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

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Phys. Rev. D 95 115040 (2017)

Introduction

- 標準模型は実験結果をうまく再現

- しかし、いくつか謎が残っている
  - フェルミオンの質量階層
  - 電荷の量子化
  - 暗黒物質
  - …

- それらは標準模型を超える新物理のヒント

Introduction

- フェルミオンの質量階層

$$\begin{tikzcd}
m_u = 2.2^{+0.6}_{-0.4}\ \text{MeV} \arrow[r, bend left, "\times 580"] & m_c = 1.28 \pm 0.03\ \text{GeV} \arrow[r, bend left, "\times 135"] & m_t = 173.1 \pm 0.6\ \text{GeV} \\
m_d = 4.7^{+0.5}_{-0.4}\ \text{MeV} \arrow[r, bend left, "\times 20"] & m_s = 96^{+8}_{-4}\ \text{MeV} \arrow[r, bend left, "\times 43"] & m_b = 4.18^{+0.04}_{-0.03}\ \text{GeV} \\
m_e = 0.511\ \text{MeV} \arrow[r, bend left, "\times 207"] & m_\mu = 105.658\ \text{MeV} \arrow[r, bend left, "\times 17"] & m_\tau = 1776.86 \pm 0.12\ \text{MeV}
\end{tikzcd}$$

from PDG

- どうやってこれらの階層性を理論的に得るのか？

Introduction

- この階層性を説明できる模型を構築

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

  - ✓ 新たにU(1)′ ゲージ対称性を課す
  - ✓ このもとでフェルミオンはフレーバーによる電荷を持つ
  - ✓ 湯川相互作用を書くため新たにHiggs doublet も導入

- 新たな粒子たち
  - U(1)′ ゲージ対称性に対応するゲージボソン：Z′
  - Higgs doublet の中で残る物理的な自由度

SM: $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ → 物理的な自由度は中性成分の実部のみ

Introduction

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- 新たな粒子たち
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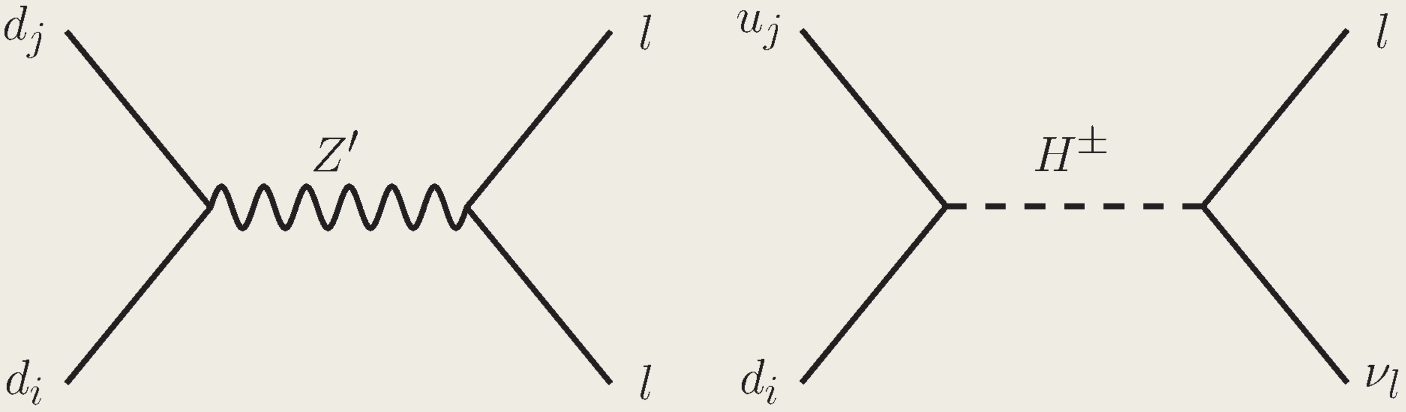
  - Higgs doublet の中で残る物理的な自由度

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

→ 荷電成分なども物理的自由度として残る

Introduction

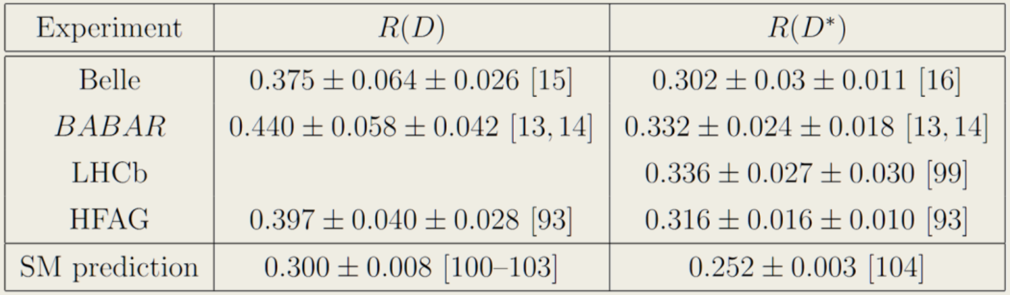
- これらの新たな粒子との結合がフレーバーを破る
  - U(1)′ 電荷がフレーバーによって異なる
  - tree level で生じ得る



⇨ フレーバー物理に影響する

Introduction

- 今回注目するフレーバー物理：bクォークを含む物
  - $b \rightarrow sll$ （R(K)） R. Aaij *et al.* [LHCb Collab.], PRL **113**, 151601 (2014).
  - ΔM_{Bs}
  - $B \rightarrow X_s \gamma$
  - 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).
[15] M. Huschle *et al.* [Belle Collab.], PRD **92**, 072014 (2015).
[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].
[99] R. Aaij *et al.* [LHCb Collab.], PRL **115**, 111803 (2015).
[100] J.F. Kamenik and F. Mescia, PRD **78** 014003 (2008).
[101] M. Tanaka and R. Watanabe, PRD **82**, 034027 (2010).
[102] J.A. Bailey *et al.* [MILC Collab.], PRD **92** 034506 (2015).
[103] H. Na *et al.* [HPQCD Collab.], PRD **92**, 054510 (2015).
[104] S. Fajfer, J.F. Kamenik, and I. Nisandzic, PRD **85**, 094025 (2012).

