Vectorlike lepton in Higgs cascade decays:
Episode I - The Three Resonances

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R. Dermisek, E. Lunghi, S. Shin, arXiv:1512.07837, Accepted by JHEP
Why Vectorlike Leptons?

- Unification of gauge couplings in non-SUSY models (SM + 3VF)
  Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)

- Simple framework explaining various anomalies
  (Acquire masses independently of their Yukawa couplings)
  
  - muon g-2 (VLL mixing with $\mu$)
    Dermisek, Raval, PRD88, 013017 (2013)

  - For charged fermion, $h \rightarrow \gamma \gamma$ or $X \rightarrow \gamma \gamma$ (750 GeV ?)

- Raise Higgs mass in SUSY models

- Pure bino LSP scenario with right relic without resonance or co-ann.
  (new ann. channel without helicity suppression)
  Abdullah, Feng, Phys. Rev. D 93, 015006 (2016)
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Direct search at the LHC is required!
Direct search at the LHC needed

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forbid mixing with the SM leptons?
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forbid mixing with the SM leptons?

Direct search classified by the production channels of VLL

- Gauge interaction: Drell-Yan process
- Yukawa interaction: Higgs (or BSM scalar) decay
Direct search at the LHC needed

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forbid mixing with the SM leptons?

My setup

- Scenario of VLL mixing with SM lepton: here, $\mu$ from muon g-2
- $\mu, \nu_\mu$ gauge/Yukawa couplings modified & off-diagonal couplings $(\mu, \nu_\mu)$-$(e_4, \nu_4)$
- Approximate muon number on VLL: to avoid huge LFV
Productions of VLL: Drell-Yan (pair)

\[ e_4 : \text{charged} \]
\[ \nu_4 : \text{neutral} \]

Multilepton (3+ charged SM leptons) + missing \( E_T \)


- 8TeV data already constrain \( \sigma \times \text{BR} \): particularly \( e_4 \nu_4 \) (up to 500-600 GeV)

- Mixing with \( \tau \) : about an order of magnitude weaker except \( \sim 105 \) GeV

See also Kumar and Martin, Phys. Rev. D 92, 115018
Productions of VLL: Drell-Yan (pair)

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\[ 3\ell \text{ from } e_4 \]

Direct search
ATLAS arXiv:1506.01291

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Productions of VLL: Drell-Yan (single)

$W, Z, h \quad \text{or} \quad 4f \text{ (from } h\text{)}$

Productions of VLL: Drell-Yan (single)

off-diagonal coupling: constrained by EWPT

\[ \mu, \nu_\mu \]

\[ e_4, \nu_4 \]

\[ W, Z, h \]

or \( 4f \) (from \( h \))


- 8TeV results: multilepton signal constrain weaker than EWPT
- Sensitive in the future data: HL-LHC, ILC
Productions of VLL: Higgs decay

- **SM Higgs exotic decay producing WW* and ZZ* like final states**
- **Heavy BSM Higgs cascade decays**
VLL extended THDM type-II

Heavy Higgs decays: WW, ZZ, Zh like signals


- Alignment limit: $H \to WW, ZZ$
- Dominant when $m_H \lesssim 340$ GeV
  Focus on this region
(multi-) Higgs cascade decay

- The three resonances from $H$, $e_4$, and $h$
- Unique signature

\[ \gamma \gamma \mu^+ \mu^- \]
\[ 4\ell + E_T^{\text{miss}} \]
\[ 6\ell \]
VLL extended THDM type-II

Final state categories

\[ h \rightarrow b\bar{b} \]
\[ h \rightarrow \tau^+\tau^- \]
\[ h \rightarrow WW^* \rightarrow 2\ell2\nu_\ell \]
\[ h \rightarrow \gamma\gamma \]
\[ h \rightarrow \mu^+\mu^- \]
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Final state categories

- $h \rightarrow bb \rightarrow b\bar{b}\mu^+\mu^-$
- $h \rightarrow \tau^+\tau^-$
- $h \rightarrow WW^* \rightarrow 2\ell 2\nu_\ell$
- $h \rightarrow \gamma\gamma \rightarrow \gamma\gamma\mu^+\mu^-$
- $h \rightarrow \mu^+\mu^-$
- $h \rightarrow ZZ^* \rightarrow 4\ell$

Many signals & backgrounds

Less signals & almost no backgrounds

Experimental sensitivities on the BR of the new decay mode

$$BR(H \rightarrow h\mu\mu) \equiv BR(H \rightarrow e_4^+\mu^-) \times BR(e_4^+ \rightarrow h\mu^+) + BR(H \rightarrow e_4^-\mu^+) \times BR(e_4^- \rightarrow h\mu^-)$$
VLL extended THDM type-II

Crucial selection cuts

In a large range of masses $m_H, m_{e_4}$

dimuon invariant mass $|m_{\mu\mu} - M_Z| > 15 \text{ GeV}$

(but still $m_{\mu\mu} > 20 \text{ GeV}$) \(\text{off-Z}\)

distinguish from background: $Z + \text{jets}, ZZ, hZ$
VLL extended THDM type-II

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$\bar{b}b\mu^+\mu^-$ no missing E: distinguish from $t\bar{t}$, $h\bar{t}\bar{t}$

$\gamma\gamma\mu^+\mu^-$ $\mathcal{E}_T$ cut
Experimental sensitivities

- EW precision data, multilepton + $E_T$, $h \to \gamma \gamma$, $H \to WW, \gamma \gamma$

