Flavor, flavon, factory

-

(Probing FN models with low flavor-scale through LFV Flavon decays at hadron colliders becoming a flavon factory)

J. Lorenzo Diaz-Cruz
Centro Internacional de Fisica Fundamental (CIFFU)
FCFM-BUAP (Mexico)

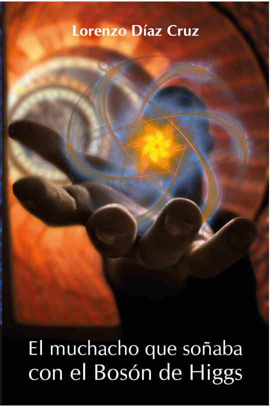
-

Talk at Annual Meeting DPYC-SMF
(CINVESTAV-IPN, CdMx, 2017)

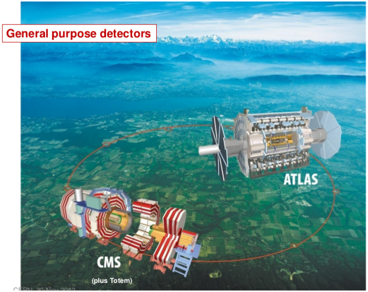
May 24, 2017

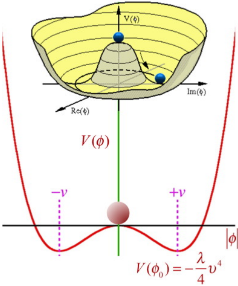
Multi-Higgs doublet models- our work

- "The Two Higgs Doublet Model with textures: 2HDM-Tx", J.L. Diaz-cruz, E. Diaz, M. Arrollo, J. Orduz,
- "Inert Dark Matter Model with an extra CP violation induced by a complex singlet", arXive: [hep-ph], D. Sokolowska, C. Bonilla, J. L. Diaz-Cruz, N. Darvishi, M. Krawczyk,
- "Higgs couplings and new signals from Flavon-Higgs mixing effects within multi-scalar model", J. L. Diaz-Cruz, U. J. Saldaña-Salazar,
- "Higgs-Flavon mixing and LFV decays at future colliders", M. Arroyo, A. Bolanos, J.L. Diaz-Cruz, G. Hernandez-Tome, G. Tavares,
- "Linking Higgs LFV and CPV", E. Barradas, J.L.D.-C., O. Felix, U. Saldana, work in progress,



The Higgs discovery at LHC

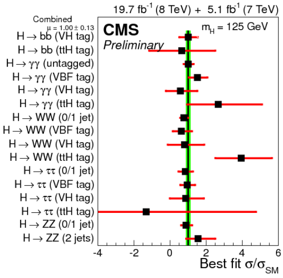
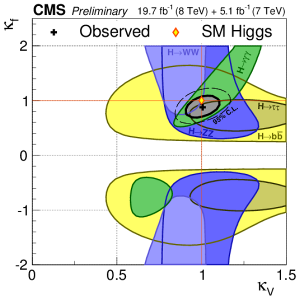
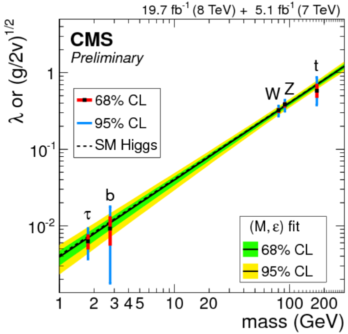
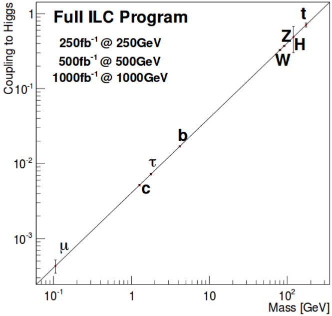




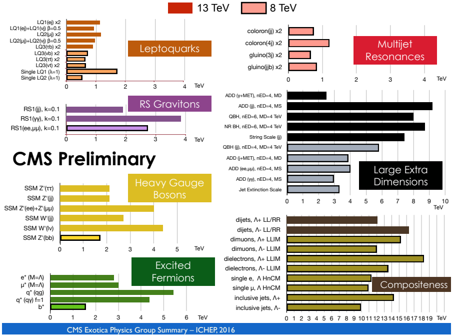
$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$

Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$

$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$


19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
mH = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb (VH tag)
H → bb (ttH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → γγ (VH tag)
H → γγ (ttH tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → WW (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → ττ (ttH tag)
H → ZZ (0/1 jet)
H → ZZ (2 jets)
Best fit σ/σSM

CMS Preliminary 19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
Observed
SM Higgs
κf
κV
H→WW
H→γγ
H→ττ
H→ZZ
H→bb̄
95% C.L.

19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
68% CL
95% CL
SM Higgs
(M, ε) fit
68% CL
95% CL
λ or (g/2v)1/2
mass (GeV)

Full ILC Program
250fb-1 @ 250GeV
500fb-1 @ 500GeV
1000fb-1 @ 1000GeV
Coupling to Higgs
Mass [GeV]

New Physics from LHC? Not yet ...



Is the party over?

I do not think so.... the field is rich, glamorous and alive!

Beyond the SM through the Higgs sector

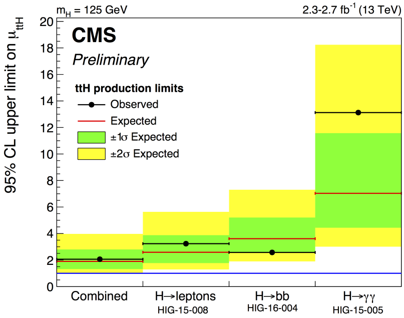
Although the Higgs looks like the SM Higgs, and no signs of new physics have been detected, Physics BSM is well motivated, e.g.

