Top FCNC

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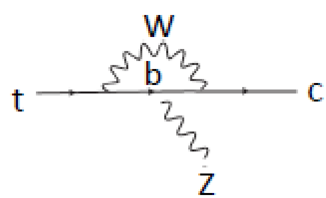
The 16th LHC Physics Monthly Meeting,
KIAS, Korea, Jun 01, 2015

Flavor changing neutral currents

- In the SM, FCNCs are absent at the tree level

ex.) $t \rightarrow c\, Z$



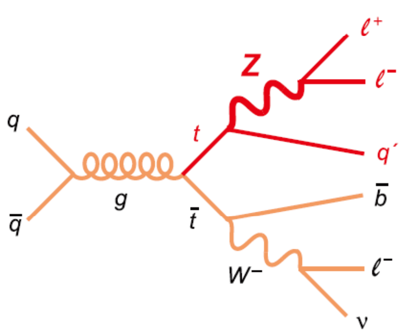
Loop suppressed
CKM suppressed
GIM supressed

- FCNCs are good probe of new physics.

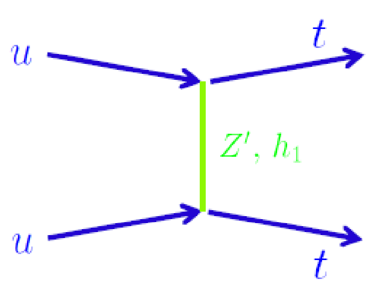
- FCNCs for bound states

$$K^0 - \bar{K}^0, B^0 - \bar{B}^0, B_s - \bar{B}_s, D^0 - \bar{D}^0 \text{ mixing.}$$

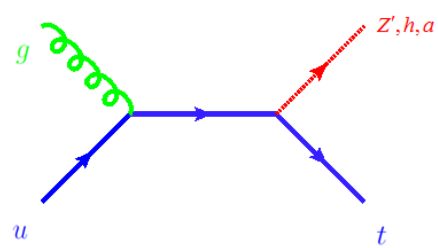
- Which processes are proper for the test of the top FCNC?



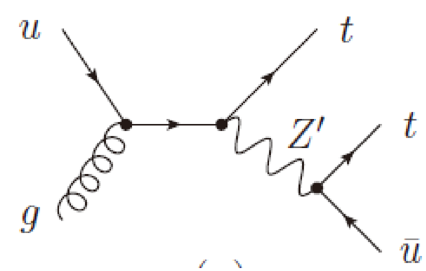
top decay



same sign top



singlet top production



t+j resonance

Top FCNC

Snowmass, arXiv:1311.2028

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

- FCNC in the SM cannot be observed at the LHC
  - Top quark at LHC run II & III: $517\ \text{pb} \times 3000\ \text{fb}^{-1} \sim 2 \times 10^{9}$
- Any measurement on top FCNC implies the existence of new physics
- many models introduces tree-level top FCNCs
- Experimental anomalies might require large top FCNCs

Top FCNC search results

EXP.	$\sqrt{s}$	Lumi .	$\mathcal{B}(t \to u\gamma)$ %	$\mathcal{B}(t \to c\gamma)$ %	Ref .
CDF	1.8 TeV	110 pb^{-1}	3.2		PRL 80 (1998) 2525
CMS	8 TeV	19.1 fb^{-1}	0.0161	0.182	CMS PAS TOP-14-003
			$\mathcal{B}(t \to uZ)$ %	$\mathcal{B}(t \to cZ)$ %	
CDF	1.96 TeV	1.9 fb^{-1}	3.7		PRL 101 (2008) 192002
D0	1.96 TeV	4.1 fb^{-1}	3.2		PRL 701 (2011) 313
CMS	7 TeV	4.9 fb^{-1}	0.51	11.40	CMS PAS TOP-12-021
ATLAS	7 TeV	2.1 fb^{-1}	2.73		JHEP 90 (2012) 139
CMS	7&8 TeV	$(5 + 19.7)fb^{-1}$	0.05		PRL 112 (2014) 171802
			$\mathcal{B}(t \to ug)$ %	$\mathcal{B}(t \to cg)$ %	
CDF	1.96 TeV	2.2 fb^{-1}	0.039	0.57	PRL 102 (2009) 151801
D0	1.96 TeV	2.3 fb^{-1}	0.02	0.39	PLB 693 (2010) 81
CMS	7 TeV	4.9 fb^{-1}	0.56	7.12	CMS PAS TOP-12-021
CMS	7 TeV	4.9 fb^{-1}	0.035	0.34	CMS PAS TOP-14-007
ATLAS	8 TeV	14.2 fb^{-1}	0.0031	0.016	ATLAS CONF -2013-063
			$\mathcal{B}(t \to uH)$ %	$\mathcal{B}(t \to cH)$ %	
ATLAS	7&8 TeV	$(4.7 + 20.3)fb^{-1}$	0.79		JHEP 06 (2014) 008
CMS	8 TeV	19.5 fb^{-1}	0.56		CMS PAS HIG-13-034

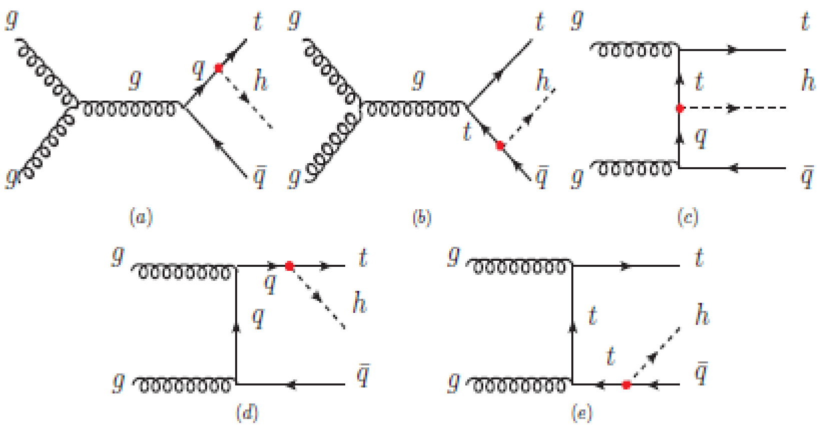
Goldouzian, TOP2014

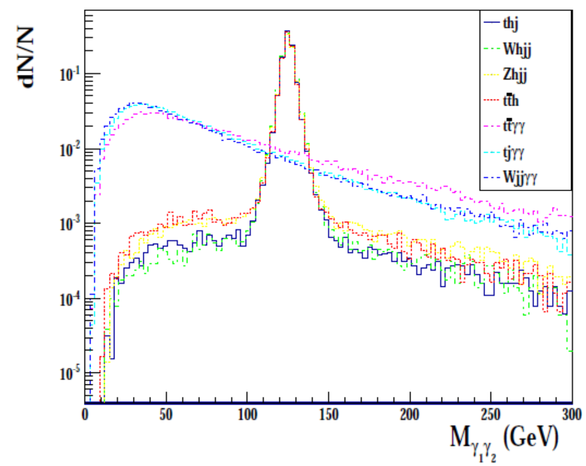
FCNH coupling

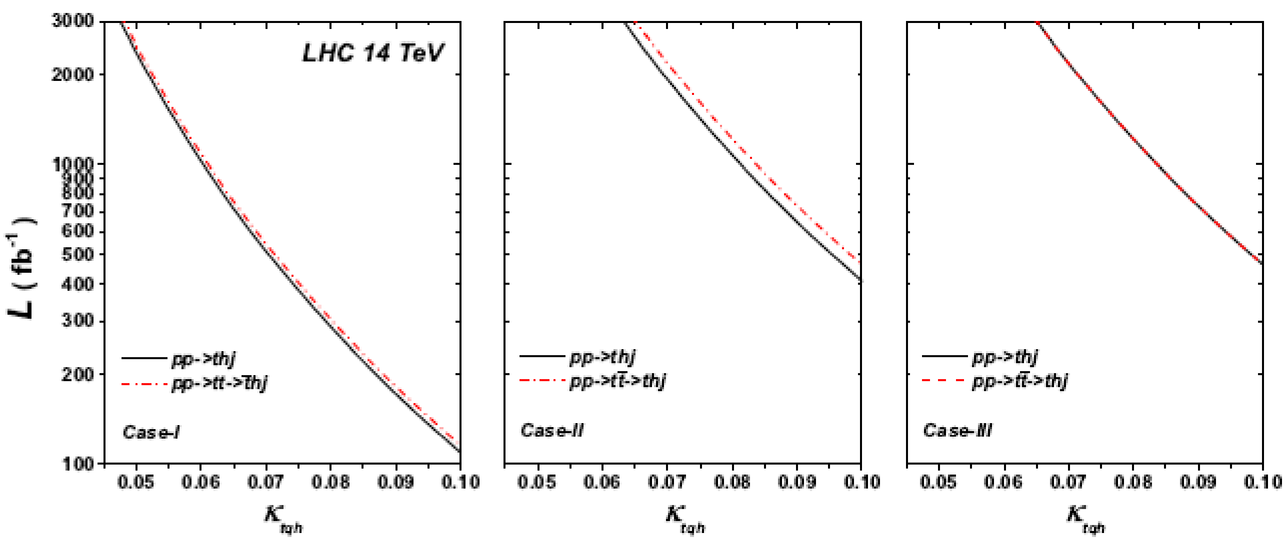
$pp \to thj$

Wu, arXiv:1407.6113

$$-\mathcal{L}_{tqh} = \kappa^{L}_{tqh}\bar{t}_L q_R h + \kappa^{R}_{tqh}\bar{t}_R q_L h + h.c.$$

