2HDM Scalar Phenomenology: Role of Vector-like Fermions

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Outline of the Talk

- Motivation to study 2HDM and VLFs together.
- Models with both 2HDM and VLFs, with their mutual interaction.
  - $t - t'$ (VL-SM) mixing.
  - $\psi - \chi$ (VL-VL) mixing.
  - Effects of VLQs on CP-even (odd) scalar production and decay in 2HDM.
- $SU(6)/Sp(6)$ little-Higgs (LSS) model:
  - LSS model description: 2HDM+VLF structure
  - Constraints on the LSS model
  - Production and decay of heavy BSM scalars of LSS model
- This talk is based on arXiv:1504.01074 (PRD) and arXiv:1512.05731 (PRD) by S. Gopalakrishna, T. Mukherjee and S. Sadhukhan.

Why one should study 2HDM+VLF

- 2HDMs: Extra scalars of the minimally extended scalar sector can be the first BSM at the LHC.
- Vectorlike fermions are some of the minimal fermionic extensions beyond the SM. Presence of those can be investigated indirectly through scalar phenomenology.
- These kind of 2HDM+VLF constructions are not adhoc and they can be realized in specific BSM models i.e. $SU(6)/Sp(6)$ little Higgs model.
- All non-SM scalars are realised as pNGBs in these models with extended symmetries making them relatively lighter. For TeV scale completion of those models heavier vector-like fermions are required to be introduced so that they can complete representation of some bigger group embedding the SM.

2HDM Models

- The doublets are given by (i=1,2):

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix}.$$

- 2HDM have total 5 scalar degrees of freedom:
  Two CP even (h,H), one CP-odd (A) and two charged ($H^\pm$).
- The Yukawa sector in the 2HDM of **type-II**:

$$\mathcal{L} \supset -y_d \bar{q}_L \Phi_1 d_R - y_u \bar{q}_L \tilde{\Phi}_2 u_R + y_e \bar{l}_L \Phi_1 e_R + h.c.$$

- The Yukawa sector in the 2HDM of **type-X**:

$$\mathcal{L} \supset \quad -(y_d \bar{q}_L \Phi_2 d_R + y_u \bar{q}_L \tilde{\Phi}_2 u_R + y_e \bar{l}_L \Phi_1 e_R) + h.c$$

- We work in **alignment** limit where tree level gauge and fermion couplings are SM-like and HWW/HZZ vanish. AWW/AZZ vanish due to CP invariance of the theory.

Vectorlike Fermions

- The left handed and right handed chiral parts of a vectorlike fermion ψ transform in a similar way under the SM gauge groups.

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left(J^{\mu-} W^+_\mu + J^{\mu+} W^-_\mu \right) \qquad \text{Charged current Lagrangian}$$

- Only left handed charged currents are there for the SM chiral fermions.
- Both left handed and right handed currents are there for the vector-like fermions which looks like a vector current.

$$J^{\mu+} = J^{\mu+}_L + J^{\mu+}_R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d,$$

- Such vector-like fermions are seen in many new physics models.
  - in extra-dimensional models as KK excitations of bulk fields.
  - in Little Higgs models as partners of SM fermions in larger group representations which ensure cancellation of divergent loops.

2HDM+ $t - t'$ $(b - b')$ Mixing

- An SU(2)-singlet VLF pair (ψ, ψ^c) with EM charge 2/3, added to the 2HDM-II with the terms:

$$\mathcal{L} \supset M_\psi \, \bar{\psi}\psi - \left(y_1 \, \bar{q}_L \tilde{\Phi}_1 \psi_R + h.c. \right).$$

- After EWSB the mass terms for top-like fermions:

$$\mathcal{L}^{mass} = -\frac{1}{\sqrt{2}} \left(y_u v_2 \bar{t}_L t_R + y_1 v_1 \bar{t}_L \psi_R + h.c. \right) + M_\psi \bar{\psi}\psi.$$

- The mass eigenstates $t^0_{L,R}, t_{2L,R}$ are obtained as mixed states of $t_{L,R}$ and $\psi_{L,R}$ with mixing angles θ^U_L, θ^U_R.

