Signals of vectorlike leptons in a heavy Higgs cascade decay

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R. Dermisek, E. Lunghi, S. Shin, arXiv:1509.04292, Accepted by JHEP
R. Dermisek, E. Lunghi, S. Shin, Work in progress
Contents

❖ Motivations of vectorlike lepton (mix with a SM lepton)
❖ Drell-Yan production of vectorlike leptons : EW gauge interaction
❖ In cascade decays of a Higgs boson : Yukawa interaction
  - SM Higgs exotic decays (VV*-like signals)
  - Heavy BSM Higgs decays
❖ Contributions of heavy Higgs cascade decays mediated by a neutral vectorlike lepton to $\sigma(pp\rightarrow WW)$ measurements
❖ An explicit example : a VLL extension of THDM (type-II)
❖ Conclusions
Why Vectorlike Leptons?

Unification of gauge couplings in a simple non-SUSY model (SM + 3VF)

- A unification with large $\alpha_G$ : infrared fixed point behavior
- Threshold corrections from Vectorlike Fermion masses $< O(100$ TeV)
- Some vectorlike fermions $< 1$ TeV : investigation at the LHC is possible

Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)

\[ \alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \log \frac{M_G}{M_Z} + \alpha_G^{-1} \]

\[ \frac{\alpha_i(M_Z)}{\alpha_j(M_Z)} \approx \frac{b_i}{b_j} \]

\[ \frac{d\alpha_i}{dt} = \beta(\alpha_i) = \frac{\alpha_i^2}{2\pi} b_i \]

\[ b_i = \left( \frac{1}{10} + \frac{4}{3} n_f, -\frac{43}{6} + \frac{4}{3} n_f, -11 + \frac{4}{3} n_f \right) \]

\[ n_f = 3 + 2 \times 3 = 9 \]
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\[
\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \log \frac{M_G}{M_Z} + \alpha_i^{-1} - 1
\]

\[
\alpha_i(M_Z) \sim \frac{b_i}{b_j}
\]

\[
m_{\text{VF}} = 10 \text{ TeV}
\]

\[
\frac{\alpha_i}{\alpha_j} = \frac{\alpha_i^2}{2\pi} b_i
\]

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Left: the RG evolution of gauge couplings, $\alpha_3$ (top), $\alpha_2$ (middle), and $\alpha_1$ (bottom), in the SM extended by three vectorlike families for $\alpha_G = 0.3$ at $M_G = 2 \times 10^{16}$ GeV. Right: the RG evolution of the Higgs quartic coupling for $m_h = 126 \text{ GeV}$, the top Yukawa coupling, and the $\lambda$ with the EW scale value of 0.5. The masses of vectorlike fermions are $M_{d_1} = M_{E_1} = 150 \text{ GeV}$, $M_{E_{23}} = 2.0 \times 10^6 \text{ GeV}$, $M_{E_{23}} = 2.4 \times 10^7 \text{ GeV}$, $M_G = 520 \text{ GeV}$, $M_U = 1.4 \times 10^5 \text{ GeV}$, and $M_D = 2.5 \times 10^3 \text{ GeV}$. 
Why Vectorlike Leptons?

- Unification of gauge couplings in non-SUSY model
  Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)

- A simple framework explaining various anomalies
  - muon g-2 Dermisek, Raval, PRD88, 013017 (2013)
  - $h \rightarrow \gamma \gamma$ Carena, Low, Wagner JHEP 1208, 060

- Acquire masses independently of their Yukawa couplings:
  - Weakly constrained in the absence of mixing with SM leptons
    Direct bounds are only from LEPII

- Decay products are SM leptons: clean signal (diboson-like)

- Phenomenological results are easily convertible to different NP scenarios: electroweakinos (SUSY), triplet fermions (Seesaw)

- Avoid the overclose of the universe in pure bino scenario without resonance or co-annihilation
  (additional annihilation channel without helicity suppression) Abdullah, Feng, arXiv:1510.06089
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Direct search of VLL at the LHC required!
Vectorlike Leptons

Basic structure of our scenario:

- Mixing with the SM muon: inspired from the muon $g-2$
- No mixing with other generations of the SM lepton: to avoid LFV
- Mass eigenstates after mixing (after EW breaking): $e_4, e_5 & \nu_4, \nu_5$

*Dermisek, Raval, PRD88, 013017 (2013)*
Vectorlike Leptons

Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$
Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Correlated with the physical muon mass

\[ \Delta a_{\mu} \approx c \frac{m_{\mu} m_{\mu}^{LE}}{(4\pi v)^2} \approx 0.85c \frac{m_{\mu}^{LE}}{m_{\mu}} \Delta a_{\mu}^{exp}. \]
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$$\Delta a_\mu^{\text{obs}}.$$

$$m_{\mu}^{\text{LE}}/m_{\mu} \simeq -1 \text{ for } M_L \gg M_Z$$

$$y_\mu = -(y_\mu)^{\text{SM}}$$

$\Delta a_\mu \simeq c \frac{m_\mu m_{\mu}^{\text{LE}}}{(4\pi)^2} \simeq 0.85 c \frac{m_{\mu}^{\text{LE}}}{m_\mu} \Delta a_\mu^{\text{exp}}.$
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$$\frac{m_\mu^{LE}/m_\mu}{m_\mu^{LE}/m_\mu} \simeq 1 \quad \text{for } M_L \simeq M_Z$$

$$y_\mu = 3(y_\mu)^{\text{SM}}$$

$$h \to \mu\mu$$ fully from the mixing satisfying $(g-2)_\mu$
Vectorlike Leptons

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- Mixing with the SM muon: inspired from the muon g-2  
  Dermisek, Raval, PRD88, 013017 (2013)
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Flavor changing interactions (SM lepton and VLL):
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- Mixing with the SM muon: inspired from the muon g-2
- No mixing with other generations of the SM lepton: to avoid LFV
- Mass eigenstates after mixing (after EW breaking): $e_4, e_5 \& \nu_4, \nu_5$

Flavor changing interactions (SM lepton and VLL):

Leptons from a gauge boson decay

Diboson-like signals (+ $\ell$’s)
Drell-Yan production of vectorlike leptons

Production of vectorlike leptons in DY processes (gauge interactions)

Multilepton (3+ charged SM leptons) + missing $E_T$:

- Express the results in terms of $\sigma \times$BRs: assume $m_{e4} = m_{\nu_4}$ & $e_4$ is either doublet or singlet $\nu_4$ is only doublet
- Mixing with $e$: expect to give similar results
- Mixing with $\tau$: about an order of magnitude weaker except $\sim 105$ GeV
Analysis pipeline

Event generation

MG5 + Pythia + tauola

Decay W, Z, h & τ
Analysis pipeline

HEP files converted to root files

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Decay W, Z, h & \( \tau \)
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Event generation
MG5 + Pythia + tauola

Decay W, Z, h & \(\tau\)

Homemade root macro

Particle identification
(jets : Fastjet)

Event categorization

Event selection

Event category
- \(\geq 3e/\mu\) on-\(Z\),
- \(2e/\mu+\tau_h\) on-\(Z\),
- \(\geq 3e/\mu\) off-\(Z\),
- \(2e/\mu+\tau_h\) off-\(Z\).