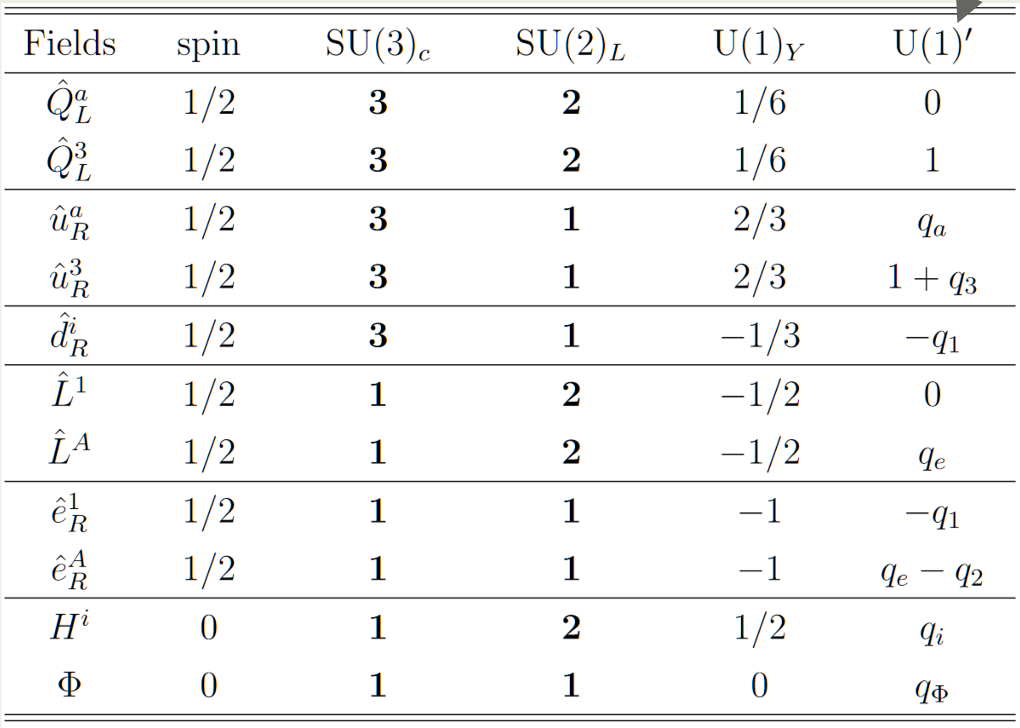
- これらの観測値を説明できるか？

Flavored Z' Model

- Charge assignment

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

New gauge sym.



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

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

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

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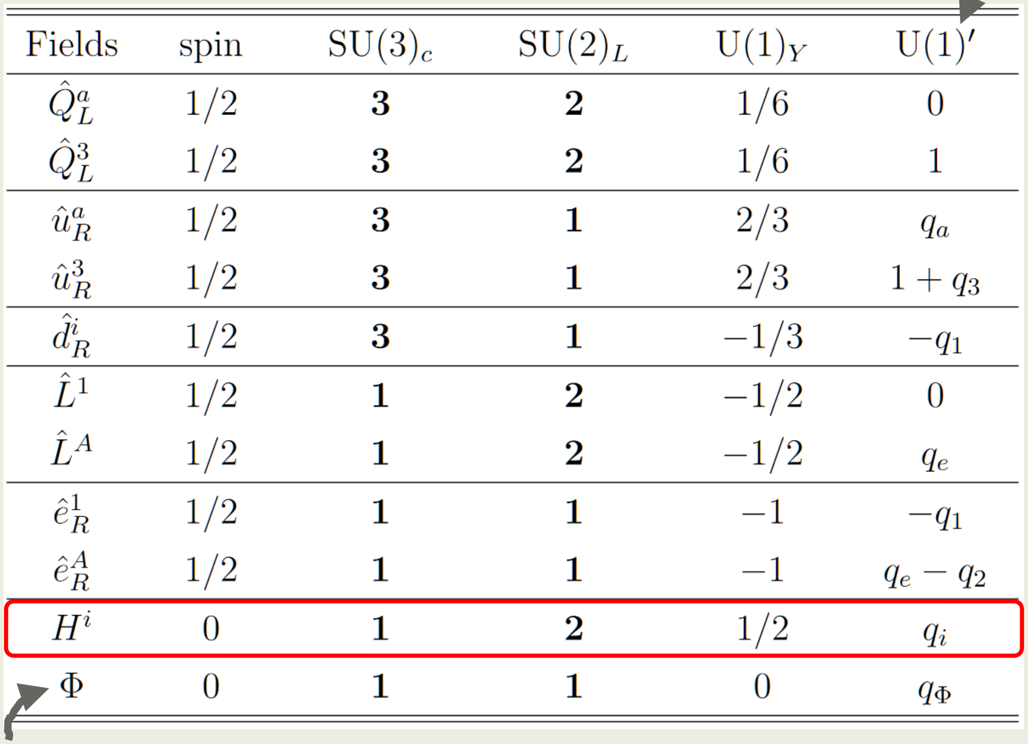

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Φ	0	$\mathbf{1}$	$\mathbf{1}$	0	q_Φ

３つの
Higgs doublets

新しいSM singletスカラー

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

✓ 今回のモデルでは $(q_1,\, q_2,\, q_3,\, q_\Phi) = (0,\, 1,\, 3,\, -1)$

Flavored Z' Model

- スカラーセクター：3 Higgs doublets + 1 singlet

  → フェルミオン質量階層のためにはVEVは

$$\langle H_1 \rangle \ll \langle H_2 \rangle \ll \langle H_3 \rangle$$

- H_1の質量 $V_H \supset m_{H_1}^2 |H_1|^2$ が電弱スケールより大きい場合、H_1はintegrate outされる

$$H_1 \to \frac{A_1}{m_{H_1}^2} \Phi H_2$$

A_1：H_1-H_2-Φ coupling

  → 有効理論は2 Higgs doublet model + 1 singlet

- 残りのHiggsのVEV：$\langle H_2 \rangle = \frac{v}{\sqrt{2}} \cos\beta,\ \langle H_3 \rangle = \frac{v}{\sqrt{2}} \sin\beta,\ \langle \Phi \rangle = \frac{v_\Phi}{\sqrt{2}}$

Flavored Z' Model

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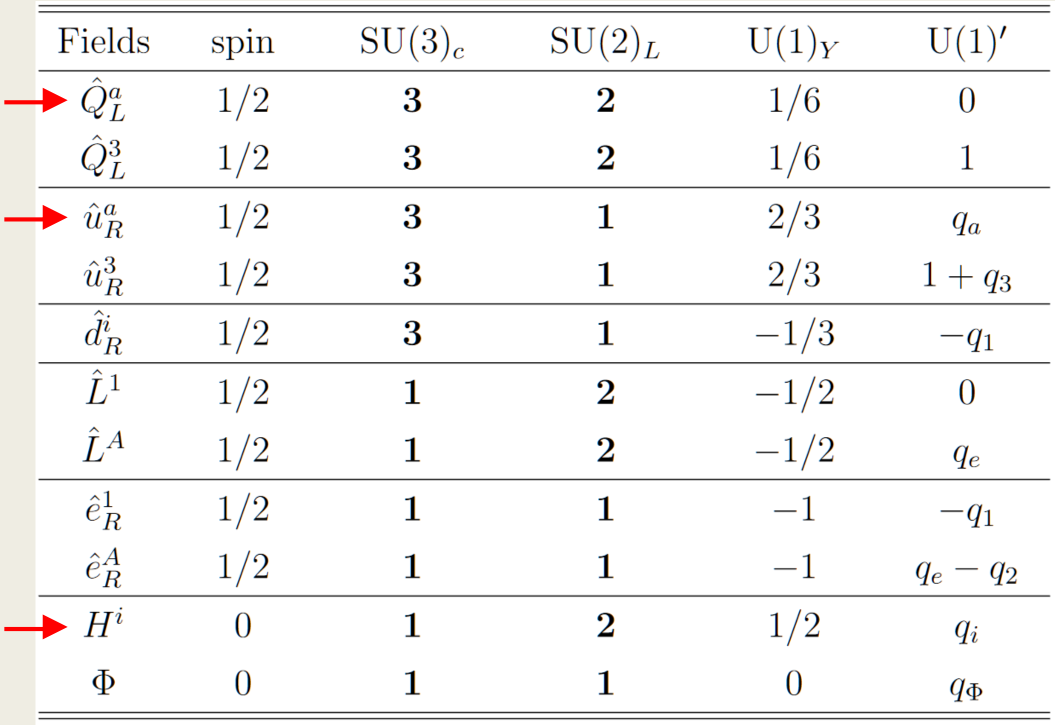
  → large $\tan\beta$ & small $\epsilon \equiv \frac{A_1}{m_{H_1}^2}\langle\Phi\rangle$

