Heavy Higgs Search in the Models with Vectorlike Fermions

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Collaborations with R. Dermisek, E. Lunghi
Why Vectorlike Fermions?

SM: 3 generation of fermions

• No symmetric reason why only 3: additional fermions?

• Chiral 4th: strongly constrained by Yukawa & experiments
  • SM4 excluded: EWPT, LEP, Higgs at the LHC
  • Strong dynamics above TeV scale with extra Higgs? enhanced $h \rightarrow \tau \tau$
  • $Z_2$ parity? constrained by SUSY searches

• Vectorlike fermion: mass and Yukawa independent
  (Heavy fermion easily allowed without gauge anomaly)
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  • SM4 excluded: EWPT, LEP, Higgs at the LHC  Djouadi, Lenz (2012)

  • Strong dynamics above TeV scale with extra Higgs? enhanced $h \rightarrow \tau \tau$
    Geller, Bar-Shalom, Eilam, Soni (2012)

  • $Z_2$ parity? constrained by SUSY searches  Lee, Soni (2012)

• Vectorlike fermion: mass and Yukawa independent
  (Heavy fermion easily allowed without gauge anomaly)

  Only vector current exists  $J^{\mu(+)} = J^\mu_L + J^\mu_R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$
Why Vectorlike Fermions?

Expected in various BSM categories

• Composite Higgs models, Little Higgs models

• Invisible axion models

• $Z'$ models (anomaly cancellation)

• Supersymmetric model (little hierarchy problem, pheno reasons)

• Simple SM + VLF

Kim, Seo, Shin, PRD83, 036003 (2011)
Dermisek, PRD95, 015002 (2017)
Martin, PRD81, 035004 (2010)
Why Vectorlike Fermions?

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  Kim, Seo, Shin, PRD83, 036003 (2011), ……..

• Supersymmetric model (little hierarchy problem, pheno reasons)


• Simple SM + VLF
  
  - Gauge coupling unification (UV insensitive)
    Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)

  - Anomalous muon g-2 (VLL mixing with $\mu$)
    Kannike, Raidal, Straub, Strumia, JHEP 1202, 106 (2012)
Direct searches at the LHC

- Single fermion which is pure iso-singlet or doublet (or triplet)
- Production through gauge interaction
- Focus on VLQ
Direct searches at the LHC

- Single fermion which is pure iso-singlet or doublet (or triplet)
- Production through gauge interaction
- Focus on VLQ

This talk

- Introduce both iso-singlet and doublet (general vectorlike copy of SM fermions)
- Production through Yukawa interaction (BSM heavy Higgs)
- Focus on VLQ + VLL
Model framework

e.g., VLF with THDM type II

\[
\begin{array}{cccccccc}
\mu_L & \mu_R & L_{L,R} & E_{L,R} & N_{L,R} & H_d & H_u \\
SU(2)_L & 2 & 1 & 2 & 1 & 1 & 2 & 2 \\
U(1)_Y & -\frac{1}{2} & -1 & -\frac{1}{2} & -1 & 0 & \frac{1}{2} & -\frac{1}{2} \\
Z_2 & + & - & + & - & + & - & + \\
\end{array}
\]

Dermisek, Lunghi, Shin, JHEP 1602, 119

\[
\begin{array}{ccccccc}
q^i_L & u^i_R & d^i_R & Q_{L,R} & T_{L,R} & B_{L,R} \\
SU(2)_L & 2 & 1 & 1 & 2 & 1 & 1 \\
U(1)_Y & \frac{1}{6} & \frac{2}{3} & -\frac{1}{3} & \frac{1}{6} & \frac{2}{3} & -\frac{1}{3} \\
Z_2 & + & + & + & + & - \\
\end{array}
\]

Dermisek, Lunghi, Shin, Work in progress
**Model framework**

e.g., VLF with THDM type II

![Model framework table](image1.png)

Dermisek, Lunghi, Shin, JHEP 1602, 119

New fermions (SM fermion copies + singlet neutral lepton)

![New fermions table](image2.png)

