LHCb anomaly and B physics in flavored Z' models with flavored Higgs doublets

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Phys. Rev. D 95 115040 (2017)

Introduction

- The SM can explain almost all the exp. data

- However, there are some problems
  - fermion mass hierarchy ←
  - charge quantization
  - dark matter
  - …

- These are hints of physics beyond the SM

Introduction

- Fermion mass hierarchy

$\times$ 580 ($m_u \rightarrow m_c$), $\times$ 135 ($m_c \rightarrow m_t$)

$m_u = 2.2^{+0.6}_{-0.4}$ MeV $m_c = 1.28 \pm 0.03$ GeV $m_t = 173.1 \pm 0.6$ GeV

$\times$ 20 ($m_d \rightarrow m_s$), $\times$ 43 ($m_s \rightarrow m_b$)

$m_d = 4.7^{+0.5}_{-0.4}$ MeV $m_s = 96^{+8}_{-4}$ MeV $m_b = 4.18^{+0.04}_{-0.03}$ GeV

$\times$ 207 ($m_e \rightarrow m_\mu$), $\times$ 17 ($m_\mu \rightarrow m_\tau$)

$m_e = 0.511$ MeV $m_\mu = 105.658$ MeV $m_\tau = 1776.86 \pm 0.12$ MeV

from PDG

- How obtain these hierarchy?

Introduction

- We consider U(1)′ extended model

  flavored Higgs doublets model P. Ko, Y. Omura, YS, C. Yu, PRD **95**, 115040 (2017)

  ✓ all fermions have flavor dependent charge

  ✓ new Higgs doublets for Yukawa couplings

  → can explain SM fermion mass hierarchy

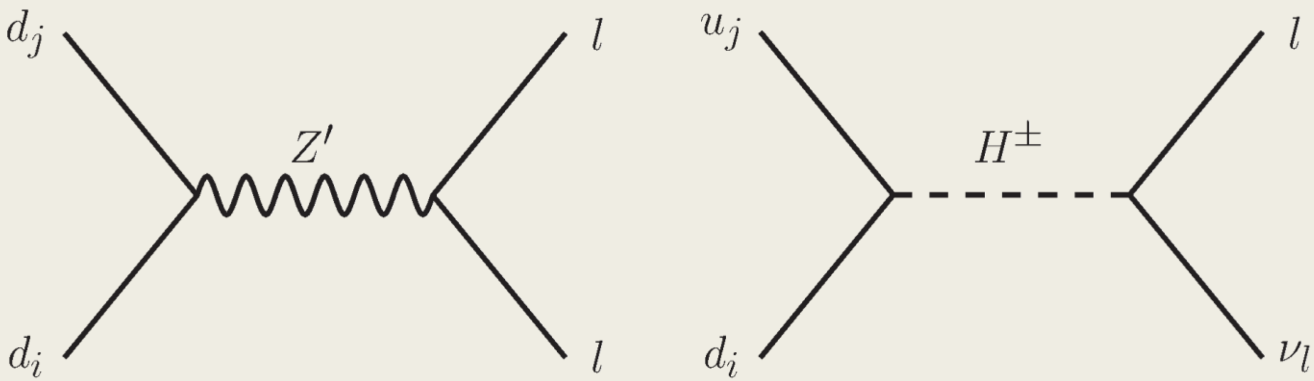
- New particles
  - new gauge boson, Z′ (← U(1)′ gauge sym.)
  - physical modes in Higgs doublet

$$H^1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, \quad H^2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad \cdots$$

→ many physical modes (e.g. charged Higgs, ...)

Introduction

- These particles cause FCNC processes
  - U(1)′ charges are flavor dependent
  - tree level processes



⇨ Affect flavor physics

- We focus on B physics $b \to sll$ (R(K), ΔM_{Bs}, $B \to X_s \gamma$, R(D), R(D*))

  possibility of explanation, any predictions

Model

Flavored Z' Model

- Charge assignment

P. Ko, Y. Omura, YS, C. Yu, PRD **95**, 115040 (2017)

New gauge sym. (→ $U(1)'$)

Fields	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$\hat{Q}_L^a$	1/2	**3**	**2**	1/6	0
$\hat{Q}_L^3$	1/2	**3**	**2**	1/6	1
$\hat{u}_R^a$	1/2	**3**	**1**	2/3	q_a
$\hat{u}_R^3$	1/2	**3**	**1**	2/3	$1+q_3$
$\hat{d}_R^i$	1/2	**3**	**1**	−1/3	$-q_1$
$\hat{L}^1$	1/2	**1**	**2**	−1/2	0
$\hat{L}^A$	1/2	**1**	**2**	−1/2	q_e
$\hat{e}_R^1$	1/2	**1**	**1**	−1	$-q_1$
$\hat{e}_R^A$	1/2	**1**	**1**	−1	$q_e - q_2$
H^i	0	**1**	**2**	1/2	q_i
Φ	0	**1**	**1**	0	q_Φ

3 Higgs doublets (H^i)

New SM singlet scalar (Φ)

a = 1, 2; A = 2, 3; i = 1, 2, 3

- ✓ In this work, $(q_1,\, q_2,\, q_3,\, q_\Phi) = (0,\, 1,\, 3,\, -1)$
- ✓ Extra fermions to cancel the U(1)′ anomaly

Flavored Z' Model

- Scalar potential

$$V_H = m_{H_i}^2 |H_i|^2 + m_\Phi^2 |\Phi|^2 + \lambda_H^{ij} |H_i|^2 |H_j|^2 + \lambda_{H\Phi}^i |H_i|^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$
$$- A_1 H_1^\dagger H_2 (\Phi)^{\frac{q_1 - q_2}{q_\Phi}} - A_2 H_2^\dagger H_3 (\Phi)^{\frac{q_2 - q_3}{q_\Phi}} - A_3 H_1^\dagger H_3 (\Phi)^{\frac{q_1 - q_3}{q_\Phi}} + \text{H.c.}$$

