B-physics anomaly and U(2) flavour symmetry

Kei Yamamoto
(Hiroshima University/University of Zurich)

PPP2019
30 Jul. 2019

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

B anomalies

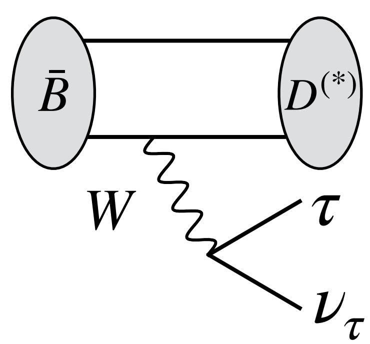
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

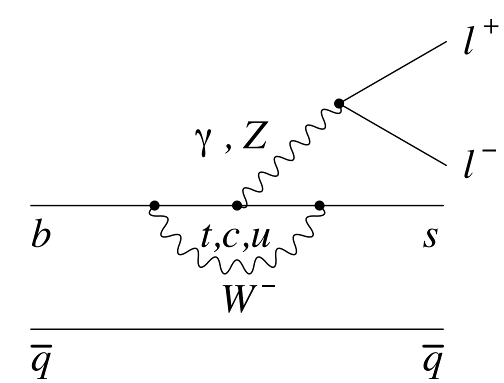


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\exp} < R_{K^{(*)}}^{\rm SM}$

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

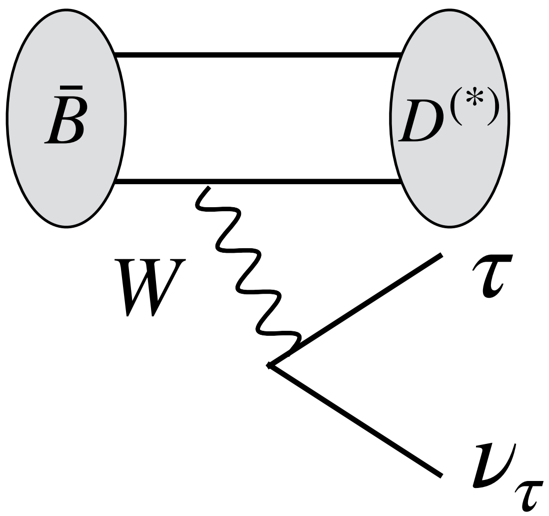
loop-level in SM

LFUV in μ vs e



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

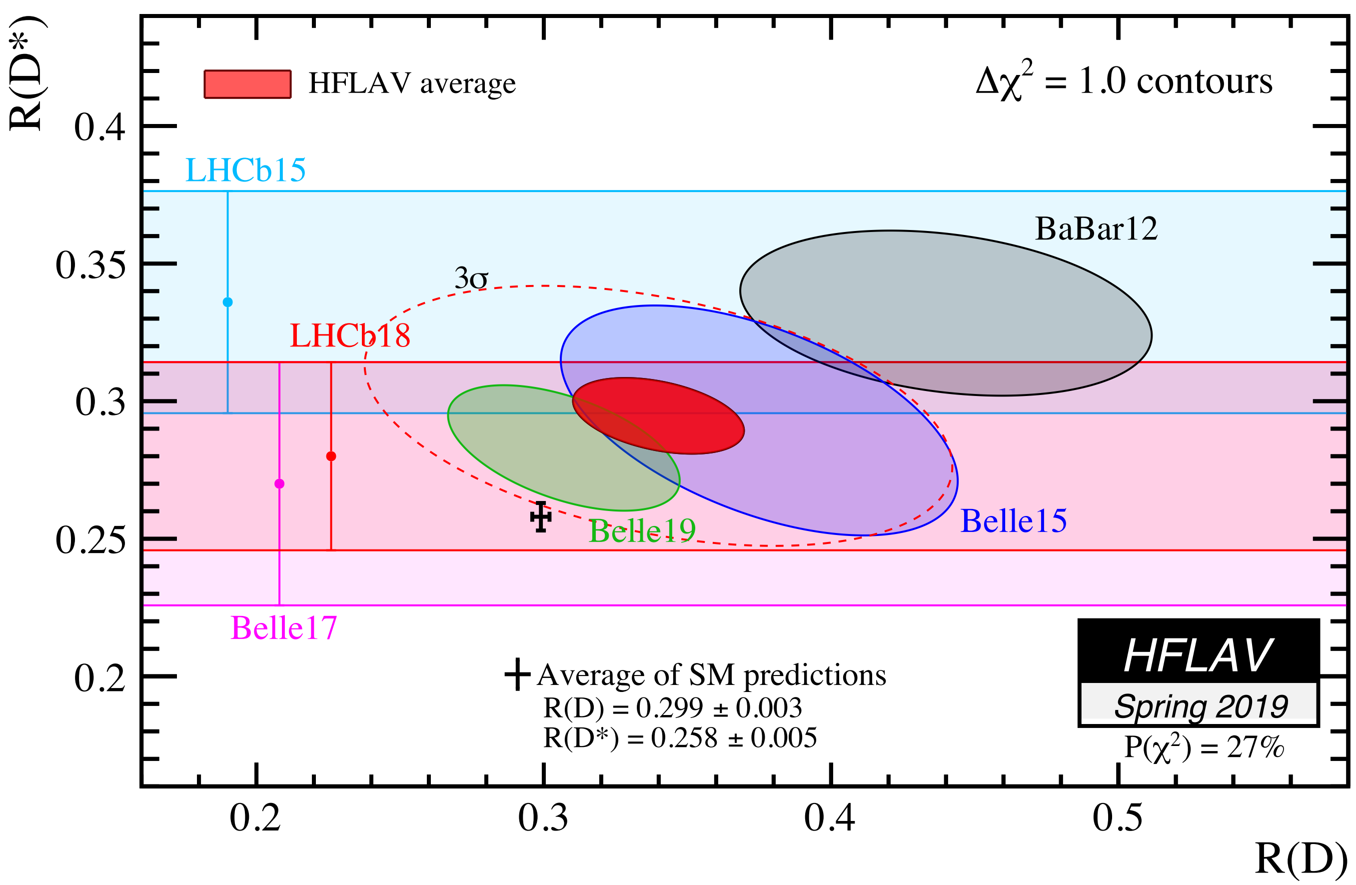
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

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

B anomalies

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

Experiment [spring 2019]



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

R_D : Barbar, Belle

R_{D*} : Barbar, Belle and LHCb

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

Related observables → NP model discrimination

- Polarisation

Longitudinal D^* polarisation

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

τ polarisation asymmetries

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

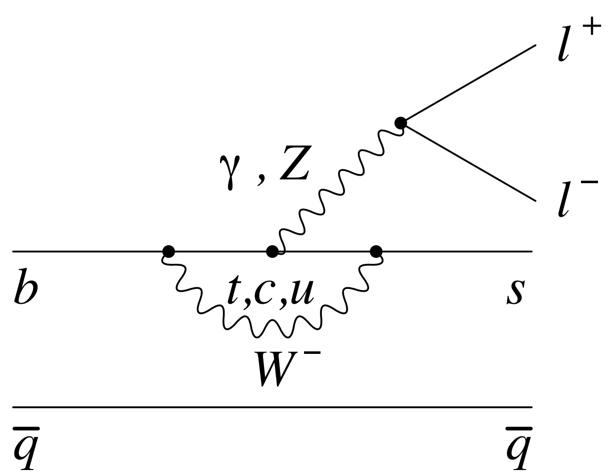
	$F_L(D^*)$	$P_\tau(D)$	$P_\tau(D^*)$
SM	$0.46(4)$	$0.325(9)$	$-0.497(13)$
data	$0.60(9)$ [Belle '18]	-	$-0.38(55)$ [Belle '17]
Belle II	0.04	3%	0.07