Dermisek, Lunghi, Shin, Work in progress
Model framework

Most general renormalizable Lagrangian

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

\text{example}

- VLL mixing with SM lepton: In my papers, \( \mu \) from muon g-2 (Approximate muon number VLL: to avoid dangerous LFV)

- Mass eigenstates: (e_4,e_5), (\nu_4,\nu_5)

- \( \mu, \nu_\mu \) gauge/Yukawa couplings modified: EWPT
Model framework

Most general renormalizable Lagrangian

**VLQ**

\[
\mathcal{L} \supset -y_d^{ij} \bar{q}^i_L d^j_R H_d - \lambda^i_B q^i_L B_R H_d - \lambda^j_Q \bar{Q}^j_L d^j_R H_d - \lambda^i_Q H_d^i \tilde{B}_L Q_R - y_u^{ij} \bar{q}^i_L u^j_R H_u - \kappa^i_T q^i_L T_R H_u - \kappa^j_Q \bar{Q}^j_L u^j_R H_u - \kappa^i_Q T_R H_u - \bar{\kappa}^i_H T_L Q_R - M_Q \tilde{Q}_L Q_R - M_T \tilde{T}_L T_R - M_B \tilde{B}_L B_R + \text{h.c.},
\]

- VLQ mixing with SM quark: here, 3rd generation exclusively
- Mass eigenstates: \((t_4, t_5), (b_4, b_5)\)
- EWPT: oblique corrections, \(R_b\)
Heavy Higgs cascade decay

VLL

Promising channel searching for both H and VLF
Heavy Higgs cascade decay

Promising channel searching for both H and VLF

In the alignment limit, $H \rightarrow WW, ZZ$ mostly compete with $H \rightarrow \tau^+ \tau^-$
Comparison with $H \to \tau^+ \tau^-$

95% C.L. from $H \to \tau^+ \tau^-$

ATLAS 36.1 fb$^{-1}$

THDM-II,

$\sin(\beta-\alpha) = 1,$

without VLF

$\tan\beta$

$\tau^+$

$\tau^-$

Alignment limit

$\tan\beta$

$\tau^+$

$\tau^-$

$\tan\beta$

$\tau^+$

$\tau^-$

$\tan\beta$

$\tau^+$

$\tau^-$

$\tan\beta$

$\tau^+$

$\tau^-$

$\tan\beta$

$\tau^+$

$\tau^-$

$\tan\beta$

$\tau^+$

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$\tau^+$

$\tau^-$

$\tan\beta$
Comparison with $H \rightarrow \tau^+ \tau^-$

95% C.L. from $H \rightarrow \tau^+ \tau^-$

ATLAS 36.1 fb$^{-1}$

Purple: with VLF
Heavy Higgs cascade decay

- $pp \rightarrow WW$ & $H \rightarrow WW$
- Semileptonic final states ($W \rightarrow jj$): find $H$ & $\nu_4$
- Dileptonic: $M_{T2}$ cut


Dermisek, Raval, Shin, PRD 90, 034023 (2014)
Heavy Higgs cascade decay

Dermisek, Lunghi, Shin, JHEP1605, 148

• Constraints from the DM search at the LHC
• Identifying this separately from DM nontrivial
Heavy Higgs cascade decay

- Resonance search if $Z \rightarrow$ visible particles
- Two leptons are not from $Z$

Future work
Heavy Higgs cascade decay

- The three resonances from $H$, $e_4$, $h$

- Unique signature $\gamma\gamma\mu^+\mu^- 4\ell + E_T^{\text{miss}} 6\ell$

Dermisek, Lunghi, Shin, JHEP1610, 081

VLL
multi-Higgs cascade

Final state categories

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

Dermisek, Lunghi, Shin, JHEP1610, 081
multi-Higgs cascade

Final state categories

$h \rightarrow bb$ \quad $b\bar{b}\mu^+\mu^-$

$h \rightarrow \tau^+\tau^-$ \quad Many signals & backgrounds

$h \rightarrow WW^* \rightarrow 2\ell 2\nu_\ell$

$h \rightarrow \gamma\gamma$ \quad $\gamma\gamma\mu^+\mu^-$

$h \rightarrow \mu^+\mu^-$ \quad Less signals & almost no backgrounds

$h \rightarrow ZZ^* \rightarrow 4\ell$

Experimental sensitivities on the BR of the new decay mode

$$\text{BR}(H \rightarrow h\mu\mu) \equiv \text{BR}(H \rightarrow e_4^+\mu^-) \times \text{BR}(e_4^+ \rightarrow h\mu^+) + \text{BR}(H \rightarrow e_4^-\mu^+) \times \text{BR}(e_4^- \rightarrow h\mu^-)$$