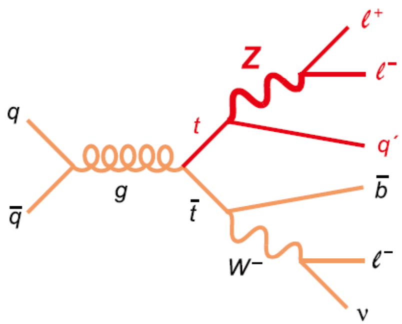




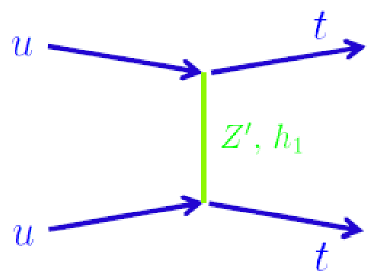


the contours of statistical significance $S/\sqrt{B} = 3\sigma$ of $pp \to thj$

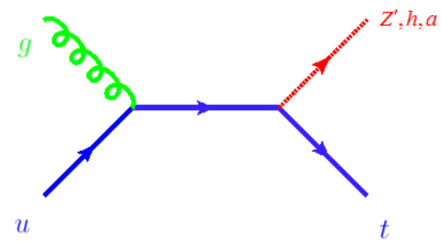
Top FCNC



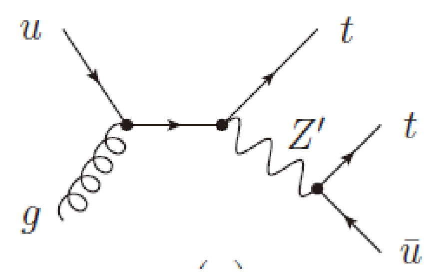
top decay



same sign top



singlet top production



t+j resonance

$m_X < m_t$

any m_X

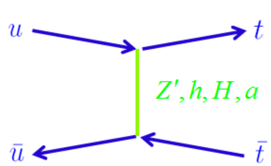
less BG, but
small xsec

any m_X

large xsec, but
large BG

$m_X > m_t$

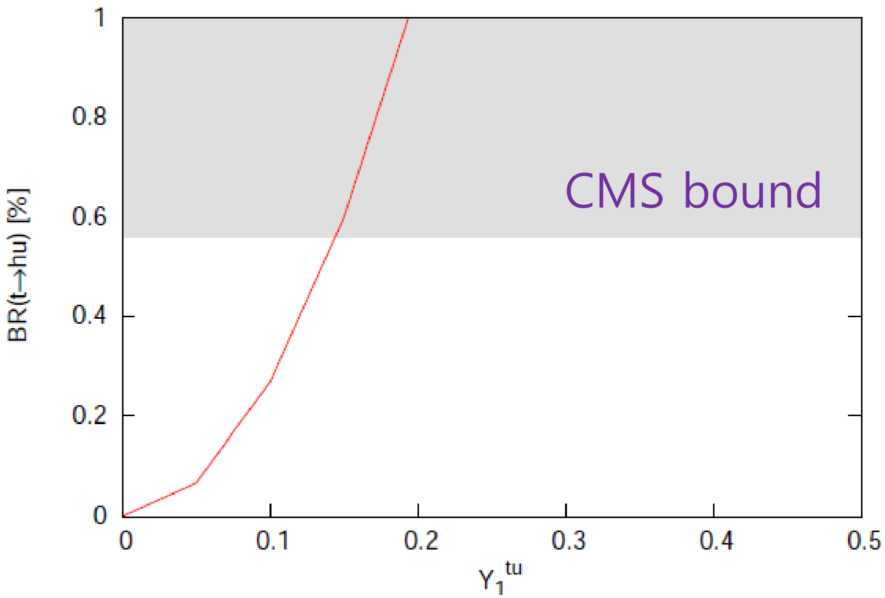
- FCNCs change the total cross section for top pair production

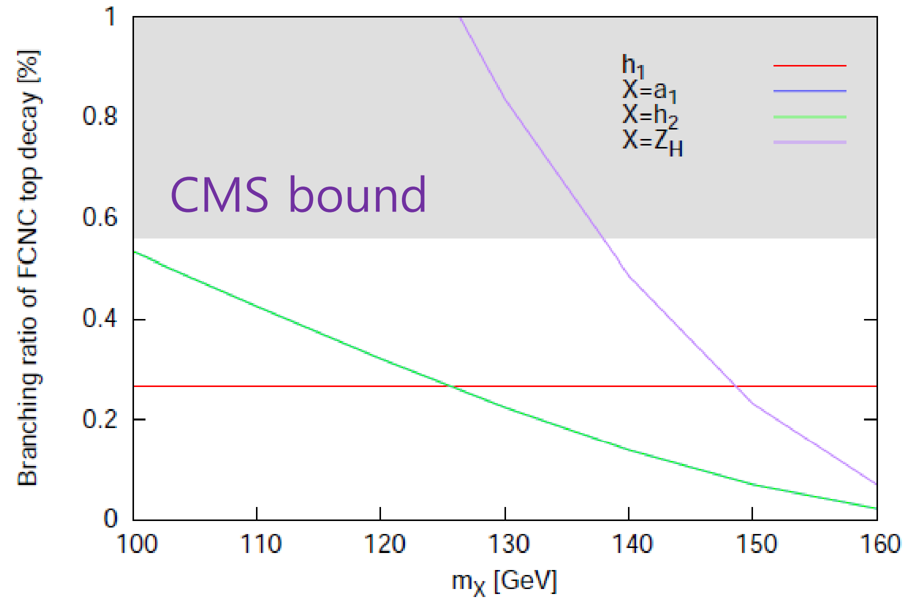


$\Delta\sigma/\sigma$	1.96 TeV	8 TeV	13 TeV
Y_{tu}=0.1	-0.5%	-0.3%	-0.1%
Y_{tu}=1	-27%	-3.8%	-2.5%