$(q_1, q_2, q_3, q_\Phi) = (0, 1, 3, -1)$

- Integrate H_1 out : $H_1 \to \dfrac{A_1}{m_{H_1}^2} \Phi H_2$

Higgs VEVs $\langle H_2^0 \rangle = \dfrac{v}{\sqrt{2}} \cos\beta, \ \langle H_3^0 \rangle = \dfrac{v}{\sqrt{2}} \sin\beta, \ \langle \Phi \rangle = \dfrac{v_\Phi}{\sqrt{2}}$

Fields	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
$\hat{Q}_L^a$	1/2	**3**	**2**	1/6	0
$\hat{Q}_L^3$	1/2	**3**	**2**	1/6	1
$\hat{u}_R^a$	1/2	**3**	**1**	2/3	q_a
$\hat{u}_R^3$	1/2	**3**	**1**	2/3	$1 + q_3$
$\hat{d}_R^i$	1/2	**3**	**1**	−1/3	$-q_1$
$\hat{L}^1$	1/2	**1**	**2**	−1/2	0
$\hat{L}^A$	1/2	**1**	**2**	−1/2	q_e
$\hat{e}_R^1$	1/2	**1**	**1**	−1	$-q_1$
$\hat{e}_R^A$	1/2	**1**	**1**	−1	$q_e - q_2$
H^i	0	**1**	**2**	1/2	q_i
Φ	0	**1**	**1**	0	q_Φ

H_3 → Top Yukawa
H_1, H_2 → Others

→ For fermion mass hierarchy,

large $\tan\beta$ & small $\epsilon \equiv \dfrac{A_1}{m_{H_1}^2} \langle \Phi \rangle$

Flavored Z' Model

- Fermion mass matrices

$$(Y^u_{ij}) = \begin{pmatrix} y^u_{11}\epsilon & y^u_{12} & 0 \\ y^u_{21}\epsilon & y^u_{22} & 0 \\ 0 & y^u_{32}\epsilon & y^u_{33} \end{pmatrix} \begin{pmatrix} \cos\beta & & \\ & \cos\beta & \\ & & \sin\beta \end{pmatrix},$$

$$(Y^d_{ij}) = \cos\beta \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix} \begin{pmatrix} y^d_{11} & y^d_{12} & y^d_{13} \\ y^d_{21} & y^d_{22} & y^d_{23} \\ y^d_{31} & y^d_{32} & y^d_{33} \end{pmatrix}, \quad (Y^e_{ij}) = \cos\beta \begin{pmatrix} \epsilon & & \\ & 1 & \\ & & 1 \end{pmatrix} \begin{pmatrix} y^e_{11} & 0 & 0 \\ 0 & y^e_{22} & y^e_{23} \\ 0 & y^e_{32} & y^e_{33} \end{pmatrix}$$

$$\Rightarrow \frac{v}{\sqrt{2}} Y^I = (U^I_L)^\dagger \mathrm{diag}(m^I_1,\, m^I_2,\, m^I_3) U^I_R \quad (I = u,\, d,\, e)$$

Important for flavor physics

each elements

$$|(U^d_L)_{33}| \simeq 1,\ |(U^d_L)_{23}| = \mathcal{O}(\epsilon),\ |(U^d_L)_{13}| = \mathcal{O}(\epsilon)$$

&

$$|(U^u_R)_{33}| \simeq 1,\ |(U^u_R)_{23}| = \mathcal{O}(\epsilon),\ |(U^u_R)_{23}| \gg |(U^u_R)_{13}|.$$

Note: $m_s/m_b = \mathcal{O}(\epsilon),\ m_e/m_\mu = \mathcal{O}(\epsilon)$

Flavored Z' Model

- Yukawa couplings with charged Higgs

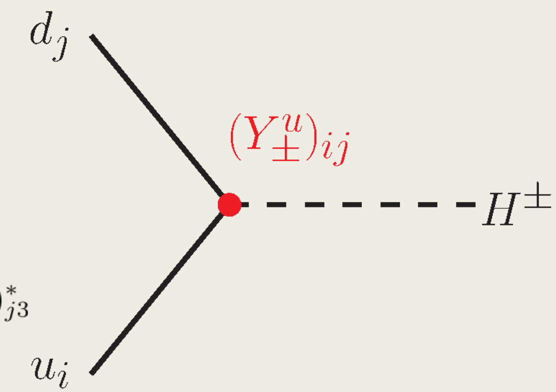
$$-\mathcal{L}_{Y_\pm} = (Y^u_\pm)_{ij} H^- \overline{d^i_L} u^j_R + (Y^d_\pm)_{ij} H^+ \overline{u^i_L} d^j_R + (Y^e_\pm)_{ij} H^+ \overline{\nu^i_L} e^j_R + \mathrm{H.c.}$$

$$\begin{cases} (Y^u_\pm)_{ij} = -\dfrac{m^k_u \sqrt{2}}{v} (V_{\mathrm{CKM}})^*_{ki} G_{kj} \\ (Y^d_\pm)_{ij} = -(V_{\mathrm{CKM}})_{ij} \dfrac{m^j_d \sqrt{2}}{v} \tan\beta \end{cases}$$

$$G_{ij} = \left(U^u_R \begin{pmatrix} -\tan\beta & & \\ & -\tan\beta & \\ & & \frac{1}{\tan\beta} \end{pmatrix} U^{u\dagger}_R \right)_{ij}$$

$$= -\tan\beta\, \delta_{ij} + \underline{\left(\tan\beta + \frac{1}{\tan\beta} \right) (G^u_R)_{ij}}$$

