B-physics anomaly and U(2) flavour symmetry

Kei Yamamoto
(Hiroshima University/University of Zurich)

FCCP2019@Capri, Italy
30 Aug. 2019

In collaboration with **Javier Fuentes-Martín, Gino Isidori** and **Julie Pagès**
(University of Zurich)

B anomalies

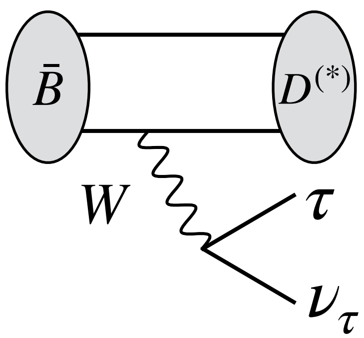
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

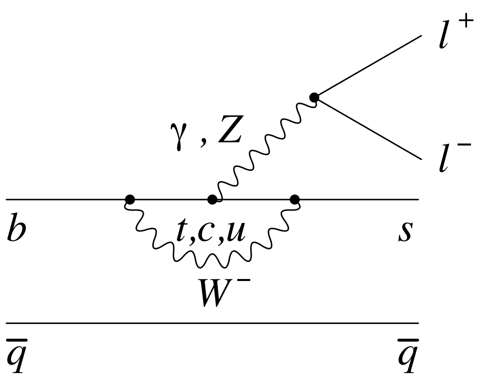


$$b \to s\ell\ell \qquad R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

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

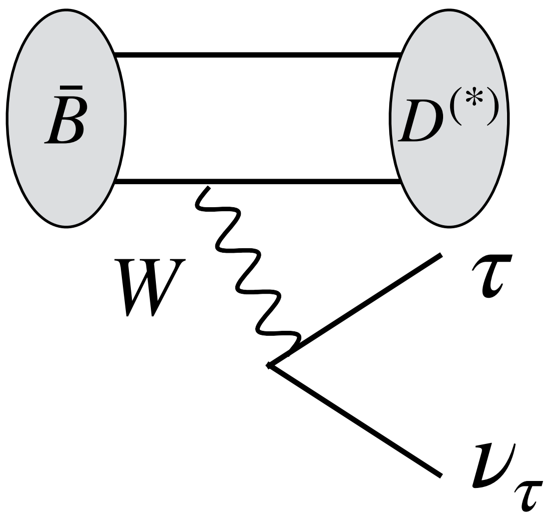
loop-level in SM

LFUV in μ vs e



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

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→c charged current) in SM

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

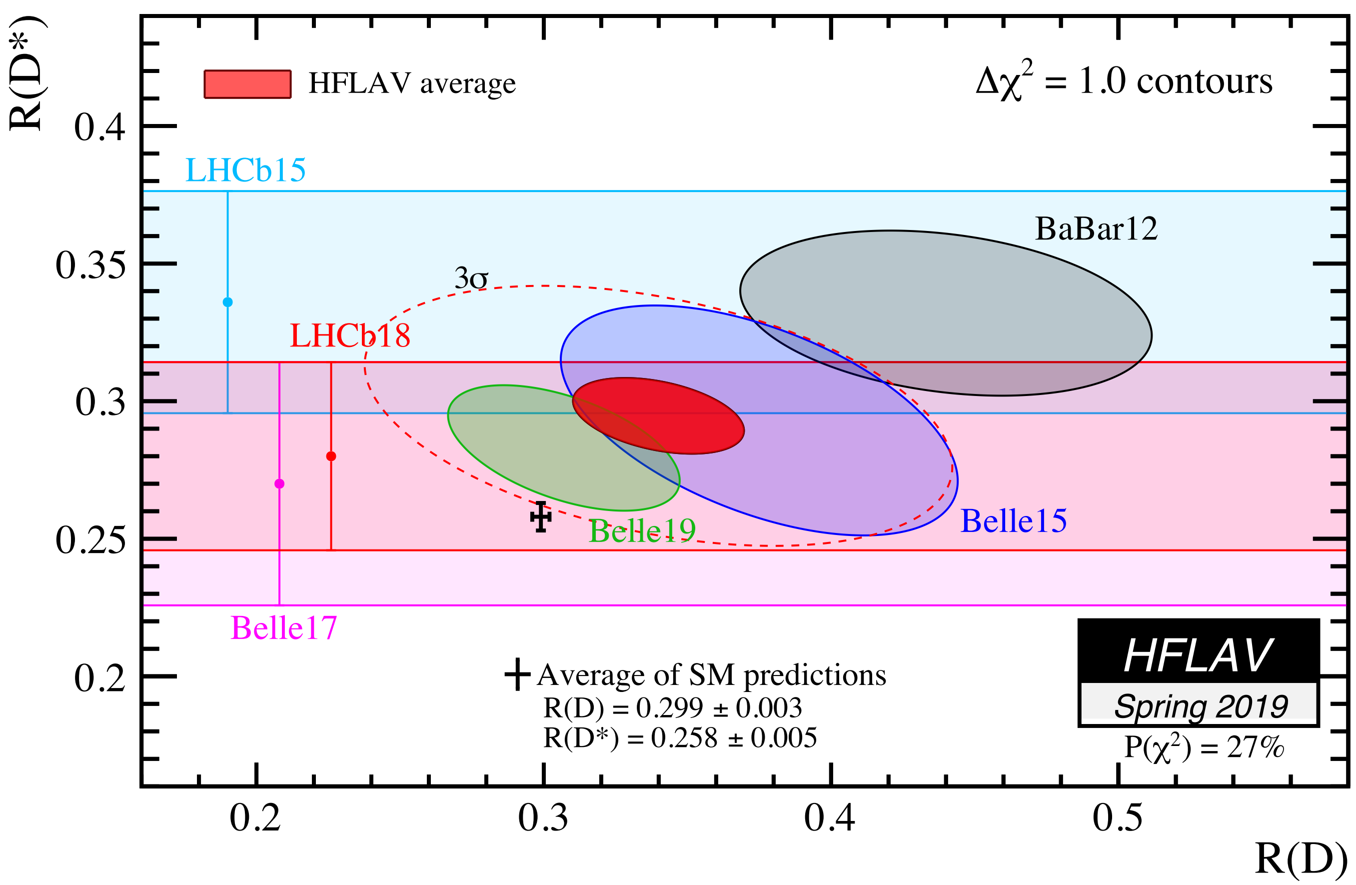
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

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

B anomalies

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

Experiment [spring 2019]



$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$$

R_D : Barbar, Belle

R_{D*} : Babar, Belle and LHCb

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

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

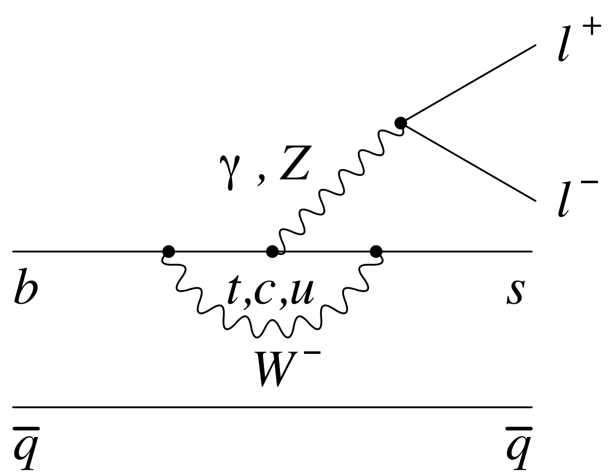
	$F_L(D^*)$	$P_\tau(D)$	$P_\tau(D^*)$
SM	$0.46(4)$	$0.325(9)$	$-0.497(13)$
data	$0.60(9)$ [Belle '18]	-	$-0.38(55)$ [Belle '17]
Belle II	0.04	3%	0.07

↑ Recent Belle result is slightly above the SM

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

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 ?