FCNCs can be mediated not only by one particle but also several particles

Top decay





$t \to hq$

$h \to WW, ZZ, \tau\tau, \gamma\gamma$

$\sqrt{Y_{tu}^2 + Y_{tc}^2} < 0.14$

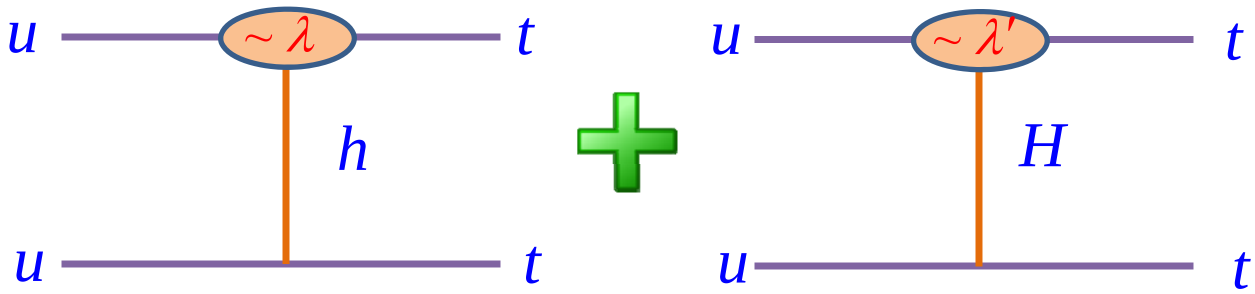
$t \to Xu(X = a, H, Z')$

assume Y_{tu} or $g'=0.1$

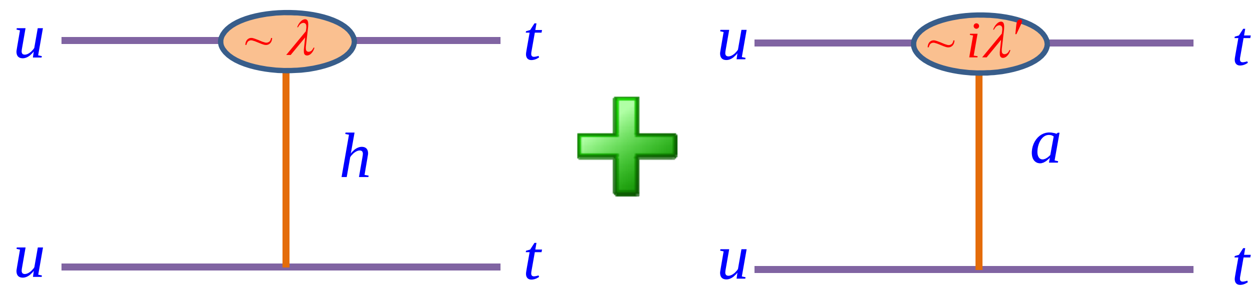
but, depends on the decay channel of X

Same sign top production

- constructive interference

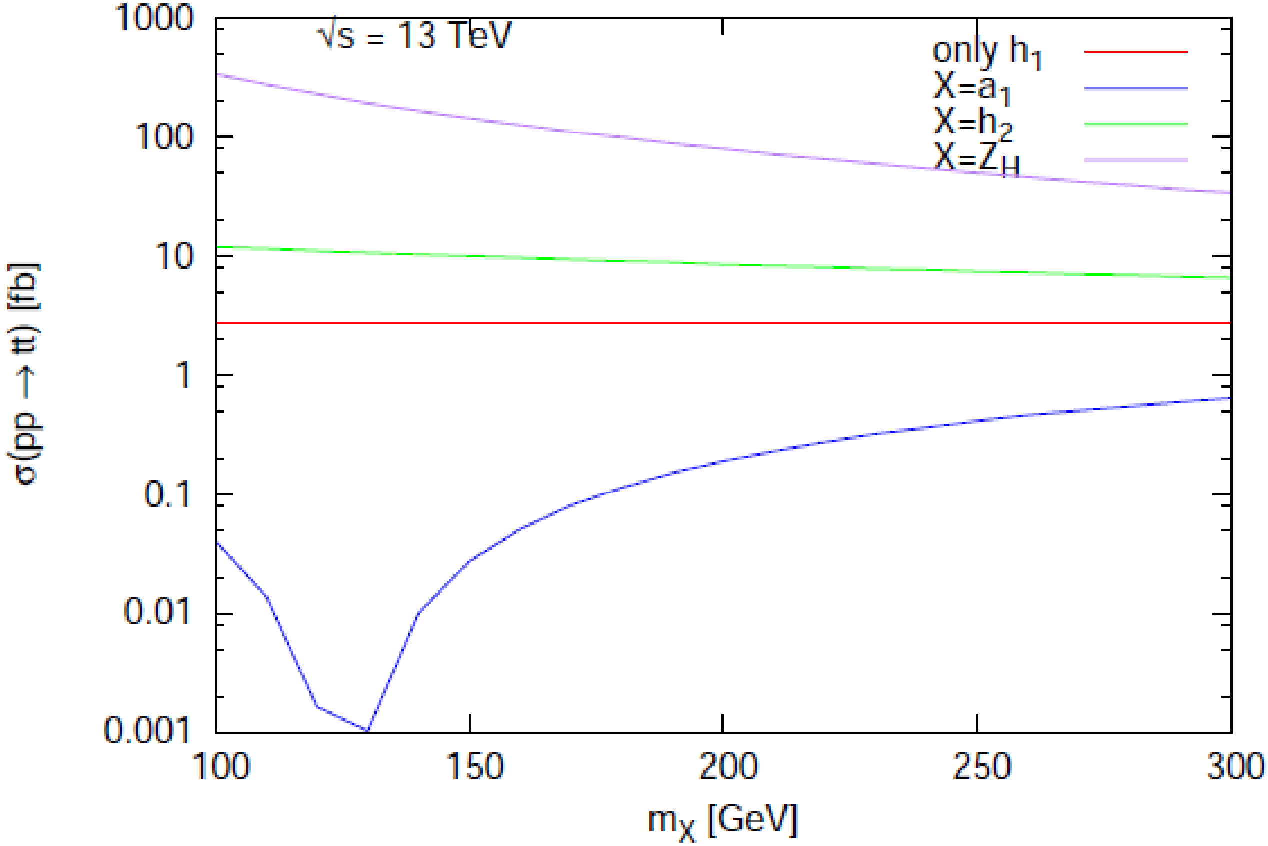


- destructive interference



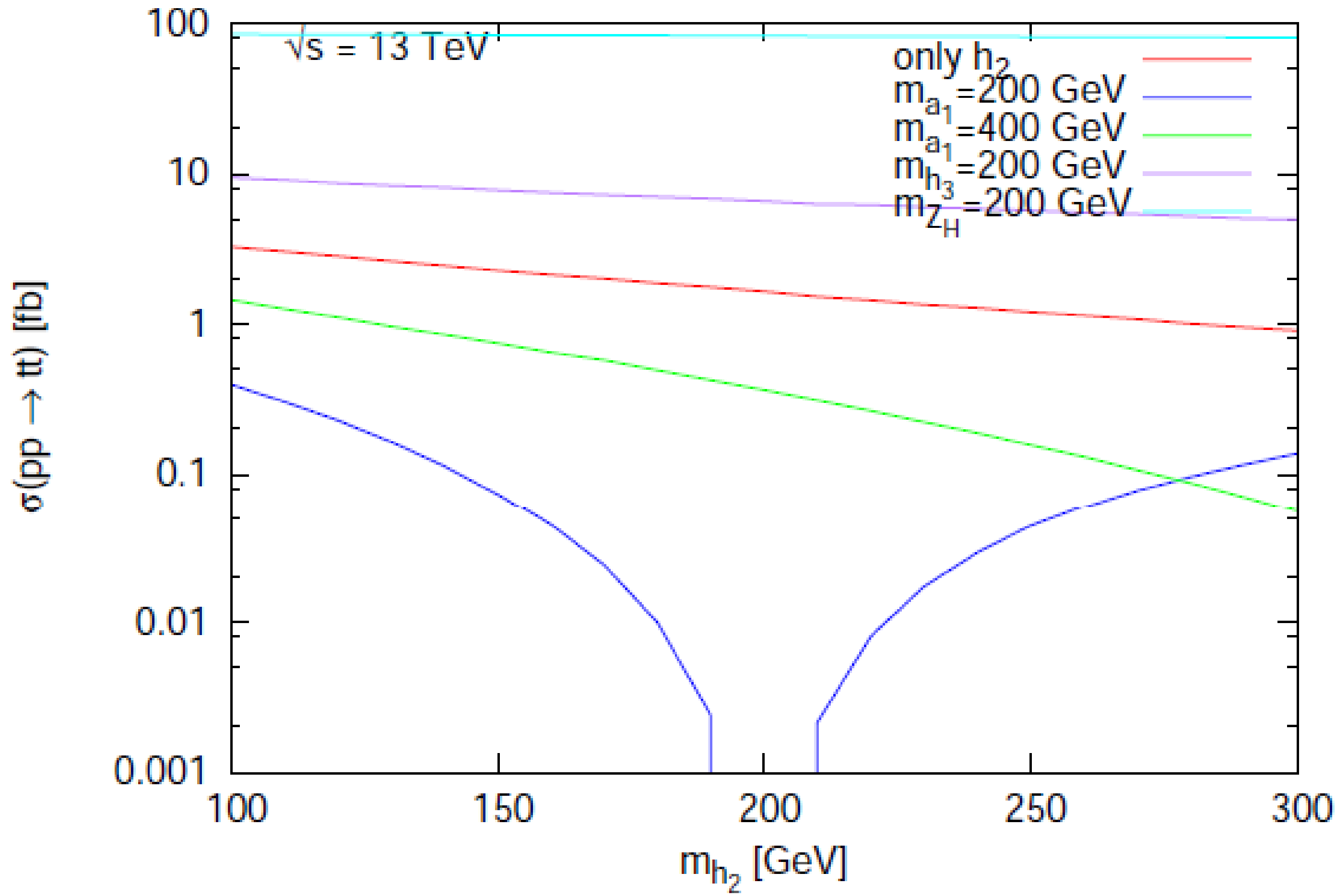
Same sign top production

$$Y_{tu}^{h_1} = Y_{tu}^{h_2} = Y_{tu}^{a_1} = g_H = 0.1$$



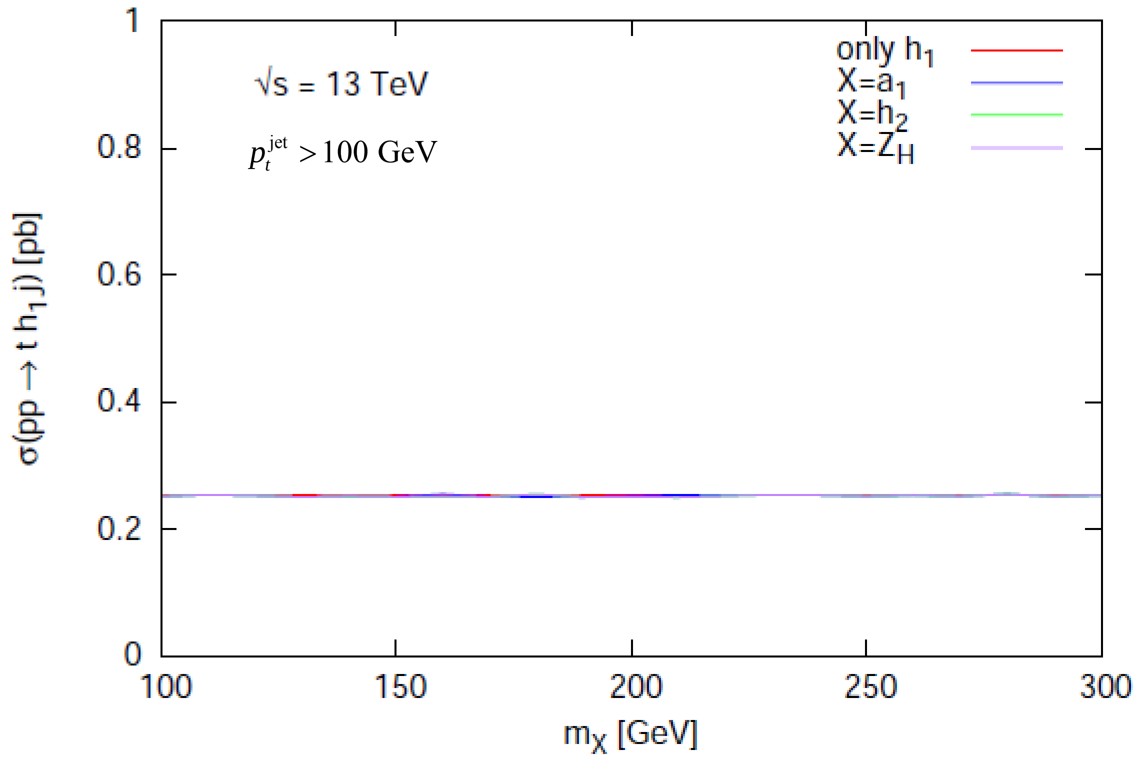
Same sign top production

$$Y_{tu}^{h_2} = Y_{tu}^{h_3} = Y_{tu}^{a_1} = g_H = 0.1$$



thj production

$pp \to thj$



• the same cross section for the thj production, but different for the same sign pair production

How can we make top special?

Top 2HDM

Models by Das, C.Kao (1996); Soni et al (2000),⋯

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

- Z_2 symmetry

$$\phi_1, l_R, d_R, u_R^\alpha : - \qquad \alpha = 1,2$$

$$\phi_2, L_L, Q_L, u_R^3 : +$$

- The top quark is naturally heavy due to a large VEV of ϕ_2
- Flavor changing neutral Higgs couplings
- U(1) extension $\Longrightarrow$ Flavor-dependent chiral U(1)′ model (Ko,Omura,Yu)

Flavor-dependent U(1)′ model

- Charge assignment : SM fermions

Ko,Omura,Yu, JHEP1201,147

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	$1/6$	q_L
Q_2	3	2	$1/6$	q_L
Q_3	3	2	$1/6$	q_L
$\overline{D_1}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	$1/3$	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	$1/2$	0

Left-handed quarks and right-handed down-type quarks have universal couplings.

Flavor-dependent

Higgs

H cannot generate mass terms for right-handed up-type quarks

Flavor-dependent U(1)′ model

- Charge assignment : Higgs fields

Ko,Omura,Yu, JHEP1201,147

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to H uncharged under U(1)′.

$$
\begin{aligned}
V_y &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\
&+ y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\
&+ y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i .
\end{aligned}
$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Anomaly Cancelation

- Anomaly cancelation requires extra fermions: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1+q_2+q_3)$
D'_R	3	1	−1/3	$-(d_1+d_2+d_3)$
U'_R	3	1	2/3	$-(u_1+u_2+u_3)$
L'	1	2	−1/2	0
E'	1	1	−1	0
l_{L1}	1	2	−1/2	Q_L
l_{R1}	1	2	−1/2	Q_R
l_{L2}	1	2	−1/2	$-Q_L$
l_{R2}	1	2	−1/2	$-Q_R$

one extra generation

vector-like pairs

a candidate for CDM

Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0,0,1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$V_y = y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{R2} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{R3}$$
$$+ y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}HE_{Rj} + h.c.\,.$$

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta),$$
$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\delta_{ij},$$

$\propto$ the fermion mass

Flavor-dependent U(1)′ model

- Gauge coupling in the flavor eigenstates

$$\mathcal{L}_{Z' f \bar{f}} = g' Z'_\mu \left[q_i \overline{U^i_L} \gamma^\mu U^i_L + q_i \overline{D^i_L} \gamma^\mu D^i_L + u_i \overline{U^i_R} \gamma^\mu U^i_R + d_i \overline{D^i_R} \gamma^\mu D^i_R \right]$$

- The 3 X 3 coupling matrix g^u_R is defined by

$$(g^u_R)_{ij} = (U^u_R)_{ik} u_k (U^u_R)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix

- Gauge coupling in the mass eigenstates

- Z′ interacts only with the right-handed up-type quarks

$$g' Z'_\mu \left[(g^u_L)_{ij} \overline{\hat{U}^i_L} \gamma^\mu \hat{U}^j_L + (g^d_L)_{ij} \overline{\hat{D}^i_L} \gamma^\mu \hat{D}^j_L + (g^u_R)_{ij} \overline{\hat{U}^i_R} \gamma^\mu \hat{U}^j_R + (g^d_R)_{ij} \overline{\hat{D}^i_R} \gamma^\mu \hat{D}^j_R \right]$$

~0 or δ_{ij} | flavor off-diagonal couplings | ~0 or δ_{ij}

B physics

- Charged Higgs contributes to B physics.

