZZ\gamma$, $Z\gamma\gamma$, forbidden in SM

- Physics beyond SM can introduce anomalous TGCs (aTGC)
  - Can be experimentally probed in high $p_T$ region

- Effective Lagrangian approach is used to test aTGC

\[ \mathcal{L}_{ZZV} = -\frac{e}{M_Z^2} \left[ f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right] \]

- In SM at tree level: $f_j^V = 0$ \((j=4,5)\)
- $f_5^V$ is CP-conserving, $f_4^V$ is CP-violating
aTGC parameterization

- aTGC can enhance the cross section significantly

\[
\frac{d\sigma_{\text{SM+TGC}}}{d\Omega} = F_{00} + f_{4}^{\gamma} F_{01} + f_{4}^{Z} F_{02} + f_{5}^{\gamma} F_{03} + f_{5}^{Z} F_{04} \\
+ \left( f_{4}^{\gamma} \right)^2 F_{11} + f_{4}^{\gamma} f_{4}^{\gamma} F_{12} + f_{4}^{\gamma} f_{5}^{\gamma} F_{13} + f_{4}^{\gamma} f_{5}^{Z} F_{14} \\
+ \left( f_{4}^{Z} \right)^2 F_{22} + f_{4}^{Z} f_{5}^{\gamma} F_{23} + f_{4}^{Z} f_{5}^{Z} F_{24} \\
+ \left( f_{5}^{\gamma} \right)^2 F_{33} + f_{5}^{\gamma} f_{5}^{Z} F_{34} \\
+ \left( f_{5}^{Z} \right)^2 F_{44}
\]

Signature is the increased event yield in the boson’s high $p_T$ region

- aTGC MC samples are generated by Sherpa generator
- aTGC coefficients ($F_{ij}$) are derived from matrix element calculation
- No significant deviation from SM is observed
aTGC limits

- Z $p_T$ is used as the discriminant to probe aTGC
  - The optimized binning is $[0, 340], [340, 1500]$ GeV

<table>
<thead>
<tr>
<th></th>
<th>$p_T^H &lt; 340$ GeV</th>
<th>$340 &lt; p_T^H &lt; 1500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>103.15 $\pm$ 1.29 $\pm$ 10.46</td>
<td>0.84 $\pm$ 0.10 $\pm$ 0.19</td>
</tr>
<tr>
<td>WZ</td>
<td>32.04 $\pm$ 0.99 $\pm$ 4.23</td>
<td>0.09 $\pm$ 0.05 $\pm$ 0.01</td>
</tr>
<tr>
<td>WW/Top/Z $\rightarrow \tau\tau$</td>
<td>27.17 $\pm$ 1.74 $\pm$ 1.40</td>
<td>0.13 $\pm$ 0.06 $\pm$ 0.01</td>
</tr>
<tr>
<td>$Z(\rightarrow ee/\mu\mu) + X$</td>
<td>9.85 $\pm$ 4.14 $\pm$ 6.23</td>
<td>0.00</td>
</tr>
<tr>
<td>$W(\rightarrow e\nu/\mu\nu) + X$</td>
<td>0.95 $\pm$ 0.63 $\pm$ 0.31</td>
<td>0.00</td>
</tr>
<tr>
<td>Other BGs</td>
<td>1.20 $\pm$ 0.18 $\pm$ 0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Observed</td>
<td>210</td>
<td>1</td>
</tr>
</tbody>
</table>

- Limit results
  - The most stringent limits today

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Expected ($10^{-3}$)</th>
<th>Observed ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_4^Z$</td>
<td>[-4.53, 4.43]</td>
<td>[-3.92, 3.93]</td>
</tr>
<tr>
<td>$f_4^Z$</td>
<td>[-3.91, 3.85]</td>
<td>[-3.40, 3.38]</td>
</tr>
<tr>
<td>$f_5^Z$</td>
<td>[-4.51, 4.51]</td>
<td>[-3.98, 3.93]</td>
</tr>
<tr>
<td>$f_5^Z$</td>
<td>[-3.96, 3.90]</td>
<td>[-3.41, 3.44]</td>
</tr>
</tbody>
</table>
Summary of SM ZZ Measurements

