EXPLORING TOP QUARK FCNC FROM COLLIDER IN ASSOCIATION WITH FLAVOR PHYSICS

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Based on 1509.00491

We are looking forward to seeing something new…

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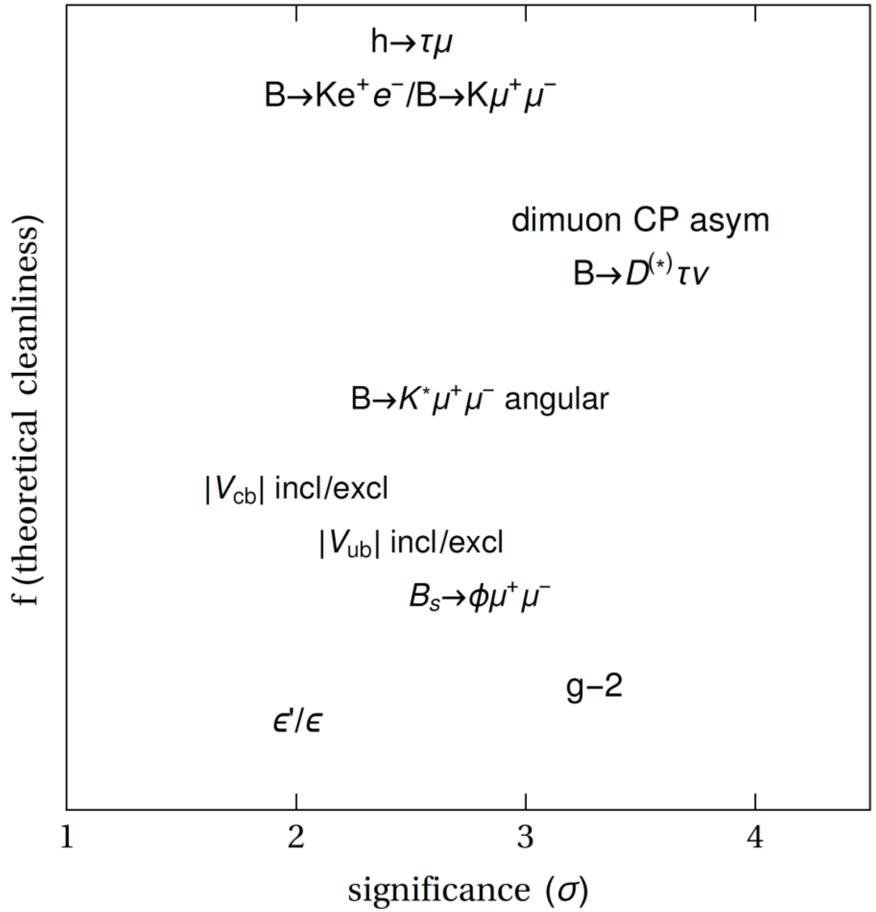
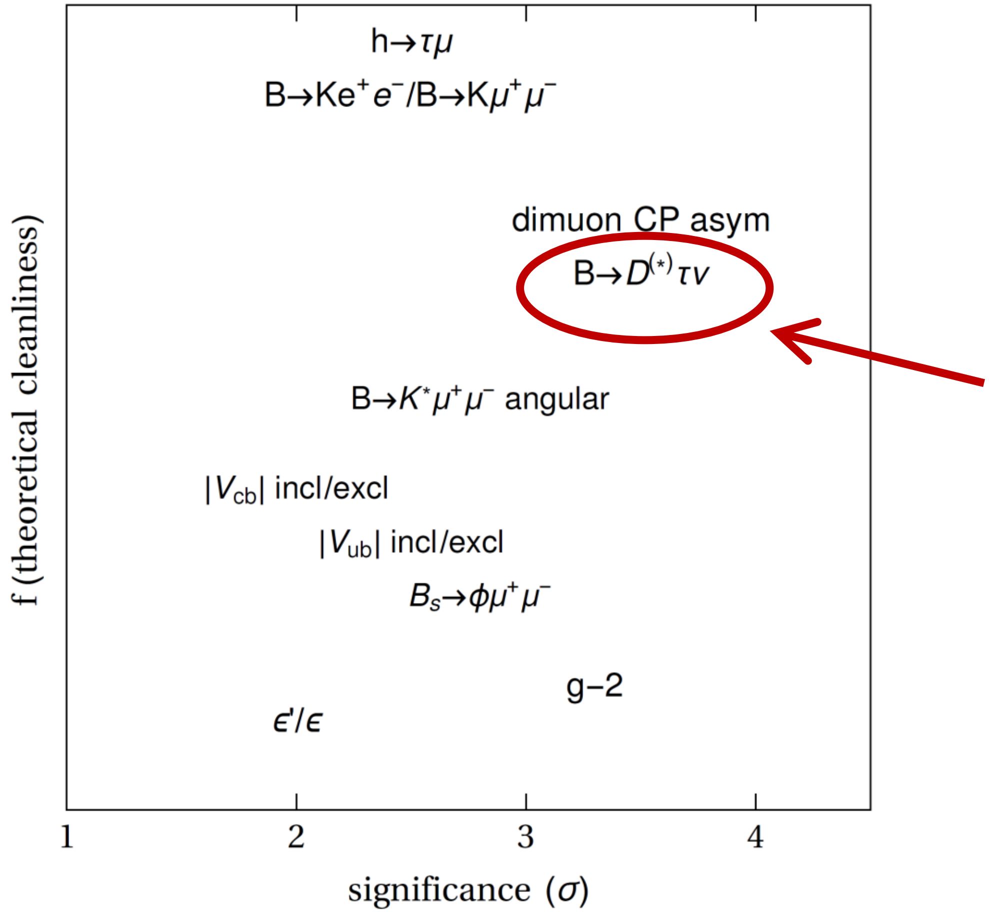
In flavor physics



Z. Ligeti, talk @ 2015 Lepton-Photon Symposium

We are looking forward to seeing something new…

In flavor physics



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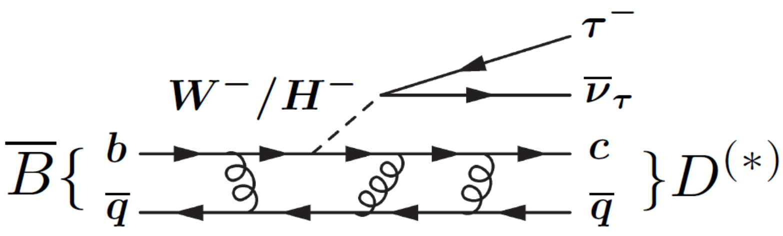
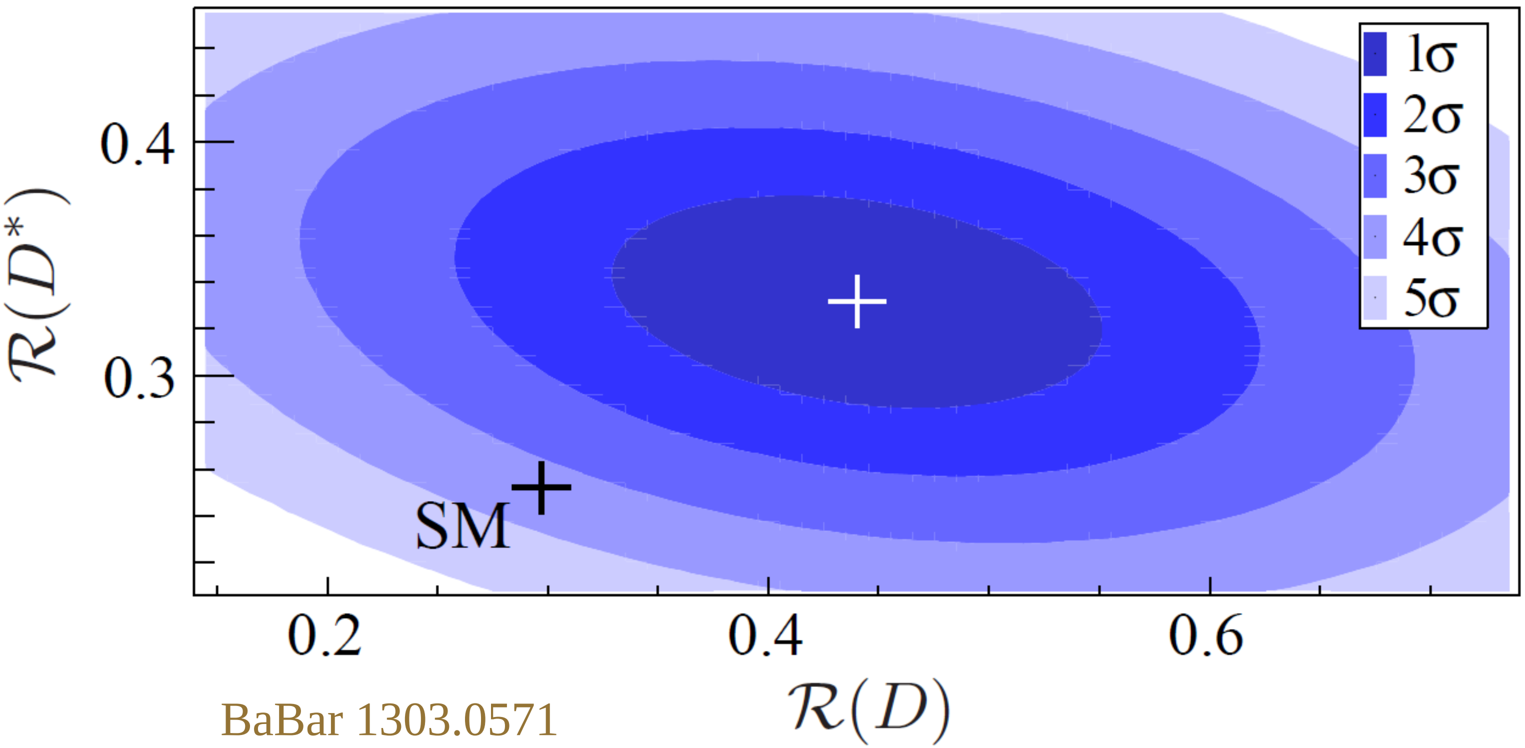
$B \to D^{(*)}\tau\nu$ anomaly

