When the Higgs meets the Top

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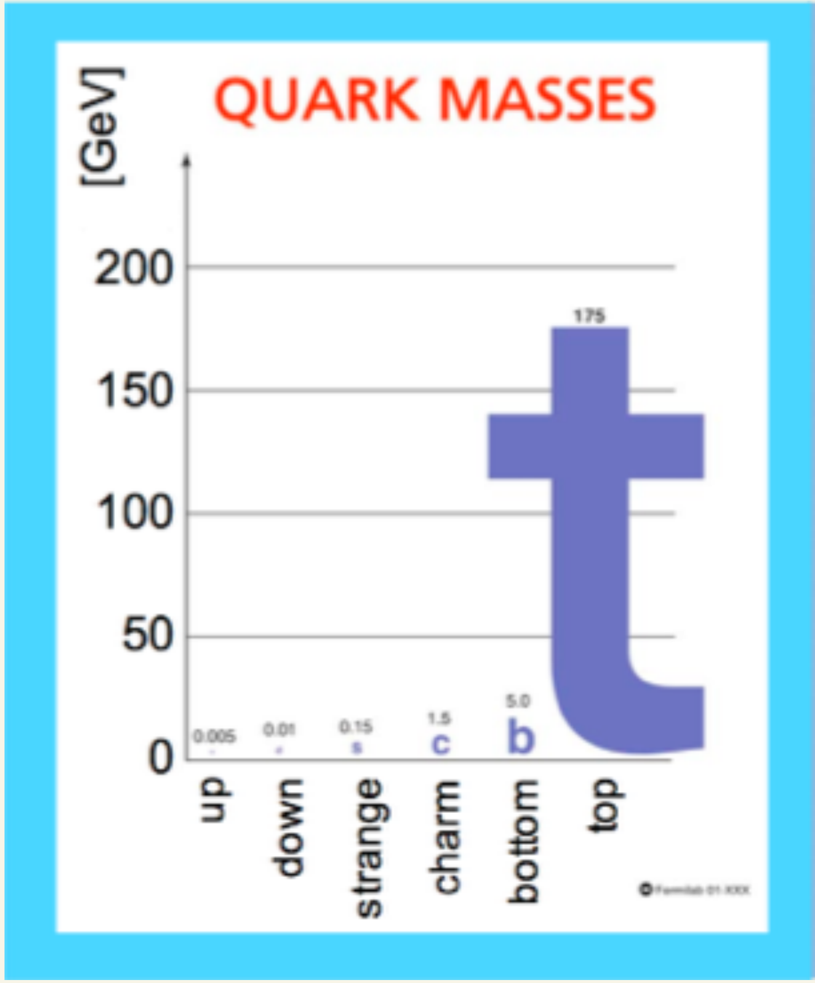
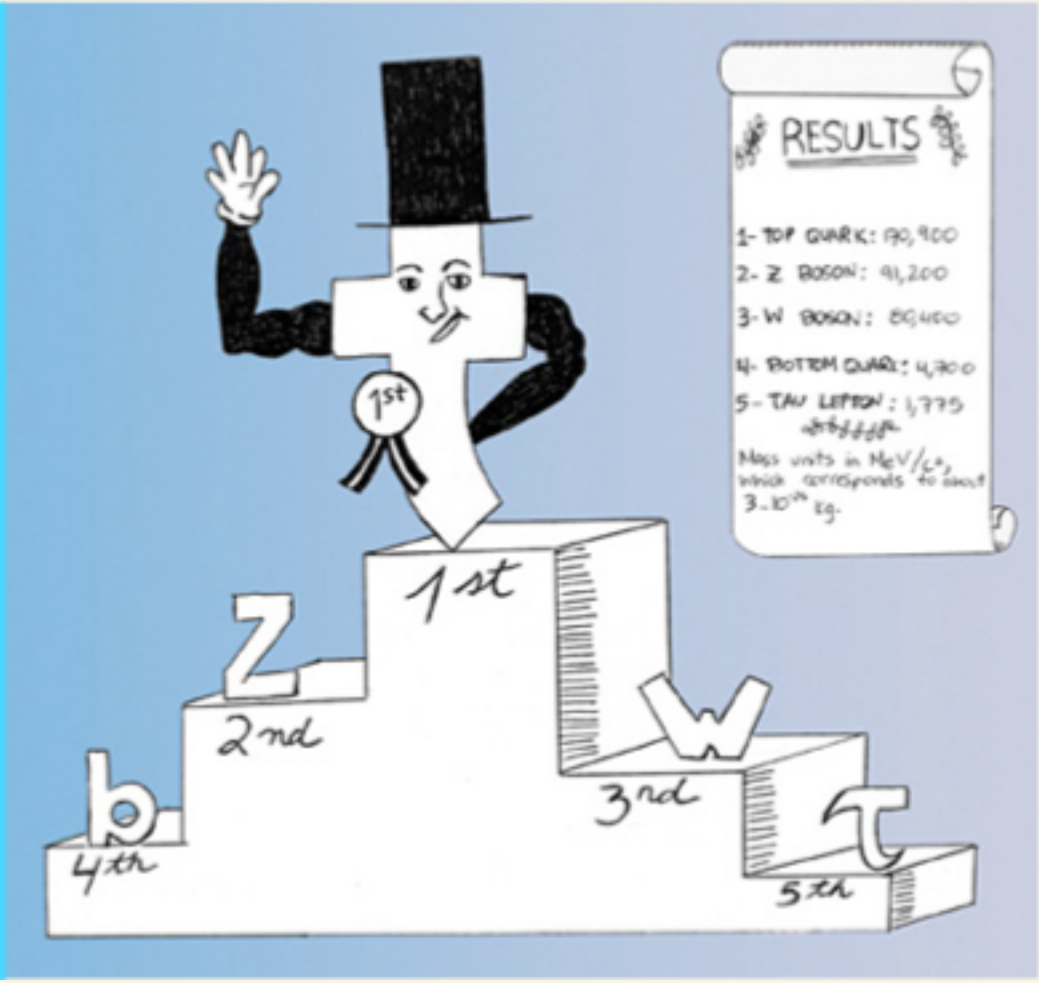
When the Higgs meets the Top

Altunkaynak, Hou, Kao, Kohda, and McCoy (2015);
Chen, Hou, Kao, and Kohda, Phys. Lett. B 725 (2013) 378;
Kao, Cheng, Hou, and Sayre, Phys. Lett. B 716 (2012) 225.

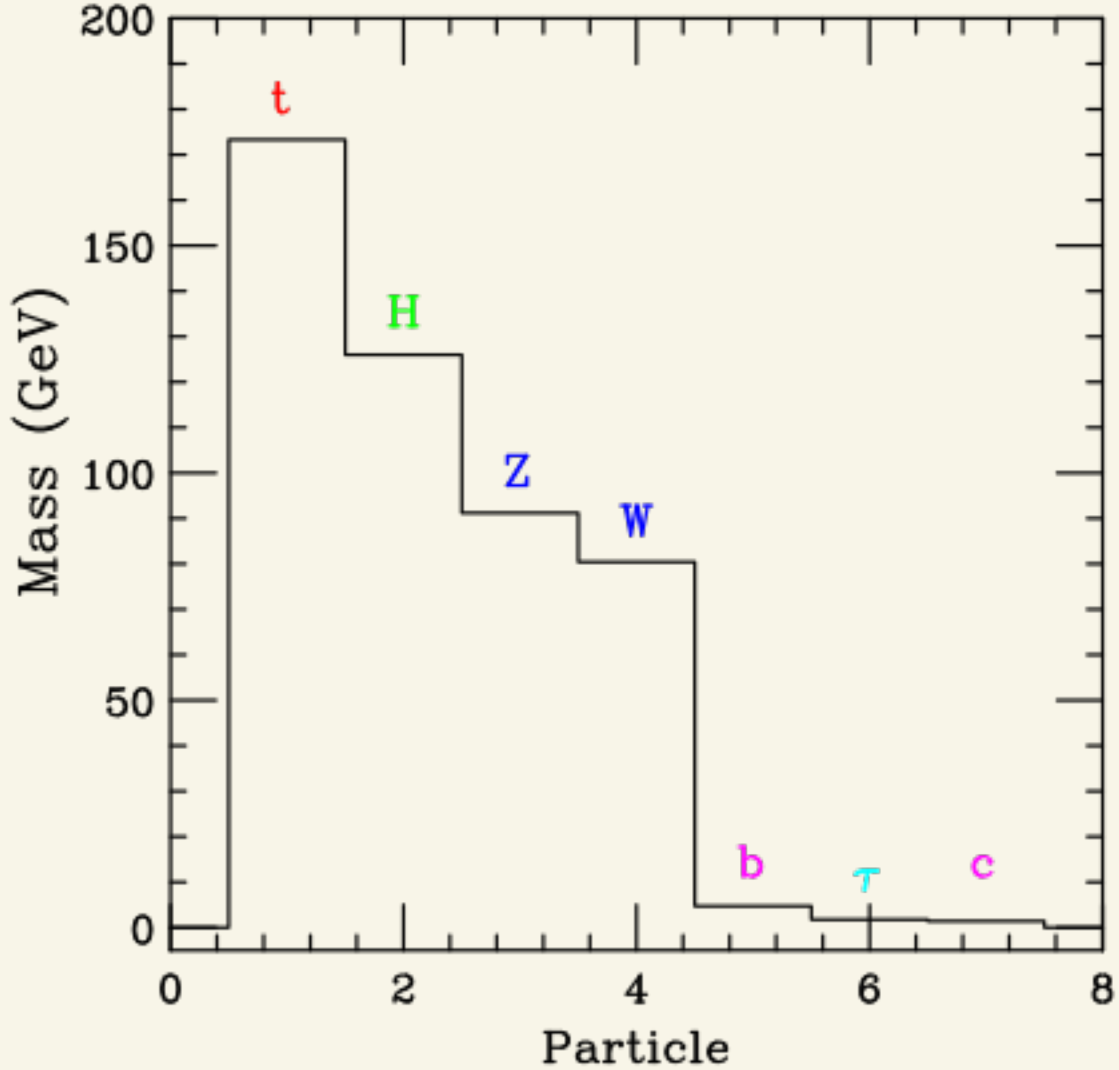
- Introduction and Motivation
- General Two Higgs Doublet Models
- When the Higgs Meets the Top
- The Discovery Potential at the LHC
- Conclusions

Heavyweight Champion before July 4, 2012





The New Runner-up



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 (ϕ_2) with a much larger VEV ($v_2 >> v_1$).
- 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.

