The 750 GeV Resonance at LHC and HEP Christmas

J. Lorenzo Diaz-Cruz
FCFM-BUAP (Mexico)

Talk at ICN/IFUNAM
(Mexico, 2016)

February 3, 2016
1. The winter of our “discontent”

2. Profile of the suspected 750 Resonance

3. Theory I (Models for all)

4. Theory II: (N+1) HDM with LFV Higgs, DM and 750 Resonance

5. Conclusions.
1.0 From the Higgs “extasis” ...

"Particle Fever makes particle physicists look like rock stars, which is how I think they should be treated."

Mark Levinson
To the SM domain

A summary of Standard Model measurements

Similar beautiful results from ATLAS

The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics
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: $3.6\sigma$ (local) $\rightarrow 2.3\sigma$ (after LEE),

With $2.6 \, fb^{-1}$ CMS: $2.6\sigma$ (local) $\rightarrow 2.0\sigma$ (after LEE),

"BUAP"
New physics or a statistical fluctuation?

(Not to mention a 145 GeV Higgs signal from Atlas too)
3.0 Profile of the suspected resonance - ATLAS

Search for a Two Photons Resonance (II)

**Results:** Events with mass in excess of 200 GeV are included in **unbinned fit**

- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_{0} of 750 GeV

- Taking a LEE in a mass range (fixed before unblinding) of **200 GeV to 2.0 TeV** the **global significance** of the excess is **2.0σ**

In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV (Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to **3.9σ**

- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)
Profile of the suspected resonance - CMS

Search for diphoton resonances

- Two categories: barrel-barrel (EBEB), barrel-endcap (EBEE)
- $p_T(\gamma) > 75$ GeV, $I_{ch} < 5$ GeV (in 0.3 cone around photon direction)
- Efficiency, scale and resolution calibrated on $Z \rightarrow ee$ and high-mass DY events
- Search for RS graviton with three assumptions on coupling: $	ilde{\kappa} = 0.01$ (narrow), 0.1, 0.2 (wide)
- Blind analysis, no changes have been made to the analysis since unblinding data in the signal region
Number of events for Atlas and CMS

ATLAS finds an excess of events with invariant mass of 750 GeV:

<table>
<thead>
<tr>
<th>Bin[GeV]</th>
<th>650</th>
<th>690</th>
<th>730</th>
<th>770</th>
<th>810</th>
<th>850</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{events}}$</td>
<td>10</td>
<td>10</td>
<td>14</td>
<td>9</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>$N_{\text{background}}$</td>
<td>11.0</td>
<td>8.2</td>
<td>6.3</td>
<td>5.0</td>
<td>3.9</td>
<td>3.1</td>
</tr>
</tbody>
</table>

while CMS events are peaked at 760 GeV\(^1\).

\(^1\)Tables from Jester arXive:1512.05777 [hep-ph]
Summary of 750 GeV resonance data

- 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, although 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 $2\sigma$ if the signal cross section grows by at least a factor of 5.

---

Production of $S$ resonance at LHC

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

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

- $S$ is a new uncoloured boson with mass $M$, spin $J$, and total width $\Gamma$, 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
  $$\frac{\Gamma_{\gamma\gamma}\Gamma_{gg}}{MM} \approx 1.1 \times 10^{-6} \frac{\Gamma}{M} \approx 6 \times 10^{-8}$$,
- When resonance $S$ is produced from bottom quark annihilation, the signal is reproduced for
  $$\frac{\Gamma_{\gamma\gamma}\Gamma_{bb}}{MM} \approx 1.9 \times 10^{-4} \frac{\Gamma}{M} \approx 1.1 \times 10^{-5}$$,
Their numerical values, computed for a resonance at \( M = 750 \text{ GeV} \) using the MSTW set of pdfs evaluated at the scale \( \mu = M \), are:

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>( C_{b\bar{b}} )</th>
<th>( C_{c\bar{c}} )</th>
<th>( C_{s\bar{s}} )</th>
<th>( C_{d\bar{d}} )</th>
<th>( C_{u\bar{u}} )</th>
<th>( C_{gg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>1.07</td>
<td>2.7</td>
<td>7.2</td>
<td>89</td>
<td>158</td>
<td>174</td>
</tr>
<tr>
<td>13 TeV</td>
<td>15.3</td>
<td>36</td>
<td>83</td>
<td>627</td>
<td>1054</td>
<td>2137</td>
</tr>
</tbody>
</table>

Thus, the gain factors \( r = \sigma_{13\text{TeV}} / \sigma_{8\text{TeV}} = [C_{gg}/s]_{13\text{TeV}} / [C_{gg}/s]_{8\text{TeV}} \) from 8 to 13 TeV:

<table>
<thead>
<tr>
<th>( r_{b\bar{b}} )</th>
<th>( r_{c\bar{c}} )</th>
<th>( r_{s\bar{s}} )</th>
<th>( r_{d\bar{d}} )</th>
<th>( r_{u\bar{u}} )</th>
<th>( r_{gg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>5.1</td>
<td>4.3</td>
<td>2.7</td>
<td>2.5</td>
<td>4.7</td>
</tr>
</tbody>
</table>
A quick profile of the 750 resonance

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

$$\mathcal{L} = g_s^2 \left( \frac{S}{2\Lambda_g} G_{a\mu\nu} G^{a\mu\nu} + d.t. \right) + e^2 \left( \frac{S}{2\Lambda_\gamma} F_{\mu\nu} F^{\mu\nu} + d.t. \right) + \frac{S}{\Lambda_b} Q^3_{LHD} D^3_R \quad (1)$$

Then:

$$\Gamma(S \rightarrow gg) = \pi \alpha_s^2 M \left( \frac{M^2}{\Lambda_\gamma} + d.t. \right)$$

$$\Gamma(S \rightarrow \gamma\gamma) = 8\pi \alpha_s^2 M \left( \frac{M^2}{\Lambda_g} + d.t. \right)$$

$$\Gamma(S \rightarrow bb) = \frac{3M}{8\pi} \left( \frac{v^2}{\Lambda_b} \right)$$
A quick profile of the 750 resonance
Model Classification

- General Approach / Effective Lagrangian,
- Multi-particle models (2HDM, SUSY, extra fermions, LR, etc),
- Composite Higgs models,
- Exotics (Axions, KK gravitons, dilaton, low unification, etc)

Multi-particle models (2HDM, SUSY, extra fermions, LR, etc),


Exotics (Axions, KK gravitons, dilaton, low unification, etc)

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 $\Gamma(S \rightarrow \gamma\gamma)/M \simeq 10^{-6}$ and $\Gamma(S \rightarrow gg)/M \simeq 10^{-3} - 10^{-6}$.

- 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 $\Gamma(S \rightarrow gg)/\Gamma(S \rightarrow \gamma\gamma) \simeq 36/Q^4$, which equals $\simeq 3000$ for $Q = 1/3$.

- Any ratio of $\Gamma(S \rightarrow gg)/\Gamma(S \rightarrow \gamma\gamma)$ 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 $Q$. 
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 \( \Gamma/M \approx y^2/4\pi \); 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 \( m_H \approx m_A \), 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 $M \leq O(\text{TeV})$ were "predicted" in Slim SUSY (Diaz-Cruz et al)
BSM with Multi-Higgs models

- The lack of understanding for the SM structure (Parameters, gauge unification, DM, BAU, etc) have motivated the search for extensions of the SM where such problems could be addressed,

- We know now that nature likes 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)

- Here, we would like to explore model with extended Higgs sector that includes:
  - N active Higgs doublets + 1 inert-type Higgs doublet + 1 singlet of FN type