- Recast from the existing searches $A \to hZ$, $h \to \gamma \gamma$ + a SM lepton

- Expected experimental sensitivities: new cut at 8 TeV & future data
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ATLAS, 1503.08089  ATLAS, 1407.4222

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$bb\mu\mu$ is more sensitive!
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- Expected experimental sensitivities: new cut at 8 TeV & future data
Experimental sensitivities

- $bb\mu\mu$ is more sensitive than $\gamma\gamma\mu\mu$: background subtraction good

- Multi-Variate Analysis: even 5 times better with naive assumptions

- Our results apply for general models with heavy Higgs & VLL
Conclusions

- Charged vectorlike lepton in a Higgs cascade decay:
  3 resonance signals from H, e_4, h

- Expected discovery: bb\mu\mu, \tau\tau\mu\mu, 4\ell2\nu, \gamma\gamma\mu\mu, 6\ell (or 4\mu)
  Background subtraction is good enough (off-Z cut)

- Heavier lepton: compete with H→tt (check for large tan\beta)

- Pair production from H: doubled final states (antler topologies)
  phase space small

- Similar approaches are possible in searching Vectorlike Quarks
Unification of gauge couplings in a simple non-SUSY model (SM + 3VF)

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

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

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

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

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

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

\[
n_f = 3 + 2 \times 3 = 9
\]

$\alpha_G = 0.3$

$M_G = 2 \times 10^{16} \text{ GeV}$

$log_{10} Q [\text{GeV}]$

$\alpha_{1, 2, 3}$
A unification with large $\alpha$: infrared fixed point behavior

Threshold corrections from Vectorlike Fermion masses $< O(100 \text{ TeV})$

Some vectorlike fermions $< 1 \text{ TeV}$: investigation at the LHC is possible

Insensitive unification

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

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

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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 $m_h = 126$ GeV, the top Yukawa coupling, and the $\lambda$ with the EW scale value of 0.5. The masses of vectorlike fermions are $M_{E_1} = M_{E_3} = 150$ GeV, $M_{E_{23}} = 2.0 \times 10^6$ GeV, $M_{E_{23}} = 2.4 \times 10^7$ GeV, $M_G = 520$ GeV, $M_U = 1.4 \times 10^5$ GeV, and $M_D = 2.5 \times 10^5$ GeV.
Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)
Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)

same chiral structure

Correlated with the physical muon mass

\[
\begin{align*}
L_{\text{eff}} & \supset -\bar{\mu}_L \left( y_\mu + \frac{\lambda^L \tilde{\lambda}^L}{M_L M_E} H H^\dagger \right) \mu_R H + \text{H.c.} \\
& \quad \rightarrow -(m_\mu^H + m_\mu^{LE}) \bar{\mu}_L \mu_R + \text{H.c.,}
\end{align*}
\]

\[
\Delta a_\mu \approx c \frac{m_\mu m_\mu^{LE}}{(4\pi^2)^2} \approx 0.85 c \frac{m_\mu^{LE}}{m_\mu} \Delta a_\mu^{\text{exp}}.
\]
Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Correlated with the physical muon mass

$\Delta a_\mu^{\text{obs.}}$

Effective Yukawa coupling

$\frac{m^L_{\mu} / m_\mu}{m^L_{\mu} / m_\mu} \simeq -1$ for $M_L \gg M_Z$

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

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

Yukawa between VLL & muon (doublets and singlets)

same chiral structure

Correlated with the physical muon mass

\[
L_{\text{eff}} \supset -\bar{\mu}_L (y_\mu + \lambda^L \lambda^E M_{LE} H H^\dagger) \mu_R H + \text{H.c.}
\]

\[
\rightarrow -(m^H_\mu + m^{LE}_\mu) \bar{\mu}_L \mu_R + \text{H.c.}
\]

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

\[
h \rightarrow \mu\mu \text{ fully from the mixing satisfying } (g-2)_\mu
\]

Effective Yukawa coupling

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

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

Dermisek, Raval, PRD88, 013017 (2013)

Black: upper bounds
Red: predicted production cross sections of doublets
Blue: predicted production cross sections of singlets
Strong constraints for the decay mode $\nu_4 \rightarrow W\mu$
20 possible processes
\[ m_H = 215 \text{ GeV} \ , \ m_{e_4} = 170 \text{ GeV} \]

\[ m_H = 340 \text{ GeV} \ , \ m_{e_4} = 170 \text{ GeV} \]
Most general renormalizable Lagrangian

\[ \mathcal{L} \supset -y_\mu \bar{\nu}_L \mu_R H_d - \lambda E \bar{\nu}_L E_R H_d - \lambda L \bar{L}_L \mu_R H_d - \lambda \bar{L}_L E_R H_d - \lambda H_d^+ \bar{E}_L L_R \\
- \kappa N \bar{\nu}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H_u^+ \bar{N}_L L_R \\
- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + \text{h.c.,} \]
Back up: VLL extended THDM type-II


Most general renormalizable Lagrangian

\[
\mathcal{L} = -y_\mu \bar{\mu}_L \mu_R H_d - \lambda E \bar{\mu}_L E_R H_d - \lambda_{LL} \bar{L}_L \mu_R H_d - \lambda_{LE} \bar{L}_L E_R H_d - \lambda_{Hd} \bar{H}_d \tilde{E}_L L_R \\
- \kappa_N \bar{\mu}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H^\dagger_u \tilde{N}_L L_R \\
- M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + h.c.,
\]