Flavor-violating $\quad (G^u_R)_{ij} \equiv (U^u_R)_{i3} (U^u_R)^*_{j3}$



Flavored Z' Model

- Z' couplings

interaction basis

$(q_1,\, q_2,\, q_3,\, q_\Phi) = (0,\, 1,\, 3,\, -1)$

$$\mathcal{L}_{Z'} = g'\hat{Z}'_\mu \left(\overline{\hat{Q}^3_L}\gamma^\mu \hat{Q}^3_L + q_1 \overline{\hat{u}^1_R}\gamma^\mu \hat{u}^1_R + (1+q_1)\overline{\hat{u}^2_R}\gamma^\mu \hat{u}^2_R + (1+q_3)\overline{\hat{u}^3_R}\gamma^\mu \hat{u}^3_R \right)$$
$$+ g'\hat{Z}'_\mu \left(q_e \overline{\hat{L}^A}\gamma^\mu \hat{L}^A - q_1 \overline{\hat{d}^i_R}\gamma^\mu \hat{d}^i_R - q_1 \overline{\hat{e}^1_R}\gamma^\mu \hat{e}^1_R + (q_e - q_2)\overline{\hat{e}^A_R}\gamma^\mu \hat{e}^A_R \right)$$

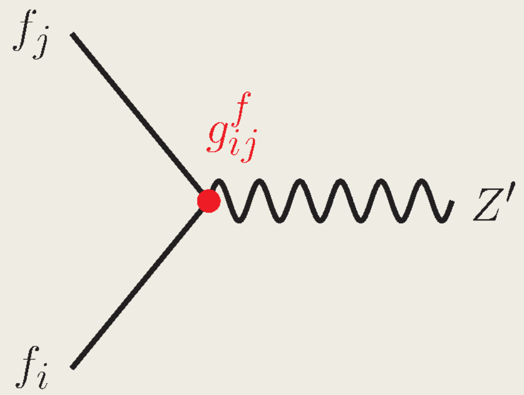
$$\frac{v}{\sqrt{2}} Y^I = (U^I_L)^\dagger \mathrm{diag}(m^I_1,\, m^I_2,\, m^I_3) U^I_R \quad (I = u,\, d,\, e)$$

mass basis

$$\mathcal{L}_{Z'} = g'\hat{Z}'_\mu \left\{ (g^u_L)_{ij}\overline{u^i_L}\gamma^\mu u^j_L + (g^d_L)_{ij}\overline{d^i_L}\gamma^\mu d^j_L + (g^u_R)_{ij}\overline{u^i_R}\gamma^\mu u^j_R - q_1 \overline{d^i_R}\gamma^\mu d^i_R \right\}$$
$$+ g'\hat{Z}'_\mu \left\{ q_e\left(\overline{\mu_L}\gamma^\mu \mu_L + \overline{\tau_L}\gamma^\mu \tau_L\right) + (g^\nu_L)_{ij}\overline{\nu^i_L}\gamma^\mu \nu^j_L - q_1 \overline{e^1_R}\gamma^\mu e^1_R + (q_e - q_2)\overline{e^A_R}\gamma^\mu e^A_R \right\}$$

Flavor-violating couplings

Flavored Z' Model



- Z' couplings

$$
\begin{aligned}
(g_L^d)_{ij} &= (U_L^d)_{i3}(U_L^d)^*_{j3},\\
(g_L^u)_{ij} &= (U_L^u)_{i3}(U_L^u)^*_{j3} = (V_{\rm CKM})_{ik}(g_L^d)_{kk'}(V_{\rm CKM})^*_{jk'},\\
(g_R^u)_{ij} &= (U_R^u)_{ik}q_k(U_R^u)^*_{jk},\\
(g_L^\nu)_{ij} &= q_e^k\left\{(U_L^\nu)_{ik}(U_L^\nu)^*_{jk}\right\} = q_e\left\{\delta_{ij} - (V^\dagger_{\rm PMNS})_{i3}(V^\dagger_{\rm PMNS})^*_{j3}\right\}.
\end{aligned}
$$

$$\frac{v}{\sqrt{2}}Y^I = (U_L^I)^\dagger {\rm diag}(m_1^I,\, m_2^I,\, m_3^I)U_R^I \quad (I = u,\, d,\, e)$$

- The size of each g_{ij}

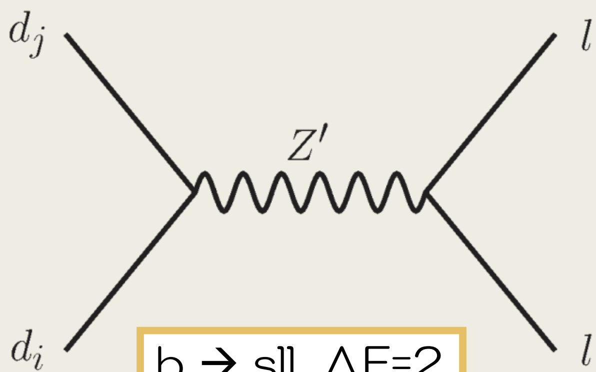
$$|(U_L^d)_{33}| \simeq 1,\ |(U_L^d)_{23}| = \mathcal{O}(\epsilon),\ |(U_L^d)_{13}| = \mathcal{O}(\epsilon)$$
$$|(U_R^u)_{33}| \simeq 1,\ |(U_R^u)_{23}| = \mathcal{O}(\epsilon),\ |(U_R^u)_{23}| \gg |(U_R^u)_{13}|.$$

$$
\begin{aligned}
&(g_L^d)_{sb} = \mathcal{O}(\epsilon),\ (g_L^d)_{db} = \mathcal{O}(\epsilon),\ (g_L^d)_{sd} = \mathcal{O}(\epsilon^2),\\
&(g_L^u)_{ij} \simeq (g_L^d)_{ij},\ (g_R^u)_{ct} = q_3 \times \mathcal{O}(\epsilon),\ |(g_R^u)_{ct}| \gg |(g_R^u)_{ut}|,\ |(g_R^u)_{uc}|.
\end{aligned}
$$

