Flavor, Higgs couplings and DM within multi-Higgs models

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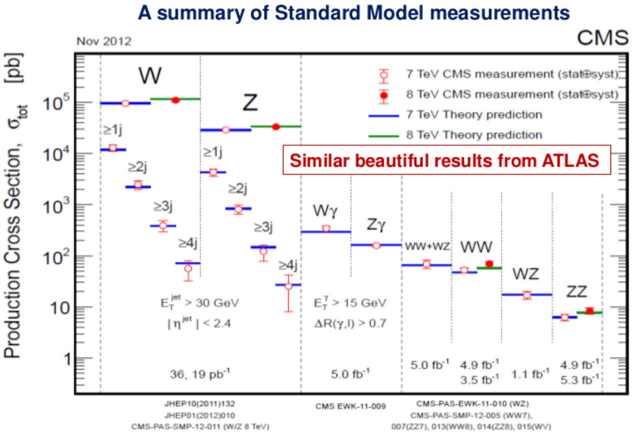
1.0 The 2012 Higgs party

The SM domain



The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

CERN, 20-Nov-2012
P Jenni (CERN) LHC experiments and results 72

Is the party over?

Before ICHEP16:

- Hints of LFV Higgs decay ($h \to \tau\mu$) i.e. CMS limits: $B.R.(h \to \tau\mu) \leq 10^{-2}$,
- LHC reported hints of new Resonance ($S \to \gamma\gamma$)
- Plenty of (gravitational) evidence for Dark matter $\to$ New Physics!
- Deviations from SM (few sigmas) are around (Δa_μ, B-decays,...)

After ICHEP16:

First two turned out to be just fluctuations, while the third one could be a WIMP, but..

Then what?

We can only keep going...

BSM Physics with Multi-Higgs models

- The lack of understanding for the SM structure (Flavor parameters, gauge unification, DM, BAU, etc) have motivated the search for extensions of the SM,
- We know now that nature accepts scalars, so may be more will be detected at LHC or future colliders,
- In particular, models with an extended Higgs sector have been studied considerably for several reasons (Hierarchy problem (SUSY), Composite Higgs, Flavor, DM, etc)
- Here, we would like to explore (N+1) Higgs doublet models with extra singlet (FN type or as new source of SCPV),
  - N active Higgs doublets + 1 inert-type Higgs doublet
- We like to explore : Higgs couplings -FC and FV, Dark matter constraints, Heavy resonances (flavons).

(N+1)- Higgs doublet models

- "Higgs couplings and new signals from Flavon-Higgs mixing effects within multi-scalar model", arXive: [hep-ph], J. L. Diaz-Cruz, U. J. Saldaña-Salazar,
- "Inert Dark Matter Model with an extra CP violation induced by a complex singlet", J. Phys. G16, arXive: [hep-ph], C. Bonilla, D. Sokolowska, N. Darvishi, J. L. Diaz-Cruz, M. Krawczyk,
- "The Two Higgs Doublet Model with textures: 2HDM-Tx", arXive: [hep-ph], J.L. Diaz-cruz, E. Diaz, M. Arrollo, J. Orduz, J.Ch.Phys.16
- "Has a Higgs-Flavon with $m_S = 750$ GeV mass been detected at LHC13?", Phys.Lett B16, arXive: [hep-ph], A. Bolanos, J.L. Diaz-Cruz, G. Hernandez-Tome, G. Tavares,

Construction of a 3+1 Higgs doublets model

- To study possible deviations from the SM Higgs couplings, we shall work with a 3+1 - Higgs doublet model (Φ_1, Φ_2, Φ_3 and Φ_4)
- The Higgs doublets only couple to one fermion type each, and thus do not induce FCNC,

  $\Phi_1 \to$ up-, $\Phi_2 \to$ down- and $\Phi_3 \to$ l,
- The model also includes one Froggart-Nielsen singlet (S) , which works to reproduce the fermion masses and CKM,
- Through Higgs-Flavon mixing, it is possible to induce Flavor Violating interactions for the Higgs boson(s),
- Φ_4 is odd under a discrete symmetry, and therefore its ligthest state is stable and a possible DM candidate,

Scalar field decomposition and Potential

These fields are written as follows

$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ \frac{v_i + \phi_i^0 + i\chi_i^0}{\sqrt{2}} \end{pmatrix}, \ (i = 1, 2, 3) \qquad \Phi_4 = \begin{pmatrix} s^+ \\ \frac{s^0 + iP^0}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

and

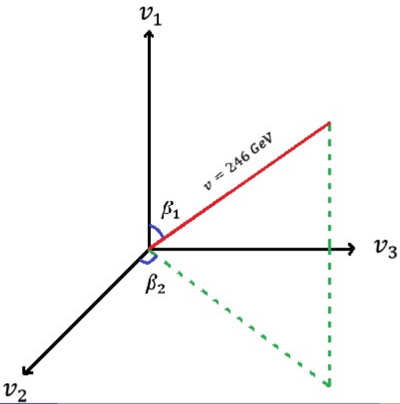
$$S = \frac{1}{\sqrt{2}}(u + s_1 + is_2). \tag{2}$$

