Flavor Changing Heavy Higgs Interactions with Leptons at Hadron Colliders

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Content

General 2HDM and FCNC

General 2HDM

- Standard Model is great but its doesn't explain everything around us.
- Two Higgs doublet model is one of the simplest extension.
- It introduces a standard model like Higgs doublet into the theory and such that every Neutral component of the doublet has its own vaccum expectation value, v_1 and v_2.

In a general basis, Higgs doublet looks like

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{H_1 + v_1 + iIm(\phi_1^0)}{\sqrt{2}} \end{pmatrix} \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{H_2 + v_2 + Im(\phi_2^0)}{\sqrt{2}} \end{pmatrix} \tag{1}$$

$$v = \sqrt{v_1^2 + v_2^2}$$

General 2HDM

- A rotation of β is performed to write these doublets in Higgs Basis, such that only one neutral Component among the two higgs doublets takes the VEV (the one we know),

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} cos\beta, -sin\beta \\ sin\beta,\ cos\beta \end{pmatrix} \begin{pmatrix} v \\ 0 \end{pmatrix} \tag{2}$$

  Hence we have,

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{H+v+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{S+iA^0}{\sqrt{2}} \end{pmatrix} \tag{3}$$

- Then there is one last rotation of α which serves as a Higgs mixing angle, it rotates it into a Higgs mass basis.

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} cos\alpha, -sin\alpha \\ sin\alpha, \quad cos\alpha \end{pmatrix} = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \tag{4}$$

Tree level FCNC in 2HDM

- After performing all this rotation when we write our yukawa type lagrangian in Higgs mass basis in the most general 2HDM(Only Neutral scalar interactions are shown)[1, 4],

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

Tree level FCNC in 2HDM

- Here κ's are the yukawa coupling of standard
- When we diagonalize the yukawa couplings in SM, there is no rule of thumb, that ρ 's will be diagonalized as well.
- Also ρ matrix is not hermitian, hence $\rho_{ij} \neq \rho_{ji}$, so we use an effective coupling,

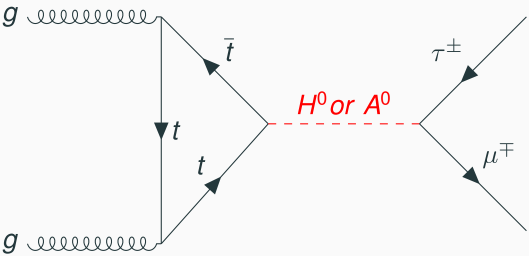
$$\tilde{\rho}_{ij} = \frac{1}{\sqrt{2}} \sqrt{|\rho_{ji}|^2 + |\rho_{ij}|^2} \tag{5}$$

Tree level FCNC in 2HDM and Alignment Limit

- the non diagonal terms in the ρ matrix can potentially give rise to FCNC at Tree level in General 2HDM
- Since Experiments so far have favored SM expectations, it is important for any extension of SM to show a similar behaviour, the process of aligning the effective 2HDM couplings to match with SM at tree level, is called Alignment Limit[8].
- Here, setting $cos(\beta - \alpha) = 0$, removes all the non diagonal couplings of the h^0 with the fermions and removes all the FCNC's mediated by h^0.
- On the other hand this process, generates flavor changing decays for H^0 and A^0.

Channel of Study

Channel of Study



- Feynman diagram of the process under study

$$\mathcal{L}_I = \frac{-1}{\sqrt{2}} \bar{\tau}\{[-\rho^{\tau\mu} s_{\beta-\alpha}]\, H^0 - i\{\mathrm{sgn}(\mathrm{Q})\}\rho^{\tau\mu}\mathrm{A}^0\}\mathrm{P_R}\mu + \mathrm{h.c}$$

Experimental Bounds

Experimental Bounds

- Since H^0, A^0 haven't been found, there are no direct experimental constraints on $H^0, A^0 \to \tau^\pm \mu^\mp$.
- But there are constraints from CMS and ATLAS on $h^0 \to \tau^\pm \mu^\mp$ decay, which are,
  - B($h^0 \to \tau^\pm \mu^\mp$) $<$ 0.25% (95% C.L.) (CMS [1])
  - B($h^0 \to \tau^\pm \mu^\mp$) $< 0.77 \pm 0.62\%$ (1σ) ATLAS[2])

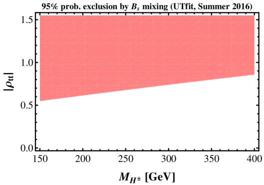
  Considering CMS constraints The FCNH coupling $Y_{\tau\mu} < 1.43 \times 10^{-3}$, where $Y_{\tau\mu} = \rho_{\tilde{\tau\mu}} cos(\beta - \alpha)/\sqrt{2}$.

