Current status of the B-meson charged current anomalies

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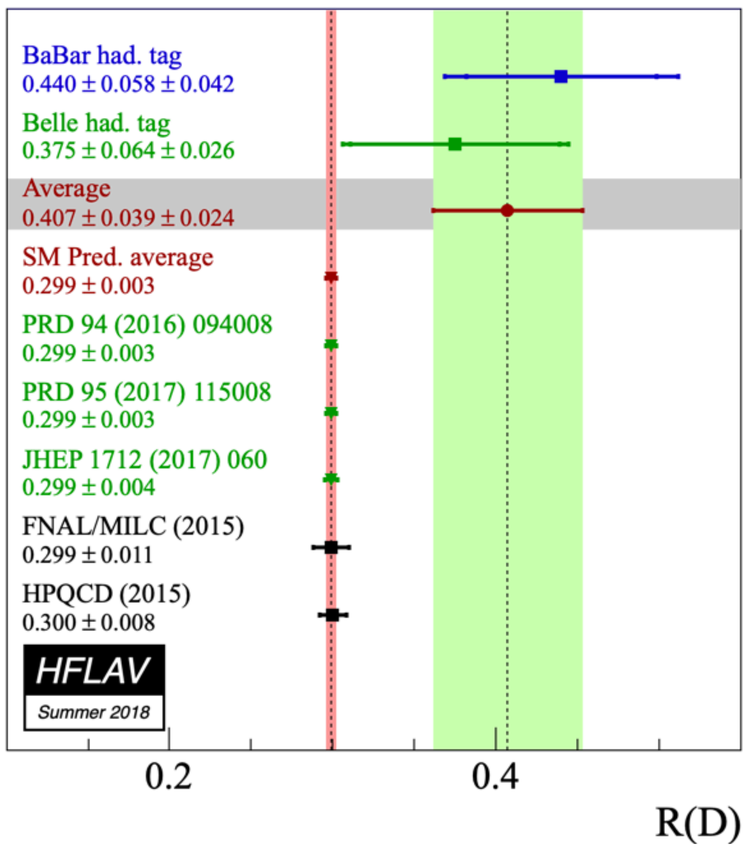
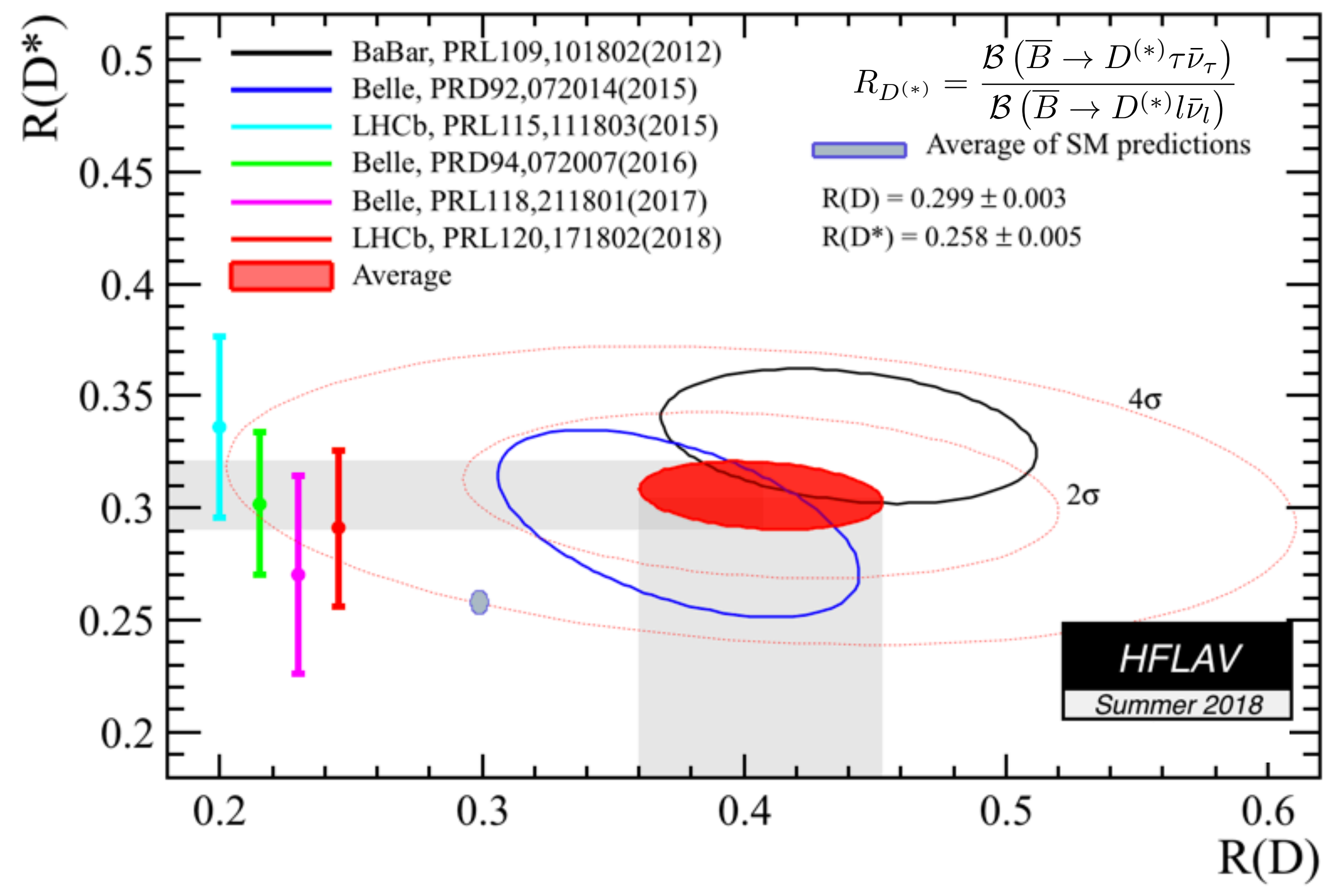
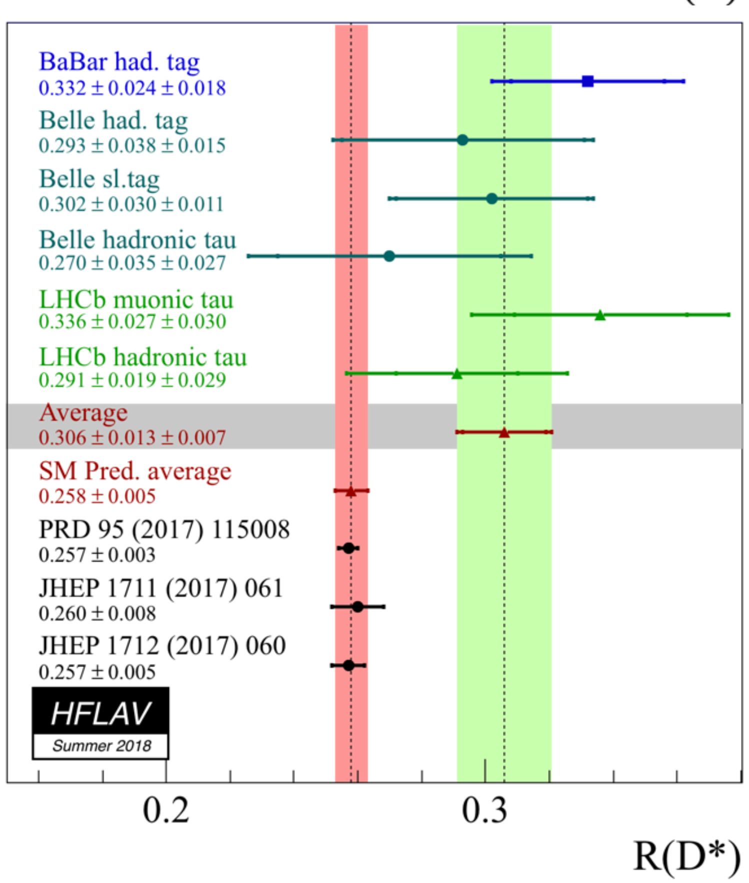
Experiments vs. the Standard Model

*New Belle results not included







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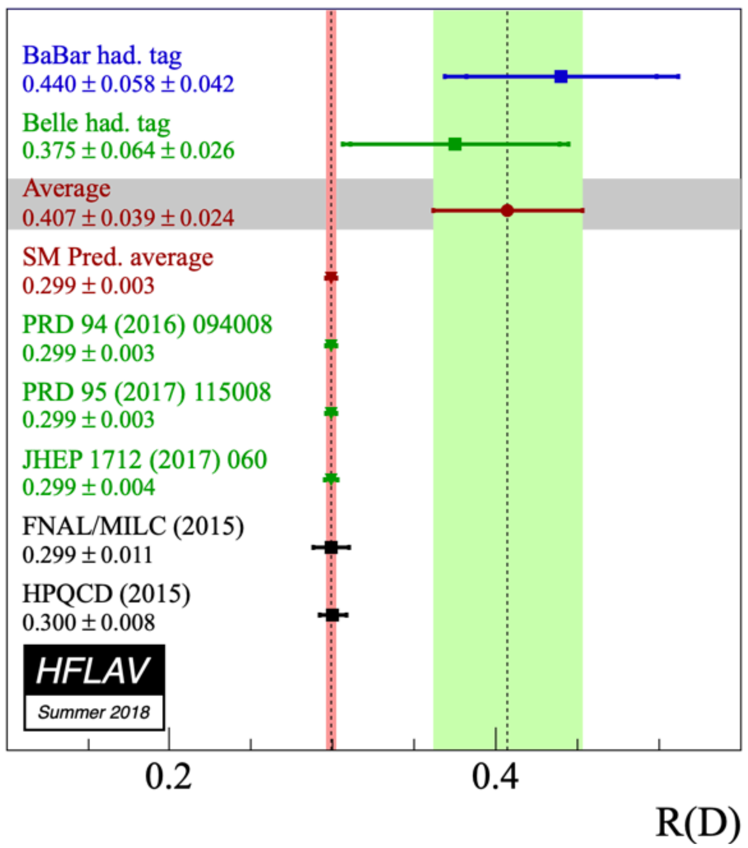

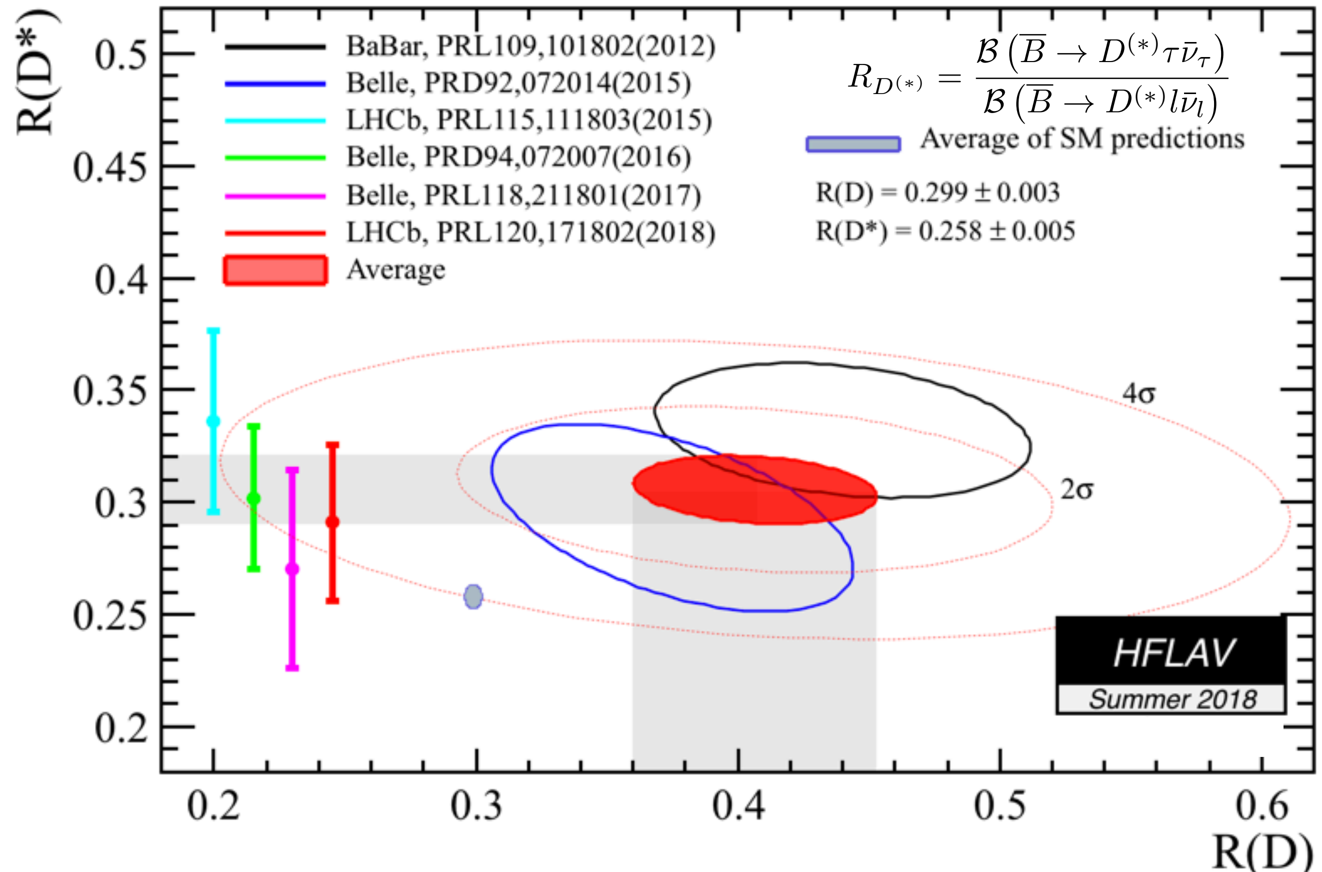

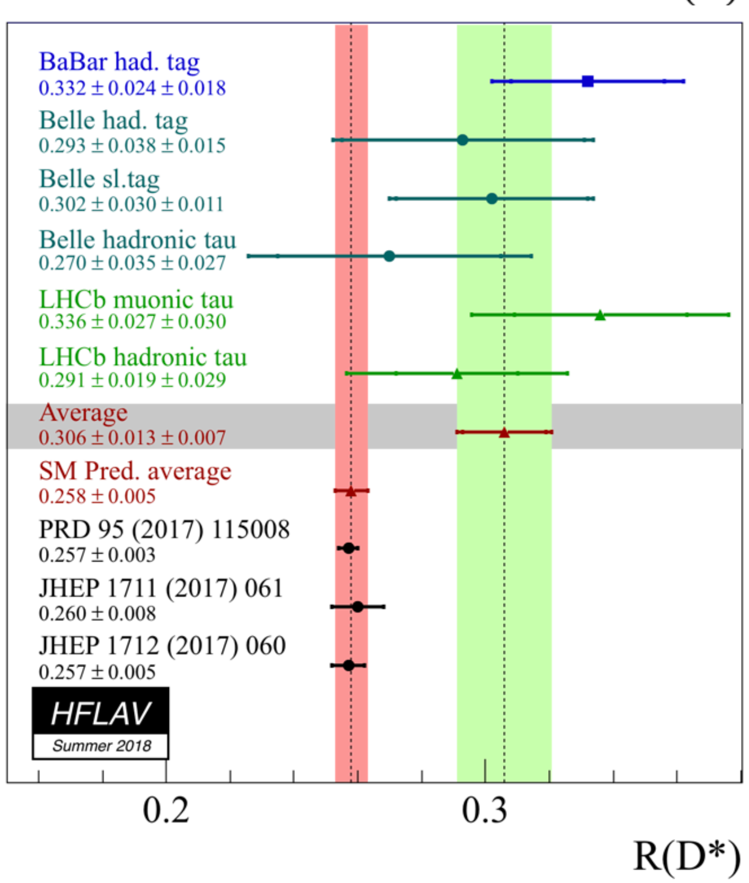

$$P_\tau(D^{(*)}) = \frac{\Gamma_\tau^{D^{(*)}}(+) - \Gamma_\tau^{D^{(*)}}(-)}{\Gamma_\tau^{D^{(*)}}(+) + \Gamma_\tau^{D^{(*)}}(-)}$$

$$P_\tau(D^*) = -\,0.38 \pm 0.51^{+0.21}_{-0.16}\ \text{(Belle)}$$

$$P_{\tau,SM}(D^*) = -0.497 \pm 0.01$$

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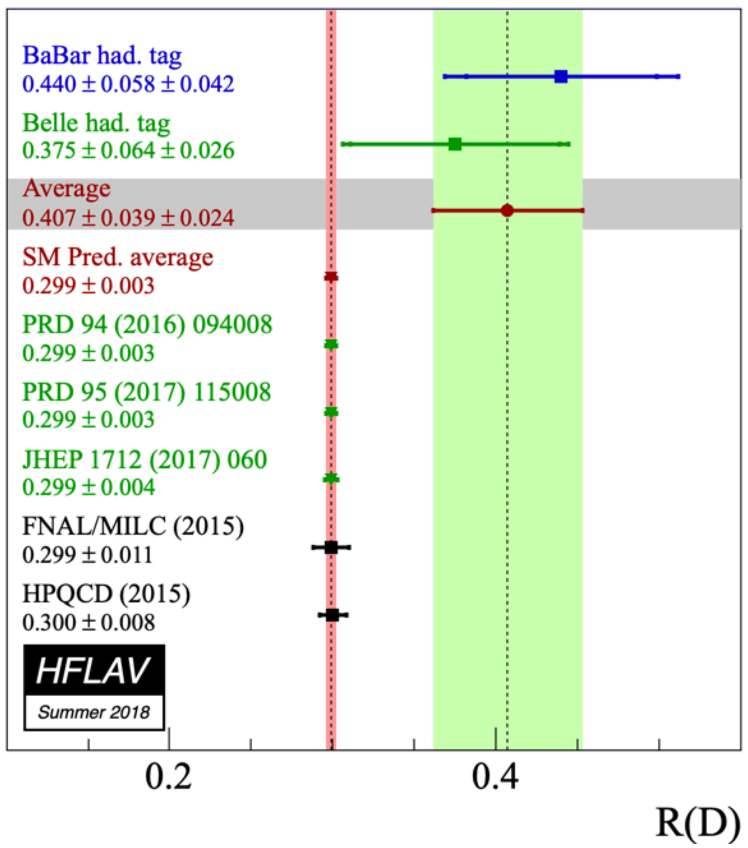