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

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

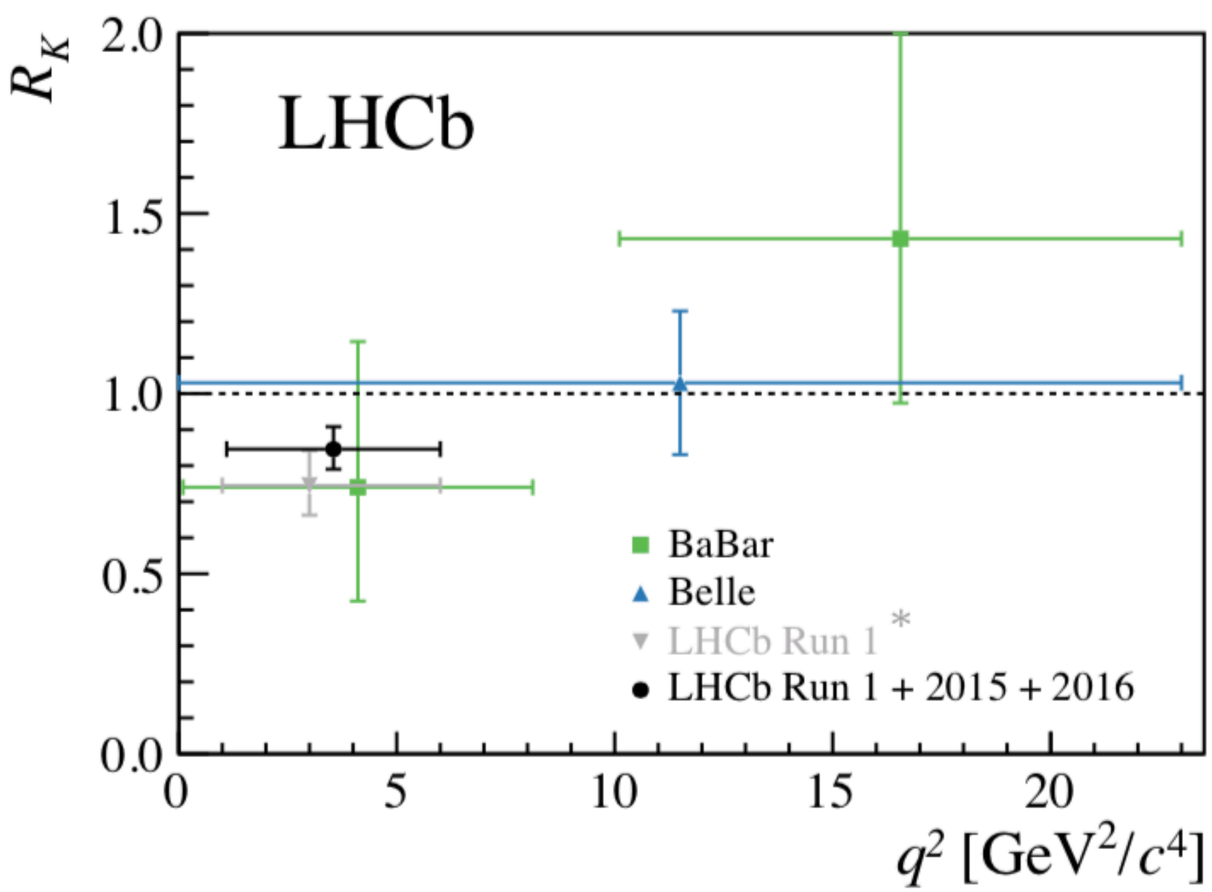
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\approx} 1$$

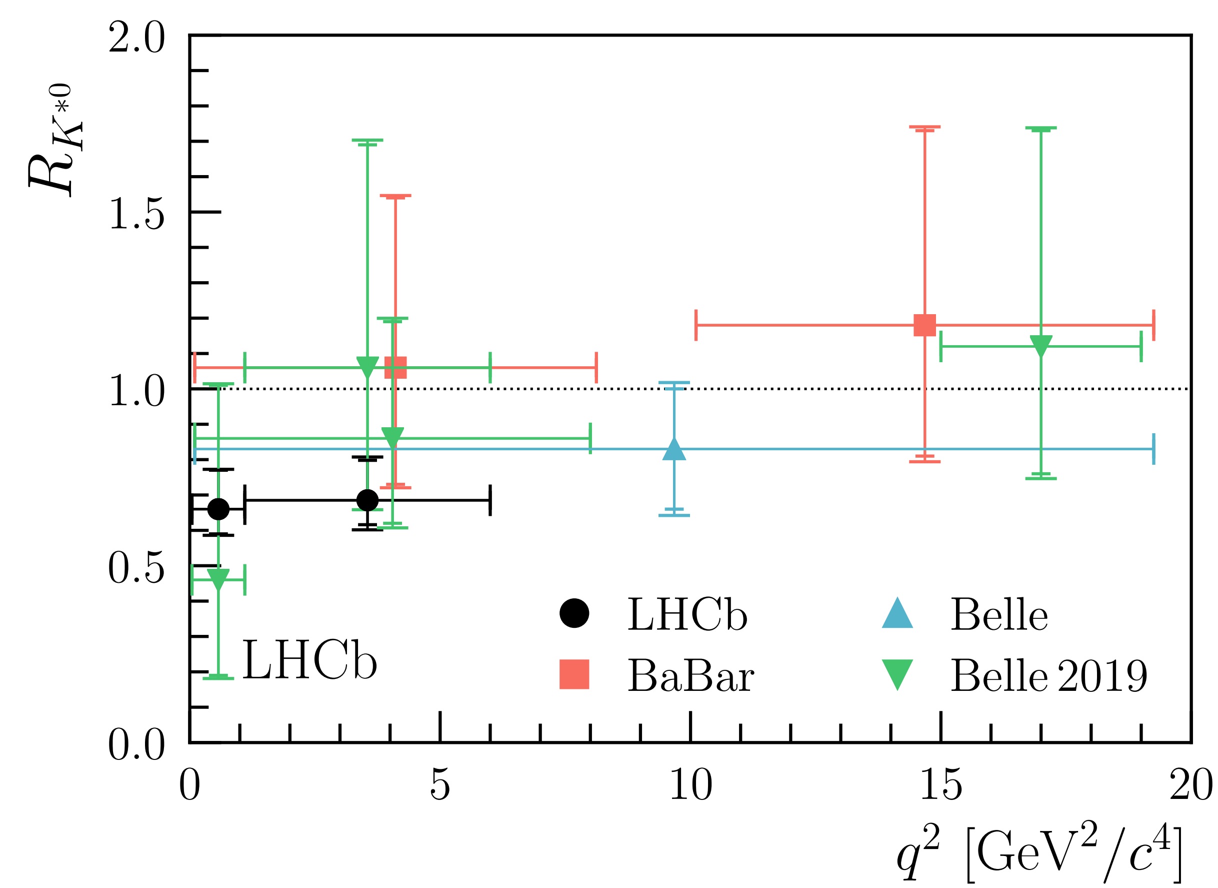
Theoretically clean, hadronic uncertainties cancel to large extent in the ratio

