Search for high-mass resonances decaying into leptonic final states using the ATLAS detector

’19 7/11 Yosuke Takubo (KEK)

On behalf of the ATLAS Collaboration
Introduction

• The resonance search is the most standard way to find a new particle.

• There are many physics models beyond the Standard Model (SM) that predict new heavy particles decaying into lepton final states:

  Spin-0 scalar (H)
  • Minimal Supersymmetric SM (MSSM)

  Spin-2 excited states of graviton
  • Randall-Sundrum model with a warped extra dimension

  Spin-1 vector (Z’, W’)
  • E6-motivated Grand Unification model
  • Left-Right symmetry models
  • Little Higgs models
  • Models with extra dimensions

• ATLAS experiment took good data for physics analyses of 139 fb\(^{-1}\) with 13 TeV pp colliding energy at LHC during Run2 (2015 ~ 2018).

  New spin-1 vector bosons (W’, Z’) were explored in the ATLAS experiment with a full Run2 dataset. ([arXiv:1906.05609], [arxiv1903.06248])
Benchmark models

- 3 benchmark models were used in this search:

  **Sequential Standard Model (SSM)**
  - \( W'/Z' \) couples to fermions with the same strength as SM \( W/Z \).
  - Couplings to \( W/Z \) are ignored.

  **E6-motivated Grand Unification model**
  - Two \( Z \)'s (\( Z'_\chi \), \( Z'_\psi \)) are predicted.

  **Heavy Vector Triplet (HVT) model**
  - Provides generic framework with couplings of \( W'/Z' \) to fermions and Higgs.

- \( W'/Z' \) can decay into a single/two charged lepton final states.
- No interference effect between \( W'/Z' \) and \( W/Z \) was taken into account.
Signal selection

- A single and two isolated electron(s) or muon(s) with high-$p_T$ were selected as the signal candidates.

- Final discriminants to be fit for the signal extraction:
  - Single charged lepton ($W'$): Transverse mass ($m_T$)
    \[ m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \varphi_{\ell\nu})} \]
  - Two charged leptons ($Z'$): Di-lepton invariant mass ($m_{\ell\ell}$)

- Signal $\text{DY-W}$

- Signal $\text{DY-Z}$
Background estimation

**Single charged lepton final states (W’)**

- DY W, Z/γ*, top pair, single top and diboson were modeled with MC.
- Fake electrons/muons originated from multi-jet production were extracted from data using the matrix method.
- Top-quark, diboson and fake backgrounds were extrapolated to high \( m_T \) by using smoothly falling functions due to short of statistics in MC samples at high \( m_T \).

**Two charged lepton final states (Z’)**

- A functional form fit was used to evaluate the background inclusively for all of DY, top pair, single top, diboson and fakes.
- The fit function was optimized, based on performance studies on a MC background template.
Transverse mass distribution (W’)

- Transverse mass distributions were created after all selection cuts.
- No excess from SM expectation was observed.
- Possible reason of deviation at low $m_T$ is mis-modeling of jet energy resolution and $E_T^{\text{miss}}$ track soft term, but it is covered by uncertainty.

Transverse mass distributions for electron and muon channels
Cross-section limit (W’)

- The cross-section limit was investigated as a function of mass, based on SSM.
- The mass limits were improved significantly from the previous results with 36.1 fb⁻¹.

### 95% CL upper limits on $\sigma \times B$

**ATLAS**

- $\sqrt{s} = 13$ TeV, 139 fb⁻¹
- $W' \rightarrow \ell \nu$
- 95% CL

**36.1 fb⁻¹**

<table>
<thead>
<tr>
<th>Decay</th>
<th>$m_{W'}$, lower limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>$W' \rightarrow e\nu$</td>
<td>5.1</td>
</tr>
<tr>
<td>$W' \rightarrow \mu\nu$</td>
<td>4.7</td>
</tr>
<tr>
<td>$W' \rightarrow \ell\nu$</td>
<td>5.2</td>
</tr>
</tbody>
</table>

**139 fb⁻¹**

<table>
<thead>
<tr>
<th>Decay</th>
<th>$m(W')$ lower limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>$W' \rightarrow e\nu$</td>
<td>6.0</td>
</tr>
<tr>
<td>$W' \rightarrow \mu\nu$</td>
<td>5.1</td>
</tr>
<tr>
<td>$W' \rightarrow \ell\nu$</td>
<td>6.0</td>
</tr>
</tbody>
</table>
Di-lepton mass distribution (Z’)

- Di-lepton invariant mass distributions were created with events after all selection cuts.
- Highest di-lepton mass: 4.06 TeV for $m_{ee}$ and 2.75 TeV for $m_{\mu\mu}$
- The distributions are consistent with the smoothly falling background expectations.

