Searching for a flavor changing decay t → c h at the LHC

Masaya Kohda (National Taiwan Univ.)

甲田 昌也

Based on:

K.-F. Chen, W.-S. Hou, C. Kao, and MK, arXiv:1304.8037

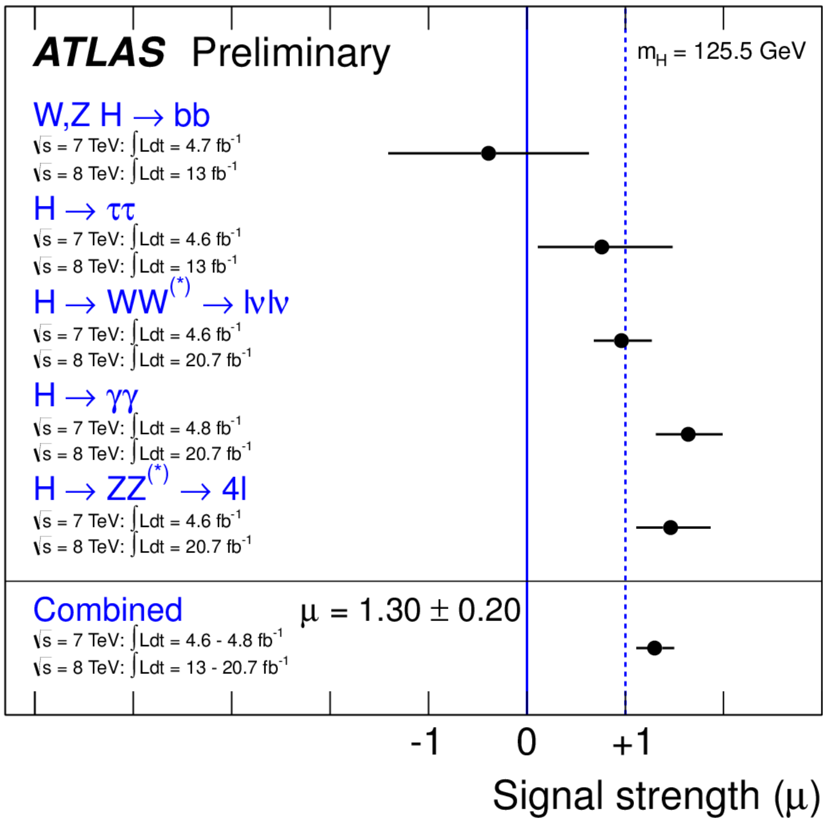
June 13, 2013 @ NCTS/NTHU Thursday HEP seminar

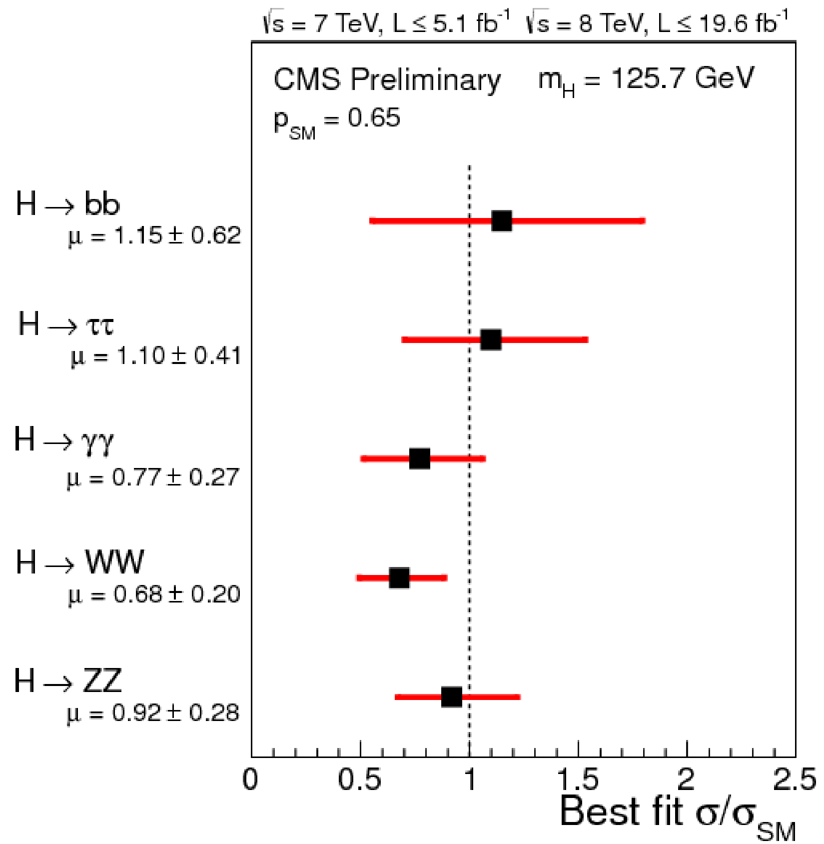
Historical discovery of a new boson with mass ~126 GeV at LHC in 2012

Pool photo by Denis Balibouse

So far, consistent with the SM Higgs boson

- ATLAS & CMS results with 7 TeV & 8 TeV data





But, not the end of the story

- The 126 GeV boson is the genuine Higgs boson of the standard model?

- Any other Higgs bosons, like repetition of quarks and leptons?

This talk: **Two Higgs Doublet Model**

Two Higgs Doublet Model with general Yukawa interactions (Type-III 2HDM)

- Flavor-Changing-Neutral-Higgs (FCNH) interactions (tree level)

  e.g., $\lambda_{ds} h \bar{d} s$ $\lambda_{ct} h \bar{c} t$

  - FCNH in d-type sector is severely constrained by flavor phys.
  - In usual Type-II 2HDM, absent due to discrete symmetry

  S.L. Glashow and S. Weinberg (1977)

- A way to control FCNH in 2HDM-III: Cheng-Sher ansatz

  T.P. Cheng and M. Sher (1987)

  $$\lambda_{ij} \sim \frac{\sqrt{m_i m_j}}{v}$$ x (mixing angle)

  - suppressed d-type FCNH, but allow ***large*** **h-t-c coupling**!

