Flavor Violating Heavy Higgs Decays at the LHC

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based on arXiv:1506.00651
in collaboration with Wei-Shu Hou, Chung Kao, Masaya Kohda, Brent McCoy.

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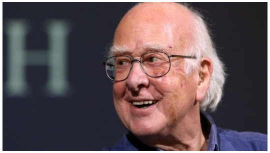
→ 

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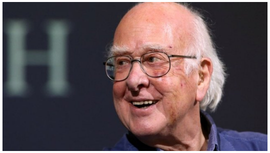
→  $m_{PH} = 4 \times 10^{28}$ GeV

→ . $m_h = 125$ GeV

Standard Model Higgs

- Standard Model Higgs (the most general gauge invariant renormalizable potential):

$$\mathcal{V}(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- The Higgs doublet gets a VEV and breaks the electroweak symmetry:

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

- Generates mass for W/Z and for charged fermions.
- It is very simple hence predictive. All the interaction vertices are fixed:

$$g_{HHH} = 3i \frac{m_H^2}{v} \quad g_{HHHH} = 3i \frac{m_H^2}{v^2}$$

$$g_{Hf\bar{f}} = i \frac{m_f}{v} \quad g_{HVV} = -2i \frac{m_V^2}{v} \quad g_{HHVV} = -2i \frac{m_H^2}{v^2}$$

- Corrections to Higgs mass square goes like cut-off scale square. Supersymmetry comes to rescue us from the undesired fine-tuning.

$$\delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2} \left[\Lambda_{UV}^2 + \cdots \right]$$

$$\delta m_H^2 = 2 \frac{\lambda_S^2}{8\pi^2} \left[\Lambda_{UV}^2 + \cdots \right]$$

- Standard Model is the most succesful theory we have today, but it needs to be extended to explain dark matter, dark energy, neutrino masses, baryogenesis, etc. Most extensions include a second Higgs doublet.

Extended Higgs Sector

- Standard Model has the simplest scalar sector for an $SU(2) \times U(1)$ gauge theory.
- At lowest order

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$$

- For a more general scalar sector with n scalar multiplets with (isospin, hypercharge, vev) $=$ $(T_i,\ Y_i,\ v_i)$ we have

$$\rho = \frac{\sum_{i=1}^{n} (T_i(T_i+1) - \frac{1}{4} Y_i^2) v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i}$$

- Extra singlets and doublets do not break the custodial symmetry, hence the relation $\rho = 1$ is not effected.

Two Higgs Doublet Model

- So let us introduce a second doublet. The most general gauge invariant scalar potential can be written as

$$\mathcal{V}(\Phi_1, \Phi_2) = Y_{ab}\left(\Phi_a^\dagger \Phi_b\right) + Z_{ab,cd}\left(\Phi_a^\dagger \Phi_b\right)\left(\Phi_c^\dagger \Phi_d\right) \quad \text{where} \quad a, b, c, d = 1, 2$$

Or in a more explicit way

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

- In general m_{11}^2, m_{22}^2 and $\lambda_{1,2,3,4}$ are real, m_{12}^2, $\lambda_{5,6,7}$ are complex.
  $\rightarrow$ 14 Parameters in the scalar potential. Some of them can be eliminated by redefining the fields Φ_1 and Φ_2.
- Vacuum is not unique, can spontaneously break the CP symmetry.

[*T.D. Lee*, 1973]

- For CP invariance all parameters can be chosen to be real.

[*Gunion,Haber*, 2003]

Two Higgs Doublet Model

- In a general basis, the doublet fields acquire VEVs in the form below with $\tan\beta = v_2/v_1$.

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

- Minimizing the potential we obtain

$$\begin{aligned} m_{11}^2 &= m_{12}^2 t_\beta - \frac{1}{2}v^2\left[\lambda_1 c_\beta^2 + \lambda_{345} s_\beta^2 + 3\lambda_6 s_\beta c_\beta + \lambda_7 s_\beta^2 t_\beta\right] \\ m_{22}^2 &= m_{12}^2 t_\beta^{-1} - \frac{1}{2}v^2\left[\lambda_2 s_\beta^2 + \lambda_{345} c_\beta^2 + \lambda_6 c_\beta^2 t_\beta^{-1} + 3\lambda_7 s_\beta c_\beta\right] \end{aligned}$$

