Search for heavy ZZ resonances in the $\ell\ell\nu\nu$ and $4\ell$ final states

Xiangyang Ju

Meeting of APS Division of Particles and Fields
FNAL, August 3 2017
Measurements of the SM Higgs boson.

- Excellent agreement entails the success of the SM and places stringent constraint on theories beyond SM.
- Current experimental results cannot rule out the possibility that it is part of an extended Higgs sector.
- Typical benchmark model is CP-conserved 2HDM (two-Higgs-doublet-models).
2HDM interpretation

- Introduce two Higgs doublets: $\phi_1$ and $\phi_2$.
- Spontaneous symmetry breaking results in 5 Higgs bosons:
  - CP-even ($h, H$); CP-odd ($A$), charged Higgs ($H^{+/−}$).
- Free parameters in the physics basis:
  - masses of all Higgs bosons.
  - ratio of vacuum expectation values: $\tan\beta = v_2/v_1$.
  - Higgs mixing angle in the CP-even sector $\alpha$, $H^{SM} = \sin(\beta -\alpha)h + \cos(\beta -\alpha)H$.
- $m_A$, $m_{H^{+/−}}$, is assumed to be heavy enough that $H$ won’t decay to them.
- Coupling modifiers:
  - $\kappa(h, V) = \sin(\beta -\alpha)$, $\kappa(H, V) = \cos(\beta -\alpha)$.
  - $\kappa(H, t) = - \sin(\beta -\alpha)/\tan\beta + \cos(\beta -\alpha)$.
  - TypeI: $\kappa(H, b) = \kappa(H, t)$
  - TypeII: $\kappa(H, b) = \sin(\beta -\alpha) \tan\beta + \cos(\beta -\alpha)$. 

<table>
<thead>
<tr>
<th></th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
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</thead>
<tbody>
<tr>
<td><strong>Type I</strong></td>
<td>$u,d,l$</td>
<td></td>
</tr>
<tr>
<td><strong>Type II</strong></td>
<td>$u$</td>
<td>$d,l$</td>
</tr>
<tr>
<td><strong>flipped</strong></td>
<td>$u,l$</td>
<td>$d$</td>
</tr>
<tr>
<td><strong>lepton-specific</strong></td>
<td>$u,d$</td>
<td>$l$</td>
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</table>
General analysis strategy in event selections

- First define an **inclusive signal region**.
- To enhance the sensitivity on the VBF production, VBF-like category is defined by looking for **VBF signatures**: two forward jets, leading to large $m_{jj}$ and $\Delta\eta_{jj}$.
  - $4l$: $m_{jj} > 400$ GeV and $\Delta\eta_{jj} > 3.3$.
- Events in inclusive SR containing the VBF signatures are classified to VBF-like category, otherwise to the ggF-like category.
• Search for the events with two leptons originating from a on-shell Z and large missing transverse momentum $E_T^{\text{miss}}$.
• Interesting signature, can result from different phenomena, depending on the origin of $E_T^{\text{miss}}$.
  - Dark matter: mono-Z, Invisible Higgs (ZH) or $Z \rightarrow \nu \nu$.
• Large branching ratio, good sensitivity in the high mass region.
• Due to different resolution and background composition of electrons and muons, the events are classified into ee and mm channels.
• Look for excesses in the transverse mass:

$$m_T \equiv \sqrt{\left[ \sqrt{m_Z^2 + (p_T^{\ell \ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} \right]^2 - |\vec{p}_T^{\ell \ell} + \vec{E}_{T}^{\text{miss}}|^2}$$
Inclusive signal regions

Single electron/muon trigger, \( \varepsilon \sim 99\% \).

- \( m_{\ell\ell} \) in [76, 106] GeV.
- \( \Delta R(\ell, \ell) < 1.8 \)
- \( \Delta \Phi(\ell\ell, E_T^{\text{miss}}) > 2.7 \)
- \( E_T^{\text{miss}} > 120 \) GeV.
- \( \Delta \Phi(\text{jet}, E_T^{\text{miss}}) > 0.4 \)
- \( E_T^{\text{miss}}/H_T > 0.4 \)
- \( |p_T^{\text{miss,jet}} - p_T^{\parallel}\ell|/p_T^{\parallel\ell} < 0.2 \)

No third lepton, no bottom-quark tagged jets!
Background composition

1. **qqZZ (~55%)**: simulated by PowHeg, corrected to NNLO QCD and NLO EW calculation.