- **Our approach**: consider large h-t-c coupling, but not assume CS
  - FCNH couplings are free parameters ← constrained by data
  - also motivated by BaBar anomaly in B → $D^{(*)}\tau\,\nu$ decay (discussed later)

t → c h decay

W.-S. Hou (1992)

- Immediate consequence of large h-t-c coupling & 126 GeV (SM-like) Higgs boson (h) is t → c h decay

$$\frac{\Gamma(t \to ch)}{\Gamma(t \to bW)} \simeq 0.57|\lambda_{ct}|^2$$

Γ(t→ch): LO
Γ(t→bW): NLO

- In SM, loop-induced t → c h is highly suppressed by GIM & CKM

$$\mathcal{B}(t \to ch) \simeq 3 \times 10^{-15}$$

J.A. Aguilar-Saavedra (2004)

- So, t → c h is a good place to see New Physics

Plan of this talk

- Introduction
- Type-III Two Higgs Doublet Model (2HDM-III)
- Flavor Physics in 2HDM-III
  - BaBar anomaly in B → $D^{(*)}\tau\,\nu$
- t → c h search at the LHC
- Summary and discussion

Type-III Two Higgs Doublet Model

Following, Mahmoudi and Stal, PRD (2010)

- introduce two Higgs doublets Φ_1, Φ_2 with VEVs:

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \qquad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}$$

- most general Yukawa interaction terms (quark sector)

$$\mathcal{L}_Y = -\overline{Q'_L}(\eta_1^d\Phi_1 + \eta_2^d\Phi_2)d'_R - \overline{Q'_L}(\eta_1^u\tilde{\Phi}_1 + \eta_2^u\tilde{\Phi}_2)u'_R + \text{H.c.}$$

- can choose other basis for Φ_1, Φ_2 via a rotation in “Higgs space”

$$\begin{pmatrix} \Phi'_1 \\ \Phi'_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

  - $\tan\beta = v_2/v_1$ depends on basis, thus, not physical parameter
  - This rotation is not allowed in 2HDM-II due to Z_2-symmetry

Yukawa terms in Higgs basis

- it is useful to move to "Higgs basis" by the rotation by angle β

$$\langle \Phi_1^H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \langle \Phi_2^H \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad v = \sqrt{v_1^2 + v_2^2} \simeq 246 \text{ GeV}$$

- then, Yukawa terms become

$$\mathcal{L}_Y = -\overline{Q'_L}(\kappa_0^d \Phi_1^H + \rho_0^d \Phi_2^H) d'_R - \overline{Q'_L}(\kappa_0^u \tilde{\Phi}_1^H + \rho_0^u \tilde{\Phi}_2^H) u'_R + \text{H.c.}$$

➢ new Yukawa matrices (f = u, d)

$$\kappa_0^f \equiv \eta_1^f \cos\beta + \eta_2^f \sin\beta, \quad \rho_0^f \equiv -\eta_1^f \sin\beta + \eta_2^f \cos\beta$$

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mass matrices

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mass matrices (κ_0^d, κ_0^u)

free parameters (non-diagonal in general) (ρ_0^d, ρ_0^u)

- ➢ new Yukawa matrices (f = u, d)

$$\kappa_0^f \equiv \eta_1^f \cos\beta + \eta_2^f \sin\beta, \quad \rho_0^f \equiv -\eta_1^f \sin\beta + \eta_2^f \cos\beta$$

Yukawa terms in mass eigenstate basis

$$\mathcal{L}_Y^{\rm phys} =$$

$$- \frac{1}{\sqrt{2}}\bar{d}\left(\kappa^d s_{\beta-\alpha} + \rho^d c_{\beta-\alpha}\right) dh - \frac{1}{\sqrt{2}}\bar{d}\left(\kappa^d c_{\beta-\alpha} - \rho^d s_{\beta-\alpha}\right) dH - \frac{i}{\sqrt{2}}\bar{d}\rho^d\gamma_5 dA$$

$$- \frac{1}{\sqrt{2}}\bar{u}\left(\kappa^u s_{\beta-\alpha} + \rho^u c_{\beta-\alpha}\right) uh - \frac{1}{\sqrt{2}}\bar{u}\left(\kappa^u c_{\beta-\alpha} - \rho^u s_{\beta-\alpha}\right) uH + \frac{i}{\sqrt{2}}\bar{u}\rho^u\gamma_5 uA$$

$$- \left[\bar{u}\left(V\rho^d P_R - \rho^u V P_L\right) dH^+ + {\rm H.c.}\right]$$

- assume CP-conservation in Higgs potential

  CP-even Higgs: h, H   CP-odd Higgs: A   Charged Higgs: H^+

- assume h is the 126 GeV boson
- physical mixing parameter (keep Type-II notation)

  $$s_{\beta-\alpha} \equiv \sin(\beta-\alpha) \qquad c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$$

- assume $(\rho^f)^\dagger = \rho^f$ (f = u, d)

Yukawa terms in mass eigenstate basis

$$-\frac{1}{\sqrt{2}}\rho_{ct}\cos(\beta-\alpha)\bar{c}th + \text{H.c.} \qquad \rho_{ct} \equiv (\rho^u)_{23}$$

$$\mathcal{L}_Y^{\text{phys}} =$$

$$-\frac{1}{\sqrt{2}}\bar{d}\left(\kappa^d s_{\beta-\alpha}+\rho^d c_{\beta-\alpha}\right) \quad \frac{1}{\sqrt{2}}\bar{d}\left(\kappa^d c_{\beta-\alpha}-\rho^d s_{\beta-\alpha}\right)dH - \frac{i}{\sqrt{2}}\bar{d}\rho^d\gamma_5 dA$$

$$-\frac{1}{\sqrt{2}}\bar{u}\left(\kappa^u s_{\beta-\alpha}+\rho^u c_{\beta-\alpha}\right)uh - \frac{1}{\sqrt{2}}\bar{u}\left(\kappa^u c_{\beta-\alpha}-\rho^u s_{\beta-\alpha}\right)uH + \frac{i}{\sqrt{2}}\bar{u}\rho^u\gamma_5 uA$$

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- assume $(\rho^f)^\dagger = \rho^f$ (f = u, d)

Decoupling limit

Gunion and Haber, PRD (2003)

- decoupling limit:

$$s_{\beta-\alpha} \equiv \sin(\beta-\alpha) \rightarrow 1 \qquad c_{\beta-\alpha} \equiv \cos(\beta-\alpha) \rightarrow 0$$

$$\mathcal{L}_Y^{\rm phys} =$$

$$-\frac{1}{\sqrt{2}}\bar{d}\left(\kappa^d s_{\beta-\alpha} + \cancel{\rho^d c_{\beta-\alpha}}\right) dh - \frac{1}{\sqrt{2}}\bar{d}\left(\cancel{\kappa^d c_{\beta-\alpha}} - \rho^d s_{\beta-\alpha}\right) dH - \frac{i}{\sqrt{2}}\bar{d}\rho^d\gamma_5 dA$$