- Around the minima we have

$$\Phi_a = \frac{1}{\sqrt{2}}\begin{bmatrix} \sqrt{2}\,\phi_a^+ \\ v_a + \rho_a + i\eta_a \end{bmatrix}$$

- Physical fields are obtained by rotating the fields ϕ, η, ρ.

$$\begin{aligned} \begin{bmatrix} G^\pm \\ H^\pm \end{bmatrix} &= \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} \phi_1^\pm \\ \phi_2^\pm \end{bmatrix} \\ \begin{bmatrix} G^0 \\ A^0 \end{bmatrix} &= \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} \eta_1^0 \\ \eta_2^0 \end{bmatrix} \\ \begin{bmatrix} H^0 \\ h^0 \end{bmatrix} &= \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix}\begin{bmatrix} \rho_1^0 \\ \rho_2^0 \end{bmatrix} \end{aligned}$$

Two Higgs Doublet Model

- We started with 8 scalar degrees of freedom
  $\rightarrow$ 3 Goldstone bosons ($G^{\pm}$ and G^0 are absorbed by the $W^{\pm}$ and Z).
  $\rightarrow$ Remaining 5 mass eigenstates give us two CP- even scalars h and H, one CP-odd scalar (A), and a charged Higgs pair ($H^{\pm}$).

- By diagonalizing the mass matrices of the ϕ and η fields, we obtain the pseudoscalar mass, and the charged Higgs mass:

$$\begin{aligned} m_A^2 &= \frac{m_{12}^2}{s_\beta c_\beta} - \frac{1}{2} v^2 (2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta) \\ m_{H^\pm}^2 &= m_A^2 + \frac{1}{2} v^2 (\lambda_5 - \lambda_4) \end{aligned}$$

- CP-even neutral states mix in a more complicated way, which needs special care. We have the mass matrix in the form

$$\mu_\rho^2 = \begin{bmatrix} A & B \\ B & C \end{bmatrix} \quad \text{where} \quad \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} m_{12}^2 t_\beta + v^2 \left[c_\beta^2 \lambda_1 + \frac{3}{2} c_\beta s_\beta \lambda_6 - \frac{1}{2} s_\beta^2 t_\beta \lambda_7 \right] \\ -m_{12}^2 + v^2 \left[c_\beta s_\beta \lambda_{345} + \frac{3}{2} c_\beta^2 \lambda_6 + \frac{3}{2} s_\beta^2 \lambda_7 \right] \\ m_{12}^2 t_\beta^{-1} + v^2 \left[s_\beta^2 \lambda_2 - \frac{1}{2} c_\beta^2 t_\beta^{-1} \lambda_6 + \frac{3}{2} c_\beta s_\beta \lambda_7 \right] \end{bmatrix}$$

Two Higgs Doublet Model

- After digonalizing it, we obtain the mass eigenvalues and the mixing angle

$$m^2_{h,H} = \frac{1}{2}\left[A + B \pm \sqrt{(A-C)^2 + 4B^2}\right] \qquad t_{2\alpha} = \frac{2B}{A-C}$$

- We obtained all the masses in terms of the Lagrangian parameters. We can invert these relations to get the Lagrangian parameters in terms of the masses of the physical states (physical basis). Can switch between $\{m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}, m^2_{12}\} \to \{\lambda_{1..5}\}$.
- Now let us write down the most general Yukawa Lagrangian for the quark sector

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

- And we write the Higgs doublets in terms of physical fields, so the mass term for the up type quarks become

$$M_U \bar{U} U = \frac{1}{\sqrt{2}}\, \bar{U}^0 \left[(v_1\eta_1^{U,0} + v_2\eta_2^{U,0})P_R + (v_1\eta_1^{U,0\dagger} + v_2\eta_2^{U,0\dagger})P_L\right] U^0$$

Yukawa Lagrangian

- where the mass eigenstates are given by

$$P_{L,R}U = V^U_{L,R} P_{L,R} U^0 \quad , \quad P_{L,R}D = V^D_{L,R} P_{L,R} D^0,$$

- and the diagonal mass matrix is

$$M_{U,D} = \frac{1}{\sqrt{2}} (v_1 \eta_1^{U,D} + v_2 \eta_2^{U,D}),$$

- where rotated coupling matrices are given by

$$\eta_i^U = V_L^U \eta_i^{U,0} V_R^{U\dagger} \quad , \quad \eta_i^D = V_L^D \eta_i^{D,0} V_R^{D\dagger}.$$