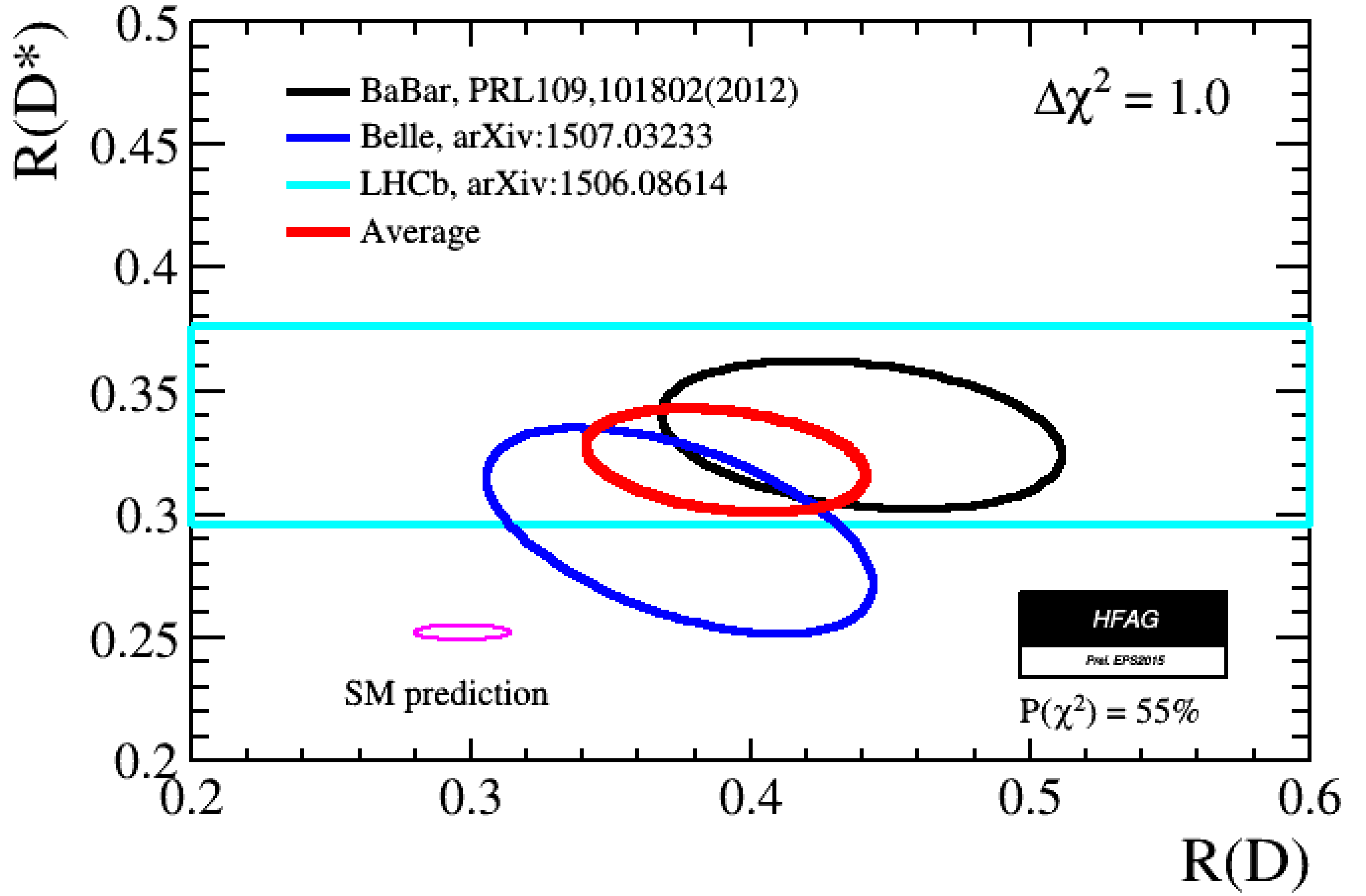


$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^-\overline{\nu}_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}$$



