Charming Top Decays with Flavor Changing Neutral Higgs Interactions at Hadron Colliders

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Heavyweight Champion before July 4, 2012
Elementary Fermion Hierarchy

**Top quark: motivation**

*Elementary particle with the largest mass ($y_t \sim 1$)*

- no bound states
- role in SM loop diagrams
- decays from and to BSM
- important background to SM & BSM searches

Mass $\text{In GeV/c}^2$

1 GeV/$c^2 = 1.8 \times 10^{-27}$ kg

- top $173$
- charm $1.5$
- up $0.005$
- down $0.01$
- strange $0.15$
- bottom $5.0$

## Standard Higgs Branching Fractions

<table>
<thead>
<tr>
<th></th>
<th>(B^{SM})</th>
<th>(\Gamma^{SM})</th>
<th>(\Gamma)</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>(WW^*)</td>
<td>21.6%</td>
<td>0.98</td>
<td>hard to change</td>
<td>(\sin(\beta - \alpha) \simeq 1)</td>
</tr>
<tr>
<td>(ZZ^*)</td>
<td>2.67%</td>
<td>0.12</td>
<td>hard to change</td>
<td>(\sin(\beta - \alpha) \simeq 1)</td>
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<tr>
<td>(\gamma\gamma)</td>
<td>0.228%</td>
<td>0.011</td>
<td>hard to change</td>
<td>(W)-loop dom.</td>
</tr>
<tr>
<td>(bb)</td>
<td>57.5%</td>
<td>2.70</td>
<td>hard to change</td>
<td>(b \rightarrow s\gamma)</td>
</tr>
<tr>
<td>(\tau\tau)</td>
<td>6.30%</td>
<td>0.26</td>
<td>within fac. 2</td>
<td>direct</td>
</tr>
<tr>
<td>(cc)</td>
<td>2.90%</td>
<td>0.12</td>
<td>up to (\sim \Gamma_{bb})</td>
<td>not measured</td>
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<tr>
<td>(gg)</td>
<td>8.56%</td>
<td>0.35</td>
<td>up to fac. 2</td>
<td>(\rho_{tt} \sim 1)</td>
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Theoretical Values for FCNC Top Decays

ATLAS-PHYS-PUB-2013-012

<table>
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<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
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<tbody>
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<td>$t \to u\gamma$</td>
<td>$3.7 \cdot 10^{-16}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$t \to uZ$</td>
<td>$8 \cdot 10^{-17}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>—</td>
<td>—</td>
<td>$2 \cdot 10^{-6}$</td>
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<tr>
<td>$t \to uH$</td>
<td>$2 \cdot 10^{-17}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$5.5 \cdot 10^{-6}$</td>
<td>—</td>
<td>$10^{-5}$</td>
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<tr>
<td>$t \to c\gamma$</td>
<td>$4.6 \cdot 10^{-14}$</td>
<td>$7.5 \cdot 10^{-9}$</td>
<td>$\sim 10^{-6}$</td>
<td>$\sim 10^{-9}$</td>
<td>$2 \cdot 10^{-6}$</td>
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<tr>
<td>$t \to cZ$</td>
<td>$1 \cdot 10^{-14}$</td>
<td>$1.1 \cdot 10^{-4}$</td>
<td>$\sim 10^{-7}$</td>
<td>$\sim 10^{-10}$</td>
<td>$2 \cdot 10^{-6}$</td>
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<tr>
<td>$t \to cH$</td>
<td>$3 \cdot 10^{-15}$</td>
<td>$4.1 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>$\sim 10^{-5}$</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
Introduction and Motivation
Das and Kao (1996)

- A special two Higgs doublet model explains why top quark is the most massive elementary particle by suggesting that it is the only fermion that couples to a Higgs doublet ($\phi_2$) with a much larger VEV ($v_2 \gg v_1$).

- This model leads to flavor changing neutral Higgs (FCNH) interactions and CP violation.