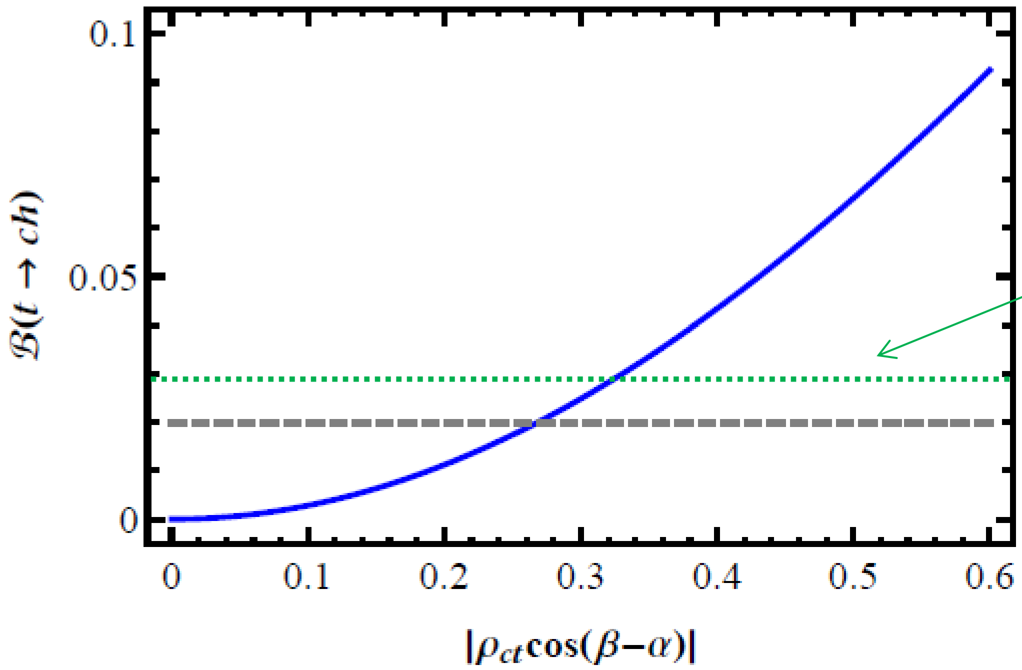
$$-\frac{1}{\sqrt{2}}\bar{u}\left(\kappa^u s_{\beta-\alpha} + \cancel{\rho^u c_{\beta-\alpha}}\right) uh - \frac{1}{\sqrt{2}}\bar{u}\left(\cancel{\kappa^u c_{\beta-\alpha}} - \rho^u s_{\beta-\alpha}\right) uH + \frac{i}{\sqrt{2}}\bar{u}\rho^u\gamma_5 uA$$

$$-\left[\bar{u}\left(V\rho^d P_R - \rho^u V P_L\right) dH^+ + {\rm H.c.}\right]$$

  - ➢ No FCNH coupling for “SM Higgs boson” h
  - ➢ Only extra scalars, H, A, H^+ have FCNH coupligs

- We keep finite $c_{\beta-\alpha}$ to study t → ch

B(t → c h) in 2HDM-III

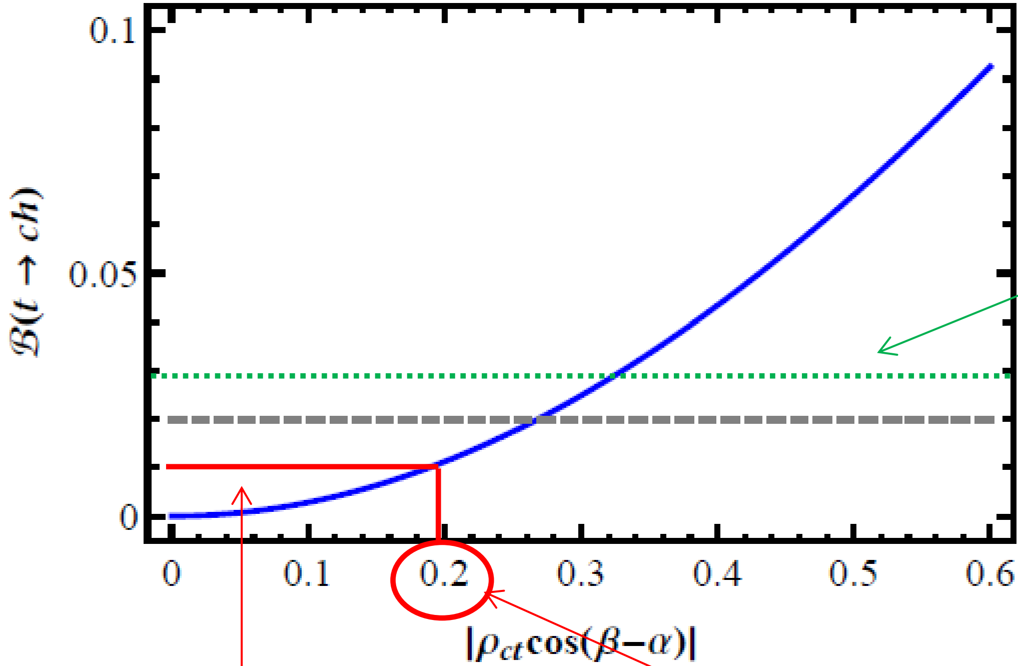


- A study of multi-lepton final states using CMS 7TeV data:

  B(t→ch) < 2.7%

  Craig et al., PRD (2012)

B(t → c h) in 2HDM-III



- A study of multi-lepton final states using CMS 7TeV data:

  B(t→ch) < 2.7%

  Craig et al., PRD (2012)

Our target: B(t→ch) ~ 1%

[Fiducial values]

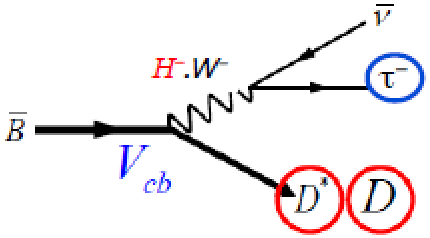
$$\rho_{ct} \sim 1 \qquad \cos(\beta - \alpha) = 0.2$$

$$\sin(\beta - \alpha) \simeq 0.98$$

Flavor Physics in 2HDM-III

BaBar anomaly in B → $D^{(*)}\tau\,\nu$

BaBar, PRL (2012)