Flavored Z' Model

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

- 湯川結合はどうなるか $\mathcal{L}_{\rm Y} = y\overline{F_L} H f_R$



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

○

$$\overline{Q_L^1}\widetilde{H}^a u_R^a$$

0 + (-q_a) + q_a

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

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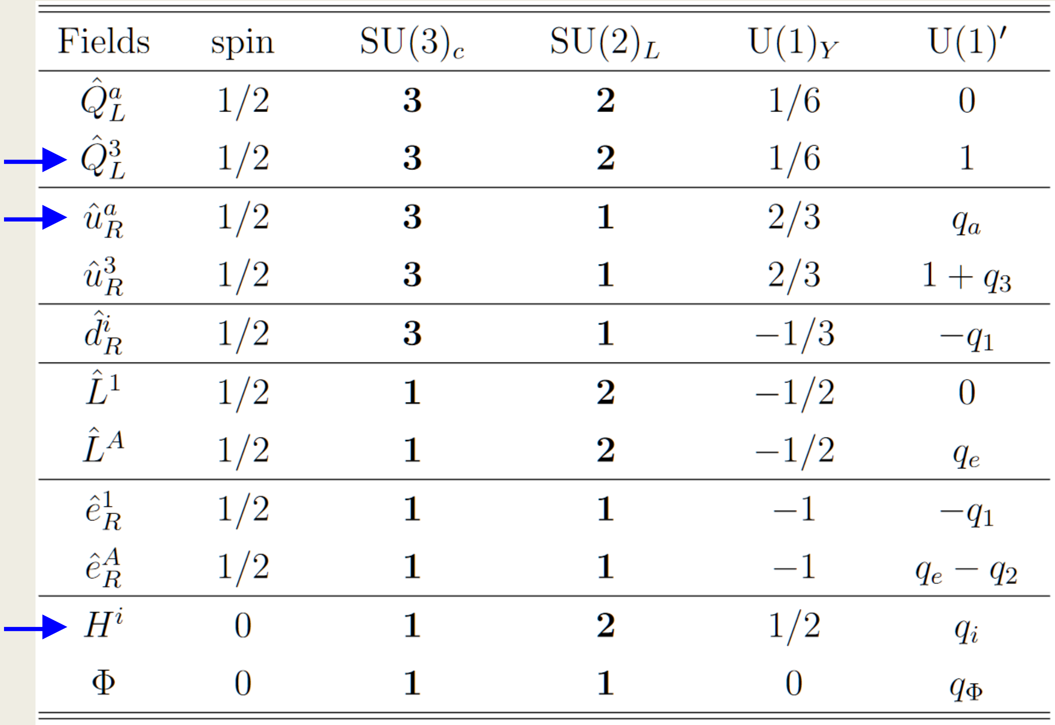

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→ $\hat{Q}^3_L$	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	1
→ $\hat{u}^a_R$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	q_a
$\hat{u}^3_R$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$2/3$	$1+q_3$
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→ H^i	0	$\mathbf{1}$	$\mathbf{2}$	$1/2$	q_i
Φ	0	$\mathbf{1}$	$\mathbf{1}$	0	q_Φ

○

$$\overline{Q^1_L}\widetilde{H}^a u^a_R$$

0 + (-q_a) + q_a

✕

$$\overline{Q^3_L}\widetilde{H}^a u^a_R$$

-1 + (-q_a) + q_a

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

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H^i	0	**1**	**2**	$1/2$	q_i
Φ	0	**1**	**1**	0	q_Φ

○

$$\overline{Q_L^1}\widetilde{H^a}u_R^a$$

0 + (-q_a) + q_a

×

$$\overline{Q_L^3}\widetilde{H^a}u_R^a$$

-1 + (-q_a) + q_a

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

⇨ 湯川結合のいくつかはU(1)'で禁止される

Flavored Z' Model

- 湯川行列

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

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

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

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

⇨

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

- 対角化行列の成分

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

&

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

Flavored Z' Model

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

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

- 湯川行列

$$(m_u, m_c, m_t) \sim (\epsilon\cos\beta, \cos\beta, \sin\beta)$$

$$(m_d, m_s, m_b) \sim (\epsilon\cos\beta, \epsilon\cos\beta, \cos\beta)$$

$$(m_e, m_\mu, m_\tau) \sim (\epsilon\cos\beta, \cos\beta, \cos\beta)$$

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

- 対角化行列の成分

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

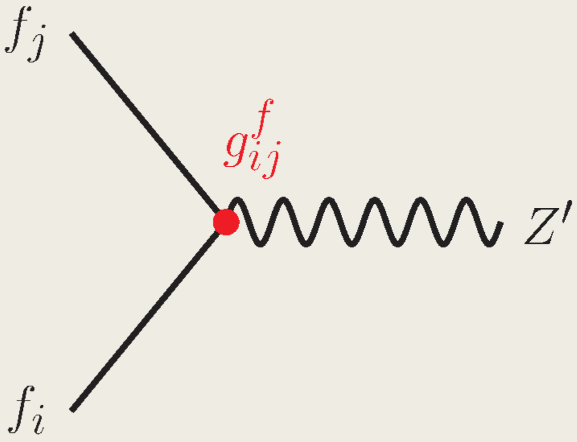
&

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

→ フレーバー物理
において重要

Flavored Z' Model

- Z′ couplings $$\mathcal{L}_{Z'} = g' Z'_\mu \left(q_{f_i} \overline{\hat{f}_i} \gamma^\mu \hat{f}_i \right)$$



⇨ U(1)′ 電荷が世代によって異なると、フレーバーを破るcoupling が生じる

質量固有状態にする際に湯川行列の対角化行列がかかる
$q_1 \neq q_2$ならば、$U_{ik} q_k U^*_{jk} \neq \delta_{ij}$

- この模型でのg_{ij}の大きさ

$$(g^d_L)_{sb} = \mathcal{O}(\epsilon),\ (g^d_L)_{db} = \mathcal{O}(\epsilon),\ (g^d_L)_{sd} = \mathcal{O}(\epsilon^2),$$
$$(g^u_L)_{ij} \simeq (g^d_L)_{ij},\ (g^u_R)_{ct} = q_3 \times \mathcal{O}(\epsilon),\ |(g^u_R)_{ct}| \gg |(g^u_R)_{ut}|,\ |(g^u_R)_{uc}|.$$

