The prospect of New Physics in $b \to cl\nu$ decays

Elena Venturini

SISSA and INFN Trieste

21/09/2018

Based on: hep-ph/1805.03209, with A.Azatov, D.Bardhan, D.Ghosh, F.Sgarlata

Getting to Grips with QCD - Summer Edition

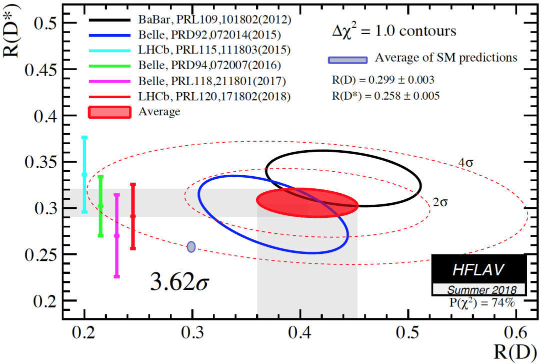
Primošten, 18-22 September 2018

SISSA 40!

Standard Model usually explains very well experimental data BUT

In the **Semileptonic B-meson decays** there are hints of New Physics $\rightarrow$
$\rightarrow$ Lepton Non Universality

FOCUS: **Charged current decays**: $\mathbf{R_{D^{(*)}}} = \dfrac{\mathcal{B}\left(\mathbf{B} \rightarrow \mathbf{D}^{(*)}\, \tau\, \nu\right)}{\mathcal{B}\left(\mathbf{B} \rightarrow \mathbf{D}^{(*)}\, \mathbf{l}\, \nu\right)}$, $l = e, \mu$



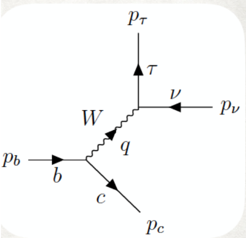
NP $\sim 10 - 20\%$ *SM*:

Large BSM effect $\Rightarrow$

Possibile tension with other observables

Similar anomaly also in $\mathbf{R_{K^{(*)}}} = \dfrac{\mathcal{B}\left(\mathbf{B} \rightarrow \mathbf{K}^{(*)}\, \mu\, \mu\right)}{\mathcal{B}\left(\mathbf{B} \rightarrow \mathbf{K}^{(*)}\, \mathbf{e}\, \mathbf{e}\right)}$

- **Standard Model**



$$\mathcal{L}_{\rm eff}^{b\to c\,\ell\,\nu}|_{\rm SM} = -\frac{1}{\Lambda_{SM}^2}[\bar{c}\,\gamma^\mu\,(1-\gamma_5)\,b][\bar{\ell}\,\gamma_\mu\,P_L\,\nu] = -\frac{1}{\Lambda_{SM}^2}\left(\mathcal{O}_{\rm VL}^{cb\ell\nu} - \mathcal{O}_{\rm AL}^{cb\ell\nu}\right)$$

$$\Lambda_{SM}^2 = \frac{1}{\sqrt{2}G_F\,V_{cb}} = (1.2\,TeV)^2$$

- **Model independent explanation of $R_{D^{(*)}}$: EFT DIM-6**

$$\mathcal{L}_{\rm eff}^{b\to c\,\ell\,\nu} = \mathcal{L}_{\rm eff}^{b\to c\,\ell\,\nu}|_{\rm SM} - \sum \frac{g_i^{cb\ell\nu}}{\Lambda^2}\mathcal{O}_i^{cb\ell\nu} + \text{h.c.} =$$

$$= -\frac{1}{\Lambda_{SM}^2}\sum C_i^{cb\ell\nu}\mathcal{O}_i^{cb\ell\nu} + \text{h.c.} \quad (\ell = \text{e}, \mu, \tau)$$

Assumption: **Absence of ν_{RH}** $\rightarrow$

Scenarios with ν_{RH}:

1804.04135, 1804.04642, 1807.10745

$$\mathcal{O}_{\rm VL}^{cb\ell\nu} = [\bar{c}\,\gamma^\mu\,b][\bar{\ell}\,\gamma_\mu\,P_L\,\nu]$$

$$\mathcal{O}_{\rm AL}^{cb\ell\nu} = [\bar{c}\,\gamma^\mu\gamma_5\,b][\bar{\ell}\,\gamma_\mu\,P_L\,\nu]$$

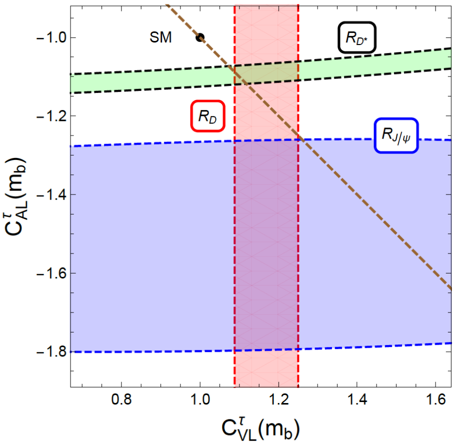
$$\mathcal{O}_{\rm SL}^{cb\ell\nu} = [\bar{c}\;b][\bar{\ell}\;P_L\,\nu]$$

$$\mathcal{O}_{\rm PL}^{cb\ell\nu} = [\bar{c}\,\gamma_5\,b][\bar{\ell}\;P_L\,\nu]$$

$$\mathcal{O}_{\rm TL}^{cb\ell\nu} = [\bar{c}\,\sigma^{\mu\nu}\,b][\bar{\ell}\,\sigma_{\mu\nu}\,P_L\,\nu]$$

Only $\mathcal{O}^{cb\tau\nu}_{\rm VL} = \mathcal{O}^{\tau}_{\rm VL}$ and $\mathcal{O}^{cb\tau\nu}_{\rm AL} = \mathcal{O}^{\tau}_{\rm AL}$

No QCD induced RG running: $C^{\tau}_{\rm VL,AL}(m_b) = C^{\tau}_{\rm VL,AL}(\Lambda)$

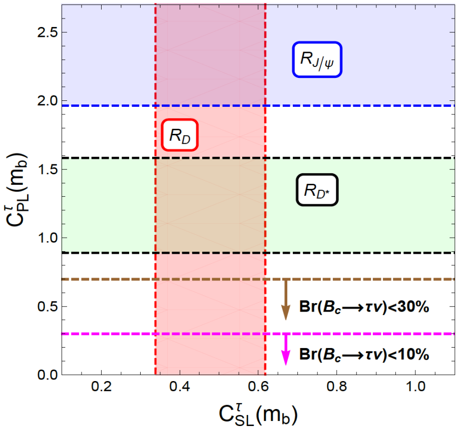


R_D: $C^{\tau}_{\rm VL}$ only

$R_D - R_{D^*}$ overlap with:

- $C^{\tau}_{\rm VL} = -C^{\tau}_{\rm AL}$
  $(SU(2)_L \times U(1)_Y)$
- $C^{\tau}_{\rm VL}(= -C^{\tau}_{\rm AL}) = 1.1 \rightarrow$
  $\rightarrow \Delta C^{\tau}_{\rm VL,AL} = 10\%$