↑ 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

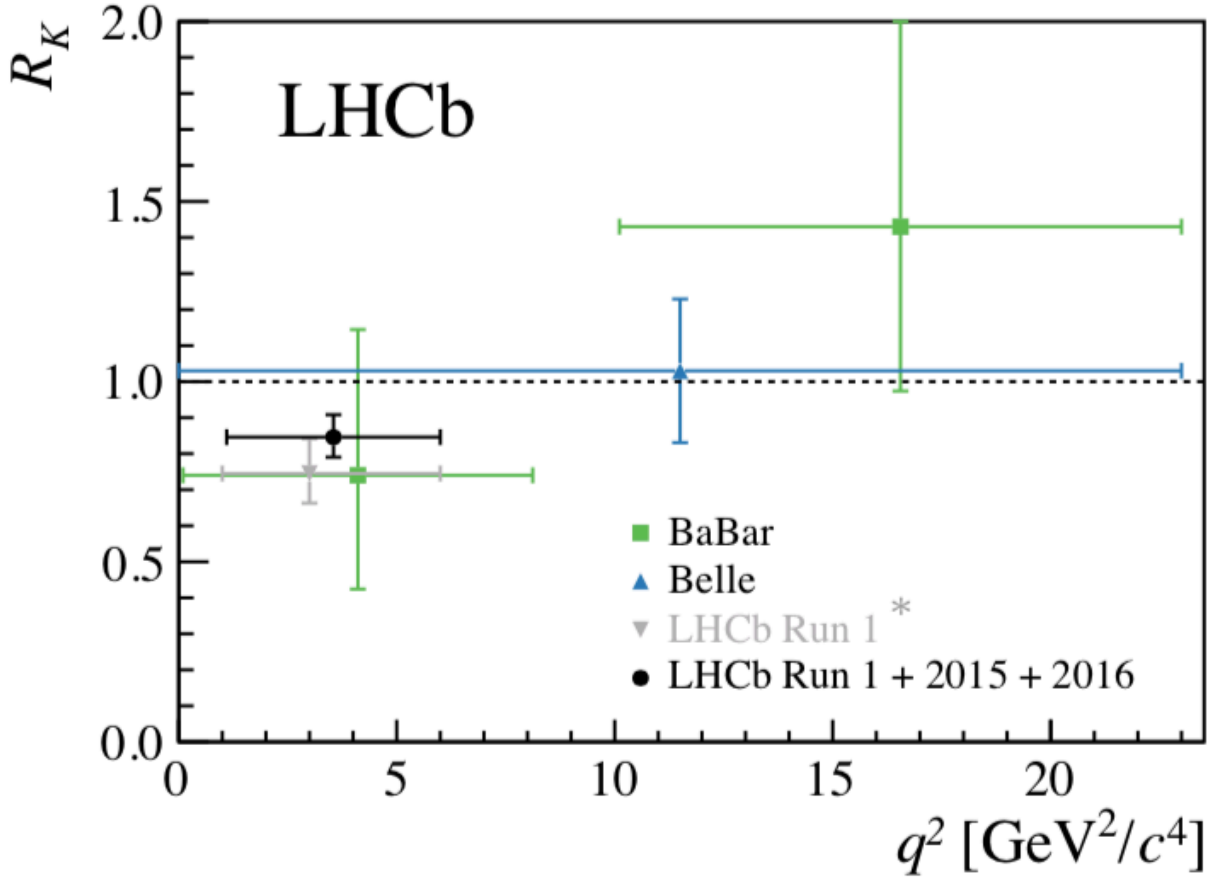
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\approx} 1$$

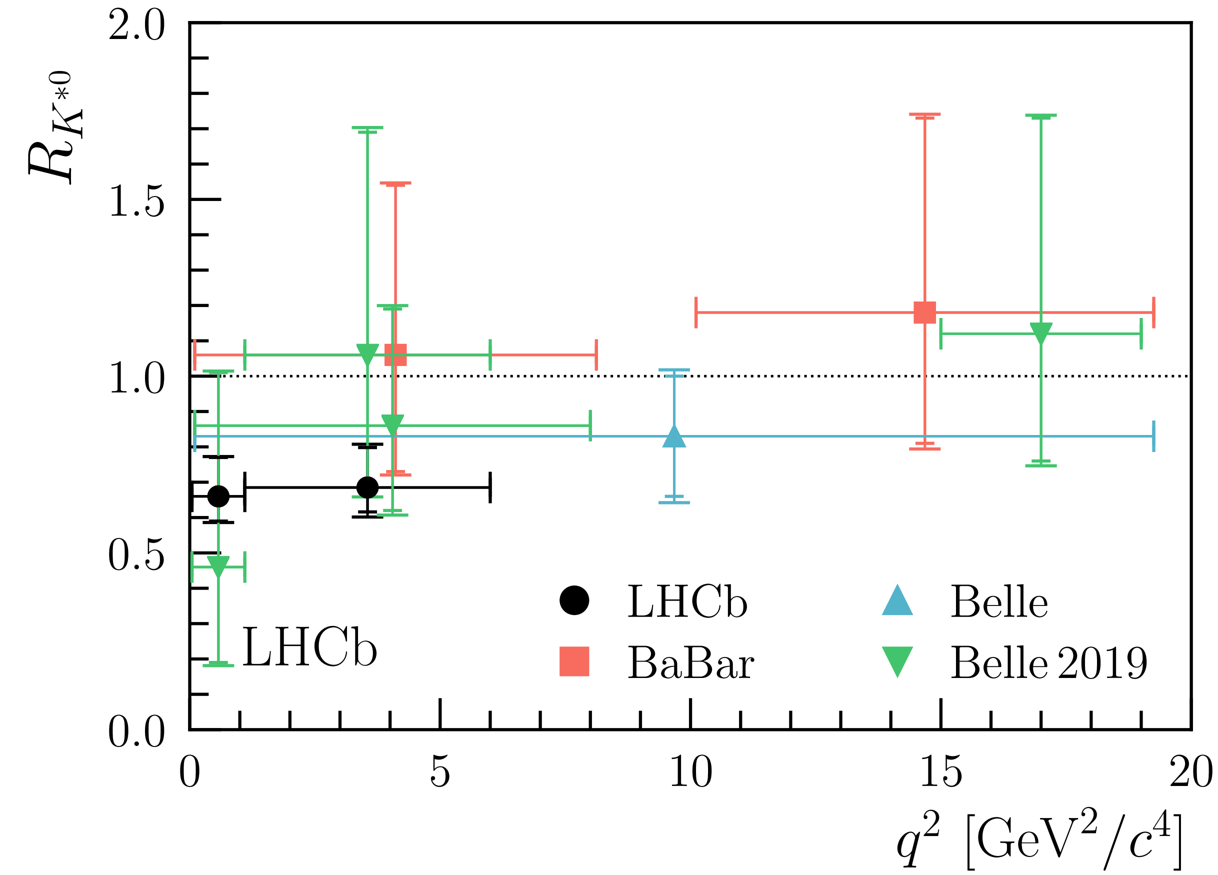
Theoretically clean, hadronic uncertainties cancel to large extent in the ratio