- SM ZZ cross section measurement

\[ \sigma_{ZZ}^{\text{tot}} = 8.84_{-0.88}^{+1.04} \text{(stat)} + 0.87_{-0.85}^{+0.91} \text{(syst)} + 0.33_{-0.28}^{+0.2} \text{(lumi)}. \]

- Measured cross section is consistent with the NNLO QCD calculation

\[ 7.74_{-0.31}^{+0.35} \text{ pb}. \]

- aTGC limit setting: most stringent limits
Measurement of Higgs Couplings in Off-shell production $H^* \rightarrow ZZ \rightarrow ll\nu\nu$
and Constraints on Higgs Width
Physics motivation

- In SM, the on-shell Higgs has a width of $4.1 \text{ MeV}$ at 125.5 GeV
- Off-shell $H^* \rightarrow VV$ process enhances the event rate at high mass
- Sensitive to new physics (non-SM $\Gamma_H$, and couplings)

- Measurement of off-shell Higgs coupling can be used to further constrain the Higgs width
  - Direct $\Gamma_H$ measurement in m4l distribution leads to $\Gamma_H < 2.6 \ (3.4) \text{ GeV} @ 95\% \text{ CL}$ from ATLAS (CMS)
• Using the high mass events, we can directly measure the off-peak Higgs couplings

$$\frac{d\sigma_{pp \rightarrow H \rightarrow ZZ}}{dM_{4l}^2} \sim \frac{g_H g_g g_H g_{ZZ}}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{\kappa_{g, on}^2 \kappa_{V, on}^2}{\Gamma_H / \Gamma_{SM}} = \mu_{\text{on-shell}}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \sim \kappa_{g, off}^2 \kappa_{V, off}^2 = \mu_{\text{off-shell}}$$

Assuming the on-shell and off-shell couplings are the same, we can constrain the Higgs total width

$$\kappa_{g, on} = \kappa_{g, off}$$

$$\kappa_{V, on} = \kappa_{V, off}$$

$$\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \cdot \frac{\Gamma_H / \Gamma_{SM}}{\Gamma_H}$$
Interference

- The \( gg \rightarrow ZZ \) continuum production and the interference (destructive) between them must be considered in this measurement.

\[
|\mathcal{M}_{VV}|^2 = |\mathcal{M}_H + \mathcal{M}_{\text{cont}}|^2 = |\mathcal{M}_H|^2 + |\mathcal{M}_{\text{cont}}|^2 + 2 \text{Re}(\mathcal{M}_H \mathcal{M}_{\text{cont}}^*)
\]
Theoretical Calculations and Treatments

- Theoretical calculations for \( gg \rightarrow (H^* \rightarrow ZZ/WW \) are only performed at LO QCD (MCFM, gg2VV).
- Theorists only provided higher order (NNLO) QCD corrections (k-factor) as a function of \( m_{ZZ} \) for off-shell Higgs production.
- For the background \( gg \rightarrow ZZ \) and the interference:
  - In soft-collinear approximation, the k-factors for \( gg \rightarrow H \rightarrow ZZ \) are applicable to \( gg \rightarrow ZZ \) process.
  - 30% uncertainty on the interference to assess the validity of this assumption (CMS used 10% uncertainty).

\[
R^B_{H^*} = \frac{K(gg \rightarrow ZZ)}{K(gg \rightarrow H^* \rightarrow ZZ)} = \frac{K^B(m_{ZZ})}{K^H_{gg}(m_{ZZ})}
\]

Present results as a function of the k-factor ratio:

Many interactions with the theorists
Analysis strategy

- \( m_T \) is used as the discriminating variable in this analysis
  
  \[
  m_T^2 \equiv \left[ \sqrt{m_Z^2 + \vec{p}_T^{\ell\ell}}^2 + \sqrt{m_Z^2 + \vec{E}_{T}^{\text{miss}}}^2 \right] - \left[ \vec{p}_T^{\ell\ell} + \vec{E}_{T}^{\text{miss}} \right]^2
  \]