Only $\mathcal{O}^{cb\tau\nu}_{\rm SL} = \mathcal{O}^{\tau}_{\rm SL}$ and $\mathcal{O}^{cb\tau\nu}_{\rm PL} = \mathcal{O}^{\tau}_{\rm PL}$



R_D: $C^{\tau}_{\rm SL}$ only

R_{D^*}: $C^{\tau}_{\rm PL}$ only

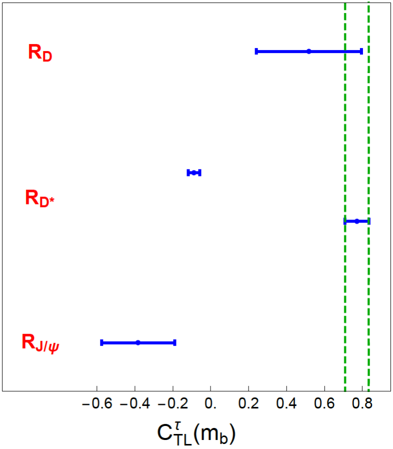
Bound on $C^{\tau}_{\rm PL}$ from $\mathcal{B}(B_c \to \tau\,\nu)$

30%: PRL 118 (2017) 081802

10%: PRD 96 (2017) 075011

$\rightarrow$ $R_{D^*} - \mathcal{B}(B_c \to \tau\,\nu)$ tension in presence of $\mathcal{O}^{\tau}_{\rm PL}$ (Real $C^{\tau}_{\rm PL}$)

Only $\mathcal{O}_{\rm TL}^{cb\tau\nu} = \mathcal{O}_{\rm TL}^{\tau}$



$R_{J/\Psi} \sim 0.17 - 0.23$:

Far from SM and experimental data

No Bound on $C_{\rm TL}^{\tau}$ from $\mathcal{B}(B_c \to \tau\,\nu)$

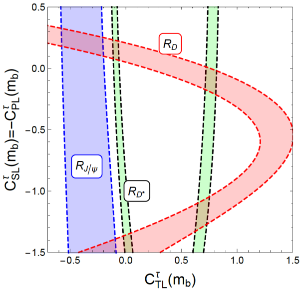
Only $\mathcal{O}_{\rm SL}^{cb\tau\nu} = \mathcal{O}_{\rm SL}^{\tau}$, $\mathcal{O}_{\rm PL}^{cb\tau\nu} = \mathcal{O}_{\rm PL}^{\tau}$ and $\mathcal{O}_{\rm TL}^{cb\tau\nu} = \mathcal{O}_{\rm TL}^{\tau}$

Scenario as in scalar leptoquark models $R_2 \sim (\mathbf{3},\mathbf{2})_{7/6}$

(Viable in case of imaginary WC [1803.10112, 1806.05689])

$$(\bar{c}P_L\nu)(\bar{\tau}P_L b) = -\frac{1}{8}\left[2(\mathcal{O}_{\rm SL}^{\tau} - \mathcal{O}_{\rm PL}^{\tau}) + \mathcal{O}_{\rm TL}^{\tau}\right] \to C_{\rm SL}^{\tau}(\Lambda) = -C_{\rm PL}^{\tau}(\Lambda) = 2C_{\rm TL}^{\tau}(\Lambda)$$

Assumption $C_{\rm SL}^{\tau} = -C_{\rm PL}^{\tau}$



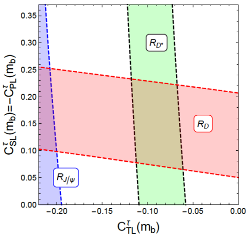
Adding $\mathcal{O}_{\rm TL}^{\tau}$ to $\mathcal{O}_{\rm SL}^{\tau} - \mathcal{O}_{\rm PL}^{\tau}$:

Relaxed R_{D^*}-$\mathcal{B}(B_c \to \tau\nu)$ tension ($C_{\rm PL}^{\tau} < 1$)

Zoomed upper left $R_D - R_{D^*}$ overlap:

$C_{\rm SL}^{\tau}(m_b) \in [0.08, 0.23]$ and $C_{\rm TL}^{\tau}(m_b) \in [-0.11, -0.06]$

Scalar LQ expl.: Not Viable w/ Real $C_{\rm S(T)L}^{\tau}$ + RG flow



Scenarios for $R_{D^{(*)}}$ explanation consistently with bounds from $\Delta F = 1$ ($\mathcal{B}(B_c \to \tau \nu)$) processes and with $R_{J/\Psi}$ measurements

1. $\mathcal{O}^{\tau}_{\mathrm{VL}}$ & $\mathcal{O}^{\tau}_{\mathrm{AL}}$ $\rightarrow$ Our focus
2. $\mathcal{O}^{\tau}_{\mathrm{SL}}$ & $\mathcal{O}^{\tau}_{\mathrm{PL}}$ & $\mathcal{O}^{\tau}_{\mathrm{TL}}$ $\rightarrow$ Viable scenario with scalar LQ and imaginary WC [1803.10112, 1806.05689]

$SU(2)_L \times U(1)_Y$ gauge invariant DIM-6 operators leading to $b \to c\tau\nu$

$$\mathcal{L}^{\rm dim6} = -\frac{1}{\Lambda^2}\sum_{p'r's't'}\Big\{[C^{(3)}_{lq}]'_{p'r's't'}\,(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'})\,(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}) + \text{h.c.}$$

$$+[C_{ledq}]'_{p'r's't'}\left(\bar{l}'^{j}_{p'}e'_{r'}\right)\left(\bar{d}'_{s'}q'^{j}_{t'}\right) + \text{h.c.} \qquad \leftarrow$$

$$+[C^{(1)}_{lequ}]'_{p'r's't'}\left(\bar{l}'^{j}_{p'}e'_{r'}\right)\epsilon_{jk}\left(\bar{q}'^{k}_{s'}u'_{t'}\right) + \text{h.c.}$$

$$+[C^{(3)}_{lequ}]'_{p'r's't'}\left(\bar{l}'^{j}_{p'}\sigma_{\mu\nu}e'_{r'}\right)\epsilon_{jk}\left(\bar{q}'^{k}_{s'}\sigma^{\mu\nu}u'_{t'}\right) + \text{h.c.}$$

- -

$$+[C^{(3)}_{\phi l}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}\right) + \text{h.c.} \qquad \leftarrow$$

- -

$$+[C^{(3)}_{\phi q}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar{q}'_{p'}\,\sigma^I\gamma^\mu\, q'_{r'}\right) + \text{h.c.}$$

$$+[C_{\phi ud}]'_{p'r'}\left(\phi^j\epsilon_{jk}\,i(D_\mu\phi)^k\right)\left(\bar{u}'_{p'}\gamma^\mu d'_{r'}\right) + \text{h.c.}\Big\}$$