$$\tan 2\theta^U_L = \frac{2\sqrt{2} y_1 v_1 M_\psi}{y_u^2 v_2^2 - 2M_\psi^2 + y_1^2 v_1^2},$$

$$\tan 2\theta^U_R = \frac{2\sqrt{2} y_1 y_u v_1 v_2}{y_u^2 v_2^2 - 2M_\psi^2 - y_1^2 v_1^2}.$$

- An SU(2)-singlet VLF pair (χ, χ^c) with EM charge -1/3, added to the 2HDM-II with the terms:

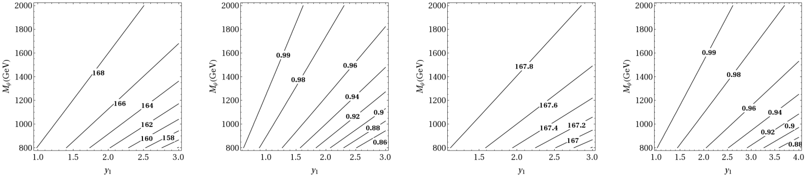
$$\mathcal{L} \supset M_\chi \, \bar{\chi}\chi - \left(y_2 \, \bar{q}_L \Phi_1 \chi_R + h.c. \right).$$

Results

- $t - t'$ mixing affects SM top mass and top-Higgs Yukawa coupling.
- Effective top Yukawa coupling after mixing:

$$y_{htt} = (-y_u c_L^U c_R^U \cos\alpha + y_1 c_L^U s_R^U \sin\alpha)$$

- We fix $m_t^{\bar{MS}} = 163$ GeV by choosing y_u appropriately. $\kappa_{htt} = y_{htt}/y_{htt}^{SM}$.
- Parameter space with top mass and κ_{htt} fixed:



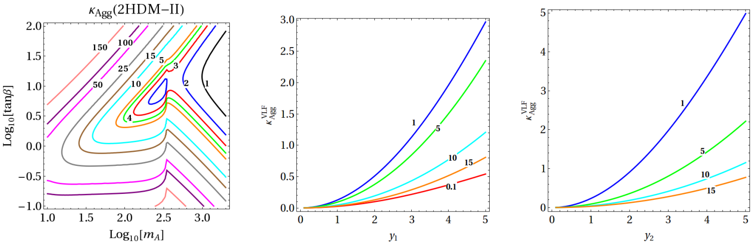
- First two with $\tan\beta = 1, y_u = 1.4$, last two with $\tan\beta = 5, y_u = 1$.
- At kinematically allowed region, $BR(A \to t_2 t)$ becomes dominant at moderate $\tan\beta$.

Results

- In our parameter space of interest the CP even and odd scalar looks similar. The effective interaction:

$$\mathcal{L}_{eff} = -\frac{1}{64\pi^2 M}\kappa_{\phi\gamma\gamma}\phi Y_{\mu\nu\sigma\tau}F^{\sigma\tau}F^{\mu\nu} - \frac{1}{64\pi^2 M}\kappa_{\phi gg}\phi Y_{\mu\nu\sigma\tau}G^{a\sigma\tau}G^{a\mu\nu}$$

- Gluon fusion effective parameter $\kappa_{\phi gg}$ comparison (2HDM vs VLF):



- Here $m_A = 1000$ GeV and $m_\psi = 1250$ GeV.
- VLF contribution can be significant in parts of the parameter space.

