Search for Higgs boson decays to BSM light bosons in four-lepton events with the ATLAS detector

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\textit{on behalf of the ATLAS Collaboration}
Motivation

- Current measurements allow Higgs to BSM branching ratio to be as large as $\mathcal{O}(30 \text{--} 50\%)$ [1, 2]
- 125 GeV Higgs has a narrow width: $\Gamma_h/m_h \sim \mathcal{O}(10^{-5})$ vs. $\Gamma_Z/m_Z \sim \mathcal{O}(10^{-2})$
  - $\text{Br}(H \rightarrow X_{BSM}X_{BSM}) \propto (\Gamma_{BSM})/(\Gamma_{BSM} + \Gamma_{SM})$
  - Small BSM coupling could open up sizeable decay modes
- New particles could couple to the Higgs and provide a portal to a hidden dark sector or extended Higgs sector
- Addition of U(1) dark gauge symmetry to the SM introduces a new dark vector boson $Z_d$

Curtin et al. [1312.4992, 1412.0018]
Motivation

Curtin et al. [1312.4992]

Hypercharge portal

Region of interest for this search

Kinetic mixing $\epsilon$ controls coupling strength between $Z_d$ and SM particles

Objective: Search for 125 GeV Higgs decays to four leptons ($e, \mu$) via one or two intermediate U(1) dark sector particles $Z_d$
Two channels:

\[ H \rightarrow Z_dZ_d \rightarrow 4\ell \ (15 \text{ GeV} < m_{Z_d} < 60 \text{ GeV}) \]
\[ H \rightarrow ZZ_d \rightarrow 4\ell \ (15 \text{ GeV} < m_{Z_d} < 55 \text{ GeV}) \]

- \( H \rightarrow Z_dZ_d \rightarrow 4\ell \):
  - Look for four prompt leptons that form two same-flavour (e, \(\mu\)) opposite-charge pairs
  - with \(m_{4\ell}\) compatible with 125 GeV Higgs
  - with \(m_{2\ell}\) of both pairs incompatible with Z

- \( H \rightarrow ZZ_d \rightarrow 4\ell \):
  - with one pair compatible with Z (labelled \(m_{12}\))

\[ H \rightarrow Z_dZ_d \rightarrow 4\ell \ m_{\ell\ell} \text{ distribution} \]
(two entries per event corresponding to two lepton pairs in final state)
ATLAS 8 TeV $[1505.07645]$

$H \rightarrow Z_d Z_d \rightarrow 4\ell \ m_{\ell\ell}$ distribution
(two entries per event corresponding to two lepton pairs in final state)

$H \rightarrow Z_d Z_d$ branching ratio limit
8 TeV 20.3 fb\(^{-1}\) analysis: ZZ\(_d\) channel

\(m_H = 125\) GeV

\(H \rightarrow ZZ^* \rightarrow 4\ell\) \(m_{34}\) distribution

(lepton pair second-closest in mass to \(m_Z\))

\(H \rightarrow ZZ_d \rightarrow 4\ell\) branching ratio limit
Expands on 8 TeV analysis with the addition of a low-mass channel and pseudo-scalar benchmark model:

\[ H \rightarrow XX \rightarrow 4\ell \ (15 \text{ GeV} < m_X < 60 \text{ GeV}) \]
\[ H \rightarrow ZX \rightarrow 4\ell \ (15 \text{ GeV} < m_X < 55 \text{ GeV}) \]
\[ H \rightarrow XX \rightarrow 4\mu \ (1 \text{ GeV} < m_X < 15 \text{ GeV}) \]

\[ \ell = e, \mu \quad X = Z_d, a \]

Higgs decay to pseudo-scalars aa (2HDM+S)

\[ H \rightarrow Z_d Z_d \rightarrow 4\ell \]

Distribution of average dilepton mass

\[ \langle m_{\ell \ell} \rangle = (m_{12} + m_{34})/2 \]
13 TeV 36.1 fb$^{-1}$ analysis

- Highly constrained signal region dominated by Higgs and ZZ background
- Simulation-driven background estimates
- Event at $\langle m_{\ell\ell} \rangle \approx 20$ GeV corresponds to a local (global) significance of $3.2 \ (1.9)$ $\sigma$

