University of Zurich[UZH]

Universality violations in tau decays

La Thuile 2022 - Les Rencontres de Physique de la Vallée d'Aoste

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University of Zurich

Based on work with:

L. Allwicher and G. Isidori

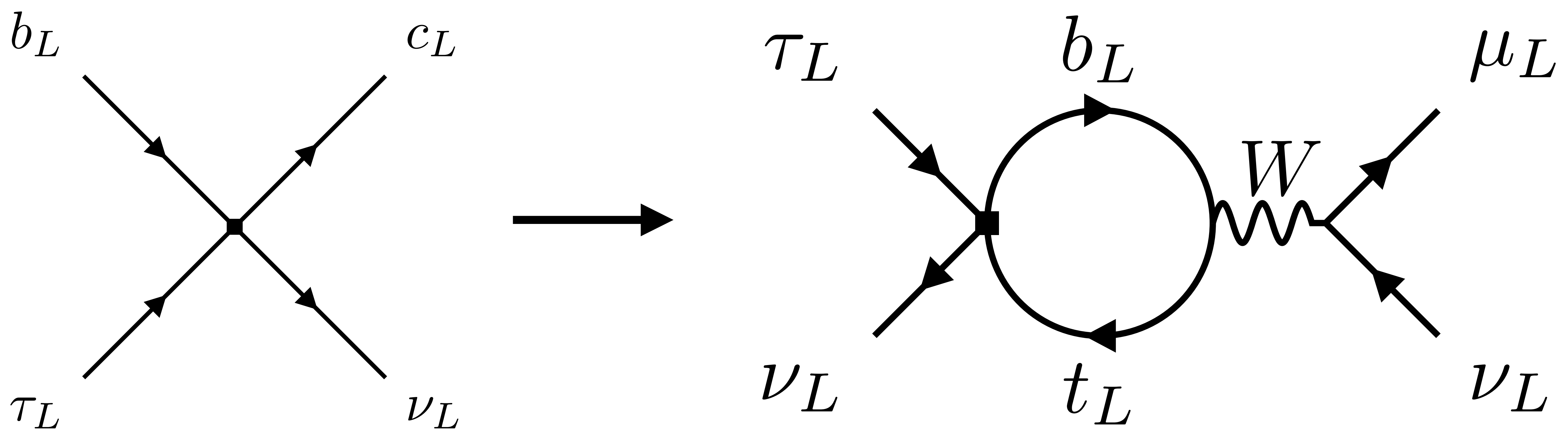
LFU violations in leptonic τ decays and B-physics anomalies: ***arXiv:2109.03833***

B-anomalies $\leftrightarrow$ LFUV in τ decays

[See talk by Claudia]

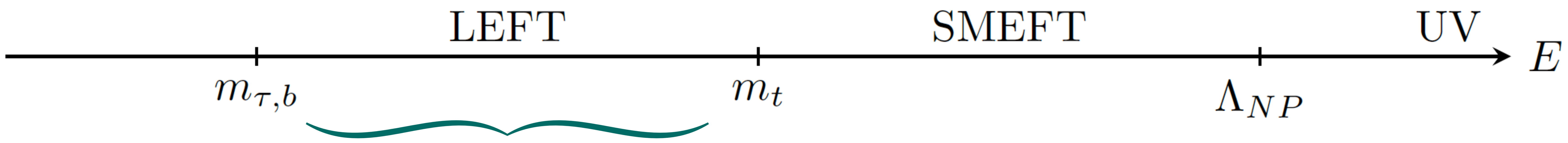
$$[O^{(1)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^{\alpha}_{L}\gamma_{\mu}\ell^{\beta}_{L})(\bar{q}^{i}_{L}\gamma^{\mu}q^{j}_{L})$$

$$[O^{(3)}_{\ell q}]_{\alpha\beta ij} = (\bar{\ell}^{\alpha}_{L}\sigma^{I}\gamma_{\mu}\ell^{\beta}_{L})(\bar{q}^{i}_{L}\sigma^{I}\gamma^{\mu}q^{j}_{L})$$



[F. Feruglio, P. Paradisi, A. Pattori arXiv: 1606.00524]

EFT for τ decays



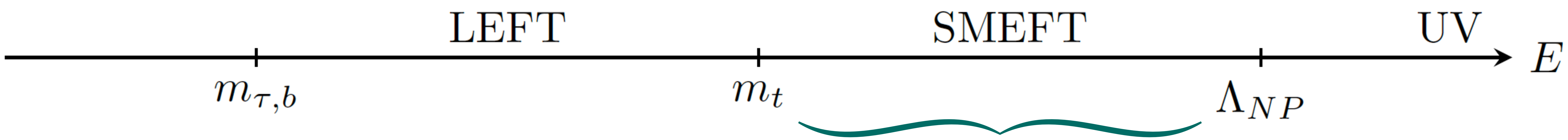
$$\boxed{\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2}\left[L_{\nu e}^{V,LL}\right]^{\alpha\beta\gamma\delta}\left(\bar{\nu}_L^{\alpha}\gamma_\mu\nu_L^{\beta}\right)\left(\bar{e}_L^{\gamma}\gamma^\mu e_L^{\delta}\right)}$$

In the SM: $\left[L_{\nu e}^{V,LL}\right]_{SM}^{\alpha\beta\beta\alpha} = 1$

Deviation parametrised by:

$$R_{\beta\alpha} \equiv \frac{\Gamma(\ell_\beta \to \ell_\alpha \nu\bar{\nu})}{\Gamma_{\text{SM}}(\ell_\beta \to \ell_\alpha \nu\bar{\nu})} \equiv 1 + \delta R_{\beta\alpha} \approx 1 + 2\,\text{Re}[L_{\nu e}^{V,LL}]_{\alpha\beta\beta\alpha}^{\text{NP}}$$

