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Top Signature of Flavor Changing Neutral Higgs Interactions with W W at the LHC

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Introduction to Two Higgs Doublet Model

- 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

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

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

Introduction to Two Higgs Doublet Model

- 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.

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

Yukawa type Lagrangian in 2HDM

- After performing all this rotation when we write our yukawa type lagrangian in Higgs mass basis in the most general 2HDM[3],

$$
\begin{aligned}
-\sqrt{2}\mathcal{L}_I &= \bar{U}_i[\kappa_{U_iU_j} cos(\beta-\alpha) - \rho_{U_iU_j} sin(\beta-\alpha)]U_jH \\
&+ \bar{U}_i[\kappa_{U_iU_j} sin(\beta-\alpha) - \rho_{U_iU_j} cos(\beta-\alpha)]U_jh \\
&+ \bar{D}_i[\kappa_{D_iD_j} cos(\beta-\alpha) - \rho_{D_iD_j} sin(\beta-\alpha)]D_jH \\
&+ \bar{D}_i[\kappa_{D_iD_j} sin(\beta-\alpha) + \rho_{D_iD_j} cos(\beta-\alpha)]D_jh + h.c
\end{aligned}
$$

Introduction to Two Higgs Doublet Model

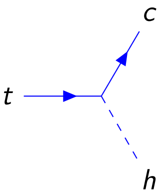
- Here κ's are the yukawa coupling of standard models, where ρ is the extra contribution from 2HDM.
- We are working in CP conserving interaction lagrangian(matter of choice), making ρ real.
- When we diagonalize the yukawa couplings in SM, there is no rule of thumb, that ρ 's will be diagonalized as well.
- Also ρ matrix is not hermitian, hence $\rho_{ij} \neq \rho_{ji}$, so we use an effective coupling,

$$\tilde{\rho_{tc}} = \frac{1}{\sqrt{2}}\sqrt{\rho_{ct}^2 + \rho_{tc}^2} \quad (5)$$

Part of Lagrangian under investigation

Our main focus of study is ,

$$-\sqrt{2}\mathcal{L} = -\bar{c}\rho_{ct} cos(\beta - \alpha) t + h.c \qquad (6)$$



QCD Corrections and Running of tch

- Branching Ratio for t →c h process is given [1] as, with LO order QCD corrections,

$$BR(t \to ch) = \frac{\lambda_{tch}^2}{\sqrt{2} m_t^2 G_F} \frac{(1 - x_h^2)^2 \kappa_{QCD}}{(1 - x_w^2)^2 (1 + 2x_w^2)} \quad (7)$$

  - where $\kappa_{QCD} = 1 + 0.97 * \alpha_s \approx 1.1$ is the Leading order QCD corrections to the t → b W and t → c h
  - $\lambda_{tch} = \tilde{\rho_{tc}} cos(\beta - \alpha)/\sqrt{2}$
  - $x_i = m_i/m_t$

QCD Corrections and Running of tch

- The running of this FCNH coupling gives[2]

$$\lambda_{tch}(\Lambda) = \lambda_{tch}(\Lambda_0)\left(\frac{\alpha_s(\Lambda)}{\alpha_s(\Lambda_0)}\right)^{4/\beta_0} \tag{8}$$

  - $\beta_0 = 11 - \frac{2}{3}n_f$ is the one loop coefficients of the QCD β function.
  - Λ is the Energy scale of Renormalization.

Theoretical Constraints and Decoupling Limit

- Any SM extension has one basic need, reproducing SM, in our interaction lagrangian if we put $\cos(\beta - \alpha) = 0$, the all ρ coupling with light Higgs goes to zero , hence we reproduce SM, this is known as decoupling limit[3].
- So we usually take a small value, for $\cos(\beta - \alpha)$ to stay close to SM, which suppresses the SM Higgs mediated FCNC.
- But this suppression behaves in opposite way for H^0, heavy Higgs state, as it has $\sin(\beta - \alpha)$ in its coupling.
- Due to lack of experimental evidence, there are some constrainted 2HDM models which suppresses these FCNC by including a symmetry.
- These models constraints the interaction of doublets with fermions to preserve FCNC at tree level.

Experimental Constraints on tch

- BR(t $\to$ch) $<$ 0.56% (CMS Collaboration, Multilepton and diphoton channel)[3]
- BR(t $\to$ch) $<$ 0.46% (ATLAS Collaboration)[4],
- BR(t $\to$ch) $<$ (0.09 - 0.29)% (B Mixing , LHCb)[3]

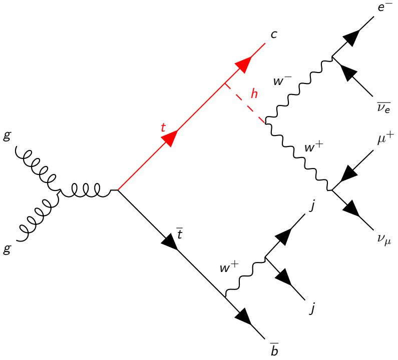
This sets a limit to ,

- $\lambda_{tch} = \tilde{\rho}_{tc} cos(\beta - \alpha)/\sqrt{2} < 0.14$[4]
- Staying close to decoupling limit, cos$(\beta - \alpha) < 0.2$, and $\tilde{\rho_{tc}} < 1$.

