Flavor Changing Neutral Higgs Interactions with Top and Tau at Hadron Colliders

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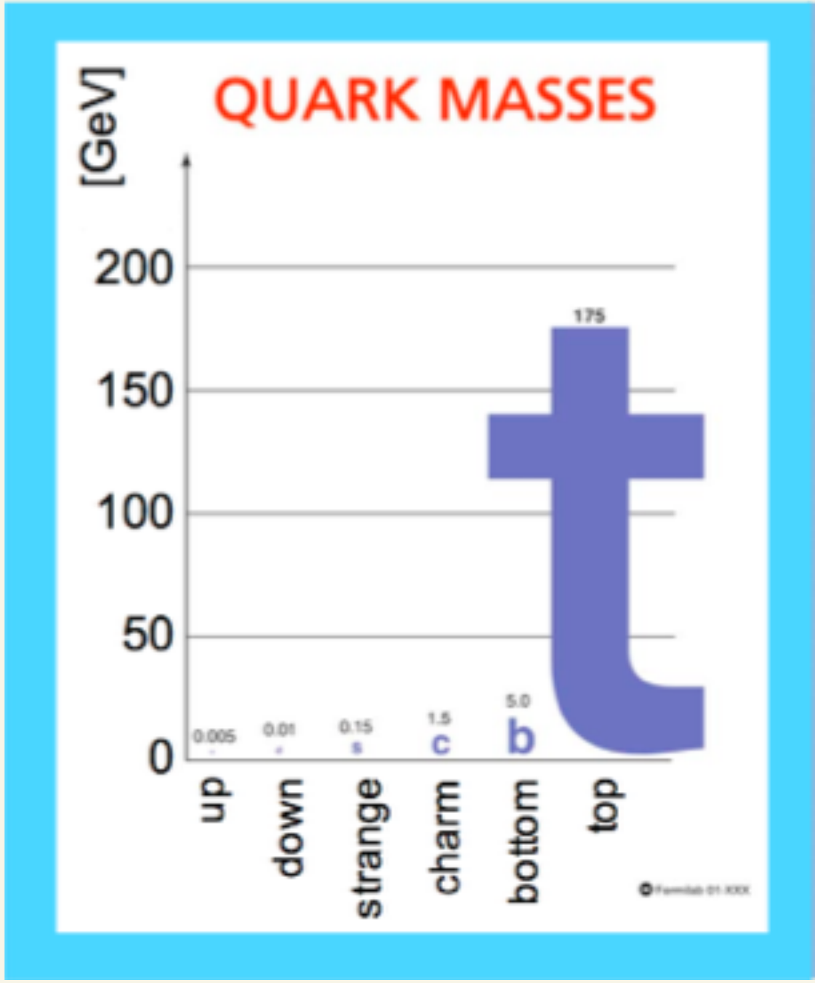
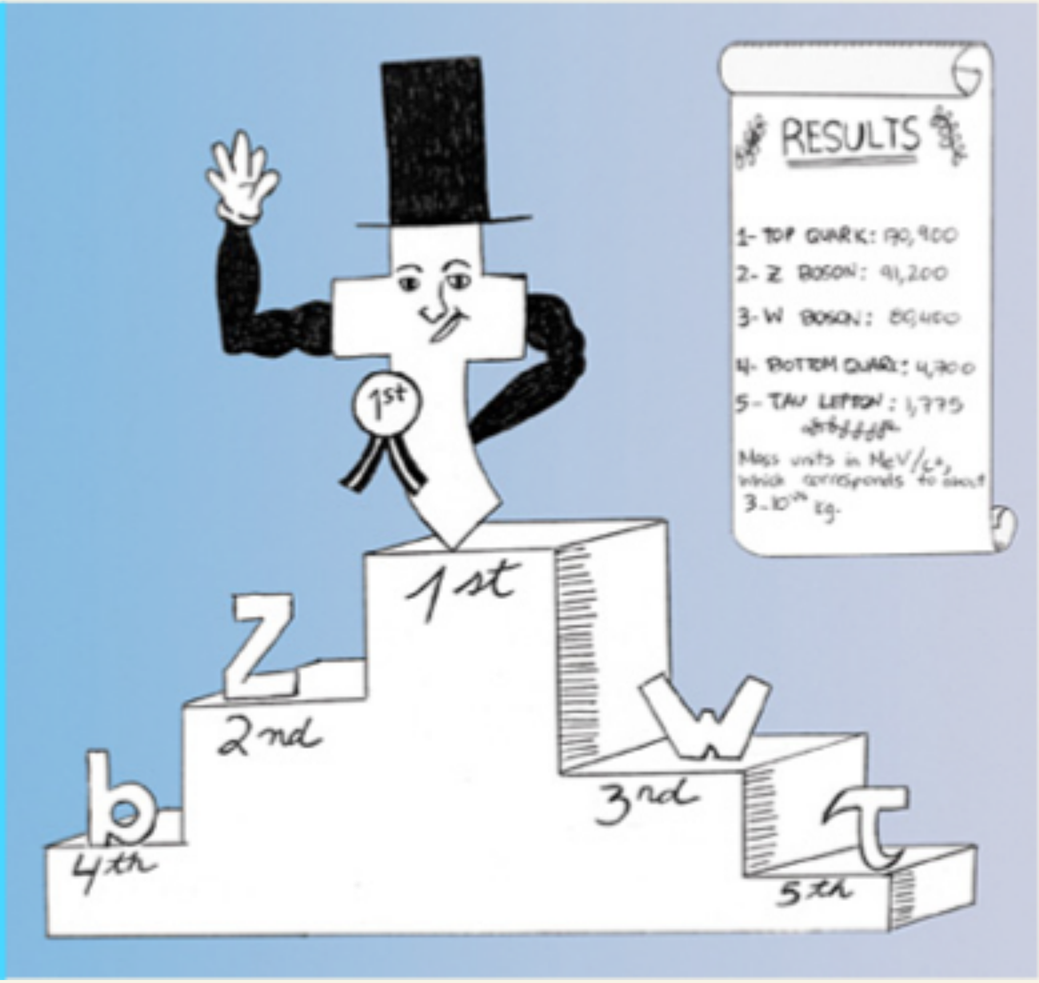
Heavyweight Champion before July 4, 2012





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, $m = \lambda(v/\sqrt{2})$.