B anomalies

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

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





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

B anomalies

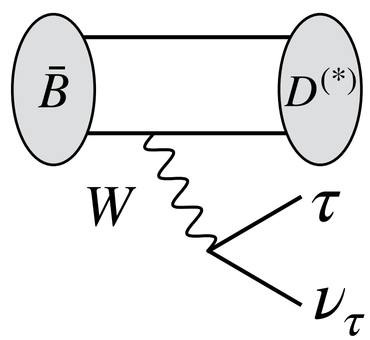
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

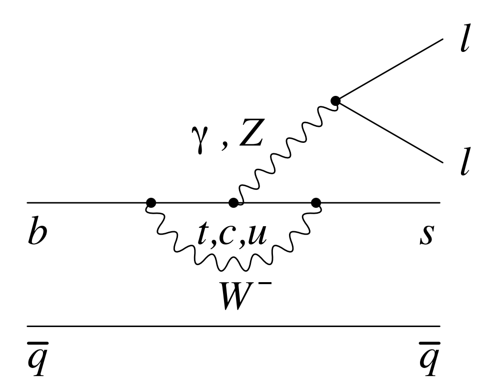


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\text{exp}} < R_{K^{(*)}}^{\text{SM}}$

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

loop-level in SM

LFUV in μ vs e



B anomalies

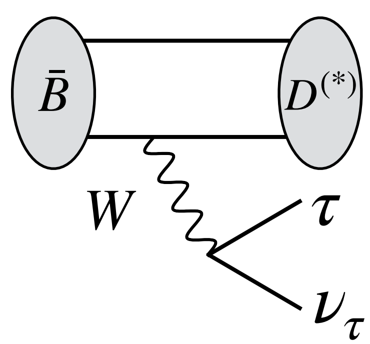
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

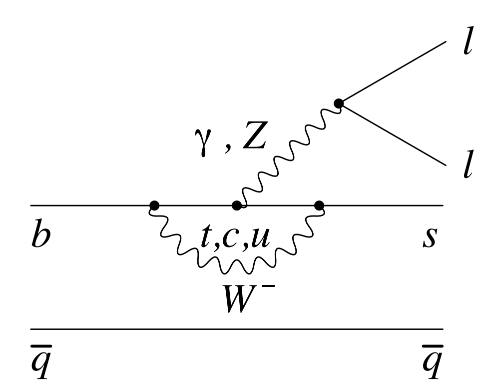


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\rm exp} < R_{K^{(*)}}^{\rm SM}$

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

loop-level in SM

LFUV in μ vs e



両方のanomalyを説明できるNP

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

B anomalies

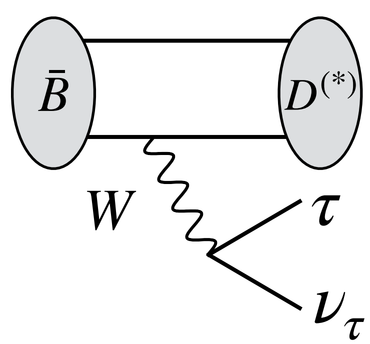
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

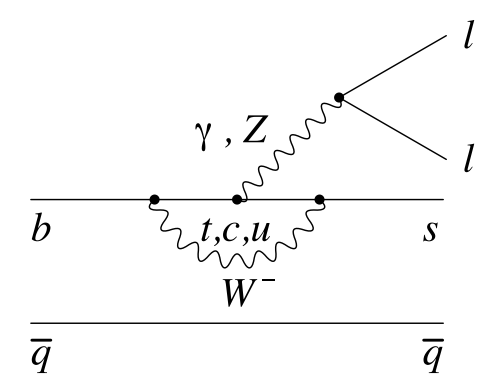


$b \to s\ell\ell$ $\quad R_{K^{(*)}}^{\rm exp} < R_{K^{(*)}}^{\rm SM}$

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

loop-level in SM

LFUV in μ vs e



両方のanomalyを説明できるNP : 3rd >> 2nd

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

3rd 2nd

B anomalies

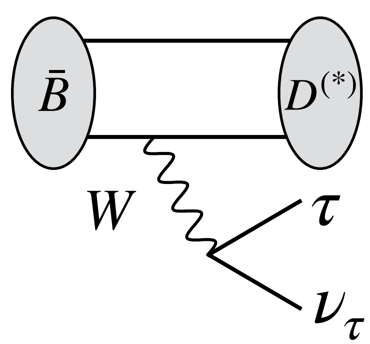
Lepton Flavour Universality Violation in semileptonic B decays

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

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

Tree-level in SM

LFUV in τ vs μ/e

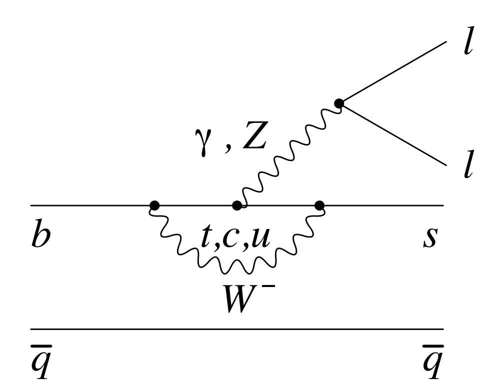


$b \to s\ell\ell$ $\quad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$

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

loop-level in SM

LFUV in μ vs e



両方のanomalyを説明できるNP : 3rd >> 2nd

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

3rd 2nd

Yukawaの階層的構造と一緒。関係がある？

Flavor puzzle in SM

SM Yukawa sectorは 13 parametersで特徴付けられている

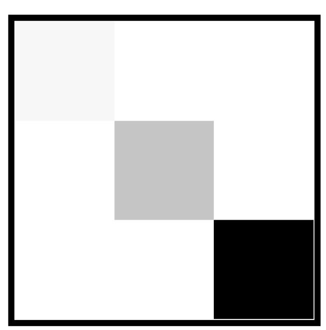
[3 lepton masses + 6 quark masses + 3+1 CKM parameters] ← fixed by data

1st	e	u	d
2nd	μ	c	s
3rd	τ	t	b

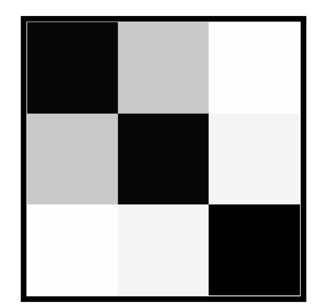
The 3 gen. as “identical” copies
Flavour puzzle

質量、CKM行列は階層的構造を持っている

Mass : 3rd > 2nd > 1st

$M_{u,d} \sim$ 

CKM

$V_{\mathrm{CKM}} \sim$ 

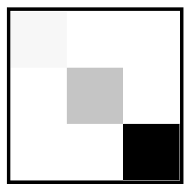
Flavor theory?

