# Probing non-standard flavour and helicity structures in semi-leptonic B decays

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Zürich PhD Seminar

October 9, 2019

based on arXiv:1909.02519
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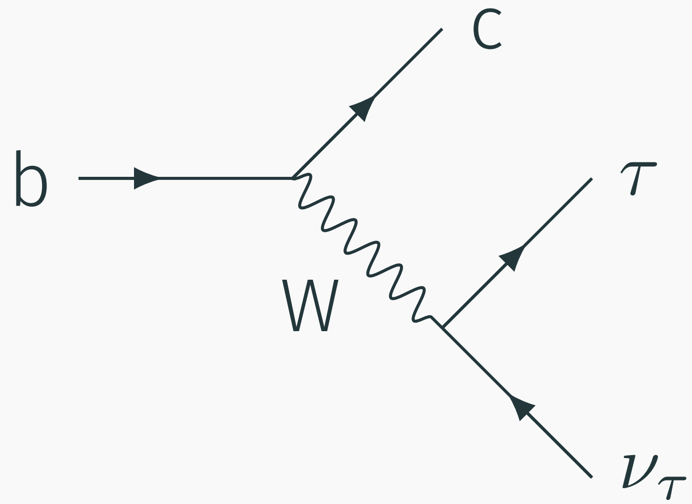
# B anomalies

Tests of Lepton Flavour Universality (LFU)

**Charged current**

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

$\tau/e,\mu$ ratio

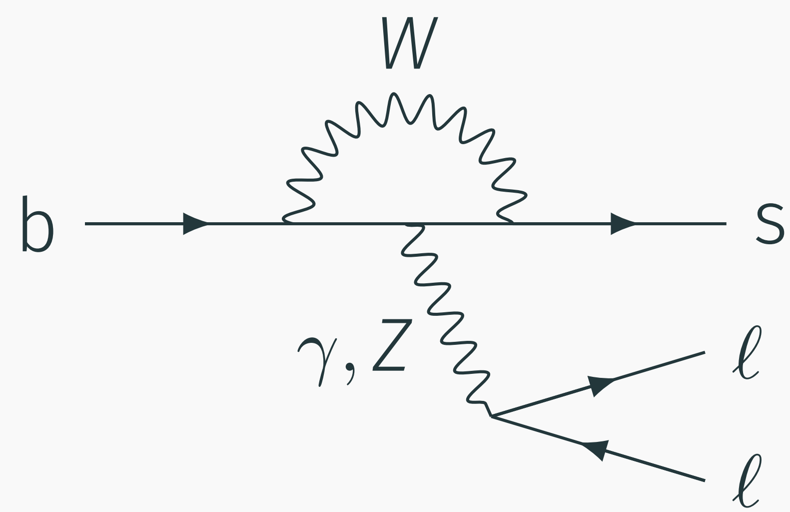



**Tree** level

**Neutral current**

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

$\mu/e$ ratio




**Loop** level

**Anomalies** hint TeV scale **NP**, a common explanation implies

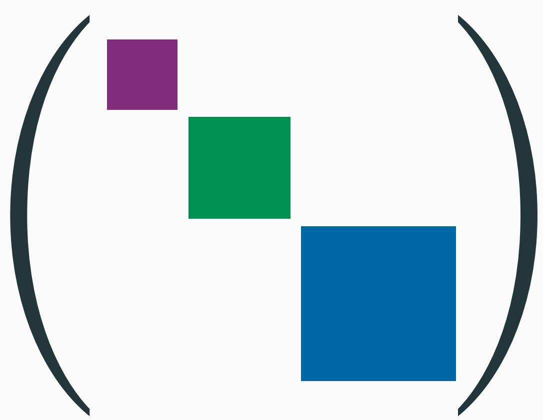
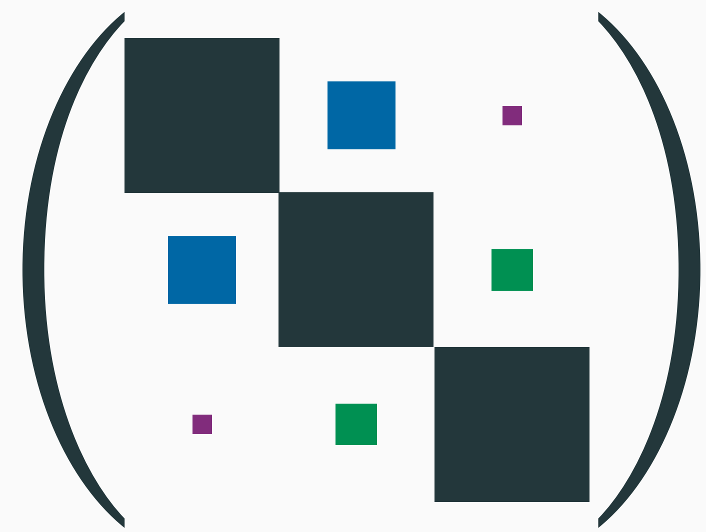
$$\text{NP in } \tau \quad \gg \quad \text{NP in } \mu/e\ ,$$

same hierarchy as in the **Yukawa**. Could it be more than coincidence?