BaBar 1303.0571

$B \to D^{(*)}\tau\nu$ anomaly

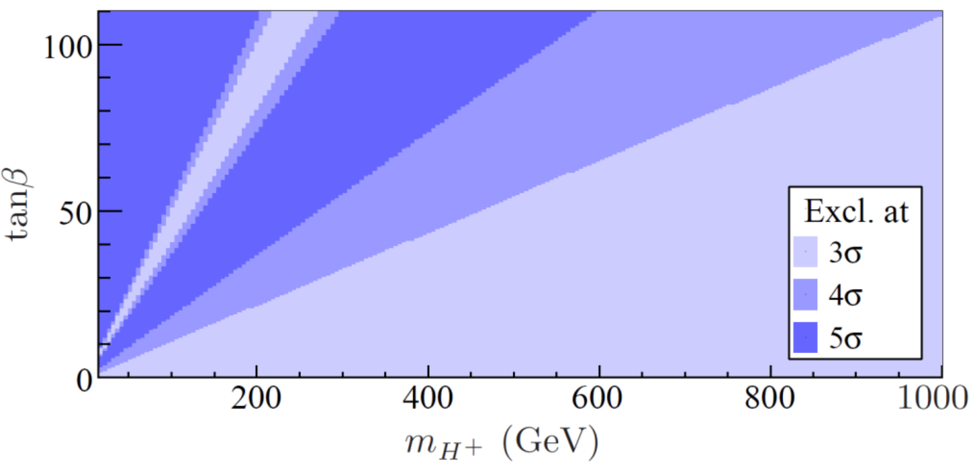


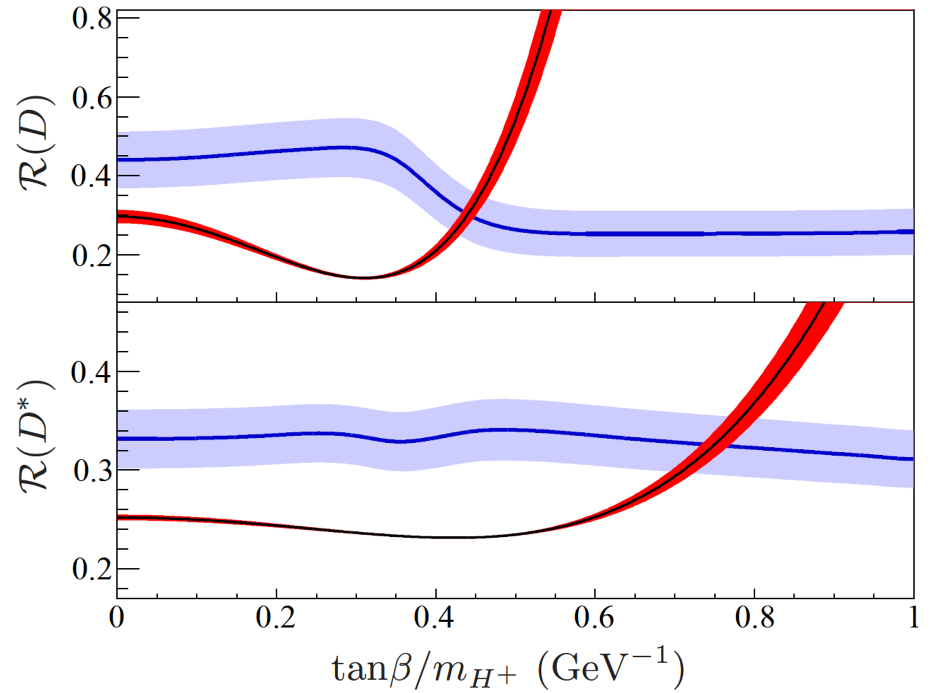
The difference with the SM is 3.9 σ level.

$B \to D^{(*)}\tau\nu$ anomaly

not only SM
but also MSSM

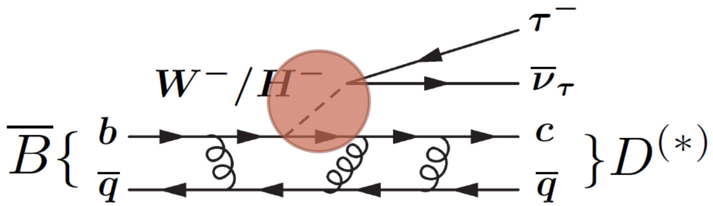
BaBar 1303.0571





$0.04\,\mathrm{GeV}^{-1}$, respectively. However, the combination of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ excludes the type II 2HDM charged Higgs boson at 99.8% confidence level for any value of $\tan\beta/m_{H^+}$, as illustrated in Fig. 21. This calculation is

Possible solutions for $B \to D^{(*)}\tau\nu$ anomaly



$$O_{\rm SM}^{qb} = \bar{q}\gamma_\mu P_L b\, \bar{\tau}\gamma_\mu P_L \nu_\tau$$

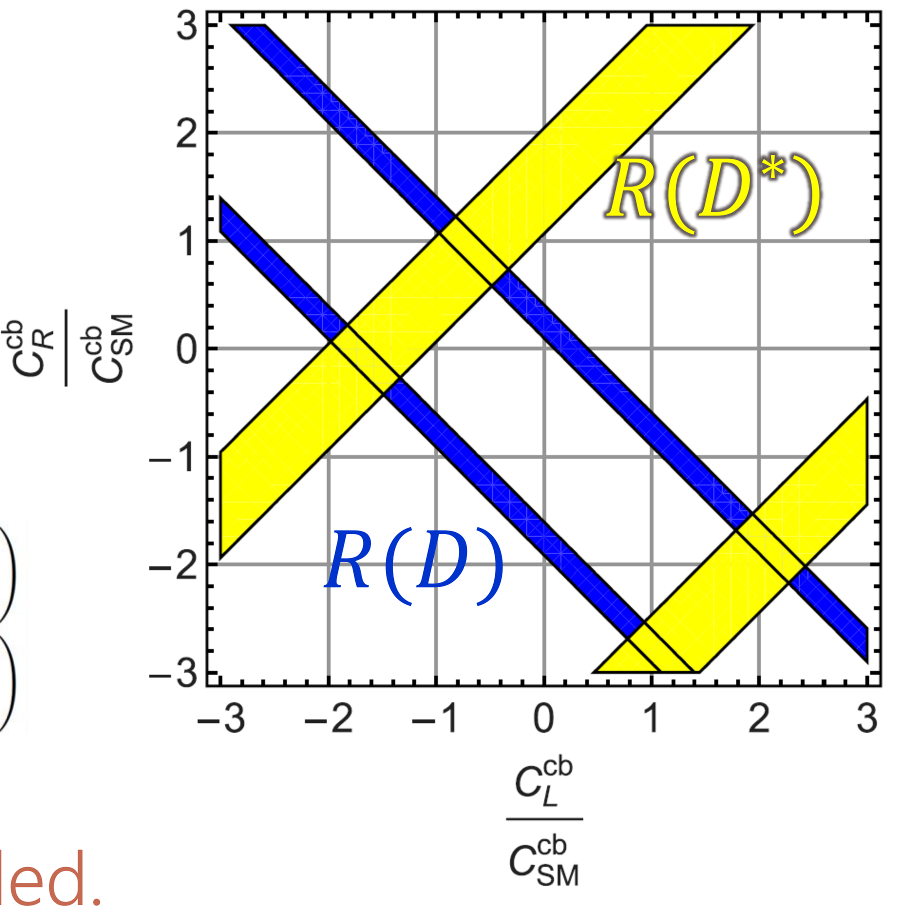
$$O_R^{qb} = \bar{q} P_R b\, \bar{\tau} P_L \nu_\tau \,,$$

$$O_L^{qb} = \bar{q} P_L b\, \bar{\tau} P_L \nu_\tau \,.$$

$$\mathcal{R}(D) = \mathcal{R}_{\rm SM}(D)\left(1 + 1.5\Re\left[\frac{C_R^{cb}+C_L^{cb}}{C_{SM}^{cb}}\right] + 1.0\left|\frac{C_R^{cb}+C_L^{cb}}{C_{SM}^{cb}}\right|^2\right)$$

$$\mathcal{R}(D^*) = \mathcal{R}_{\rm SM}(D^*)\left(1 + 0.12\Re\left[\frac{C_R^{cb}-C_L^{cb}}{C_{SM}^{cb}}\right] + 0.05\left|\frac{C_R^{cb}-C_L^{cb}}{C_{SM}^{cb}}\right|^2\right)$$

Crivellin, Greub, Kokulu (2012)



Very sizable C_L^{cb} is needed.

Possible solutions for $B \to D^{(*)}\tau\nu$ anomaly

MSSM (2HDM II) charged Higgs Yukawa sector:

$$C_L^{cb} \qquad C_R^{cb}$$

$$\mathcal{L}_Y \supset -V_{cb}\bar{c}\left(\frac{m_c}{t_\beta}P_L - m_b t_\beta P_R\right)bH^+$$

Possible solutions for $B \to D^{(*)}\tau\nu$ anomaly

MSSM (2HDM II) charged Higgs Yukawa sector:

C_L^{cb} C_R^{cb}

$$\mathcal{L}_Y \supset -V_{cb}\bar{c}\left(\frac{m_c}{t_\beta}P_L - m_b t_\beta P_R\right)bH^+$$

New term in 2HDM Type III : $\bar{c}\xi_{ct}V_{tb}P_L bH^+$

→ Large ξ_{ct} can explain $B \to D^{(*)}\tau\nu$ but causes large top-FCNC

FCNC

- The tree level FCNC is forbidden in the SM by GIM mechanism.
- The Observed FCNC processes are all severely suppressed:

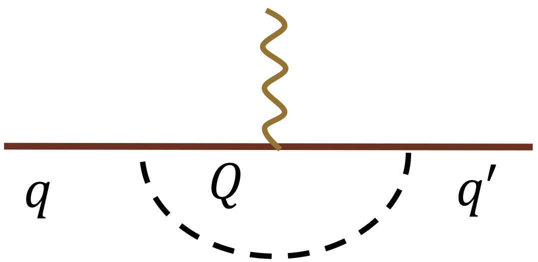
$$\mathrm{Br}(B \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$$
$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$
$$\Delta m_{B_s} = (1.1691 \pm 0.0014) \times 10^{-11}\ \mathrm{GeV}$$

LHCb, CMS (2015) Nature

- NP models that have tree-level FCNC is dangerous.