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

4 Flavor Changing Neutral Higgs Interactions

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

$$
\begin{aligned}
\mathcal{L}_Y^N &= -\sum_{d=d,s,b}\frac{m_d}{v}\bar{d}d(H_1-\tan\beta H_2) \\
&-i\sum_{d=d,s,b}\frac{m_d}{v}\bar{d}\gamma_5 d(G^0-\tan\beta A) \\
&-\sum_{u=u,c}\frac{m_u}{v}\bar{u}u[H_1-\tan\beta H_2] \\
&+i\sum_{u=u,c}\frac{m_u}{v}\bar{u}\gamma_5 u[G^0-\tan\beta A] \\
&-\frac{m_t}{v}\bar{t}t[H_1+\cot\beta H_2]+i\frac{m_t}{v}\bar{t}\gamma_5 t[G^0+\cot\beta A]+\mathcal{L}_{\rm FCNH}, \\
\mathcal{L}_{\rm FCNH} &= \{-\epsilon_1^*\epsilon_2\bar{u}c[(m_u+m_c)H_2+i(m_c-m_u)A] \\
&-\epsilon_1^*\bar{u}t[(m_u+m_t)H_2+i(m_t-m_u)A] \\
&-\epsilon_2^*\bar{c}t[(m_c+m_t)H_2+i(m_t-m_c)A] \\
&+\epsilon_1^*\epsilon_2\bar{u}\gamma_5 c[(m_c-m_u)H_2+i(m_u+m_c)A] \\
&+\epsilon_1^*\bar{u}\gamma_5 t[(m_t-m_u)H_2+i(m_u+m_t)A] \\
&+\epsilon_2^*\bar{c}\gamma_5 t[(m_t-m_c)H_2+i(m_c+m_t)A]\}\times(\frac{1}{v\sin 2\beta})+\text{H.c.}
\end{aligned}
$$

A General Two Higgs Doublet Model

Mahmoudi and Stal (2009)

- Let us express the general Yukawa interaction Lagrangian for neutral Higgs bosons as

$$\begin{aligned}\sqrt{2}\,\mathcal{L}_l^{\mathrm{N}} \;=\;& \bar{U}\left[-\kappa^U s_{\beta-\alpha} - \rho^U c_{\beta-\alpha}\right] U h^0 + \bar{D}\left[-\kappa^D s_{\beta-\alpha} - \rho^D c_{\beta-\alpha}\right] D h^0 \\ & + \bar{U}\left[-\kappa^U c_{\beta-\alpha} + \rho^U s_{\beta-\alpha}\right] U H^0 + \bar{D}\left[-\kappa^D c_{\beta-\alpha} + \rho^D s_{\beta-\alpha}\right] D H^0 \\ & + \bar{U}\left[+i\gamma_5 \rho^U\right] U A^0 + \bar{D}\left[-i\gamma_5 \rho^D\right] D A^0\end{aligned}$$

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

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

	Type I	Type II	Type III	Type 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	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$	$\kappa^E \cot\beta$	$-\kappa^E \tan\beta$

- In a general model without Z_2 symmetries, ρ 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 FCNH Couplings

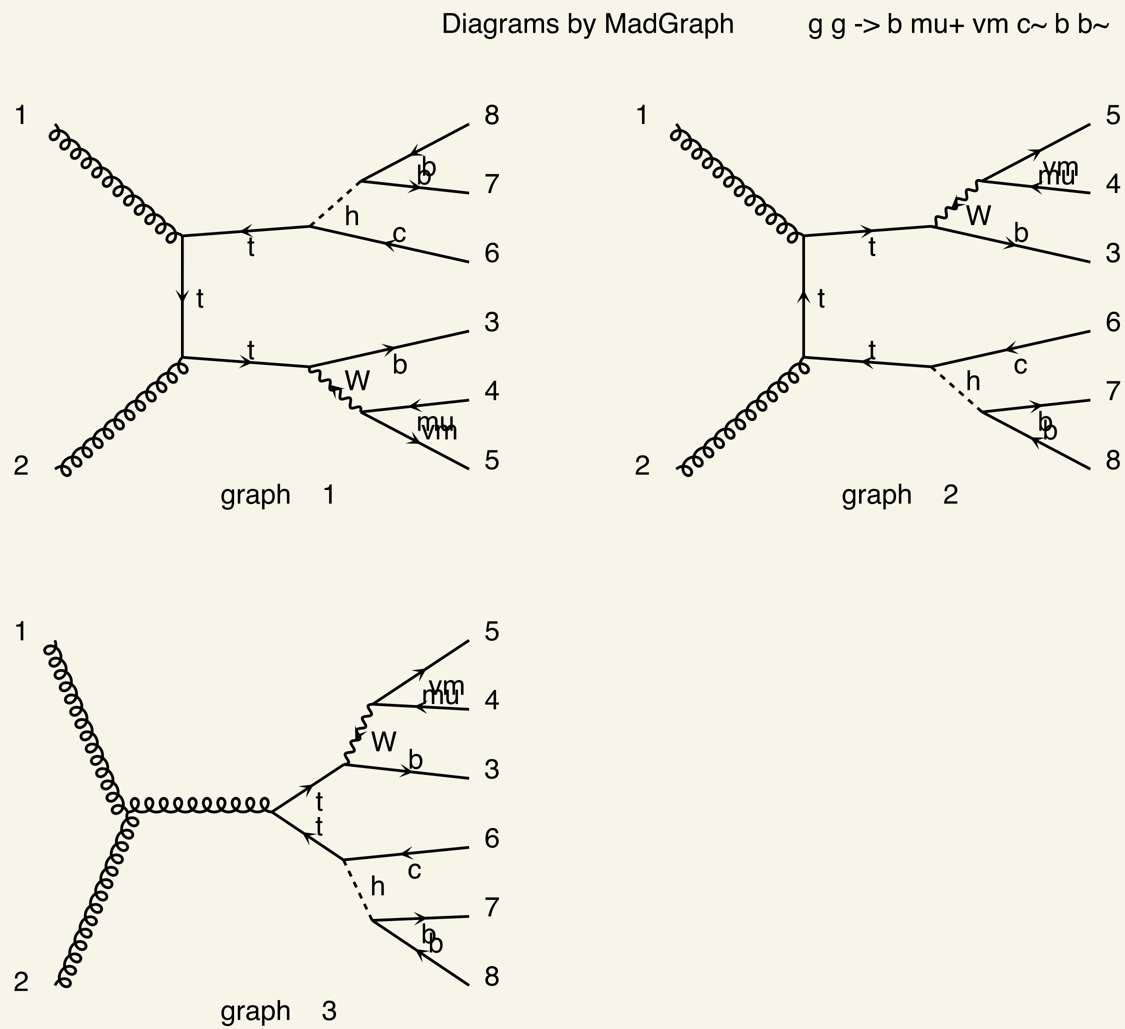
- ATLAS and CMS data have placed a tight constraint:
  - the top decay should have $B(t \to ch^0) < 0.56\%$,
  - or $\sqrt{\lambda_{ct}^2 + \lambda_{tc}^2} < 0.14$, where $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$.
- If we choose ρ_{ct} and ρ_{tc} to be real, then $b \to s\gamma$ and $B_S - \bar{B}_S$ mixing imply that $\rho_{tc} < 0.3$.
- If the ρ-matrix is not Hermitian, then we have $|\rho_{tc}| < 0.3$, while $|\rho_{ct}|$ can be close to 1.

When the Higgs Meets the Top

- The Higgs is the mass giver while the top is most massive particle. Their interactions might give us guidance to search for new physics.
- The LHC has become a top factory.
- We might be able to observe $t \to ch^0$ if $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$ can lead to observable signal.
- Or we might be able to discover $H^0 \to t\bar{c} + \bar{t}c$ with the coupling proportional to $\rho_{ct} \sin(\beta-\alpha)$.