# Flavour Puzzle

In the SM, only the **Yukawa** couplings distinguish between **flavours**.
They are the main source of free parameters (9 masses, 3+1 mixings), and yet they obey a very specific structure :

- Strong **hierarchy** between generations $m_3 \gg m_2 \gg m_1$
- Small mixings in the CKM

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

The gauge sector of the SM has few degrees of freedom and is fixed by symmetries $\Rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

Can we find a symmetry describing the Yukawa sector? A **flavour symmetry**?

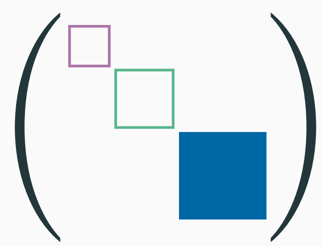
# U(2) Flavour Symmetry

Approximate $U(2)^5$ flavour symmetry : [Barbieri et al. 1105.2296]
at first order, light families are massless and indistinguishable

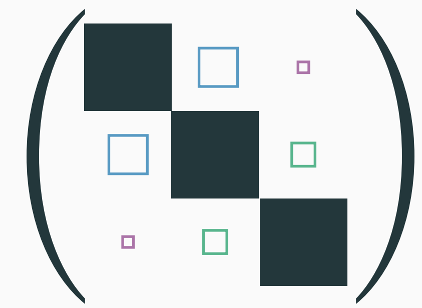
$$U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Exact limit :

$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \rightarrow \quad M_{u,d,e} \sim$$



$$V_{\rm CKM} \sim$$



Largest breaking in SM is of order $\epsilon = \left[ Tr(Y_u Y_u^\dagger) - \frac{Tr(Y_u Y_u^\dagger Y_d Y_d^\dagger)}{Tr(Y_d Y_d^\dagger)} \right]^{1/2} \approx y_t |V_{ts}| \approx 0.04$

Introduce 5 **spurions** to recover SM patterns

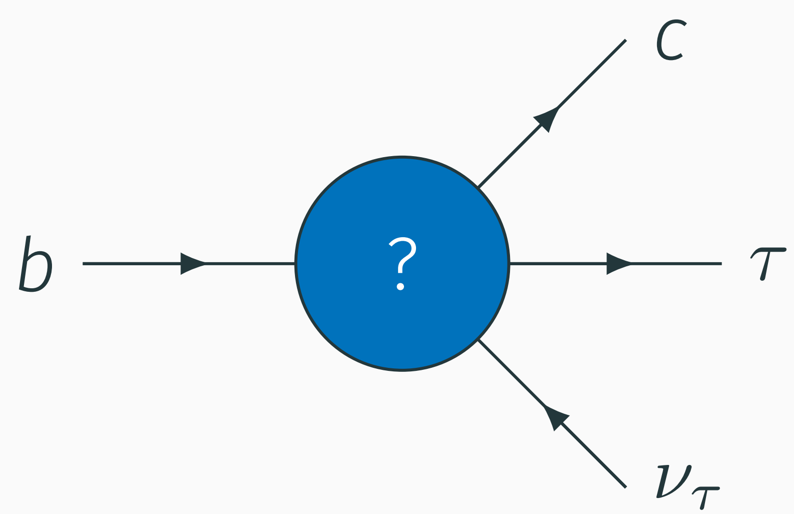
$$Y_{u,d,e} = y_{t,b,\tau} \begin{pmatrix} \Delta_{u,d,e} & V_{q,\ell} \\ 0 & 1 \end{pmatrix} \qquad \begin{aligned} V_q &\sim \mathcal{O}(\epsilon) \\ \Delta_{u,d,e} &\sim y_{c,s,\mu} \end{aligned}$$

This symmetry and spurions can be a guiding principle for the **anomalies!**

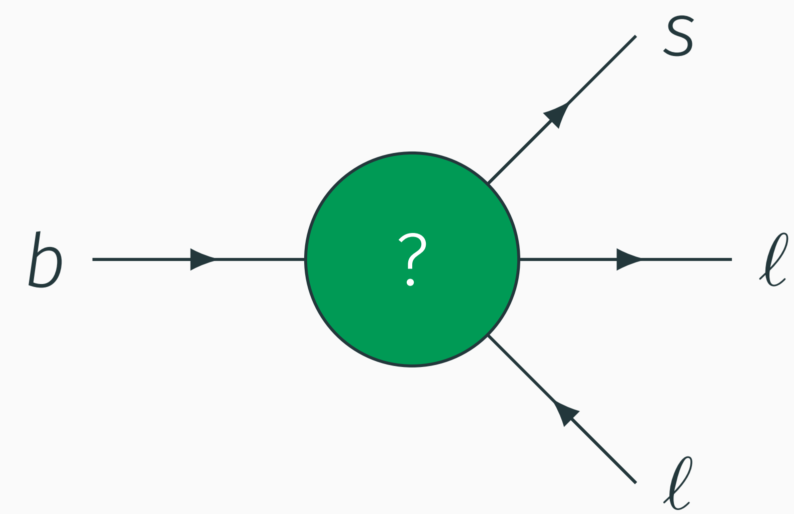
# (SM)EFT framework

Semileptonic dimension six 4-fermions operators mediating B decays

**Charged current**




**Neutral current**




$$O_{\ell q}^{(3)} = (\bar{\ell}_L \gamma^\mu \tau^I \ell_L)(\bar{q}_L \gamma_\mu \tau^I q_L) \qquad O_{\ell q}^{(1)} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{q}_L \gamma_\mu q_L)$$

