Anatomy of R_D, R_{D^*} and $R_{J/\psi}$ from an EFT perspective

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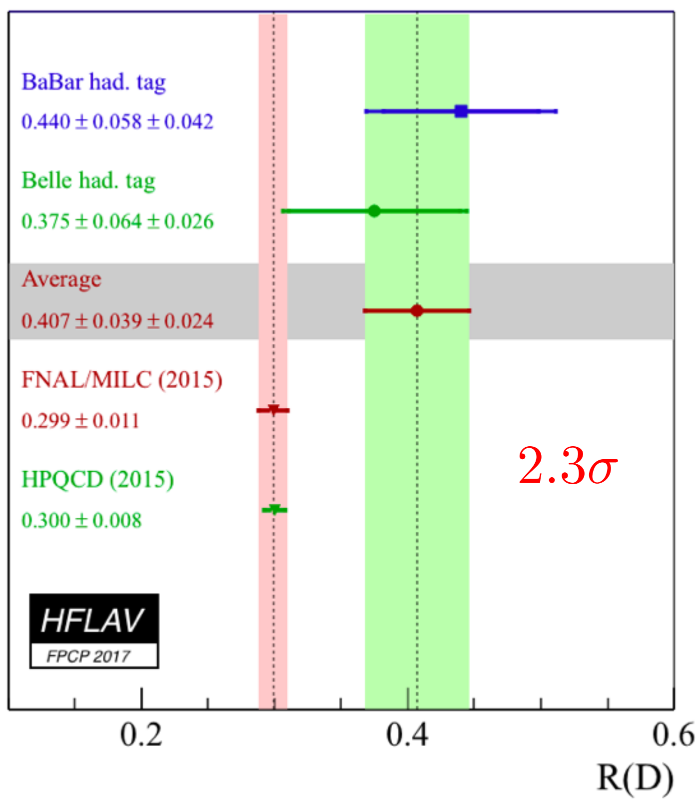
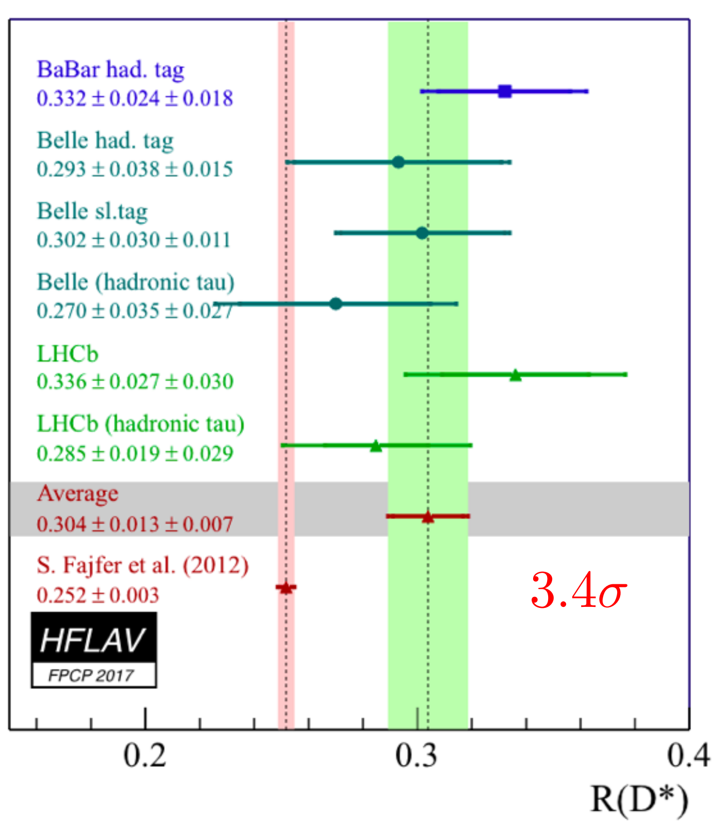
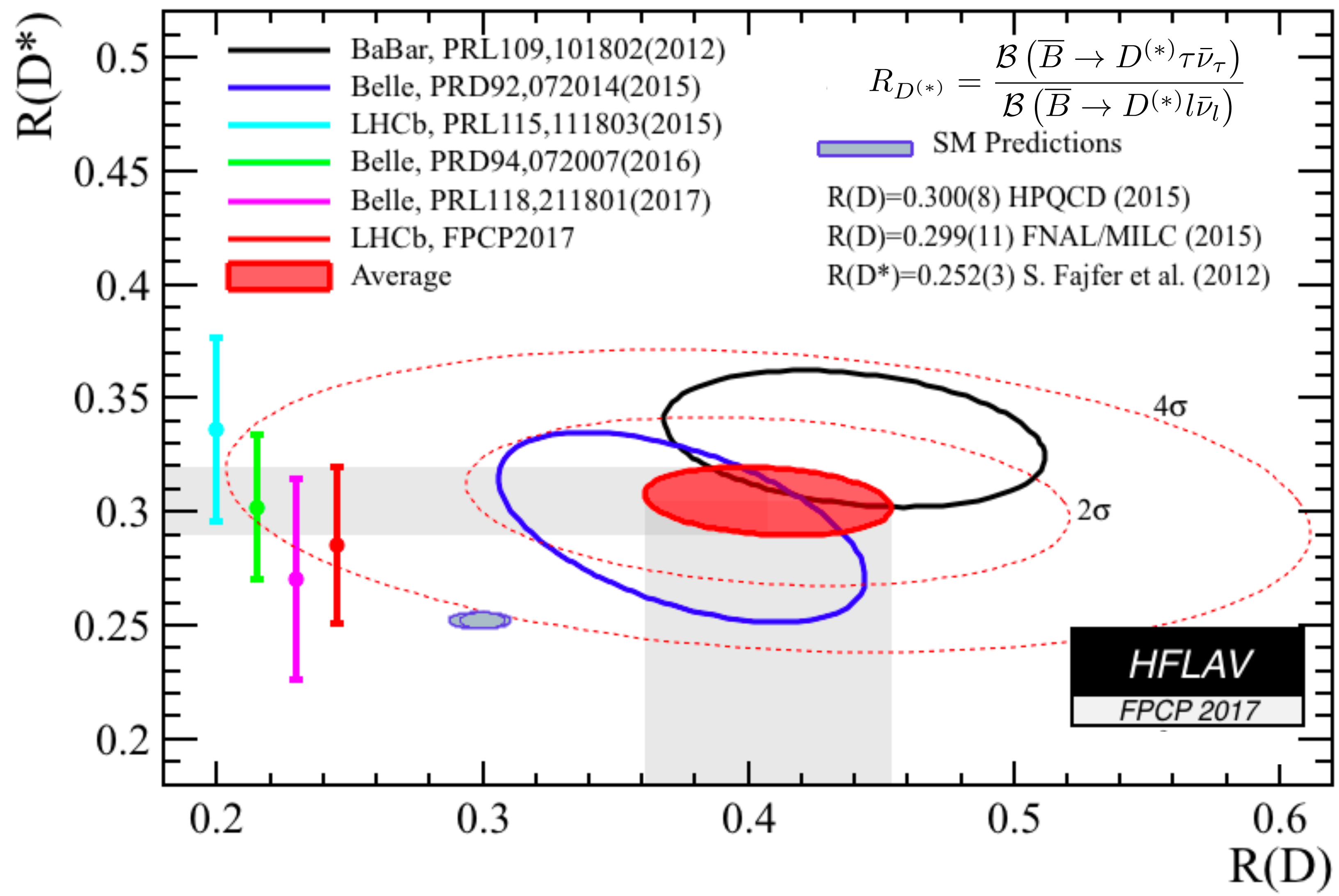
w/ D. Bardhan and P. Byakti
& 18xx.xxxxx

Workshop on the "Impact of $B \to \mu\,\mu$ on New Physics Searches", Paul Scherrer Institute, Villigen, Switzerland
Dec 19, 2017

Experiments vs. Standard Model







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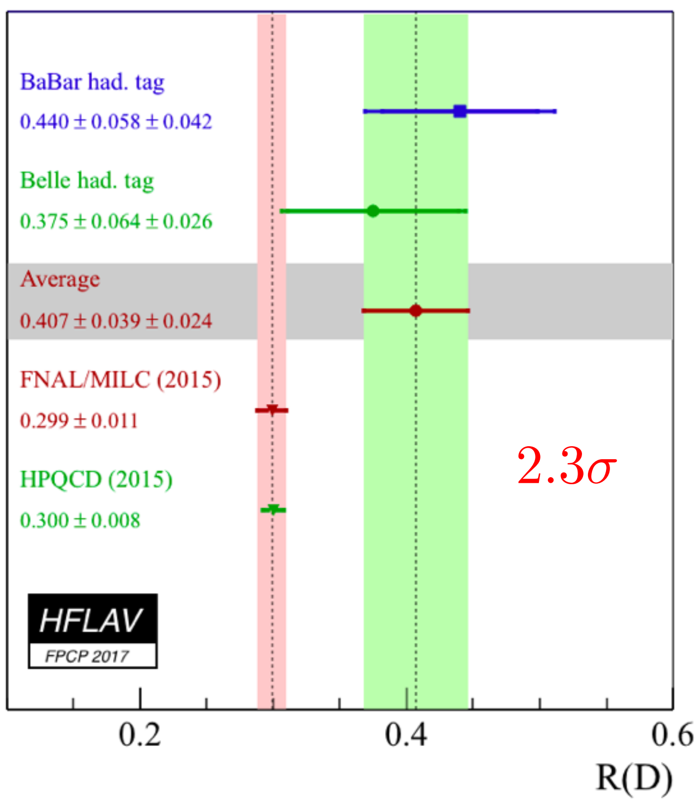

