Flavor symmetry and New physics

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Based on
Javier Fuentes-Martín, Gino Isidori, Julie Pagès, KY [1909.02519]
Darius A. Faroughy, Gino Isidori, Felix Wilsch, KY [2005.05366]
(University of Zurich)

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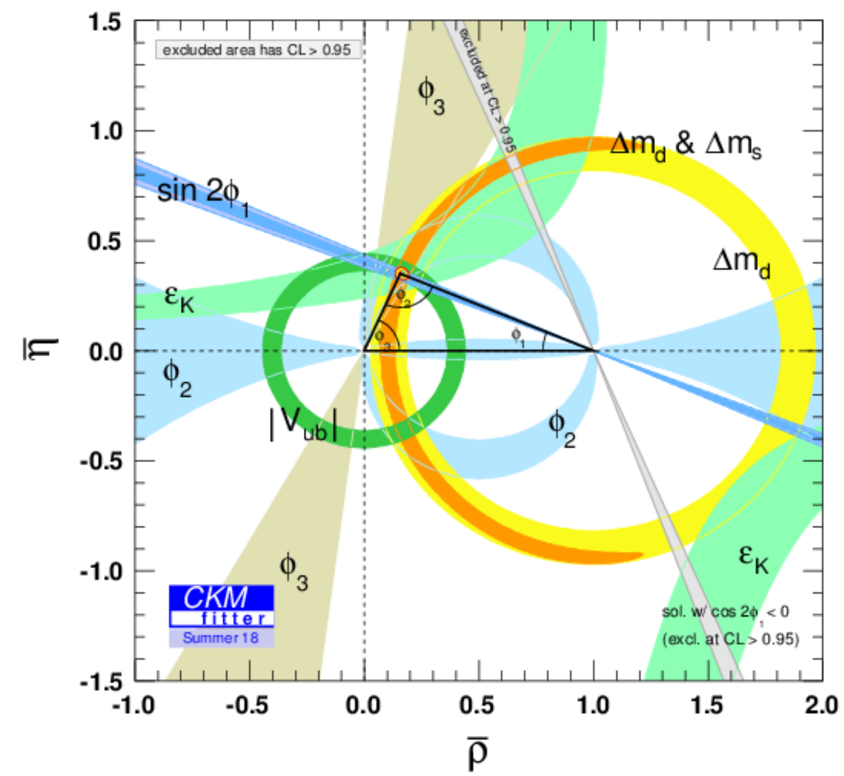
The Flavor Problem

- Theoretical arguments based on the hierarchy problem
  → TeV scale NP



- The measurements of quark flavor-violating observables show a remarkable overall success of the SM

- New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} \mathscr{O}_i^{d=6} \text{(NP)}$$

$$|C_{NP}| \sim 1 \quad \longrightarrow \quad \Lambda_{NP} \sim \begin{cases} 500 \text{ TeV} & : \quad B_s \\ 2000 \text{ TeV} & : \quad B_d \\ 10^4 - 10^5 \text{ TeV} & : \quad K^0 \end{cases}$$

- if we insist with the theoretical prejudice that NP has to emerge in the TeV region, we have to conclude that NP have a highly non-generic flavor structure

  → Flavor symmetry

Flavor symmetry in SM

$$\mathscr{L}_{SM}^{\text{fermion}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Yukawa}}$$

fermion sector $\displaystyle\sum_{i=1}^{3}\sum_{\psi_i}\bar{\psi}_i i\not{D}\psi_i$

- in gauge sector $\mathscr{L}_{\text{gauge}}$, there is 3 identical replica of the basic fermion family $[\psi = Q_L, u_R, d_R, L_L, e_R]$

$\Rightarrow$ big flavor symmetry is found in gauge sector

$$U(3)^5 = U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{L_L} \times U(3)_{e_R}$$
$$= SU(3)^5 \times U(1)^5$$

controll flavor dynamics

can be identified with B, L and hypercharge

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- $U(3)^5$ flavor symmetry is broken only by the Yukawa couplings $Y_{D,U,E}$

Flavor symmetry in SM + NP

$$\mathscr{L}^{\text{fermion}}_{SM+NP} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Yukawa}} + \mathscr{L}_{NP}$$

fermion sector $\sum_{i=1}^{3} \sum_{\psi_i} \bar{\psi}_i i \not{D} \psi_i$ $\quad \mathscr{L}_Y = \bar{Q}^i_L Y^{ij}_D d^j_R H + \bar{Q}^i_L Y^{ij}_U u^j_R \tilde{H} + \bar{L}^i_L Y^{ij}_E e^j_R H + (h.c.)$

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controll flavor dynamics can be identified with B, L and hypercharge

- $U(3)^5$ flavor symmetry is broken only by the Yukawa couplings $Y_{D,U,E}$

- Assumption that flavor structure in NP is also controlled by Yukawa is the most reasonable solution to the flavor problem

⇒ Minimal Flavor Violation paradigm

Minimal Flavor Violation (MFV)

D'Ambrosio, Giudice, Isidori, Strumia [hep-ph/0207036]

$$\mathscr{L}_Y = \bar{Q}_L^i Y_D^{ij} d_R^j H + \bar{Q}_L^i Y_U^{ij} u_R^j \tilde{H} + \bar{L}_L^i Y_E^{ij} e_R^j H + (h.c.)$$

- assume that $G_F \equiv SU(3)^5$ is a good symmetry, promoting the $Y_{U,D,E}$ to be dynamical fields with non-trivial transformation properties under G_F :

under $G_F = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{L_L} \times SU(3)_{e_R}$

$$Y_U \sim (3,\bar{3},1,1,1),\ \ Y_D \sim (3,1,\bar{3},1,1),\ \ Y_E \sim (1,1,1,3,\bar{3})$$

$$Q_L \sim (3,1,1,1,1), u_R \sim (1,3,1,1,1), d_R \sim (1,1,3,1,1),$$
$$L_L \sim (1,1,1,3,1),\ \ e_R \sim (1,1,1,1,3)$$

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$\bar{3}_{Q_L}$ $\quad 3_{Q_L} \times \bar{3}_{u_R}$ $\quad 3_{u_R}$

$\longrightarrow$ G_F invariant

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We then define that an effective theory satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and $Y_{U,D,E}$ (spurion) fields

$$\mathcal{L}_{NPinMFV} = \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{d=6}(\text{SM fields} + Y_{U,D,E})$$

Minimal Flavor Violation (MFV)

- By introducing $Y_{U,D,E}$ fields, we can write higher-dimensional operators in G_F invariant way

$$G_F = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$$

$$Y_U \sim (3,\bar{3},1)$$

$$(\bar{Q}_L^i \qquad \gamma_\mu Q_L^j)$$

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G_F invariant

$Y_U Y_U^\dagger$ is transforming as $(8,1,1)$

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e.g.) $b_i \to b_j$ FCNC transition

int basis $(\bar{b}_L^i Y_U Y_U^\dagger \gamma_\mu b_L^j)$

$$Y_D = \lambda_d \qquad \lambda_d = \mathrm{diag}(m_d, m_s, m_b)/v$$

$$Y_U = V_{CKM}^\dagger \lambda_u \quad \text{where} \quad \lambda_u = \mathrm{diag}(m_u, m_c, m_t)/v \sim \mathrm{diag}(0,0,1)$$

$$Y_E = \lambda_e \qquad \lambda_e = \mathrm{diag}(m_e, m_\mu, m_\tau)/v$$

$$\boxed{(Y_U Y_U^\dagger)^{ij} = (V^\dagger \lambda_u^2 V)^{ij} \simeq \lambda_t^2 V_{ti}^* V_{tj}}$$

mass basis $\lambda_t^2 V_{ti}^* V_{tj} (\bar{b}_L^i \gamma_\mu b_L^j)$ $\propto \left(\frac{m_t}{v}\right)^2$ most big effect

Minimal Flavor Violation (MFV)

$$A(d_i \to d_j) = A_{SM} + A_{NP}$$

$$\frac{C_{SM}}{16\pi^2 v^2}\lambda_t^2 V_{ti}^* V_{tj} \qquad \frac{C_{NP}}{\Lambda^2}\lambda_t^2 V_{ti}^* V_{tj}$$

$$\propto \text{(CKM factor)} \left[\frac{C_{SM}}{16\pi^2 v^2} + \frac{C_{NP}}{\Lambda^2}\right]$$

In MFV, flavor violation is completely determined by Yukawa couplings and all CP violation originates from the CKM phase

- Different flavor transitions are correlated, differences are only CKM

$$A(b \to s) = (V_{tb} V_{ts}^*) \left[\frac{C_{SM}}{16\pi^2 v^2} + \frac{C_{NP}}{\Lambda^2}\right]$$

$$A(s \to d) = (V_{ts} V_{td}^*) \left[\quad '' \quad \right]$$

exactly same structure

very predictive

Minimal Flavor Violation (MFV)

- $b_i \to b_j$ FCNC transitions in MFV

$(\bar{L}L)$ type $\quad (\bar{b}^i_L \, Y_U Y_U^\dagger \, b^j_L)$

$(\bar{L}R)$ type $\quad (\bar{b}^i_L \, Y_U Y_U^\dagger Y_D \, b^j_R)$

$(\bar{R}R)$ type $\quad (\bar{b}^i_R \, Y_D^\dagger Y_U Y_U^\dagger Y_D \, b^j_R)$

From MFV to $U(2)^5$

$$U(3)^5 = U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{L_L} \times U(3)_{e_R} \text{ flavor symmetry}$$

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^5$ by SM Yukawa couplings

MFV virtue

Naturally small effects in FCNC observables assuming TeV-scale NP

MFV main problem

No explanation for Yukawa hierarchies (masses and mixing angles)

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$U(2)^5$ flavor symmetry

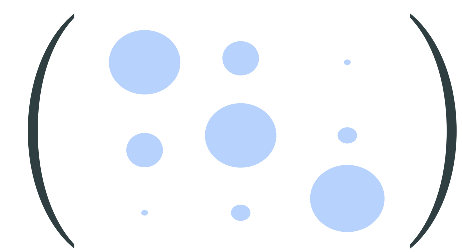
Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

SM flavor puzzle

SM flavor sector contains a large number of free parameters

[3 lepton masses + 6 quark masses + 3+1 CKM parameters] ← fixed by data

Striking hierarchy   Mass : 3rd > 2nd > 1st   Almost diagonal CKM matrix

$M_{u,d} \sim$  $V_{CKM} \sim$ 

- $U(2)^5$ symmetry gives “natural” explanation of why 3rd Yukawa couplings are large (being allowed by the symmetry)

  distinguish the first two generations of fermions from the 3rd $\psi = (\underline{\psi_1, \psi_2}, \psi_3)$

- The symmetry is a good approximation in the SM Yukawa

  exact symmetry for $m_u, m_d, m_c, m_s = 0$ & $V_{CKM} = 1$

  $\Rightarrow$ we only need small breaking terms

$U(2)^5$ flavor symmetry

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- The set of breaking terms necessary to reproduce the quark spectrum, while keeping small FCNCs beyond the SM

Under $U(2)^3 = U(2)^q \times U(2)^u \times U(2)^d$ symmetry

quark

$$\begin{array}{ll} Q^{(2)} = (Q^1, Q^2) \sim (2,1,1) & Q^3 \sim (1,1,1) \\ u^{(2)} = (u^1, u^2) \sim (1,2,1) & t \sim (1,1,1) \\ d^{(2)} = (d^1, d^2) \sim (1,1,2) & b \sim (1,1,1) \end{array}$$

Spurion

(U(2) breaking term)

$$V_q \sim (2,1,1),\ \Delta_u \sim (2,\bar{2},1),\ \Delta_d \sim (2,1,\bar{2})$$

Unbroken symmetry

$$Y_u = y_t \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$U(2)_q$

$U(2)_u$

After breaking

$$\longrightarrow \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\Delta_u} & V_q \\ \hline 0 & 0 & 1 \end{array}\right)$$

U(2) breaking term

$$|V| \sim |V_{ts}|$$

$$|\Delta_u| \sim y_c$$

$U(2)$ flavour symmetry provides natural link to the Yukawa couplings

From MFV to $U(2)^5$

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- acting on 1st & 2nd generations only
- The exact symmetry limit is good starting point for the SM quark spectrum $(m_u, m_d, m_c, m_s = 0 \;\&\; V_{CKM} = 1)$ $\Rightarrow$ we only need small breaking terms
- B-anomalies are compatible with U(2) flavor symmetry cf [1909.02519]