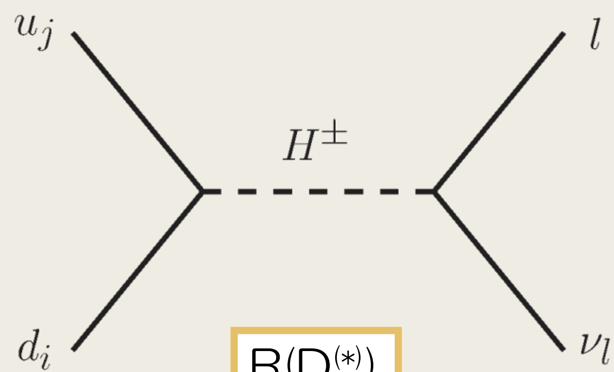
Flavor Physics

Flavor Physics Involving *b*

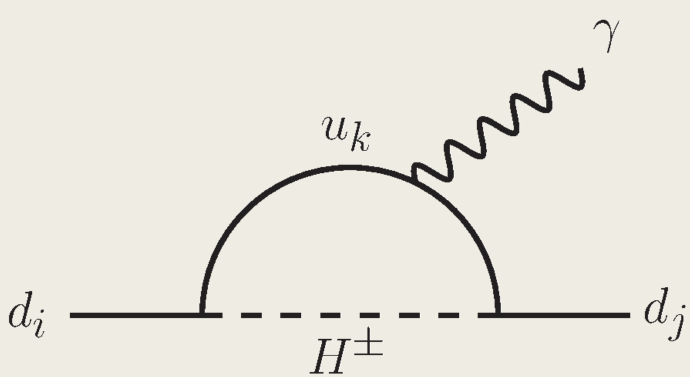
- Flavor-violating processes



b → sll, ΔF=2



R(D(*))