Distribution of average dilepton mass $\langle m_{\ell\ell} \rangle = (m_{12} + m_{34})/2$
13 TeV 36.1 fb$^{-1}$ branching ratio limits

**$H \rightarrow ZZ_d$**

$\mathcal{O}(10^{-3})$

**Branching ratio limits for**

$H \rightarrow ZZ_d$  $H \rightarrow Z_dZ_d$  $H \rightarrow aa$

**Addition of 4e and 2e2mu states**

$H \rightarrow Z_dZ_d$  $\mathcal{O}(10^{-4})$

**$H \rightarrow aa$**

$\mathcal{O}(10^{-1})$

**quarkonia veto regions**

$\mathcal{O}(10^{-3})$

[1802.0338]
Limit on kinetic mixing parameter $\epsilon$ set using $\text{Br}(H \rightarrow ZZ_d \rightarrow 4\ell)$ (slide 9) and $\text{Br}(Z_d \rightarrow \ell\ell)$ from theory [1312.0018]
Conclusions and current efforts

- Search for 125 GeV Higgs decays to BSM light bosons in four-lepton final states
  - Three channels: $H \rightarrow XX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 60 \text{ GeV}$) \hfill $\ell = e, \mu$
  - $H \rightarrow ZX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 55 \text{ GeV}$) \hfill $X = Z_d, a$
  - $H \rightarrow XX \rightarrow 4\mu$ ($1 \text{ GeV} < m_X < 15 \text{ GeV}$)
  - No statistically significant excesses in 8 TeV (20.1 fb$^{-1}$) and 2015-6 13 TeV (36.1 fb$^{-1}$) results
- Working towards a result encompassing the full 2015-8 dataset (~140 fb$^{-1}$)
- Two new channels:
  - Four tau leptons in final state: $H \rightarrow aa \rightarrow 4\tau$
  - Scalar progenitor ($S < 115 \text{ GeV}$ and $S > 130 \text{ GeV}$): $S \rightarrow Z_dZ_d \rightarrow 4\ell$
- Data-driven fake background estimate
- Search for $Z_d$ of different mass: $H \rightarrow Z_{d1}Z_{d2} \rightarrow 4\ell$
- Possibility of broader $Z_d$ width under consideration
Look for a light resonance in a channel similar to the “golden” channel of the Higgs ($H \rightarrow ZZ^* \rightarrow 4l$)
High-mass analysis selection

Lepton quadruplet formation and selection

- Each lepton must be responsible for firing at least one trigger
- In each event, form quadruplets consisting of two same-flavour opposite sign lepton pairs: “1, 2” & “3, 4”
- Three leading-pT leptons must have pT > 20, 15, and 10 GeV
- $\Delta R(\ell, \ell') > 0.10 \ (0.20)$ for all pairings of same-flavour (different-flavour) leptons; $\Delta R = \sqrt{\Delta(\eta)^2 + \Delta(\phi)^2}$

Quadruplet ranking

- Select quadruplet with smallest difference in mass between lepton pairs: $\Delta m_{\ell\ell} \equiv |m_{12} - m_{34}|$

Event selection

- Higgs window: 115 GeV < $m_{4\ell}$ < 130 GeV
- Compatibility of lepton pair masses: $m_{34}/m_{12} > 0.85$
- Z veto on lepton pairs: 10 GeV < $m_{12,34}$ < 64 GeV
- Additional Z veto on alternative pairings (only for 4e and 4\(\mu\) quadruplets): 5 GeV < $m_{14,32}$ < 75 GeV
- Quarkonia veto: reject event if $m_{J/\Psi} - 0.25 \text{ GeV} < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30 \text{ GeV}) \ || \ (m_{\Upsilon(1S)} - 0.70 \text{ GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75 \text{ GeV})$
Comparison of high-mass, low-mass, and ZX selections