- Gauge invariance $\to$ Correlation of operators relevant for $R_{D^{(*)}}$ $[(\bar{\tau}\gamma^\mu P_L\nu_\tau)(\bar{c}\gamma_\mu P_L b),\ (\bar{\tau}\gamma^\mu P_L\nu_\tau)\,W_\mu]$ with other operators (neutral current processes, $Z\tau\tau$, $Z\nu\nu$)
- $\mathcal{O}^{(3)}_{\phi q}$ and $\mathcal{O}_{\phi ud}$: Not leading to lepton flavour non universality

FOCUS on $\mathcal{O}^{\tau}_{\rm VL}$ and $\mathcal{O}^{\tau}_{\rm AL}$ terms of $\mathcal{L}^{\rm dim6}$

4 - fermion operator $\rightarrow$ $[\mathcal{O}^{(3)}_{\mathbf{lq}}]'_{\mathbf{p'r's't'}} = (\mathbf{\bar{l}'}_{\mathbf{p'}}\gamma_\mu \sigma^{\mathbf{I}} \mathbf{l}'_{\mathbf{r'}})\,(\mathbf{\bar{q}'}_{\mathbf{s'}}\gamma^\mu \sigma^{\mathbf{I}} \mathbf{q}'_{\mathbf{t'}})$

Scalar - fermion operator $\rightarrow$ $[\mathcal{O}^{(3)}_{\phi\mathbf{l}}]'_{\mathbf{p'r'}} = \left(\phi^\dagger \mathbf{i} \overleftrightarrow{D}^{\mathbf{I}}_{\mu} \phi\right)(\mathbf{\bar{l}'}_{\mathbf{p'}}\, \sigma^{\mathbf{I}} \gamma^\mu\, \mathbf{l}'_{\mathbf{r'}})$

- Gauge invariance and lepton non universality (absence of ν_{RH}) $\Rightarrow$
  $\Rightarrow$ Only V-A interactions at DIM-6
- Wilson Coefficients of $\mathcal{O}^{\tau}_{\rm VL}$ and $\mathcal{O}^{\tau}_{\rm AL}$

$$\Delta C^{cb\tau\nu_3}_{\rm VL} = -\Delta C^{cb\tau\nu_3}_{\rm AL} = \frac{\Lambda^2_{\rm SM}}{\Lambda^2}\left[[\tilde{C}^{(3)e\nu ud}_{lq}]_{3323} + \left([\tilde{C}^{(3)\nu edu}_{lq}]_{3332}\right)^*\right] - \frac{\Lambda^2_{\rm SM}}{\Lambda^2}\left[[\tilde{C}^{(3)e\nu}_{\phi l}]_{33} + \left([\tilde{C}^{(3)\nu e}_{\phi l}]_{33}\right)^*\right] V_{cb}$$

with $\tilde{C}^{(3)}_{lq}$ $\rightarrow$ Mass eigenstates basis

e.g. $[\tilde{C}^{(3)e\nu ud}_{lq}]_{prst} \equiv \sum_{p',r',s',t'} [C^{(3)}_{lq}]'_{p'r's't'} (V^e_L)^\dagger_{pp'} (V^\nu_L)_{r'r} (V^u_L)^\dagger_{ss'} (V^d_L)_{t't}$

Scalar - Fermion Operator

$$\Delta C^{cb\tau\nu_3}_{\mathrm{VL}} = -\Delta C^{cb\tau\nu_3}_{\mathrm{AL}} = -\frac{\Lambda^2_{\mathrm{SM}}}{\Lambda^2}\left[[\tilde{C}^{(3)e\nu}_{\phi l}]_{33} + \left([\tilde{C}^{(3)\nu e}_{\phi l}]_{33}\right)^*\right] V_{cb}$$

$$[\mathcal{O}^{(3)}_{\phi \mathbf{l}}]_{\mathbf{p}'\mathbf{r}'} = \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{l'}_{p'}\, \sigma^I \gamma^\mu\, l'_{r'}\right) =$$

$$= \Big[-\tfrac{1}{2}\tfrac{g_2}{\cos\theta_W} Z_\mu \left(\overline{\nu'}_{p'}\gamma^\mu P_L \nu'_{r'}\right) + \tfrac{1}{2}\tfrac{g_2}{\cos\theta_W} Z_\mu \left(\overline{e'}_{p'}\gamma^\mu P_L e'_{r'}\right)$$

$$-\tfrac{g_2}{\sqrt{2}} W^+_\mu \left(\overline{\nu'}_{p'}\gamma^\mu P_L e'_{r'}\right) - \tfrac{g_2}{\sqrt{2}} W^-_\mu \left(\overline{e'}_{p'}\gamma^\mu P_L \nu'_{r'}\right)\Big] \left(v^2 + 2vh + h^2\right)$$

- For $R_{D(*)}$: $C^{(3)'}_{\phi l}$ - Modification of $Wl\nu$ vertex with lepton non universality

$\mathbf{C}_{\phi l}^{(3)'}$ - **Modification of W$\tau\nu$ & Z$\tau\tau$ & Z$\nu\nu$ vertices**

- **W**$\tau\nu$

$$\mathcal{L}_{W\tau\nu} = -\frac{g_2}{\sqrt{2}}(1+\Delta g_W)\left(W_\mu^- \bar{\tau}\gamma^\mu P_L \nu_\tau + h.c.\right), \quad \Delta g_W = \left[\left([\tilde{C}_{\phi l}^{(3)e\nu}] + [\tilde{C}_{\phi l}^{(3)\nu e}]^\dagger\right)_{33}\right]\frac{v^2}{\Lambda^2}$$

– LEP bounds: $\frac{\text{Br}(W^+\to\tau^+\nu)}{[\text{Br}(W^+\to\mu^+\nu)+\text{Br}(W^+\to e^+\nu)]/2} = 1.077 \pm 0.026$

$$\mathbf{\Delta C}_{\mathrm{VL}}^{\tau} = -\mathbf{\Delta C}_{\mathrm{AL}}^{\tau} < \mathbf{0.05} \rightarrow \textbf{Too small for } R_{D^{(*)}} \textbf{ explanation}$$

– Indirect bounds from τ **decay measurements**

$$\mathbf{\Delta C}_{\mathrm{VL}}^{\tau} = -\mathbf{\Delta C}_{\mathrm{AL}}^{\tau} < \mathbf{2.6 \times 10^{-3}} \rightarrow \textbf{Even stronger bounds}$$

- **Z**$\tau\tau$ and **Z**$\nu\nu$

$Z\tau\tau : |\Delta g_L^\tau| \lesssim 6 \times 10^{-4} \Rightarrow \mathbf{\Delta C}_{\mathrm{VL}}^{\tau} \lesssim \mathbf{0.001} \rightarrow$ **Even stronger LEP bounds**

$\Longrightarrow$ $\mathcal{O}_{\phi l}^{(3)}$ **is NOT sufficient ALONE to explain** $\mathbf{R_{D^{(*)}}}$

[hep-ex/0511027], [*Prog. Part. Nucl. Phys.* **75** (2014) 41-85], [hep-ex/0509008]

