Chasing light vector-like leptons from the SM Higgs to ZZ* search

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Work in progress with R. Dermisek, A. Raval
Contents

- SM Higgs discovery and new physics BSM
- Vector-like lepton (VLL) : mixing with SM $\mu$ for $(g-2)_\mu$
- Constraint of light VLL parameters from $h_{SM} \rightarrow ZZ^* \rightarrow 4\ell$
- Conclusions
SM Higgs discovery

SM Higgs-like particle was discovered

- An important quest of the LHC

- Fundamental scalar in the nature!!

- Higgs boson mass: Large quantum correction from UV physics around $\Lambda_{\text{SM}}$
  - Discovery of Higgs: main theoretical motivation of NP BSM at TeV (or $>\ ?$)

- No direct NP signal found: prepare the next LHC running

\[
\begin{align*}
5\sigma & \quad h \to \gamma\gamma \quad h \to ZZ^* \to 4\ell \\
4\sigma & \quad h \to WW \to 2\ell2\nu \quad h \to 2\tau
\end{align*}
\]
Search of BSM signal at the LHC

Top-down approach: From well-motivated models (e.g., SUSY SM scenarios)

- Gauge hierarchy problem & DM candidate: attractive for theorists
- Easy to expect collider signals
  - New particle spectrum and interactions are correlated by model parameters
- Signals are (too much) model dependent: Not easy to apply the LHC null results

Bottom-up approach: Simple extensions of SM (motivated by experiment results)

- Independent parameters: easy to directly apply the LHC results (useful for exp.)
- Hard to combine experimental results (e.g. + DM, B-physics, ..)
- Higgs extensions: 2HDM, .. + $\alpha$  
  Dermisek, Hall, Lunghi, Shin  JHEP 1404, 140 and various talks here
- Matter extensions: DM, new fermions, matter scalars, ..
Vector-like leptons (new matter)

- Mass term arbitrarily set theoretically
- Weak direct bound LEPII
- Contribute to Higgs to VV channel \((h \rightarrow \gamma \gamma)\) ATLAS \(\text{Carena, Low, Wagner JHEP 1208, 060}\)
- No in the Higgs production process
- Raise Higgs mass : MSSM Martin PRD81, 035004 (2010)
- Composite models Bae, Jung, Kim PRD87, 015014 (2013)

<table>
<thead>
<tr>
<th>Minimal</th>
<th>(L_{L,R})</th>
<th>(E_{L,R})</th>
<th>+ SM singlet (DM with (Z_2)) ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SU(2)_{L})</td>
<td>2</td>
<td>1</td>
<td>Joglekar, Schwaller, Wagner JHEP 1212, 064</td>
</tr>
<tr>
<td>(U(1)_Y)</td>
<td>-1/2</td>
<td>-1</td>
<td></td>
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</tbody>
</table>
Vector-like lepton mixing with SM $\ell$

- Decay signals contain SM leptons (Good for collider search)
- Non-standard leptonic SM Higgs decays (Large decay width, LFV decays)
- Precision measurements
  1) Radiative lepton decays (lepton flavour violation)
  2) Electron EDM
  3) Muon anomalous magnetic moment *(motivated in this work)*

- Model dependent issue: how the mixing is realised
  e.g., Yukawa type [Dermisek, Raval PRD88, 013017 (2013)] vector-like [Falkowski, Straub, Vicente, 1312.5329]

Production: EW processes

- Weak direct bounds so far
- DY process: pair production $< O(\text{pb})$ 8TeV

Weak direct bounds so far

- Higgs decay: depends on Br. *(light VLL)*
Vector-like lepton mixing with SM $\mu$

Muon anomalous magnetic moment

Minimally

Large for heavy leptons

Large for light leptons

- Heavy new leptons $\gg M_Z$  
  Kannike, Raidal, Straub, Strumia JHEP 1202, 106

- Light new leptons $\simeq M_Z$  
  Dermisek, Raval PRD88, 013017 (2013)

Correlated with the physical muon mass &

\[ R_{\mu\mu} \equiv \frac{\Gamma(h \rightarrow \mu^+\mu^-)}{\Gamma(h \rightarrow \mu^+\mu^-)_{\text{SM}}} \]
Light Vector-like lepton signal from $h_{SM} \rightarrow ZZ^* \rightarrow 4\ell$

Considering light VLL mixing with SM $\mu$ motivated from $(g-2)_\mu$

$L$: lightest charged vector-like lepton (assume only one lepton is involved)

$\ell = \mu$ or $e$

Contribute to $4\mu$ or $2e2\mu$ final states of $h_{SM} \rightarrow ZZ^* \rightarrow 4\ell$

$\mathcal{L} \supset (g_Z^L \bar{L}_L \gamma^\mu \mu_L + g_Z^R \bar{L}_R \gamma^\mu \mu_R) Z_\mu - \frac{1}{\sqrt{2}} (g_h^L \bar{L}_L \mu_R + g_h^R \bar{L}_R \mu_L) h + \text{h.c.}$,

General parameters (can be effective couplings)
Light Vector-like lepton signal from $h_{\text{SM}} \to ZZ^* \to 4\ell$

5σ discovery $\sigma / \sigma_{\text{SM}} \sim 1$: strong constraint on light VLL

Kinematic topology of VLL contributed process different from SM $h$

- The efficiency of $4\ell$ selection cut (for SM $h$) is different
  - Define kinematic acceptance $\xi = \eta / \eta_{\text{SM}}$ (relative cut eff.)
  - More than two processes in $\xi$ (SM + NP only + interference)
    - depends on masses + couplings (relative $\sigma$)

$\xi$ by MadGraph5 + Pythia6

$m_h = 125$ GeV

$\text{Br}(L^\pm \to Z\mu^\pm) = 1$. 