**Di-electron mass distribution**

**Di-muon mass distribution**
Cross-section limit (Z’)

The fiducial cross-section limits was calculated, taking account of only signal peak region in Breit-Wigner shape.

→ Can be supposed as model independent result

95% CL upper limits on fiducial \( \sigma \cdot B \)

### 36.1 fb\(^{-1} \)

<table>
<thead>
<tr>
<th>Model</th>
<th>Lower limits on ( m_{Z'} ) [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( ee )</td>
</tr>
<tr>
<td></td>
<td>obs</td>
</tr>
<tr>
<td>( Z'_\psi )</td>
<td>3.6</td>
</tr>
<tr>
<td>( Z'_\chi )</td>
<td>3.9</td>
</tr>
<tr>
<td>( Z'_{SSM} )</td>
<td>4.3</td>
</tr>
</tbody>
</table>

### 139 fb\(^{-1} \)

<table>
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<tr>
<th>Model</th>
<th>Lower limits on ( m_{Z'} ) [TeV]</th>
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</tr>
<tr>
<td>( Z'_\chi )</td>
<td>4.6</td>
</tr>
<tr>
<td>( Z'_{SSM} )</td>
<td>4.9</td>
</tr>
</tbody>
</table>

\( \Gamma/m = 10, 3, 0\% \)

\( \Gamma/m = 6, 1.2, 0.5\% \)
The constraint on couplings was studied, based on HVT model.

- \((g_f, g_h)\) with \(g_f = g_\ell = g_q\)
- \((g_\ell, g_q)\) with \(g_h = 0\)

\[
\mathcal{L}_{\text{int}}^W = -g_q W^a_\mu \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell W^a_\mu \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left( W^a_\mu H^+ \frac{\sigma_a}{2} iD^\mu H + \text{h.c.} \right)
\]
Comparison with combination analysis (1)

- The constraint on HVT couplings was studied by using 36.1 fb$^{-1}$, combining single/two charged lepton final states and di-boson final states. [arXiv:1808.02380]

- The combination with 36.1 fb$^{-1}$ gives stronger constraint than $Z' \rightarrow \ell\ell$ only result with 139 fb$^{-1}$.

  > $W' \rightarrow \ell\nu$ result gives the strongest constraint.

Addition of $\ell\nu$ results with 139 fb$^{-1}$ and a further combination will provide the strongest limit on the couplings.

Constraint on ($g_f$ v.s. $g_h$)

- $Z' \rightarrow \ell\ell$ only (139 fb$^{-1}$)
- $\ell\nu/\ell\ell$ comb. (36.1 fb$^{-1}$)
- VV/VH/\ell\nu/\ell\ell$ comb. (36.1 fb$^{-1}$)
Comparison with combination analysis (2)

- The constraint on HVT couplings was studied by using 36.1 fb\(^{-1}\), combining single/two charged lepton final states and di-boson final states. [arXiv:1808.02380]
- The combination with 36.1 fb\(^{-1}\) gives stronger constraint than \(Z' \rightarrow \ell\ell\) only result with 139 fb\(^{-1}\).

\(W'\) result gives the strongest constraint.

The combination analysis with a full Run2 dataset (139 fb\(^{-1}\)) is the next important step.
Prospect at HL-LHC

- LHC will be upgraded to High Luminosity LHC (HL-LHC) in ~2026.
- The sensitivity to $W'/Z'$ masses will be improved drastically.
  - 1.5~2 TeV improvements at 3000 fb$^{-1}$ from Run2 with 139 fb$^{-1}$.

The resonance searches with lepton final states are important also at HL-LHC!

<table>
<thead>
<tr>
<th>Decay</th>
<th>Exclusion [TeV]</th>
<th>Discovery [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W'_{SSM} \to e\nu$</td>
<td>6.0</td>
<td>6.4</td>
</tr>
<tr>
<td>$W'_{SSM} \to \mu\nu$</td>
<td>5.5</td>
<td>5.8</td>
</tr>
<tr>
<td>$W'_{SSM} \to \ell\ell$</td>
<td>6.1</td>
<td>6.5</td>
</tr>
</tbody>
</table>