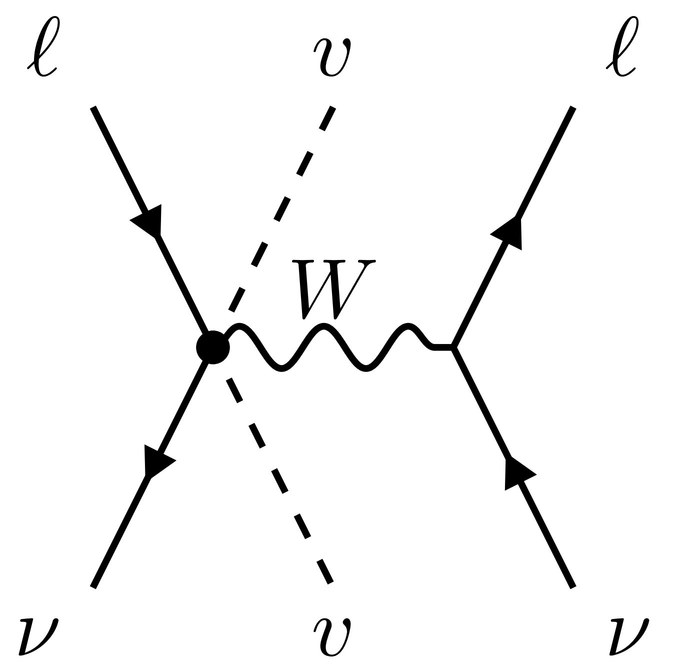
EFT for τ decays



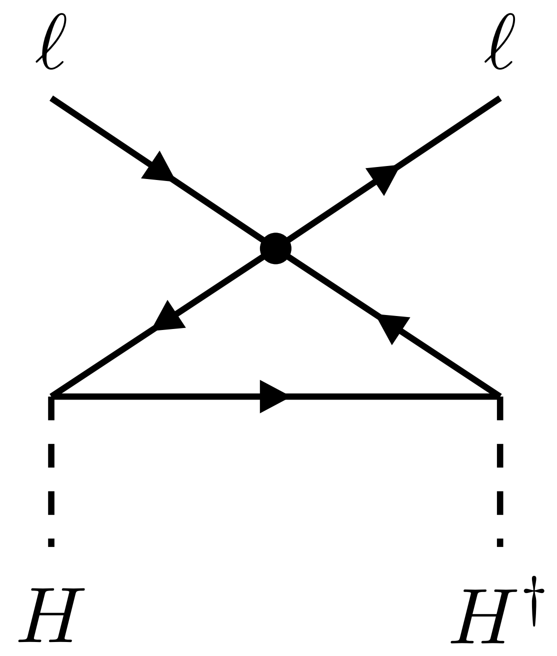
$$\mathcal{L}_{\text{SMEFT}} = -\frac{2}{v^2}\left[C_{\ell q}^{(3)}\right]^{\alpha\beta ij}\left(\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta\right)\left(\bar{q}^i\gamma^\mu\sigma^I q^j\right)$$

LEFT - SMEFT matching (tree-level):

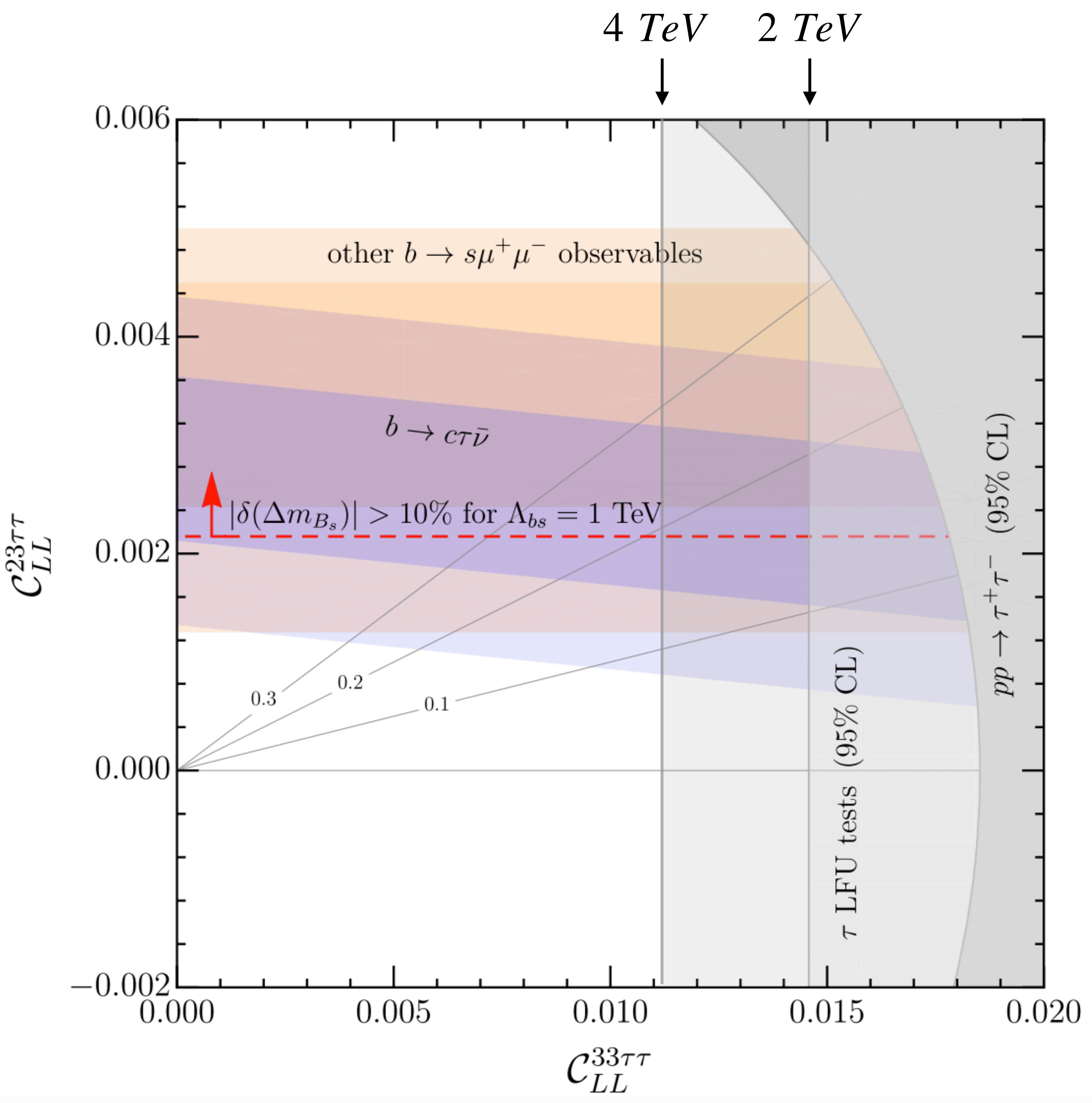
$$[L_{\nu e}^{V,LL}]^{\alpha\beta\beta\alpha}_{\text{NP}-\text{LL}} = -2\sum_{\gamma=\alpha,\beta}\left[C_{H\ell}^{(3)}\right]_{\gamma\gamma}(m_t) = -\frac{y_t^2 N_c}{8\pi^2}\log\frac{\Lambda^2_{\text{NP}}}{m_t^2}\sum_{\gamma=\alpha,\beta}[C_{\ell q}^{(3)}]_{\gamma\gamma 33}$$



$$[O_{H\ell}^{(3)}]_{\alpha\beta} = (\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta)(H^\dagger i\overleftrightarrow{D}^\mu\sigma^I H)$$



$$[L_{\nu e}^{V,LL}]^{\tau\beta\beta\tau}_{\text{NP}-\text{LL}} = -\frac{y_t^2 N_c}{8\pi^2} \log \frac{\Lambda_{\text{NP}}^2}{m_t^2} C_{LL}^{33\tau\tau}$$



[C. Cornella, D. Faroughy, J. Fuentes, G. Isidori, M. Neubert]
arXiv:2103.16558

- The finite (1-loop) corrections can modify the leading-log result: effectively changing the Λ_{NP} scale

4321 Models

[See talk by Claudia]

[L. Di Luzio, A. Greljo and M. Nardecchia, arXiv: 1708.08450]
[L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia, S. Renner, arXiv: 1808.00942]
[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv: 1712.01368, 1805.09328]
[H. Georgi, Y. Nakai, arXiv: 1606.05865] [J. Fuentes-Martın, P. Stangl, arXiv: 2004.11376]
[D. Guadagnoli, M. Reboud, P. Stangl, arXiv: 2005.10117] …

$$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	1/2
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2