4 - Fermion operator

$$\Delta C_{\mathrm{VL}}^{cb\tau\nu_3} = -\Delta C_{\mathrm{AL}}^{cb\tau\nu_3} = \frac{\Lambda_{\mathrm{SM}}^2}{\Lambda^2}\left[[\tilde{C}_{lq}^{(3)e\nu ud}]_{3323} + ([\tilde{C}_{lq}^{(3)\nu edu}]_{3332})^* \right]$$

$\mathcal{O}_{\mathbf{lq}}^{(3)}$ contribution to $\mathbf{R_{D^{(*)}}}$

$$\mathbf{C_{lq}^{(3)\prime}} \mathcal{O}_{\mathbf{lq}}^{(3)} = [C_{lq}^{(3)}]'_{p'r's't'} \left(\bar{l}'_{p'}\gamma_\mu \sigma^I l'_{r'}\right)\left(\bar{q}'_{s'}\gamma^\mu \sigma^I q'_{t'}\right) \supset$$

$$\supset -2\left(([C_{lq}^{(3)}]'_{3313} + ([C_{lq}^{(3)}]'_{3331})^*)\mathbf{V_{cd}} + ([C_{lq}^{(3)}]'_{3323} + ([C_{lq}^{(3)}]'_{3332})^*)\mathbf{V_{cs}} \right.$$
$$\left. + ([C_{lq}^{(3)}]'_{3333} + ([C_{lq}^{(3)}]'_{3333})^*)\mathbf{V_{cb}} \right)(\bar{\tau}\gamma^\mu \mathbf{P_L}\nu_\tau)(\bar{\mathbf{c}}\gamma_\mu \mathbf{P_L b})$$

C' in the basis with $d'_{p'} = d_p$ and $e'_{p'} = e_p \to V_L^{d,e} = \mathbf{1}_{3\times 3}$
[Arbitrary choice w/o any loss of generality]

Correlation of $R_{D^{(*)}}$ with neutral current operators

$\mathbf{R_{D^{(*)}}}$ lower bound on $\mathbf{C_{lq}^{(3)\prime}}$

$$([\tilde{C}_{lq}^{(3)e\nu ud}]_{3323} + ([\tilde{C}_{lq}^{(3)\nu edu}]_{3332})^*) \gtrsim 0.06 \left(\frac{\Lambda^2}{\text{TeV}^2}\right)$$

$$\Downarrow$$

$$([C_{lq}^{(3)}]'_{3313} + ([C_{lq}^{(3)}]'_{3331})^*)V_{cd} +$$
$$+([C_{lq}^{(3)}]'_{3323} + ([C_{lq}^{(3)}]'_{3332})^*)V_{cs} +$$
$$+([C_{lq}^{(3)}]'_{3333} + ([C_{lq}^{(3)}]'_{3333})^*)V_{cb} \gtrsim 0.06 \left(\frac{\Lambda^2}{\text{TeV}^2}\right)$$

Bounds on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3313}$ and $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3323}$ from $\Delta F = 1$ processes

1. Constraints on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3313}$
   - $\mathcal{B}(\mathbf{B^0} \to \pi^{\mathbf{0}} \bar{\nu}\,\nu)$ bound [BELLE Collaboration, *Phys. Rev.* **D96** (2017) 091101]

$$-0.018 \lesssim ([C_{lq}^{(3)}]'_{3313} + [C_{lq}^{(3)}]'^{\,*}_{3331})\mathrm{TeV}^2/\Lambda^2 \lesssim 0.023$$

   - $\mathcal{B}(\mathbf{B_u} \to \tau\,\nu_\tau)$ bound [BELLE II Collaboration, *PoS*. **EPS-HEP2017** (2017) 226]

$$-0.15 \lesssim ([C_{lq}^{(3)}]'_{3313} + [C_{lq}^{(3)}]'^{\,*}_{3331})\mathrm{TeV}^2/\Lambda^2 \lesssim 0.025$$

2. Constraints on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3323}$
   - $\mathcal{B}(\mathbf{B^0} \to \mathbf{K}^{*\mathbf{0}}\,\bar{\nu}\nu)$ bound [BELLE Collaboration, *Phys. Rev.* **D96** (2017) 091101]

$$-0.005 \lesssim ([C_{lq}^{(3)}]'_{3323} + [C_{lq}^{(3)}]'^{\,*}_{3332})\mathrm{TeV}^2/\Lambda^2 \leq 0.025$$

Bounds on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3313}$ and $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3323}$ from $\Delta F = 1$ processes

$\Rightarrow$ ($[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3313}$ and ($[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3323}$ terms of $\mathcal{O}_{\mathbf{lq}}^{(3)}$ **contribution** to $\mathbf{R}_{\mathbf{D}(*)}$

AT MOST $\sim \mathbf{0.03\Lambda^2}/\mathrm{TeV}^2$

$\mathbf{R}_{\mathbf{D}(*)}$ **lower bound** on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3333} \to$

$$\to ([\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3333} + [\mathbf{C}_{\mathbf{lq}}^{(3)}]'^{*}_{3333})\mathbf{V}_{\mathbf{cb}} \gtrsim \mathbf{0.03}\left(\frac{\mathbf{\Lambda^2}}{\mathrm{TeV}^2}\right)$$

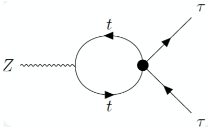
Bounds on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3333}$ from $Z\tau\tau$ vertex

3. Constraints on $[\mathbf{C}_{\mathbf{lq}}^{(3)}]'_{3333}$
   - $\mathcal{O}_{lq}^{(3)}$ contribution to the NC interaction $(\bar{\tau}\gamma^\mu \mathbf{P_L}\tau)(\bar{\mathbf{t}}\gamma_\mu \mathbf{P_L t})$

$$\left[\tilde{C}_{lq}^{(3)eeuu}\right]_{3333} + \left[\tilde{C}_{lq}^{(3)eeuu}\right]^*_{3333} \sim \left(\left[C_{lq}^{(3)}\right]'_{3333} + \left[C_{lq}^{(3)}\right]'^*_{3333}\right)|V_{tb}|^2$$

With $\mathcal{B}(B^0 \to \pi^0 \bar{\nu}\,\nu)$, $\mathcal{B}(B_u \to \tau\,\nu_\tau)$, $\mathcal{B}(B^0 \to K^{*0}\bar{\nu}\,\nu)$ and $jj \to \tau\tau$ bounds

   - $(\bar{\tau}\gamma^\mu \mathbf{P_L}\tau)(\bar{\mathbf{t}}\gamma_\mu \mathbf{P_L t}) \to$ 1-loop RG running of $\mathcal{O}_{\phi l}^{(3)}$
     1-loop contribution to Δg_L^τ [*Phys. Rev. Lett.* **118** (2017) 011801]



$$\Rightarrow \text{LEP bounds: } \left|[C_{lq}^{(3)}]'_{3333} + [C_{lq}^{(3)}]'^*_{3333}\right| \lesssim \frac{0.017}{V_{cb}}\left(\frac{\Lambda}{\text{TeV}}\right)^2 \frac{1}{1+0.6\log\frac{\Lambda}{\text{TeV}}}$$