Then, the potential is

$$V = V_{3H} + V_N + V_S + V_{HN} + V_{SH}, \tag{3}$$

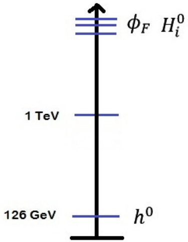
Higgs vevs in spherical coordinates

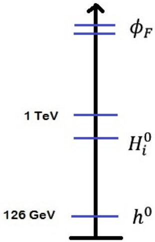
- The vevs: $< \phi_a^0 >= \frac{v_a}{\sqrt{2}}$ (a=1,3) and $< S >= \frac{u}{\sqrt{2}}$
- $v^2 = v_1^2 + v_2^2 + v_3^2 = (246GeV)^2$
- In spherical coord.:
  $v_1 = v\cos\beta_1, \quad v_2 = v\sin\beta_1\cos\beta_2 \quad \text{and} \quad v_3 = v\sin\beta_1\sin\beta_2.$

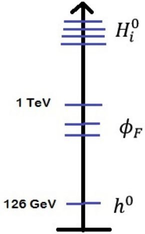


The scalar spectrum in a 3+1 Higgs doublets model

- For CPC HP 4 Real d. of f. $\rightarrow$ 4 CP-even Higgs bosons,
- To go from weak to mass-eigenstates: $\phi_a^0 = O_{ab}^T h_b$ (a,b=1,4) O_{ab} = diagonalizing matrix, it depends on form of Higgs potential,
- Imaginary components could be light, but let us focus on CP-even Higgs sector,
- Lightest state $(h_1) \simeq$ SM higgs boson, with $m_h \simeq 125$ GeV,
- Three possibilities for the spectrum are:







The Yukawa lagrangian and the FN Mechanism I

- Under Abelian Flavor symmetry ($U(1)_F$), charges of LH-fermion doublet F_i, RH- fermion singlets f_j, and the Higgs doublets Φ_a, add to $n_{ij} \neq 0$, thus Yukawa couplings are forbidden,
- Flavon field S is assumed to have flavor charge equal to -1,
- Thus, Model includes non-renormalizable operators of the type:

$$\mathcal{L}_{eff} = \alpha^a_{ij}(\frac{S}{M_F})^{n_{ij}} \bar{F}_i f_j \tilde{\Phi}_a + h.c. \quad (4)$$

  which is $U(1)_F$-invariant.
- Then, Yukawa matrices arise after the spontaneous breaking of the flavor symmetry, i.e. with vev $< S >= u$,
- The entries of Yukawa mattrices are given by $Y^f_{ij} \simeq (\frac{u}{M_F})^{n^f_{ij}}$.
- The scale M_F represents the mass of heavy fields that transmit such symmetry breaking to the quarks and leptons.

FN Mechanism- II

- Thus, the Yukawa matrices are given as: $Y_{ij}^f = \rho_{ij}^f (\lambda_F)^{n_{ij}^f}$,
- One fixes: $\lambda_F = \frac{u}{\sqrt{2}\Lambda_F} = \lambda \simeq 0.22$, which is of the order of the Cabibbo angle.
- For up-type quarks we shall consider abelian charges that give:

$$Y^u = \begin{pmatrix} \rho_{11}^u \lambda^4 & \rho_{12}^u \lambda^4 & \rho_{13}^u \lambda^4 \\ \rho_{21}^u \lambda^4 & \rho_{22}^u \lambda^2 & \rho_{23}^u \lambda^2 \\ \rho_{13}^u \lambda^4 & \rho_{23}^u \lambda^2 & \rho_{33}^u \end{pmatrix} \quad (5)$$

- Notice that $(Y^u)_{33}$ does not have a power of λ, i.e. FN mechanism does not explain top Yukawa ($\rightarrow$ Yukawa-Gauge unification?)
- This will imply that Flavon coupling with the top quark will be suppressed (in mass-eigen basis); coud be of order of charm-Higgs coupling or FV Higgs coupling htc,
- But $(Y^d)_{33}$ (and $(Y^l)_{33}$) could depend on λ,

Higgs-Flavon Mixing

- The Flavon field is written in terms of vev, real and imaginary components, as:
  $S = \frac{1}{\sqrt{2}}(u + s_1 + is_2)$,
- Then, one expands powers of Flavon field to linear order, as follows:

$$(\frac{S}{\Lambda_F})^{n_{ij}} = \lambda_F^{n_{ij}}(1 + \frac{n_{ij}}{u}(s_1 + is_2)) \quad (6)$$

- The Flavon interactions with fermions are described by the matrix:

$$Z_{ij}^f = \rho_{ij}^f n_{ij}^f (\lambda_F)^{n_{ij}^f} \quad (7)$$

- We still need to go to quark/lepton mass eigenstate basis, and take proper care of CKM matrix.