- We perform a simple cut-based analysis

- Background estimation:
  - \( qq \rightarrow ZZ \): (65%) MC based estimation with PowhegBox, reweighted to NNLO QCD + NLO EWK
  - \( WZ \): (25%) MC based estimation with Powheg at NLO QCD + NLO EWK
  - \( \text{Top}(4\%) + WW(4\%) \): estimated inclusively with e\(\mu\) events
  - \( Z+\text{jets} \): data-driven with ABCD method
Results

Limits on $\frac{\Gamma_H}{\Gamma_H^{SM}}$ as function gg→ZZ background k-factor ratio

Combined with H→ZZ→4l channel to constrain the Higgs total width

<table>
<thead>
<tr>
<th>$R_H^B = 1$</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{off-shell}}$ (4l)</td>
<td>7.2</td>
<td>10.2</td>
</tr>
<tr>
<td>$\mu_{\text{off-shell}}$ (2l2\nu)</td>
<td>11.3</td>
<td>10.0</td>
</tr>
<tr>
<td>$\mu_{\text{off-shell}}$ (4l+2l2\nu)</td>
<td>6.7</td>
<td>7.9</td>
</tr>
<tr>
<td>$\frac{\Gamma_H}{\Gamma_H^{SM}}(\mu_{\text{on-shell}} = 1)$</td>
<td>5.7</td>
<td>8.5</td>
</tr>
<tr>
<td>$\frac{\Gamma_H}{\Gamma_H^{SM}}(\mu_{\text{on-shell}} = 1.54)$</td>
<td>4.8</td>
<td>5.8</td>
</tr>
<tr>
<td>CMS $\frac{\Gamma_H}{\Gamma_H^{SM}}$</td>
<td>5.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>

We can constrain the Higgs total width to ~20 MeV at 95% CL!

Sparked a lot of theory discussions on off-shell Higgs

Search for high mass Higgs in $H \rightarrow ZZ \rightarrow ll\nu\nu$
Introduction to High Mass Higgs Search

• Search for new resonance $X \rightarrow ZZ$
  - We have already found the SM Higgs at 125 GeV, but is this Higgs fully responsible for the generation of the masses of the other SM particles?

• Theory extensions to the SM Higgs:
  - EWK singlet: SM(h) + a Real Singlet Field (H)
  - Two Higgs Doublet Model (2HDM): five Higgs $h, H, A, H^{\pm}$

Previous observed exclusion limit with 7 TeV data: $319 < m_H < 558$ GeV
Analysis overview

- Use \( m_T(ZZ) \) as the discriminant:
  \[
  m_T^2 = \left[ \sqrt{m_Z^2 + \vec{P}_{T}^{ll}}^2 + \sqrt{m_Z^2 + \vec{P}_{T}^{miss}}^2 \right]^2 - \left[ \vec{P}_{T}^{ll} + \vec{P}_{T}^{miss} \right]^2
  \]

- Separate ggF and VBF categorization:
  - ggF: MET > 70 GeV, 0+1 jet
  - VBF: MET > 70 GeV, >=2 jets, Mjj > 550 GeV, |\( \Delta \eta(jj) \)| > 4.4

- Background estimation:
  - \( qq \rightarrow ZZ \): MC based estimation with Powheg, reweighted to NNLO as function of \( m(ZZ) \) + NLO EWK correction
  - \( gg \rightarrow (H^* \rightarrow ZZ) \): MC based estimation with gg2VV, reweighted to NNLO as function of \( m(ZZ) \)
  - \( WZ \): MC based estimation with Powheg + NLO EWK correction
  - \( WW/Top/Z \rightarrow \tau\tau \): estimated inclusively with e\( \mu \) events
  - \( Z+\text{jets} \): data-driven with ABCD method
  - \( W+\text{jets} \): data-driven with fake factor method
  - Other backgrounds: tri-boson, ttV, estimated with MC
Results: ggF category