What we did

part I. SMEFT and $U(2)^5$ flavor symmetry

Darius A. Faroughy, Gino Isidori, Felix Wilsch, KY [2005.05366]

part II. B anomalies and $U(2)^5$ flavor symmetry

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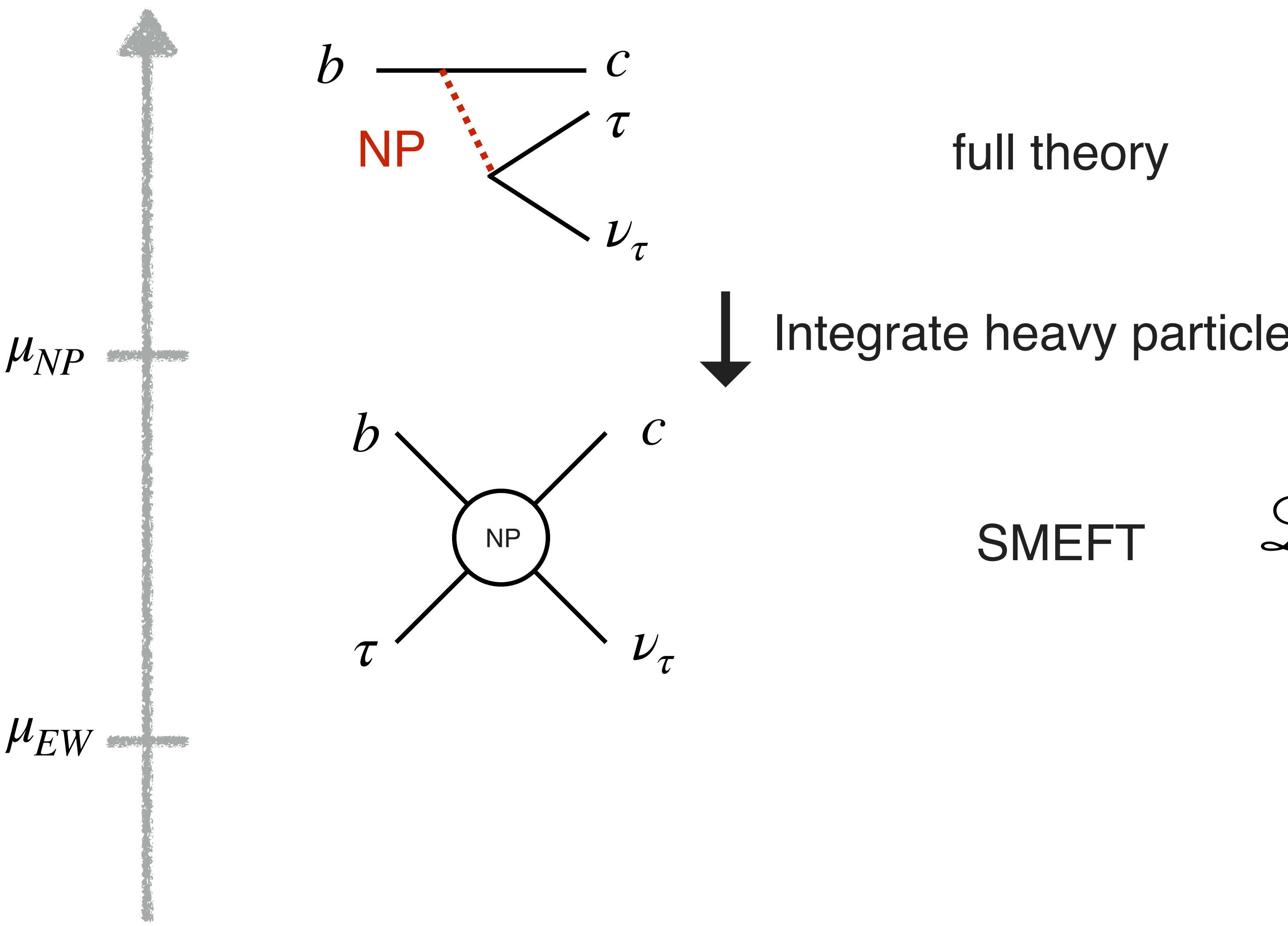
SM Effective Field Theory (SMEFT)

B. Grzadkowski, M. Iskrzynski,
M. Misiak and J. Rosiek
[1008.4884].

- SMEFT is a effective theory based on $SU(3)_c \times SU(2)_L \times U(1)_Y$ at scale $\mu_{\mathrm{EW}} < \mu < \mu_{\mathrm{NP}}$



$$\mathscr{L}_{\mathrm{eff}} \sim \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{d=6}$$

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- Complete non-redundant classification of baryon- and lepton-number conserving dimension-six operators in the SMEFT has been presented (Warsaw basis)

w/o flavor index   59 dim six operators in SMEFT

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \epsilon_{jk} (\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \epsilon_{jk} (\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \epsilon_{jk} (\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$

SM Effective Field Theory (SMEFT)

B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek [1008.4884].

- Complete non-redundant classification of baryon- and lepton-number conserving dimension-six operators in the SMEFT has been presented (Warsaw basis)

w/o flavor index 59 dim six operators in SMEFT

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

w/ flavor index $(n_g = 3)$ 2499 dim six operators in SMEFT

1350 CP-even and 1149 CP-odd

huge number of free parameters $\xrightarrow{\text{flavor symmetry}}$ reduce number of independent parameters

Our work

- We analyse how $U(3)^5$ and $U(2)^5$ flavor symmetries act on SMEFT, providing an organising principle to classify the large number of dim6 operators involving fermion fields

Class	Operators	No symmetry 3 Gen.		No symmetry 1 Gen.	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6
5	ψ^2H^3	27	27	3	3
6	ψ^2XH	72	72	8	8
7	ψ^2H^2D	51	30	8	1
8	$(\bar{L}L)(\bar{L}L)$	171	126	5	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–
	$(\bar{L}L)(\bar{R}R)$	360	288	8	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4
	total:	1350	1149	53	23

$U(3)^5$

?

$U(2)^5$

?

CP-even CP-odd

1) Case for $U(3)^5$ and MFV

2) Case for $U(2)^5$

[3) Case for beyond $U(3)^5$ and $U(2)^5$]

Operator classification

59 dim six operators in SMEFT

class 1-4 : w/o fermion ope.

class 5-7 : w/ 2-fermion ope.

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H}$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{Hud} + \text{h.c.}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Operator classification

class 8: w/ 4-fermion ope.

59 dim six operators in SMEFT

$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

I) $U(3)^5$ and MFV

e.g. class 5 : $(\bar{L}R)$ bilinear

No symmetry → (# parameters) = (flavor index)^2

non-hermitian ope. → Re + Im

$(\bar{L}R)$ type ope. → $\times$ $(\bar{q}\, u)$, $(\bar{q}\, d)$: not allowed in exact $U(3)^5$

→ $(\bar{q}Y_u u)$, $(\bar{q}Y_d d)$: allowed w/ Y_u

→ $(\bar{q}^i(Y_uY_u^\dagger)Y_d d^j)$: allowed w/ more $Y_{u,e,d}$:

$5:\ \psi^2 H^3 +$ h.c.		No sym. CP-ev	CP-odd	exact $U(3)^5$	$\sim \mathcal{O}(Y_{u,d,e})$		$\sim \mathcal{O}(Y_d Y_u^2)$	
Q_{eH}	$(H^\dagger H)(\bar{\ell}_p e_r H)$	9	9	0	1	1	1	1
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \tilde{H})$	9	9	0	1	1	1	1
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	9	9	0	1	1	2	2
		27	27	0	3	3	4	4

1) $U(3)^5$ and MFV

		No symmetry				$U(3)^5$					
Class	Operators	3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y_e^1, Y_d^1 Y_u^2)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 XH$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

1) $U(3)^5$ and MFV

Class	Operators	No symmetry				$U(3)^5$					
		3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y_e^1, Y_d^1 Y_u^2)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 XH$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

~2500 $\xrightarrow{\text{MFV}}$ ~100

II) $U(2)^5$

Yukawa in U(2)

$$Y_e = y_\tau \begin{pmatrix} \Delta_e & x_\tau V_\ell \\ 0 & 1 \end{pmatrix}, \qquad Y_u = y_t \begin{pmatrix} \Delta_u & x_t V_q \\ 0 & 1 \end{pmatrix}, \qquad Y_d = y_b \begin{pmatrix} \Delta_d & x_b V_q \\ 0 & 1 \end{pmatrix}$$

$V_q \sim (2,1,1)$, $\Delta_u \sim (2,\bar{2},1)$, $\Delta_d \sim (2,1,\bar{2})$ $\quad$ $y_{\tau,t,b}$ and $x_{\tau,t,b}$: $\mathcal{O}(1)$ free complex parameters

Transformation for spurions

$$V_{q(\ell)} = e^{i\bar{\phi}_{q(\ell)}} \begin{pmatrix} 0 \\ \epsilon_{q(\ell)} \end{pmatrix}, \quad \Delta_e = O_e^{\intercal} \begin{pmatrix} \delta'_e & 0 \\ 0 & \delta_e \end{pmatrix}, \quad \Delta_u = U_u^{\dagger} \begin{pmatrix} \delta'_u & 0 \\ 0 & \delta_u \end{pmatrix}, \quad \Delta_d = U_d^{\dagger} \begin{pmatrix} \delta'_d & 0 \\ 0 & \delta_d \end{pmatrix}$$

$$\epsilon_i = \mathcal{O}(y_t |V_{ts}|) = \mathcal{O}(10^{-1})$$

$$\delta_i = \mathcal{O}\left(\frac{y_c}{y_t}, \frac{y_s}{y_b}, \frac{y_\mu}{y_\tau}\right) = \mathcal{O}(10^{-2})$$

$$\delta'_i = \mathcal{O}\left(\frac{y_u}{y_t}, \frac{y_d}{y_b}, \frac{y_e}{y_\tau}\right) = \mathcal{O}(10^{-3})$$

$$1 \gg \epsilon_i \gg \delta_i \gg \delta'_i > 0$$

$$O_e = \begin{pmatrix} c_e & s_e \\ -s_e & c_e \end{pmatrix}, \qquad U_q = \begin{pmatrix} c_q & s_q\, e^{i\alpha_q} \\ -s_q\, e^{-i\alpha_q} & c_q \end{pmatrix}$$

II) $U(2)^5$

$$\psi = (\underbrace{\psi_1, \psi_2}_{L}, \underbrace{\psi_3}_{\ell_3})$$

e.g.) leptonic ($\bar{L}L$) bilinear

$$\bar{\ell}_p \Gamma \Lambda_{LL}^{pr} \ell_r \ , \qquad \Lambda_{LL} = \begin{pmatrix} a_1 & 0 & 0 \\ 0 & a_1 + c_1 \epsilon_\ell^2 & \beta_1 \epsilon_\ell \\ 0 & \beta_1^* \epsilon_\ell & a_2 \end{pmatrix} + \mathcal{O}(\delta_e^2)$$

a : $\mathcal{O}(V^0)$

β : $\mathcal{O}(V)$

c : $\mathcal{O}(V^2)$

※ laten $(a, b, c, , ,)$: real, greek$(\alpha, \beta, \gamma, , ,)$: complex

Spurions	Operator	Explicit expression in flavour components
V^0	$a_1 \bar{L}L + a_2 \bar{\ell}_3 \ell_3$	$a_1 \left(\bar{\ell}_1 \ell_1 + \bar{\ell}_2 \ell_2\right) + a_2 \left(\bar{\ell}_3 \ell_3\right)$
V^1	$\beta_1 \bar{L} V_\ell \ell_3$ + h.c.	$\beta_1 \epsilon_\ell \left(\bar{\ell}_2 \ell_3\right)$ + h.c.
V^2	$c_1 \bar{L} V_\ell V_\ell^\dagger L$	$c_1 \epsilon_\ell^2 \left(\bar{\ell}_2 \ell_2\right)$
Δ^1, $\Delta^1 V^1$	–	–
Δ^2	$h_1 \bar{L} \Delta_e \Delta_e^\dagger L$	$\approx h_1 \left[\delta_e^2 (\bar{\ell}_2 \ell_2) - s_e \delta_e^2 (\bar{\ell}_1 \ell_2 + \bar{\ell}_2 \ell_1) + (s_e^2 \delta_e^2 + \delta_e'^2)(\bar{\ell}_1 \ell_1)\right]$
$\Delta^2 V^1$	$\lambda_1 \bar{L} \Delta_e \Delta_e^\dagger V_\ell \ell_3$ + h.c.	$\approx \lambda_1 \epsilon_\ell \delta_e^2 (\bar{\ell}_2 \ell_3 - s_e \bar{\ell}_1 \ell_3)$ + h.c.
$\Delta^2 V^2$	$\mu_1 \bar{L} \Delta_e \Delta_e^\dagger V_\ell V_\ell^\dagger L$ + h.c.	$\approx \mu_1 \epsilon_\ell^2 \delta_e^2 (\bar{\ell}_2 \ell_2 - s_e \bar{\ell}_1 \ell_2)$ + h.c.