Yukawa Lagrangian for 3+1-HDM

The lagrangian for the fermion couplings of the light Higgs boson is,

$$\mathcal{L}_Y = [\frac{\eta^u}{v}\bar{U}M_uU + \frac{\eta^d}{v}\bar{D}M_dD + \frac{\eta^l}{v}\bar{L}M_lL + \kappa^u\bar{U}_i\tilde{Z}^uU_j + \kappa^d\bar{D}_i\tilde{Z}^dD_j + \kappa^l\bar{L}_i\tilde{Z}^lL_j]h^0 \quad (8)$$

For FC Higgs couplings:

$$\eta^u = O^T_{11}/\cos\beta_1, \quad \eta^d = O^T_{21}/\sin\beta_1\cos\beta_2, \quad \eta^l = O^T_{31}/\sin\beta_1\sin\beta_2,$$

For FV Higgs couplings:

$$\kappa^u = \frac{v}{u}O^T_{41}\cos\beta_1, \quad \kappa^d = \frac{v}{u}O^T_{41}\sin\beta_1\cos\beta_2, \quad \kappa^l = \frac{v}{u}O^T_{41}\cos\beta_1\sin\beta_2.$$

A 3+1 HDM - Gauge interactions

- The Higgs couplings of the lightest Higgs state ($h^0 = h^0_1$) with vector bosons are written as $g_{hVV} = g^{sm}_{hVV}\chi_V$, with χ_V:

$$\begin{aligned} \chi_V &= \frac{v_1}{v}O^T_{11} + \frac{v_2}{v}O^T_{21} + \frac{v_3}{v}O^T_{31} \\ &= \cos\beta_1\, O^T_{11} + \sin\beta_1\cos\beta_2\, O^T_{21} + \sin\beta_1\sin\beta_2\, O^T_{31} \end{aligned} \tag{9}$$

- Sum rule for light Higgs couplings:

$$\chi_V = \cos^2\beta_1\,\eta^u + \sin^2\beta_1\cos^2\beta_2\,\eta^d + \sin^2\beta_1\sin^2\beta_2\,\eta^l \tag{10}$$

- To compare with LHC limits one needs to choose a pattern for v_i and O_{ab},
- For instance, we can choose: $v_1 >> v_2 = v_3$ i.e. $\beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta >> 1$ in 2HDM)
- Another possibility is to assume equal vevs i.e. $\beta_1 = \beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta = 1$ in 2HDM)

The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{11}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ ($\epsilon_W = -0.15 \pm 0.14$),
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

Parameter scenarios in 3+1 HDM

- We will work in the 2-family limit for yukawa couplings, i.e. $V_{cb} \simeq s_{23} = s_{23}^d - s_{23}^u \simeq 0.04$
- With $s_{23}^u = r_2^u(1 + r_1^u)$, where: $r_1^u \simeq r_u$, $r_u = m_c/m_t$ and:

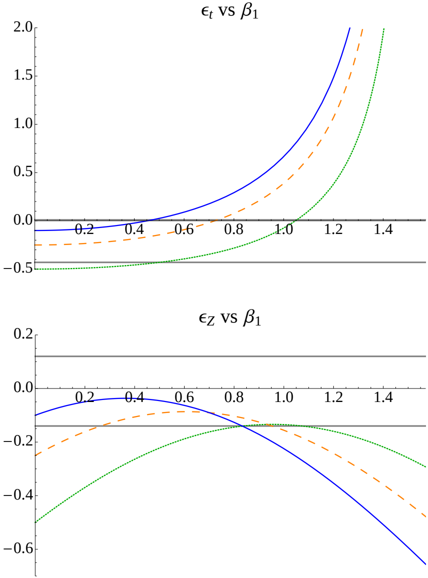
$$r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{12}$$

- For up quarks the $\tilde{Z}$-matrix is given by:

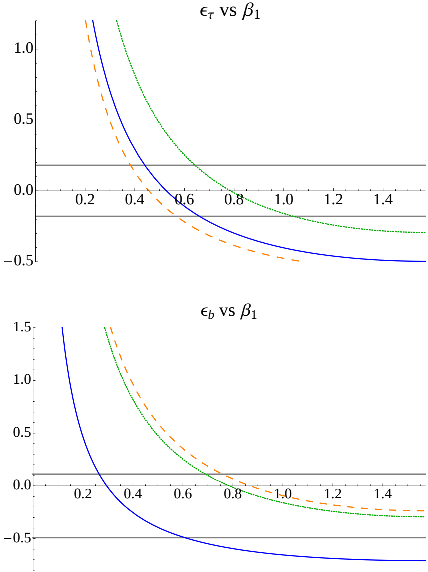
$$\tilde{Z}^u = \begin{pmatrix} Y_{22}^u & Y_{23}^u \\ Y_{23}^u & 2s_u Y_{23}^u \end{pmatrix} \tag{13}$$

- $Y_{22}^u = r_1^u Y_{33}^u, \quad Y_{23}^u = r_2^u Y_{33}^u \quad \text{and} \quad Y_{33}^u \simeq \tilde{Y}_{33}^u = \sqrt{2} m_t / v,$
- For vevs: $\cos\theta \simeq 1$ and $\sin\theta \simeq \epsilon$
- For Higgs rotation: $\alpha_1 = -\alpha_2$ and $\alpha_3 = 0$