Too small for $R_{D^{(*)}}$ explanation

Possibility to cure $\mathbf{R_{D^{(*)}}}$- $\mathbf{\Delta F = 1}$ and NC observables tension $\to$

$\to \mathcal{O}_{\mathbf{lq}}^{(\mathbf{3})}$ is NOT sufficient ALONE

Combination with $\mathcal{O}_{\mathbf{lq}}^{(\mathbf{1})} = \left(\bar{l}'\gamma_\mu l'\right)\left(\bar{q}'\gamma^\mu q'\right)$:

Cancellation with $\mathcal{O}_{lq}^{(3)}$ in $b \to s\bar{\nu}\nu$ (or $b \to s\bar{\tau}\tau$) and Δg_L^τ (or Δg_L^ν)

[*Phys. Rev. Lett.* **118** (2017) 011801], [*JHEP* **11** (2017) 044], [*JHEP* **09** (2017) 061]

BUT it is NOT possible to cancel SIMULTANEOUSLY:

- $b \to s\bar{\nu}\nu$ and $b \to s\bar{\tau}\tau$
- Δg_L^τ and Δg_L^ν

Combination of Δg_L^τ, Δg_L^ν and Δg_W bounds $\Rightarrow$

$\Rightarrow$ Scenario with $[\mathbf{C}_{\mathbf{lq}}^{(\mathbf{3})}]'_{3333}$-dominated $\mathbf{R_{D^{(*)}}}$ RULED OUT
even in presence of both $\mathcal{O}_{\mathbf{lq}}^{(\mathbf{3})}$ & $\mathcal{O}_{\mathbf{lq}}^{(\mathbf{1})}$

Possible scenarios

1. **Scenario I**: $[C_{lq}^{(3)}]'_{3323}$**-dominated** $R_{D^{(*)}}$ **and** $\mathcal{B}(B^0 \to K^{*0}\,\bar{\nu}\nu)$ **bound softened by** $\mathcal{O}_{lq}^{(1)}$-$\mathcal{O}_{lq}^{(3)}$ **cancellation**
2. **Scenario II**: $[C_{lq}^{(3)}]'_{3333}$**-dominated** $R_{D^{(*)}}$ **and** $\Delta g_L^{\tau,\nu}$ **bounds softened by appropriate additional effective operators**

$R_{D^{(*)}}$ correlation with $\Delta F = 2$ processes: requirement of UV assumption

- **Composite Higgs (MCHM5)** [*Phys. Lett.* **136B** (1984) 183-186] :
  Higgs as pNGB of $SO(5) \to SU(2)_L \times SU(2)_R$
- **Partial Compositeness (PC) and Two site model** [*Nucl. Phys.* **B365** (1991) 259-278] :
  SM fermion masses arise from linear mixing with composite fermions

Elementary ($\tilde{\psi}$, A_μ) - Composite ($\tilde{\mathcal{O}}$, $\tilde{\rho}_\mu$) Mixing $\Rightarrow$

$\Rightarrow$ SM fermion - Heavy vector interaction

$$\bar{\psi}'_i \left[\sqrt{g_*^2 - g^2} \left[\hat{s}^\dagger T_A^{co} \hat{s}\right]^i_j - \frac{g^2}{\sqrt{g_*^2 - g^2}} \left[\hat{c}^\dagger T_A^{el} \hat{c}\right]^i_j \right] \gamma^\mu \psi'^j \rho^A_\mu$$

FOCUS: DIM-6 4 - Fermion Operator $(g_* \gg g)$

$$\frac{\mathbf{g_*^2}}{\mathbf{M_*^2}} \left[\bar{\psi}' \,\hat{\mathbf{s}}^\dagger \mathbf{T_A^{co}} \hat{\mathbf{s}}\, \gamma^\mu \psi'\right] \left[\bar{\psi}' \,\hat{\mathbf{s}}^\dagger \mathbf{T_A^{co}} \hat{\mathbf{s}}\, \gamma_\mu \psi'\right]$$

Contribution to $\mathbf{R_{D^{(*)}}}$: **Exchange of heavy charged SU(2)$_\mathbf{L}$vector** $(\rho^{\pm}_{L\mu})$

$$\mathcal{L}_{b\to c\,\tau\,\nu} = -\frac{g_*^2}{2M_*^2}\left(\bar{\tau}_L\,\left[V_L^{e\dagger}\hat{s_l}^\dagger\hat{s_l}V_L^{\nu}\right]^3_3\gamma^\mu\,\nu_{\tau L}\right)\left(\bar{c}_L\,\left[V_{\rm CKM}V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^{d}\right]^2_3\gamma^\mu\,b_L\right)$$

Lepton Sector

Agnostic:

$$\left|\left[V_L^{e\dagger}\hat{s_l}^\dagger\hat{s_l}V_L^{\nu}\right]^3_3\right| < 1$$

Quark Sector

$\mathbf{R_{D^{(*)}}}$ **lower bound**:

$$\left[V_{\rm CKM}V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^{d}\right]^2_3 \gtrsim 0.2\left(\frac{M_*/g_*}{\rm TeV}\right)^2$$

$\Longrightarrow$ $\mathbf{R_{D^{(*)}}}$ **lower bound**:

$$|V_{cd}|\left|\left[V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^{d}\right]^1_3\right| + |V_{cs}|\left|\left[V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^{d}\right]^2_3\right| + |V_{cb}|\left|\left[V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^{d}\right]^3_3\right| \gtrsim 0.2\left(\frac{M_*/g_*}{\rm TeV}\right)^2$$

Contribution to $\mathbf{\Delta F = 2}$: **Exchange of heavy neutral** $\mathbf{SU(3)}$, $\mathbf{SU(2)_{L,R}}$, $\mathbf{U(1)_X}$ **vectors** $({\rho_3}_\mu, {\rho^3_{L,R}}_\mu, {\rho_X}_\mu)$

$$\mathcal{L}_{\Delta F=2} \simeq \frac{g_*^2}{M_*^2}\left(\bar{\psi}_{i\,L}\left[V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^d\right]^i_{\;j}\gamma^\mu\,\psi_{j\,L}\right)^2$$

Upper bounds on $\mathbf{\bar{K}-K}$, $\mathbf{\bar{B}_d - B_d}$ **and** $\mathbf{\bar{B}_s - B_s}$ **mixings** $\Rightarrow$

$\Rightarrow$ **Upper bounds on** $\left|\left[\mathbf{V_L^{d\dagger}\hat{s_q}^\dagger\hat{s_q}V_L^d}\right]^{\mathbf{i}}_{\;\mathbf{j}}\right|$, $\mathbf{i \neq j}$