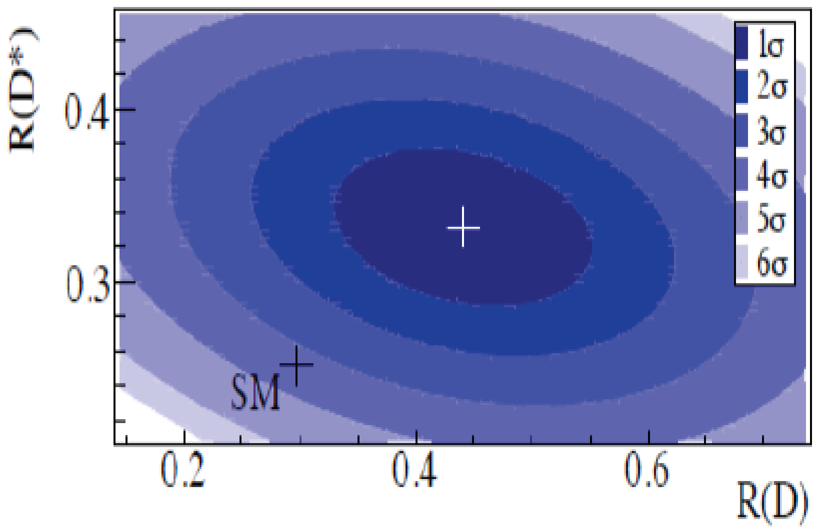
- measured quantities

$$\mathcal{R}(D) = \frac{\Gamma(\bar{B} \to D\tau^-\bar{\nu})}{\Gamma(\bar{B} \to D\ell^-\bar{\nu})} \qquad \mathcal{R}(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau^-\bar{\nu})}{\Gamma(\bar{B} \to D^*\ell^-\bar{\nu})} \qquad \ell = e \text{ or } \mu$$

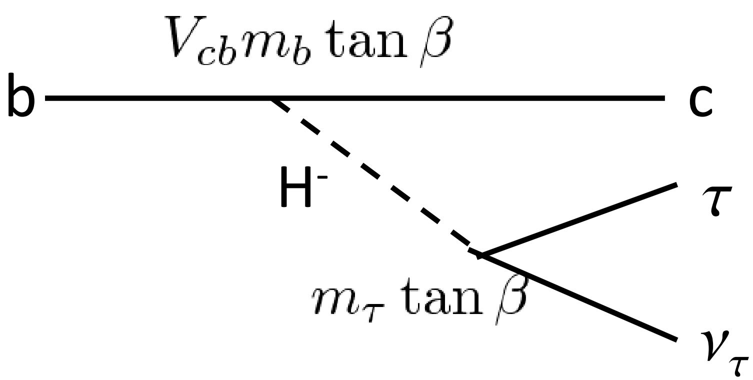
- both R(D) and R(D*) deviate from SM prediction

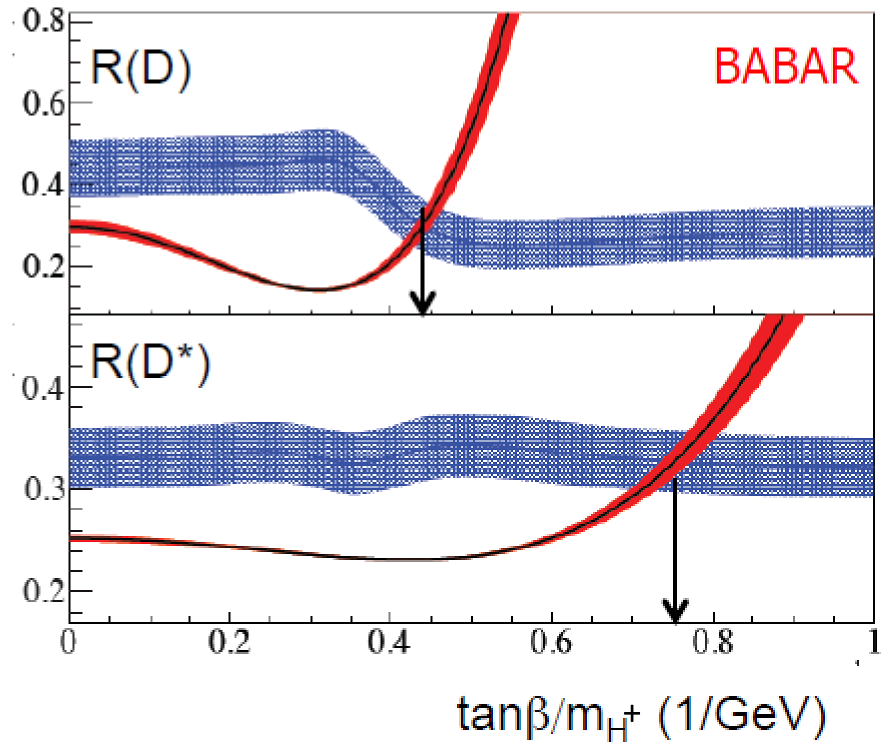
	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	**2.0 σ**	**2.7 σ**

combo: 3.4 σ deviation from SM



Implication for Type-II 2HDM





- each data match 2HDM-II at

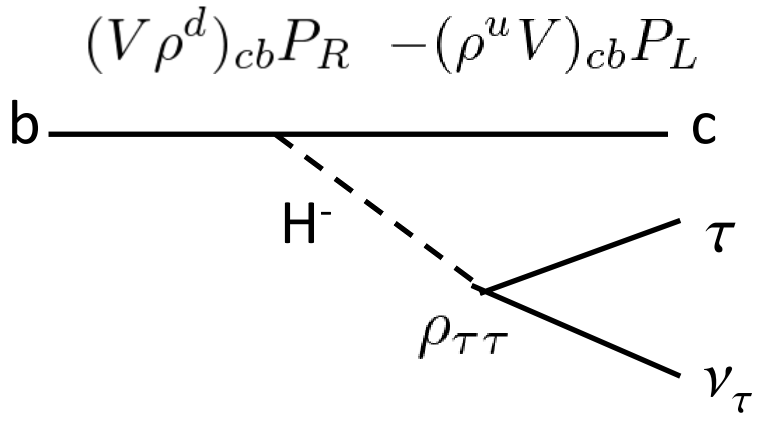
$$\tan\beta/m_{H^+} = 0.44 \pm 0.02 \quad \text{for } R(D)$$

$$\tan\beta/m_{H^+} = 0.75 \pm 0.04 \quad \text{for } R(D^*)$$

- however, the combination of R(D) and R(D*) **excludes 2HDM-II with 99.8% C.L.**! [assuming m_{H+} > 10 GeV]

Explain BaBar anomaly by Type-III 2HDM

Fajfer, Kamenik, Nisandzic and Zupan, PRL(2012)
Crivellin, Greub and Kokulu (CGK), PRD(2012)