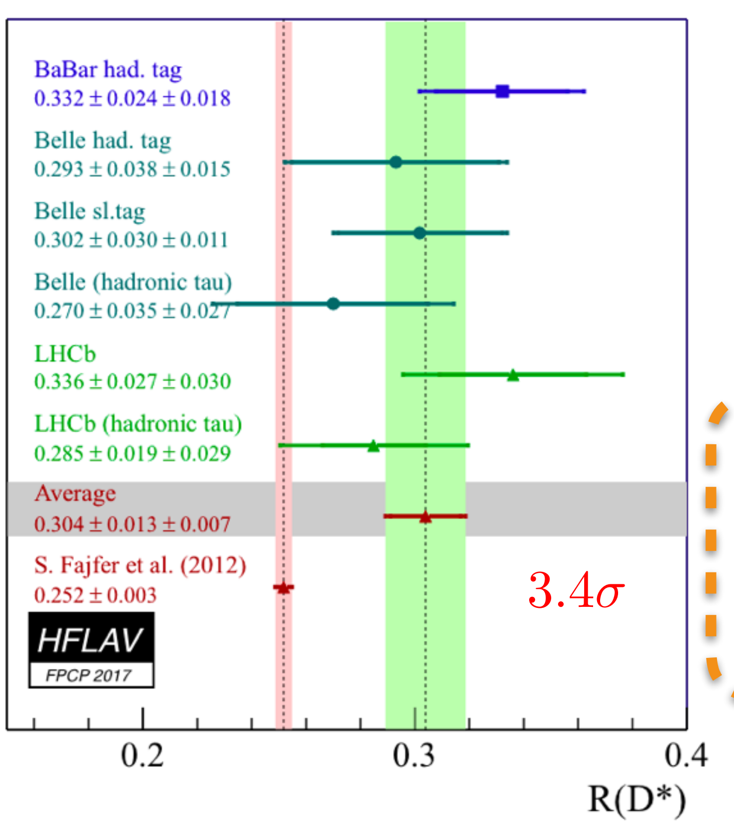

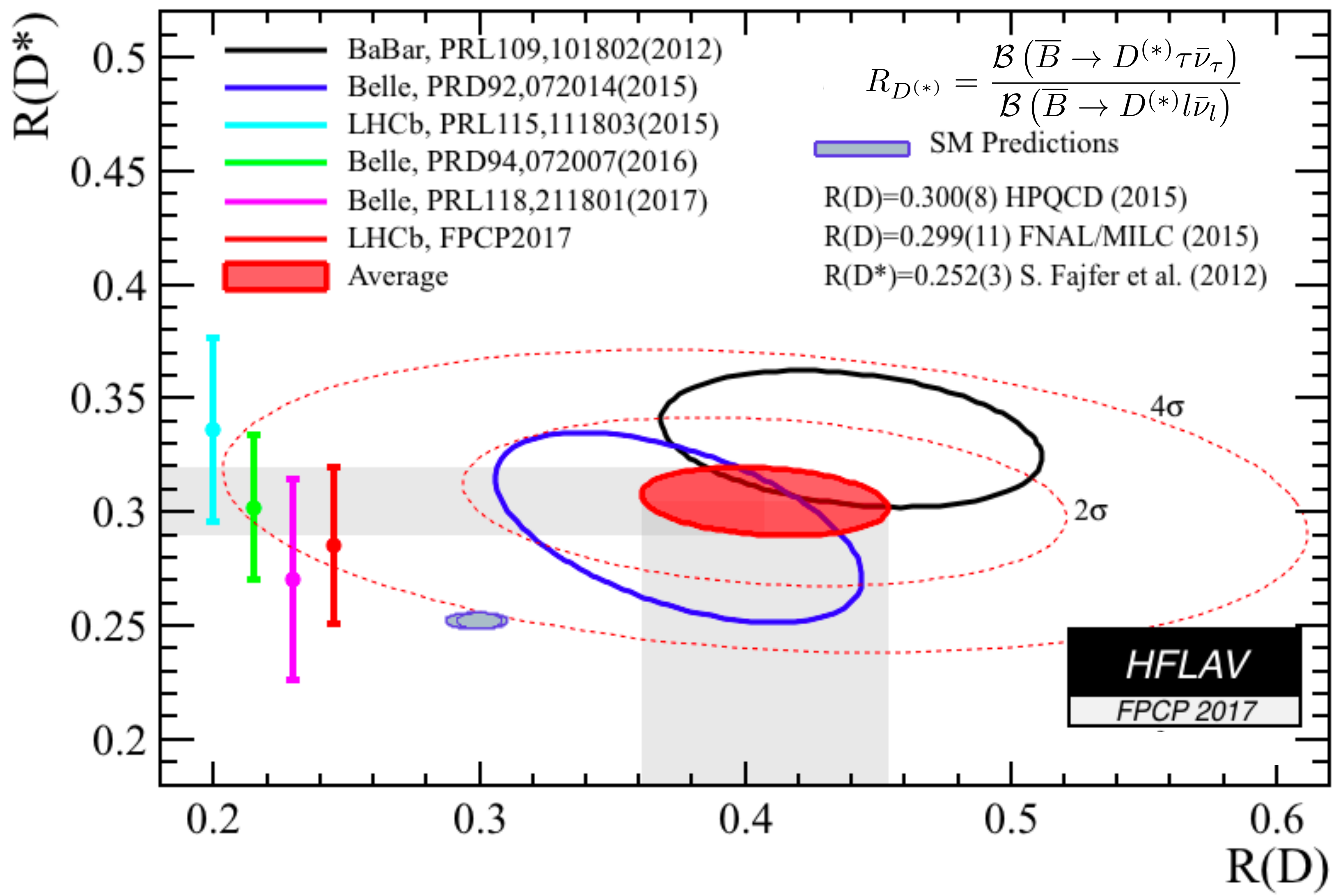

However, assuming

$R_{D^*} = 0.260 \pm 0.008$

[Bigi, Gambino, Schacht (arXiv:1707.09509)]

the deviation reduces to 2.6σ

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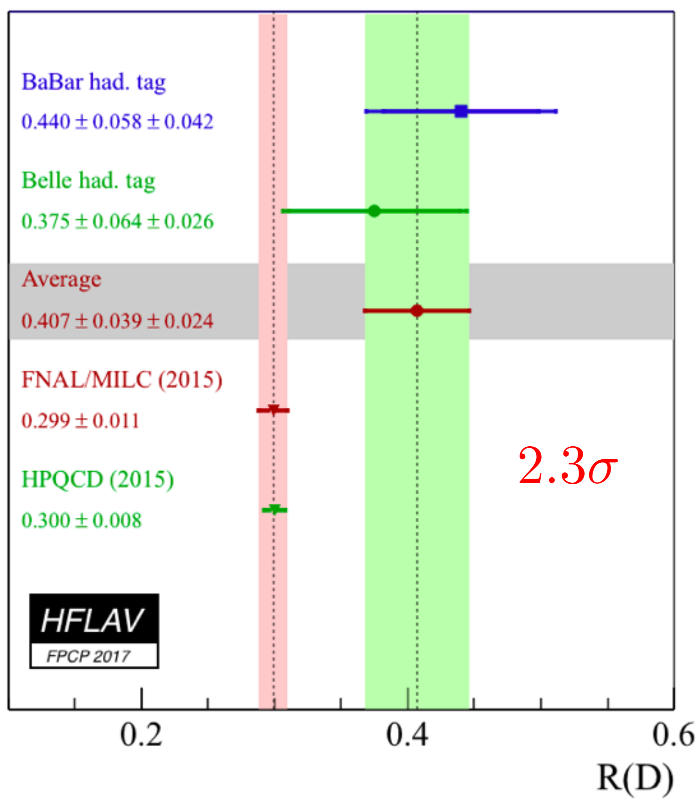

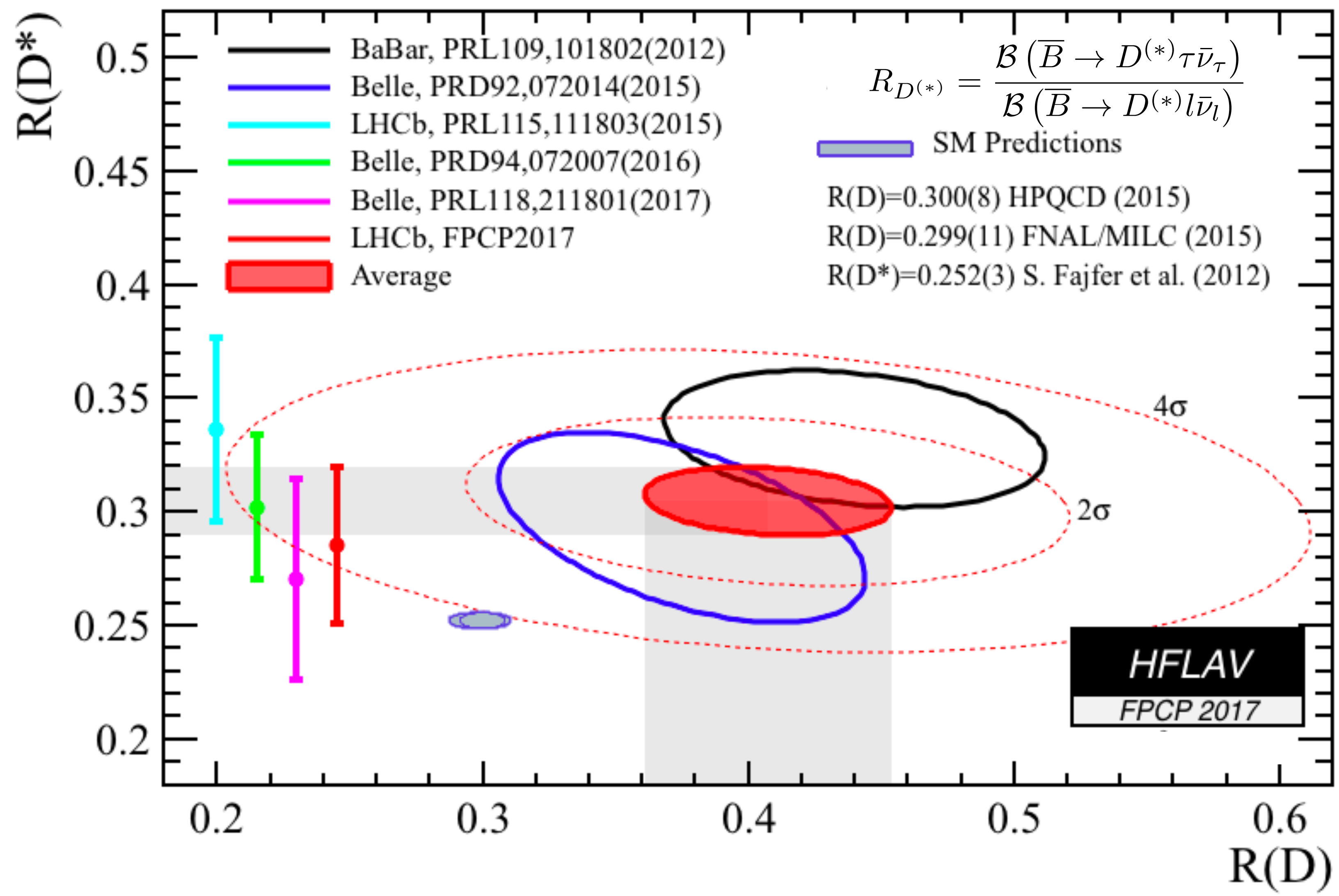

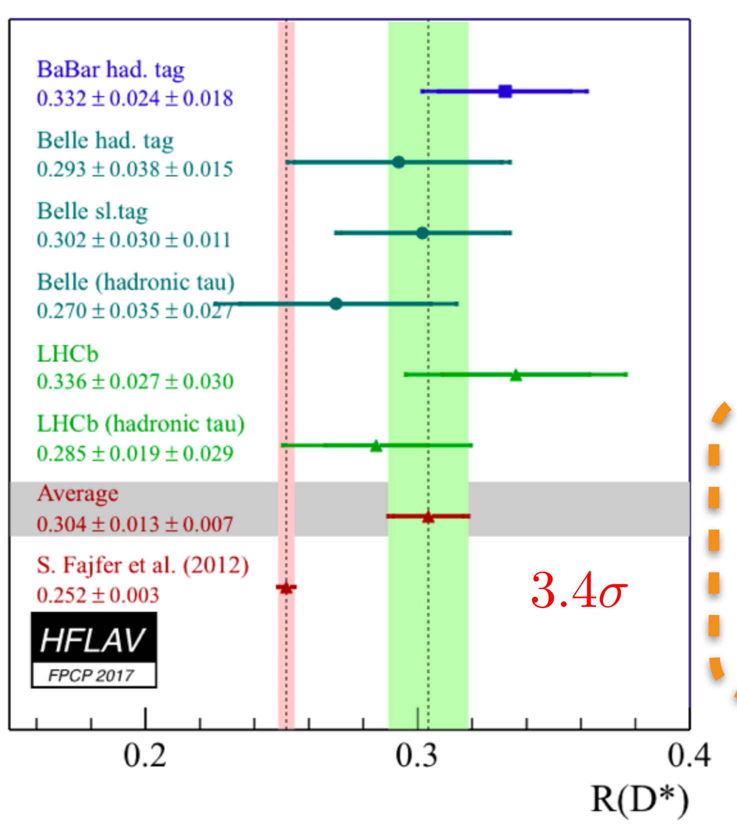

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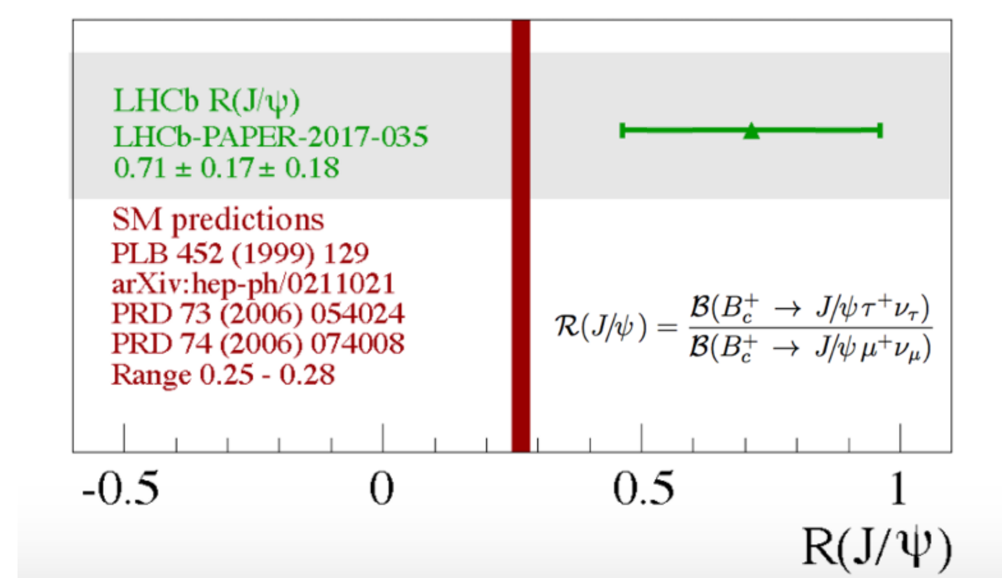


Comment on Form Factor induced uncertainties

$\mathcal{B}\left(\overline{B} \to D\tau\bar{\nu}_\tau\right)$	$\mathbf{0.633 \pm 0.014}\,\%$	~ 2.2%
$\mathcal{B}\left(\overline{B} \to Dl\bar{\nu}_l\right)$	$\mathbf{2.11^{+0.12}_{-0.10}}\,\%$	~ 5%
R_D	$\mathbf{0.300 \pm 0.011}$	~ 3.7%

$$R_{D^{(*)}} = \frac{\mathcal{B}\left(\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to D^{(*)}l\bar{\nu}_l\right)}$$

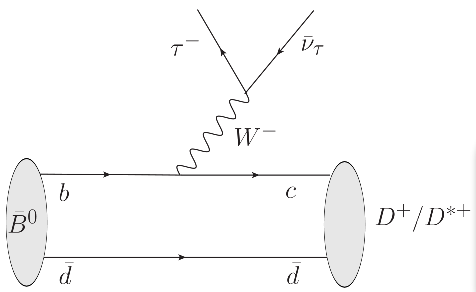
$$\begin{aligned}
\mathrm{Br}\left(B \to D\tau\nu_\tau\right) &= [0.370\%]_{F_0^2} + [0.263\%]_{F_+^2} = [0.633\%]_{\mathrm{Total}} \\
\mathrm{Br}\left(B \to D\ell\nu_\ell\right) &= [0.016\%]_{F_0^2} + [2.095\%]_{F_+^2} = [2.111\%]_{\mathrm{Total}}
\end{aligned}$$