- Most LHC data are consistent with the Standard Model. FCNH interactions might lead to new physics beyond SM.
A Special Higgs Model for the Top Quark

1 Introduction

In the Standard Model (SM) of electroweak interactions:

1. There is one Higgs doublet to generate mass for gauge bosons as well as for fermions. A neutral Higgs scalar ($H^0$) remains after spontaneous symmetry breaking.

2. The top quark has a large mass because its Yukawa coupling with the $H^0$ is large.†

In a special two Higgs doublet model, the top quark is much heavier than the other quarks and the leptons, because it is the only elementary fermion getting a mass from a much larger vacuum expectation value (VEV) of a second Higgs doublet.

This model has a few interesting features:

1. The ratio of the Higgs VEVs, $\tan \beta \equiv |v_2|/|v_1|$, is chosen to be large.

2. The Yukawa couplings of the lighter fermions are highly enhanced.

3. There are flavor changing neutral Higgs interactions.

†The mass of a fermion is equal to its Yukawa coupling with the $H^0$ times the vacuum expectation value of the Higgs field, $m = \lambda(v/\sqrt{2})$. 
2 Two Higgs Doublet Models

A two Higgs doublet model has doublets $\phi_1$ and $\phi_2$. After spontaneous symmetry breaking, there remain five ‘Higgs bosons’:
1. a pair of singly charged Higgs bosons $H^+$ and $H^-$,
2. two neutral CP-even scalars $H_1$ and $H_2$, and
3. a neutral CP-odd pseudoscalar $A$.

2.1 Yukawa Interactions

Several interesting two Higgs doublet models, with different Yukawa interactions between the fermions and the spin-0 bosons, have been suggested:

1. In Model I, the different mass scales of the fermions and the gauge bosons are set by the Higgs VEVs.\(^{\dagger}\)

2. In Model II, one Higgs doublet couples to down-type quarks and charged leptons while another doublet couples to up-type quarks and neutrinos.\(^{\S}\)

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2.2 The Higgs Potential

In multi-Higgs doublet models, a discrete symmetry is usually required for flavor symmetry to be conserved. In two Higgs doublet models, this discrete symmetry is often chosen to be

$$\phi_1 \rightarrow -\phi_1, \quad \phi_2 \rightarrow +\phi_2. \quad (1)$$

If this discrete symmetry is only softly broken: (a) Higgs boson exchange can generate CP violation, and (b) the flavor changing neutral Higgs interactions can be kept at an acceptable level.

The Higgs potential of a general two Higgs doublet model with the discrete symmetry softly broken, can be written as

$$V[\phi_1, \phi_2] = m_1 \phi_1^\dagger \phi_1 + m_2 \phi_2^\dagger \phi_2 + \eta \phi_1^\dagger \phi_2 + \eta^* \phi_2^\dagger \phi_1$$

$$+ \frac{1}{2} g_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} g_2 (\phi_2^\dagger \phi_2)^2$$

$$+ g (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + g' (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1)$$

$$+ \frac{1}{2} h (\phi_1^\dagger \phi_2)^2 + \frac{1}{2} h^* (\phi_2^\dagger \phi_1)^2. \quad (2)$$

---


Introducing a transformation, which takes the Higgs doublets to their Higgs eigenstates ($\Phi_1$ and $\Phi_2$), we have

$$
\begin{pmatrix}
\Phi_1 \\
\Phi_2
\end{pmatrix}
= 
\begin{pmatrix}
\cos \beta & \sin \beta e^{-i\theta} \\
-\sin \beta & \cos \beta e^{-i\theta}
\end{pmatrix}
\begin{pmatrix}
\phi_1 \\
\phi_2
\end{pmatrix},
$$

$$
\Phi_1 = \begin{pmatrix}
G^+ \\
\frac{v+H_1+iG^0}{\sqrt{2}}
\end{pmatrix},
$$

$$
\Phi_2 = \begin{pmatrix}
H^+ \\
\frac{H_2+iA}{\sqrt{2}}
\end{pmatrix},
$$

(3)

where $v = \sqrt{|v_1|^2 + |v_2|^2}$, and

1. $G^\pm$ and $G^0$ are Goldstone bosons,

2. $H^\pm$ are singly charged Higgs bosons,

3. $H_1$ and $H_2$ are CP-even scalars, and

4. $A$ is a CP-odd pseudoscalar.