- And would like to see if such model can accomodate: LFV Higgs anomaly, Dark matter constraints and the heavy resonance with $m_h = 750$ GeV observed recently at LHC,

The answer is yes ...
2.0 SM Higgs Review

- SSB occurs in the SM through a Higgs doublet (Minimal SM) i.e. \( \Phi = (\phi^+, \phi^0) \),
- The neutral scalar component gets a v.e.v. : \( \phi^0 \rightarrow \langle \phi^0 \rangle = v \), which leads to : \( SU(2)_L \times U(1)_Y \rightarrow U(1)_{em} \),
- Gauge bosons masses are generated, \( M_V = \frac{1}{4} g^2 v^2 \),
- Fermion masses also arise from SSB:
  \[
  m_f = v y_f , \quad g_{hhh} = y_f
  \]
- The essential feature of the SM Higgs is that it couples proportional to the masses of the particles,
  \[
  (hVV) : \quad \frac{2m_V^2}{v} , \quad (hff) : \quad \frac{m_f}{v} \\
  (hhh) : \quad \frac{3}{2} \lambda v , \quad (hhhh) : \quad \frac{3}{2} \lambda
  \]
SM Higgs Decays and production

![Graph showing Higgs boson decay branching ratios and production cross-sections.]

- **BR(H)**: Branching ratios of Higgs boson decays into various channels.
- **σ(pp → H)**: Production cross-sections of Higgs boson at the LHC for different production modes.

- Channels include: bb, WW, ττ, gg, cc, ZZ, γγ, Zγ, s̅s, μμ, gg → H, qqH, WH, ZH, ttH. 
- Mass scale: M_H = 125 GeV, MSTW-NNLO.
- Energy range: √s [TeV] from 78 to 33 TeV.
2.1 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.
LFV Higgs decays

Very recently CMS (LHC) have found an small B.R. for LFV Higgs decay, with $B.R.(h \rightarrow \tau\mu) \simeq 10^{-2}$,

- LFV Higgs decays $h \rightarrow l_i l_j$ were first studied by Pilaftsis (PLB92),
- Diaz-Cruz and Toscano (PRD2000) focus on $h \rightarrow \tau\mu$ within eff. Lagr. , 2HDM (with $B.R.(h \rightarrow \tau\mu) \simeq 10^{-2} - 10^{-3}$),
- For SUSY (MSSM): $B.R.(h \rightarrow \tau\mu) \simeq 10^{-5}$ (Diaz-Cruz, JHEP2003),
A 3+1 Higgs doublets model with LFV, DM and 750 resonance

So, I want to build a model where:

1. up-, down- and lepton masses come from a different doublet,
2. Flavor violation is allowed at consistent rates with FCNC phenomenology,
3. It includes a dark matter candidate (IDM),
4. And it also reproduce the 750 GeV resonance,

Could it be done? I think so....
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 ($\Phi_1, \Phi_2, \Phi_3$ and $\Phi_0$).
- The Higgs doublets only couple to one fermion type each, and thus do not induce FCNC,
  $\Phi_1 \rightarrow \text{up-}, \quad \Phi_2 \rightarrow \text{down-} \quad \text{and} \quad \Phi_3 \rightarrow l$,
- 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),
- $\Phi_0$ is odd under a discrete symmetry, and therefore its lightest state is stable and a possible DM candidate,
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 \(\Phi_a\), 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:

\[
\mathcal{L}_{eff} = \alpha^a_{ij} \left( \frac{S}{M_F} \right)^{n_{ij}} \bar{F}_i f_j \tilde{\Phi}_a + h.c.
\] (2)

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 matrices are given by \(Y_{ij}^f \simeq \left( \frac{u}{M_F} \right)^{n_{ij}^f}\).
- The scale \(M_F\) represents the mass of heavy fields that transmit such symmetry breaking to the quarks and leptons.
Thus, the Yukawa matrices are given as: \( Y_{ij}^f = \rho_{ij}^f (\lambda_F)^{n_{ij}} \),

