Flavor violating decays of the Neutral Higgs bosons at the LHC

Baris Altunkaynak

with
Chung Kao and *Brent McCoy*
(in progress)

University of Oklahoma

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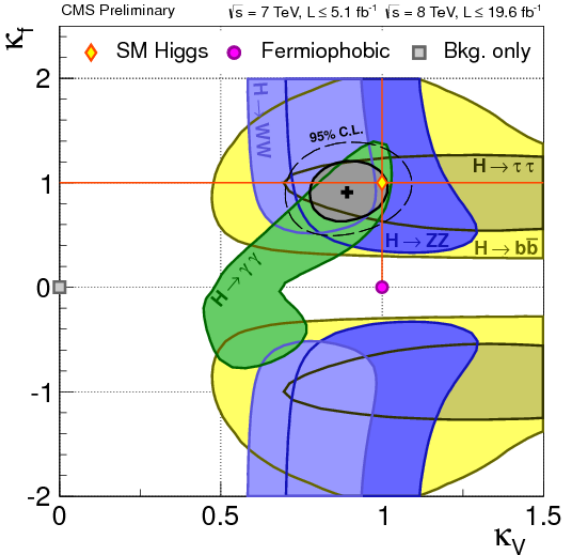
Where do we stand?



- No signs of physics beyond a 126 GeV Higgs boson.
- 126 GeV within the MSSM limits but requires heavy scalars and large mixing.
- 126 GeV Higgs looks almost the Standard Model Higgs. (Alignment)
- Where is the new physics hiding? A second Higgs doublet?

Two Higgs Doublet Model

Two Higgs Doublet Model:

- Two complex $SU(2)_L$ doublets with $Y = 1$
- The most general gauge invariant scalar potential is given by:

$$\begin{aligned}\mathcal{V}(\Phi_1, \Phi_2) &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{H.c.} \right] \\ &+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_2\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\ &+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right) \right] \Phi_1^\dagger \Phi_2 + \mathrm{H.c.} \right\}\end{aligned}$$

[*Gunion and Haber*, 1986]

- The doublet fields acquire VEVs in the form

$$\langle \Phi_a \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_a \end{bmatrix}$$

- The most general Yukawa Lagrangian for the quark sector is in the form

$$\mathcal{L}_Y = -\sum_i \left[\bar{Q}_L^0 \tilde{\Phi}_i \eta_i^{U,0} U_R^0 + \bar{Q}_L^0 \Phi_i \eta_i^{D,0} D_R \right] + \mathrm{H.c.}$$

Two Higgs Doublet Model (2)

- We can then rewrite the interaction Lagrangian for the neutral states as

$$\begin{aligned}\sqrt{2}\,\mathcal{L}_{int}^{neutral} = \quad & \bar{U}\left[-\kappa^U s_{\beta-\alpha} - \rho^U c_{\beta-\alpha}\right] Uh + \bar{D}\left[-\kappa^D s_{\beta-\alpha} - \rho^D c_{\beta-\alpha}\right] Dh \\ & + \bar{U}\left[-\kappa^U c_{\beta-\alpha} + \rho^U s_{\beta-\alpha}\right] UH + \bar{D}\left[-\kappa^D c_{\beta-\alpha} + \rho^D s_{\beta-\alpha}\right] DH \\ & + \bar{U}\left[+i\gamma_5\rho^U\right] UA + \bar{D}\left[-i\gamma_5\rho^D\right] DA\end{aligned}$$

- There are 4 models with Z_2 symmetry, where ρ matrices are constrained to be in the following form:

	Type			
	I	II	III	IV
ρ^D	$\kappa^D \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^D \tan\beta$	$\kappa^D \cot\beta$
ρ^U	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$
ρ^E	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$

- In the general model without a Z_2 symmetry ρ matrices are free.

Alignment with/without decoupling

- Decoupling limit:
  Integrate out the heavy Higgs doublet (m_S).
  $m_h = \mathcal{O}(v)$ and $m_H, m_A, m_{H^\pm} = m_S + \mathcal{O}(v^2/m_S)$
  $\cos^2(\beta - \alpha) = \mathcal{O}(v^4/m_S^4)$

  [*Gunion and Haber*, 2003]

- Recently there has been an interest in the 2HDM parameter space where the alignment is obtained without decoupling and without fine tuning. The heavier states can be light and the light Higgs behaves like the SM Higgs.