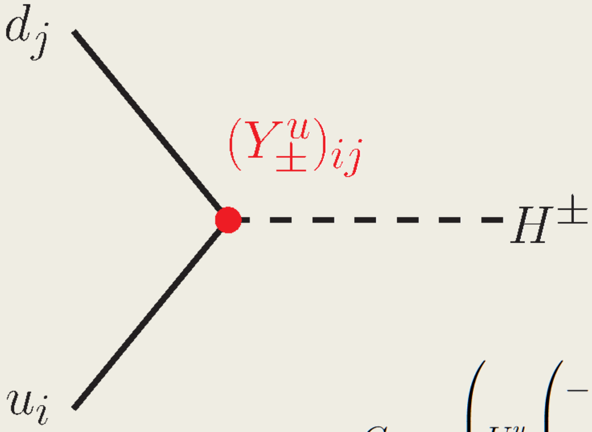
Flavored Z' Model

- 2 Higgs doublet model：SMに無いスカラー

  中性ヒッグス（CP-even, CP-odd）

  荷電ヒッグス

⇨ これらとup-type quarkとの相互作用もフレーバーを破る



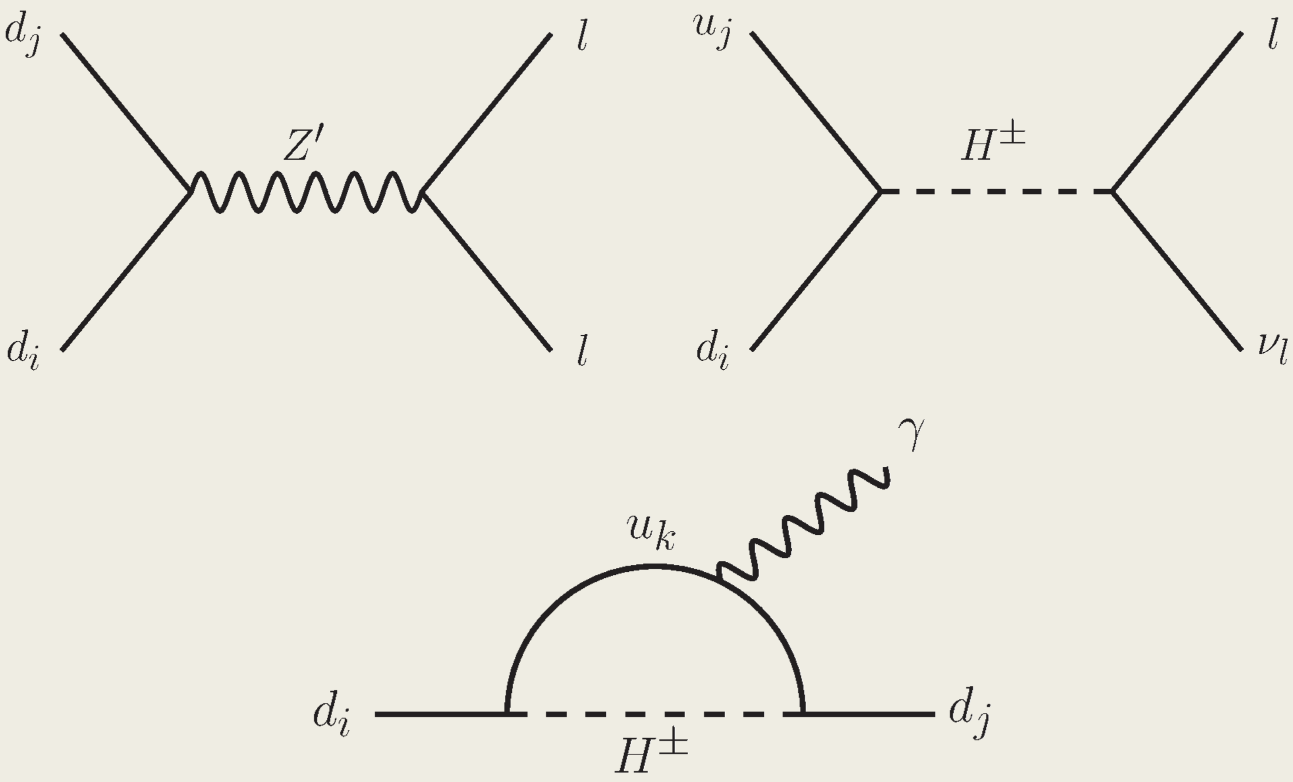
$$(Y^u_\pm)_{ij} = -\frac{m_u^k \sqrt{2}}{v} (V_{\mathrm{CKM}})^*_{ki} G_{kj}$$