U(2) flavour symmetry

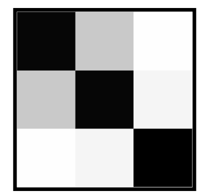
Barbieri, Isidori, Jones-Perez, Lodone, Straub [1105.2296]

SM Yukawa respect an approximate $U(2)$ symmetry

Mass matrix

$M_{u,d} \sim$ 

CKM

$V_{\rm CKM} \sim$ 

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

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

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

Unbroken symmetry

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

$U(2)_q$, $U(2)_u$

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

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

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

Yukawa & CKM の階層的構造が、small breaking termで説明できる

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

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

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

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

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

$U(2)$ symmetryの元でYukawaの形が決まっている → 対角化行列の成分に関係がつく

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

DIagonal forn

$$Q_L \to L_d^\dagger Q_L$$
$$d_R \to R_d{}^\dagger d_R$$

$$\mathrm{diag}(Y_f) = L_f^\dagger Y_f R_f \quad (f = u, d)$$

where

$$L_d = \begin{pmatrix} c_d & -s_d\, e^{i\alpha_d} & 0 \\ s_d\, e^{-i\alpha_d} & c_d & -s_b\, e^{i\phi_b} \\ s_d\, s_b\, e^{-i(\alpha_d+\phi_b)} & s_b\, c_d\, e^{-i\phi_b} & 1 \end{pmatrix}$$

with $\frac{s_d}{c_d} = \frac{|V_{td}|}{|V_{ts}|}$

$$R_d = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \frac{m_s}{m_b} s_b e^{i\phi_d} \\ 0 & -\frac{m_s}{m_b} s_b e^{i\phi_d} & 1 \end{pmatrix}$$

U(2) flavour symmetry

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

↓ mass basis

$$\mathcal{L}_{\text{eff}} = C\begin{pmatrix} 0 & 0 & \frac{s_d}{c_d}e^{i\alpha_d}c_d V_q \\ 0 & 0 & c_d V_q \\ 0 & 0 & 1 \end{pmatrix}^{ij} (\bar{u}_L^i\gamma_\mu b_L^j)(\bar{\tau}_L\gamma_\mu\nu_L^\tau)$$

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

$$\frac{b \to u}{b \to c} = \frac{s_d}{c_d}e^{i\alpha_d} = \frac{|V_{ts}|}{|V_{td}|}e^{i\alpha_d}$$

U(2)の元では、違うflavor遷移の間に関係がつく

U(2) flavour symmetry

$$\bar{Q}_L \Gamma Q_L \quad \text{and} \quad \bar{Q}_L \Gamma U_R$$

↓ mass basis

$$\bar{Q}_L \Gamma Q_L \quad \text{and} \quad \bar{Q}_L L_d R_u^\dagger \Gamma U_R$$

with $Q_L^i = \begin{pmatrix} V_{ji}^* u_j \\ d_i \end{pmatrix}$

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

$$\bar{b}_L V_{cb}^* c_L \qquad \bar{b}_L \frac{m_c}{m_t} \underbrace{s_t}_{\approx |V_{cb}|} \underbrace{e^{-i\phi_t}}_{\approx 1} c_R \longrightarrow \frac{b_L \to c_R}{b_L \to c_L} \sim \frac{m_c}{m_t}$$

U(2)の元では、右巻きの軽いクォークを含んだOperatorはsuppressされる

U(2) flavour symmetry

$U(2)$ flavour symmetry のまとめ

Motivation : Yukawa & CKM の階層的構造が、small breaking termで説明できる

特徴：3世代目 > 2世代目　→ B anomalyが示唆する新物理の特徴と一緒

違うflavor遷移の間に関係がつく

右巻きの軽いクォークを含んだOperatorはsuppressされる

What we did

Charged current $b \to c$ & $b \to u$ に注目。$U(2)$ flavour symmetry の元で、flavor & helicity structureがどのようにテストできるか議論する

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

B anomaly $B \to D^{(*)}\tau\nu_\tau$ $[R_{D^{(*)}}]$

$B_c \to \tau\nu_\tau$

polarizations

Correlations under

$U(2)$

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

$B \to \pi\tau\nu_\tau$ $[R_\pi]$

$B^+ \to \tau\nu_\tau$

$R_\pi^{\rm SM} = 0.641 \pm 0.016$ Tanaka and Wtanabe [1608.05207]

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

Effective theory for charged-current semileptonic decay

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

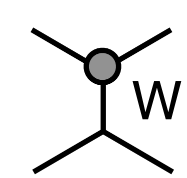
$$\mathscr{L}_{\mathrm{EFT}} = \frac{1}{v^2} \sum_{k,[ij\alpha\beta]} C_k^{[ij\alpha\beta]} \mathcal{O}_k^{[ij\alpha\beta]} + \mathrm{h.c.}$$

右巻きの軽いクォークを含んだOperatorはU(2)ではsuppress

$$\begin{aligned}
\mathcal{O}_{\ell q}^{(3)} &= (\bar{\ell}_L^\alpha \gamma^\mu \tau^a \ell_L^\beta)(\bar{q}_L^i \gamma_\mu \tau^a q_L^j)\,, \\
\mathcal{O}_{\ell edq} &= (\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j)\,, \\
\cancel{\mathcal{O}_{\ell equ}^{(1)}} &= (\bar{\ell}_L^{a,\alpha} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{a,i} u_R^j)\,, \\
\cancel{\mathcal{O}_{\ell equ}^{(3)}} &= (\bar{\ell}_L^{a,\alpha} \sigma_{\mu\nu} e_R^\beta)\epsilon_{ab}(\bar{q}_L^{b,i} \sigma^{\mu\nu} u_R^j)
\end{aligned}$$

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

※ W couplingを変えるようなoperator [ex. $(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$]はhighly suppressed & LFUVを出さないのでneglect



Effective theory for charged-current semileptonic decay

$$\mathscr{L}_{\rm EFT}^{\rm CC} = \frac{1}{v^2}\left[C_V\,\Lambda_V^{[ij\alpha\beta]}\,(\bar{\ell}_L^\alpha\gamma^\mu\tau^a\ell_L^\beta)(\bar{q}_L^i\gamma_\mu\tau^a q_L^j) + C_S\,\Lambda_S^{[ij\alpha\beta]}\,(\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j)\right]$$

※ このトークでは、$\alpha = \beta = 3$の場合のみ議論する

in mass basis with $q_L^i = \begin{pmatrix} V_{ji}^* u_j \\ d_i \end{pmatrix}$ and normalized as $\Lambda_{V,S}^{[3333]} = 1$

$$\Lambda_V^{[ij33]} = \Lambda_S^{[ij33]} = \begin{pmatrix} 0 & 0 & \lambda_q^d \\ 0 & 0 & \lambda_q^s \\ 0 & 0 & 1 \end{pmatrix}$$

※ $s_b \ll 1$ and $R_d \approx 1$

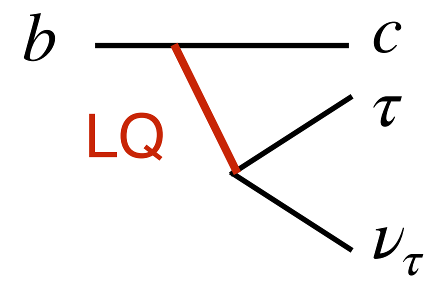
$$\lambda_q^s = O(|V_q|) \qquad \frac{\lambda_q^d}{\lambda_q^s} = \frac{|V_{td}|}{|V_{ts}|}e^{i\alpha_d}$$

Parameters: C_V, C_S and spurion $|V_q|$

U1 Leptoquarks

$$\mathscr{L}_{\rm EFT}^{\rm CC} = \frac{1}{v^2}\left[C_V\,\Lambda_V^{[ij\alpha\beta]}\,(\bar{\ell}_L^\alpha\gamma^\mu\tau^a\ell_L^\beta)(\bar{q}_L^i\gamma_\mu\tau^a q_L^j) + C_S\,\Lambda_S^{[ij\alpha\beta]}\,(\bar{\ell}_L^\alpha e_R^\beta)(\bar{d}_R^i q_L^j)\right]$$