2. **ggZZ (~4%)**: simulated by gg2VV in LO QCD calculation, corrected with NLO k-factor of $1.7 \pm 1.0$.

3. **WZ (~32%)**: simulated by PowHeg, using a k-factor of 1.29 derived from 3l control region (CR) to correct the overall normalization predicted by MC simulation.

4. **Z+jets (~6%)**: data-driven, use **Boolean** ABCD method.

5. **WW/tt/Z\(\tau\tau\) (~3%)**: data-driven using the e\(\mu\) control region.
• mT distributions in inclusive signal region before the fit.
• Expected background: 612.6 ± 36.7 while observed: 681, compatibility is about 1.5 σ.
• In VBF category, expected 4.6 ± 1.0, while observed 9, compatibility is about 1.6 σ.
4ℓ analysis

• Search for the events with four leptons originating from two on-shell Zs.

• Events are classified into 4e, 4μ, 2e2μ and VBF-like categories.

• Experimental features include:
  - Excellent mass resolution:
    - 38 GeV (4μ) and 16 GeV (4e) for $m_H = 1$ TeV.
    - Challenge is to maximize the acceptance.

• Look for excesses in the four-lepton invariant mass.

• Search range for mH is [200, 1200] GeV.
Inclusive signal regions

Fire electron/muon triggers, $\varepsilon = 98\%$.

only one quadruplet: lepton pair closest $(m_{12})$ and second closest $(m_{34})$ to the pole mass of $Z$.

$50 < m_{12} < 106$ GeV, $50 < m_{34} < 115$ GeV for $m_{4\ell} > 190$ GeV

J/$\psi$ veto, isolation and small impact-parameters criteria on leptons, $\chi^2$/NDF in the vertex fit.

Further improvement on mass resolution:

1. Add final-state-radiation photons

2. Apply $Z$-mass constraint on both $Z$s.

\[ e: E_T > 7 \text{ GeV}, |\eta| < 2.47 \]
\[ \mu: p_T > 5 \text{ GeV}, |\eta| < 2.7 \]
Background composition

1. **qqZZ (~85%)**: simulated by Sherpa (NLO for 0/1 jet, LO for 2/3 jets), with NLO EW corrections applied.

2. **ggZZ (~10%)**: simulated by Sherpa in LO QCD, apply NLO correction of $1.7 \pm 1.0$.

3. **qqZZjj EW (~2%)**: simulated by Sherpa, important for VBF-like category (15%).

4. **Z+jets/tt/WZ (~2%)**: from data-driven methods. The uncertainty is about 20%.

5. **ttV/VVV (~1%)**: from MC simulations.
Results for $4\ell$

- A 3.6 (2.2) $\sigma$ local (global) excess at $\sim 240$ GeV (mostly from 4e channel).
- A 3.6 (2.2) $\sigma$ local (global) excess at $\sim 700$ GeV (excluded at 95% CL by llvv).
- In VBF category, expected 19.5 $\pm$ 8.0 while observed 31 events, compatibility: 1.2 $\sigma$. 

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Combination of $4\ell$ and $\ell\ell\nu\nu$

- **correlation schemes** for systematic uncertainties:
  - the uncertainties coming from the same source are either fully correlated or anti-correlated.

- Combined yields:
  - expected events: $1643 \pm 164$, observed 1870, $1.3 \sigma$.

- **Interpretations**:
  - Narrow width approximation (NWA)
  - Large width assumption (LWA)
NWA interpretation

- When setting limits on ggF (VBF), VBF (ggF) is profiled.
- Compared to the limits published in Run 1 [EPJC(2016)], the expected limit is significantly extended depending on $m_H$.
- A $\sim 2 (< 1)$ $\sigma$ local (global) excess is observed at about 700 GeV.
2HDM interpretation: tan\(\beta\) vs cos(\(\beta-\alpha\)), \(m_H = 200\) GeV

- For a given cos(\(\beta-\alpha\)) and tan\(\beta\), the relative rate of \(\sigma_{ggF}\) and \(\sigma_{VBF}\) is difference, therefore the limits are re-evaluated accordingly.