  [*Craig, Galloway, Thomas*, 2013]

  [*Carena et al.*, 2014]

- In this limit $\cos(\beta - \alpha) \to 0$ and can greatly suppress flavor changing couplings of the light Higgs.

Constraints on FCNC

- Flavor changing neutral currents are highly suppressed in the Standard Model.
- $\mathcal{B}(t \to ch) < 0.56\%$, $\sqrt{\lambda_{tc}^2 + \lambda_{ct}^2} < 0.14$

[*CMS,ATLAS*, 2014]

- 3.4 σ combined deviation from the SM value in $B \to D\tau\nu$.

$$\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042\,,$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018\,.$$

SM predictions are

$$\mathcal{R}_{\rm SM}(D) = 0.297 \pm 0.017\,,$$
$$\mathcal{R}_{\rm SM}(D^*) = 0.252 \pm 0.003\,,$$

[*Crivellin, Greub and Kokulu*, 2012]

[*BaBar*, 2012]

- Is the type-II 2HDM excluded at 95% confidence level?

2HDM parameter space

ATLAS and CMS report signal strength:

$$\mu(f) = \frac{\sigma(pp \to h) \times Br(h \to f)}{\sigma_{SM}(pp \to h) \times Br_{SM}(h \to f)}$$

We can express the first by using the following relation

$$\begin{aligned} \sigma(gg \to h) &= \xi^2_{hgg} \sigma_{SM}(gg \to h) \\ &= \xi^2_{htt}\, \sigma^t_{SM} + \xi^2_{hbb}\, \sigma^b_{SM} + \xi_{htt}\xi_{hbb}\, \sigma^{tb}_{SM} \end{aligned}$$

To simplify the second part let us start with the decay width of the SM Higgs boson. We assume the total width of the Higgs is approximately given by

$$\Gamma_h = \sum_f \Gamma(h \to f) \qquad \text{where} \quad f = \{b\bar{b}, \tau^+\tau^-, c\bar{c}, WW^*, ZZ^*, gg\}$$

So the ratio of the branching ratios can be expressed as

$$\begin{aligned} \frac{Br(h \to f)}{Br_{SM}(h \to f)} &= \frac{\xi^2_{hf}\, \Gamma_{SM}(h \to f)}{\sum \xi^2_k\, \Gamma_{SM}(h \to k)} \times \left[\frac{\Gamma_{SM}(h \to f)}{\Gamma_{SM}}\right]^{-1} \\ &= \frac{\xi^2_{hf}}{\sum \xi^2_k\, Br_{SM}(h \to k)} \end{aligned}$$

2HDM parameter space (2)

Therefore we have the constraint equation

$$\mu(f) = \frac{\xi_{hf}^2 \, \xi_{hgg}^2}{\sum_k \xi_k^2 \, Br_{SM}(h \to k)}$$

Scale factors are

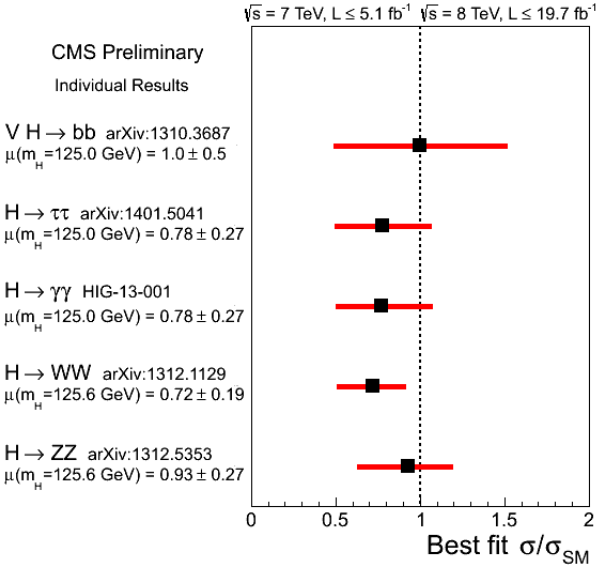
$$\begin{aligned}
\xi_{htt} &= s_{\beta-\alpha} + \chi_{tt} \, c_{\beta-\alpha} \\
\xi_{hbb} &= s_{\beta-\alpha} + \chi_{bb} \, c_{\beta-\alpha} \\
\xi_{hcc} &= s_{\beta-\alpha} + \chi_{cc} \, c_{\beta-\alpha} \\
\xi_{h\tau\tau} &= s_{\beta-\alpha} + \chi_{\tau\tau} \, c_{\beta-\alpha} \\
\xi_{hWW} &= s_{\beta-\alpha} \\
\xi_{hZZ} &= s_{\beta-\alpha}
\end{aligned}$$