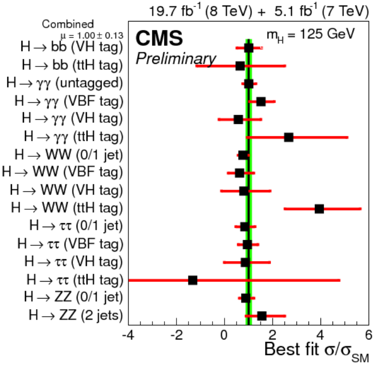
Higgs couplings in 3+1 HDM

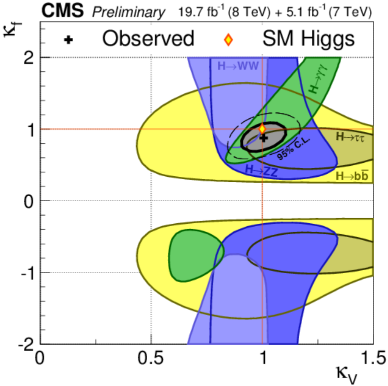


Higgs couplings in 3+1 HDM



Higgs couplings from LHC

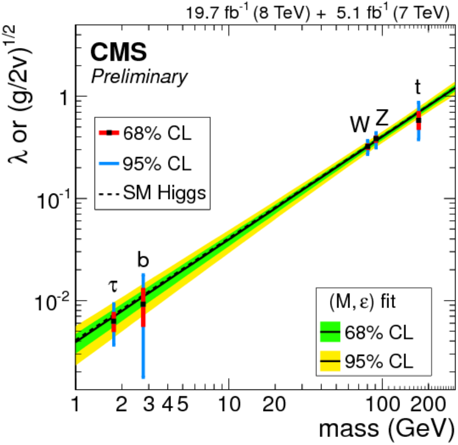


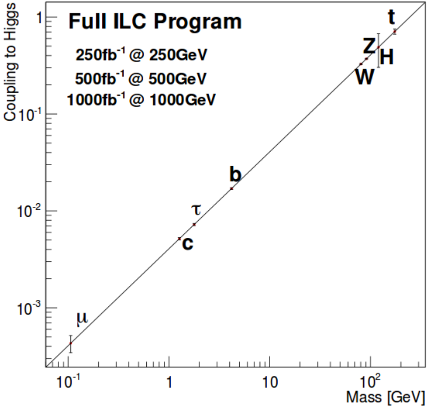


$$g_{hVV} = \kappa_V g_{hVV}^{sm}, \quad g_{hff} = \kappa_F g_{hff}^{sm},$$

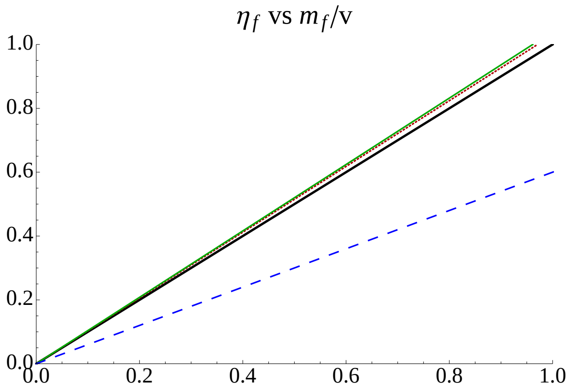
The Higgs identity from LHC:

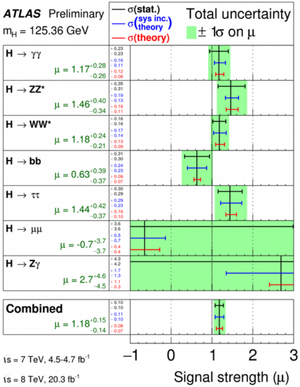
The couplings of the Higgs with particles, as a function of the mass, lays on a single line, which as been tested at LHC, i.e.





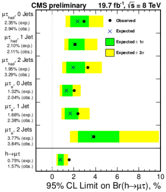
Higgs couplings in 3+1 HDM

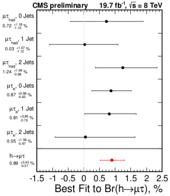




LFV Higgs decays

CMS (LHC) reported LFV Higgs decay, with $B.R.(h \to \tau\mu) \simeq 10^{-2}$,





- LFV Higgs decays $h \to l_i l_j$ first studied by Pilaftsis (PLB92),
- Diaz-Cruz and Toscano (PRD2000) focus on $h \to \tau\mu$ within eff. Lagr. , 2HDM (with $B.R.(h \to \tau\mu) \simeq 10^{-2} - 10^{-3}$),
- For MSSM: $B.R.(h \to \tau\mu) \simeq 10^{-5}$ (Diaz-Cruz, JHEP2003),
- S.Benerjee et al (arXive:1603.0592) find that HL-LHC can put limits $BR(h \to \mu\tau, e\tau) = O(0.005)$ and $BR(h \to e\mu) = O(0.0002)$. For ILC with $c.m.e. = 1$ TeV $BR(h \to e\tau, \mu\tau) = O(0.002)$.

LFV Higgs (125) BR's

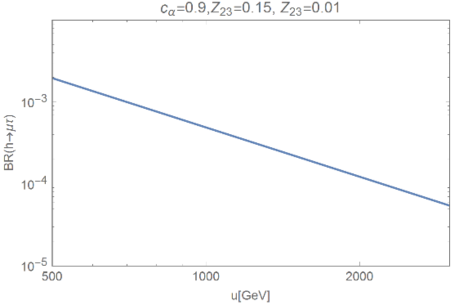
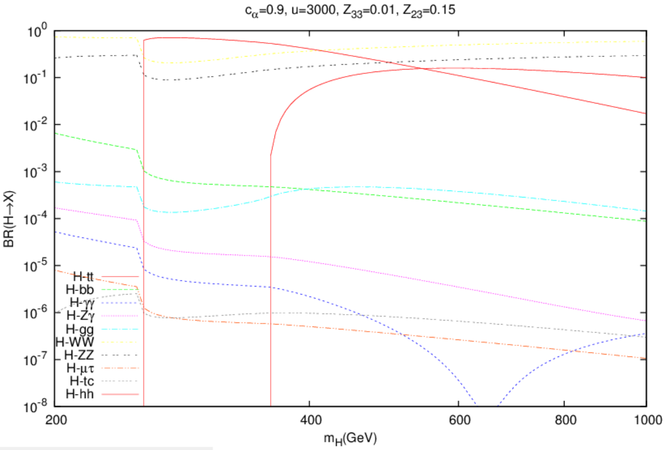