Neutral (pseudo)scalar

$$(\bar{u}_L \;\; \bar{c}_L \;\; \bar{t}_L) \begin{pmatrix} Y^{(a)}_{uu} & Y^{(a)}_{uc} & Y^{(a)}_{ut} \\ Y^{(a)}_{cu} & Y^{(a)}_{cc} & Y^{(a)}_{ct} \\ Y^{(a)}_{tu} & Y^{(a)}_{tc} & Y^{(a)}_{tt} \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} h(-ia)$$

Top FCNC

Top mass enhance

strong relation $Y^{u-}_{ij} = \sqrt{2}(V_{\mathrm{CKM}})^*_{li} Y^{au}_{lj}$

Charged Higgs sector

$$(\bar{d}_L \;\; \bar{s}_L \;\; \bar{b}_L) \begin{pmatrix} Y^-_{du} & Y^-_{dc} & Y^-_{dt} \\ Y^-_{su} & Y^-_{sc} & Y^-_{st} \\ Y^-_{bu} & Y^-_{bc} & Y^-_{bt} \end{pmatrix} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} h^-$$

$B \to \tau\nu$

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

$b \to s\gamma$ in one loop

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

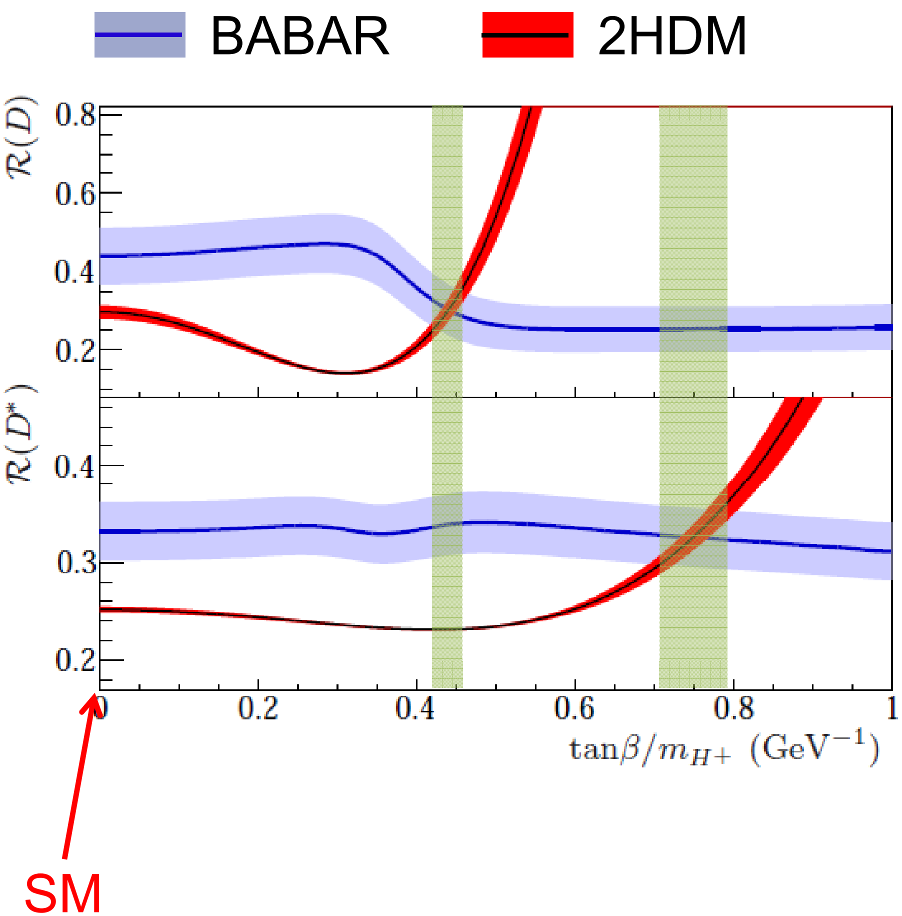
$B \to D^{(*)}\tau\nu$

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

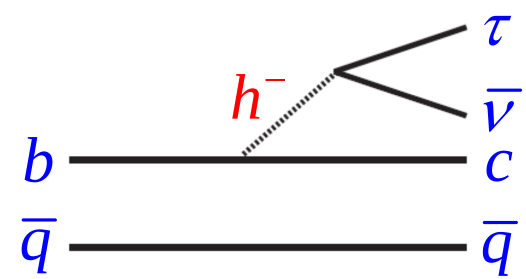
	$R(D)$	$R(D^*)$	
BABAR	0.440 ± 0.071	0.332 ± 0.029	BABAR, 1205.5442
	2.0σ	2.7σ	
SM	0.297 ± 0.017	0.252 ± 0.003	Fajfer, Kamenik, Nisandzic, Mescia

combined 3.4σ

$R(D)$ and $R(D^*)$ in 2HDM (type-II)



BABAR, 1205.5442



$$\propto m_\tau m_b \frac{\tan^2\beta}{m_{H^\pm}^2}$$

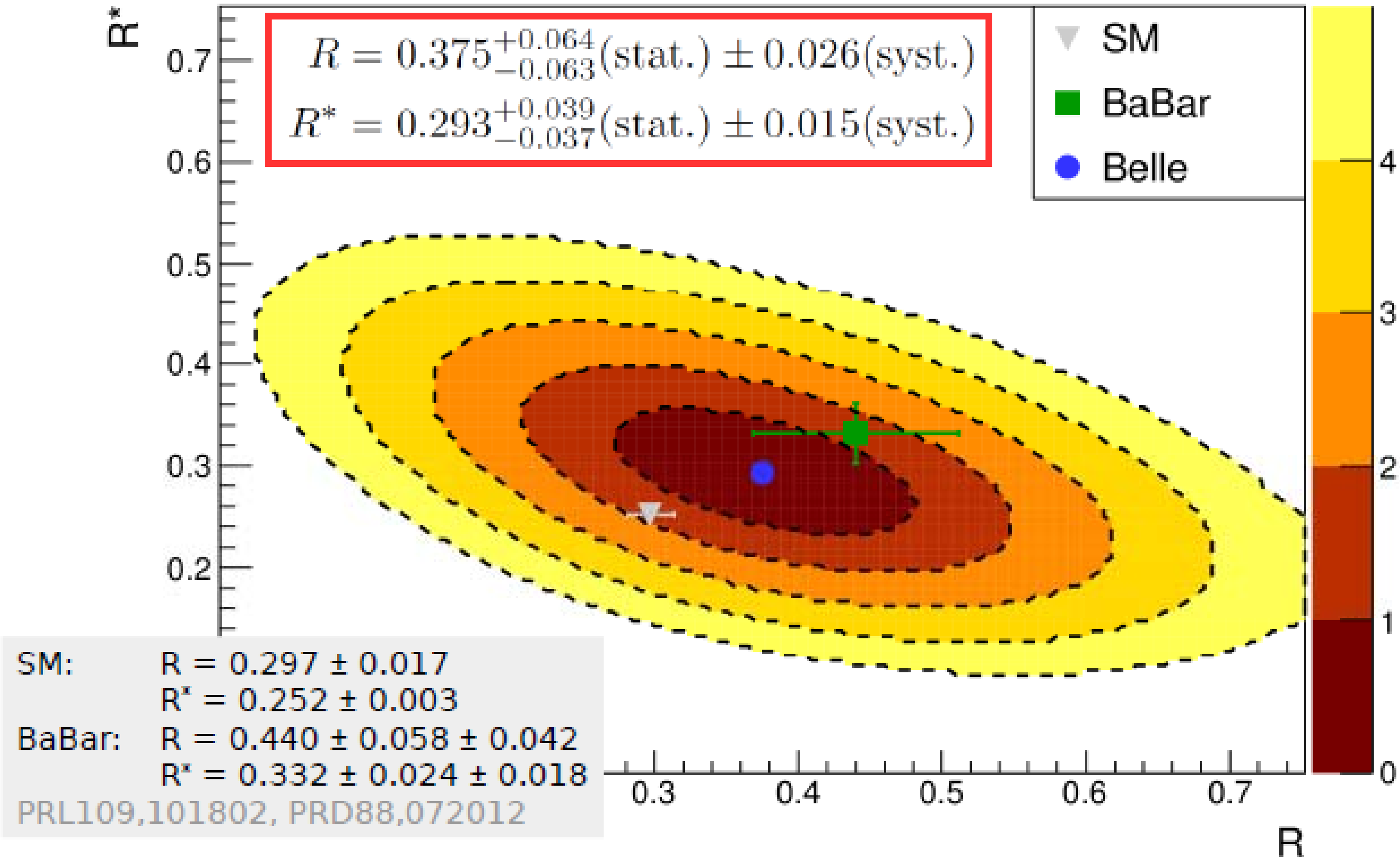
- Allowed regions:

  $\tan\beta / m_H = 0.44 \pm 0.02$ for $R(D)$

  $\tan\beta / m_H = 0.75 \pm 0.04$ for $R(D^*)$

- Combination of $R(D)$ and $R(D^*)$ excludes full parameter space with 99.8% probability.