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:

\[
Y_u = \begin{pmatrix}
\rho_{11}^u \lambda^4 & \rho_{12}^u \lambda^4 & \rho_{13}^u \lambda^4 \\
\rho_{21}^u \lambda^4 & \rho_{22}^u \lambda^2 & \rho_{23}^u \lambda^2 \\
\rho_{13}^u \lambda^4 & \rho_{23}^u \lambda^2 & \rho_{33}^u 
\end{pmatrix}
\tag{3}
\]

Notice that \((Y_u^u)_{33}\) does not have a power of \(\lambda\), i.e. FN mechanism does not explain top Yukawa (\(\rightarrow\) Yukawa-Gauge-Higgs unification?)

This will imply that Flavon coupling with the top quark will be suppressed (in mass-eigen basis); could be of order of charm-Higgs coupling or FV Higgs coupling \(htc\),

But \((Y_d^d)_{33}\) (and \((Y_l^l)_{33}\)) could depend on \(\lambda\),
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:
  \[
  \left( \frac{S}{\Lambda_F} \right)^{n_{ij}} = \lambda_F^{n_{ij}} (1 + \frac{n_{ij}}{u} (s_1 + is_2))
  \]  
  (4)

- The Flavon interactions with fermions are described by the matrix:
  \[
  Z^f_{ij} = \rho^f_{ij} n^f_{ij} (\lambda_F)^{n^f_{ij}}
  \]  
  (5)

- We still need to go to quark/lepton mass eigenstate basis, and take proper care of CKM matrix.
The scalar spectrum in a 3+1 Higgs doublets model

- For CPC HP 4 Real d. of f. → 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 \( (h_1) \approx \) SM higgs boson, with \( m_h \approx 125 \text{ GeV} \),
- Three possibilities for the spectrum are:

(See S. Davidson et al, arXive:1512.08508 ; JM Yan et al, arXive:1601.04954)
Conclusions.

- Mild evidence for new resonance with $M = 750$ GeV,
- Possible to interpret it with weakly coupled theories, but issue of large width remains open,
- More natural to interpret it with strongly interacting theories,
- Another signal of new physics provided by $h \rightarrow \tau \mu$,
- Our (N+1)HDM seems promising to explain them all,
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. → Gauge boson masses,**
  
  i.e. $\mathcal{L}_{HV} = (D^\mu \Phi)^\dagger (D_\mu \Phi)$

- **Yukawa sector → fermion masses,**
  
  i.e. $\mathcal{L}_Y = Y_u Q_L \Phi u_R$, etc.

- **Higgs potential $V(\Phi) → SSB$ and Higgs mass,**
  
  i.e. $V(\Phi) = \lambda (|\Phi|^2 - v^2)^2$

- **One unknown parameter $\lambda$,**
  - it determines Higgs mass: $m_h \simeq \lambda v$
The vevs: $< \phi_0^a > = \frac{v_a}{\sqrt{2}}$ (a=1,3) and $< S > = \frac{u}{\sqrt{2}}$

$v^2 = v_1^2 + v_2^2 + v_3^2 = (246 \text{GeV})^2$

In spherical coord.:

$v_1 = v \cos \beta_1$, $v_2 = v \sin \beta_1 \cos \beta_2$ 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,

\[
\mathcal{L}_Y = \left[ \frac{\eta_u}{v} \bar{U} M_u U + \frac{\eta_d}{v} \bar{D} M_d D + \frac{\eta_l}{v} \bar{L} M_l L \\
+ \kappa^u \bar{U}_i \tilde{Z}^u U_j + \kappa^d \bar{D}_i \tilde{Z}^d D_j + \kappa^l \bar{L}_i \tilde{Z}^l L_j \right] h^0
\] 

(6)