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.[§]

[‡] 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

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

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

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

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

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

A General Two Higgs Doublet Model

Davidson and Haber (2005); 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	II	III	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

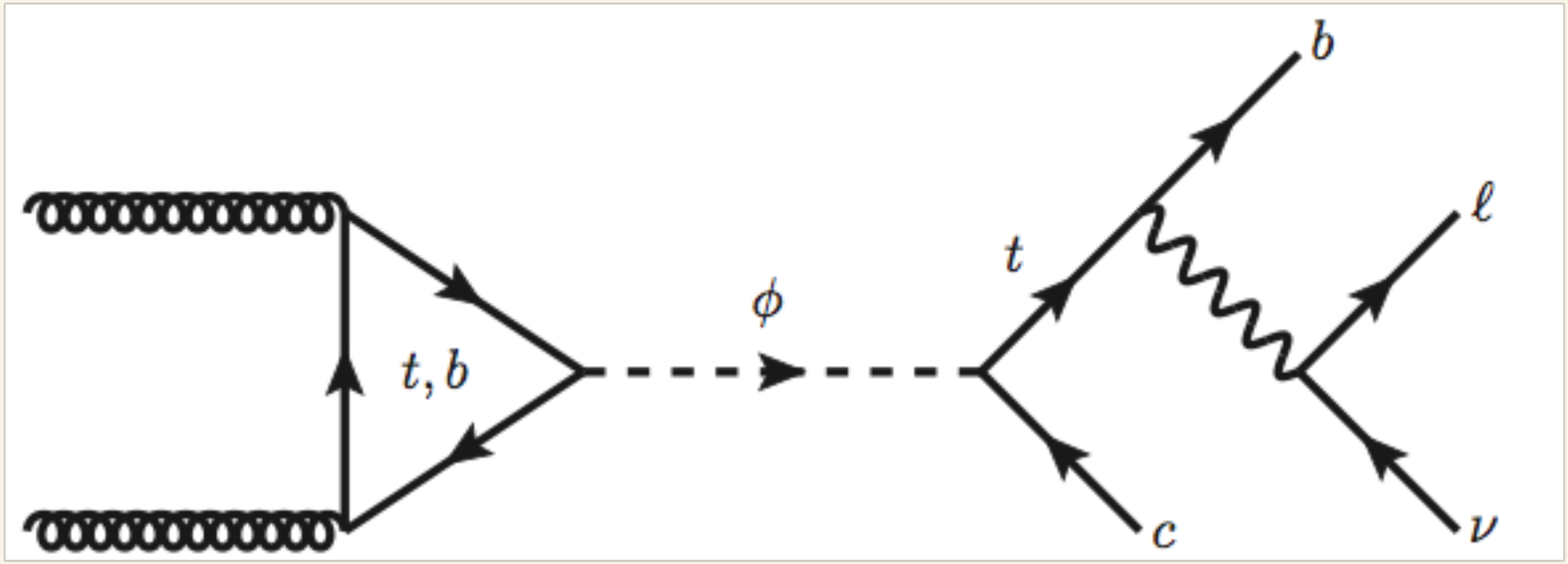
- The Higgs boson is the mass giver, while the top quark is the most massive particle. Their interactions might give us guidance to search for new physics beyond the Standard Model.
- The LHC has become a top factory.
- We might be able to observe $t \to ch^0$ if $\lambda_{ct} = \rho_{ct} \cos(\beta\text{-}\alpha)$ 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 $\lambda_{tc} = \rho_{tc} \sin(\beta\text{-}\alpha)$.

The FCNH Signal at the LHC

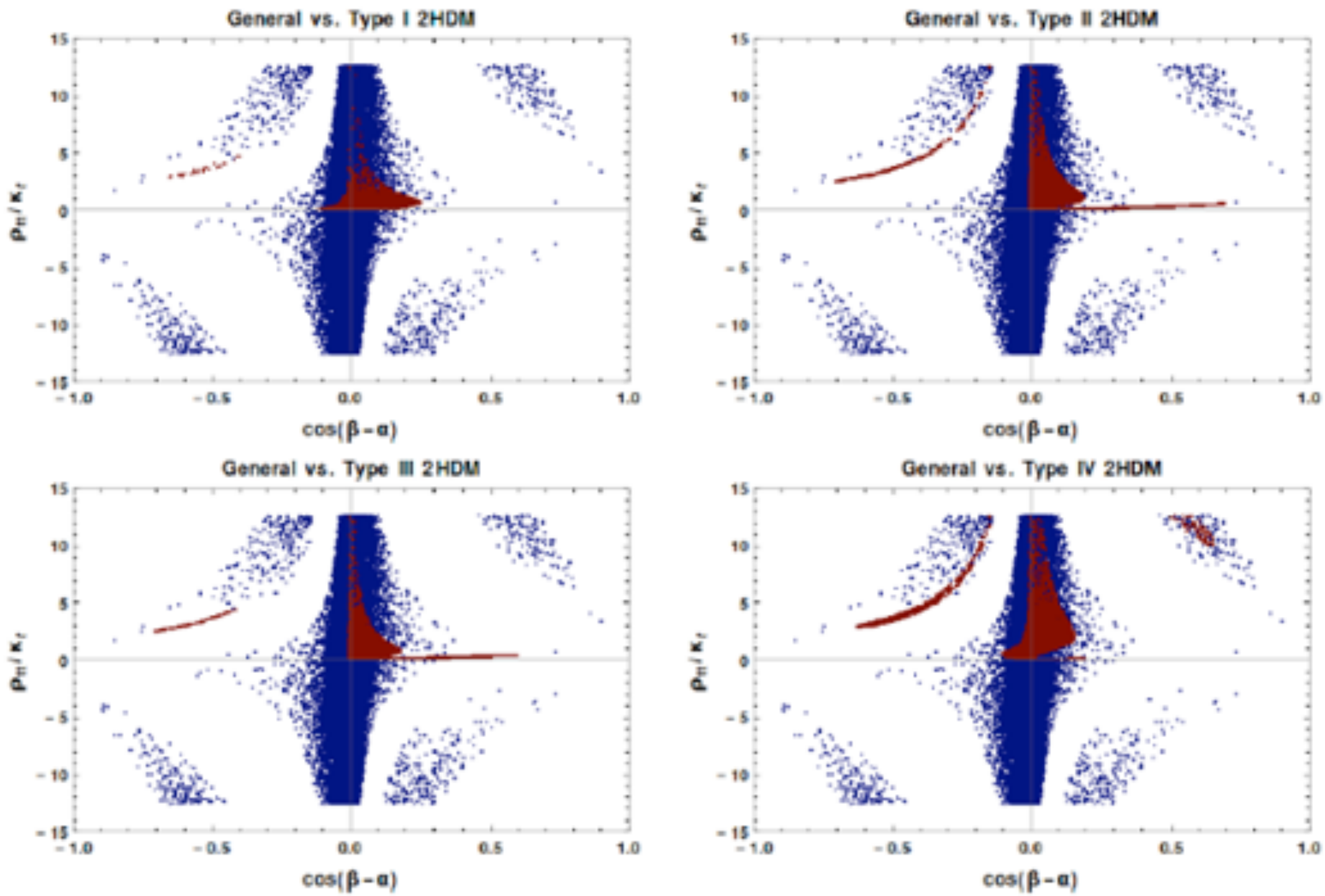
- We employ the programs MadGraph and HELAS to evaluate the exact matrix element for the FCNH signal from gluon fusion and quark-antiquark annihilation in pp collisions.
  Stelzer and Long (1994); Alwall et al. (2007); Murayama, Watanabe and Hagiwara (1991).
- In addition, we apply narrow width approximation to check the exact results.
- The cross sections are evaluated with the parton distribution functions of CTEQ6L1.