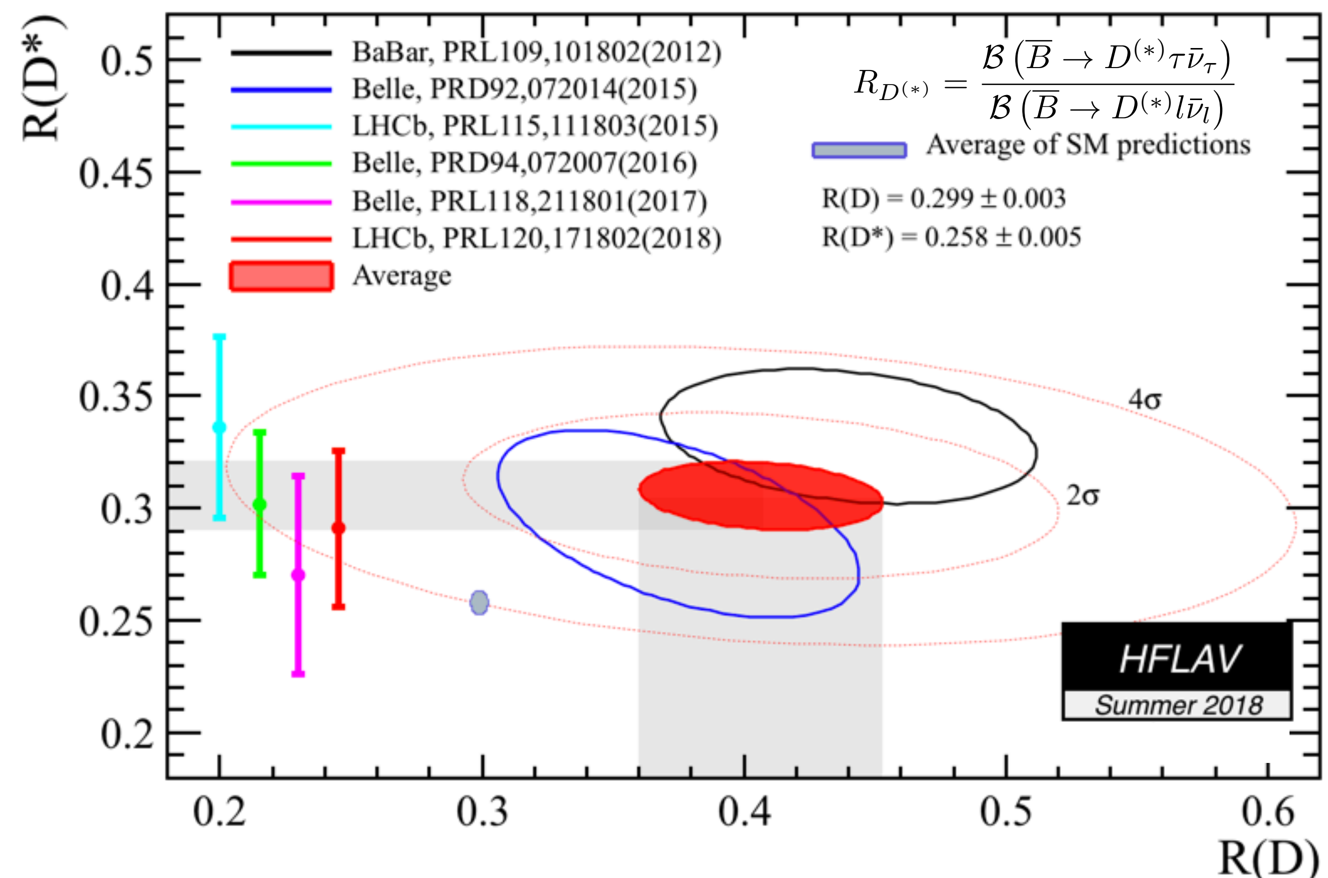

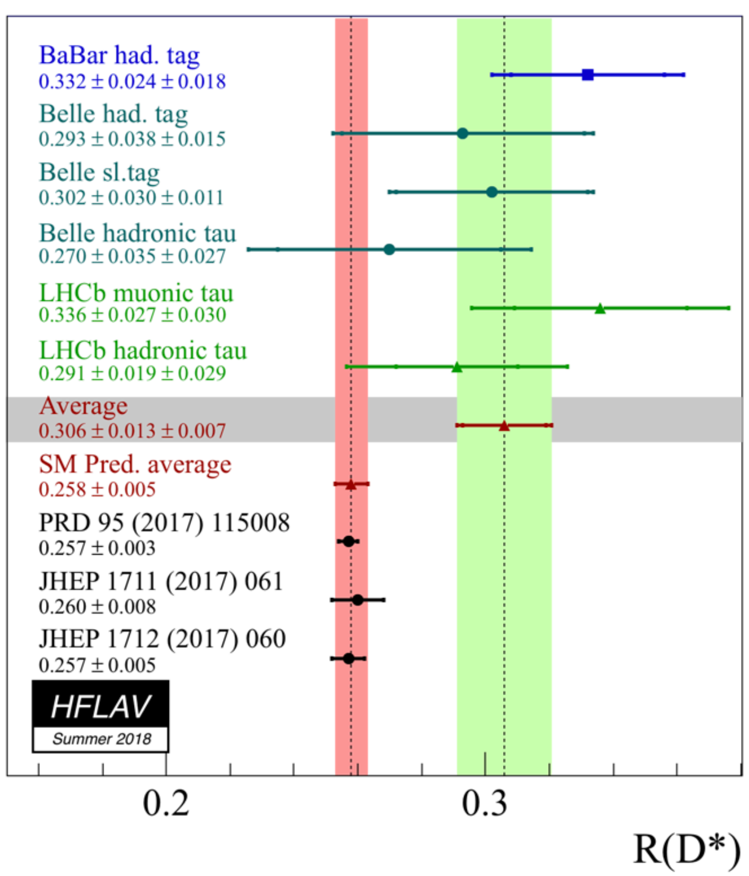

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$$P_{\tau,SM}(D^*) = -0.497 \pm 0.01$$

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

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035\ \text{(Belle)}$$

$$F_{L,\mathrm{SM}}(D^*) = 0.46 \pm 0.04$$

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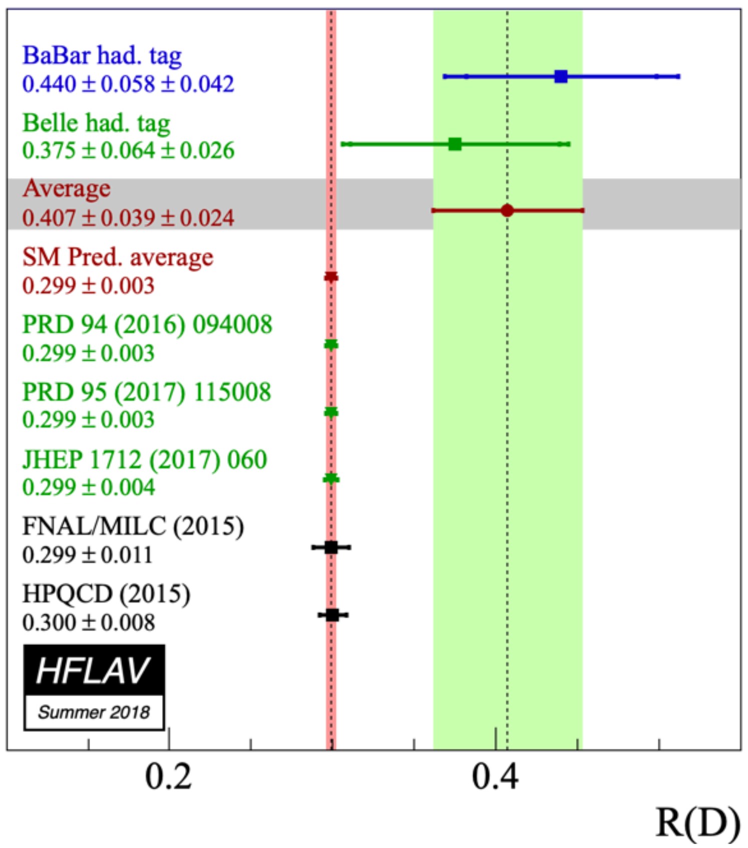

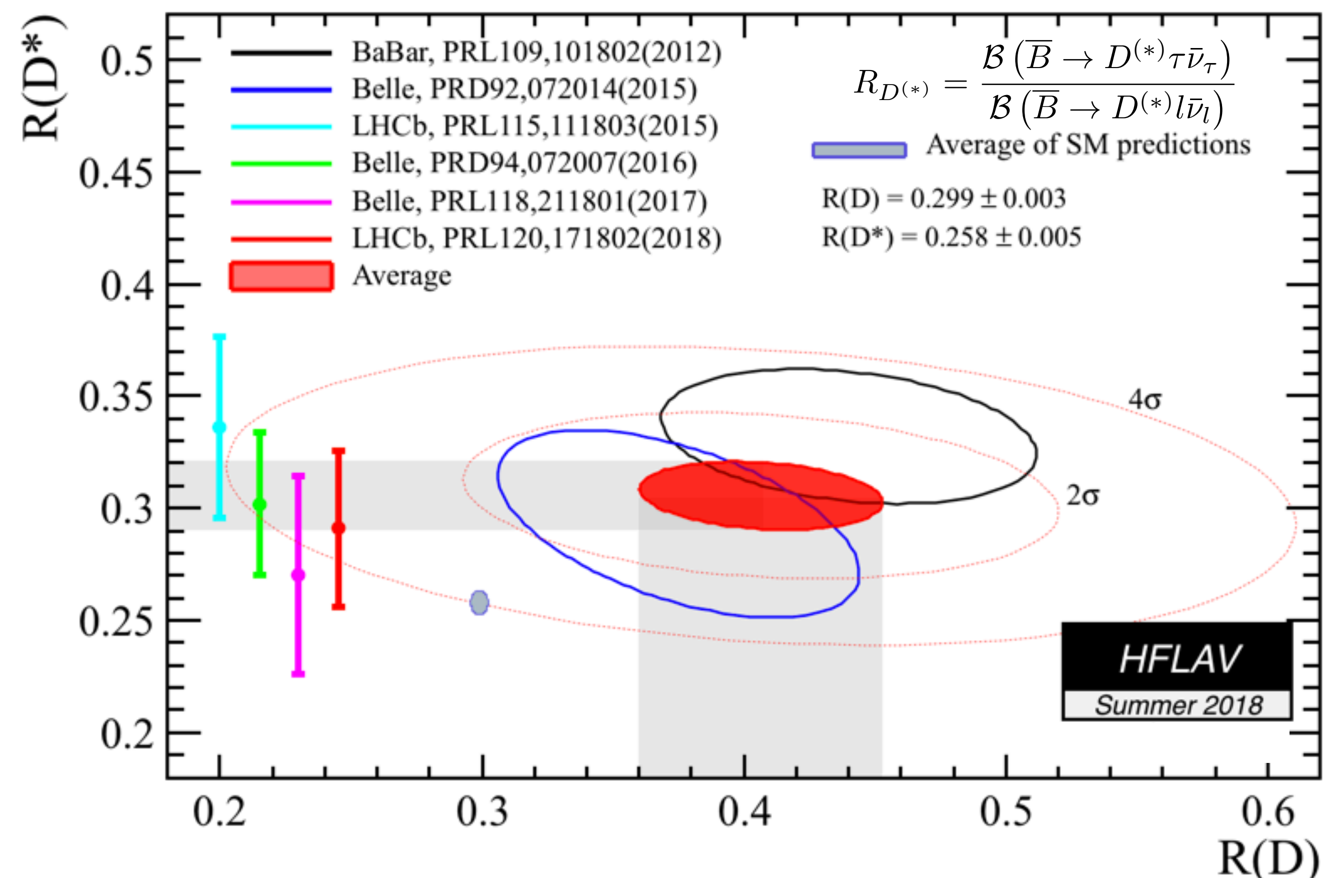

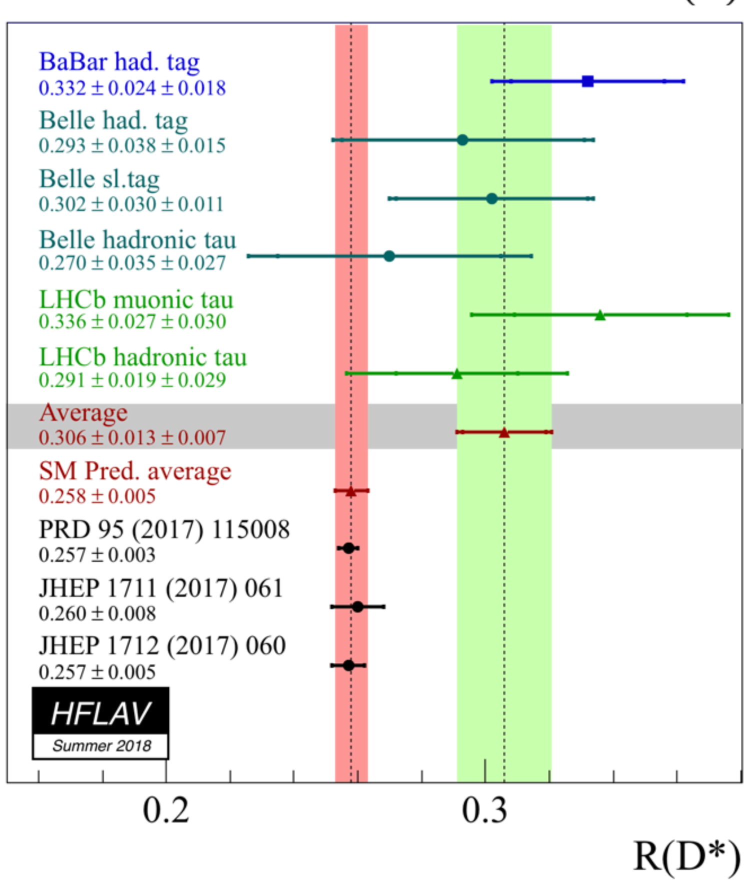

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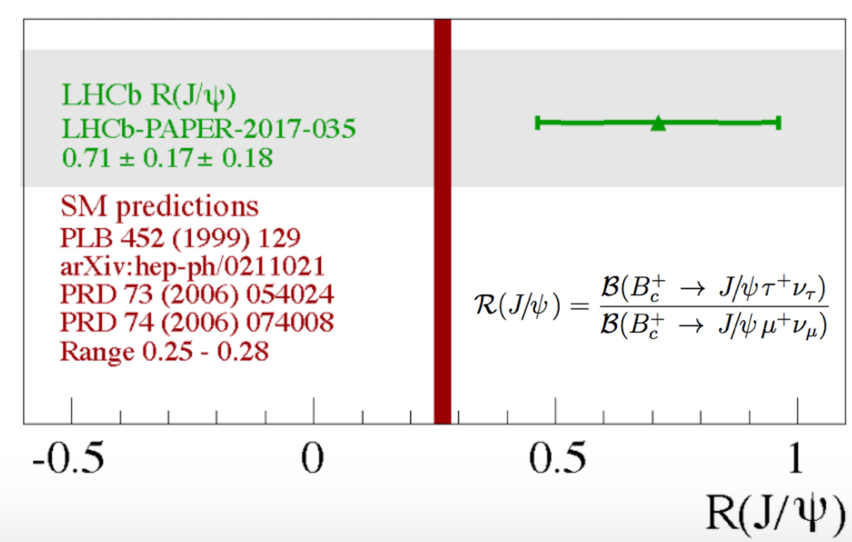
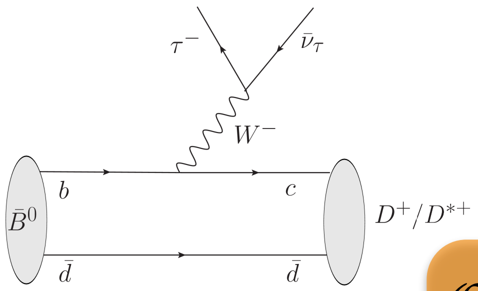


Operators

$$\mathcal{L}^{b\to c\ell\nu} = \mathcal{L}^{b\to c\ell\nu}\big|_{\rm SM} + \mathcal{L}^{b\to c\ell\nu}\big|_{\rm dim\text{-}6} + \mathcal{L}^{b\to c\ell\nu}\big|_{\rm dim\text{-}8} + ..$$



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

$$= -\frac{2G_F V_{cb}}{\sqrt{2}}(\mathcal{O}_{\rm VL}^{cb\ell} - \mathcal{O}_{\rm AL}^{cb\ell})$$

Operators

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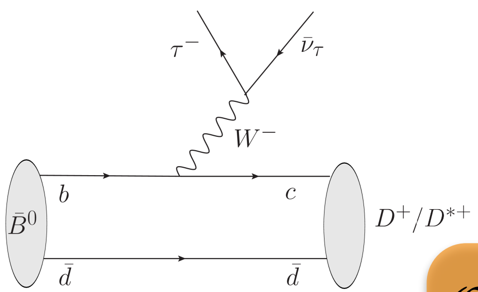


$$= -\frac{2G_F V_{cb}}{\sqrt{2}}\left(\mathcal{O}^{cb\ell}_{\rm VL} - \mathcal{O}^{cb\ell}_{\rm AL}\right) - \frac{g^{cb\ell}_{\rm VL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm VL} - \frac{g^{cb\ell}_{\rm AL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm AL} - \frac{g^{cb\ell}_{\rm SL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm SL} - \frac{g^{cb\ell}_{\rm PL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm PL} - \frac{g^{cb\ell}_{\rm TL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm TL}$$

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

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

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

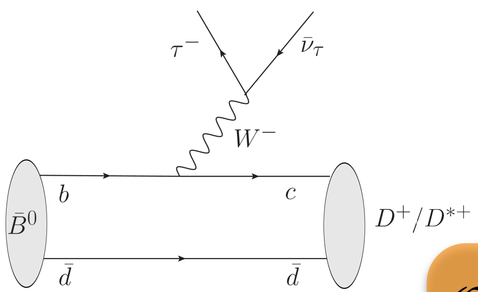
$$\mathcal{O}^{cb\ell}_{\rm PL} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\,\nu]$$

