Probing Higgs-Flavon Mixing Effects at Future Colliders

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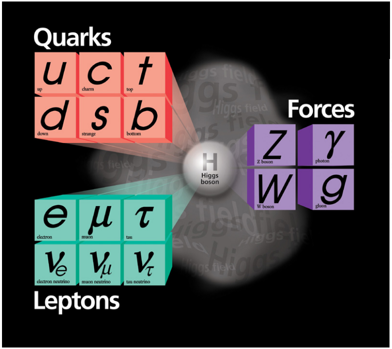
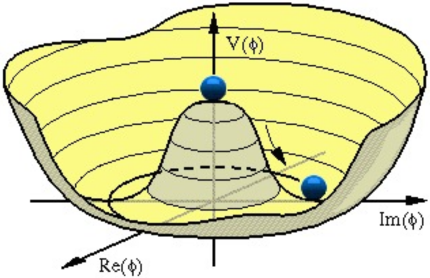
1. The Higgs Couplings in the SM and Beyond
2. Higgs couplings and 3+1 Higgs doublet model
3. Implications for the Higgs and the Top
4. Conclusions.

I) The SM Higgs Couplings and the LHC

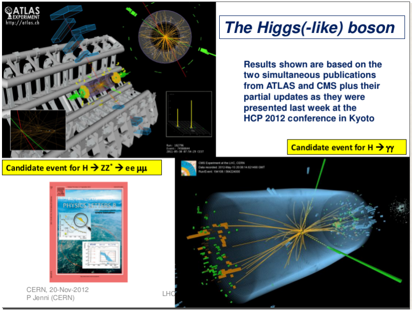
- Matter is made of quarks and leptons (3 families),
- Forces are associated with gauge symmetries ($SU(3)_c \times SU(2)_L \times U(1)_Y$ Yang-Mills),
- Masses arise from spontaneous symmetry breaking (SSB), with a light Higgs boson being the remmant of such mechanism,

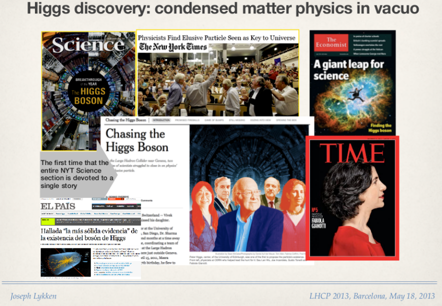




All these 3 aspects have been tested!

The discovery of the Higgs at LHC





SSB and the SM Higgs

- 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.: $\phi^0 \rightarrow < \phi^0 >= v$, 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:

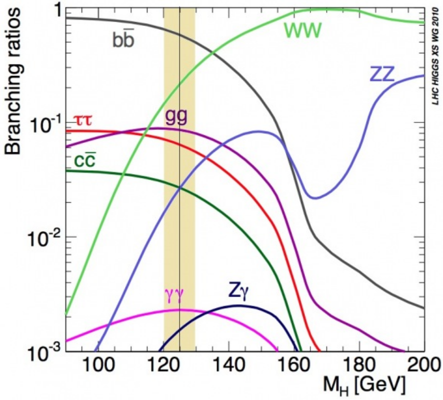
$$m_f = v\, y_f \ , \qquad g_{hff} = y_f$$

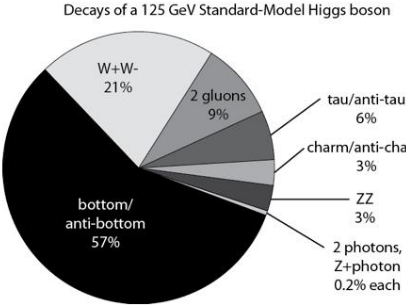
- The essential feature of the SM Higgs is that it couples proportional to the masses of the particles,

$$(hVV): \quad \frac{2m_V^2}{v}, \qquad\qquad (hff): \quad \frac{m_f}{v}$$

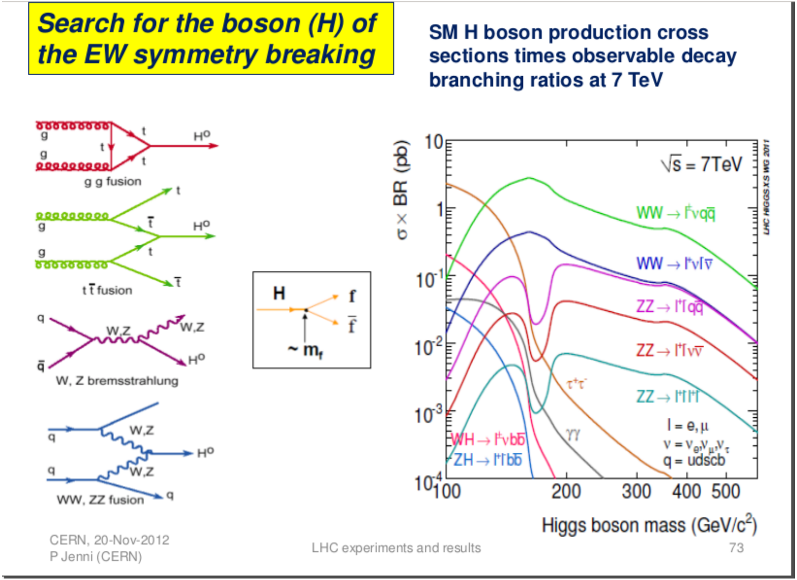
$$(hhh): \quad \frac{3}{2}\lambda v, \qquad\qquad (hhhh): \quad \frac{3}{2}\lambda$$