We also need to put some constraints on ρ_{tt} , ρ_{tc} and ρ_{ct} couplings as they directly or indirectly effects our signal.

Experimental Bounds

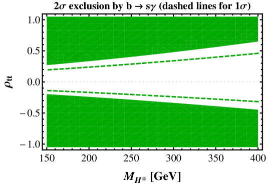
$\cos(\beta\text{-}\alpha) = 0.1,\ \rho_{\tau\tau} = \kappa_{\tau},\ \rho_{\rm bb} = \kappa_{b},\ \rho_{\rm ct} = 0,\ M_H = M_A = M_{H^{\pm}}$

- **Bs mixing**



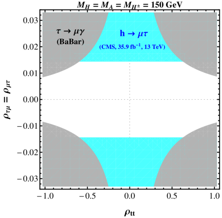
95% prob. exclusion by B_s mixing (UTfit, Summer 2016)

- **b → sγ**

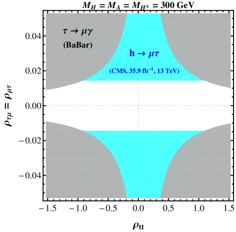


2σ exclusion by b → sγ (dashed lines for 1σ)

- **$\tau \to \mu\gamma$ (90% CL limit by BaBar) and h → $\tau\mu$ (95% CL limit by CMS: 1712.07173)**



$M_H = M_A = M_{H^{\pm}} = 150$ GeV



$M_H = M_A = M_{H^{\pm}} = 300$ GeV

Experimental Bounds and parameter selection

To keep up with the current experimental constraints, we choose,

- $\rho_{tt} = 0.2 \times (M_H/150)$
- $0.001 \leq \rho_{\tilde{\tau\mu}} \leq 0.01$
- $cos(\beta - \alpha) = 0.1$

Final states and SM backgrounds

- Signal we are considering here is $pp \to \Phi^0 \to \tau^\pm \mu^\mp$ ($\phi^0 = H^0, A^0$) and $\tau^+ \to e^+ \nu_e \bar{\nu}_t$ or $\tau^+ \to j_\tau \bar{\nu}_t$, where $j_\tau = \rho, \pi^\pm, a_1$, giving us two different final states.
- First one is $pp \to \Phi^0 \to \tau^\pm \mu^\mp \to e^\pm \mu^\mp + \not{E}_T$(Leptonic channel), and
- $pp \to \Phi^0 \to \tau^\pm \mu^\mp \to j_\tau \mu^\mp + \not{E}_T$ (Hadronic channel)

SM backgrounds

- For the Leptonic channel we have considered the following backgrounds,
  - $pp \to Z, \gamma \to \tau^+\tau^-$
  - $pp \to w^+w^-$
  - $pp \to h^0 \to w^+w^-$
  - $pp \to h^0 \to \tau^+\tau^-$
- For Hadronic channel we have considered the following major bkgs,
  - $pp \to w^\pm j$
  - $pp \to Z, \gamma \to \tau^+\tau^-$
  - $pp \to h^0 \to \tau^+\tau^-$

Selection Cuts

Parameters	$\phi^0 \to e\mu + X$	$\phi^0 \to j_\tau \mu + X$
$P_T(e)$	$> 10 GeV$	
$P_T(\mu)$	$> 26 GeV$	$> 26 GeV$
$P_T(j_\tau)$		$> 30 GeV$
$\lvert\eta_e\rvert$	< 2.3	
$\lvert\eta_\mu\rvert$	< 2.4	< 2.4
$\lvert\eta_{j_\tau}\rvert$		< 2.3
$\Delta R(e, \mu)$	> 0.3	
$\Delta R(j_\tau, \mu)$		> 0.5
$\Delta\phi(P_T(e), \not{E}_T)$	< 0.7	
$\Delta\phi(P_T(e), P_T(\mu))$	> 2.5	
$M_T(\mu)$	$< 60 GeV$	
$M_T(e)$	$> 50 GeV$	
$M_T(j_\tau)$		$< 105 GeV$
$\lvert M_{col} - M_{\phi^0}\rvert$	$< 0.2 \times M_{\phi^0}$	$< 0.2 \times M_{\phi^0}$

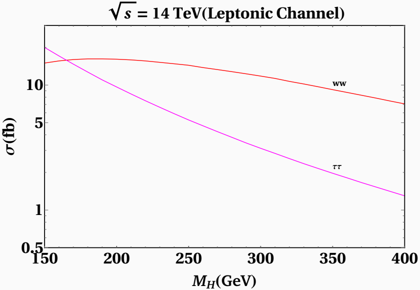
Table 1: Cuts [1]