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:

\[\kappa^u = \frac{v}{u} O^T_{41} \cos \theta, \quad \kappa^d = \frac{v}{u} O^T_{41} \sin \theta \cos \phi, \quad \kappa^l = \frac{v}{u} O^T_{41} \cos \theta \sin \phi.\]
The Higgs couplings of the lightest Higgs state \( h^0 = h_1^0 \) with vector bosons are written as \( g_{hVV} = g_{hVV}^{\text{sm}} \chi_V \), with \( \chi_V \):

\[
\chi_V = \frac{v_1}{\nu} O_{11}^T + \frac{v_2}{\nu} O_{21}^T + \frac{v_3}{\nu} O_{31}^T
\]

\[
= \cos \beta_1 O_{11}^T + \sin \beta_1 \cos \beta_2 O_{21}^T + \sin \beta_1 \sin \beta_2 O_{31}^T
\]

(7)

Sum rule for light Higgs couplings:

\[
\chi_V = \cos^2 \beta_1 \eta^u + \sin^2 \beta_1 \cos^2 \beta_2 \eta^d + \sin^2 \beta_1 \sin^2 \beta_2 \eta^l
\]

(8)

To compare with LHC limits one needs to choose a pattern for \( v_i \) and \( O_{ab} \),

- For instance, we can choose: \( v_1 \gg v_2 = v_3 \) i.e. \( \beta_2 = \frac{\pi}{4} \),
  (similar to \( \tan \beta \gg 1 \) 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: $O = \hat{O}\tilde{O}$,

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

(9)

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

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

(10)

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 $v_2 = v_3 \left( \phi = \frac{\pi}{4} \right)$

The Higgs coupling with gauge bosons is:

$$\chi_V = \cos \theta O_{11}^T + \frac{\sin \theta}{\sqrt{2}} \left[ O_{21}^T + O_{31}^T \right]$$  \hspace{1cm} (11)

The FC and FV Higgs-fermion couplings factors are:

$$\eta^u = \frac{O_{11}^T}{\cos \theta}$$
$$\eta^d = \frac{\sqrt{2}}{\sin \theta} O_{21}^T$$
$$\eta^l = \frac{\sqrt{2}}{\sin \theta} O_{31}^T$$ \hspace{1cm} (12)

$$\kappa^u = \frac{u}{v} O_{41}^T \cos \theta$$
$$\kappa^d = \frac{u}{v} O_{41}^T \frac{\sin \theta}{\sqrt{2}}$$
$$\kappa^l = \frac{u}{v} O_{41}^T \frac{\sin \theta}{\sqrt{2}}$$ \hspace{1cm} (13)
Higgs Couplings - special cases

- In this case: $O_{11}^T = c_4$, $O_{21}^T = s_4 R_{31}$, $O_{31}^T = s_4 R_{32}$ and $O_{41}^T = s_4 c_2 c_3$.

- 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: $O_{11}^T = c_4$, $O_{21}^T = s_1 c_1 s_4$, $O_{31}^T = s_1^2 s_4$ and $O_{41}^T = c_1 s_4$. 
Under the small deviations approximation:

\[ c_X = (1 + \epsilon_X) \]  \hspace{1cm} (14)

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:
  \[
  r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{15}
  \]
- For up quarks the \( \tilde{Z} \)-matrix is given by:
  \[
  \tilde{Z}^u = \begin{pmatrix}
  Y_{22}^u & Y_{23}^u \\
  Y_{23}^u & 2s_u Y_{23}^u
  \end{pmatrix} \tag{16}
  \]
  \[ Y_{22}^u = r_1^u Y_{33}^u, \quad Y_{23}^u = r_2^u Y_{33}^u \quad \text{and} \quad Y_{33}^u \simeq \tilde{Y}_{33}^u = \sqrt{2}m_t/v, \]
- 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

![Graph of Higgs couplings in 3+1 HDM](image)
Work on flavon-Higgs phenomenology