SM Higgs Decays

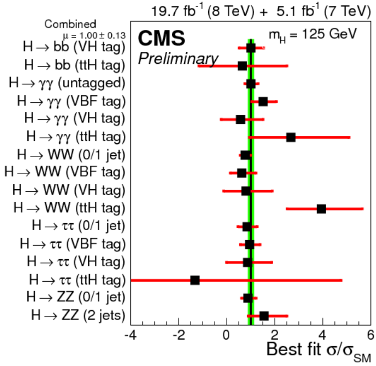


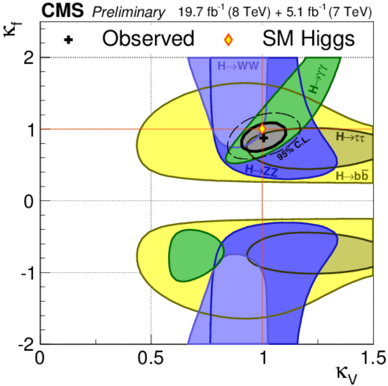


Higgs cross sections → No. of events



Higgs couplings from LHC

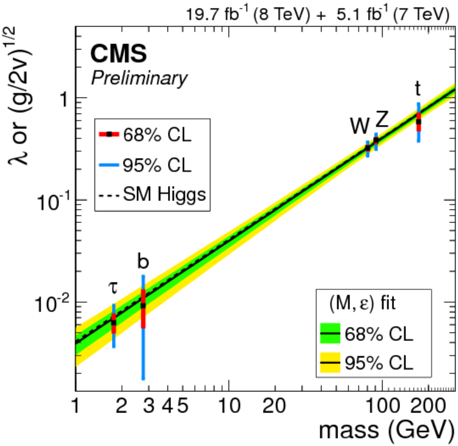




$$g_{hVV} = \kappa_V g^{sm}_{hVV}, \qquad g_{hff} = \kappa_F g^{sm}_{hff},$$

Higgs identity:

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.



Questions from the Higgs

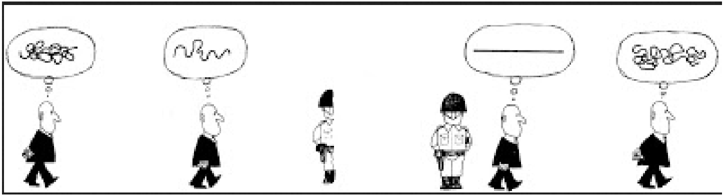
- Is it the SM Higgs? All couplings lay on a single line?
- How can we test the Higgs couplings with 2nd generation fermions?
  ($B.R.(h \to \mu^+\mu^-) \simeq 2 \times 10^{-4}$, $B.R.(h \to (c\bar{c}) + \gamma) \simeq 10^{-6}$)
- Has any signal of new physics been detected?
  (Is $h \to \gamma\gamma$ consistent with SM?)
- Signals of Flavor Violating Higgs Couplings
  (LFV Higgs decays: $h \to \tau\mu$?)
  (Top FCNC decay: $t \to c + h$?)
- Could the Higgs couplings with light quarks be extracted from:
  $\tau \to \mu + (s\bar{s})$?, $e - \mu$ conversion? DM search?
- Is the 125 GeV Higgs part of an extended Higgs Spectrum?

Open problems in the SM $\rightarrow$ New Physics

- Large/Little hierarchy problem,
- Neutrino masses and flavor problem,
- Strong CP problem,
- Dark Matter, Cosmological constant (Dark energy),
- Some deviations from the SM (a few std. dev.), e.g. Δa_μ, etc.

SM and Beyond (with Quino cartoon)

A theoretical physicist walks by thinking about SUSY, XD, Composite Higgs, GUTs, String theory..... When he/she meets LHC experimentalist, thinks all we have is the SM....



... but after passing by, thinks again in SUSY, XD,..