G_{ij} : $\tan\beta, (U^u_R)_{i3}$ で書かれる

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

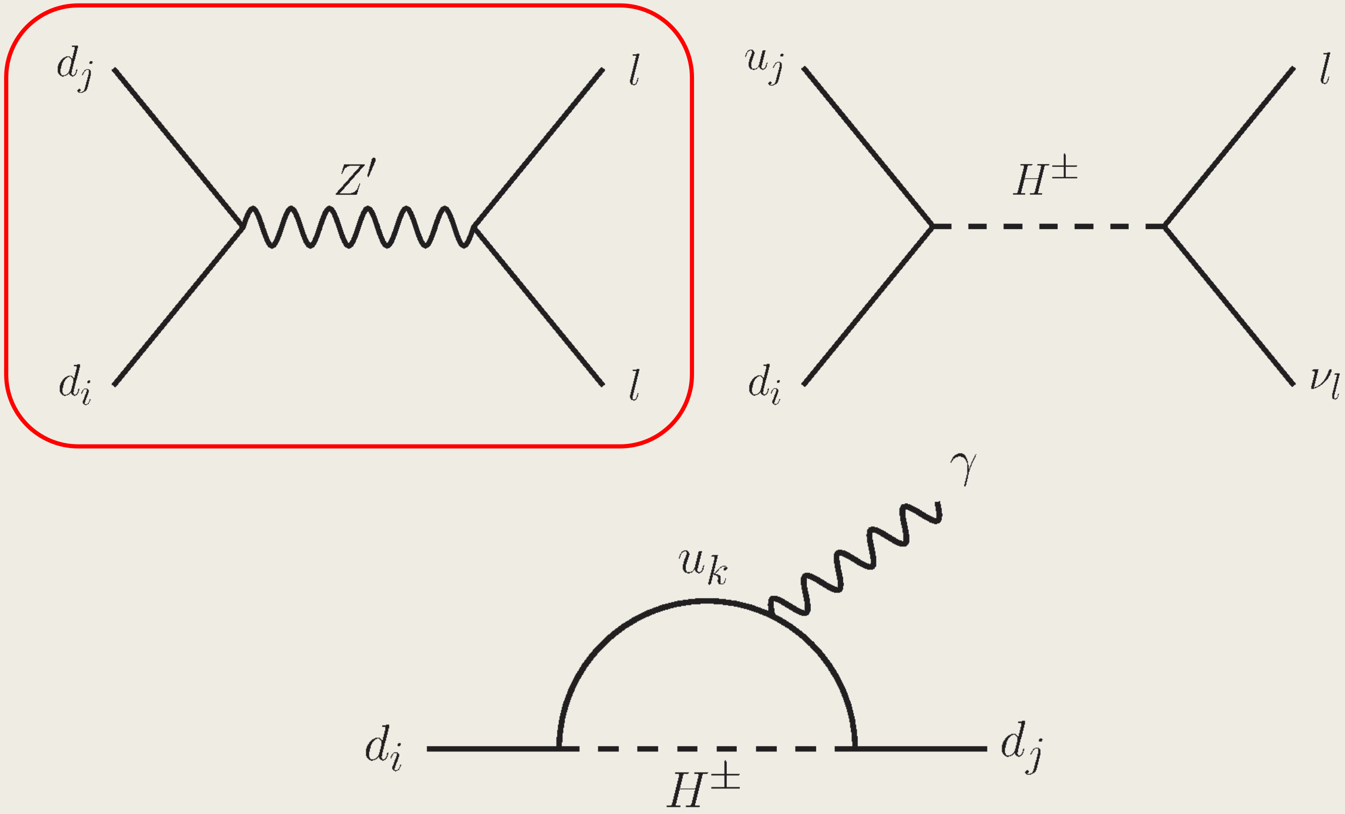
Flavor Physics Involving b

- フレーバーを破るプロセス（例）



Flavor Physics Involving *b*

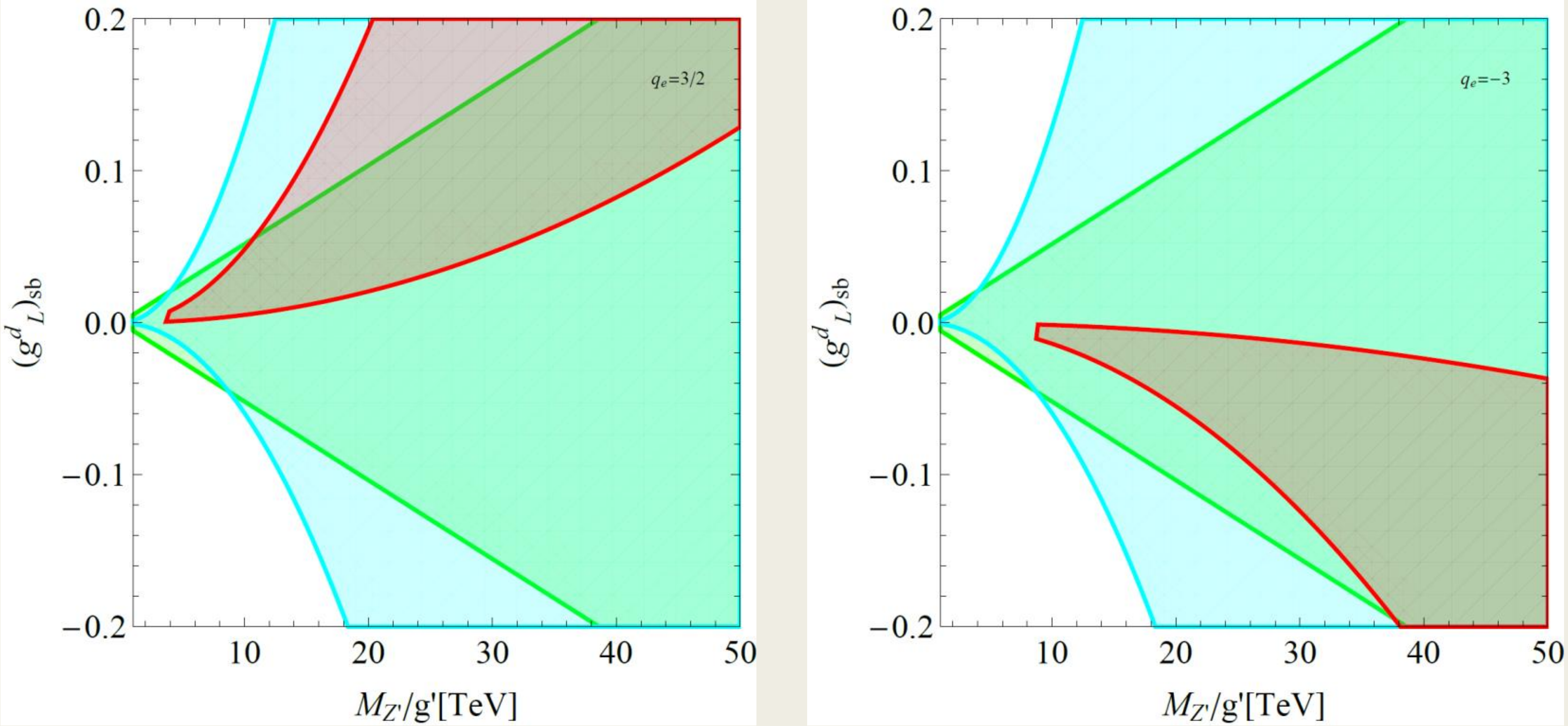
- フレーバーを破るプロセス（例）



Flavor Physics Involving *b*

- b → sll と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^μ, cyan: C_{10}^μ, green: B_s-$B_s$bar mixing

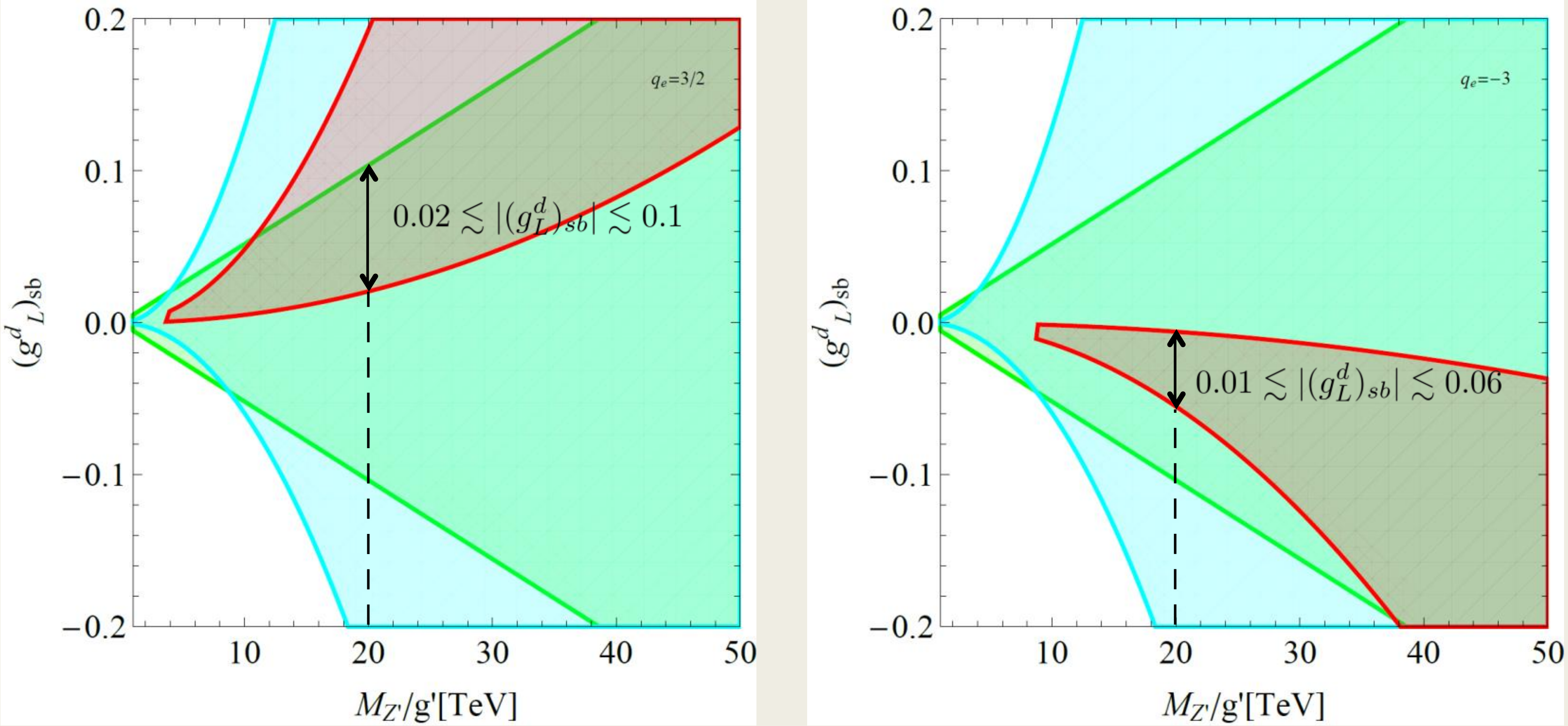
T. Hurth, F. Mahmoudi, and S. Neshatpour, NPB **909**, 737 (2016)