Cuts
- \(H_T\) — the scalar sum of all jets that define the event,
- \(p_T\) — the minimum \(p_T\) of the three leptons,
- \(H_T\) — the magnitude of the vector sum of all jet \(p_T\)s,
- \(m_{\text{eff}}\) — the scalar sum \(E_T + H_T + H_T\),
- \(E_T\) — the missing transverse energy.

ATLAS-CONF-2013-070

on-\(Z\) : OSSF within \(M_Z \pm 20\) GeV
Analysis pipeline

HEP files converted to root files

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Particle identification
(jets: Fastjet)

Event categorization

Event selection
(jets: Fastjet)
on-Z: OSSF within MZ ± 20 GeV

Signal efficiency
Limit from the data

Event category

- ≥3e/μ on-Z,
- 2e/μ+τh on-Z,
- ≥3e/μ off-Z,
- 2e/μ+τh off-Z.

Cuts

- $H_T^l$ — the scalar sum of $p_T$ of the three leptons that define the event,
- $\min p_T^l$ — the minimum $p_T$ of the three leptons,
- $H_T^j$ — the magnitude of the vector sum of all jet $p_T$'s,
- $m_{\text{eff}}$ — the scalar sum $E_T + H_T^l + H_T^j$,
- $E_T$ — the missing transverse energy.

ATLAS-CONF-2013-070

$N_{ijk} = L \sigma_i \epsilon_{ijk} < N_{95}$

$\sigma_i < \frac{N_{95}}{L} \frac{1}{\epsilon_{ijk}}$
Analysis pipeline

HEP files converted to root files

Event generation
MG5 + Pythia + tauola

Decay W, Z, h & τ

Particle identification
(jets : Fastjet)

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Event selection

Signal efficiency
Limit from the data

\[ N_{ijk} = L \sigma_i \epsilon_{ijk} < N_{95} \]

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- ≥3e/μ on-Z,
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Cuts

- \( H_T \) — the scalar sum of \( p_T \)s of the three leptons that define the event,
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- \( m_{\text{eff}} \) — the scalar sum \( E_T + H_T^f + H_T^f \),
- \( E_T \) — the missing transverse energy.

on-Z : OSSF within \( M_Z \pm 20 \text{ GeV} \)

ATLAS-CONF-2013-070

given by ATLAS
Analysis pipeline

Event generation: \( MG5 + Pythia + \tau \text{auola} \)

- Decay \( W, Z, h, \tau \)

Particle identification (jets: \( Fastjet \))
- Event categorization

Event selection

Signal efficiency
- Limit from the data

\[ N_{ijk} = L \sigma_i \epsilon_{ijk} < N_{95} \]

Reasonable analysis: single lepton (or hadronic \( \tau \)) fiducial efficiencies are given

Obtain the results without running a good enough detector simulation

The main strategy is similar for our other analyses

ATLAS-CONF-2013-070

Generalized to any NP test programs
Analysis pipeline

Event generation: MG5 + Pythia + tauola

HEP files converted to root files

Homemade root macro

Particle identification
(jets: Fastjet)

Event categorization

Event selection

Signal efficiency
Limit from the data

\[ N_{ijk} = L \sigma_i \epsilon_{ijk} < N_{95} \]

\[ \sigma_i < \frac{N_{95}}{L} \epsilon_{ijk} \]

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Generalized to any NP test programs

ATLAS-CONF-2013-070
Drell-Yan production of vectorlike leptons

Example of results: best limits

The only limits for the singlet $e_4$

Black: upper bounds
Red: predicted production cross sections of doublets
Blue: predicted production cross sections of singlets
Drell-Yan production of vectorlike leptons

Example of results: best limits
Drell-Yan production of vectorlike leptons

Example of results: best limits

- Some constraints are strong up to 300-500 GeV
- Combine the bounds we obtained
- Below Higgs threshold (125 GeV) the combined bounds are very strong but not completely rule out 105 GeV case
- Our results are also useful to other kind of scenarios with similar processes.
  e.g. electroweakinos, triplet fermion

More detailed results:
Dermisek, Hall, Lunghi, Shin JHEP 1404, 140
Drell-Yan production of vectorlike leptons

Production of vectorlike leptons in DY processes (gauge interactions)

There is one current LHC search on the three leptons resonance: ATLAS arXiv:1506.01291
Single gauge boson production in a Higgs cascade decay

NP contribution to diboson-like signals through Yukawa interactions

Higgs \rightarrow f_1 \rightarrow f_2 \rightarrow f_{1,2} : \text{SM leptons} \rightarrow V \rightarrow f_3 \rightarrow f_4 \rightarrow \text{lepton}

\begin{itemize}
  \item SM Higgs exotic decay producing VV* final states: inv. mass is (or m_T smaller than) 125 GeV
    \begin{align*}
      h_{SM} &\rightarrow e_4 \mu \rightarrow Z \mu \mu \rightarrow 4\ell \\
      h_{SM} &\rightarrow e_4 \mu \rightarrow W \mu \nu_\mu \rightarrow 2\ell 2\nu \quad \text{Dermisek, Raval, Shin, PRD90, 034023 (2014)}
    \end{align*}
  \item Heavy BSM Higgs decays result in diboson-like signals (include \( h_{SM} \) production)
    For pp\rightarrow WW or H \rightarrow WW \quad \text{Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015) & arXiv:1509.04292}
\end{itemize}
Measurements of $\sigma(pp \rightarrow WW)$

Current situation in observing $pp \rightarrow WW$ ($\rightarrow \ell \nu \ell' \nu'$)

- ATLAS at 8 TeV $\mathcal{L} \sim 20.3 \text{ fb}^{-1}$: $2\sigma$ deviation - NLO level SM expectations

\[
\begin{align*}
[\sigma(pp \rightarrow WW) + \sigma(gg \rightarrow h \rightarrow WW^*)]_{\text{exp}} &= 71.4^{+1.2}_{-1.2} \text{(stat)}^{+5.0}_{-4.4} \text{(syst)}^{+2.2}_{-2.1} \text{(lumi)} \text{ pb} \\
[\sigma(pp \rightarrow WW) + \sigma(gg \rightarrow h \rightarrow WW^*)]_{\text{th,NLO}} &= 58.7^{+3.0}_{-2.7} \text{ pb}
\end{align*}
\]

$\Delta \sigma_{\text{ATLAS}} \simeq (13 \pm 6) \text{ pb}$

- Similar deviation in the CMS at 8 TeV $\mathcal{L} \sim 3.5 \text{ fb}^{-1}$

- Signal events are generated at the NLO + parton shower using the MC tools
Measurements of $\sigma(pp\rightarrow WW)$

Current situation in observing $pp\rightarrow WW \rightarrow \ell \nu \ell' \nu'$

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- Similar deviation in the CMS at 8 TeV $\mathcal{L} \sim 3.5$ fb$^{-1}$

- Signal events are generated at the NLO + parton shower using the MC tools

  reweight with resummed $p_T^{WW}$ distribution

- CMS preliminary at 8 TeV $\mathcal{L} \sim 19.4$ fb$^{-1}$

\[
\sigma(pp \rightarrow WW)_{\text{exp}} = 60.1 \pm 0.9(\text{stat}) \pm 3.2(\text{exp}) \pm 3.1(\text{th}) \pm 1.6(\text{lumi}) \text{ pb}
\]

claim its consistency with the recent $\sigma(pp \rightarrow WW)_{\text{th,NNLO}} = 59.84^{+2.2\%}_{-1.9\%} \text{ pb}$ without $H \rightarrow WW$

\[\Delta\sigma_{\text{CMS}} \simeq (0 \pm 5) \text{ pb}\]

still large uncertainty

Gehrmann et al., PRL 113, 212001 (2014)
Measurements of $\sigma(pp\rightarrow WW)$