$\mathcal{B}\left(\overline{B} \to D^*\tau\bar{\nu}_\tau\right)$	$\mathbf{1.28 \pm 0.09}\,\%$	~ 7%
$\mathcal{B}\left(\overline{B} \to D^*l\bar{\nu}_l\right)$	$\mathbf{5.04^{+0.44}_{-0.42}}\%$	~ 8.5%
R_{D^*}	$\mathbf{0.254 \pm 0.004}$	~ 1.6%

$$\begin{aligned}
\mathrm{Br}\left(B \to D^*\tau\nu_\tau\right) &= [0.072\%]_{V^2} + [0.117\%]_{A_0^2} + [\mathbf{1.31}\%]_{\mathbf{A_1^2}} + [0.025\%]_{A_2^2} + [-0.242\%]_{A_1A_2} \\
&= [1.28\%]_{\mathrm{Total}} \\
\mathrm{Br}\left(B \to D^*\ell\nu_\ell\right) &= [0.350\%]_{V^2} + [0.012\%]_{A_0^2} + [\mathbf{7.16}\%]_{\mathbf{A_1^2}} + [0.472\%]_{A_2^2} + [-2.96\%]_{A_1A_2} \\
&= [5.03\%]_{\mathrm{Total}}
\end{aligned}$$

Operators

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



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

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

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

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

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

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

$$\frac{g^{cb\ell}_{\rm SL,PL,TL}}{\Lambda^2} = \frac{2G_F V_{cb}}{\sqrt{2}}C^{cb\ell}_{\rm SL,PL,TL}$$

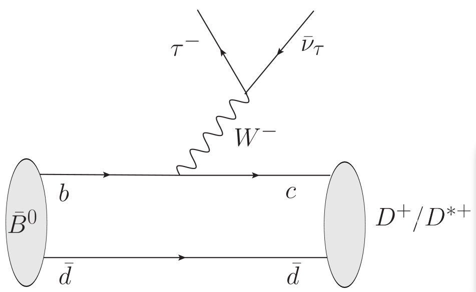
No other Tensor operators :

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

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

Operators

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



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

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

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

No right chiral Neutrinos

$$\begin{aligned}
&\cancel{\mathcal{O}^{cb\ell}_{\rm VR} = [\bar{c}\,\gamma^\mu\, b][\bar{\ell}\,\gamma_\mu\, P_R\, \nu]} \\
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\end{aligned}$$

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

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

$$\frac{g^{cb\ell}_{\rm SL,PL,TL}}{\Lambda^2} = \frac{2G_F V_{cb}}{\sqrt{2}}C^{cb\ell}_{\rm SL,PL,TL}$$

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[\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]
\end{aligned}$$

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

Observables

$$R = R_{\rm SM} + (\#)\frac{g_6}{\Lambda^2} + (\#)'\frac{g_6^2}{\Lambda^4} + \text{dim-8 contrib.} +$$

Observable

$$(\#)''\frac{g_8}{\Lambda^4} + \ldots$$

same order in $\frac{1}{\Lambda}$

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Observable

$$(\#)''\frac{g_8}{\Lambda^4} + \ldots$$

same order in $\frac{1}{\Lambda}$

For consistency of an analysis, ideally, <<

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

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

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

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

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

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

Lepton universal

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

- 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) × U(1) gauge invariance

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

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

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

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

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

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

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

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

Lepton universal

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

- 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) × U(1) gauge invariance

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

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

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

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

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

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

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

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

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

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

Lepton universal

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

- 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) × U(1) gauge invariance

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

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

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

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

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

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

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

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

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

Lepton universal

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

$$\frac{\text{Br}(W^+\to\tau^+\nu)}{[\text{Br}(W^+\to\mu^+\nu)+\text{Br}(W^+\to e^+\nu)]/2} = 1.077\pm0.026 \quad \textbf{(LEP)}$$

- 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

Correlations

$$[C_{lq}^{(3)}]'_{p'r's't'}\left(\frac{1}{4}\left(\bar{e}'_{p'}\gamma^{\mu}P_L e'_{r'}\right)\left(\bar{d}'_{s'}\gamma_{\mu}P_L d'_{t'}\right)\;+\frac{1}{2}\left(\bar{e}'_{p'}\gamma^{\mu}P_L \nu'_{r'}\right)\left(\bar{u}'_{s'}\gamma_{\mu}P_L d'_{t'}\right)\right)$$

Correlations

$$[C_{lq}^{(3)}]'_{p'r's't'}\left(\frac{1}{4}\left(\bar{e}'_{p'}\gamma^\mu P_L e'_{r'}\right)\left(\bar{d}'_{s'}\gamma_\mu P_L d'_{t'}\right)+\frac{1}{2}\left(\bar{e}'_{p'}\gamma^\mu P_L \nu'_{r'}\right)\left(\bar{u}'_{s'}\gamma_\mu P_L d'_{t'}\right)\right)$$

$$\frac{1}{4}[\tilde{C}_{lq}^{(3)eedd}]_{p,r,s,t}\left(\bar{e}_p\gamma^\mu P_L e_r\right)\left(\bar{d}_s\gamma_\mu P_L d_t\right)+\frac{1}{2}[\tilde{C}_{lq}^{(3)e\nu ud}]_{p,r,s,t}\left(\bar{e}_p\gamma^\mu P_L \nu_r\right)\left(\bar{u}_s\gamma_\mu P_L d_t\right)$$

$$\sum_{p',r',s',t'}[C_{lq}^{(3)}]'_{p'r's't'}(V_L^e)^\dagger_{pp'}(V_L^\nu)_{r'r}(V_L^u)^\dagger_{ss'}(V_L^d)_{t't} = [\tilde{C}_{lq}^{(3)e\nu ud}]_{p,r,s,t}$$

$$\sum_{p',r',s',t'}[C_{lq}^{(3)}]'_{p'r's't'}(V_L^e)^\dagger_{pp'}(V_L^e)_{r'r}(V_L^d)^\dagger_{ss'}(V_L^d)_{t't} = [\tilde{C}_{lq}^{(3)eedd}]_{p,r,s,t}$$

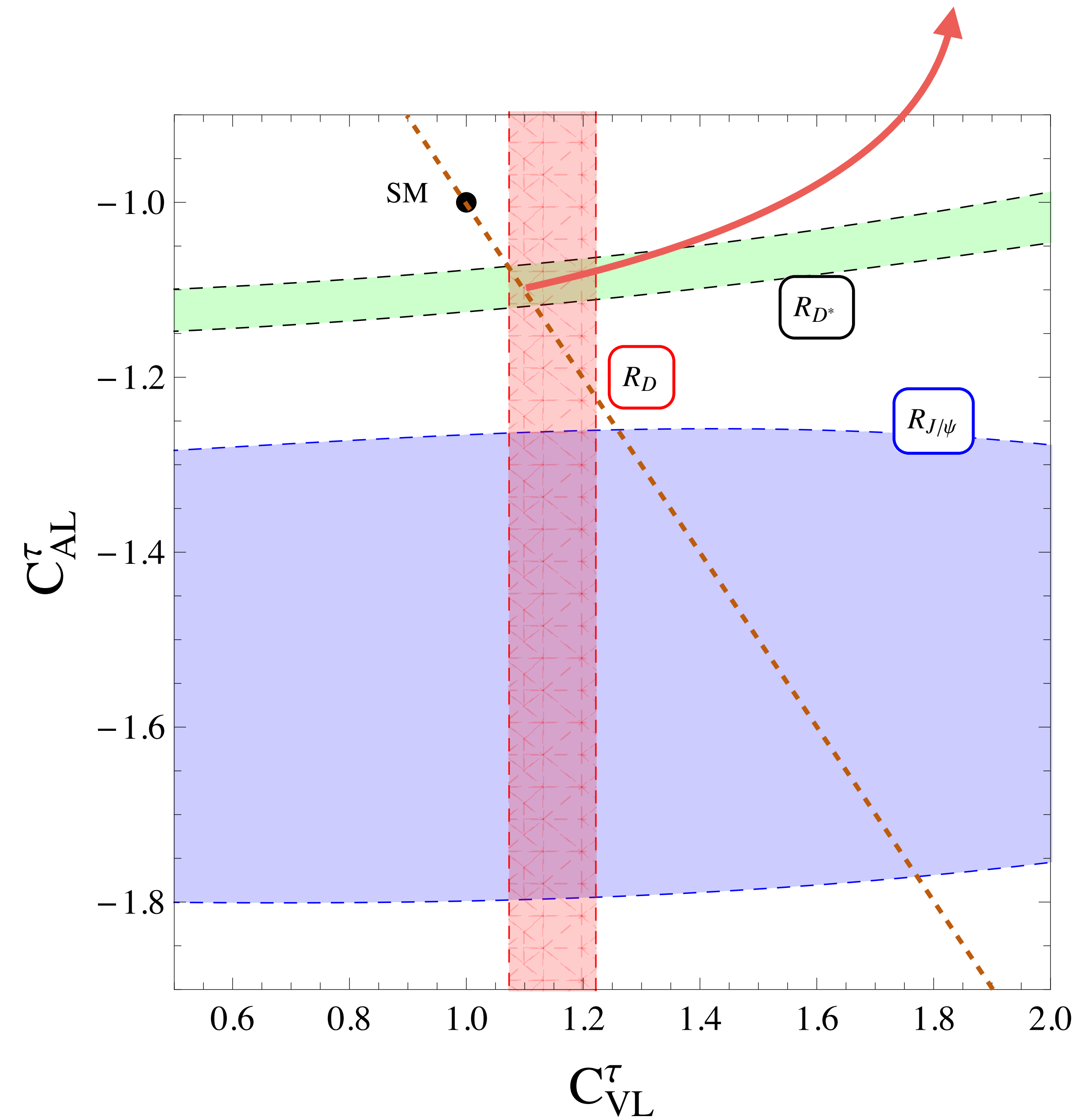
$$\frac{[\tilde{C}_{lq}^{(3)e\nu ud}]_{3323}}{[\tilde{C}_{lq}^{(3)eedd}]_{3323}} = f(V_L^\nu, V_L^u)$$

No completely model independent correlations!

Vector, Axial-Vector operators

$R_{J/\psi} : 0.34 - 0.38$

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



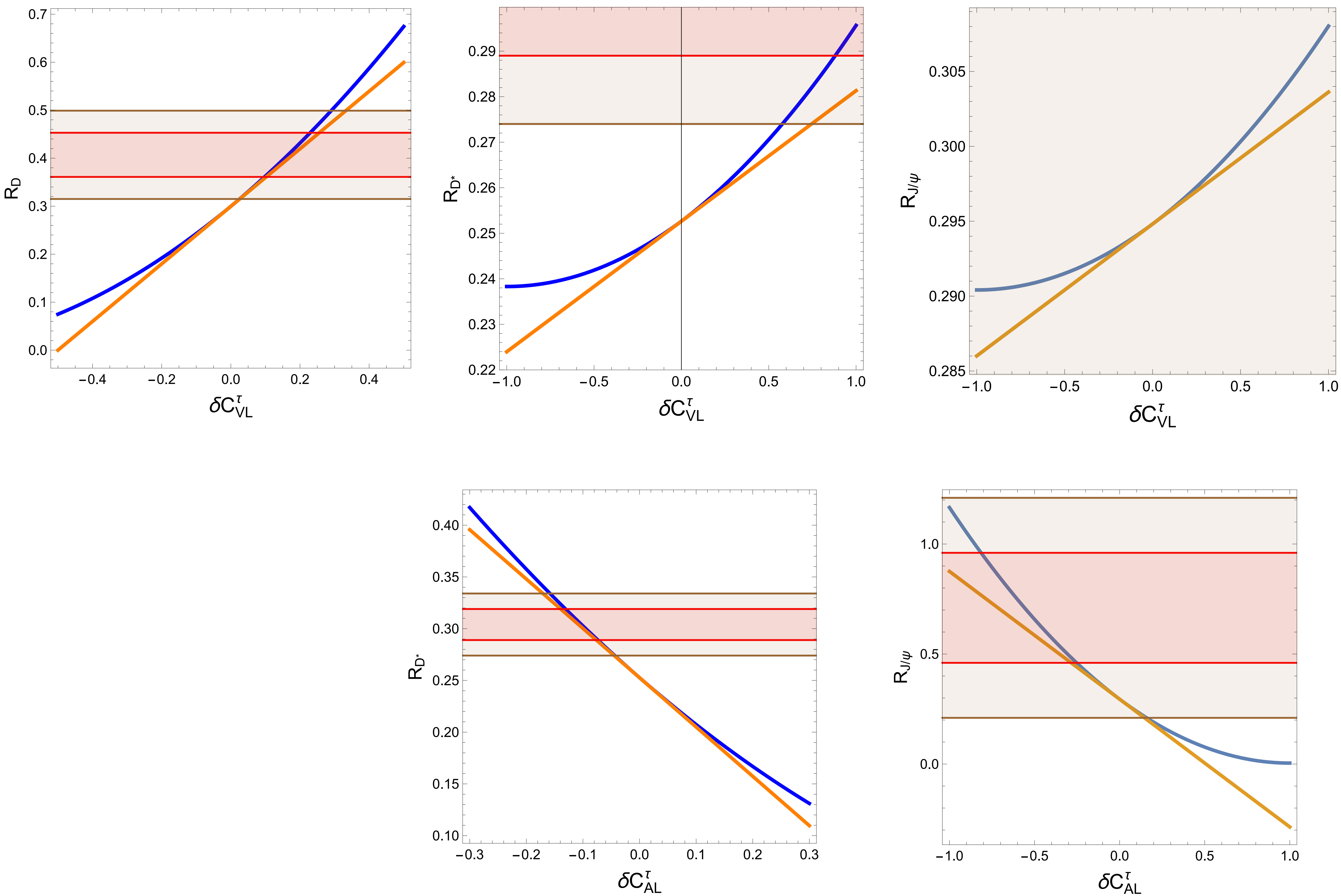
$$\langle D(p_D, M_D)|\bar{c}\gamma^\mu\gamma_5 b|\bar{B}(p_B, M_B)\rangle \quad = \quad 0$$