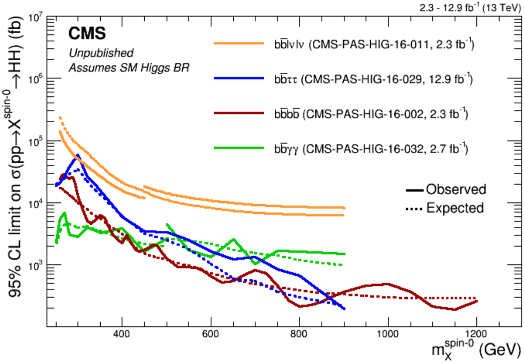
Knowing that Nature likes scalars, may be more will be detected at LHC or future colliders → Higgs sector BSM,

- Phenomenological approach (Probing Higgs couplings)
- Higgs extended models (yes, we can)
  (2HDM, singlets, triplets, LR, bla, bla ,bla)
- Model independent approach
  (Effective lagragians or Higgs portal)
- Theory and fundamental
  (SUSY, CHM, RS-XD, Emergent phenomena)

Pheno approach - Higgs

Use the LHC (and future colliders) to probe the Higgs sector:
- couplings with light fermions, Higgs self coupling, FCNC, etc etc

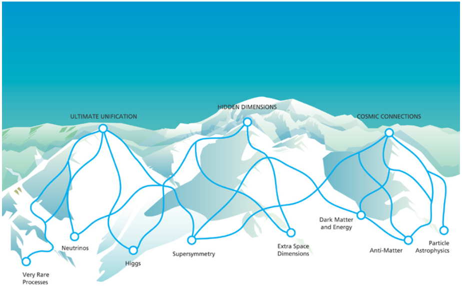




Models for BSM Physics

SM structure (Flavor parameters, gauge group, families) as well as the problems of DM, BAU, etc, motivates extensions of the SM.
In particular, Models with an extended Higgs sector have been studied extensibly:

- NHDM: SM+1s, 2HDM, 3HDM, 4HDM ($\rho = 1$)
- Triplets, LR models, .. ($\rho \neq 1$ or $\rho \simeq 1$ with some tunning)
- IDM, stable septet, etc.. ($\rightarrow$ DM candidate)
- Hierarchy problem: MSSM, Composite Higgs, XD, ..



The Higgs portal

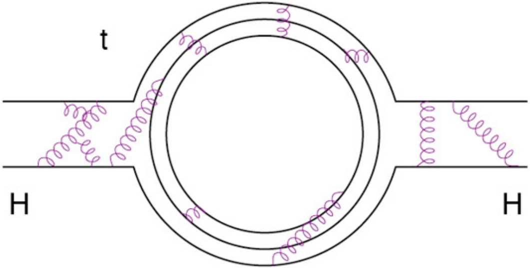
The possibility to write:

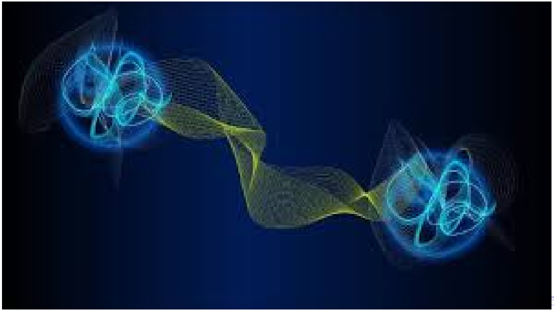
$$\mathcal{L}_{\Phi X} = \lambda_x (\Phi^\dagger \Phi)(X^\dagger X) \tag{1}$$

allows to connect the SM(Higgs) with some hidden X sector:

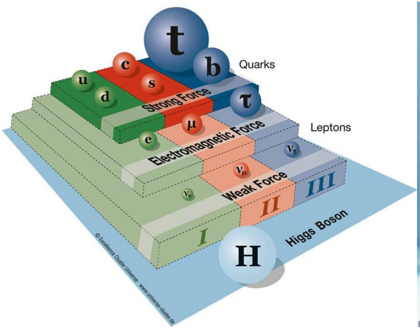
- X = Dark Matter (ex. Inert doublet),
- X = Flavon field (FN)
- X = Susy sfermion,
  ($\rightarrow$ EW phase transition, gravitational waves from early universe)
- X = Inflaton,

A theory of the Higgs sector?





Higgs and flavor physics



- SM Higgs participates in the generation of ALL fermion masses → Diagonal fermion-Higgs couplings: $\bar{F}_i f_j \Phi \rightarrow h\bar{f}_i f_i$,
- "A more flavored Higgs sector" can arise when Several Higgs multiplets participate in fermion mass generation,
- But is the Higgs the father of the 3 families?
  May be someone else is the true father ... The Flavon!

The Yukawa lagrangian and the FN Mechanism I

A model of flavor (FN) includes:

- Fermion doublets F_i (singlets f_j) and Higgs doublets (Φ_a),
- Abelian Flavor symmetry $U(1)_F$, with charges α_i that add to $n^f_{ij} = n_{F_i} + n_{f_j} + n_{\Phi_a} \neq 0 \rightarrow$ Yukawa couplings are forbidden,
- Flavon field S (complex singlet) have flavor charge,
- $U(1)_F$ symmetry allows non-renormalizable operators:

$$\mathcal{L}_{eff} = \rho^a_{ij}(\frac{S}{M_F})^{n^f_{ij}} \bar{F}_i f_j \tilde{\Phi}_a + h.c. \tag{2}$$