Dermisek, Lunghi, Shin, JHEP1610, 081
multi-Higgs cascade

Crucial selection cuts

In a large range of masses $m_H, m_{e4}$

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

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

distinguish from background: $Z + \text{jets}, ZZ, hZ$

Dermisek, Lunghi, Shin, JHEP1610, 081
multi-Higgs cascade

Crucial selection cuts

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

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

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

distinguish from background: $Z + \text{jets, ZZ, hZ}$

$\bb\mu^+\mu^-$

no missing E: distinguish from $t\bar{t}, h\bar{t}t$

$\gamma\gamma\mu^+\mu^-$

$E_T$ cut
Experimental sensitivities: HL-LHC

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

- Recast from the 8 TeV searches $A \to hZ(bbZ)$, $h \to \gamma\gamma$ + a SM lepton, $\gamma\gamma Z$
  
  ATLAS, 1503.08089  1407.4222  1604.05232

- Expected experimental sensitivities: new cut at 8 TeV & 13 TeV

Disclaimer: Old analysis (2016)

- $bb\mu\mu$ is more sensitive!
  
  (off-Z cut powerful)

- but $\gamma\gamma\mu\mu$ gets rapidly sensitive
  
  with more date
Experimental sensitivities: HE-LHC

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

- Recast from the 8 TeV searches $A \rightarrow hZ(bbZ)$, $h \rightarrow \gamma\gamma$ + a SM lepton, $\gamma\gamma Z$

- Expected experimental sensitivities: new cut at 8 TeV & 13, 27 TeV

ATLAS, 1503.08089 1407.4222 1604.05232
Experimental sensitivities: HE-LHC

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- Recast from the 8 TeV searches $A \rightarrow hZ(bbZ)$, $h \rightarrow \gamma\gamma$ + a SM lepton, $\gamma\gamma Z$

- Expected experimental sensitivities: new cut at 8 TeV & 13, 27 TeV

\[ \text{Same level sensitivity for heavier } H \ (> 600 \text{ GeV}) \]
Heavy Higgs cascade decay

- Boosted objects (VLQ mass \( \gtrsim 1 \) TeV from the constraints)
Heavy Higgs cascade decay

- Production cross section comparable with
- Production cross section smaller than
Heavy Higgs cascade decay

- Production cross section comparable with

- Production cross section smaller than

- Uniqueness of signals: kinematic topology, resonances
Heavy Higgs cascade decay

- Single top (boosted)
- $tbW$ (kinematically) different from $tt\bar{t}$
Heavy Higgs cascade decay

- \( tt \) or \( bb \) out of \( m_Z \) resonance
Heavy Higgs cascade decay

- tth or bbh-like signals

VLQ
CMS search on the same topology

$1703.06352$

Further improvement in HL/HE-LHC

$\rho_L^0$ mass [TeV]

Upper cross section limit [pb]
Conclusions

- Search of heavy Higgs & VLF possible by observing the cascade decay channel

- Many resonance signals, e.g., (multi-)Higgs cascade:
  - 3 resonance signals from H, VLF, h
  - Background subtraction is good enough (off-Z cut)

- Promising channel for the search of heavy Higgs even above $t\bar{t}$

- Pair production of VLF from H decay: doubled final states (antler topologies)
• Supersymmetric model
  • Gauge coupling unification restriction: number, mass, type
    Dermisek, Raval, PRD88, 013017 (2013)
    Kannike, Raidal, Straub, Strumia, JHEP 1202, 106 (2012)
  • Raise lightest Higgs mass
  • Reduce fine tuning in EWSB: $m_{\tilde{t}}$ from mixing with VL squark
    Dermisek, 1606.09031
  • Pure bino scenario without resonance or co-ann.
    (new ann. channel into new lepton, avoiding helicity suppression)
    Martin, PRD81, 035004 (2010)
    Abdullah, Feng, PRD93, 015006 (2016)