$\Delta F = 2$ & $R_{D^{(*)}}$ bounds

$$10^{-3}\,|V_{cd}|\,\frac{(M_*/\text{TeV})}{g_*} + 4\times 10^{-3}\,|V_{cs}|\,\frac{(M_*/\text{TeV})}{g_*} + |V_{cb}| \gtrsim 0.2\left(\frac{M_*/\text{TeV}}{g_*}\right)^2$$

$$\Longrightarrow\ |V_{cb}| \gtrsim 0.2\left(\frac{M_*/\text{TeV}}{g_*}\right)^2\ \Longrightarrow$$

$$\Longrightarrow\ \mathbf{M_*/g_*} \lesssim\ \mathbf{0.45}\,\text{TeV}\ \Longrightarrow\ \mathbf{f} \lesssim\ \mathbf{0.64}\,\text{TeV}$$

f: Compositeness Scale

Tension with EW precision measurements: $f \gtrsim 1.2\,\text{TeV}$

[*JHEP* **08** (2013) 106], [*Eur. Phys. J.* **C74** (2014) 3046]

- **Model independent explanation of $R_{K^{(*)}}$: EFT DIM-6**

$$\mathcal{L}_{b\to s\mu\mu} = -\frac{1}{\Lambda^2}\,(\bar{s}\gamma_\mu P_L\, b)(\bar{\mu}\gamma^\mu P_L\, \mu)$$

$$R_{K^{(*)}} \text{ lower bounds at } 1\,\sigma \implies 1/\Lambda^2 \gtrsim 1/(38\,\text{TeV})^2$$

- **CH Model and PC $\rightarrow$ Contribution to $R_{K^{(*)}}$:**
  Exchange of heavy neutral $SU(2)_{L,R}$, $U(1)_X$ vectors $(\rho^3_{L,R\,\mu},\, \rho_{X\,\mu})$

$$\frac{g_{*2}^2}{2M_{*2}^2}\left(\bar{s}\,[V_L^{d\,\dagger}\hat{s}_q^\dagger \hat{s}_q V_L^d]^2{}_3\gamma_\mu P_L\, b\right)\left(\bar{\mu}\,[V_L^{e\,\dagger}\hat{s}_l^\dagger \hat{s}_l V_L^e]^2{}_2\gamma^\mu P_L\, \mu\right)$$

Possibility to satisfy $\Delta F = 2$ & $R_{K^{(*)}}$ bounds

CH Model and PC + $R_{D^{(*)}}$ generated by $\rho^{\pm}_{L\ \mu}$ exchange

+ No other assumptions

$$\Downarrow$$

$$\mathbf{f} \lesssim \mathcal{O}(\text{TeV})$$

- **Favoured by electroweak hierarchy problem**
- **Tension with EW precision measurements**:
  Incompatibility unless additional UV contribution

Extra assumptions in $\tilde{\psi}$ - $\tilde{\mathcal{O}}$ Mixing

$$\Downarrow$$

$g_L^{\nu,\tau}$ and $b \to s\bar{\nu}\nu$ protection

Enhancement of $\mathbf{R_{D^{(*)}}}$
without tree-level modification of $\mathbf{\Delta F = 2}$ processes

Vector Leptoquark $V_{LQ}^{\mu} \sim (\mathbf{3}, \mathbf{1})_{2/3}$ $(U_1) \rightarrow$

$$\mathcal{L}_{LQ} = -g_* \left(\bar{q}'_{L\,i} \left[\hat{s}_q^{\dagger} \hat{s}_l \right]^i{}_j \gamma_\mu \, l'_{L\,j} \right) V_{LQ}^{\mu}$$

[*Eur. Phys. J.* **C76** (2016) 67], [*Eur. Phys. J.* **C77** (2017) 8], [1712.06844]

Contribution to $\mathbf{R_{D^{(*)}}}$ $\rightarrow$ **Exchange of heavy $\mathbf{V_{LQ}^{\mu}}$**

$$\mathcal{L}_{b \to c\,\tau\,\nu} \overset{\text{Fierz}}{=} -\frac{g_*^2}{2M_*^2} \left[V_{\text{CKM}} V_L^{d\,\dagger} \hat{s_q}^{\dagger} \hat{s}_l V_L^{\nu} \right]^2{}_3 \left[V_L^{e\,\dagger} \hat{s}_l{}^{\dagger} \hat{s_q} V_L^{d} \right]^3{}_3 \left(\bar{c}_L \, \gamma^\mu \, b_L \right) \left(\bar{\tau}_L \, \gamma^\mu \, \nu_{\tau\,L} \right)$$

Contribution to $\mathbf{R_{D^{(*)}}}$ $\rightarrow$ **Exchange of heavy** $\mathbf{V^{\mu}_{LQ}}$ **and** $\rho^{\pm}_{\mathbf{L}\ \mu}$

ΔF = 2 & $\mathbf{R_{D^{(*)}}}$ bounds

Assumption: **Only third generation mixes strongly with composite sector**

$\downarrow$

V^{μ}_{LQ} contribution to $R_{D^{(*)}}$ is V_{cb} dominated: $[V_L^{d\dagger}\hat{s}_q{}^{\dagger}]^{1,2}_{3} \ll [V_L^{d\dagger}\hat{s}_q{}^{\dagger}]^{3}_{3} \sim 1$

$$\mathbf{V^{\mu}_{LQ}} + \rho^{\pm}_{\mathbf{L}\ \mu}: \qquad 2V_{cb} \gtrsim 0.2\left(\frac{M_*/g_*}{\text{TeV}}\right)^2 \Longrightarrow$$

$$\Longrightarrow \mathbf{M_*/g_*} \lesssim \mathbf{0.63}\,\text{TeV} \Longrightarrow \mathbf{f} \lesssim \mathbf{0.90}\,\text{TeV}$$

Increase of f upper bound by a factor $\sqrt{2} \Rightarrow$

$\Rightarrow$ Almost 2σ compatibility with EW precision measurements

FOCUS: $\mathbf{R_{D^{(*)}}}$ correlation with other EW observable ($\Delta F = 1, 2$, $Z\tau\tau$, $Z\nu\nu$, $W\tau\nu$)

$\Rightarrow$ **Constraints on NP explanation**

- Model independent EFT analysis with Vector, Axial Vector, Scalar, Pseudo Scalar, Tensor operators. Possible scenarios:
  1. Vector & Axial Vector operators
  2. Scalar & Pseudo Scalar & Tensor operators

- EFT with $SU(2)_L \times U(1)_Y$ invariance $\Rightarrow$ Within $R_{D^{(*)}}$ with $\mathcal{O}^{\tau}_{\mathrm{VL}}$ and $\mathcal{O}^{\tau}_{\mathrm{AL}}$:
  1. LFU violation only in V-A interactions
  2. Scalar - Fermion operator $\mathcal{O}^{(3)}_{\phi l}$ NOT sufficient ALONE for $R_{D^{(*)}}$ ($Z\tau\tau$, $Z\nu\nu$, $W\tau\nu$)
  3. 4 - Fermion operator $\mathcal{O}^{(3)}_{lq}$ NOT sufficient ALONE for $R_{D^{(*)}}$ ($Z\tau\tau$, $\Delta F = 1$)

  $\Rightarrow$ Need of other operators ($\mathcal{O}^{(1)}_{lq}$) and appropriate UV completion

- **MCHM5 and PC with (without) vector LQ**

  1. Softened $\Delta F = 1$ and $Z\tau\tau$ $Z\nu\nu$ bounds
  2. $R_{D^{(*)}}$ & $\Delta F = 2$ correlation $\Longrightarrow$ Upper bound on the scale of compositeness f

$$\mathbf{f} \lesssim \mathbf{0.90}\,(\mathbf{0.64})\mathrm{TeV}$$

Favoured by EW hierarchy problem

Tension with direct searches and EWPT unless additional cancellation

CC Flavour Anomalies $\Longrightarrow$ Potential probes of NP at TeV scale

Non generic NP in the dynamics of flavour transitions $\Longrightarrow$
$\Longrightarrow$ Need of high precision analysis of B - physics data

Thank you!