- We can solve for η_2^U, η_1^D and eliminate them from the Lagrangian to simplify things

$$\eta_1^D = \frac{\sqrt{2} M_D - v_2 \eta_2^D}{v_1} \quad , \quad \eta_2^U = \frac{\sqrt{2} M_U - v_1 \eta_1^U}{v_2}.$$

Yukawa Lagrangian

- We can also switch to another more conventient basis by defining

$$\begin{aligned}\kappa^{U,D} &= \eta_1^{U,D}\cos\beta + \eta_2^{U,D}\sin\beta \\ \rho^{U,D} &= -\eta_1^{U,D}\sin\beta + \eta_2^{U,D}\cos\beta\end{aligned} \quad\Longrightarrow\quad \begin{aligned}\eta_1^{U,D} &= \kappa^{U,D}\cos\beta - \rho^{U,D}\sin\beta \\ \eta_2^{U,D} &= \kappa^{U,D}\sin\beta + \rho^{U,D}\cos\beta\end{aligned}$$

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

$$\begin{aligned}\mathcal{L}_Y &= \frac{-1}{\sqrt{2}}\sum_{\mathrm{F=U,D,L}} \bar{F}\left\{\left[\kappa^F s_{\beta-\alpha} + \rho^F c_{\beta-\alpha}\right] h^0 + \left[\kappa^F c_{\beta-\alpha} - \rho^F s_{\beta-\alpha}\right] H^0 - i\,\mathrm{sgn}(Q_F)\rho^F A^0\right\} P_R F \\ &\quad -\bar{U}\left[V\rho^D P_R - \rho^{U\dagger} V P_L\right] D H^+ - \bar{\nu}\left[\rho^L P_R\right] L H^+ + \mathrm{H.c.}\,,\end{aligned}$$

- Glashow-Weinberg condition: To avoid flavor-changing neutral currents, it is sufficient that each group of fermions (up-type quarks, down-type quarks and charged leptons) couples exactly to one of the two doublets.

	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	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$

- Off-diagonal elements can "naturally" be small if there is a hierarchy similar to the mass matrix:

$$\lambda_{ab} = \frac{\sqrt{m_a m_b}}{v}$$

[Cheng, Sher, 1987]

Signs of tree-level FCNC?

- Flavor changing neutral currents are highly suppressed in the Standard Model.
- BaBar collaboration observed a 3.4 σ combined deviation from the SM value in $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ where $\mathcal{R}(D^{(*)}) = \mathcal{BR}(B \to D^{(*)}\tau\nu)/\mathcal{BR}(B \to D^{(*)}\ell\nu)$.

$$\begin{aligned} \mathcal{R}(D) &= 0.440 \pm 0.058 \pm 0.042 \qquad 2.2\sigma \text{ deviation from SM} \\ \mathcal{R}(D^*) &= 0.332 \pm 0.024 \pm 0.018 \qquad 2.7\sigma \text{ deviation from SM.} \end{aligned}$$

[*BaBar*, 2012]

- BaBar and Belle average

$$\mathcal{BR}(B \to \tau\nu) = (1.67 \pm 0.3) \times 10^{-3} \qquad 2.5\sigma \text{ deviation from SM}$$

[*BaBar,Belle*, 2010]

- They can be explained simultaneously in general 2HDM with charged Higgs contributions and couplings ρ_{tu} and ρ_{tc}.

[*Crivellin, Greub and Kokulu*, 2012]

- CMS observed $H \to \tau\mu$ with 2.4σ significance.

[*CMS*, 2015]

Flavor constraints

- $B_{d,s} \to \mu^+\mu^-$, $K_L \to \mu^+\mu^-$, $\bar{D}_0 \to \mu^+\mu^-$
  loop, helicity and CKM suppressed in SM, tree level in general 2HDM. strong constraints on $\rho_{bs,sb}$, $\rho_{bd,sd}$, $\rho_{ds,sd}$, $\rho_{uc,cu}$.
- $b \to s(d)\gamma$, and $B_{d,s} - \bar{B}_{d,s}$, $K - \bar{K}$, $D - \bar{D}$ mixing.
  At tree level, strong constraints on $\rho^D_{ij}\rho^{D*}_{ji}$ and on $\rho_{uc}\rho^*_{cu}$, can be satisfied trivially if one the Yukawa couplings in the product is very small.
- The FCNH coupling ρ_{ct} affects the H^+tq couplings ($q = d, s, b$) through $(\rho^{U\dagger}V)_{tq} = \rho^*_{tt}V_{tq} + \rho^*_{ct}V_{cq} + \rho^*_{ut}V_{uq}$.