The FCNH Signal of a Heavy Higgs boson at the LHC

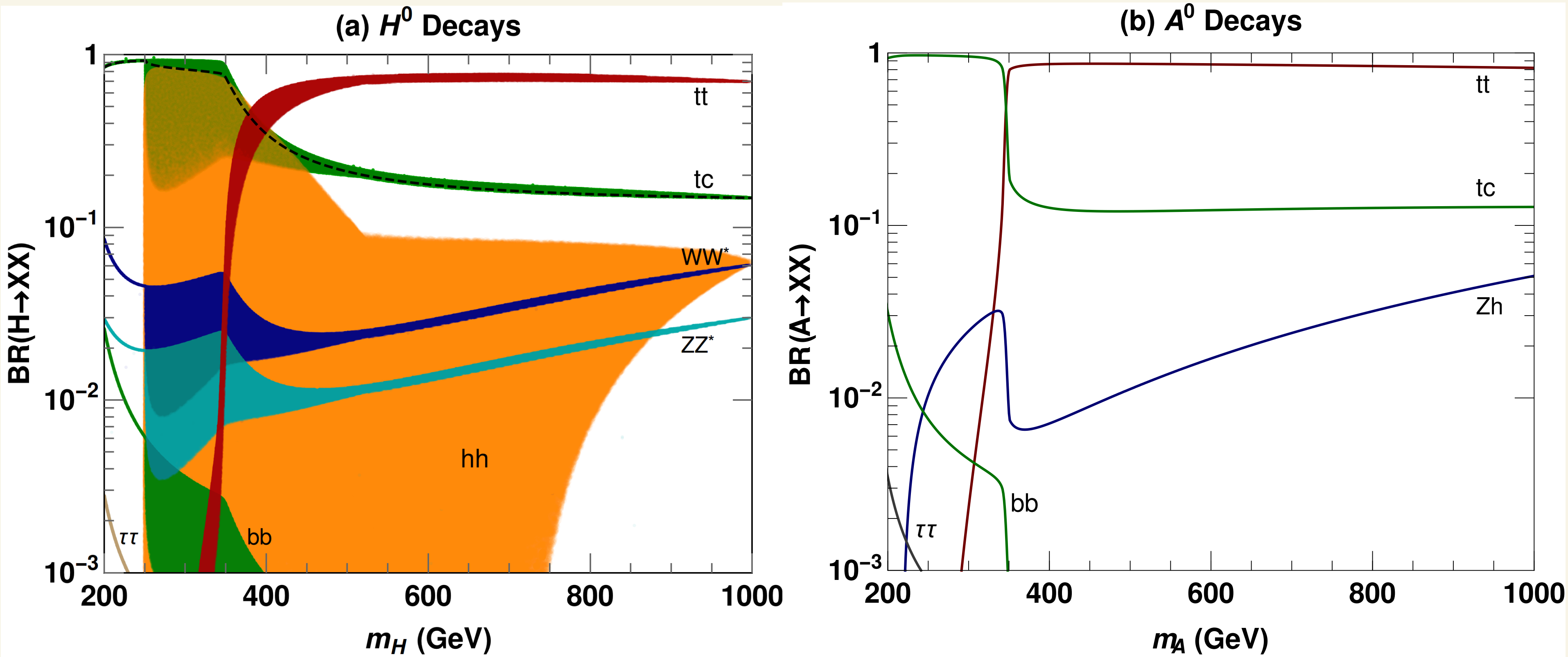
Let us consider a flavor changing neutral Higgs boson (ϕ^0) with $M_\phi > M_h$. It can be a CP-even scalar (H^0) or a CP-odd pseudoscalar (A^0) produced at the LHC followed by the Higgs decay into a top quark and a charm quark:



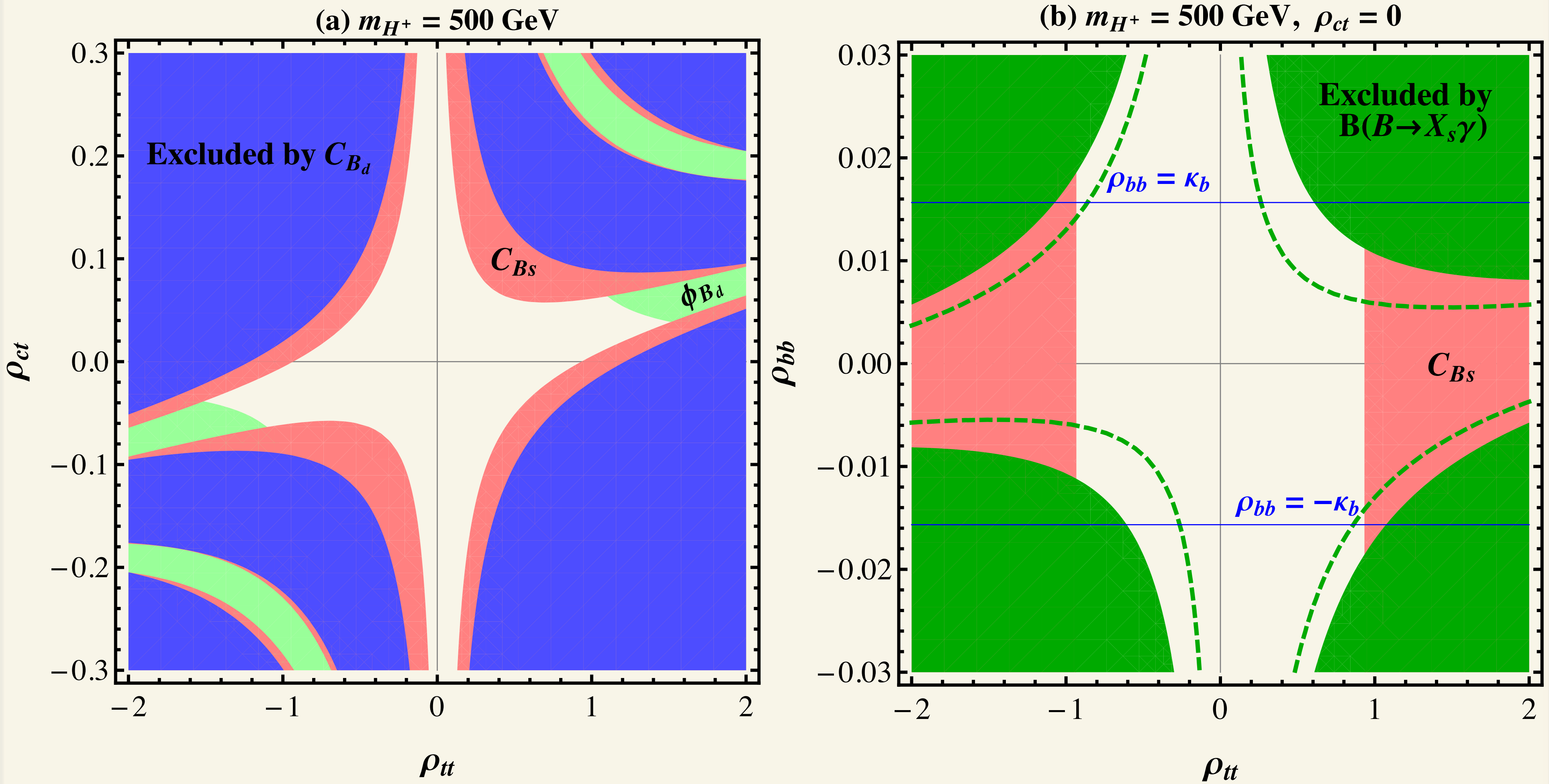
ATLAS and CMS Signal Strength Measurements



