Search for heavy ZZ resonances in the \(4\ell\) and \(\ell\ell\nu\nu\) final states with the ATLAS detector

Jing Li
University of Michigan
Shanghai Jiao Tong University
Aug. 1st, 2019
Introduction

• Benchmark models:
  • Scalars and bulk Randall-Sundrum Gravitons
• Search for heavy resonance with $X \rightarrow ZZ \rightarrow 4\ell / \ell\ell
\nu\nu$
  • $4\ell$: good mass resolution, high signal to background ratio
  • $\ell\ell\nu\nu$: larger branch ratio, dominates at high mass
  • Both ggF and VBF production
• Full Run2 analysis:
  • Search for mass range from 200 – 2000 GeV
Analysis Overview

• The analysis is performed independently in $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ final states, then combine together.

• Working on full Run2 data (139 fb$^{-1}$): analysis is still blinded with major updates of:
  • For $4\ell$ channel:
    • Optimization of VBF categorization
  • For $\ell\ell\nu\nu$ channel:
    • Bring in $E_T^{miss}$-significance
    • One-sideband method for $Z + jets$ estimation
\[ H \rightarrow ZZ \rightarrow 4\ell : \text{Signal modeling} \]

- Narrow Width Approximation
  - \( \Gamma_H = 4.07 \ \text{MeV} \)
  - Shape: sum of a Crystal Ball function and a Gaussian function
  - Fitting parameters and acceptance are interpolated between available mass points by polynomial functions
- Large Width Approximation
  - \( \Gamma_H = 1, 5, 10\% \) of mS
**H \to ZZ \to 4\ell:** Background

- **ZZ continuum (~98%), qq \to ZZ and gg \to ZZ**
  - Shape is modeled with empirical function
  - The uncertainty of parameterization (green band) will be considered as NP
  - Fit the normalization from the data
- **Reducible from data driven:** $Z + jets, t\bar{t}$
- **Others from MC:** $VVV, ttV$

Signal region:

- $50 < m_{12}(m_{34}) < 106(115)\text{ GeV}$
- $200 < m_{4\ell} < 2000\text{ GeV}$
$H \rightarrow ZZ \rightarrow 4\ell$: Control region

- To check the modeling of the background in the control region:
  - $m_4\ell$ between $[70\text{GeV}, 110\text{GeV}]$ and $[140\text{GeV}, 200\text{GeV}]$
  - Using full Run 2 datasets
  - No clear shape mismodeling
$H \rightarrow ZZ \rightarrow 4\ell$: VBF classifier for NWA

- Cut-based VBF categorization: $m_{jj} > 400$ GeV, $|\Delta \eta_{jj}| > 3.3$
  - Standard VBF cuts were also revised and found to be the most optimum in this round

- Re-optimization:
  - Deep neural network
  - Cross check with BDT

- Input variables include leptons and jets kinematics
$H \rightarrow ZZ \rightarrow 4\ell$: Systematics

- **Experimental uncertainties:**
  - Minitrees ready with all CP systematics included

- **Theoretical uncertainties:**
  - $qqZZ, ggZZ$ background modeling:
    - Normalization taken from data
    - Shape systematics from MC by varying QCD scale/PDF/shower
    - Consider acceptance uncertainties for $qqZZ, ggZZ$
  - Signal acceptance uncertainties: QCD scale/PDF/shower
    - 2% for $ggF$ signals, 10% for VBF signals
$H \rightarrow ZZ \rightarrow 4\ell$: Expected sensitivity

- Fit to $m_{4\ell}$ distribution
- Fit to 4 categories simultaneously: $ggF_{2e2\mu}, ggF_{4e}, ggF_{4\mu}, VBF_{\text{inclusive}}$

Old: 36.1 fb$^{-1}$ results (mc15)
Old scaled: scaled to 140 fb$^{-1}$
New: 140 fb$^{-1}$, mc16

---

**ATLAS**

13 TeV, 140.4 fb$^{-1}$

- ggF, 2e2\mu

**ATLAS**

Work-in-progress

13 TeV, 140.5 fb$^{-1}$

NWA

- ggF

**ATLAS**

Work-in-progress

13 TeV, 140.5 fb$^{-1}$

NWA

- VBF

---

95% CL limits on $\sigma_{ggF} \times BR(S \rightarrow ZZ \rightarrow 4\ell)$ [fb]

95% CL limits on $\sigma_{VBF} \times BR(S \rightarrow ZZ \rightarrow 4\ell)$ [fb]

- Expected $\pm 1\sigma$
- Expected $\pm 2\sigma$

---

$m_{4\ell}$ vs $m_S$ [GeV]
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: Cut optimization

- Compared to last round, some optimizations have been made.
- $E_T^{\text{miss}}$-significance is new variable in this round and replace $E_T^{\text{miss}}$/HT.
- Optimization has been done with two variables: $E_T^{\text{miss}}$-significance and $\Delta\phi(Z, E_T^{\text{miss}})$
- Additionally, for VBF categorization:
  - Apply selections on additional two leading jets
  - $m_{jj}$ and $|\Delta\eta_{jj}|$

Using overall significance $Z = \sqrt{2 \left( (S + B) \log \left(1 + \frac{S}{B}\right) - S\right)}$
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: Backgrounds

- 2 same flavor opposite sign leptons
- $76 < m_{\ell\ell} < 106 \text{ GeV}$
  - $\Delta R_{\ell\ell} < 1.8$
- $E_T^{\text{miss}}$-significance $> 10.0$
- $E_T^{\text{miss}} > 120 \text{ GeV}$
- $\Delta \phi(jet_{p_T}>100 \text{ GeV}, E_T^{\text{miss}}) > 0.4$
- $\Delta \phi(Z, E_T^{\text{miss}}) > 2.5$
- No B-jets
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: 3$\ell$CR