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$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2
$q_L^{\prime i}$	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
$\ell_L^{\prime i}$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1

$i = 1,2$

$U(2)^5$: 1st ingredient

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$$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$$

$< \Omega_1 >$ $< \Omega_3 >$ $\longrightarrow$ U_μ $(+\ G'_\mu,\ Z'_\mu)$

U_1 LQ: 2nd ingredient

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L^3)^T$	**4**	**1**	**2**	0
$\psi_R^+ = (u_R^3\ \nu_R^3)^T$	**4**	**1**	**1**	1/2
$\psi_R^- = (d_R^3\ e_R^3)^T$	**4**	**1**	**1**	−1/2
$q_L'^i$	**1**	**3**	**2**	1/6
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
$\ell_L'^i$	**1**	**1**	**2**	−1/2
e_R^i	**1**	**1**	**1**	−1
Ω_3	$\bar{\mathbf{4}}$	**3**	**0**	1/6
Ω_1	$\bar{\mathbf{4}}$	**1**	**0**	−1/2

$i = 1,2$

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$\underset{g_4}{SU(4)_3} \times \underset{g_3}{SU(3)_{1+2}} \times SU(2)_L \times U(1)'$

$< \Omega_1 >$ $< \Omega_3 >$ ⟶ U_μ $(+\ G'_\mu\,,\ Z'_\mu)$

U_1 LQ: 2nd ingredient

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\psi_L = (q_L^3\ \ell_L^3)^T$	4	1	2	0
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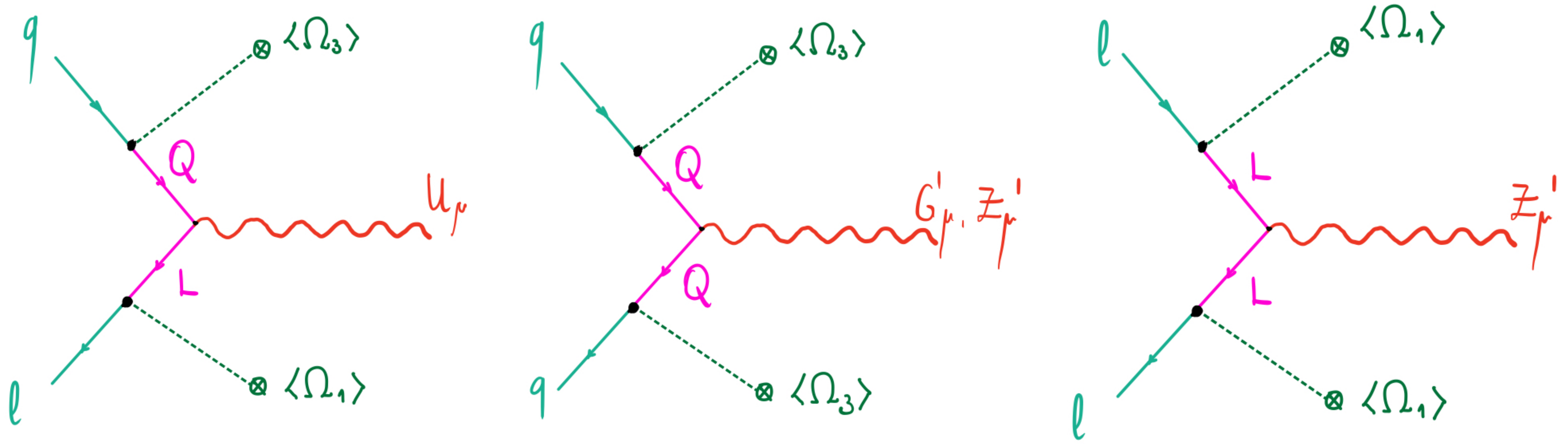
$\psi_R^- = (d_R^3\ e_R^3)^T$	4	1	1	−1/2
$q_L'^i$	1	3	2	1/6
u_R^i	1	3	1	2/3
d_R^i	1	3	1	−1/3
$\ell_L'^i$	1	1	2	−1/2
e_R^i	1	1	1	−1
Ω_3	$\bar{4}$	3	0	1/6
Ω_1	$\bar{4}$	1	0	−1/2

$i = 1,2$

$U(2)^5$: 1st ingredient

+ Vector-like fermions: $U(2)^5$ breaking

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$
$\chi_L = (Q_L'\ L_L')^T$	4	1	2	0
$\chi_R = (Q_R\ L_R)^T$	4	1	2	0



$\mathcal{L} \supset M_q \bar{Q}_R q_L^2 + M_\ell \bar{L}_R \ell_L^2$

Relevant couplings: U_1

LH U_1 interactions: $\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left(\bar{q}_L^3 \quad \bar{Q}'_L\right) W \gamma_\mu \begin{pmatrix} \ell_L^3 \\ L'_L \end{pmatrix} + \text{h.c.}$ $\quad W = \begin{pmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{pmatrix}$

VL - 2^{nd} generation mass mixing: $\mathcal{L} \supset M_q \bar{Q}_R q_L^2 + M_\ell \bar{L}_R \ell_L^2$

$\longrightarrow$ $\quad Q'_L = c_Q Q_L - s_Q q_L^2 \qquad L'_L = c_L L_L - s_L \ell_L^2$

Effectively: $\mathcal{L}_{U_1} \supset \frac{g_U}{\sqrt{2}} \beta_L^{i\alpha} U_1^\mu \bar{\psi}_{q_L}^i \gamma_\mu \psi_{\ell_L} + \text{h.c.}$

$$\psi_{q_L} = \begin{pmatrix} q_L^2 \\ q_L^3 \\ Q_L \end{pmatrix} \quad \psi_{\ell_L} = \begin{pmatrix} \ell_L^2 \\ \ell_L^3 \\ L_L \end{pmatrix} \quad \beta_L = \begin{pmatrix} \beta_L^{s\mu} & \beta_L^{s\tau} & \beta_L^{sL} \\ \beta_L^{b\mu} & \beta_L^{b\tau} & \beta_L^{bL} \\ \beta_L^{Q\mu} & \beta_L^{Q\tau} & \beta_L^{QL} \end{pmatrix}$$

$$\beta_L^{b\tau} = W_{11}\,, \quad \beta_L^{b\mu} = -s_L W_{12}\,,$$
$$\beta_L^{Q\tau} = c_Q W_{21}\,, \quad \beta_L^{Q\mu} = -c_Q s_L W_{22}$$

Relevant couplings: H & Z'