II) $U(2)^5$

e.g.) leptonic ($\bar{R}R$) bilinear

$$\bar{e}_p \Gamma \Lambda_{RR}^{pr} e_r \ , \qquad \Lambda_{RR} = \begin{pmatrix} a_1 & 0 & \sigma_1^* \epsilon_\ell s_e \delta'_e \\ 0 & a_1 & \sigma_1^* \epsilon_\ell \delta_e \\ \sigma_1 \epsilon_\ell s_e \delta'_e & \sigma_1 \epsilon_\ell \delta_e & a_2 \end{pmatrix} + \mathcal{O}(\delta_e^2)$$

a : $\mathcal{O}(V^0)$

β : $\mathcal{O}(V)$

c : $\mathcal{O}(V^2)$

Spurions	Operator ($\bar{e}e$ type)	Explicit expression in flavour components
V^0	$a_1 \bar{E}E + a_2 \bar{e}_3 e_3$	$a_1 \left(\bar{e}_1 e_1 + \bar{e}_2 e_2\right) + a_2 \left(\bar{e}_3 e_3\right)$
V^1, V^2, Δ^1	–	
$\Delta^1 V^1$	$\sigma_1 \bar{e}_3 V_\ell^\dagger \Delta_e E$ + h.c.	$\approx \sigma_1 \epsilon_\ell \left[\delta_e (\bar{e}_3 e_2) + s_e \delta'_e (\bar{e}_3 e_1)\right]$ + h.c.
Δ^2	$h_1 \bar{E} \Delta_e^\dagger \Delta_e E$	$h_1 \left[\delta_e^2 (\bar{e}_2 e_2) + \delta_e'^2 (\bar{e}_1 e_1)\right]$
$\Delta^2 V^1$	–	
$\Delta^2 V^2$	$m_1 \bar{E} \Delta_e^\dagger V_\ell V_\ell^\dagger \Delta_e E$	$\approx m_1 \epsilon_\ell^2 \left[\delta_e^2 (\bar{e}_2 e_2) + s_e \delta'_e \delta_e (\bar{e}_1 e_2 + \bar{e}_2 e_1) + s_e^2 \delta_e'^2 (\bar{e}_1 e_1)\right]$

II) $U(2)^5$

Results for bilinear structure

Class	N. indep. structures	$U(2)^5$ breaking terms V^0		V^1		V^2		Δ^1		$\Delta^1 V^1$	
5 & 6: $(\bar{L}R)$	11	11	11	11	11	–	–	11	11	11	11
7: $(\bar{L}L)$	4	8	–	4	4	4	–	–	–	–	–
7: $(\bar{R}R)$	3	6	–	–	–	–	–	–	–	3	3
7: Q_{Hud}	1	1	1	–	–	–	–	–	–	2	2
total:	19	26	12	15	15	4	–	11	11	16	16

II) $U(2)^5$

$$\psi = (\underbrace{\psi_1, \psi_2}_{L}, \underbrace{\psi_3}_{\ell_3})$$

4 fermion operator $(\bar{L}L)(\bar{L}L)$

$\mathcal{O}^{(1)}_{\ell q} = (\bar{\ell}^i \gamma_\mu \ell^j)(\bar{q}^n \gamma^\mu q^m)$ and $\mathcal{O}^{(3)}_{\ell q} = (\bar{\ell}^i \gamma_\mu \tau^I \ell^j)(\bar{q}^n \gamma^\mu \tau^I q^m)$ case

$$\begin{aligned}
V^0 :\quad & \left[a_1(\bar{L}L)(\bar{Q}Q) + a_2(\bar{L}L)(\bar{q}_3 q_3) + a_3(\bar{\ell}_3\ell_3)(\bar{Q}Q) + a_4(\bar{\ell}_3\ell_3)(\bar{q}_3 q_3)\right] ,\\
V^1 :\quad & \left[\beta_1(\bar{L}V_\ell \ell_3)(\bar{Q}Q) + \beta_2(\bar{L}V_\ell \ell_3)(\bar{q}_3 q_3) + \beta_3(\bar{L}L)(\bar{Q}V_q q_3) + \beta_4(\bar{\ell}_3\ell_3)(\bar{Q}V_q q_3) \;+\; \text{h.c.}\right] ,\\
V^2 :\quad & \left[c_1(\bar{L}^p V_\ell^p V_\ell^{\dagger\, r} L^r)(\bar{Q}Q) + c_2(\bar{L}^p V_\ell^p V_\ell^{\dagger\, r} L^r)(\bar{q}_3 q_3) + c_3(\bar{L}L)(\bar{Q}^p V_q^p V_q^{\dagger\, r} Q^r)\right.\\
& \left. + c_4(\bar{\ell}_3\ell_3)(\bar{Q}^p V_q^p V_q^{\dagger\, r} Q^r) + (\gamma_1(\bar{L}V_\ell \ell_3)(\bar{Q}V_q q_3) + \gamma_2(\bar{L}V_\ell \ell_3)(\bar{q}_3 V_q^\dagger Q) \;+\; \text{h.c.})\right] ,\\
V^3 :\quad & \left[\xi_1(\bar{L}^p V_\ell^p V_\ell^{\dagger\, r} L^r)(\bar{Q}V_q q_3) + \xi_2(\bar{L}V_\ell \ell_3)(\bar{Q}^p V_q^p V_q^{\dagger\, r} Q^r) \;+\; \text{h.c.}\right] .
\end{aligned}$$

II) $U(2)^5$

4 fermion operator $(\bar{L}L)(\bar{L}L)$

$\mathcal{O}^{(1)}_{\ell q} = (\bar{\ell}^i \gamma_\mu \ell^j)(\bar{q}^n \gamma^\mu q^m)$ and $\mathcal{O}^{(3)}_{\ell q} = (\bar{\ell}^i \gamma_\mu \tau^I \ell^j)(\bar{q}^n \gamma^\mu \tau^I q^m)$ case

$(\bar{\ell}^i \ell^j)$ →

$(\bar{q}^n q^m)$ ↓

	(11)	(12)	(13)	(21)	(22)	(23)	(31)	(32)	(33)
(11)	a_1				a_1 $c_3\epsilon_q^2$	$\beta_3\epsilon_q$		$\beta_3^*\epsilon_q$	a_2
(12)									
(13)									
(21)									
(22)	a_1 $c_1\epsilon_\ell^2$				a_1 $c_1\epsilon_\ell^2$ $c_3\epsilon_q^2$	$\beta_3\epsilon_q$ $\xi_1\epsilon_\ell^2\epsilon_q$		$\beta_3^*\epsilon_q$ $\xi_1^*\epsilon_\ell^2\epsilon_q$	a_2 $c_2\epsilon_\ell^2$
(23)	$\beta_1\epsilon_\ell$				$\beta_1\epsilon_\ell$ $\xi_2\epsilon_q^2\epsilon_\ell$	$\gamma_1\epsilon_\ell\epsilon_q$		$\gamma_2\epsilon_\ell\epsilon_q$	$\beta_2\epsilon_\ell$
(31)									
(32)	$\beta_1^*\epsilon_\ell$				$\beta_1^*\epsilon_\ell$ $\xi_2^*\epsilon_q^2\epsilon_\ell$	$\gamma_2^*\epsilon_\ell\epsilon_q$		$\gamma_1^*\epsilon_\ell\epsilon_q$	$\beta_2^*\epsilon_\ell$
(33)	a_3				a_3 $c_4\epsilon_q^2$	$\beta_4\epsilon_q$		$\beta_4^*\epsilon_q$	a_4

a : $\mathcal{O}(V^0)$

$i = j, n = m$

: quark & lepton conserving

β : $\mathcal{O}(V)$

$i \neq j$ or $n \neq m$

: ~~quark~~ or ~~lepton~~

c : $\mathcal{O}(V^2)$

$i \neq j$, $n \neq m$

: ~~quark~~ & ~~lepton~~

II) $U(2)^5$

Operators	$U(2)^5$ [terms summed up to different orders]													
	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1 V^1)$		$\mathcal{O}(V^3, \Delta^1 V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9	12	12	12	12
$\psi^2 X H$	8	8	16	16	16	16	24	24	24	24	32	32	32	32
$\psi^2 H^2 D$	15	1	19	5	23	5	19	5	23	5	28	10	28	10
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	53	24	53	24
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21	90	42	90	42
$(\bar{L}R)(\bar{R}L)$	1	1	3	3	4	4	5	5	6	6	10	10	10	10
$(\bar{L}R)(\bar{L}R)$	4	4	12	12	16	16	24	24	28	28	48	48	48	48
total:	124	23	182	81	234	93	212	111	264	123	349	208	356	215

~300

~600

Normal

~2500

U(2)^5

II) $U(2)^5$

e.g. relevant operators for semileptonic B decays

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{q}_L^i \gamma_\mu q_L^j)\,,$$

$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^\alpha \gamma^\mu \tau^I \ell_L^\beta)(\bar{q}_L^i \gamma_\mu \tau^I q_L^j)\,,$$

$$\mathcal{O}_{\ell d} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{d}_R^i \gamma_\mu d_R^j)\,,$$

$$\mathcal{O}_{qe} = (\bar{q}_L^i \gamma^\mu q_L^j)(\bar{e}_R^\alpha \gamma_\mu e_R^\beta)\,,$$

$$\mathcal{O}_{ed} = (\bar{e}_R^\alpha \gamma^\mu e_R^\beta)(\bar{d}_R^i \gamma_\mu d_R^j)\,,$$

$$\mathcal{O}_{\ell edq} = (\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j)\,,$$

$$\mathcal{O}_{\ell equ}^{(1)} = (\bar{\ell}_L^{a,\alpha} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{a,i} u_R^j)\,,$$

$$\mathcal{O}_{\ell equ}^{(3)} = (\bar{\ell}_L^{a,\alpha} \sigma_{\mu\nu} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{b,i} \sigma^{\mu\nu} u_R^j)$$

II) $U(2)^5$

e.g. relevant operators for semileptonic B decays

only few yield sizable effects if we impose a minimally broken $U(2)^5$ symmetry $\sim \mathcal{O}(V^2)$

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{q}_L^i \gamma_\mu q_L^j)\,,$$

$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^\alpha \gamma^\mu \tau^I \ell_L^\beta)(\bar{q}_L^i \gamma_\mu \tau^I q_L^j)\,,$$

$$\cancel{\mathcal{O}_{\ell d}} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{d}_R^i \gamma_\mu d_R^j)\,,$$

$$\mathcal{O}_{qe} = (\bar{q}_L^i \gamma^\mu q_L^j)(\bar{e}_R^\alpha \gamma_\mu e_R^\beta)\,,$$

$$\cancel{\mathcal{O}_{ed}} = (\bar{e}_R^\alpha \gamma^\mu e_R^\beta)(\bar{d}_R^i \gamma_\mu d_R^j)\,,$$

$$\mathcal{O}_{\ell edq} = (\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j)\,,$$

$$\cancel{\mathcal{O}_{\ell equ}^{(1)}} = (\bar{\ell}_L^{a,\alpha} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{b,i} u_R^j)\,,$$

$$\cancel{\mathcal{O}_{\ell equ}^{(3)}} = (\bar{\ell}_L^{a,\alpha} \sigma_{\mu\nu} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{b,i} \sigma^{\mu\nu} u_R^j)$$

LFV at the LHC

Lepton Flavor Violating (LFV) Drell-Yan process $pp \to \tau\bar{\ell}\ (\ell = e, \mu)$

$$\sigma(pp \to \tau\bar{\ell}) = \frac{s}{144\pi\,\Lambda^4}\,\mathrm{Tr}\left(F_q^{\ell\tau}(\{C_i\}) \cdot K_q\right)$$

SMEFT tensor

PDF tensor

semi-leptonic 4 fermion operators $\mathcal{O}_{\ell q}^{(1,3)}$

$$F_u^{\ell\tau nm} = \left| V_{\mathrm{CKM}}^{nr} V_{\mathrm{CKM}}^{ms\,*} \left(\Sigma_{\ell q}^{(1)\,\ell\tau,rs} - \Sigma_{\ell q}^{(3)\,\ell\tau,rs}\right) \right|^2,$$

$$F_d^{\ell\tau nm} = \left| \Sigma_{\ell q}^{(1)\,\ell\tau,nm} + \Sigma_{\ell q}^{(3)\,\ell\tau,nm} \right|^2,$$

$\Sigma_{\ell q}$: U(2) spurion parameters $\quad \Sigma_{\ell q}^{ij,nm}\left(\bar{\ell}_i \Gamma \ell_j\right)\left(\bar{q}_n \Gamma q_m\right)$

- Correlations with low-energy process

~~quark~~ & ~~lepton~~ contributions ← bound from $B_s \to \tau\ell$

→ their impact in CS is negligible

part I. Summary

- NP may have a highly non-generic flavor structure

→ Flavor symmetry MFV and $U(2)$ flavor symmetry

- We analyze how $U(3)^5$ and $U(2)^5$ flavor symmetries act on SMEFT

2499 in SMEFT
huge number of free parameters $\xrightarrow{\text{flavor symmetry}}$ reduce number of independent parameters

$U(3)^5$ and MFV drastic reduction : ~ 25 times smaller

$U(2)^5$ drastic reduction : ~ one order smaller

- This classification can be a useful first step toward a systematic analysis in motivated flavor versions of the SMEFT

What we did

part I. SMEFT and $U(2)^5$ flavor symmetry

Darius A. Faroughy, Gino Isidori, Felix Wilsch, KY [2005.05366]

part II. B anomalies and $U(2)^5$ flavor symmetry

Javier Fuentes-Martín, Gino Isidori, Julie Pagès, KY [1909.02519]

B anomalies

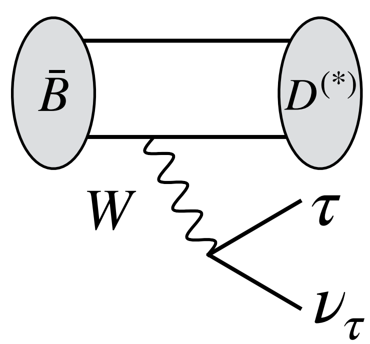
Lepton Flavour Universality Violation in semileptonic B decays

$b \to c\tau\nu$ $\quad R_{D^{(*)}}^{\text{exp}} > R_{D^{(*)}}^{\text{SM}}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Tree-level in SM

LFUV in τ vs μ/e

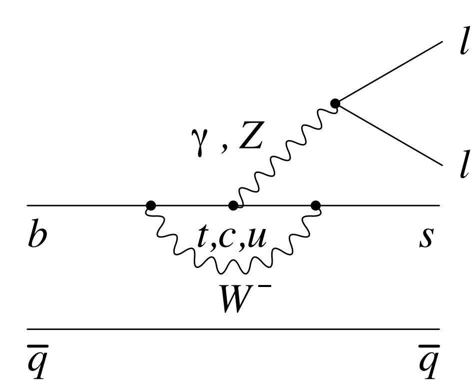


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

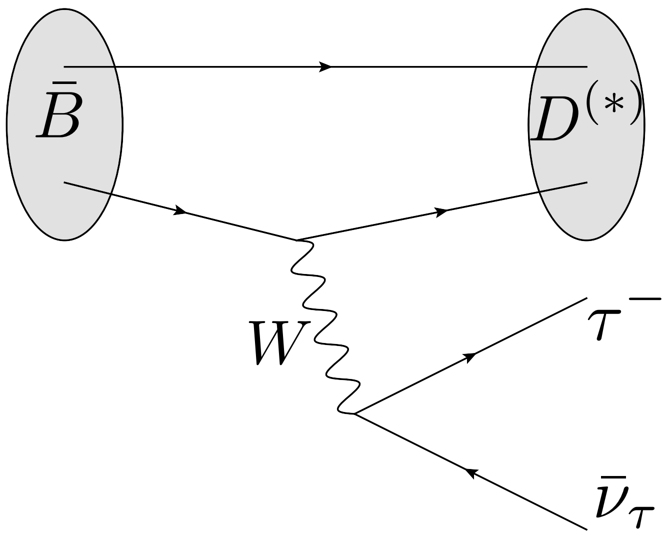
loop-level in SM

LFUV in μ vs e



B anomalies $R_{D^{(*)}} = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$

What is $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay ?