U1 LQ で出てくるoperatorと同じ



Leptoquark(LQ) solution (scalar and vector)は、B anomalyを説明できるmediator の有力候補。なかでも $U_1 = (2,1,2/3)$ vector LQ は $R_{D^{(*)}}$ & $R_{K^{(*)}}$ 両方説明可能

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

$$C_V = \frac{g_U^2}{2M_{U_1}^2}\frac{1}{2\sqrt{2}G_F}\,,\quad \frac{C_S}{C_V} = -2\beta_R^*\,,\quad \lambda_q^s = \beta_L^{s\tau}$$

EFT approach & U_1 LQ

b→c and b→u under U(2)

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

for $b \to c$

$$C^c_{V(S)} = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{cs}}{V_{cb}} + \frac{V_{cd}}{V_{cb}}\frac{|V_{td}|}{|V_{ts}|}e^{i\alpha_d}\right)\right]$$

for $b \to u$

$$C^u_{V(S)} = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{us}}{V_{ub}} + \frac{V_{ud}}{V_{ub}}\frac{|V_{td}|}{|V_{ts}|}e^{i\alpha_d}\right)\right]$$

scalar and vector

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

flavor blind & NP helicity structureにのみ依存

b→c and b→u under U(2)

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

for $b \to c$

$$C^c_{V(S)} = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{cs}}{V_{cb}} + \frac{V_{cd}}{V_{cb}}\frac{|V_{td}|}{|V_{ts}|}e^{i\alpha_d}\right)\right]$$

for $b \to u$

$$C^u_{V(S)} = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{us}}{V_{ub}} + \frac{V_{ud}}{V_{ub}}\frac{|V_{td}|}{|V_{ts}|}e^{i\alpha_d}\right)\right]$$

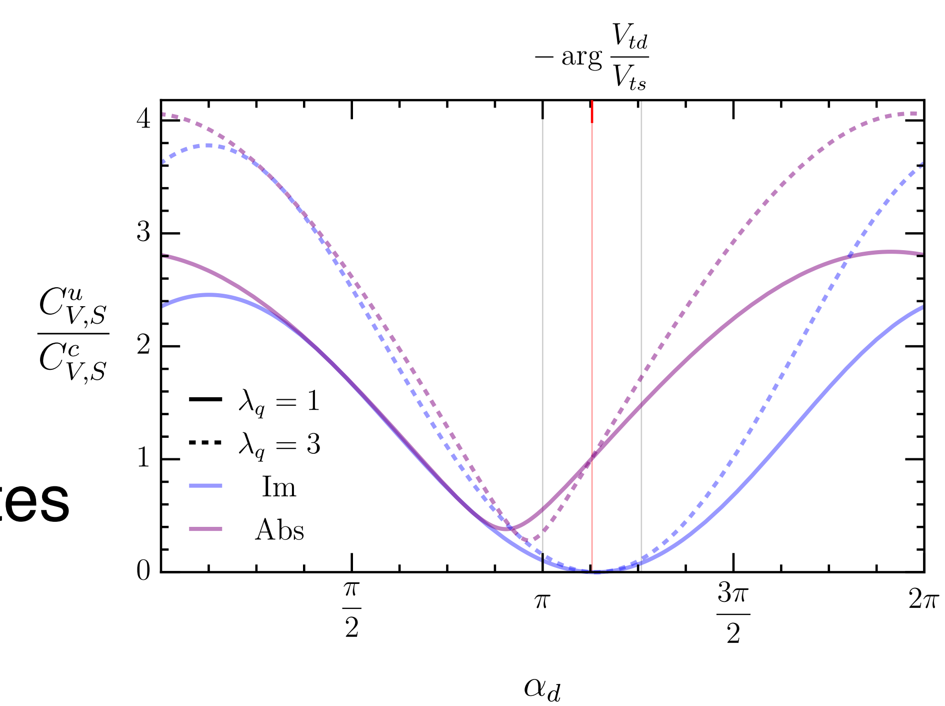
$b \to c$ vs $b \to u$

Depends on unconstrained phase α_d

$$\alpha_u - \alpha_d = \arg(V_{td}) + \arg(V_{ub}) \approx -\pi/2$$

$$\left|\frac{C^u_{V,S}}{C^c_{V,S}}\right| \begin{cases} = 1 \quad \text{in the limit } \alpha_d = -\arg\left(\frac{V_{td}}{V_{ts}}\right) \\ \sim 0.5 \text{ at } \alpha_d = \pi \end{cases}$$

(the phase of the CKM matrix originates only from the up sector)



Numerical forula for observables

Iguro, Kitahara, Omura
Watanabe and KY
[1811.08899]

$b \to c$

$$\frac{R_D}{R_D^{\rm SM}} \approx |1 + C_V^c|^2 + 1.49\,{\rm Re}[(1 + C_V^c)\eta_S\, C_S^{c^*}] + 1.02\,|\eta_S\, C_S^c|^2$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \approx |1 + C_V^c|^2 + 0.11\,{\rm Re}[(1 + C_V^c)\eta_S\, C_S^{c^*}] + 0.04\,|\eta_S\, C_S^c|^2$$

$$\frac{F_L^{D^*}}{F_{L,{\rm SM}}^{D^*}} \approx 1 + 0.13\,\eta_S\, C_S^c(1 - C_V^c) + 0.03\,\eta_S^2\, C_S^{c2}$$

$$\frac{P_\tau^D}{P_{\tau,{\rm SM}}^D} \approx 1 + 3.16\,\eta_S\, C_S^c(1 - C_V^c) - 2.55\,\eta_S^2\, C_S^{c2}$$

$$\frac{P_\tau^{D^*}}{P_{\tau,{\rm SM}}^{D^*}} \approx 1 - 0.33\,\eta_S\, C_S^c(1 - C_V^c) - 0.07\,\eta_S^2\, C_S^{c2}$$

where $\eta_S \approx 1.8$ arises by running of scalar operator from TeV scale down to mb