B anomalies

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

Experiment $R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$



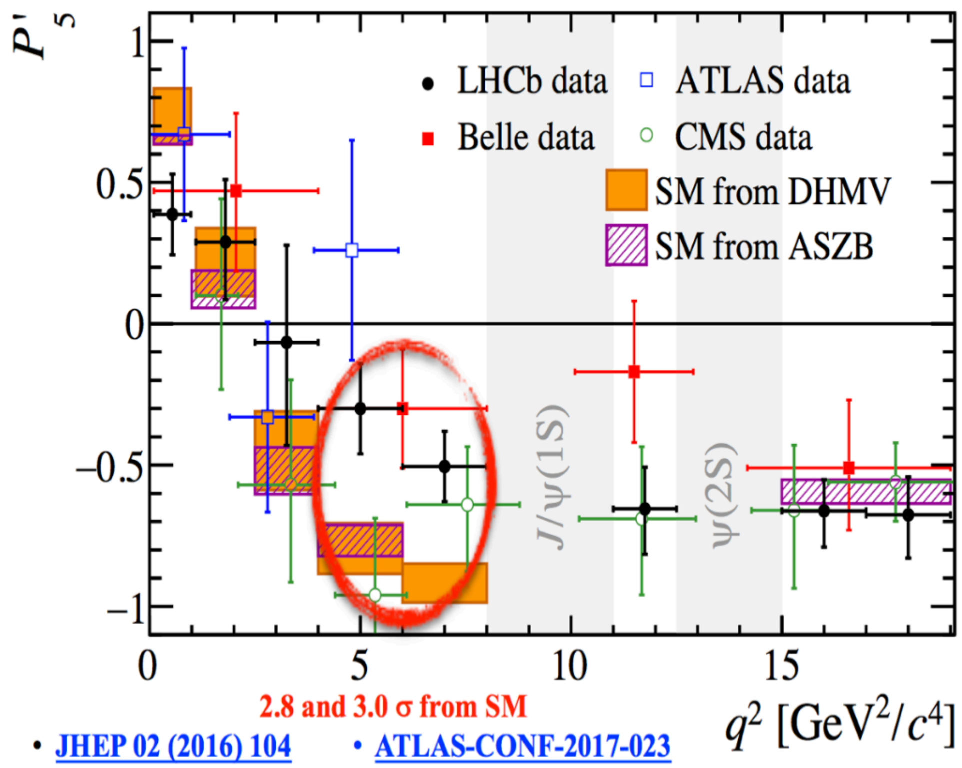


q^2 : $q^2 = (p(\ell) + p(\bar{\ell}))^2$ Lorentz invariant mass squared of lepton pair

B anomalies

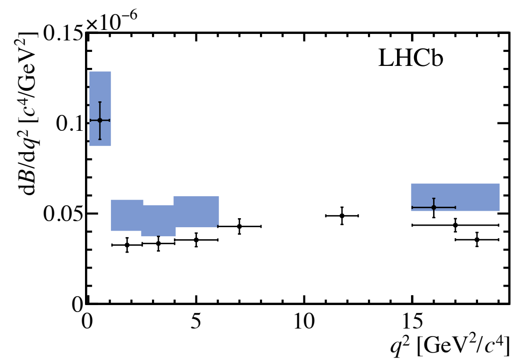
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Other $b \to s$ transitions



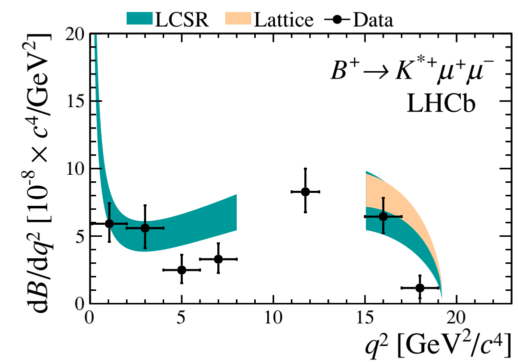
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

$d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/dq^2$



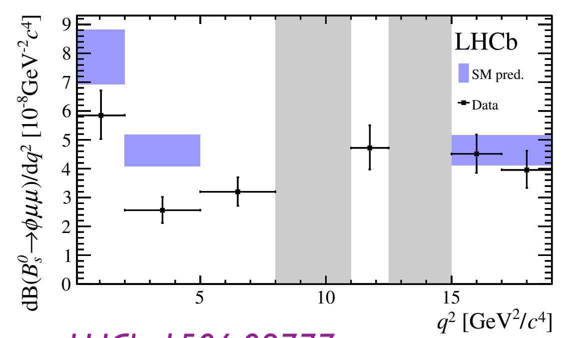
LHCb, 1606.04731

$d\mathcal{B}(B^+ \to K^{*+}\mu^+\mu^-)/dq^2$



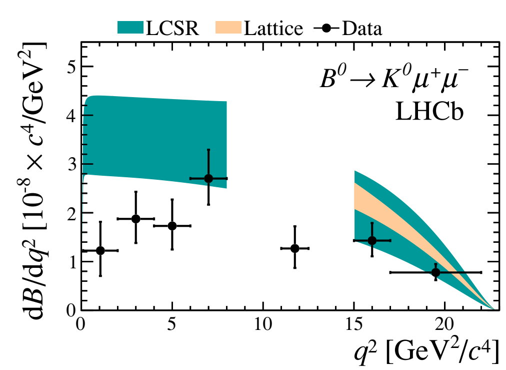
LHCb, 1403.8044

$d\mathcal{B}(B_s \to \phi\mu^+\mu^-)/dq^2$



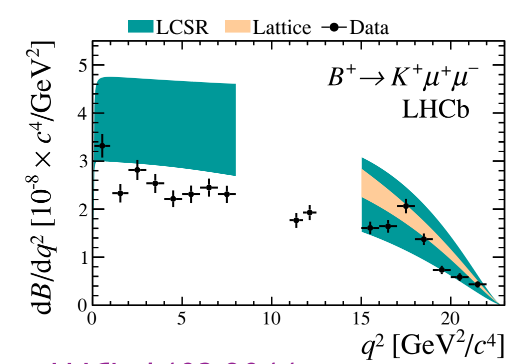
LHCb, 1506.08777

$d\mathcal{B}(B^0 \to K^0\mu^+\mu^-)/dq^2$



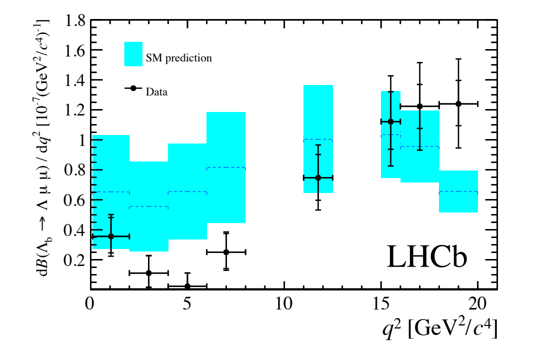
LHCb, 1403.8044

$d\mathcal{B}(B^+ \to K^+\mu^+\mu^-)/dq^2$



LHCb, 1403.8044

$d\mathcal{B}(\Lambda_b^0 \to \Lambda\mu^+\mu^-)/dq^2$



LHCb, 1503.07138

B anomalies

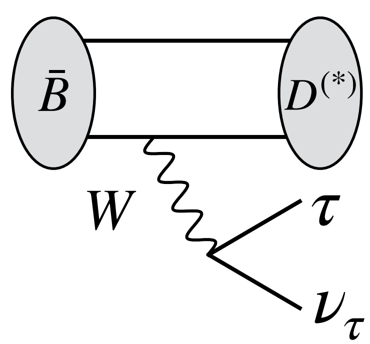
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