- Then, Yukawa matrices arise after the SSB (of flavor symmetry), i.e. with vev $< S >= u$,

$$Y^f_{ij} = \rho^a_{ij}(\frac{u}{M_F})^{n^f_{ij}} \tag{3}$$

Yukawa Matrices

- Fix ratio $\lambda_F = \frac{u}{\sqrt{2}M_F} = \lambda \simeq 0.22$. But u and M_F are free. Low-flavor scale models with $M_F = O(1)$ TeV.
- For typical charges, up-type Yukawa matrix is:

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

- Notice $(Y^u)_{33}$ does not have a power of λ, i.e. FN does not explain top Yukawa ($\rightarrow$ Yukawa-Gauge unification?)
- Then Flavon coupling with the top quark is suppressed; could be of order of hcc coupling or even htc,
- Often $(Y^d)_{33}$ and $(Y^l)_{33}$ depend on λ,

FN Mechanism- II

Higgs and flavon fields decomposition

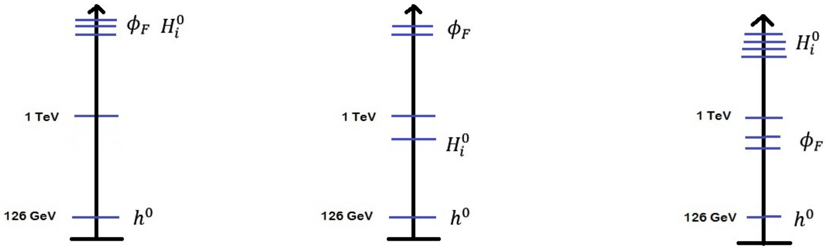
$$\Phi_a^T = [\chi_a^+, \frac{1}{\sqrt{2}}(v_a + \eta_a^0 + i\chi_a)] \tag{5}$$

$$S_F = \frac{1}{\sqrt{2}}(u + s_i + ip_i),$$

- When CP is Conserved :
  $\rightarrow$ η_a mix with s_i (and χ_a with p_i)
- When CP is violated :
  $\rightarrow$ η_a mix with s_i and p_i (and so does χ_a)

Flavon-Higgs mixing and the scalar spectrum

The possible scalar spectrum depends on the Higgs potential; it could look like:



Minimal SM extension with a singlet FN field

The model includes One Higgs doublet and one Complex singlet (FN),

$$\begin{aligned} \Phi^T &= [G^+, \frac{1}{\sqrt{2}}(v + \phi^0 + iG_z)] \qquad (6) \\ S_F &= \frac{1}{\sqrt{2}}(u + s_1 + ip_1), \end{aligned}$$

- Flavon has LFV interactions, and through mixing it can be tramsmitted to the Higgs boson,
- To go from Weak $(\phi^0, s_1, p_1) \rightarrow$ Mass-eigenstates $(\ h_b)$:

$$\phi_a^0 = O_{a1}^T h_1 + O_{ab}^T H_b \qquad (7)$$

- With CPC ϕ^0 mixes with s_1, but mass of $s_1 \geq O(1)$ TeV, which supresses LFV higgs effects,
- With CPV one can have $\phi_1^0 - p_1$ mixing $\rightarrow$ larger LFV Higgs effects.
- Lightest state $(h_1) \simeq$ SM-like higgs, with $m_h \simeq 125$ GeV,

Scalar Potential and mass eigenstates

The potential includes the terms: $V = V_\phi + V_S + V_{\phi S}$,

$$
\begin{aligned}
V_\phi &= -\frac{1}{2} m_1^2 \Phi_1^\dagger \Phi_1 + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2, \\
V_S &= -\frac{m_s^2}{2} S_F^* S_F - \frac{\mu_s^2}{2}(S_F^{*2} + S_F^2) + \lambda_s (S_F^* S_F)^2 \\
&\quad + \lambda_{s1} S_F^* S_F (S_F^{*2} + S_F^2) + \lambda_{s2}(S_F^{*4} + S_F^4) \\
&\quad + w\tilde{\lambda}_{sa}(S_F^{*3} + S_F^3) + w\tilde{\lambda}_{sb}(S_F^* S_F)(S_F^* + S_F), \\
V_{S\phi} &= \lambda_{11}(\Phi_1^\dagger \Phi_1)(S_F^* S_F) + \lambda_{12}(\Phi_1^\dagger \Phi_1)(S_F^{*2} + S_F^2) \\
&\quad + w\tilde{\lambda}_{sc}(\Phi_1^\dagger \Phi_1)(S_F^* + S_F),
\end{aligned} \tag{8}
$$

The parameters $m^2_{1,s1,s2}$, $\lambda_{s,s1,s2,11,12}$ and $\tilde{\lambda}_{sa,sb,sc}$ are all real.

Minimization and mass matrices

The minimization conditions read:

$$\begin{aligned} m_1^2 &= v^2\lambda_1 + u_1^2(\lambda_{11}+2\lambda_{12}) + u_2^2(\lambda_{11}-2\lambda_{12}) + 2\sqrt{2}\,u_1 w\tilde{\lambda}_{sc}, \\ m_s^2 &= v^2\lambda_{11} + 2u_1^2\lambda_{s12}^{+} + 2u_2^2\lambda_{s12}^{-} \\ &\quad + \frac{\sqrt{2}\,w}{2u_1}\left(v^2\tilde{\lambda}_{sc} - u_1^2\left(3\tilde{\lambda}_{sa} - 5\tilde{\lambda}_{sb}\right) + u_2^2\left(3\tilde{\lambda}_{sa} - \tilde{\lambda}_{sb}\right)\right), \\ \mu_s^2 &= v^2\lambda_{12} + u_1^2\left(\lambda_{s1} + 4\lambda_{s2}\right) + u_2^2\left(\lambda_{s1} - 4\lambda_{s2}\right) \\ &\quad + \frac{\sqrt{2}\,w}{4u_1}\left(v^2\tilde{\lambda}_{sc} + u_1^2\left(9\tilde{\lambda}_{sa} + \tilde{\lambda}_{sb}\right) - u_2^2\left(3\tilde{\lambda}_{sa} - \tilde{\lambda}_{sb}\right)\right), \end{aligned} \tag{9}$$