Without loss of generality, we will take $v_1, v_2 \in \mathcal{R}$, and

$$
\langle \phi_1 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle \phi_2 \rangle = \frac{v_2e^{i\theta}}{\sqrt{2}}.
$$
In the Higgs eigenstates, the Higgs potential becomes

\[
V[\Phi_1, \Phi_2] = \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1 - \frac{v^2}{2})^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
+ \lambda_3 (\Phi_1^\dagger \Phi_1 - \frac{v^2}{2})\Phi_2^\dagger \Phi_2 + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \lambda_5 (\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 - \frac{v^2}{2})(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\
+ (\lambda_6 \Phi_1^\dagger \Phi_2 + \lambda_6^* \Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_1 - \Phi_2^\dagger \Phi_2 - \frac{v^2}{2}) \\
+ \frac{1}{2} \lambda_7 (\Phi_1^\dagger \Phi_2)^2 + \frac{1}{2} \lambda_7^* (\Phi_2^\dagger \Phi_1)^2 \\
+ \rho (\Phi_2^\dagger \Phi_2),
\]

where the parameters \( \rho \), \( v \) and \( \lambda_i \), \( i = 1 \) through \( 5 \), are all real; \( \lambda_6 \) and \( \lambda_7 \) can be complex.

CP is violated if the imaginary part of \( \lambda_6 \) or \( \lambda_7 \) is nonvanishing.

There are two sources of CP violation in the Higgs potential:

1. the mixing of the \( A \) with the \( H_1 \) and the \( H_2 \), and
2. the CP violating interaction of \( AH^+ H^- \).
3 Special Yukawa Interactions

We choose the Lagrangian density of Yukawa interactions to be of the following form

\[
\mathcal{L}_Y = - \sum_{m,n=1}^{3} \bar{L}_L^m \phi_1 E_{mn} l_R^n - \sum_{m,n=1}^{3} \bar{Q}_L^m \phi_1 F_{mn} d_R^n - \sum_{\alpha=1}^{2} \sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_1 G_{m\alpha} u_R^\alpha - \sum_{m=1}^{3} \bar{Q}_L^m \tilde{\phi}_2 G_{m3} u_R^3 + \text{H.c.},
\]

where

\[
\phi_\alpha = \begin{pmatrix} \phi_\alpha^+ \\ v_\alpha + \phi_\alpha^0 \\ \sqrt{2} \end{pmatrix}, \quad \tilde{\phi}_\alpha = \begin{pmatrix} v_\alpha + \phi_\alpha^0 \\ \phi_\alpha^- \\ -\phi_\alpha^- \end{pmatrix}, \quad \phi_\alpha^- = \phi_\alpha^{++}, \quad \alpha = 1, 2, \quad \text{and (5)}
\]

\[
L_L^m = \begin{pmatrix} v_l \\ l \end{pmatrix}_L^m, \quad Q_L^m = \begin{pmatrix} u \\ d \end{pmatrix}_L^m, \quad m = 1, 2, 3, \quad \text{(6)}
\]

\(l^m, d^m, \) and \(u^m\) are the gauge eigenstates.

This Lagrangian respects a discrete symmetry,

\[
\phi_1 \rightarrow -\phi_1, \quad \phi_2 \rightarrow +\phi_2, \\
l_R^m \rightarrow -l_R^m, \quad d_R^m \rightarrow -d_R^m, \quad u_R^\alpha \rightarrow -u_R^\alpha, \\
L_L^m \rightarrow +L_L^m, \quad Q_L^m \rightarrow +Q_L^m, \quad u_R^3 \rightarrow +u_R^3. \quad \text{(7)}
\]
4 Flavor Changing Neutral Higgs Interactions