$$O_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q_L)$$

only $b \to s\tau\tau$

$$O_{qe} = (\bar{q}_L \gamma^\mu q_L)(\bar{e}_R \gamma_\mu e_R)$$

$$O_{\ell equ}^{(1)} = (\bar{\ell}_L^a e_R)\epsilon_{ab}(\bar{q}_L^b u_R) \qquad O_{\ell d} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{d}_R \gamma_\mu d_R)$$

$$O_{\ell equ}^{(3)} = (\bar{\ell}_L^a \sigma_{\mu\nu} e_R)\epsilon_{ab}(\bar{q}_L^b \sigma^{\mu\nu} u_R) \qquad O_{ed} = (\bar{e}_R \gamma^\mu e_R)(\bar{d}_R \gamma_\mu d_R)$$

transform under $U(2)_u \times U(2)_d \times U(2)_e$

Assumption to reduce basis :
keep only one power of each leading spurions $V_q$ and $V_\ell$

# (SM)EFT framework

$O^{(3)}_{\ell q} = (\bar{\ell}_L \gamma^\mu \tau^I \ell_L)(\bar{q}_L \gamma_\mu \tau^I q_L)$ $\quad O^{(1)}_{\ell q} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{q}_L \gamma_\mu q_L)$ $\quad O_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q_L)$

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

- strong constraints on $b \to s\nu_\tau\bar{\nu}_\tau$ can be avoided with $C_{V_1} \approx C_{V_3}$
- The $U_1 \sim (3,1)_{2/3}$ **vector leptoquark** model has a one-to-one matching with this Lagrangian with

$$C_{V_1} = C_{V_3} \equiv C_V > 0$$
$$\Lambda_{V_1} = \Lambda_{V_3} \equiv \Lambda_V$$
$$C_S = -2\beta_R C_V$$

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}} U_1^\mu \Big[\beta_L^{i\alpha}(\bar{q}^i_L \gamma_\mu \ell^\alpha_L) + \beta_R^{i\alpha}(\bar{d}^i_R \gamma_\mu e^\alpha_R)\Big]$$

$$\mathcal{L}_{\text{EFT,NP}} = -\frac{1}{v^2}\left[C_V\Lambda_V\left(O^{(1)}_{\ell q} + O^{(3)}_{\ell q}\right) + \left(2C_S\Lambda_S O_{\ell edq} + \text{h.c.}\right)\right]$$

# $U(2)_q \times U(2)_\ell$ spurions in interactions

$O_{\ell q}^{(3)} = (\bar{\ell}_L \gamma^\mu \tau^I \ell_L)(\bar{q}_L \gamma_\mu \tau^I q_L)$ $\quad O_{\ell q}^{(1)} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{q}_L \gamma_\mu q_L)$ $\quad O_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q_L)$

$$\mathscr{L}_{\mathrm{EFT,NP}} = -\frac{1}{v^2}\left[C_V \Lambda_V \left(O_{\ell q}^{(1)} + O_{\ell q}^{(3)}\right) + \left(2 C_S \Lambda_S O_{\ell edq} + \mathrm{h.c.}\right)\right]$$

Wilson coefficients encode NP strength

Flavour structure $\quad \Lambda_V = \Gamma_L^\dagger \times \Gamma_L \quad \Lambda_S = \Gamma_L^\dagger \times \Gamma_R$

In **interaction basis** $\quad \Gamma_L = \begin{pmatrix} V_q V_\ell^* & V_q \\ V_\ell^* & 1 \end{pmatrix} \quad \Gamma_R = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$

with order 1 coefficients

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

$\Rightarrow$ same size :
- for leptons and quark $\rightarrow$ common origin ?
- as the spurions in the Yukawa ✓

Common explanation makes sense !

# $U(2)^5$ in practice

$$\mathscr{L}_{\text{EFT,NP}} = -\frac{1}{v^2}\left[C_V\Lambda_V\left(O^{(1)}_{\ell q} + O^{(3)}_{\ell q}\right) + \left(2C_S\Lambda_S\,O_{\ell edq} + \text{h.c.}\right)\right]$$

Yukawa to **mass basis**

$$q_L \to L_d q_L$$
$$u_R \to R_u u_R$$
$$d_R \to R_d d_R$$

Flavour structure in EFT in **interaction basis**

$$\Gamma_L \to \hat{\Gamma}_L = L_d^\dagger \Gamma_L L_e$$
$$\Gamma_R \to \hat{\Gamma}_R = R_d^\dagger \Gamma_R R_e$$

$$\boxed{\begin{aligned} \lambda_q^s &\sim \mathcal{O}(|V_q|) \\ \lambda_\ell^\mu &\sim \mathcal{O}(|V_\ell|) \\ \Delta_{q\ell}^{s\mu} &\sim \mathcal{O}(\lambda_q^s \lambda_\ell^\mu) \end{aligned}}$$

When the mist clears...