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>ggF</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ee</td>
<td>(\mu\mu)</td>
<td>combined</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(qq \rightarrow ZZ)</td>
<td>57.3 ± 1.0 ± 5.4</td>
<td>56.3 ± 1.0 ± 5.3</td>
<td>113.7 ± 1.4 ± 10.6</td>
</tr>
<tr>
<td>(gg \rightarrow ZZ)</td>
<td>6.3 ± 0.1 ± 1.6</td>
<td>6.1 ± 0.1 ± 1.6</td>
<td>12.4 ± 0.1 ± 3.2</td>
</tr>
<tr>
<td>WZ</td>
<td>23.3 ± 0.8 ± 2.6</td>
<td>24.6 ± 0.9 ± 2.6</td>
<td>47.8 ± 1.2 ± 5.2</td>
</tr>
<tr>
<td>WW/Top/Z \rightarrow \tau\tau</td>
<td>26.3 ± 3.6 ± 1.5</td>
<td>30.2 ± 4.1 ± 1.7</td>
<td>56.5 ± 5.4 ± 3.2</td>
</tr>
<tr>
<td>(Z(\rightarrow ee/\mu\mu) + X)</td>
<td>27.2 ± 3.6 ± 17.4</td>
<td>39.3 ± 4.9 ± 21.8</td>
<td>66.5 ± 6.1 ± 39.2</td>
</tr>
<tr>
<td>Other BGs</td>
<td>2.2 ± 0.4 ± 0.2</td>
<td>2.2 ± 0.6 ± 0.2</td>
<td>4.4 ± 0.7 ± 0.4</td>
</tr>
<tr>
<td>Total</td>
<td>142.5 ± 5.3 ± 28.7</td>
<td>158.7 ± 6.6 ± 33.0</td>
<td>301.3 ± 8.4 ± 61.7</td>
</tr>
<tr>
<td>Observed</td>
<td>145</td>
<td>164</td>
<td>309</td>
</tr>
</tbody>
</table>

No significant deviation from the SM expectation is observed.

\(m_T(ZZ)\)
Results: VBF category

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>(\mu\mu)</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>(qq \rightarrow ZZ)</td>
<td>0.05 ± 0.03 ± 0.01</td>
<td>0.08 ± 0.04 ± 0.01</td>
<td>0.13 ± 0.04 ± 0.02</td>
</tr>
<tr>
<td>(gg \rightarrow ZZ)</td>
<td>0.08 ± 0.01 ± 0.02</td>
<td>0.06 ± 0.01 ± 0.02</td>
<td>0.14 ± 0.01 ± 0.04</td>
</tr>
<tr>
<td>WZ</td>
<td>0.03 ± 0.03 &lt; 0.01</td>
<td>0.08 ± 0.05 ± 0.01</td>
<td>0.11 ± 0.06 ± 0.01</td>
</tr>
<tr>
<td>(WW/Top/Z \rightarrow \tau\tau)</td>
<td>0.19 ± &lt; 0.01 ± 0.06</td>
<td>0.20 ± &lt; 0.01 ± 0.06</td>
<td>0.39 ± 0.01 ± 0.12</td>
</tr>
<tr>
<td>(Z(\rightarrow ee/\mu\mu) + X)</td>
<td>0.37 ± 0.12 ± 0.37</td>
<td>0.23 ± 0.16 ± 0.23</td>
<td>0.60 ± 0.20 ± 0.60</td>
</tr>
<tr>
<td>Total</td>
<td>0.72 ± 0.13 ± 0.46</td>
<td>0.65 ± 0.17 ± 0.32</td>
<td>1.37 ± 0.21 ± 0.78</td>
</tr>
<tr>
<td>Observed</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

No significant deviation from the SM expectation is observed.
Interpretation

- No excess is observed $\rightarrow$ set limits on new physics models
- Model independent limits: $\sigma \times \text{Br}(H \rightarrow ZZ)$

95% CL limits
Interpretation: 2HDM

- Interpret on H in type I and type II 2HDM
  - Three free parameters: $\alpha$, $\beta$, $m_H$
    - $\alpha$: mixing angle that relates physical mass eigenstates with the field doublets
    - $\beta$: where $\tan\beta = v_2/v_1$ ratio of the vacuum expectation values of the scalar fields

95% CL limits

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_V$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$\kappa_u$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
</tr>
<tr>
<td>$\kappa_d$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
</tr>
<tr>
<td>$\kappa_l$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
<td>$-\sin(\alpha)/\cos(\beta)$</td>
</tr>
</tbody>
</table>
Summary

• Big step forward to understand electroweak symmetry breaking mechanism at the LHC Run1 → highlighted by the Higgs discovery and its property measurement.