$\bar{B} = B^-(b\bar{u})$ or $\bar{B}^0(b\bar{d})$

$D = D^0(c\bar{u})$ or $D^+(c\bar{d})$

$$D^{(*)} \begin{cases} D : \text{pseudo scalar meson} \\ D^* : \text{vector meson} \end{cases}$$

Tree-level decay (b→u charged current) in SM

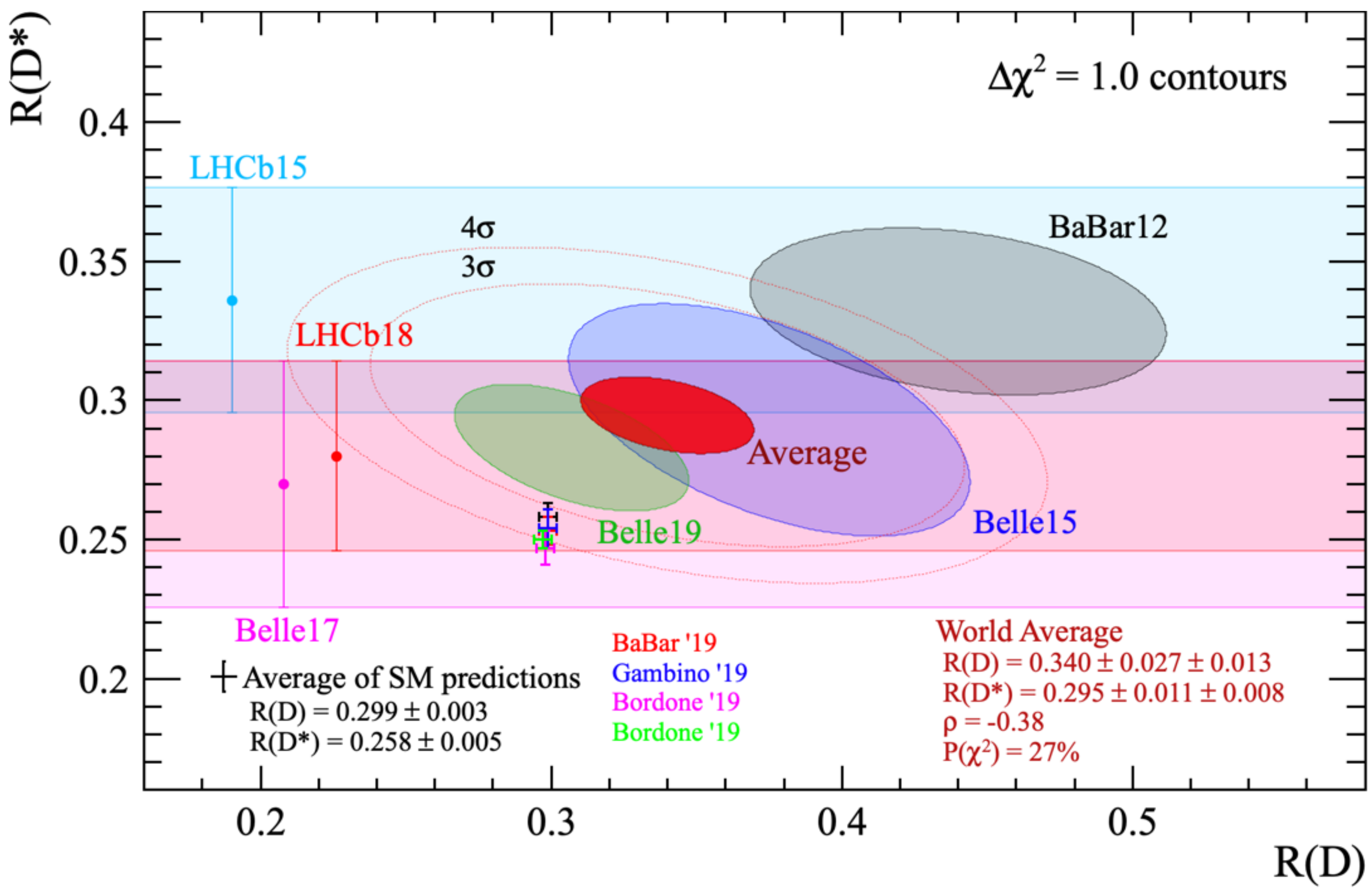
Test of lepton flavour universality τ/μ,e in semi-leptonic B decays

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

Theoretically clean, as hadronic uncertainties (form factors, Vub) largely cancel in ratio

B anomalies

$$R_{D^{(*)}} = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$



3.1σ deviation

B anomalies $R_{D^{(*)}} = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$

Related observables → NP model discrimination

- Polarisation

Longitudinal
D^* polarisation
$$F_L^{D^*} = \frac{\Gamma(\bar{B} \to D_L^* \tau\bar{\nu})}{\Gamma(\bar{B} \to D^* \tau\bar{\nu})} = \frac{\Gamma(\bar{B} \to D_L^* \tau\bar{\nu})}{\Gamma(\bar{B} \to D_L^* \tau\bar{\nu}) + \Gamma(\bar{B} \to D_T^* \tau\bar{\nu})}$$

τ polarisation
asymmetries
$$P_\tau(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau^{\lambda=+1/2}\nu) - \Gamma(B \to D^{(*)}\tau^{\lambda=-1/2}\nu)}{\Gamma(B \to D^{(*)}\tau\nu)}$$

	$F_L(D^*)$	$P_\tau(D)$	$P_\tau(D^*)$
SM	$0.46(4)$	$0.325(9)$	$-0.497(13)$
data	$0.60(9)$ [Belle '18]	-	$-0.38(55)$ [Belle '17]
Belle II	0.04	3%	0.07

↑ Recent Belle result is slightly above the SM

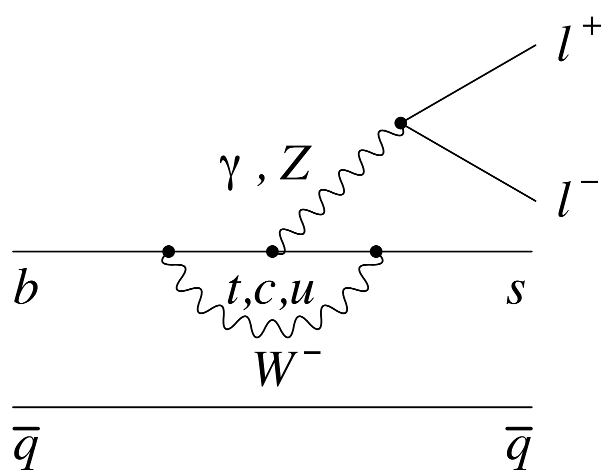
- Other LFUV ratios : $R_{J/\psi}, R_{\Lambda_c}, R_{D_s}, , ,$

- q^2 distribution ← 5 ab^-1 Belle II   Sakaki et al. 2014

B anomalies

$$R_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)}$$

What is $B \to K^{(*)}\mu^+\mu^-$ decay ?



Loop-level decay (b→s neutral current) in SM

Test of lepton flavour universality μ/e in semi-leptonic B decays

$$R_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathscr{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\approx} 1$$

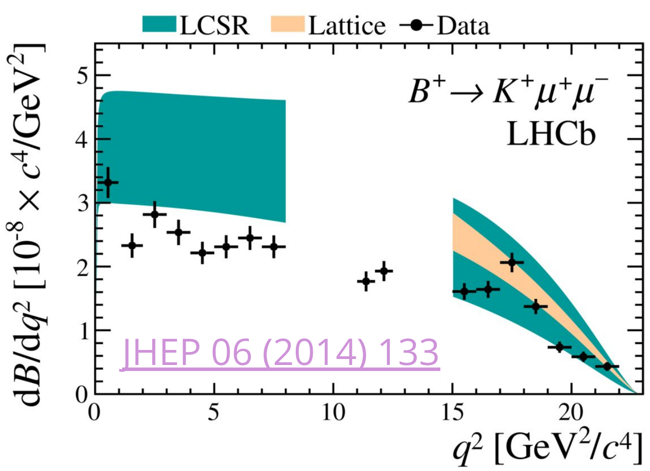
Theoretically clean, hadronic uncertainties cancel to large extent in the ratio

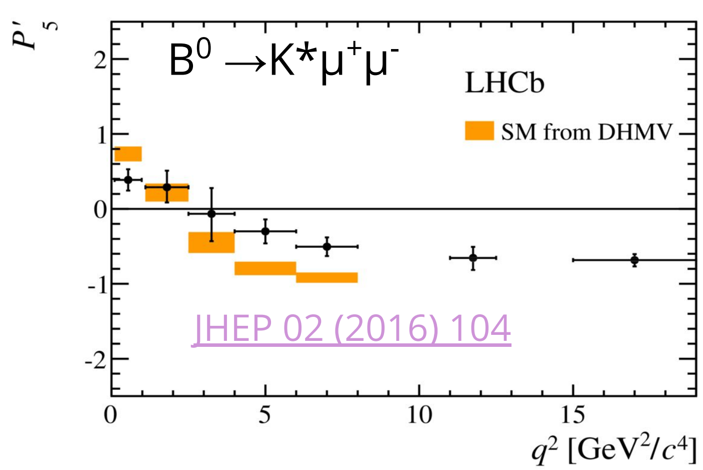
B anomalies

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

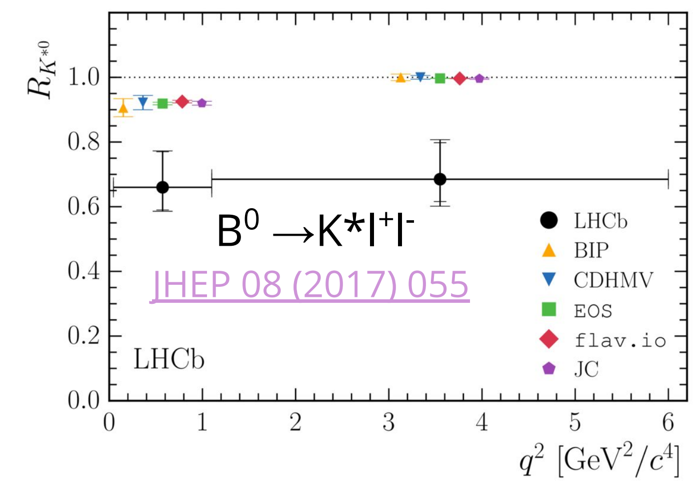
What is $B \to K^{(*)}\mu^+\mu^-$ decay ?