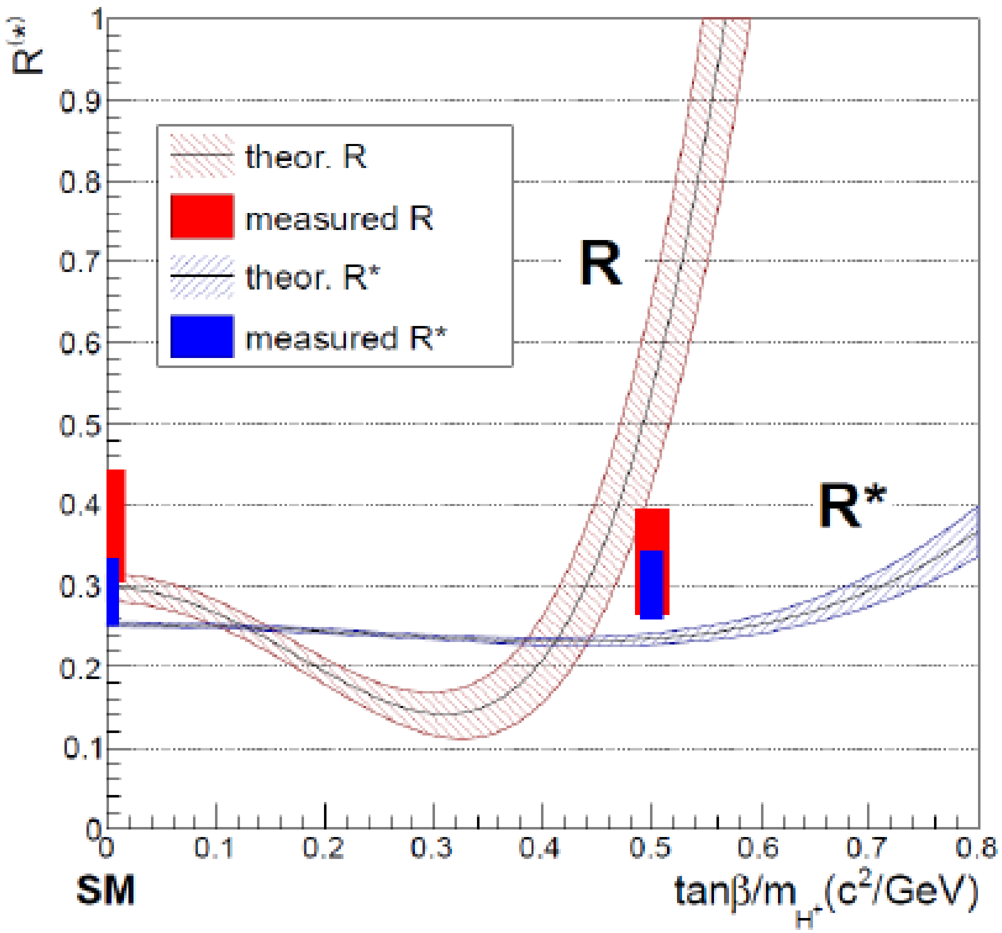
$R(D^{(*)})$ at Belle



Kuhr, FPCP2015

- consistent with the SM and BABAR
- both results are larger than SM predictions

R(D$^{(*)}$) at Belle



- Analysis repeated for 2HDM of type II with tanβ/m$_{H+}$ = 0.5 c^2/GeV:

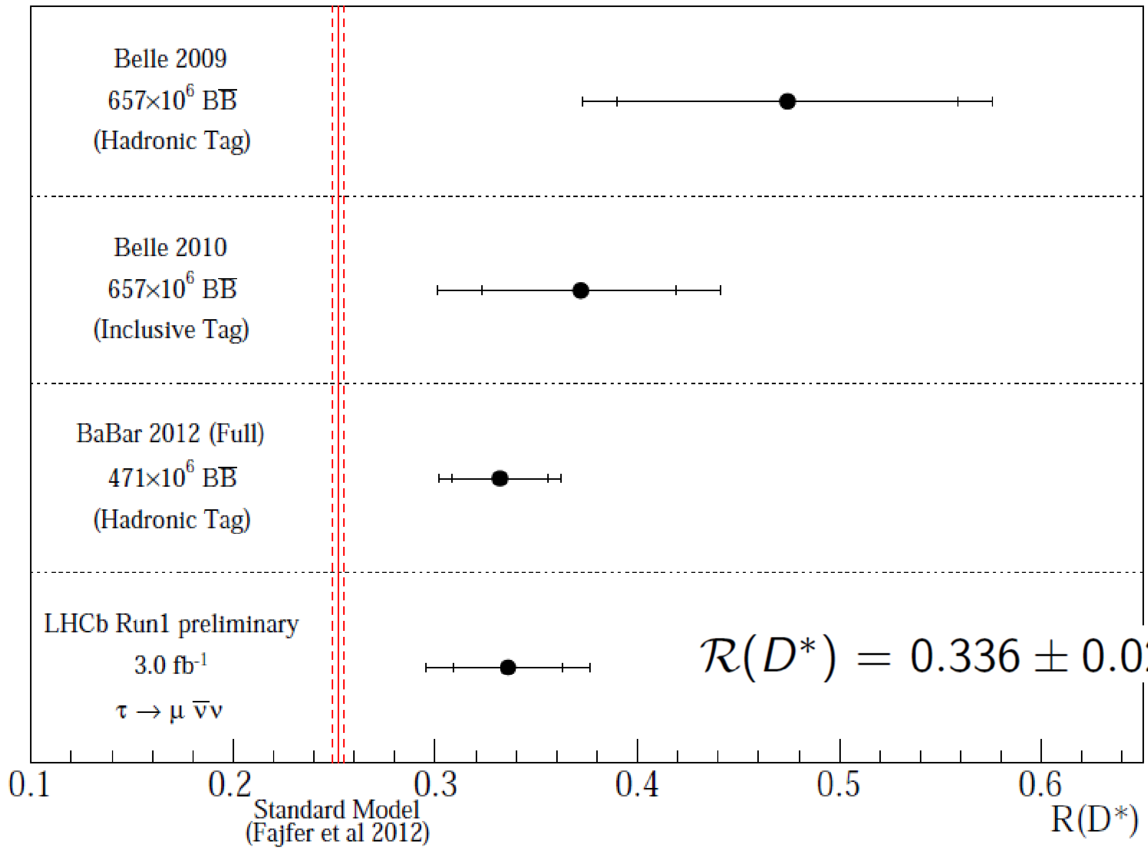
$$R = 0.329 \pm 0.060 \pm 0.022$$
$$R^* = 0.301 \pm 0.039 \pm 0.015$$

$$R_{2HDM} = 0.590 \pm 0.125$$
$$R^*_{2HDM} = 0.241 \pm 0.007$$

Kuhr, FPCP2015

- consistent with type-II 2HDM at $\tan\beta / m_{H^+}^2 \approx 0.5$

R(D*) at LHCb



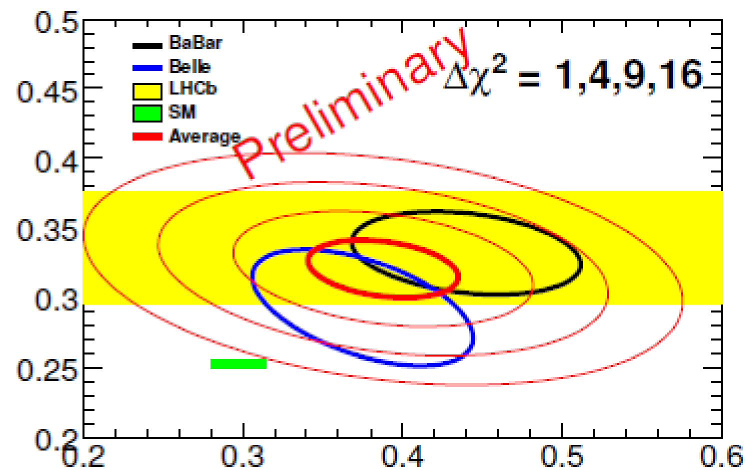
$$\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Ciezarek, FPCP2015

- Agreement with the SM at 2.1σ level
- In good agreement with the Belle and BABAR results

average

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



Ligeti, FPCP2015

$R(D)_{\rm BABAR}$ 2.0σ

$R(D^*)_{\rm BABAR}$ 2.7σ

$R(D)_{\rm BELLE}$ 1.1σ

$R(D^*)_{\rm BELLE}$ 1.0σ

$R(D)_{\rm tot}$ 1.8σ

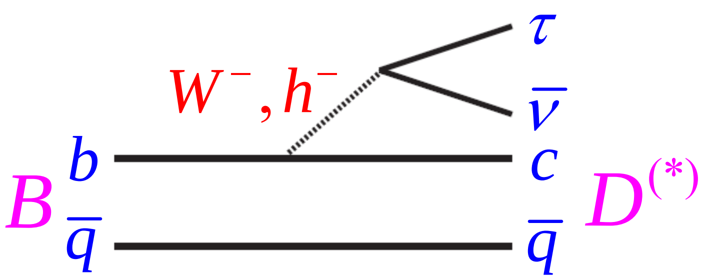
$R(D^*)_{\rm tot}$ 3.2σ

$R(D^*)_{\rm LHCb}$ 2.1σ

$R(D^{(*)})_{\rm tot}$ 3.7σ

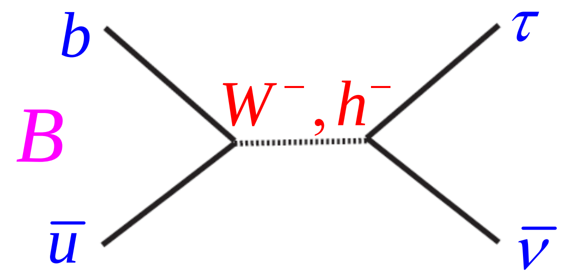
$\mathrm{BR}(B \to \tau\nu)$

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



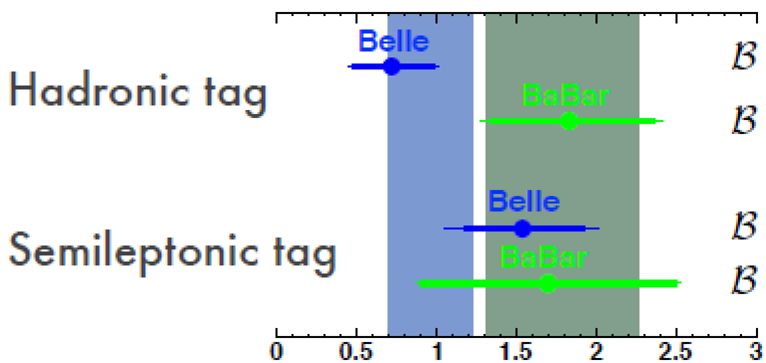
(b,c) coupling

$B \to \tau\nu$



(b,u) coupling

SM expectation $\mathcal{B} = (1.10 \pm 0.30) \times 10^{-4}$



$\mathcal{B} = [0.72^{+0.27}_{-0.25}(\mathrm{stat}) \pm 0.11(\mathrm{syst})] \times 10^{-4}$

$\mathcal{B} = [1.83^{+0.53}_{-0.49}(\mathrm{stat}) \pm 0.24(\mathrm{syst})] \times 10^{-4}$