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

$$\hat{\Gamma}_R \approx \begin{array}{c} \begin{array}{ccc} e_r & \mu_R & \tau_R \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_s}{m_b}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_\tau & 1 \end{pmatrix} \end{array} \begin{array}{c} d_R \\ s_R \\ b_R \end{array}$$

# $U(2)^5$ predictions

$$\hat{\Gamma}_L \approx \begin{array}{c} \begin{matrix} \ell_1 & \ell_2 & \ell_3 \end{matrix} \\ \begin{pmatrix} 0 & 0 & \frac{V_{td}^*}{V_{ts}^*}\lambda_q^s \\ 0 & \Delta_{q\ell}^{s\mu} & \lambda_q^s \\ s_e\lambda_\ell^\mu & \lambda_\ell^\mu & 1 \end{pmatrix} \end{array} \begin{matrix} q_1 \\ q_2 \\ q_3 \end{matrix} \qquad \hat{\Gamma}_R \approx \begin{array}{c} \begin{matrix} e_r & \mu_R & \tau_R \end{matrix} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{m_s}{m_b}s_b \\ 0 & -\frac{m_\mu}{m_\tau}s_\tau & 1 \end{pmatrix} \end{array} \begin{matrix} d_R \\ s_R \\ b_R \end{matrix}$$

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

$b \to c\tau\bar{\nu}$

**$\mathbf{U(2)}$ flavour symmetry predictions :**

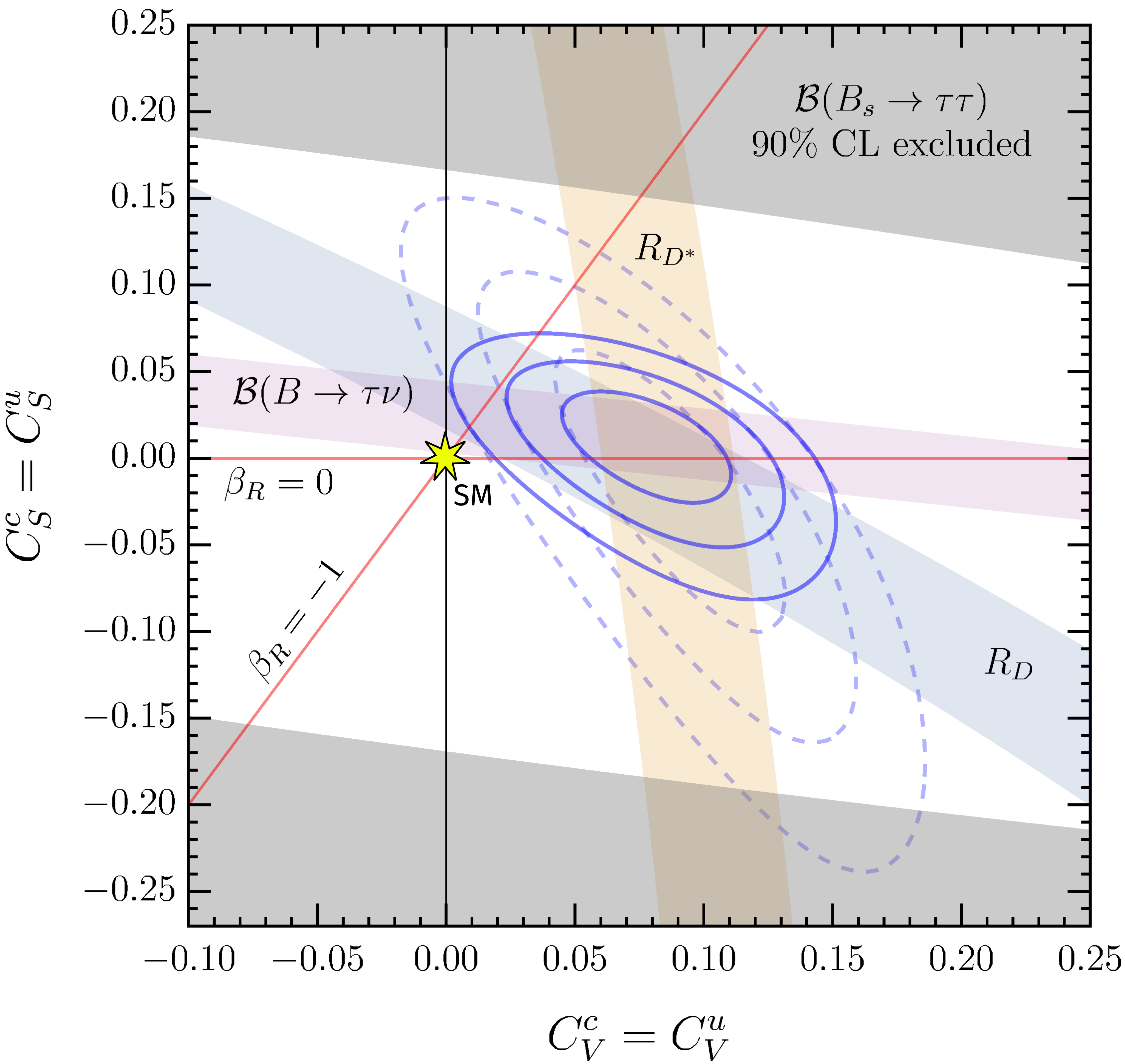
- NP in charged current $\gg$ NP in neutral current
- NP strength in $b \to c(s)$ $=$ NP strength in $b \to u(d)$
- Scalar operator with light fermions suppressed by ratio of masses

