# Charming top decays with flavor changing Higgs boson and $\tau\tau$ at LHC

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# Outline:

1. SM and FCNH
2. General Two Higgs Doublet Model(gTHDM) and FCNH
3. Why gTHDM over THDM-I, THDM-II ..
4. $t \to ch^0$
5. Conclusion and Future Work

# SM and FCNH

# The Standard Model

- In Standard model,we have six flavors of quarks and three flavors of charged leptons
- Higgs like boson's discovery in 2012, has completed the particle content, predicted by SM
- Higgs mechanism is not fully understood,hence room for new physics

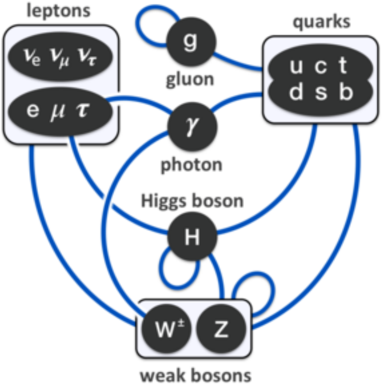

Figure: Standard Model

# FCNH in Standard Model and Limits on Flavor anomalies

- In SM Flavor Changing neutral currents like $t \to c(u)V^0, (V^0 = \gamma, Z, h^0)$ or $h^0 \to \tau\bar{\mu}$ are absent at tree level.
- At one loop level,SM predicts $\mathcal{B}(t \to qh, Z, \gamma) \simeq 10^{-14}$ from [1] and $\mathcal{B}(h^0 \to f_i f_j)$ is highly suppressed at one loop level, where $i \neq j$.
- Current limits on some of the flavor anomalous searches are,
  - $\tau \to \mu\gamma \lesssim 4.5 \times 10^{-8}$ at 90% C.L (Belle-collaboration)
  - $\tau \to e\gamma \lesssim 1.1 \times 10^{-8}$ at 90 % C.L (BaBar Collaboration)
  - $\tau \to 3\ell \lesssim (1.5 - 2.7) \times 10^{-8}$ at 90% C.L (Belle collaboration)
  - $h \to \tau\mu \lesssim$ 2.5 $\times 10^{-3}$ at 95 % C.L (CMS Collaboration)
  - $t \to ch^0 \lesssim$ 1.1 $\times 10^{-3}$ at 95 % C.L (ATLAS collaboration)

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[1] Aguilar-Saavedra arxiv:hep-ph/0409342

# General Two Higgs Doublet Model(gTHDM) and FCNH

# General Two Higgs Doublet Model(gTHDM)

- In gTHDM, we have two doublets $\phi_i$ (i = 1,2) with same hypercharge, and the Higgs potential is,[2]

$$\begin{aligned} V_{THDM} &= m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \{m_{12}^2\phi_1^\dagger\phi_2 + h.c\} \\ &+ (1/2)\lambda_1(\phi_1^\dagger\phi_1)^2 + (1/2)\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ &+ \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \{(1/2)\lambda_5(\phi_1^\dagger\phi_2) + h.c\} \\ &+ \{(\lambda_6\phi_1^\dagger\phi_1 + \lambda_7\phi_2^\dagger\phi_2)\phi_1^\dagger\phi_2 + h.c\} \end{aligned}$$

- After Electroweak symmetry the two doublets in arbitrary basis [3]

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

where $v_{1,2}$ are VEV from two doublets such that $v_1^2 + v_2^2 = v^2$,$v = 246.1$ GeV

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[2] J.Gunion & H.Haber [10.1103/PhysRevD.67.075019]

[3] G.C,Branco.et.al 10.1016/j.physrep.2012.02.002

# General Two Higgs Doublet Model(THDM)

- When we apply a $Z_2$ symmetry i.e $\phi_1 \to \phi_1$ and $\phi_2 \to -\phi_2$, for this symmetry,$m_{12}^2, \lambda_{6,7} = 0$ and now the two doublets are no longer identical.[4]
- In this basis we can define $tan\beta \equiv v_2/v_1$.
- For our study we have broken the $Z_2$ symmetry softly by considering a non zero, $m_{12}^2$.
- It is important to notethat tan$\beta$ is an not a physical parameter because I can choose a basis in which one doublet takes a vev and other one doesn't. This basis is called Higgs Basis.[5]

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[4] G.C,Branco.t.al 10.1016/j.physrep.2012.02.002