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

Only Left Chiral Neutrinos

Operators

$$\mathcal{L}^{b\to c\ell\nu} = \mathcal{L}^{b\to c\ell\nu}\big|_{\rm SM} + \mathcal{L}^{b\to c\ell\nu}\big|_{\text{dim-6}} + \mathcal{L}^{b\to c\ell\nu}\big|_{\text{dim-8}} + ..$$



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Only Left Chiral Neutrinos

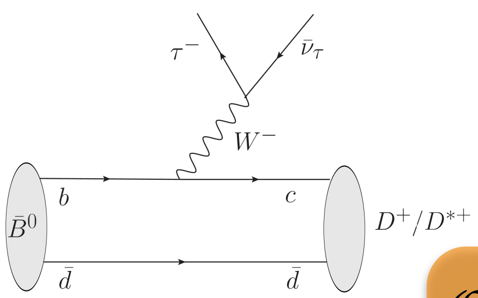
$$= -\frac{2G_F V_{cb}}{\sqrt{2}}\left(\mathcal{O}^{cb\ell}_{\rm VL} - \mathcal{O}^{cb\ell}_{\rm AL}\right) - \frac{g^{cb\ell}_{\rm VL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm VL} - \frac{g^{cb\ell}_{\rm AL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm AL}$$
$$- \frac{g^{cb\ell}_{\rm SL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm SL} - \frac{g^{cb\ell}_{\rm PL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm PL} - \frac{g^{cb\ell}_{\rm TL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm TL}$$

No other Tensor operators:

$$\epsilon_{\mu\nu\alpha\beta}[\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma^{\alpha\beta}\,\nu] = -2i\,[\bar{c}\,\sigma^{\mu\nu} b][\bar{\ell}\,\sigma_{\mu\nu}\,\gamma_5\nu]$$
$$[\bar{c}\,\sigma^{\mu\nu}\gamma_5\, b][\bar{\ell}\,\sigma_{\mu\nu}\gamma_5\,\nu] = [\bar{c}\,\sigma^{\mu\nu} b][\bar{\ell}\,\sigma_{\mu\nu}\nu]$$
$$[\bar{c}\,\sigma^{\mu\nu}\gamma_5\, b][\bar{\ell}\,\sigma_{\mu\nu}\,\nu] = [\bar{c}\,\sigma^{\mu\nu} b][\bar{\ell}\,\sigma_{\mu\nu}\,\gamma_5\nu]$$

Operators

$$\mathcal{L}^{b\to c\ell\nu} = \mathcal{L}^{b\to c\ell\nu}|_{\rm SM} + \mathcal{L}^{b\to c\ell\nu}|_{\rm dim\text{-}6} + \mathcal{L}^{b\to c\ell\nu}|_{\rm dim\text{-}8} + ..$$



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Only Left Chiral Neutrinos

$$= -\frac{2G_F V_{cb}}{\sqrt{2}}(\mathcal{O}^{cb\ell}_{\rm VL} - \mathcal{O}^{cb\ell}_{\rm AL}) - \frac{g^{cb\ell}_{\rm VL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm VL} - \frac{g^{cb\ell}_{\rm AL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm AL} - \frac{g^{cb\ell}_{\rm SL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm SL} - \frac{g^{cb\ell}_{\rm PL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm PL} - \frac{g^{cb\ell}_{\rm TL}}{\Lambda^2}\mathcal{O}^{cb\ell}_{\rm TL}$$

$$\frac{2G_F V_{cb}}{\sqrt{2}} \approx \frac{1}{(1.23\ {\rm TeV})^2}$$

$$= -\frac{2G_F V_{cb}}{\sqrt{2}}\sum C^{cb\ell}_i\,\mathcal{O}^{cb\ell}_i\ \ (i = {\rm VL,\ AL,\ SL,\ PL,\ TL})$$

No other Tensor operators:

$$\epsilon_{\mu\nu\alpha\beta}[\bar c\,\sigma^{\mu\nu}\, b][\bar\ell\,\sigma^{\alpha\beta}\,\nu] = -2i\,[\bar c\,\sigma^{\mu\nu} b][\bar\ell\,\sigma_{\mu\nu}\,\gamma_5\nu]$$
$$[\bar c\,\sigma^{\mu\nu}\gamma_5\, b][\bar\ell\,\sigma_{\mu\nu}\gamma_5\,\nu] = [\bar c\,\sigma^{\mu\nu} b][\bar\ell\,\sigma_{\mu\nu}\nu]$$
$$[\bar c\,\sigma^{\mu\nu}\gamma_5\, b][\bar\ell\,\sigma_{\mu\nu}\,\nu] = [\bar c\,\sigma^{\mu\nu} b][\bar\ell\,\sigma_{\mu\nu}\,\gamma_5\nu]$$

$$\frac{g^{cb\ell}_{\rm VL}}{\Lambda^2} = \frac{2G_F V_{cb}}{\sqrt{2}}(C^{cb\ell}_{\rm VL} - 1) \qquad \frac{g^{cb\ell}_{\rm AL}}{\Lambda^2} = \frac{2G_F V_{cb}}{\sqrt{2}}(C^{cb\ell}_{\rm AL} + 1)$$
$$\frac{g^{cb\ell}_{\rm SL,PL,TL}}{\Lambda^2} = \frac{2G_F V_{cb}}{\sqrt{2}}C^{cb\ell}_{\rm SL,PL,TL}$$

SM: $C^{cb\ell}_{\rm VL} = 1, C^{cb\ell}_{\rm AL} = -1$

Linearly realised SU(2) × U(1) gauge invariance

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

$$\mathcal{L}^{\rm dim6} = \frac{1}{\Lambda^2} \sum_{p'r's't'} \Big\{ [C_{lq}^{(3)}]'_{p'r's't'} \left(\bar{l}'_{p'}\gamma_\mu \tau^I l'_{r'}\right) \left(\bar{q}'_{s'}\gamma^\mu \tau^I q'_{t'}\right) + \text{h.c.}$$
$$+[C_{ledq}]'_{p'r's't'} \left(\bar{l}'^{j}_{p'} e'_{r'}\right) \left(\bar{d}'_{s'} q'^{j}_{t'}\right) + \text{h.c.}$$
$$+[C_{lequ}^{(1)}]'_{p'r's't'} \left(\bar{l}'^{j}_{p'} e'_{r'}\right) \epsilon_{jk} \left(\bar{q}'^{k}_{s'} u'_{t'}\right) + \text{h.c.}$$
$$+[C_{lequ}^{(3)}]'_{p'r's't'} \left(\bar{l}'^{j}_{p'} \sigma_{\mu\nu} e'_{r'}\right) \epsilon_{jk} \left(\bar{q}'^{k}_{s'} \sigma^{\mu\nu} u'_{t'}\right) + \text{h.c.}$$

$$+[C_{\phi l}^{(3)}]'_{p'r'} \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right) \left(\bar{l}'_{p'} \frac{\sigma^I}{2} \gamma^\mu l'_{r'}\right) + \text{h.c.}$$

$$+[C_{\phi q}^{(3)}]'_{p'r'} \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right) \left(\bar{q}'_{p'} \frac{\sigma^I}{2} \gamma^\mu q'_{r'}\right) + \text{h.c.}$$
$$+[C_{\phi ud}]'_{p'r'} \left(\phi^j \epsilon_{jk}\, i (D_\mu \phi)^k\right) \left(\bar{u}'_{p'} \gamma^\mu d'_{r'}\right) + \text{h.c.} \Big\}$$

- Note that $\left(\bar{l}'^{j}_{p'} \sigma_{\mu\nu} e'_{r'}\right) \left(\bar{d}'_{s'} \sigma^{\mu\nu} q'^{j}_{t'}\right)$ vanishes algebraically

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(V-A) ⊗ (V-A)

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

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

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

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

(V-A) ⊗ (V-A)

$$+[C_{\phi l}^{(3)}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar{l}'_{p'}\frac{\sigma^I}{2}\gamma^\mu l'_{r'}\right) + \text{h.c.}$$

Lepton universal

$$+[C_{\phi q}^{(3)}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar{q}'_{p'}\frac{\sigma^I}{2}\gamma^\mu q'_{r'}\right) + \text{h.c.}$$

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

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

(V-A) ⊗ (V-A)

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

$$= \frac14(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar u'_{s'}\gamma_\mu P_L u'_{t'}) + \frac14(\bar e'_{p'}\gamma^\mu P_L e'_{r'})(\bar d'_{s'}\gamma_\mu P_L d'_{t'})$$
$$-\frac14(\bar e'_{p'}\gamma^\mu P_L e'_{r'})(\bar u'_{s'}\gamma_\mu P_L u'_{t'}) - \frac14(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar d'_{s'}\gamma_\mu P_L d'_{t'})$$
$$+\frac12(\bar\nu'_{p'}\gamma^\mu P_L e'_{r'})(\bar d'_{s'}\gamma_\mu P_L u'_{t'}) + \frac12(\bar e'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar u'_{s'}\gamma_\mu P_L d'_{t'})$$

$$+[C_{ledq}]'_{p'r's't'}\left(\bar l'^j_{p'}e'_{r'}\right)(\bar d'_{s'}q'^j_{t'}) + \text{h.c.} \qquad = (\bar\nu'_{p'}P_R e'_{r'})(\bar d'_{s'}P_L u'_{t'}) + (\bar e'_{p'}P_R e'_{r'})(\bar d'_{s'}P_L d'_{t'})$$

$$+[C^{(1)}_{lequ}]'_{p'r's't'}\left(\bar l'^j_{p'}e'_{r'}\right)\epsilon_{jk}\left(\bar q'^k_{s'}u'_{t'}\right) + \text{h.c.} \qquad = (\bar\nu'_{p'}P_R e'_{r'})(\bar d'_{s'}P_R u'_{t'}) - (\bar e'_{p'}P_R e'_{r'})(\bar u'_{s'}P_R u'_{t'})$$

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

(V-A) ⊗ (V-A)

$$+[C^{(3)}_{\phi l}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar l'_{p'}\frac{\sigma^I}{2}\gamma^\mu l'_{r'}\right) + \text{h.c.}$$

$$= \Big[-\frac18\frac{g_2}{\cos\theta_W}Z_\mu(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'}) + \frac18\frac{g_2}{\cos\theta_W}Z_\mu(\bar e'_{p'}\gamma^\mu P_L e'_{r'})$$
$$-\frac{g_2}{4\sqrt2}W^+_\mu(\bar\nu'_{p'}\gamma^\mu P_L e'_{r'}) - \frac{g_2}{4\sqrt2}W^-_\mu(\bar e'_{p'}\gamma^\mu P_L\nu'_{r'})\Big]\times(v^2+2vh+h^2)$$

$$+[C^{(3)}_{\phi q}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar q'_{p'}\frac{\sigma^I}{2}\gamma^\mu q'_{r'}\right) + \text{h.c.}$$

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

Lepton universal

- Note that $\left(\bar l'^j_{p'}\sigma_{\mu\nu}e'_{r'}\right)(\bar d'_{s'}\sigma^{\mu\nu}q'^j_{t'})$ vanishes algebraically

Linearly realised SU(2) × U(1) gauge invariance

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(V-A) ⊗ (V-A)

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

$$= \frac{1}{4}(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar u'_{s'}\gamma_\mu P_L u'_{t'}) + \frac{1}{4}(\bar e'_{p'}\gamma^\mu P_L e'_{r'})(\bar d'_{s'}\gamma_\mu P_L d'_{t'}) - \frac{1}{4}(\bar e'_{p'}\gamma^\mu P_L e'_{r'})(\bar u'_{s'}\gamma_\mu P_L u'_{t'}) - \frac{1}{4}(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar d'_{s'}\gamma_\mu P_L d'_{t'}) + \frac{1}{2}(\bar\nu'_{p'}\gamma^\mu P_L e'_{r'})(\bar d'_{s'}\gamma_\mu P_L u'_{t'}) + \frac{1}{2}(\bar e'_{p'}\gamma^\mu P_L\nu'_{r'})(\bar u'_{s'}\gamma_\mu P_L d'_{t'})$$

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

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

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

(V-A) ⊗ (V-A)

$$+[C_{\phi l}^{(3)}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar l'_{p'}\frac{\sigma^I}{2}\gamma^\mu l'_{r'}\right) + \text{h.c.}$$

$$= \Big[-\frac{1}{8}\frac{g_2}{\cos\theta_W}Z_\mu(\bar\nu'_{p'}\gamma^\mu P_L\nu'_{r'}) + \frac{1}{8}\frac{g_2}{\cos\theta_W}Z_\mu(\bar e'_{p'}\gamma^\mu P_L e'_{r'}) - \frac{g_2}{4\sqrt2}W^+_\mu(\bar\nu'_{p'}\gamma^\mu P_L e'_{r'}) - \frac{g_2}{4\sqrt2}W^-_\mu(\bar e'_{p'}\gamma^\mu P_L\nu'_{r'})\Big]\times(v^2+2vh+h^2)$$

$\Delta g_L^\tau,\ \Delta g_L^\nu,\ \Delta g_W^\tau$

Lepton universal

$$+[C_{\phi q}^{(3)}]'_{p'r'}\left(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi\right)\left(\bar q'_{p'}\frac{\sigma^I}{2}\gamma^\mu q'_{r'}\right) + \text{h.c.}$$

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

- Note that $\left(\bar l'^{j}_{p'}\sigma_{\mu\nu}e'_{r'}\right)\left(\bar d'_{s'}\sigma^{\mu\nu}q'^{j}_{t'}\right)$ vanishes algebraically

Linearly realised $SU(2) \times U(1)$ gauge invariance

- Presence/absence of right handed quark current

$$\mathcal{O}^8_{\rm RL} = \frac{1}{\Lambda^4}\left(\bar{l'}_{p'}\phi\right)\gamma_\mu\left(l'_{r'}\phi\right)\left(\bar{u'}_{s'}\gamma^\mu d'_{t'}\right)$$

$$\Rightarrow \quad \frac{v^2}{\Lambda^2}\,\frac{1}{\Lambda^2}\,[\bar{\ell}\,\gamma_\mu\,P_L\,\nu][\bar{c}\,\gamma^\mu\,P_R\,b]$$

Linearly realised $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge invariance

- Presence/absence of right handed quark current

$$\mathcal{O}^8_{\mathrm{RL}} = \frac{1}{\Lambda^4}\,(\bar{l'}_{p'}\phi)\,\gamma_\mu\,(l'_{r'}\phi)\,(\bar{u'}_{s'}\gamma^\mu d'_{t'})$$

$$\Rightarrow \quad \frac{v^2}{\Lambda^2}\,\frac{1}{\Lambda^2}\,[\bar{\ell}\,\gamma_\mu\,P_L\,\nu][\bar{c}\,\gamma^\mu\,P_R\,b]$$

- $(\text{Dim-6})^2$ vs. $(\text{Dim-8})\times$ SM

$$\mathcal{M} = E^{\#}\left(\frac{V_{cb}}{v^2} + N_6\,g_6\,\frac{1}{\Lambda^2} + N_8\,g_8\,\frac{E^2}{\Lambda^4} + N'_8\,g'_8\,\frac{v^2}{\Lambda^4} + ..\right)$$

N_6, N_8, N'_8 : loop/tree

g_6, g_8, g'_8 : coupling strength, flavour structure

Linearly realised SU(2) × U(1) gauge invariance

- Presence/absence of right handed quark current

$$\mathcal{O}^8_{\rm RL} = \tfrac{1}{\Lambda^4}\,(\bar{l'}_{p'}\phi)\,\gamma_\mu\,(l'_{r'}\phi)\,(\bar{u'}_{s'}\gamma^\mu d'_{t'})$$

$$\rightarrow \quad \frac{v^2}{\Lambda^2}\,\frac{1}{\Lambda^2}\,[\bar{\ell}\,\gamma_\mu\,P_L\,\nu][\bar{c}\,\gamma^\mu\,P_R\,b]$$

- $(\text{Dim-6})^2$ vs. $(\text{Dim-8})\times$ SM

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N_6, N_8, N'_8 : loop/tree

g_6, g_8, g'_8 : coupling strength, flavour structure

$$(\text{Dim-6})^2 : \; N_6^2\,g_6^2\,\frac{1}{\Lambda^4}$$

$$(\text{Dim-8})\times \text{SM} : \; V_{cb}\,N_8\,g_8\,\frac{1}{\Lambda^4}\,\frac{E^2}{v^2}\;,\quad V_{cb}\,N'_8\,g'_8\,\frac{1}{\Lambda^4}$$

Linearly realised $SU(2) \times U(1)$ gauge invariance

- Presence/absence of right handed quark current

$$\mathcal{O}^8_{\rm RL} = \frac{1}{\Lambda^4}\,(\bar{l'}_{p'}\phi)\,\gamma_\mu\,(l'_{r'}\phi)\,(\bar{u'}_{s'}\gamma^\mu d'_{t'})$$

$$\rightarrow \quad \frac{v^2}{\Lambda^2}\,\frac{1}{\Lambda^2}\,[\bar{\ell}\,\gamma_\mu\,P_L\,\nu][\bar{c}\,\gamma^\mu\,P_R\,b]$$

- $(\text{Dim-6})^2$ vs. $(\text{Dim-8})\times$ SM

$$\mathcal{M} = E^{\#}\left(\frac{V_{cb}}{v^2} + N_6\,g_6\,\frac{1}{\Lambda^2} + N_8\,g_8\,\frac{E^2}{\Lambda^4} + N'_8\,g'_8\,\frac{v^2}{\Lambda^4} + ..\right)$$

N_6, N_8, N'_8 : loop/tree

g_6, g_8, g'_8 : coupling strength, flavour structure

$$(\text{Dim-6})^2 : \; N_6^2\,g_6^2\,\frac{1}{\Lambda^4}$$

$$(\text{Dim-8})\times\text{ SM} : \; V_{cb}\,N_8\,g_8\,\frac{1}{\Lambda^4}\,\frac{E^2}{v^2}, \quad V_{cb}\,N'_8\,g'_8\,\frac{1}{\Lambda^4}$$

strongly suppressed

Linearly realised $SU(2) \times U(1)$ gauge invariance

- Presence/absence of right handed quark current

$$\mathcal{O}^{8}_{\rm RL} = \frac{1}{\Lambda^4} (\bar{l'}_{p'} \phi)\, \gamma_\mu\, (l'_{r'} \phi)\, (\bar{u'}_{s'} \gamma^\mu d'_{t'})$$

$$\rightarrow \quad \frac{v^2}{\Lambda^2} \frac{1}{\Lambda^2} [\bar{\ell}\, \gamma_\mu\, P_L\, \nu][\bar{c}\, \gamma^\mu\, P_R\, b]$$