DIM-8 Operators that contribute to $b \to c\tau\nu$, w.r.t. DIM-6 Operators, have extra factors:

$$\left(\frac{\partial}{\Lambda}\right)^2 \qquad \left(\frac{\phi}{\Lambda}\right)^2 \qquad \left(\frac{\phi\,\partial}{\Lambda^2}\right)$$

where ϕ is the Higgs doublet

In $b \to c\tau\nu$ amplitude, DIM-8 contribution, w.r.t. DIM-6 one, has extra factors:

$$\sim \left(\frac{M_B}{\Lambda}\right)^2 \qquad \left(\frac{v}{\Lambda}\right)^2 \qquad \sim \left(\frac{v\,M_B}{\Lambda^2}\right)$$

$$\Downarrow$$

DIM-8 contribution is suppressed w.r.t. DIM-6 contribution

Model with 2 scalar leptoquarks

- $R_2 \sim (\mathbf{3}, \mathbf{2})_{7/6} \to C^\tau_{\rm SL}(\Lambda) = -C^\tau_{\rm PL}(\Lambda) = 2C^\tau_{\rm TL}(\Lambda)$

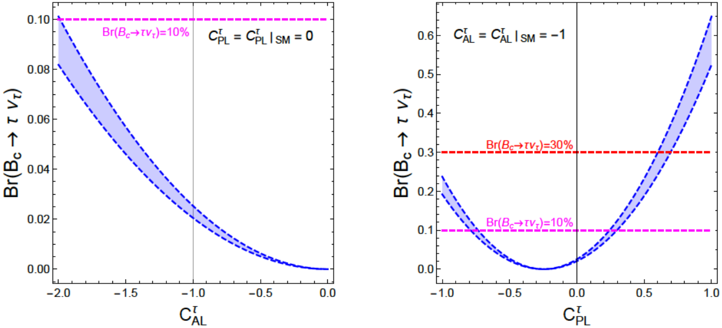
  After RG flow $C^\tau_{\rm SL}(m_b) \simeq 4C^\tau_{\rm TL}(m_b)$

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3} \to C^\tau_{\rm VL}(\Lambda) = -C^\tau_{\rm AL}(\Lambda)$
  $C^\tau_{\rm SL}(\Lambda) = -C^\tau_{\rm PL}(\Lambda) = -2C^\tau_{\rm TL}(\Lambda)$

  After RG flow $C^\tau_{\rm SL}(m_b) \simeq -4C^\tau_{\rm TL}(m_b)$

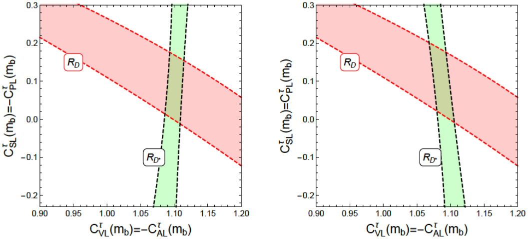
It is possible to choose particular R_2 and S_1 couplings in UV theory such that there is a cancellation of WC $C^\tau_{\rm SL}(m_b)(= -C^\tau_{\rm PL}(m_b))$ in IR theory

Bounds from $\mathcal{B}(B_c \to \tau\nu)$



Only $\mathcal{O}^{cb\tau\nu}_{\rm VL} = \mathcal{O}^{\tau}_{\rm VL}$, $\mathcal{O}^{cb\tau\nu}_{\rm AL} = \mathcal{O}^{\tau}_{\rm AL}$, $\mathcal{O}^{cb\tau\nu}_{\rm SL} = \mathcal{O}^{\tau}_{\rm SL}$ amd $\mathcal{O}^{cb\tau\nu}_{\rm PL} = \mathcal{O}^{\tau}_{\rm PL}$

$$C^{\tau}_{\rm VL} = -C^{\tau}_{\rm AL} \text{ and } C^{\tau}_{\rm SL} = \pm C^{\tau}_{\rm PL}$$



Adding $\mathcal{O}^{\tau}_{\rm SL,PL}$ to $\mathcal{O}^{\tau}_{\rm VL,AL}$

$\downarrow$

Only an extension of $\mathcal{O}^{\tau}_{\rm VL,AL}$ only:

$[C^{\tau}_{\rm VL}, C^{\tau}_{\rm SL}] = [1.1, 0]$ inside overlap region

For a model: 1712.01368

Two site model

Elementary Sector

$$G^{elem} = SU(3) \times SU(2)_L \times U(1)_Y$$

$\tilde{\psi}$: fermions, A_μ: bosons

Composite Sector

$$G^{comp} = U(1)_X \times SU(3) \times SU(2)_L \times SU(2)_R$$

$\tilde{\mathcal{O}}$: fermions, $\tilde{\rho}_\mu$: bosons

Elementary ($\tilde{\psi}$, A_μ) - Composite ($\tilde{\mathcal{O}}$, $\tilde{\rho}_\mu$) Mixing

$$\mathbf{G^{elem}} \times \mathbf{G^{comp}} \to \mathbf{G^{SM}}\,, \quad \text{with } T_Y^{comp} = T_X^{comp} + T_R^{3\,comp}$$

- Fermion sector

$$\begin{pmatrix} \tilde{\psi} \\ \tilde{\mathcal{O}} \end{pmatrix} = \begin{pmatrix} \hat{c} & .. \\ \hat{s} & .. \end{pmatrix} \begin{pmatrix} \psi' \\ \mathcal{O} \end{pmatrix}$$

- Vector sector

$$\begin{pmatrix} A_\mu \\ \tilde{\rho}_\mu \end{pmatrix} \to \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu^{SM} \\ \rho_\mu \end{pmatrix}, \qquad \cos\theta = \frac{g_*}{\sqrt{g_*^2 + g_{el}^2}}$$