[5] H.Haber & D.O'Neil 10.1103/PhysRevD.74.059905

# General Two Higgs Doublet Model

- $\beta$ is also the rotation angle that diagonalizes the mass matrix of $\phi_i^+$ and $Im(\phi_0)_i$.
- $\alpha$ rotation diagnalizes the mass matrix of $\phi_i^0$.

$$\begin{aligned}
\phi_1 &= \begin{pmatrix} c_\beta G^+ - s_\beta H^+ \\ \frac{1}{\sqrt{2}}(c_\alpha H^0 - s_\alpha h^0 + v c_\beta + i c_\beta G^0 - i s_\beta A^0) \end{pmatrix} \\
\phi_2 &= \begin{pmatrix} s_\beta G^+ + c_\beta H^+ \\ \frac{1}{\sqrt{2}}(s_\alpha H^0 + c_\alpha h^0 + v s_\beta + i s_\beta G^0 + i c_\beta A^0) \end{pmatrix}
\end{aligned}$$

J.Gunion & H.Haber [10.1103/PhysRevD.67.075019]

- $H^\pm$, is a charged scalar,$A^0$ ,CP odd $h^0$ and $H^0$ CP even scalars.

# THDM and Corrections to Yukawa sector

- The mixing of the two doublets, induce corrections to Yukawa couplings. The effective yukawa lagrangian in General 2HDM is,

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

  where $P_{L,R} \equiv (1 \mp \gamma_5)/2$, $c_{\beta-\alpha} = \cos(\beta - \alpha)$, $s_{\beta-\alpha} = \sin(\beta - \alpha)$, and $\alpha$ is the mixing angle between neutral Higgs scalars in the Type II (2HDM-II) notation[6], $\kappa$ matrices are diagonal and fixed by fermion masses to $\kappa^F = \sqrt{2}m_F/v$ with $v \simeq 246$ GeV, while $\rho$ matrices are free and have both diagonal and off diagonal term.

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[6] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, Front. Phys. **80**, 1 (2000).

# THDM and Flavor Changing Neutral Currents

- With $\rho$ matrix containing non diagonal terms, we have tree level FCNC's possible in gTHDM
- This property of gTHDM was considered dangerous.
- So Paschchos-Glashow-Weinberg, proposed that by restricting one doublet to interact with certain kind fermion, we can remove these FCNH couplings at tree level(Natural flavor Conservation(NFC))[7],[8]
- Following this we have Type I, Type II, Lepton Specific , Lepton Flipped models of 2HDM.
- These model only effect the yukawa sector, Higgs couplings to bosons are independent of these model variations.

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[7] Glashow.et.al 10.1103/PhysRevD.15.1958

[8] Paschos 10.1103/PhysRevD.15.1966

# Why gTHDM over THDM-I, THDM-II ..

# Limitations of NFC THDM models

- NFC models cannot simultaneously explain the anomalies observed in the Tauonic B meson decays ($b \to c\tau\nu$),namely R(D), R(D*) and $B_u \to \tau\nu$.
- Current experimental anomalies in the measurements of R(D*), R(D), R(K*) etc, points towards a flavor violating side of the Nature.

| Anomaly | SM expectation | Observed |
|---|---|---|
| R(D) | 0.299 ±0.011 | 0.407±0.039±0.024 (WA) |
| R(D*) | 0.252± 0.003 | 0.304 ± 0.013 ± 0.007 (WA) |
| $B_u \to \tau\nu$ | [ (0.84 $\pm 0.11$) $\times 10^{-4}$] [9] | (1.67 $\pm 0.3$) $\times 10^{-4}$ |

Table: Current Flavor Anomalies measurements, WA = World Average, From LHCb,Belle and BaBar Collaborations[10]. $B_u \to \tau\nu$ is taken from doi:10.1103/PhysRevD.86.054014

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[9] doi:10.1016/j.physletb.2010.02.063 [arXiv:0908.3470 [hep-ph]]

[10] doi:10.1016/j.nuclphysb.2017.10.014

# Limitations of NFC THDM models

- As shown by Crivellin.et.al [11], THDM-II and THDM of type III with MFV can only explain $B_u \to \tau\nu$ and again by Iguru.et.al [12], there results are shown below,

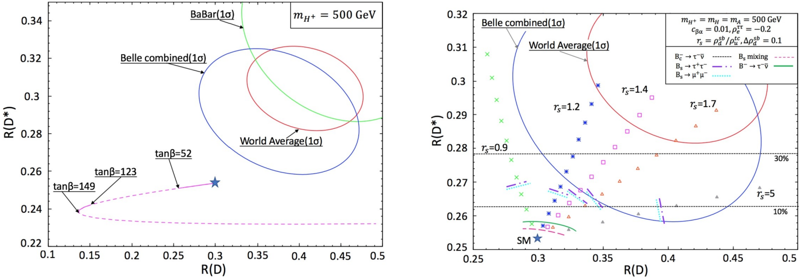

Figure: Predictions for R(D) and R(D*) from THDM-II (left) and gTHDM(right) [doi:10.1016/j.nuclphysb.2017.10.014]