- $(\text{Dim-6})^2$ vs. $(\text{Dim-8})\times$ SM

$$\mathcal{M} = E^{\#} \left(\frac{V_{cb}}{v^2} + N_6\, g_6\, \frac{1}{\Lambda^2} + N_8\, g_8\, \frac{E^2}{\Lambda^4} + N'_8\, g'_8\, \frac{v^2}{\Lambda^4} + .. \right)$$

N_6, N_8, N'_8 : loop/tree

g_6, g_8, g'_8 : coupling strength, flavour structure

$$(\text{Dim-6})^2 : \; N_6^2\, g_6^2\, \frac{1}{\Lambda^4}$$

$$(\text{Dim-8})\times \text{SM} : \; V_{cb}\, N_8\, g_8\, \frac{1}{\Lambda^4} \frac{E^2}{v^2}, \quad V_{cb}\, N'_8\, g'_8\, \frac{1}{\Lambda^4}$$

strongly suppressed

can in principle be comparable to $(\text{Dim-6})^2$

- $(\text{Dim-6})^2$ vs. $(\text{Dim-8})\times$ SM

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

Real Wilson Coefficients
Only Left Chiral Neutrinos

$$\begin{aligned} R_D &= 0.30 + 0.60\,\Delta C^{\tau}_{\rm VL} + 0.51\,\Delta C^{\tau}_{\rm SL} + 0.15\,\Delta C^{\tau}_{\rm TL} \\ &+ 0.30\,(\Delta C^{\tau}_{\rm VL})^2 + 0.40\,(\Delta C^{\tau}_{\rm SL})^2 + 0.05\,(\Delta C^{\tau}_{\rm TL})^2 \\ &+ 0.51\,\Delta C^{\tau}_{\rm VL}\Delta C^{\tau}_{\rm SL} + 0.15\,\Delta C^{\tau}_{\rm VL}\Delta C^{\tau}_{\rm TL} \end{aligned}$$

$$\begin{aligned} R_{D^*} &= 0.25 + 0.03\,\Delta C^{\tau}_{\rm VL} - 0.48\,\Delta C^{\tau}_{\rm AL} + 0.03\,\Delta C^{\tau}_{\rm PL} - 0.52\,\Delta C^{\tau}_{\rm TL} \\ &+ 0.01\,(\Delta C^{\tau}_{\rm VL})^2 + 0.24\,(\Delta C^{\tau}_{\rm AL})^2 + 0.01\,(\Delta C^{\tau}_{\rm PL})^2 + 0.77\,(\Delta C^{\tau}_{\rm TL})^2 \\ &+ 0.10\,\Delta C^{\tau}_{\rm VL}\Delta C^{\tau}_{\rm TL} - 0.03\,\Delta C^{\tau}_{\rm AL}\Delta C^{\tau}_{\rm PL} + 0.62\,\Delta C^{\tau}_{\rm AL}\Delta C^{\tau}_{\rm TL} \end{aligned}$$

As we will see later, in most cases

$(\text{Dim-6})^2 << (\text{Dim-6}) \times$ SM

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

Right Chiral Neutrinos

Greljo, Robinson, Shakya, Zupan: 2018
Asadi, Buckley, Shih: 2018
Azatov, Barducci, DG, Marzocca, Ubaldi 2018

$$\mathcal{O}_{\rm VR}^{cb\ell} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_R\,\nu]$$
$$\mathcal{O}_{\rm AR}^{cb\ell} = [\bar{c}\,\gamma^\mu\,\gamma_5\, b][\bar{\ell}\,\gamma_\mu\, P_R\,\nu]$$
$$\mathcal{O}_{\rm SR}^{cb\ell} = [\bar{c}\, b][\bar{\ell}\, P_R\,\nu]$$
$$\mathcal{O}_{\rm PR}^{cb\ell} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_R\,\nu]$$
$$\mathcal{O}_{\rm TR}^{cb\ell} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_R\,\nu]$$

Right Chiral Neutrinos

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$$\mathcal{O}^{cb\ell}_{\rm PR} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_R\,\nu]$$
$$\mathcal{O}^{cb\ell}_{\rm TR} = [\bar{c}\,\sigma^{\mu\nu}\, b][\bar{\ell}\,\sigma_{\mu\nu}\, P_R\,\nu]$$

$$\begin{aligned}\mathcal{L}^{\rm dim6} \supset -\frac{1}{\Lambda^2}\sum_{p'r's't'} \Big\{ & [\tilde{C}_{\nu edu}]'_{prst}\left(\bar{\nu}'_p\gamma^\mu e'_r\right)\left(\bar{d'}_s\gamma_\mu u'^j_t\right) + \text{h.c.}\\ & +[\tilde{C}^{(1)}_{\nu ldq}]'_{prst}\left(\bar{\nu}'_p l'^j_r\right)\epsilon_{jk}\left(\bar{d'}_s q'^j_t\right) + \text{h.c.}\\ & +[\tilde{C}^{(1)}_{\nu lqu}]'_{prst}\left(\bar{\nu}'_p l'^j_r\right)\left(\bar{q'}^j_s u'_t\right) + \text{h.c.}\\ & +[\tilde{C}^{(3)}_{\nu ldq}]'_{prst}\left(\bar{\nu}'_p\sigma^{\mu\nu} l'^j_r\right)\epsilon_{jk}\left(\bar{d'}_s\sigma_{\mu\nu} q'^j_t\right) + \text{h.c.}\end{aligned}$$

$$+[\tilde{C}_{\phi\nu e}]'_{pr}\left(\phi^j\epsilon_{jk}\, i(D_\mu\phi)^k\right)\left(\bar{\nu}'_p\gamma^\mu e'_r\right) + \text{h.c.}\Big\}$$

Right Chiral Neutrinos

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

$(\mathrm{V+A}) \otimes (\mathrm{V+A})$

$$\mathcal{L}^{\rm dim6} \supset -\frac{1}{\Lambda^2}\sum_{p'r's't'}\Big\{[\tilde{C}_{\nu edu}]'_{prst}\,(\bar{\nu}'_p\gamma^\mu e'_r)\,(\bar{d}'_s\gamma_\mu u'^j_t) + \text{h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu ldq}]'_{prst}\left(\bar{\nu}'_p l'^j_r\right)\epsilon_{jk}\left(\bar{d}'_s q'^j_t\right) + \text{h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu lqu}]'_{prst}\left(\bar{\nu}'_p l'^j_r\right)\left(\bar{q}'^j_s u'_t\right) + \text{h.c.}$$
$$+[\tilde{C}^{(3)}_{\nu ldq}]'_{prst}\left(\bar{\nu}'_p\sigma^{\mu\nu} l'^j_r\right)\epsilon_{jk}\left(\bar{d}'_s\sigma_{\mu\nu} q'^j_t\right) + \text{h.c.}$$
$$+[\tilde{C}_{\phi\nu e}]'_{pr}\left(\phi^j\epsilon_{jk}\, i(D_\mu\phi)^k\right)\left(\bar{\nu}'_p\gamma^\mu e'_r\right) + \text{h.c.}\Big\}$$

Right Chiral Neutrinos

Greljo, Robinson, Shakya, Zupan: 2018
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$$\mathcal{O}^{cb\ell}_{\rm VR} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_R\,\nu]$$
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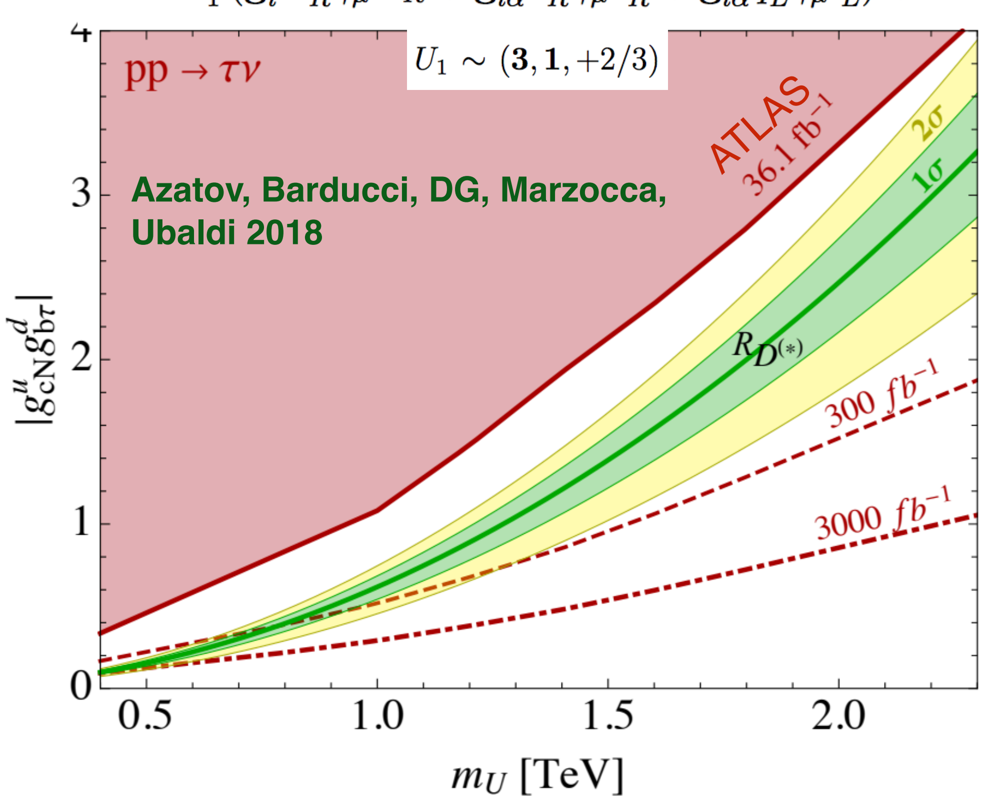
(V+A) ⊗ (V+A)

$$\mathcal{L}^{\rm dim6} \supset -\frac{1}{\Lambda^2}\sum_{p'r's't'}\Big\{[\tilde{C}_{\nu edu}]'_{prst}\,(\bar{\nu}'_p\gamma^\mu e'_r)\,(\bar{d}'_s\gamma_\mu u'^j_t) + \text{h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu ldq}]'_{prst}\,(\bar{\nu}'_p l'^j_r)\,\epsilon_{jk}\,(\bar{d}'_s q'^j_t) + \text{h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu lqu}]'_{prst}\,(\bar{\nu}'_p l'^j_r)\,(\bar{q}'^j_s u'_t) + \text{h.c.}$$
$$+[\tilde{C}^{(3)}_{\nu ldq}]'_{prst}\,(\bar{\nu}'_p\sigma^{\mu\nu} l'^j_r)\,\epsilon_{jk}\,(\bar{d}'_s\sigma_{\mu\nu} q'^j_t) + \text{h.c.}$$
$$+[\tilde{C}_{\phi\nu e}]'_{pr}\,(\phi^j\epsilon_{jk}\,i(D_\mu\phi)^k)\,(\bar{\nu}'_p\gamma^\mu e'_r) + \text{h.c.}\Big\}$$

$$\mathcal{L} = U_1^\mu(\mathbf{g}^u_i\bar{u}^i_R\gamma_\mu N_R + \mathbf{g}^d_{i\alpha}\bar{d}^i_R\gamma_\mu e^\alpha_R + \mathbf{g}^q_{i\alpha}\bar{q}^i_L\gamma_\mu l^\alpha_L) + h.c.$$



Right Chiral Neutrinos

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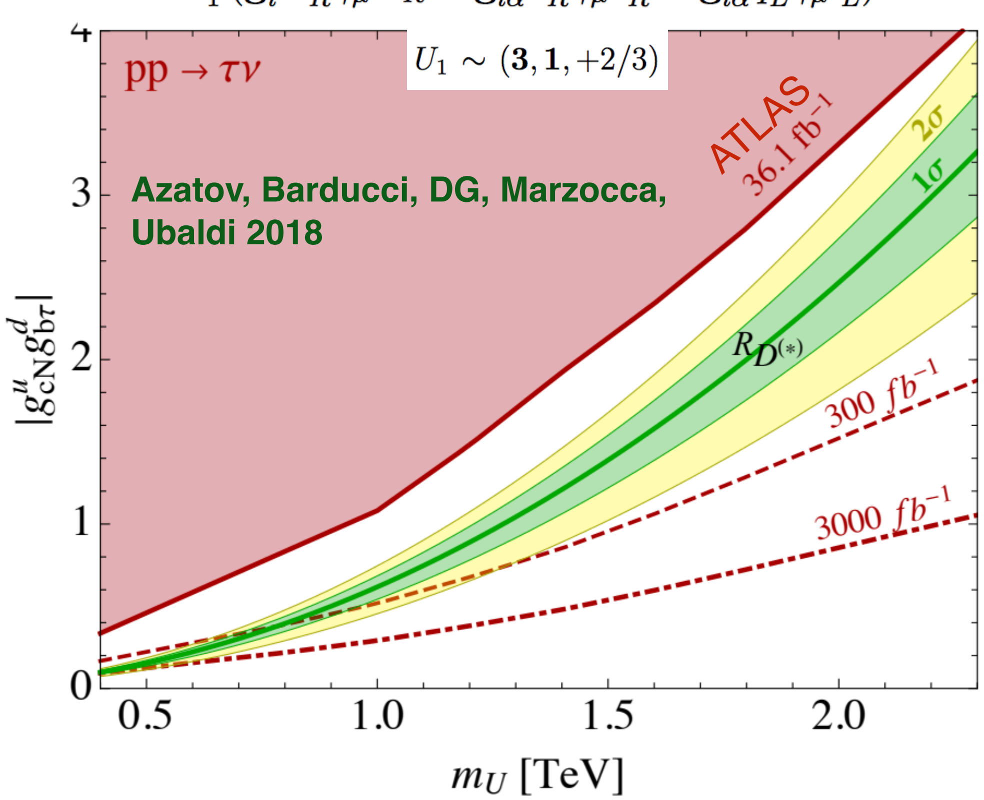
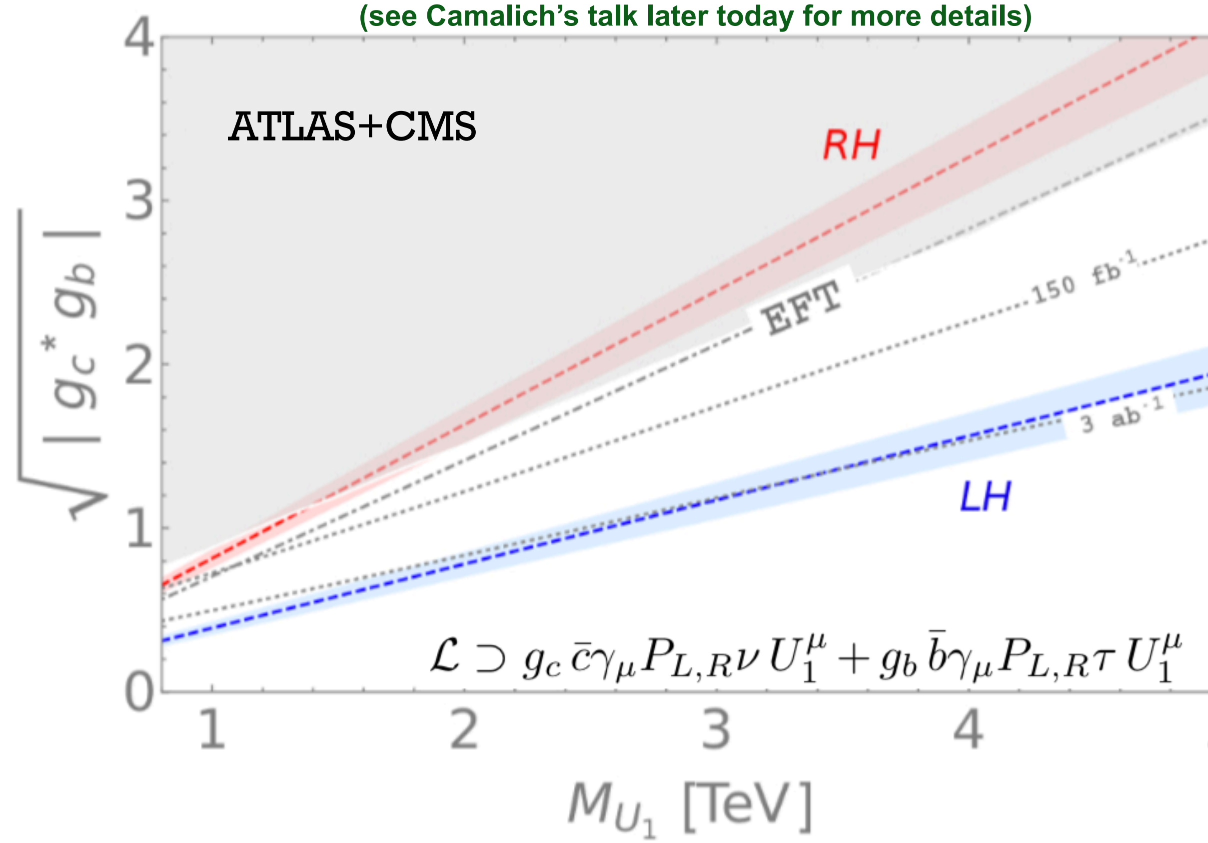
(V+A) $\otimes$ (V+A)

$$\mathcal{L}^{\rm dim6} \supset -\frac{1}{\Lambda^2}\sum_{p'r's't'}\Big\{[\tilde{C}_{\nu edu}]'_{prst}\,(\bar{\nu}'_p\gamma^\mu e'_r)\,(\bar{d}'_s\gamma_\mu u'^j_t) + {\rm h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu ldq}]'_{prst}\,(\bar{\nu}'_p l'^j_r)\,\epsilon_{jk}\,(\bar{d}'_s q'^j_t) + {\rm h.c.}$$
$$+[\tilde{C}^{(1)}_{\nu lqu}]'_{prst}\,(\bar{\nu}'_p l'^j_r)\,(\bar{q}'^j_s u'_t) + {\rm h.c.}$$
$$+[\tilde{C}^{(3)}_{\nu ldq}]'_{prst}\,(\bar{\nu}'_p\sigma^{\mu\nu} l'^j_r)\,\epsilon_{jk}\,(\bar{d}'_s\sigma_{\mu\nu} q'^j_t) + {\rm h.c.}$$
$$+[\tilde{C}_{\phi\nu e}]'_{pr}\,(\phi^j\epsilon_{jk}\, i(D_\mu\phi)^k)\,(\bar{\nu}'_p\gamma^\mu e'_r) + {\rm h.c.}\Big\}$$

$$\mathcal{L} = U_1^\mu(\mathbf{g}_i^u\bar{u}_R^i\gamma_\mu N_R + \mathbf{g}^d_{i\alpha}\bar{d}^i_R\gamma_\mu e^\alpha_R + \mathbf{g}^q_{i\alpha}\bar{q}^i_L\gamma_\mu l^\alpha_L) + h.c.$$