2HDM + VLF-VLF Mixing

- One vector-like SU(2) doublet $\psi = (\psi_L, \psi_R)_{Y=1/6}$ and one down type singlet $\chi = (\chi_L, \chi_R)_{Y=-1/3}$ $(MVQD_{11})$ or one up type singlet $\xi = (\xi_L, \xi_R)_{Y=2/3}$ $(MVQU_{12})$ are added.
- $MVQD_{11}$ model: χ_L, χ_R both couple to Φ_1.

$$\mathcal{L} \supset \bar{\psi} iD\psi + \bar{\chi} iD\chi - (y_1 \bar{\psi}_L \Phi_1 \chi_R + \tilde{y}_1 \bar{\psi}_R \Phi_1 \chi_L + \text{h.c}) - M_\psi \bar{\psi}\psi - M_\chi \bar{\chi}\chi.$$

- $MVQU_{12}$ model: ξ_R couples to Φ_1 and ξ_L couples to Φ_2.

$$\mathcal{L} \supset \bar{\psi} iD\psi + \bar{\xi} iD\xi - (y_1 \bar{\psi}_L \tilde{\Phi}_1 \xi_R + \tilde{y}_1 \bar{\psi}_R \tilde{\Phi}_2 \xi_L + \text{h.c}) - M_\psi \bar{\psi}\psi - M_\xi \bar{\xi}\xi.$$

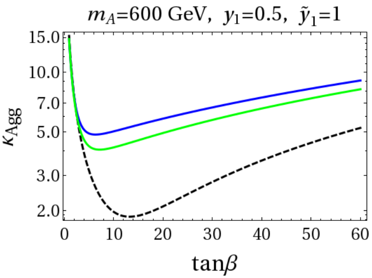
- After EWSB vectorlike fermions mix amongst them to give mass eigenstates with angles $\theta_{L,R}$.

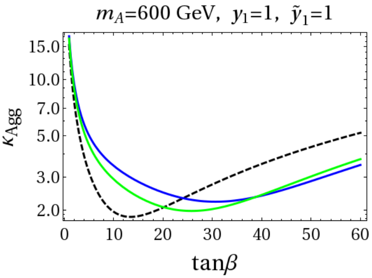
$$\tan 2\theta_L = \frac{2\sqrt{2} v c_\beta (y_1 M_\chi + \tilde{y}_1 M_\psi)}{2(M_\psi^2 - M_\chi^2) - v^2 s_\beta^2 (\tilde{y}_1^2 - y_1^2)},$$

$$\tan 2\theta_R = \frac{2\sqrt{2} v c_\beta (y_1 M_\chi + \tilde{y}_1 M_\psi)}{2(M_\psi^2 - M_\chi^2) + v^2 s_\beta^2 (\tilde{y}_1^2 - y_1^2)}.$$

- The Yukawa sector of the 2HDM-X is modified in a way similar to $MVQD_{11}$.
- The relative sign between $y_1, \tilde{y}_1$ changes numbers. We take $y_1 = \tilde{y}_1$ $(+M_\chi = M_\psi)$ for $MVQU_{12}$ but this can not be taken for $MVQD_{11}$.

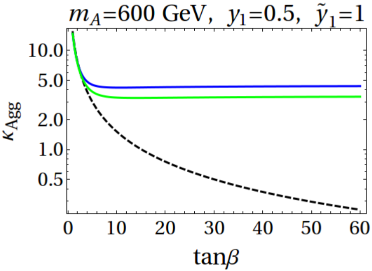
Results





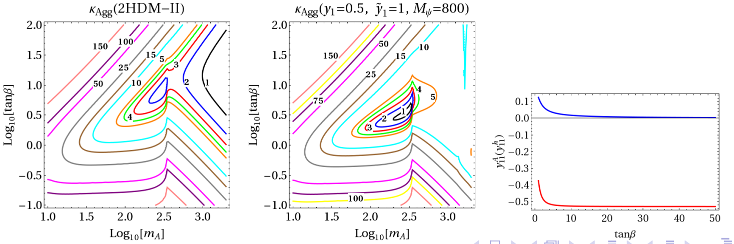
- Top plot is for $MVQD_{11}$ model. Bottom plot is for $MVQU_{12}$ model
- VLF masses are 800 GeV (Blue) and 1000 GeV (Green). Only 2HDM-II with SM fermion contribution (dashed one).
- For $MVQD_{11}$ the effective Agg coupling always increses adding VLFs compared to the 2HDM only case. The increse in 2-3 times for all $\tan\beta > 3$.
- But for the $MVQU_{12}$ the effective Agg coupling increses upto $\tan\beta \sim 20$, then decreases. The change is of $1.25 - 1.5$ times.