Extraction of the cross section $\sigma(pp\rightarrow WW)$

- Cross section $\sigma(pp\rightarrow WW) = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot A \cdot \epsilon \cdot \text{BR})$ (data : $\ell\nu\ell'\nu'$)

- What the detector measures : $\sigma^{\text{fid}} = \sigma(pp\rightarrow WW\rightarrow\ell\nu\ell'\nu') \cdot A$

  observations $\iff$ theoretical expectations (MC : NLO + shower)

  $[\sigma^{\text{fid}}]_{\text{exp}} = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot \epsilon) \iff [\sigma^{\text{fid}}]_{\text{th.}} = \sigma(pp\rightarrow WW\rightarrow\ell\nu\ell'\nu') \cdot A_{\text{MC:NLO+shower}}$

  fixed by the observation

purely theoretical calculations

In terms of $\sigma(pp\rightarrow WW)$

$\sigma(pp\rightarrow WW)_{\text{exp}} = [\sigma^{\text{fid}}]_{\text{exp}} / (A_{\text{MC:NLO+shower}} \cdot \text{BR}) \iff \sigma(pp\rightarrow WW)_{\text{th}}$

purely theoretical calculations

fixed by the observation
Measurements of \( \sigma(pp \rightarrow WW) \)

Extraction of the cross section \( \sigma(pp \rightarrow WW) \)

- Cross section \( \sigma(pp \rightarrow WW) = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot A \cdot \epsilon \cdot \text{BR}) \) (data : \( \ell\nu\ell'\nu' \))

- What the detector measures : \( \sigma^{\text{fid}} = \sigma(pp \rightarrow WW \rightarrow \ell\nu\ell'\nu') \cdot A \) observations \( \Leftrightarrow \) theoretical expectations (MC : NLO + shower)

\[
[\sigma^{\text{fid}}]_{\text{exp}} = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot \epsilon) \quad \Leftrightarrow \quad [\sigma^{\text{fid}}]_{\text{th.}} = \sigma(pp \rightarrow WW \rightarrow \ell\nu\ell'\nu') \cdot A_{\text{MC:NLO+shower}}
\]

Explanations of the excess

- New Physics : EW production of NP particles with gauge couplings
  Curtin, Jaiswal, Meade, Tien, JHEP 1308, 068 (2013), Curtin, Meade, Tien, PRD 90, 115012 (2014)
  Rolbiecki, Sakurai, JHEP 1309, 004 (2013), Kim, Rolbiecki, Sakurai, Tattersall, JHEP 1412, 010 (2014), ...

- Jet-veto efficiency : jets vetoed to suppress the top quark backgrounds (main)
  \( \varepsilon_{\text{j-veto}} = \sigma_{\text{jet-vetoed}} / \sigma \quad \Rightarrow \quad \text{change} \ [\sigma^{\text{fid}}]_{\text{th}} \)
Measurements of $\sigma(pp\to WW)$

**Extraction of the cross section $\sigma(pp\to WW)$**

- Cross section $\sigma(pp\to WW) = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot A \cdot \epsilon \cdot \text{BR})$ (data : $\ell\nu\ell'\nu'$)

- What the detector measures : $\sigma_{\text{fid}} = \sigma(pp\to WW\to \ell\nu\ell'\nu') \cdot A$
  
  observations $\iff$ theoretical expectations (MC : NLO + shower)
  
  $[\sigma_{\text{fid}}]_{\text{exp}} = (N_{\text{data}} - N_{\text{bkg}})/(\mathcal{L} \cdot \epsilon) \iff [\sigma_{\text{fid}}]_{\text{th.}} = \sigma(pp\to WW\to \ell\nu\ell'\nu') \cdot A_{\text{MC:NLO+shower}}$

  fixed by the observation  
  purely theoretical calculations

**Explanations of the excess**

- New Physics : EW production of NP particles with gauge couplings

- Jet-veto efficiency : jets vetoed to suppress the top quark backgrounds (main)
  
  $\mathcal{E}_{\text{j-veto}} = \sigma_{\text{jet-vetoed}} / \sigma \Rightarrow \text{change } [\sigma_{\text{fid}}]_{\text{th}}$

- NNLL level $p_T$ resummation of WW or jet-veto
  

- Parton level NLO enhances $\mathcal{E}_{\text{j-veto}}$ but NNL contributions to $\sigma \cdot A$ cancels (NLO is enough)
  
  Monni, Zanderighi, 1410.4745

Still allow some deviations
Measurements of $\sigma(pp \rightarrow WW)$

Our brief summary of $pp \rightarrow WW$

$$\Delta\sigma_{ATLAS} \approx (13 \pm 6)\, \text{pb} \quad \text{or} \quad \Delta\sigma_{CMS} \approx (0 \pm 5)\, \text{pb}$$

- NNLO level MC generators are on their way: better situation in the future
- At face value we take NLO prediction to compare with the ATLAS result
- Experimental uncertainties are at the 5pb level

We can take the current result as being compatible with $O(10)\, \text{pb}$ NP contribution either as an explanation of the excess or a $2\sigma$ upper limit
Heavy BSM Higgs decay to WW-like signal

Large contribution to WW-like signal $pp \rightarrow \ell \nu \ell' \nu'$

- $pp \rightarrow H$ cross section is $O(10)$ pb at 8 TeV
- The new decay mode of H can be large when $m_H < 2m_t$ (practically $m_H < 2m_h$)
- Only one W decaying leptonically: avoiding an extra BR($W \rightarrow \ell \nu \ell'$) suppression

Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015)
Heavy BSM Higgs decay to WW-like signal

Simplified model

\[ H - \nu_4 - \nu_\mu \]
\[ W - \nu_4 - \nu_\mu \]
\[ H - W - W \]

new neutral lepton

Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015)

Large contribution to WW-like signal \( pp \rightarrow \ell \nu \ell' \nu \ell' \)

- \( pp \rightarrow H \) cross section is \( O(10) \)pb at 8TeV
  - Not too heavy \( H \)
- The new decay mode of \( H \) can be large when \( m_H < 2m_t \) (practically \( m_H < 2m_h \))
- Only one \( W \) decaying leptonically: avoiding an extra \( BR(W \rightarrow \ell \nu \ell') \) suppression

We are in an excellent position to explain a significant excess or to place strong constraints in large range of \( (m's, \text{BR's}) \)
Allowed parameter space & constraints from H searches

- For an easy understanding of NP contribution
  - Define an alternative quantity corresponding to $\Delta \sigma(pp\to WW) : O(10)\text{pb}$
    (Our process $H\to W\ell\nu\ell\nu$ has only one $W$)

- Contributions of our process to $H\to WW$ are controlled by the acceptance $H\to WW$

- Contributions of our process to $pp\to \ell\nu\ell'\nu'$ (WW search) are by the acceptance $WW$

The bound by $H\to WW$ on $H\to W\ell\nu\ell\nu \to \ell\nu\ell'\nu'$ weakened : $A_{WW}^W / A_{H\to WW}^W$
Allowed parameter space & constraints from H searches