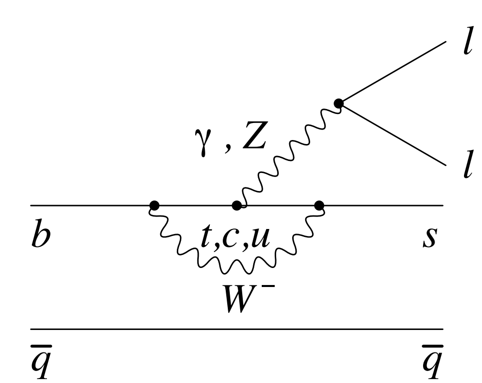


$b \to s\ell\ell$ $\quad R^{\mathrm{exp}}_{K^{(*)}} < R^{\mathrm{SM}}_{K^{(*)}}$

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

loop-level in SM

LFUV in μ vs e



Combined explanation in NP :

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

B anomalies

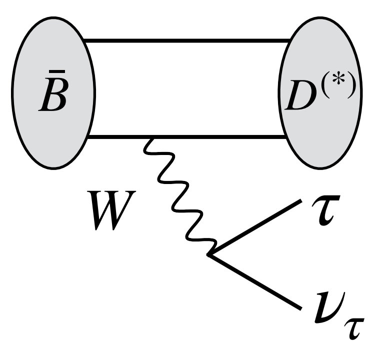
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

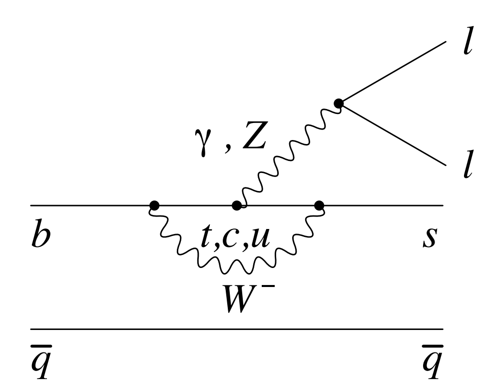


$b \to s\ell\ell$ $\quad R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$

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

loop-level in SM

LFUV in μ vs e



Combined explanation in NP : 3rd >> 2nd

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

3rd 2nd

B anomalies

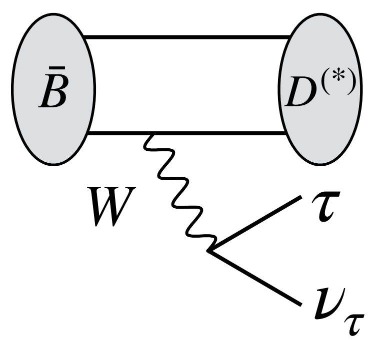
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

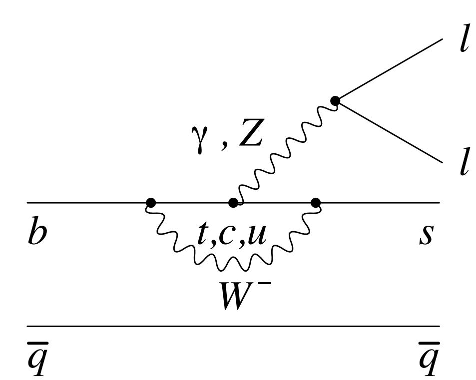


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\exp} < R_{K^{(*)}}^{\rm SM}$

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

loop-level in SM

LFUV in μ vs e



Combined explanation in NP : 3rd >> 2nd

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

3rd $\qquad$ 2nd

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

NP hint in SM flavor puzzle?

SM Yukawa sector is characterised by 13 parameters

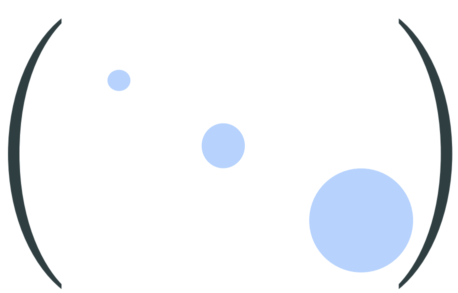
[3 lepton masses + 6 quark masses + 3+1 CKM parameters] ← fixed by data

1st	e	u	d
2nd	μ	c	s
3rd	τ	t	b

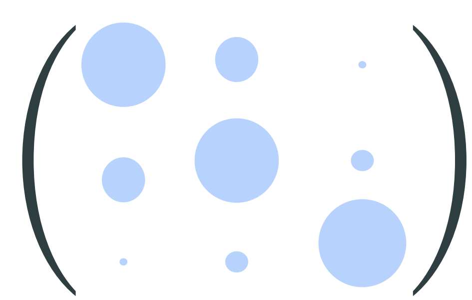
The 3 generation as "identical" copies
Flavour puzzle

Striking hierarchy

Mass : 3rd > 2nd > 1st

$M_{u,d} \sim$ 

CKM

$V_{CKM} \sim$ 

Flavor theory?

U(2) flavour symmetry

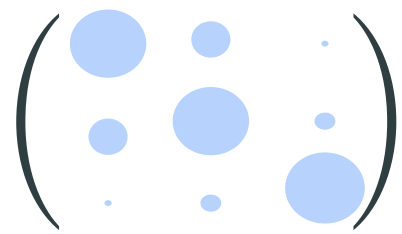
Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

SM Yukawa respect approximate $U(2)$ symmetry

Mass matrix

$M_{u,d} \sim$ 

CKM

$V_{CKM} \sim$ 

$$\psi = (\psi_1, \psi_2, \psi_3)$$

$$U(2)_q \times U(2)_u \times U(2)_d$$

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

Unbroken symmetry

$$Y_u = y_u \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad U(2)_q, \; U(2)_u$$

$\longrightarrow$

After breaking

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

U(2) breaking term

$$|V_q| \sim |V_{ts}| \sim \mathcal{O}(10^{-1})$$

$$|\Delta_u| \sim y_c \sim \mathcal{O}(10^{-2})$$

U(2) flavour symmetry

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

Under $U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$ symmetry

quark

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

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

U(2) breaking Order : $|V_q| \sim \mathcal{O}(10^{-1}), \;\; |\Delta_{u,d}| \sim \mathcal{O}(10^{-2})$

NP lagrangian is invariant under U(2) symmetry apart from breaking terms proportional to spurions

$$\mathscr{L}_{\text{eff}} = C\left[(\bar{t}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L^\tau) + V_q\,(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L^\tau)\right]$$

with

$$V = |V|\begin{pmatrix}0\\1\end{pmatrix}$$

NP in 3rd : $\mathcal{O}(1)$ > NP in 2nd : $\mathcal{O}(10^{-1})$

U(2) flavour symmetry

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

$$Y_f = \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\Delta_f} & V_q \\ \hline 0 & 0 & 1 \end{array}\right) \xrightarrow[\substack{Q_L \to L_d^\dagger Q_L \\ d_R \to R_d^\dagger d_R}]{} \mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

where

$$L_d \approx \begin{pmatrix} c_d & -s_d\, e^{i\alpha_d} & 0 \\ s_d\, e^{-i\alpha_d} & c_d & s_b \\ -s_d\, s_b\, e^{-i(\alpha_d+\phi_q)} & -c_d\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix}$$

with

$$\frac{s_d}{c_d} = \frac{|V_{td}|}{|V_{ts}|}, \quad \alpha_d = \arg\left(\frac{V_{td}^*}{V_{ts}^*}\right)$$

$$R_d \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \frac{m_s}{m_b}\, s_b \\ 0 & -\frac{m_s}{m_b}\, s_b\, e^{-i\phi_q} & e^{-i\phi_q} \end{pmatrix}$$