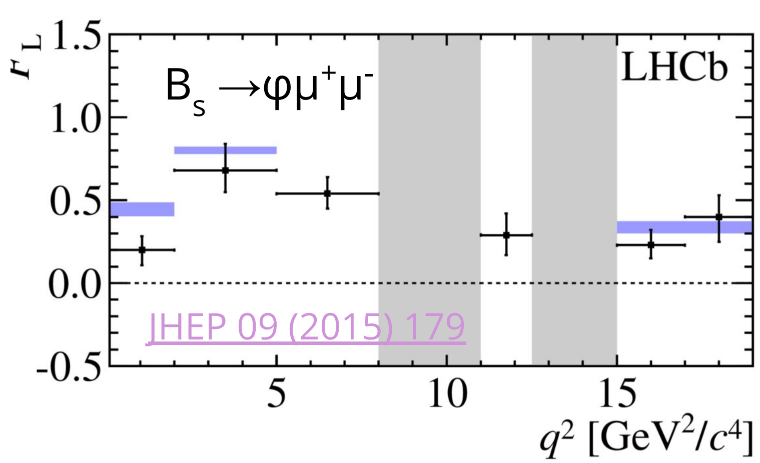
Differential BR and angular distributions

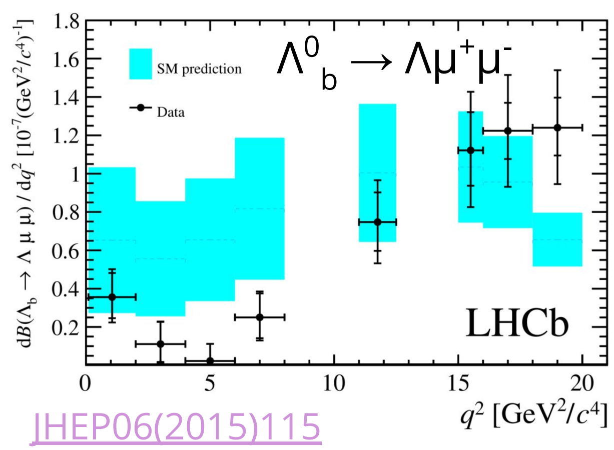


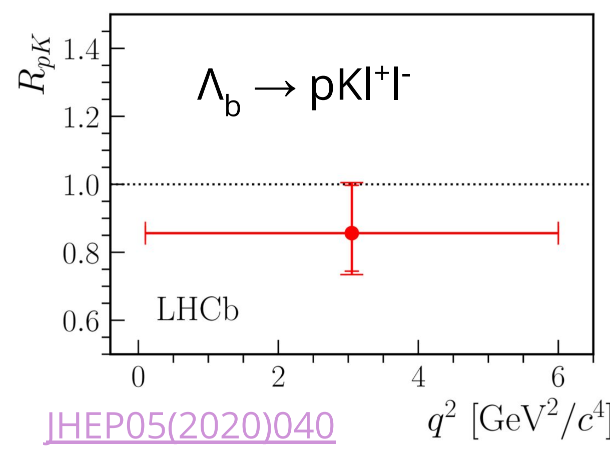


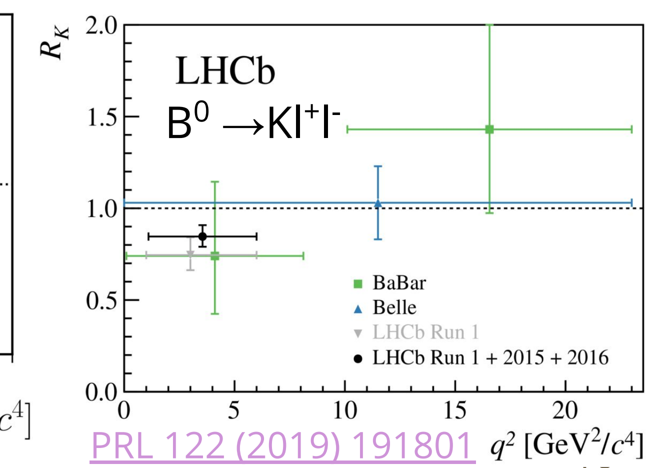
Lepton Universality tests











B anomalies

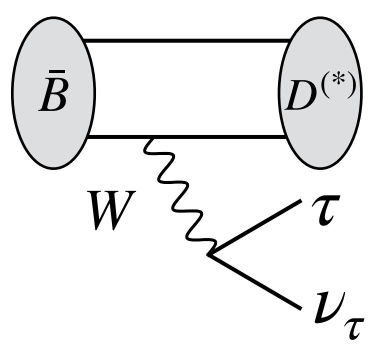
Lepton Flavour Universality Violation in semileptonic B decays

$b \to c\tau\nu$ $\quad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

Tree-level in SM

LFUV in τ vs μ/e

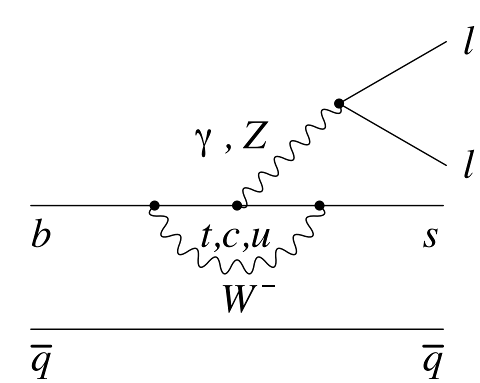


$b \to s\ell\ell$ $\quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

loop-level in SM

LFUV in μ vs e



Model independent consideration for B anomalies

- Anomalies are seen in only **semi-leptonic** (quark × lepton) operators
- **left-handed** current current operators are favored
- Hierarchical NP is needed

NP in $b \to c\tau\nu_\tau$ $\gg$ NP in $b \to s\mu\mu$

~15% of a SM **tree-level** effect ~20% of a SM **loop** effect

Similar hierarchy in Yukawa… Are these anomalies connected to them?

What we did

Yukawa (SM flavor hierarchies) $\longleftrightarrow$ B-physics anomaly

$U(2)^5$symmetry

Focus on non-standard flavor and helicity structures in semileptonic B decays

$$b \to c\tau\nu_\tau$$

B anomaly

$$R_{D^{(*)}} = \frac{B \to D^{(*)}\tau\nu_\tau}{B \to D^{(*)}\ell\nu_\ell}$$

$$B_c \to \tau\nu_\tau$$

polarizations

$$b \to u\tau\nu_\tau$$

$$R_\pi = \frac{B \to \pi\tau\nu_\tau}{B \to \pi\ell\nu_\ell}$$

$$B^+ \to \tau\bar{\nu}_\tau, \mu\bar{\nu}$$

Correlations under $U(2)^5$

$$b \to s\ell\bar{\ell}$$

B anomaly

$$R_{K^{(*)}} = \frac{B \to K^{(*)}\mu\bar{\mu}}{B \to K^{(*)}e\bar{e}}$$

$$B_s \to \tau\bar{\tau}, \mu\bar{\mu}, \tau\bar{\mu}$$

$$b \to d\ell\bar{\ell}$$

$$B_d \to \pi\mu\bar{\mu}$$

$$B_d \to \mu\bar{\mu}$$

$U(2)^5$ flavor symmetry

Yukawa after removing unphysical parameters

$$Y_u = |y_t| \begin{pmatrix} U_q^\dagger O_u^\intercal \hat{\Delta}_u & |V_q||x_t| e^{i\phi_q} \vec{n} \\ 0 & 1 \end{pmatrix}$$

$$Y_d = |y_b| \begin{pmatrix} U_q^\dagger \hat{\Delta}_d & |V_q||x_b| e^{i\phi_q} \vec{n} \\ 0 & 1 \end{pmatrix}$$

$$Y_e = |y_\tau| \begin{pmatrix} O_e^\intercal \hat{\Delta}_e & |V_e||x_\tau| \vec{n} \\ 0 & 1 \end{pmatrix}$$

$\hat{\Delta}_{u,d,e}$: 2×2 diagonal positive matrix

$O_{u,e}$: 2×2 orthogonal matrix

$$U_q = \begin{pmatrix} c_d & s_d e^{i\alpha_d} \\ -s_d e^{-i\alpha_d} & c_d \end{pmatrix}, \quad \vec{n} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Structure of Yukawa is fixed under $U(2)$ symmetry
→ elements in diagonal matrixes are described by CKM elements & fermions masses

$$Y_f \xrightarrow{Q_L \to L_d^\dagger Q_L \quad d_R \to R_d^\dagger d_R} \mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

where

$$L_d \approx \begin{pmatrix} c_d & -s_d e^{i\alpha_d} & 0 \\ s_d e^{-i\alpha_d} & c_d & s_b \\ -s_d s_b e^{-i(\alpha_d+\phi_q)} & -c_d s_b e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix} \qquad R_d \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \frac{m_s}{m_b} s_b \\ 0 & -\frac{m_s}{m_b} s_b e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix}$$

$s_d/c_d = |V_{td}/V_{ts}|$, $\alpha_d = -\mathrm{Arg}(V_{td}/V_{ts})$, $s_t = s_b - V_{cb}$, s_u

$U(2)^5$ flavor symmetry

Yukawa after removing unphysical parameters

$$Y_u = |y_t| \begin{pmatrix} U_q^\dagger O_u^\intercal \hat{\Delta}_u & |V_q| \, |x_t| \, e^{i\phi_q} \vec{n} \\ 0 & 1 \end{pmatrix}$$

$$Y_d = |y_b| \begin{pmatrix} U_q^\dagger \hat{\Delta}_d & |V_q| \, |x_b| \, e^{i\phi_q} \vec{n} \\ 0 & 1 \end{pmatrix}$$

$$Y_e = |y_\tau| \begin{pmatrix} O_e^\intercal \hat{\Delta}_e & |V_e| \, |x_\tau| \, \vec{n} \\ 0 & 1 \end{pmatrix}$$

$\hat{\Delta}_{u,d,e}$: 2×2 diagonal positive matrix

$O_{u,e}$: 2×2 orthogonal matrix

$$U_q = \begin{pmatrix} c_d & s_d \, e^{i\alpha_d} \\ -s_d \, e^{-i\alpha_d} & c_d \end{pmatrix}, \quad \vec{n} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Structure of Yukawa is fixed under $U(2)$ symmetry

→ elements in diagonal matrixes are described by CKM elements & fermions masses

$$Y_f \xrightarrow{\quad Q_L \to L_d^\dagger Q_L \quad d_R \to R_d^\dagger d_R \quad} \mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

Parameters constrained

quark $s_d/c_d = |V_{td}/V_{ts}|$, $\alpha_d = -\mathrm{Arg}(V_{td}/V_{ts})$, $s_t = s_b - V_{cb}$, s_u $s_b/c_b = |x_b| \, |V_q|$, ϕ_q

lepton $s_\tau/c_\tau = |x_\tau| \, |V_\ell|$, s_e

Effective field theory + $U(2)^5$ for semileptonic decay

Relevant semileptonic operators in SMEFT ($\mu_{\mathrm{EW}} < \mu < \mu_{\mathrm{NP}}$)

$$\mathscr{L}_{\mathrm{EFT}} = -\frac{1}{v^2} \sum_{k,[ij\alpha\beta]} C_k^{[ij\alpha\beta]} \mathscr{O}_k^{[ij\alpha\beta]} + \mathrm{h.c.}$$

$$\mathcal{O}_{\ell q}^{(1)} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{q}_L^i \gamma_\mu q_L^j) \,,$$

$$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^\alpha \gamma^\mu \tau^I \ell_L^\beta)(\bar{q}_L^i \gamma_\mu \tau^I q_L^j) \,,$$

$$\mathcal{O}_{\ell d} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{d}_R^i \gamma_\mu d_R^j) \,,$$

$$\mathcal{O}_{qe} = (\bar{q}_L^i \gamma^\mu q_L^j)(\bar{e}_R^\alpha \gamma_\mu e_R^\beta) \,,$$

$$\mathcal{O}_{ed} = (\bar{e}_R^\alpha \gamma^\mu e_R^\beta)(\bar{d}_R^i \gamma_\mu d_R^j) \,,$$

$$\mathcal{O}_{\ell edq} = (\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j) \,,$$

$$\mathcal{O}_{\ell equ}^{(1)} = (\bar{\ell}_L^{a,\alpha} e_R^\beta) \epsilon_{ab} (\bar{q}_L^{b,i} u_R^j) \,,$$

$$\mathcal{O}_{\ell equ}^{(3)} = (\bar{\ell}_L^{a,\alpha} \sigma_{\mu\nu} e_R^\beta) \epsilon_{ab} (\bar{q}_L^{b,i} \sigma^{\mu\nu} u_R^j)$$

Effective field theory + $U(2)^5$ for semileptonic decay

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$$\cancel{\mathcal{O}_{qe}} = (\bar q_L^i\gamma^\mu q_L^j)(\bar e_R^\alpha\gamma_\mu e_R^\beta)\,,$$

$$\cancel{\mathcal{O}_{ed}} = (\bar e_R^\alpha\gamma^\mu e_R^\beta)(\bar d_R^i\gamma_\mu d_R^j)\,,$$

$$\mathcal{O}_{\ell edq} = (\bar\ell_L^\alpha e_R^\beta)(\bar d_R^i q_L^j)\,,$$

$$\cancel{\mathcal{O}_{\ell equ}^{(1)}} = (\bar\ell_L^{a,\alpha}e_R^\beta)\epsilon_{ab}(\bar q_L^{b,i}u_R^j)\,,$$

$$\cancel{\mathcal{O}_{\ell equ}^{(3)}} = (\bar\ell_L^{a,\alpha}\sigma_{\mu\nu}e_R^\beta)\epsilon_{ab}(\bar q_L^{b,i}\sigma^{\mu\nu}u_R^j)$$

contribute at tree-level only to $b\to s\tau\bar\tau$ which is currently poorly constrained
→ do not consider for simplicity

Right handed light fermion operators are suppressed under U(2)

only few yield sizable effects if we impose a minimally broken $U(2)^5$ symmetry

Effective field theory + $U(2)^5$ for semileptonic decay

$$\mathscr{L}_{\text{EFT}} \supset \mathscr{L}_{\text{SM}} - \frac{1}{v^2}\left[C_{V_1}\Lambda_{V_1}^{[ij\alpha\beta]}\mathcal{O}_{\ell q}^{(1)} + C_{V_3}\Lambda_{V_3}^{[ij\alpha\beta]}\mathcal{O}_{\ell q}^{(3)} + \left(2\,C_S\,\Lambda_S^{[ij\alpha\beta]}\,\mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\right]$$

(NP contribution) = (NP strength C_{V_i}, C_S) × (Flavor structure Λ_{V_i}, Λ_S)

Need relation $C_{\ell q}^{(1)} \approx C_{\ell q}^{(3)}$ to avoid constraint from $B \to K^{(*)}\nu\bar{\nu}$

3rd

$$BR(B \to K^{(*)}\nu\bar{\nu}) = BR(B \to K^{(*)}\nu_e\bar{\nu}_e) + BR(B \to K^{(*)}\nu_\mu\bar{\nu}_\mu) + BR(B \to K^{(*)}\nu_\tau\bar{\nu}_\tau)$$