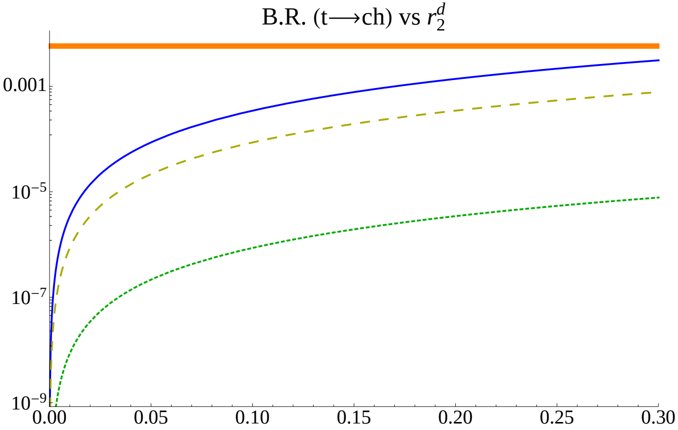
FIG. 1: Branching ratio of the flavor violating decay $h \to \bar{\mu}\tau$ of the VEV u in the IDMS-FN.

$$B.R.(h_{sm} \to \mu^+\mu^-) \simeq 2 \times 10^{-4},\ B.R.(h_{sm} \to (c\bar{c}) + \gamma) \simeq 10^{-6},$$

Heavy Higgs Decays



FCNC top Decays



Conclusions.

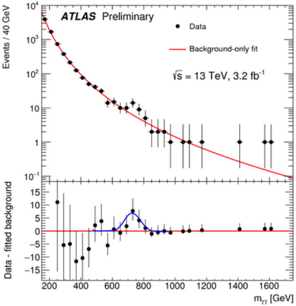
- Our (N+1)HDM provides interesting phenomenology to explore at the LHC,
- Higgs couplings could deviate from SM (single line) predictions,
- Another signal of new physics provided by $h \to \tau\mu$, with $B.R. \leq 10^{-3}$,
- Possible to have a light Flavon within the model which could be searched at LHV and beyond,
- Dark matter constrains studied within IDMS context,

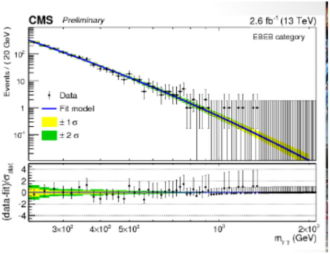
Work on flavon-Higgs phenomenology

1. I. Dorsner and S. M. Barr, “Flavon exchange effects in models with Abelian flavor symmetry,” Phys. Rev. D **65**, 095004 (2002) [hep-ph/0201207].
2. J.L. Diaz-Cruz, “A More flavored Higgs boson in supersymmetric models,” JHEP **0305**, 036 (2003) [hep-ph/0207030];
3. K. Tsumura and L. Velasco-Sevilla, “Phenomenology of flavon fields at the LHC,” Phys. Rev. D **81**, 036012 (2010) [arXiv:0911.2149 [hep-ph]].
4. E.L. Berger, S.B. Giddings, H. Wang and H. Zhang, “Higgs-flavon mixing and LHC phenomenology in a simplified model of broken flavor symmetry,” Phys. Rev. D **90**, no. 7, 076004 (2014) [arXiv:1406.6054 [hep-ph]].

And now a 750 GeV resonance shows up at LHC13 ?

A possible new particle with mass $m_X = 750$ GeV has been reported both by CMS and ATLAS from run2 data (13 TeV) in the di-photon channel:





With 3.2 fb^1 ATLAS: 3.6σ (local) $\to$ 2.3σ (after LEE),
With 2.6 fb^1 CMS: 2.6σ (local) $\to$ 2.0σ (after LEE),

Summary of 750 GeV resonance data [1]

- ATLAS excess of about 14 events (with selection efficiency 0.4) appear in at least two energy bins, suggesting a width of about 45 GeV (i.e. $\Gamma/M \simeq 0.06$),
- For CMS best fit has a narrow width, while assuming a large width ($\Gamma/M \simeq 0.06$), decreases the significance, which corresponds to a cross section of about 6 fb.
- The anomalous events are not accompanied by significant missing energy, nor leptons or jets. No resonances at invariant mass 750 GeV are seen in the new data in ZZ, W+ W- , or jj events.
- No $\gamma\gamma$ resonances were seen in Run 1 data at s = 8 TeV, altought both CMS and ATLAS data showed a mild upward fluctuation at $m_{\gamma\gamma} = 750$ GeV.
- The data at s = 8 and 13 TeV are compatible at 2σ if the signal cross section grows by at least a factor of 5.