- One $ee/\mu\mu$ pair + one additional lepton
- Veto any other lepton
- $|m_{\ell\ell} - m_Z| < 15$ GeV
- $m_W > 60$ GeV and $E_T^{miss}$-significance > 3 to suppress non-WZ processes
- Purity of WZ sample: $\sim 92\%$
- Use scale factor to constrain the normalization of WZ in signal region

$$SF = \frac{data - nonWZ}{WZ}$$
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: $e\mu$CR

- Non-resonant $\ell\ell$ backgrounds: $t\bar{t}, WW, Wt, Z \rightarrow \tau\tau$

- $\epsilon$-factor represents the reconstruction efficiency difference between electrons and muons:
  \[
  \epsilon = \sqrt{\frac{N_{ee}}{N_{\mu\mu}}}
  \]

- Apply $\epsilon$-factor on $e\mu$ Data events:
  \[
  N_{SRee}^{estimation} = \frac{1}{2} \times \epsilon \times N_{e\mu}^{data, sub}
  \]
  \[
  N_{SR\mu\mu}^{estimation} = \frac{1}{2} \times \frac{1}{\epsilon} \times N_{e\mu}^{data, sub}
  \]
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: $Z + jets$

- 1D sideband method for $Z \rightarrow ee, Z \rightarrow \mu\mu$ backgrounds
- Control region: $E_T^{miss}$-significance < 9
- Control region purity: 79%
- Extrapolate to the signal region:
  \[ N_{SR}^{estimation} = N_{CR}^{data,sub} \times \frac{N_{SR}^{MC}}{N_{CR}^{MC}} \]
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: VBF backgrounds

- **WZ**
  - Based on the inclusive $3\ell$CR, require additional two jets
  - Purity $\sim 90\%$, apply scale factor = 0.84 on the signal region contribution

- **Non-resonant $\ell\ell$**
  - Require additional two jets, propagate into the VBF signal region:
    
    \[
    \text{DataDriven}(n_j \geq 2) \times \frac{MC(n_j \geq 2; m_{jj} > 550; \Delta\eta_{jj} > 4.4)}{MC(n_j \geq 2)}
    \]
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: Systematics

- (ongoing) Experimental uncertainties
- Theoretical uncertainties:
  - $qqZZ, ggZZ$ background modeling:
    - Same as 4l: normalization taken from data
    - Shape systematics from MC and acceptance difference between $qqZZ$ and $ggZZ$
$H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$: Expected sensitivity

- Discriminant for the limit setting: $m_T$
  
  $m_T^2 = \left[ \sqrt{m_Z^2 + |\vec{p}_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\text{miss}}|^2} \right]^2 - \left[ \vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}} \right]^2$

- Fit to 4 categories simultaneously: $ggF_{ee}, ggF_{\mu\mu}, VBF_{ee}, VBF_{\mu\mu}$

- NWA model

- Statistic uncertainty only
Summary and outlook

• The overall status of high mass heavy resonance search in ZZ decay is presented.
• The analysis is in good shape now.
• Ongoing:
  • To finalize the systematic studies for both channels.
  • Combination of two channels for further results.
backup

\[ f^{ggZZ,qqZZ,qqZZEW}(m_{4\ell}) = (f_1(m_{4\ell}) + f_2(m_{4\ell})) \times H(m_0 - m_{4\ell}) \times C_0 + f_3^{ggZZ,qqZZ,qqZZEW}(m_{4\ell}) \times H(m_{4\ell} - m_0), \]

where:

\[ f_1(m_{4\ell}) = \exp(a_1 + a_2 \cdot m_{4\ell} + a_3 \cdot m_{4\ell}^2), \]

\[ f_2(m_{4\ell}) = \left\{ \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{m_{4\ell} - b_1}{b_2} \right) \right\} \times \frac{1}{1 + \exp \left( \frac{m_{4\ell} - b_1}{b_3} \right)}, \]

\[ f_3^{qqZZEW}(m_{4\ell}) = \exp \left( c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^{2.7} \right), \]

\[ f_3^{qqZZ,ggZZ}(m_{4\ell}) = \exp \left( c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^3 + c_5 \cdot m_{4\ell}^{4} + c_6 \cdot m_{4\ell}^5 \right), \]

\[ C_0 = \frac{f_3(m_0)}{f_1(m_0) + f_2(m_0)}. \]
$H \rightarrow ZZ \rightarrow 4\ell$: DNN

- Background events use MC weights that normalize to the same luminosity
- Re-weight signal samples to perfectly match falling background spectrum in training
- Significance and expected limit scan for several DNN cut, and $>0.6$ was chosen to be the best one

<table>
<thead>
<tr>
<th></th>
<th>$m_H = 300\text{GeV}$</th>
<th>$m_H = 700\text{GeV}$</th>
<th>$m_H = 1400\text{GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XS_ggF</strong></td>
<td>0.5159</td>
<td>0.09836</td>
<td>0.03856</td>
</tr>
<tr>
<td><strong>XS_VBF</strong></td>
<td>0.2088</td>
<td>0.06842</td>
<td>0.03453</td>
</tr>
<tr>
<td><strong>Cut-based</strong></td>
<td>0.5159</td>
<td>0.09836</td>
<td>0.03856</td>
</tr>
<tr>
<td><strong>DNN&gt;0.6</strong></td>
<td>0.4990</td>
<td>0.09643</td>
<td>0.03838</td>
</tr>
<tr>
<td><strong>Diff (%)</strong></td>
<td>3.3%</td>
<td>2.0%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

No mass sculpting effect for bkg events