**Aim of this work :**

- Test $U(2)$ flavour symmetry in B decays to $1^{\text{st}}$ and $2^{\text{nd}}$ generations
- Identify observables to disentangle between different $U(2)$ models by studying $C_S$ and the lepton spurion

# Status today

Since NP couples mainly to **3rd** generation, test $U(2)^5$ with **charged current**




- Dashed ellipses: $R_D, R_{D^*}$ only
- Full ellipses: + $\mathcal{B}(B \to \tau\nu)$
- $1\sigma$ lines for each observable
- Neutral current with maximum spurion size not very constraining
- Two specific vector leptoquark scenario (red)

# Future prospects - polarisation observables

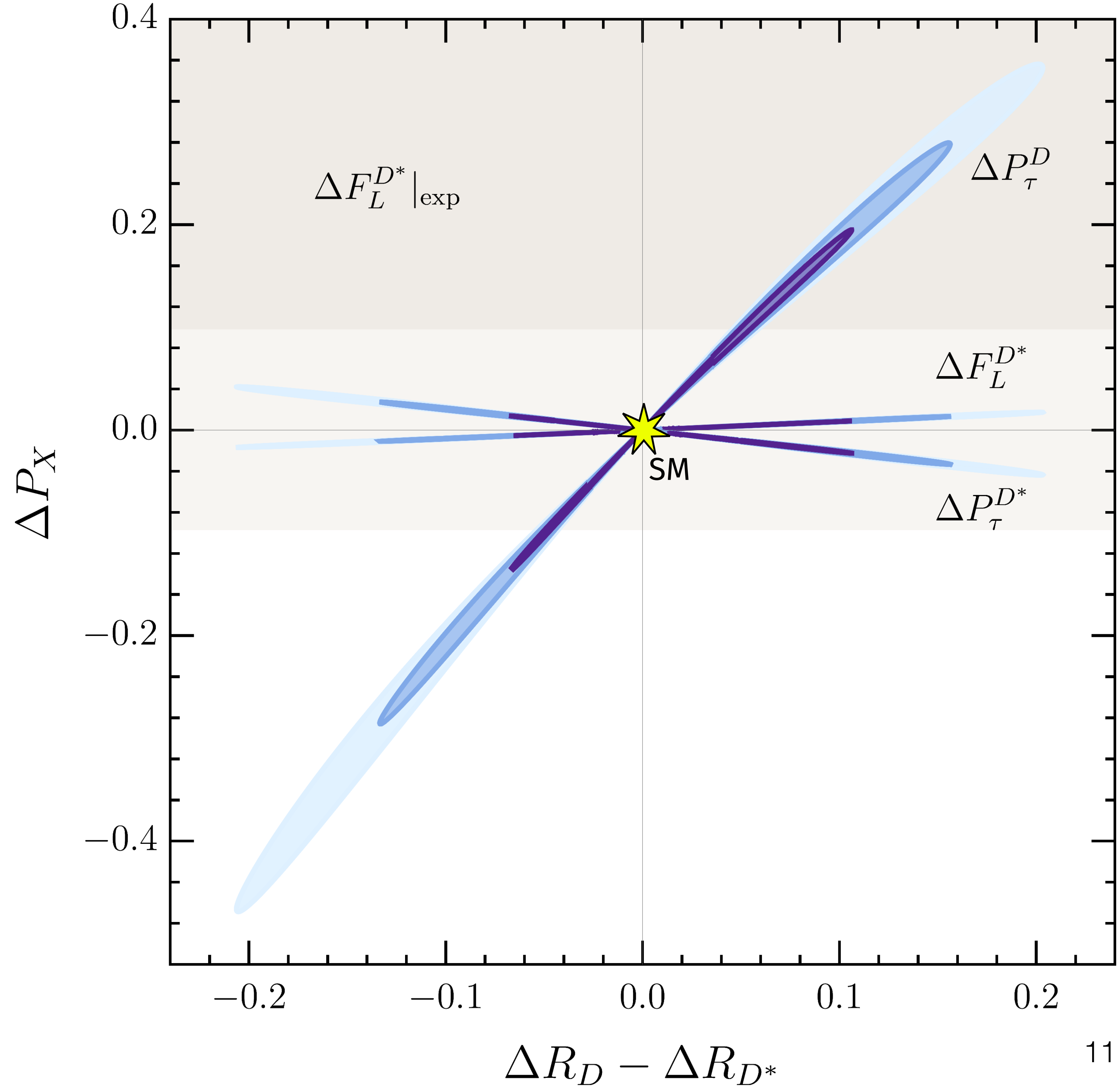
$$P_\tau^{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau^{(+)}\bar{\nu}) - \Gamma(\bar{B} \to D^{(*)}\tau^{(-)}\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\tau^{(+)}\bar{\nu}) + \Gamma(\bar{B} \to D^{(*)}\tau^{(-)}\bar{\nu})} \qquad F_L^{D^*} = \frac{\Gamma(\bar{B} \to D_L^*\tau\bar{\nu})}{\Gamma(\bar{B} \to D^*\tau\bar{\nu})}$$