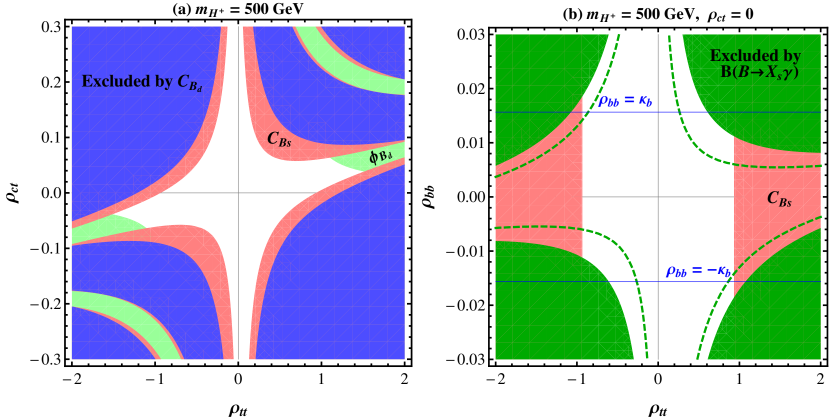


Figure: Exclusions (at 95% C.L.) from (a) $B_{d,s}$-mixing, (b) from $b \to s\gamma$ with $\rho_{ct} = 0$ and $m_{H^+} = 500$ GeV.

- ATLAS and CMS report signal strengths:

$$\mu(f) = \frac{\sigma(pp \to h) \times Br(h \to f)}{\sigma_{SM}(pp \to h) \times Br_{SM}(h \to f)} \implies \mu(f) = \frac{\xi_{hf}^2 \, \xi_{hgg}^2}{\sum_k \xi_k^2 \, Br_{SM}(h \to k)}$$

Final state	μ(ATLAS)	μ(CMS)	μ(comb.)
$h^0 \to \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	$1.14^{+0.26}_{-0.23}$	1.16 ± 0.18
$h^0 \to ZZ^* \to 4\ell$	$1.44^{+0.40}_{-0.33}$	$0.93^{+0.29}_{-0.25}$	1.13 ± 0.22
$h^0 \to WW^* \to \ell\nu\ell\nu$	$1.09^{+0.23}_{-0.21}$	$0.72^{+0.20}_{-0.18}$	0.89 ± 0.14
$h^0 \to \tau\tau$	$1.43^{+0.43}_{-0.37}$	$0.78^{+0.27}_{-0.27}$	0.99 ± 0.22
$h^0 \to b\bar{b}$	$0.52^{+0.40}_{-0.40}$	$1.00^{+0.50}_{-0.50}$	0.71 ± 0.31

Table: Signal strengths for the Higgs boson at the LHC. The last column is our combination. The combined signal strength for $h^0 \to WW^* + ZZ^*$ (VV) is $\mu(VV) = 0.96 \pm 0.12$.

- By studying how the couplings scale in 2HDM, we find the favorable regions in the parameter space of 2HDM. An especially important one is the ρ_{tt} vs. $\cos(\beta - \alpha)$ plane.

