Flavor Changing Heavy Higgs Interactions at the LHC

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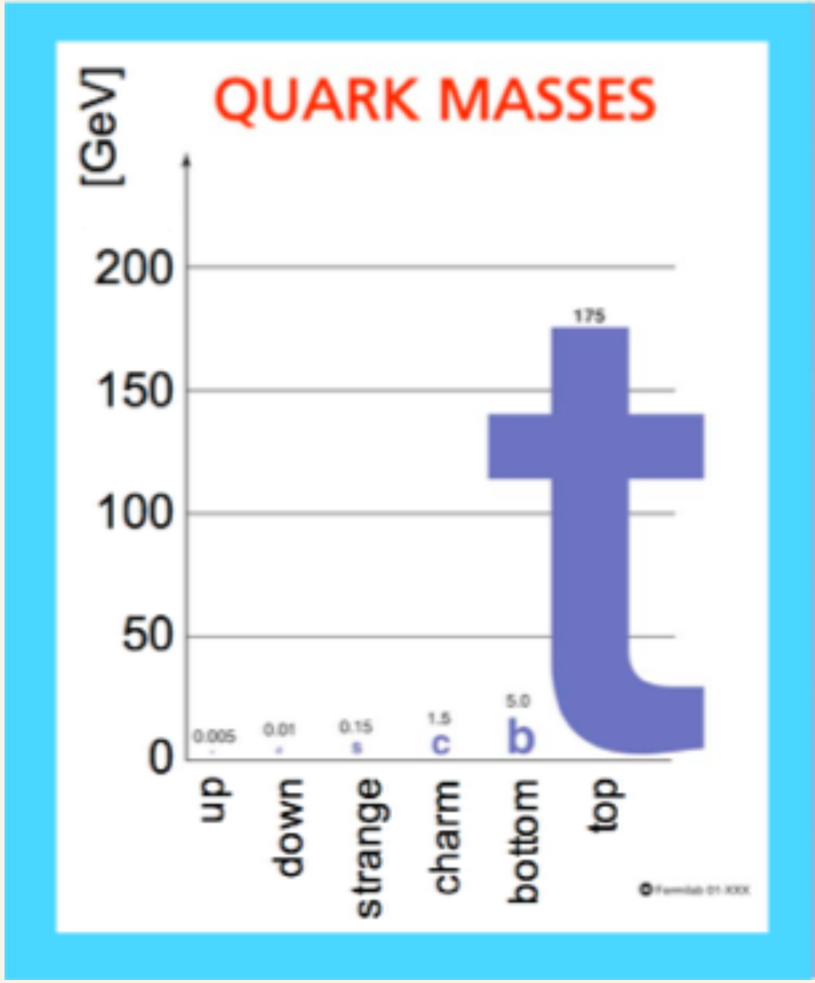
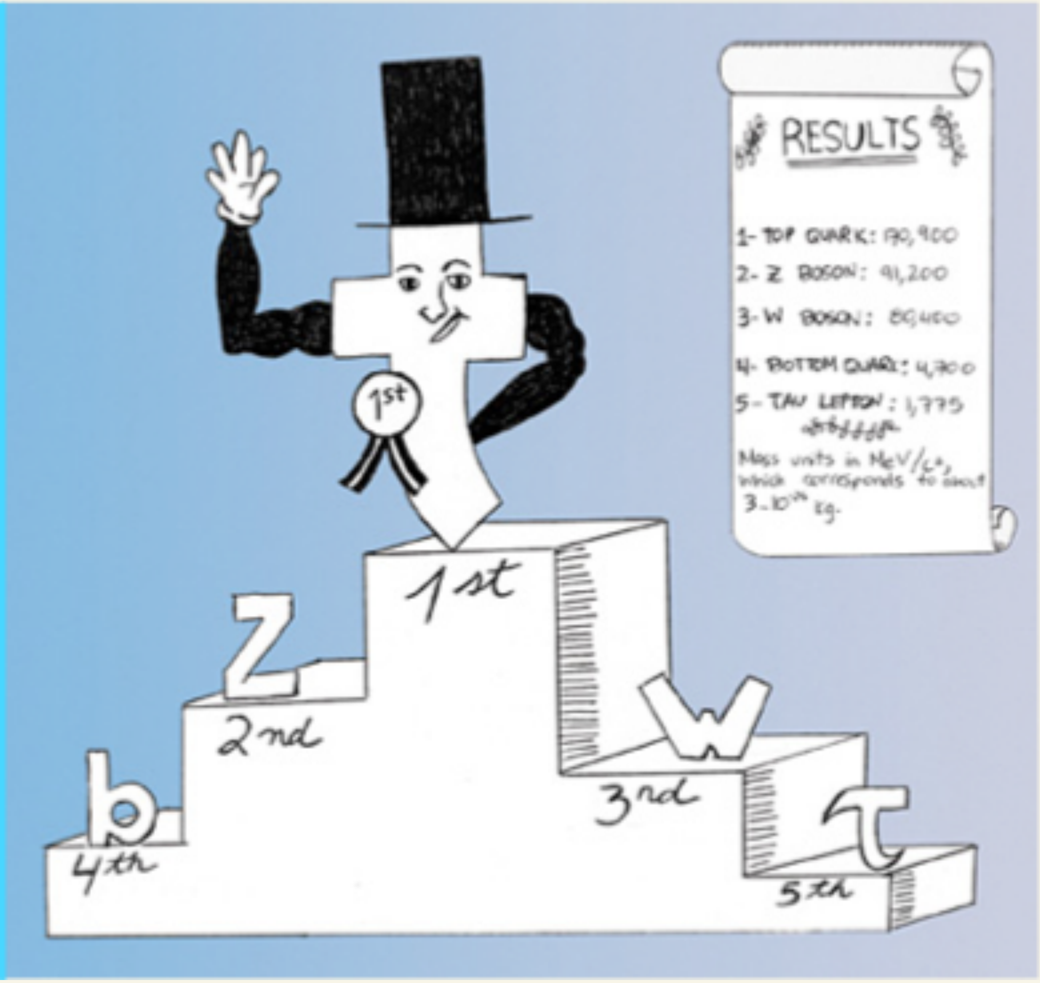
Flavor Changing Heavy Higgs Interactions

Altunkaynak, Hou, Kao, Kohda, and McCoy (2014);
Chen, Hou, Kao, and Kohda, Phys. Lett. B 725 (2013) 378;
Kao, Cheng, Hou, and Sayre, Phys. Lett. B 716 (2012) 225.