$\lambda_{s12}^{+} = \lambda_s + \lambda_{s1} - 2\lambda_{s2}$, and $\lambda_{s12}^{-} = \lambda_s - \lambda_{s1} - 2\lambda_{s2}$,

Minimization and mass matrices

The mass matrix in this basis (ϕ^0, s_1, p_1) is given as,

$$
\begin{aligned}
M_s^2(1,1) &= v^2\lambda_1, && (10)\\
M_s^2(1,2) &= v\left(u_1(\lambda_{11}+2\lambda_{12})+\sqrt{2}\,w\tilde{\lambda}_{sc}\right), && (11)\\
M_s^2(1,3) &= vu_2(\lambda_{11}-2\lambda_{12}), && (12)\\
M_s^2(2,2) &= 2u_1^2\left(\lambda_s+2(\lambda_{s1}+\lambda_{s2})\right) && (13)\\
&\quad +\frac{\sqrt{2}\,w}{2u_1}\left(3u_1^2(\tilde{\lambda}_{sa}+\tilde{\lambda}_{sb})+u_2^2(3\tilde{\lambda}_{sa}-\tilde{\lambda}_{sb})-v^2\tilde{\lambda}_{sc}\right), && (14)\\
M_s^2(2,3) &= u_2\left(2u_1(\lambda_s-6\lambda_{s2})-\sqrt{2}\,w(3\tilde{\lambda}_{sa}-\tilde{\lambda}_{sb})\right), && (15)\\
M_s^2(3,3) &= 2u_2^2(\lambda_s-2\lambda_{s1}+2\lambda_{s2}). && (16)\\
& && (17)
\end{aligned}
$$

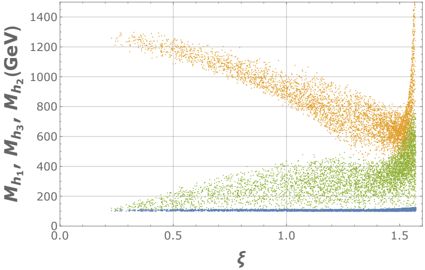
Parameter scenarios

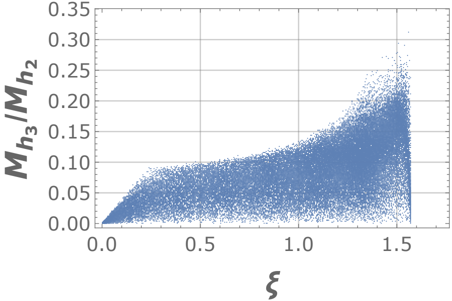
- We shall look for the following spectrum
  123 GeV $\leq m_{h_1} \leq$ 126 GeV, with $m_{h_3} < m_{h_3}$,
- Simplify the parameters of the potential with:

$$\lambda_{12} \simeq \lambda_{11}, \quad \lambda_{s2} \simeq \lambda_{s1}, \quad \tilde{\lambda}_{sb} \simeq \tilde{\lambda}_{sa}, \tag{18}$$

- One takes: $0 < \lambda_x < 0.5$ and $\lambda_1 = 0.125$, as in the SM, which is a good approximation.
- For the phase ξ we consider: $0 \leq \xi \leq \pi$,
- Fixing $v = 246$ GeV, we shall use the ratio $r_s = \frac{v}{\sqrt{2}w}$, with $0.5 \leq w \leq 10$ TeV.

Heavy Higgs and PGB flavon





Yukawa Lagrangian for CP Conserving scenario ($\xi = 0$)

Mixing only occurs between ϕ^0 and s_1, i.e.

$$\mathcal{O} = \begin{pmatrix} c_{\alpha_2} & s_{\alpha_2} & 0 \\ -s_{\alpha_2} & c_{\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{19}$$

- The Flavon field is written as: $S = \frac{1}{\sqrt{2}}(w + s_1 + ip_1)$,
- Expand to linear order: $(\frac{S}{\Lambda_F})^{n_{ij}} = \lambda_F^{n_{ij}}(1 + \frac{n_{ij}}{u}(s_1 + ip_1)) \rightarrow$

$$\mathcal{L}_Y = \rho_{ij}^f \lambda_F^{n_{ij}}[1 + \frac{n_{ij}}{u}(s_1 + ip_1)](v + \phi^0)\bar{F}_i f_j \tag{20}$$