Greljo, Camalich, Ruiz-Álvarez 2018
(see Camalich's talk later today for more details)



Right Chiral Neutrinos

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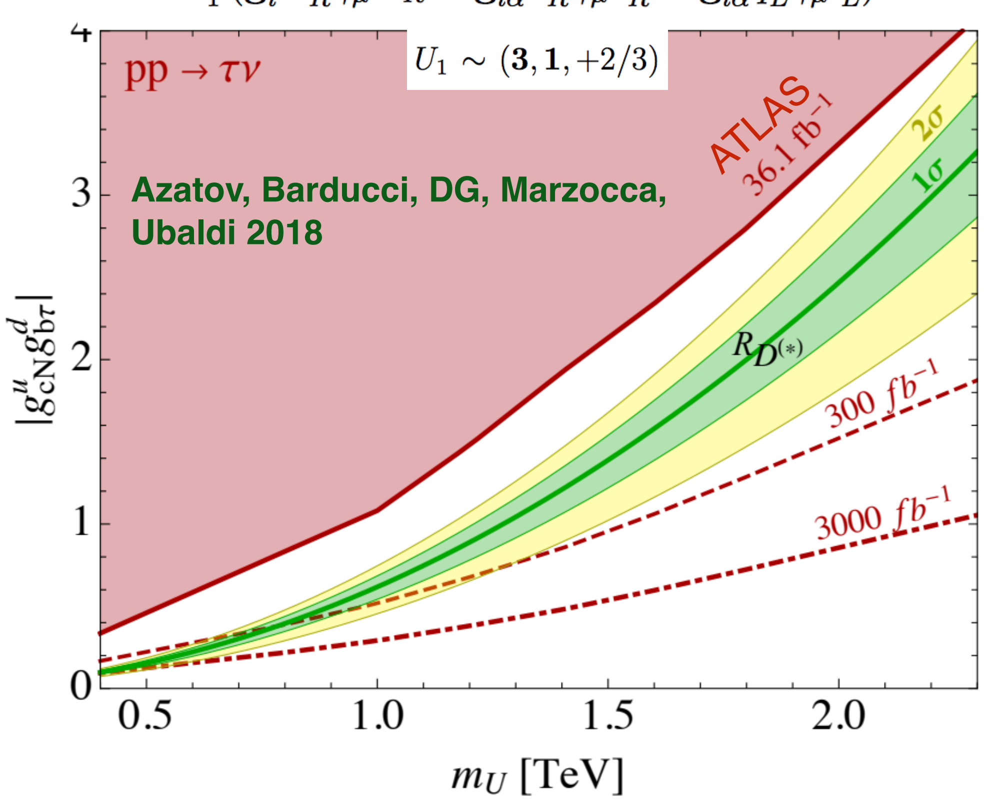
$$\mathcal{O}^{cb\ell}_{\rm TR} = [\bar c\,\sigma^{\mu\nu}\, b][\bar\ell\,\sigma_{\mu\nu}\, P_R\,\nu]$$

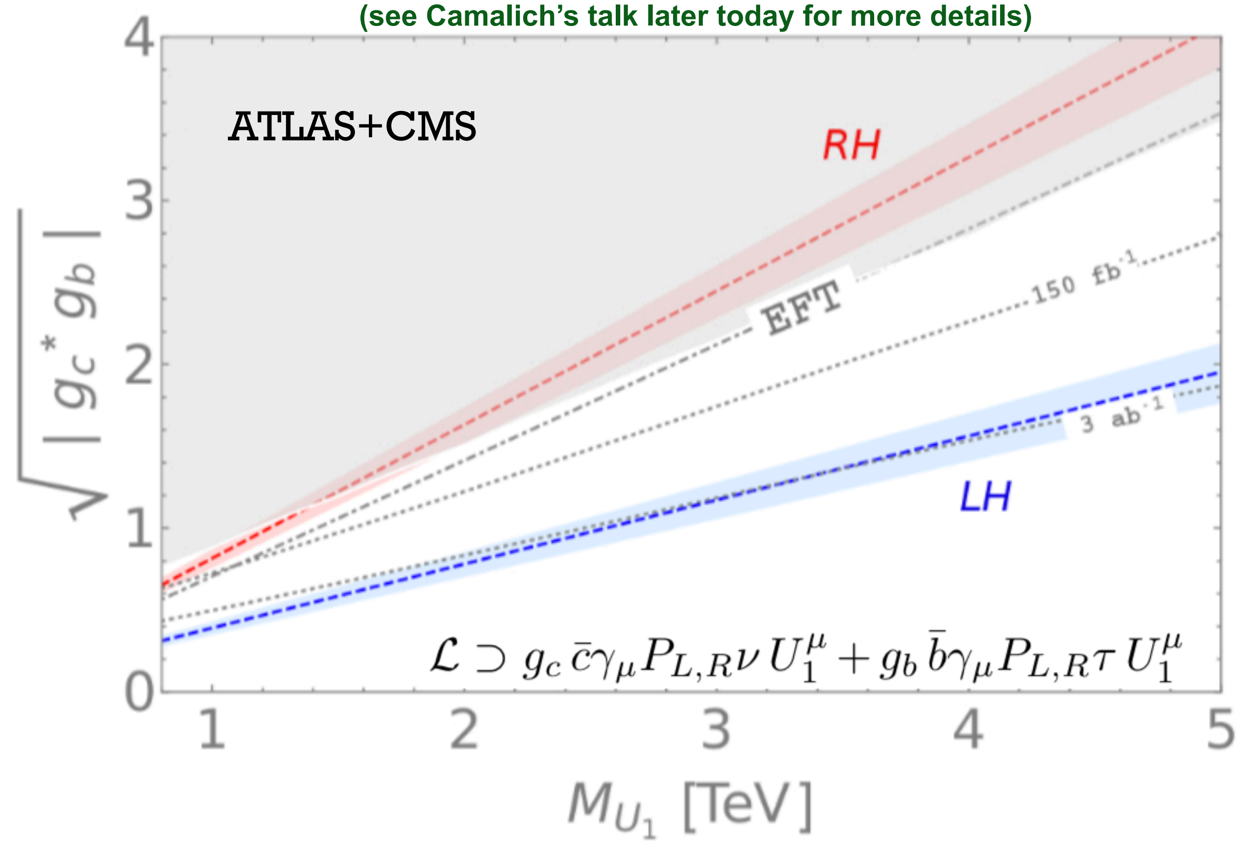
(V+A) ⊗ (V+A)

$$\mathcal{L}^{\rm dim6} \supset -\frac{1}{\Lambda^2}\sum_{p'r's't'}\Big\{[\tilde C_{\nu edu}]'_{prst}\,(\bar\nu'_p\gamma^\mu e'_r)\,(\bar d'_s\gamma_\mu u'^j_t) + \text{h.c.}$$
$$+[\tilde C^{(1)}_{\nu ldq}]'_{prst}\,(\bar\nu'_p l'^j_r)\,\epsilon_{jk}\,(\bar d'_s q'^j_t) + \text{h.c.}$$
$$+[\tilde C^{(1)}_{\nu lqu}]'_{prst}\,(\bar\nu'_p l'^j_r)\,(\bar q'^j_s u'_t) + \text{h.c.}$$
$$+[\tilde C^{(3)}_{\nu ldq}]'_{prst}\,(\bar\nu'_p \sigma^{\mu\nu} l'^j_r)\,\epsilon_{jk}\,(\bar d'_s \sigma_{\mu\nu} q'^j_t) + \text{h.c.}$$
$$+[\tilde C_{\phi\nu e}]'_{pr}\,(\phi^j\epsilon_{jk}\, i(D_\mu\phi)^k)\,(\bar\nu'_p\gamma^\mu e'_r) + \text{h.c.}\Big\}$$

$$\mathcal{L} = U_1^\mu(\mathbf{g}^u_i \bar u^i_R\gamma_\mu N_R + \mathbf{g}^d_{i\alpha}\bar d^i_R\gamma_\mu e^\alpha_R + \mathbf{g}^q_{i\alpha}\bar q^i_L\gamma_\mu l^\alpha_L) + h.c.$$



Greljo, Camalich, Ruiz-Álvarez 2018
(see Camalich's talk later today for more details)



(V+A)⊗(V+A) solution strongly disfavoured by $pp \to \tau\nu$ data.

Scalar, Pseudo-Scalar operators

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

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

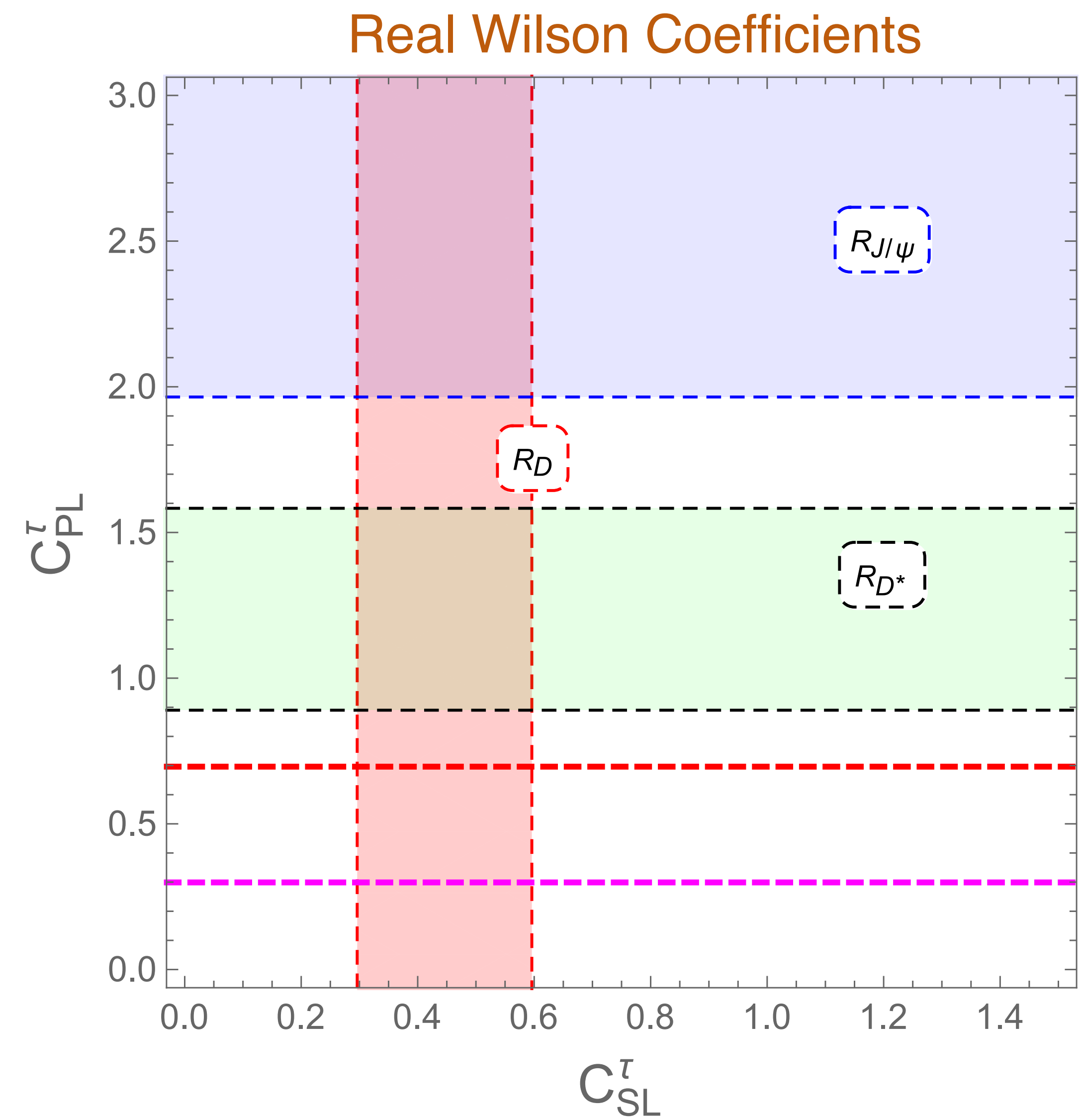
$$\mathcal{O}^{cb\ell}_{\rm SL} = [\bar{c}\,b][\bar{\ell}\,P_L\,\nu]$$

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

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

$$\langle D(p_D, M_D)|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle = 0$$

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}b|\bar{B}(p_B, M_B)\rangle = 0$$



Scalar, Pseudo-Scalar operators

[redacted]

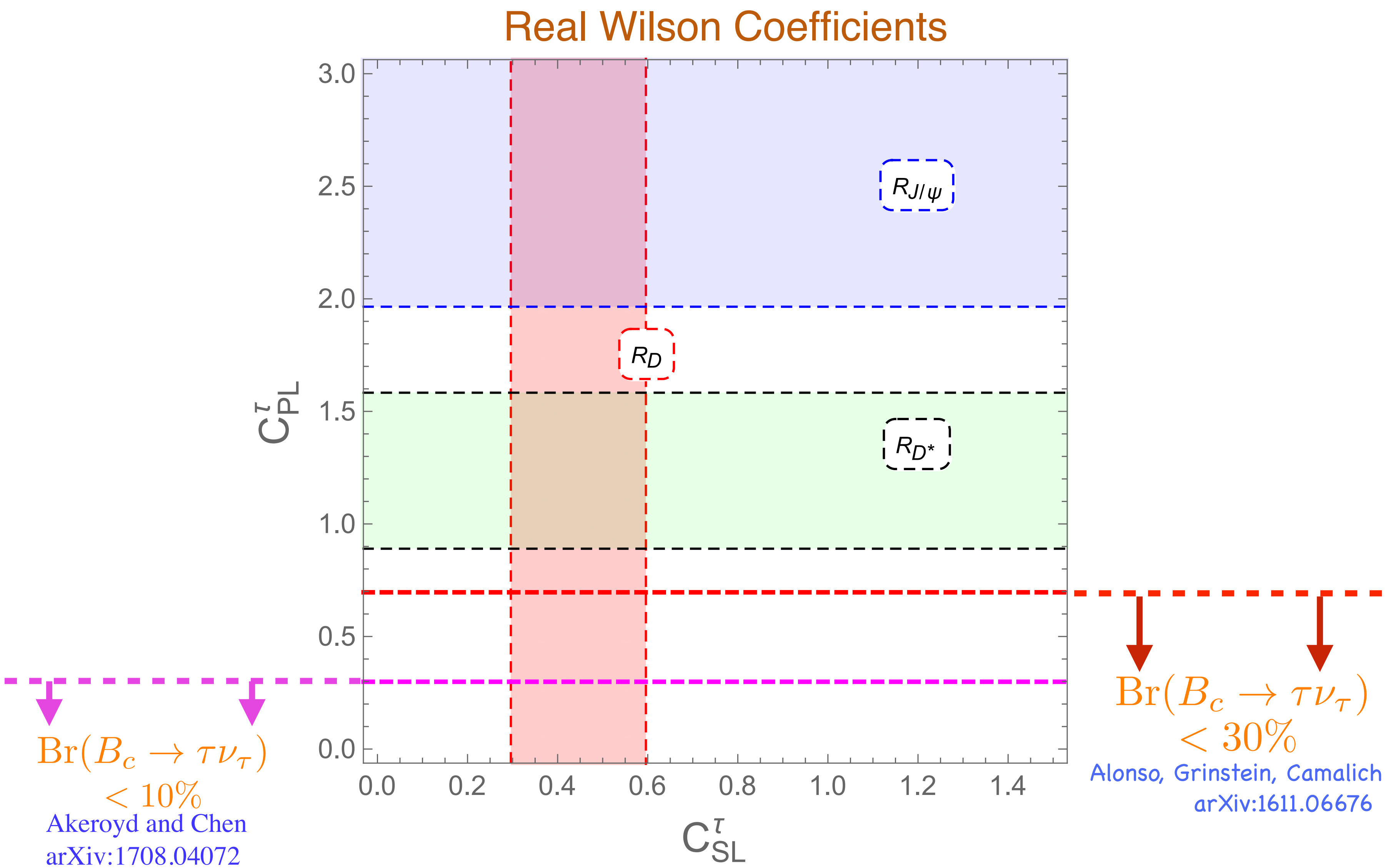
$$\mathcal{O}_{\rm SL}^{cb\ell} = [\bar{c}\, b][\bar{\ell}\, P_L\, \nu]$$

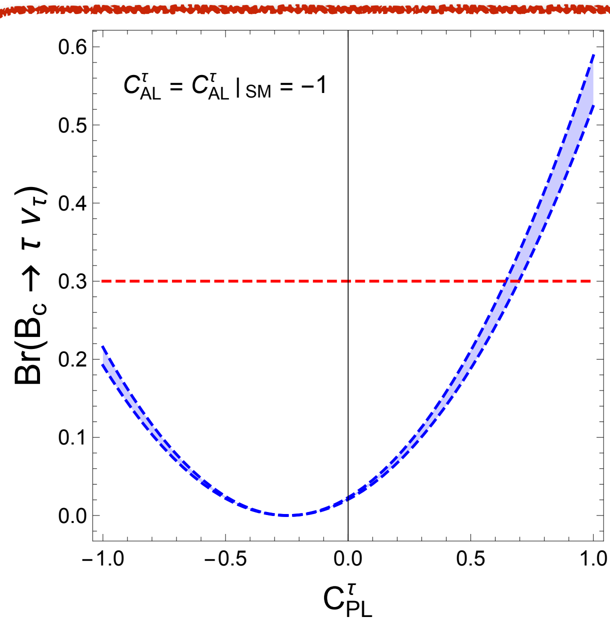
$$\mathcal{O}_{\rm PL}^{cb\ell} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\, \nu]$$