$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\mathrm{stat})^{+0.29}_{-0.31}(\mathrm{syst})] \times 10^{-4}$

$\mathcal{B} = [1.7 \pm 0.8(\mathrm{stat}) \pm 0.2(\mathrm{syst})] \times 10^{-4}$

Belle combined: $\mathcal{B} = (0.96 \pm 0.26) \times 10^{-4}$

BaBar combined: $\mathcal{B} = (1.79 \pm 0.48) \times 10^{-4}$

Effective Hamiltonian

- Effective Hamiltonian

$$H_{\text{eff}} = C^{qb}_{\text{SM}}(\overline{q_L}\gamma_\mu b_L)(\overline{\tau_L}\gamma^\mu \nu_L) + C^{qb}_R(\overline{q_L} b_R)(\overline{\tau_R}\nu_L) + C^{qb}_L(\overline{q_R} b_L)(\overline{\tau_R}\nu_L)$$

Charged Higgs

$$R(D) = R_{\text{SM}}\left(1 + 1.5\ \text{Re}\left(\frac{C^{cb}_R + C^{cb}_L}{C^{cb}_{SM}}\right) + \left|\frac{C^{cb}_R + C^{cb}_L}{C^{cb}_{SM}}\right|^2\right)$$

$$R(D^*) = R^*_{\text{SM}}\left(1 + 0.12\ \text{Re}\left(\frac{C^{cb}_R - C^{cb}_L}{C^{cb}_{SM}}\right) + 0.05\left|\frac{C^{cb}_R - C^{cb}_L}{C^{cb}_{SM}}\right|^2\right)$$

$$\text{BR}(B \to \tau\nu) = \frac{G_F^2|V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \tau_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|1 + \frac{m_B^2}{m_b m_\tau}\left(\frac{C^{ub}_R - C^{ub}_L}{C^{ub}_{SM}}\right)\right|^2$$

Wilson coefficients

$$\frac{C_L^{qb}}{C_{\rm SM}^{qb}} = \frac{m_q m_\tau}{m_{h^+}^2}\tan^2\beta - \sum_l \frac{V_{lb}}{V_{qb}}\frac{m_l^u m_\tau (g_R^u)_{lq}}{m_{h^+}^2\cos^2\beta},$$

$$\frac{C_R^{qb}}{C_{\rm SM}^{qb}} = -\frac{m_b m_\tau}{m_{h^+}^2}\tan^2\beta.$$

New terms in flavor-dependent U(1)´ model

Flavor-independent

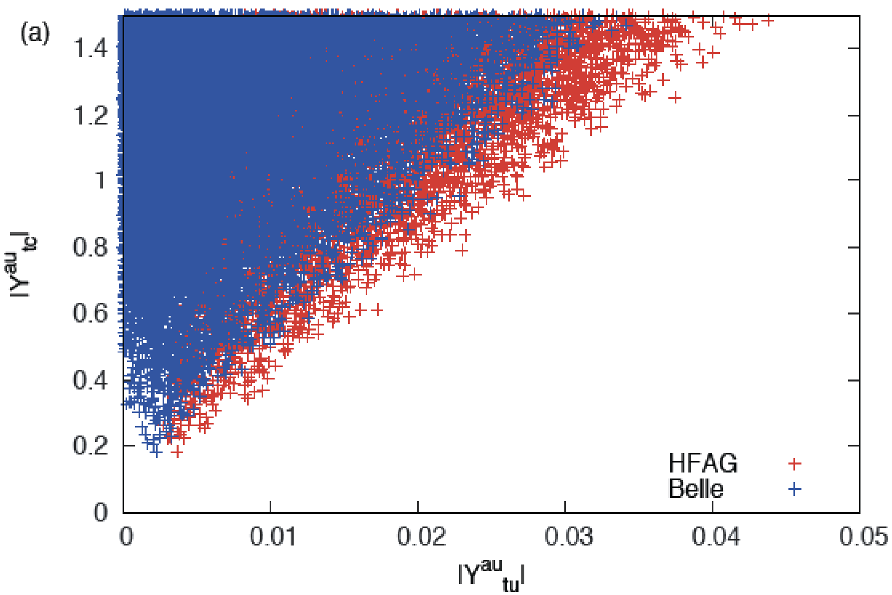
- diagonalization matrix g_R

$(g_R^u)_{ij} = \delta_{ij}$: the same as the type-II 2HDM.

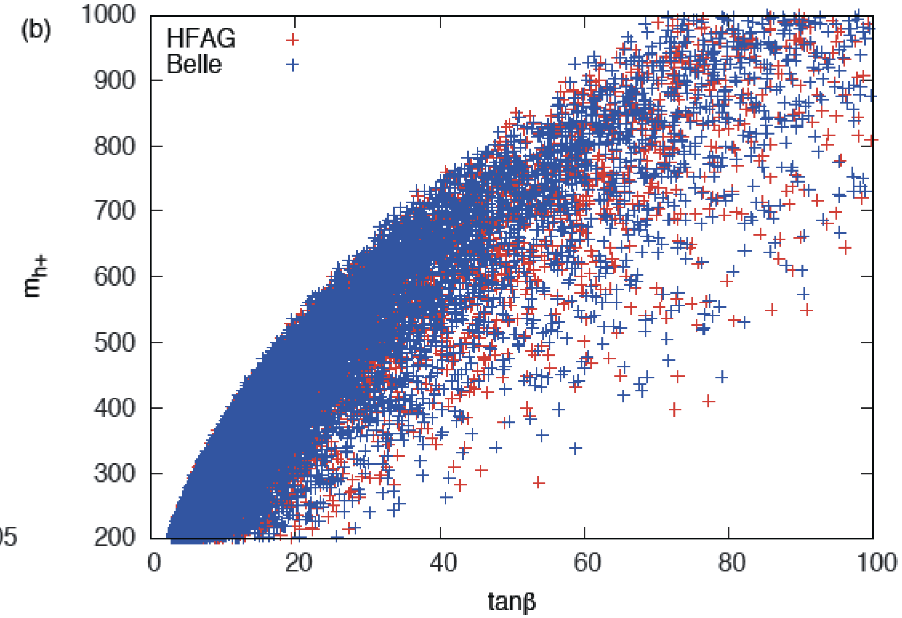
$(g_R^u)_{ij} \neq \delta_{ij}$: generate non-MFV interactions.

2HDM

Ytc vs Ytu of pseudo scalar



mH+ vs tan β



- The BABAR discrepancies require large charged Higgs contribution

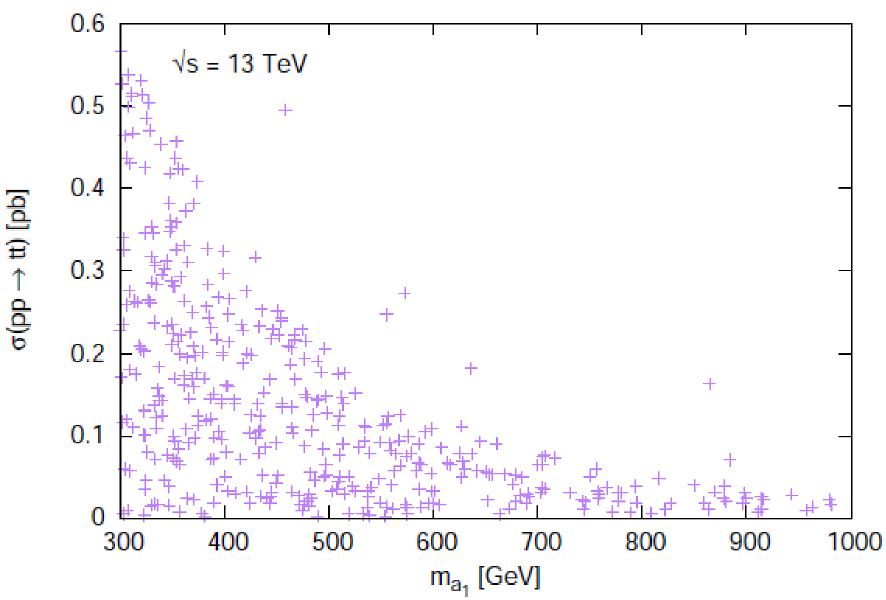
$$0.2 \lesssim |Y^{au}_{tc}|, \quad m_{h^+}/\tan\beta \lesssim O(10).$$

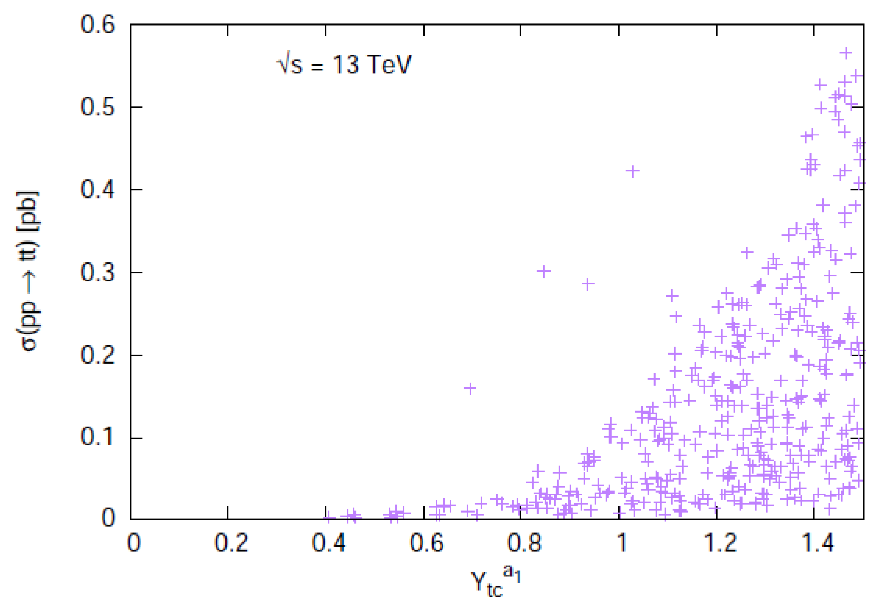
- B→$\tau\nu$ requires small (t,u) coupling, $|Y^{au}_{tu}| \lesssim 0.03.$

Same sign top production in 2HDM

$t-q-h$ $$Y_{ij}^{u(1)} = \frac{m_i^u \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij} + \frac{2m_i^u}{v\sin 2\beta}(g_R^u)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi$$

$t-q-a$ $$Y_{ij}^{au} = \frac{m_i^u \tan\beta}{v}\delta_{ij} - \frac{2m_i^u}{v\sin 2\beta}(g_R^u)_{ij}$$





Summary

• FCNCs are good probe of new physics.