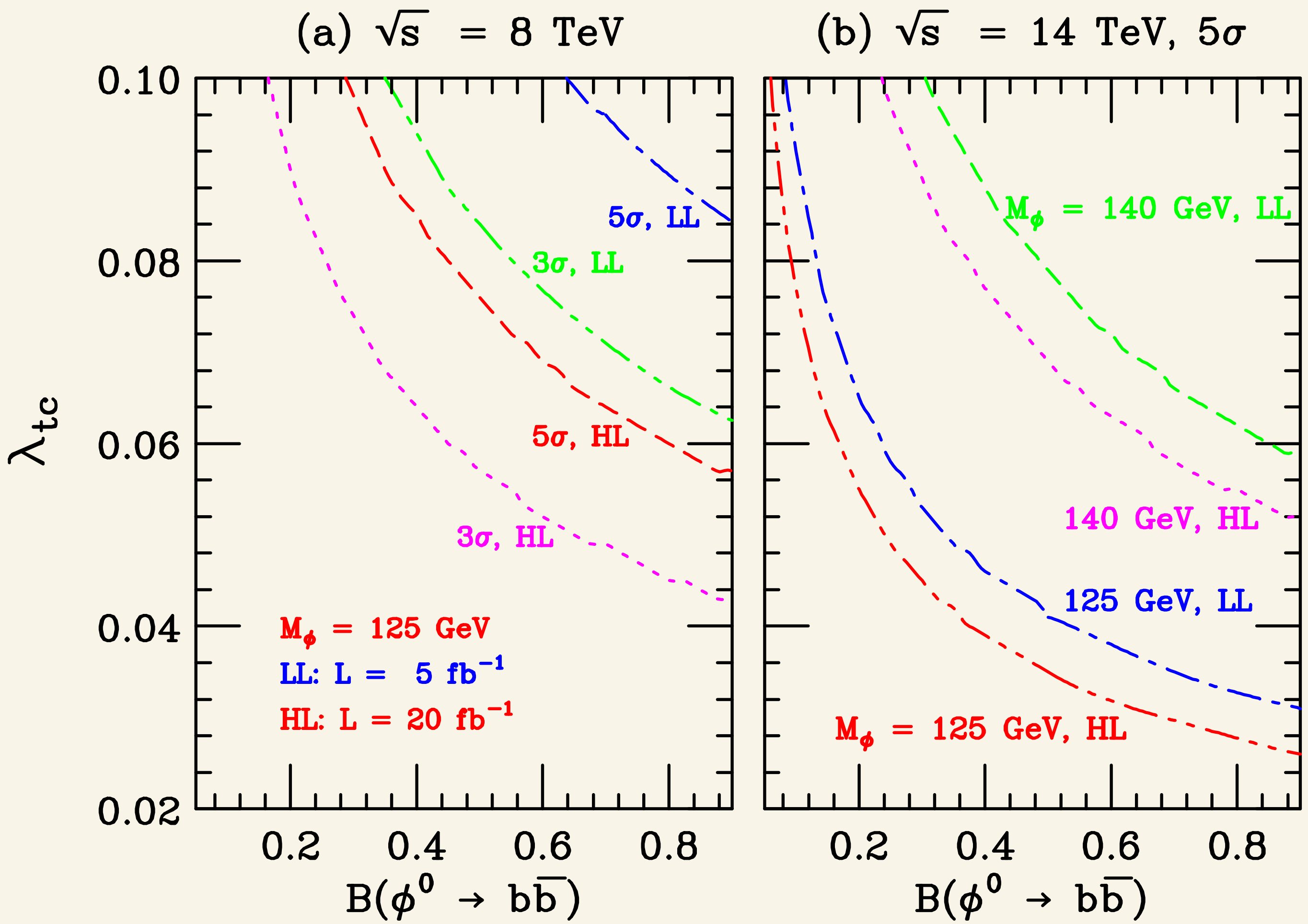
FCNH signal of

$$t \to ch^0 \to cb\bar{b}$$



Discovery Contours

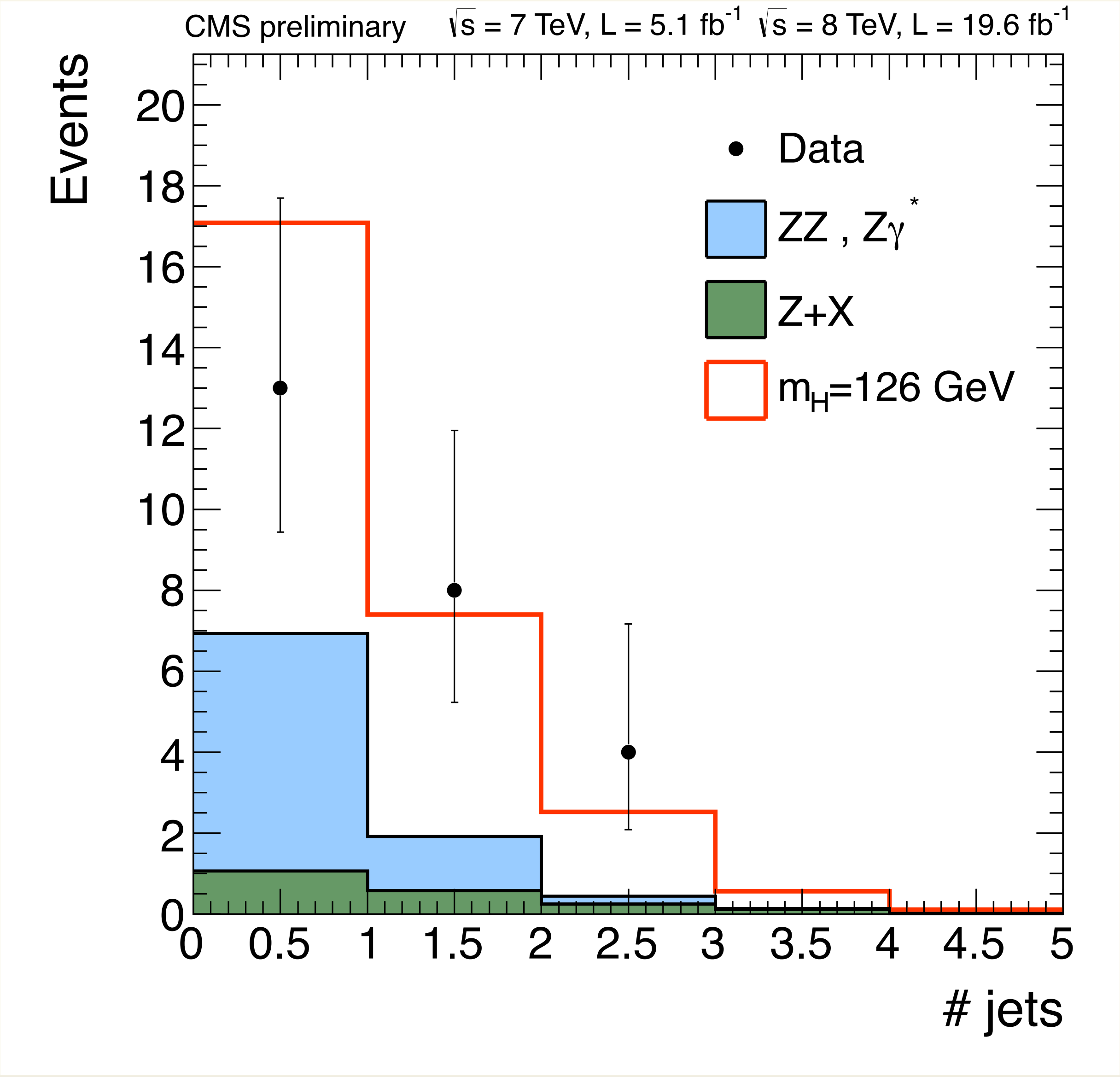
L = 20 fb^{-1} at 8 TeV; 30 fb^{-1} at 14 TeV



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 GeV $< M_{4l} <$ 130.5 GeV.
- The resulting 95% confidence level limit on the relative signal strength between t to ch^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 ch^0 at 8 TeV, or a branching ratio limit around 1.5%.