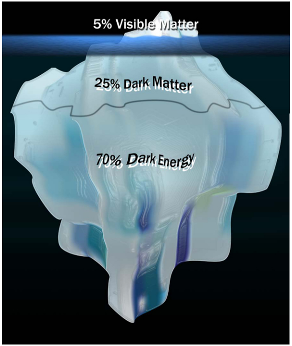
BSM with Multi-Higgs models

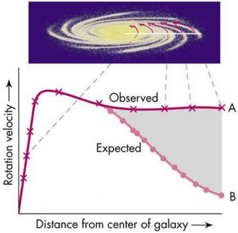
- For a while, multi-higgs models were mainly motivated by its connection with Hierarchy problem (e.g. minimal SUSY needs 2HDM),
- But may be a one-by-one solutions to SM problemas is not realized in nature, rather new physics will be more barroque,
- We know that nature likes scalars, so may be more will be detected at LHC or future colliders, and from their properties we will build the new theory BSM,
- In particular, it could be interesting to search for the association between Higgs physics and flavor problem,
- The SM Higgs boson knows about flavor to a certain extent, i.e. it distinguish generations through the diagonal fermion masses,
- But in extentions of the SM one could get a "more flavored Higgs sector", where the Higgs couples with fermions of different families.

Multi-Higgs doublet model- Higgs couplings

- In multi-Higgs doublet models, it is possible that Higgs couplings with fermions could lay on multiple lines, i.e.
- One doublet: fermion couplings could lay on a single line,
- Two doublets: " " " " two lines,
- Three doublets: " " " " three lines
- ex. In 2HDM-II d-type and lepton masses come from one doublet, while up-type masses come from the second doublet, thus Higgs couplings with d-type quarks and leptons will lay on one line, while up-type quark couplings will lay on a second line, (modulo decoupling limit issues)

Dark Matter Connections





Within multi-higgs models it is possible to imposse a discrete symmetry (ex Z_2), such that a Z_2-odd Higgs doublet does not develops a vev and contains a viable DM candidate (IDM, IDMS).

A 3+1 Higgs doublets model

So, I want to build a model where:

1. To study possible deviations from the SM Higgs couplings, we shall assume that up-, down- and lepton masses, come from its own Higgs doublet,
2. Flavor violation is allowed, at consistent rates with FCNC phenomenology, including an observable rate for $h \to \tau\mu$,
3. It includes a dark matter candidate, which is assumed to arise from an inert Higgs doublet (IDM)

$\rightarrow$ 3+1 Higgs doublet model,

Construction of a 3+1 Higgs doublets model

- We shall work with a 3+1 - Higgs doublet model:
  Φ_1, Φ_2, Φ_3 and Φ_0
- The Higgs doublets only couple to one fermion type each, and thus do not induce FCNC, (Glashow-Weinberg theorem)

  $\Phi_1 \to$ up-, $\Phi_2 \to$ down- and $\Phi_3 \to$ l,
- The model also includes one Froggart-Nielsen singlet (S) , to reproducuce the hierarchy in fermion masses and CKM,
- Through Higgs-Flavon mixing, it is possible to induce Flavor Violating interactions for the Higgs boson(s),
- Φ_0 is odd under a discrete symmetry, and therefore its ligthest 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 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:

$$\mathcal{L}_{eff} = \alpha_{ij}^a (\frac{S}{M_F})^{n_{ij}} \bar{F}_i f_j \tilde{\Phi}_a + h.c. \tag{1}$$

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 $Y_{ij}^f \simeq (\frac{u}{M_F})^{n_{ij}^f}$.
- 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: $Y^f_{ij} = \rho^f_{ij}(\lambda_F)^{n^f_{ij}}$,
- 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:

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

- Notice that $(Y^u)_{33}$ does not have a power of λ, 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), i.e. it could be of order of $hc\bar{c}$ coupling or the FV coupling $ht\bar{c}$,
- 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:

$$(\frac{S}{\Lambda_F})^{n_{ij}} = \lambda_F^{n_{ij}}(1 + \frac{n_{ij}}{u}(s_1 + is_2)) \tag{3}$$

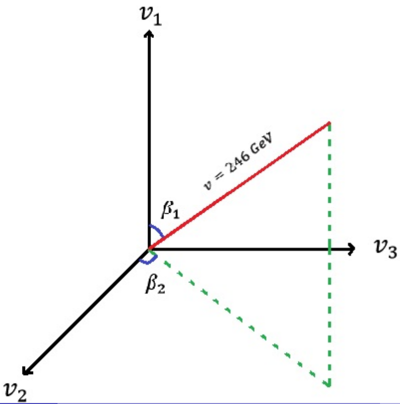
- The Flavon interactions with fermions are described by the matrix:

$$Z_{ij}^f = \rho_{ij}^f n_{ij}^f (\lambda_F)^{n_{ij}^f} \tag{4}$$

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

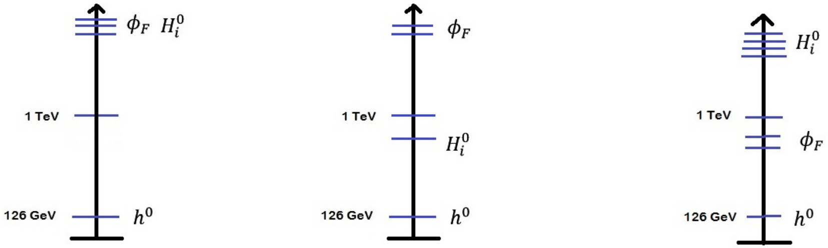
Higgs vevs in spherical coordinates

- 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:



Yukawa Lagrangian for 3+1-HDM

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

$$\begin{aligned} \mathcal{L}_Y &= [\frac{\eta^u}{v}\bar{U}M_uU + \frac{\eta^d}{v}\bar{D}M_dD + \frac{\eta^l}{v}\bar{L}M_lL \\ &\quad +\kappa^u\bar{U}_i\tilde{Z}^uU_j + \kappa^d\bar{D}_i\tilde{Z}^dD_j + \kappa^l\bar{L}_i\tilde{Z}^lL_j]h^0 \end{aligned} \tag{5}$$

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:

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

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:

$$\begin{aligned}\chi_V &= \frac{v_1}{v}O_{11}^T + \frac{v_2}{v}O_{21}^T + \frac{v_3}{v}O_{31}^T \\ &= \cos\beta_1\, O_{11}^T + \sin\beta_1\cos\beta_2\, O_{21}^T + \sin\beta_1\sin\beta_2\, O_{31}^T\end{aligned} \tag{6}$$

- Sum rule for FC light Higgs couplings:

$$\chi_V = \cos^2\beta_1\,\eta^u + \sin^2\beta_1\cos^2\beta_2\,\eta^d + \sin^2\beta_1\sin^2\beta_2\,\eta^l \tag{7}$$

- 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 Couplings - For special case $v_2 = v_3$ $(\beta_2 = \frac{\pi}{4})$

The Higgs coupling with gauge bosons is:

$$\chi_V = \cos\beta_1\, O^T_{11} + \frac{\sin\beta_1}{\sqrt{2}}\left[O^T_{21} + O^T_{31}\right] \tag{8}$$

The FC and FV Higgs-fermion couplings factors are:

$$\begin{aligned} \eta^u &= O^T_{11}/\cos\beta_1 \\ \eta^d &= \frac{\sqrt{2}}{\sin\beta_1} O^T_{21} \\ \eta^l &= \frac{\sqrt{2}}{\sin\beta_1} O^T_{31} \end{aligned} \tag{9}$$

$$\begin{aligned} \kappa^u &= \frac{v}{u} O^T_{41} \cos\beta_1 \\ \kappa^d &= \frac{v}{u} O^T_{41} \frac{\sin\beta_1}{\sqrt{2}} \\ \kappa^l &= \frac{v}{u} O^T_{41} \frac{\sin\beta_1}{\sqrt{2}} \end{aligned} \tag{10}$$

Higgs rotation - special cases

We shall also assume: $O^T_{11} > O^T_{i1}$ and $O^T_{i1} \simeq O^T_{j1}$

Then, using $O^T O = O O^T = I$, one can write:

$$(O^T_{11})^2 + (O^T_{21})^2 + (O^T_{31})^2 + (O^T_{41})^2 = 1 \tag{11}$$

Finally, one can express O^T_{j1} in terms of O^T_{11}:

$$O^T_{j1} = \sqrt{\frac{1 - (O^T_{11})^2}{3}} \tag{12}$$

Then, we consider several values: $O_{11} = 0.5,\ 0.75,\ 0.9,$

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

Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{13}$$

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:

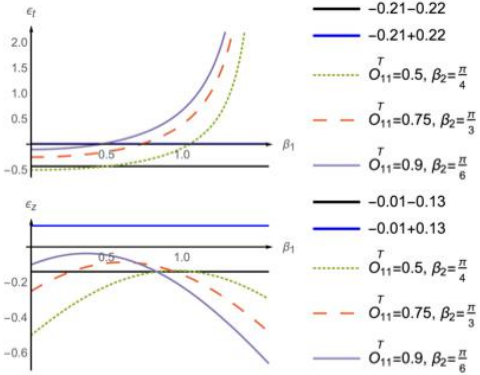
$$r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \tag{14}$$