• This thesis work performed stringent test of the SM and studied Higgs physics with $Z(\rightarrow \ell\ell)Z(\rightarrow \nu\nu)$ production at the LHC
  – Measure the SM $pp\rightarrow ZZ$ cross section
  – Off-shell Higgs signal strength measurement and constraint on Higgs total width
  – Search for High mass Higgs

• Rich and interesting results achieved with Run 1, looking forward to exploit the Run 2 physics at the LHC!
Selected publications

- “Evidence for Electroweak Production of $W \pm W \pm jj$ in pp Collisions at 8 TeV with the ATLAS Detector”, *PhysRevLett.113.141803*, arXiv:1405.6241
- “Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector”, *PhysRevD.90.012004*, arXiv:1404.0051
- “Cross-section measurements of single resonance $Z \rightarrow 4\ell$ in pp collisions at 7 TeV and 8 TeV with the ATLAS detector”, *PhysRevLett.112.231806*, arXiv:1403.5657
- “Measurement of ZZ production in pp collisions at $s\sqrt{v}=7$ TeV and limits on anomalous ZZZ and ZZ$\gamma$ couplings with the ATLAS”, *JHEP03(2013)128*, arXiv:1211.6096
Selected conference talks

- August 2013, *ATLAS results on gauge coupling measurements*, LPC Workshop on Gauge Boson Couplings, Fermilab, Batavia, IL, US.
- August 2013, *Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS*, Meeting of the American Physical Society (APS) Division of Particles and Fields (DPF), UC Santa Cruz, Santa Cruz, CA, US.
- April 2013, *Measurement of the ZZ production cross section in 20.7 fb⁻¹ of proton-proton collisions at 8 TeV with the ATLAS detector*, APS April Meeting 2013, Sheraton Denver Hotel, Denver, CO, US.
- August 2014, *Determination of off-shell Higgs couplings and contraints on Higgs total width in the ZZ decay channel*, also presented a poster with the same title, 2014 US ATLAS Physics Workshop, Seattle, WA, US.
- April 2014, *Search for invisible Higgs decay in ZH→ll + invisible channel*, 2014 ATLAS Higgs Workshop, Rome, Italy.
- January 2014, *Higgs spin and parity measurements in H→ZZ→4l channel*, ATLAS HSG7 Workshop, CERN.
Awards

• 2014, Scholarship for Innovative Thesis Research, USTC.

• 2014, ATLAS PhD Grant, CERN, one of the first three recipients of the ATLAS PhD Grant, founded by ATLAS ex-spokesperson Peter Jenni and Fabiola Ginanotti.

• 2011-2013, PhD Fellowship for co-education, China Scholarship Council, selected by the Ministry of Education of the People’s Republic of China.

• 2012, Young Scholar of Distinction, Ministry of Education of the People’s Republic of China.
backup
Detector work experience
R&D on Resistive Plate Chambers

• Detector R&D:
  – Multi-gap Resistive Plate Chambers (MRPC) for Time-of-Flight system of BESIII experiment
    • Construction of the prototypes and responsible for the development of a LabVIEW based DAQ system for test-beam experiment
  – Thin-gap RPC for ATLAS Muon Phase I upgrade:
    • Prototypes and test beams

*Fig. 1. Cross-sectional view of the glass RPC.*
Muon Detector Commissioning, M&O