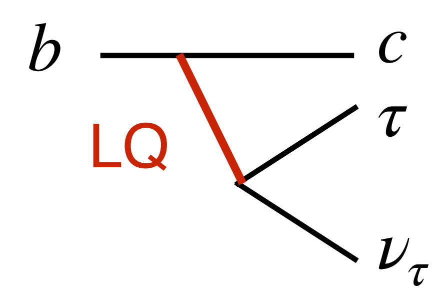
$$\mathscr{L}_{\text{EFT}} \supset \mathscr{L}_{\text{SM}} - \frac{1}{v^2}\left[C_V\Lambda_V^{[ij\alpha\beta]}\left(\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right) + \left(2\,C_S\,\Lambda_S^{[ij\alpha\beta]}\,\mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\right]$$

Effective field theory + $U(2)^5$ for semileptonic decay

$$\mathscr{L}_{\rm EFT} \supset \mathscr{L}_{\rm SM} - \frac{1}{v^2}\left[C_V \Lambda_V^{[ij\alpha\beta]} \left(\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right) + \left(2\, C_S \Lambda_S^{[ij\alpha\beta]}\, \mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\right]$$

(NP contribution) = (NP strength C_V, C_S) × (Flavor structure Λ_V, Λ_S)

Nicely matches the structure in U_1 Leptoquark (LQ)



Leptoquark(LQ) solution (scalar and vector) is the best solution for B anomaly so far.
Especially, $U_1 = (3,1,2/3)$ vector LQ can access both $R_{D^{(*)}}$ & $R_{K^{(*)}}$

$$\Lambda_{V_1} = \Lambda_{V_3} = \Lambda_V$$

$$C_{V_1} = C_{V_3} = \frac{g_U^2 v^2}{4M_U^2} \equiv C_V > 0$$ ← arise naturally

$$\frac{C_S}{C_V} = -\,2\,\beta_R$$

$$\mathscr{L}_{U_1} = \frac{g_U}{\sqrt{2}}\left[\beta_L^{i\alpha}\,(\bar{q}_L^{\,i}\gamma_\mu \ell_L^{\alpha}) + \beta_R^{i\alpha}\,(\bar{d}_R^{\,i}\gamma_\mu e_R^{\alpha})\right] U_1^\mu + \mathrm{h.c.}$$

EFT approach & U_1 LQ

Effective field theory + $U(2)^5$ for semileptonic decay

$$\mathscr{L}_{\rm EFT} \supset \mathscr{L}_{\rm SM} - \frac{1}{v^2}\left[C_V \Lambda_V^{[ij\alpha\beta]}\left(\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right) + \left(2\, C_S \Lambda_S^{[ij\alpha\beta]}\, \mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\right]$$

(NP contribution) = (NP strength C_V, C_S) × (Flavor structure Λ_V, Λ_S)

Flavor structure Λ_{V_i}, Λ_S $\quad \Lambda_V^{[ij\alpha\beta]} = (\Gamma_L^{V\dagger})^{\alpha j} \times (\Gamma_L^V)^{i\beta}, \quad \Lambda_S^{[ij\alpha\beta]} = (\Gamma_L^\dagger)^{\alpha j} \times \Gamma_R^{i\beta}$

in the interaction basis

$$\Gamma_L = \begin{pmatrix} V_q V_\ell^* & V_q \\ V_\ell^* & 1 \end{pmatrix} \qquad \Gamma_R = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

In order to explain B anomalies, we need $V_q \sim V_\ell \sim \mathcal{O}(10^{-1})$

→ same size as spurions in Yukawa

Common explanation makes sense

$U(2)^5$symmetry

Yukawa (SM flavor hierarchies) ⟷ B-physics anomaly

Effective field theory + $U(2)^5$ for semileptonic decay

$$\mathscr{L}_{\mathrm{EFT}} \supset \mathscr{L}_{\mathrm{SM}} - \frac{1}{v^2}\left[C_V \Lambda_V^{[ij\alpha\beta]} \left(\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right) + \left(2\, C_S \Lambda_S^{[ij\alpha\beta]}\, \mathcal{O}_{\ell edq} + \mathrm{h.c.}\right)\right]$$

(NP contribution) = (NP strength C_V, C_S) × (Flavor structure Λ_V, Λ_S)

Flavor structure Λ_{V_i}, Λ_S $\quad \Lambda_V^{[ij\alpha\beta]} = (\Gamma_L^{V\dagger})^{\alpha j} \times (\Gamma_L^{V})^{i\beta}, \quad \Lambda_S^{[ij\alpha\beta]} = (\Gamma_L^{\dagger})^{\alpha j} \times \Gamma_R^{i\beta}$

in mass basis $\quad Q_L \to L_d^\dagger Q_L \quad d_R \to R_d^\dagger d_R$

$$\Gamma_L \approx \begin{array}{cc} & \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\ & \left(\begin{array}{ccc} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{array}\right) \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \end{array} \qquad \Gamma_R \approx \begin{array}{cc} & \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\ & \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_b}{m_s}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_\tau & 1 \end{array}\right) \begin{array}{c} d_R \\ s_R \\ b_R \end{array} \end{array}$$

$\lambda_q^s,\ \lambda_\ell^\mu \sim O(|V_q|) \sim O(10^{-1})$

$\Delta_{q\ell}^{s\mu} \sim O(\lambda_q^s \lambda_\ell^\mu) \sim O(10^{-2})$

$\frac{m_s}{m_b}, \frac{m_\mu}{m_\tau} \sim O(10^{-2})$

$O(10^{-2}) < O(10^{-1}) < O(1)$

At lowest order in the spurion ($V_{q,\ell}$) expansion

$U(2)^5$ predictions

$$\Gamma_L \approx \begin{array}{c c} \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} & \\ \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix} & \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \end{array} \qquad \Gamma_R \approx \begin{array}{c c} \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} & \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_b}{m_s}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_\tau & 1 \end{pmatrix} & \begin{array}{c} d_R \\ s_R \\ b_R \end{array} \end{array}$$

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$\frac{m_s}{m_b}, \frac{m_\mu}{m_\tau} \sim O(10^{-2})$

$O(10^{-2}) < O(10^{-1}) < O(1)$

NC $b \to s\mu\mu \ll$ CC $b \to c\tau\nu$

U(2) Predictions:

- NP in NC $b \to s\mu\mu \ll$ NP in CC $b \to c\tau\nu$

$U(2)^5$ predictions

$$\Gamma_L \approx \begin{array}{cc} & \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\ & \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix} & \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array} \end{array} \qquad \Gamma_R \approx \begin{array}{cc} & \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\ & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_b}{m_s}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_\tau & 1 \end{pmatrix} & \begin{array}{c} d_R \\ s_R \\ b_R \end{array} \end{array}$$

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$O(10^{-2}) < O(10^{-1}) < O(1)$

$$b \to u\tau\nu \;/\; b \to c\tau\nu = \frac{V_{ub}}{V_{cb}}$$

U(2) Predictions:

- NP in NC $b \to s\mu\mu$ $\ll$ NP in CC $b \to c\tau\nu$
- NP strength in $b \to c(s)$ = NP strength in $b \to u(d)$

$$\frac{b \to c\ell\nu}{b \to u\ell\nu} = \left.\frac{b \to c\ell\nu}{b \to u\ell\nu}\right|_{\rm SM} \qquad \frac{b \to s\ell\ell}{b \to d\ell\ell} = \left.\frac{b \to s\ell\ell}{b \to d\ell\ell}\right|_{\rm SM}$$

$U(2)^5$ predictions

$$\Gamma_L \approx \begin{array}{c} \\ \end{array}\begin{array}{c} \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\ \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e \lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ q_1 \\ q_2 \\ q_3 \end{array} \qquad \Gamma_R \approx \begin{array}{c} \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \frac{m_b}{m_s} s_b \\ 0 & \frac{m_\mu}{m_\tau} s_\tau & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ d_R \\ s_R \\ b_R \end{array}$$

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- Scalar operator with light fermions suppressed by $\frac{m_s}{m_b}, \frac{m_\mu}{m_\tau}$

$U(2)^5$ Prediction in CC & NC

$$
\Gamma_L \approx
\begin{array}{c c}
 & \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\
 & \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix}
\end{array}
\begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array}
\quad V_q
$$

V_ℓ

	Charged current	Neutral current
quark sector V_q	$b \to c(u)\tau\nu$ $R_{D^{(*)}}, R_\pi, B^+_{u,c} \to \tau\nu$ *polarizations*	$b \to s\nu\nu$ No tree level ($C_{\ell q}^{(1)} \approx C_{\ell q}^{(3)}$) $b \to s\tau\tau$ $B_s \to \tau\tau$
lepton sector V_ℓ	$b \to c(u)\mu\nu$ $R_{D^{(*)}}^{\mu e} \equiv \frac{\mathscr{B}(B \to D^{(*)}\mu\bar{\nu})}{\mathscr{B}(B \to D^{(*)}e\bar{\nu})}$ $B^+ \to \mu\bar{\nu}$	$b \to s(d)\mu\mu$ $R_{K^{(*)}}, B_{s,d} \to \mu\mu$ $\frac{\mathscr{B}(B \to \pi\mu\bar{\mu})}{\mathscr{B}(B \to \pi e\bar{e})}$ Others $B_s \to \tau\bar{\mu}, \tau \to \mu\gamma$

$U(2)^5$ Prediction in CC & NC

$$\Gamma_L \approx \begin{array}{c} \\ \end{array} \begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array}$$

$$\Gamma_L \approx \begin{pmatrix} 0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix} \begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array}$$

V_q

V_ℓ

	Charged current	Neutral current
quark sector V_q	$b \to c(u)\tau\nu$ $R_{D^{(*)}}, R_\pi, B^+_{u,c} \to \tau\nu$ *polarizations*	$b \to s\nu\nu$ No tree level ($C^{(1)}_{\ell q} \approx C^{(3)}_{\ell q}$) $b \to s\tau\tau$ $B_s \to \tau\tau$
lepton sector V_ℓ	$b \to c(u)\mu\nu$ $R^{\mu e}_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}{\mathcal{B}(B \to D^{(*)}e\bar{\nu})}$ $B^+ \to \mu\bar{\nu}$	$b \to s(d)\mu\mu$ $R_{K^{(*)}}, B_{s,d} \to \mu\mu$ $\frac{\mathcal{B}(B \to \pi\mu\bar{\mu})}{\mathcal{B}(B \to \pi e\bar{e})}$ Others $B_s \to \tau\bar{\mu}, \tau \to \mu\gamma$

Prediction in CC : b→c & b→u

For convenience, re-define effective couplings as $\mathscr{A}^{\rm SM} \to (1 + C_V^{u,c})\mathscr{A}^{\rm SM}$

in mass basis with $q_L^i = \begin{pmatrix} V_{ji}^* u_j \\ d_i \end{pmatrix}$

for $b \to c$

$$C_{V(S)}^c \equiv \frac{1}{V_{cb}} C_{V(S)} \left[(V_{CKM})_{ci} \Lambda_{V(S)}^{[ib\tau\tau]} \right] = C_{V(S)} \left(1 - \lambda_q^s \frac{V_{tb}^*}{V_{ts}^*} \right)$$

for $b \to u$

$$C_{V(S)}^u \equiv \frac{1}{V_{ub}} C_{V(S)} \left[(V_{CKM})_{ui} \Lambda_{V(S)}^{[ib\tau\tau]} \right] = C_{V(S)} \left(1 - \lambda_q^s \frac{V_{tb}^*}{V_{ts}^*} \right) = C_{V(S)}^c$$

$b \to c$ vs $b \to u$

$$C_{V(S)}^c = C_{V(S)}^u$$

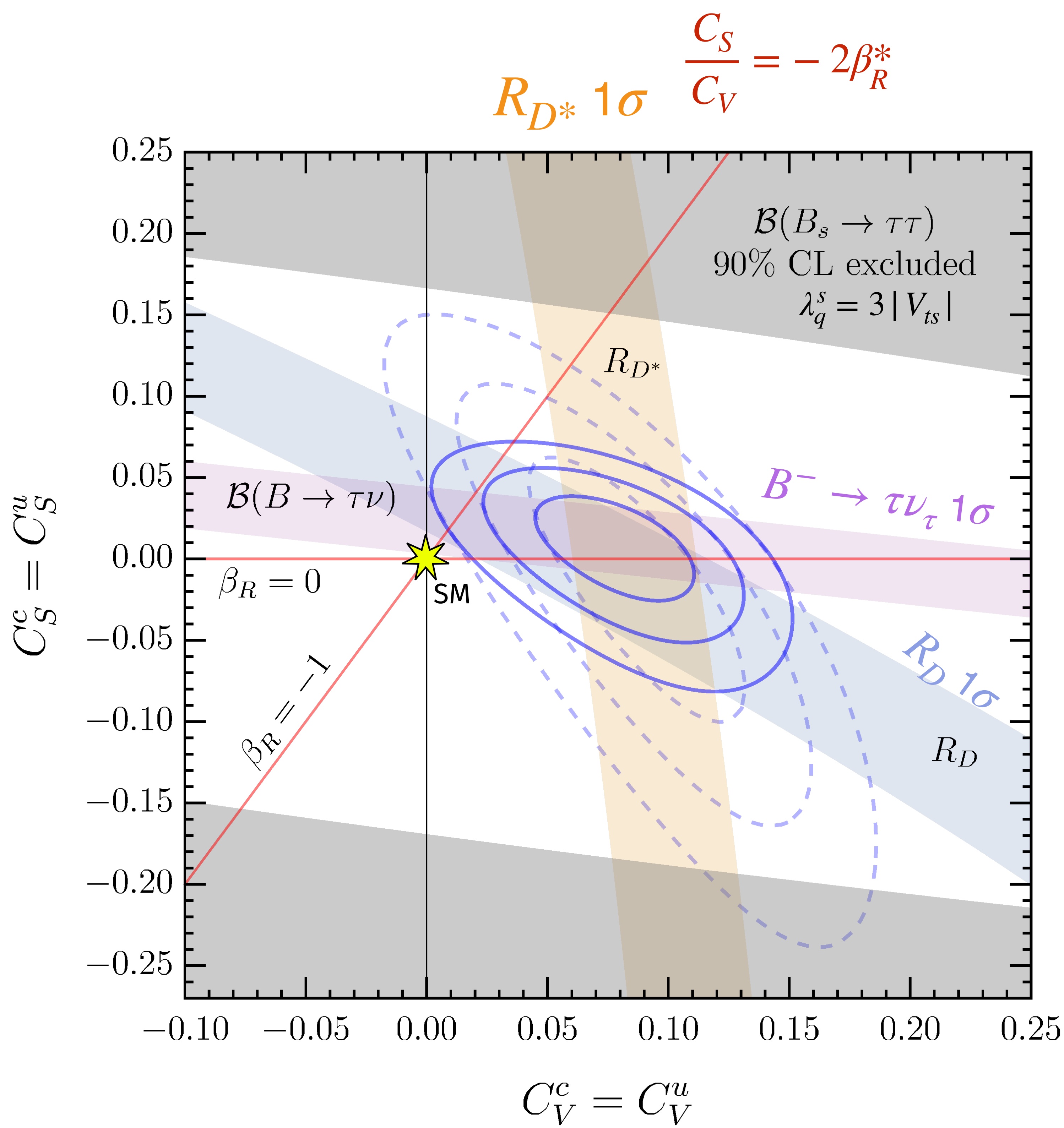
SM -like CKM scaling

scalar and vector

$$\frac{C_S^c}{C_V^c} = \frac{C_S^u}{C_V^u} = \frac{C_S}{C_V}$$

flavor blind & depend on only NP helicity structure

C_S vs C_V



- - - : Chi2 w $R_{D^{(*)}}$ (b→c)