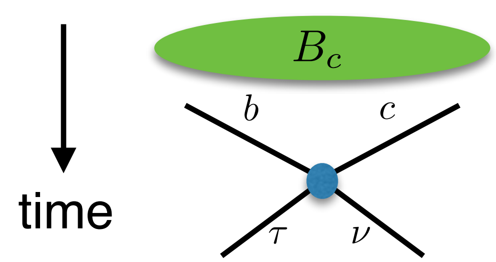
[redacted]

$$\langle D(p_D, M_D)|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle = 0$$

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}b|\bar{B}(p_B, M_B)\rangle = 0$$







$$\mathcal{B}(B_c^- \to \tau^-\bar{\nu}_\tau) = \frac{1}{8\pi} G_F^2 |V_{cb}|^2 f_{B_c}^2 m_\tau^2 m_{B_c} \tau_{B_c} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left(\left|C_{AL}^{cb\tau} - \frac{m_{B_c}^2}{m_\tau(m_b + m_c)} C_{PL}^{cb\tau}\right|^2\right)$$

Scalar+ Tensor operator

$$\left(\bar{l'}^k u'\right)\epsilon_{jk}\left(\bar{q'}^j e'\right) \rightarrow 4\left(\bar{l'}^j e'\right)\epsilon_{jk}\left(\bar{q'}^k u'\right) + \left(\bar{l'}^j \sigma_{\mu\nu} e'\right)\epsilon_{jk}\left(\bar{q'}^k \sigma^{\mu\nu} u'\right)$$

$$\mathrm{C}^{\tau}_{\mathrm{SL}} = -\mathrm{C}^{\tau}_{\mathrm{PL}} \quad = \quad 2\ \mathrm{C}^{\tau}_{\mathrm{TL}}$$

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

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

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

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

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

Scalar+ Tensor operator

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$R_2(3, 2, 7/6)$
Leptoquark

$C^{\tau}_{\rm SL} = -C^{\tau}_{\rm PL}$ = $2\ C^{\tau}_{\rm TL}$

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

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

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$R_2(3,2,7/6)$ Leptoquark

$$C^{\tau}_{SL} = -C^{\tau}_{PL} \quad = \quad 2\ C^{\tau}_{TL}$$

$$\left(\bar{l'}^k q'^{Cj}\right)\epsilon_{jk}\left(\overline{u'^C} e'\right) \to 4\left(\bar{l'}^j e'\right)\epsilon_{jk}\left(\bar{q'}^k u'\right) - \left(\bar{l'}^j \sigma_{\mu\nu} e'\right)\epsilon_{jk}\left(\bar{q'}^k \sigma^{\mu\nu} u'\right)$$

$S_1(\bar{3},1,1/3)$ Leptoquark

$$C^{\tau}_{SL} = -C^{\tau}_{PL} \quad = \quad -2\ C^{\tau}_{TL}$$

$$\mathcal{O}^{cb\ell}_{VL} = [\bar{c}\,\gamma^{\mu}\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{AL} = [\bar{c}\,\gamma^{\mu}\,\gamma_5\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{SL} = [\bar{c}\,b][\bar{\ell}\,P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{PL} = [\bar{c}\,\gamma_5\,b][[\bar{\ell}\,P_L\,\nu]$$
$$\mathcal{O}^{cb\ell}_{TL} = [\bar{c}\,\sigma^{\mu\nu}\,b][\bar{\ell}\,\sigma_{\mu\nu}\,P_L\,\nu]$$

Scalar+ Tensor operator

$$\left(\bar{l}'^{k} u'\right) \epsilon_{jk} \left(\bar{q}'^{j} e'\right) \to 4 \left(\bar{l}'^{j} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} u'\right) + \left(\bar{l}'^{j} \sigma_{\mu\nu} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} \sigma^{\mu\nu} u'\right)$$

$R_2(3,2,7/6)$ Leptoquark

$$C^{\tau}_{SL} = -C^{\tau}_{PL} \quad = \quad 2\ C^{\tau}_{TL}$$

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$S_1(\bar{3},1,1/3)$ Leptoquark

$$C^{\tau}_{SL} = -C^{\tau}_{PL} \quad = \quad -2\ C^{\tau}_{TL}$$

[redacted]

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

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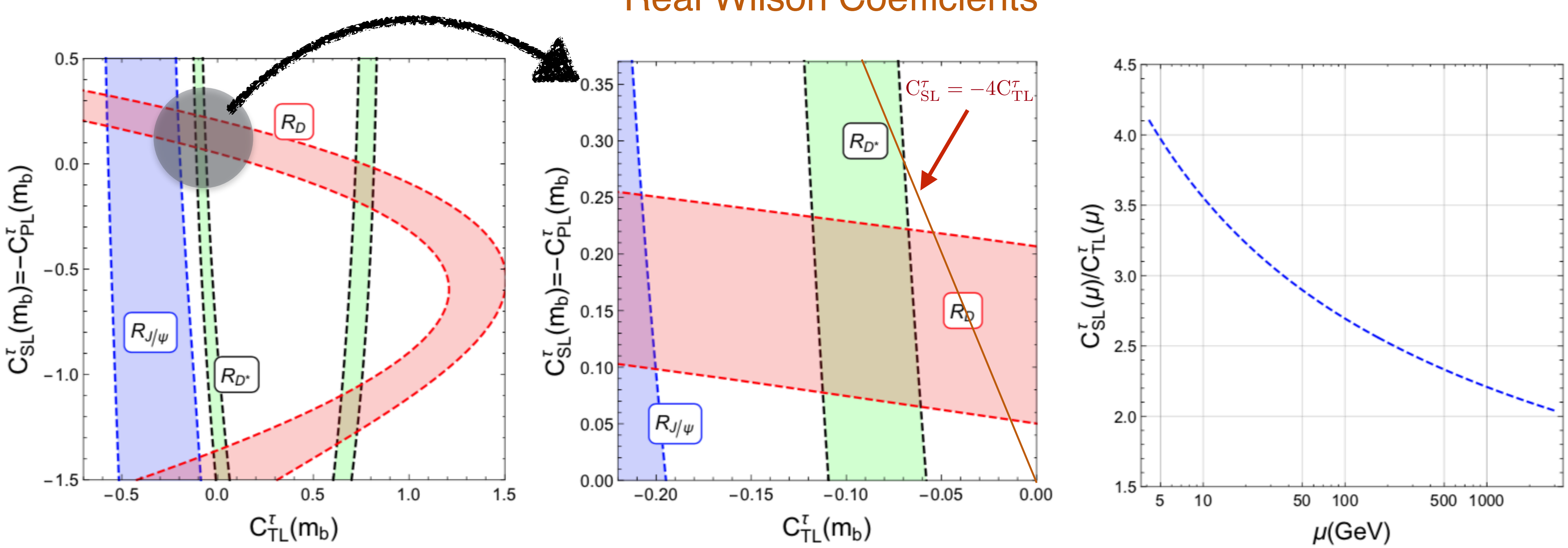
Real Wilson Coefficients



Scalar+ Tensor operator

$$\left(\bar{l}'^{k} u'\right) \epsilon_{jk} \left(\bar{q}'^{j} e'\right) \to 4 \left(\bar{l}'^{j} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} u'\right) + \left(\bar{l}'^{j} \sigma_{\mu\nu} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} \sigma^{\mu\nu} u'\right)$$

$R_2(3,2,7/6)$ Leptoquark

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$$\left(\bar{l}'^{k} q'^{Cj}\right) \epsilon_{jk} \left(\overline{u'^{C}} e'\right) \to 4 \left(\bar{l}'^{j} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} u'\right) - \left(\bar{l}'^{j} \sigma_{\mu\nu} e'\right) \epsilon_{jk} \left(\bar{q}'^{k} \sigma^{\mu\nu} u'\right)$$

$S_1(\bar{3},1,1/3)$ Leptoquark

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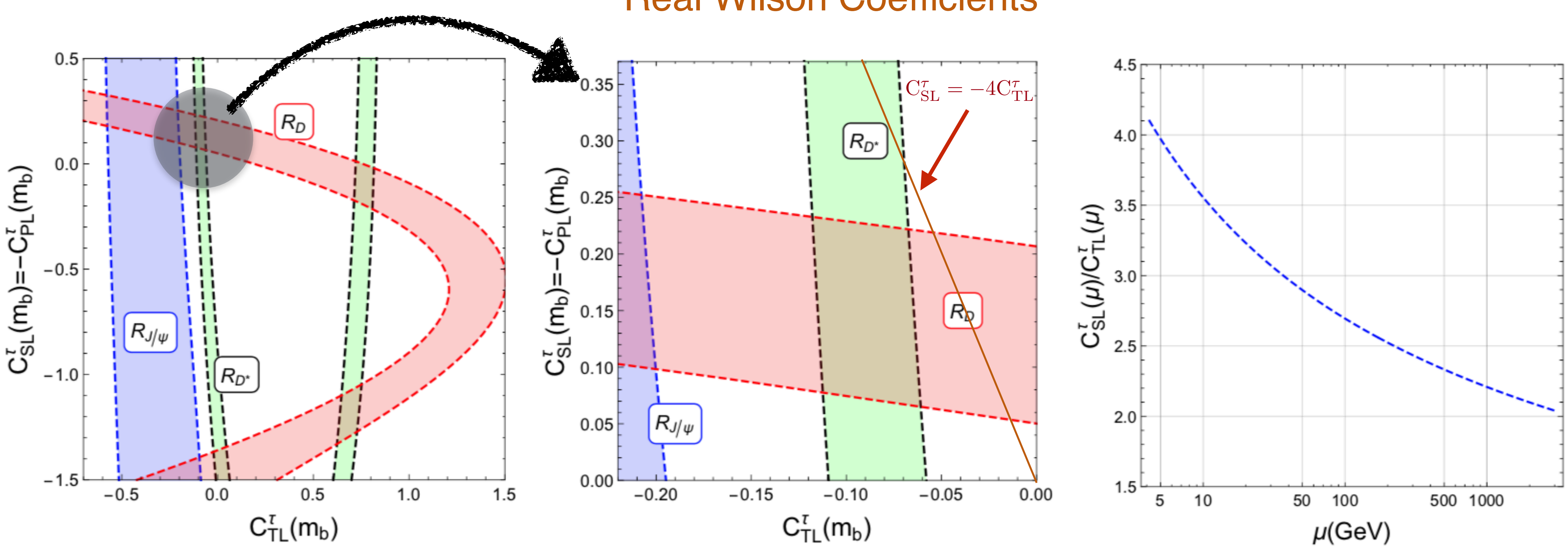
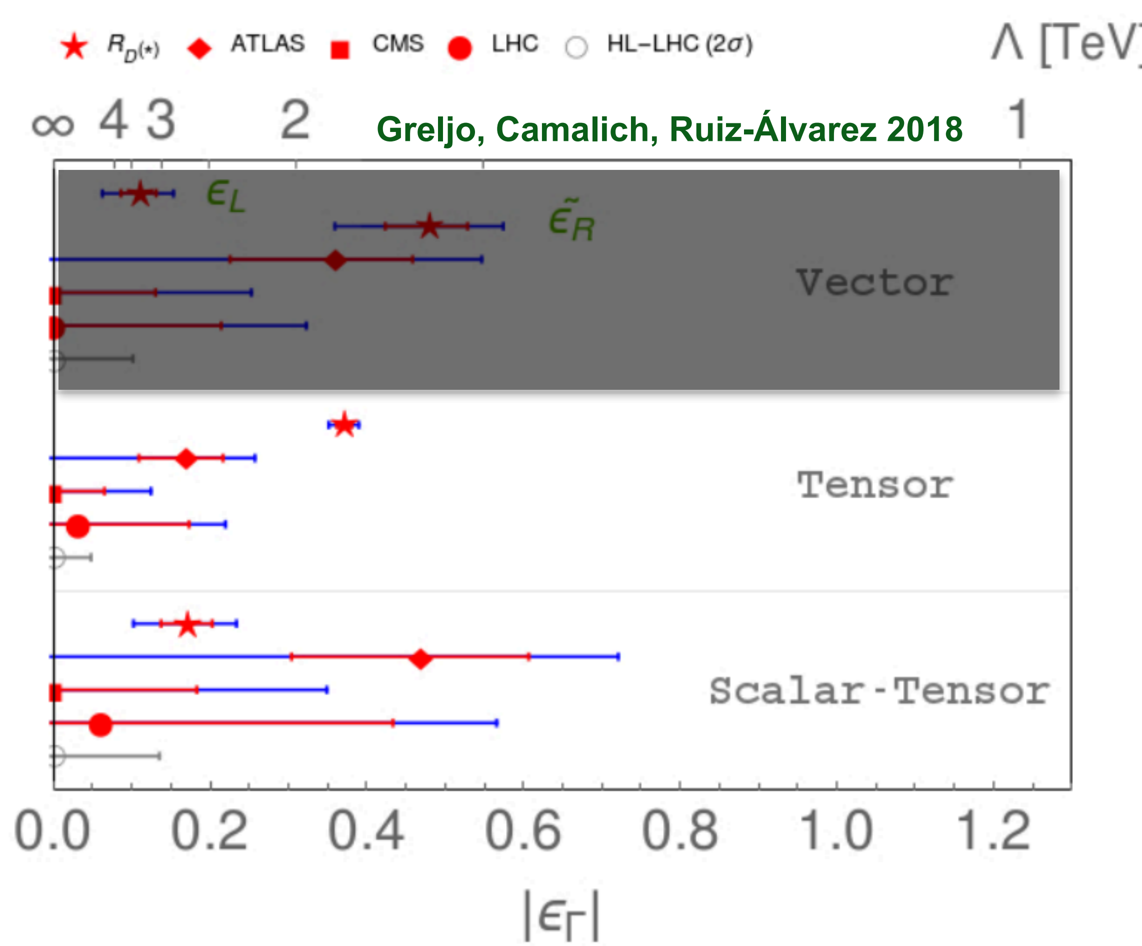
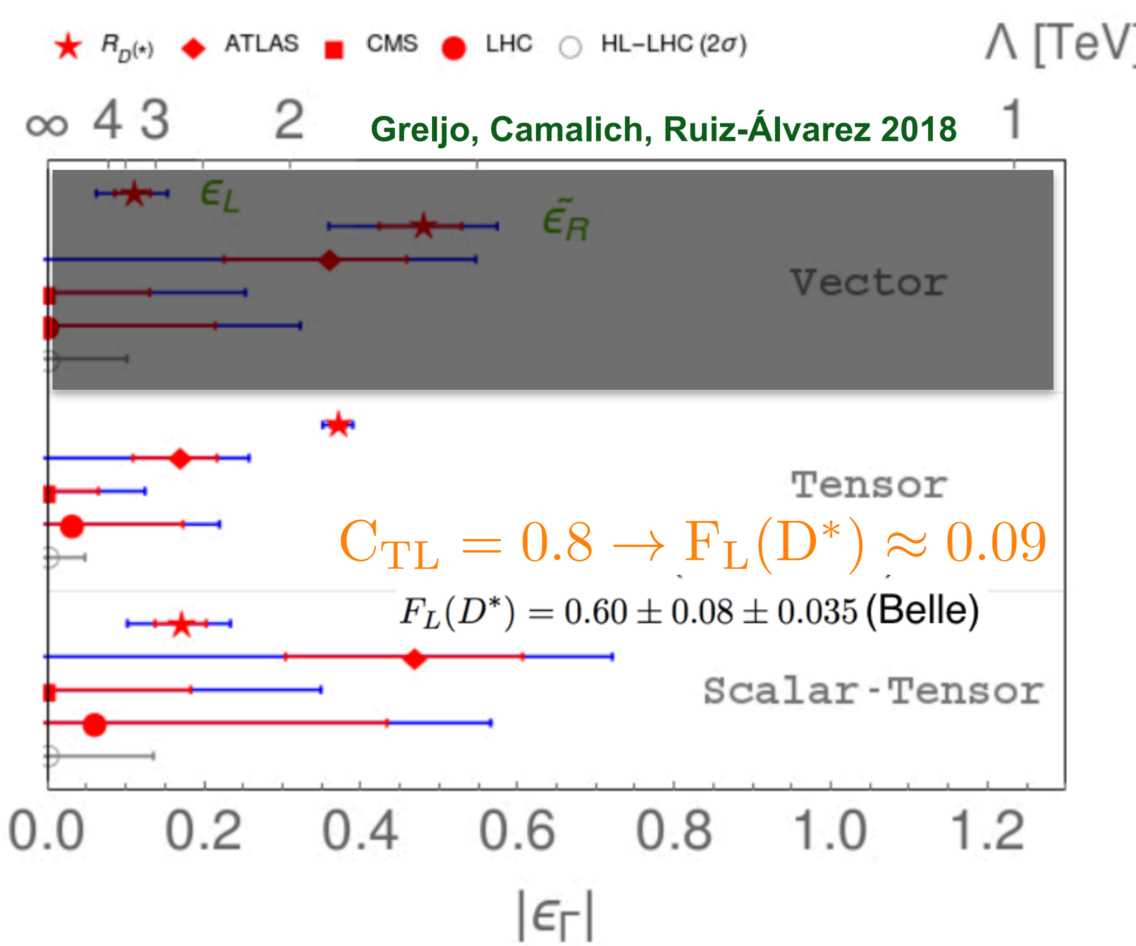
Real Wilson Coefficients