FCNC

- Even the loop contribution is strongly constrained by FCNC.



$$\sim V_{Qq} V^*_{Qq'} \frac{\alpha_e}{4\pi} \left(\frac{m_Q}{M_W} \right)^2$$

- Down type FCNC is severely constrained by the enhancement factor.
- UP type FCNC (top FCNC) is highly suppressed and therefore not much constrained by experiment.
- Top FCNC has still much room for NP. It must be explored by collider physics (direct search) or by flavor physics (indirect search).
- We focus on Higgs mediated top FCNC.

General 2HDM (Type III)

- The 2HDM is the simplest extension of SM Higgs sector

$$\rho = \frac{\sum_{i=1}^{n} \left[I_i (I_i + 1) - \frac{1}{4} Y_i^2 \right] v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i} = 1 \quad \text{for } I_i = \frac{1}{2},\ Y_i = 1 \text{ (Doublet with Y=1)}$$

- The 2HDM is well motivated by MSSM

$$g_{ij}^{u}\, \overline{Q_i} \tilde{\phi}_1 u_j + g_{ij}^{d}\, \overline{Q_i} \phi_1 d_j + g_{ij,2}^{u}\, \overline{Q_i} \tilde{\phi}_2 u_j + g_{ij,2}^{d}\, \overline{Q_i} \phi_2 d_j + \text{h.c.}$$

→ The tree level FCNC inevitably arises after SB and mass diagonalization

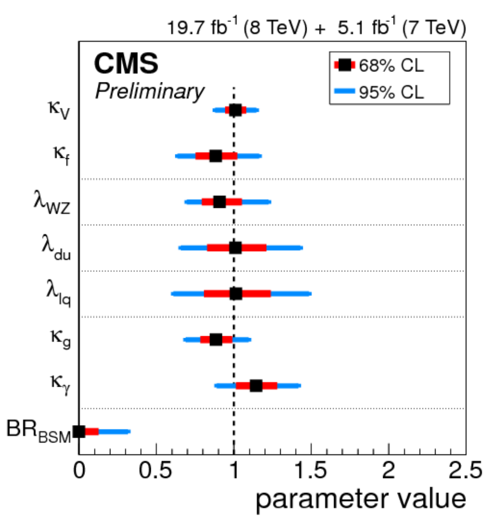
General 2HDM (Type III) in alignment limit

- We have 3 neutral Higgses and 2 charged Higgses. Other 3 are eaten by weak gauge bosons after SB.

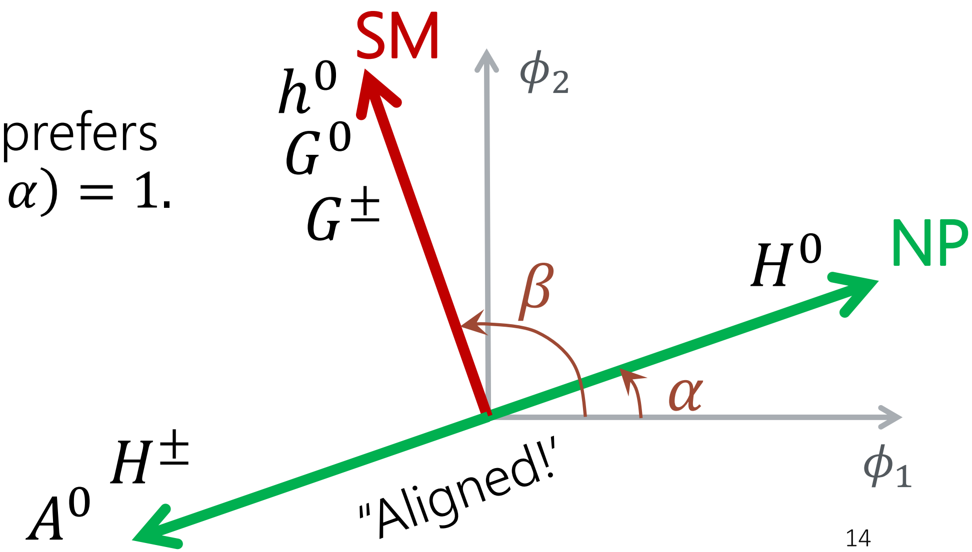
$$h^0, H^0, A^0, \quad H^+, H^-$$

- The SM Higgs is replaced by

$$h^0_{SM} = \sin(\beta - \alpha)h^0 + \cos(\beta - \alpha)H^0$$



Exp. data prefers $\sin(\beta - \alpha) = 1.$



General 2HDM (Type III) in alignment limit

- Within alignment Limit, after SB and mass diagonalization

$$\mathcal{L}_Y = -Y_u\,\bar{U}Uh - Y_u\,\bar{D}Dh - Y_e\,\bar{L}Lh$$ Light Higgs (SM Higgs) Yukawa

$$+\bar{U}\frac{\xi^U}{\sqrt{2}}UH + \bar{D}\frac{\xi^D}{\sqrt{2}}DH + \bar{L}\frac{\xi^L}{\sqrt{2}}LH$$ Neutral CP-even Higgs Yukawa

$$-i\bar{U}\gamma_5\frac{\xi^U}{\sqrt{2}}UA - i\bar{D}\gamma_5\frac{\xi^D}{\sqrt{2}}DA - i\bar{L}\gamma_5\frac{\xi^L}{\sqrt{2}}LA$$ Neutral CP-odd Higgs Yukawa

$\bar{c}\xi_{ct}V_{tb}P_L bH^+$ →

$$+[\bar{U}(\xi^U VP_L - V\xi^D P_R)DH^+ + \bar{\nu}\xi^L P_R H^+ + h.c.]$$ Charged Higgs Yukawa

ξ^U, ξ^D are non-diagonal:

$$\xi^U = \begin{pmatrix} \xi_{uu} & \xi_{uc} & \xi_{ut} \\ \xi_{cu} & \xi_{cc} & \xi_{ct} \\ \xi_{tu} & \xi_{tc} & \xi_{tt} \end{pmatrix}, \quad \xi^D = \begin{pmatrix} \xi_{dd} & \xi_{ds} & \xi_{db} \\ \xi_{sd} & \xi_{ss} & \xi_{sb} \\ \xi_{bd} & \xi_{bs} & \xi_{bb} \end{pmatrix}$$

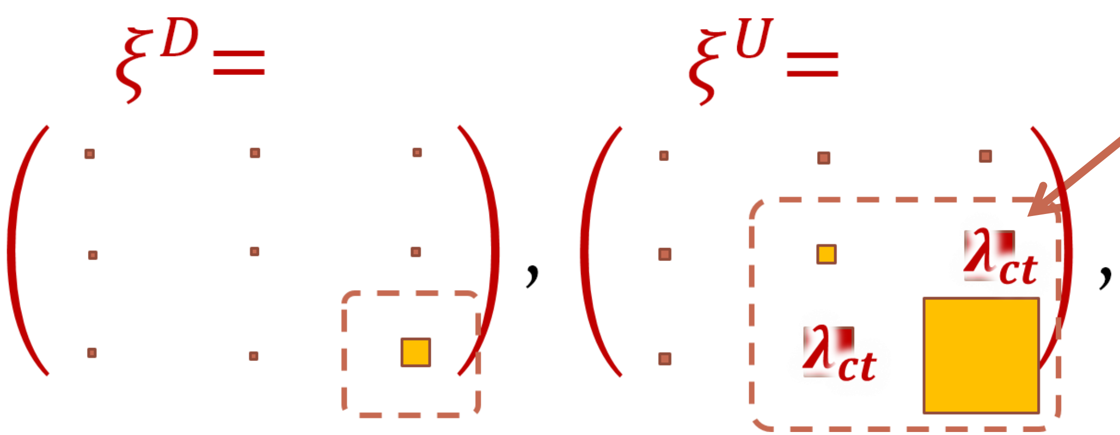
→ These cause dangerous tree level FCNC

General 2HDM (Type III) in alignment limit

- ξ^D are severely constrained by flavor physics than ξ^U.
- To avoid down-type FCNC we adopt Cheng-Sher ansatz:

$$\xi_{ij} = \frac{\sqrt{2m_i m_j}}{v}\lambda_{ij} \quad , \lambda_{ij} = \mathcal{O}(1)$$