The Golden Mode for Higgs Discovery



Future ATLAS Expectations

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

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

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

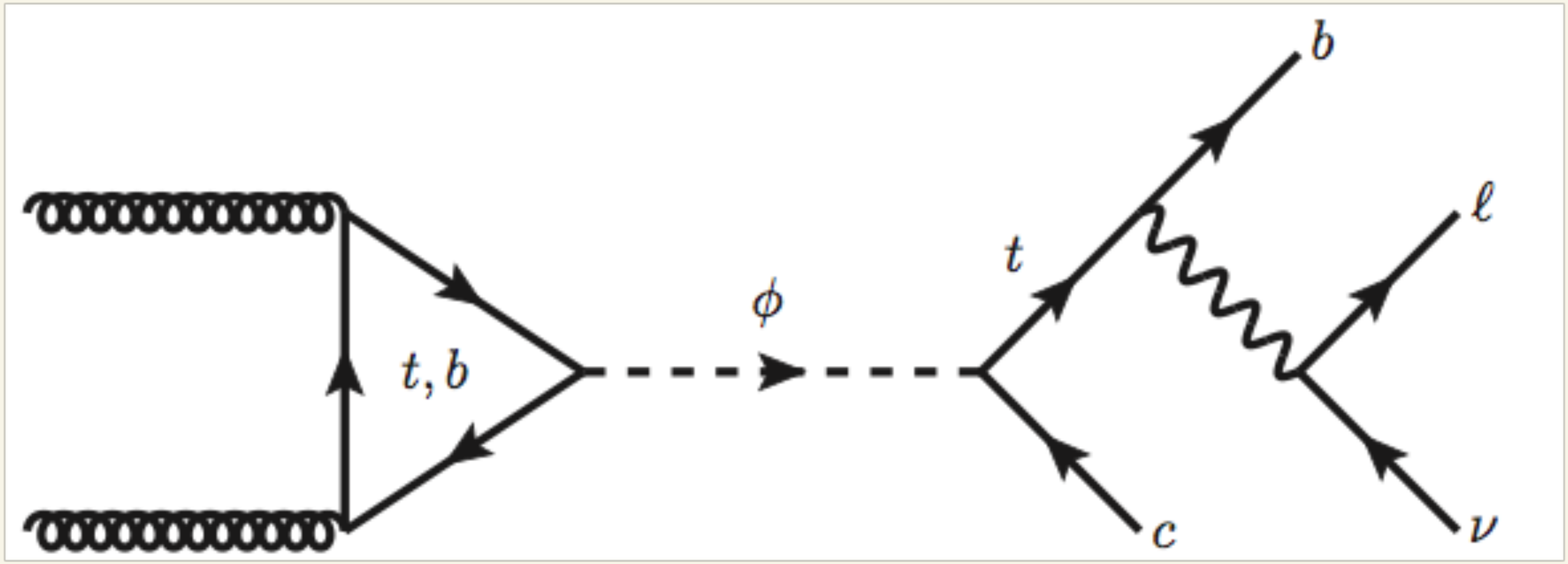
$$B(t \to ch^0) < 1.5 \times 10^{-4} \text{ or } \rho_{tc} \cos(\beta - \alpha) < 0.0234$$

Summary for t to ch^0

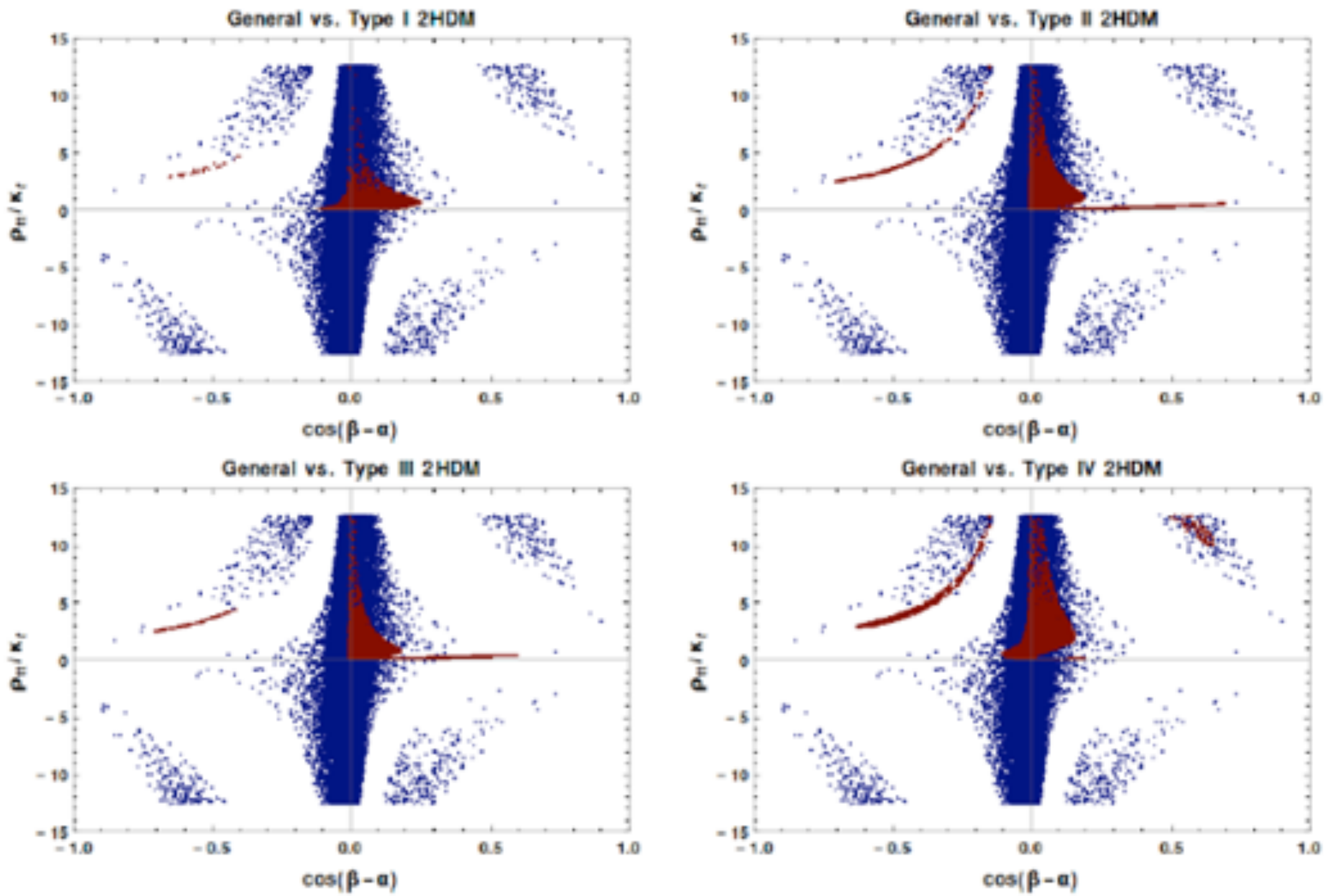
- It is of great interest to search for the link between the top quark (t) and the Higgs boson (h^0).
- A discovery of t to ch^0 process would suggest the existence of an extended Higgs sector beyond the usual 2HDM-II and MSSM.
- Experimental studies for h^0 to bb, ZZ*, WW*, $\tau^+\tau^-$ and $\gamma\gamma$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

The FCNH Signal of a Heavy Higgs boson at the LHC

Let us consider a flavor changing neutral Higgs boson (ϕ^0) with $M_\phi > M_h$. It can be a CP-even scalar (H^0) or a CP-odd pseudoscalar (A^0) produced at the LHC followed by the Higgs decay into a top quark and a charm quark:

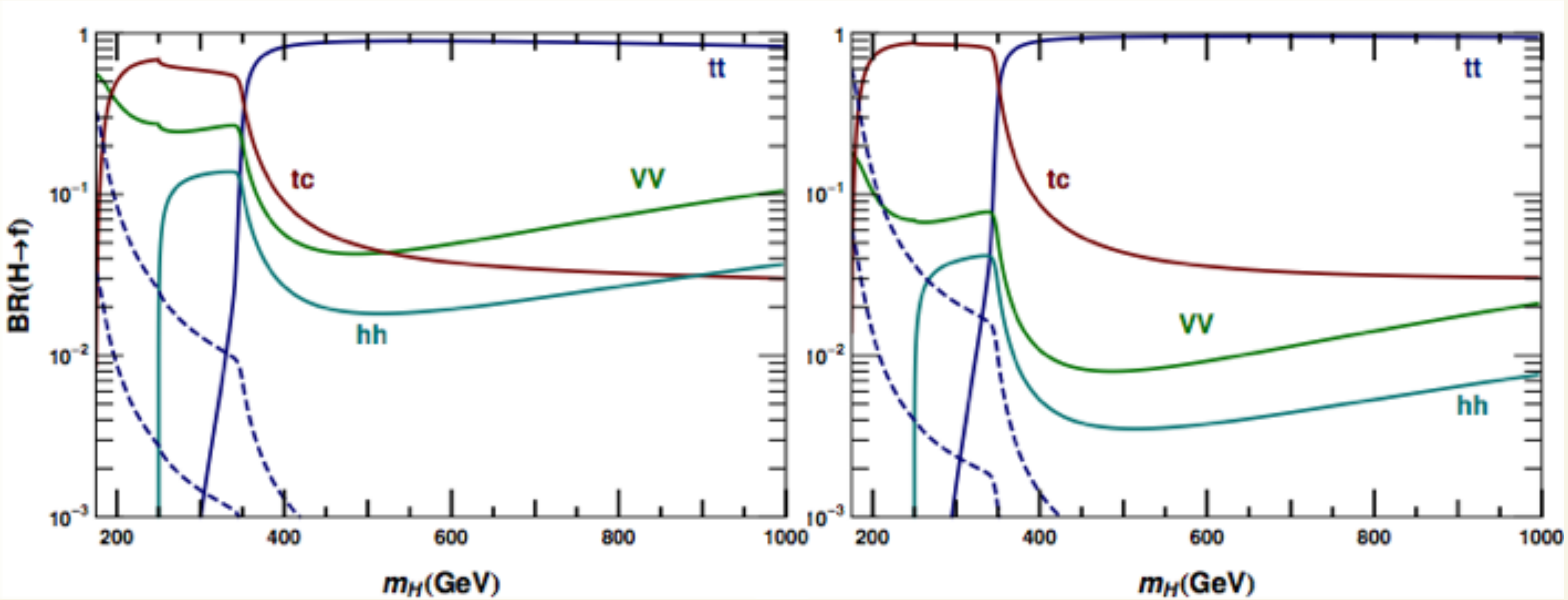


ATLAS and CMS Signal Strength Measurements



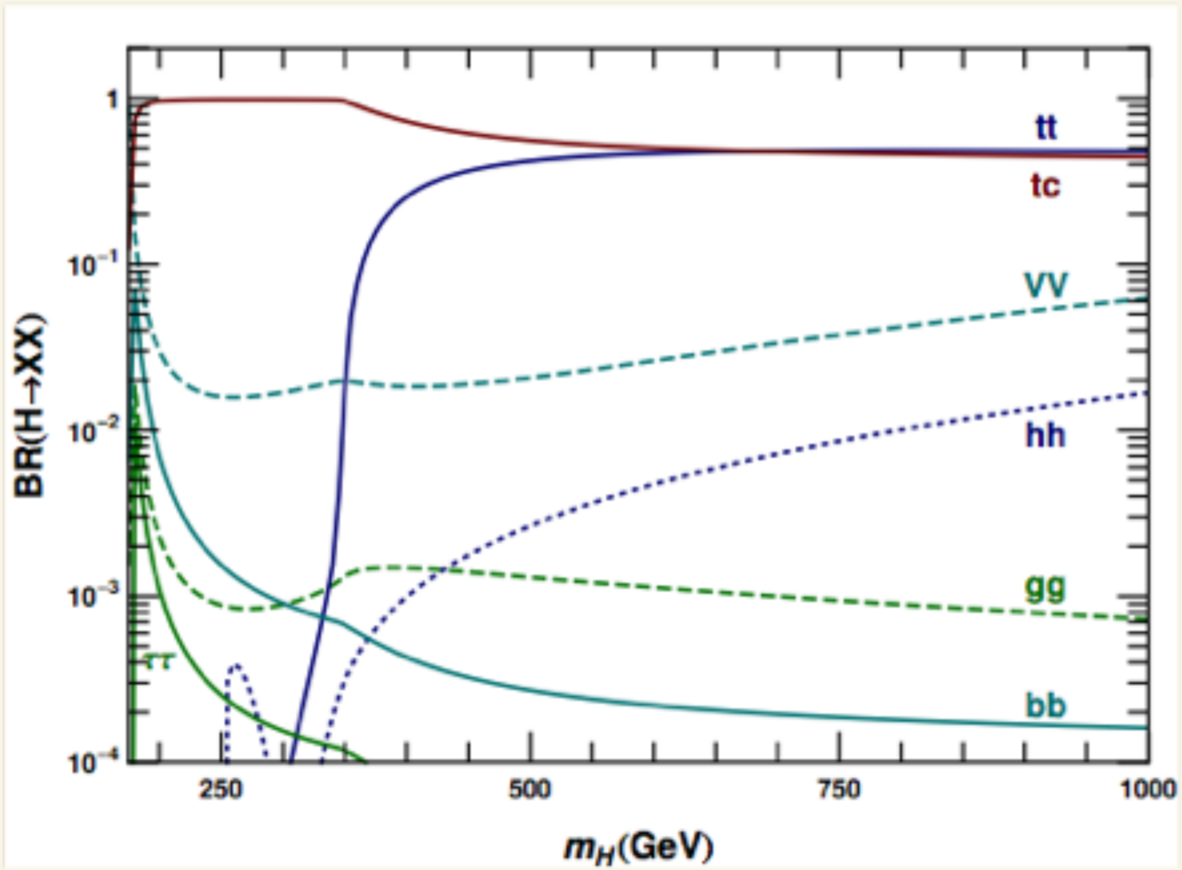
Heavy Higgs Decay Branching Fractions

$\rho_{ct} = \rho_{tc} = 0.1, \cos(\beta\text{-}\alpha) = 0.1$ (L) or 0.05 (R)

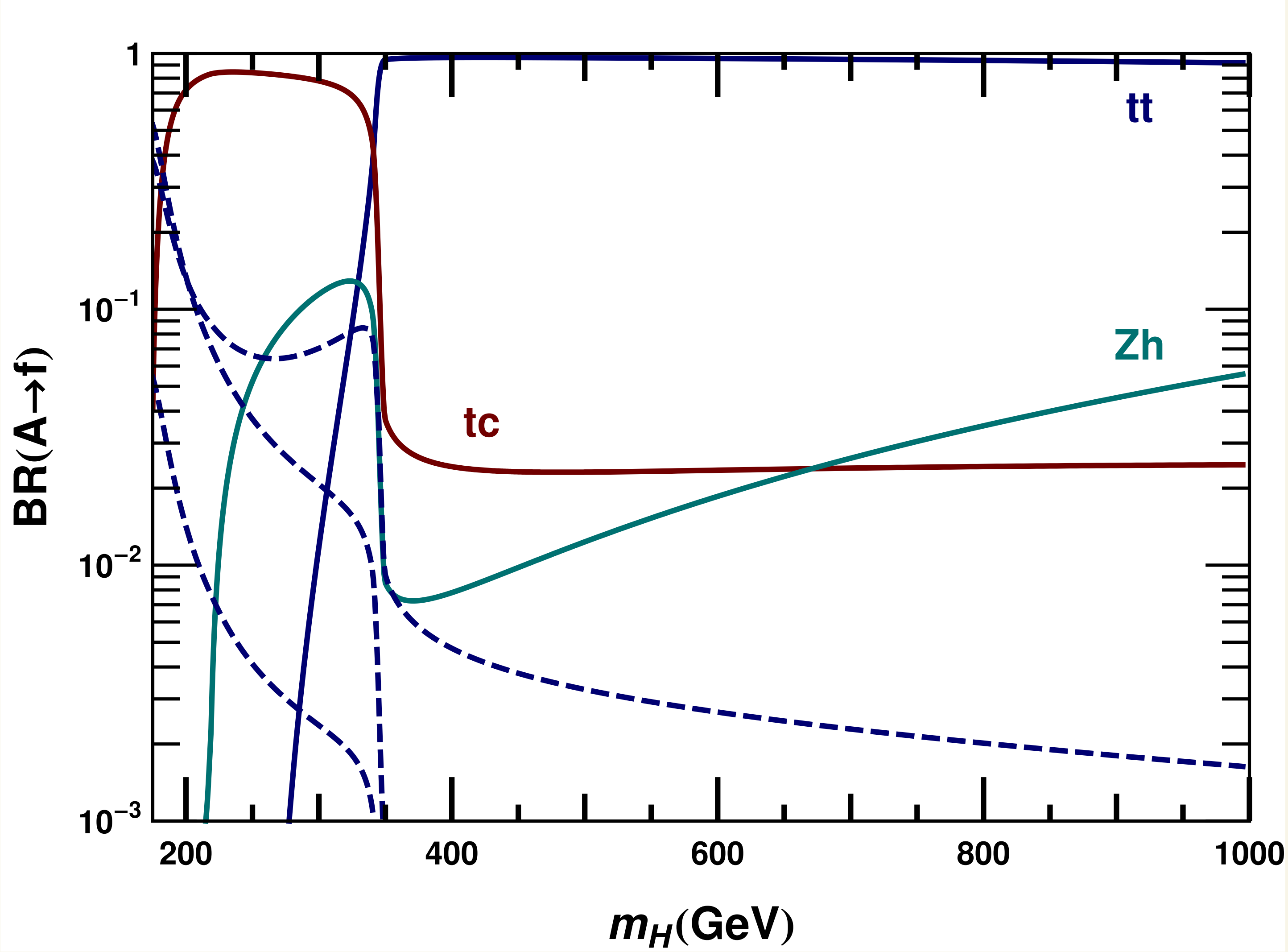


Heavy Higgs Decay Branching Fractions

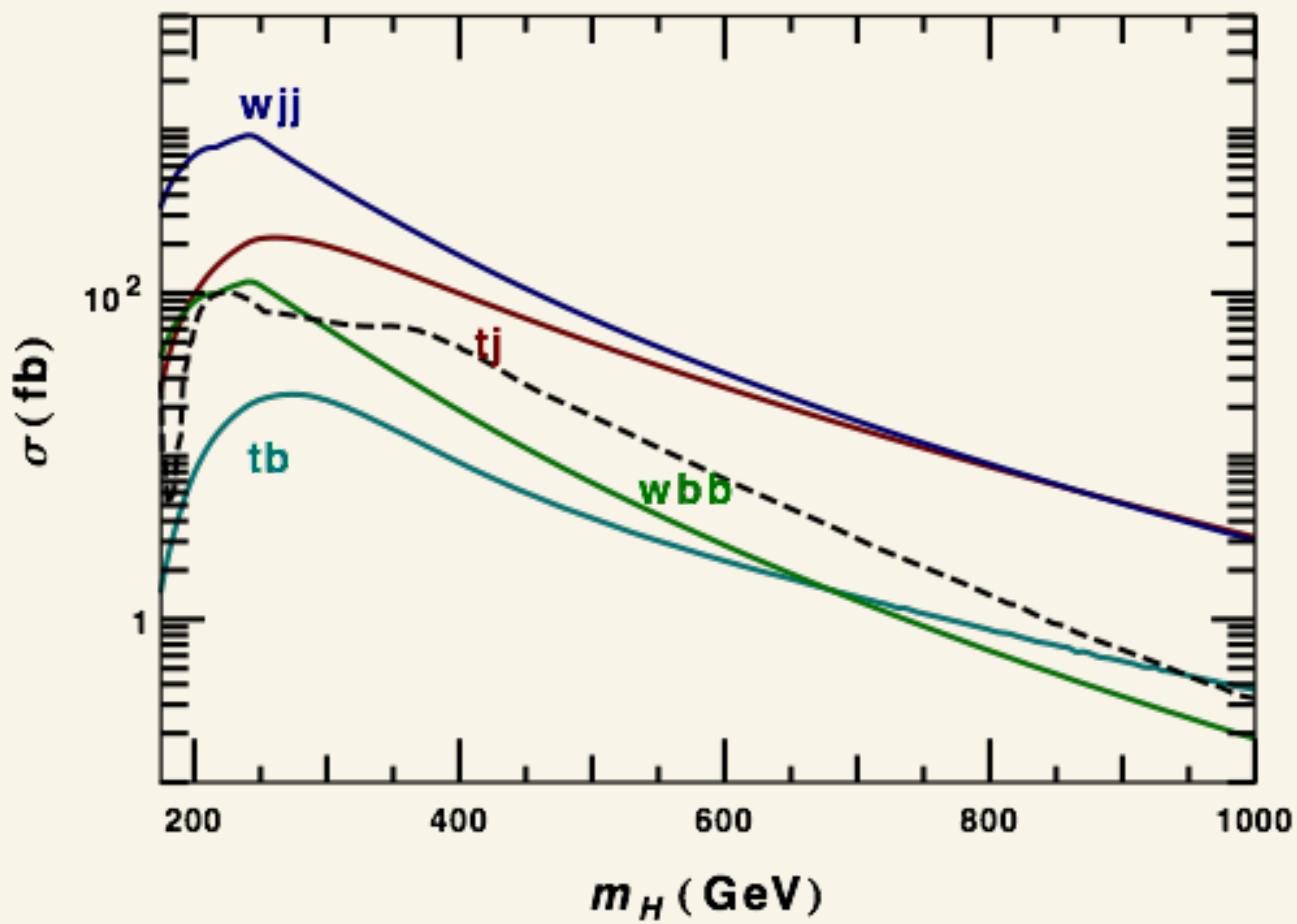
$\rho_{ct} = \rho_{tc} = 0.5$ and $\cos(\beta\text{-}\alpha) = 0.1$