Numerical forula for observables

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

Chiral enhancement factor

$b \to u$

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

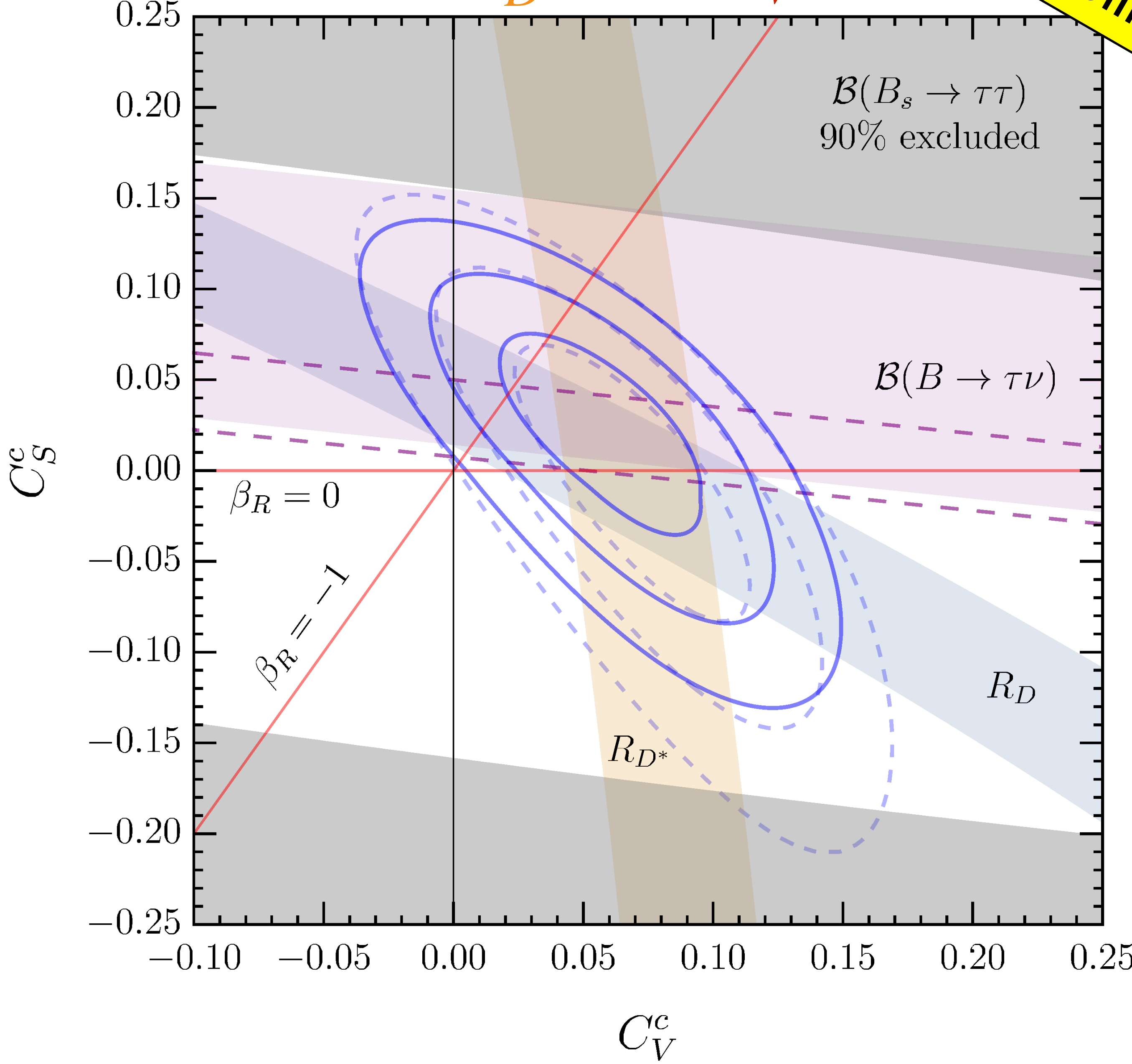
$$\frac{\mathscr{B}(B^+ \to \tau^+\nu)}{\mathscr{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM}} = \left|1 + C_V^u + \frac{m_{B^+}^2}{m_\tau\left(\overline{m}_b + \overline{m}_u\right)}\, C_S^u\right|^2 \approx \left|1 + C_V^u + 3.75 C_S^u\right|$$

C_S vs C_V

Recall : $\dfrac{C_S^c}{C_V^c} = \dfrac{C_S^u}{C_V^u} = \dfrac{C_S}{C_V}$ flavor blind & NP helicity structure

R_{D^*} 1σ $\dfrac{C_S}{C_V} = -2\beta_R^*$

preliminary



- - - : Chi2 w $R_{D^{(*)}}$

– : Chi2 w $R_{D^{(*)}}, B^+$

$B^- \to \tau\nu_\tau$ 1σ $\alpha_d = \pi, \lambda_q^s \in [1,3]\,|V_{ts}|$

- - - : $\alpha_d = -\arg\left(\dfrac{V_{td}}{V_{ts}}\right)$

R_D 1σ

※ There is constraint from neutral current obs. $B_s \to \tau\tau$

$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}_L^\alpha \gamma^\mu \tau^a \ell_L^\beta)(\bar{q}_L^i \gamma_\mu \tau^a q_L^j)$ → CC & NC

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

$$\frac{R_D}{R_D^{\rm SM}} \approx |1 + C_V^c|^2 + 1.49\,\mathrm{Re}[(1 + C_V^c)\eta_S\,C_S^{c*}] + 1.02\,|\eta_S\,C_S^c|^2$$

$$\frac{R_{D*}}{R_{D*}^{\rm SM}} \approx |1 + C_V^c|^2 + 0.11\,\mathrm{Re}[(1 + C_V^c)\eta_S\,C_S^{c*}] + 0.04\,|\eta_S\,C_S^c|^2$$

$$\frac{F_L^{D*}}{F_{L,\rm SM}^{D*}} \approx 1 + 0.13\,\eta_S\,C_S^c(1 - C_V^c) + 0.03\,\eta_S^2\,C_S^{c2}$$

$$\frac{P_\tau^D}{P_{\tau,\rm SM}^D} \approx 1 + 3.16\,\eta_S\,C_S^c(1 - C_V^c) - 2.55\,\eta_S^2\,C_S^{c2}$$

$$\frac{P_\tau^{D*}}{P_{\tau,\rm SM}^{D*}} \approx 1 - 0.33\,\eta_S\,C_S^c(1 - C_V^c) - 0.07\,\eta_S^2\,C_S^{c2}$$

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

$$\frac{R_D}{R_D^{\rm SM}} \approx |1 + C_V^c|^2 + 1.49\,\mathrm{Re}[(1 + C_V^c)\eta_S\, C_S^{c*}] + 1.02\,|\eta_S\, C_S^c|^2$$

$$\frac{R_{D*}}{R_{D*}^{\rm SM}} \approx |1 + C_V^c|^2 + 0.11\,\mathrm{Re}[(1 + C_V^c)\eta_S\, C_S^{c*}] + 0.04\,|\eta_S\, C_S^c|^2$$

→ $\Delta R_D - \Delta R_{D*} \approx 1.38\ \eta_S\ \mathrm{Re}C_S^c$ $\left(\Delta O_X = \frac{O_X}{O_X^{\rm SM}} - 1\right)$

$$\frac{F_L^{D*}}{F_{L,\rm SM}^{D*}} \approx 1 + 0.13\,\eta_S\, C_S^c(1 - C_V^c) + 0.03\,\eta_S^2\, C_S^{c2}$$