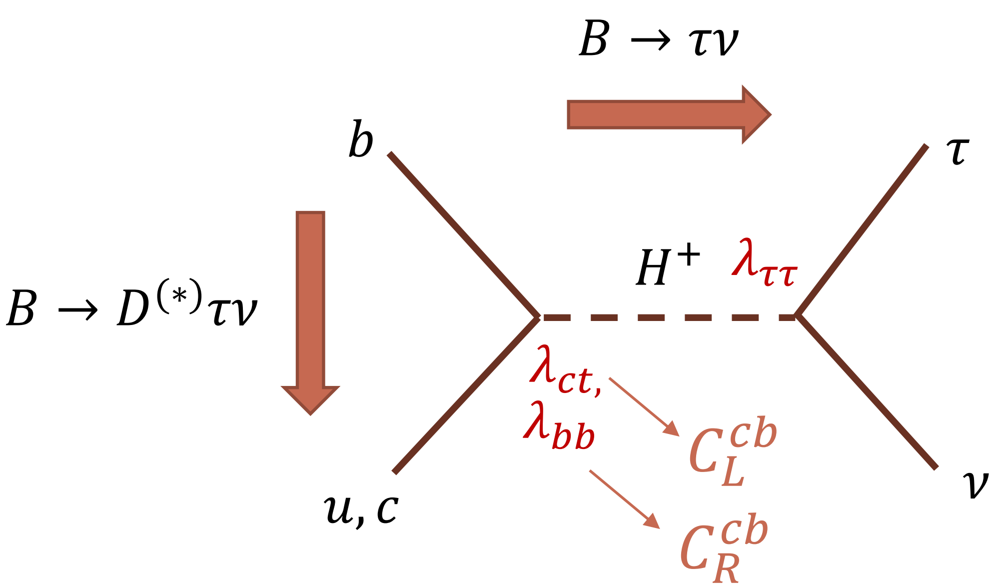
Cheng, Sher (1987) PRD



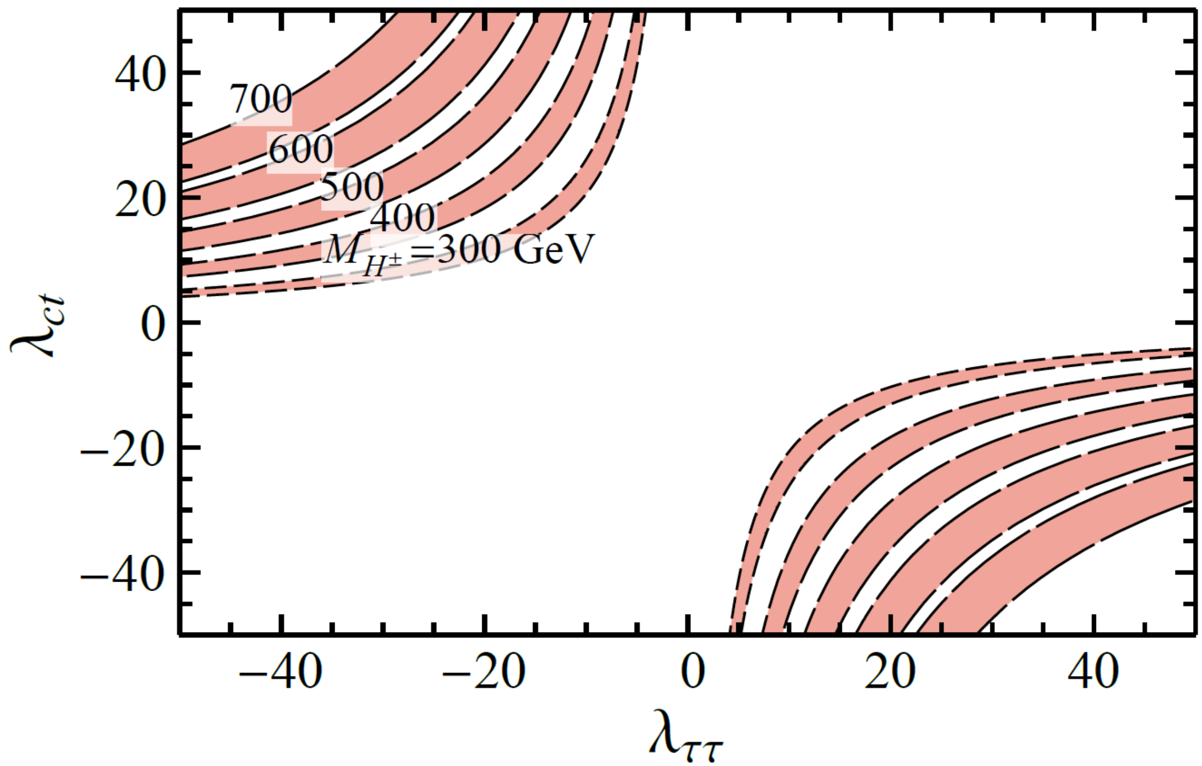
Large λ_{ct} can explain $B \to D^{(*)}\tau\nu$ but causes large top-FCNC

Fit into $B \to D^{(*)}\tau\nu$ anomaly

- The charged Higgs mimics W boson and it contribute to most of Weak decays of B meson
- The top FCNC Yukawa coupling λ_{ct} contributes to bcH^+ Yukawa coupling. Therefore it contribute to $B \to D^{(*)}\tau\nu$ at tree level.



Fit into $B \to D^{(*)}\tau\nu$ anomaly

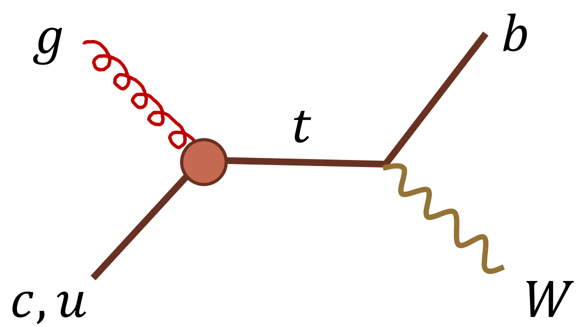


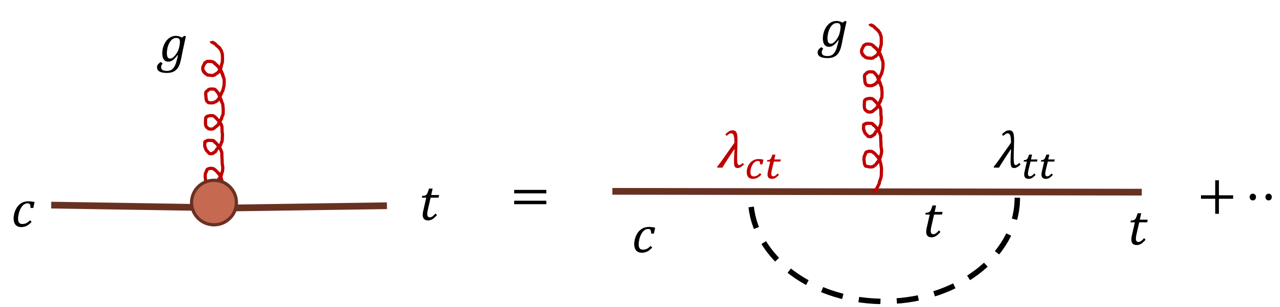
Allows region at 95% CL.

Very large, $\lambda_{\tau\tau}$, λ_{ct}, (order 10) are prefered.

Constraints from Top FCNC at collider - 1

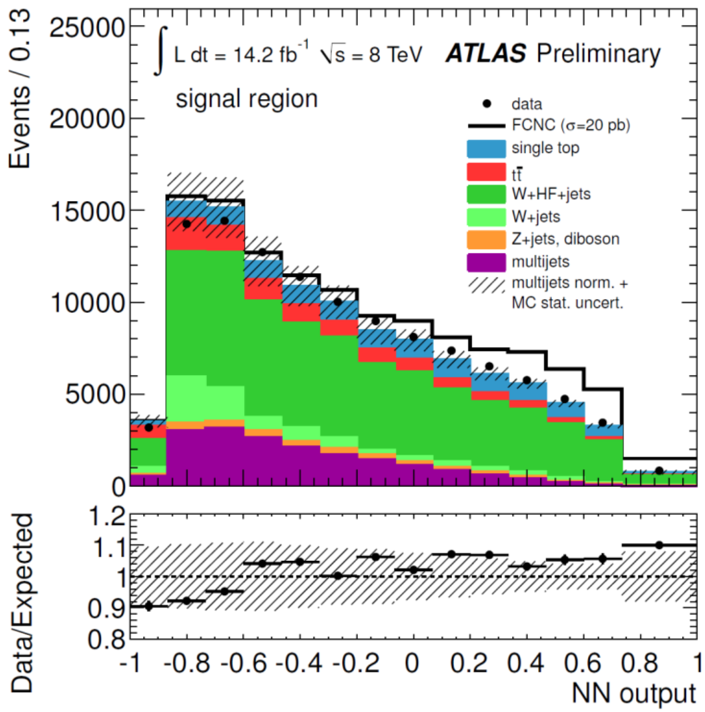
- Anomalous Single Top Production with gct effective vertex.