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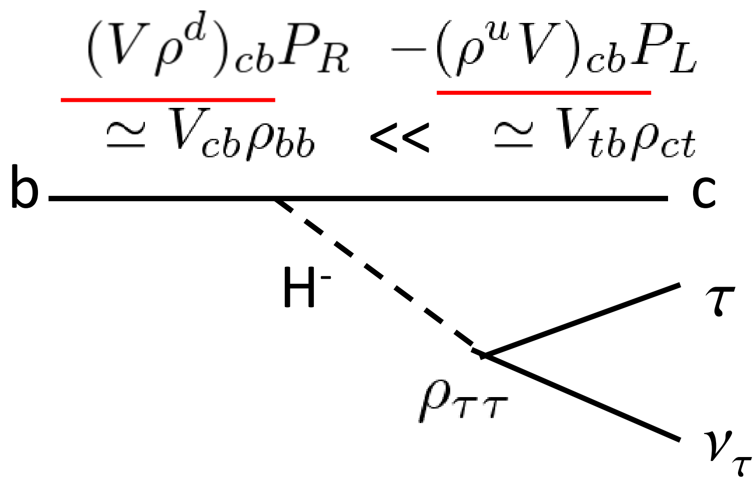

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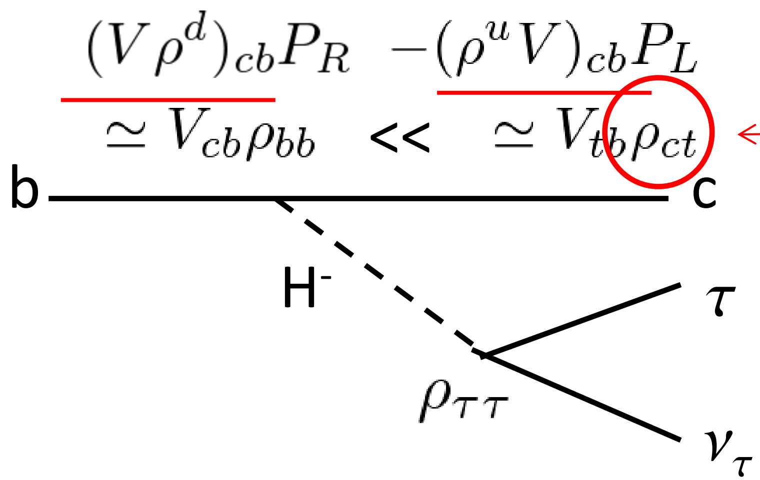


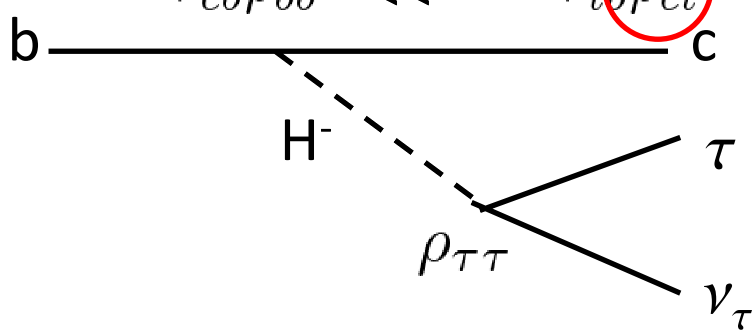
- absent in Type-II
- driving force to explain BaBar anomaly

Explain BaBar anomaly by Type-III 2HDM

Fajfer, Kamenik, Nisandzic and Zupan, PRL(2012)
Crivellin, Greub and Kokulu (CGK), PRD(2012)

$$(V\rho^d)_{cb}P_R \quad -(\rho^u V)_{cb}P_L$$

$$\simeq V_{cb}\rho_{bb} \quad << \quad \simeq V_{tb}\rho_{ct}$$



- absent in Type-II
- driving force to explain BaBar anomaly

- CGK adopted: $\rho_{\tau\tau} = -\tan\beta\sqrt{2}m_\tau/v \simeq -0.5$ $\quad \tan\beta = 50 \quad M_{H^+} = 500$ GeV

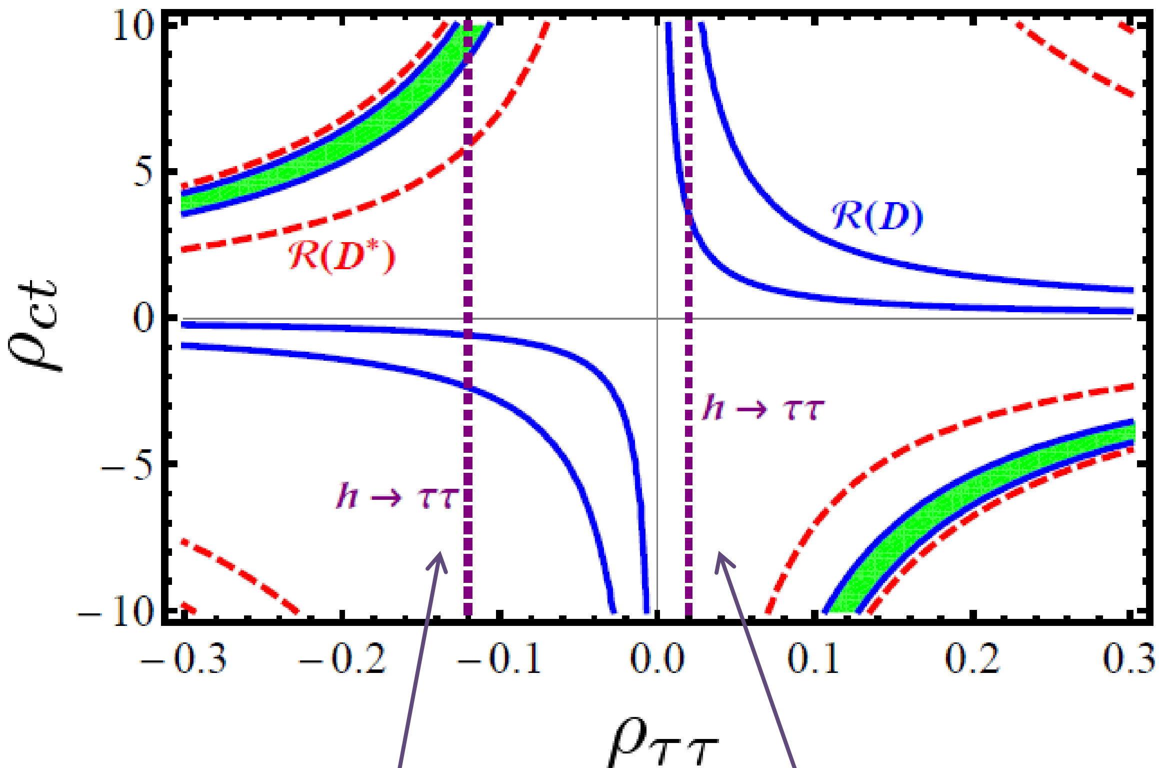
→ found solution for $\rho_{ct} \sim 1$

- x50 larger compared to $\kappa_{\tau\tau} \sim 0.01$
- h$\tau\tau$ coupling $\propto \kappa_{\tau\tau}s_{\beta-\alpha} + \rho_{\tau\tau}c_{\beta-\alpha}$