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

$$Z_{ij}^f = \rho_{ij}^f n_{ij}^f (\lambda_F)^{n_{ij}^f} \tag{21}$$

CP Conserving Yukawa Lagrangian

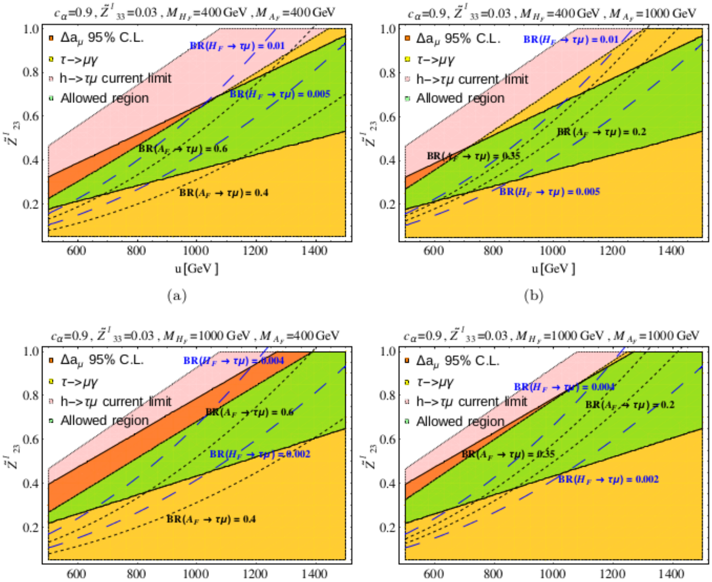
$$
\begin{aligned}
\mathcal{L}_Y &= \frac{1}{v}[\bar{U} M_u U + \bar{D} M_d D + \bar{L} M_l L](c_\alpha h + s_\alpha H_F) \\
&\quad + \frac{v}{\sqrt{2}u}[\bar{U}_i \tilde{Z}^u U_j + \bar{D}_i \tilde{Z}^d D_j + \bar{L}_i \tilde{Z}^l L_j] \\
&\quad (-s_\alpha h + c_\alpha H_F + i A_F) + h.c. \qquad (22)
\end{aligned}
$$

Thus, the (diagonal and non-diagonal) interactions of the scalars (h, H_F, A_F) with any fermion f are:

$$
\begin{aligned}
(\bar{f}_i f_i h) &= \frac{c_\alpha}{v} \bar{M}^f_{ii} - s_\alpha r_s \tilde{Z}^f_{ii} \\
(\bar{f}_i f_j h) &= -s_\alpha r_s \tilde{Z}^f_{ij} \\
(\bar{f}_i f_i H_F) &= \frac{s_\alpha}{v} \bar{M}^f_{ii} + c_\alpha r_s \tilde{Z}^f_{ii} \\
(\bar{f}_i f_j H_F) &= c_\alpha r_s \tilde{Z}^f_{ij} \\
(\bar{f}_i f_j A_F) &= i r_s \tilde{Z}^f_{ij} \gamma_5 \qquad (23)
\end{aligned}
$$

Another interesting interaction: $H_F h f_i f_j$,

LFV low energy constraints



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

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{24}$$

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:

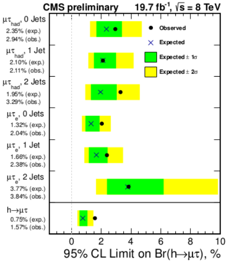
- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ $(\epsilon_W = -0.15 \pm 0.14)$,
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

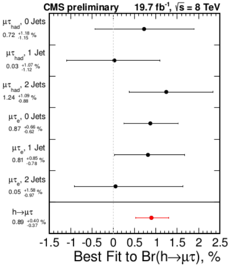
LFV Higgs decays - mini mini review

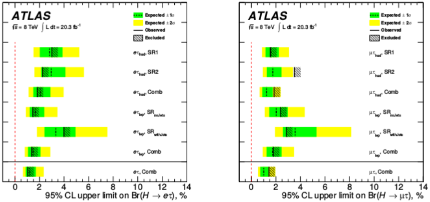
1. Earky work:
   - Bjorken and Weinberg (PRL1977): LFV can be mediated by scalars,
   - Pilaftsis (PLB92): study decays $h \to l_i l_j$ with massive neutrinos,
   - Diaz-Cruz and Toscano (PRD2000) identified that large rates for $h \to \tau\mu$ are consistent with LFV tau decays, within effective Lagrangians, 2HDM-III and SUSY (Finding: $B.R.(h \to \tau\mu) \simeq 10^{-2} - 10^{-3}$ for 2HDM and similar results for effective operators
2. Collider searches:
   - Han and Marfatia (PRL86,2001), M. Sher (PLB487,2000), K. Asamargan et al (PRD67,2003), ...
   - S.Benerjee et al (arXive:1603.0592) find that HL-LHC can put limits $BR(h \to \mu\tau, e\tau) \leq O(0.005)$ and $BR(h \to e\mu) \leq O(0.002)$.
   - S. Kanemura, T. Ota, K. Tsumura, (PRD73,2006): ILC with $c.m.e. = 1$ TeV $BR(h \to e\tau, \mu\tau) \leq O(0.002)$.
3. More 2HDM results:
   - Diaz-Cruz et al., R. Martinez et al,...
   - Harnik, Kopp, Zupan (JHEP03(2013)026)
4. LFV from SUSY loops:
   - Diaz-Cruz (JHEP2003): $B.R.(h \to \tau\mu) \simeq 10^{-5} - 10^{-6}$ with large A-terms,
   - Brignole and Rossi, PLB ; MJ Herrero et al, A. Arhrib et al (RPV-SUSY)
5. More models: Effective lagrangians, massive neutrinos see-saw, Vector-like fermions, Little Higgs, Flavons, RS-XD, ..

LFV Higgs limits from LHC7,8

Both CMS and ATLAS have presented bounds on LFV Higgs decays,



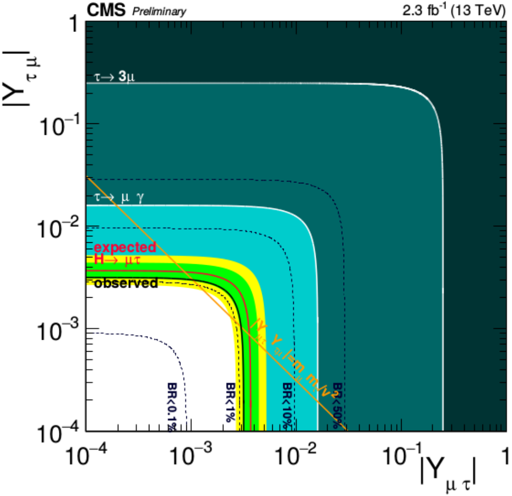




(a) (b)

Figure 5: Upper limits on LFV decays of the Higgs boson in the $H\to e\tau$ hypothesis (left) and $H\to\mu\tau$ hypothesis (right). The limits are computed under the assumption that either Br($H\to\mu\tau$)=0 or Br($H\to e\tau$)=0. The $\mu\tau_{\rm had}$ channel is from Ref. [22].