BF of a Higgs Pseudoscalar

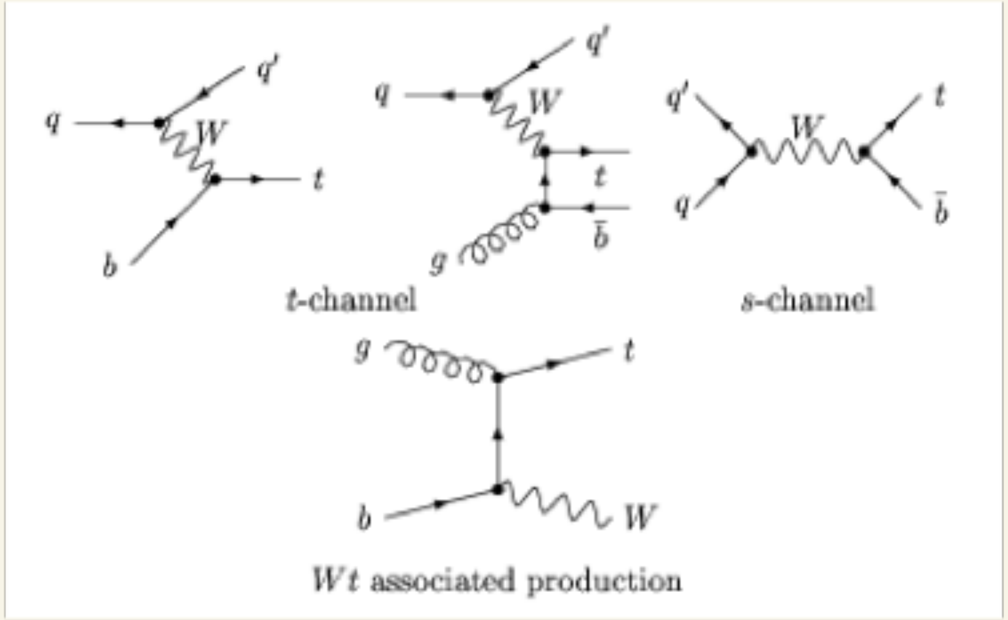


Signal versus Physics Background at the LHC with 8 TeV



Physics Background

- pp to Wjj +X, j = u, d, s, c, or g
- pp to Wbb +X
- Single top:



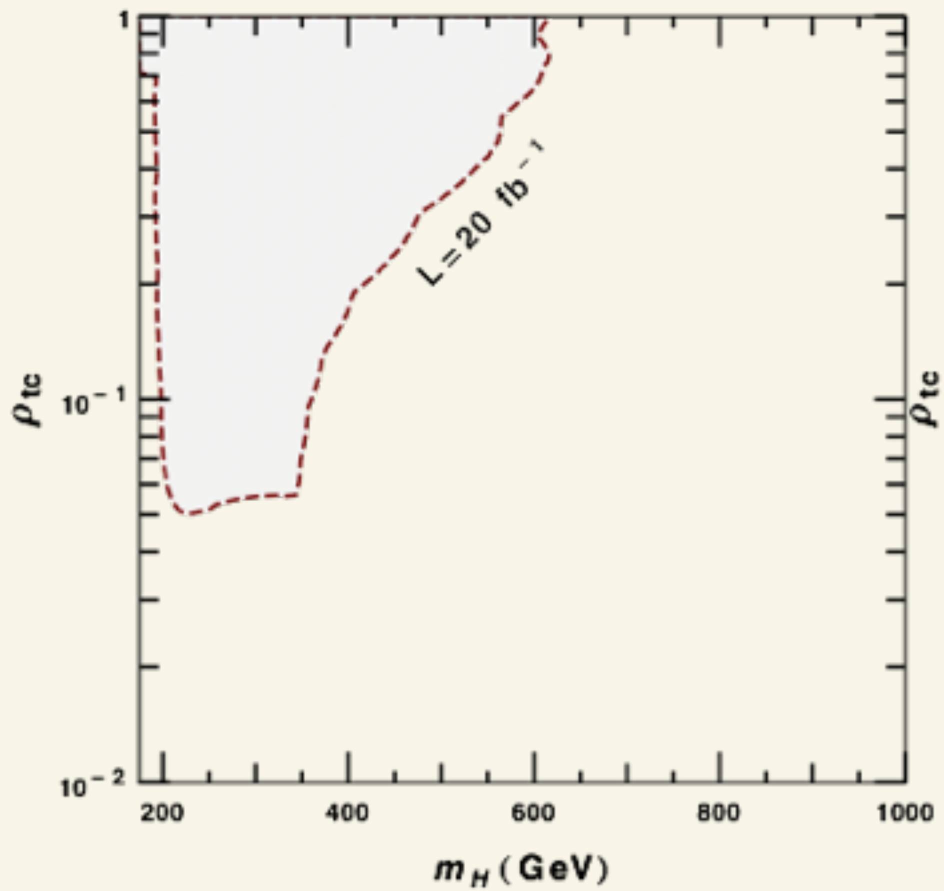
Realistic Acceptance Cuts

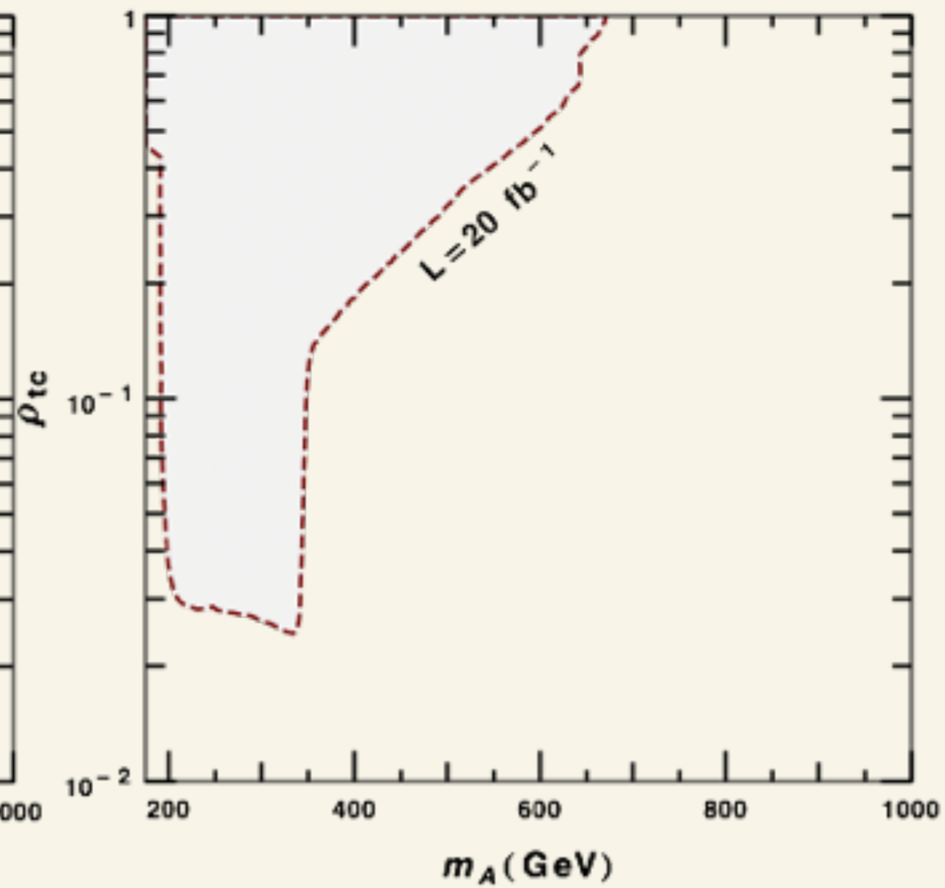
We require that in every event there must be

- exactly 2 jets with $p_T > 20$ GeV, $|\eta| < 2.5$ and exactly one of the jets must be tagged as a b-jet;
- an isolated lepton with $p_T > 20$ GeV, $|\eta| < 2.5$;
- the missing transverse energy must be greater than 20 GeV;
- the angular separation between jets and the lepton must be $\Delta R(b,j,l) > 0.4$.