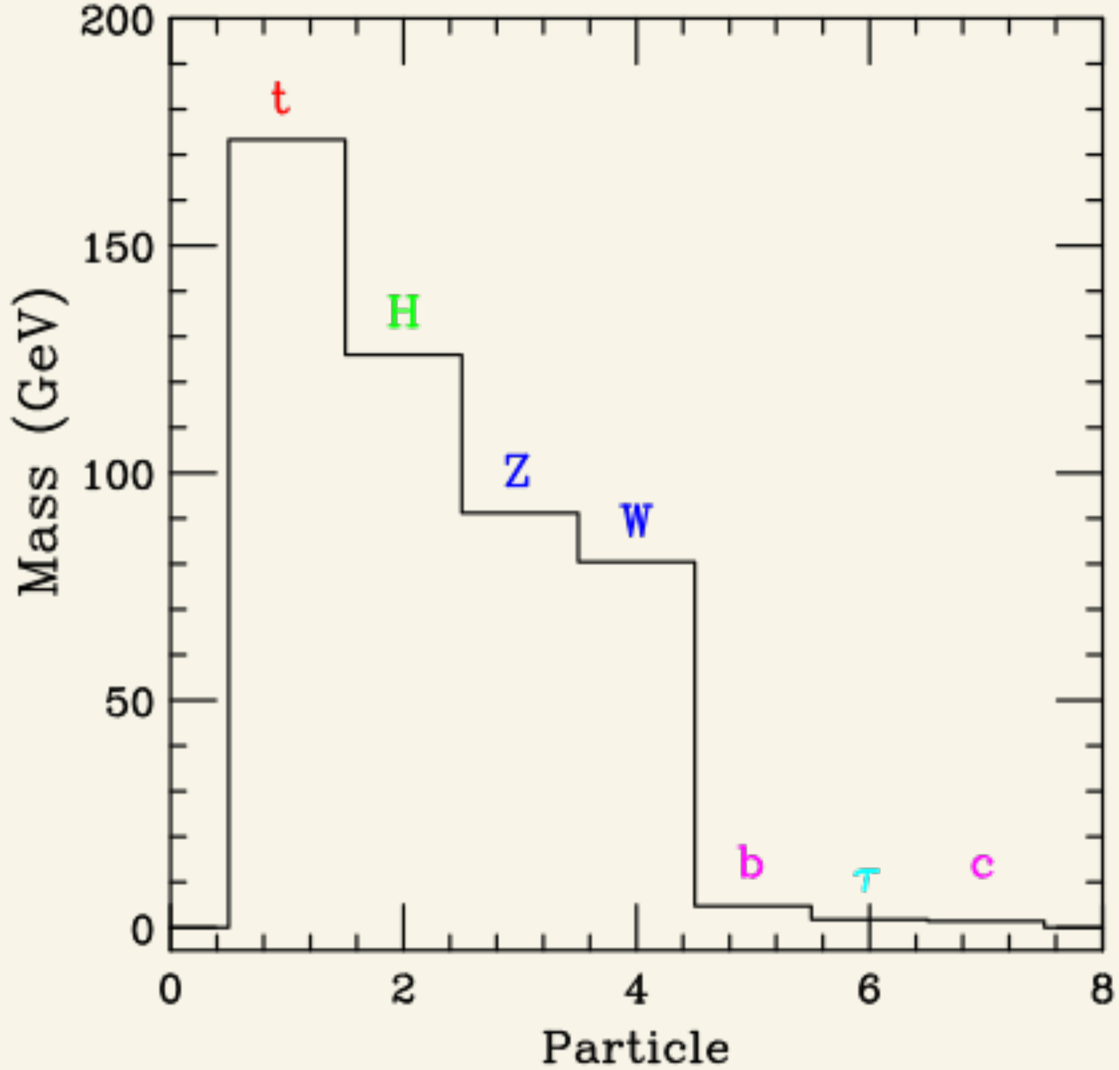
- Introduction and Motivation
- General Two Higgs Doublet Models
- When the Higgs Meets the Top
- The Discovery Potential at the LHC
- Conclusions

Heavyweight Champion before July 4, 2012





The New Runner-up



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}

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.

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

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

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

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

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

This Lagrangian respects a discrete symmetry,

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

4 Flavor Changing Neutral Higgs Interactions

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

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

A General Two Higgs Doublet Model

Mahmoudi and Stal (2009)

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

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

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 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 $0.5 < |\rho_{tt}| < 2$.

Constraints on FCNH Couplings

- ATLAS and CMS data have placed tight constraints on λ_{tc} and λ_{ct} with $t \to ch^0 \to c\gamma\gamma$:
  - the top decay should have $B(t \to ch^0) < 0.56\%$,
  - or $\sqrt{\lambda_{tc}^2 + \lambda_{ct}^2} < 0.14$, with $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$.
- If we choose ρ-matrix to be Hermitian, then $b \to s\gamma$ and $B - \bar{B}$ mixing imply $|\rho_{ct}| < 0.1$.
- If the ρ-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 $t \to ch^0$ if $\lambda_{ct} = \rho_{ct} \cos(\beta-\alpha)$ can lead to observable signal.
- Or we might discover $H^0, A^0 \to t\bar{c} + \bar{t}c$ in the decoupling limit with $\lambda_{tc} = \rho_{tc} \sin(\beta-\alpha)$.

Top Decay Width

Hou (1991)

- The FCNH top decay with is

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

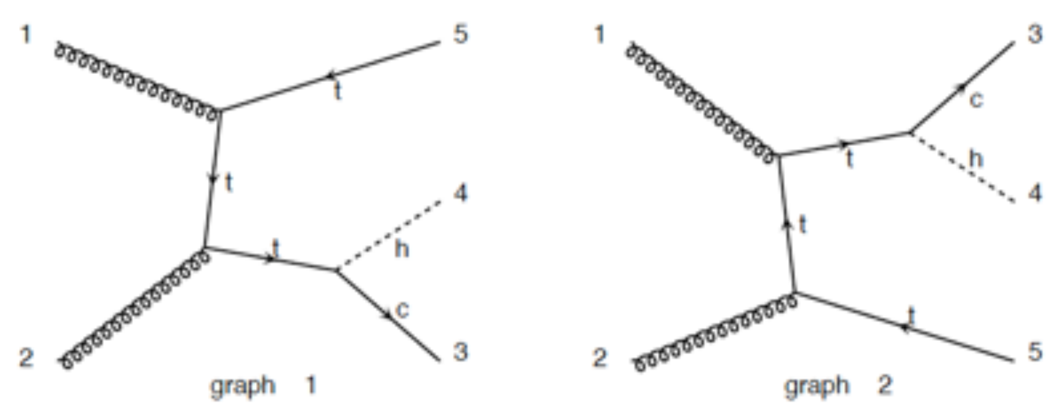
$\rho_c = m_c/m_t$, $\rho_H = M_H/m_t$, + for H^0 and - for A^0.

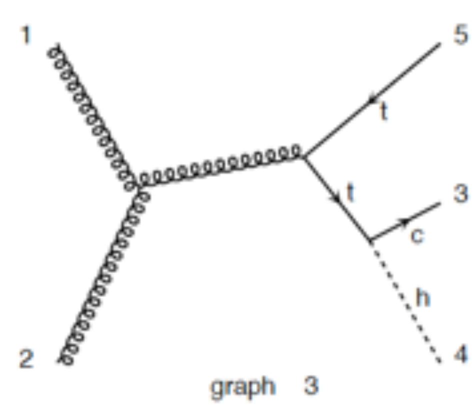
- The total width is

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

FCNH Top Decays at the LHC

Hou (1991); Hall and Weinberg (1993); Aguilar-Saavedra and Branco (2000);
Kao, Cheng, Hou, and Sayre (2012); Chen, Hou, Kao, and Kohda (2013);
Atwood, Gupta, Soni (2013).