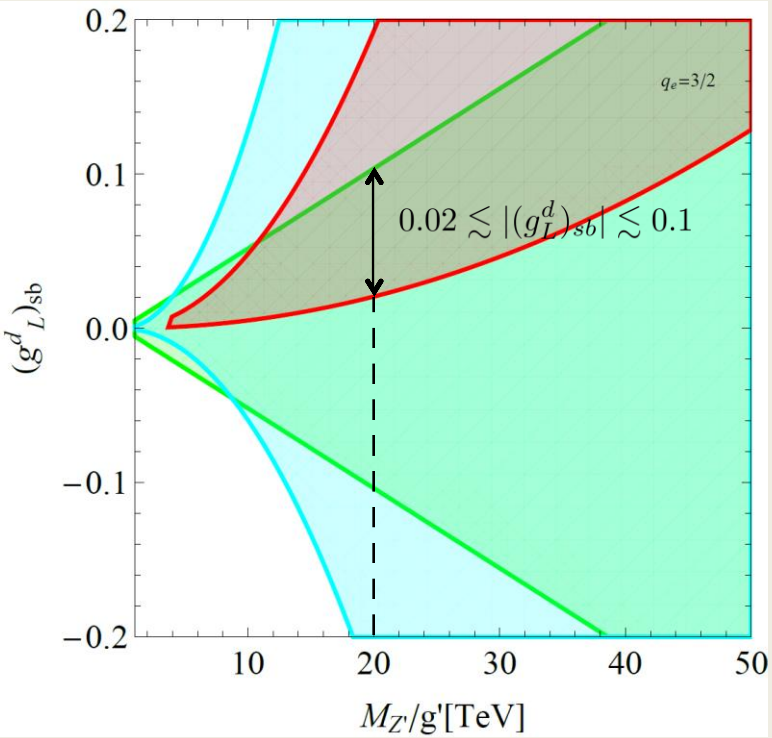
b → s γ

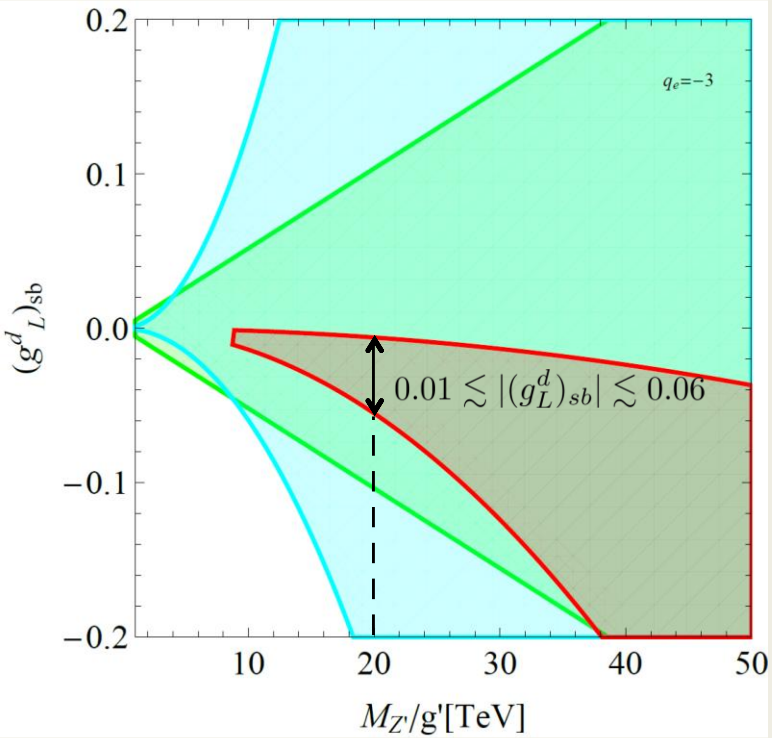
Flavor Physics Involving *b*

$$(g_L^d)_{sb} = \mathcal{O}(\epsilon)$$

- b → sll & ΔF=2 processes

S. Aoki *et al.*, EPJC **77**, 112 (2017).
Y. Amhis *et al.* [HFAG], arXiv:1412.7515 [hep-ex].





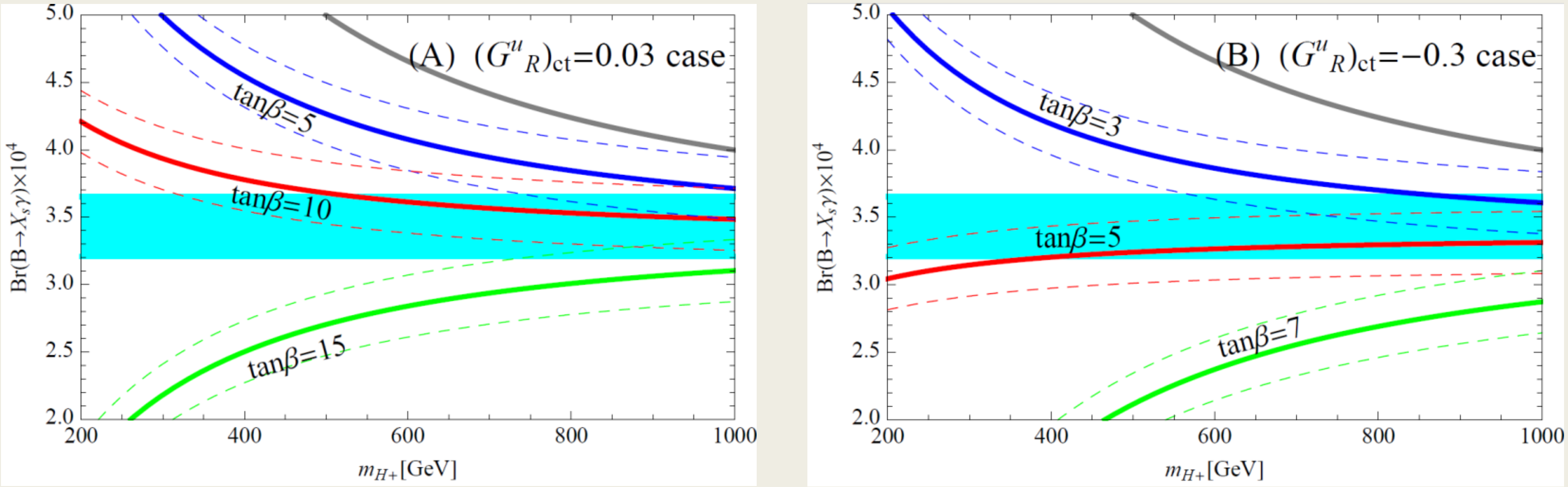
Allowed region for red: $C_9{}^{\mu}$, cyan: $C_{10}{}^{\mu}$, green: B_s-$B_s$bar mixing

T. Hurth, F. Mahmoudi, and S. Neshatpour, NPB **909**, 737 (2016)

Flavor Physics Involving *b*

- $B \to X_s \gamma$

- (A) $((G^u_R)_{tt}, (G^u_R)_{tc}, (G^u_R)_{cc}, (G^u_R)_{uu}) = (1-(G^u_R)_{cc}, 0.03, 10^{-3}, 0)$
- (B) $((G^u_R)_{tt}, (G^u_R)_{tc}, (G^u_R)_{cc}, (G^u_R)_{uu}) = (1-(G^u_R)_{cc}, -0.3, 0.1, 0)$



cyan band: experimental results (HFAG, arXiv:1412.7515)

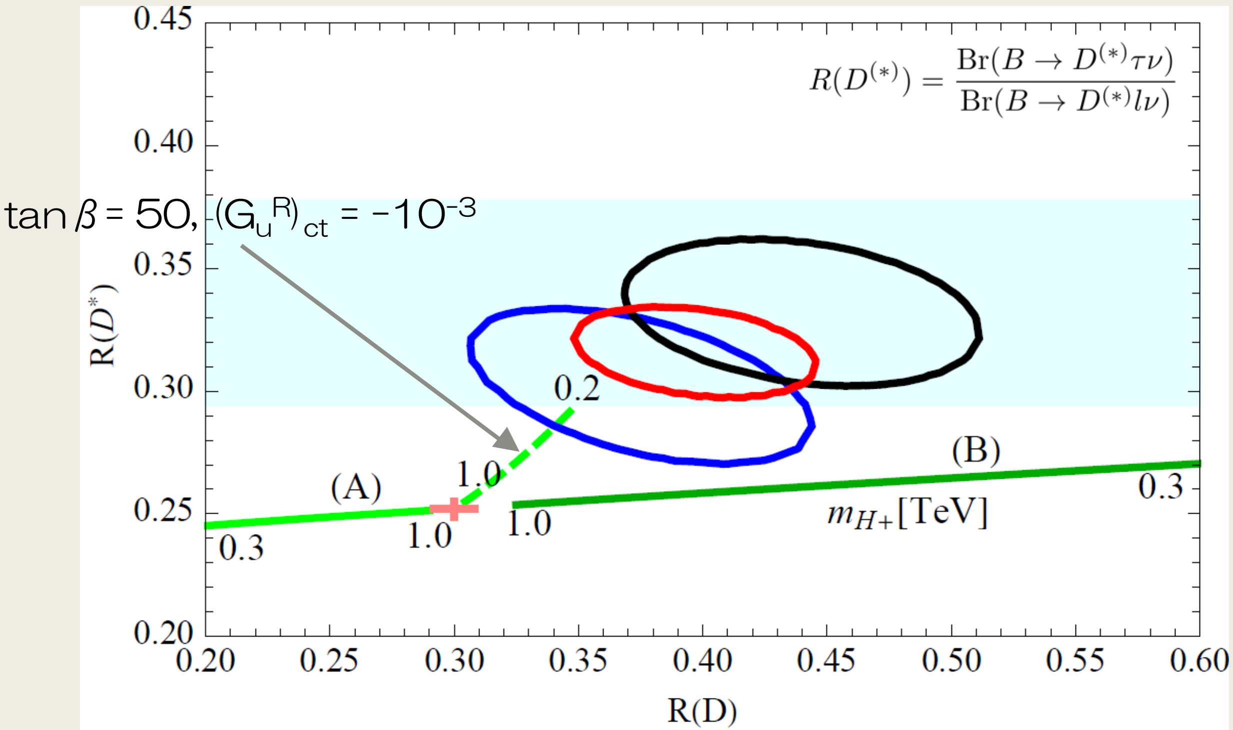
gray line: $\tan\beta = 50$, $(G^u_R)_{ct} = -10^{-3}$ (→ for $R(D^{(*)})$)

difference : couplings of charged Higgs

$$(Y^u_\pm)_{st} \simeq -\frac{m_t\sqrt{2}}{v} V^*_{ts} G_{tt} - \frac{m_c\sqrt{2}}{v} V^*_{cs} G_{ct}$$