![Graphs showing 2HDM interpretation](image)
2HDM interpretation: $\tan \beta$ vs $m_H$, $\cos(\beta-\alpha) = -0.1$

- Below 300 GeV only 4l contributes, above 300 GeV both 4l and llvv contribute.
- Exclusion region in 13 TeV is about 2 times better than the one in Run 1.
• Consider only the gluon-fusion production.
• Take into account the **interferences**, but limits are on the “signal only” cross section of the ggF production times BR(ZZ).
• Set limits on three benchmark scenarios for the width of 1, 5, 10% of the $m_H$. 
• A search for heavy ZZ resonances in the $\ell\ell\nu\nu$ and $4\ell$ final states has been presented.

• The maximum deviation in data is observed at around 700 GeV with a local (global) significance of about 2 ($<1$) $\sigma$.

• Current exclusion limits in context of 2HDM are twice stringent than the one published in Run 1.

• Other interesting studies can be found in the conference note ATLAS-CONF-2017-058
Additional Materials
Figure 3: Distribution of the four-lepton reconstructed invariant mass $m_{4l}$ in the full mass range (left) and the low-mass range (right). Points with error bars represent the data and stacked histograms represent expected distributions. The SM Higgs boson signal with $m_H = 125$ GeV, denoted as $H(125)$, and the ZZ backgrounds are normalized to the SM expectation, the $Z+X$ background to the estimation from data. The order in perturbation theory used for the normalization of the irreducible backgrounds is described in Section 7.1. No events are observed with $m_{4l} > 1$ TeV.

The reconstructed dilepton invariant masses selected as $Z_1$ and $Z_2$ are shown in Fig. 5 for $70 < m_{4l} < 130$ GeV, with their correlation. The correlation of the kinematic discriminant $D_{\text{kin}}$ with the four-lepton invariant mass is shown in Fig. 6. The distribution of the discriminants used for event categorization along with the corresponding working point values are shown in Fig. 7.

10.1 Signal strength

To extract the signal strength for the excess of events observed in the Higgs boson peak region, we perform a multi-dimensional fit that relies on two variables: the four-lepton invariant mass $m_{4l}$ and another variable that characterizes the kinematic properties of the event. The fit is performed in the mass range of interest, and the signal strength is determined by comparing the number of observed events in the Higgs boson signal region to the expected number of events from the background processes.
Signal modeling for NWA

- $4\ell$: analytical function (Crystal-Ball + Gaussian) as a function of $m_H$.

- $\ell\ell\nu\nu$, templates obtained from MC simulation and interpolated with moment morphing for any other mass.

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Modeling of signal and interferences.

**ATLAS Simulation**  \( \sqrt{s} = 13 \text{ TeV} \)

**Preliminary**

- **Signal + Interference**
- **Signal only**
- **H-h Interference**
- **H-B Interference**

**Particle-level** \( m_{4j} \) [GeV]
yields

Table 4: $\ell^+\ell^-\ell^+\ell^-$ search: Number of expected and observed events for $m_{4\ell} > 130$ GeV, together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

<table>
<thead>
<tr>
<th>Process</th>
<th>4$\mu$ channel</th>
<th>ggF-enriched categories</th>
<th>4e channel</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2$e$2$\mu$ channel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>297 ± 1 ± 40</td>
<td>480 ± 1 ± 60</td>
<td>193 ± 1 ± 25</td>
<td>15 ± 0.1 ± 6.0</td>
</tr>
<tr>
<td>ZZ (EW)</td>
<td>1.92 ± 0.11 ± 0.19</td>
<td>3.36 ± 0.14 ± 0.33</td>
<td>1.88 ± 0.12 ± 0.20</td>
<td>3.0 ± 0.1 ± 2.2</td>
</tr>
<tr>
<td>Z + jets/tt/WZ</td>
<td>3.7 ± 0.1 ± 0.8</td>
<td>7.8 ± 0.1 ± 1.1</td>
<td>4.4 ± 0.1 ± 0.8</td>
<td>0.37 ± 0.01 ± 0.05</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>5.1 ± 0.1 ± 0.6</td>
<td>8.7 ± 0.1 ± 1.0</td>
<td>4.0 ± 0.1 ± 0.5</td>
<td>0.80 ± 0.02 ± 0.30</td>
</tr>
</tbody>
</table>

| Total background              | 308 ± 1 ± 40    | 500 ± 1 ± 60            | 203 ± 1 ± 25 | 19.5 ± 0.2 ± 8.0    |

| Observed                     | 357             | 545                     | 256         | 31                    |

Table 5: $\ell^+\ell^-\nu\bar{\nu}$ search: Number of expected and observed events together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