$$\Delta P_X = \frac{P_X}{P_X^{\mathrm{SM}}} - 1$$

- $C_V$ is just a rescaling of the SM piece
- $C_S$ can only be NP

$$\Delta R_D - \Delta R_{D^*} \propto C_S$$

Noticeable enhancement of $\Delta P_\tau^D$



# Future prospects - $b \to u$ transition

Expanding analysis in the quark direction

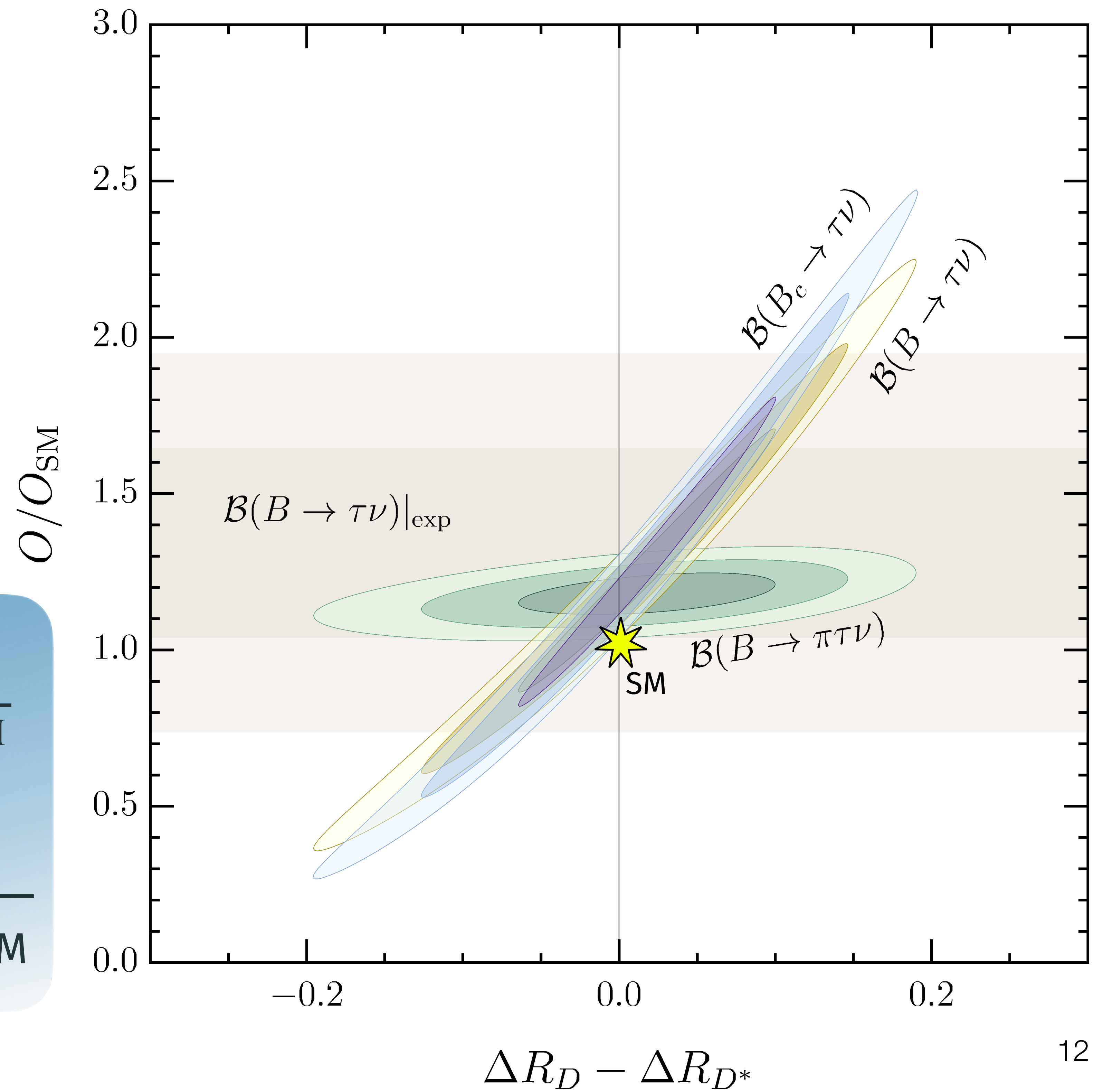
$$R_\pi = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu})}{\mathcal{B}(B \to \pi\ell\bar{\nu})}$$

$$\Delta R_D - \Delta R_{D^*} \propto C_S$$

Clear predictions for $b \to u$

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

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



# Lepton spurion

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

quark direction

lepton direction ?

## In **charged current**

- $R_{D^{(*)}}^{\mu e}$, $\mathcal{B}(\bar{B} \to \mu\bar{\nu})$: NP $\lesssim 10^{-3}$
  $\to$ beyond experimental reach