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

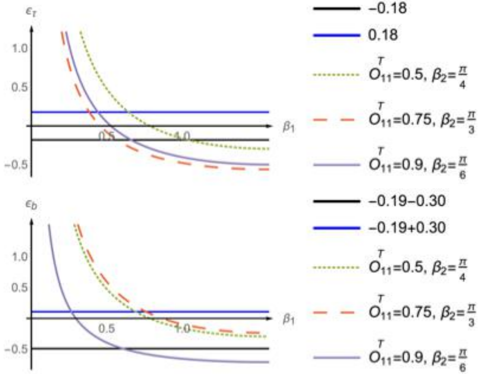
$$\tilde{Z}^u = \begin{pmatrix} Y_{22}^u & Y_{23}^u \\ Y_{23}^u & 2s_u Y_{23}^u \end{pmatrix} \tag{15}$$

- $Y_{22}^u = r_1^u Y_{33}^u, \quad Y_{23}^u = r_2^u Y_{33}^u \quad$ and $\quad Y_{33}^u \simeq \tilde{Y}_{33}^u = \sqrt{2} m_t/v,$
- For vevs: β_1 free, $\beta_2 = \frac{\pi}{3}, \frac{\pi}{4}, \frac{\pi}{6}$
- For Higgs rotation: $O_{11} = 0.5, 0.75, 0.9,$

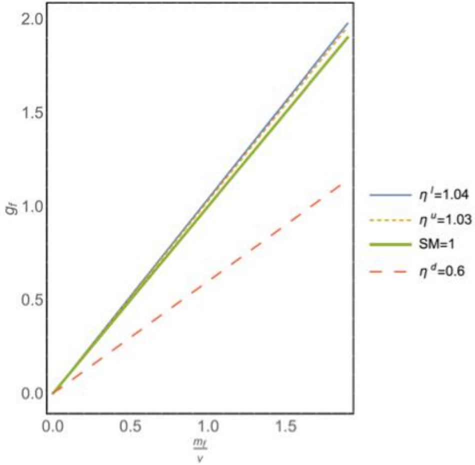
Higgs couplings in 3+1 HDM

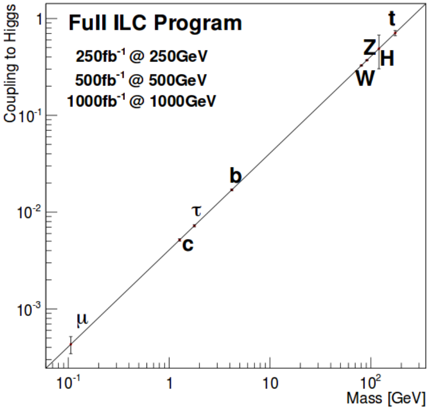


Higgs couplings in 3+1 HDM



Higgs couplings in 3+1 HDM





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]].

FCNC Constraints

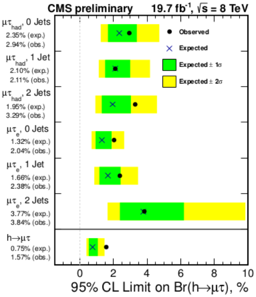
"Peligro" = Danger

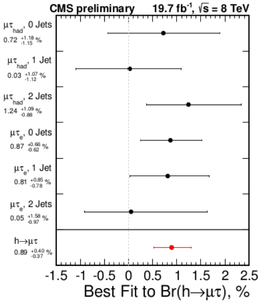
4) Higgs-Flavon Mixing phenomenology

- LFV Higgs decays
- FCNC top decays
- Higgs+top production at LHC

LFV Higgs decays

- LFV Higgs decays $h \to l_i l_j$ were first studied by Pilaftsis (PLB92),
- $h \to \tau\mu$ proposed by Diaz-Cruz and Toscano (PRD2000) within eff. Lagr. , 2HDM and MSSM (with $B.R.(h \to \tau\mu) \simeq 10^{-2} - 10^{-3}$ in 2HDM-III),
- For MSSM: $B.R.(h \to \tau\mu) \simeq 10^{-5}$ (Diaz-Cruz et al, etc),
- Very recently CMS (LHC) have found an small effect that looks like LFV Higgs decay, with $B.R.(h \to \tau\mu) \simeq 10^{-2}$!!!!!!!





FCNC Top Decays

- The heaviest SM particle, with $m_t = 173$ GeV $\simeq v = 246$ GeV,
- Used to say that it could give some clues to understand EWSB,
- Its decays are dominated by the 2-body (CKM-favored) decay: $t \to Wb$, with $\Gamma(t \to bW) \simeq 1.5$ GeV,
- Possible to consider decays into new particles $t \to X + Y$, where X, Y could be new particles BSM, e.g. $t \to b + H^+$,
- Rare decays could also be relevant, e.g. $t \to c + X$ (FCNC), which have very small BR's in SM,
- But FCNC decays could be greatly enhanced with physics BSM,