[1] Giudice et al, arXive: 1512.05332 [hep-ph]

Production of S resonance at LHC

Resonant process $pp \to S \to \gamma\gamma$:

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{Ms\Gamma}[C_{gg}\Gamma(S \to gg) + C_{qq}\Gamma(S \to qq)]\Gamma(S \to \gamma\gamma)$$

- S is a new uncoloured boson with mass M , spin J, and total width Γ, coupled to partons in the proton, with proton c.of.m. energy s,
- Resonance S could be an scalar (spin=0) or tensor (spin=2),
- For a spin-0 resonance produced from gluon fusion and decays into two photons, the signal rate is reproduced for $\frac{\Gamma_{\gamma\gamma}\Gamma_{gg}}{MM} \simeq 1.1 \times 10^{-6}\frac{\Gamma}{M} \simeq 6 \times 10^{-8}$,
- When resonance S is produced from bottom quark annihilation, the signal is reproduced for $\frac{\Gamma_{\gamma\gamma}\Gamma_{bb}}{MM} \simeq 1.9 \times 10^{-4}\frac{\Gamma}{M} \simeq 1.1 \times 10^{-5}$,

A quick profile of the 750 resonance

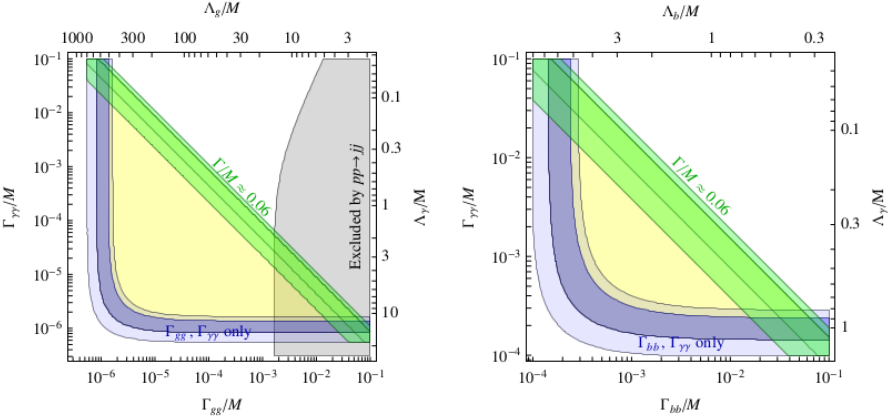
Assume the new particle S couples with photons, gluons and heavy quarks through the effective lagrangian:

$$\mathcal{L} = g_s^2(\frac{S}{2\Lambda_g}G^{a\mu\nu}G^a_{\mu\nu} + d.t.) + e^2(\frac{S}{2\Lambda_\gamma}F^{\mu\nu}F_{\mu\nu} + d.t.) + \frac{S}{\Lambda_b}Q_L^3 H D_R^3 \quad (14)$$

Then:

$$\begin{aligned}
\Gamma(S \to gg) &= \pi\alpha^2 M(\frac{M^2}{\Lambda_\gamma} + d.t.) \\
\Gamma(S \to \gamma\gamma) &= 8\pi{\alpha_s}^2 M(\frac{M^2}{\Lambda_g} + d.t.) \\
\Gamma(S \to bb) &= \frac{3M}{8\pi}(\frac{v^2}{\Lambda_b})
\end{aligned}$$

A quick profile of the 750 resonance



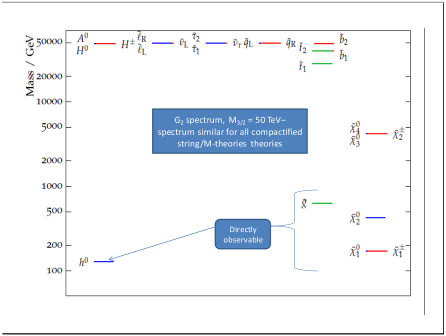
The 750 resonance in weakly coupled models

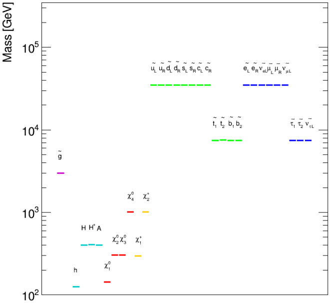
- Extended the SM by adding one (or more) scalar S and extra vector-like fermions Q f (or scalars) with mass M_f , hypercharge Y_f , charge Q_f and in the colour representation r_f , with the Yukawa coupling Y_f,
- Then the partial widths should lie in the neighbourhood of $\Gamma(S \to \gamma\gamma)/M \simeq 10^{-6}$ and $\Gamma(S \to gg)/M \simeq 10^{-3} - 10^{-6}$.
- Such widths can be easily achieved with with order one electric charges and conventional colour reps. For example, a heavy quark triplet with charge Q gives $\Gamma(S \to gg)/\Gamma(S \to \gamma\gamma) \simeq 36/Q^4$, which equals $\simeq 3000$ for Q $= 1/3$.
- Any ratio of $\Gamma(S \to gg)/\Gamma(S \to \gamma\gamma)$ can be obtained by including the appropriate content of heavy leptons and quarks with different masses.
- $Q > 5/3$ are strongly constrained by same-sign dilepton searches and the lower limit on their mass is of order 1 TeV, depending on Q.