LFV Higgs limits from LHC13



LFV Higgs (125) BR's

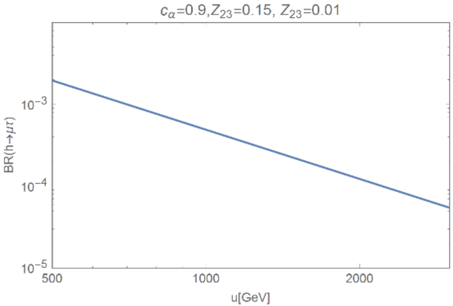
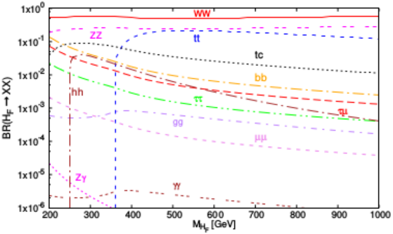


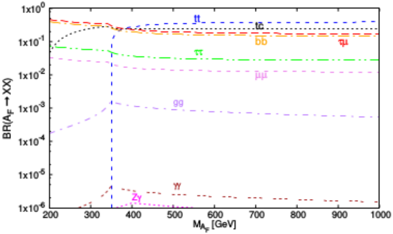
FIG. 1: Branching ratio of the flavor violating decay $h \to \bar{\mu}\tau$ of the VEV u in the IDMS-FN.

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

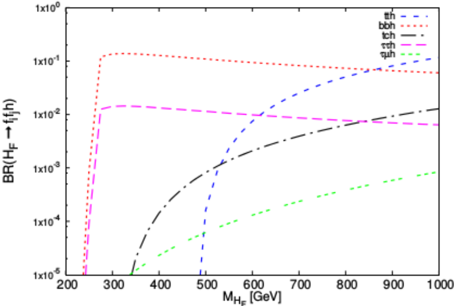
Heavy Higgs Decays



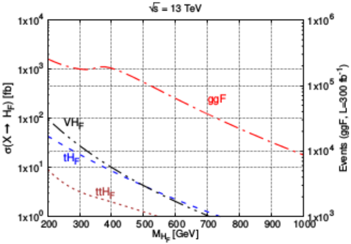
(a)



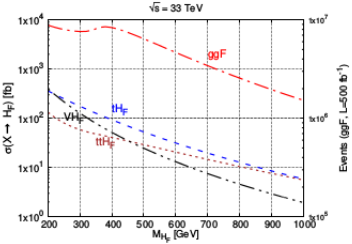
(b)



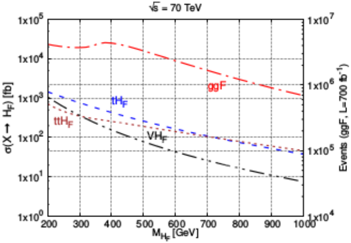
Flavon production at hadron colliders



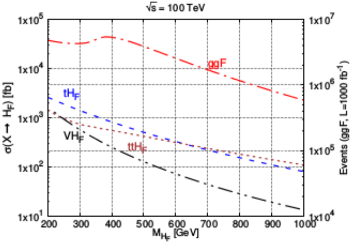
(a)



(b)

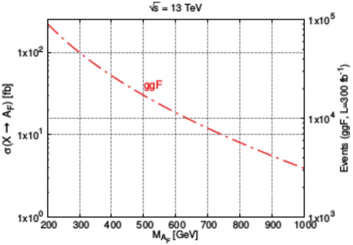


(c)

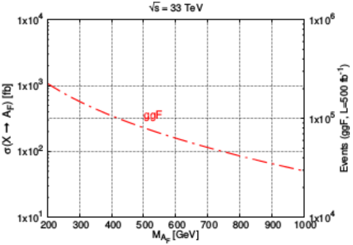


(d)

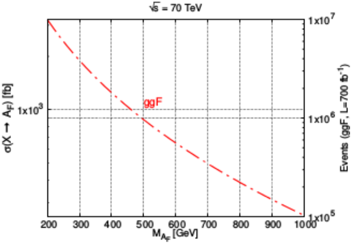
Flavon production at hadron colliders



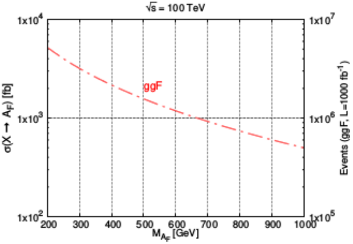
(a)



(b)

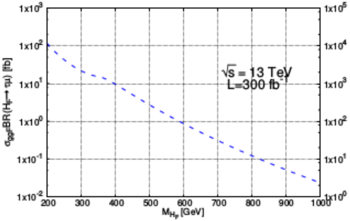


(c)

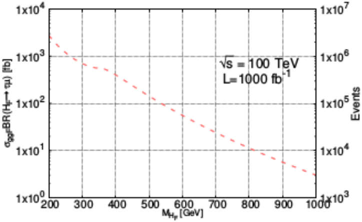


(d)