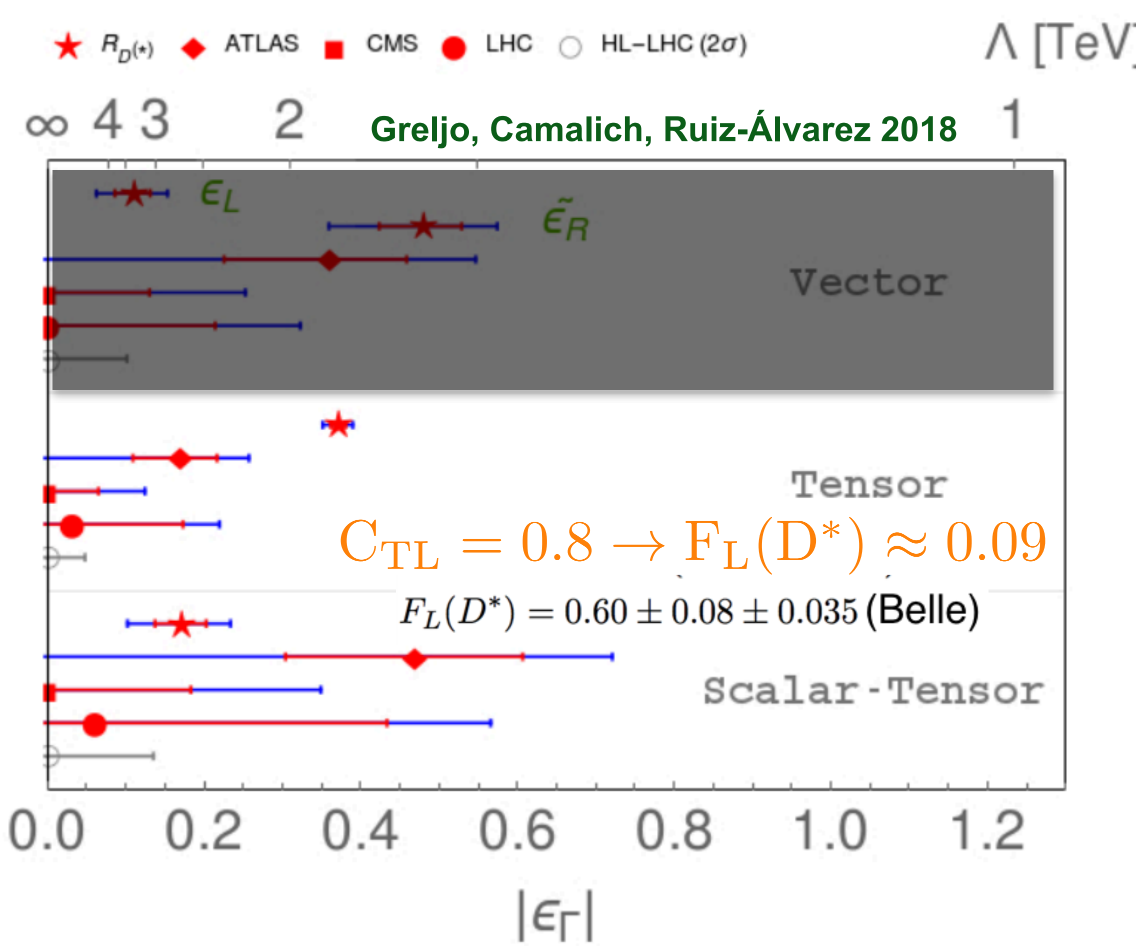
Scalar+ Tensor operator



Scalar+ Tensor operator



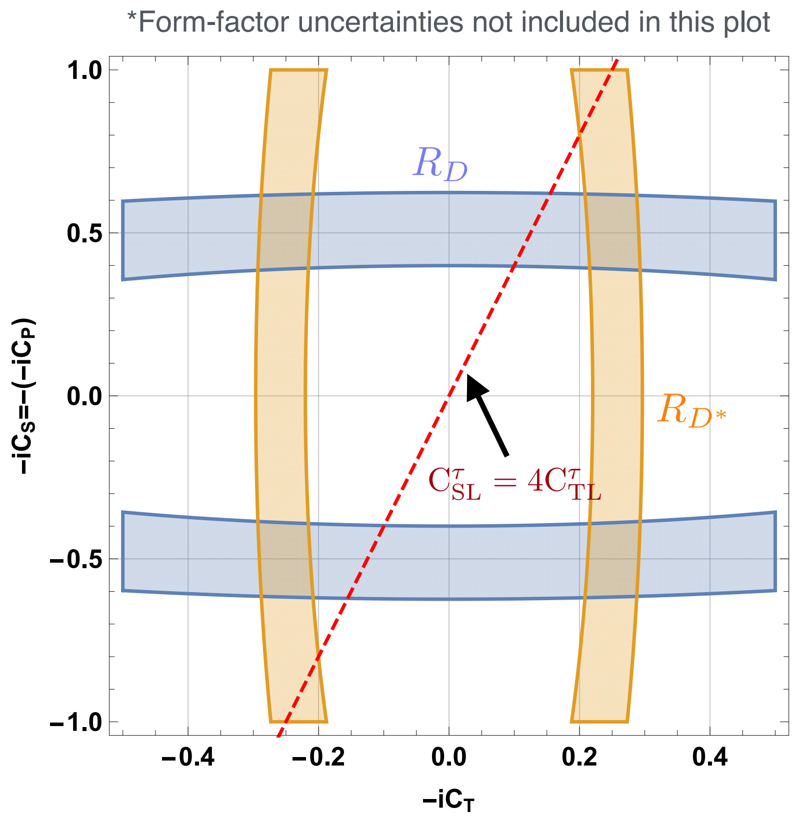
Scalar+ Tensor operator



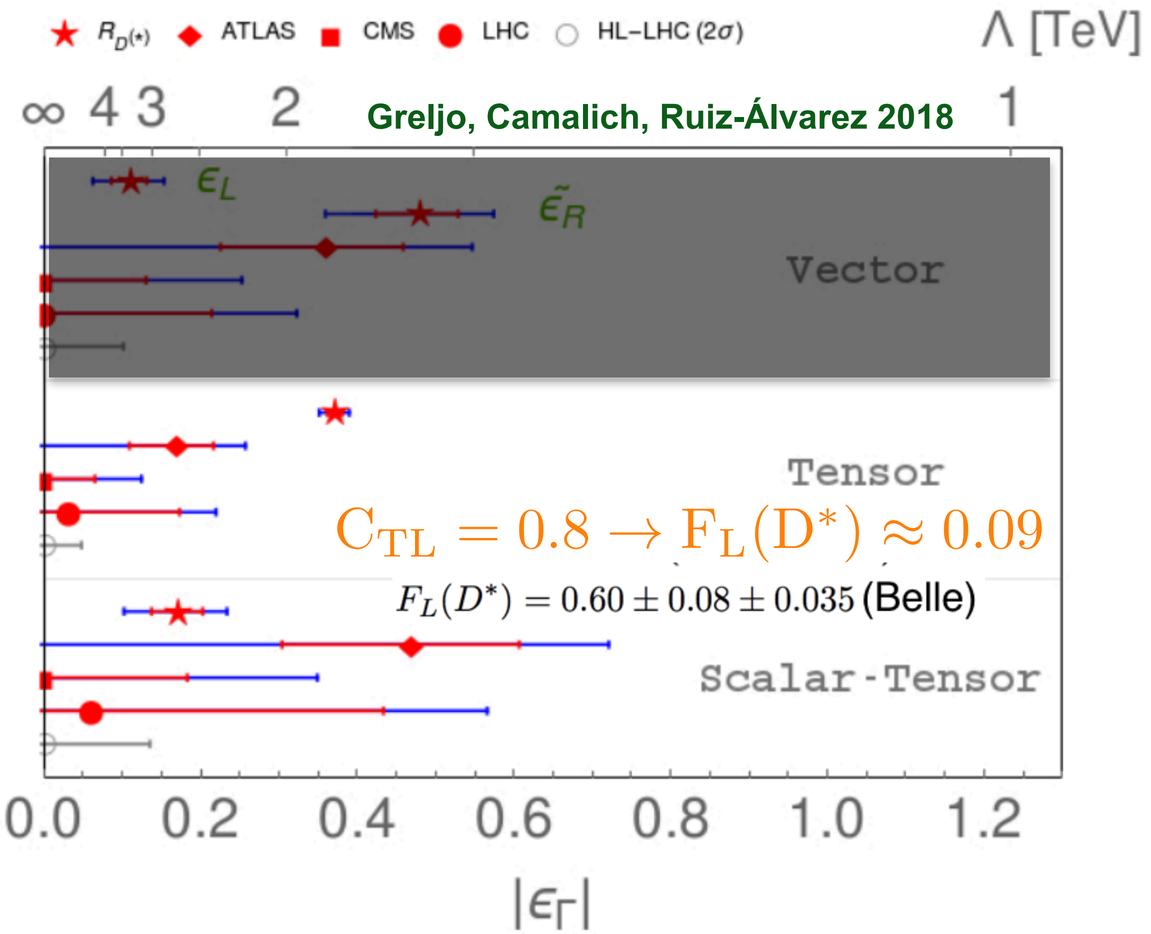
Only-tensor solution ruled out both by $pp \to \tau\nu$ and $F_L(D^*)$.

Scalar+ Tensor operator

Imaginary Wilson Coefficients



Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari (arXiv:1806.05689)
See also: Blanke, Crivellin, Kitahara 2018



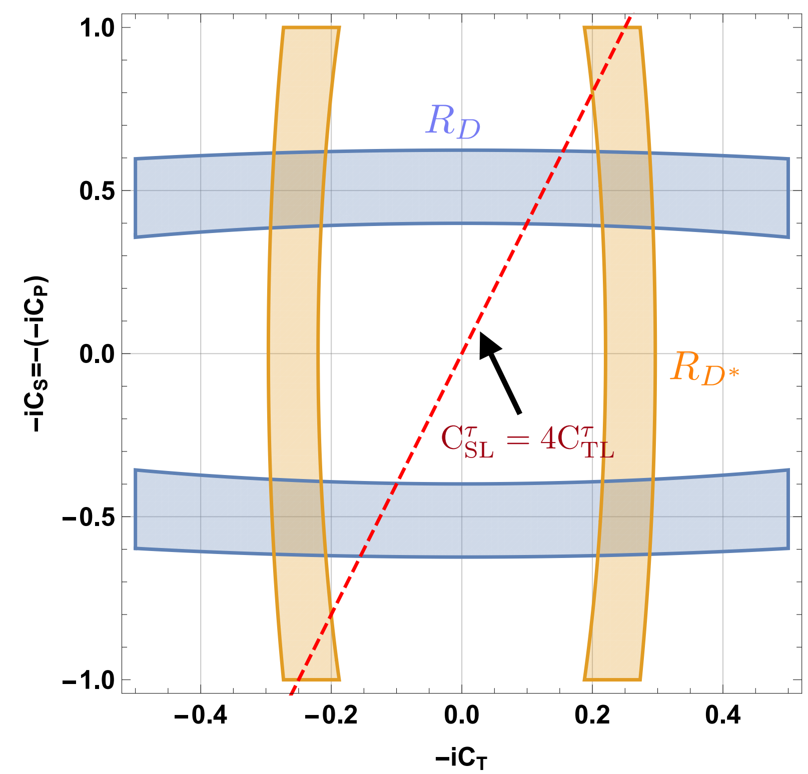
$C_{TL} = 0.8 \rightarrow F_L(D^*) \approx 0.09$

$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035$ (Belle)

Only-tensor solution ruled out both by $pp \to \tau\nu$ and $F_L(D^*)$.

Scalar+ Tensor operator

*Form-factor uncertainties not included in this plot



Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari (arXiv:1806.05689)
See also: Blanke, Crivellin, Kitahara 2018

Imaginary Wilson Coefficients

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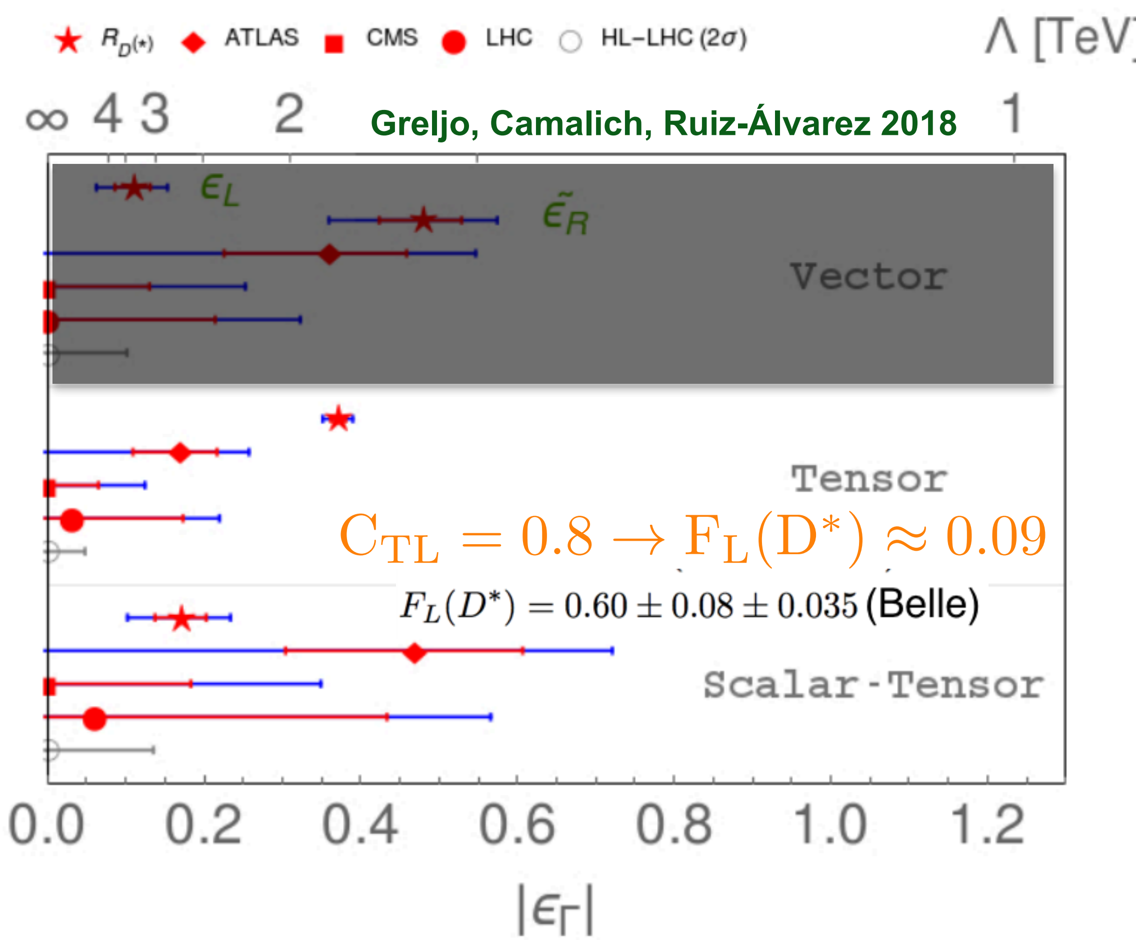
$R_2(3,2,7/6)$
Leptoquark

$C^\tau_{SL} = -C^\tau_{PL}$ = $2\ C^\tau_{TL}$ ✔



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Scalar+ Tensor operator

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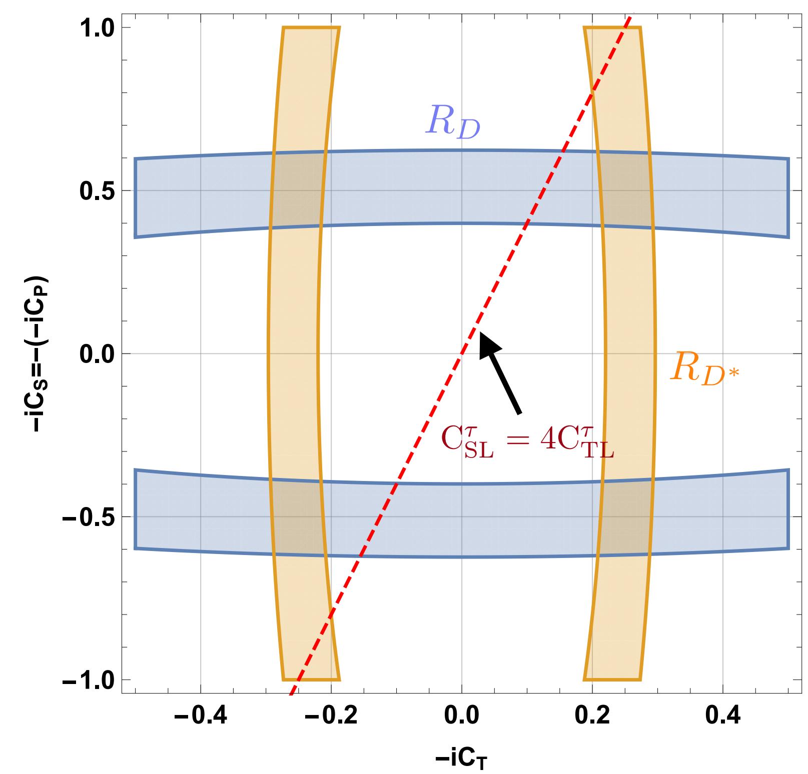

Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari (arXiv:1806.05689)
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Imaginary Wilson Coefficients