• There are several top FCNC observables, and they are complementary to each other.

• A few particles which have FCNC couplings can exist in the model and their effects may be interfered constructively or destructively.

• $B \to D(*)\tau\nu$ anomaly may be resolved by flavor-dependent $U(1)'$ model, but it predicts large FCNCs. In particular, a lot of parameter spaces may be tested by the same sign top pair production at LHC run 2.

$R(D^{(*)})$ at Belle (non-official)

SM expectations: (S.Fajfer, J.Kamenik, I.Nisandzic, PRD 85, 094025 (2012))

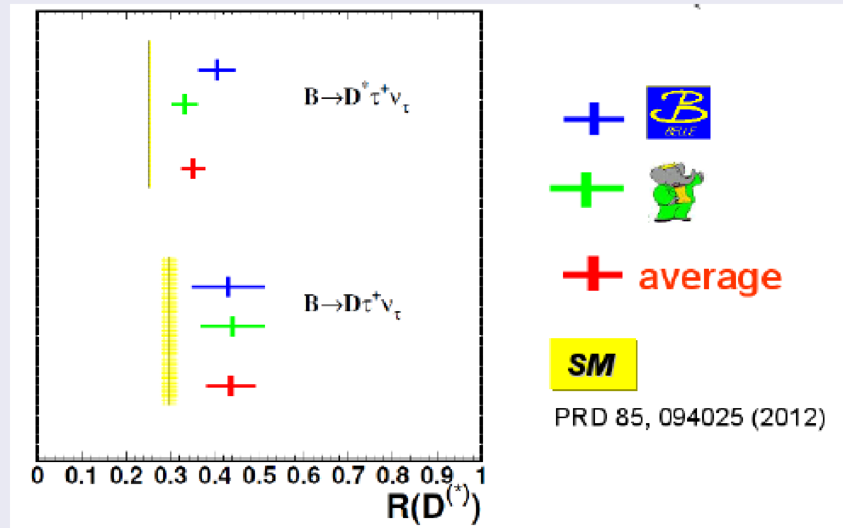
$R(D) = 0.297 \pm 0.017,\ R(D^*) = 0.252 \pm 0.003$

BABAR SM deviations

- $R(\overline{D}^*)$ 2.7σ
- $R(\overline{D})$ 2.0σ
- $R(\overline{D}^{(*)})$ 3.4σ

Belle average SM deviations

- $R(\overline{D}^*)$ 3.0σ
- $R(\overline{D})$ 1.4σ
- $R(\overline{D}^{(*)})$ 3.3σ



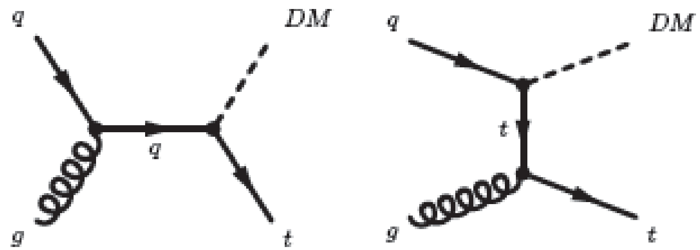
private average of Belle results

Belle and *BABAR* average deviation from **SM**

- $R(\overline{D}^*)$ 3.8σ
- $R(\overline{D})$ 2.4σ
- $R(\overline{D}^{(*)})$ 4.8σ

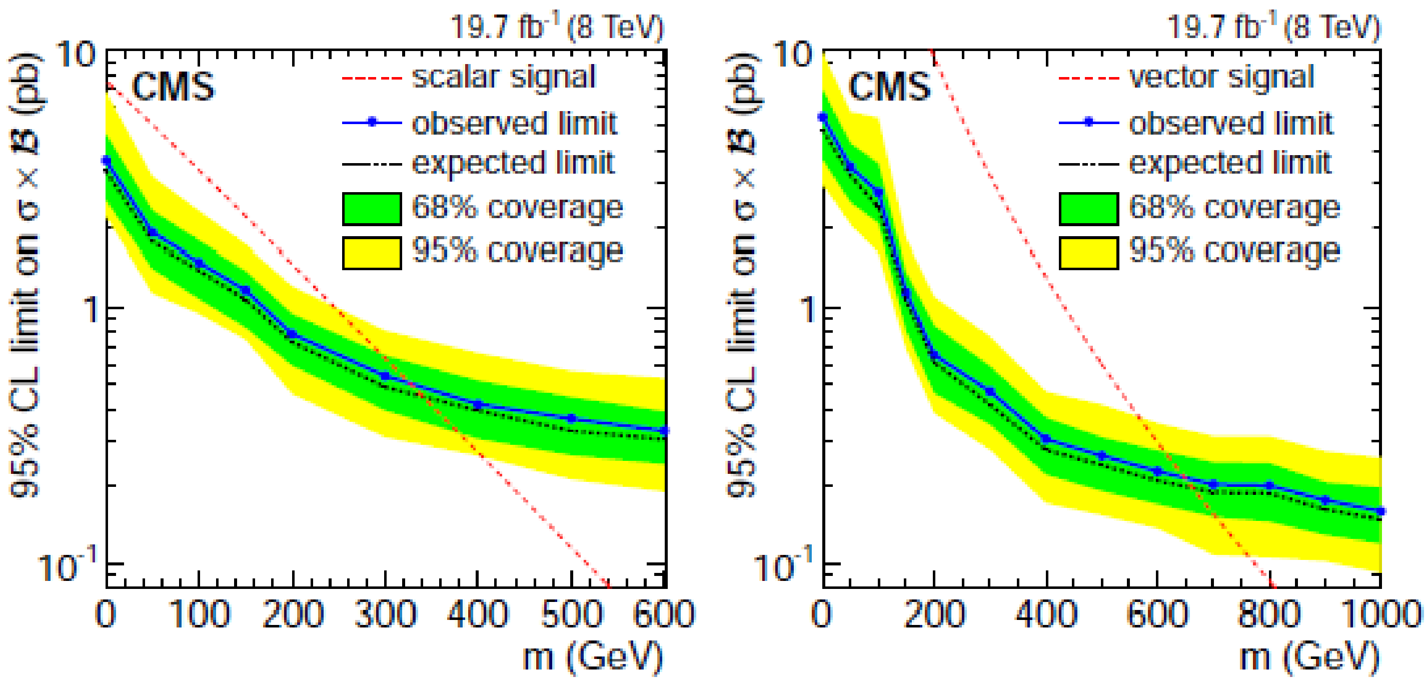
From A. Bozek's slide at FPCP2013

Mono-top



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + a^0_{\rm FC}\phi\bar{u}u + a^1_{\rm FC}v_\mu\bar{u}\gamma^\mu u + {\rm h.c.},$$

Andrea,Fuks,Maltoni, arXiv:1106.6199



CMS, arXiv:1410.1149

Top FCNC search results

EXP.	$\sqrt{s}$	Lumi .	$\mathcal{B}(t \to u\gamma)$ %	$\mathcal{B}(t \to c\gamma)$ %	Ref .
CDF	1.8 TeV	110 pb^{-1}	3.2		PRL 80 (1998) 2525
CMS	8 TeV	19.1 fb^{-1}	0.0161	0.182	CMS PAS TOP-14-003
			$\mathcal{B}(t \to uZ)$ %	$\mathcal{B}(t \to cZ)$ %	
CDF	1.96 TeV	1.9 fb^{-1}	3.7		PRL 101 (2008) 192002
D0	1.96 TeV	4.1 fb^{-1}	3.2		PRL 701 (2011) 313
CMS	7 TeV	4.9 fb^{-1}	0.51	11.40	CMS PAS TOP-12-021
ATLAS	7 TeV	2.1 fb^{-1}	2.73		JHEP 90 (2012) 139
CMS	7&8 TeV	$(5 + 19.7)fb^{-1}$	0.05		PRL 112 (2014) 171802
			$\mathcal{B}(t \to ug)$ %	$\mathcal{B}(t \to cg)$ %	
CDF	1.96 TeV	2.2 fb^{-1}	0.039	0.57	PRL 102 (2009) 151801
D0	1.96 TeV	2.3 fb^{-1}	0.02	0.39	PLB 693 (2010) 81
CMS	7 TeV	4.9 fb^{-1}	0.56	7.12	CMS PAS TOP-12-021
CMS	7 TeV	[illegible]	[illegible]	[illegible]	[illegible] PAS TOP-14-007
ATLAS	8 TeV	[illegible]	[illegible]	[illegible]	[illegible] S CONF -2013-063
			[illegible]	[illegible]	
ATLAS	7&8 TeV	$(4.7 + 20.3)fb^{-1}$	0.79		JHEP 06 (2014) 008
CMS	8 TeV	19.5 fb^{-1}	0.56		CMS PAS HIG-13-034