Channel of Study

In this project we look at the following channel,

$$pp \to t\bar{t} + X, t \to ch, h \to e^{+}\ \mu^{-}\ \nu_e\ \bar{\nu_\mu},\ \bar{t} \to b\ j\ j \tag{9}$$



One of the most dominant mode of production

Dominant Backgrounds

Most dominant backgrounds we have is

- ttjj,
- bbjjww
- bbccww
- ccjjww
- jjjj ww
- j means only light jets like u d and s

Realistic basic Cuts for Selecting the events

- PT(jets) $>$ 25 GeV
- PT(LLepton) $>$ 25 GeV
- PT(NLLepton) $>$ 15 GeV
- Missing ET $>$ 25 GV
- $\Delta R(jj) > 0.4$
- $\Delta R(jl) > 0.4$
- $\Delta R(ll) > 0.4$
- $|\eta| < 2.4$
- |M(b j1,j2) - MT| $<$ 0.20*MT
- |M(j1,j2) - MW| $<$ 0.15*MW

[1]

[1] arxiv 1307.1427v2 , CMS Collaboration

Cross section table at 14 TeV

Here is the cross section table after applying the basic cuts for 14 TeV, for Signal we have used $\lambda_{tch} = \sqrt{m_t\, m_c}/vev$ and CT14LLO for PDFs.

Process	With Basic Cuts(fb)
Signal	0.5048
ttjj	195.84
bbjjww	0.064
bbccww	0.000622
ccjjww	0.03972
Total Backgrounds	195.94

We have used K factors ≈ 2 , to include the leading order QCD corrections for top pair production at LHC.

Other Important Mass cuts

- Cluster Transverse mass cuts
  - 50 GeV < MT(l1 ,l2) < 150 GeV
  - 100 GeV < MT(c,l1,l2) < 210 GeV
- Cluster transverse mass is defined as [5]

$$M_{T\,cluster} = \sqrt{\left(\sqrt{p_{cT}^2 + M_c^2} + \not{E}_T\right)^2 - \left(p_{cT} + \not{E}_T\right)^2} \qquad (10)$$

  - Where p_{cT} is the total transverse momentum of the particle to be considered in the cluster.
  - M_c is the invariant mass of those particle
  - $\not{E}_T$ is the total missing transverse energy.

Results after all Cuts

Process	With all Cuts(fb)
Signal	0.463
ttjj	21.236
bbjj	0.0058
bbcc	0.000056
ccjj	0.00394
Total Backgrounds	21.25

- The statistical significance of the Signal is given as

$$Nss = \frac{N_s}{\sqrt{N_s + N_b}} = \frac{L\sigma_s}{\sqrt{L\sigma_s + L\sigma_b}} \tag{11}$$

Discovery Contours at 13 and 14 TeV

Statistical Significance Nss at $3000 fb^{-1}$

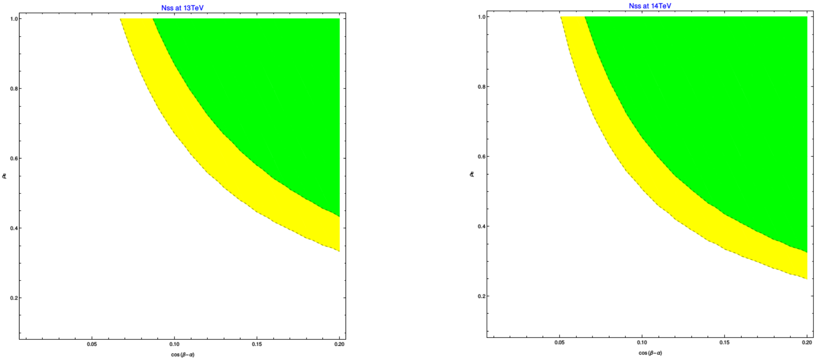


Figure: Variation of Statistical Significance while changing $0.1 < \rho_{tc} < 1$ and $0.01 < cos(\beta - \alpha) < 0.2$ at 13 and 14 TeV for 3000 fb^{-1}. Green Region is for Nss > 5 , which corresponds for 5σ or more , yellow is between 3σ and 5σ.

Conclusion and Future Works

- We have large parameter region of signal that can be probed at HL-LHC in the future.
- When we go from 13 to 14 TeV the green area increases, hence at larger energies like 33 and 100 TeV, we expect LHC to probe a very low λ_{tch}.
- To accurately calculate jjjj ww backgrounds to get a more clearer picture of the total background.
- We will be using TOP 2++ for NLO and NNLO contributions for the top pair production to more acurately predict the K factors.

Conclusion and Future Works

- Also include Discovery contours for $\sqrt{\hat{s}} = 33$ and 100 TeV
- Include the same flavor channels as well to enhance the signal.
- Look for FCNC in g c $\rightarrow$ t ϕ_i^0 channel.

References

- [1] arXiv:1605.01179 [hep-ph].
- [2] Physical Review D 86,094014
- [3] Phys.Lett. B751,135(2015)[arxiv:1506.00651[hep-ph]]
- [4] arxiv 1601.02616v2
- [5] HEP-PH/9309250

Questions??