New Yukawa couplings between VL fermions and RH 3rd generation:

$$\Delta\mathcal{L}_Y = Y'_-\bar{\chi}_L\psi_R^- H + Y'_+\bar{\chi}_L\psi_R^+ H + \text{h.c.}$$

$$\to c_Q Y_-\bar{Q}_L d_R^3 H + c_Q Y_+\bar{Q}_L u_R^3 \tilde{H}$$

$$+ \underbrace{s_Q Y_-}_{[Y_d]^{23}}\bar{q}_L^2 d_R^3 H + \underbrace{s_Q Y_+}_{[Y_u]^{23}}\bar{q}_L^2 u_R^3 \tilde{H} + \text{h.c.}$$

$$|Y_+| \sim \frac{y_t V_{cb}}{s_Q} \gg |Y_-|$$

Z' interactions are flavour conserving in $SU(4)$ - space:

$$\mathcal{L}_{Z'} \supset -\frac{3g_U}{2\sqrt{6}} Z'_\mu \left(\bar{\ell}_L^3 \quad \bar{L}'_L\right)\gamma^\mu \begin{pmatrix}\ell_L^3 \\ L'_L\end{pmatrix} + \text{h.c.}$$

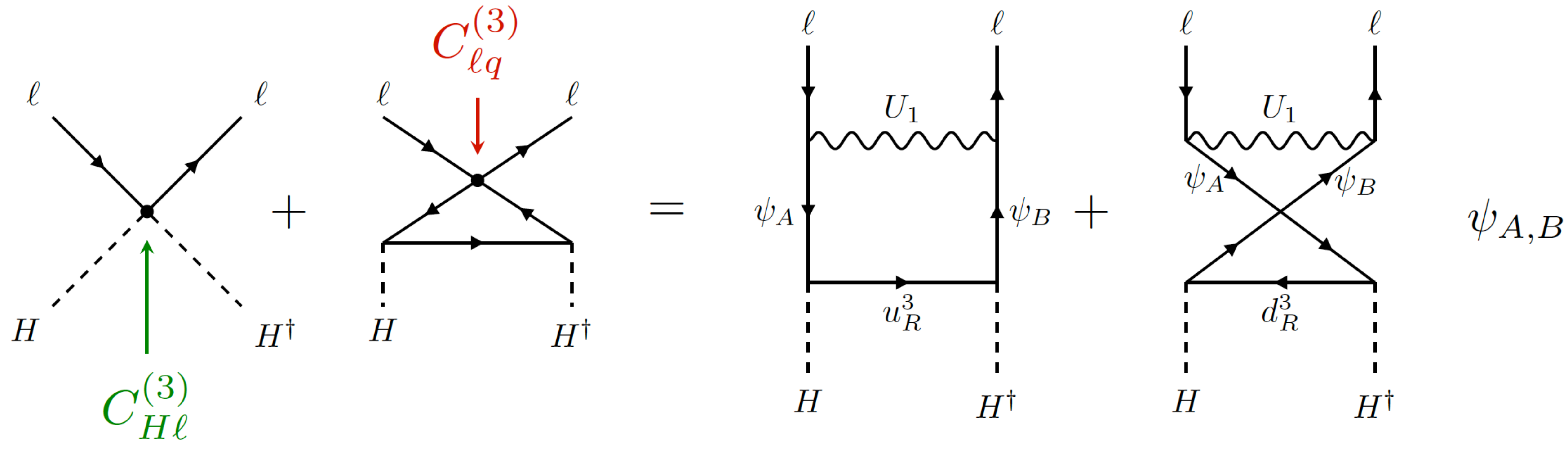
A small angle s_τ diagonalises lepton Yukawas in the 2-3 sector, $L_e^{23} = s_\tau$:

$$\ell_L^3 \to \ell_L^3 + s_\tau \ell_L^2$$

4321 - SMEFT matching @ 1-loop

1. Contribution to $C_{H\ell}^{(3)}$: $\langle \ell_\beta^b(0)\bar{\ell}_\alpha^a(0)H^c(q)H^{\dagger d}(-q)\rangle$

$$\left[O_{H\ell}^{(3)}\right]^{\alpha\beta} = \left(\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta\right)\left(H^\dagger i\overleftrightarrow{D}^\mu\sigma^I H\right) \qquad \left[O_{\ell q}^{(3)}\right]^{\alpha\beta ij} = \left(\bar{\ell}^\alpha\gamma_\mu\sigma^I\ell^\beta\right)\left(\bar{q}^i\gamma^\mu\sigma^I q^j\right)$$



$\psi_{A,B} = q, Q$

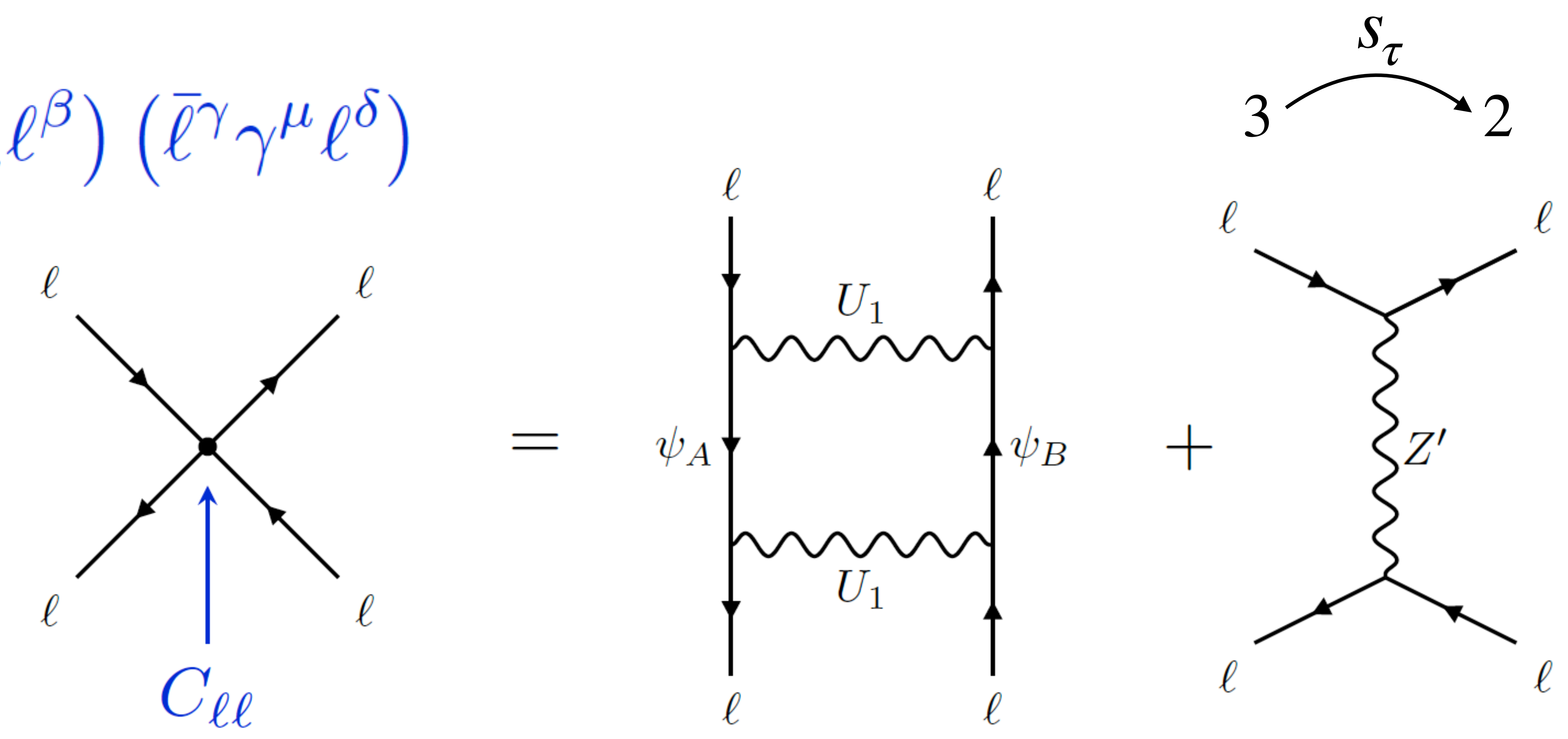
$$[C_{H\ell}^{(3)}]_{\tau\tau}(\mu) = -\frac{1}{16\pi^2}\frac{N_c C_U}{2}\Bigg[|\beta_L^{b\tau}|^2|y_t|^2\left(1+\log\frac{\mu^2}{m_U^2}\right)$$
$$+ c_Q 2\mathrm{Re}(\beta_L^{b\tau^*}\beta_L^{Q\tau}Y_+^* y_t)B_0(x_Q)$$
$$+ c_Q^2|\beta_L^{Q\tau}|^2(|Y_+|^2+|Y_-|^2)F(x_Q, x_Q^R)\Bigg]$$