U(2) flavour symmetry

$$\mathscr{L}_{\rm eff} = C\left[(\bar{\tau}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L^\tau) + V_q\,(\bar{c}_L\,\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L^\tau)\right]$$

$$\big\downarrow \text{ mass basis}$$

$$\mathscr{L}_{\rm eff} = C\; V_{CKM}^{ik}\begin{pmatrix} 0 & 0 & \frac{s_d}{c_d}e^{i\alpha_d}c_d V_q \\ 0 & 0 & c_d V_q \\ 0 & 0 & 1 \end{pmatrix}^{kj}(\bar{u}_L^i\gamma_\mu b_L^j)(\bar{\tau}_L\gamma_\mu\nu_L^\tau)$$

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

$$\boxed{\frac{b \to u}{b \to c} = \frac{V_{ub}}{V_{cb}}}$$

Relations between different flavour transitions under U(2) symmetry

U(2) flavour symmetry

For $b_L \to c_L$ vs $b_L \to c_R$

$$(\bar{b}_L V_q \gamma_\mu c_L), \qquad (\bar{b}_L V_q \gamma_\mu c_R)$$

$$\Big\downarrow \quad \text{mass basis}$$

$$(\bar{b}_L V_q \gamma_\mu c_L), \qquad \frac{m_c}{m_t} s_t (\bar{b}_L V_q \gamma_\mu c_R)$$

$$\boxed{\frac{b_L \to c_R}{b_L \to c_L} \lesssim \frac{m_c}{m_t} V_{cb}}$$

Operator with right handed light quark can be assumed to be suppressed under U(2)

U(2) flavour symmetry

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

Features：

- NP in 3rd : $\mathcal{O}(1)$ > NP in 2nd : $\mathcal{O}(10^{-1})$ → Favored by B anomaly
- Relations between different flavour transitions under U(2) symmetry
- Operator with right handed light fermion can be assumed to be suppressed under U(2) → NP helicity structure

What we did

With or without U(2)? Probing non-standard flavor and helicity structures in semileptonic B decays

$U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$

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

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

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

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

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

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

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

$$K \to \ell\bar{\ell}' \quad \tau \to \mu\gamma$$

Effective theory for semileptonic decay

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

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

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

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

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

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

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

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

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

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

Effective theory for semileptonic decay

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

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

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

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

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

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

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

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

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

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

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

Operator with right handed light fermion can be assumed to be suppressed under U(2)

Effective theory for charged-current semileptonic decay

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

parametrisation of flavour structure

$$\Lambda_S^{[ij\alpha\beta]} = (\Gamma_L^\dagger)^{\alpha j} \times \Gamma_R^{i\beta}, \quad \Lambda_{V_i}^{[ij\alpha\beta]} = (\Gamma_L^{V_i\dagger})^{\alpha j} \times (\Gamma_L^{V_i})^{i\beta}$$

$$L_d^\dagger \Gamma_L L_e = e^{i\phi_q}\begin{pmatrix} \Delta_{q\ell}^{de} & \Delta_{q\ell}^{d\mu} & \lambda_q^d \\ \Delta_{q\ell}^{se} & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ \lambda_\ell^e & \lambda_\ell^\mu & x_{q\ell}^{b\tau} \end{pmatrix} \approx e^{i\phi_q}\begin{pmatrix} 0 & 0 & \lambda_q^d \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ \lambda_\ell^e & \lambda_\ell^\mu & 1 \end{pmatrix} \qquad R_d^\dagger \Gamma_R R_e \approx e^{i\phi_q}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_s}{m_b}\,s_b \\ 0 & -\frac{m_\mu}{m_\tau}\,s_\tau & 1 \end{pmatrix}$$

$$\lambda_q^s = \mathcal{O}(|V_q|)\,, \lambda_\ell^\mu = O(|V_\ell|)\,, \Delta_{q\ell}^{s\mu} = \mathcal{O}(\lambda_q^s \lambda_\ell^\mu)$$

$$\frac{\lambda_q^d}{\lambda_q^s} = \frac{\Delta_{q\ell}^{d\alpha}}{\Delta_{q\ell}^{s\alpha}} = \frac{V_{td}^*}{V_{ts}^*}, \quad \frac{\lambda_\ell^e}{\lambda_\ell^\mu} = \frac{\Delta_{q\ell}^{ie}}{\Delta_{q\ell}^{i\mu}} = s_e$$

Parameters: C_V, C_S and spurion $|V_{q,\ell}|$

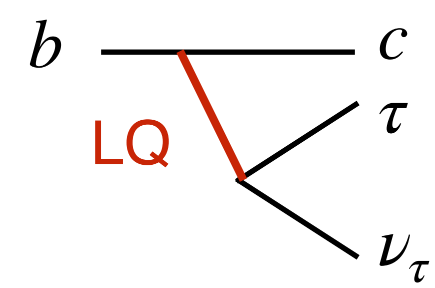
※ Assume $C_{V_1} = C_{V_2} \equiv C_V$ to avoid constraint from $b \to s\nu\bar{\nu}$

(ϕ_b : not affect discussion, s_b : $|s_b| \lesssim 0.1\ \mathcal{O}(V_q)$ to avoid constraints from $\Delta F = 2$)

U_1 Leptoquark

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

nicely matches the structure in U1 LQ



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

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

$$\Gamma_L^{V_1} = \Gamma_L^{V_3} = \Gamma_L, C_V \equiv C_{V_1} = C_{V_3} = \frac{g_U^2 v^2}{4M_U^2} > 0$$

$$\frac{C_S}{C_V} = -2\,\beta_R\ , \lambda_q^s = \beta_L^{s\tau}\ , \lambda_\ell^\mu = \beta_L^{b\mu}\ , \Delta_{q\ell}^{s\mu} = \beta_L^{s\mu}$$

EFT approach & U_1 LQ

b→c and b→u under U(2)

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 $b \to u$

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

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

Numerical formula for observables

$b \to c$

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

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

$$\frac{F_L^{D^*}}{F_{L,\rm SM}^{D^*}} \approx 1 + 0.14\,\eta_S\,C_S^c(1 - C_V^c) + 0.03\,\eta_S^2\,C_S^{c2}$$

$$\frac{P_\tau^D}{P_{\tau,\rm SM}^D} \approx 1 + 3.1\,\eta_S\,C_S^c(1 - C_V^c) - 2.6\,\eta_S^2\,C_S^{c2}$$

$$\frac{P_\tau^{D^*}}{P_{\tau,\rm SM}^{D^*}} \approx 1 - 0.34\,\eta_S\,C_S^c(1 - C_V^c) - 0.08\,\eta_S^2\,C_S^{c2}$$

where $\eta_S \approx 1.7$ arises by running of scalar operator from TeV scale down to mb