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

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

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

$$\left(\mathrm{SM}+\mathrm{SM}\times\frac{1}{\Lambda}\right)\ \text{vs.}\ \left(\mathrm{SM}+\mathrm{SM}\times\frac{1}{\Lambda}+\frac{1}{\Lambda^2}\right)$$



Scalar, Pseudo-Scalar operators

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

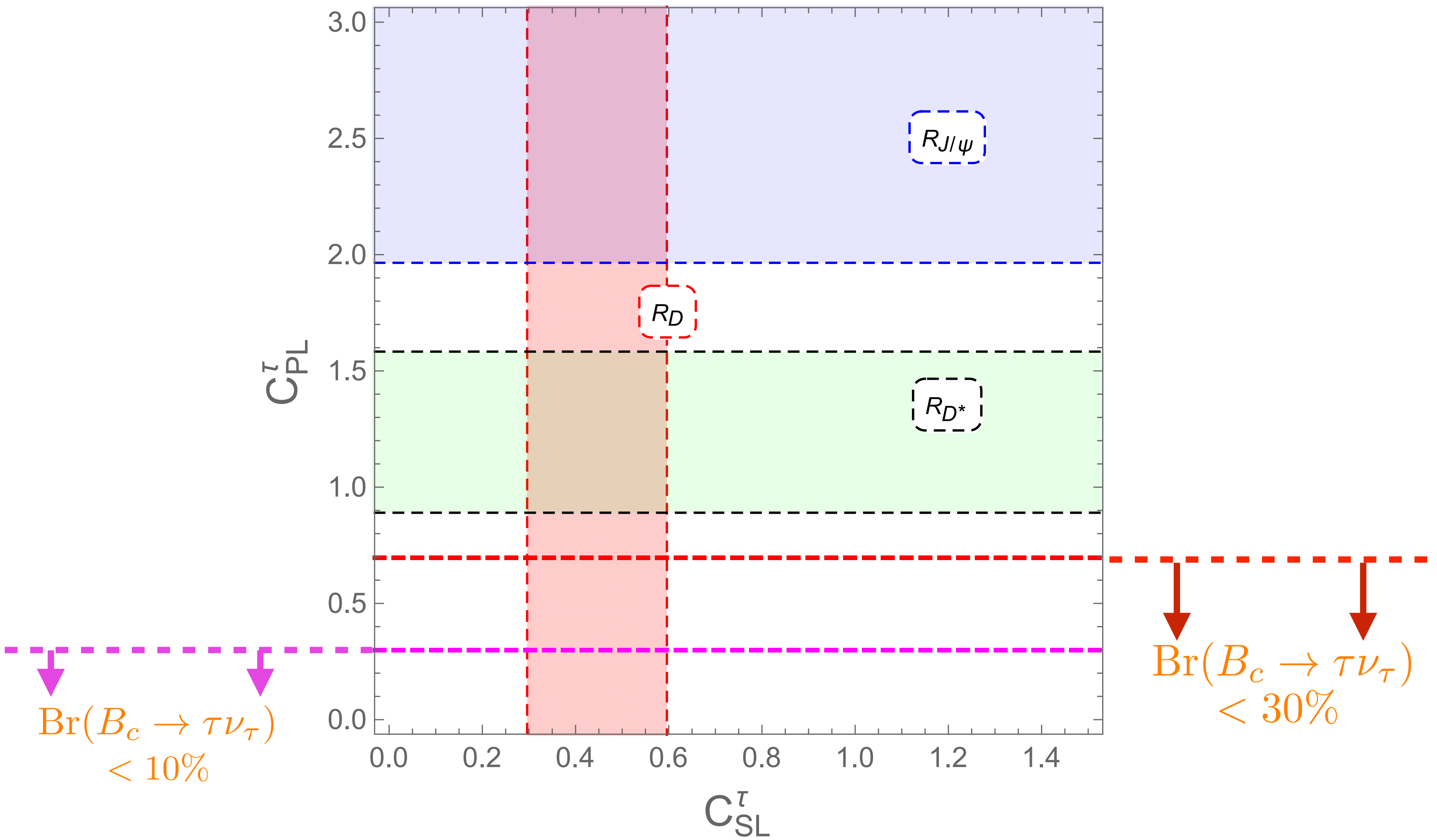
$$\mathcal{O}^{cb\ell}_{\rm AL} = [\bar{c}\,\gamma^{\mu}\,\gamma_5\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$$

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

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

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

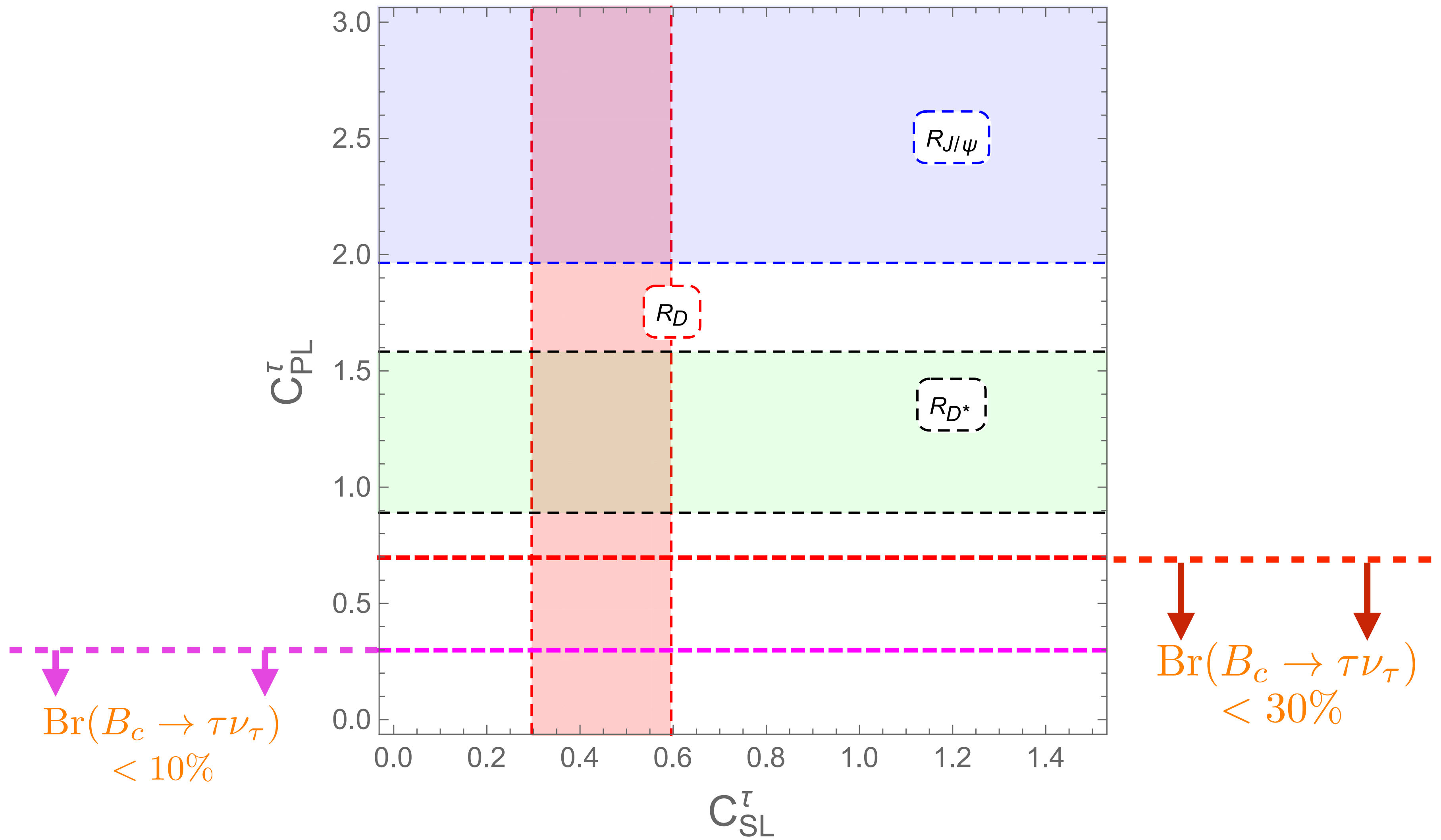
$$\begin{aligned} \langle D(p_D, M_D)|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle &= 0 \\ \langle D^*(p_{D^*}, M_{D^*})|\bar{c}b|\bar{B}(p_B, M_B)\rangle &= 0 \end{aligned}$$

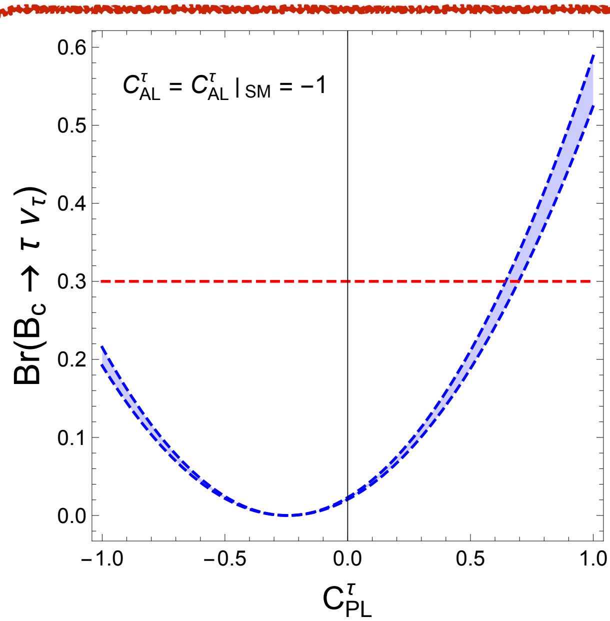


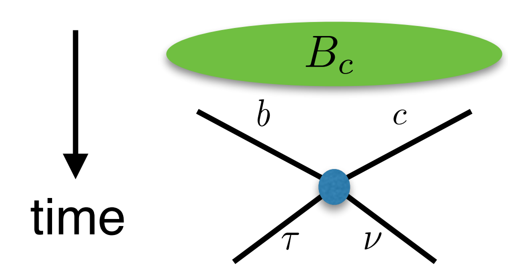
Scalar, Pseudo-Scalar operators

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

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







First pointed out by
Alonso, Grinstein, Camalich (arXiv:1611.06676)

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

Tensor operator

$R_{J/\psi}$: $0.17 - 0.21$

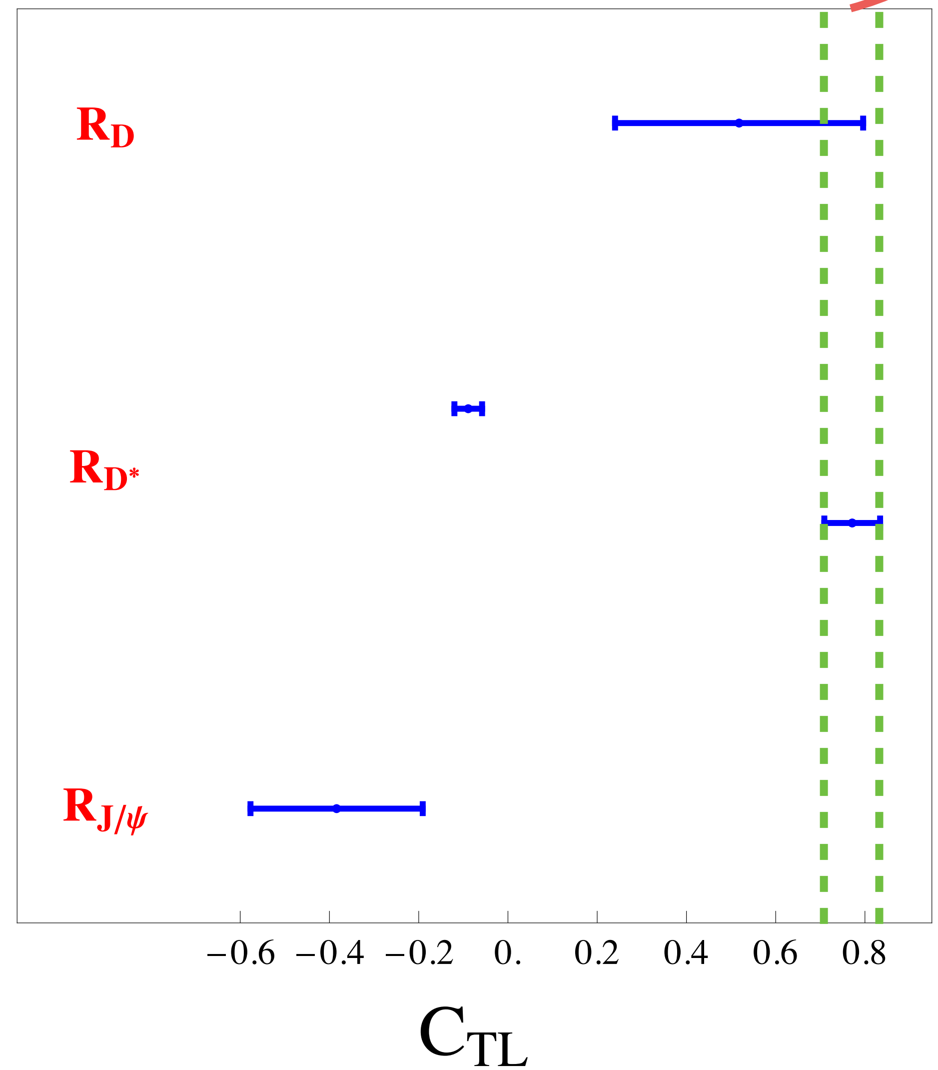
$$\mathcal{O}^{cb\ell}_{\mathrm{VL}} = [\bar{c}\,\gamma^{\mu}\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$$