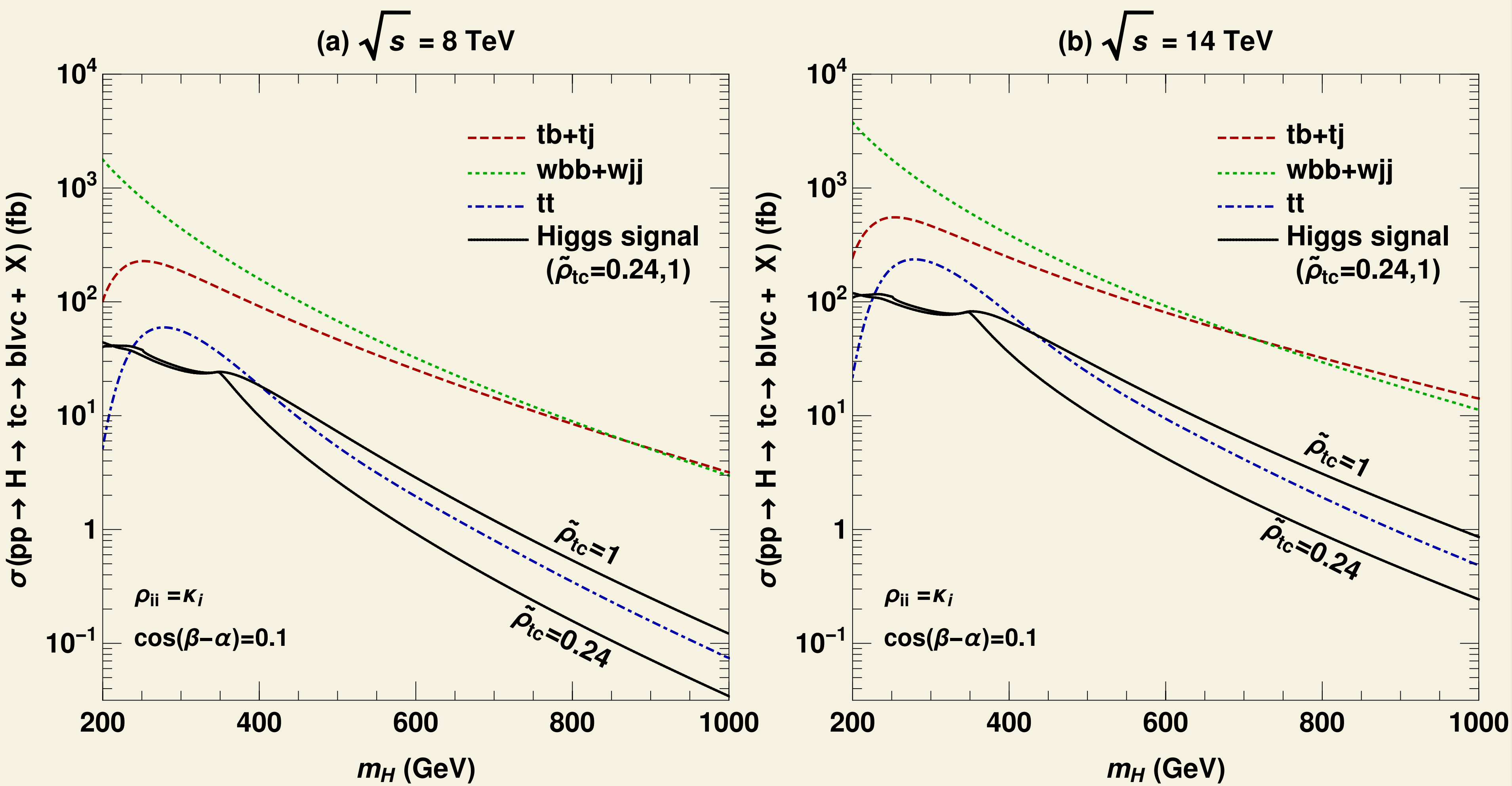
Heavy Higgs Decay Branching Fractions



Constraints from B Physics



Signal and Background at the LHC

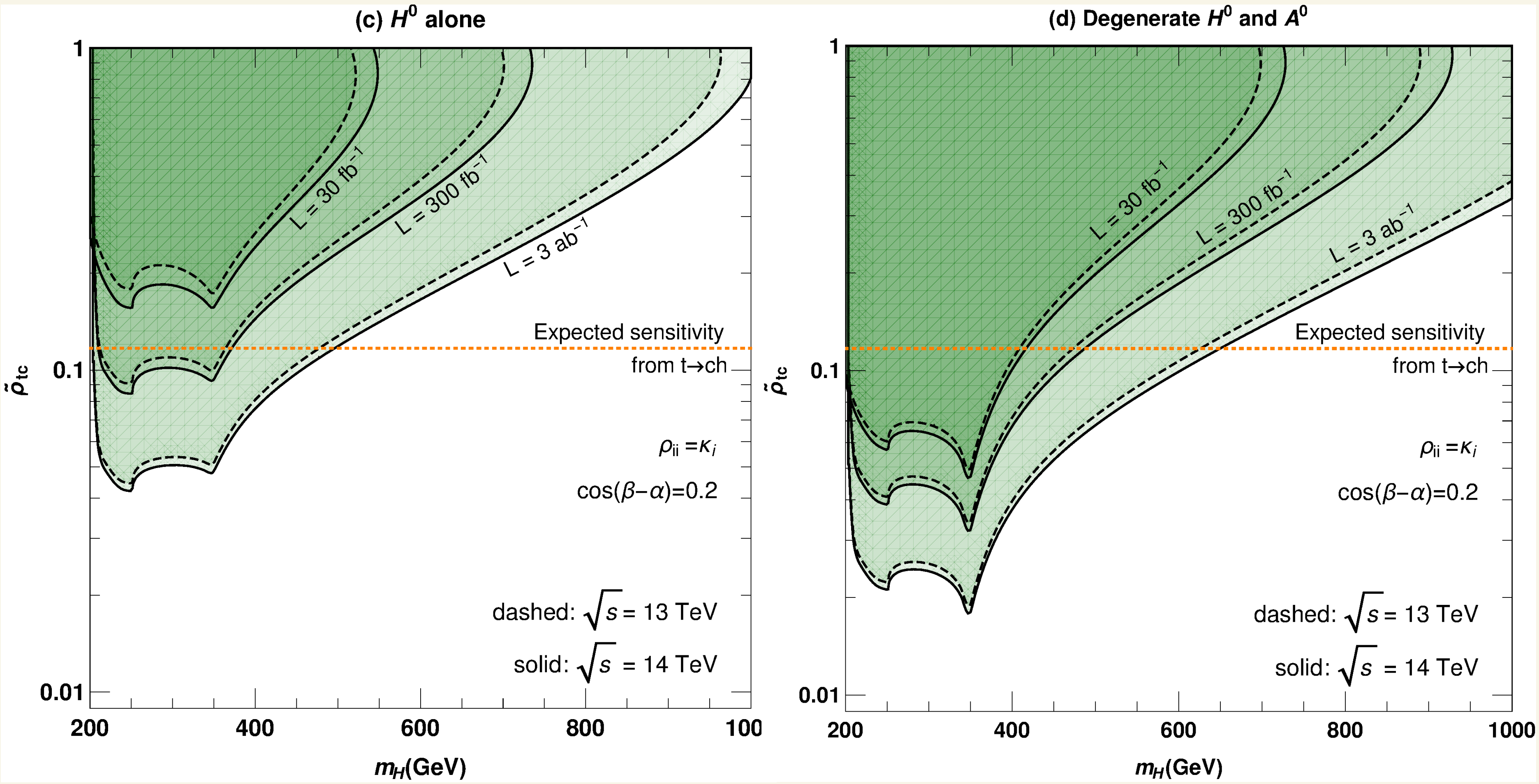


Mass Reconstruction

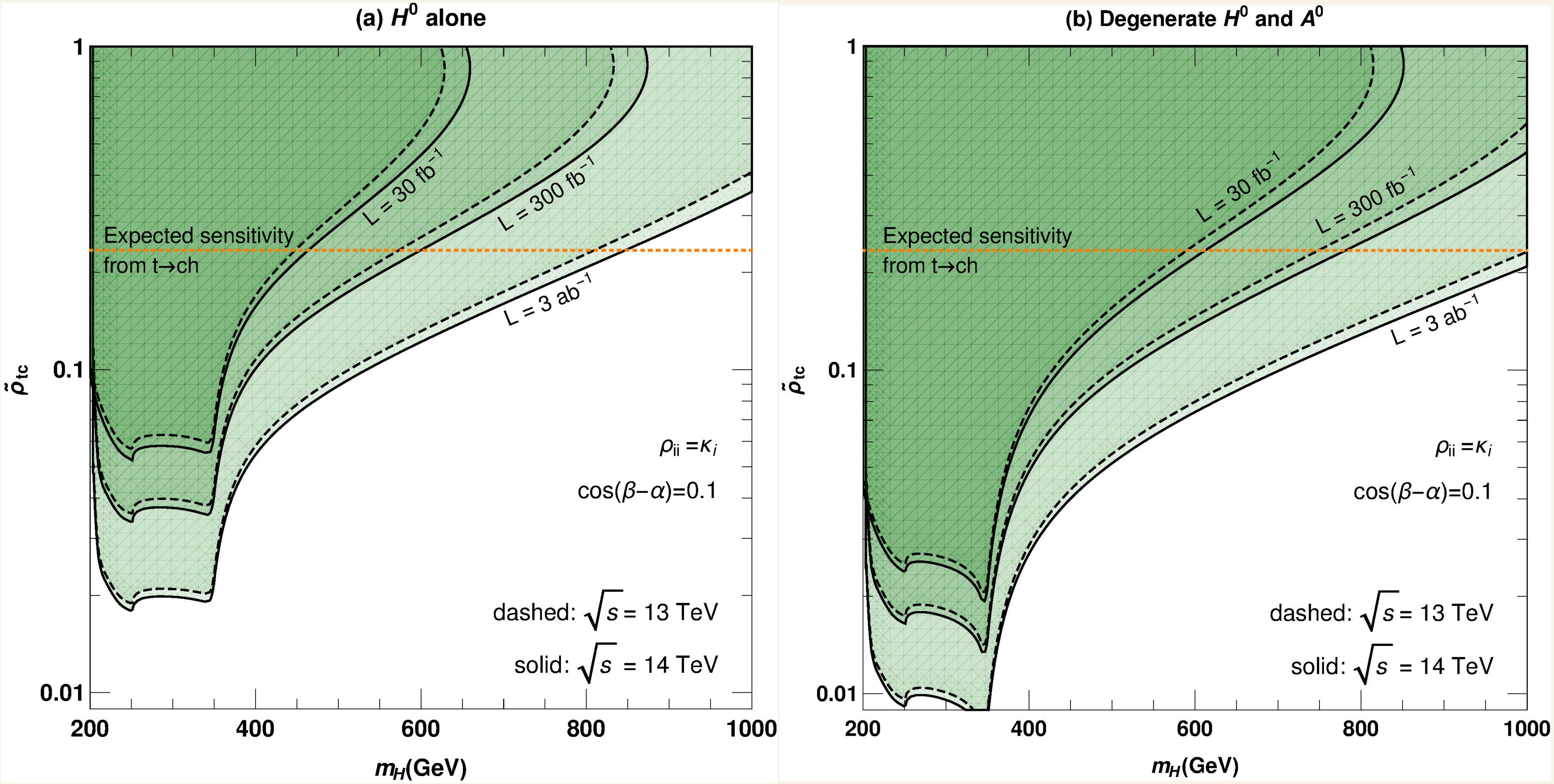
We require that the reconstructed invariant masses should center around m_t, m_W, and M_ϕ .

- 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: $\mathrm{Min}[m_t^2 - (k+p+p_b)^2]$, and define the reconstructed top mass as $M_t^R = M_{bl\nu}$ such that $|M_{bl\nu} - m_t| < 0.15m_t$ or $0.20m_t$.
- The invariant mass of the top and the charm should have a peak near M_ϕ: $|M_{bl\nu j} - m_\phi| < 0.15M_\phi$ or $0.20M_\phi$.

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



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



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(β-α)~ 1.
- The FCNH decay of heavy Higgs bosons will be observable for $\rho_{tc} > 0.1$ and cos(β-α) ~ 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.

Flavor Changing Higgs Decays to $\tau\mu$

- Recent CMS data has set a limit on the branching fraction B(h to $\tau\mu$) < 0.25%
- In a general 2HDM, the FCNH coupling of $h\tau\mu$ is proportional to $\cos(\beta-\alpha)$ while the FCNH couplings of $H\tau\mu$ and $A\tau\mu$ are proportional to $\sin(\beta-\alpha)$.
- In the decoupling limit or the alignment limit of 2HDMs, we expect $\cos(\beta-\alpha) \sim 0$, and $\sin(\beta-\alpha) \sim 1$.