$$C_U = \frac{g_U v^2}{4m_U^2}$$

4321 - SMEFT matching @ 1-loop

2. Contribution to $C_{\ell\ell}$:

$$[O_{\ell\ell}]^{\alpha\beta\gamma\delta} = \left(\bar{\ell}^\alpha \gamma_\mu \ell^\beta\right)\left(\bar{\ell}^\gamma \gamma^\mu \ell^\delta\right)$$



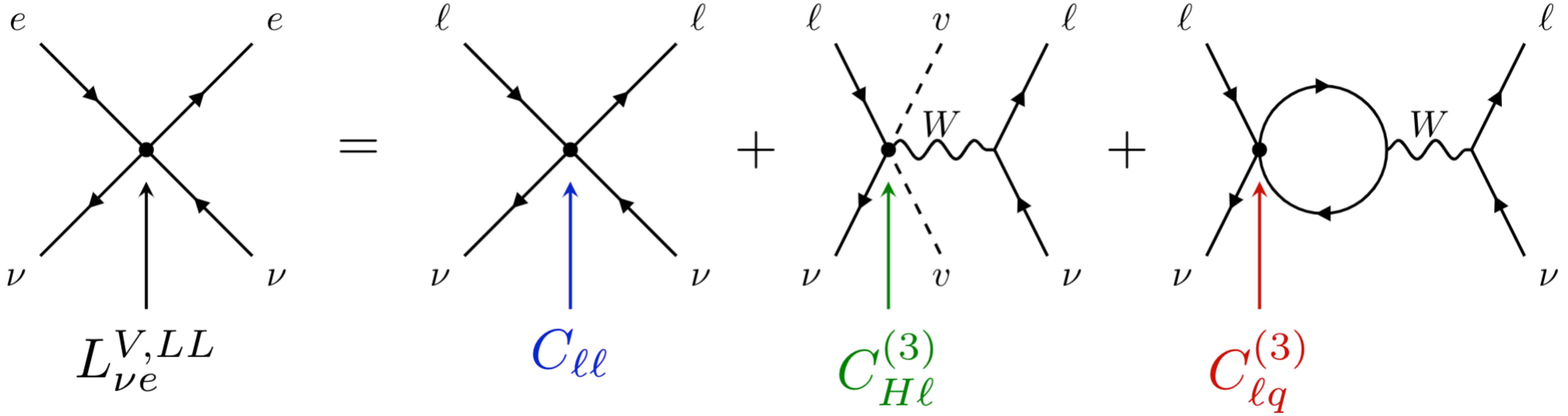
$$[C_{\ell\ell}]_{\tau\mu\mu\tau} = [C_{\ell\ell}]_{\mu\tau\tau\mu} = C_U \frac{g_U^2}{16\pi^2} s_L^2 B_{\ell\ell}^{1212} + \frac{3 g_U^2 v^2}{16 m_{Z'}^2} s_\tau^2$$

[J. Fuentes-Martın, G. Isidori, M. König, N. Selimović arXiv: 2009.11296]

SMEFT - LEFT matching @ 1-loop

1. Contribution to $L_{\nu e}^{V,LL}$:

$$[\mathcal{O}_{\nu e}^{V,LL}]^{\alpha\beta\gamma\delta} = \left(\bar{\nu}_L^\alpha \gamma_\mu \nu_L^\beta\right)\left(\bar{e}_L^\gamma \gamma^\mu e_L^\delta\right)$$



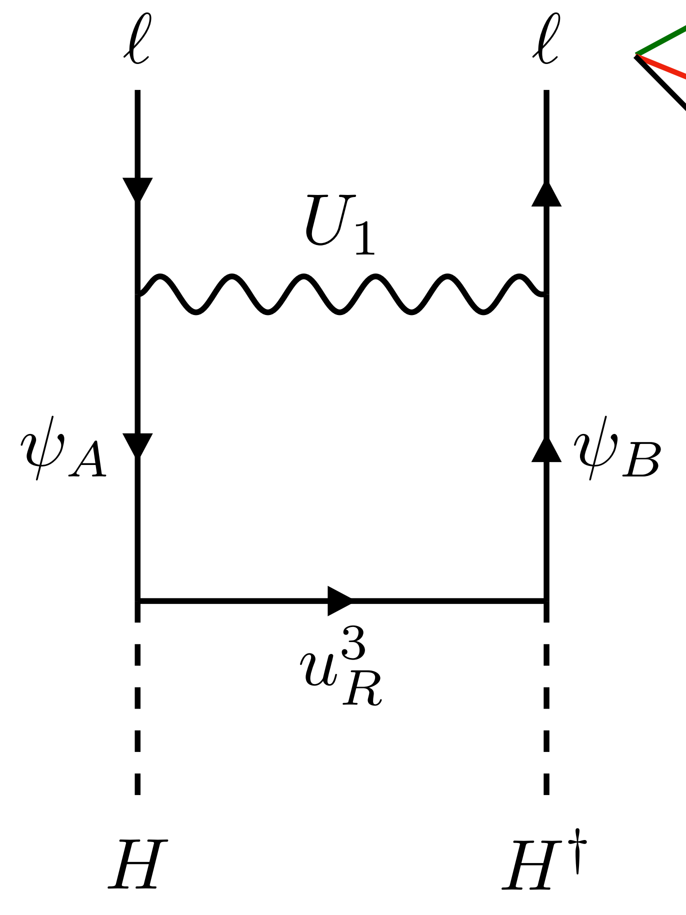
$$[L_{\nu e}^{V,LL}]_{\alpha\beta\beta\alpha}^{\mathrm{NP-full}} = -2\sum_{\gamma=\alpha,\beta}[C_{H\ell}^{(3)}]_{\gamma\gamma}(\mu) + [C_{\ell\ell}]_{\alpha\beta\beta\alpha} + [C_{\ell\ell}]_{\beta\alpha\alpha\beta} - \frac{m_t^2 N_c}{8\pi^2 v^2}\sum_{\gamma=\alpha,\beta}[C_{\ell q}^{(3)}]_{\gamma\gamma 33}\left(1 + 2\log\frac{\mu^2}{m_t^2}\right)$$