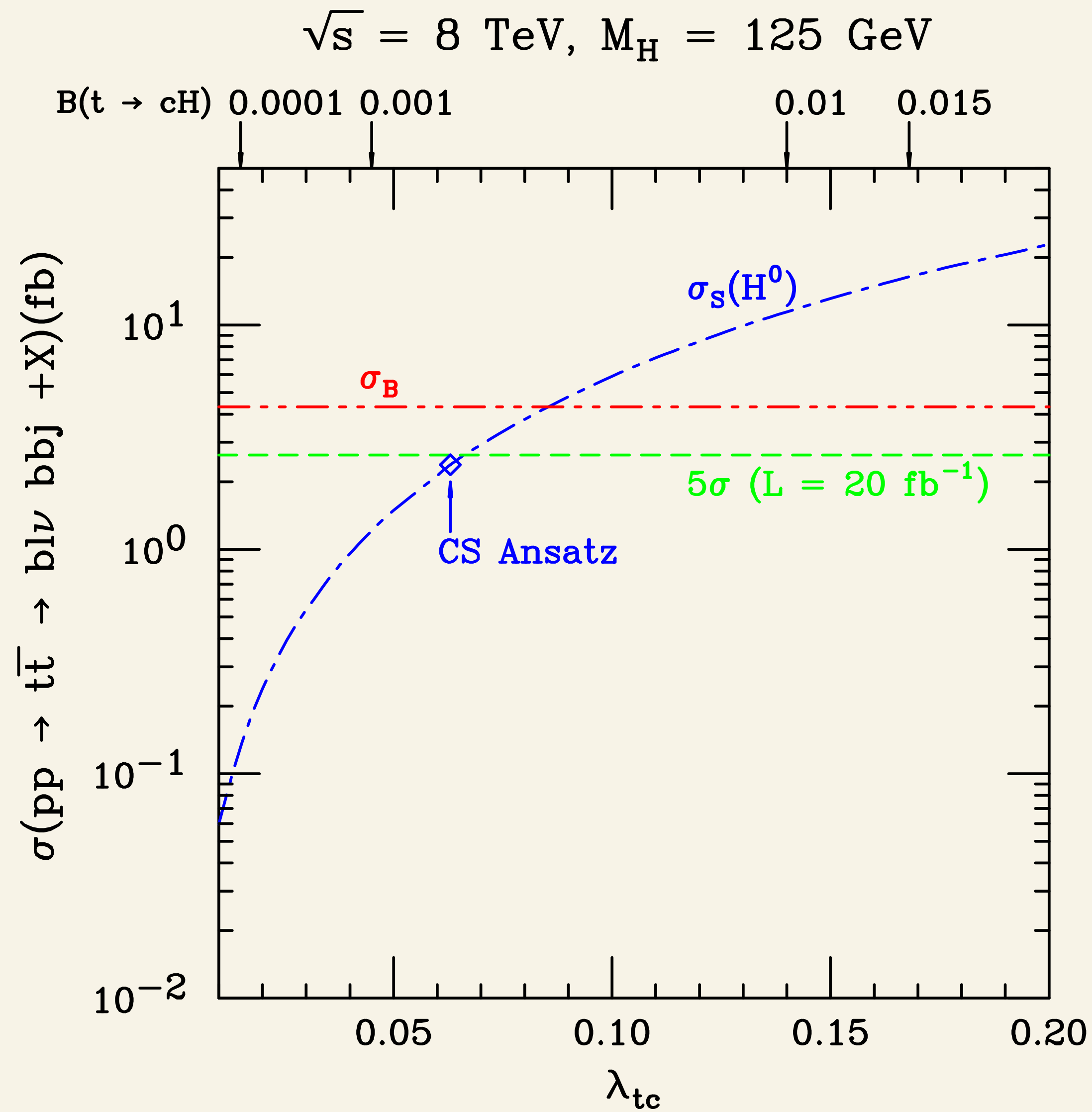




$$g_{htc}(\mathrm{CS}) = \frac{\sqrt{m_t m_c}}{v} \sim 0.06$$

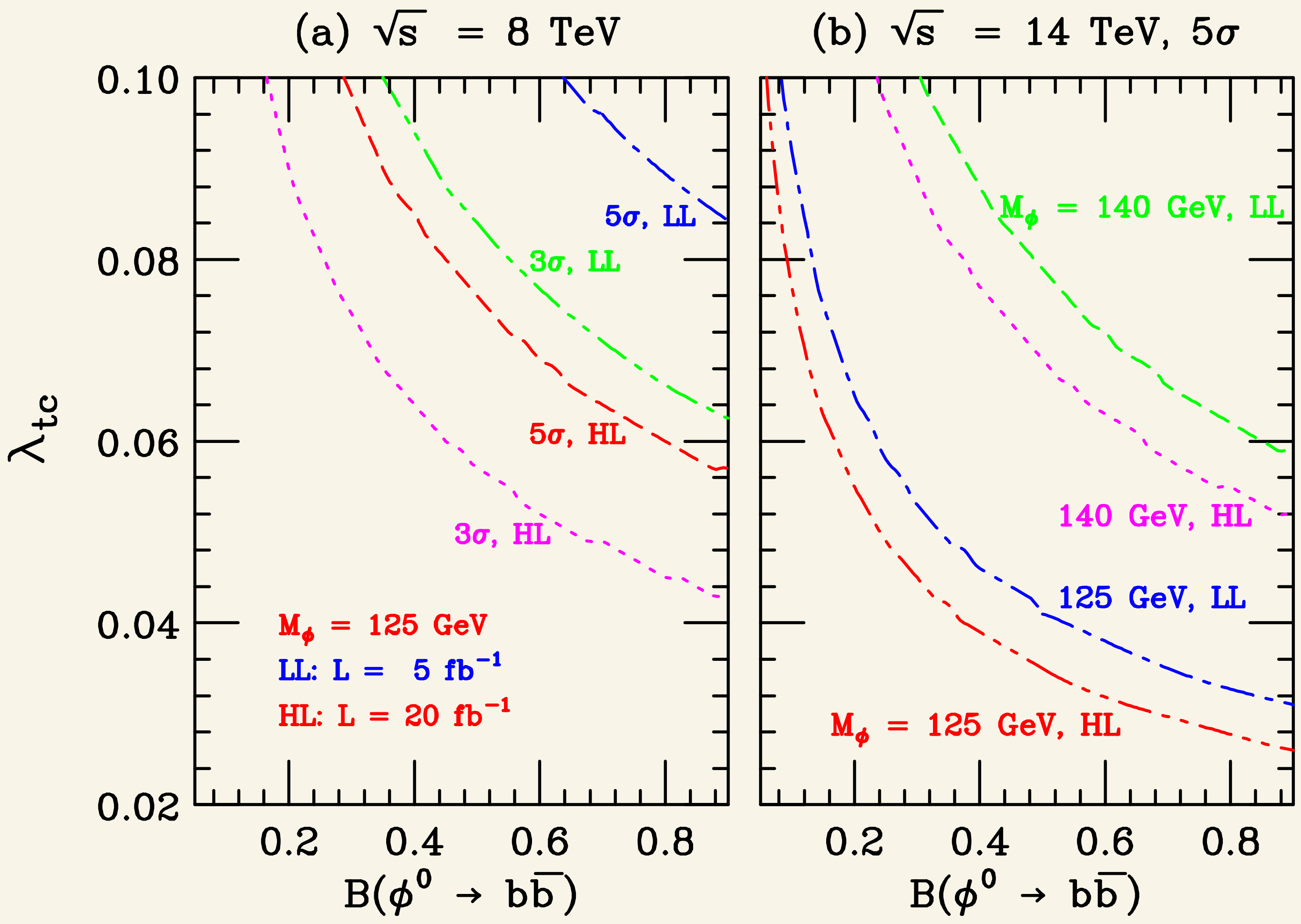
$$\lambda_{htc}(\mathrm{HW}) = \epsilon_{Q3}\epsilon_{U2} \sim 0.2$$