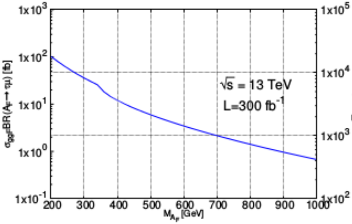
Flavon production at hadron colliders



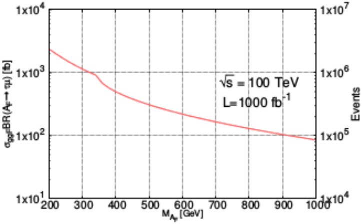
(a)



(b)



(c)



(d)

Flavon detection at hadron colliders - cuts

1. Focus on $H_F, A_F \to \tau\mu$
2. Event topology depends on tau decays:
   $\tau \to e\nu\nu$ (0-jet), $qq\nu$ (1-jet), $qq\nu$ (2-jet)
3. Cuts improve significance

	0-jet	1-jet	2-jet
P_T^μ	$> 50GeV$	$> 45GeV$	$> 25GeV$
P_T^e	$> 10GeV$	$> 10GeV$	$> 10GeV$
$\Delta\phi_{\vec{P}_P^e - \vec{E}_T^\mu}$	> 2.7	> 1.0	-
$\Delta\phi_{\vec{P}_P^e - \vec{P}_P^{miss}}$	< 0.5	< 0.5	< 0.3
M_T^e	$< 65GeV$	$< 65GeV$	$< 25GeV$
M_T^μ	$> 50GeV$	$> 40GeV$	$> 15GeV$

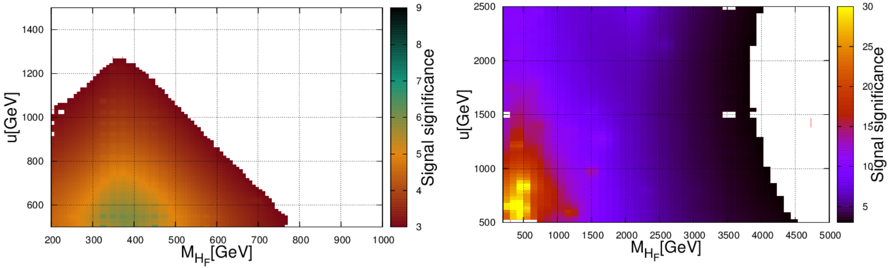
Table I: Selection criteria for each category.

Cuts for $H_F, A_F \to \tau\mu$

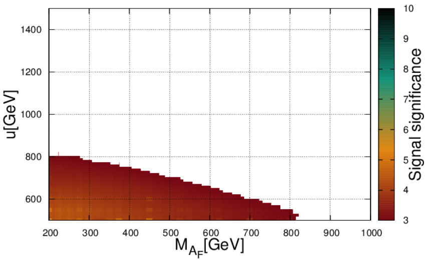
Cuts (GeV)	Signal	Background	Signal Significance
Initial (no cuts)	4813	865647480	1.6e-01
$M_{inv}(e\mu) > 300$	4055.9	17568160	0.96756
$P_T(e) > 50$	3597.0	14653738	0.93955
$P_T(\mu) > 100$	3587.2	8771524	1.2110
$\Delta\phi_{\vec{P}_e - \vec{P}_{miss}} < 0.5$	2084.4	5076039	0.9250
$N(jets) \leq 1$	2084.4	86626	6.998
MET$>$ 150	1605.2	3834.6	21.764

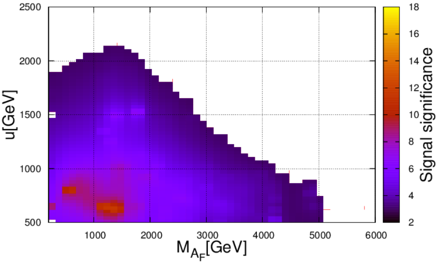
Table : Signal and Background comparison. We consider $M_{H_F} = 500$ GeV and $u = 800$ GeV.

Significance of $H_F \to \tau\mu$



Significance of $A_F \to \tau\mu$





Conclusions.

- LFV Higgs decays $H_i \to \tau\mu$ could be THE signal of BSMP (NHDM+FN),
- Our models provides plenty of signals to be searched at LHC,
- CPV flavon can be used to trasmit LFV to the light Higgs,
- 100 TeV pp collider can work as a flavon factory,

CIFFU BUAP


CIFFU
Centro Internacional de Física Fundamental
"Ciencia de Frontera desde México"
Inicio
Calenda
Inicio
¿Qué es el CIFFU?
Investigadores del CIFFU
Seminario BNFAC
Programa de visitantes
Talleres
Actividades de Investigación
Comunicados
Eventos 2017
Conferencias

FCNC in the 2HDM-III

Model includes two Higgs doublets: Φ_1 and Φ_2, with vevs (CPC): $<\phi_1^0>= v_1$ and $<\phi_2^0>= v_2$

- FCNC can be avoided with ad hoc assignment of Yukawa couplings,
- Glashow-Weinberg "Theorem": When the mass of a fermion type (u,d,l) comes from more than one Higgs doublet, FCNC are induced at tree-level,
- Used for: 2HDM-I, 2HDM-II, 2HDM-X,Y,Z , f-specific, IDM, ...
- FCNC can also be avoided with: $Y_1^f = k_f Y_2^f$ (Yukawa Alignment),
- But when general couplings are assumed, FCNC/LFV can arise at tree level, with interesting signals, e.g. $h \to \tau\mu$, $t \to ch$,
- Here we shall focus on $H_i \to \tau\mu$,

FCNC Higgs interactions and the 2HDM

Yukawa couplings for the light Higgs sometimes are written as:

$$-\mathcal{L}_Y = \bar{f}_{Li}[\frac{m_i}{v}\delta_{ij} + Y_{ij}]f_{Rj}h + \bar{f}_{Lj}[\frac{m_i}{v}\delta_{ij} + Y_{ji}]f_{Ri}h \qquad (25)$$

Low-energy FCNC and LFV processes are used to constrain the Higgs-fermion couplings Y_{ij}:

- K-K mixing, $b \to s + \gamma$, B-B mixing, $B \to D + \tau\nu$, ...
- $l_i \to l_j l_k l_k$, $l_i \to l_j \gamma$, $e - \mu$ conversion, δa_μ, etc.