• Non-supersymmetric model \textbf{VLL}
  • Gauge coupling unification without SUSY: number, mass, type
    Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)
  • Several exp. anomalies: muon g-2 (VLL mixing with $\mu$), $X \rightarrow \gamma \gamma$
    Dermisek, Raval, PRD88, 013017 (2013)
    Kannike, Raidal, Straub, Strumia, JHEP 1202, 106 (2012)
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 TeV)
- Some vectorlike fermions < 1 TeV: investigation at the LHC is possible

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

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

\[ \alpha_G = 0.3 \]
\[ M_G = 2 \times 10^{16} \text{ GeV} \]

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

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

\[ n_f = 3 + 2 \times 3 = 9 \]
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 $< O(100 \text{ TeV})$
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\[
\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \log \frac{M_G}{M_Z} + \alpha_G^{-1} \mu_i
\]

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

Insensitive unification

\[
\alpha_G = 0.3
\]

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

\[
\frac{d\alpha_i}{dt} = \beta(\alpha_i) = \frac{\alpha_i^2}{2\pi} b_i
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$\alpha_G = 0.3, \ M_G = 2 \times 10^{16} \text{ GeV}$

$M_{L_1} = M_{E_1} = 150 \text{ GeV}, \ M_Q = 520 \text{ GeV}$

$\lambda^h$ : Yukawa (new doublet & singlet)
Dermisek, Raval, PRD88, 013017 (2013)

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

Yukawa between VLLs $\lambda$ & with muon $\lambda_L, \lambda_E$

Correlated with the physical muon mass

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

Effective Yukawa coupling

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

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

m$\mu$ fully from the mixing with VLL

$$R_{\mu\mu} = \frac{\Gamma(h \rightarrow \mu^+ \mu^-)}{\Gamma(h \rightarrow \mu^+ \mu^-)^{\text{SM}}}$$
Red: predicted production cross sections of doublets

Black: 95%CL upper bounds

Gray point: 5-lepton cut
Green point: b-tag cut
true without SM singlet N

\( m_{e4} > 200 \text{ GeV} \)!!!

- Orange: \( m_{e4} > 200 \text{ GeV} \)
- Blue: \( m_{e4} > 300 \text{ GeV} \)
- Green: \( m_{e4} > 400 \text{ GeV} \)
- Purple: \( m_{e4} > 500 \text{ GeV} \)

strongly constrained!
Back up

Focused on $m_H \approx 340$ GeV to avoid competition with $H \rightarrow t\bar{t}$

True: $\text{BR}(H \rightarrow \nu_4 \nu_\mu)$ but False: $\text{BR}(H \rightarrow e_4 \mu)$ when $\tan\beta > 1$?

- Low $\tan\beta$ compete with $H \rightarrow t\bar{t}$
- New Yukawa coupling: large

Example below 340 GeV

We may beat $H \rightarrow b\bar{b}$ OK with $\tan\beta > 1$?
For $4 \leq \tan\beta \leq 17$ with $|\text{Yukawa}| < 0.5$

For $4 \leq \tan\beta \leq 32$ with $|\text{Yukawa}| < 1.0$

We beat both $H \rightarrow t\bar{t}$ & $H \rightarrow b\bar{b}$

Promising in H discovery: better than $H \rightarrow t\bar{t}$ (interference)
Constraints from flavor physics (for low $\tan\beta$)

- $b \rightarrow s\gamma$
- $R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\Gamma(Z \rightarrow \text{hadrons})}$
  - strong for $\tan\beta < 0.8$
  - OK for $m_{H^\pm} : 400 - 500 \text{ GeV}$
  - OK with a VLQ mixing with $b$
- $\Delta M_b$ weak

Song, Yoon, PRD91, 113012 (2015)