Discovery Potential with 8 TeV



Discovery Contours

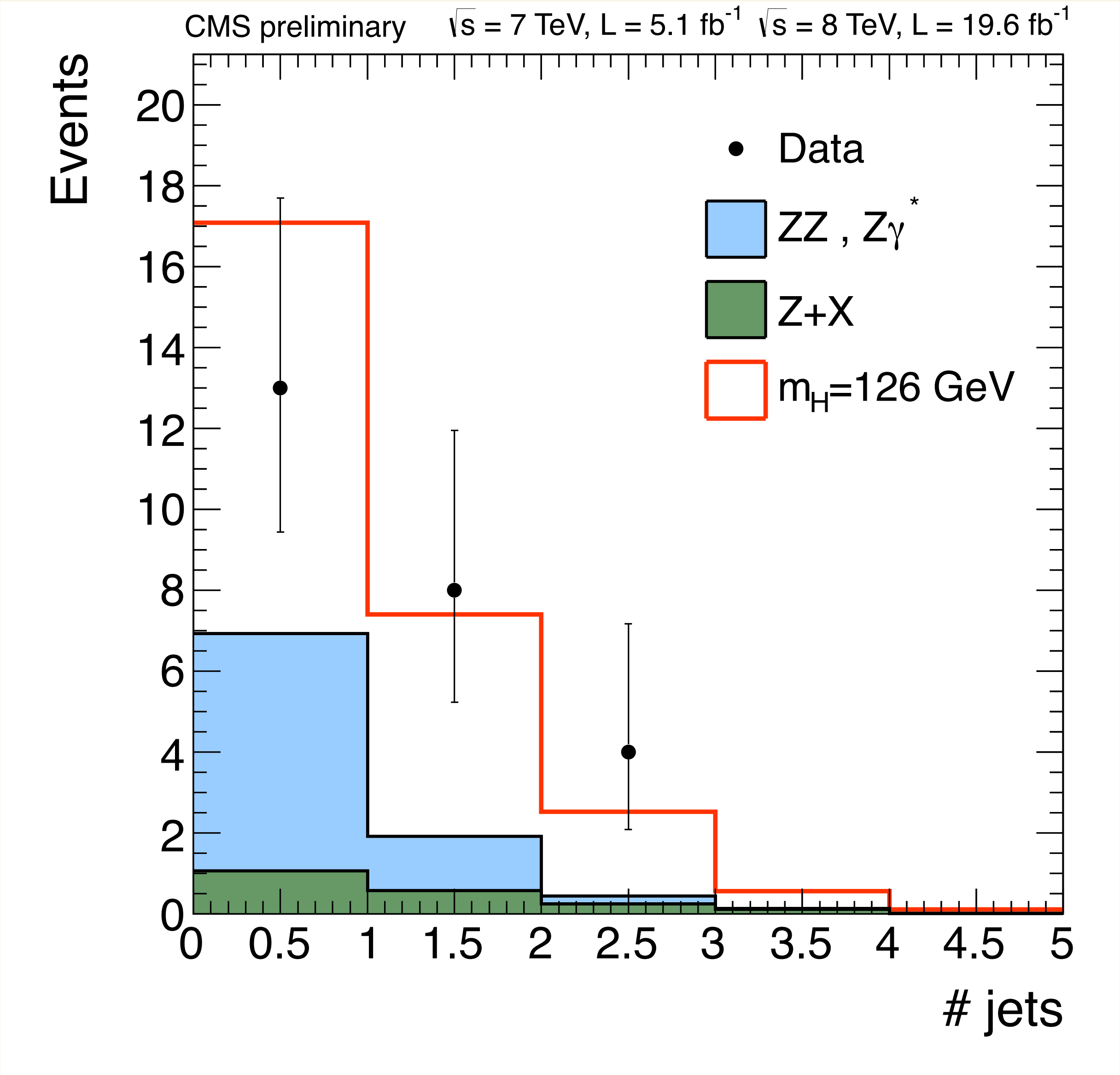
L = 20 fb^{-1} at 8 TeV; 30 fb^{-1} at 14 TeV



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

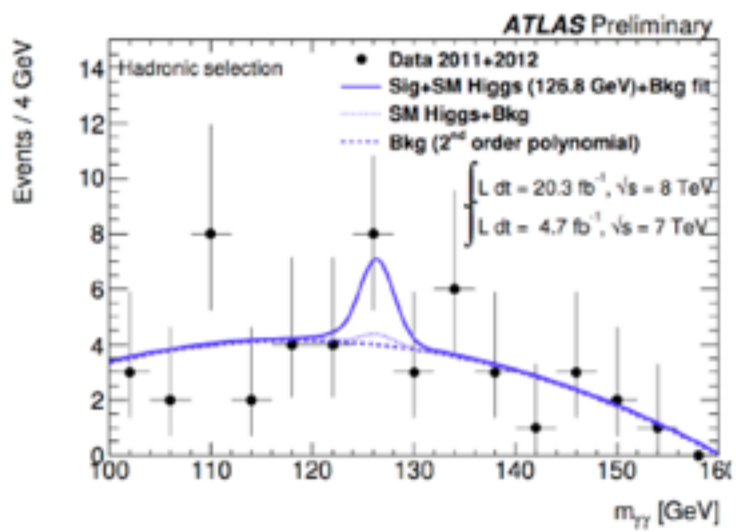


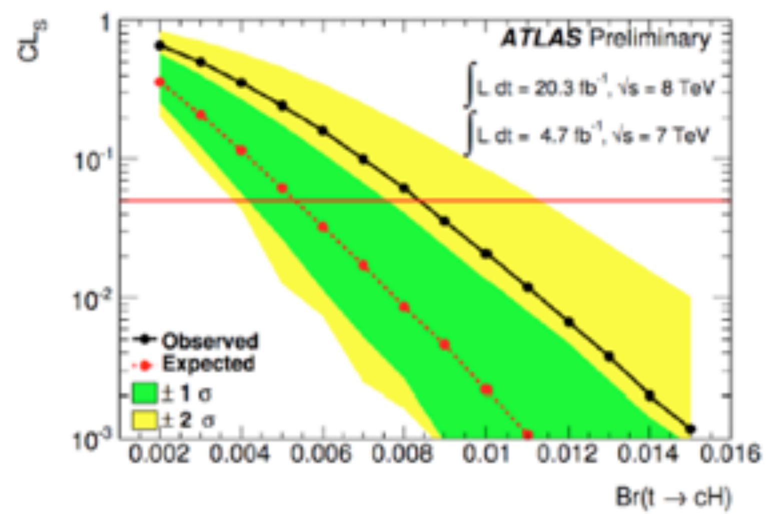
ATLAS Results presented by Ashutosh Kotwal

Neutral Higgs Bosons with Non-SM Properties

"Search for flavour changing neutral currents in top quark decays $t \to cH$, with $H \to \gamma\gamma$, and limit on the tcH coupling with the ATLAS detector at the LHC"
[ATLAS-CONF-2013-081]

- Look for Higgs in diphoton mass spectrum
  - Model background shape with *SHERPA*





BR(t → cH) < 0.83% (observed) at 95% CL (< 0.53 % expected for SM)

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

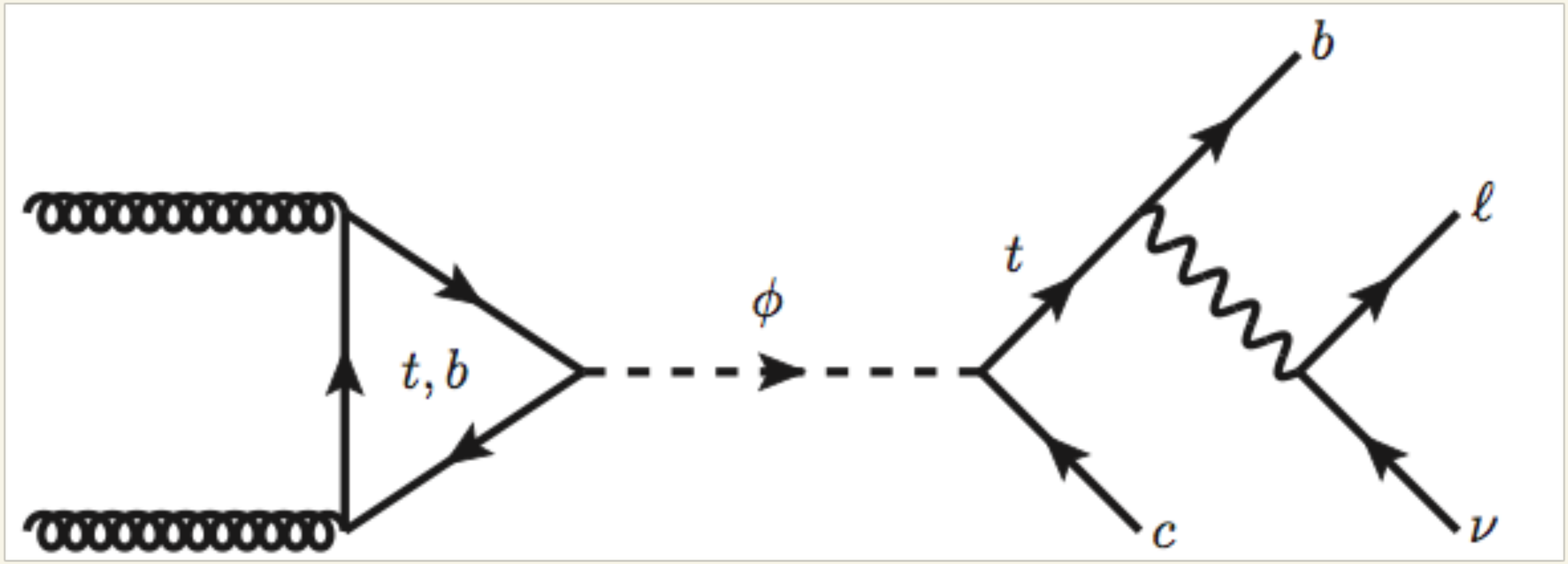
$$B(t \to ch^0) < 1.5 \times 10^{-4} \text{ or } \rho_{tc} \cos(\beta - \alpha) < 0.0234$$