- $Z'_{SSM} \to ee$
  - $\sqrt{s} = 13$ TeV: 6.0, 5.9
  - $\sqrt{s} = 14$ TeV: 6.4, 6.3
  - $\sqrt{s} = 15$ TeV: 6.7, 6.6
- $Z'_{SSM} \to \mu\mu$
  - $\sqrt{s} = 13$ TeV: 5.5, 5.4
  - $\sqrt{s} = 14$ TeV: 5.8, 5.7
  - $\sqrt{s} = 15$ TeV: 6.0, 5.9
- $Z'_{SSM} \to \ell\ell$
  - $\sqrt{s} = 13$ TeV: 6.1, 6.1
  - $\sqrt{s} = 14$ TeV: 6.5, 6.4
  - $\sqrt{s} = 15$ TeV: 6.7, 6.7

- $Z'_{\psi} \to ee$
  - $\sqrt{s} = 13$ TeV: 5.3, 5.3
  - $\sqrt{s} = 14$ TeV: 5.7, 5.6
  - $\sqrt{s} = 15$ TeV: 6.1, 6.0
- $Z'_{\psi} \to \mu\mu$
  - $\sqrt{s} = 13$ TeV: 4.9, 4.6
  - $\sqrt{s} = 14$ TeV: 5.2, 5.0
  - $\sqrt{s} = 15$ TeV: 5.5, 5.2
- $Z'_{\psi} \to \ell\ell$
  - $\sqrt{s} = 13$ TeV: 5.4, 5.4
  - $\sqrt{s} = 14$ TeV: 5.8, 5.7
  - $\sqrt{s} = 15$ TeV: 6.1, 6.1

Expected upper limits on $\sigma \times B$ @ 3000 fb$^{-1}$
Summary and Conclusions

- New resonance searches are powerful probes to explore physics beyond the Standard Model.

- Searches for high mass resonance with lepton final states have been performed in the ATLAS experiment by using a full Run2 dataset (139 fb$^{-1}$).

- No excess from the SM expectation was observed.

- The cross-section and mass limits were improved, compared to the previous analysis results with 36.1 fb$^{-1}$.

- The combination analysis with a full Run2 dataset is the next important step.

- The resonance searches with lepton final states are important also at HL-LHC.
Backup
Estimation of multi-jet backgrounds (W’)

The matrix method is used to estimate backgrounds from fake leptons.

**Measurable quantities**
- T: passes “signal” selection
- L: passes “loose” selection

**Truth quantities**
- R: real leptons
- L: fake leptons

\[
\begin{pmatrix}
N_T \\
N_L
\end{pmatrix}
=egin{pmatrix}
r & f \\
(1 - r) & (1 - f)
\end{pmatrix}
\begin{pmatrix}
N_R \\
N_F
\end{pmatrix}
\] (for W’ analysis)

- r: fraction of real leptons passing signal selection (evaluated with MC W sample)
- f: fraction of fake leptons passing signal selection (evaluated with jet enriched data sample)

\[
N_T^{\text{Multijet}} = f N_F = \frac{f}{r - f} \left( r (N_L + N_T) - N_T \right).
\]
## Systematic uncertainties (W’)

<table>
<thead>
<tr>
<th>Source</th>
<th>Electron channel</th>
<th></th>
<th>Muon channel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Background</td>
<td>Signal</td>
<td>Background</td>
<td>Signal</td>
</tr>
<tr>
<td></td>
<td>$m_T = 2$ (6) TeV</td>
<td>$m_T = 2$ (6) TeV</td>
<td>$m_T = 2$ (6) TeV</td>
<td>$m_T = 2$ (6) TeV</td>
</tr>
<tr>
<td>Trigger</td>
<td>negl. (negl.)</td>
<td>negl. (negl.)</td>
<td>1.1% (1.0%)</td>
<td>1.2% (1.2%)</td>
</tr>
<tr>
<td>Lepton reconstruction and identification</td>
<td>4.1% (1.4%)</td>
<td>4.3% (4.3%)</td>
<td>8.9% (37%)</td>
<td>6.6% (38%)</td>
</tr>
<tr>
<td>Lepton momentum scale and resolution</td>
<td>3.9% (2.7%)</td>
<td>2.7% (4.5%)</td>
<td>12% (47%)</td>
<td>13% (20%)</td>
</tr>
<tr>
<td>$E_T^{miss}$ resolution and scale</td>
<td>&lt;0.5% (&lt;0.5%)</td>
<td>&lt;0.5% (&lt;0.5%)</td>
<td>&lt;0.5% (&lt;0.5%)</td>
<td>&lt;0.5% (&lt;0.5%)</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>&lt;0.5% (&lt;0.5%)</td>
<td>&lt;0.5% (&lt;0.5%)</td>
<td>&lt;0.5% (0.6%)</td>
<td>&lt;0.5% (&lt;0.5%)</td>
</tr>
<tr>
<td>Multijet background</td>
<td>4.4% (420%)</td>
<td>N/A (N/A)</td>
<td>0.8% (1.5%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>Top-quark background</td>
<td>0.8% (1.9%)</td>
<td>N/A (N/A)</td>
<td>0.7% (&lt;0.5%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>Diboson extrapolation</td>
<td>1.5% (47%)</td>
<td>N/A (N/A)</td>
<td>1.3% (9.7%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>PDF choice for DY</td>
<td>1.0% (10%)</td>
<td>N/A (N/A)</td>
<td>&lt;0.5% (1.0%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>PDF variation for DY</td>
<td>8.1% (13%)</td>
<td>N/A (N/A)</td>
<td>7.4% (14%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>EW corrections for DY</td>
<td>4.2% (4.5%)</td>
<td>N/A (N/A)</td>
<td>3.7% (7.0%)</td>
<td>N/A (N/A)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.6% (1.1%)</td>
<td>1.7% (1.7%)</td>
<td>1.7% (1.7%)</td>
<td>1.7% (1.7%)</td>
</tr>
<tr>
<td>Total</td>
<td>12% (430%)</td>
<td>5.4% (6.4%)</td>
<td>17% (62%)</td>
<td>15% (43%)</td>
</tr>
</tbody>
</table>
## Systematic uncertainties (Z’)