- Commission of MDT chambers at CERN for the transition region

- Operation and maintenance:
  - ATLAS Monitored Drift Tube (MDT) Gas Monitor
    - Monitor the gas quality of the input to/output from the MDT system
  - MDT Gas System M&O and serve as the on-call expert (since Nov. 2013)
    - Repairing of the leaking chambers
    - Leak rate measurement of the MDT chambers

Intense physical access to the chambers in the ATLAS cavern
Looking forward to Run 2
First collimator "splash" event seen by the ATLAS experiment in LHC Run-2, Apr. 5, 2015
LHC’s latest schedule for restart

Expected integrated luminosity:
~10 fb$^{-1}$ during 2015; ~100 fb$^{-1}$ for Run 2

50 ns beam
Cross section Ratios at 13 TeV/ 8 TeV

<table>
<thead>
<tr>
<th>Object</th>
<th>Ratio (13 TeV / 8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>1.2</td>
</tr>
<tr>
<td>W(\ln)</td>
<td>1.6</td>
</tr>
<tr>
<td>Z(\ln)</td>
<td>1.7</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.0</td>
</tr>
<tr>
<td>t (s-channel)</td>
<td>2.2</td>
</tr>
<tr>
<td>t (t-channel)</td>
<td>2.5</td>
</tr>
<tr>
<td>H (ggF)</td>
<td>2.3</td>
</tr>
<tr>
<td>H (VBF)</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>2.9</td>
</tr>
<tr>
<td>tt</td>
<td>3.3</td>
</tr>
<tr>
<td>ttZ</td>
<td>3.6</td>
</tr>
<tr>
<td>ttH</td>
<td>3.9</td>
</tr>
<tr>
<td>A(0.5 TeV, ggF+bbA)</td>
<td>4.0</td>
</tr>
<tr>
<td>stop pair (0.7 TeV)</td>
<td>8.4</td>
</tr>
<tr>
<td>gluino pair (1.5 TeV)</td>
<td>46</td>
</tr>
<tr>
<td>Z' SSM (3 TeV)</td>
<td>10</td>
</tr>
<tr>
<td>Q* (4 TeV)</td>
<td>56</td>
</tr>
<tr>
<td>QBH (5 TeV)</td>
<td>370</td>
</tr>
<tr>
<td>QBH (6 TeV)</td>
<td>9000</td>
</tr>
</tbody>
</table>

Substantial discovery potential for high-mass objects already with 1 fb\(^{-1}\)
Other materials
SM ZZ: Z+jets estimation

- Measure the correction factor as function of axial-ETmiss cut
## SM ZZ: Azz and Czz

<table>
<thead>
<tr>
<th>Process</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$0.0422 \pm 0.0005$</td>
<td>$0.0409 \pm 0.0005$</td>
<td>$0.0415 \pm 0.0004$</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$</td>
<td>$0.0232 \pm 0.0014$</td>
<td>$0.0212 \pm 0.0013$</td>
<td>$0.0222 \pm 0.0010$</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$0.6768 \pm 0.0159$</td>
<td>$0.7574 \pm 0.0177$</td>
<td>$0.7164 \pm 0.0119$</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$</td>
<td>$0.7318 \pm 0.0677$</td>
<td>$0.7282 \pm 0.0698$</td>
<td>$0.7301 \pm 0.0486$</td>
</tr>
</tbody>
</table>
SM ZZ: Form factor

- With non-SM coupling parameters, the amplitudes of gauge boson pair production grow with energy and violate unitarity eventually.

- To avoid unitarity violation, an effective cutoff scale $\Lambda$ is introduced.

- Dipole form factor of coupling parameters:

  $$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^n}$$

  - $\alpha_0$: coupling in the low energy limit
  - $n$: exponent chosen to ensure unitarity
    - $n=2$ for WWV,
    - $n=3$ for ZZV,
    - $Z\gamma V$: $n=3$ for $h_3^V$, $n=4$ for $h_4^V$

- aTGC Limits are set for both with and without form factor.
SM ZZ: Cross section extraction