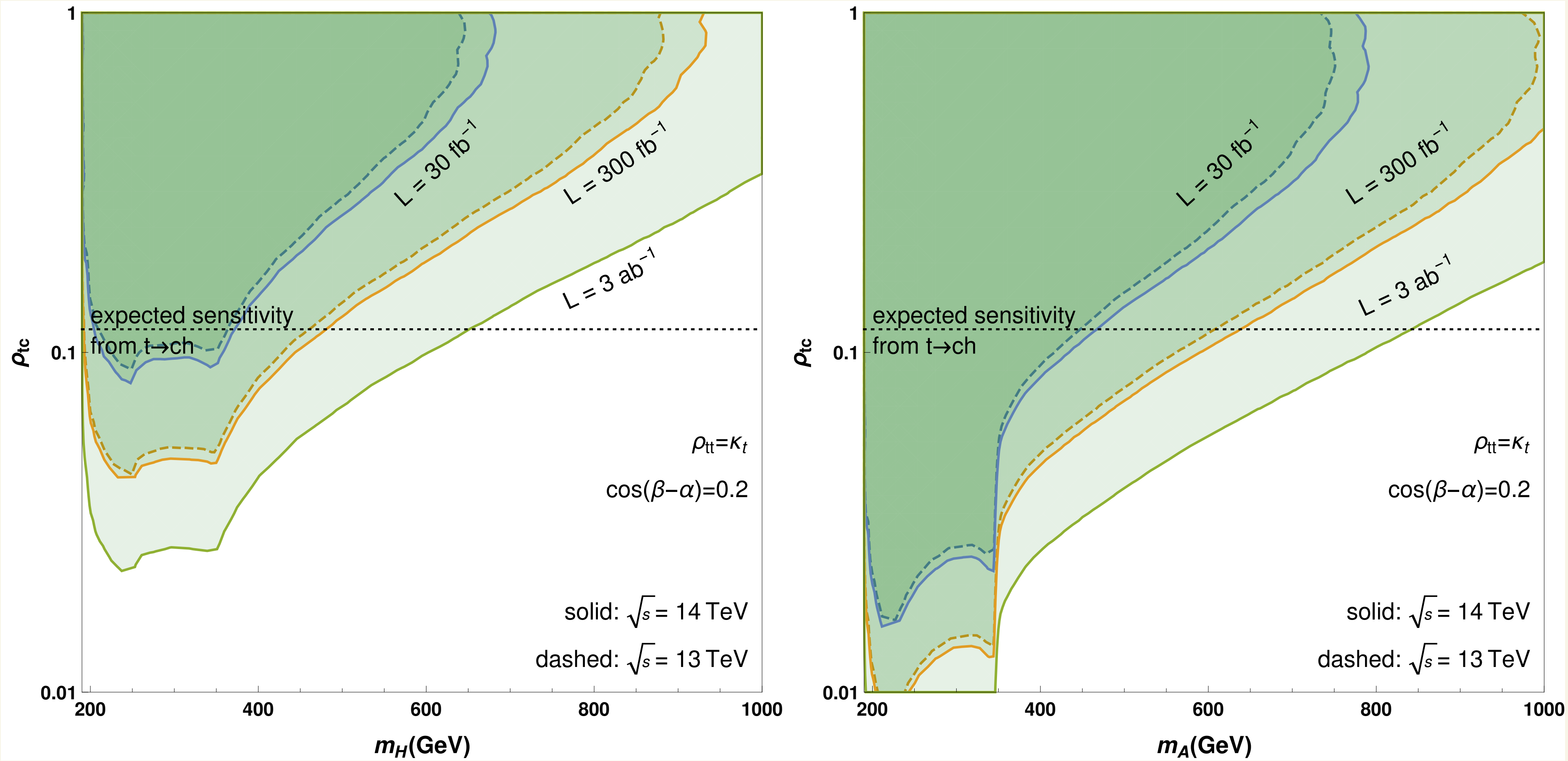
Discovery Potential with 8 TeV

$\cos(\beta-\alpha) = 0.1$, $\rho_{tt,bb,\tau\tau} = \kappa_{tt,bb,cc,\tau\tau}$

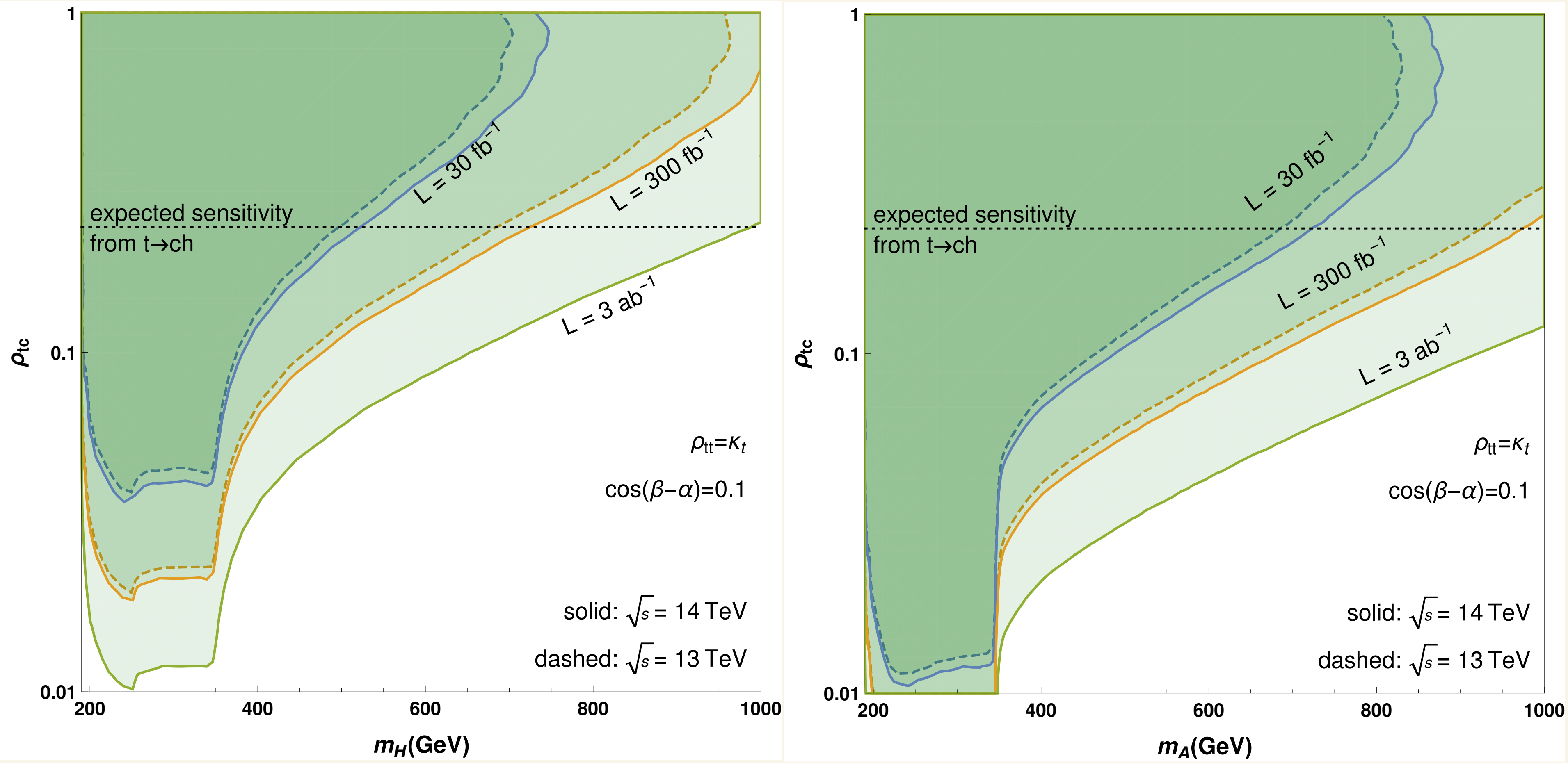




Discovery Contours for H to tc



Discovery Contours for H to tc



Heavy Higgs Decays into Top Pairs

- The top quark pair channel has been suggested as a promising signature for heavy Higgs bosons with peak-dip structure in the invariant mass distribution. [Gaemers, Googeveen (1984); Dicus, Stange, Willenbrock (1994)]
- However, recent study claims that the peak-dip structure will be swamped by NLO contributions involving a non-resonant Higgs boson. [Moretti and Ross (2012)]
- The FCNH signal might offer the best opportunity to discover a heavy Higgs boson in the decoupling or alignment limit.