Flavor Physics Involving *b*

- R(D) & R(D*)
  - (A) $((G_R^u)_{tt},\ (G_R^u)_{tc},\ (G_R^u)_{cc},\ (G_R^u)_{uu}) = (1-(G_R^u)_{cc},\ 0.03,\ 10^{-3},\ 0)$ ($\tan\beta = 10$)
  - (B) $((G_R^u)_{tt},\ (G_R^u)_{tc},\ (G_R^u)_{cc},\ (G_R^u)_{uu}) = (1-(G_R^u)_{cc},\ -0.3,\ 0.1,\ 0)$ ($\tan\beta = 5$)



Belle: PRD **92**, 072014 (2015);
arXiv:1603.06711 [hep-ex].
BABAR: PRL **109**, 101802 (2012);
PRD **88**, 072012 (2013).
HFAG: arXiv:1412.7515 [hep-ex].
LHCb: PRL **115**, 111803 (2015).
SM pred.: PRD **92**, 054510 (2015);
PRD **85**, 094025 (2012).

Ellipse → 1 σ results for the Bell (blue), *BABAR* (black), HFAG (red)
cyan band: LHCb 1 σ result

Summary

Summary

- We consider U(1)′ extended model

  new Higgs doublets → can explain fermion masses

- focus on B physics by Z′ and charged Higgs

  b → sll & ΔF=2 : can explain simultaneously

  B → $X_s \gamma$: $m_{H\pm}$>500 GeV, $\tan\beta \sim$ 5-10

  R(D) & R(D*) : hard to explain

- In this model, (t,c)-element becomes large

  if the sensitivity of LHC is improved, $(G_R^u)_{tc} \sim \mathcal{O}(0.01)$

  this model can be tested via t → ch channel

$$\frac{m_t}{v} \tan\beta (G_R^u)_{tc} \{\sin(\alpha-\beta)h + \cos(\alpha-\beta)H - iA\} \overline{t_L} c_R + \mathrm{H.c.}$$

Buck up

Flavored Z' Model

- Yukawa terms

$$V_{\mathrm{Y}} = y^u_{1a}\overline{\hat{Q}^1_L}\widetilde{H^a}\hat{u}^a_R + y^u_{2a}\overline{\hat{Q}^2_L}\widetilde{H^a}\hat{u}^a_R + y^u_{33}\overline{\hat{Q}^3_L}\widetilde{H^3}\hat{u}^3_R + y^u_{32}\overline{\hat{Q}^3_L}\widetilde{H^1}\hat{u}^2_R$$
$$+ y^d_{ai}\overline{\hat{Q}^a_L}H^1\hat{d}^i_R + y^d_{3i}\overline{\hat{Q}^3_L}H^2\hat{d}^i_R$$
$$+ y^e_{11}\overline{\hat{L}^1}H^1\hat{e}^1_R + y^e_{AB}\overline{\hat{L}^A}H^2\hat{e}^B_R + \mathrm{H.c.}$$

a = 1, 2; A = 2, 3; i = 1, 2, 3

- Fermion mass matrices

$$(Y^u_{ij}) = \begin{pmatrix} y^u_{11}\epsilon & y^u_{12} & 0 \\ y^u_{21}\epsilon & y^u_{22} & 0 \\ 0 & y^u_{32}\epsilon & y^u_{33} \end{pmatrix} \begin{pmatrix} \cos\beta & & \\ & \cos\beta & \\ & & \sin\beta \end{pmatrix},$$

$$\epsilon \equiv \frac{A_1}{m^2_{H_1}}\langle\Phi\rangle$$

$$(Y^d_{ij}) = \cos\beta \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix} \begin{pmatrix} y^d_{11} & y^d_{12} & y^d_{13} \\ y^d_{21} & y^d_{22} & y^d_{23} \\ y^d_{31} & y^d_{32} & y^d_{33} \end{pmatrix}, \quad (Y^e_{ij}) = \cos\beta \begin{pmatrix} \epsilon & & \\ & 1 & \\ & & 1 \end{pmatrix} \begin{pmatrix} y^e_{11} & 0 & 0 \\ 0 & y^e_{22} & y^e_{23} \\ 0 & y^e_{32} & y^e_{33} \end{pmatrix}$$

Extra matters

Fields	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'_R	1/2	**3**	**2**	1/6	1
Q'_L	1/2	**3**	**2**	1/6	0
u'_L	1/2	**3**	**1**	2/3	1
u'_R	1/2	**3**	**1**	2/3	0
u''_L	1/2	**3**	**1**	2/3	$1+q_3$
u''_R	1/2	**3**	**1**	2/3	0
R'_μ	1/2	**1**	**2**	$-1/2$	q_e
L'_μ	1/2	**1**	**2**	$-1/2$	0
R'_τ	1/2	**1**	**2**	$-1/2$	q_e
L'_τ	1/2	**1**	**2**	$-1/2$	0
μ'_L	1/2	**1**	**1**	-1	q_e-1
μ'_R	1/2	**1**	**1**	-1	0
τ'_L	1/2	**1**	**1**	-1	q_e-1
τ'_R	1/2	**1**	**1**	-1	0
Φ_l	0	**1**	**1**	0	q_e
Φ_r	0	**1**	**1**	0	q_e-1

Table 4: The extra chiral fermions for the anomaly-free conditions with $(q_1, q_2) = (0, 1)$. The bold entries "**3**" ("**2**") show the fundamental representation of SU(3) (SU(2)) and "**1**" shows singlet under SU(3) or SU(2).