Numerical formula for observables

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

Chiral enhancement factor

$b \to u$

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

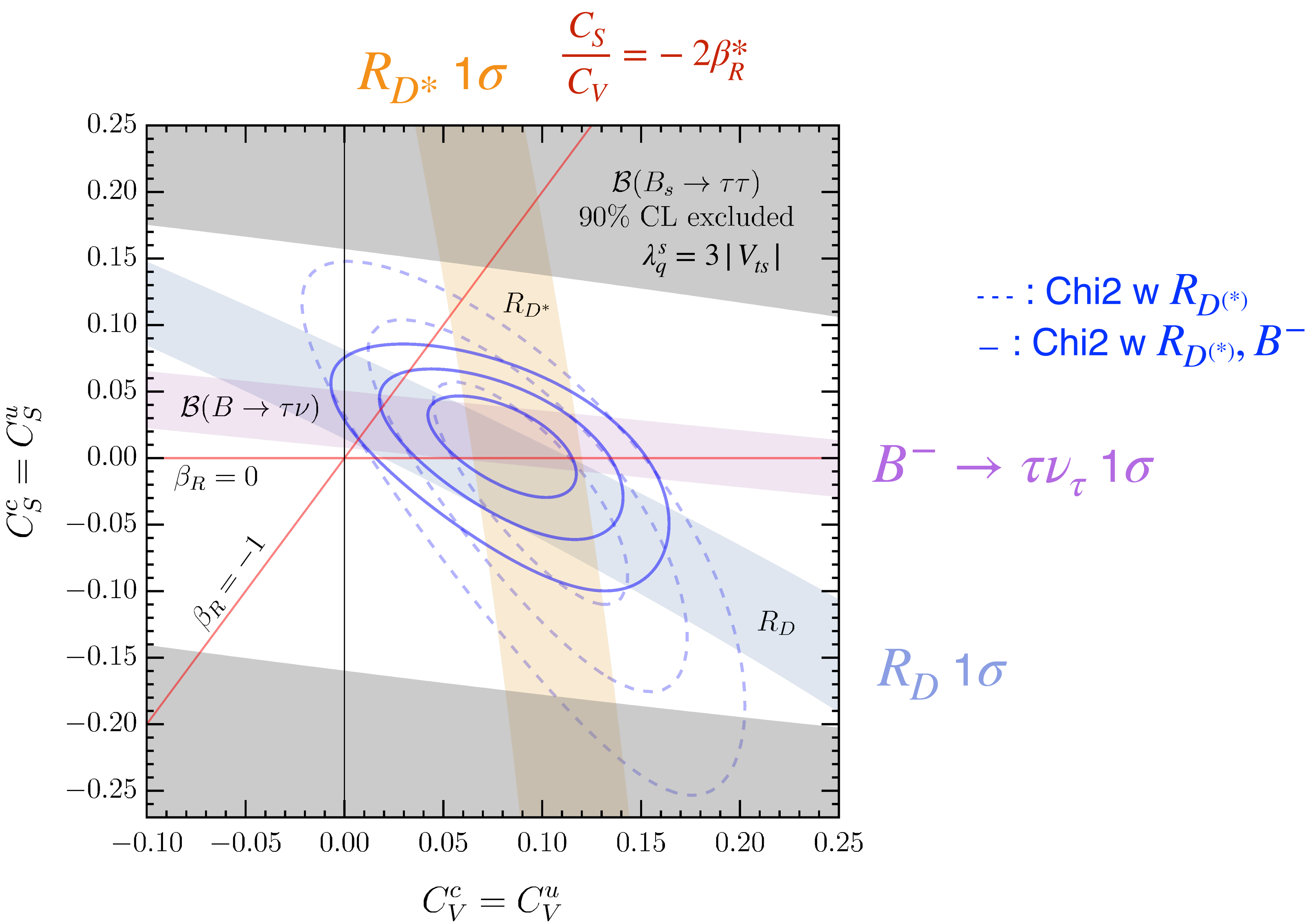
$$\frac{\mathcal{B}(B^+ \to \tau^+ \nu)}{\mathcal{B}(B^+ \to \tau^+ \nu_\tau)_{\rm SM}} = \left| 1 + C_V^u + \underbrace{\frac{m_{B^+}^2}{m_\tau \left(\overline{m}_b + \overline{m}_u \right)}}_{\approx 3.75} C_S^u \right|^2$$

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

$$\frac{\mathcal{B}(B_s \to \tau\bar{\tau})}{\mathcal{B}(B_s \to \tau\bar{\tau})_{\rm SM}} = \left| 1 + \frac{2\pi\,\lambda_q^s}{\alpha\, V_{tb} V_{ts}^* C_{10}^{\rm SM}} \left(C_V + \chi_s \eta_S C_S \right) \right|^2 + \left(1 - \frac{4 m_\tau^2}{m_{B_s}^2} \right) \left| \frac{2\pi\,\lambda_q^s}{\alpha\, V_{tb} V_{ts}^* C_{10}^{\rm SM}} \chi_s \eta_S C_S \right|^2$$

$$\frac{\mathcal{B}(B_s \to \tau\bar{\tau})}{\mathcal{B}(B_s \to \tau\bar{\tau})_{\rm SM}} < 8.8 \times 10^3 \quad (95\,\%\ \mathrm{CL})$$

C_S vs C_V



R_{D*} 1σ
$\frac{C_S}{C_V} = -2\beta_R^*$
$\mathcal{B}(B_s \to \tau\tau)$
90% CL excluded
$\lambda_q^s = 3|V_{ts}|$
R_{D^*}
$\mathcal{B}(B \to \tau\nu)$
$\beta_R = 0$
$\beta_R = -1$
R_D
$C_S^c = C_S^u$
$C_V^c = C_V^u$
- - - : Chi2 w $R_{D^{(*)}}$
– : Chi2 w $R_{D^{(*)}}, B^-$
$B^- \to \tau\nu_\tau$ 1σ
R_D 1σ

C_S dependence i) $\Delta R_D - \Delta R_{D*}$ vs polarisations

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

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

$$\longrightarrow \quad \Delta R_D - \Delta R_{D*} \approx 1.4\ \eta_S\ \mathrm{Re}C_S^c \qquad \left(\Delta O_X = \frac{O_X}{O_X^{\mathrm{SM}}} - 1\right)$$

$$\frac{F_L^{D*}}{F_{L,\mathrm{SM}}^{D*}} \approx 1 + 0.14\,\eta_S\, C_S^c(1 - C_V^c) + 0.03\,\eta_S^2\, C_S^{c2}$$