Summary for FCNH top Decay

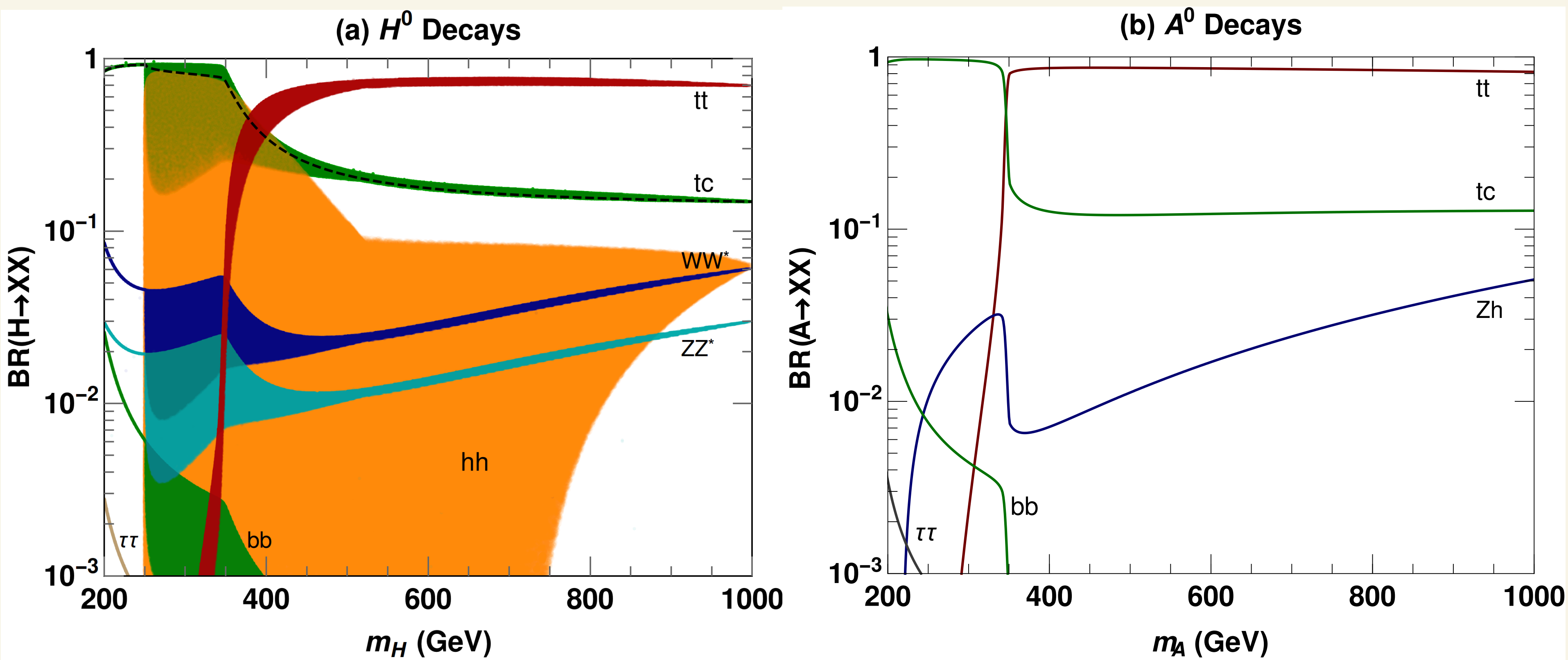
- It is of great interest to search for the link between the top quark (t) and the Higgs bosons (H^0, h^0, A^0).
- A discovery of $t \to ch^0$ would suggest the existence of an extended Higgs sector beyond the usual 2HDM-II and MSSM.
- Experimental studies of h^0 to bb, WW*, ZZ*, $\tau^+\tau^-$ and $\gamma\gamma$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

The FCNH Signal of a Heavy Higgs boson at the LHC

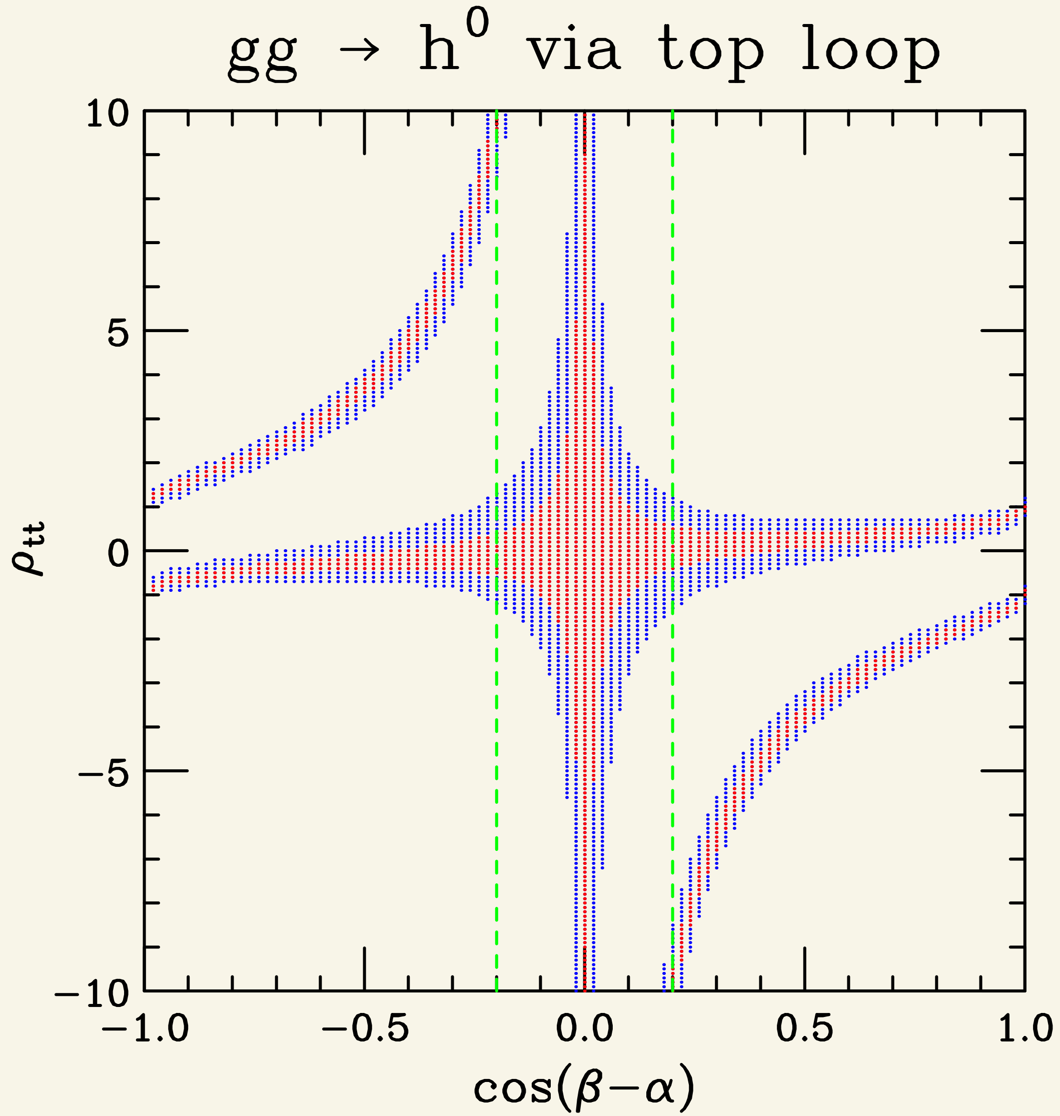
Let us consider a flavor changing neutral Higgs boson (ϕ^0) with $M_\phi > M_h$. It can be a CP-even scalar (H^0) or a CP-odd pseudoscalar (A^0) produced at the LHC followed by the Higgs decay into a top quark and a charm quark:



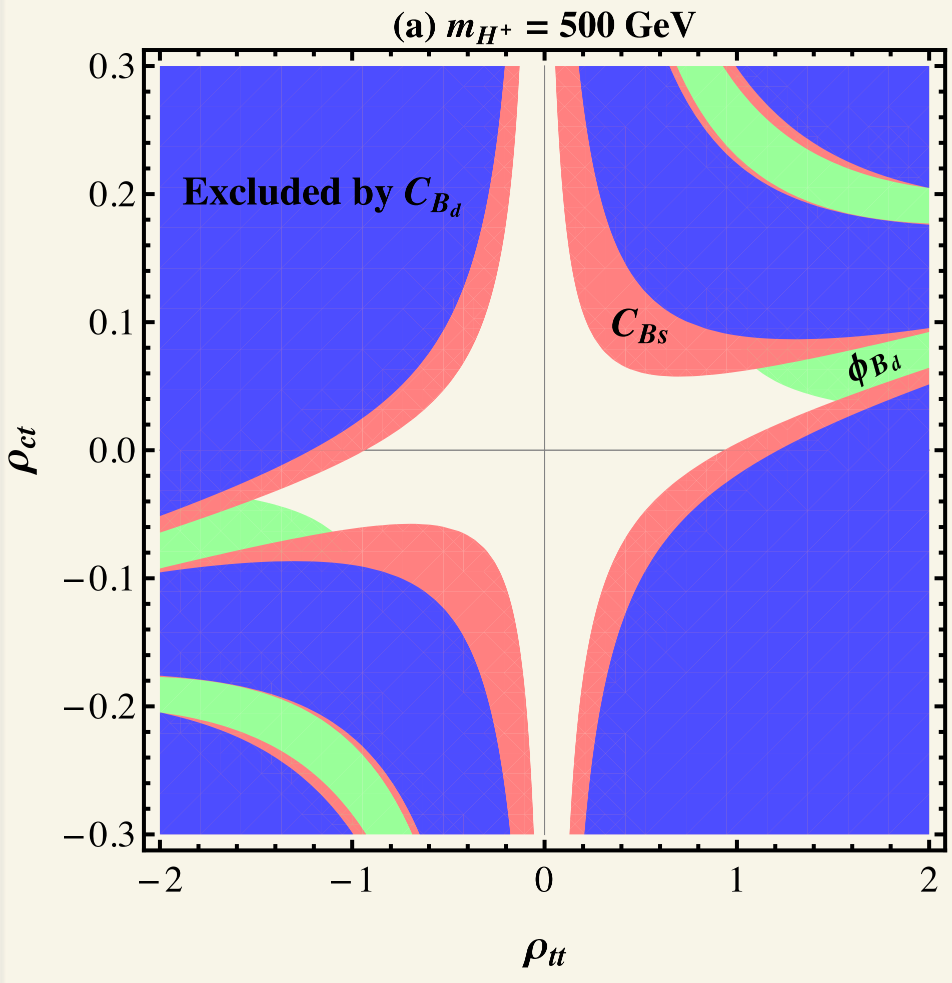
Heavy Higgs Decay Branching Fractions

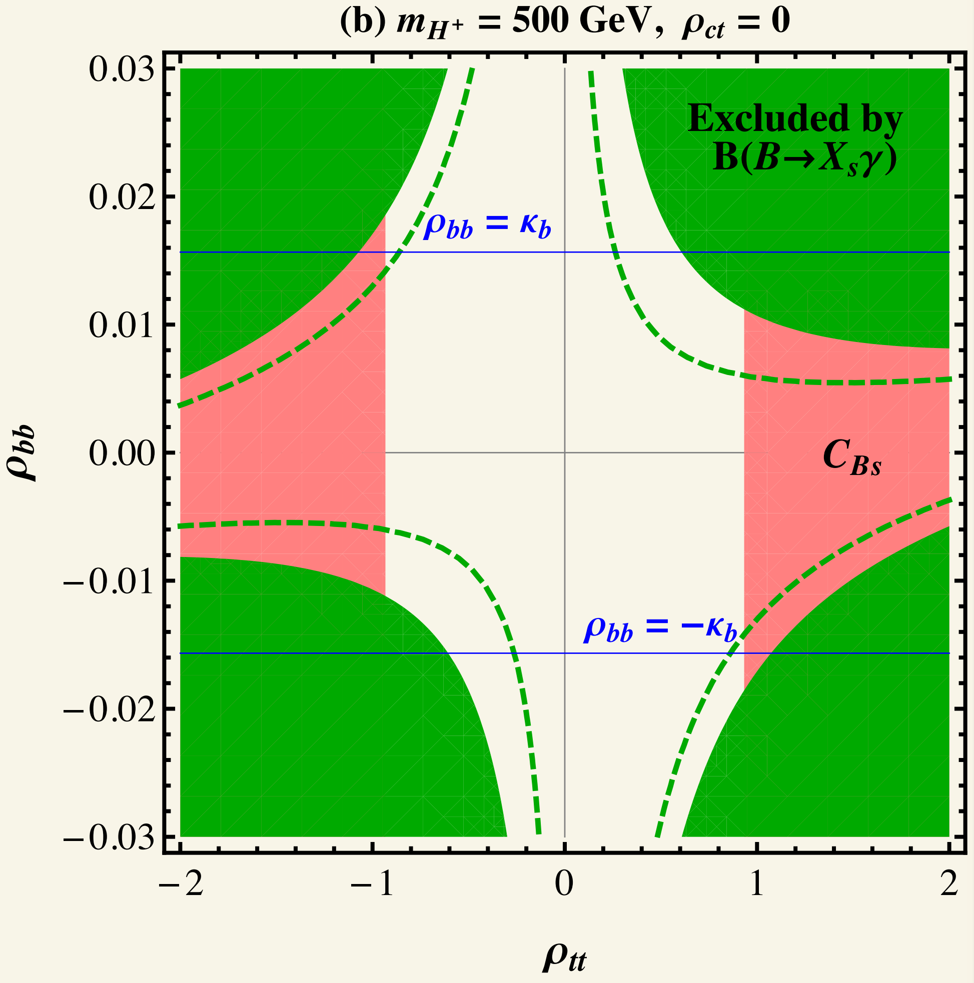


Constraints from Higgs Production

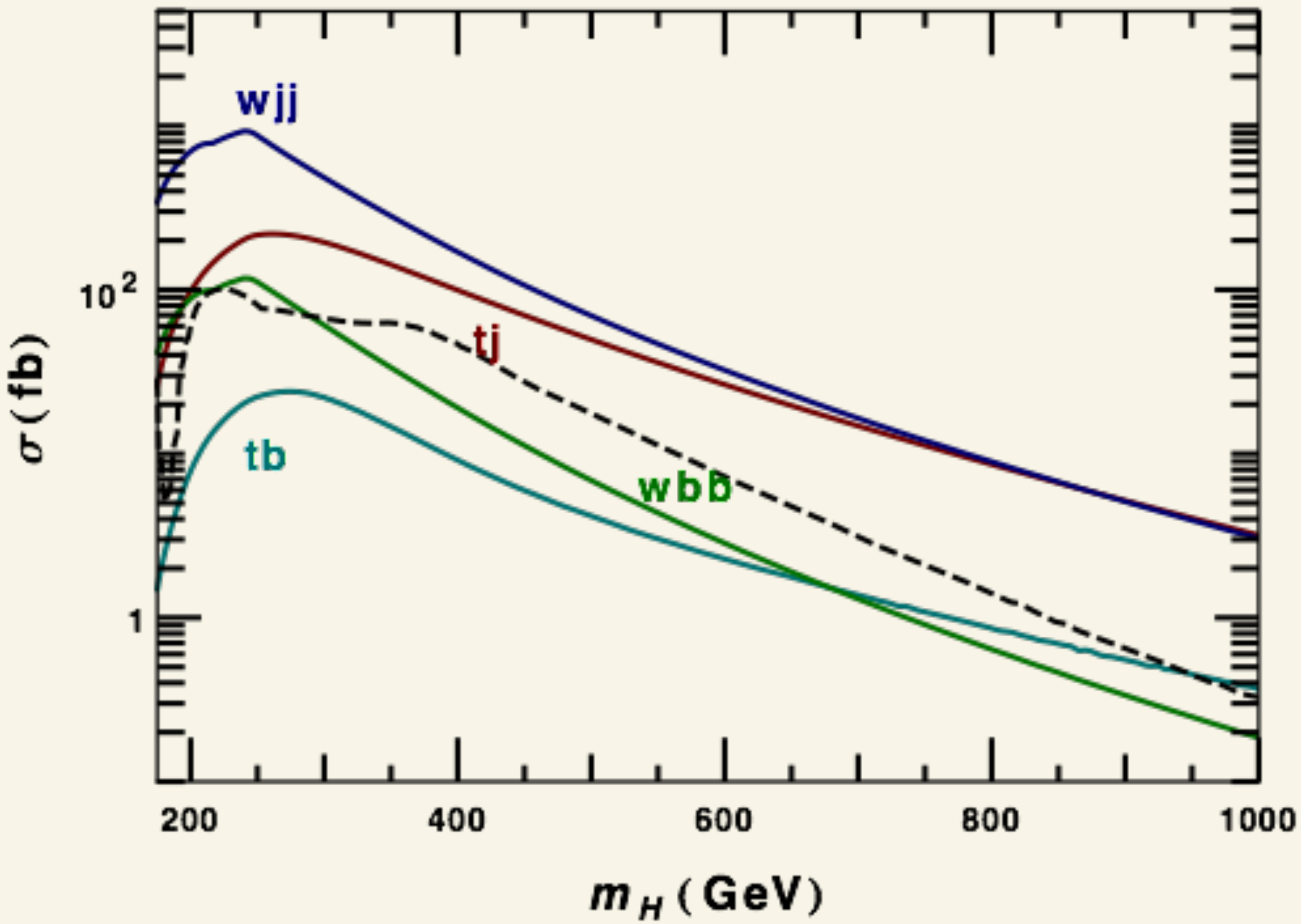


Constraints from B Physics



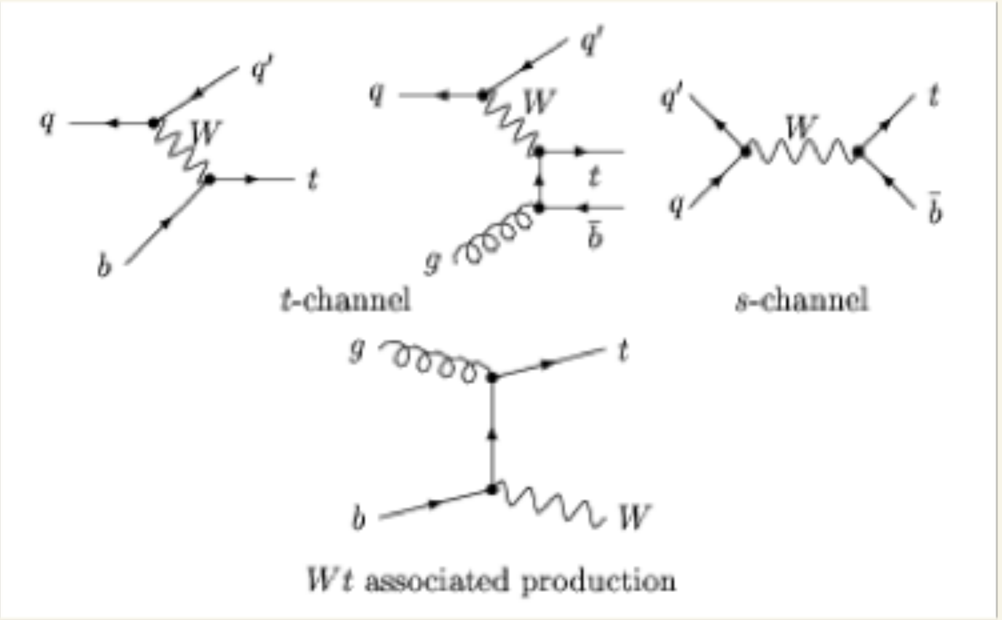


Signal versus Physics Background at the LHC with 8 TeV



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 $\Delta R(b,j,l) > 0.4$.

Mass Reconstruction

We require that the reconstructed invariant masses should center around m_t, m_W, and M_ϕ .

- Assuming an on-shell W, we evaluate k_z of the neutrino with lepton momentum (p) and missing transverse energy. Usually, there are two possible values for k_z. We select whichever leads to a better reconstruction of the top-quark mass: Min[$m_t^2 - (k+p+p_b)^2$], and define the reconstructed top mass as $M_t^R = M_{bl\nu}$ such that $|M_{bl\nu} - m_t| < 0.15 m_t$ or $0.20 m_t$.
- The invariant mass of the top and the charm should have a peak near M_ϕ: $|M_{bl\nu j} - m_\phi| < 0.15 M_\phi$ or $0.20 M_\phi$.