<table>
<thead>
<tr>
<th>Process</th>
<th>ggF-enriched categories</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e$^+e^-$ channel</td>
</tr>
<tr>
<td>ZZ</td>
<td>177 ± 3 ± 21</td>
</tr>
<tr>
<td>WZ</td>
<td>93 ± 2 ± 4</td>
</tr>
<tr>
<td>WW/tt/Wt/Z → $\tau\tau$</td>
<td>9.2 ± 2.2 ± 1.4</td>
</tr>
<tr>
<td>Z + jets</td>
<td>17 ± 1 ± 11</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>1.12 ± 0.04 ± 0.08</td>
</tr>
</tbody>
</table>

| Total background              | 297 ± 4 ± 24 | 311 ± 5 ± 27         | 4.6 ± 0.4 ± 0.9 |

| Observed                     | 320           | 352                     | 9             |
**ATLAS** Preliminary

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

\( H \to ZZ \to l^+l^-l^+l^- + l^+l^-\nu\bar{\nu} \)

NWA

Global significance for largest excess (l^+l^-l^+l^-): 2.2\( \sigma \)

Combined

\( m_H \) [GeV]
Limits on LWA

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

\[ H \rightarrow ZZ \rightarrow l^+l^-l'^+l'^- + l'^+\nu\bar{\nu} \]

LWA, \( \Gamma_H = 0.1 \times m_H \)

95\% C.L. limit on \( \sigma(gg \rightarrow H) \times BR(H \rightarrow ZZ) \) [pb]

- Observed \( CL_S \) limit
- Expected \( CL_S \) limit
- Expected \( CL_S \) limit (\( l'^+\nu\bar{\nu} \))

Observed limit (\( CL_S \))

Expected ± 1σ

Expected ± 2σ

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The Modeling for signal-only.

4ℓ: use analytical function to describe the truth line-shape, convolved with detector resolution.

\[
\sigma_{pp\rightarrow H\rightarrow ZZ}(m_{4\ell}) = 2 \cdot m_{4\ell} \cdot L_{gg} \cdot \frac{1}{|s - s_H|^2} \cdot \Gamma_{H\rightarrow gg}(m_{4\ell}^2) \cdot \Gamma_{H\rightarrow ZZ}(m_{4\ell}^2)
\]

The difference in the line-shape at another mass and width comes from the propagator. \(1/|s - s_H|^2\)

ℓℓvv: Reweight full-simulated signal samples to obtain mT distribution in reco. for any mass and width.
Modeling for Large Width Assumption

The Modeling for interference of \((h-H)\), described by:

\[
\sigma_{pp}(m_{4\ell}) = 4 \cdot m_{4\ell} \cdot \mathcal{L}_{gg} \cdot \text{Re} \left[ \frac{1}{s - s_H} \cdot \frac{1}{(s - s_h)^*} \right] \cdot \Gamma_{H \rightarrow gg}(m_{4\ell}) \cdot \Gamma_{H \rightarrow ZZ}(m_{4\ell})
\]

obtained from signal only samples by applying the following weight:

\[
w(m_{4\ell}) = \frac{2 \cdot \text{Re} \left[ \frac{1}{s - s_H} \cdot \frac{1}{(s - s_h)^*} \right]}{\frac{1}{|s - s_H|^2}}
\]

at truth-level for \(4\ell\) and at reco-level for \(\ell\ell\nu\nu\). For \(4\ell\), it then convolves with detector resolution.
The Modeling for interference of (H-B), similar in $4\ell$ and $\ell\ell\nu\nu$.

- Generated truth samples for SBI using gg2VV for $\ell\ell\nu\nu$ and MCFM for $4\ell$. From that subtract the S and B to get the interference.

- Fit the interference with following formula in $m_{ZZ}$ with to obtain its line-shape in truth:

$$\sigma_{pp}(m_{4\ell}) = L_{gg} \cdot \frac{1}{m_{4\ell}} \cdot \text{Re} \left[ \frac{1}{s - s_H} \cdot ((a_0 + a_1 \cdot m_{4\ell} + ...) + i \cdot (b_0 + b_1 \cdot m_{4\ell} + ...)) \right]$$

For $4\ell$, it convolves with detector resolution;

For $\ell\ell\nu\nu$, a ‘c-factor’ is applied to obtain the shape at reco. level.
• $llvv$ excludes the region of $mG^* < \sim 1.3$ TeV.
• $llqq + vvqq$ excludes the region of $mG^* < \sim 1.3$ TeV.