ψ', $A_\mu^{SM} \to$ SM massless fields

$g_{el} \to G^{elem}\,, \quad g_* \to G^{comp}$

	$SU(3)^{co}$	$SU(2)^{co}_L$	$SU(2)^{co}_R$	$U(1)^{co}_X$
$\tilde{\mathcal{O}}_{q_1}$	**3**	**2**	**2**	$2/3$
$\tilde{\mathcal{O}}_{q_2}$	**3**	**2**	**2**	$-1/3$
$\tilde{\mathcal{O}}_{u}$	**3**	**1**	**1**	$2/3$
$\tilde{\mathcal{O}}_{d}$	**3**	**1**	**1**	$-1/3$
$\tilde{\mathcal{O}}_{\ell_1}$	**1**	**2**	**2**	0
$\tilde{\mathcal{O}}_{\ell_2}$	**1**	**2**	**2**	-1
$\tilde{\mathcal{O}}_{e}$	**1**	**1**	**1**	-1

	$SU(3)^{el}$	$SU(2)^{el}_L$	$U(1)_Y{}^{el}$
$\tilde{q}_L$	**3**	**2**	$1/6$
$\tilde{u}_R$	**3**	**1**	$2/3$
$\tilde{d}_R$	**3**	**1**	$-1/3$
$\tilde{\ell}_L$	**1**	**2**	$-1/2$
$\tilde{e}_R$	**1**	**1**	-1
$\tilde{\nu}_R$	**1**	**1**	0

$$\tilde{\mathcal{O}}_{q_1} = \left(\tilde{\mathcal{O}}^{q_1}_{\mathbf{EX}}\, \tilde{\mathcal{O}}^{q_1}_{\mathbf{SM}}\right), \qquad \tilde{\mathcal{O}}^{q_1}_{\mathbf{SM}} = \begin{pmatrix} U \\ D \end{pmatrix}, \qquad \tilde{\mathcal{O}}^{q_1}_{\mathbf{EX}} = \begin{pmatrix} \chi_{5/3} \\ \chi_{2/3} \end{pmatrix}$$

$$\text{5-plet} \quad \Psi_{q_1} = \left(\tilde{\mathcal{O}}_{q_1}, \tilde{\mathcal{O}}_u\right)$$

$$\tilde{\mathcal{O}}_{q_2} = \left(\tilde{\mathcal{O}}^{q_2}_{\mathbf{SM}}\, \tilde{\mathcal{O}}^{q_2}_{\mathbf{EX}}\right), \qquad \tilde{\mathcal{O}}^{q_2}_{\mathbf{SM}} = \begin{pmatrix} U' \\ D' \end{pmatrix}, \qquad \tilde{\mathcal{O}}^{q_2}_{\mathbf{EX}} = \begin{pmatrix} \chi_{-1/3} \\ \chi_{-4/3} \end{pmatrix}$$

$$\text{5-plet} \quad \Psi_{q_2} = \left(\tilde{\mathcal{O}}_{q_2}, \tilde{\mathcal{O}}_d\right)$$

$$\tilde{\mathcal{O}}_{\ell_1} = \left(\tilde{\mathcal{O}}^{\ell_1}_{\mathbf{EX}}\, \tilde{\mathcal{O}}^{\ell_1}_{\mathbf{SM}}\right), \qquad \tilde{\mathcal{O}}^{\ell_1}_{\mathbf{SM}} = \begin{pmatrix} N \\ E \end{pmatrix}, \qquad \tilde{\mathcal{O}}^{\ell_1}_{\mathbf{EX}} = \begin{pmatrix} \chi_{+1} \\ \chi_{0} \end{pmatrix}$$

$$\text{5-plet} \quad \Psi_{l_1} = \left(\tilde{\mathcal{O}}_{l_1}, \tilde{\mathcal{O}}_N\right)$$

$$\tilde{\mathcal{O}}_{\ell_2} = \left(\tilde{\mathcal{O}}^{\ell_2}_{\mathbf{SM}}\, \tilde{\mathcal{O}}^{\ell_2}_{\mathbf{EX}}\right), \qquad \tilde{\mathcal{O}}^{\ell_2}_{\mathbf{SM}} = \begin{pmatrix} N' \\ E' \end{pmatrix}, \qquad \tilde{\mathcal{O}}^{\ell_2}_{\mathbf{EX}} = \begin{pmatrix} \chi_{-1} \\ \chi_{-2} \end{pmatrix}$$

$$\text{5-plet} \quad \Psi_{l_2} = \left(\tilde{\mathcal{O}}_{l_2}, \tilde{\mathcal{O}}_e\right)$$

Contribution to $\mathbf{\Delta F = 2}$: **Exchange of heavy neutral $\mathbf{SU(3)}$, $\mathbf{SU(2)_{L,R}}$, $\mathbf{U(1)_X}$ vectors** $(\rho_{3\,\mu},\ \rho^3_{L,R\,\mu},\ \rho_{X\,\mu})$

$$\mathcal{L}_{\Delta F=2} = -\text{const} \times \frac{g_*^2}{M_*^2}\left(\bar{\psi}_{i\,L}\left[V_L^{d\dagger}\hat{s}_q{}^\dagger \hat{s}_q V_L^d\right]^i{}_j \gamma^\mu \psi_{j\,L}\right)^2$$

$$\text{const} = \frac{M_*^2}{2g_*^2}\left(\frac{1}{3}\frac{g_{*3}^2}{M_{*3}^2} + \frac{1}{2}\frac{g_{*2}^2}{M_{*2}^2} + \frac{4}{9}\frac{g_{*X}^2}{M_{*X}^2}\right)$$

Upper bounds on $\mathbf{\bar{K} - K}$, $\mathbf{\bar{B}_d - B_d}$ and $\mathbf{\bar{B}_s - B_s}$ mixings

$$\left|\left[V_L^{d\dagger}\hat{s}^\dagger \hat{s} V_L^d\right]^i{}_j\right| \lesssim \frac{(M_*/\text{TeV})}{g_*\sqrt{\text{const}}}\begin{cases} 10^{-3}\ , \text{ from } \bar{K}\text{-}K \text{ mixing, i.e., } i=1, j=2 \ [1] \\ 1.1\times 10^{-3}\ , \text{ from } \bar{B}_d\text{-}B_d \text{ mixing, i.e., } i=1, j=3 \ [2] \\ 4\times 10^{-3}\ , \text{ from } \bar{B}_s\text{-}B_s \text{ mixing, i.e., } i=2, j=3 \ [2] \end{cases}$$

[1]: *JHEP* **03** (2008) 049 (0707.0636), [2]: *JHEP* **03** (2014) 016 (1308.1851)

$\mathbf{\Delta F = 2}$ & $\mathbf{R_{D^{(*)}}}$ bounds

$$1.1\times 10^{-3}\,|V_{cd}|\,\frac{(M_*/\text{TeV})}{g_*\sqrt{\text{const}}} + 4\times 10^{-3}\,|V_{cs}|\,\frac{(M_*/\text{TeV})}{g_*\sqrt{\text{const}}} + |V_{cb}| \gtrsim 0.2\left(\frac{M_*/\text{TeV}}{g_*}\right)^2$$