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

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

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

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

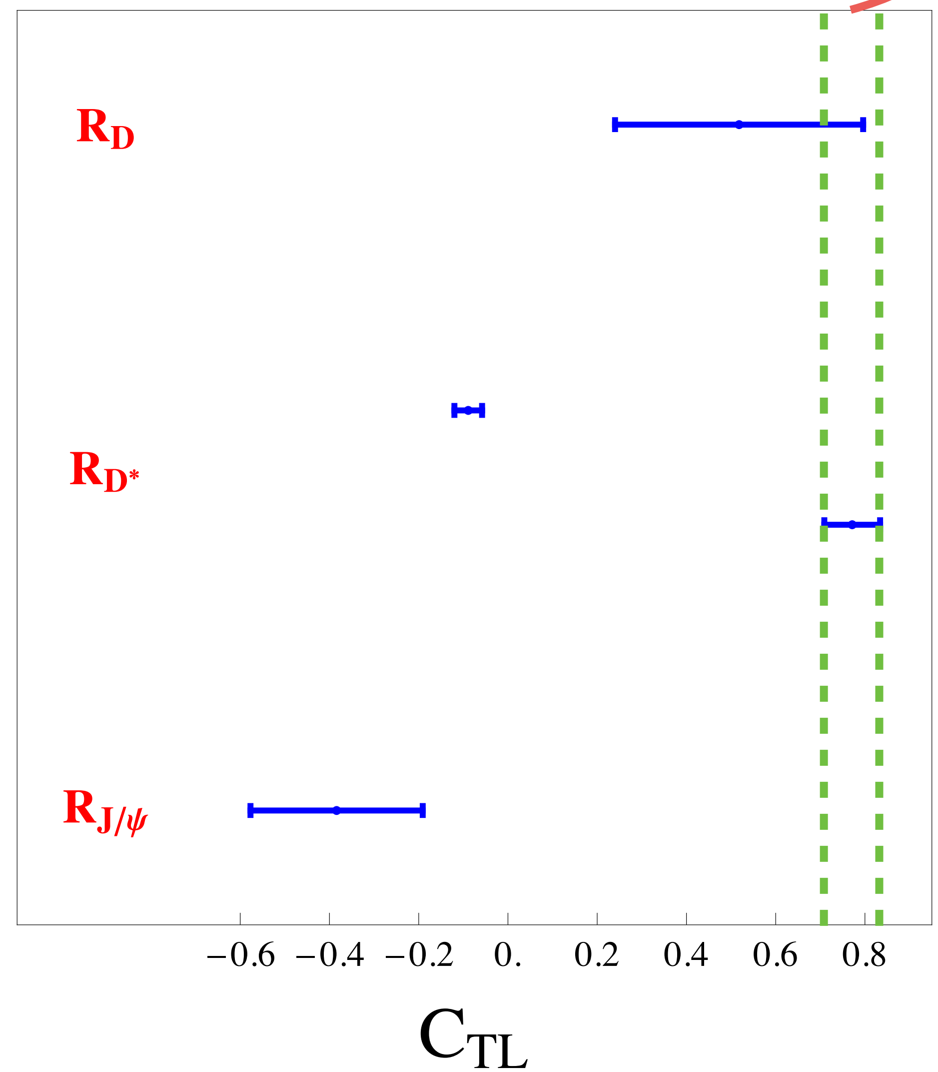


Tensor operator

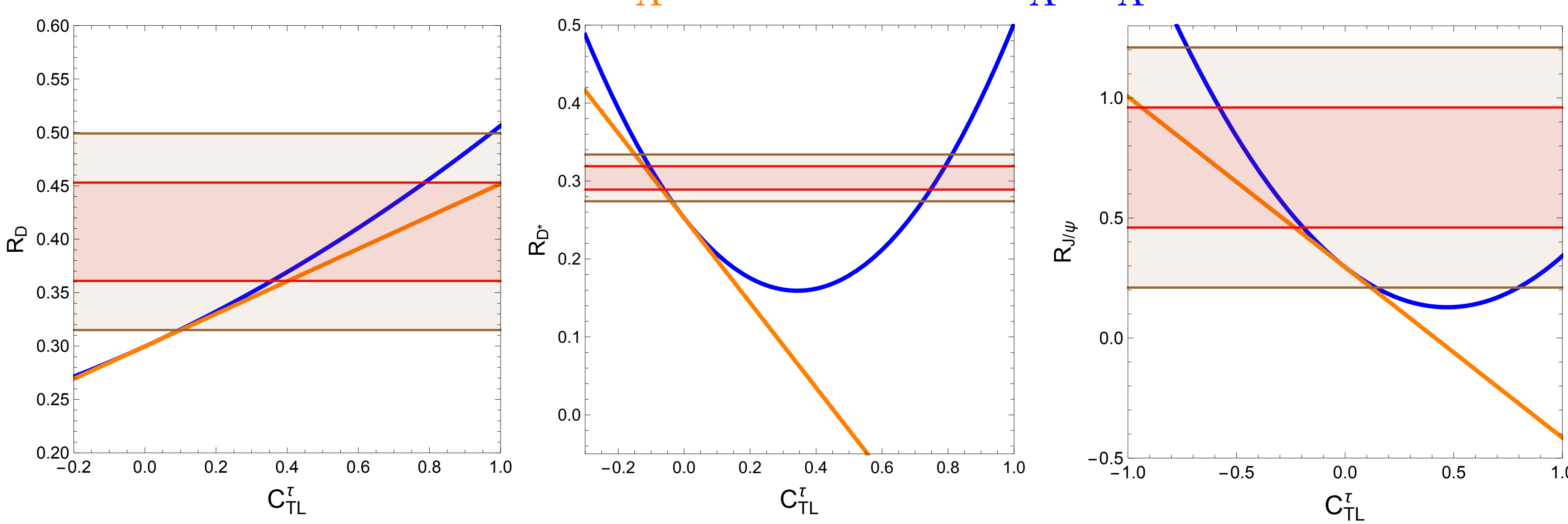
$R_{J/\psi}: 0.17 - 0.21$

[redacted]

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



$(\mathrm{SM} + \mathrm{SM} \times \frac{1}{\Lambda})$ vs. $(\mathrm{SM} + \mathrm{SM} \times \frac{1}{\Lambda} + \frac{1}{\Lambda^2})$



Tensor+Scalar operator

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

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

Tensor+Scalar operator

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

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

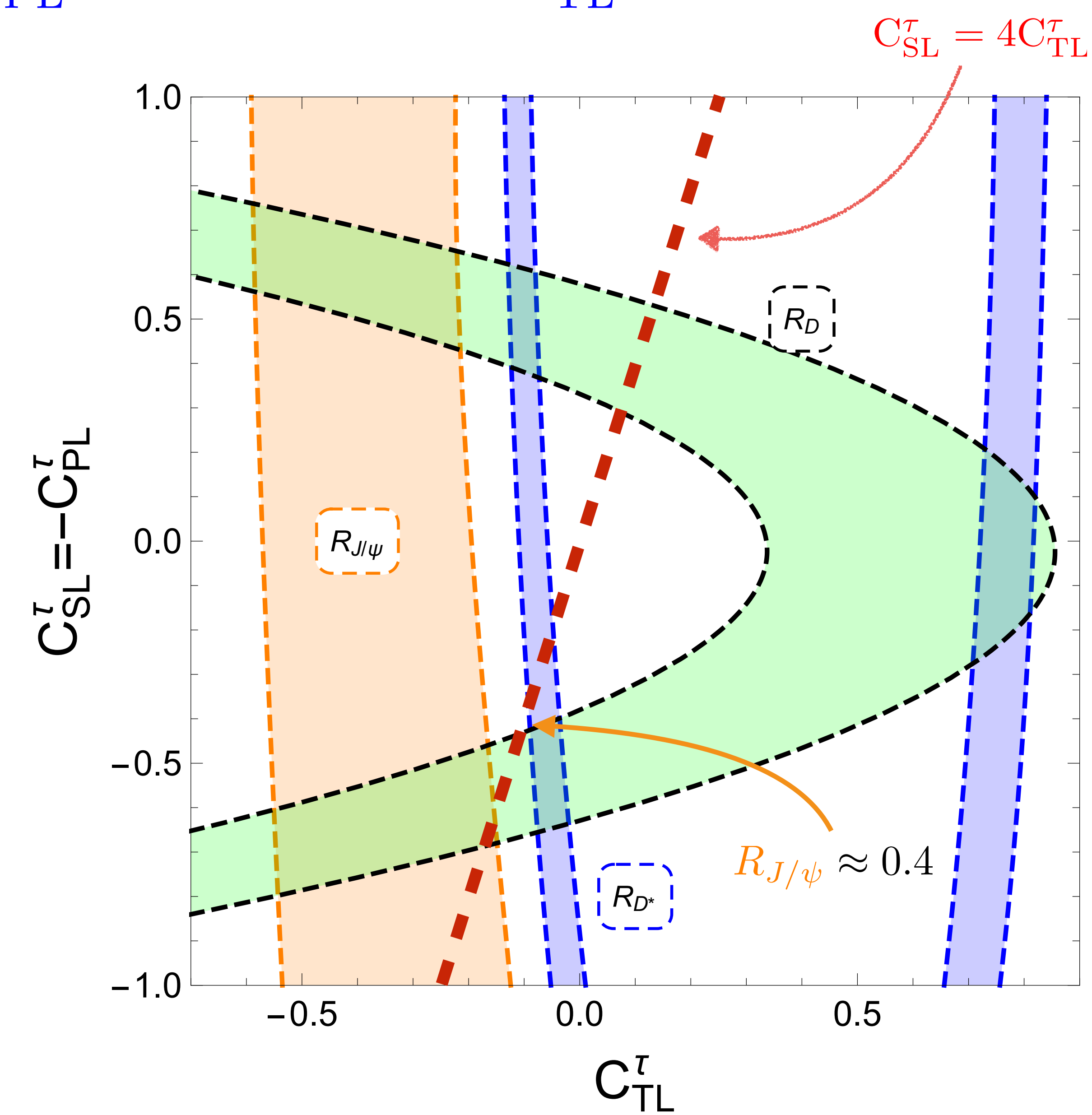
$\mathcal{O}^{cb\ell}_{\mathrm{VL}} = [\bar{c}\,\gamma^{\mu}\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$

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

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

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

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



Tensor+Scalar operator

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

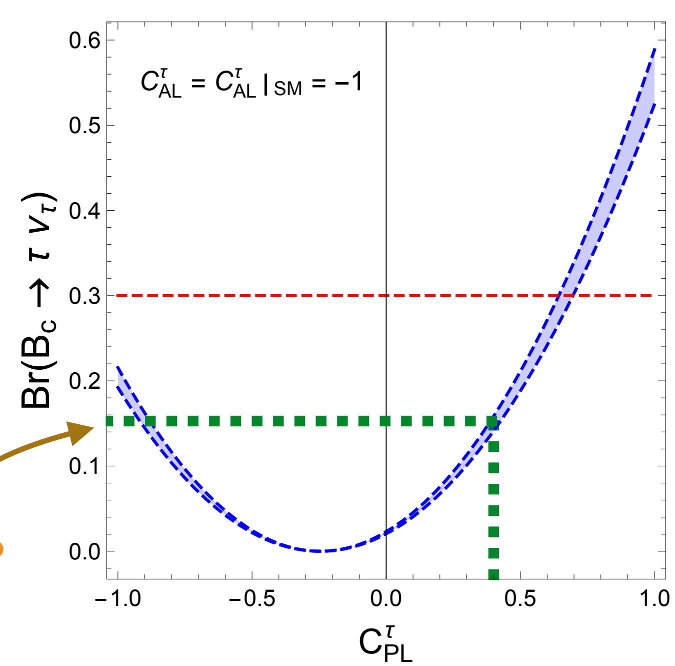
$$\mathrm{C}^\tau_{\mathrm{SL}} = -\mathrm{C}^\tau_{\mathrm{PL}} \qquad\qquad \mathrm{C}^\tau_{\mathrm{TL}}$$