— : Chi2 w $R_{D^{(*)}}$ (b→c) + B^- (b→u)

~3σ from SM point

U(2) prediction for $B^- \to \tau\nu$ is compatible with them

Numerical formula for observables

$$\frac{R_D}{R_D^{\rm SM}} \approx |1+C_V^c|^2 + 1.50(1)\,{\rm Re}[(1+C_V^c)\,\eta_S\,C_S^{c*}] + 1.03(1)\,|\eta_S\,C_S^c|^2$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \approx |1+C_V^c|^2 + 0.12(1)\,{\rm Re}[(1+C_V^c)\,\eta_S\,C_S^{c*}] + 0.04(1)\,|\eta_S\,C_S^c|^2$$

form factors : HQET

Bernlochner, et al [1703.05330]

$$\longrightarrow \quad \Delta R_D - \Delta R_{D^*} \approx 1.4\;\eta_S\;{\rm Re}C_S^c$$

$$\left(\Delta O_X = \frac{O_X}{O_X^{\rm SM}} - 1\right)$$

$$\frac{F_L^{D^*}}{F_{L,{\rm SM}}^{D^*}} \approx \left(\frac{R_{D^*}}{R_{D^*}^{\rm SM}}\right)^{-1}\Big(|1+C_V^c|^2 + 0.087(4)\,|\eta_S\,C_S^c|^2 + 0.253(8)\,{\rm Re}[(1+C_V^c)\,\eta_S\,C_S^{c*}]\Big)$$

$$\frac{P_\tau^D}{P_{\tau,{\rm SM}}^D} \approx \left(\frac{R_D}{R_D^{\rm SM}}\right)^{-1}\Big(|1+C_V^c|^2 + 3.24(1)\,|\eta_S\,C_S^c|^2 + 4.69(2)\,{\rm Re}[(1+C_V^c)\,\eta_S\,C_S^{c*}]\Big)$$

$$\frac{P_\tau^{D^*}}{P_{\tau,{\rm SM}}^{D^*}} \approx \left(\frac{R_{D^*}}{R_{D^*}^{\rm SM}}\right)^{-1}\Big(|1+C_V^c|^2 - 0.079(5)\,|\eta_S\,C_S^c|^2 - 0.23(1)\,{\rm Re}[(1+C_V^c)\,\eta_S\,C_S^{c*}]\Big)$$

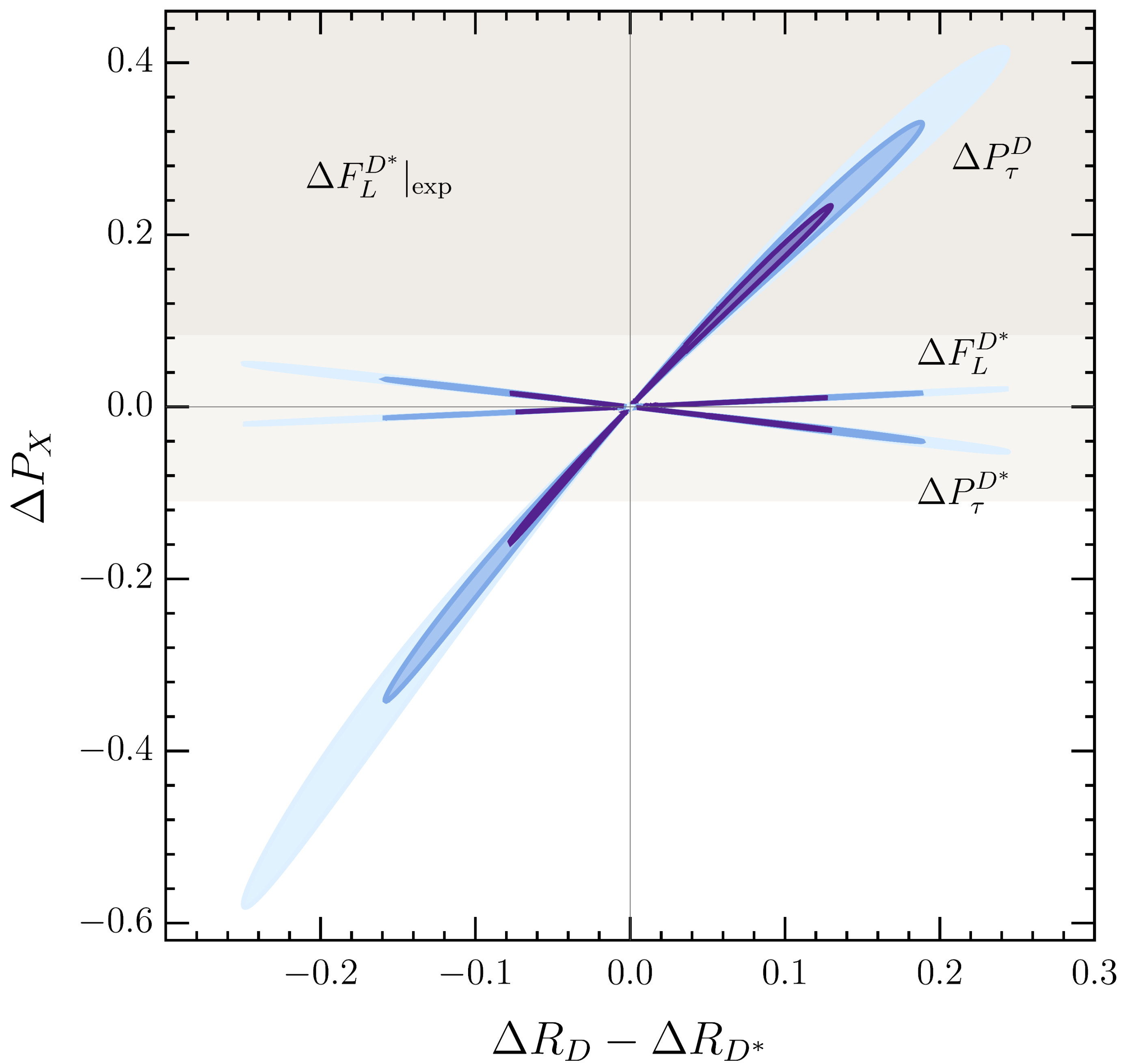
vector C_V is just rescaling of SM

scalar C_S can be NP

$$\longrightarrow \quad \Delta R_D - \Delta R_{D^*} \text{ vs } \Delta P_X$$

※ $\eta_S \approx 1.7$: running effect of scalar ope. from TeV down to m_b

Polarisations



$\propto C_S^c$

$$\Delta R_D - \Delta R_{D^*} \approx 2.4\, C_S^c$$

$$\left(\Delta O_X = \frac{O_X}{O_X^{\rm SM}} - 1 \right)$$

— : Chi2 w $R_{D^{(*)}}$ (b→c) + B^- (b→u)

D transition (ΔP_τ^D) : ~ 40% enhance

D^* transition ($\Delta P_\tau^{D^*}, F_L^{D^*}$) : few %

sharp predictions → Belle II

R_π, B^+, B_c^+

$b \to c$

Chiral enhancement factor

$$\frac{\mathcal{B}(B_c^+ \to \tau^+\nu)}{\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)_{\text{SM}}} = \left|1 + C_V^c + \frac{m_{B_c}^2}{m_\tau\left(\overline{m}_b + \overline{m}_c\right)}\, C_S^c\right|^2 \approx \left|1 + C_V^c + 4.33 C_S^c\right|$$

$b \to u$

$$\frac{\mathcal{B}(B^+ \to \tau^+\nu)}{\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\text{SM}}} = \left|1 + C_V^u + \frac{m_{B^+}^2}{m_\tau\left(\overline{m}_b + \overline{m}_u\right)}\, C_S^u\right|^2 \approx \left|1 + C_V^u + 3.75 C_S^u\right|$$

$$R_\pi = \frac{B \to \pi\tau\nu_\tau}{B \to \pi\ell\nu_\ell}$$

$$\frac{R_\pi}{R_\pi^{\text{SM}}} = |1 + C_V^u|^2 + 1.13\,\text{Re}\left[(1 + C_V^u)C_S^{u*}\right] + 1.36\,|C_S^u|^2$$

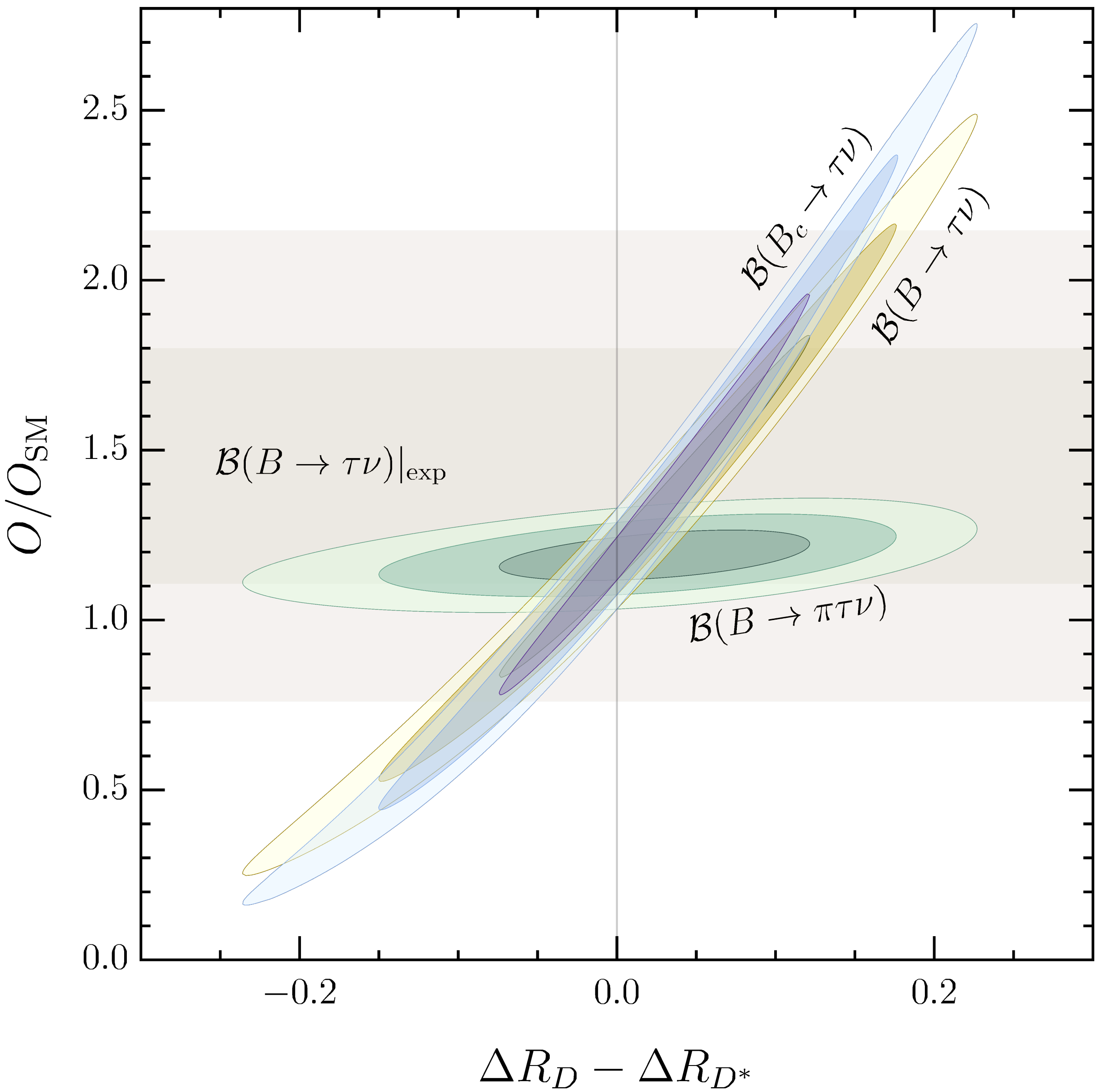
$\Delta R_D - \Delta R_{D^*}$ vs $\dfrac{O}{O^{\text{SM}}}$