- Show the allowed contributions of $H \rightarrow W \ell \nu \ell' \nu'$ (possibly excess in the future) in terms of $\sigma_{WW}$, e.g., $e\mu$ channel

- To obtain $H \rightarrow WW$ bound (95% C.L.) we proceed the cut-based analysis considering the cuts in each Higgs mass hypothesis given in the CMS search [CMS, JHEP 1401, 096 (2014)]

$$\text{BR}(H \rightarrow W \ell \nu \ell') \equiv \text{BR}(H \rightarrow \nu_4 \nu_\mu) \text{ BR}(\nu_4 \rightarrow W \mu)$$

general BR: simple rescaling
Kinematic distributions

Taking the recent $\sigma(pp\to WW)$ by ATLAS at face value

Reference: $m_H = 155$ GeV, $m_{\nu_4} = 135$ GeV, BR($H\to W\ell\nu$) = 0.16 ($e\mu$), possibly with additional lepton for ee
THDM with VLL extension

An explicit model: VLL extension in type-II THDM


One of easiest ways

i) Introduce a SM singlet like type-I seesaw

ii) Introduce additional Higgs doublet

Flavor changing couplings (between SM lepton and VLL) can arise because of the mixing between SU(2) doublet & singlet

a heavy Higgs interaction $H - \nu_4 - \nu_\mu$

FC Yukawa
THDM with VLL extension

An explicit model: VLL extension in type-II THDM


<table>
<thead>
<tr>
<th>$\mu_L$</th>
<th>$\mu_R$</th>
<th>$L_{L,R}$</th>
<th>$E_{L,R}$</th>
<th>$N_{L,R}$</th>
<th>$H_d$</th>
<th>$H_u$</th>
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<td>1</td>
<td>1</td>
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<tr>
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</tr>
<tr>
<td>$Z_2$</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Most general renormalizable Lagrangian with these matter contents

$$\mathcal{L} \supset - y_\mu \bar{\mu}_L \mu_R H_d - \lambda_E \bar{E}_L E_R H_d - \lambda_L \bar{L}_L \mu_R H_d - \lambda_L \bar{E}_L E_R H_d - \bar{\lambda}_d \tilde{E}_L L_R$$

$$- \kappa_N \bar{\mu}_L N_L H_u - \kappa \bar{L}_L N_R H_u - \kappa H_u \tilde{N}_L L_R$$

$$- M_L \bar{L}_L L_R - M_E \tilde{E}_L E_R - M_N \tilde{N}_L N_R + \text{h.c.} ,$$

- Heavy CP even Higgs (by $h - 100\%$ SM gauge interaction)
- CP odd Higgs
THDM with VLL extension

An explicit model: VLL extension in type-II THDM


<table>
<thead>
<tr>
<th>SU(2)_L</th>
<th>H-V-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(-\frac{1}{2})</td>
<td>-1</td>
</tr>
<tr>
<td>Z_2</td>
<td>+</td>
</tr>
</tbody>
</table>

Most general renormalizable Lagrangian with these matter contents

\[
\mathcal{L} \supset -y_\mu \bar{\mu}_L \mu_R H_d - \lambda E \bar{\mu}_L E_R H_d - \lambda_l \bar{L}_L \mu_R H_d - \lambda L \bar{L}_L E_R H_d - \lambda H_d^\dagger \bar{E}_L L_R \\
- \kappa_N \bar{\mu}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \kappa H_u^\dagger \bar{N}_L L_R \\
- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + \text{h.c.}
\]

- Heavy CP even Higgs (by h - 100% SM gauge interaction) ✓
- CP odd Higgs
THDM with VLL extension

An explicit model: VLL extension in type-II THDM


Most general renormalizable Lagrangian with these matter contents

\[
\mathcal{L} \supset -y_{\mu} \tilde{\mu}_L \mu_R H_d - \lambda E \tilde{\mu}_L E_R H_d - \lambda L \tilde{L}_L \mu_R H_d - \lambda \tilde{L}_L E_R H_d - \lambda H_d^\dagger \tilde{E}_L L_R \\
- \kappa N \tilde{\mu}_L N_R H_u - \kappa \tilde{L}_L N_R H_u - \kappa H_u^\dagger \tilde{N}_L L_R \\
- M_L \tilde{L}_L L_R - M_E \tilde{E}_L E_R - M_N \tilde{N}_L N_R + \text{h.c.} ,
\]

- Heavy CP even Higgs (by h - 100% SM gauge interaction) ✔
- CP odd Higgs
THDM with VLL extension

An explicit model: VLL extension in type-II THDM


With the given model mixing changes all the SM couplings related with $\nu_\mu$

i) Show the parameter region allowed by

- The EW precision data: Z-pole observables (including inv. Z-width), muon lifetime, $W$ partial width, oblique corrections, neutral current parameters
- Constraints from the DY pair or single production of vectorlike leptons (multi $\ell + E_T$)

Dermisek, Hall, Lunghi, Shin  JHEP 1404, 140

ii) Discuss other processes of VLL contributing to the WW-like signal ($pp \rightarrow \ell e\ell'\nu\nu$): $\sim 1$ pb

- $H \rightarrow e_4\mu \rightarrow W\mu\nu_\mu \rightarrow \ell\ell\ell'\nu\nu$: (few pb)
- $h_{SM} \rightarrow \nu_4\nu_\mu$ or $e_4 \rightarrow W\mu\nu_\mu$
- DY productions (including single $\nu_4$ production)
THDM with VLL extension

Practical parameter scan: allow mixing only in the neutral lepton sector

$pp \rightarrow \nu_4 \nu_4 \rightarrow WW \mu \mu$

<table>
<thead>
<tr>
<th>$m_{\nu_4}$ [GeV]</th>
<th>105</th>
<th>125</th>
<th>150</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[R_{\nu_4\nu_4} \times BR^2(\nu_4 \rightarrow W\mu)]_{\text{max}}$</td>
<td>0.090</td>
<td>0.141</td>
<td>0.141</td>
<td>0.164</td>
<td>0.582</td>
</tr>
<tr>
<td>$[R_{e_4\nu_4} \times BR(\nu_4 \rightarrow W\mu)]_{\text{max}}$</td>
<td>0.109</td>
<td>0.203</td>
<td>0.267</td>
<td>0.355</td>
<td>1</td>
</tr>
</tbody>
</table>
THDM with VLL extension

Practical parameter scan: allow mixing only in the neutral lepton sector

\[ pp \rightarrow \nu_4 e_4 \rightarrow WW \mu \bar{\nu}_\mu \]
THDM with VLL extension

Single production of a neutral VLL

\[ pp \rightarrow W^* \rightarrow \nu_4 \mu \rightarrow W \mu \mu, \ Z \nu_\mu \mu, \ h \nu_\mu \mu \]

\[ R_{\nu_4 \mu} \equiv \left[ (V_L^\dagger)_{42} (U_L)_{22} + (V_L^\dagger)_{44} (U_L)_{42} \right]^2 + \left[ (V_R^\dagger)_{44} (U_R)_{42} \right]^2 \]

The combination of branching ratios the constraint on \( R_{\nu_4 \mu} \) is at most of \( \mathcal{O}(10^{-2}) \). This limit is much weaker than those obtained from precision EW data; in fact, for the surviving points in figure 1 the maximum value of \( R_{\nu_4 \mu} \) is of \( \mathcal{O}(10^{-3}) \).