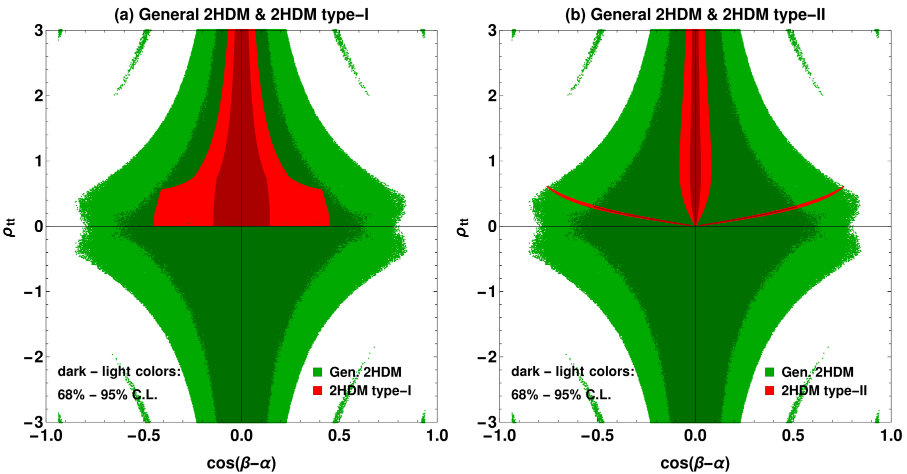


Figure: Favored regions in $\cos(\beta-\alpha)$–ρ_{tt} plane at 68% (95%) C.L. of LHC Higgs data in dark (light) green for a general 2HDM, and for (a) Type-I 2HDM and (b) Type-II 2HDM, both in red.

Limits on FCNC from ATLAS and CMS

- ATLAS limit on $t \to ch \to c\gamma\gamma$:

$$\Gamma(t \to ch) = \frac{\alpha}{32 s_W^2} g_{tcH}^2 m_t \left[1 - \frac{m_h^2}{m_t^2}\right]^2$$
$$\Gamma(t \to bW) = \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_w^2} (1 - 3x^4 + 2x^6)$$

where $x = m_w/m_t$. If we assume that top mostly decays into bW final state we simply get

$$Br(t \to ch) \approx \frac{\Gamma(t \to ch)}{\Gamma(t \to bW)} \implies \lambda_{tch} = 1.91\sqrt{Br} \implies \rho_{tc} = \frac{1.91\sqrt{BR}}{\cos(\beta - \alpha)}$$

Current limit of $Br < 0.83$ % corresponds to

$$\rho_{tc} < \frac{0.174}{\cos(\beta - \alpha)}$$

[ATLAS-CONF-2013-081]

- Expected sensitivity at 14 TeV, with 95% confidence limit of $Br < 0.015$ % corresponds to

$$\rho_{tc} < \frac{0.0234}{\cos(\beta - \alpha)}.$$

[ATL-PHYS-PUB-2013-012]

Well behaved Scalar potential

- We would like the scalar potential to be positive, to satisfy tree level unitarity and perturbativity.
- In the decoupling limit, H^0, A^0 and $H^{\pm}$ become degenerate, $\cos(\beta - \alpha) = \mathcal{O}(v^2/m_A^2)$.

[*Gunion,Haber*, 2003]

- Assume $\lambda_{6,7} = 0$, then the positivity constraint $\lambda_3 + \lambda_4 - |\lambda_5| > -(\lambda_1\lambda_2)^{1/2}$ implies

$$m_{12}^2 < \frac{m_A^2 m_h^2 \sin(2\beta)}{m_A^2 + m_h^2 + (m_A^2 - m_h^2)\cos(2(\beta - \alpha))}.$$

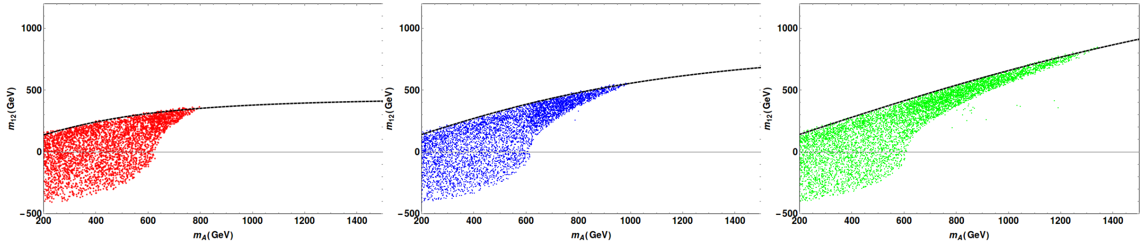


Figure: Valid points that satisfy positivity, unitarity and perturbativity constraints. $c_{\beta-\alpha} = 0.1$ allows up to $m_A = 1$ TeV but $c_{\beta-\alpha} = 0.2$ only allows up to $m_A = 800$ GeV.