Results



- This plot is for $MVQD_{11}$ like model with original 2HDM-X setup.
- VLF masses are 800 GeV (Blue) and 1000 GeV (Green). Only 2HDM-X with SM fermion contribution (dashed one).

- $\kappa_A gg$ in 2HDM-II and $MVQD_{11}$ (left and middle), Effective Yukawa couplings in SM Higgs and non-SM scalar (right).



Low-Skiba-Smith (LSS) Model

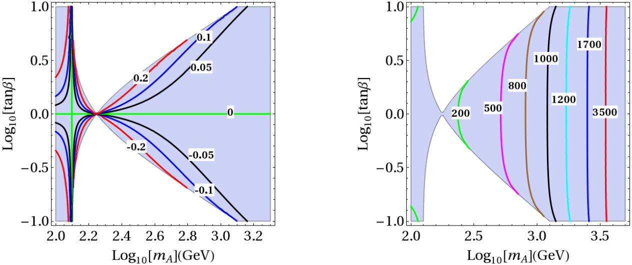
- It is a little Higgs model: Higgs is a pseudo-Goldstone boson.
- Quadratic divergent corrections to the Higgs mass get cancelled in one loop: solves the Hierarchy problem, therefore natural.
- $SU(6)$ spontaneously broken to $Sp(6)$: 8 Goldstones form two $SU(2)$ doublets that mimic 2HDM structure with 4 BSM scalars.
- To cancel fermionic divergences, vectorlike fermions have to be added.
- Other Goldstones provide heavier BSM gauge bosons and a singlet scalar. So at relatively lower energy, LSS model can be treated as a 2HDM+VLF structure.

LSS-2HDM

- The scalar potential (with $Y_{\phi_1} = 1/2$, $Y_{\phi_2} = -1/2$) is given as:

$$\mathcal{V}_{LSS} = m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 + (b^2\phi_1^T \cdot \phi_2 + \mathrm{h.c.}) + \lambda_5'|\phi_1^T \cdot \phi_2|^2$$

- $m_1^2, m_2^2, b^2, \lambda_5'$ are generated through LSS model heavier fermion, gauge boson and scalar loops.
- For λ_5' non-imaginary and with the Higgs mass and vev fixed, allowed charged scalar mass and deviation from alignment limits are shown.



- The sufficient condition for EWSB here: $m_{1/2}^2 > 0$ and $m_1^2 m_2^2 - b^4 < 0$.

LSS-Yukawa

- A VLQ doublet Weyl pair with $Y = 1/6$, one each of top like and bottom like singlet Weyl pairs are introduced.
- Expanding the Yukawa coupling with the $SU(6)$ symmetry being broken:

$$\begin{aligned}\mathcal{L}^{\text{ferm}} = &-y_1 \left(f\psi_1 t^c - iQ'^T \phi_2^* t^c - iQ^T \cdot \phi_1 t^c \right) \\ &+ y_2 \left(fQ^T \cdot Q'^c + Q^T \phi_1^* \psi_2^c + iQ^T \phi_2^* \psi_1^c \right) \\ &+ y_3 f Q'^T \cdot Q'^c + y_4 f \psi_1^c \psi_1 + \\ & y_5 f \psi_2^c \psi_2 + h.c..\end{aligned}$$

- In the top sector, it couples with both the scalar doublets: a 2HDM-III structure. Other light fermion Yukawa couplings are either type I or type II.
- Unlike the previous cases, the fermion mixing of LSS originates from both the $SU(6)$ (breaking scale f) breaking and EWSB (breaking scale v).
- The symmetry breaking must be of collective nature i.e. both of the Yukawa coupling should take part in the breaking.

Constraints on LSS Model

- Mass and Yukawa matrix are diagonalized in two steps to get κ_{htt}, m_t.
- Scan over 9 parameters done imposing the constraints below.

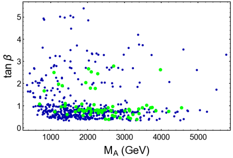
Table: The experimental constraints at about the 2 to 3 σ level.