Implications of h to τμ from CMS Data

CMS arXiv:1502.07400; ATLAS arXiv:1508.03372; CMS arXiv:1712.07173

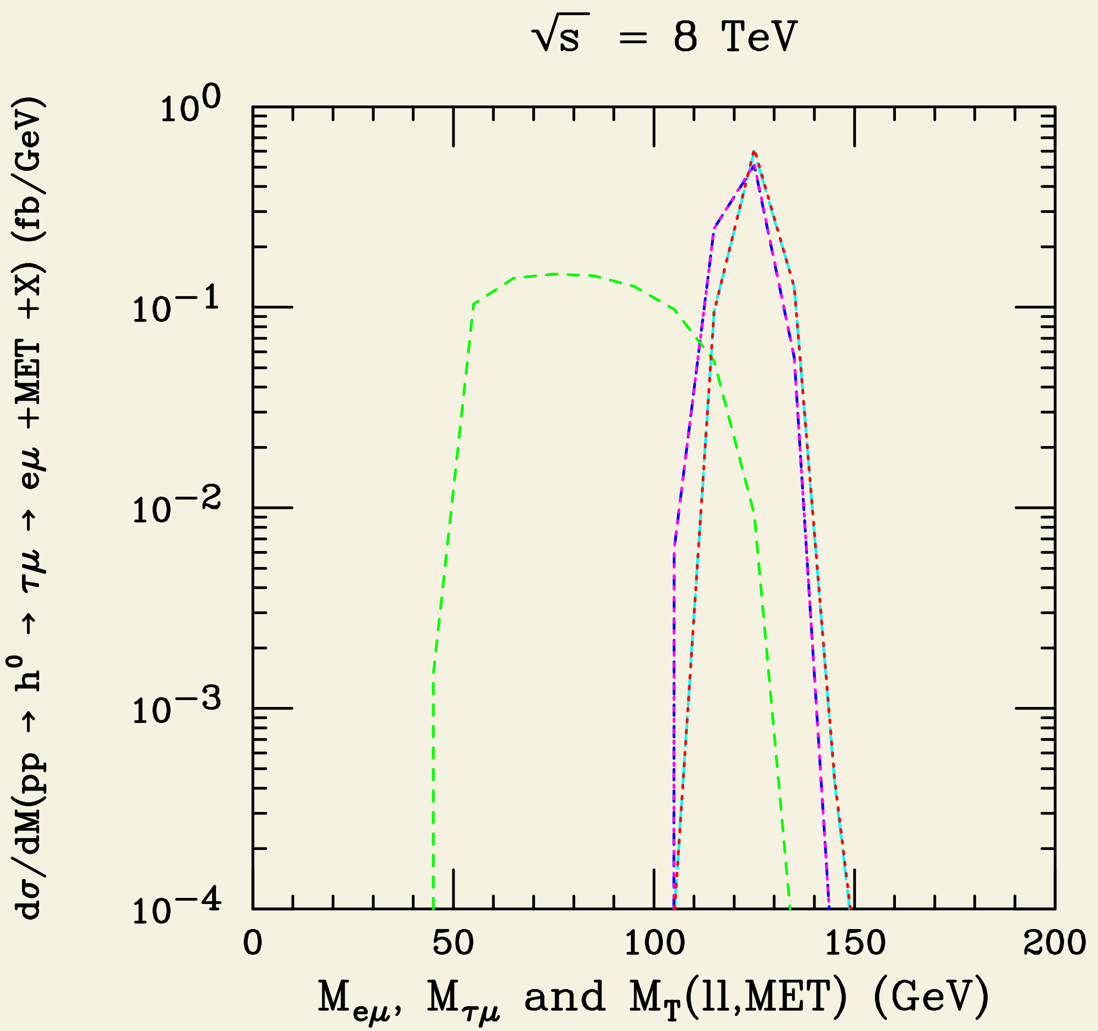
- CMS data in Run 1 had a 2.4σ excess
  - Best fit branching fraction: 0.84 +-0.38%
- It is compatible with 1σ excess from ATLAS
  - Best fit branching fraction: 0.77+-0.62%
- The 2.4σ excess is ruled out by 2016 CMS data
- An upper limit is set for B(h to τμ) < 0.25%

Implication of New CMS Data

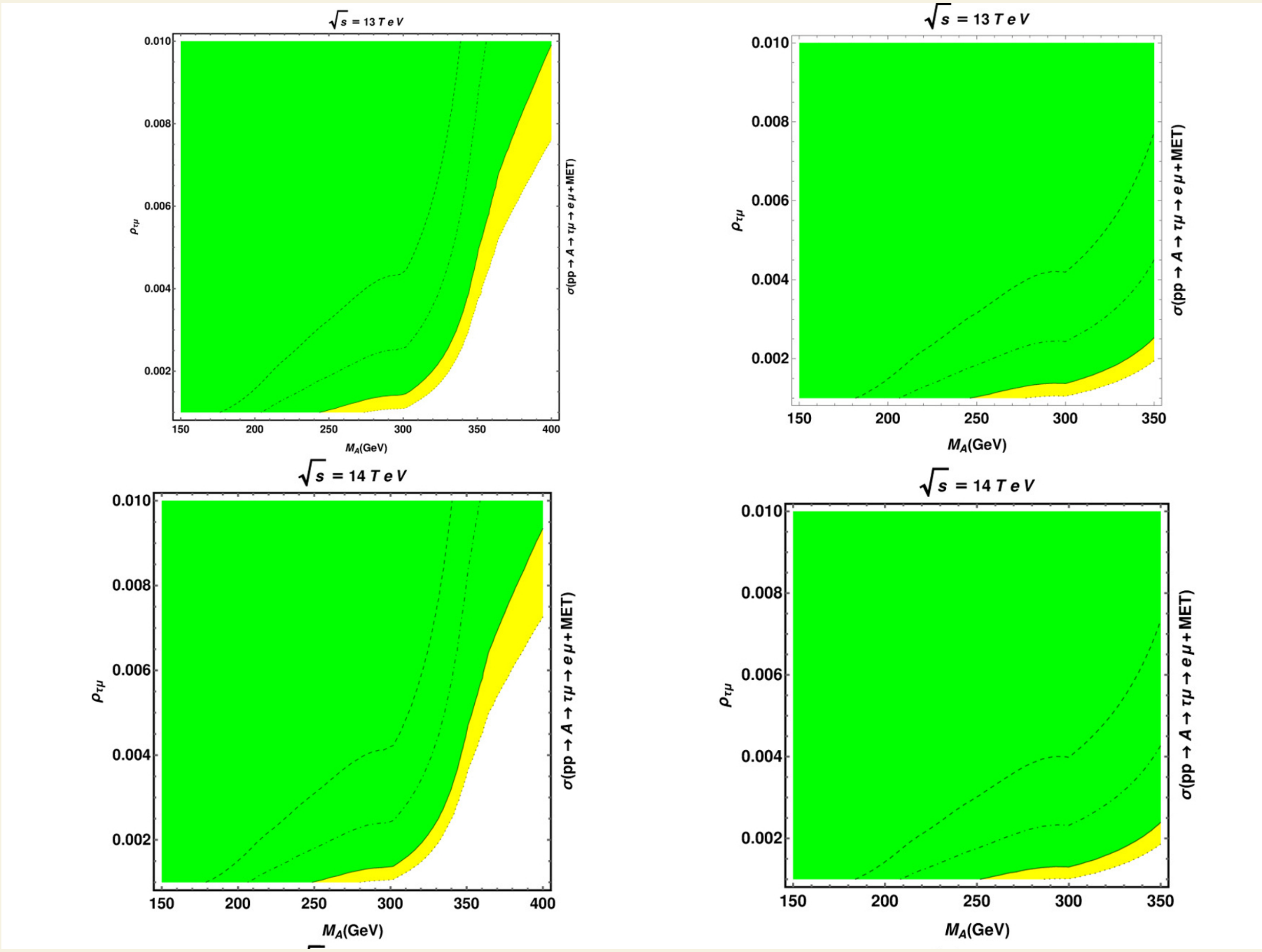
- CMS-HIG-17-001
- $B(h^0$ to $\tau\mu) < 0.25\%$ at 95% C.L.
- $(|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2)^{1/2} < 1.43 \times 10^{-3}$
- For $\cos(\beta-\alpha) = 0.1$, $\rho_{\tau\mu} < 2 \times 10^{-2}$
- $g_{\tau\mu} = Y_{\tau\mu} = \lambda_{\tau\mu}/\mathrm{sqrt}(2) = \rho_{\tau\mu} \cos(\beta-\alpha)/\mathrm{sqrt}(2)$