Flavor Physics Involving *b*

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

- b → sll と 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

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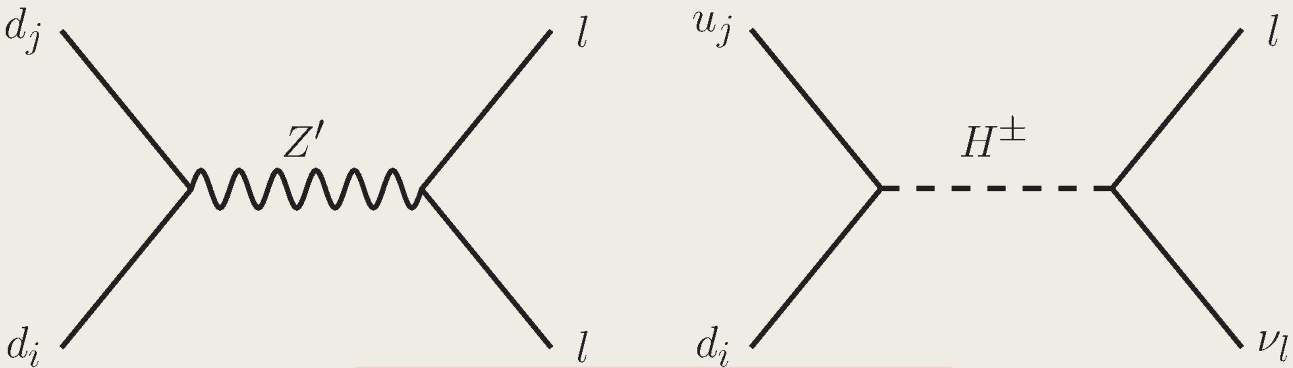
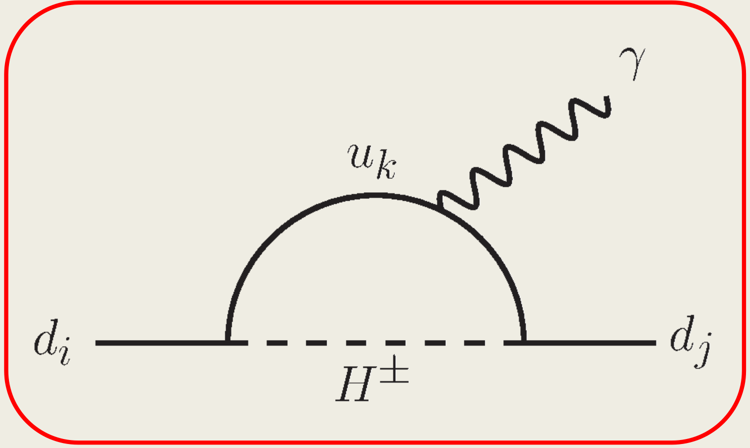
Flavor Physics Involving *b*

- フレーバーを破るプロセス（例）

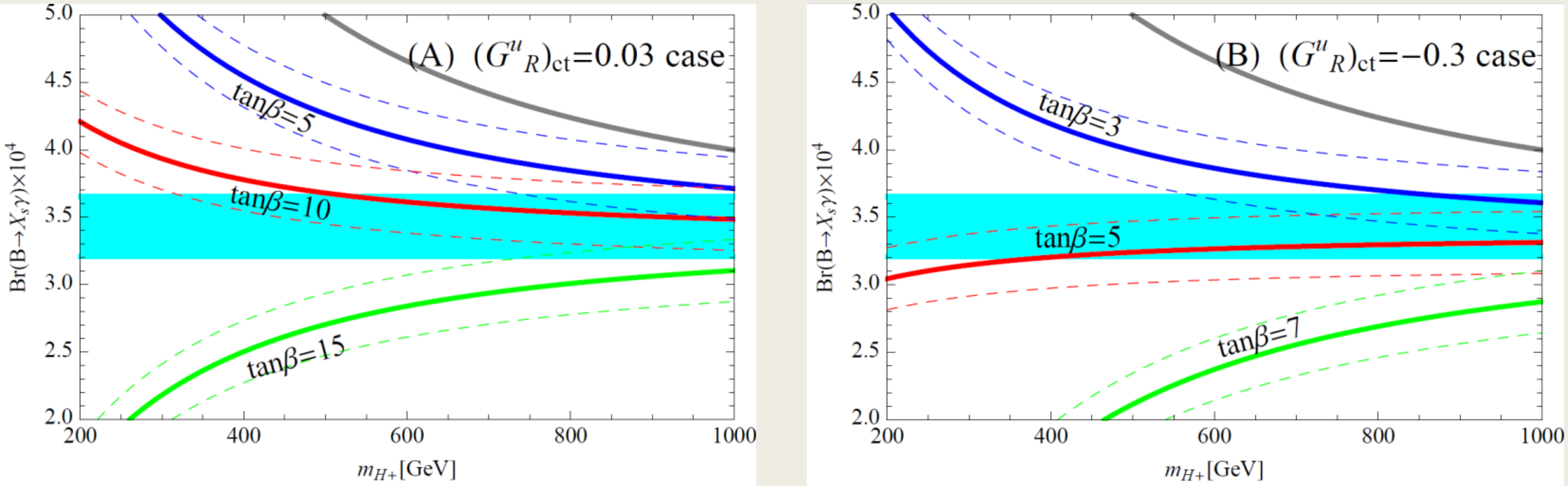




Flavor Physics Involving *b*

- B → $X_s\gamma$

- (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)