■ B physics

- b → sll (R(K)) R. Aaij *et al.* [LHCb Collab.], PRL **113**, 151601 (2014).
- ΔM_{Bs}
- $B \to X_s \gamma$
- R(D)、R(D*)

Experiment	$R(D)$	$R(D^*)$
Belle	$0.375 \pm 0.064 \pm 0.026$ [15]	$0.302 \pm 0.03 \pm 0.011$ [16]
BABAR	$0.440 \pm 0.058 \pm 0.042$ [13, 14]	$0.332 \pm 0.024 \pm 0.018$ [13, 14]
LHCb		$0.336 \pm 0.027 \pm 0.030$ [99]
HFAG	$0.397 \pm 0.040 \pm 0.028$ [93]	$0.316 \pm 0.016 \pm 0.010$ [93]
SM prediction	0.300 ± 0.008 [100–103]	0.252 ± 0.003 [104]

[13,14] J.P. Lees *et al.* [BaBar Collab.], PRL **109**, 101802 (2012); PRD **88**, 072012 (2013).
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[16] A. Abdesselam *et al.* [Belle Collab.], arXiv:1603.06711 [hep-ex].
[93] Y. Amhis *et al.* [Heavy Flavor Averaging Group (HFAG)], arXiv:1412.7515 [hep-ex].
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[101] M. Tanaka and R. Watanabe, PRD **82**, 034027 (2010).
[102] J.A. Bailey *et al.* [MILC Collab.], PRD **92** 034506 (2015).
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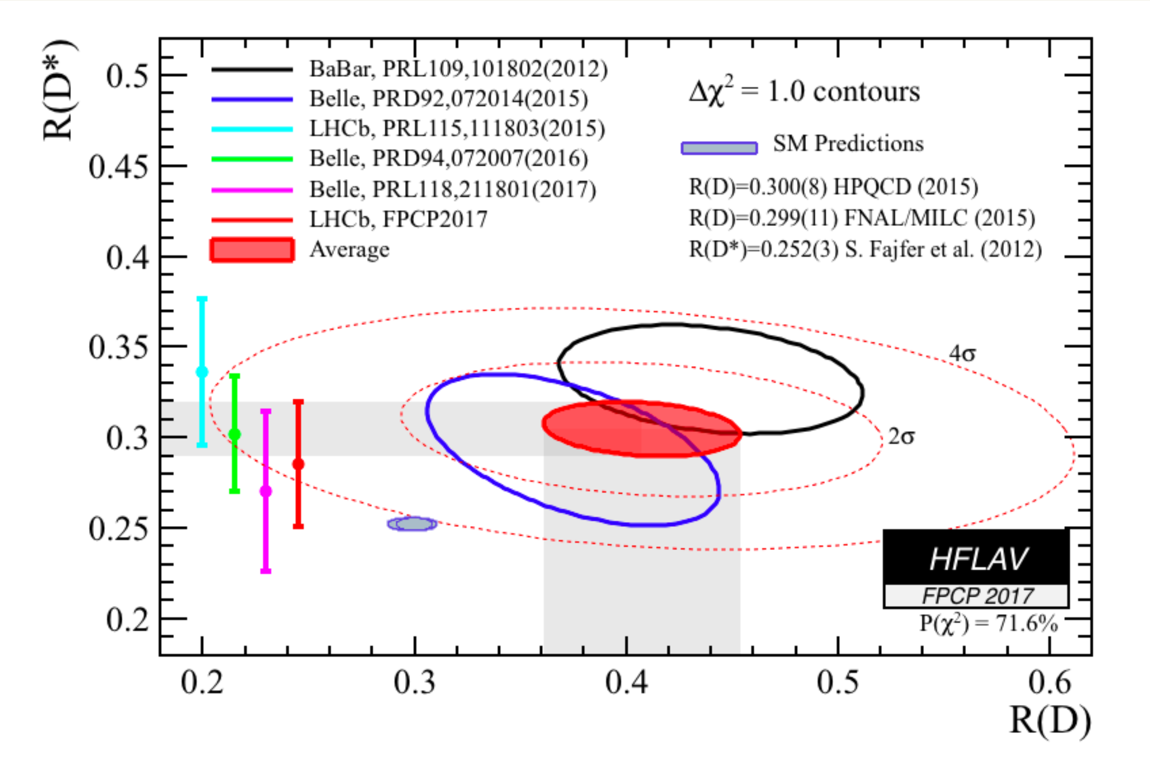
[104] S. Fajfer, J.F. Kamenik, and I. Nisandzic, PRD **85**, 094025 (2012).

Introduction

- B anomalies



From talk slide of FPCP2017

Yukawa couplings

- Yukawa couplings (S = h, H, A)

$$-\mathcal{L}_Y = (Y^u_S)_{ij} S \overline{u^i_L} u^j_R + (Y^d_S)_{ij} h \overline{d^i_L} d^j_R + (Y^e_S)_{ij} H \overline{e^i_L} e^j_R$$
$$+ (Y^u_\pm)_{ij} H^- \overline{d^i_L} u^j_R + (Y^d_\pm)_{ij} H^+ \overline{u^i_L} d^j_R + (Y^e_\pm)_{ij} H^+ \overline{\nu^i_L} e^j_R + \text{H.c.}$$

Up-type

$$(Y^u_h)_{ij} = \frac{m^i_u \sin(\alpha-\beta)}{v} G_{ij} + \frac{m^i_u \cos(\alpha-\beta)}{v} \delta_{ij},$$
$$(Y^u_H)_{ij} = \frac{m^i_u \cos(\alpha-\beta)}{v} G_{ij} - \frac{m^i_u \sin(\alpha-\beta)}{v} \delta_{ij},$$
$$(Y^u_A)_{ij} = -i \frac{m^i_u}{v} G_{ij},$$
$$(Y^u_\pm)_{ij} = -\frac{m^k_u \sqrt{2}}{v} V^*_{ki} G_{kj},$$

Down-type

$$(Y^d_h)_{ij} = -\delta_{ij} \frac{m^i_d}{v} \frac{\cos\alpha}{\cos\beta},$$
$$(Y^d_H)_{ij} = \delta_{ij} \frac{m^i_d}{v} \frac{\sin\alpha}{\cos\beta},$$
$$(Y^d_A)_{ij} = -i\delta_{ij} \frac{m^i_d}{v} \tan\beta,$$
$$(Y^d_\pm)_{ij} = -V_{ij} \frac{m^j_d \sqrt{2}}{v} \tan\beta$$