Branching Ratios

- So for our case study we choose: $\rho_{ii} = \kappa_{ii}$, $\lambda_{6,7} = 0$, $\tan\beta = 1$.
- Combine ρ_{tc} and ρ_{ct} into an effective coupling $\tilde{\rho}_{tc} = \sqrt{|\rho_{tc}|^2 + |\rho_{ct}|^2}$.

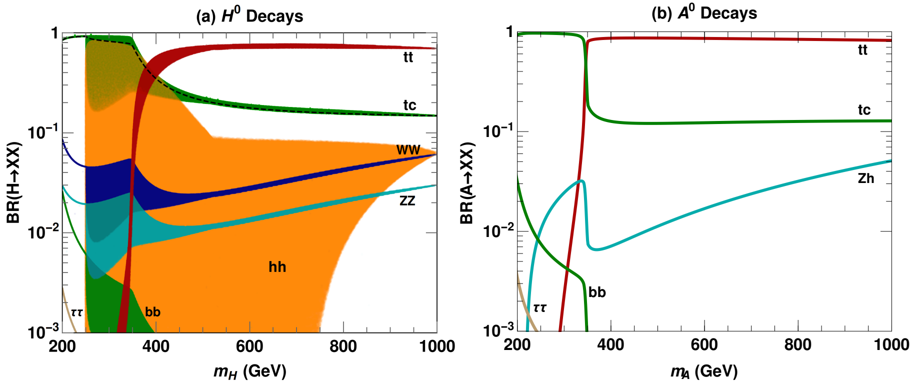
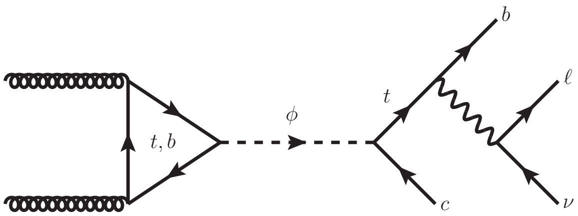


Figure: Branching fraction of (a) heavier Higgs scalar H^0 and (b) Higgs pseudoscalar A^0 versus m_ϕ, with $\cos(\beta - \alpha) = 0.1$, $\tilde{\rho}_{tc} = 0.24$, and $\rho_{ii} = \kappa_i$ for diagonal couplings. We show the allowed regions when $\tan\beta$ and m_{12}^2 are varied. Branching fraction $\mathcal{B}(H^0 \to tc)$ for the LHC case study is shown as a dashed curve.

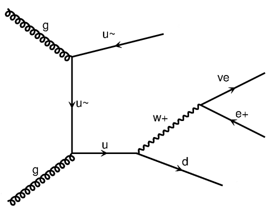
Flavor changing decay of the Higgs

- 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:



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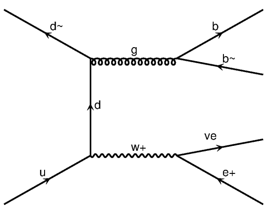

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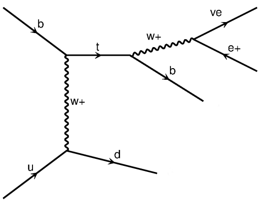
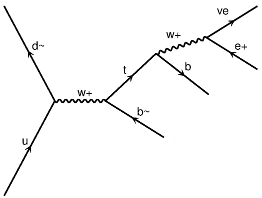


single top (t-channel)



single top (s-channel)

Technical details

- Parton level event generation:

  $\rightarrow$ We use MadGraph5 to generate HELAS subroutines and VEGAS for phase space integration.

  $\rightarrow$ MSTW parton distribution functions are used.

  $\rightarrow$ Signal: $\mu_R = \mu_F = m_H$ SM: $\mu_R = \mu_F = m_W(m_t)$.

  $\rightarrow$ K-factors: HIGLU (Higgs), MCFM (SM).

[*Spira*, 1995]

[*Campbell,Ellis*, 2010]

- Detector effects:
  $\rightarrow$We apply smearing to simulate the detector effects.

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

  $\rightarrow$ b-tagging/mistagging efficiency: $\epsilon_b = 0.6$, $\epsilon_c = 0.14$, $\epsilon_j = 0.01$.

Kinematic cuts

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

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

- There is only one neutrino in the signal process therefore only one unknown which is the longitudinal component of the neutrino momentum. We can reconstruct the event completely assuming an on-shell W.