$\delta R_{\tau\mu}$

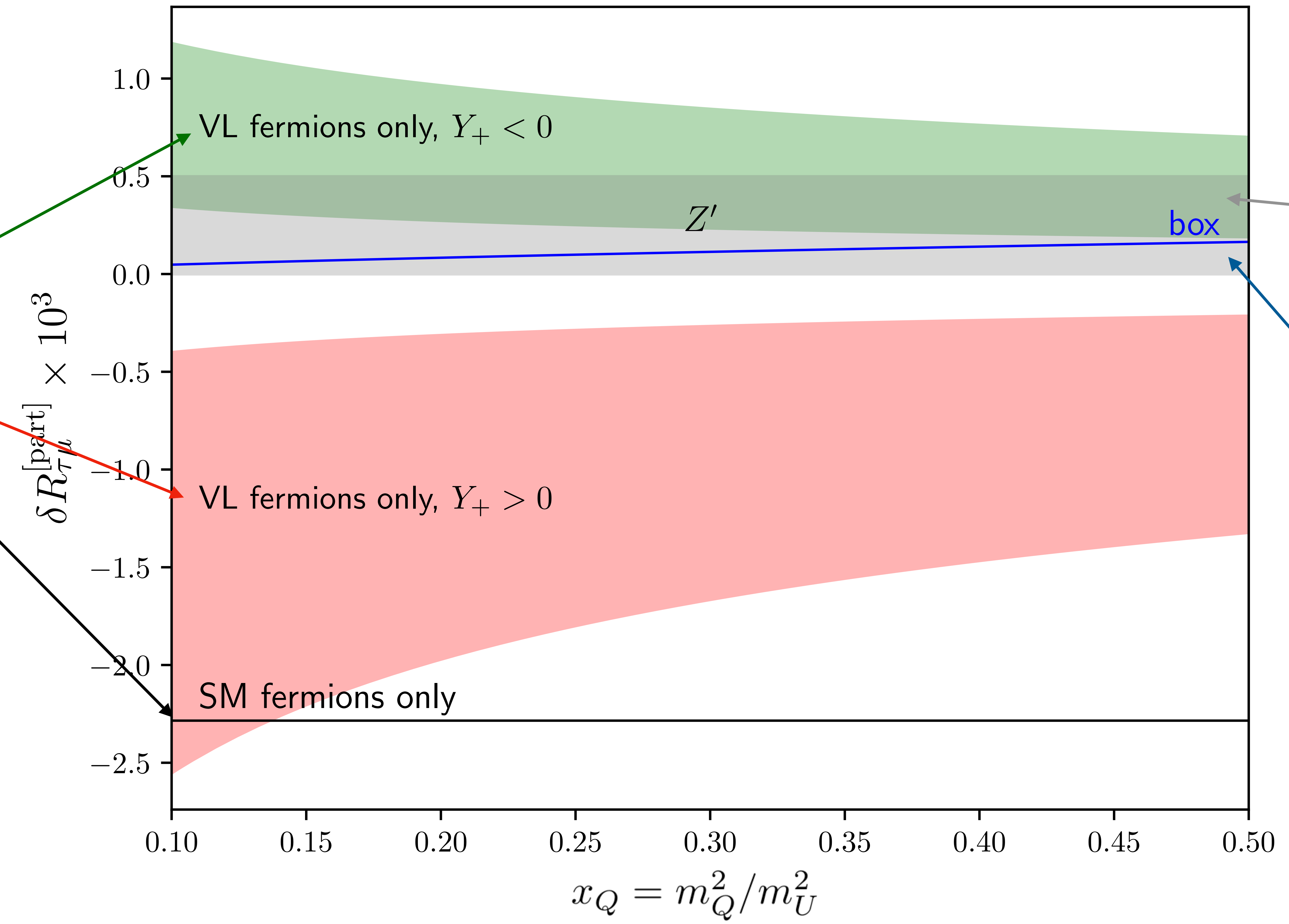
$$R_{\beta\alpha} \equiv \frac{\Gamma(\ell_\beta \to \ell_\alpha \nu\bar{\nu})}{\Gamma_{\text{SM}}(\ell_\beta \to \ell_\alpha \nu\bar{\nu})} \equiv 1 + \delta R_{\beta\alpha} \approx 1 + 2\,\text{Re}[L^{V,LL}_{\nu e}]^{\text{NP}}_{\alpha\beta\beta\alpha}$$

Parameters fixed to fit B-anomalies

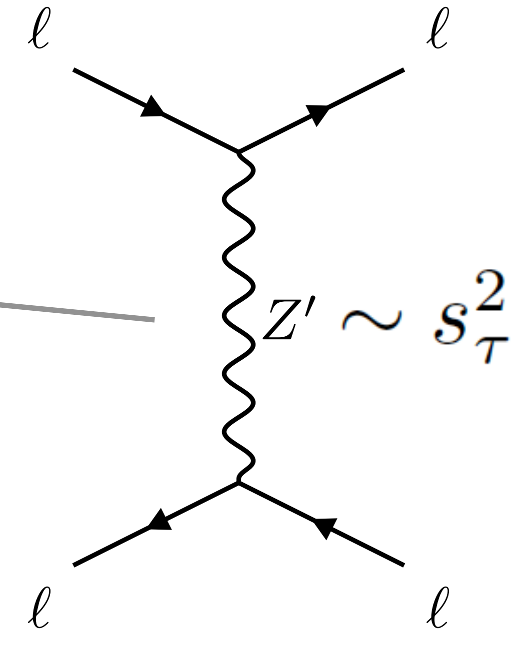
[C. Cornella, D. Faroughy, J. Fuentes, G. Isidori, M. Neubert] arXiv:2103.16558