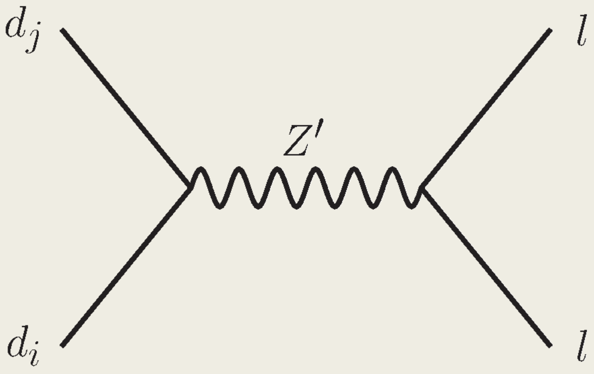
gray line: tan β = 50, $(G^u{}_R)_{ct}$ = -10^{-3} （→ R(D$^{(*)}$) のためのもの）

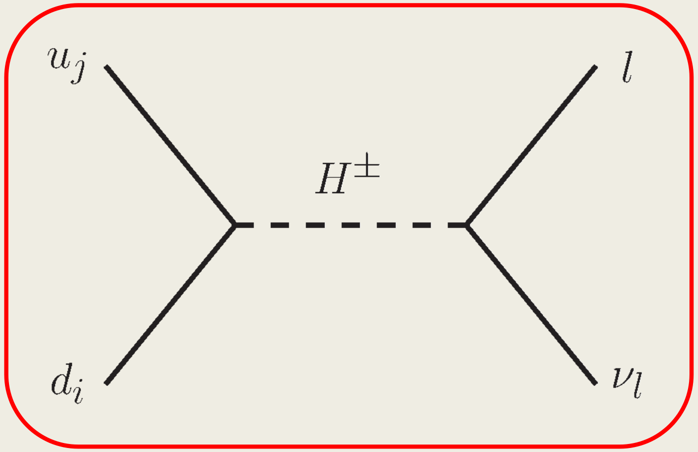
振る舞いの違い：charged Higgs との結合

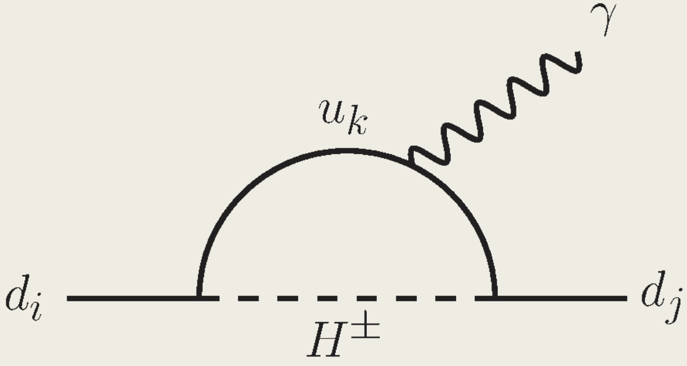
$$(Y^u_{\pm})_{st} \simeq -\frac{m_t\sqrt{2}}{v}V^*_{ts}G_{tt} - \frac{m_c\sqrt{2}}{v}V^*_{cs}G_{ct}$$

Flavor Physics Involving b

- フレーバーを破るプロセス（例）



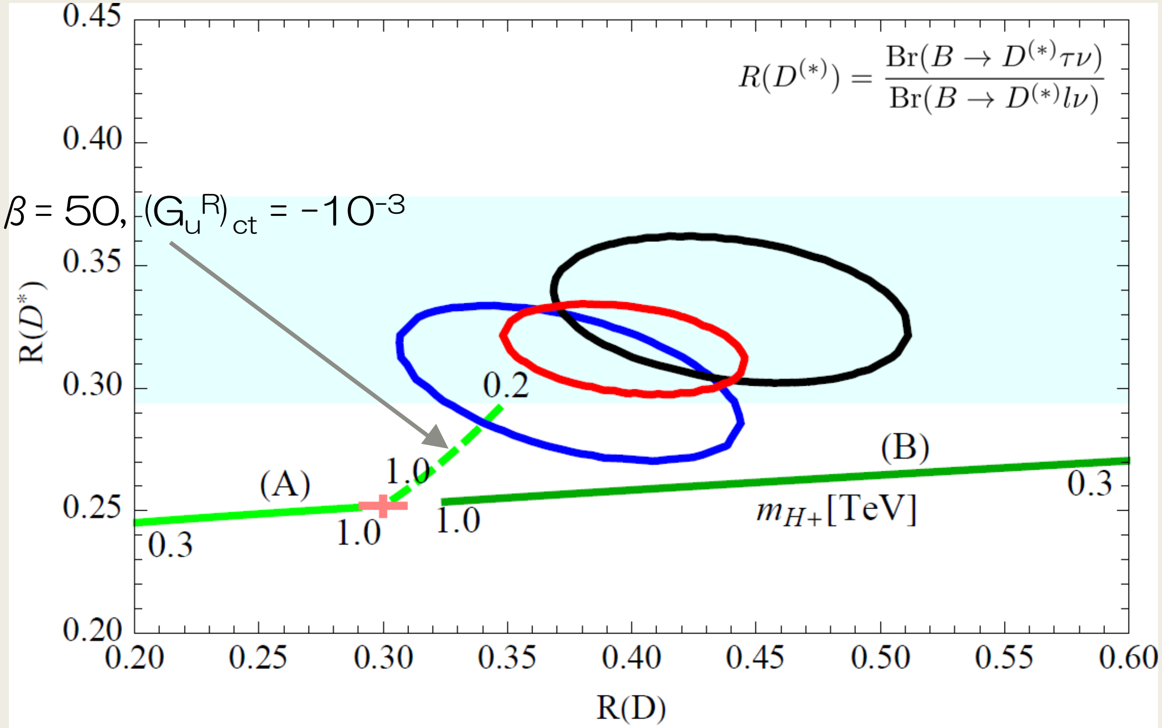




Flavor Physics Involving b

- R(D)と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) $((G_R^u)_{tt}, (G_R^u)_{tc}, (G_R^u)_{cc}, (G_R^u)_{uu}) = (1-(G_R^u)_{cc}, -0.3, 0.1, 0)$ ($\tan\beta = 5$)



$\tan\beta = 50$, $(G_u^R)_{ct} = -10^{-3}$

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).