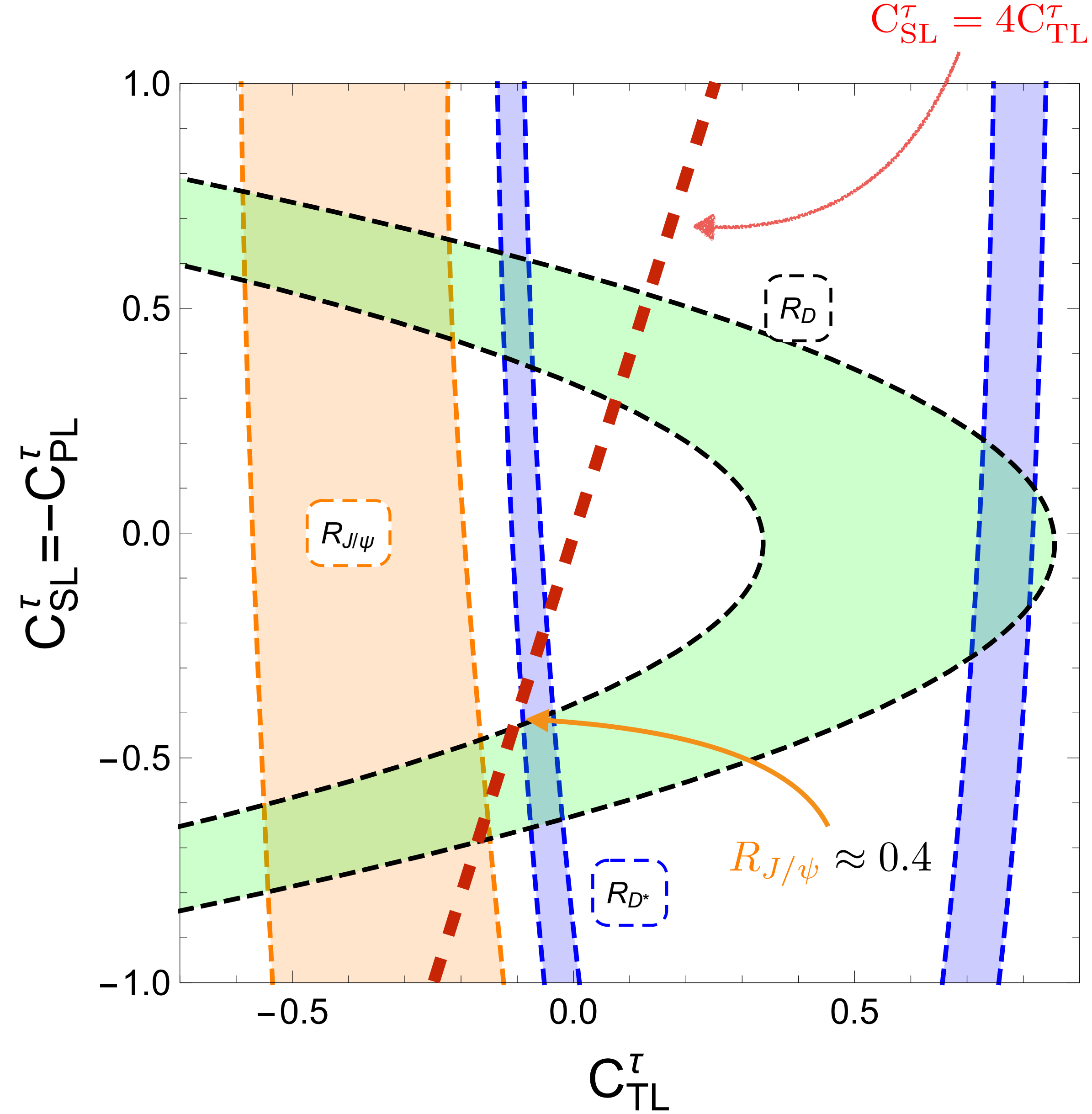
[redacted]

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

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

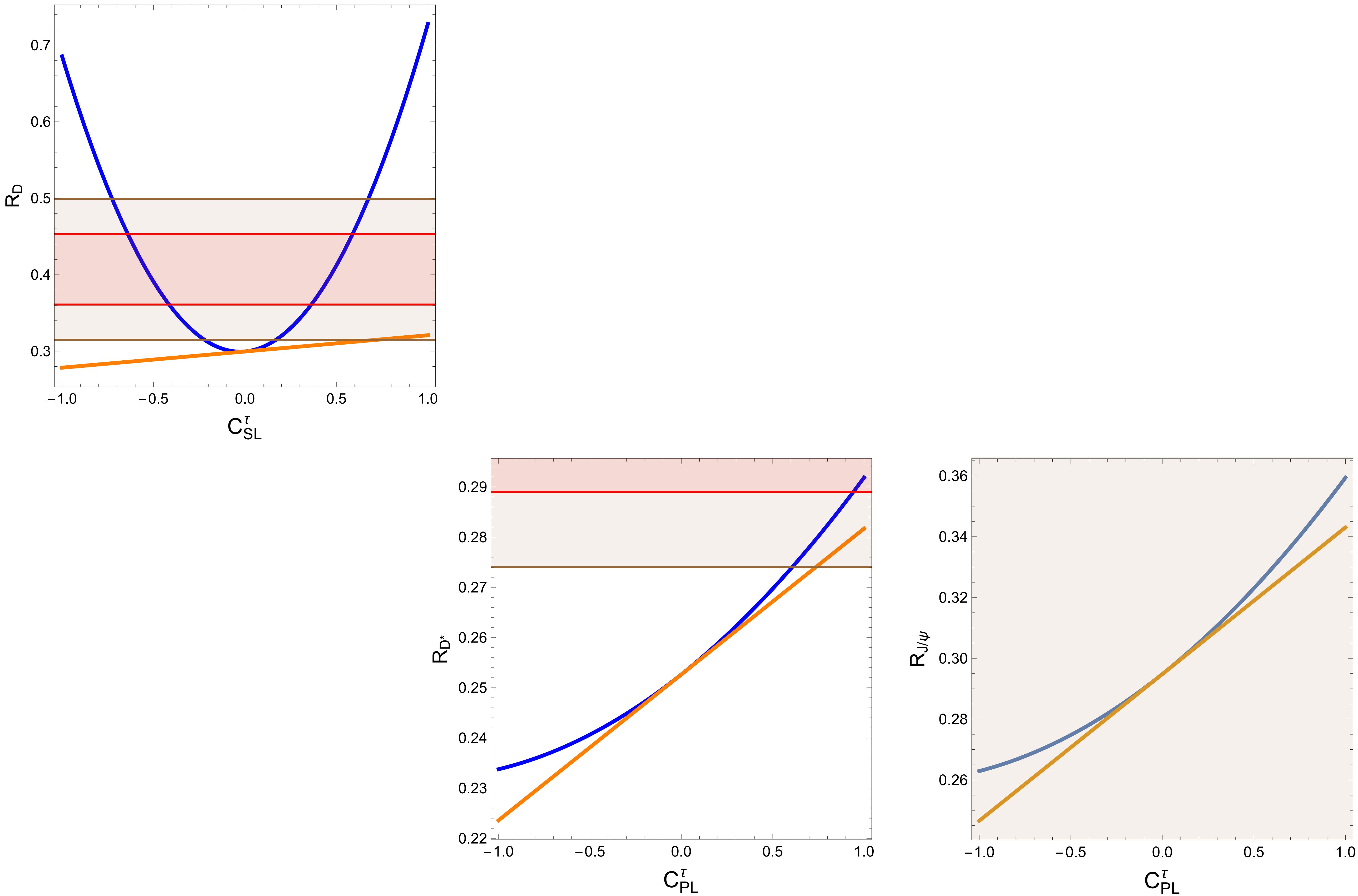
$$\mathcal{O}^{cb\ell}_{\mathrm{TL}} = [\bar{c}\, \sigma^{\mu\nu}\, b][\bar{\ell}\, \sigma_{\mu\nu}\, P_L\, \nu]$$



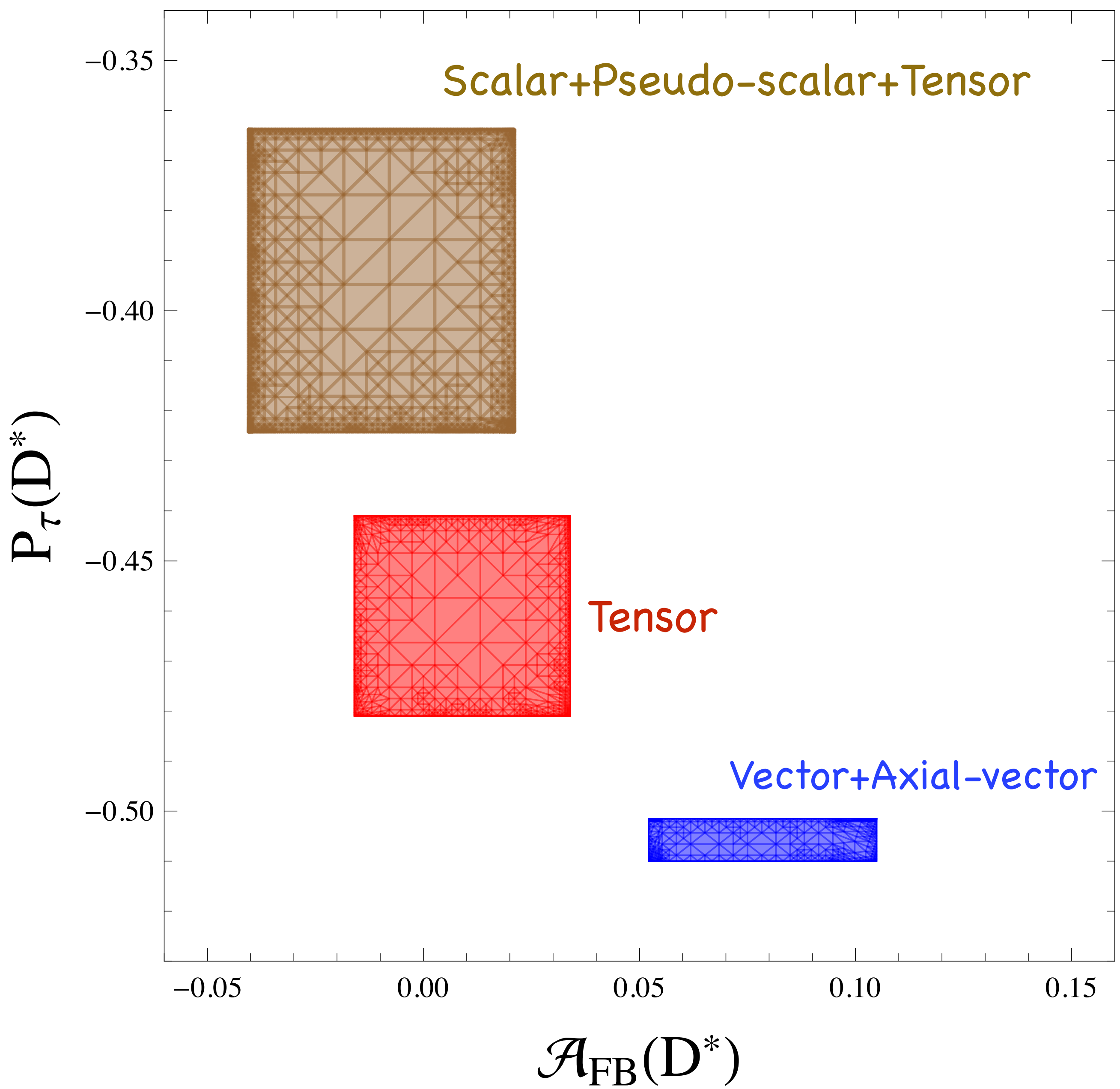


Claim by Akeroyd and Chen (arXiv:1708.04072) : $\mathrm{Br}(B_c \to \tau\nu) < 10\%$ disfavours this scenario

$$(\mathrm{SM} + \mathrm{SM} \times \frac{1}{\Lambda}) \quad \text{vs.} \quad (\mathrm{SM} + \mathrm{SM} \times \frac{1}{\Lambda} + \frac{1}{\Lambda^2})$$

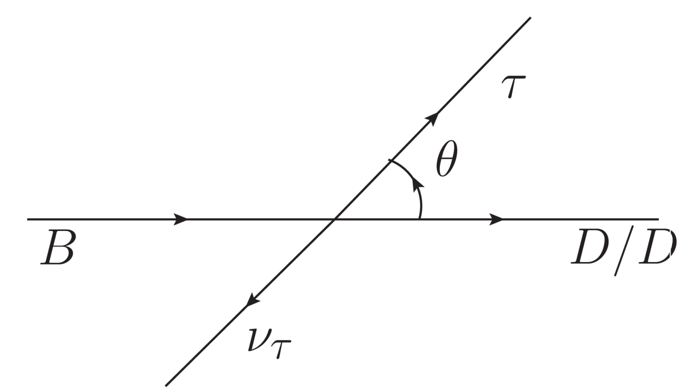


Distinguishing the various explanations



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

$$\mathcal{A}_{FB}^{D^{(*)}} = \frac{\int_0^{\pi/2} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta - \int_{\pi/2}^{\pi} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta}{\int_0^{\pi/2} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta + \int_{\pi/2}^{\pi} \frac{d\Gamma^{D^{(*)}}}{d\theta} d\theta}$$



Belle-II prospect for $P_\tau^{D^*}$

50 ab^{-1} : $\pm 0.06(\text{stat.}) \pm 0.04(\text{syst.})$

Thank you

for

Listening!