The 750 resonance in weakly coupled models

- These weakly-coupled models can reproduce easily the event rates, however they face a challenge to reproduce the total width,
- The typical expression for a tree-level decay width is $\Gamma/M \simeq y^2/4\pi$; so the relatively large total width can be reproduced through a tree-level decay if the relevant coupling y is of order one (beyond pert.?).
- Other solution with many more states gets too barroque...
- one possibility; work within 2HDM ($\rightarrow h, H, A, H^+$), then it is possible that $m_H \simeq m_A$, and the large width is because there are two particles being produced,
- The data can not be reproduced with the simplest 2HDM,
- The data can no be reproduced within the minimal MSSM, but it does in extensions with extra quarks or NMSSM,

What about predictions for Heavy Higgses?





Heavy Higgses with $M \leq$ O(TeV) were "predicted" in Slim SUSY (Diaz-Cruz et al)

SM Higgs interactions

In the SM a Higgs doublet can work (Minimal)
SM lagrangian for a Higgs doublet $\Phi = (\phi^+, \phi^0)$ includes:

- Gauge ints. $\rightarrow$ Gauge boson masses,

  i.e. $\mathcal{L}_{HV} = (D^\mu \Phi)^\dagger (D_\mu \Phi)$

- Yukawa sector $\rightarrow$ fermion masses,

  i.e. $\mathcal{L}_Y = Y_u Q_L \Phi u_R$, etc.

- Higgs potential $V(\Phi) \rightarrow$ SSB and Higgs mass,

  i.e. $V(\Phi) = \lambda(|\Phi|^2 - v^2)^2$,

- One unknown parameter λ,
  - it determines Higgs mass: $m_h \simeq \lambda v$

Higgs vevs in spherical coordinates

- The vevs: $< \phi_a^0 >= \frac{v_a}{\sqrt{2}}$ (a=1,3) and $< S >= \frac{u}{\sqrt{2}}$
- $v^2 = v_1^2 + v_2^2 + v_3^2 = (246GeV)^2$
- In spherical coord.:
  $v_1 = v\cos\beta_1, \quad v_2 = v\sin\beta_1\cos\beta_2$ and $v_3 = v\sin\beta_1\sin\beta_2.$

Yukawa Lagrangian for 3+1-HDM

The lagrangian for the fermion couplings of the light Higgs boson is,

$$\begin{aligned}\mathcal{L}_Y &= [\frac{\eta^u}{v}\bar{U}M_uU + \frac{\eta^d}{v}\bar{D}M_dD + \frac{\eta^l}{v}\bar{L}M_lL \\ &\quad +\kappa^u\bar{U}_i\tilde{Z}^uU_j + \kappa^d\bar{D}_i\tilde{Z}^dD_j + \kappa^l\bar{L}_i\tilde{Z}^lL_j]h^0 \end{aligned} \tag{15}$$

For FC Higgs couplings:

$$\eta^u = O^T_{11}/\cos\theta, \quad \eta^d = O^T_{21}/\sin\theta\cos\phi, \quad \eta^l = O^T_{31}/\sin\theta\sin\phi,$$

For FV Higgs couplings:

$$\kappa^u = \frac{v}{u}O^T_{41}\cos\theta, \quad \kappa^d = \frac{v}{u}O^T_{41}\sin\theta\cos\phi, \quad \kappa^l = \frac{v}{u}O^T_{41}\cos\theta\sin\phi.$$

A 3+1 HDM - Gauge interactions

- The Higgs couplings of the lightest Higgs state ($h^0 = h_1^0$) with vector bosons are written as $g_{hVV} = g_{hVV}^{sm} \chi_V$, with χ_V:

$$\begin{aligned} \chi_V &= \frac{v_1}{v} O_{11}^T + \frac{v_2}{v} O_{21}^T + \frac{v_3}{v} O_{31}^T \\ &= \cos\beta_1\, O_{11}^T + \sin\beta_1 \cos\beta_2\, O_{21}^T + \sin\beta_1 \sin\beta_2\, O_{31}^T \end{aligned} \tag{16}$$

- Sum rule for light Higgs couplings:

$$\chi_V = \cos^2\beta_1\, \eta^u + \sin^2\beta_1 \cos^2\beta_2\, \eta^d + \sin^2\beta_1 \sin^2\beta_2\, \eta^l \tag{17}$$

- To compare with LHC limits one needs to choose a pattern for v_i and O_{ab},
- For instance, we can choose: $v_1 >> v_2 = v_3$ i.e. $\beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta >> 1$ in 2HDM)
- Another possibility is to assume equal vevs i.e. $\beta_1 = \beta_2 = \frac{\pi}{4}$, (similar to $\tan\beta = 1$ in 2HDM)

Higgs rotation

- We shall consider the special case when the light Higgs only mixes with the Flavon, i.e. the rotation matrix is written as: $O = \hat{O}\tilde{O}$,

$$\tilde{O} = \begin{pmatrix} c_4 & 0 & 0 & s_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_4 & 0 & 0 & c_4 \end{pmatrix} \tag{18}$$

- $\hat{O}$ diagonalizes the $3x3$ subsystem of heavy Higges-flavon:

$$\hat{O} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_1c_2 & s_1c_2 & s_2 \\ 0 & R_{21} & R_{22} & c_2s_3 \\ 0 & R_{31} & R_{32} & c_2c_3 \end{pmatrix} \tag{19}$$

where: $R_{21} = -c_1s_2s_3 - s_1c_3$, $R_{22} = c_1c_3 - s_1s_2s_3$, $R_{31} = s_1s_3 - c_1s_2c_3$, $R_{32} = -c_1s_3 - s_1s_2c_3$, and $s_i = \sin\alpha_i$, $c_i = \cos\alpha_i$.