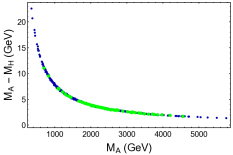
Quantity	Constraint	Reference
Top mass (MSbar)	$158 < m_t^{\overline{MS}} < 168.7$ GeV	arXiv:1207.0980
Higgs VEV	$v \equiv 246$ GeV	
Higgs mass	$123 < m_h < 127$ GeV	CMS, ATLAS
Higgs Yukawa	$0.63 < \lvert\kappa_{htt}\rvert < 1.2$	ATLAS
hW^+W^- coupling	$\lvert\cos(\beta-\alpha)\rvert < 0.4$	ATLAS
VLQ mass	$M_{t',\,b'} > 750$ GeV	ATLAS

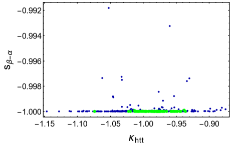
- Precision EW constraints are taken into account also.

Phenomenology of BSM Scalars

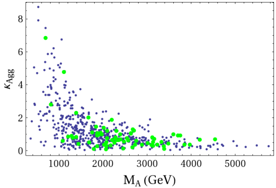
- Lower $\tan\beta$ values are favored.
- All of the extra scalars are almost degenerate in mass.
- The alignment limit is very precisely achieved.

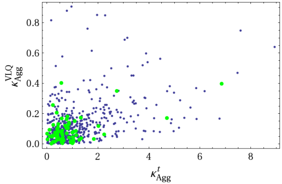




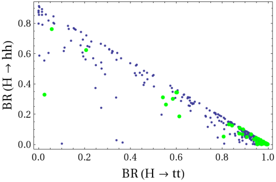


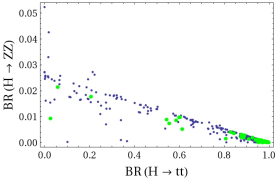
- Gluon fusion scalar production through triangle loop of quarks:



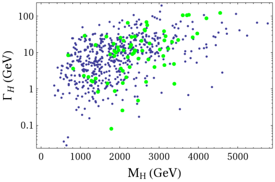


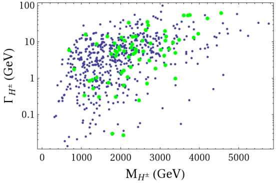
- CP-even neutral scalar decay to the $\gamma\gamma, \tau\tau, bb, tt, WW, ZZ, Zh, hh$ modes.
- CP-odd neutral scalar decay to the $\gamma\gamma, \tau\tau, bb, tt, Zh$ modes.
- H/A decay to tt dominant, other channels become important when accidental cancellations happen in Htt, Att Yukawa couplings.





- Charged scalar decay to $tb, \tau\nu, cs, Wh$ modes.





Conclusion

- For a heavy resonance, order of magnitude larger $\sigma \times BR_{\gamma\gamma}$ than the 2HDM only set up is possible. Addition of VLLs can boost $\gamma\gamma$ branching ratio also.
- In some LSS model parameter points, VLF contribution can be significant compared to the SM fermion contribution in BSM scalar production and decay. VLFs can do these modifications keeping all SM Higgs observables within experimental limit.
- Modification of the heavy scalar phenomenology due to the SM-VLF mixing is of similar kind to those due to the VLF-VLF mixing.
- LHC signatures of neutral and charged scalars in different channels will be interesting.