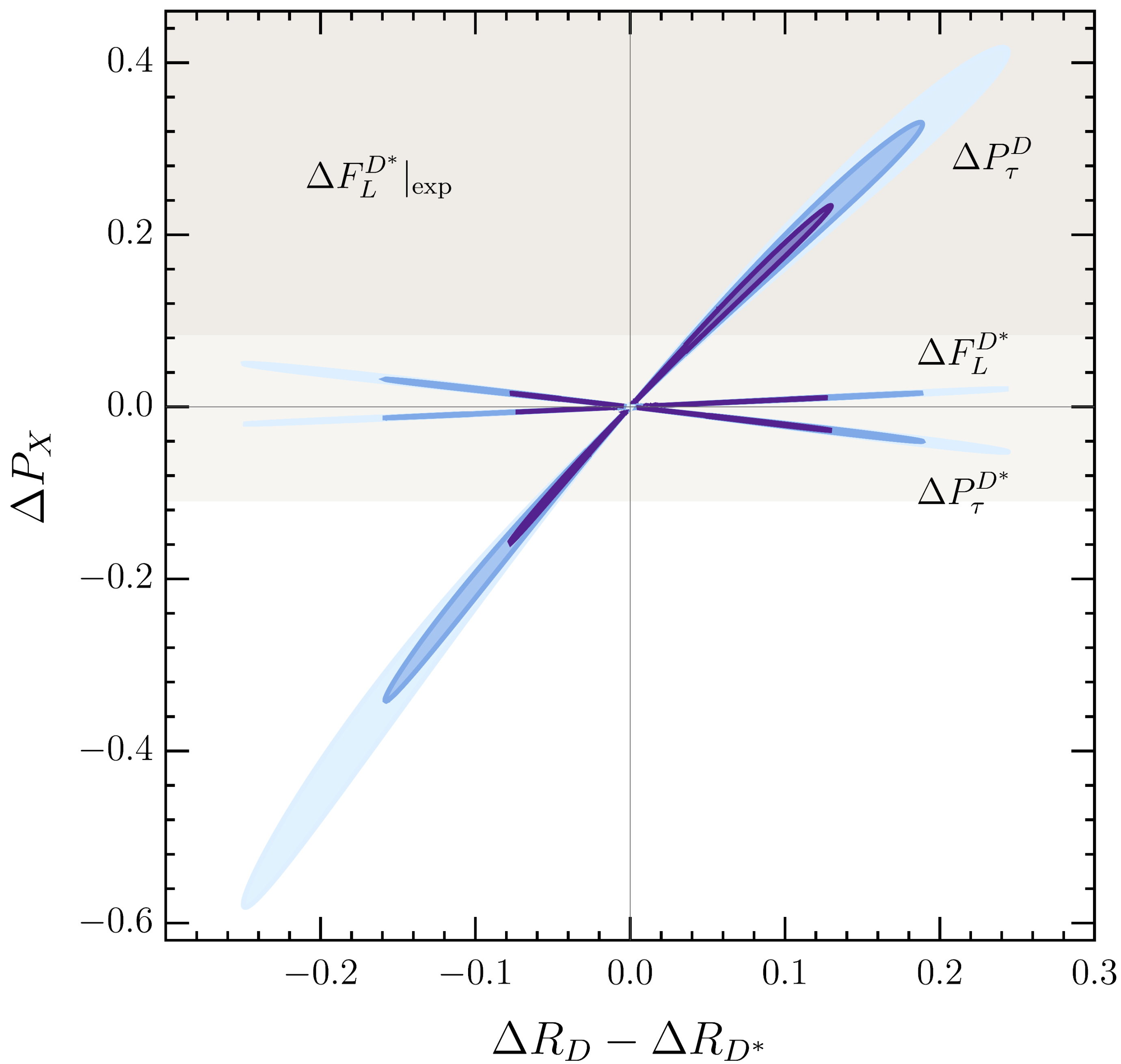
$$\frac{P_\tau^D}{P_{\tau,\mathrm{SM}}^D} \approx 1 + 3.1\,\eta_S\, C_S^c(1 - C_V^c) - 2.6\,\eta_S^2\, C_S^{c2}$$

scalar C_S^c dominant

$$\frac{P_\tau^{D*}}{P_{\tau,\mathrm{SM}}^{D*}} \approx 1 - 0.34\,\eta_S\, C_S^c(1 - C_V^c) - 0.08\,\eta_S^2\, C_S^{c2}$$

$\longrightarrow$ $\Delta R_D - \Delta R_{D*}$ vs ΔP_X

C_S dependence i) $\Delta R_D - \Delta R_{D^*}$ vs polarisations



$\propto C_S^c$

– : Chi2 w $R_{D^{(*)}}, B^+$

D transition (ΔP_τ^D) : ~ 40% enhance

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

not possible to reach $F_L^{D^{(*)}}\Big|_{\rm exp}$

C_S dependence ii) $\Delta R_D - \Delta R_{D^*}$ vs R_π, B^+, B_c^+

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

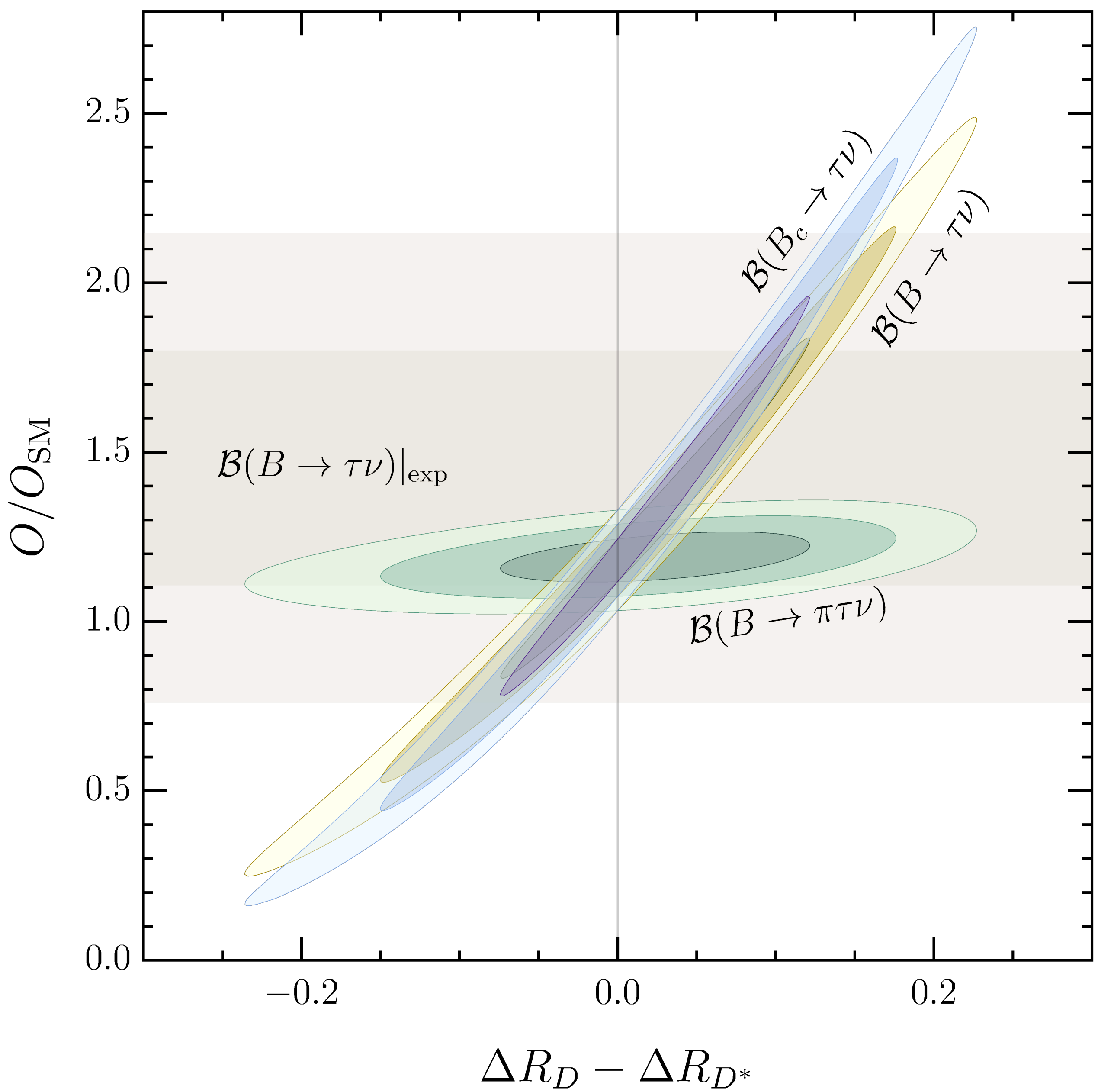
$$\frac{\mathcal{B}(B^+ \to \tau^+\nu)}{\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM}} = \left|1 + C_V^u + \frac{m_{B^+}^2}{m_\tau\left(\overline{m}_b + \overline{m}_u\right)} C_S^u\right|^2 \approx \left|1 + C_V^u + 3.75 C_S^u\right|$$

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

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

$$\rightarrow \quad \Delta R_D - \Delta R_{D^*} \text{ vs } \frac{O}{O^{\rm SM}}$$

C_S dependence ii) $\Delta R_D - \Delta R_{D^*}$ vs R_π, B^+, B_c^+



$\propto C_S^c = C_S^u$

– : 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]

b→s under U(2)