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

where k is neutrino's momentum, p is lepton's momentum and R is given by

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

Complex solutions $\rightarrow$ We drop the event.
Real solutions $\rightarrow$ We pick the solution that minimizes $|m_{bl\nu} - m_t|$.

Kinematic cuts

- 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.

- In summary we apply the following two sided cuts:

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

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

$$0.85\, p_c < p_T(c) < 1.10\, p_c$$

Signal and Background Cross Sections

- Signal is not very strong at high mass but can be resolved with enough integrated luminosity.

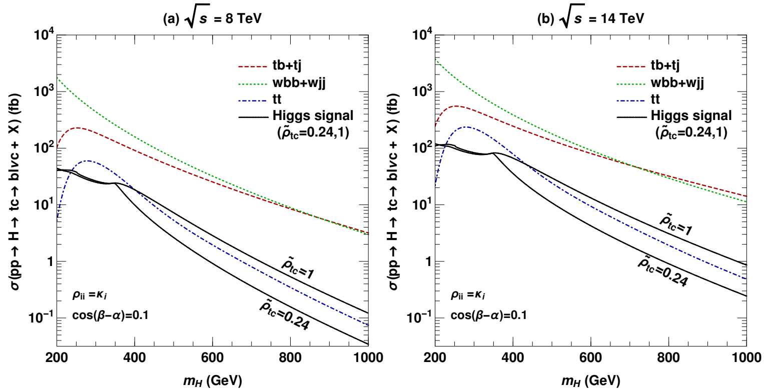


Figure: The cross section of the Higgs signal $\sigma(pp \to H^0 \to t\bar{c} + \bar{t}c \to bj\ell + \not{E}_T + X)$ and the SM background.

LHC Discovery Reach

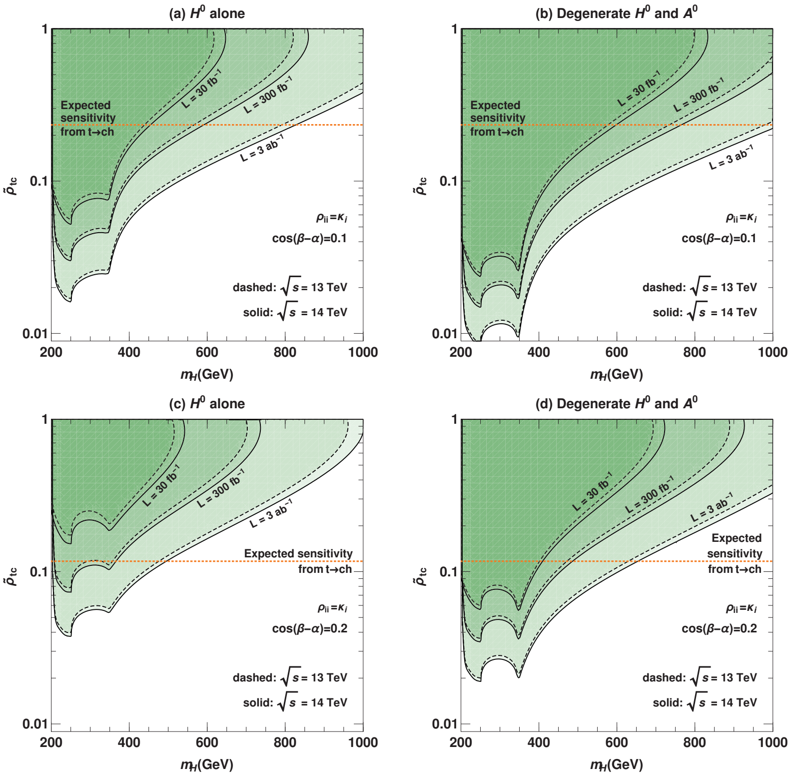


Figure: Discovery reach at 5σ in the m_ϕ–ρ_{tc} plane f

Conclusions

- The 125 GeV boson looks pretty much like the SM Higgs boson.
- Is there only a single Higgs boson as in the Standard Model?
- Are we in the alignment or decoupling limit of an extended Higgs sector?
- If $\cos(\beta - \alpha)$ is small, discovering the flavor changing Higgs interactions may be easier by using the havier scalar and pseudoscalar states.
- Run-2 hopefully will show us what is beyond the Standard Model.