Conclusions

- It is of great interest to search for the link between the heaviest particle (top) and the Higgs boson(s).
- There is a win-win situation to search for $t \to ch^0$ and $H^0, A^0 \to t\bar{c} + \bar{t}c$. In the decoupling limit, the production ($gg \to H^0$) and decay ($H^0 \to tc$) can be sustained by sin(β-α) ~ 1.
- The FCNH decay of the heavy Higgs will be observable for ρ_{tc} = 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.

Bonus Slides

Top Decay Width

Hou (1991)

- The FCNH top decay with is

$$\Gamma(t \to c\phi^0) = \frac{|\lambda_{tc}|^2}{16\pi} \times (m_t) \times [(1 \pm \rho_c)^2 - \rho_\phi^2] \times \sqrt{1-(\rho_\phi+\rho_c)^2}\sqrt{1-(\rho_\phi-\rho_c)^2}$$

$\rho_c = m_c/m_t$, $\rho_H = M_H/m_t$, + for H^0 and - for A^0.

- The total width is

$$\Gamma_t = \Gamma(t \to bW) + \Gamma(t \to c\phi^0)$$

Theoretical Values for FCNC Top Decays

ATLAS-PHYS-PUB-2013-012

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

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 ϕ_1 and ϕ_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.[‡]

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.[§]

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‡H.E. Haber, G.L. Kane and T. Stirling, Nucl. Phys. **B161** (1979) 493.
§J.F. Donoghue and L.-F. Li, Phys. Rev. **D19** (1979) 945; L. Hall and M. Wise, Nucl. Phys. **B187** (1981) 397.

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

$$\phi_1 \rightarrow -\phi_1, \quad \phi_2 \rightarrow +\phi_2. \tag{1}$$

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

$$\begin{aligned} V[\phi_1, \phi_2] \ = \ & m_1 \phi_1^\dagger \phi_1 + m_2 \phi_2^\dagger \phi_2 + \eta \phi_1^\dagger \phi_2 + \eta^* \phi_2^\dagger \phi_1 \\ & + \frac{1}{2} g_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} g_2 (\phi_2^\dagger \phi_2)^2 \\ & + g (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + g' (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\ & + \frac{1}{2} h (\phi_1^\dagger \phi_2)^2 + \frac{1}{2} h^* (\phi_2^\dagger \phi_1)^2. \end{aligned} \tag{2}$$

¶ S. L. Glashow and S. Weinberg, Phys. Rev. **D15** (1977) 1958.

‖ G.C. Branco and M.N. Rebelo, Phys. Lett. **B160** (1985) 117; J. Liu and L. Wolfenstein, Nucl. Phys. **B289** (1987) 1.

** S. Weinberg, Phys. Rev. **D42** (1990) 860.

Introducing a transformation, which takes the Higgs doublets to their Higgs eigenstates (Φ_1 and Φ_2), we have

$$\begin{aligned}
\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} &= \begin{pmatrix} \cos\beta & \sin\beta e^{-i\theta} \\ -\sin\beta & \cos\beta e^{-i\theta} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \\
\Phi_1 &= \begin{pmatrix} G^+ \\ \frac{v+H_1+iG^0}{\sqrt{2}} \end{pmatrix}, \\
\Phi_2 &= \begin{pmatrix} H^+ \\ \frac{H_2+iA}{\sqrt{2}} \end{pmatrix},
\end{aligned} \tag{3}$$

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

$$\langle\phi_1\rangle = \frac{v_1}{\sqrt{2}}, \quad \langle\phi_2\rangle = \frac{v_2 e^{i\theta}}{\sqrt{2}} .$$

In the Higgs eigenstates, the Higgs potential becomes

$$\begin{aligned}
V[\Phi_1, \Phi_2] \quad &= \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1 - \frac{v^2}{2})^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
&+\lambda_3(\Phi_1^\dagger\Phi_1 - \frac{v^2}{2})\Phi_2^\dagger\Phi_2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&+\lambda_5(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 - \frac{v^2}{2})(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) \\
&+(\lambda_6\Phi_1^\dagger\Phi_2 + \lambda_6^*\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_1 - \Phi_2^\dagger\Phi_2 - \frac{v^2}{2}) \\
&+\frac{1}{2}\lambda_7(\Phi_1^\dagger\Phi_2)^2 + \frac{1}{2}\lambda_7^*(\Phi_2^\dagger\Phi_1)^2 \\
&+\rho(\Phi_2^\dagger\Phi_2), \qquad (4)
\end{aligned}$$

where the parameters ρ, v and λ_i, $i = 1$ through 5, are all real; λ_6 and λ_7 can be complex.

CP is violated if the imaginary part of λ_6 or λ_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

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

where

$$\phi_\alpha = \begin{pmatrix} \phi_\alpha^+ \\ \frac{v_\alpha+\phi_\alpha^0}{\sqrt{2}} \end{pmatrix}, \; \tilde{\phi}_\alpha = \begin{pmatrix} \frac{v_\alpha^*+\phi_\alpha^{0*}}{\sqrt{2}} \\ -\phi_\alpha^- \end{pmatrix}, \; \phi_\alpha^- = \phi_\alpha^{+*}, \; \alpha = 1,2, \quad \text{and} \tag{5}$$

$$L_L^m = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L^m, \quad Q_L^m = \begin{pmatrix} u \\ d \end{pmatrix}_L^m, \; m = 1,2,3, \tag{6}$$

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

This Lagrangian respects a discrete symmetry,

$$\begin{aligned} \phi_1 &\to -\phi_1, \; \phi_2 \to +\phi_2, \\ l_R^m &\to -l_R^m, \; d_R^m \to -d_R^m, \; u_R^\alpha \to -u_R^\alpha, \\ L_L^m &\to +L_L^m, \; Q_L^m \to +Q_L^m, \; u_R^3 \to +u_R^3. \end{aligned} \tag{7}$$

The Yukawa interactions between the up quarks and the neutral Higgs bosons are

$$\mathcal{L}_N^U = -\sum_{u=u,c,t} m_u \bar{u}_L u_R \frac{\phi_1^{0*}}{v_1^*} - \sum_{ab} \bar{u}_L^a \Sigma_{ab} u_R^b \left(\frac{\phi_2^{0*}}{v_2^*} - \frac{\phi_1^{0*}}{v_1^*} \right) + \text{H.c.}, \tag{8}$$

where $u^{a,b} = u, c, t$ are the mass eigenstates and

$$\Sigma = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} U_R^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} U_R, \tag{9}$$

with U_R and U_L being the unitary transformations that diagonalize the mass matrix of the up-type quarks.

To a good approximation, the unitary matrix U_R has the following form

$$U_R = \begin{pmatrix} \cos\phi & -\sin\phi & -\cos\phi\epsilon_1^* + \sin\phi\epsilon_2^* \\ \sin\phi & \cos\phi & -\sin\phi\epsilon_1^* - \cos\phi\epsilon_2^* \\ \epsilon_1 & \epsilon_2 & 1 \end{pmatrix}. \tag{10}$$

We have introduced two small parameters

$$\epsilon_1 = |\epsilon_1| e^{i\delta_1}, \quad \epsilon_2 = |\epsilon_2| e^{i\delta_2}, \quad |\epsilon_1| \le |\epsilon_2| \sim m_c/m_t. \tag{11}$$

4 Flavor Changing Neutral Higgs Interactions

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

$$
\begin{aligned}
\mathcal{L}_Y^N &= -\sum_{d=d,s,b} \frac{m_d}{v}\bar{d}d(H_1 - \tan\beta H_2) \\
&\quad -i\sum_{d=d,s,b} \frac{m_d}{v}\bar{d}\gamma_5 d(G^0 - \tan\beta A) \\
&\quad -\sum_{u=u,c} \frac{m_u}{v}\bar{u}u[H_1 - \tan\beta H_2] \\
&\quad +i\sum_{u=u,c} \frac{m_u}{v}\bar{u}\gamma_5 u[G^0 - \tan\beta A] \\
&\quad -\frac{m_t}{v}\bar{t}t[H_1 + \cot\beta H_2] + i\frac{m_t}{v}\bar{t}\gamma_5 t[G^0 + \cot\beta A] + \mathcal{L}_{\rm FCNH}, \\
\mathcal{L}_{\rm FCNH} &= \{-\epsilon_1^*\epsilon_2\bar{u}c[(m_u + m_c)H_2 + i(m_c - m_u)A] \\
&\quad -\epsilon_1^*\bar{u}t[(m_u + m_t)H_2 + i(m_t - m_u)A] \\
&\quad -\epsilon_2^*\bar{c}t[(m_c + m_t)H_2 + i(m_t - m_c)A] \\
&\quad +\epsilon_1^*\epsilon_2\bar{u}\gamma_5 c[(m_c - m_u)H_2 + i(m_u + m_c)A] \\
&\quad +\epsilon_1^*\bar{u}\gamma_5 t[(m_t - m_u)H_2 + i(m_u + m_t)A] \\
&\quad +\epsilon_2^*\bar{c}\gamma_5 t[(m_t - m_c)H_2 + i(m_c + m_t)A]\} \times (\frac{1}{v\sin 2\beta}) + \text{H.c.}
\end{aligned}
$$

Constraints on Elements of ρ-matrices

- The LHC data indicate that $\Gamma(h^0$ to $bb)$ and $\Gamma(h^0$ to $\tau\tau)$ are consistent with SM expectations. Thus ρ_{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 $0.5 < |\rho_{tt}| < 2$.