**Figure 2.** Upper bounds on \( R_{\nu_4 \mu} \times \text{BR}(\nu_4 \rightarrow W \mu, Z \nu_\mu, h \nu_\mu) \) as functions of \( m_{\nu_4} \).
THDM with VLL extension

All EW precision + multilepton search constraints

- Red: SM singlet-like, Blue: SU(2) doublet-like, Yellow: constrained by \( H \rightarrow WW \)
- Contours: effective contributions to \( pp \rightarrow WW \) and \( pp \rightarrow H \rightarrow WW \)
- LHC 13 with 100 fb\(^{-1}\) can test most of the allowed parameter space

\[
\text{BR}(H \rightarrow W\mu\nu_\mu) = \text{BR}(H \rightarrow \nu_4\nu_\mu)\text{BR}(\nu_4 \rightarrow W\mu) \quad \text{both} \quad \nu_4\bar{\nu}_\mu + \bar{\nu}_4\nu_\mu
\]
THDM with VLL extension

All EW precision + multilepton search constraints

- Red: SM singlet-like, Blue: SU(2) doublet-like, Yellow: constrained by $H \rightarrow WW$
- Contours: effective contributions to $pp \rightarrow WW$ and $pp \rightarrow H \rightarrow WW$
- LHC 13 with 100 fb$^{-1}$ can test most of the allowed parameter space

$$\text{BR}(H \rightarrow W\mu\nu_\mu) = \text{BR}(H \rightarrow \nu_4\nu_\mu)\text{BR}(\nu_4 \rightarrow W\mu)$$

both $\nu_4\bar{\nu}_\mu + \bar{\nu}_4\nu_\mu$
THDM with VLL extension

After imposing all EW precision + multilepton search constraints + H→WW

- Large BR(H → ν₄νμ) ≤ 35% is possible (depending on the choice of masses m_H < 2m_h)
- Effects on SM gauge couplings \( g_L^W ν_μ^μ, g_L^Z ν_μ ν_μ < 0.1\% \)
- New flavor changing gauge couplings \( g_{L,R}^W ν_μ^μ, g_L^Z ν_μ ν_μ < O(10^{-2}) \)
- New flavor changing Yukawa couplings < 0.05 (\( λ_H^{ν_4 ν_μ} \)) and 0.17 (\( λ_H^{ν_4 ν_μ} \))
- Constraints from single production of vectorlike leptons (multi ℓ + E_T) are negligible (also applied in TeV scale seesaw models with very small LNV)

All other VLL processes that contribute to the WW-like signal (pp→ℓνℓ′νℓ′) ~ 1 pb

- H → e₄μ → Wμ ν_μ → ℓνℓ′νℓ′ (few pb)
- h_{SM} → ν_4 ν_μ or e₄μ → Wμ ν_μ
- DY productions (including single ν₄ production)

\[
\begin{align*}
    pp &\rightarrow (γ, Z) \rightarrow e_4^± e_4^{±} \rightarrow W^± W^{±} ν_μ ν_μ \rightarrow 2ℓ4ν, \\
    pp &\rightarrow Z \rightarrow ν_4 ν_μ \rightarrow Wμ ν_μ \rightarrow ℓμ2ν .
\end{align*}
\]
THDM with VLL extension

$H \rightarrow \gamma \gamma$ only through top Yukawa

Suppressed compared to the SM-like Higgs (dominated by WW loop + interference with t)

Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015)

CMS-PAS-HIG-14-006

model independent search
THDM with VLL extension

H → γγ only through top Yukawa

Suppressed compared to the SM-like Higgs (dominated by WW loop + interference with t)

enhanced by cotβ in type-II THDM !!!

Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015)

CMS-PAS-HIG-14-006
THDM with VLL extension

All EW precision + multilepton search constraints

$H \rightarrow \gamma \gamma$
THDM with VLL extension

All EW precision + multilepton search constraints

H → γγ

Dermisek, Lunghi, Shin, work in progress

Inclusion of the charged vectorlike leptons (heavier than ν4 & no mixing with μ)

\[ \Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha^2_{EM} m_h^3}{128 \sqrt{2} \pi^3} \left| - \frac{4}{3} \cot \beta A_{1/2}(\tau^H_t) + v \left\{ \frac{\lambda^{H}_{e_4e_4}}{m_{e_4}} A_{1/2}(\tau^H_{e_4}) + \frac{\lambda^{H}_{e_5e_5}}{m_{e_5}} A_{1/2}(\tau^H_{e_5}) \right\} \right|^2 \]
**THDM with VLL extension**

All EW precision + multilepton search constraints

\[ H \rightarrow \gamma \gamma \]

Dermisek, Lunghi, Shin, work in progress

Inclusion of the charged vectorlike leptons (heavier than \( \nu_4 \) & no mixing with \( \mu \))
THDM with VLL extension

All EW precision + multilepton search constraints

Inclusion of the charged vectorlike leptons (heavier than $\nu_4$ & no mixing with $\mu$)

Dermisek, Lunghi, Shin, work in progress

\[ \Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2_{\text{EM}} m_h^3}{128 \sqrt{2} \pi^3} \left| -\frac{4}{3} \cot \beta A_{1/2}(\tau^H_t) + v \left\{ \frac{\lambda^H_{e_4e_4}}{m_{e_4}} A_{1/2}(\tau^H_{e_4}) + \frac{\lambda^H_{e_5e_5}}{m_{e_5}} A_{1/2}(\tau^H_{e_5}) \right\} \right|^2 \]
THDM with VLL extension

All EW precision + multilepton search constraints

\[ + H \rightarrow WW + H \rightarrow \gamma\gamma \]

\[ m_H < 2m_t \]

Dermisek, Lunghi, Shin, work in progress
More search on Higgs cascade decays

Additional heavy Higgs cascade decays are possible: WW, ZZ, Zh like signals (correlated)

Dermisek, Lunghi, Shin, Work in progress

Several interesting signals

- jj$\mu + \mathcal{E}_T$
- Monojet or Mono-Z
- $\mathcal{E}_T + \gamma\gamma$
- $\mathcal{E}_T + bb$
- High multiplicity lepton: 6
More search on Higgs cascade decays

Additional heavy Higgs cascade decays are possible: WW, ZZ, Zh like signals (correlated)

Dermisek, Lunghi, Shin, Work in progress

Several interesting signals
- \( jj\mu + \slashed{E}_T \)
- Monojet or Mono-Z
- \( \slashed{E}_T + \gamma\gamma \)
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Dermisek, Lunghi, Shin, Work in progress

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Additional heavy Higgs cascade decays are possible: $WW, ZZ, Zh$ like signals (correlated)

Dermisek, Lunghi, Shin, Work in progress

Several interesting signals

- $jj\mu + E_T$
- Monojet or Mono-Z
- $E_T + \gamma\gamma$
- $E_T + bb$
- High multiplicity lepton: 6

Apparently unrelated experimental searches can be connected
More search on Higgs cascade decays

Connection with
Mahbubani, Matchev, Park, 1212.1720

Dermisek, Lunghi, Shin, Work in progress

dileptonic channel
$M_{T2}$ can be used for discovery
More search on Higgs cascade decays

Connection with

Dermisek, Lunghi, Shin, Work in progress

Mahbubani, Matchev, Park, 1212.1720

dileptonic channel
More search on Higgs cascade decays

Connection with

Dermisek, Lunghi, Shin, Work in progress

Mahbubani, Matchev, Park, 1212.1720

ν
ν
ν
ν
W resonance

Dileptonic channel

Cho, Kim, Matchev, Park, 1206.1546
Conclusions

- Extra vectorlike leptons that mix with a SM lepton (with flavor violating Yukawa and gauge couplings).