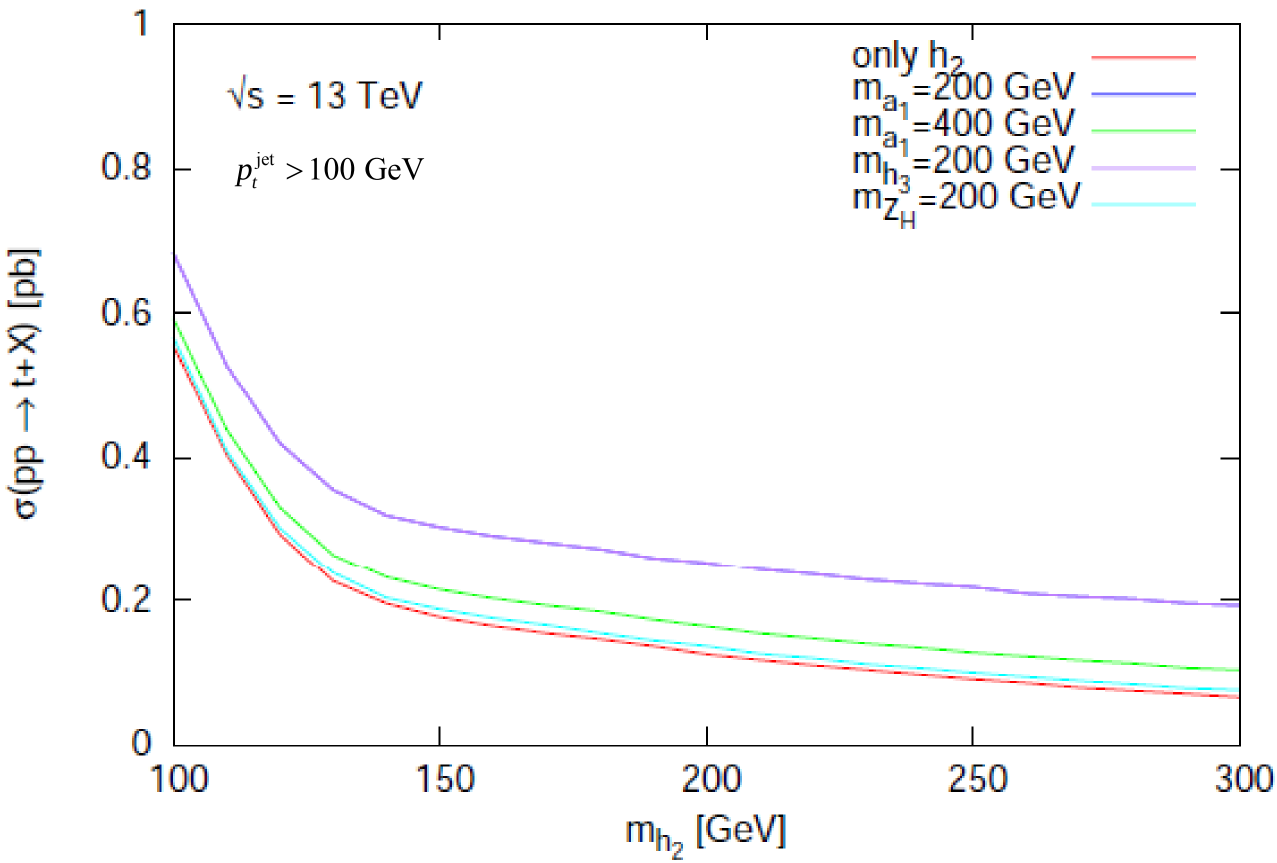
$Br(t \to Zq) < 0.05\%$

$Br(t \to hq) < 0.56\%(0.79\%)$ at 95% C.L.

Goldouzian, TOP2014

Single top production

$pp \to t + X$



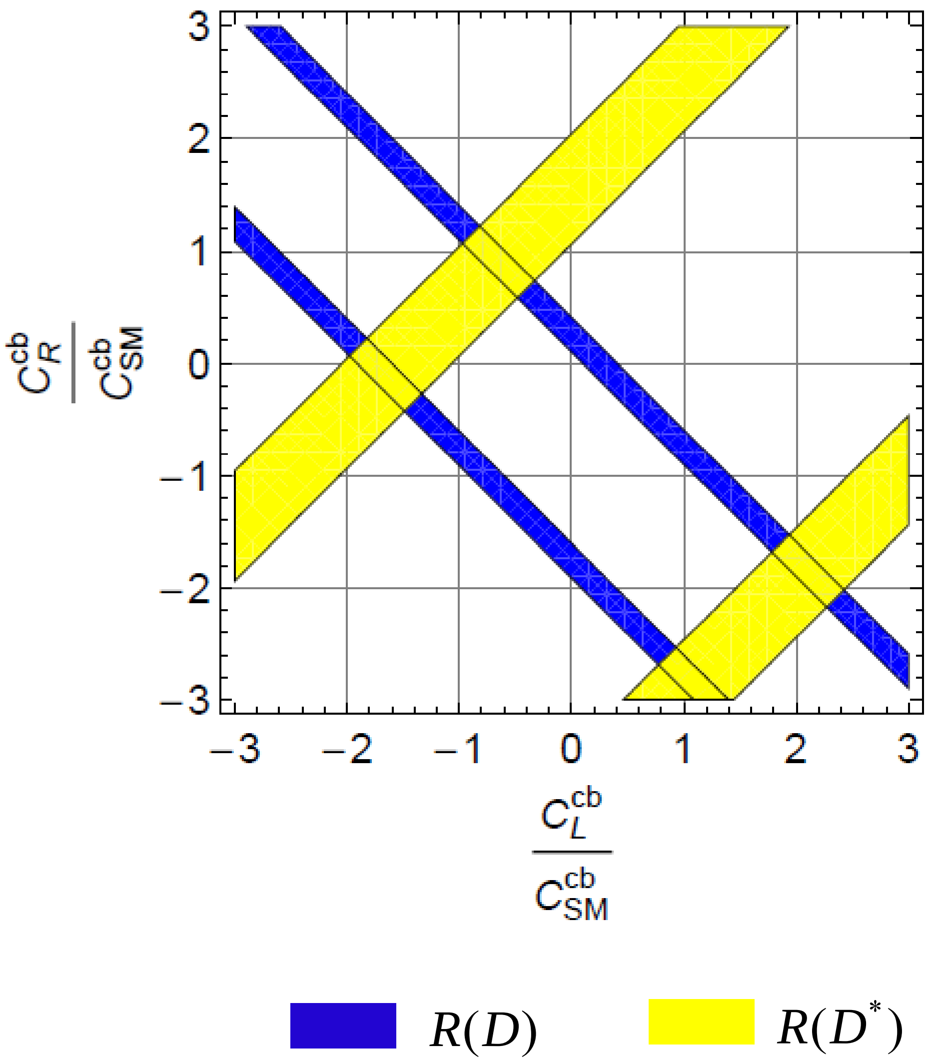
Chiral U(1)′ model

- 3 Higgs doublet model: $(u_1, u_2, u_3) = (-q, 0, q)$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
H_1	1	2	$1/2$	q
H_2	1	2	$1/2$	0
H_3	1	2	$1/2$	$-q$
Φ	1	1	0	-1

$$\begin{aligned}\mathcal{L}_{\mathrm{Y}} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H_2^\dagger \overline{D_j} Q_i + y^e_{ij} H_2^\dagger \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i .\end{aligned}$$

2HDM



- Large C_L with C_R=0 could explain data.
- Large C_R is not capable of achieving $R(D^{(*)})$ without sizable C_L.
- Type-II 2HDM (or 2HDM III with MFV) generate only C_R. → could not explain $R(D^{(*)})$ at BABAR.

Crivellin,Greub,Kokulu,1206.2634

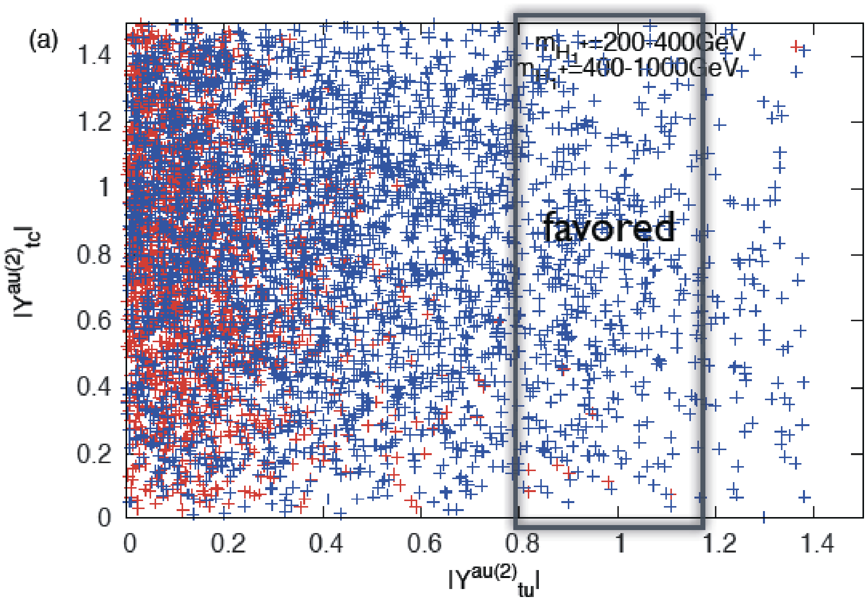
3HDM

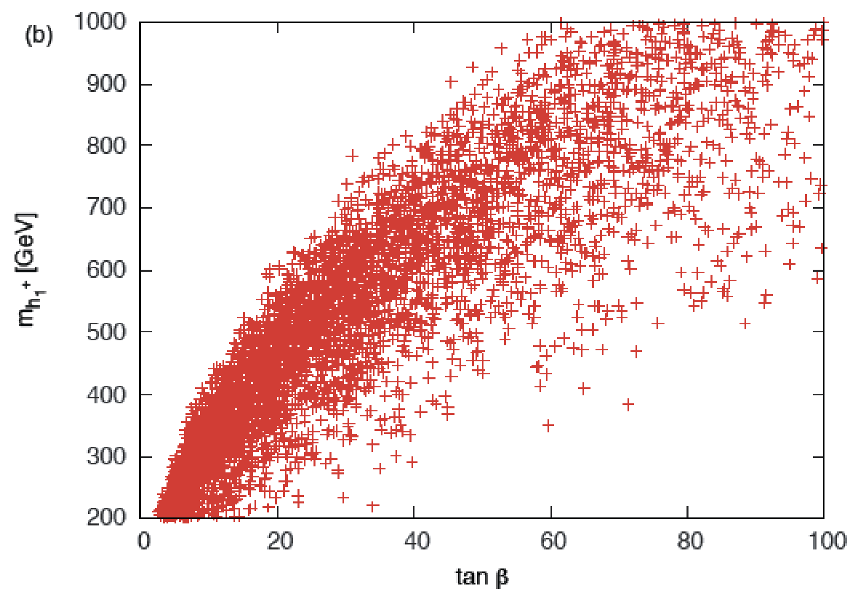
$(u_k) = (1, 0, -1)$

- 2 pairs of charged Higgs + 2 CP-odd pseudoscalars.

- parameter spaces are large → not difficult to find the allowed region without fine-tuning.

- ex) degenerate case $m_{h_1^+} = m_{h_2^+}$





$+ \ \ldots \ 200\text{GeV} \leq m_{h_1^+} \leq 400\text{GeV}$

$+ \ \ldots \ 400\text{GeV} \leq m_{h_1^+} \leq 1000\text{GeV}$

Wilson coefficients

Type-II 2HDM

$$\frac{C_L^{qb}}{C_{\rm SM}^{qb}} = \frac{m_q m_\tau}{m_{h^+}^2} \tan^2\beta \quad \sim 0$$

$$\frac{C_R^{qb}}{C_{\rm SM}^{qb}} = -\frac{m_b m_\tau}{m_{h^+}^2} \tan^2\beta.$$

- only C_R has sizable contribution.

Single top production

$pp \rightarrow t + X$