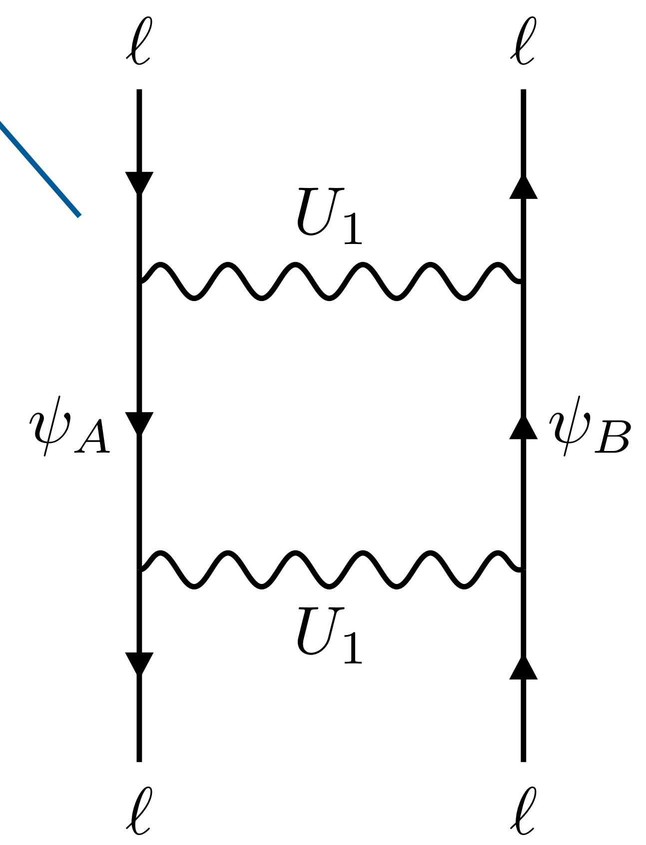


$0.2 < |Y_+| < 1$



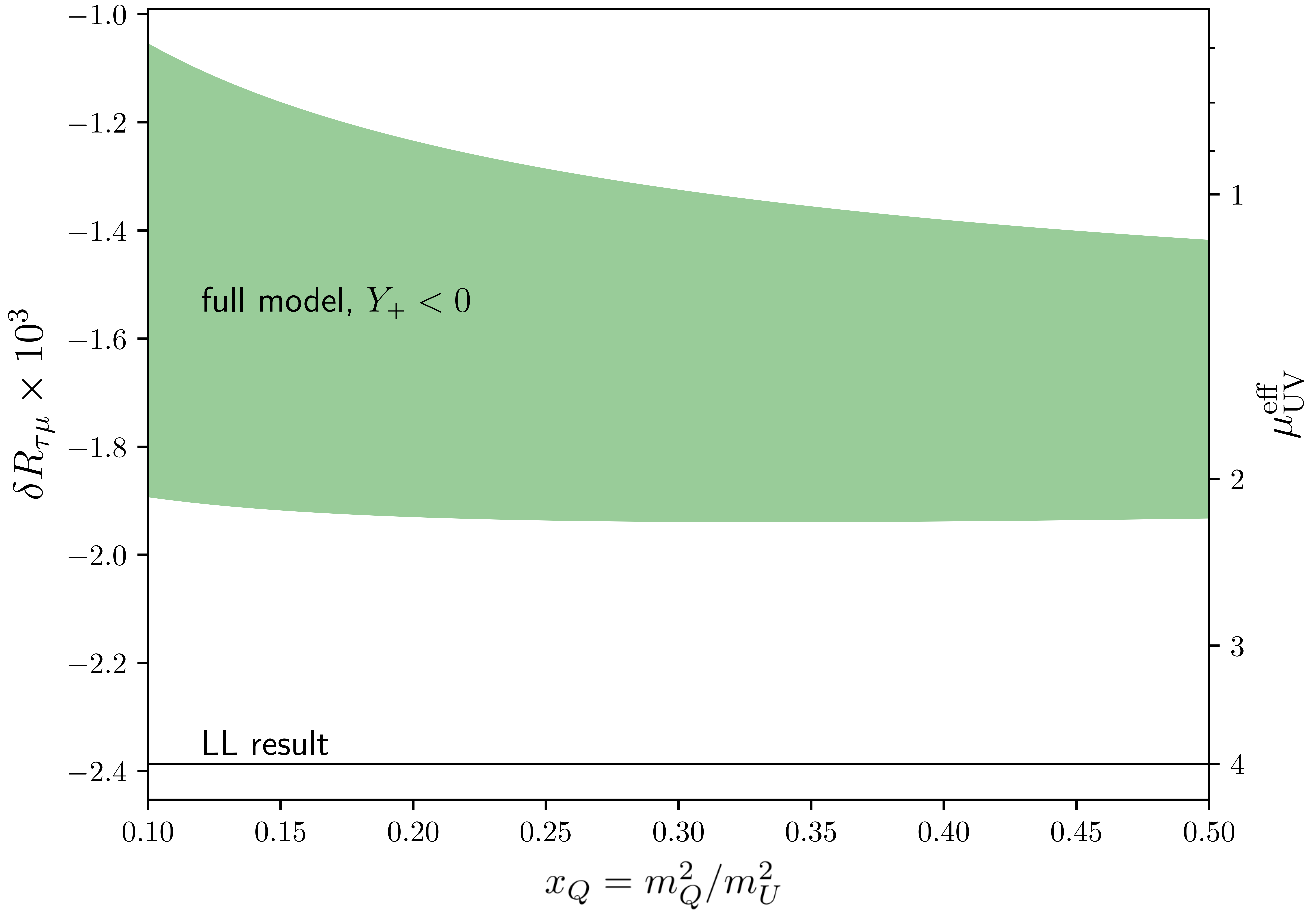
Negligible for $0 < s_\tau \lesssim 0.7$