The Yukawa interactions of the quarks with neutral Higgs bosons now become

$$\mathcal{L}_Y^N = - \sum_{d=d,s,b} \frac{m_d}{v} \bar{d}d(H_1 - \tan \beta H_2)$$

$$- i \sum_{d=d,s,b} \frac{m_d}{v} \bar{d}\gamma_5 d(G^0 - \tan \beta A)$$

$$- \sum_{u=u,c} \frac{m_u}{v} \bar{u}u[H_1 - \tan \beta H_2]$$

$$+ i \sum_{u=u,c} \frac{m_u}{v} \bar{u}\gamma_5 u[G^0 - \tan \beta A]$$

$$- \frac{m_t}{v} \bar{t}t[H_1 + \cot \beta H_2] + i \frac{m_t}{v} \bar{t}\gamma_5 t[G^0 + \cot \beta A] + \mathcal{L}_{FCNH},$$

$$\mathcal{L}_{FCNH} = \{-\epsilon_1^* \epsilon_2 \bar{u}c[(m_u + m_c)H_2 + i(m_c - m_u)A]$$

$$- \epsilon_1^* \bar{t}t[(m_u + m_t)H_2 + i(m_t - m_u)A]$$

$$- \epsilon_2^* \bar{c}t[(m_c + m_t)H_2 + i(m_t - m_c)A]$$

$$+ \epsilon_1^* \epsilon_2 \bar{u}\gamma_5 c[(m_c - m_u)H_2 + i(m_u + m_c)A]$$

$$+ \epsilon_1^* \bar{t}\gamma_5 t[(m_t - m_u)H_2 + i(m_u + m_t)A]$$

$$+ \epsilon_2^* \bar{c}\gamma_5 t[(m_t - m_c)H_2 + i(m_c + m_t)A]\} \times \left(\frac{1}{v \sin 2\beta}\right) + \text{H.c.}$$
Let us express the general Yukawa interaction Lagrangian for neutral Higgs bosons as

\[ \sqrt{2} \mathcal{L}^N_i = \bar{U} \left[ -\kappa^U s_{\beta} - \rho^U c_{\beta} \right] U h^0 + \bar{D} \left[ -\kappa^D s_{\beta} - \rho^D c_{\beta} \right] D h^0 \\
+ \bar{U} \left[ -\kappa^U c_{\beta} + \rho^U s_{\beta} \right] U h^0 + \bar{D} \left[ -\kappa^D c_{\beta} + \rho^D s_{\beta} \right] D h^0 \\
+ \bar{U} \left[ +i\gamma_5 \rho^U \right] U A^0 + \bar{D} \left[ -i\gamma_5 \rho^D \right] D A^0 \]

where \( \kappa^f = \frac{\sqrt{2m_f}}{v} \), \( \tan \beta \equiv \frac{v_2}{v_1} \), and \( v = \sqrt{v_1^2 + v_2^2} \).

There are 4 flavor conserving models with \( Z_2 \) symmetries, such that \( \rho \)'s are related to \( \kappa \)'s in the following form [Barger, Hewett and Phillips, PRD 41 (1990) 3421.]:

<table>
<thead>
<tr>
<th>Type</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
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<tr>
<td></td>
<td>( \rho^D )</td>
<td>( \kappa^D \cot \beta )</td>
<td>(-\kappa^D \tan \beta )</td>
<td>(-\kappa^D \tan \beta )</td>
</tr>
<tr>
<td></td>
<td>( \rho^U )</td>
<td>( \kappa^U \cot \beta )</td>
<td>( \kappa^U \cot \beta )</td>
<td>( \kappa^U \cot \beta )</td>
</tr>
<tr>
<td></td>
<td>( \rho^E )</td>
<td>( \kappa^E \cot \beta )</td>
<td>(-\kappa^E \tan \beta )</td>
<td>( \kappa^E \cot \beta )</td>
</tr>
</tbody>
</table>

In a general model without \( Z_2 \) symmetries, \( \rho \) matrices are free.
The Decoupling Limit of 2HDM
Gunion and Haber (2003)

- In the decoupling limit of 2HDM, we expect
  
  - $M_h = O(v)$
  
  - $M_{H^+}, M_A, M_{H^+} = M_S + O(v^2/M_S)$
  
  - $|\cos(\beta-\alpha)| = O(v^2/M_S^2)$
  
  - If $\cos(\beta-\alpha) = 0$, $h^0$ becomes the SM Higgs boson.