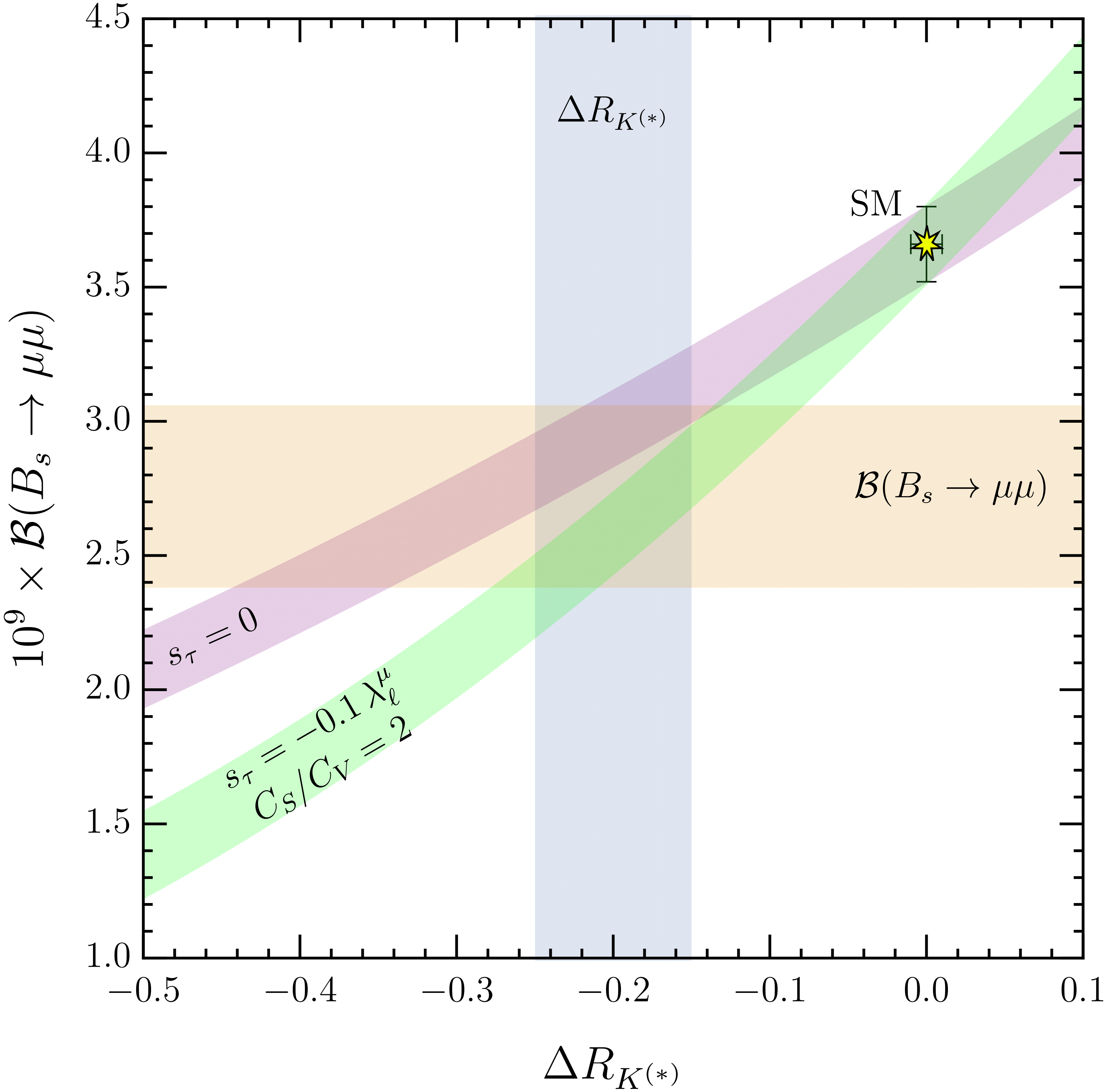
- $R_{D^{(*)}}$, Polarisations, $\mathcal{B}(B_{(c)} \to \tau\nu)$, $R_\pi$

## In **neutral current**

- $R_{K^{(*)}}$, $\mathcal{B}(B_{s,d} \to \ell\bar{\ell}^{(\prime)})$, $\mathcal{B}(B \to \pi\ell\bar{\ell})$
  $\to$ already accessible !

- no tree level for $b \to s\nu\bar{\nu}$ ($C_{V_1} = C_{V_3}$), $b \to s\tau\bar{\tau}$ poorly constrained

# Lepton spurion - neutral currents




- Tension with SM in $b \to s\mu\bar{\mu}$ transitions
- Consistent with $U(2)$ (see predictions for 2 benchmarks points)

$B_s \to \tau\bar{\mu}$ and $\tau \to \mu\gamma$ could help over constrain the lepton spurions

$$R_K \approx R_{K^*} \approx \frac{\mathcal{B}(B \to \pi\mu\bar{\mu})}{\mathcal{B}(B \to \pi e\bar{e})}$$

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

# Conclusion

**B anomalies** hint NP coupled mainly to $3^{\text{rd}}$ generation ⟷ **Yukawa** couplings have similar hierarchy

↓

$U(2)^5$ flavour symmetry

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

- B decays to $2^{\text{nd}}$ vs $1^{\text{st}}$ generation fixed
- Possible big contribution to $C_S$
- Lepton spurion

Since $U(2)$ is very predictive,

future data in **charged** and **neutral** current will be able verify or discard this hypothesis, and point us towards the right $U(2)$ model ($U_1$ leptoquark ?)

So...