Constraints from Top FCNC at collider - 1

- Non-observation of gq→t put the limit on $\mathcal{B}(t \to u/cg)$.



$$\mathcal{B}(t \to ug) < 3.1 \times 10^{-5}$$

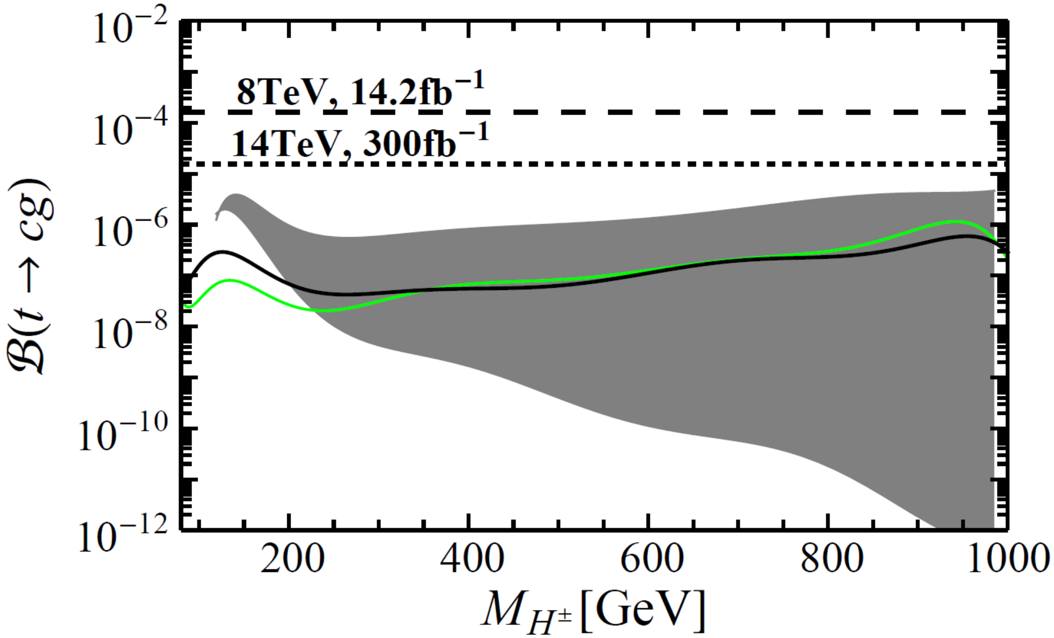
$$\mathcal{B}(t \to cg) < 1.6 \times 10^{-4}$$

ATLAS, at 8 TeV, (14.2fb^{-1})

ATLAS-CONF-2013-063

→ Currently the best upper limit.

Constraints from Top FCNC at collider - 1

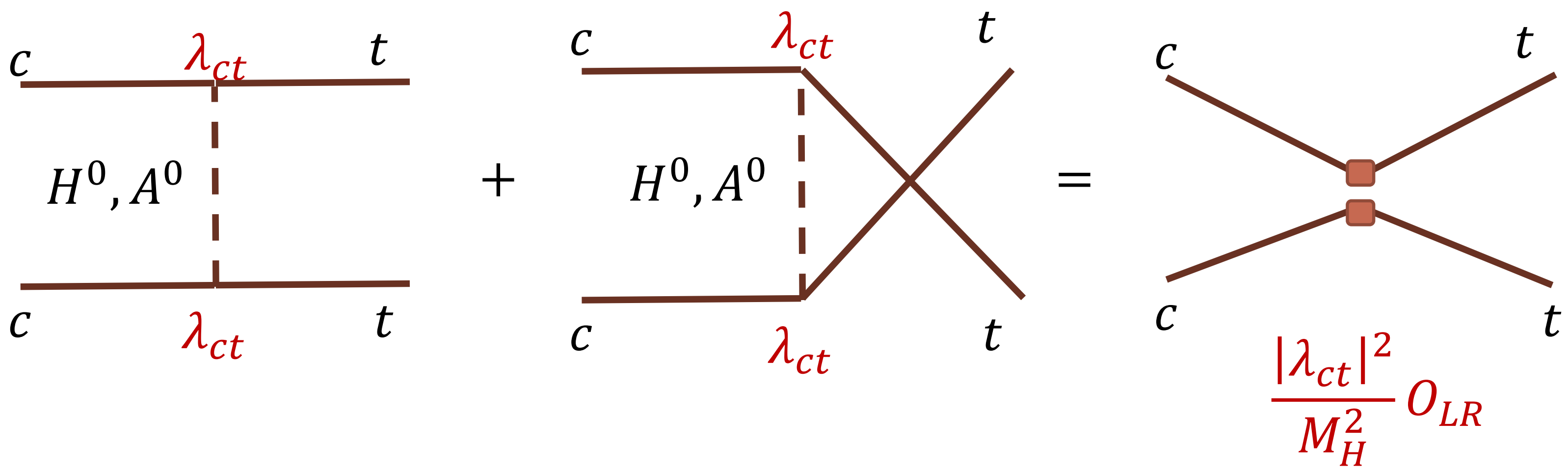


Gray region is allowed region by $\Delta\rho$ and flavor constraints

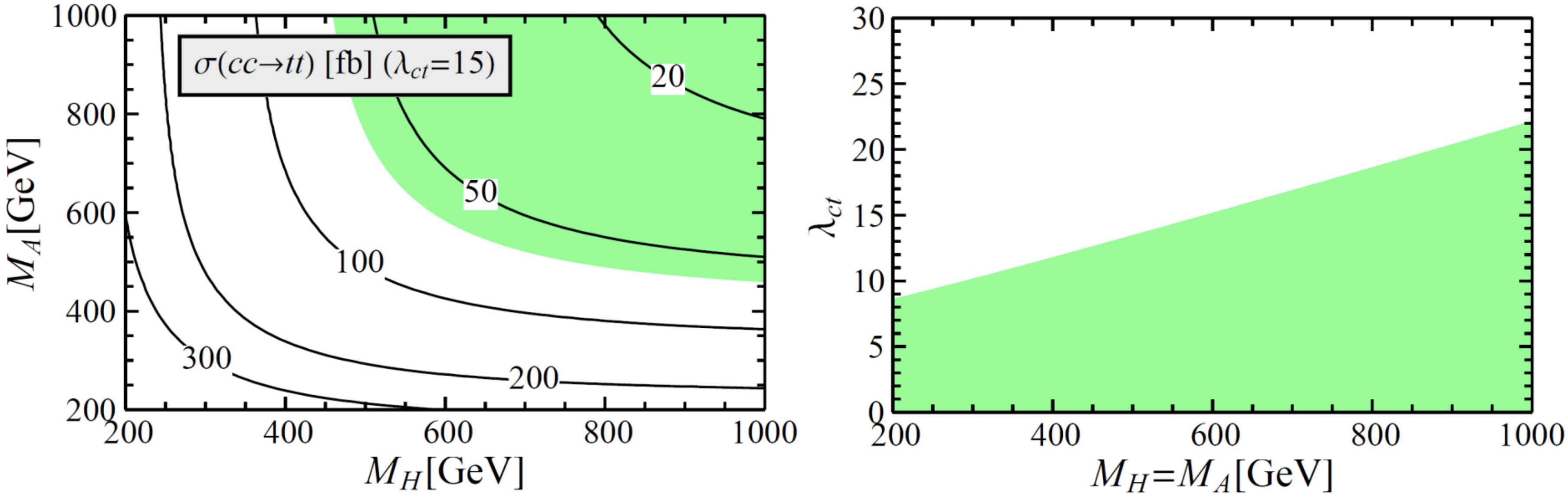
The constraint from is very weak due to the loop suppression

Constraints from Top FCNC at collider - 2

- Same sign top pair production is a tree level process and the signal rate is very large.
- It significantly constrains or rule out many top FCNC models. For example, Z′ model that explains ttbar FBA anomaly is excluded by this.