- Possibly large contributions to diboson-like signals in DY production of VLL with flavor changing gauge interactions or in cascade decays of a Higgs boson with flavor changing Yukawa interactions.

- The cascade decay of a heavy BSM Higgs $H \rightarrow \nu_4 \nu_\mu \rightarrow W \mu \nu_\mu$ can contribute to the measurement of $\sigma(pp\rightarrow WW)$; it nicely fits the nominal excess claimed by ATLAS.

- Explicit model: a VLL extension of type-II THDM
  - Constraints from EW precision & multilepton + $E_T$ (DY production)
    - Large effective contribution to $pp\rightarrow WW$ or $pp\rightarrow H \rightarrow WW$ with small tan$\beta$

- Additional cascade decays produce signals like $WW$, $ZZ$, $Zh$: produce interesting mono-jet, mono-Z, mono-h, …. signals depending on the decay modes
\[ b_i = \left( \frac{1}{10} + \frac{4}{3} n_f, -\frac{43}{6} + \frac{4}{3} n_f, -11 + \frac{4}{3} n_f \right), \quad (2) \]

where \( n_f \) is the number of families. For \( n_f = 3 \) we get the usual result, \( b_i = (41/10, -19/6, -7) \), while with extra 3VF, \( n_f = 3 + 2 \times 3 = 9 \) (a vector-like partner contributes in the same way), we find \( b_i = (121/10, 29/6, +1) \). Thus in the SM + 3VF all three couplings are asymptotically divergent.

\[
\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha_G^{-1} - T_i, \quad (3)
\]

where \( T_i \) are the threshold corrections that depend on masses of the extra vector-like fermions. They can be approximated by the leading logarithmic corrections:

\[
T_i \simeq \frac{1}{2\pi} \sum_f b_i^f \ln \frac{M_f}{M_Z}, \quad (4)
\]
Contribution to the muon mass by the mixing

\[ m^{LE}_\mu \]

\[ m^{LE}_\mu / m_\mu \approx -1 \quad \text{for } M_L \gg M_Z \]

h-loop contribution in muon g-2

\[ h\rightarrow\mu\mu \ (\text{-3}) \text{ from the mixing} \]

\[ m^{LE}_\mu / m_\mu \approx 1 \quad \text{for } M_L \sim M_Z \]

W-loop contribution in muon g-2

\[ h\rightarrow\mu\mu \text{ fully from the mixing} \]
Contribution to the muon mass by the mixing

\[ \frac{m_\mu^{LE}}{m_\mu} \sim -1 \text{ for } M_L \gg M_Z \]

W-loop contribution in muon g-2

\[ \frac{m_\mu^{LE}}{m_\mu} \sim 1 \text{ for } M_L \sim M_Z \]

h-loop contribution in muon g-2

\[ m_\mu^{LE} / m_\mu \sim 1 \text{ for } M_L \sim M_Z \]

h→µµ twice from the mixing

h→µµ fully from the mixing

\[ \delta a^h_\mu = -\frac{m_\mu}{32\pi^2 M_h^2} \sum_{h=1}^{1} \left[ (|\lambda_{\mu e_\mu}|^2 + |\lambda_{e_\mu,\mu}|^2) m_\mu F_h(x_{hb}) + \text{Re}(\lambda_{\mu e_\mu,\lambda_{e_\mu,\mu}}) m_e G_h(x_{hb}) \right] \quad (29) \]

where \( x_{hb} = (m_e / M_h)^2 \), the couplings are given in Eq. (26) with index \( \mu = e_2 \), and the loop functions are as follows:

\[ F_h(x) = -\frac{x^3 - 6x^2 + 3x + 6x \ln(x) + 2}{6(1-x)^3} \quad (30) \]

\[ G_h(x) = \frac{x^2 - 4x + 2 \ln(x) + 3}{(1-x)^3} \quad (31) \]

The contribution from the Z diagram is given by

\[ \delta a^Z_\mu = -\frac{m_\mu}{8\pi^2 M_Z^2} \sum_{h=1}^{1} \left[ (|s_L^{\mu e_{\mu}}|^2 + |s_{R_{\mu e_{\mu}}}|^2) m_\mu F_Z(x_{Zb}) + \text{Re}(s_L^{\mu e_{\mu}, s_{R_{\mu e_{\mu}}}}) m_e G_Z(x_{Zb}) \right] \quad (32) \]

where \( x_{Zb} = (m_e / M_Z)^2 \), the couplings are given in Eqs. (12) and (13) with index \( \mu = e_2 \), and the loop functions are as follows:
Back-up
we also implement a five-lepton cut that simply requires that there are five reconstructed electrons and muons.

Let \( n \) be the observed number of events that we will set to zero and let \( \mu \) be the expected number of events

\[
\mu = L(\sigma_b \epsilon_b + \sigma_i \epsilon_i),
\]

(3.3)

where \( \sigma_b \epsilon_b \) is the expected background cross-section times the background efficiency and \( \sigma_i \epsilon_i \) is the cross-section we want to place a limit on times its efficiency for the five-lepton cut; \( L \) is the integrated luminosity. To get sensible 95\% C.L. limits the question to ask is what is the cross-section \( \sigma_i \) such that \([43]\)

\[
0.05 = \frac{p(n|\sigma_i)}{p(n|\sigma_i = 0)}. 
\]

(3.4)

Here the likelihoods \( p \) are given by the Poisson distribution \( \mathcal{P} \)

\[
p(n|\sigma_i) = \mathcal{P}(n|\mu) = \frac{\mu^n e^{-\mu}}{n!}.
\]

(3.5)

Rearranging and setting \( n = 0 \) yields

\[
0.05 = e^{-L \sigma_i \epsilon_i} \quad \Rightarrow \quad \sigma_i = \frac{-\ln(0.05)}{L \epsilon_i},
\]

(3.6)

where \(- \ln(0.05) = 3.00\). Note that this limit is independent of the expected background \( \sigma_b \) as long as \( n = 0 \). All we need to know is the efficiency \( \epsilon_i \) and the integrated luminosity \( L \).
Single gauge boson production in a Higgs cascade decay

- SM Higgs exotic decay producing VV\* final states: inv. mass is (or m_T smaller than) 125 GeV
  \[ h_{\text{SM}} \rightarrow e_4 \mu \rightarrow Z \mu \mu \rightarrow 4\ell \]
  \[ h_{\text{SM}} \rightarrow e_4 \mu \rightarrow W \mu \nu_\mu \rightarrow 2\ell 2\nu \]
  Dermisek, Raval, Shin, PRD90, 034023 (2014)

- Heavy BSM Higgs decays result in diboson-like signals (include h_{\text{SM}} production)
  For pp\rightarrow WW (\rightarrow \ell\nu\ell'\nu')
Single gauge boson production in a Higgs cascade decay

NP contribution to diboson-like signals through Yukawa interactions

SM Higgs exotic decay producing $VV^*$ final states: inv. mass is (or $m_T$ smaller than) 125 GeV