  → need to take decoupling limit to be consistent with h → $\tau\tau$ data

More general allowed region

Chen, Hou, Kao and MK, arXiv:1304.8037



$\cos(\beta - \alpha) = 0.2$

$m_{H^+} = 700$ GeV

1 σ allowed region

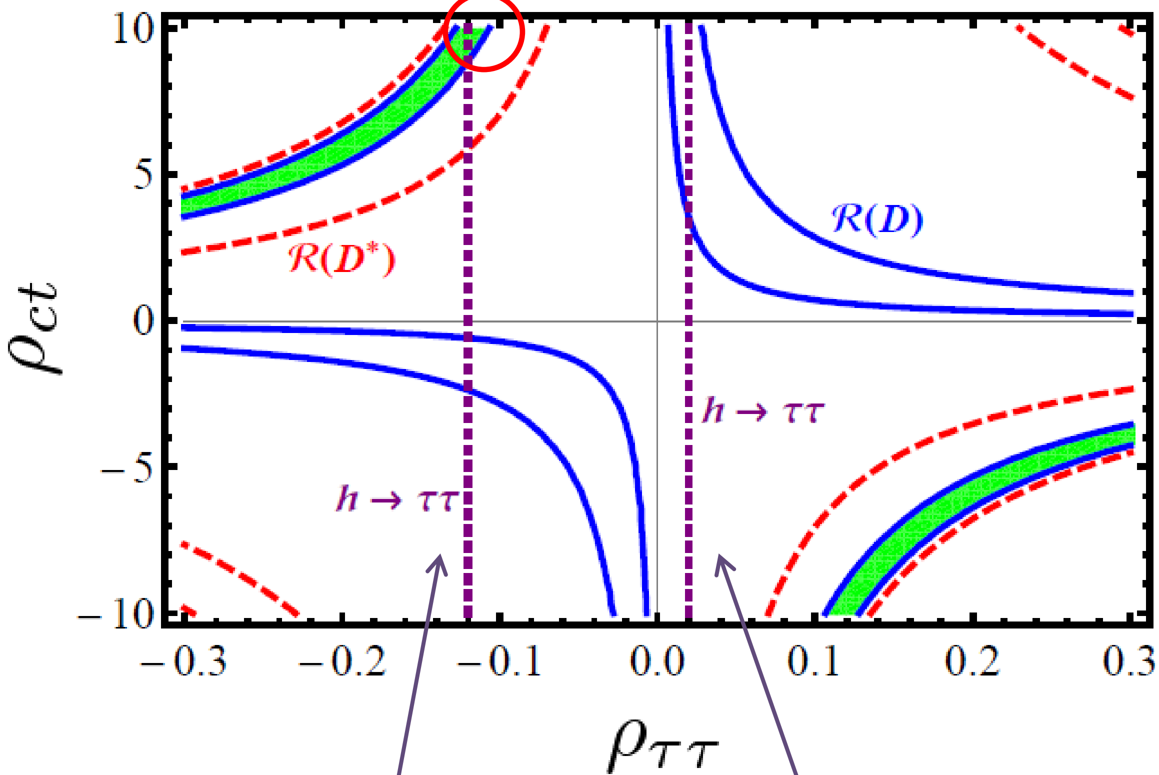
bound from h → $\tau\tau$ (VBF) data (within a factor of 2 from SM at 95%CL)

ATLAS-CONF-2012-160

More general allowed region

Chen, Hou, Kao and MK, arXiv:1304.8037

$\rho_{ct} \sim 10 \rightarrow$ nonperturbative!



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1 σ allowed region

bound from h $\rightarrow$ $\tau\tau$ (VBF) data (within a factor of 2 from SM at 95%CL)

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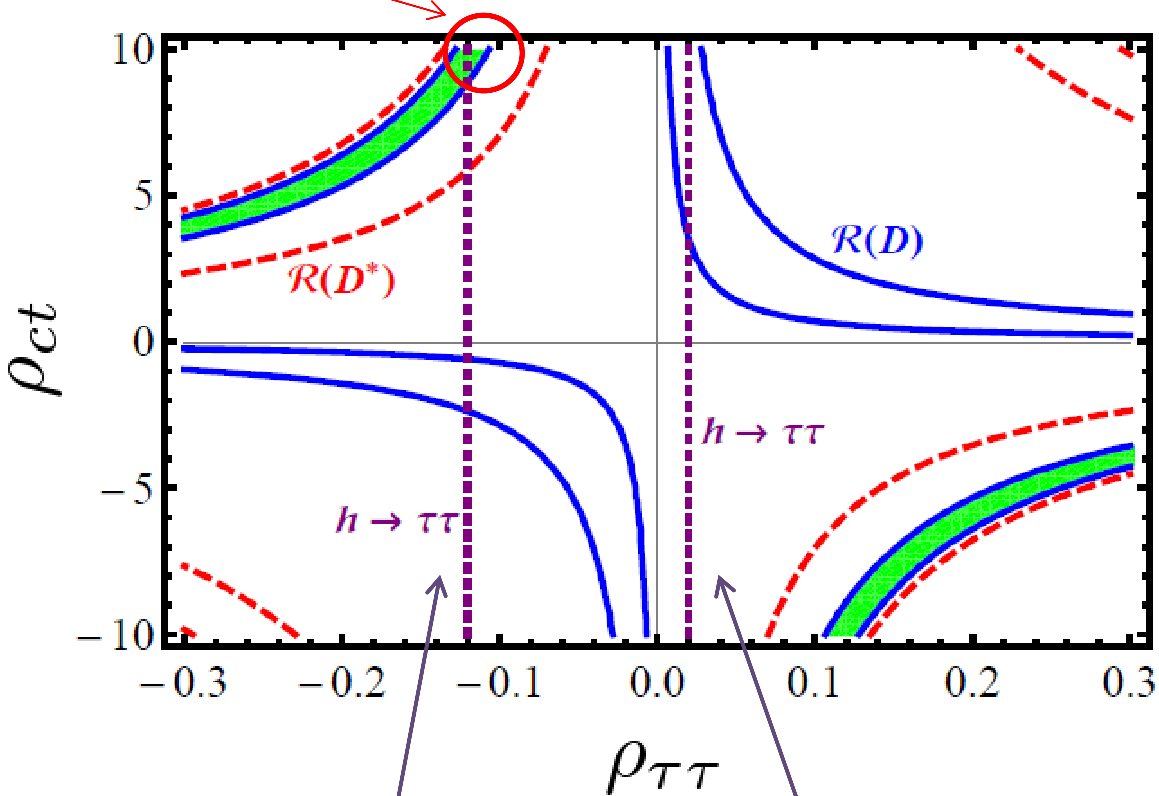
More general allowed region

1304.8037

ρ_{ct} ~ 10 → nonperturbative!