<table>
<thead>
<tr>
<th>Uncertainty source for $m_X$ [GeV]</th>
<th>Dielectron 300</th>
<th>Dielectron 5000</th>
<th>Dimuon 300</th>
<th>Dimuon 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spurious signal</td>
<td>±12.5 (12.0)</td>
<td>±0.1 (1.0)</td>
<td>±11.7 (11.0)</td>
<td>±2.1 (2.2)</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>±1.6 (1.6)</td>
<td>±5.6 (5.6)</td>
<td>±1.8 (1.8)</td>
<td>±25 (25) (-20)</td>
</tr>
<tr>
<td>Isolation</td>
<td>±0.3 (0.3)</td>
<td>±1.1 (1.1)</td>
<td>±0.4 (0.4)</td>
<td>±0.4 (0.5)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>-1.7 (+1.0)</td>
<td>+0.1 (±0.8)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electron energy resolution</td>
<td>-8.3 (+1.0)</td>
<td>+0.4 (±0.1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Muon ID resolution</td>
<td>-</td>
<td>-</td>
<td>+0.8 (+0.3)</td>
<td>+0.6 (+0.5)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-2.3 (-0.8)</td>
<td>-0.4 (-0.3)</td>
</tr>
<tr>
<td>Muon MS resolution</td>
<td>-</td>
<td>-</td>
<td>+2.8 (+1.0)</td>
<td>±2.4 (2.1)</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-3.8 (-1.3)</td>
<td>-</td>
</tr>
<tr>
<td>‘Good muon’ requirement</td>
<td>-</td>
<td>-</td>
<td>±0.6 (0.6)</td>
<td>+55 (+55) (-35)</td>
</tr>
</tbody>
</table>
Model-independent cross-section limit (W’)

- The model-independent upper limits of the cross-section were also provided by varying the minimum $m_T$ value ($m_T^{\text{min}}$).
Cross-section limit with different $\Gamma (W')$

- The variation of cross-section limit was checked with different $W'$ mass width.

![Graph showing cross-section limits with different W' masses and their ratio to m(W') as a function of m(W').](image)

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<table>
<thead>
<tr>
<th>$\Gamma(W') / m(W')$</th>
<th>Line Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>Pink</td>
</tr>
<tr>
<td>0.10</td>
<td>Orange</td>
</tr>
<tr>
<td>0.05</td>
<td>Blue</td>
</tr>
<tr>
<td>0.02</td>
<td>Green</td>
</tr>
<tr>
<td>0.01</td>
<td>Red</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$  
$W' \rightarrow l\nu$  
Observed limits at 95% CL  
$m_{\nu} > 0.3 \ m(W')$
Improvement of cross-section limit ($Z'$)

The cross-section limits were improved by higher pp colliding energy at LHC and larger statistics.
Local p-value ($W'$)
Local p-value with different $\Gamma$ ($Z'$)

\[ \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1} \]

\[ \mu\mu \text{ channel} \]
\[ \ell\ell \text{ channel} \]

\[ \Gamma / m = 10\% \]
Di-electron candidate with $m_{ee} = 4.06$ TeV
Di-muon candidate with $m_{ee} = 2.75$ TeV