Jacobian Peak in $p_T(c)$ Distribution

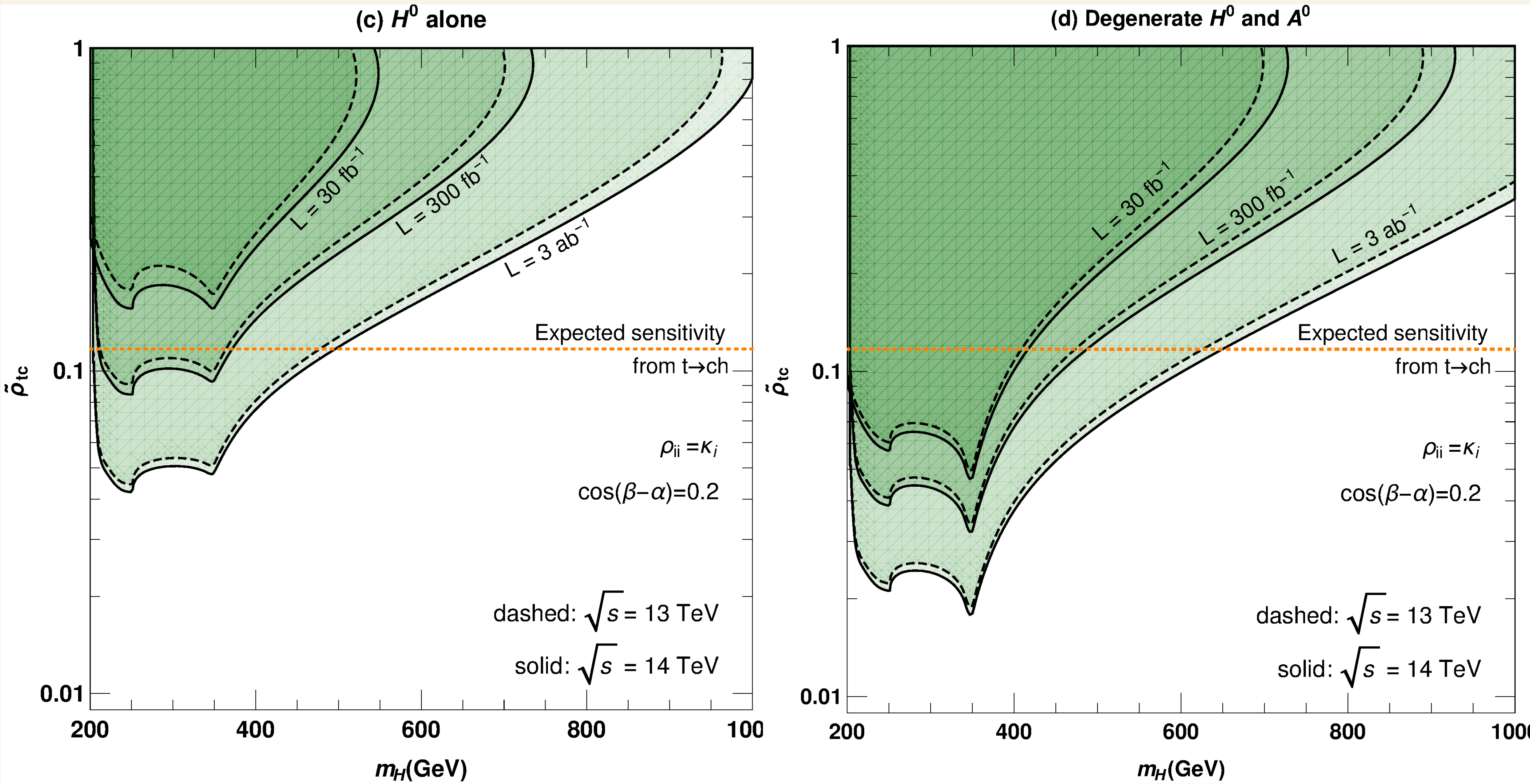
In the rest frame of the Higgs boson, there is a Jacobian peak in the charm transverse momentum distribution

$$p^* = \frac{\lambda^{1/2}\left(m_\phi^2, m_t^2, m_c^2\right)}{2m_\phi} \approx \frac{m_{\ \phi}}{2}\left[1 - \frac{m_t^2}{m_\phi^2}\right]$$

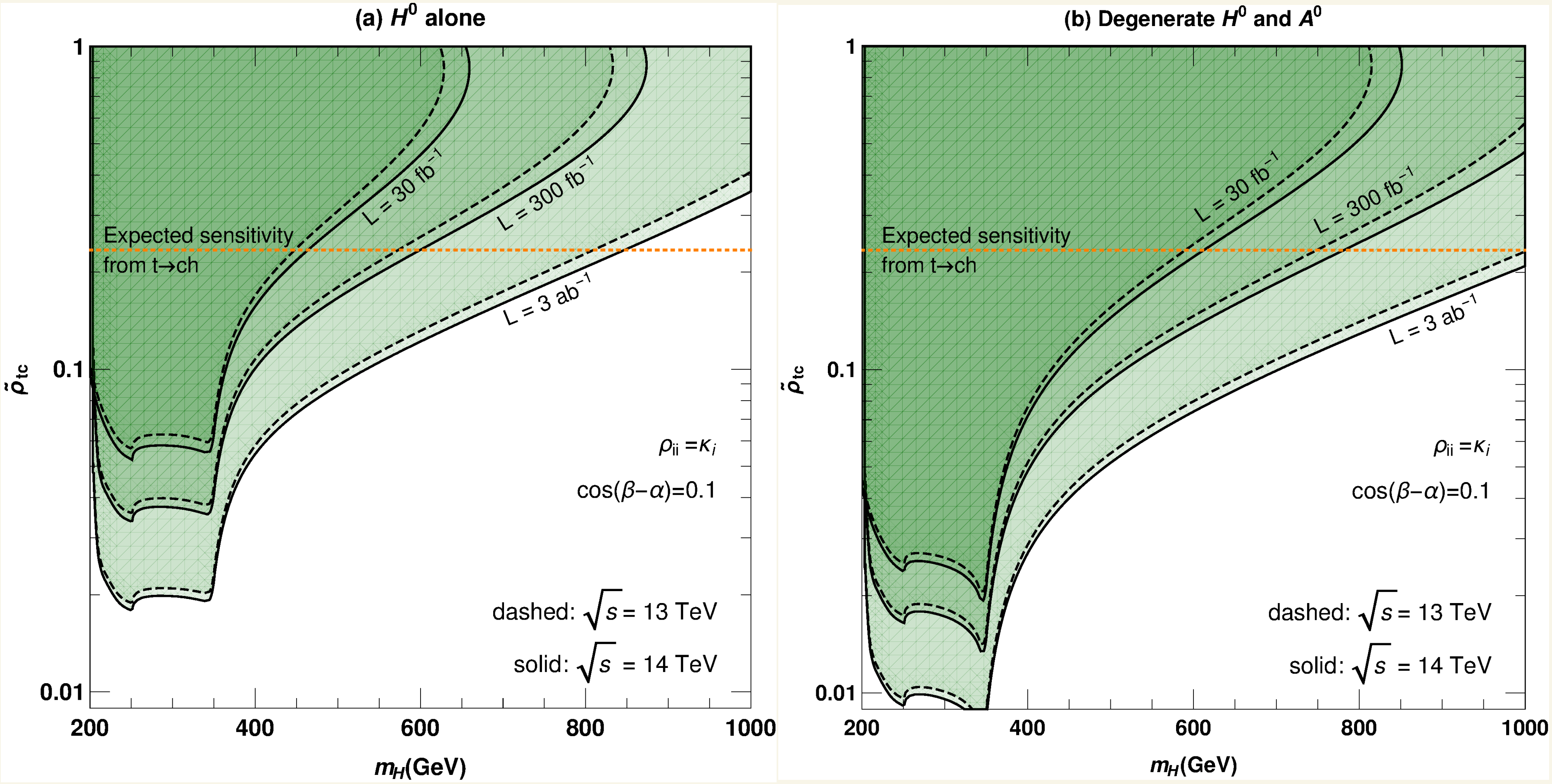
where λ(x,y,z) = x2 +y2 +z2 -2(xy +xz +yz).

Therefore, we require $|p_T(j)-p^*| < 0.20\ p^*$
for the transverse momentum of the light jet.

Discovery Contour at the LHC
cos(β-α) = 0.2



Discovery Contour at the LHC
cos(β-α) = 0.1



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 mass giver (Higgs).
- It is a win-win strategy to search for the FCNH top decay $t \to ch^0$ and the heavy Higgs decay $H^0, A^0 \to t\bar{c} + t\bar{c}$. In the decoupling limit, the production ($gg \to H^0$) and the FCNH decay $H^0 \to tc$ 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.