Higgs Couplings - For special case $v_2 = v_3$ ($\phi = \frac{\pi}{4}$)

The Higgs coupling with gauge bosons is:

$$\chi_V = \cos\theta \, O^T_{11} + \frac{\sin\theta}{\sqrt{2}} \left[O^T_{21} + O^T_{31} \right] \tag{20}$$

The FC and FV Higgs-fermion couplings factors are:

$$\begin{aligned} \eta^u &= \frac{O^T_{11}}{\cos\theta} \\ \eta^d &= \frac{\sqrt{2}}{\sin\theta} O^T_{21} \\ \eta^l &= \frac{\sqrt{2}}{\sin\theta} O^T_{31} \end{aligned} \tag{21}$$

$$\begin{aligned} \kappa^u &= \frac{v}{u} O^T_{41} \cos\theta \\ \kappa^d &= \frac{v}{u} O^T_{41} \frac{\sin\theta}{\sqrt{2}} \\ \kappa^l &= \frac{v}{u} O^T_{41} \frac{\sin\theta}{\sqrt{2}} \end{aligned} \tag{22}$$

Higgs Couplings - special cases

- In this case: $O^T_{11} = c_4$, $O^T_{21} = s_4 R_{31}$, $O^T_{31} = s_4 R_{32}$ and $O^T_{41} = s_4 c_2 c_3$.
- When we also assume: $\theta_2 = -\theta_1$, we have: $R_{31} = s_1 s_3 + c_1 s_1 c_3$, $R_{32} = -c_1 s_3 + s_1^2 c_3$,
- Further, when also $\theta_3 = 0$, which means that the heavy higgses do not mix with the flavon, we get: $O^T_{11} = c_4$, $O^T_{21} = s_1 c_1 s_4$, $O^T_{31} = s_1^2 s_4$ and $O^T_{41} = c_1 s_4$.

The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{23}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ ($\epsilon_W = -0.15 \pm 0.14$),
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

Parameter scenarios in 3+1 HDM

- We will work in the 2-family limit for yukawa couplings, i.e. $V_{cb} \simeq s_{23} = s^d_{23} - s^u_{23} \simeq 0.04$
- With $s^u_{23} = r^u_2(1 + r^u_1)$, where: $r^u_1 \simeq r_u$, $r_u = m_c/m_t$ and:

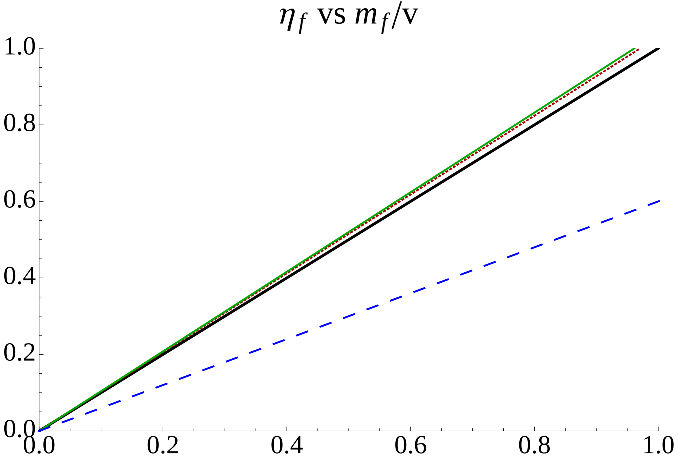
$$r^u_2 = r^d_2 \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{24}$$

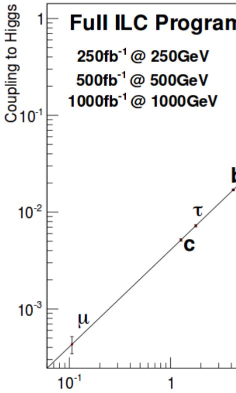
- For up quarks the $\tilde{Z}$-matrix is given by:

$$\tilde{Z}^u = \begin{pmatrix} Y^u_{22} & Y^u_{23} \\ Y^u_{23} & 2s_u Y^u_{23} \end{pmatrix} \tag{25}$$

- $Y^u_{22} = r^u_1 Y^u_{33}, \quad Y^u_{23} = r^u_2 Y^u_{33} \quad$ and $\quad Y^u_{33} \simeq \tilde{Y}^u_{33} = \sqrt{2} m_t/v$,
- For vevs: $\cos\theta \simeq 1$ and $\sin\theta \simeq \epsilon$
- For Higgs rotation: $\alpha_1 = -\alpha_2$ and $\alpha_3 = 0$

Higgs couplings in 3+1 HDM





Work on flavon-Higgs phenomenology

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2. J.L. Diaz-Cruz, "A More flavored Higgs boson in supersymmetric models," JHEP **0305**, 036 (2003) [hep-ph/0207030];
3. K. Tsumura and L. Velasco-Sevilla, "Phenomenology of flavon fields at the LHC," Phys. Rev. D **81**, 036012 (2010) [arXiv:0911.2149 [hep-ph]].
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