LFV Higgs couplings bounds

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$\lvert \mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \dots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu} Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau} Y_{\tau e}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

(From Harni, Kopp and Zupan, JHEP03(2013)026)

Higgs couplings in 2HDM-Tx

For d-type quarks (and leptons) the complete expressions are:

$$
\begin{aligned}
\mathcal{L}_Y^q \;=\; & \frac{g}{2}\left(\frac{m_d}{m_W}\right)\bar{d}\left[\frac{\cos\alpha}{\cos\beta}\delta_{dd'}+\frac{\sqrt{2}\,\sin(\alpha-\beta)}{g\,\cos\beta}\left(\frac{m_W}{m_d}\right)(\tilde{Y}_2^d)_{dd'}\right]d'H^0 \\
& +\frac{g}{2}\left(\frac{m_d}{m_W}\right)\bar{d}\left[-\frac{\sin\alpha}{\cos\beta}\delta_{dd'}+\frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\cos\beta}\left(\frac{m_W}{m_d}\right)(\tilde{Y}_2^d)_{dd'}\right]d'h^0 \\
& +\frac{ig}{2}\left(\frac{m_d}{m_W}\right)\bar{d}\left[-\tan\beta\delta_{dd'}+\frac{\sqrt{2}}{g\,\cos\beta}\left(\frac{m_W}{m_d}\right)(\tilde{Y}_2^d)_{dd'}\right]\gamma^5 d'A^0 \\
& +\frac{g}{2}\left(\frac{m_u}{m_W}\right)\bar{u}\left[\frac{\sin\alpha}{\sin\beta}\delta_{uu'}-\frac{\sqrt{2}\,\sin(\alpha-\beta)}{g\,\sin\beta}\left(\frac{m_W}{m_u}\right)(\tilde{Y}_2^u)_{uu'}\right]u'H^0 \\
& +\frac{g}{2}\left(\frac{m_u}{m_W}\right)\bar{u}\left[\frac{\cos\alpha}{\sin\beta}\delta_{uu'}-\frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\sin\beta}\left(\frac{m_W}{m_u}\right)(\tilde{Y}_2^u)_{uu'}\right]u'h^0 \\
& +\frac{ig}{2}\left(\frac{m_u}{m_W}\right)\bar{u}\left[-\cot\beta\delta_{uu'}+\frac{\sqrt{2}}{g\,\sin\beta}\left(\frac{m_W}{m_u}\right)(\tilde{Y}_2^u)_{uu'}\right]\gamma^5 u'A^0.
\end{aligned}
$$

The texturized 2HDM (2HDM-Tx)

Higgs couplings get some structure when the Yukawa matrices include textures, i.e. 2HDM-III $\rightarrow$ 2HDM-Tx

For instance, one can use the (Hermitic) 4-texture Yukawas:

$$Y^f = \begin{pmatrix} 0 & D_f & 0 \\ D_f^* & C_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix} \tag{26}$$

For Parallel, Semi-Parallel (vs Complementary) cases

$\rightarrow$ Cheng-Sher ansatz: $\bar{Y}_{ij} = \chi_{ij} \frac{\sqrt{m_i m_j}}{v}$,

For instance, considering; $\sin(\beta - \alpha) = 0.9$ and $\tan\beta \simeq 1$, one gest that $\tau \rightarrow \mu\gamma$ implies: $|\chi_{\mu\tau}| < 10^2$, while δa_μ gives $|\chi_{\mu\tau}| < 10$.

So, essentially all constraints are satisfied with $|\chi_{\mu\tau}| < O(1)$.

Yukawa Lagrangian

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

$$\mathcal{L}_Y = [\frac{\eta^u}{v}\bar{U}M_uU + \frac{\eta^d}{v}\bar{D}M_dD + \frac{\eta^l}{v}\bar{L}M_lL + \kappa^u\bar{U}_i\tilde{Z}^uU_j + \kappa^d\bar{D}_i\tilde{Z}^dD_j + \kappa^l\bar{L}_i\tilde{Z}^lL_j]h^0 \quad (27)$$

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:

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

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:

$$\begin{aligned} \chi_V &= \frac{v_1}{v} O_{11}^T + \frac{v_2}{v} O_{21}^T + \frac{v_3}{v} O_{31}^T \\ &= \cos\beta_1 \, O_{11}^T + \sin\beta_1 \cos\beta_2 \, O_{21}^T + \sin\beta_1 \sin\beta_2 \, O_{31}^T \end{aligned} \tag{28}$$

- Sum rule for light Higgs couplings:

$$\chi_V = \cos^2\beta_1 \, \eta^u + \sin^2\beta_1 \cos^2\beta_2 \, \eta^d + \sin^2\beta_1 \sin^2\beta_2 \, \eta^l \tag{29}$$

Parameter scenarios in Higgs-Flavon model

- 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:

$$r^u_2 = r^d_2 \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{30}$$

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

$$\tilde{Z}^u = \begin{pmatrix} Y^u_{22} & Y^u_{23} \\ Y^u_{23} & 2s_u Y^u_{23} \end{pmatrix} \tag{31}$$

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

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]].
5. K. Heitu, V. Keus, N. Koivunen, O. Lebedev, "Higgs-flavon mixing and h -¿ mu tau", JHEP 1605 (2016) 026