Flavor Physics Involving b

- input parameters from PDG [73]

$\alpha_s(M_Z)$	$0.1193(16)$ [73]	λ	$0.22537(61)$ [73]
G_F	$1.1663787(6)\times 10^{-5}$ GeV^{-2} [73]	A	$0.814^{+0.023}_{-0.024}$ [73]
m_b	4.18 ± 0.03 GeV [73]	$\overline{\rho}$	$0.117(21)$ [73]
m_t	160^{+5}_{-4} GeV [73]	$\overline{\eta}$	$0.353(13)$ [73]
m_c	1.275 ± 0.025 GeV [73]		

Flavor Physics Involving b

- b → sll

$$\mathcal{H}_{\rm eff} = -g_{\rm SM}\left[C_9^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu l) + C_{10}^l(\overline{s_L}\gamma_\mu b_L)(\bar{l}\gamma^\mu\gamma_5 l) + \text{H.c.}\right]$$

$$C_9^e = C_{10}^e = \frac{g'^2}{2g_{\rm SM}M_{Z'}^2}(g_L^d)_{sb}\,q_1$$

$$g_{\rm SM} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}$$

$$C_9^\mu = C_9^\tau = -\frac{g'^2}{2g_{\rm SM}M_{Z'}^2}(g_L^d)_{sb}\,(2q_e - q_2)$$

$$C_{10}^\mu = C_{10}^\tau = \frac{g'^2}{2g_{\rm SM}M_{Z'}^2}(g_L^d)_{sb}\,q_2$$

exp. bounds

$$-0.29\,(-0.34) \leq \; C_9^\mu/C_9^{\rm SM} \; \leq -0.013\,(0.053)$$

$$-0.19\,(-0.29) \leq C_{10}^\mu/C_{10}^{\rm SM} \; \leq 0.088\,(0.15)$$

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- ΔF=2

$$\mathcal{H}_{\rm eff}^{\Delta F=2} = C_1^{ij}(\overline{d_L^i}\gamma_\mu d_L^j)(\overline{d_L^i}\gamma_\mu d_L^j), \quad C_1^{ij} = \frac{g'^2}{2M_{Z'}^2}(g_L^d)_{ij}(g_L^d)_{ij}$$

Flavor Physics Involving *b*

- $B \to X_s \gamma$

$$\mathcal{H}_{\rm eff}^{b\to s\gamma} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left(C_7 \mathcal{O}_7 + C_8 \mathcal{O}_8 \right)$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\overline{s_L} \sigma^{\mu\nu} b_R) F_{\mu\nu}, \; \mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b (\overline{s_L} t^a \sigma^{\mu\nu} b_R) G^a_{\mu\nu}$$

$$C_7 = \left(\frac{m_j^u m_k^u}{m_t^2} \right) \frac{V_{kb} V_{js}^*}{V_{tb} V_{ts}^*} G_{ki}^* G_{ji} C_7^{(1)}(x_i) + \left(\frac{m_k^u}{m_t} \right) \frac{V_{ib} V_{ks}^*}{V_{tb} V_{ts}^*} G_{ki} \tan\beta \, C_7^{(2)}(x_i)$$

$$C_8 = \left(\frac{m_j^u m_k^u}{m_t^2} \right) \frac{V_{kb} V_{js}^*}{V_{tb} V_{ts}^*} G_{ki}^* G_{ji} C_8^{(1)}(x_i) + \left(\frac{m_k^u}{m_t} \right) \frac{V_{ib} V_{ks}^*}{V_{tb} V_{ts}^*} G_{ki} \tan\beta \, C_8^{(2)}(x_i)$$

Loop integrals:

$$C_7^{(1)}(x) = \frac{x}{72} \left\{ \frac{-8x^3 + 3x^2 + 12x - 7 + (18x^2 - 12x)\ln x}{(x-1)^4} \right\},$$

$$C_7^{(2)}(x) = \frac{x}{12} \left\{ \frac{-5x^2 + 8x - 3 + (6x - 4)\ln x}{(x-1)^3} \right\},$$

$$C_8^{(1)}(x) = \frac{x}{24} \left\{ \frac{-x^3 + 6x^2 - 3x - 2 - 6x\ln x}{(x-1)^4} \right\},$$

$$C_8^{(2)}(x) = \frac{x}{4} \left\{ \frac{-x^2 + 4x - 3 - 2\ln x}{(x-1)^3} \right\}.$$

Flavor Physics Involving *b*

- R(D) & R(D*) $R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}l\nu)}$

$$\mathcal{H}_{\rm eff}^{B-\tau} = C_{\rm SM}^{cb}(\overline{c_L}\gamma_\mu b_L)(\overline{\tau_L}\gamma^\mu \nu_L) + C_R^{cb}(\overline{c_L}b_R)(\overline{\tau_R}\nu_L) + C_L^{cb}(\overline{c_R}b_L)(\overline{\tau_R}\nu_L)$$

$$R(D) = R_{\rm SM}\left(1 + 1.5\ \mathrm{Re}\left(\frac{C_R^{cb}+C_L^{cb}}{C_{\rm SM}^{cb}}\right) + \left|\frac{C_R^{cb}+C_L^{cb}}{C_{\rm SM}^{cb}}\right|^2\right),$$

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

SM & our model coef.:

$$C_{\rm SM}^{cb} = 2V_{cb}/v^2,$$

$$\frac{C_L^{cb}}{C_{\rm SM}^{cb}} = \frac{m_c m_\tau}{m_{H_\pm}^2}\tan^2\beta - \sum_k \frac{V_{kb}}{V_{cb}}\frac{m_k^u m_\tau (G_R^u)_{kc}^*}{m_{H_\pm}^2\cos^2\beta},$$

$$\frac{C_R^{cb}}{C_{\rm SM}^{cb}} = -\frac{m_b m_\tau}{m_{H_\pm}^2}\tan^2\beta.$$