**With or without $U(2)$ ?**

# Back-up slides

# Back-up

## Charged current

| | SM | $\exp\|_{\rm now}$ | Experiment |
|---|---|---|---|
| $R_D$ | 0.297(3) | 0.34(3) | LHCb,Belle II $\to$ 3% |
| $R_{D*}$ | 0.250(3) | 0.295(14) | LHCb, Belle II $\to$ 2% |
| $F_L^{D*}$ | 0.464(10) | 0.60(9) | Belle II $\to$ 0.04 |
| $P_\tau^{D*}$ | 0.496(15) | $-0.38(55)$ | Belle II $\to$ 0.07 |
| $P_\tau^D$ | 0.321(3) | | Belle II $\to$ 3% |
| $\mathcal{B}(B\to\tau\bar\nu)_{/\rm SM}$ | 0.812(54) | 1.09(24) | LHCb |
| $\mathcal{B}(B_c\to\tau\bar\nu)$ | 0.02 | $\lesssim 30\%$ | |
| $R_\pi$ | 0.641(16) | $1.05\pm0.51$ | Belle II $\to 0.641\pm0.071$ |

# Back-up

## Neutral current

| | SM | $\exp\|_{\text{now}}$ | Experiment |
|---|---|---|---|
| $R_{K^{(*)}}$ | $1.00 \pm 0.01$ | $0.80 \pm 0.05$ | LHCb, Belle II |
| $\mathcal{B}(B_s \to \tau\bar{\tau})_{/\text{SM}}$ | LHCb $7.73(49) \times 10^{-7}$ | $< 8.8 \times 10^{3}$ | LHCb |
| $\mathcal{B}(B_s \to \mu\bar{\mu})$ | $3.60(5) \times 10^{-9}$ | $2.72(34) \times 10^{-9}$ | LHCb |
| $\mathcal{B}(B_s \to \tau\bar{\mu})$ | 0 | $< 4.2 \times 10^{-5}$ | LHCb |
| $\mathcal{B}(B \to \mu\bar{\mu})$ | $1.06(9) \times 10^{-10}$ | $1.6(1.1) \times 10^{-10}$ | LHCb |
| $\mathcal{B}(B \to \pi\mu\bar{\mu})_{[1,6]}$ | $1.31(25) \times 10^{-9}$ | $0.91(21) \times 10^{-9}$ | LHCb |
| $\mathcal{B}(B \to \pi\mu\bar{\mu})_{[15,22]}$ | $0.72(7) \times 10^{-9}$ | $0.47(11) \times 10^{-9}$ | LHCb |
| $\mathcal{B}(\tau \to \mu\gamma)$ | 0 | $< 0(3) \times 10^{-8}$ | Belle II |

# Back-up - fields and spurions representations

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

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

$$U(2)_\ell \times U(2)_e$$

$$\begin{aligned} L^{(2)} &= (L^1, L^2) \sim (2,1) & L^3 &\sim (1,1) \\ e^{(2)} &= (e^1, e^2) \sim (1,2) & \tau &\sim (1,1) \end{aligned}$$

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

$$V_q \sim (2,1,1,1,1) \qquad V_\ell \sim (1,2,1,1,1)$$

$$\Delta_u \sim \left(2,1,\bar{2},1,1\right) \qquad \Delta_e \sim \left(1,2,1,1,\bar{2}\right)$$

$$\Delta_{u(d)} \sim \left(2,1,1,\bar{2},1\right)$$

# Back-up - $U(2)^5$ parameters

**Yukawa** after removing unphysical parameters

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

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

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

with

$$U_q = \begin{pmatrix} c_d & s_d e^{i\alpha_d} \\ -s_d e^{-i\alpha_d} & c_d \end{pmatrix},$$

$\hat{\Delta}_{u,d,e}$ diagonal,

$O_{q,e}$ orthogonal and

$\vec{n} = (0 \quad 1)^T$

$$L_f^\dagger Y_f R_f = \mathrm{diag}(Y_f)$$
$$V_{\mathrm{CKM}} = L_u^\dagger L_d$$

to **mass basis**

$$q_L^i = \begin{pmatrix} V_{ji}^* u_L^j \\ d_L^i \end{pmatrix} \qquad \ell_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix}$$

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

Free: $s_b/c_b = |x_b||V_q|$ , $s_\tau/c_\tau = |x_\tau||V_\ell|$ , $s_e$ , $\phi_q$

# Back-up

$$\mathscr{A}^{\mathrm{SM}} \to (1 + C_V^c)\mathscr{A}^{\mathrm{SM}}$$

$b \to c\tau\bar{\nu}$

$$C_{V(S)}^c = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{cs}}{V_{cb}} + \frac{V_{cd}}{V_{cb}}\frac{V_{td}^*}{V_{ts}^*}\right)\right]$$

$$= C_{V(S)}\left(1 - \lambda_q^s\frac{V_{tb}^*}{V_{ts}^*}\right)$$

$b \to u\tau\bar{\nu}$

$$C_{V(S)}^u = C_{V(S)}\left[1 + \lambda_q^s\left(\frac{V_{us}}{V_{ub}} + \frac{V_{ud}}{V_{ub}}\frac{V_{td}^*}{V_{ts}^*}\right)\right]$$

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

$b \to c\ell\bar{\nu}$

$$C_V^{c\mu} = \lambda_\ell^\mu C_V\left[1 - \frac{\Delta_{q\ell}^{s\mu}}{\lambda_\ell^\mu}\frac{V_{tb}^*}{V_{ts}^*}\right] = \mathcal{O}(\lambda_\ell^\mu C_V^c)$$