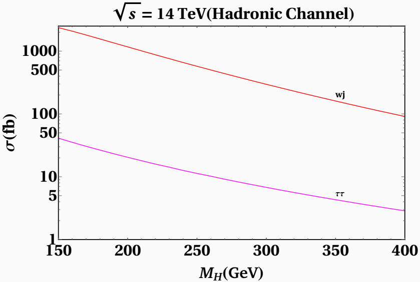
Background Cross sections after Cuts

$\sqrt{s}$	14 TeV	27 TeV	100 TeV
Backgrounds for $\tau \to e + X$			
p p $\to \tau\tau$ + X	31.96	58.74	195.09
p p $\to W^+W^-$ + X	12.27	23.73	86.29
p p $\to h \to \tau\tau$ + X	1.92	5.06	27.9
p p $\to h \to W^+W^-$ + X	0.95	2.51	13.87
Total	47.1	90.04	323.15
Backgrounds for $\tau \to j_\tau + X$			
p p $\to W^\pm j$ + X	2895.7	6200.6	25748.4
p p $\to \tau\tau$ + X	109.8	202.3	676.9
p p $\to h \to \tau\tau$ + X	6.4	16.9	93.3
Total	3011.5	6419.8	26518.6

Table 2: All Cross sections are in fb, assuming the tagging efficiency of e and μ to be 1. And ϵ_j = 0.01, [3, 4] and ϵ_{j_τ} = 0.7 ,[5, 6],here $M_{\phi^0} = 125.1 GeV$

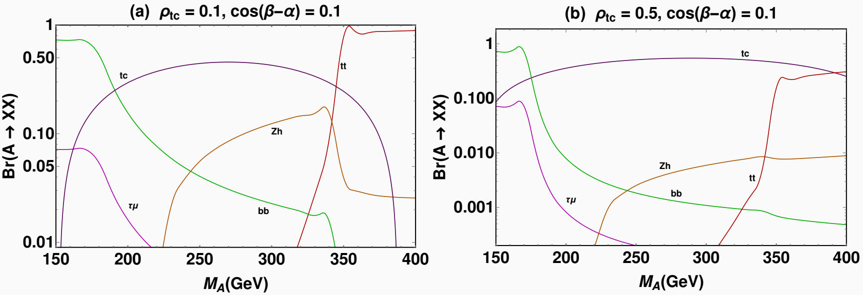
Background Cross section vs M_{ϕ^0}





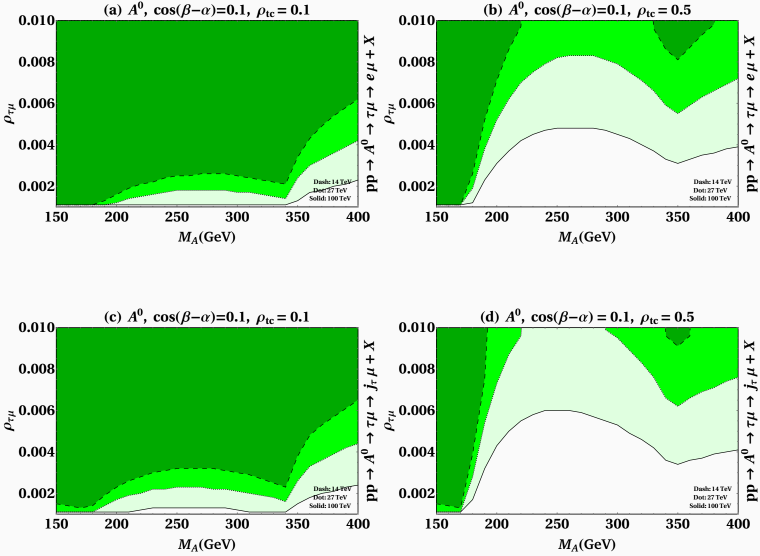
Significance contours for A^0

Two Body decays of A^0



- There is no $A^0 \to h^0 h^0$ decay even at higher mass
- At $M_A > 2m_t$ $A^0 \to tt$ channel starts to dominates
- We are doing this study for a degenerate case i.e $M_H = M_A = M_{H^\pm}$

Significance contours for A^0



Significance contours for H^0

Important parameters for H^0 decays

- Unlike A^0 , $H^0 \to h^0 h^0$ decays are possible, which heavily depends on λ_5(from 2HDM Higgs potential) and $tan\beta$.

$$\begin{aligned} g_{Hhh} &= \frac{\cos(\beta-\alpha)}{v}\{(3m_A^2 + 3\lambda_5 v^2 - 2m_h^2 - m_H^2)(\cos(2\beta - 2\alpha) \\ &- \frac{\sin(2\beta - 2\alpha)}{\tan(2\beta)}) - m_A^2 - \lambda_5 v^2\} \end{aligned}$$

- $\mathcal{B}(H^0 \to h^0 h^0)$ increases with λ_5,Assuming $M_H \geq 2m_h$
- We choose λ_5 = -1 ,0 as a case study.