- Recently, there has been interests in the 2HDM parameter space where the alignment is obtained without decoupling and without fine tuning where $H^0$ and $A^0$ can be light and $h^0$ is like SM Higgs. Craig, Galloway, Thomas (2013); Carena et al. (2014)
Constraints on Elements of $\rho$-matrices

- The LHC data indicate that $\Gamma(h^0 \to bb)$ and $\Gamma(h^0 \to \tau\tau)$ are consistent with SM expectations. Thus $\rho_{bb}$ and $\rho_{\tau\tau}$ must be small.
- Data of $D_s \to \tau\nu$ and $D_s \to \mu\nu$ suggest $\rho_{cc} < 0.2$ [Crivellin et al. (2013)].
- The SM Higgs cross section ($|\sigma-\sigma_{SM}| < 0.2 \sigma_{SM}$) implies that $-10 < \rho_{tt} < 0.5$ or $-9 < \rho_{tt} < -0.4$ for $\cos(\beta-\alpha) = 0.2$.
- We will take $0.5 < |\rho_{tt}| < 2$. 
Constraints on FCNH Couplings

• ATLAS and CMS data have placed tight constraints on $\lambda_{tc}$ and $\lambda_{ct}$ with $t \rightarrow ch^0 \rightarrow c\gamma\gamma$:
  - the top decay should have $B(t \rightarrow ch^0) < 0.56\%$,
  - or $\sqrt{\lambda_{tc}^2 + \lambda_{ct}^2} < 0.14$, with $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$.

• If we choose $\rho$-matrix to be Hermitian, then $b \rightarrow s\gamma$ and $B - \bar{B}$ mixing imply $|\rho_{ct}| < 0.1$.

• If the $\rho$-matrix is not Hermitian, then we must have $|\rho_{ct}| < 0.1$, while $|\rho_{tc}|$ can be close to 1.
When the Higgs Meets the Top

• The Higgs boson is the mass giver, while the top quark is the most massive particle. Their interactions might give us guidance to search for new physics beyond the Standard Model.

• The LHC has become a top factory.

• We might be able to observe $t \rightarrow ch^0$ if $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$ can lead to observable signal.

• Or we might discover $H^0, A^0 \rightarrow t\bar{c} + \bar{t}c$ in the decoupling limit with $\lambda_{tc} = \rho_{tc} \sin(\beta-\alpha)$. 
The FCNH Signal at the LHC

- We employ the programs MadGraph and HELAS to evaluate the exact matrix element for the FCNH signal from gluon fusion and quark-antiquark annihilation in pp collisions. Stelzer and Long (1994); Alwall et al. (2007); Murayama, Watanabe and Hagiwara (1991).

- In addition, we apply narrow width approximation to check the exact results.

- The cross sections are evaluated with the parton distribution functions of CTEQ6L1.
FCNH Top Decays at the LHC

Hou (1991); Hall and Weinberg (1993);
Aguilar-Saavedra and Branco (2000);
Kao, Cheng, Hou, and Sayre (2012);

$$g_{htc}(CS) = \frac{\sqrt{m_t m_c}}{v} \sim 0.06$$

$$\lambda_{htc}(HW) = \epsilon_{Q3}\epsilon_{U2} \sim 0.2$$
Discovery Potential with 8 TeV

$\sqrt{s} = 8$ TeV, $M_H = 125$ GeV

$B(t \to cH) \quad 0.0001 \quad 0.001 \quad 0.01 \quad 0.015$

$\sigma(pp \to tt \to bl{\bar{\nu}} bbj +X) (\text{fb})$

$\sigma_B$

$\sigma_{S(H^0)}$

$5\sigma \ (L = 20 \text{ fb}^{-1})$

CS Ansatz
Constraint from the Golden Mode for Higgs Discovery

- The CMS preliminary result with full 7 and 8 TeV data shows 13, 8, and 4 events with 0, 1, and 2 jets, respectively, after selecting events with $121.5 \text{ GeV} < M_{4l} < 130.5 \text{ GeV}$.