U(2) Predictions: b→c= b→u

$$\frac{\mathcal{B}(\bar{B}_u \to \tau\bar{\nu})}{\mathcal{B}(\bar{B}_u \to \tau\bar{\nu})_{\text{SM}}} \approx \frac{\mathcal{B}(\bar{B}_c \to \tau\bar{\nu})}{\mathcal{B}(\bar{B}_c \to \tau\bar{\nu})_{\text{SM}}}$$

$$\frac{R_\pi}{R_\pi^{\text{SM}}} \approx 0.75\,\frac{R_D}{R_D^{\text{SM}}} + 0.25\,\frac{R_{D^*}}{R_{D^*}^{\text{SM}}}$$

R_π, B^+, B_c^+



$\propto C_S^c$

– : Chi2 w $R_{D^{(*)}}, B^+$

$R_\pi / R_\pi^{\rm SM} \lesssim 1.3$

$R_\pi^{\rm SM} = 0.641 \pm 0.016$

$R_\pi^{\rm exp} \simeq 1.05 \pm 0.51$

→ Belle II $R_\pi^{\rm BelleII} = 0.641 \pm 0.071$

Tanaka and Wtanabe [1608.05207]

U(2) Predictions: b→c= b→u

$$\frac{\mathscr{B}(\bar{B}_u \to \tau\bar{\nu})}{\mathscr{B}(\bar{B}_u \to \tau\bar{\nu})_{\rm SM}} \approx \frac{\mathscr{B}(\bar{B}_c \to \tau\bar{\nu})}{\mathscr{B}(\bar{B}_c \to \tau\bar{\nu})_{\rm SM}}$$

$$\frac{R_\pi}{R_\pi^{\rm SM}} \approx 0.75\,\frac{R_D}{R_D^{\rm SM}} + 0.25\,\frac{R_{D^*}}{R_{D^*}^{\rm SM}}$$

$U(2)^5$ Prediction in CC & NC

So far focus on observables with tau lepton

What about lepton spurion?

$$
\Gamma_L \approx
\begin{array}{c}
\begin{array}{ccc} \ell_1 & \ell_2 & \ell_3 \end{array} \\
\begin{pmatrix}
0 & 0 & \frac{V_{tb}^*}{V_{ts}^*}\lambda_q^s \\
0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\
s_e \lambda_\ell^\mu & \lambda_\ell^\mu & 1
\end{pmatrix}
\end{array}
\begin{array}{c} q_1 \\ q_2 \\ q_3 \end{array}
\quad V_q
$$

$$V_\ell$$

	Charged current	Neutral current
quark sector V_q	$b \to c(u)\tau\nu$ $R_{D^{(*)}}, R_\pi, B^+_{u,c} \to \tau\nu$ *polarizations*	$b \to s\nu\nu$ No tree level ($C_{\ell q}^{(1)} \approx C_{\ell q}^{(3)}$) $b \to s\tau\tau$ $B_s \to \tau\tau$ poorly constraint
lepton sector V_ℓ	$b \to c(u)\mu\nu$ $R_{D^{(*)}}^{\mu e} \equiv \frac{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}{\mathcal{B}(B \to D^{(*)}e\bar{\nu})}$ $B^+ \to \mu\bar{\nu}$ 10^{-3} level NP beyond future exp reach	$b \to s(d)\mu\mu$ $R_{K^{(*)}}, B_{s,d} \to \mu\mu$ $\frac{\mathcal{B}(B \to \pi\mu\bar{\mu})}{\mathcal{B}(B \to \pi e\bar{e})}$ Others $B_s \to \tau\bar{\mu}, \tau \to \mu\gamma$

Prediction in NC : b→s

$$\mathscr{H}_{\rm WET}^{b\to s} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{tb}V_{ts}^* \sum_{i=9,10,S,P} C_i^\ell\,\mathcal{O}_i^\ell$$

$$\mathcal{O}_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,\ \mathcal{O}_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

$$\mathcal{O}_S^\ell = (\bar{s}P_R b)(\bar{\ell}\ell)\,,\ \mathcal{O}_P^\ell = (\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)$$

$$\Delta C_9^\mu = -\Delta C_{10}^\mu = -\frac{2\pi}{\alpha V_{tb}V_{ts}^*}C_V\,\Delta_{q\ell}^{s\mu}\,\lambda_\ell^{\mu\,*}\,,\quad C_S^\mu = -C_P^\mu = \frac{2\pi}{\alpha V_{tb}V_{ts}^*}\frac{m_\mu}{m_\tau}C_S^*\,\Delta_{q\ell}^{s\mu}\,s_\tau$$

$$C_i = C_i^{\rm SM} + \Delta C_i$$

$R_{K^{(*)}}$

$$R_K \approx R_{K^*} \approx 1 + 0.47\,\Delta C_9^\mu$$

$$\Delta C_9^\mu = -0.43 \pm 0.11 \longrightarrow C_V > 0,\ \Delta_{q\ell}^{s\mu}\,\lambda_\ell^{\mu\,*} < 0$$

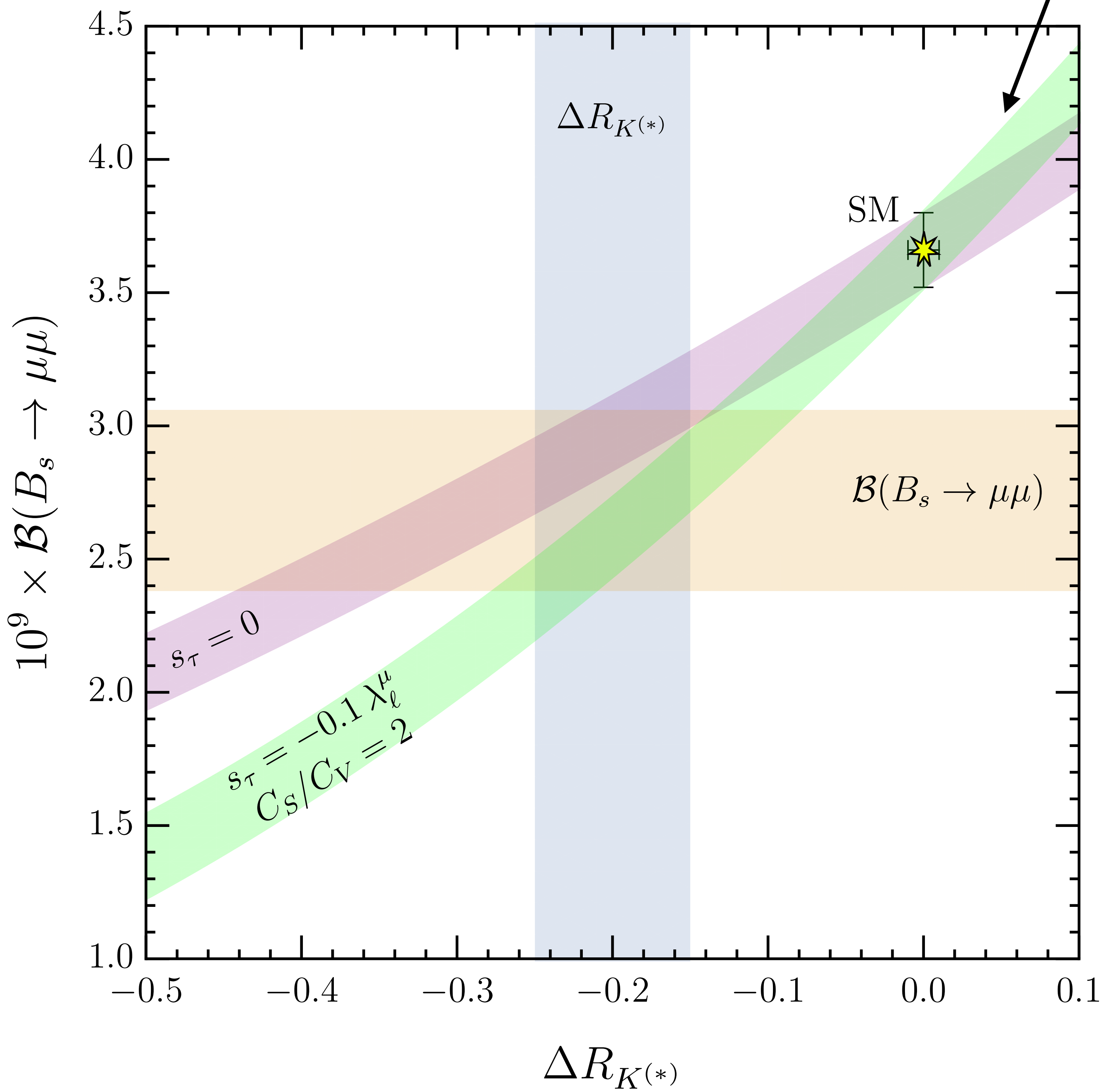
$\mathscr{B}(B_s \to \mu\bar{\mu})$

$$\frac{\mathscr{B}(B_s\to\mu\bar{\mu})}{\mathscr{B}(B_s\to\mu\bar{\mu})_{\rm SM}} = \left|1 - \frac{\Delta R_{K^{(*)}}}{0.47\,C_{10}^{\rm SM}}\left(1-\chi_s\,\eta_S\,\frac{s_\tau}{\lambda_\ell^\mu}\frac{C_S}{C_V^*}\right)\right|^2 + \left(1-\frac{4m_\mu^2}{m_{B_s}^2}\right)\left|\frac{\Delta R_{K^{(*)}}}{0.47\,C_{10}^{\rm SM}}\chi_s\,\eta_S\,\frac{s_\tau}{\lambda_\ell^\mu}\frac{C_S}{C_V^*}\right|^2$$

$\Delta R_{K^{(*)}}$ vs $\mathscr{B}(B_s \to \mu\bar{\mu})$

$R_{K^{(*)}}^{\rm exp} = 0.80 \pm 0.05$

Two bench mark point



Data show tension with SM
(the tension gets mild recently)

Consistent with U(2) prediction

part II. Summary

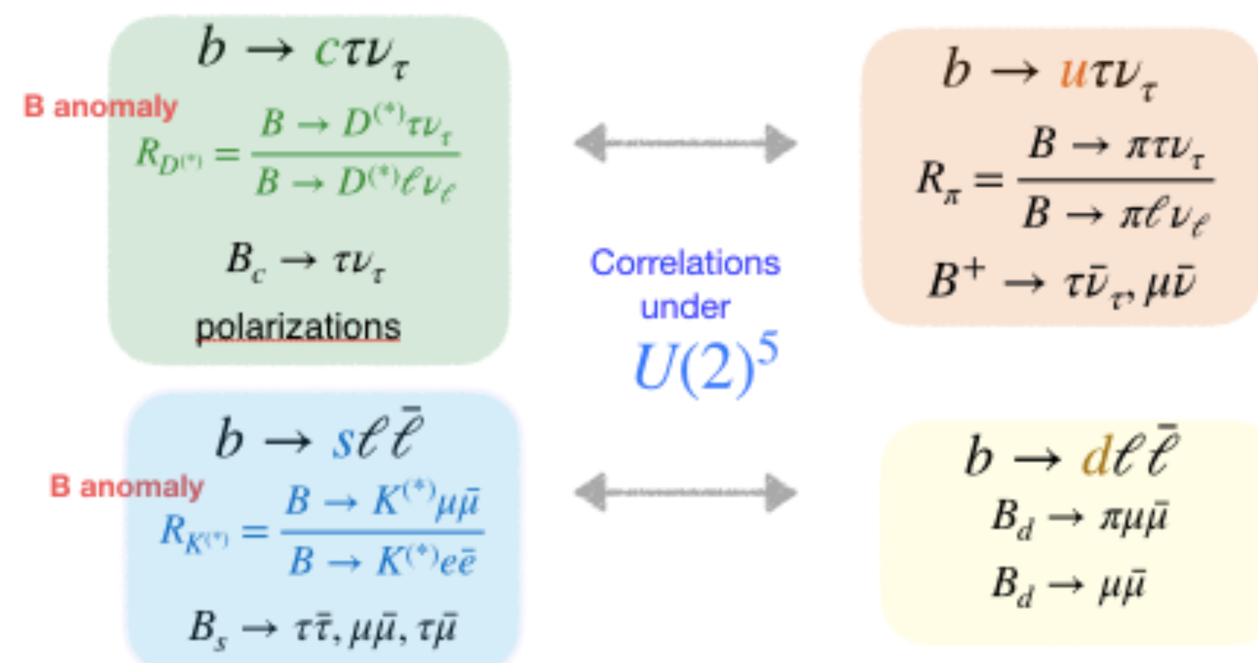
Yukawa (SM flavor hierarchies) $\longleftrightarrow$ B-anomaly hint NP coupled dominantly to 3rd generation

$U(2)^5$ flavor symmetry

Current data is incompatible with SM and consistent with U(2) flavour symmetry

U(2) is very predictive

- $b \to s\mu\mu < b \to c\tau\nu$
- b→c = b→u & b→s = b→d
- Scalar operator with light fermions suppressed



Updated Belle II & LHCb data will be able test this hypothesis, and point us towards the right U(2) model (U_1 leptoquark ?)