Two Body Decays of H^0

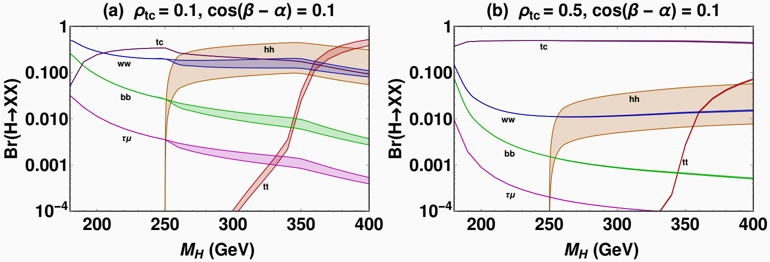


Figure 5: Branching ratios of different decay modes for H^0,for $\lambda_5 = 0$ and $1 \leq tan\beta \leq 10$.

Effect of λ_5

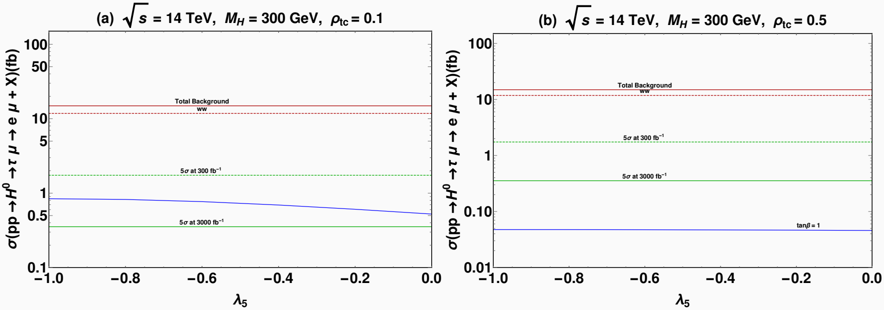
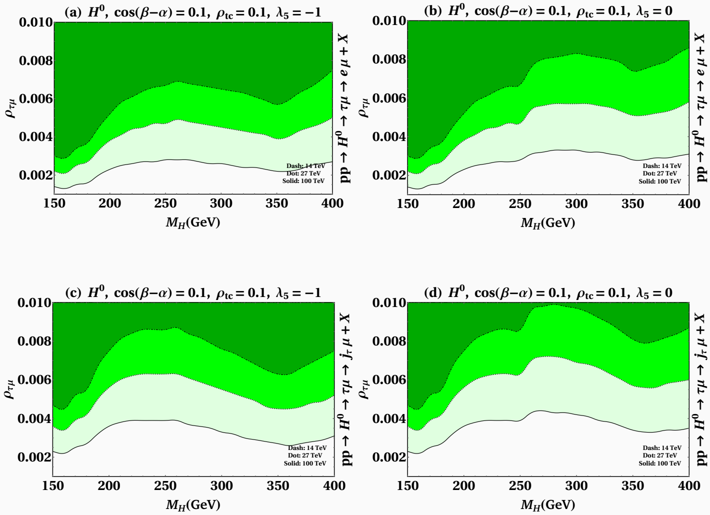


Figure 6: Effect of λ_5 on the sensitivity of the $H^0 \to \tau\mu \to e\mu + \not{E}_T$ for $M_H = 300$GeV, as we increase from -1 to 0.

Discovery contours



Conclusion

Conclusion

- The general 2HDM offers a very rich phenomenology for flavor changing neutral Higgs interactions with fermions, because of the absence of any symmetry to suppress them.
- Strong experimental constraints exist for these FCNH interactions, but third generation of fermions, offers a good parameter space, that can be probed.
- We have found promising results for LHC with the observable $\cos(\beta - \alpha) = 0.1$, $\rho_{tc} = 0.1$ for M_H up to 300 GeV.
- It should be noted that A^0 is more promising than H^0 because of its higher production cross section and fewer parameters affecting its decay to $\tau\mu$.

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Thank you for your attention

Any questions?