Branching ratios for an SM Higgs of mass $m_H = 126 \text{ GeV}$

final state	branching ratio
$b\bar{b}$	56.1 %
WW^*	23.1 %
gg	8.48 %
$\tau^+\tau^-$	6.16 %
ZZ^*	2.89 %
$c\bar{c}$	2.83 %

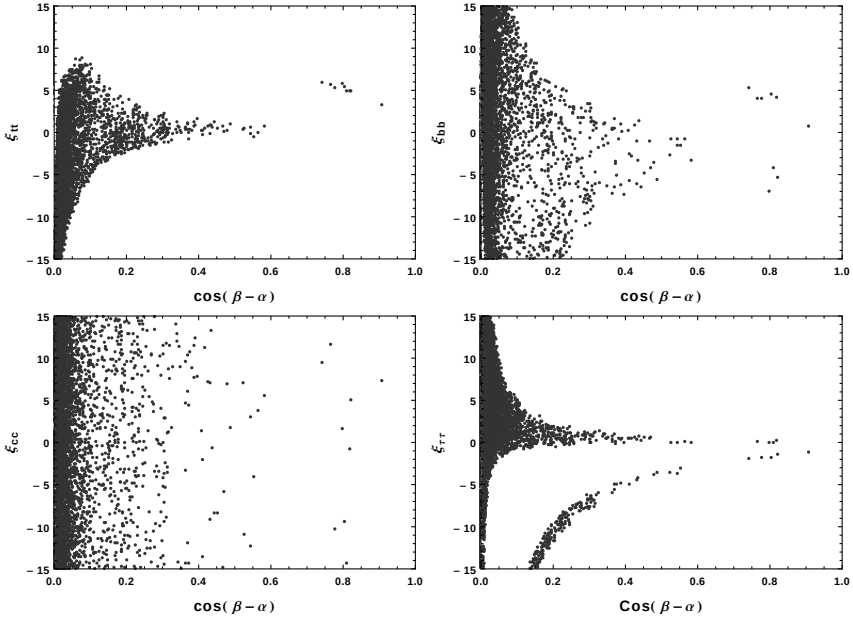
2HDM parameter space (3)

We do a scan and apply the CMS coupling fits to obtain parameters regions compatible with CMS results.