Detach from BaBar anomaly



$\cos(\beta - \alpha) = 0.2$

$m_{H^+} = 700$ GeV

1 σ allowed region

bound from h → $\tau\tau$ (VBF) data (within a factor of 2 from SM at 95%CL)

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$b \to s\gamma$ bound with $\rho_{ct} = 1$

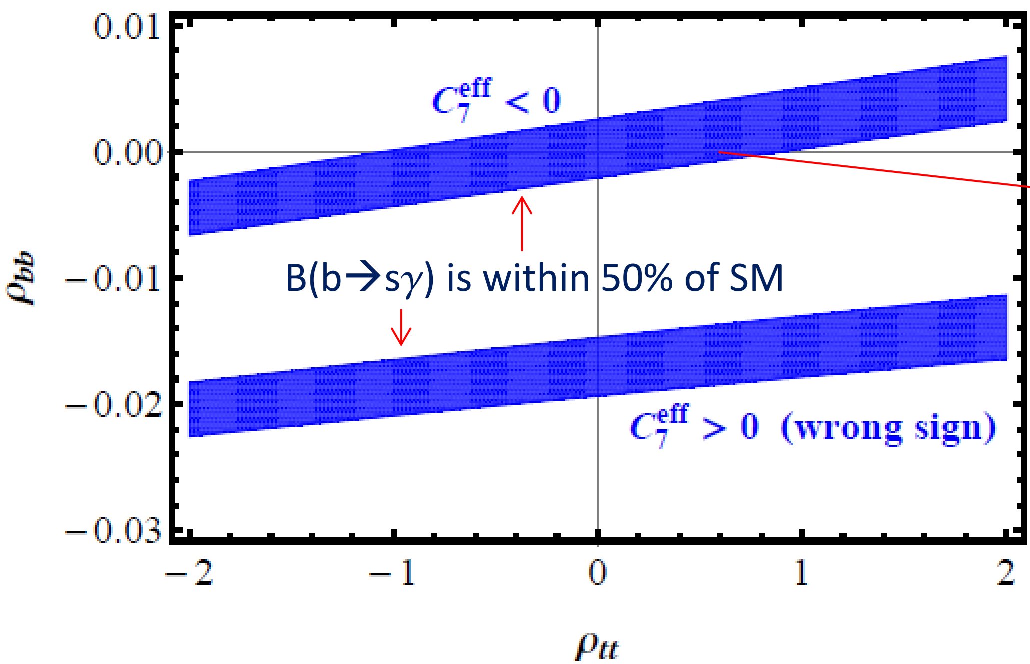
Notation follows, Ciuchini et al., NPB (1998)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} C_7 Q_7 + \dots \qquad Q_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$\delta C_{7,8}(\mu_W) \simeq \frac{1}{3}\left(\rho_{tt} + \frac{V_{cs}^*}{V_{ts}^*}\rho_{ct}\right)\left(\rho_{tt}^* + \frac{V_{cb}}{V_{tb}}\rho_{ct}^*\right)\frac{F_{7,8}^{(1)}(y)}{2m_t^2/v^2} - \left(\rho_{tt} + \boxed{\frac{V_{cs}^*}{V_{ts}^*}}\rho_{ct}\right)\rho_{bb}\frac{F_{7,8}^{(2)}(y)}{2m_t m_b/v^2}$$

CKM enhanced

$m_{H^+} = 700$ GeV



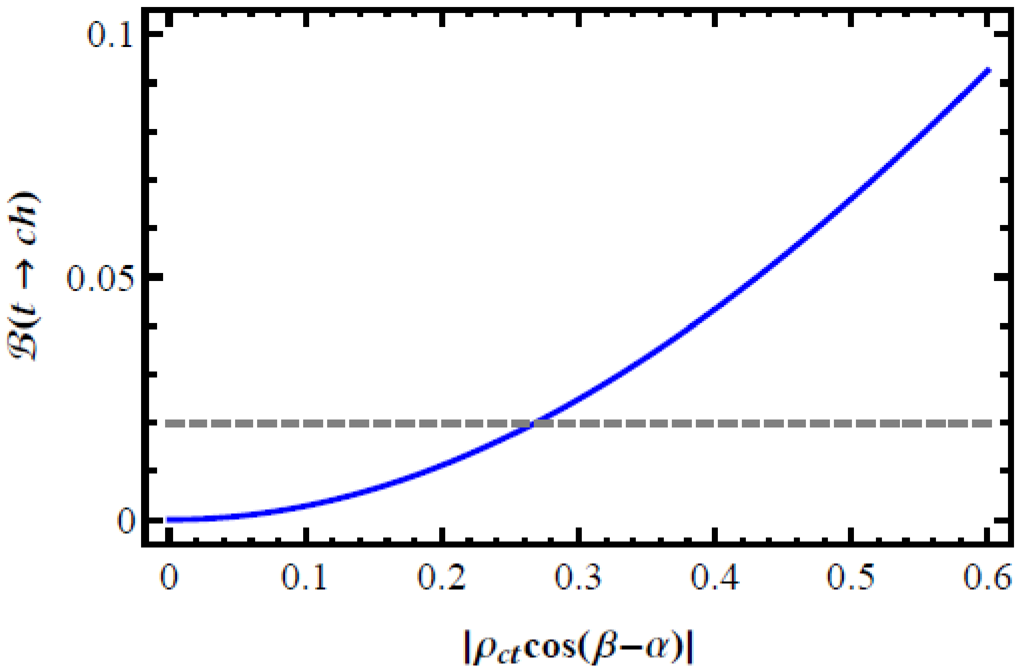
$\rho_{ct} \sim 1 \to$ tiny ρ_{bb}

$$|\rho_{bb}| \lesssim 0.01$$

cf. $\kappa_{bb} \simeq 0.02$

→ hbb coupling is SM-like

t → c h search at the LHC



Search for t → c h in top-anti-top events

- tt(bar) production cross section is large

  $\sigma_{t\bar{t}} = 220 \text{ pb}$ [LHC8] Czakon and Mitov, JHEP (2013)