Theoretical Bounds on λ_5 and $tan\beta$

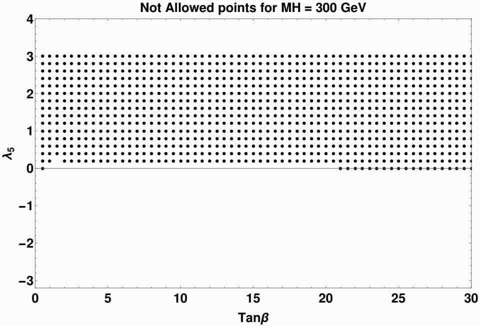
Potential Stability

- For vacumm stability, the 2HDM higgs potential should be bounded from below,this gives us the following stability condition,

$$\lambda_1, \lambda_2 > 0 \, \lambda_3 > -\sqrt{(\lambda_1 \lambda_2)} \tag{6}$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{(\lambda_1 \lambda_2)} \tag{7}$$

So assuming $M_H = 300$ GeV , we performed a scan over all those points where minimum value of potential is negative.



Perturbativity

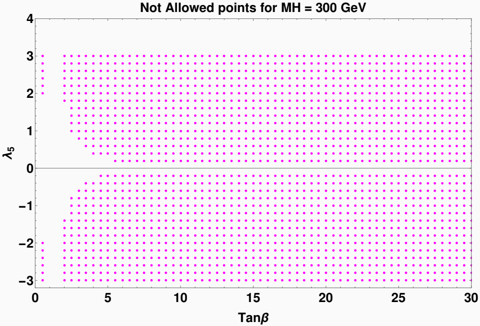


Figure 2 : Point at which perturbation theory fails, based on the condition that quartic coupling $G_{hhhh}/4\pi < 1$

Allowed Parameter space

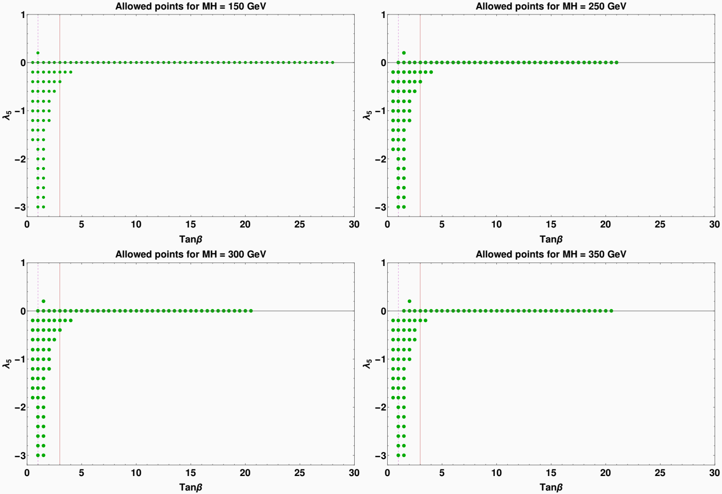
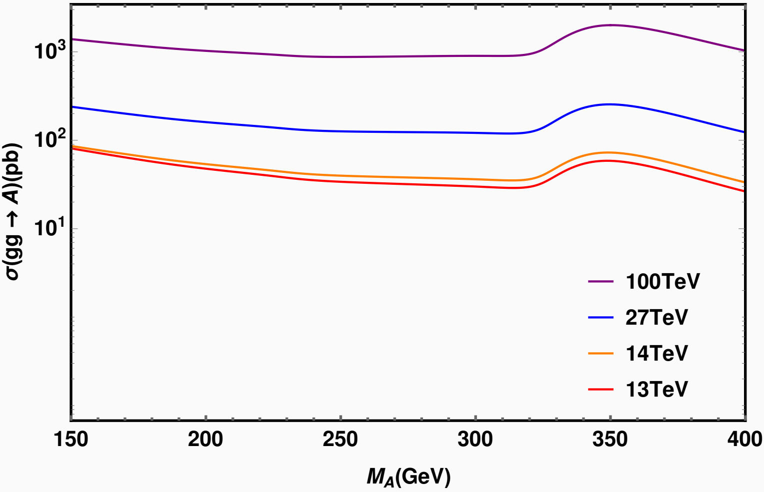


Figure 3 : Allowed parameter space for M_H = 150,250,300,350 GeV in (λ_5, $tan\beta$) plane.

Allowed Paramter space

- Since we don't know the exact mass of H^0 and A^0, and based on the above analysis, for a stable solution Assuming M_A, M_H are in mass range of (150 - 400 GeV), then
    - $-1 \leq \lambda_5 \leq 0$
    - $tan\beta \leq 4$

Production Cross section



G_{Hhh} vs λ_5