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[11] doi:10.1103/PhysRevD.86.054014

[12] [doi:10.1016/j.nuclphysb.2017.10.014]

# $t \rightarrow ch^0$

# Motivation

- Top mass
- Current Experimental Limits are 12 orders of magnitude higher than SM expectation
- FCNH coupling $\rho_{tc}$ can also drive Electroweak Baryogenesis[13].
- Discovery will lead to definitive signature of new physics either at tree level or at loop level.

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[13] Fuyuto.et.al doi:10.1016/j.physletb.2017.11.073

# Translating Experimental Constraints

- The Branching Fraction for $t \to ch^0$ is given as, Using $m_t = 173.2$ GeV, $M_h = 125.1$ GeV and $m_c = 1.42$ GeV

$$\mathcal{B}_{t\to ch^0} = \frac{c_{\beta\alpha}^2 m_t}{32\pi\Gamma_t}\{0.48|\tilde{\rho}_{tc}|^2\} \times \lambda^{1/2}(1, x_c^2, x_h^2) \tag{1}$$

Where $\tilde{\rho}_{tc} = \sqrt{\frac{|\rho_{tc}|^2 + |\rho_{ct}|^2}{2}}$ ,
$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$, $x_i = m_i/m_t$

- Current limits $\mathcal{B}_{t\to ch^0} \lesssim 1.1 \times 10^{-3}$ gives $\lambda_{tc} = \tilde{\rho_{tc}} c_{\beta-\alpha} \lesssim 0.064$ [14]

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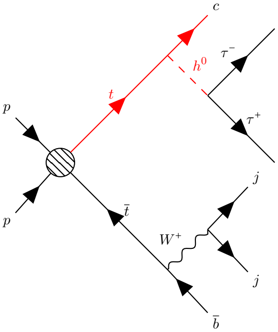
[14] doi 10.1007/JHEP05(2019)123, ATLAS Collaboration

# Parameters and Channel of study

- Our production channel is top pair production at LHC. With the following following decay modes,
    - $t \to ch^0 \to c\tau^+\tau^-$, Other top decays via $t \to bjj$ [ Work in progress]



# Channel of Study and Important Backgrounds

- We are considering the two different final states here,
  - $\tau^+ \to \ell^+ \nu_\ell \bar{\nu_\tau}, \tau^- \to \ell^- \bar{\nu_\ell} \nu_\tau$
  - $\tau^+ \to \ell^+ \nu_\ell \bar{\nu_\tau}$, $\tau^- \to j_\tau \nu_\tau$
- Where $j_\tau = \pi^\pm, \rho$ and $a_1$
- For this talk I am only considering the two leptonically decaying $\tau' s$
- Important backgrounds are
  - $t\bar{t}jj$
  - $t\bar{t}W^\pm$ and $t\bar{t}Z$
  - $b\bar{b}jjW^+W^-$,
  - $b\bar{b}jj\tau^+\tau^-$

# Event Generation and Selection

- We have used MadGraph5 to generate parton level events and then use Pythia8 to mimic hadronization and showering effect, and later pass on to Delphes for detector modeling.
- We apply minimal cuts to get a stable cross section for event generation at tree-level and later use K-factor to scale them to NLO.
- After this we extract events from the samples by applying the following selection rules,
    - $P_T(b, j) \geq$ 20 GeV
    - $|\eta(b)| \leq$ 4.7 , $|\eta(j)| \leq$ 2.5
    - $P_T(\ell) \geq$ 10 GeV, and two OS leptons ,$|\eta(\ell)|$ ≤2.5
    - $E_T \geq$ 25 GeV, $(\ell\ell, jj, bj, bb, \ell j, \ell b) \geq$ 0.4
    - $P_T(leading\ell) \geq 20$ GeV
    - We also apply b veto. Remove all the event having more than one b with $P_T \geq 20$ GeV and $|\eta| < 4.7$
    - To reconstruct Higgs mass we apply collinear approximation to reconstruct $\tau$ momenta.