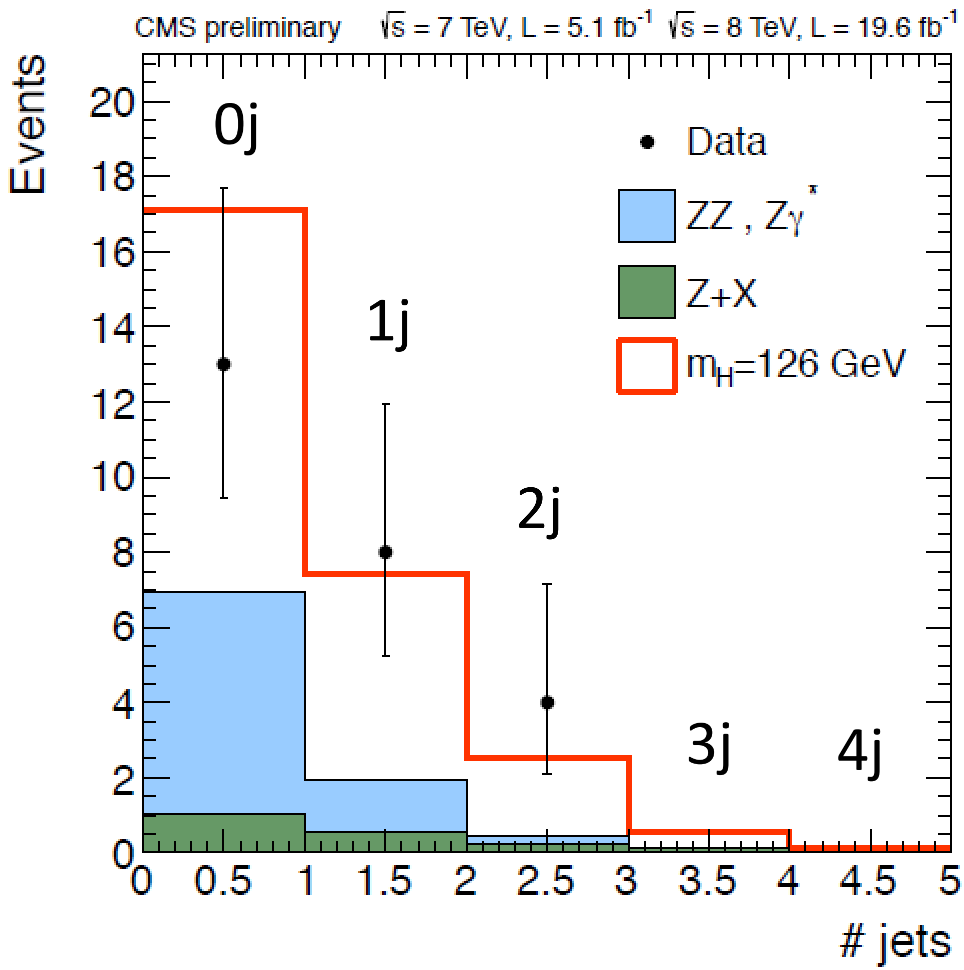
- $pp \to t\bar{t} \to bWch$ → h + 4jets / h + 2jets + l + MET

  $$\sigma(pp \to t\bar{t} \to bWch) \sim 9 \text{ pb} \times \left[\frac{\mathcal{B}(t \to ch)}{0.02}\right]$$ [LHC8]

  vs. $\sigma_{gg \to h} \sim 19 \text{ pb}$ [LHC8]

- may show up in current LHC data if B(t→ch) ~ 2%

Any extra jets in h → ZZ* →4l events?



- M_{4l} = [121.5 –130.5] GeV
- sum of 4e, 4μ, 2e2μ channels

- No evidence for extra jets → bound on B(t → ch)
- 95%CL limit obtained by simple use of standard CLs method:

$$\sigma(pp \to t\bar{t} \to bWch) < 6.5\ \text{pb}$$

$$\to \mathcal{B}(t \to ch) < 1.5\%$$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki

Use of other Higgs decay modes

- h → WW* & $\tau\tau$ Craig et al., PRD (2012)
  - study of multi-lepton final states using CMS 7TeV data:

    B(t→ch) < 2.7% … can be updated w/ latest data

- h → bb C. Kao, H.-Y. Cheng, W.-S. Hou and J. Sayre, PLB (2012)
  - Signal: $pp \to t\bar{t} \to bWch \to bbb + c + \ell\nu$
  - With full LHC8 data, 5σ discovery is possible for B(t→ch) > 0.3% [for SM-like B(h→bb)]

- h → $\gamma\gamma$
  - Our method may be applied, but not so clean?

Discussions

$\rho_{ct}, \quad \rho_{tt}, \quad \rho_{cc}$

- Properties of the light Higgs h can be modified in 2HDM-III
- Need simultaneous study of t → c h and Higgs properties (not done in our study)
- Light Higgs properties when ρ_{ct} ~ 1 with small finite cos($\beta-\alpha$)

	$\mathcal{B}^{SM}$	Γ^{SM}[MeV]	Γ	Comment
WW^*	21.5%	0.98	hard to change	$\sin(\beta-\alpha)\simeq 1$
ZZ^*	2.7%	0.12	hard to change	$\sin(\beta-\alpha)\simeq 1$
$\gamma\gamma$	0.24%	0.011	hard to change	W-loop dom.
bb	59.4%	2.70	hard to change	$b\to s\gamma$
$\tau\tau$	5.7%	0.26	within fac. 2	direct
cc	2.6%	0.12	up to $\sim\Gamma_{b\bar{b}}$	not measured ($\rho_{cc}\lesssim 0.2$)
gg	7.7%	0.35	up to fac. 2	$\rho_{tt}\sim 1$

Crivellin et al., arXiv:1303.5877

Summary

- It is of great interest to search for the link between the top quark (t) and the Higgs boson (h)

- Large t-c-h coupling has great impact on flavor physics

- Existing LHC data can already probe B(t → ch) at 1% level by various methods

- Actual experimental studies will provide important information for the FCNH couplings

- A discovery of t → ch with present data would suggest the existence of an extended Higgs sector beyond the usual 2HDM-II implied by MSSM