$\mathcal{h}_{SM} \to e_4 \mu \to Z \mu \mu \to 4\ell$

$\mathcal{h}_{SM} \to e_4 \mu \to W \mu \nu \mu \to 2\ell 2\nu$

Heavy BSM Higgs decays result in diboson-like signals (include $h_{SM}$ production)

For $pp \to WW \to \ell^+\ell^-\nu\ell'\nu'$

Dermisek, Raval, Shin, PRD90, 034023 (2014)

SM exotic decay to a charged vectorlike lepton

Golden channel

\[ e_4^\pm : \text{lightest charged vectorlike lepton} \]
\[ Z \rightarrow \mu \text{ or } e \text{ pair} \]

Contribute to \(4\mu\) or \(2e2\mu\) final states of

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

Considering the mixing in the charged lepton sector

- The EW precision data : Z-pole observables, \(\tau_\mu, \Gamma_W\rightarrow\nu\), oblique corrections
- \(h \rightarrow \mu\mu\) from the CMS : CMS-PAS-HIG-13-007
- Also show the parameters explaining the muon g-2 anomaly
SM exotic decay to a charged vectorlike lepton

Dermisek, Raval, Shin, PRD90, 034023 (2014)

Golden channel

\[ h \rightarrow e^+_4, \mu^-, \nu_\mu, W^\pm \]

- \( e_4 \): lightest charged vectorlike lepton
- \( Z \rightarrow \mu \) or e pair

Contribute to 4\( \mu \) or 2e2\( \mu \) final states of

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

2\( \mu \)2\( \nu \) or \( \mu e2\nu \) final states of

\[ h_{\text{SM}} \rightarrow WW^* \rightarrow 2\ell 2\nu \]

Considering the mixing in the charged lepton sector

- The EW precision data: Z-pole observables, \( \tau_\mu \), \( \Gamma_{W\rightarrow\mu\nu} \), oblique corrections
- \( h \rightarrow \mu\mu \) from the CMS: CMS-PAS-HIG-13-007
- Also show the parameters explaining the muon g-2 anomaly
SM exotic decay to a charged vectorlike lepton

e.g., $h_{SM} \to ZZ^* \to 4\mu$

- All the points (including the light shaded points) satisfy the EW and $h \to \mu\mu$
- $m_{e4} > 116$ GeV explaining muon g-2 within $1\sigma$
- Our contributions are larger for $h_{SM} \to Z\mu\mu$ because $\text{BR}(h_{SM} \to ZZ^*)$ is small
Light Vector-like lepton signal from $h_{SM} \rightarrow ZZ^* \rightarrow 4\ell$

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

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

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

$\xi$ by MadGraph5 + Pythia

$m_h = 125$ GeV

$\text{BR}(e4 \rightarrow Z) = 1$
Light Vector-like lepton signal from $h_{SM} \rightarrow ZZ^* \rightarrow 4\ell$

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

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

- The efficiency of $4\ell$ selection cut (for SM $h$) is different
  - Define kinematic acceptance $\xi = \eta / \eta_{SM}$ (relative cut eff.)

NP + SM: $h \rightarrow 4\mu$ (2e2$\mu$)

- More than two processes in $\xi$ (SM + NP only + interference)
  - depends on masses + couplings (relative $\sigma$)

$\xi$ by MadGraph5 + Pythia

$m_h = 125$ GeV

$BR(e4 \rightarrow Z) = 1$
SM exotic decay to a charged vectorlike lepton

- All the points (including the light shaded points) satisfy the EW and $h \rightarrow \mu\mu$
- Contours are the relative ratio of decay rates (Red: 95% upper limit in the ATLAS search)
- Bounds from the SM Higgs search is strong for $m_{e_4} \lesssim 118$ GeV (phase space)
- However there are still allowed parameters for $m_{e_4} \lesssim 118$ GeV explaining muon $g-2$ within $1\sigma$
POWHEG : NLO + Pythia : shower

GG2WW

ATLAS

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section [pb]</th>
<th>Scale $[\text{pb}]$</th>
<th>PDF+$\alpha_s$ $[\text{pb}]$</th>
<th>Branching fraction [pb]</th>
<th>Calculation</th>
<th>Total [pb]</th>
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<tbody>
<tr>
<td>$q\bar{q} \rightarrow WW$</td>
<td>53.2</td>
<td>$+^{2.3}_{-1.9}$</td>
<td>$+^{1.0}_{-1.1}$</td>
<td>-</td>
<td>NLO MCFM [1]</td>
<td>$^{+2.5}_{-2.2}$</td>
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<tr>
<td>$gg \rightarrow WW$</td>
<td>1.4</td>
<td>$+^{0.3}_{-0.2}$</td>
<td>$+^{0.1}_{-0.1}$</td>
<td>-</td>
<td>LO MCFM [1]</td>
<td>$^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>$gg \rightarrow H \rightarrow WW$</td>
<td>4.1</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.2$</td>
<td>NNLO+NNLL QCD, NLO EW [3]</td>
<td>$^{\pm 0.5}$</td>
</tr>
</tbody>
</table>
Event generation: MG5 + Pythia6 (parton shower) from our model (FeynRules)

The resulting StdHEP file ⇒ ROOT format by Delphes

Jet clustering: handled by FastJet (∆R = 0.4 for our signal)
The dominant constraint on $\sigma_{\text{NP}}^{\text{fid}}$ comes from the $H \to WW$ CMS search presented in refs. [25, 26] where a number of different cuts, each optimized to be sensitive to a SM-like heavy Higgs of a given mass, are considered. For each cut (that we label $\mathcal{H}$) CMS, effectively, places a 95% C.L. upper limit on a fiducial cross section:

$$\sigma_{\mathcal{H}}^{\text{fid}} = A_{\text{NP}}^{\mathcal{H}} \sigma_{\text{NP}}^{\mathcal{H}} < \beta_{95}^{\mathcal{H}},$$

(3.1)

where $\sigma_{\text{NP}}$ is the same total cross section (including branching ratios) that appears in eq. (2.3) and $A_{\text{NP}}^{\mathcal{H}}$ is the acceptance for the cut selection $\mathcal{H}$. Since CMS does not present the results of the analysis in terms of fiducial cross sections, the extraction of these upper limits is not straightforward. We list in table 2 the $\beta_{95}^{\mathcal{H}}$ that we obtain and relegate the technical details to appendix A. In the table we consider six CMS analyses (labelled by the value $\hat{m}_H$ of the Higgs mass for which each analysis is optimized) and present separately the $e\mu$ and $\mu\mu$ channels. The implied upper limit on the fiducial cross section (2.3) is then

$$\sigma_{\text{NP}}^{\text{fid}} < A_{\text{NP}} \min_{\mathcal{H}} \left[ \frac{\beta_{95}^{\mathcal{H}}}{A_{\text{NP}}^{\mathcal{H}}} \right].$$

(3.2)

<table>
<thead>
<tr>
<th>$\hat{m}_H$ [GeV]</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>160</th>
<th>200</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>5.1 fb</td>
<td>4.8 fb</td>
<td>4.9 fb</td>
<td>3.3 fb</td>
<td>9.7 fb</td>
<td>3.7 fb</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>5.6 fb</td>
<td>5.8 fb</td>
<td>4.5 fb</td>
<td>3.6 fb</td>
<td>6.3 fb</td>
<td>4.0 fb</td>
</tr>
</tbody>
</table>