Higgs to tau mu

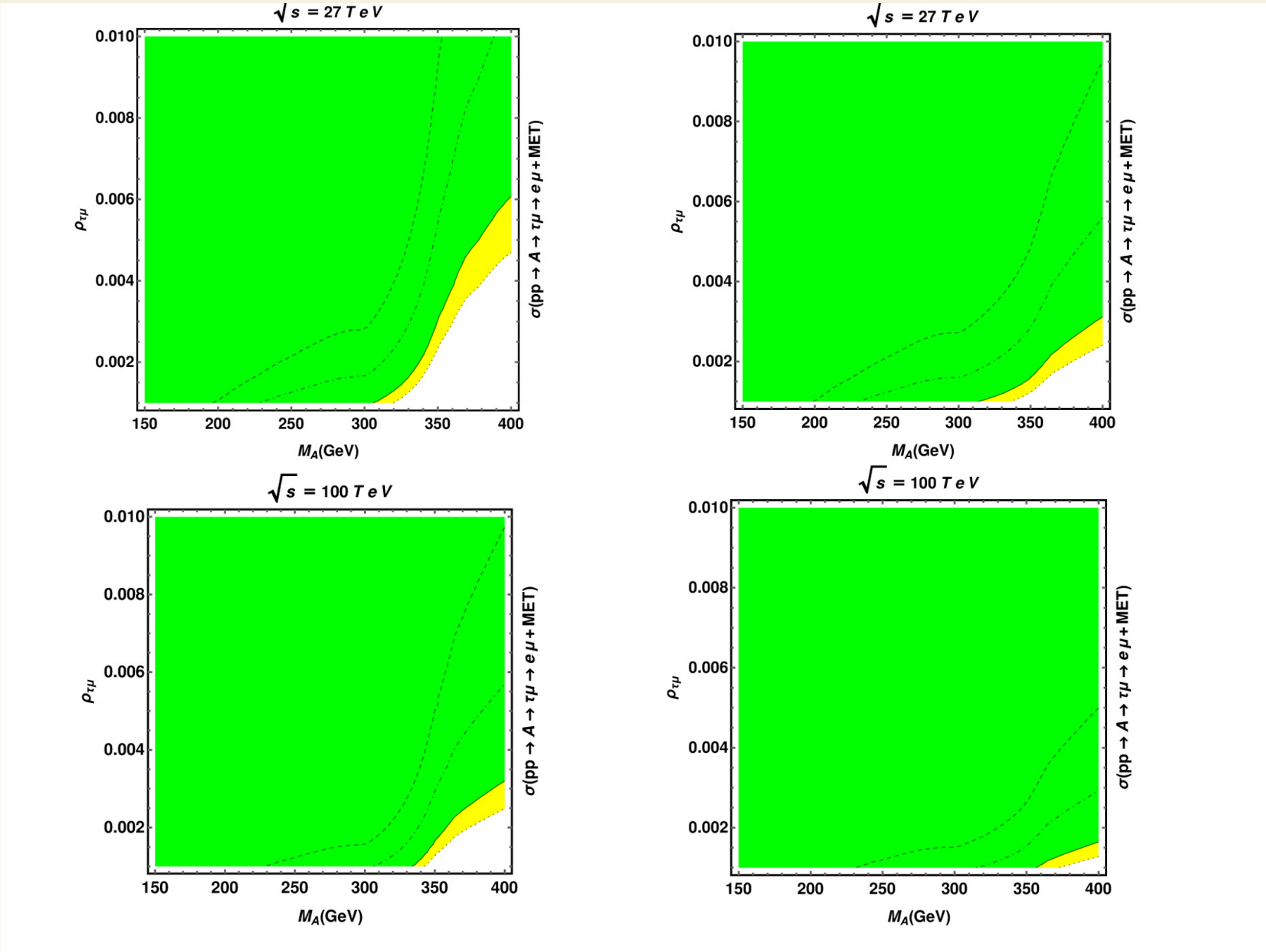
Hou, Jain, Kao, Kohda, McCoy, Soni (2018)



Discovery Contours for 13 TeV and 14 TeV



Discovery Contours
for 27 TeV and 100 TeV



Results for $h^0 \to \tau\mu$

Table 1 shows the cross section in fb of the $pp \to h^0 \to \tau\mu \to e\mu + X$ with all CMS acceptance cuts for $g_{h\tau\mu} = \rho_{\tau\mu} \cos(\beta - \alpha)/\sqrt{2} = \sqrt{m_\tau m_\mu}/v \simeq 1.75 \times 10^{-3}$, dominant physics backgrounds are also presented.

Collider Energy	$h^0 \to \tau\mu$	$Z \to \tau\tau$	W^+W^-
8 TeV (CMS)	1.17	3.3	2.08
8 TeV (PM)	3.71	9.62	2.18
13 TeV (PM)	8.17	15.49	3.66
14 TeV (PM)	9.14	16.64	3.96

Table: $\sigma(pp \to h^0 \to \tau\mu \to e\mu + X)$[fb] for $\sqrt{s} = 8, 13$, and 14 TeV. PM means parton level cross section.

Our cross sections at the parton level for $h^0 \to \tau\mu$ and $Z \to \tau\tau$ are both significantly higher than CMS data. We plan to carry out Monte Carlo simulations for $H^0, A^0 \to \tau\mu$.