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

Summary

- 標準模型粒子の質量階層を説明できる模型を構築
  - U(1)’対称性、新たなHiggs doublets
- bクォークが関連するflavor physicsを見た
  - b → sll とΔF=2：同時に説明可能な領域有り
  - B → $X_s \gamma$ ：$m_{H\pm}$>500 GeV, tanβ～ 5-10
  - R(D)とR(D*)：説明は厳しい
- この模型では湯川の(t,c)成分が大きくなる $(G_R^u)_{tc} \sim \mathcal{O}(0.01)$
  - LHCの感度が上がれば、t → chでこの模型をテストできる

Buck up

Yukawa and Higgs potential

- Yukawa terms

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

- Higgs potential

$$
\begin{aligned}
V_H = {} & m^2_{H_i}|H_i|^2 + m^2_\Phi|\Phi|^2 + \lambda^{ij}_H|H_i|^2|H_j|^2 + \lambda^i_{H\Phi}|H_i|^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 \\
& - A_1H_1^\dagger H_2\left(\Phi\right)^{\frac{q_1-q_2}{q_\Phi}} - A_2H_2^\dagger H_3\left(\Phi\right)^{\frac{q_2-q_3}{q_\Phi}} - A_3H_1^\dagger H_3\left(\Phi\right)^{\frac{q_1-q_3}{q_\Phi}} + \text{H.c.}
\end{aligned}
$$

Yukawa couplings

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

$$
\begin{aligned}
-\mathcal{L}_Y &= (Y_S^u)_{ij} S \overline{u_L^i} u_R^j + (Y_S^d)_{ij} h \overline{d_L^i} d_R^j + (Y_S^e)_{ij} H \overline{e_L^i} e_R^j \\
&\quad + (Y_\pm^u)_{ij} H^- \overline{d_L^i} u_R^j + (Y_\pm^d)_{ij} H^+ \overline{u_L^i} d_R^j + (Y_\pm^e)_{ij} H^+ \overline{\nu_L^i} e_R^j + \mathrm{H.c.}
\end{aligned}
$$

Up-type

$$
\begin{aligned}
(Y_h^u)_{ij} &= \frac{m_u^i \sin(\alpha-\beta)}{v} G_{ij} + \frac{m_u^i \cos(\alpha-\beta)}{v} \delta_{ij}, \\
(Y_H^u)_{ij} &= \frac{m_u^i \cos(\alpha-\beta)}{v} G_{ij} - \frac{m_u^i \sin(\alpha-\beta)}{v} \delta_{ij}, \\
(Y_A^u)_{ij} &= -i \frac{m_u^i}{v} G_{ij}, \\
(Y_\pm^u)_{ij} &= -\frac{m_u^k \sqrt{2}}{v} V_{ki}^* G_{kj},
\end{aligned}
$$

Down-type

$$
\begin{aligned}
(Y_h^d)_{ij} &= -\delta_{ij} \frac{m_d^i}{v} \frac{\cos\alpha}{\cos\beta}, \\
(Y_H^d)_{ij} &= \delta_{ij} \frac{m_d^i}{v} \frac{\sin\alpha}{\cos\beta}, \\
(Y_A^d)_{ij} &= -i\delta_{ij} \frac{m_d^i}{v} \tan\beta, \\
(Y_\pm^d)_{ij} &= -V_{ij} \frac{m_d^j \sqrt{2}}{v} \tan\beta
\end{aligned}
$$

Z' couplings

- Interaction basis

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

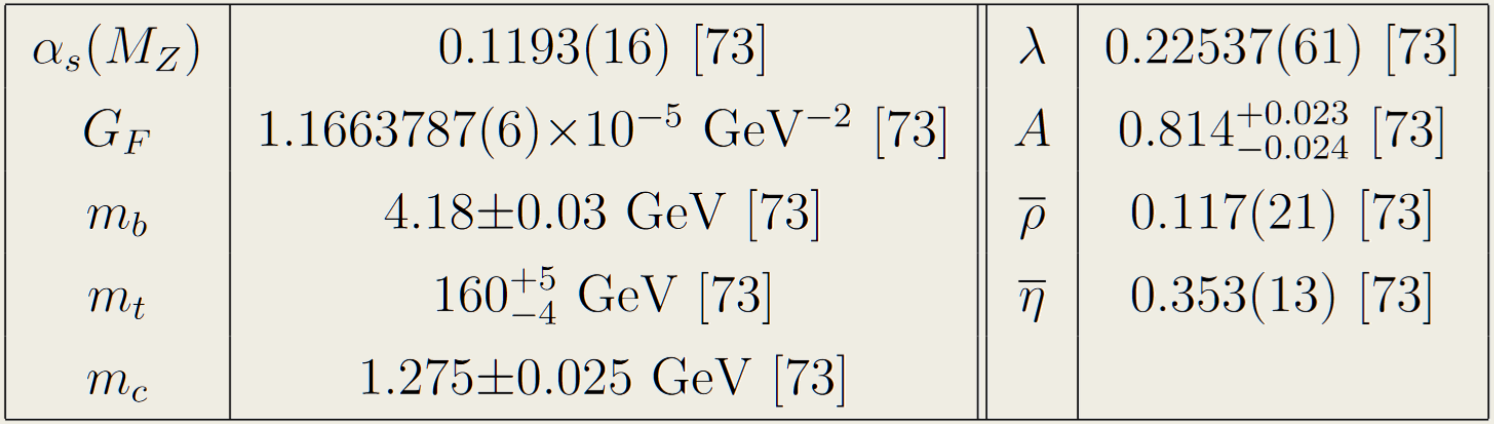
- Mass basis

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

$$\begin{aligned} (g^d_L)_{ij} &= (U^d_L)_{i3}(U^d_L)^*_{j3}, \\ (g^u_L)_{ij} &= (U^u_L)_{i3}(U^u_L)^*_{j3} = (V_{\text{CKM}})_{ik}(g^d_L)_{kk'}(V_{\text{CKM}})^*_{jk'}, \\ (g^u_R)_{ij} &= (U^u_R)_{ik} q_k (U^u_R)^*_{jk}, \\ (g^\nu_L)_{ij} &= q^k_e \left\{(U^\nu_L)_{ik}(U^\nu_L)^*_{jk}\right\} = q_e \left\{ \delta_{ij} - (V^\dagger_{\text{PMNS}})_{i3}(V^\dagger_{\text{PMNS}})^*_{j3} \right\}. \end{aligned}$$

Flavor Physics Involving *b*

- input parameters from PDG [73]



$\alpha_s(M_Z)$	0.1193(16) [73]	λ	0.22537(61) [73]
G_F	$1.1663787(6)\times10^{-5}$ 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

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

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

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

- ΔF=2

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

$$C_1^{ij} = \frac{g'^2}{2M_{Z'}^2}(g_L^d)_{ij}(g_L^d)_{ij}$$

Flavor Physics Involving *b*

- B → $X_s \gamma$

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

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

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

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

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) とR(D*) $R(D^{(*)}) = \dfrac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}l\nu)}$

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

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

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

SM & our model coef.:

$$\begin{aligned} C_{\mathrm{SM}}^{cb} &= 2V_{cb}/v^2, \\ \frac{C_L^{cb}}{C_{\mathrm{SM}}^{cb}} &= \frac{m_c m_\tau}{m_{H_\pm}^2}\tan^2\beta - \sum_k \frac{V_{kb}}{V_{cb}}\frac{m_k^u m_\tau (G_R^u)_{kc}^*}{m_{H_\pm}^2\cos^2\beta}, \\ \frac{C_R^{cb}}{C_{\mathrm{SM}}^{cb}} &= -\frac{m_b m_\tau}{m_{H_\pm}^2}\tan^2\beta. \end{aligned}$$