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

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

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

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

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

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

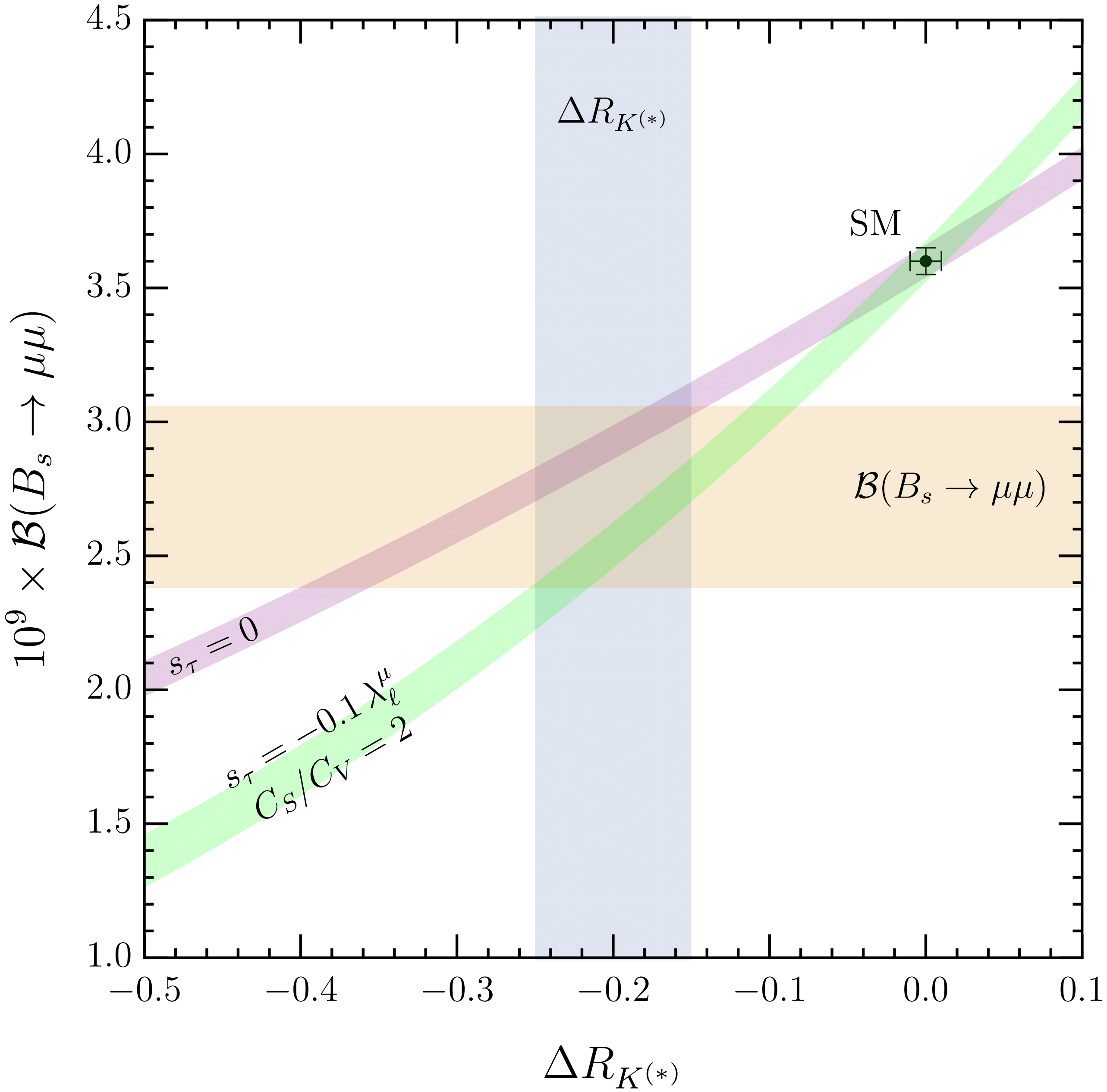
$$R_K \approx R_{K^*} \approx 1 + 0.47\,\Delta C_9^{\mu} \qquad \Delta C_9^{\mu} = -0.43 \pm 0.11$$

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

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

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

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



$\mathscr{B}(B_s \to \mu\bar{\mu})_{\rm SM} = 3.60(5) \times 10^{-9}$

Benekea , Bobetha and Szafron [1908.07011]

$\mathscr{B}(B_s \to \mu\bar{\mu})_{\rm exp} = 2.72(34) \times 10^{-9}$

$\Delta R_{K^{(*)}}$ is well compatible with $\mathscr{B}(B_s \to \mu\bar{\mu})_{\rm exp}$

Others

$b \to s\tau\bar{\mu}$

$$\mathcal{B}(B_s \to \tau^- \mu^+) \approx \frac{\tau_{B_s} m_{B_s} f_{B_s}^2 G_F^2}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_s}^2}\right)^2 \Delta_{q\ell}^{s\mu}|^2 \left| C_V + 2\chi_s \eta_S C_S^* \right|^2$$

= few 10^{-6}
$@C_{S(V)} = O(10^{-2}), \Delta_{q\ell}^{s\mu} = O(10^{-2})$

$\mathcal{B}(B_s \to \tau^\pm \mu^\mp) < 4.2 \times 10^{-5}$ (95 % CL)

→ LHCb

$b \to d$

$$\frac{\mathcal{B}(B \to \pi\mu\bar{\mu})_{[\Delta q^2_{\rm pert}]}}{\mathcal{B}(B \to \pi e\bar{e})_{[\Delta q^2_{\rm pert}]}} \approx R_{K^{(*)}}$$

deviation ~ 2σ

$\mathcal{B}(B \to \pi\mu\bar{\mu})_{[1,6]} = 0.91(21) \times 10^{-9}$

$\mathcal{B}(B \to \pi\mu\bar{\mu})^{\rm SM}_{[15,22]} = 0.72(7) \times 10^{-9}$ ↔ $\mathcal{B}(B \to \pi\mu\bar{\mu})_{[15,22]} = 0.46(11) \times 10^{-9}$

→ LHCb

$$\frac{\mathcal{B}(B_d \to \mu\bar{\mu})}{\mathcal{B}(B_d \to \mu\bar{\mu})_{\rm SM}} \approx \frac{\mathcal{B}(B_s \to \mu\bar{\mu})}{\mathcal{B}(B_s \to \mu\bar{\mu})_{\rm SM}}$$

$\mathcal{B}(B_d \to \mu\bar{\mu})_{\rm SM} = 1.06(9) \times 10^{-10}$

$\mathcal{B}(B_d \to \mu\bar{\mu})_{\rm exp} = 1.6(1.1) \times 10^{-10}$

→ LHCb

Others

$\tau \to \mu\gamma$

$$\mathcal{B}(\tau \to \mu\gamma) \approx \frac{1}{\Gamma_\tau} \frac{\alpha}{256\pi^4} \frac{m_\tau^3 m_b^2}{v^4} |C_S \, \lambda_\ell^{\mu\,*}|^2$$

= few 10^{-9}
$@C_S = O(10^{-2}), \lambda_\ell^\mu = O(10^{-1})$

$\mathscr{B}(\tau \to \mu\gamma)_{\mathrm{exp}} < 0.0(3.0) \times 10^{-8}$

→ Belle II

Kaon decay

constraints obtained from K decays do not yield significant bounds to our framework

Summary

B anomalies suggest NP coupled dominantly to 3rd generation

→ U(2) flavour symmetry

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 $U(2)$

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

B anomaly

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

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

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

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

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

$K \to \ell\bar{\ell}'$ $\quad \tau \to \mu\gamma$

updated Belle II & LHCb data