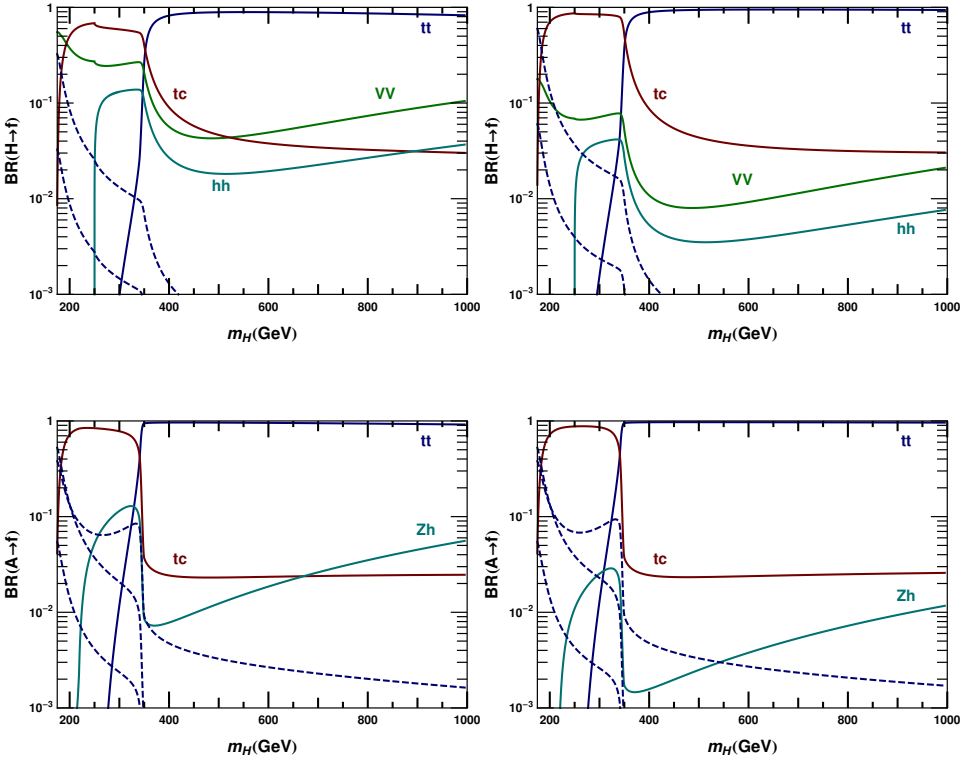
2HDM parameter space (4)

The regions are dense for $\cos(\beta - \alpha) < 0.1$.



Branching fractions

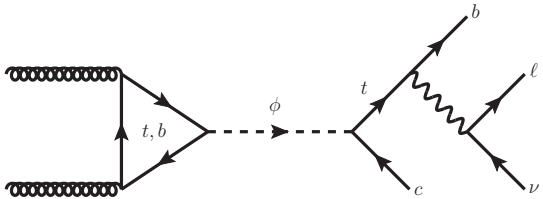
Case study: $|\cos(\beta-\alpha)| = 0.1(L), 0.05(R)$, $\rho_{tt,bb,cc,\tau\tau} = \kappa_{tt,bb,cc,\tau\tau}$,



Flavor changing decay of the Higgs

Signal and background:

- Signal:



$$gg \to \phi \to t\bar{c} + \bar{t}c \to b\ell\nu c \quad \text{where} \quad \phi = H, A$$

- SM background:

wjj
single top / t-channel, s-channel
wbb

- Event generation:
  We use MadGraph5 to generate HELAS subroutines and VEGAS for phase space integration.

  – Signal: $\mu_R = \mu_F = m_H$ SM: $\mu_R = \mu_F = m_W(m_t)$
  – b-tagging/mistagging efficiency: $\epsilon_b = 0.6$, $\epsilon_c = 0.14$, $\epsilon_j = 0.01$.
  We apply smearing to simulate the detector effects.

$$\text{hadrons: } \frac{\delta E}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\% \qquad \text{leptons: } \frac{\delta E}{E} = \frac{25\%}{\sqrt{E}} \oplus 1\%$$

Kinematic cuts and distributions

We require exactly one b-tagged jet, one non-tagged jet and a lepton. We apply the following basic kinematic cuts.

$$p_T(b, j, \ell) > 20 \text{ GeV}$$
$$\not{E}_T > 20 \text{ GeV}$$
$$|\eta(b, j, \ell)| < 2.5$$
$$\Delta R(b, j, \ell) > 0.4$$

We solve for the longitudinal neutrino momentum by assuming an on-shell W.

$$(k+p)^2 = m_W^2 \quad \rightarrow \quad k_z^{\pm} = \frac{R p_z \pm E_l \sqrt{R^2 - 4k_T^2(m_l^2 + p_T^2)}}{2(m_l^2 + p_T^2)}$$

where R is given by

$$R = 2\vec{k_T}.\vec{p_T} + m_W^2 - m_l^2$$

We pick the solution that gives the smallest $|m_{bl\nu} - m_t|$.
In the rest frame of the Higgs we have

$$p^* = \frac{\lambda^{1/2}\left(m_\phi^2, m_t^2, m_c^2\right)}{2m_\phi} \approx \frac{m_\phi}{2}\left[1 - \frac{m_t^2}{m_\phi^2}\right]$$

Since the Higgs doesn't have transverse momentum, $p_T(c)$ peaks at the above value.