Rare Top Decays in SM

	Mode	SM BR	Refs.
CKM-suppressed	$BR(t \to sW)$	1.6×10^{-3}	B. Mele, hep-ph/0003064
3-body modes	$BR(t \to cWW)$	1.3×10^{-13}	E. Jenkins et al. PRD56 (97)
(near threshold)	$BR(t \to bWZ)_{res}$	2×10^{-6} ($m_t = 175$ GeV)	G. Altarelli et al. PLB502 (2001)
3-body radiative	$BR(t \to bW\gamma)$	3.5×10^{-3}	Decker et al. ZPhys.C57 (93)
4-body modes	$BR(t \to bWe^+e^-)$	$10^{-5} - 10^{-6}$	N. Quintero et al. PRD (2014)

Table : Branching ratios rare top decays

FCNC Top Decays in SM

Mode	SM BR	Refs	Refs
$BR(t \to c + \gamma)$	5×10^{-13}	Diaz-Cruz etal PRD41(90)	Eilam etal PRD44(91)
$BR(t \to c + Z)$	1.3×10^{-13}		PRD44(91)
$BR(t \to c + g)$	5×10^{-11}		PRD44(91)
$BR(t \to c + h)$	5×10^{-14}	PRD44(91) Errat. D59 (99)	Mele et al. PLB 435 (98)

Table : Branching ratios for FCNC top decays

FCNC Top Decays in SM, 2HDM-Tx and MSSM (SUSY)

Mode	SM	2HDM-Tx	SUSY MSSM
$BR(t \to c + \gamma)$	5×10^{-13}	$\simeq 10^{-7}$	$\simeq 10^{-8}$
$BR(t \to c + Z)$	1.3×10^{-13}	$\simeq 10^{-6}$	$\simeq 10^{-8}$
$BR(t \to c + g)$	5×10^{-11}	$\simeq 10^{-5}$	$\simeq 10^{-6}$
$BR(t \to c + h)$	5×10^{-14}	2×10^{-2}	$\simeq 10^{-4}$

Table : Branching ratios for FCNC top decays

FCNC top Limits

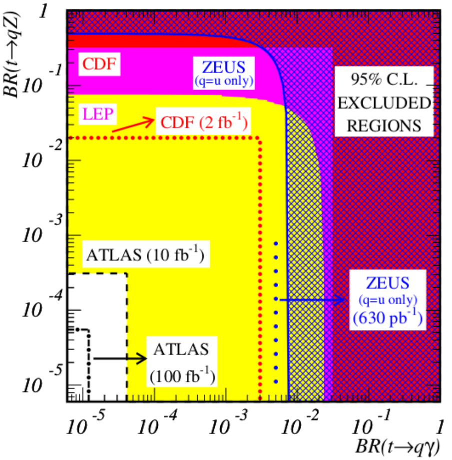


Figure 22: The present 95% CL limits on the $BR(t \to q\gamma)$ vs. $BR(t \to qZ)$ plane are shown. The expected sensitivity at the HERA ($L = 630$ pb^{-1}), Tevatron (run II) and LHC is also represented.

LHC limits on FCNC top decays

- FCNC decay: $t \to q + \gamma$ (from assoc. production $t + \gamma$), CMS (TOP-14-003): $BR(t \to u + \gamma) < 1.61 \times 10^{-4}$, $BR(t \to c + \gamma) < 1.82 \times 10^{-3}$,
- FCNC decay: $t \to q + Z$,
  CMS (arXive 1208.0957): $BR(t \to q + Z) < 2.1 \times 10^{-3}$,
  ATLAS (JHEP 2012:139): $BR(t \to c + \gamma) < 1.82 \times 10^{-3}$,
- FCNC decay into Higgs: $t \to qh$ $q = u, c$, $m_h = 125 - 126$ GeV,
  CMS (arXive 1207.6794): $BR(t \to c + h) < 5.6 \times 10^{-3}$,
  $(BR < 1.3 \times 10^{-2})$
  ATLAS (JHEP 2012:139): $BR(t \to c + h) < 7.9 \times 10^{-3}$,

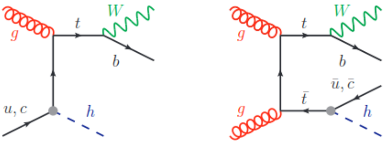
Top FCNC Decay in 3+1 HDM

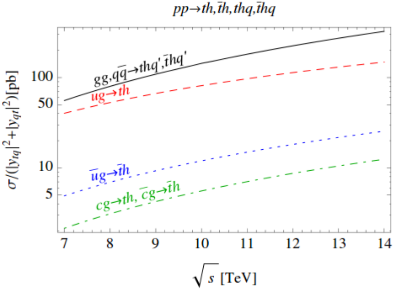
Scenario	u[TeV]	$\kappa^u \times \tilde{Z}_{23}$	$B.R.(t \to ch)$
X1	0.5	1.2×10^{-4}	8.6×10^{-9}
X2	1	6.1×10^{-5}	2.2×10^{-9}
X3	10	6.1×10^{-6}	2.2×10^{-11}
Y1	0.5	6.9×10^{-3}	2.7×10^{-5}
Y2	1	3.4×10^{-3}	6.8×10^{-6}
Y3	10	3.4×10^{-4}	6.8×10^{-8}
Z1	0.5	2.9×10^{-2}	4.8×10^{-4}
Z2	1	1.4×10^{-2}	1.2×10^{-4}
Z3	10	1.4×10^{-3}	1.2×10^{-6}