- Maximize likelihood function to fit the cross section:

\[ -\ln L(\sigma, \{x_k\}) = \sum_{i=1}^{2} -\ln \left( \frac{e^{-(N_s^i(\sigma, \{x_k\}) + N_b^i(\{x_k\})) \times (N_s^i(\sigma, \{x_k\}) + N_b^i(\{x_k\}))^{N_{obs}^i}}}{(N_{obs}^i)!} \right) + \sum_{k=1}^{n} \frac{x_k^2}{2}. \]

for fiducial cross section, remove Br and Azz
SM ZZ

Ranking of systematics for the fitted cross section

\[ ZZ \rightarrow 2l2\nu \]

\( \frac{(\theta - \theta_0)}{\Delta \theta} \)
SM ZZ: Likelihood and test statistics

- **Likelihood function:**

\[
L(\mu, \theta) = \prod_{i=1}^{m} \text{Poisson}(N_{\text{data}}^i, \psi^i(\mu, \theta)) \times \frac{1}{(2\pi)^{m/2}} e^{-\frac{1}{2}(\theta^T C^{-1} \theta)},
\]

\[
\psi^i(\mu, \theta) = N_{\text{sig}}^i(\mu) \left\{ 1 + \sum_{k} \sigma_{ik} \theta_k \right\} + N_{\text{bkg}} \left\{ 1 + \sum_{k} \sigma_{(i+m)k} \theta_k \right\}
\]

\[
N_{\text{sig}} = (Y_{\text{SM}} + Y_{f_{i}^V} \cdot f_{i}^V + Y_{f_{i}^V f_{i}^V} \cdot (f_{i}^V)^2) \cdot L \cdot C_{ZZ}.
\]

\(\mu\): TGC parameters

\(\sigma_{ik}\): systematic uncertainty

\(\theta_k\): nuisance parameter with Gaussian constraint

\(C\): covariance matrix

- **Test statistics:**

  - Profiled likelihood ratio: conditional maximum LL

\[
\lambda(\mu_{\text{test}}) = \frac{L(\mu_{\text{test}}, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}
\]

\[
t_{\mu} = -2\ln \lambda(\mu).
\]

- \(t_{\mu}\) follows a Chi-squared distribution
SM ZZ: Limit setting procedure

• Generate large number of pseudo experiments (toys) and calculate the p-value

• The observed profile likelihood ratio:  $\lambda(\mu)_{obs}$

• Pseudo experiment:
  – Randomly generate number of events following the Poisson distribution with the mean of $N_{sig(\mu_{test})} + N_{bkg}$
  – Calculate the profile likelihood ratio for each toy $\lambda(\mu)_{toy}$
  – If $\lambda(\mu)_{toy} < \lambda(\mu)_{obs}$, the toy is considered as “less likely”
  – By default, at each $\mu_{test}$, 10,000 toys are generated

• p-value for the tested $\mu$:

\[
p-value(\mu_{test}) = \frac{\text{Number of pseudo expts. with less likely results than actual}}{\text{Total number of pseudo experiments}}
\]

• Scan $\mu_{test}$ until p-value is less than 5% $\rightarrow$ 95%CL limit on $\mu$. 
HZZ: Object selection

Electrons
- “Medium++” (loose++ for 3\textsuperscript{rd} lepton veto)
- \(p_T > 20\ \text{GeV}, |\eta| < 2.47\) (>7 GeV for 3\textsuperscript{rd} lepton veto)
- Detector quality checks
- Track isolation: \(p_T/\text{cone20}/p_T < 0.10\)

Jets
- \(\text{Anti-}k_T R=0.4, \text{EM+JES, using in-situ calibration}\)
- \(p_T > 20\ \text{GeV, } |\eta| < 4.5\)
  \((p_T > 25\ \text{GeV, } |\eta| < 2.5 \text{ for jet veto})\)
- \(I_{JVF} > 0.75\) (>0.5 for 2012) if \(p_T < 50\ \text{GeV} \& |\eta| < 2.4\)

Missing \(E_T\)
- \(\text{ReFFinal (non-STVF for both 2011&2012)}\)
- Object calibration/rescaling transferred to \(E_T^{\text{miss}}\) calculation.
- Fixes applied for e-jet overlap issues.