# Event Selection

- Under collinear approximation[15],

$$P_{\tau_i} = P_{\ell_i}/x_i$$

- We only select those event which satisfy $0 \le x_i \le 1$ Where i = 1,2.
- After applying all these selection rules,Background cross section at $\sqrt{s} = 13$ TeV

| Process | Cross-section(fb) |
|---|---|
| $t\bar{t}jj$ | 711.324 |
| $t\bar{t}W^{\pm}$ | 0.5516 |
| $t\bar{t}Z$ | 0.362 |
| $b\bar{b}jjW^+W^-$ | 1.404 |
| $b\bar{b}jj\tau^+\tau^-$ | 2.052 |

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[15] Higgs decay to $\tau^+\tau^-$ a possible signature of intermediate mass higgs bosons at high energy hadron colliders. Nuclear Physics B, 297(2):221 – 243, 1988.

# Training Variables and BDT outcome

- We use the following variables training.
    - Invariant mass of two light jets M(j,j) and Invariant mass of b jet and two light jets M(b,j,j)
    - Invariant Mass of two$\tau$'s and Invariant mass of c and two $\tau$'s. Using collinear approximation
    - $P_T(b,j,j,\ell_1,\ell_2)$ and $E_T$
    - Invariant mass of two leptons.
- After the selecting the events, we create two different samples for Signal by randomly selecting 80% events and train both of them with the total background sample.
- We also apply some Mass window cuts before training,
    - $40 \leq M(j_1,j_2) \leq 120$GeV
    - $100 \leq M(b,j_1,j_2) \leq 246$GeV
    - $M(\ell,\ell) \leq 80$ GeV

Here we have used TMVA [16] for our BDT analysis,

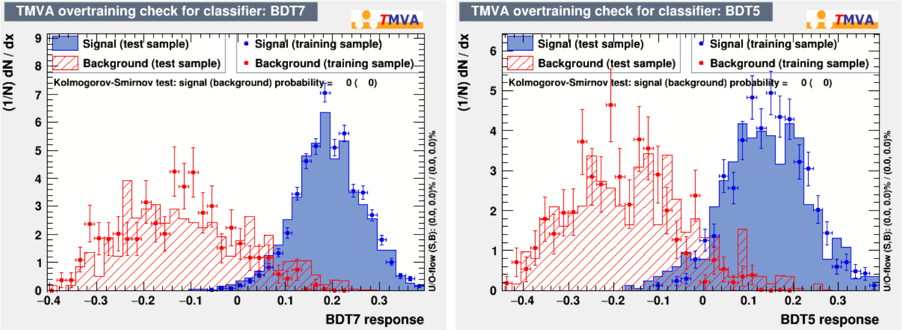

Figure: BDT discriminator from the two different samples

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[16] TMVA,arXiv:physics/0703039

# Current Estimate on the Significance

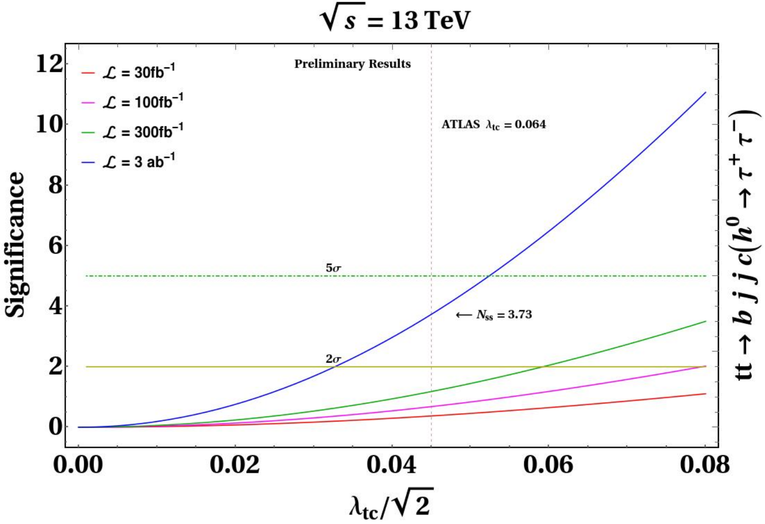

Figure: Preliminary Estimates of Significance

# Conclusion and Future Work

- FCNC's presents an exciting new physics channel to probe. If detected, can improve our understanding of the flavor structure of the Nature.
- The $t \to ch^0$ also holds promising future. However the study we presented is limited for one $\tau$ decay modes. Including other decay modes for $\tau$, can really improve the expectation for current and future hadron colliders.
- The $tc\phi$ coupling holds a very rich phenomenology, and In the future I would like work more on this, to find out what it can tell us about nature.