4μ final state
Light Vector-like lepton signal from \( h_{\text{SM}} \rightarrow ZZ^* \rightarrow 4\ell \)

\[ h_{\text{SM}} \rightarrow ZZ^* \rightarrow 4\ell \]

- 5\( \sigma \) discovery \( \sigma / \sigma_{\text{SM}} \sim 1 \) : strong constraint on light VLL

**Kinematic topology of VLL contributed process different from SM h**

- The efficiency of 4\( \ell \) selection cut (for SM h) is different
  - Define kinematic acceptance \( \xi = \eta / \eta_{\text{SM}} \) (relative cut eff.)
  - More than two processes in \( \xi \) (SM + NPonly + interference)
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\( \xi \) by MadGraph5 + Pythia6

\[ m_h = 125 \text{ GeV} \]

\[ \text{Br}(L^\pm \rightarrow Z\mu^\pm) = 1. \]
Light Vector-like lepton signal from $h_{SM} \rightarrow ZZ^* \rightarrow 4\mu$

Apply modified frequentist construction 95% C.L. exclusion limit $\sigma / \sigma_{SM}$

$$\text{Br}(L^\pm \rightarrow Z\mu^\pm) = 1.$$
Light Vector-like lepton signal from $h_{SM} \to ZZ^* \to 4\mu$

Apply modified frequentist construction 95\% C.L. exclusion limit $\sigma / \sigma_{SM}$

$\text{Br}(L^\pm \to Z\mu^\pm) = 1.$

ATLAS

4\mu final state

$m_h = 125$ GeV

CMS

Lower limit $m_L \sim 120$ GeV for large FV Yukawa couplings $\geq 0.1$
Contours of $\mu = \sigma / \sigma_{\text{SM}}$

- Red line: 95% CLs upper bound
  
  \[ g_2^L = 0.01, \ g_h^R = g_2^R = 0 \]

- VLL $\lesssim 120$ GeV & FV Yukawa $g_h \gg 0.05$ excluded in our ref.: powerful!!! (general param.)

- FCNC coupling $g_z \lesssim 0.01$ from EWP data & $\text{Br}(L \to Z\mu) = 1$ : Results similar

$m_h = 125$ GeV

Br($L^\pm \to Z\mu^\pm$) = 1.
Light Vector-like lepton signal from $h_{\text{SM}} \rightarrow ZZ^* \rightarrow 4\ell$

Still not enough….

- More parameter scan to provide exact bound and contours
- Add analysis on 2e2\(\mu\) final state
  : expect similar contours of $\sigma / \sigma_{\text{SM}}$ and bound 3.02 from ATLAS
- Analyse $h_{\text{SM}} \rightarrow WW^* \rightarrow 2\ell 2\nu$, $\sigma / \sigma_{\text{SM}}$ closer to $\sim 1$
  : stronger bound? Work in progress with R. Dermisek, J. Hall, E. Lunghi
Conclusions

❖ Vector-like leptons at the LHC bottom-up toward NP BSM expecting non-standard phenomena.

❖ Mixing with SM $\mu$, light charged VLL parameters can be constrained from the well-observed SM $h \rightarrow ZZ^* \rightarrow 4\ell$ search. ($4\mu$, 2e2$\mu$)

❖ In terms of general parameters, 95% CL excl. obtained from 7+8 TeV LHC results of 4$\mu$ final state. Powerful!
   (roughly VLL $\lessapprox$ 120 GeV & FV Yukawa $g_h$ $\gg$ 0.05 at our ref. parameters)

❖ More analyses are needed: 2e2$\mu$ and $h_{SM} \rightarrow WW^* \rightarrow 2\ell2\nu$
Back-up

**CMS Preliminary**

**Individual Results**

- $V H \rightarrow b \bar{b}$ arXiv:1310.3687
  - $\mu (m_H = 125.0 \text{ GeV}) = 1.0 \pm 0.5$

- $H \rightarrow \tau \tau$ arXiv:1401.5041
  - $\mu (m_H = 125.0 \text{ GeV}) = 0.78 \pm 0.27$

- $H \rightarrow \gamma \gamma$ HIG-13-001
  - $\mu (m_H = 125.0 \text{ GeV}) = 0.78 \pm 0.27$

- $H \rightarrow WW$ arXiv:1312.1129
  - $\mu (m_H = 125.6 \text{ GeV}) = 0.72 \pm 0.19$

- $H \rightarrow ZZ$ arXiv:1312.5353
  - $\mu (m_H = 125.6 \text{ GeV}) = 0.93 \pm 0.27$

**ATLAS Prelim.**

$m_H = 125.5 \text{ GeV}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mu$ (statistical)</th>
<th>$\mu$ (syst.incl.theo)</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow YY$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$1.55^{+0.33}_{-0.28}$</td>
<td>$-0.04$</td>
<td>$0.09$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow h \nu$</td>
<td>$1.38^{+0.40}_{-0.35}$</td>
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<td>$0.09$</td>
</tr>
<tr>
<td>Combined: $H \rightarrow \gamma \gamma, ZZ^<em>, WW^</em>$</td>
<td>$1.33^{+0.21}_{-0.18}$</td>
<td>$-0.10$</td>
<td>$0.09$</td>
</tr>
</tbody>
</table>

**CMS 1401.5041, background includes $H \rightarrow WW$**
Back-up

Dermisek, Raval PRD88, 013017 (2013)
Back-up

\[ \mu \equiv \sigma / \sigma_{SM} \equiv \xi \sigma^0 / \sigma^0_{SM} < \frac{\ell_{95}}{E_{SM}} \]

\[ \sigma^0 / \sigma^0_{SM} < \frac{\ell_{95}}{\xi \cdot E_{SM}} \]