Constraints from Top FCNC at collider - 2



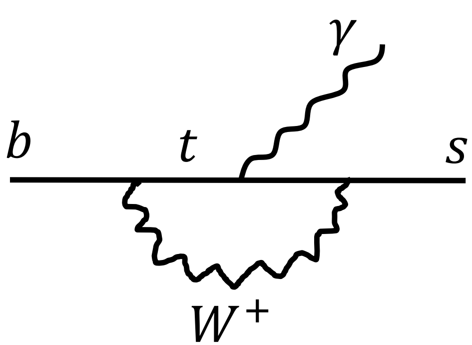
Green region is allows by using

$$\sigma(pp \to tt) < 62\,\mathrm{fb} \quad (\mathrm{ATLAS\ 95\%\ CL\ [48]})\,.$$

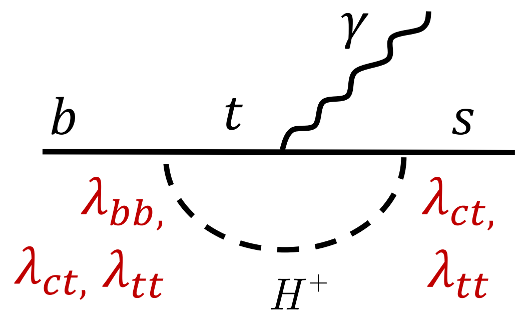
λ_{ct} is strongly upper bounded as 10~20 !

Constraints from flavor – loop process

- $B \to X_s \gamma$



$\Rightarrow C_{7,8}(\mu_W)$



$\Rightarrow \delta C_{7,8}(\mu_W)$

By comparing with Data $8.22\mathrm{Re}C_7^{\mathrm{NP}} + 1.99\mathrm{Re}C_8^{\mathrm{NP}} = -0.07 \pm 0.32\,.$

$$\delta C_{7,8} = \left(\lambda_{tt} + 2.1\lambda_{ct}\right)\left(\frac{1}{3}\lambda_{tt}F_{7,8}^{(1)} - \lambda_{bb}F_{7,8}^{(2)}\right)$$

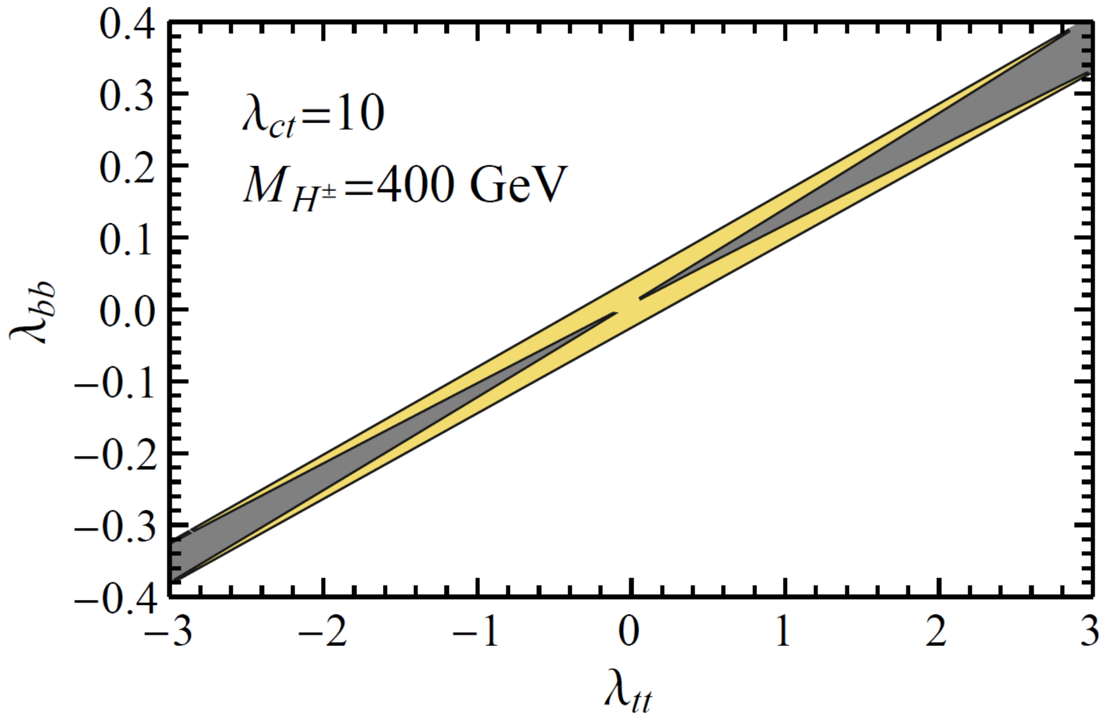
This can be large

There would be strong correlation between λ_{tt} and λ_{bb}.

In order to avoid fine tuning between λ_{tt} and λ_{bb}, we consider $\lambda_{tt}, \lambda_{bb} \sim \mathcal{O}(1)$

Constraints from flavor – loop process

- $B \to X_s\gamma$

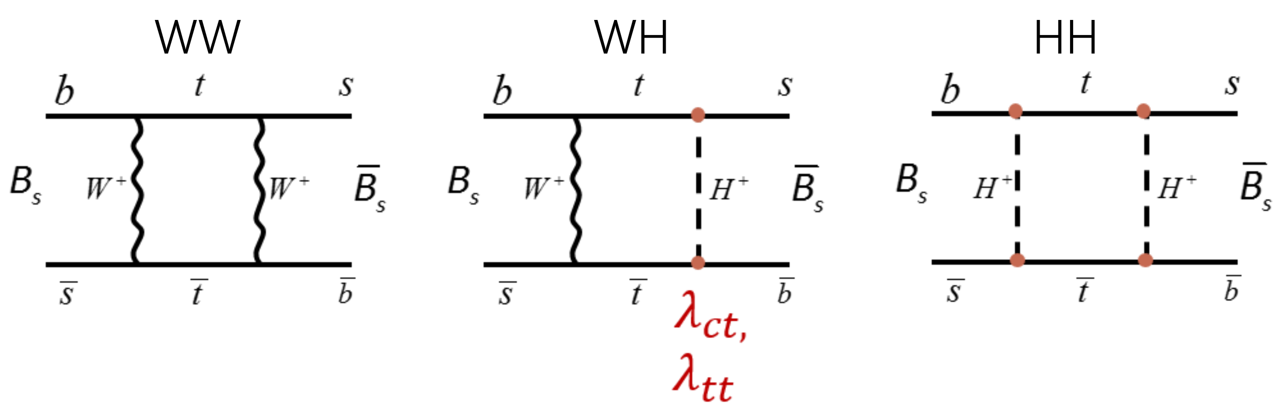


Allows region at 95% CL.

λ_{bb} is highly suppressed.