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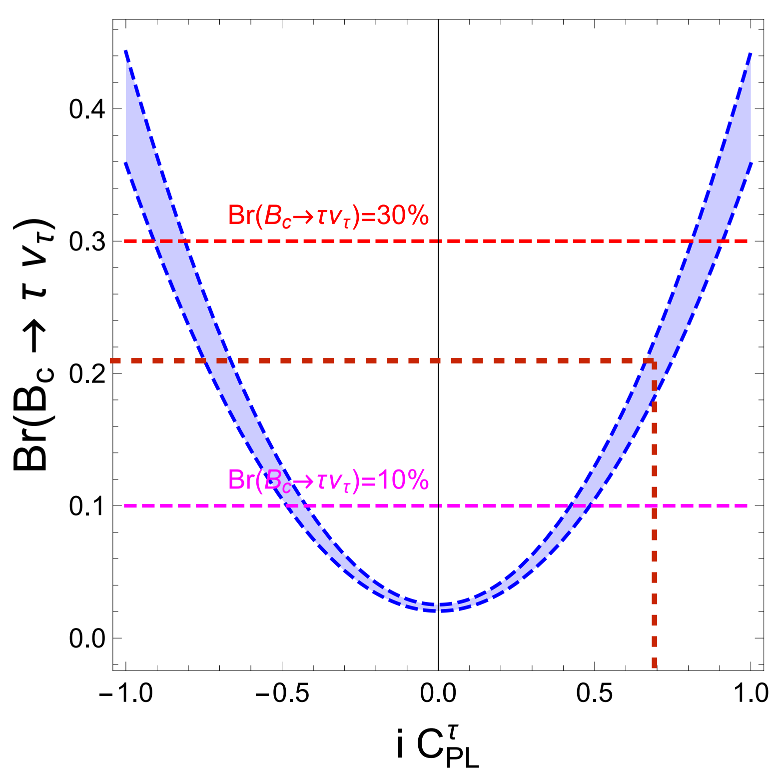
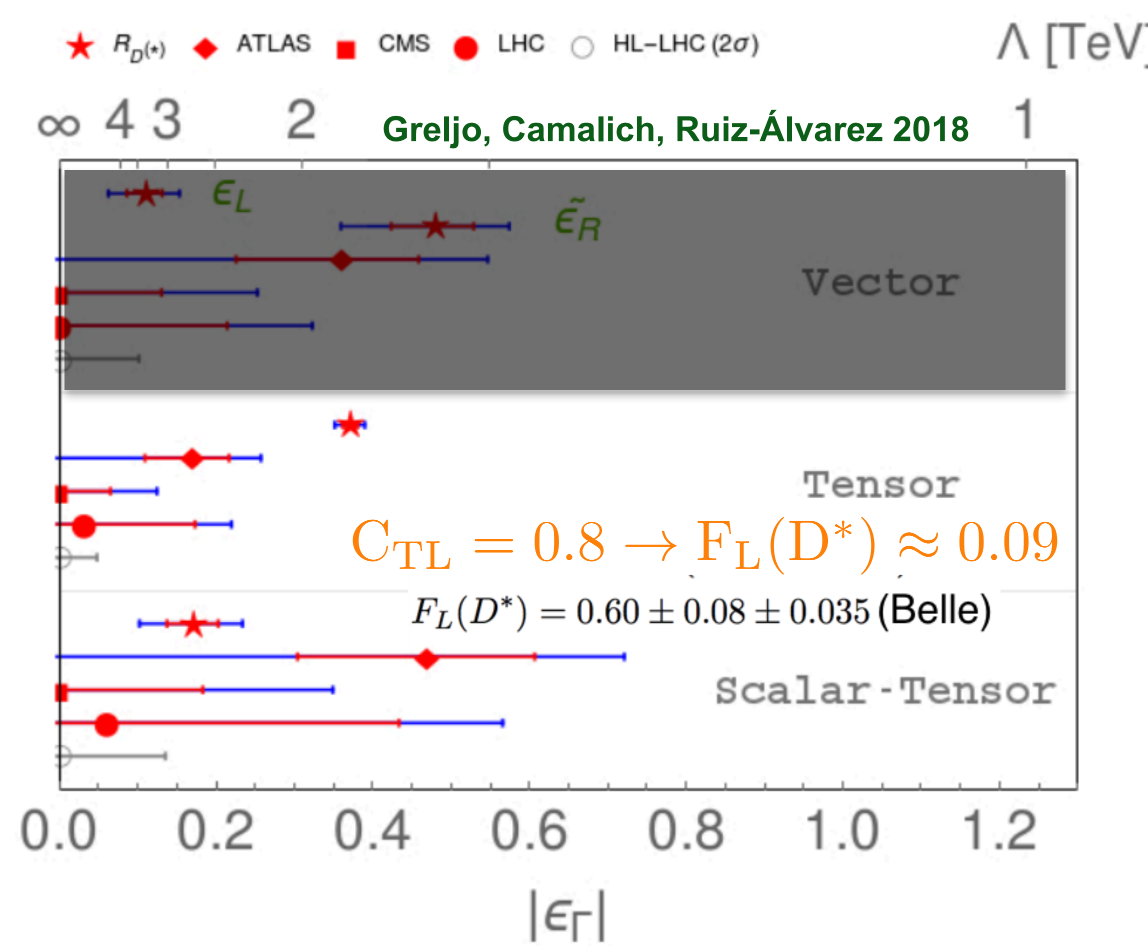
$R_2(3,2,7/6)$
Leptoquark

$$C^{\tau}_{SL} = -C^{\tau}_{PL} = 2\ C^{\tau}_{TL}$$





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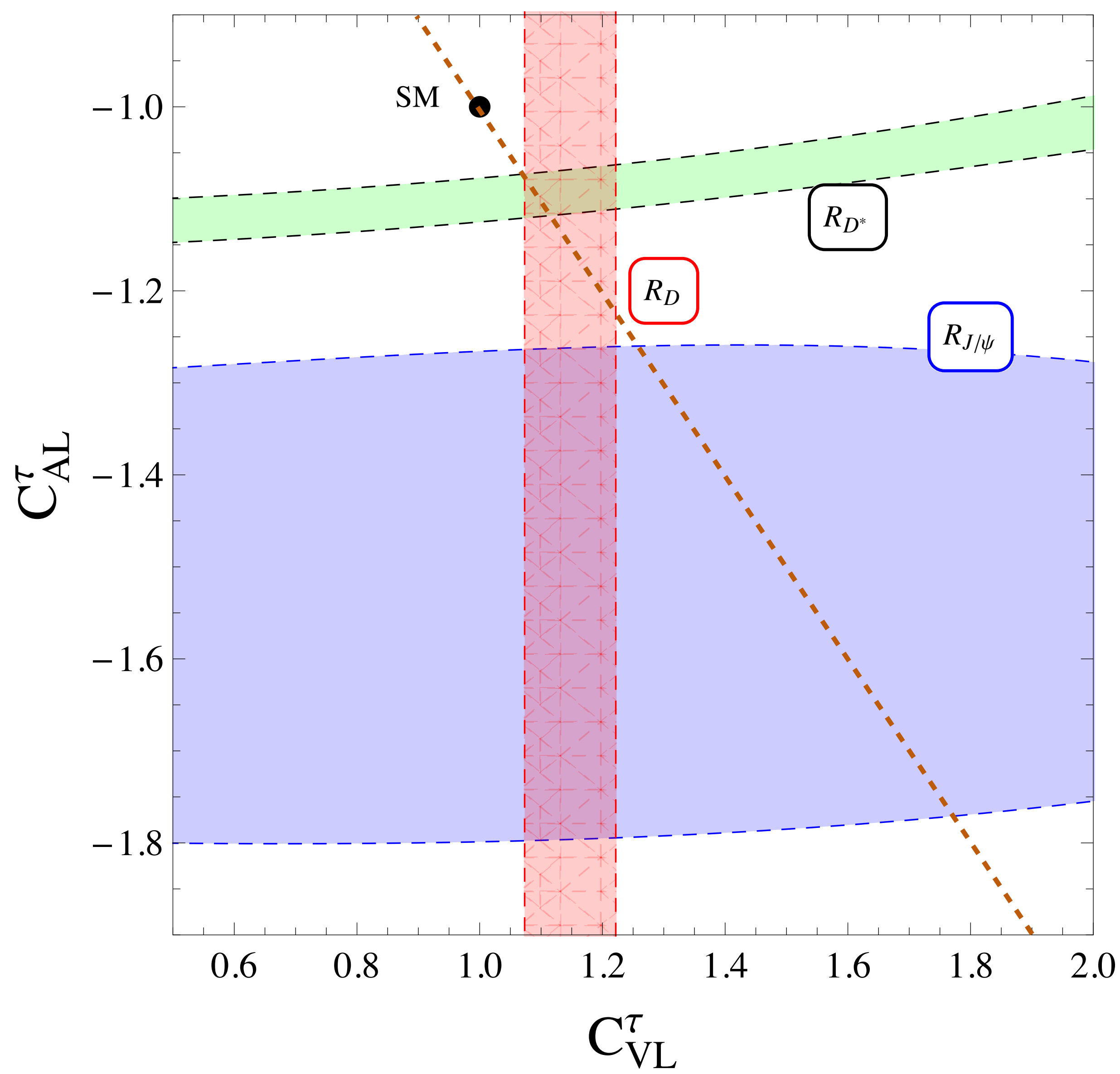
Only-tensor solution ruled out both by $pp \to \tau\nu$ and $F_L(D^*)$.

Vector, Axial-Vector operators

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

$$\langle D(p_D, M_D)|\bar{c}\gamma^{\mu}\gamma_5 b|\bar{B}(p_B, M_B)\rangle \;=\; 0$$

→ $\mathcal{O}^{cb\ell}_{\rm AL}$ does not contribute to R_D



$C^{\tau}_{\rm VL} = -C^{\tau}_{\rm AL} \approx 1.1$ explains both R_D and R_{D^*}

→ $\frac{g^2_{NP}}{\Lambda^2}\,[\bar{c}\gamma^{\mu}{\rm P}_L b]\,[\bar{\ell}\,\gamma_{\mu}{\rm P}_L\,\nu]$ → $\Lambda \approx g_{\rm NP}\,2.7\,{\rm TeV}$

Vector, Axial-Vector operators: correlations

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

Vector, Axial-Vector operators: correlations

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

$b \to c\,\tau\,\nu$:

$$([C_{lq}^{(3)}]'_{3313} + ([C_{lq}^{(3)}]'_{3331})^*)V_{cd} + ([C_{lq}^{(3)}]'_{3323} + ([C_{lq}^{(3)}]'_{3332})^*)V_{cs} + ([C_{lq}^{(3)}]'_{3333} + ([C_{lq}^{(3)}]'_{3333})^*)V_{cb} \gtrsim 0.06 \left(\frac{\Lambda^2}{\mathrm{TeV}^2}\right) \quad (R_D, R_{D^*} \ @\ 1\sigma)$$

$[C_{lq}^{(3)}]'_{p'r's't'}$ are defined in the mass basis of the left-chiral down quarks and left-chiral charged leptons.

$[C_{lq}^{(3)}]'_{p'r's't'}$ are also assumed to be diagonal in the Lepton flavours.

Vector, Axial-Vector operators: correlations

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

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$[C_{lq}^{(3)}]'_{p'r's't'}$ are also assumed to be diagonal in the Lepton flavours.

$\text{Br}(B^0 \to \pi^0 \bar{\nu}\,\nu)$ →

$$-0.018\left(\frac{\Lambda^2}{\text{TeV}^2}\right) \lesssim [C_{lq}^{(3)}]'_{3313} + [C_{lq}^{(3)}]'^{*}_{3331} \lesssim 0.023\left(\frac{\Lambda^2}{\text{TeV}^2}\right)$$

$\text{Br}(B^0 \to K^{*0}\bar{\nu}\nu)$ →

$$-0.005\left(\frac{\Lambda^2}{\text{TeV}^2}\right) \lesssim [C_{lq}^{(3)}]'_{3323} + [C_{lq}^{(3)}]'^{*}_{3332} \leq 0.025\left(\frac{\Lambda^2}{\text{TeV}^2}\right)$$

For $\mathrm{R}_{\mathrm{D,D^*}}$ one needs:

$$([C_{lq}^{(3)}]'_{3333} + [C_{lq}^{(3)}]'^{*}_{3333})V_{cb} \gtrsim 0.03\left(\frac{\Lambda^2}{\text{TeV}^2}\right)$$

Vector, Axial-Vector operators: correlations

Feruglio, Paradisi, Pattori 2016

$$\left(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'}\right)\left(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}\right) \to \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}\right) \to \Delta g^\tau_L,\ -\Delta g^\nu_L$$

Vector, Axial-Vector operators: correlations

Feruglio, Paradisi, Pattori 2016

$$(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'})\,(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}) \to \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}) \to \Delta g_L^\tau,\ -\Delta g_L^\nu$$

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

Vector, Axial-Vector operators: correlations

Feruglio, Paradisi, Pattori 2016

$$\left(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'}\right)\left(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}\right) \to \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}\right) \to \Delta g_L^\tau,\ -\Delta g_L^\nu$$

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

Vector, Axial-Vector operators: correlations

Feruglio, Paradisi, Pattori 2016

$$(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'})\,(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}) \to \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}) \to \Delta g^\tau_L,\ -\Delta g^\nu_L$$

$$\left|[C^{(3)}_{lq}]'_{3333} + [C^{(3)}_{lq}]'^{*}_{3333}\right| \lesssim \frac{0.017}{V_{cb}}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^2 \frac{1}{1+0.6\log\frac{\Lambda}{\mathrm{TeV}}}$$

Introduce:

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

$$\to \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)(\bar{l}'_{p'}\,\gamma^\mu\, l'_{r'}) \to +\Delta g^\tau_L,\ +\Delta g^\nu_L$$

Vector, Axial-Vector operators: correlations

Feruglio, Paradisi, Pattori 2016

$$(\bar{l}'_{p'}\gamma_\mu\sigma^I l'_{r'})\,(\bar{q}'_{s'}\gamma^\mu\sigma^I q'_{t'}) \to \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\,(\bar{l}'_{p'}\,\sigma^I\gamma^\mu\, l'_{r'}) \to \Delta g^\tau_L,\ -\Delta g^\nu_L$$

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

$$\to \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\,(\bar{l}'_{p'}\,\gamma^\mu\, l'_{r'}) \to +\Delta g^\tau_L,\ +\Delta g^\nu_L$$

$\Delta g^\tau_L,\ \Delta g^\nu_L,\ \Delta g^\tau_W$ →

$$\left|[C^{(3,1)}_{lq}]'_{3333} + [C^{(3,1)}_{lq}]'^{*}_{3333}\right| \lesssim \frac{0.025}{V_{cb}}\left(\frac{\Lambda}{\text{TeV}}\right)^2 \frac{1}{1+0.6\log\frac{\Lambda}{\text{TeV}}}\,.$$

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

Vector, Axial-Vector operators: correlations

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

Vector, Axial-Vector operators: correlations

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Assume appropriate UV contributions at the matching scale that take care of the $\Delta g_L^{\tau,\nu}$ constraints. In this case, one can explain the anomalies by the term proportional to V_{cb} .

See, for example, Barbieria and Tesi 2017

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✓

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→ Achieved automatically by the $U_1 \sim (\mathbf{3}, \mathbf{1}, +2/3)$ Leptoquark

Alonso , Grinstein , Camalich 2015

Barbieria, Isidori, Pattori, Senia 2015

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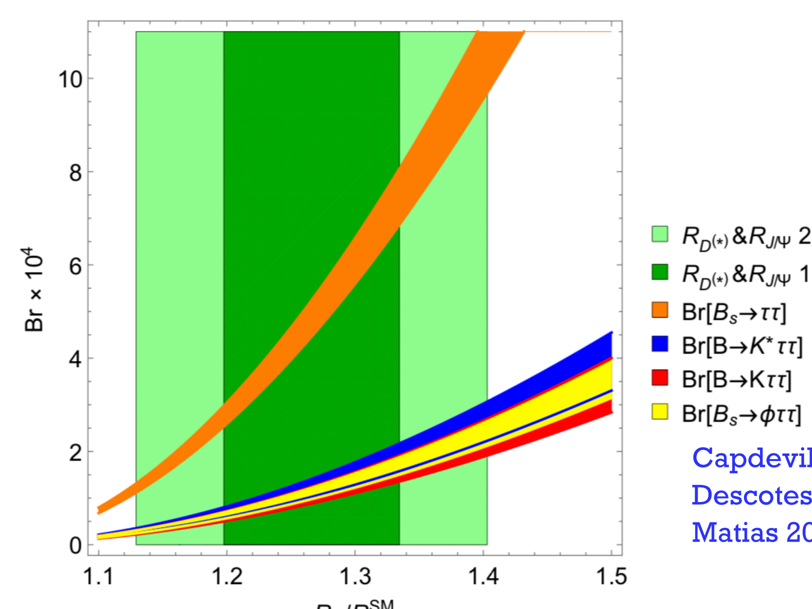
Large enhancements in $b \to s\tau\tau$ modes:
$B_s \to \tau^+\tau^-$, $B \to K/K^*\,\tau^+\tau^-$



Capdevila, Crivellin, Descotes-Genon, Hofer, Matias 2017

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$\mathrm{Br}(B^0 \to \pi^0 \bar{\nu}\,\nu)$ →

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→ **Thus, this possibility is strongly disfavoured**

$\Delta F = 2$ constraints

SU(2)$_L$ vector → $[C_{qq}^{(3)}]'_{p'r's't'} \left(\bar{q}'_{p'}\gamma_\mu \tau^I q'_{r'}\right) \left(\bar{q}'_{s'}\gamma^\mu \tau^I q'_{t'}\right)$

$$\mathcal{L}_{\Delta F=2} = \left(\bar{\psi}_{i\,L} \left[\qquad \right]^i_{\ j} \gamma^\mu \psi_{j\,L}\right)^2$$

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

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

Minimal composite Higgs + partial compositeness

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

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$$\rightarrow\ M_*/g_* \lesssim\ 0.45\,\mathrm{TeV}$$

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

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$$\rightarrow\; M_*/g_* \lesssim 0.45\,\mathrm{TeV}$$

Composite Leptoquark $\Longrightarrow$ $M_*/g_* \lesssim 0.63\,\mathrm{TeV}$

SO(5) × SU(4)

↓ (3,1,2/3)

Assuming that the electroweak triplet and the leptoquarks have the same mass and coupling, and hierarchrical $\hat{s}_q$, $(\hat{s}_l)_{33}\sim 1$

Azatov, Bardhan, DG, Sgarlata, Venturini 2018

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$\rightarrow$

Composite Leptoquark = 

TeV

SO(5) $\times$ SU(4) $\downarrow$ (3,1,2/3)

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Azatov, Bardhan, DG, Sgarlata, Venturini 2018

Summary

(V+ A) : **disfavoured by** High-p_T searches

(V - A) : U_1^μ (3, 1, 2/3) Leptoquark

Large enhancements in $b \to s\,\tau\,\tau$ modes

Scalar : **disfavoured by** $B_c \to \tau\,\nu$

Tensor : **disfavoured by** F_L and High-p_T searches

Scalar + tensor : S_1 $(\overline{3}, 1, 1/3)$ Leptoquark (Real couplings)

R_2 (3, 2, 7/6) Leptoquark (Imaginary couplings)

"slight tension" with $B_c \to \tau\,\nu$

Thank you
for
Listening!