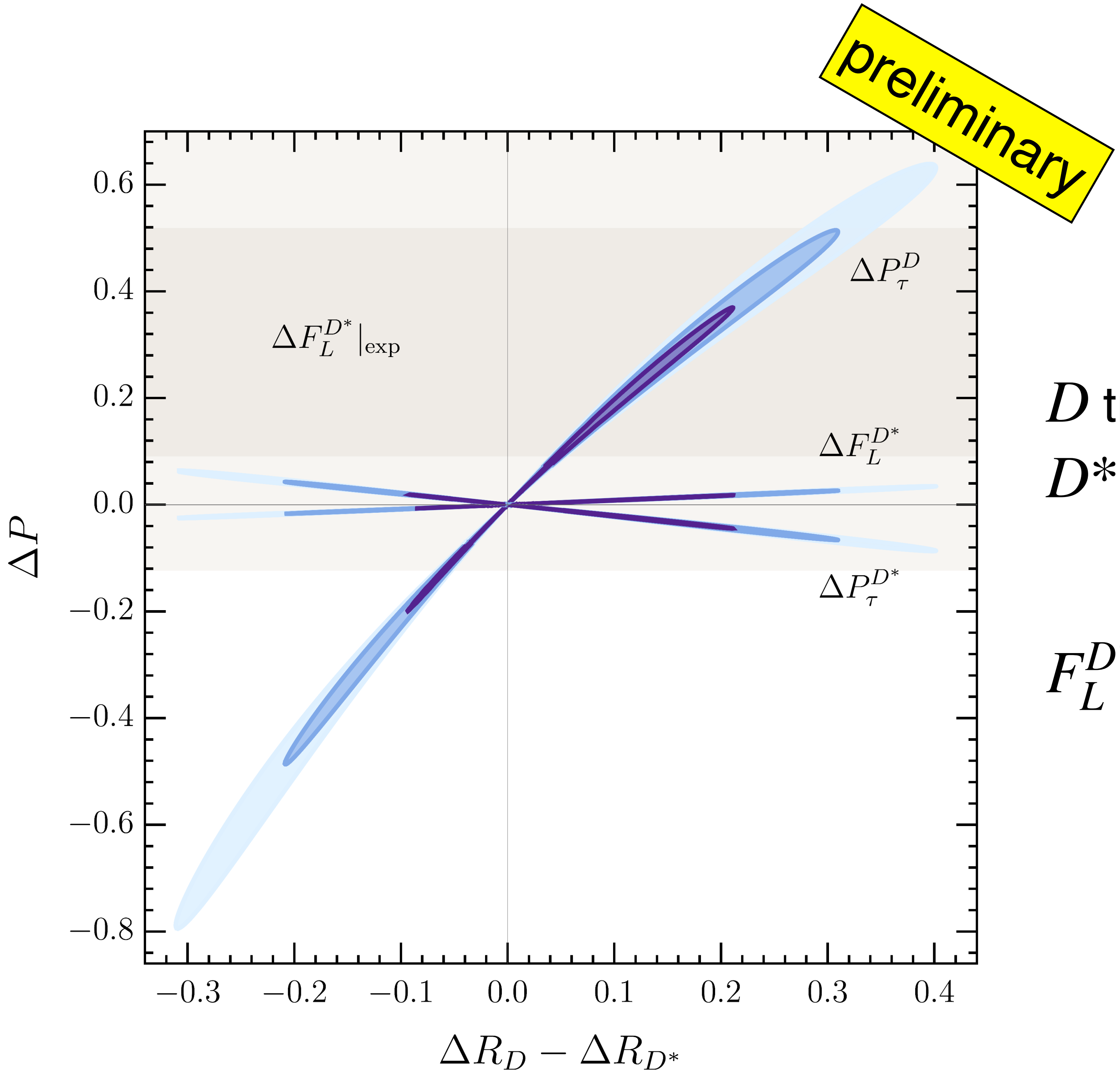
$$\frac{P_\tau^{D}}{P_{\tau,\rm SM}^{D}} \approx 1 + 3.16\,\eta_S\, C_S^c(1 - C_V^c) - 2.55\,\eta_S^2\, C_S^{c2}$$

scalar C_S^c dominant

$$\frac{P_\tau^{D*}}{P_{\tau,\rm SM}^{D*}} \approx 1 - 0.33\,\eta_S\, C_S^c(1 - C_V^c) - 0.07\,\eta_S^2\, C_S^{c2}$$

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

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



– : Chi2 w $R_{D^{(*)}}, B^+$

D transition (ΔP_τ^D) : ~ 40% enhance

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

$F_L^{D^{(*)}}\Big|_{\rm exp}$ の中心値は再現できない

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

$$\frac{R_D}{R_D^{\rm SM}} \approx |1 + C_V^c|^2 + 1.49\,{\rm Re}[(1 + C_V^c)\eta_S\, C_S^{c*}] + 1.02\,|\eta_S\, C_S^c|^2$$

$$\frac{R_{D^*}}{R_{D^*}^{\rm SM}} \approx |1 + C_V^c|^2 + 0.11\,{\rm Re}[(1 + C_V^c)\eta_S\, C_S^{c*}] + 0.04\,|\eta_S\, C_S^c|^2$$

$$\longrightarrow \quad \Delta R_D - \Delta R_{D^*} \approx 1.38\ \eta_S\ {\rm Re}C_S^c \qquad \left(\Delta O_X = \frac{O_X}{O_X^{\rm SM}} - 1\right)$$

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

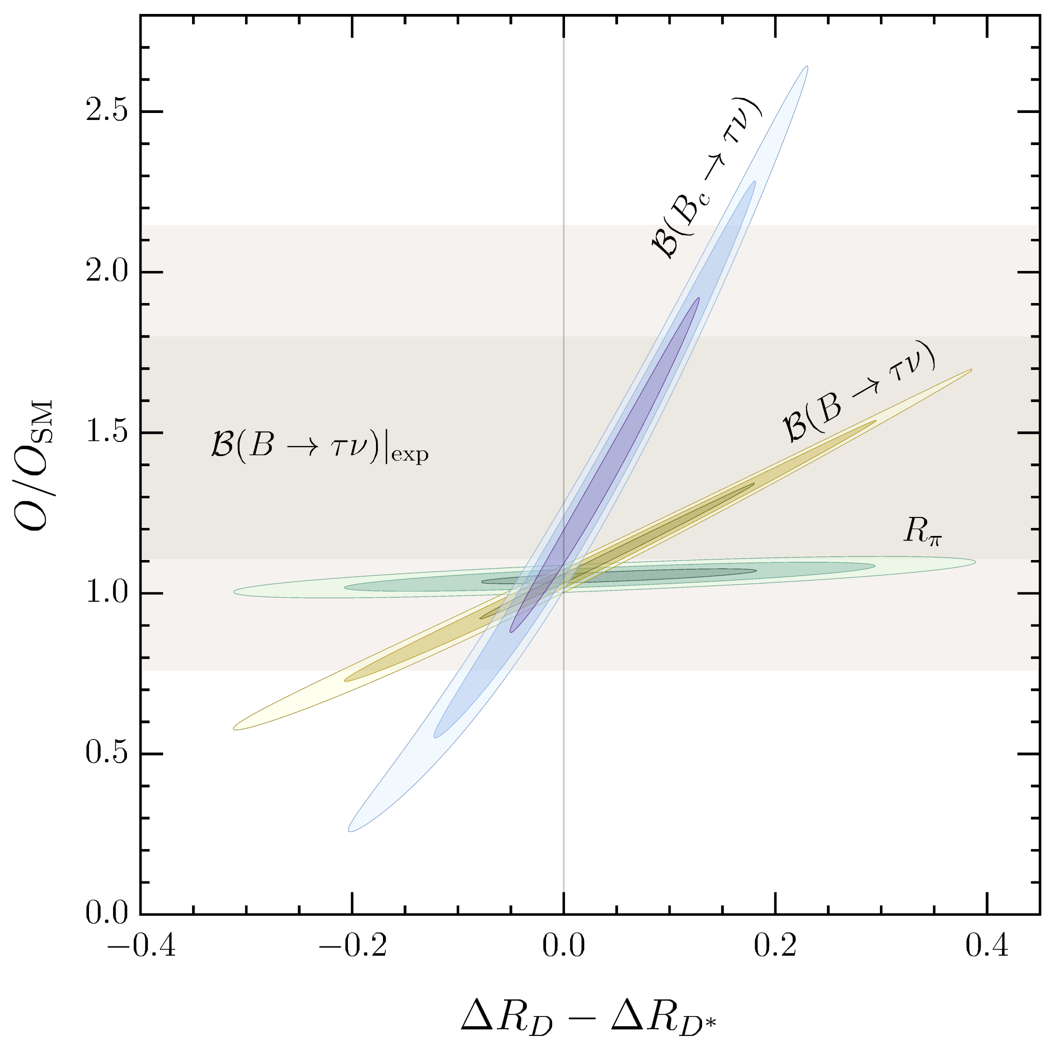
$$\frac{R_\pi}{R_\pi^{\rm SM}} = |1 + C_V^u|^2 + 1.13\,{\rm Re}\left[(1 + C_V^u)C_S^{u*}\right] + 1.36\,|C_S^u|^2$$