Kinematic cuts and distributions (2)

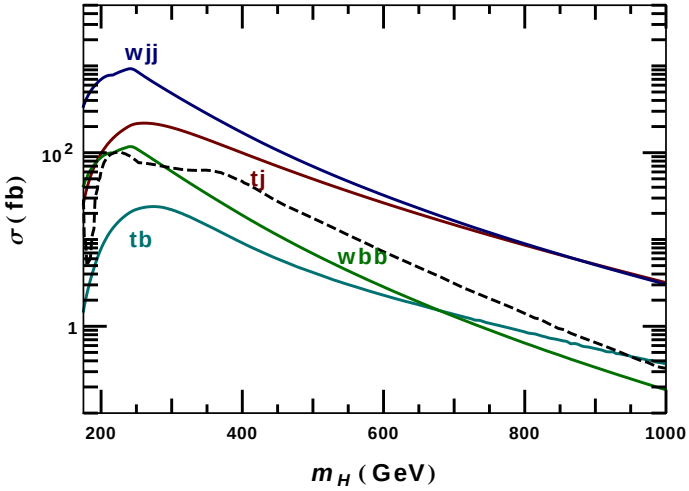
In summary we apply the following two sided cuts:

$$|m_{bl\nu} - m_t| < 0.2\, m_t$$

$$|p_T(c) - p^*| < 0.2\, p^*$$

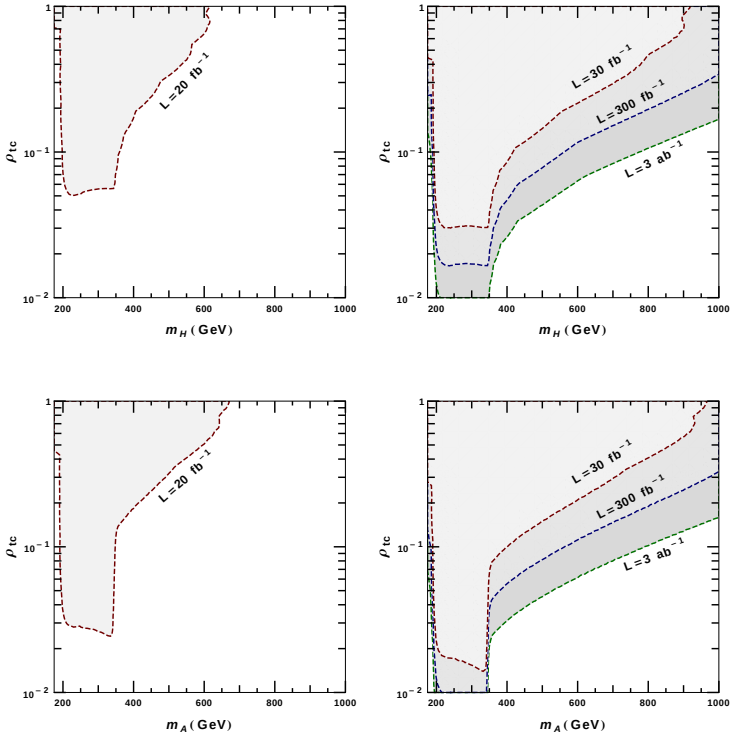
$$|m_{bl\nu c} - m_\phi| < 0.2\, m_\phi$$

Cross section with all the cuts applied for LHC8.



LHC Reach

Finally we go back to our case study with $\cos(\beta - \alpha) = 0.1$, and $\rho_{tt,bb,cc,\tau\tau} = \kappa_{tt,bb,cc,\tau\tau}$ and calculate the 5σ LHC reach at 8 TeV (left) and 14 TeV (right).



Conclusions

- No signs of new physics beyond the 126 GeV Higgs boson.
- We can take it as a problem / an opportunity to come up with new ideas.
- 2HDM parameter space is getting constrained towards the alignment limit.
- Flavor violating decays of the heavier Higgs can be probed with the current 8 TeV data and with the future 14 TeV data up to a level $\rho_{tc} \sim 10^{-2}$.
- And hopefully we have more discoveries on the way.