Table : The factor $\kappa^u \times \tilde{Z}^u_{23}$ and Branching ratios for $t \to ch$

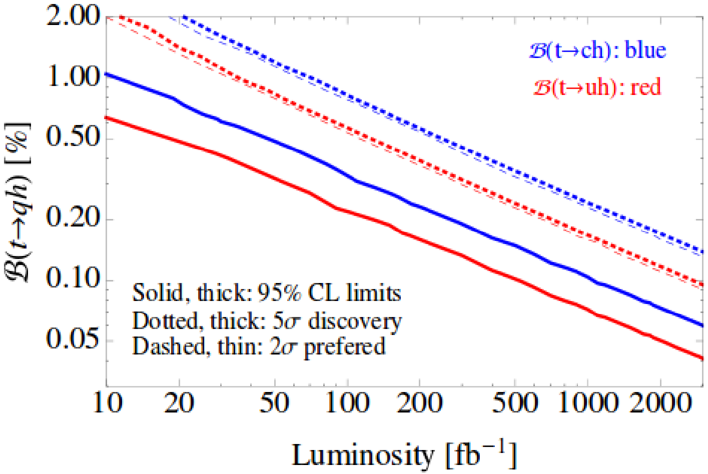
Effects of Higgs-Flavon mixing on th production at LHC

(From: A. Grekjo et al, arXive: 1404.1278 [hep-ph])





Effect on limits for $br(t \to ch)$ at LHC (from Grejko et al)



Conclusions.

- Evidence, so far, for a SM-like Higgs with $m_h = 125$ GeV,
- Tests of Higgs couplings at LHC could show deviations from SM (3+1 HDM),
- Still possible to find new physics at LHC13,
  $h \to \tau\mu$
- FCNC decays of top quark could also provide another window into PBSM,

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: $m_h \simeq \lambda v$

Multi-Higgs doublet model - FCNC

- In fact, by just adding another Higgs doublet to the SM, one could induce plenty of new flavor signals,
- 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,
- Example: 2HDM-III $\rightarrow$ 2HDM-Tx (2HDM with Yukawa Textures) $\rightarrow$ Cheng-Sher ansazt :

$$Y^f = \begin{pmatrix} 0 & D_f & 0 \\ D_f^* & C_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix} \tag{16}$$

$$\rightarrow g_{hij} = \chi_{ij} \frac{\sqrt{m_i m_j}}{v} \tag{17}$$

- Low-energy FCNC processes constraints the Higgs-fermion couplings: K-K mixing, $b \rightarrow s + \gamma$, B-B mixing, $B \rightarrow D + \tau\nu$, ..etc

Open problems in the SM with Scalars in the "solution"

- Large/Little hierarchy problem $\rightarrow$
  SUSY-2HDM, ($h, H, A, H^{\pm}$, $\tilde{q}, \tilde{l}$...),
- Neutrino masses and flavor problem $\rightarrow$
  Higgs triplets- LR symmetry, Flavons (FN),
- Strong CP problem $\rightarrow$ Axions,
- Dark Matter $\rightarrow$ IDM (2HDM),
- Cosmological constant (Dark energy) (?) ,
- Some deviations from the SM, e.g. Δa_μ, etc.

Thank you nature (for the 125 GeV Higgs)...but give us more!

The top quark decays

- 2-body (CKM-favored) decay: $t \to Wb$,
- 2-body (CKM-suppressed) decay: $t \to Wq$, $q = s, d$,
- 3-body (Radiative modes): $t \to Wb\gamma(g)$,
- FCNC decay into vector bosons: $t \to q + X$, $X = \gamma, Z, g$, $q = u, c$,
- FCNC decay into Higgs: $t \to qh$ $q = u, c$, $m_h = 125 - 126$ GeV,

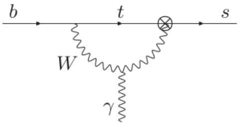
FCNC top decays in the SM

The decays width for $t \to q + V$ is of the form:

$$\Gamma(t \to c + V) \simeq |V_{cb}|^2 {\alpha_{em}}^2 \alpha_V m_t (\frac{m_b}{m_W})^4 (F_{Ph.S.}) \quad (18)$$