Thank You

$$
\begin{aligned}
\lambda_5' &= \frac{c g_1^2\left[g_2^2 + (c'/c) y_2^2\right])}{g_1^2 + g_2^2 + (c'/c) y_2^2}\ , \quad b^2 = \frac{3f^2}{8\pi^2} y_1^2 y_2 (y_3 - y_4) \log\frac{\Lambda^2}{M_f^2}\ , \\
m_{1\,f}^2 &= \frac{3f^2}{8\pi^2}(y_1^2 - y_2^2)(y_3^2 - y_4^2)\log\frac{\Lambda^2}{M_f^2}\ , \\
m_{2\,f}^2 &= \frac{3f^2}{8\pi^2}(y_1^2 y_2^2 + y_2^2 y_5^2 - y_2^2 y_3^2 - y_1^2 y_4^2)\log\frac{\Lambda^2}{M_f^2}\ , \\
m_{1g}^2 &= m_{2g}^2 = \frac{3}{64\pi^2}\left[3g^2 M_g^2 \log\frac{\Lambda^2}{M_g^2} + g'^2 M_{g'}^2 \log\frac{\Lambda^2}{M_{g'}^2}\right]\ , \\
m_{1s}^2 &= m_{2s}^2 = \frac{\lambda_5'}{16\pi^2} M_s^2 \log\frac{\Lambda^2}{M_S^2}\ ,
\end{aligned} \tag{1}
$$

where Λ is the cut-off which is taken to be $4\pi f$. M_f is the heavy vector-like fermion mass-scale. The heavy gauge-boson masses are $M_g = f\sqrt{(g_1^2 + g_2^2)/2}$ and $M_{g'} = f\sqrt{(g_1'^2 + g_2'^2)/2}$. The singlet scalar ($s$) mass is $M_s = f\sqrt{c(g_1^2 + g_2^2) + c' y_2^2}$, where c and c' are $O(1)$ parameters.

Scalar Production and Decay

- $f(\tau_i)$ used there is of form:

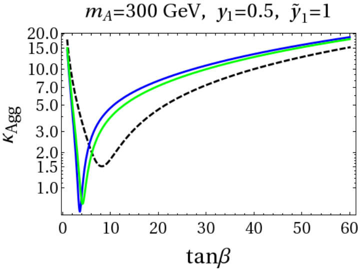
$$f(\tau_i) = (\sin^{-1}[\frac{1}{\sqrt{\tau_i}}])^2.$$

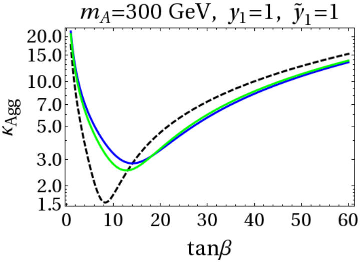
- For our case of $m_Z^2 << m_{H_1}^2$ the decay width to $Z\gamma$ and ZZ are given by

$$\begin{aligned}
\Gamma(H_1 \to Z\gamma) &= \frac{\alpha^2 m_{H_1}}{32\pi^3 s_W^2 c_W^2} \left| 2N_c \sum_{i=X,Y} f_i Q_i(-Q_i s_W^2)\sqrt{\tau_i}(1 + (1-\tau_i) f(\tau_i) \right|^2, \\
\Gamma(H_1 \to ZZ) &= \frac{\alpha^2 m_{H_1}}{64\pi^3 s_W^4 c_W^4} \left| 2N_c \sum_{i=X,Y} f_i(-Q_i s_W^2)^2 \sqrt{\tau_i}(1 + (1-\tau_i) f(\tau_i) \right|^2
\end{aligned}$$

Back Up

- $MVQD_{11}$ and $MVQU_{12}$ at $m_A = 300\text{GeV}$:





Other Proposed works

- Inert HDM has a scalar DM candidate. This model is modified adding vectorlike leptons. Relic density constraint can put better limits on new lepton mass and Yukawas.
- The sign of Yukawa couplings of 125 GeV Higgs are not known. In SM, Yukawas do not have relative sign. No conventional decay channel can probe if they have relative sign. Exotic Higgs decays can be studied to use for this purpose.
- In variants of 2HDM there are parameter region where BSM scalar search can not be done in conventionally popular decay channels. For low mass particle search at high $\tan\beta$ region unconventional decay modes can be helpful.
- Scalar and Fermion DM candidates are well studied. I want to ephasize on vector boson DM models. The effective interaction of vector boson DM can be realised in UV complete models which can be constructed in different ways.
- It is interesting to explain lepton flavor violation and neutrino mixing in 2HDM models with discrete symmetries.