Muons
- Staco algorithm, combined
- \(p_T > 20\ \text{GeV, } |\eta| < 2.5\) (>7 GeV for 3\textsuperscript{rd} lepton veto)
- MCP recommended track cuts
- \(|L_0| < 10\ \text{mm, } |L_0| < 1\ \text{mm}\)
- Track isolation: \(p_T/\text{cone20}/p_T < 0.10\)

Overlap removal
- \(e-\mu\): remove e when \(dR(e,\mu) < 0.2\)
- \(j-e\): remove jets when \(dR(j,e) < 0.2\)
- \(e-j\): remove e when \(0.2 < dR(e,j) < 0.4\)
- \(\mu-j\): remove \(\mu\) when \(dR(\mu,j) < 0.4\)

Track Missing \(E_T\)
- Re-computed offline from ID-tracks and electron clusters: “Track\_MET\_cl”
criteria in https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/TrackMET
Constraints on off-shell Higgs couplings and Higgs total width

- Using the high mass events, we can directly measure the off-peak Higgs couplings

\[
\frac{d\sigma_{pp\rightarrow H\rightarrow ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}
\]

on-shell: \(m_{4l} \sim m_H\)

\[
\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{on-shell}} \sim \frac{\kappa_{g,\text{on}}^2 \kappa_{V,\text{on}}^2}{\Gamma_H / \Gamma_{SM}} = \mu_{\text{on-shell}}
\]

off-shell: \(m_{4l} - m_H >> \Gamma_H\)

\[
\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{off-shell}} \sim \kappa_{g,\text{off}}^2 \kappa_{V,\text{off}}^2 = \mu_{\text{off-shell}}
\]

- Assuming the on-shell and off-shell couplings are the same, we can reinterpret the coupling measurements as constraints on Higgs total width

\[
\mu_{\text{on-shell}} = \frac{\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{on-shell}}}{\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{on-shell}}(SM)} \quad \mu_{\text{off-shell}} = \frac{\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{off-shell}}}{\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{off-shell}}(SM)}
\]

\[
\kappa_{g,\text{on}} = \kappa_{g,\text{off}} \quad \kappa_{V,\text{on}} = \kappa_{V,\text{off}}
\]

\[
\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \cdot \Gamma_H / \Gamma_H^{SM}
\]
HZZ: 2HDM

• Extension to the SM Higgs:
  – Two Higgs Doublet Model (2HDM):
    • five Higgs: two neutral CP-even bosons $h$ and $H$, one neutral CP-odd boson $A$, and two charged bosons $H^\pm$
    • Six free parameters:

Higgs masses ($m_h, m_H, m_A, m_{H^\pm}$)
$\alpha$: mixing angle that relates physical mass eigenstates with the field doublets
$\beta$: where $\tan\beta = v_2/v_1$ ratio of the vacuum expectation values of the scalar fields

• Couplings to vector bosons and fermions are scaled by different factors as in SM

**Coupling to vector bosons:**

$$g_{hVV}^{2HDM} / g_{hVV}^{SM} = \sin(\beta - \alpha)$$
$$g_{HVV}^{2HDM} / g_{HVV}^{SM} = \cos(\beta - \alpha).$$

**Coupling to fermions:**

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
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<tr>
<td>$\kappa_u$</td>
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<tr>
<td>$\kappa_d$</td>
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<tr>
<td>$\kappa_l$</td>
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<td>$-\sin(\alpha)/\cos(\beta)$</td>
<td>$\cos(\alpha)/\sin(\beta)$</td>
</tr>
</tbody>
</table>
HZZ: combined results

- ATLAS combined $H \rightarrow ZZ$ results:

- CMS combined $H \rightarrow ZZ$ results:

  arXiv:1504.00936
ATLAS muon spectrometer:
- Precision chambers: MDT, Cathod Strip Chambers
- Trigger chambers: Resistive Plate Chambers, Thin Gap Chambers
ATLAS performance

- Electron ID efficiency
- Muon reconstruction efficiency
- Missing transverse energy resolution

5/4/2015

Lailin Xu