Additional slides

Experimental strategies

$$\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau$$

B-factories :

- Multiple neutrinos prevent to fully determine the kinematics

- Exploit unique experimental set-up: knowledge of initial state and known production process

$$e^+e^- \to \Upsilon(4S) \to B_{\rm comp}\overline{B}_{\rm sig}$$

The companion *B* meson reconstruction

- **Hadronic**: *sum of exclusive hadronic decays*

  $$B \to \overline{D}^{(*)}n\pi,\ \overline{D}^{(*)}D^{(*)}K,\ \overline{D}_s^{(*)}D^{(*)},\ J/\psi Kn\pi$$

- **Semi-leptonic**: *sum of exclusive semi-leptonic decays*

  $$B \to \overline{D}^{(*)}\ell\nu_\ell$$

- ***Untagged/Inclusive***: *sum all tracks/clusters not used for B_{sig} reconstruction*

Slide taken from a talk by Anže Zupanc

Experimental status : $\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau$

Experiment	Mode	Technique	Observables
BaBar [PRL109, 101802; PRD88, 072012]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2
Belle [PRL99,191807; PRD82,072005;]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Inclusive	Br
Belle [PRD92,072014]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2, $\lvert p_l^*\rvert$
Belle [PRD94, 072007]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Semi-leptonic	R(D*), $\lvert p^*_l\rvert$, $\lvert p^*_{D^*}\rvert$
Belle [arXiv:1608.06391]	$B \to \overline{D}^{*}\tau\nu_\tau$ $\tau \to \pi\nu_\tau,\ \rho\nu_\tau$	Hadronic	R(D*), P_τ
LHCb [PRL115,111803]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \mu\overline{\nu}_\mu\nu_\tau$		R(D*)

Copied from a talk by Anže Zupanc

$$R_{D^{(*)}} = \frac{\mathcal{B}\left(\overline{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to D^{(*)}l\bar{\nu}_l\right)}$$

- $B^0 \to D^{*+}\tau^-\overline{\nu}$ with $\tau^- \to \mu^-\nu\overline{\nu}$ and $B^0 \to D^{*+}\mu^-\overline{\nu}$ have same final state.

Disentangled by kinematical variables : q^2, E_μ, m^2_{miss}.

Belle II Prospect

$$(R_D)_{\rm HFAG} = 0.403 \pm 0.040 \pm 0.024$$

~10% ~6%

$$(R_{D^*})_{\rm HFAG} = 0.310 \pm 0.015 \pm 0.008$$

~5% ~2.5%

$$(P_\tau^{D^*})_{\rm Belle} = -0.44 \pm 0.47\,^{+0.20}_{-0.17}$$

$R(D)$

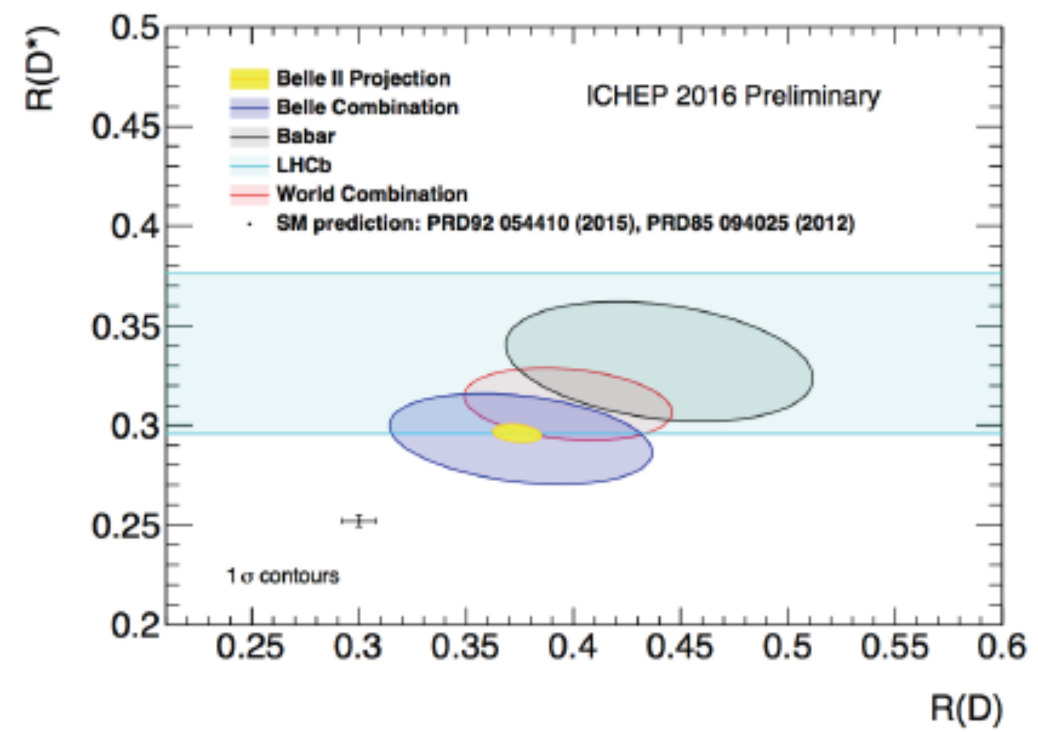
- 5 ab^{-1}: 6% (stat.) ± 4% (syst.)
- 50 ab^{-1}: 2% (stat.) ± 3% (syst.)

$R(D^*)$

- 5 ab^{-1}: 3% (stat.) ± 3% (syst.)
- 50 ab^{-1}: 1% (stat.) ± 2% (syst.)

P_τ

- 5 ab^{-1}: 0.18 (stat.) ± 0.08 (syst.)
- 50 ab^{-1}: 0.06 (stat.) ± 0.04 (syst.)



We are perhaps close to finding evidence of New Physics in B decays !

$\overline{B} \to D$ Form Factors

R_D

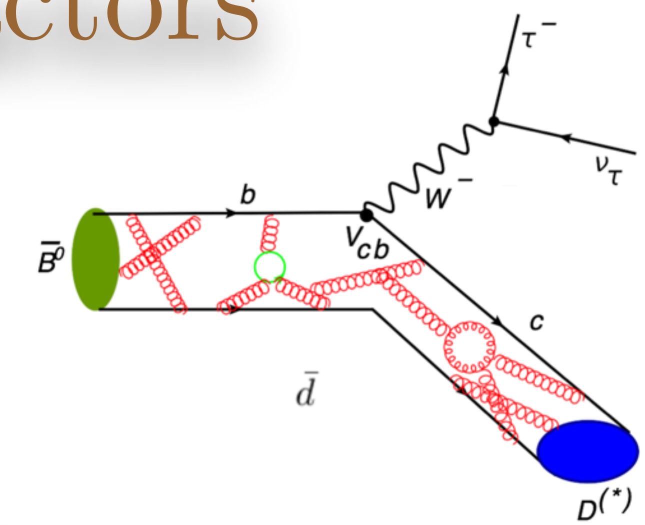
$\mathcal{O}^{cb\ell}_{\rm VL} = [\bar{c}\,\gamma^{\mu}\,b][\bar{\ell}\,\gamma_{\mu}\,P_L\,\nu]$

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

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

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

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



$$q = p_\tau + p_{\nu_\tau} \\ = p_{\bar{B}^0} - p_{D^{(*)}}$$

$$\langle D(p_D, M_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B, M_B)\rangle = F_+(q^2)\left[(p_B + p_D)^\mu - \frac{M_B^2 - M_D^2}{q^2}q^\mu\right] + F_0(q^2)\frac{M_B^2 - M_D^2}{q^2}q^\mu$$

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

$$\langle D(p_D, M_D)|\bar{c}b|\bar{B}(p_B, M_B)\rangle = F_0(q^2)\frac{M_B^2 - M_D^2}{m_b - m_c}$$

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

$$\langle D(p_D, M_D)|\bar{c}\sigma^{\mu\nu}b|\bar{B}(p_B, M_B)\rangle = -i(p_B^\mu p_D^\nu - p_B^\nu p_D^\mu)\frac{2F_T(q^2)}{M_B + M_D}$$

$\overline{B} \to D^*$ Form Factors

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_\mu b|\bar{B}(p_B, M_B)\rangle = i\varepsilon_{\mu\nu\rho\sigma}\epsilon^{\nu *} p_B^\rho p_{D^*}^\sigma \frac{2V(q^2)}{M_B + M_{D^*}}$$

$$\begin{aligned}\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_\mu\gamma_5 b|\bar{B}(p_B, M_B)\rangle &= 2M_{D^*}\frac{\epsilon^*.q}{q^2}q_\mu A_0(q^2) + (M_B + M_{D^*})\left[\epsilon^*_\mu - \frac{\epsilon^*.q}{q^2}q_\mu\right]A_1(q^2)\\ &\quad - \frac{\epsilon^*.q}{M_B + M_{D^*}}\left[(p_B + p_{D^*})_\mu - \frac{M_B^2 - M_{D^*}^2}{q^2}q_\mu\right]A_2(q^2)\end{aligned}$$

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

$$\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\gamma_5 b|\bar{B}(p_B, M_B)\rangle = -\epsilon^*.q\frac{2M_{D^*}}{m_b + m_c}A_0(q^2)$$

$$\begin{aligned}\langle D^*(p_{D^*}, M_{D^*})|\bar{c}\sigma_{\mu\nu} b|\bar{B}(p_B, M_B)\rangle &= -\varepsilon_{\mu\nu\alpha\beta}\Big[-\epsilon^{\alpha *}(p_{D^*} + p_B)^\beta T_1(q^2)\\ &\quad + \frac{M_B^2 - M_{D^*}^2}{q^2}\epsilon^{*\alpha}q^\beta\left(T_1(q^2) - T_2(q^2)\right)\\ &\quad + 2\frac{\epsilon^*.q}{q^2}p_B^\alpha p_{D^*}^\beta\left(T_1(q^2) - T_2(q^2) - \frac{q^2}{M_B^2 - M_{D^*}^2}T_3(q^2)\right)\Big]\end{aligned}$$

R_{D^*}

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

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

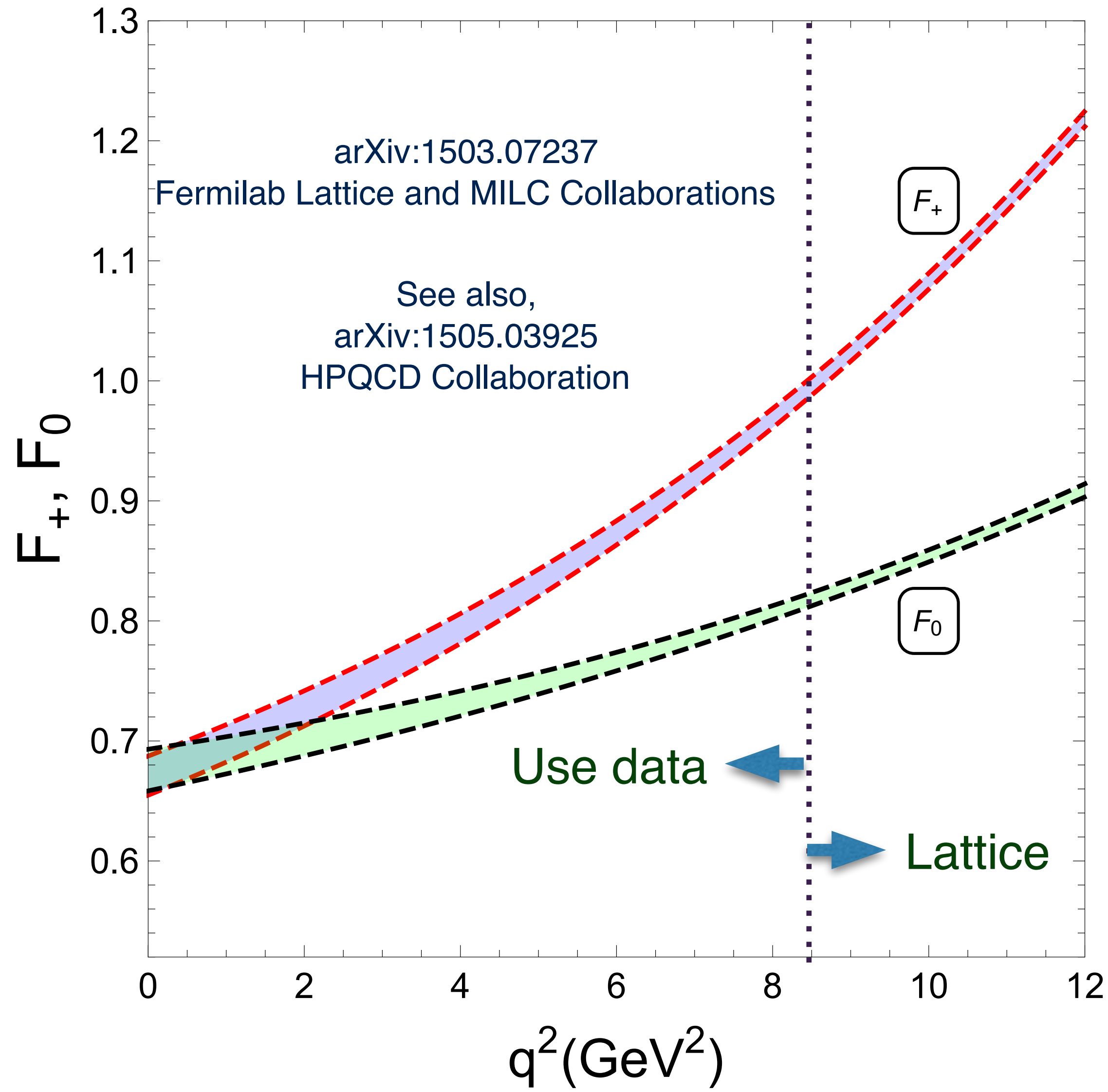
$\mathcal{O}^{cb\ell}_{\rm SL} = [\bar{c}\, b][\bar{\ell}\, P_L\,\nu]$