<table>
<thead>
<tr>
<th>QUADRUPLET SELECTION</th>
<th>( H \rightarrow ZX \rightarrow 4\ell ) (15 GeV &lt; ( m_X ) &lt; 55 GeV)</th>
<th>( H \rightarrow XX \rightarrow 4\ell ) (15 GeV &lt; ( m_X ) &lt; 60 GeV)</th>
<th>( H \rightarrow XX \rightarrow 4\mu ) (1 GeV &lt; ( m_X ) &lt; 15 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta R(\ell, \ell') &gt; 0.10 ) (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td>
<td>Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>QUADRUPLET RANKING</td>
<td>Select first surviving quadruplet from channels, in the order: 4( \mu ), 2e2( \mu ), 2( \mu )2e, 4e</td>
<td>Select quadruplet with smallest ( \Delta m_{\ell \ell} =</td>
<td>m_{12} - m_{34}</td>
</tr>
<tr>
<td>EVENT SELECTION</td>
<td>115 GeV &lt; ( m_{4\ell} ) &lt; 130 GeV</td>
<td>120 GeV &lt; ( m_{4\ell} ) &lt; 130 GeV</td>
<td></td>
</tr>
<tr>
<td>( m_{34}/m_{12} &gt; 0.85 ) ( m_{12} )</td>
<td>( (m_{T}/\psi - 0.25 \text{ GeV}) &lt; m_{12,34,14,32} &lt; (m_{\psi(2S)} + 0.30 \text{ GeV}), ) or ( (m_{T(1S)} - 0.70 \text{ GeV}) &lt; m_{12,34,14,32} &lt; (m_{T(3S)} + 0.75 \text{ GeV}) )</td>
<td>10 GeV &lt; ( m_{12,34} &lt; 64 \text{ GeV} ) ( 4e ) and ( 4\mu ) channels: 5 GeV &lt; ( m_{14,32} &lt; 75 \text{ GeV} )</td>
<td>0.88 GeV &lt; ( m_{12,34} &lt; 20 \text{ GeV} ) No restriction on alternative pairing</td>
</tr>
</tbody>
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Background predictions in high-mass analysis

- All background predictions from simulation
- Dominant backgrounds are $H \rightarrow ZZ^*$ and non-resonant $ZZ^*$:
  - $H \rightarrow ZZ^* \rightarrow 4\ell$: 63%
  - $ZZ^* \rightarrow 4\ell$: 19%
  - Triboson production (VVV): 17%
  - $Z + \bar{t}t, J/\Psi, or Y \rightarrow 4\ell$: ~1%
  - Reducible backgrounds ($Z + \text{jets, } \bar{t}t$): ~1%

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
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<tbody>
<tr>
<td>$ZZ^* \rightarrow 4\ell$</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$2.6 \pm 0.3$</td>
</tr>
<tr>
<td>VVV/VBS</td>
<td>$0.51 \pm 0.18$</td>
</tr>
<tr>
<td>$Z + (t\bar{t}/J/\Psi) \rightarrow 4\ell$</td>
<td>$0.004 \pm 0.004$</td>
</tr>
<tr>
<td>Reducible Background</td>
<td>Negligible</td>
</tr>
<tr>
<td>Total</td>
<td>$3.9 \pm 0.3$</td>
</tr>
<tr>
<td>Data</td>
<td>6</td>
</tr>
</tbody>
</table>

(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution

[1802.0338]
Plots from 2015-6 ATLAS result

(a) VR1

(b) VR2

(c) VR3
Figure 4: Distribution of (a) \( \langle m_{\ell\ell} \rangle = \frac{1}{2} (m_{12} + m_{34}) \) and (b) \( m_{34} \) vs \( m_{12} \), for events selected in the \( H \rightarrow XX \rightarrow 4\ell \) (15 < \( m_X \) < 60 GeV) analysis. The example signal distributions in (a) correspond to the expected yield normalized with \( \sigma(pp \rightarrow H \rightarrow ZdZd \rightarrow 4\ell) = \frac{1}{10} \sigma_{SM}(pp \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell) \). The crossed-through points in (b) fail the Z Veto. The events outside the (shaded green) signal region in figure (b) are events that fail the \( m_{34}/m_{12} > 0.85 \) requirement. The diagonal dashed line marks where \( m_{12} = m_{34} \), and in this range of dilepton masses all events will have \( m_{34} < m_{12} \).
Figure 14: The 95% confidence level upper bound on the signal strength $\mu_g = 2 \times \text{BR}(H \rightarrow Z_g Z_g \rightarrow 4\ell)$ of $H \rightarrow Z_g Z_g \rightarrow 4\ell$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

[1505.07645]