- The resulting 95% confidence level limit on the relative signal strength between $t \to c h^0$ and inclusive Higgs production is around 31%.

- That can be converted to a limit of 6.5 pb on the effective cross section of $t \to c h^0$ at 8 TeV, or a branching ratio limit around 1.5%.
The Golden Mode for Higgs Discovery

[Graph showing the number of events for different jet counts.]

- Data
- $ZZ, Z\gamma^*$
- $Z+X$
- $m_H=126$ GeV

CMS preliminary $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$ $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$
Future ATLAS Expectations

• At the LHC with collider energy of 8 TeV and an integrated luminosity $L \sim 25 \text{ fb}^{-1}$, ATLAS set a limit for the branching fraction

$$B(t \rightarrow ch^0) < 0.83\% \text{ or } \rho_{tc} \cos(\beta - \alpha) < 0.174$$

• At the LHC with collider energy of 14 TeV and an integrated luminosity $L = 3000 \text{ fb}^{-1}$, ATLAS expects to set a limit for the branching fraction

$$B(t \rightarrow ch^0) < 1.5 \times 10^{-4} \text{ or } \rho_{tc} \cos(\beta - \alpha) < 0.0234$$
Summary for FCNH top Decay

- It is of great interest to search for the link between the top quark (t) and the Higgs bosons (H^0, h^0, A^0).
- A discovery of \( t \rightarrow ch^0 \) would suggest the existence of an extended Higgs sector beyond the usual 2HDM-II and MSSM.
- Experimental studies of h^0 to bb, WW^*, ZZ^*, \( \tau^+\tau^- \) and \( \gamma\gamma \) modes will provide important information for FCNH interactions.
Discovery Potential of $t \to ch$ with $h \to WW$

Jain and Kao (2018)

- $h \to WW$ has the second largest BF.
- We study $WW \to ll +MET$.
- The cluster traverse mass of $ll$ offers good approximation to reconstruction the Higgs mass ($ll$) and the top quark mass ($cll$).
Invariant Mass Distributions

\[ \sqrt{s} = 14 \text{ TeV} \]
Transverse Mass Distributions

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \frac{d\sigma}{dM(T^{\ell\ell}, M_{\text{T}(\ell\ell, \text{MET})}) \text{ (fb/GeV)}} \]

\[ \frac{d\sigma}{dM(T^{\ell}, M_{\text{T}(\ell, \text{MET})}) \text{ (fb/GeV)}} \]

\[ M_{T(\ell\ell): \text{ttjj}} \]

\[ M_{T(c\ell\ell): \text{ttjj}} \]

\[ M_{T(c\ell\ell): t \rightarrow c\text{WW}} \]

\[ M_{T(\ell\ell): t \rightarrow c\text{WW}} \]
Cross Section of Signal and Background
Discovery Potential of
\[ t \rightarrow ch^0 \rightarrow cWW \]
Discovery Potential of
\[ t \rightarrow ch^0 \rightarrow cWW \]
Conclusions

- It is of great interest to search for the link between the heaviest particle (top) and the mass giver (Higgs).
- It is a win-win strategy to search for the FCNH top decay $t \rightarrow ch^0$ and the heavy Higgs decay $H^0, A^0 \rightarrow t\bar{c} + t\bar{c}$. In the decoupling limit, the production ($gg \rightarrow H^0$) and the FCNH decay $H^0 \rightarrow tc$ can be sustained by $\sin(\beta-\alpha) \sim 1$.
- The FCNH decay of heavy Higgs bosons will be observable for $\rho_{tc} > 0.1$ and $\cos(\beta-\alpha) \sim 0.1$ up to $M_H = 800$ GeV with 3000 fb$^{-1}$ of data.
- We might find out if nature chooses the same mechanism for electroweak symmetry breaking and tree-level FCNC.