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

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

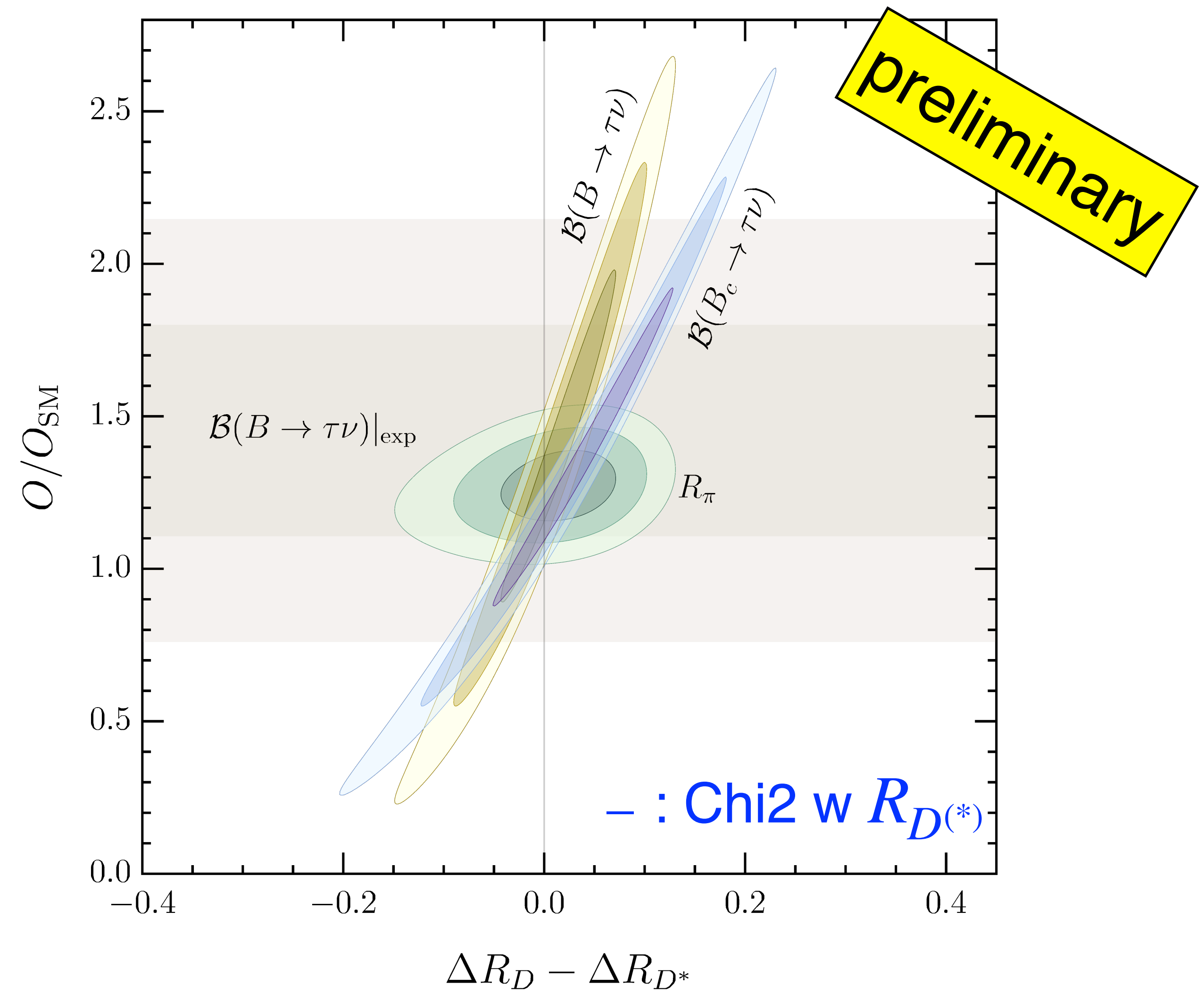
C_S dependence ii) $\Delta R_D - \Delta R_{D^*}$ vs R_π, B^+, B_c^+

$\alpha_d = \pi \quad (|C^u/C^c| \sim 0.5)$



$\Delta R_\pi \lesssim 10\,\%$

$\alpha_d = -2\arg(V_{td}/V_{ts}) - \pi \quad (|C^u/C^c| \sim 1.5)$



$\Delta R_\pi \lesssim 50\,\%$

$\lambda_q^s = 3\,|V_{ts}|$

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

$R_\pi^{\rm exp} \simeq 1.05 \pm 0.51$ → Belle II $R_\pi^{\rm BelleII} = 0.641 \pm 0.071$

Tanaka and Wtanabe [1608.05207]

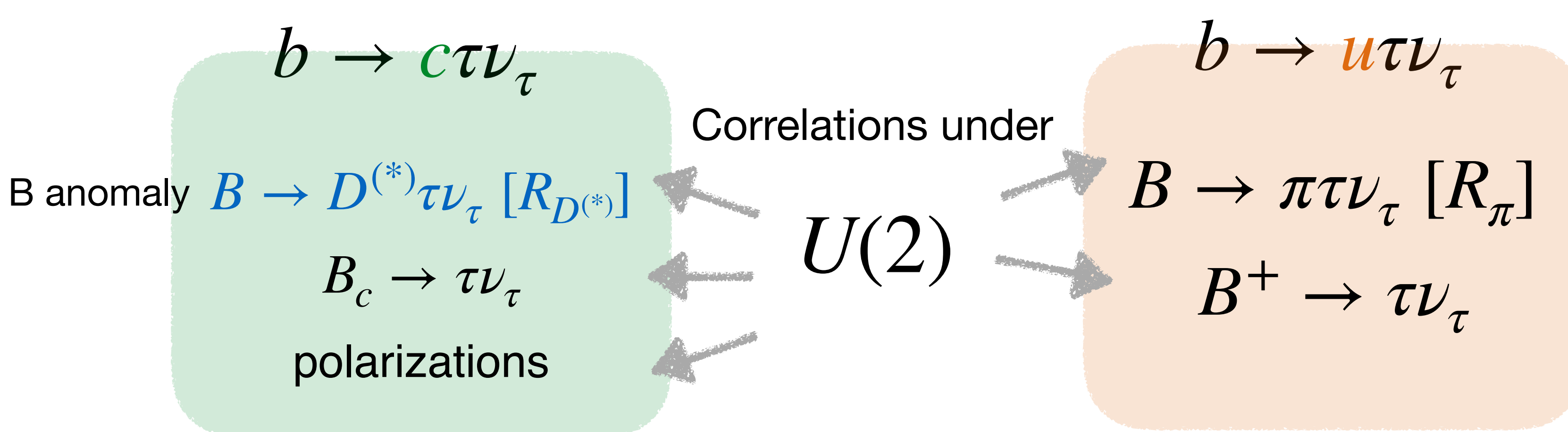
Summary

B semi-leptonic decay において、LFUV が報告されている (B anomalies)

3世代目に強くcoupleするNPが示唆

→ U(2) flavour symmetry

Charged current $b \to c$ & $b \to u$ に注目。$U(2)$ flavour symmetry の元で、flavor & helicity structureがどのようにテストできるか議論した



もしB anomaliesがNPによるものであれば、$b \to u$, polarization等に兆候が現れ得る

updated Belle II & LHCb data に期待