Constraints from flavor – loop process

- $B_s - \bar{B}_s$ mixing



$$\Delta M_{B_s} = \frac{G_F^2}{6\pi^2} |V_{ts}^* V_{tb}|^2 f_{B_s}^2 B_{B_s} m_{B_s} \eta_b M_W^2 S_{2HDM}(x_W, x_H)$$

Non perturbative quantity. Use Lattice QCD result (with 7% error)

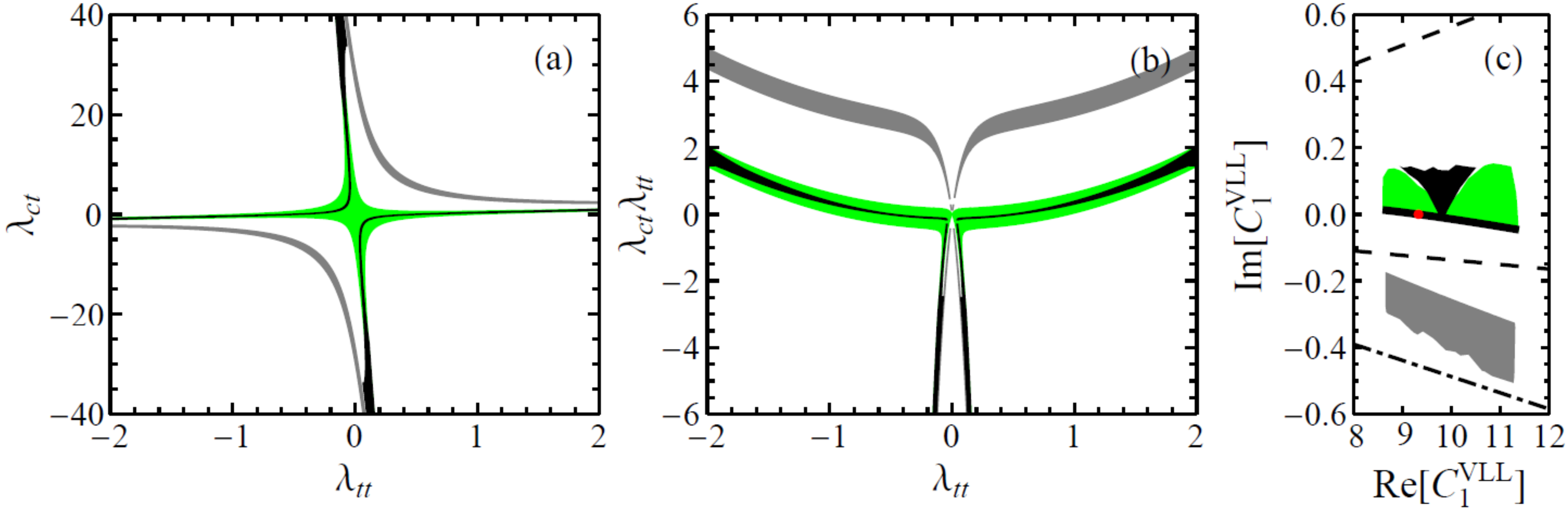
Perturbative quantity. $\eta_b = 0.552$

CKM factor 7% error

Constraints from flavor – loop process

- $B_s - \bar{B}_s$ mixing

Allows region at 95% CL.

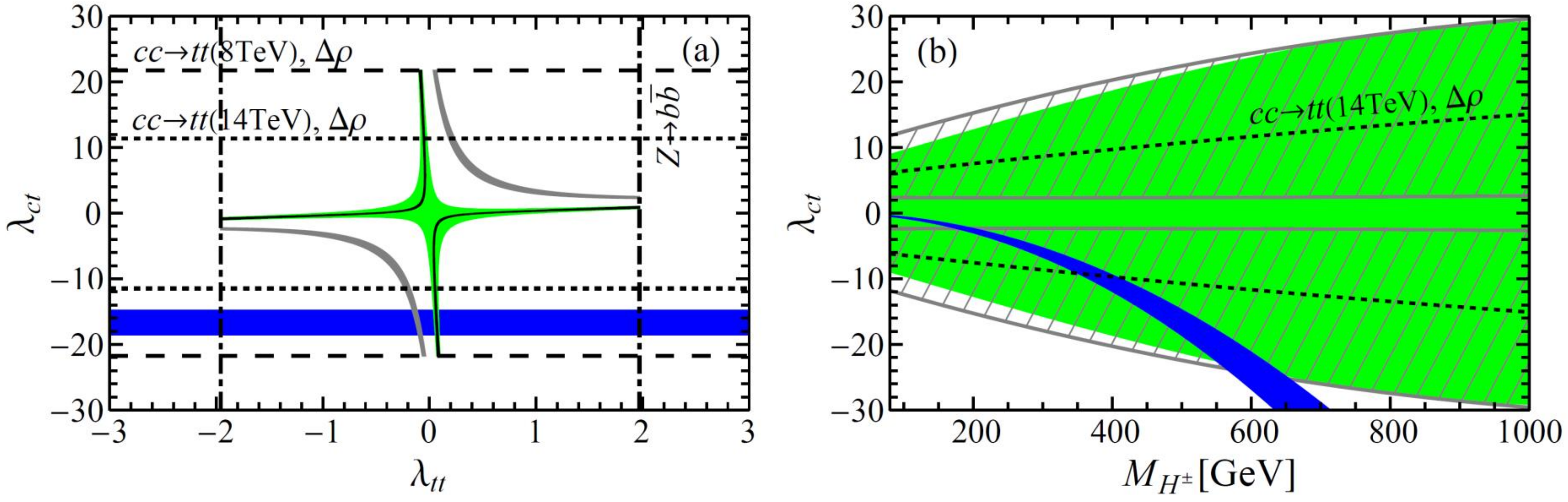


Green: No fine tuning. Gray, Black : Need fine tuning more than 10%

Gray region represent large cancelation between C_{WH} and C_{HH}

Combined constraints

Blue band is from $B \to D^{(*)}\tau\nu$ constraints with $\lambda_{\tau\tau} = 40$.

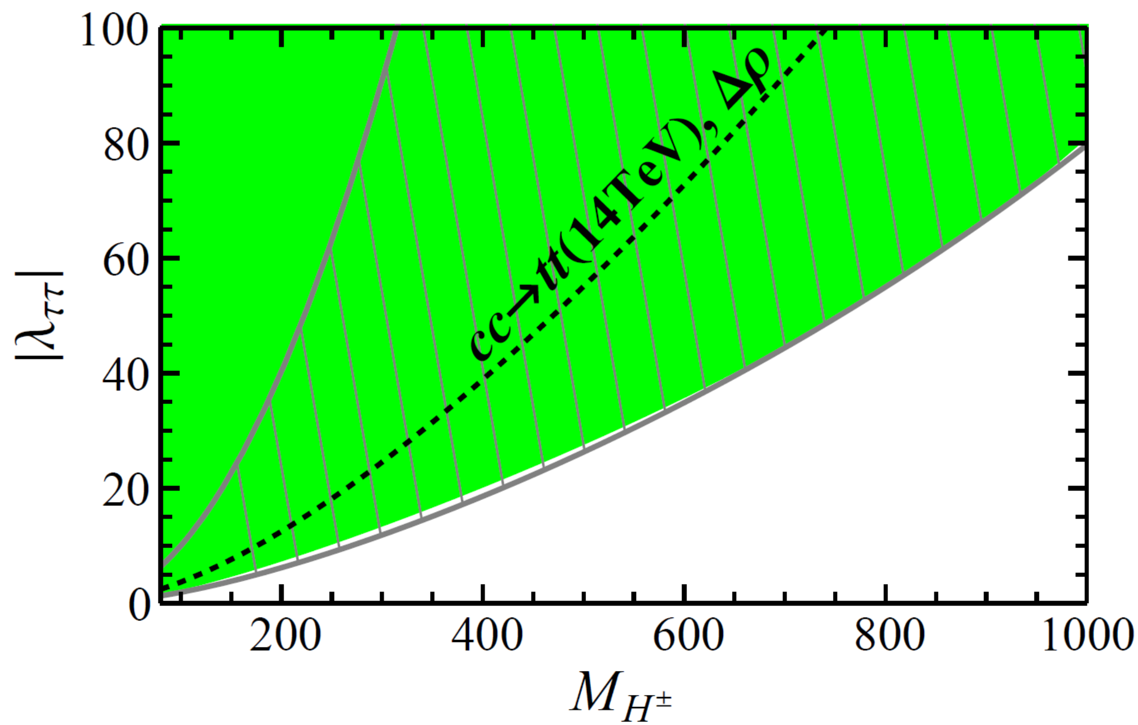


Mostly, constraints from cc→tt is important.

Bs-Bs mixing without fine-tuing give also strong constraints

Concerning $B \to D^{(*)}\tau\nu$ constraints, $\lambda_{\tau\tau}$ can not arbitrary small.

Combined constraints



The lower bound of $\lambda_{\tau\tau}$ is quite significant.

It may affect significantly $H \to \tau\tau$ decay.

SUMMARY

- $B \to D^{(*)}\tau\nu$ anomaly can be successfully explained by 2HDM type III with very large tcH^+coupling λ_{ct}.
- Large λ_{ct} is severely constrained by same sign top pair production.
- Among other flavor constraints, Bs-Bs mixing without fine-tuning also gives similar strong constraints on λ_{ct}.
- Combining them all we find that $\lambda_{\tau\tau}$ is strongly lower bounded