- The factor $(\frac{m_b}{m_W})^4$ produces a large suppression,
- Furthermore, $BR(t \to c + V) \simeq \Gamma(t \to c + V)/\Gamma(t \to bW)$,

  with $\Gamma(t \to bW) \simeq 1.55$ GeV (a two-body, CKM-favored decay)
- To be contrasted with: $b \to s + \gamma$, whose BR gets large because:
  i) Decay width goes like $f(m_t/m_W)$,
  ii) Total width is dominated by a 3-body decay $(b \to c + f\bar{f}')$,



Top FCNC decays within Supersymmetry

Although LHC is providing stronger bounds on the masses of superpartners, and, and natural solution of hierarchy problem seems less feasible, SUSY is still attractive,

- Improves Unification and o.k. with proton decay,
- Favors a light Higgs boson, in agreement with EWPT and LHC, i.e. $m_h = 125 - 126$ GeV,
- New sources of flavor and CP violation may help to get the right BAU,
- LSP is stable and a possible Dark matter candidate,
- Further, it is a new kind of symmetry, with lots of beauty ...

FCNC top decays in MSSM

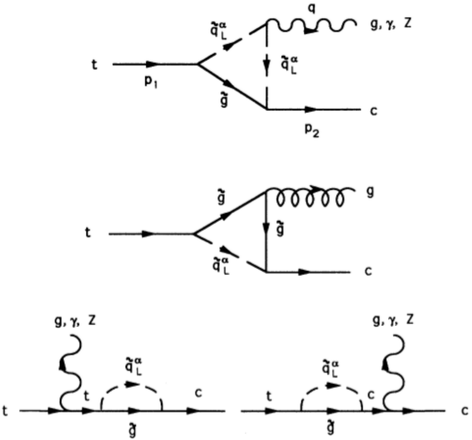


FIG. 1. The diagrams with scalar quarks and gluinos within the loop, which contribute to the top quark decay into a charm quark and a Z boson, photon, or gluon.

MSSM top FCNC top results- Y. Yang ("Short top review")

TABLE I. Maximal predictions for top-quark FCNC processes induced by stop-scharm mixings via gluino-squark loops in the MSSM. For the productions we show the hadronic cross sections at the LHC and include the corresponding charge-conjugate channels. For the decays we show the branching ratios.

	$\delta_{LL} \neq 0$		$\delta_{LR} \neq 0$	
	constraints masses	constraints all	constraints masses	constraints all
$cg \to t$	1450 fb	225 fb	3850 fb	950 fb
$gg \to t\bar{c}$	1400 fb	240 fb	2650 fb	700 fb
$cg \to tg$	800 fb	85 fb	1750 fb	520 fb
$cg \to t\gamma$	4 fb	0.4 fb	8 fb	1.8 fb
$cg \to tZ$	11 fb	1.5 fb	17 fb	5.7 fb
$cg \to th$	550 fb	18 fb	12000 fb	24 fb
$t \to ch$	1.2×10^{-3}	2.0×10^{-5}	2.5×10^{-2}	6.0×10^{-5}
$t \to cg$	5.0×10^{-5}	5.0×10^{-6}	1.3×10^{-4}	3.2×10^{-5}
$t \to cZ$	5.0×10^{-6}	5.7×10^{-7}	1.2×10^{-5}	1.8×10^{-6}
$t \to c\gamma$	9.0×10^{-7}	1.5×10^{-7}	1.3×10^{-6}	5.2×10^{-7}

Large trilinear A-terms $\to BR(t \to ch) \simeq 10^{-4}$, DC, He, Yuan, PLB (2003)

FCNC top results in MSSM (YM Yang)

Table 1: Maximal predictions for the branching ratios of FCNC top quark decays and production cross sections (hadronic) at the LHC.

	MSSM	TC2	LHC 3σ sensitivity
$t \to cZ$	1.8×10^{-6} [4]	$O(10^{-4})$ [7]	3.6×10^{-5} [11]
$t \to c\gamma$	5.2×10^{-7} [4]	$O(10^{-6})$ [7]	1.2×10^{-5} [11]
$t \to ch$	6.0×10^{-5} [4]	$O(10^{-1})$ [7]	5.8×10^{-5} [11]
$t \to cg$	3.2×10^{-5} [4]	$O(10^{-3})$ [7]	
$t \to cgg$	3.5×10^{-5} [4]	$O(10^{-3})$ [7]	
$gg \to t\bar{c}$	700 fb [4]	30 pb [8]	
$cg \to t$	950 fb [4]	1.5 pb [8]	
$cg \to tg$	520 fb [4]	3 pb [8]	
$cg \to t\gamma$	1.8 fb [4]	20 fb [8]	
$cg \to tZ$	5.7 fb [4]	100 fb [8]	
$cg \to th$	24 fb [4]	1 pb [8]	