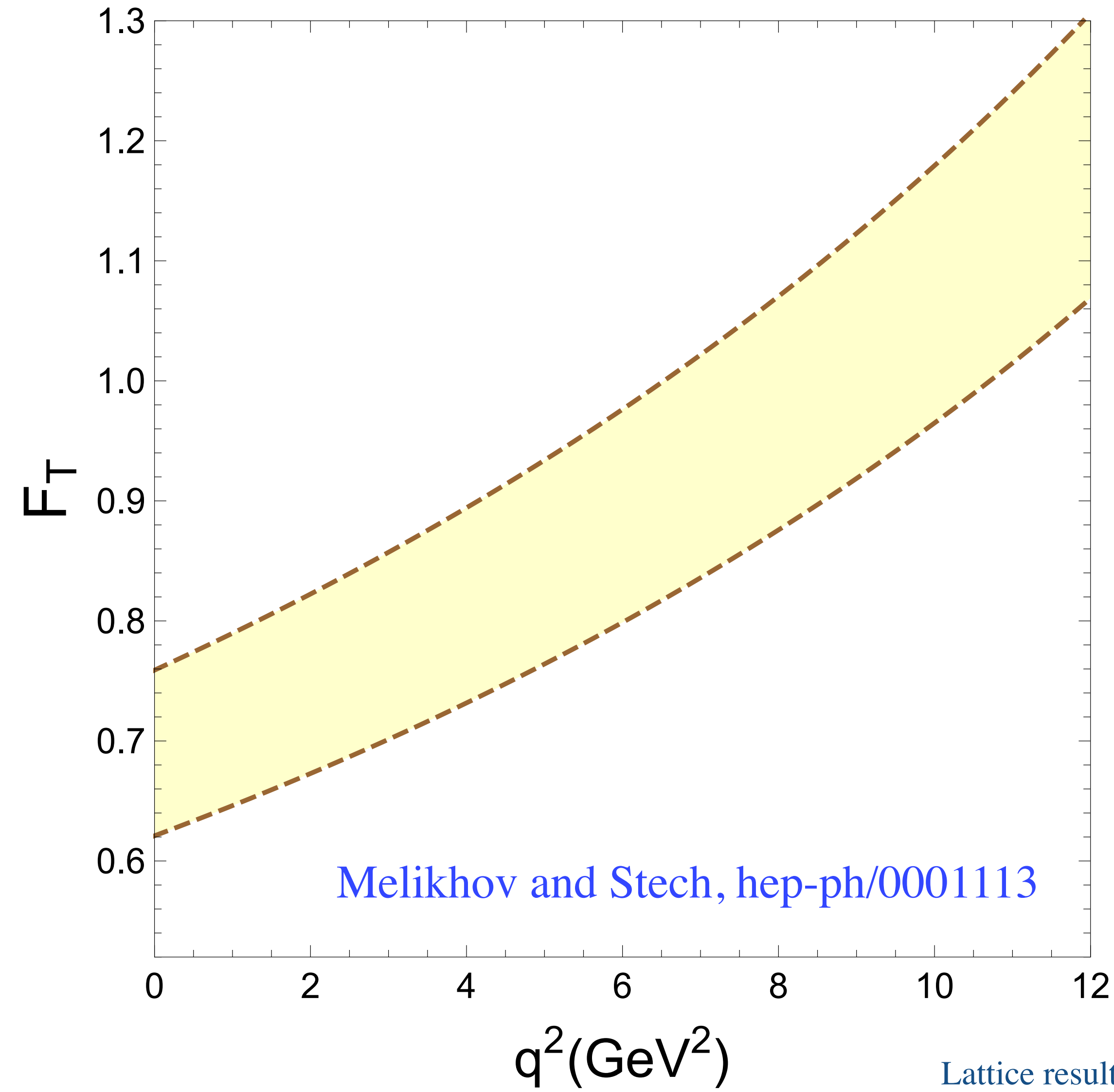
$\mathcal{O}^{cb\ell}_{\rm PL} = [\bar{c}\,\gamma_5\, b][[\bar{\ell}\, P_L\,\nu]$

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

The two decays $\overline{B} \to D^*\tau\bar{\nu}_\tau$ and $\overline{B} \to D\tau\bar{\nu}_\tau$ are in general theoretically independent

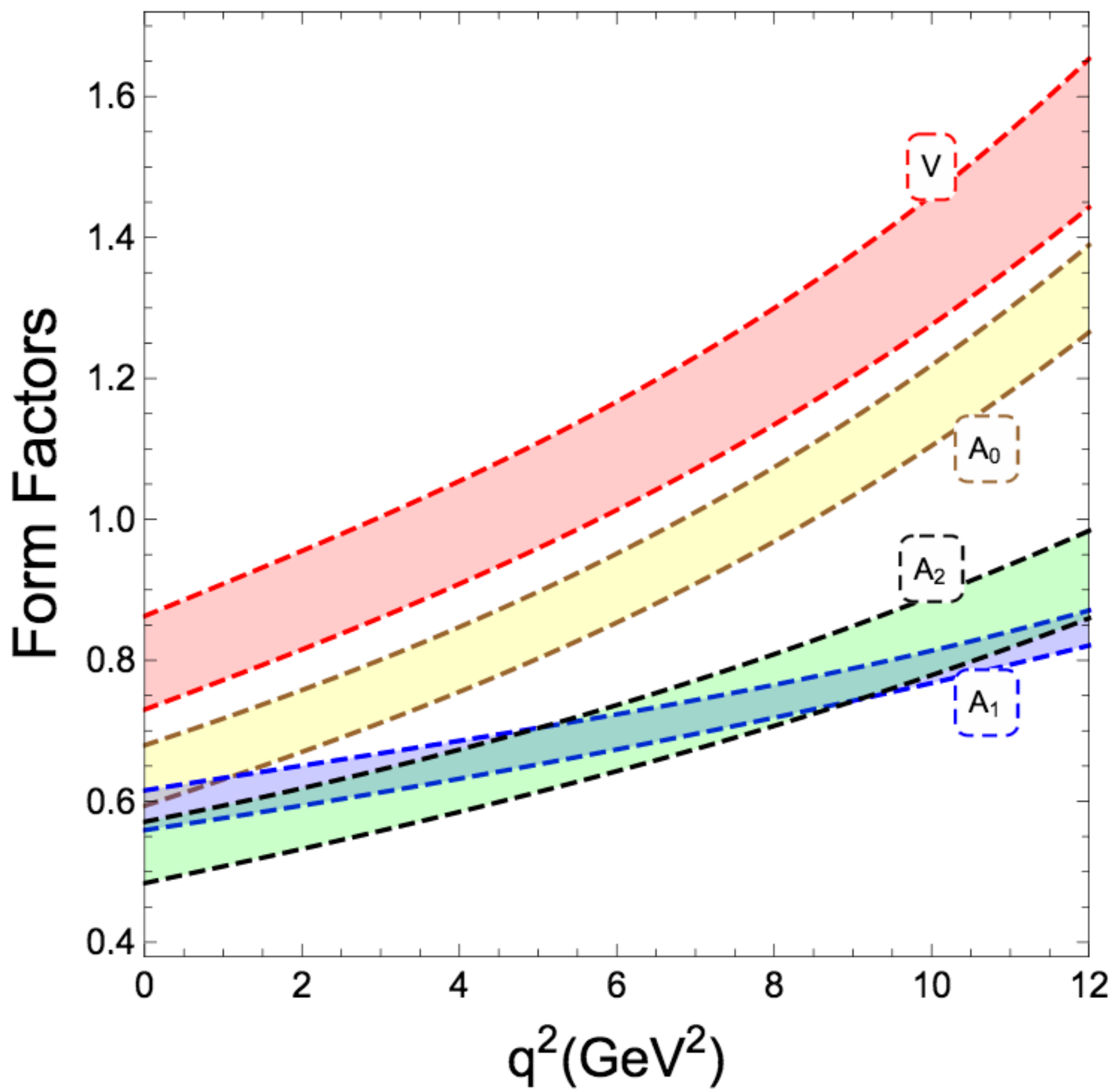
$\overline{B} \to D$ Form Factors

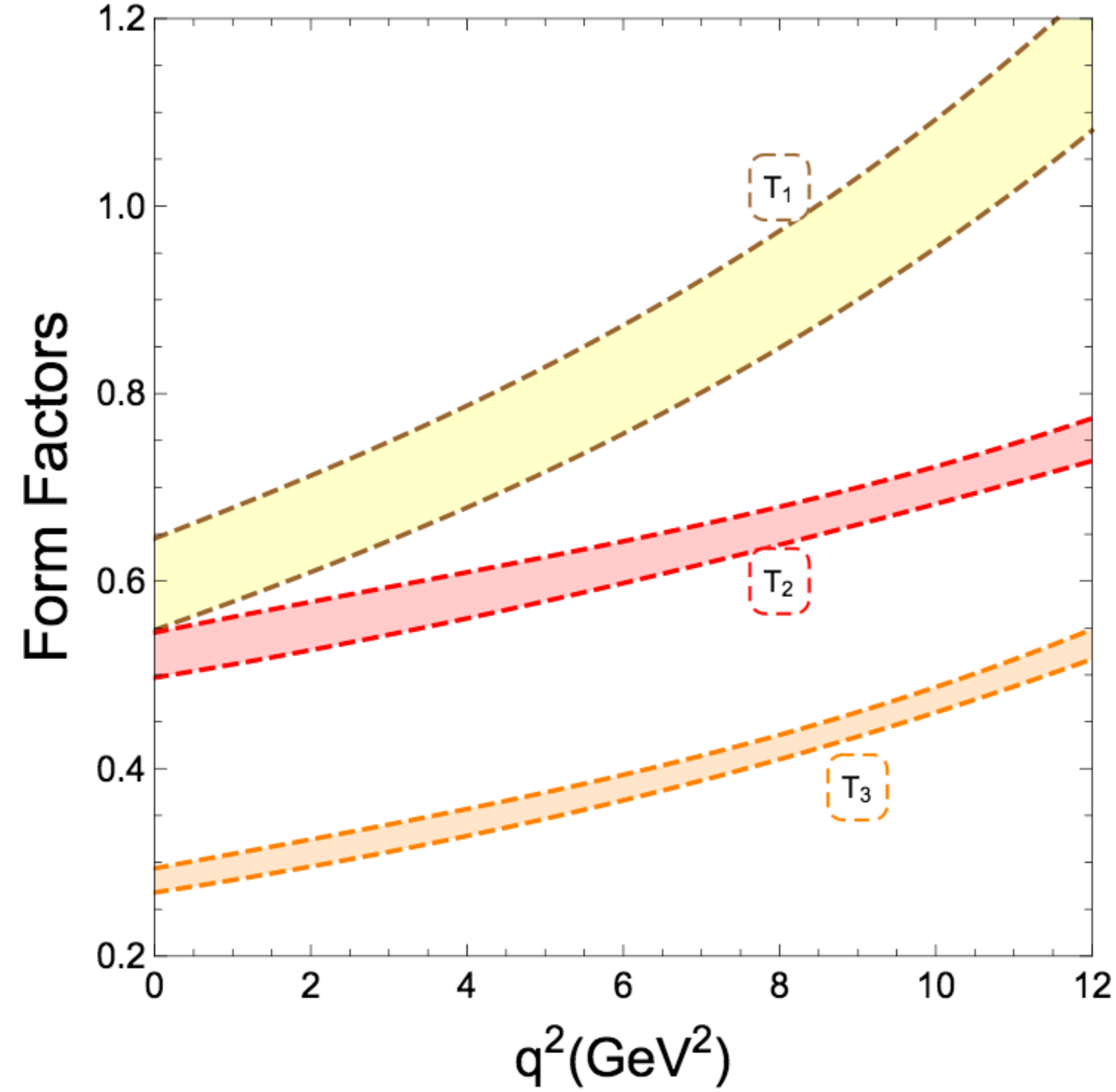




Lattice results exist only
in the zero recoil region
arXiv:1310.5238

$\overline{B} \to D^*$ Form Factors





Caprini, Lellouch, Neubert : hep-ph/9712417
Sakaki, Tanaka, Tayduganov, Watanabe : arXiv:1309.0301
Updated numbers from HFAG and
arXiv:1403.0635 (Fermilab Lattice, MILC collaboration)