Table 2. The quantities $\beta_{95}^{\mathcal{H}}$ for the $e\mu$, ee and $\mu\mu$ channels and for each of the six CMS analyses that we consider (labelled by their $\hat{m}_H$ value).
$pp \rightarrow H \rightarrow \nu_4 \nu_\mu \rightarrow W\mu\nu_\mu \rightarrow \ell\nu_\ell\mu\nu_\mu$

$pp \rightarrow H \rightarrow \nu_5 \nu_e \rightarrow We\nu_e \rightarrow \ell\nu_\ell\nu_\ell\nu_e$

$$\text{BR}(H \rightarrow W\ell\nu_\ell) \equiv \text{BR}(H \rightarrow \nu_4 \nu_\mu) \cdot \text{BR}(\nu_4 \rightarrow W\mu) + \text{BR}(H \rightarrow \nu_5 \nu_e) \cdot \text{BR}(\nu_5 \rightarrow We)$$
We first set $\ell = \mu$ contributing to $e\mu\nu_e\nu_\mu$ and $\mu\mu\nu_\mu\nu_\mu$ final states
- NP mostly affect the statistically dominant $e\mu$ channel
- In order to contribute to $ee$ mode as well, if desirable, additional neutral lepton

This scenario can arise, e.g., 2HDM with vectorlike leptons


Simplified model $\Rightarrow$ present the results simply with $m_H, m_{\nu_4}, BR(H \to W\ell\nu_\ell)$

$$BR(H \to W\ell\nu_\ell) \equiv BR(H \to \nu_4\nu_\mu) \cdot BR(\nu_4 \to W\mu)$$
**Allowed parameter space & constraints from H searches**

- ATLAS results are presented in terms of $\sigma_{\text{fid}}$
  - Our analysis done in terms of $\sigma_{\text{fid}}$ without detailed detector simulation

- For an easy understanding of NP contribution
  - Define an alternative quantity corresponding to $\Delta\sigma(p p \rightarrow W W)$: $O(10)\text{pb}$
    (Our process $H \rightarrow W \ell \nu \ell$ has only one $W$)

- Even without direct coupling $H - WW$, constraints from $H \rightarrow WW, \gamma\gamma$ should be considered (due to the Yukawa couplings of $H$ in our simplified model)
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- Even without direct coupling $H - WW$, constraints from $H\to WW, \gamma\gamma$ should be considered (due to the Yukawa couplings of $H$ in our simplified model)

$H\to \gamma\gamma$ only through top Yukawa

Suppressed compared to the SM-like Higgs (dominated by $WW$ loop + interference with $t$)
Back-up

- Check the contributions of our process $H \rightarrow W\ell\nu \rightarrow \ell\nu\ell'\nu\ell$ to the kinematic variables (following the ATLAS result)
  - $p_T$ of leading and subleading leptons
  - $p_T$, azimuthal angle, invariant mass of $\ell\ell$
  - $p_T, m_T$ of $\ell\ell' + \nu\nu\ell$ (WW)

- Reference parameter: $m_H = 155$ GeV, $m_{\nu_4} = 135$ GeV, BR($H \rightarrow W\ell\nu\ell$) = 0.16 (e$\mu$)
  - $N_{events} \sim 90\%$ of the central excess observed by the ATLAS

Representative plots
Representative plots (crucial for the choice of our reference parameter)
Back-up

Representative plots (crucial for the choice of our reference parameter)

parent particle mass $m_H$

$\ell\ell$ come from $\nu_4 : m_{\nu_4}$
Back-up

The rest of the results are in the paper

- The contributions by $H \rightarrow W\ell\nu_e \rightarrow \ell\nu\ell'\nu_e$ agree well with the data (with proper parameter)
- Better fitting in $m_T$: more complex scenarios, e.g., $h_{SM} \rightarrow W\ell\nu_e$ with larger $m_H$
Back-up

Alternative contributions (small) in $pp \rightarrow \ell \nu \ell' \nu'$:

- $pp \rightarrow H \rightarrow \nu_4 \nu_{\tau} \rightarrow W \nu_{\tau} \rightarrow \ell \nu \ell' \nu_{\mu} \mu$ with leptonic decay of $\tau \rightarrow \ell \nu \ell' \nu_{\tau}$.

\[ \sim 5 \text{ time suppression in } \sigma_{\text{fid}} \]

additional missing $E$: lower $p_T$ of $\ell$ lowers $A$

Our scenarios can be also connected with the neutrino mass generations e.g., TeV seesaw models Bhupal Dev, Franceschini, Mohapatra, PRD 86, 093010 (2012)
\( pp \rightarrow Z \rightarrow e_4^\pm e_4^\mp \rightarrow W^\pm W^\mp \nu_\mu \bar{\nu}_\mu \rightarrow 2\ell 4\nu \)

\( pp \rightarrow Z \rightarrow \nu_4 \nu_\mu \rightarrow W \mu \nu_\mu \rightarrow \ell \mu 2\nu \)

**Figure 13.** The effective cross section \( \sigma_{NP}^{WW} \) [pb] for Drell-Yan processes. In the left panel we consider the channel \( pp \rightarrow (\gamma, Z) \rightarrow e_4^\pm e_4^\mp \rightarrow W^\pm W^\mp \nu_\mu \bar{\nu}_\mu \rightarrow 2\ell 4\nu \) assuming SM-like strength of the \( Z - e_4 - e_4 \) vertex, \( \text{BR}(e_4 \rightarrow W \nu_\mu) = 1 \) and \( m_{e_4} = 105 - 250 \text{ GeV} \). In the right panel we show \( pp \rightarrow Z \rightarrow \nu_4 \nu_\mu \rightarrow W \mu \nu_\mu \rightarrow \ell \mu 2\nu \) for \( R_{\nu_4 \nu_\mu} \cdot \text{BR}(\nu_4 \rightarrow W \mu) = 10^{-3} \) and \( m_{\nu_4} = 95 - 250 \text{ GeV} \).

\[
R_{e_4 e_4} \equiv \frac{(g_L^2 e_4 e_4) + (g_R^2 e_4 e_4)^2}{2(g/cos \theta_W)^2(1/2 - sin^2 \theta_W)^2} ,
\]

\[
R_{\nu_4 \nu_\mu} \equiv \frac{(g_L^2 \nu_4 \nu_\mu)^2}{g^2/4 cos^2 \theta_W}.
\]

**Figure 12.** Allowed values of \( R_{\nu_4 \nu_\mu} \) and \( g_R^2 \nu_4 \nu_\mu \) for \( m_{\nu_4} = 110 \text{ GeV} \). We see that \( R_{\nu_4 \nu_\mu} \lesssim 1.5 \times 10^{-3} \) and \( |g_R^2 \nu_4 \nu_\mu| \lesssim 0.02 \). Similar bounds are found for different \( \nu_4 \) masses.
Heavy Higgs decay to pair of $e_4$ or $\nu_4$ can produce $WW$, $WZ$, $ZZ$

- phase space suppressed for $m_H < 340$ GeV but still large for very heavy $H$
- Increase of production $pp \rightarrow H$ required: e.g. vectorlike quarks
m_H = 330 GeV, m_{\nu_4} = 140 GeV