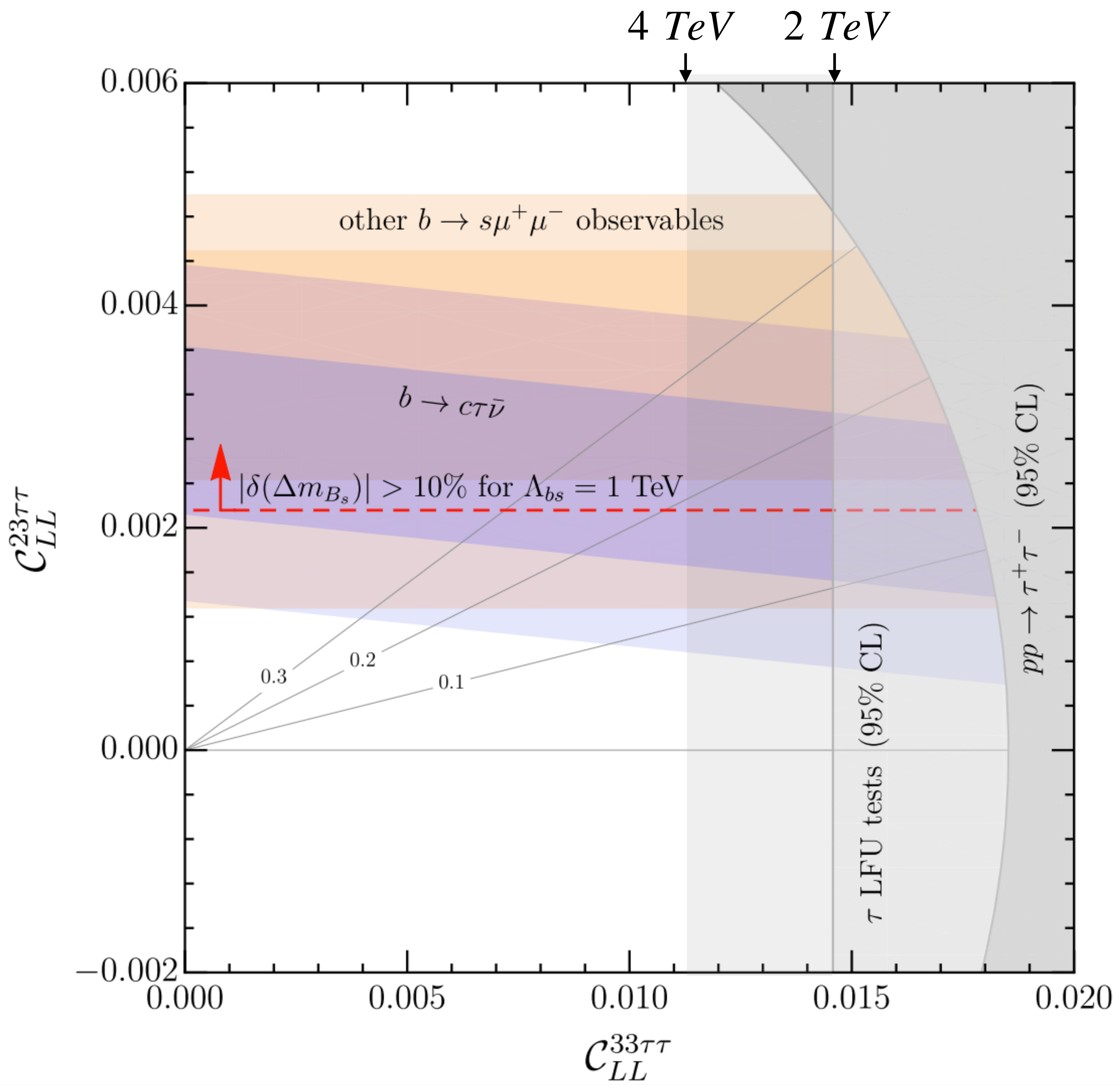




Effective NP scale

$$[L^{V,LL}_{\nu e}]^{\tau\beta\beta\tau}_{\rm NP-LL} = -\frac{y_t^2 N_c}{8\pi^2} \log \frac{\Lambda^2_{\rm NP}}{m_t^2} C^{33\tau\tau}_{LL}$$





W-coupling modification

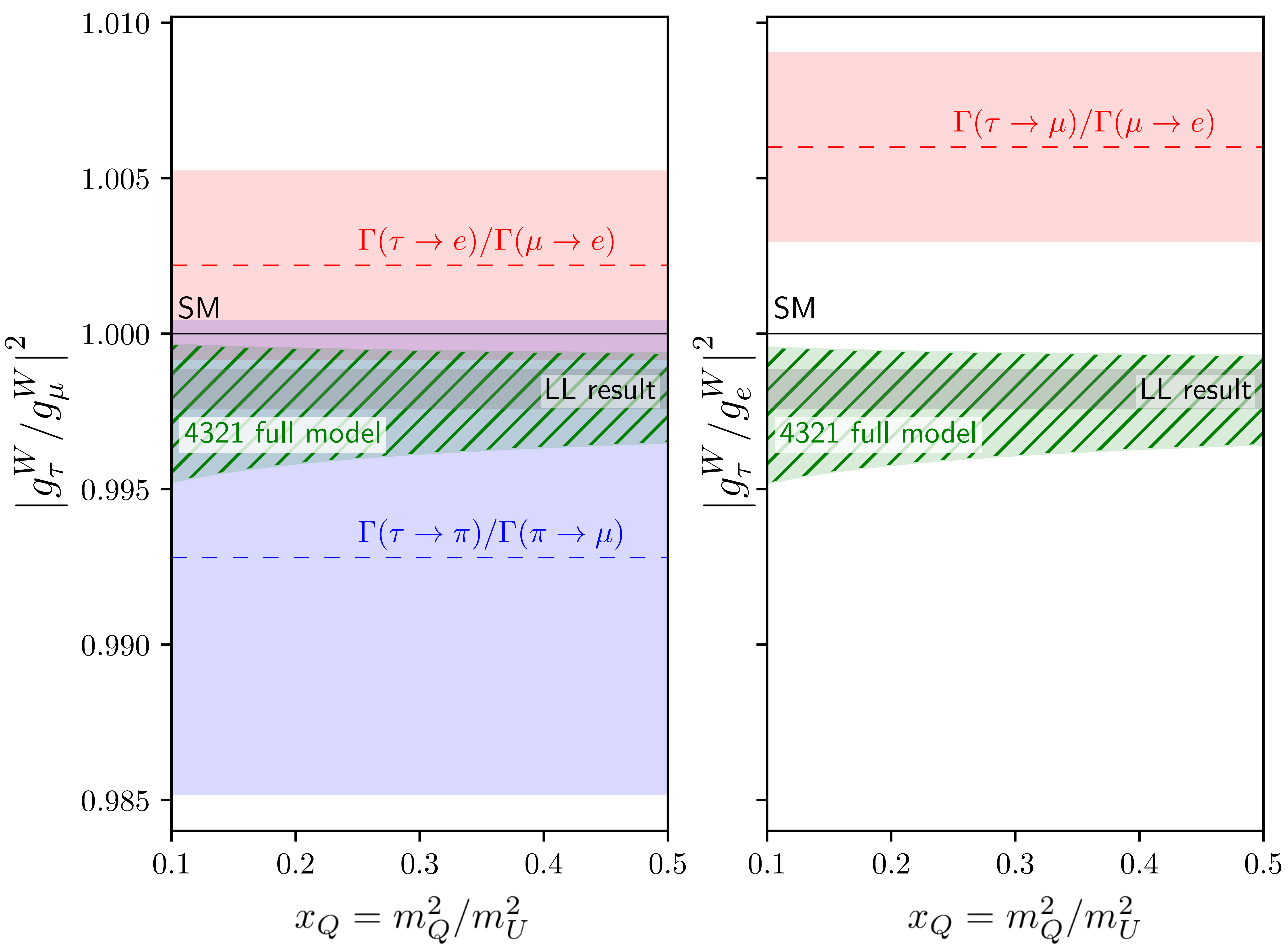
$$\left|\frac{g_e^{(\tau)}}{g_e^{(\mu)}}\right|^2 \equiv \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\mu\to e\nu\bar{\nu})}\times\left[\frac{\Gamma_{SM}(\tau\to e\nu\bar{\nu})}{\Gamma_{SM}(\mu\to e\nu\bar{\nu})}\right]^{-1}$$

Neglecting the contributions from $C_{\ell\ell}$:

$$\left|\frac{g_e^{(\tau)}}{g_e^{(\mu)}}\right|^2 \approx \left|\frac{g_\tau^W}{g_\mu^W}\right|^2$$

$$\mathcal{L}_{\rm eff}^{(\ell,W)} = -\frac{g_\ell^W}{\sqrt{2}}\,\bar{\nu}_\ell\gamma^\mu P_L \ell\; W_\mu^+ + \text{h.c.}$$

- Including VL fermions can sizeably change the LL result
- Need for $\mathcal{O}(10^{-4})$ LFU tests to exclude/confirm the model



Z-coupling modification

$$\mathcal{L}_{\text{eff}}^{(\ell,Z)} = -\frac{g_2}{c_W}\left[g^Z_{\ell_L}(\bar{\ell}\gamma^\mu P_L \ell) + g^Z_{\nu_\ell}(\bar{\nu}_\ell\gamma^\mu P_L \nu_\ell)\right] Z_\mu$$

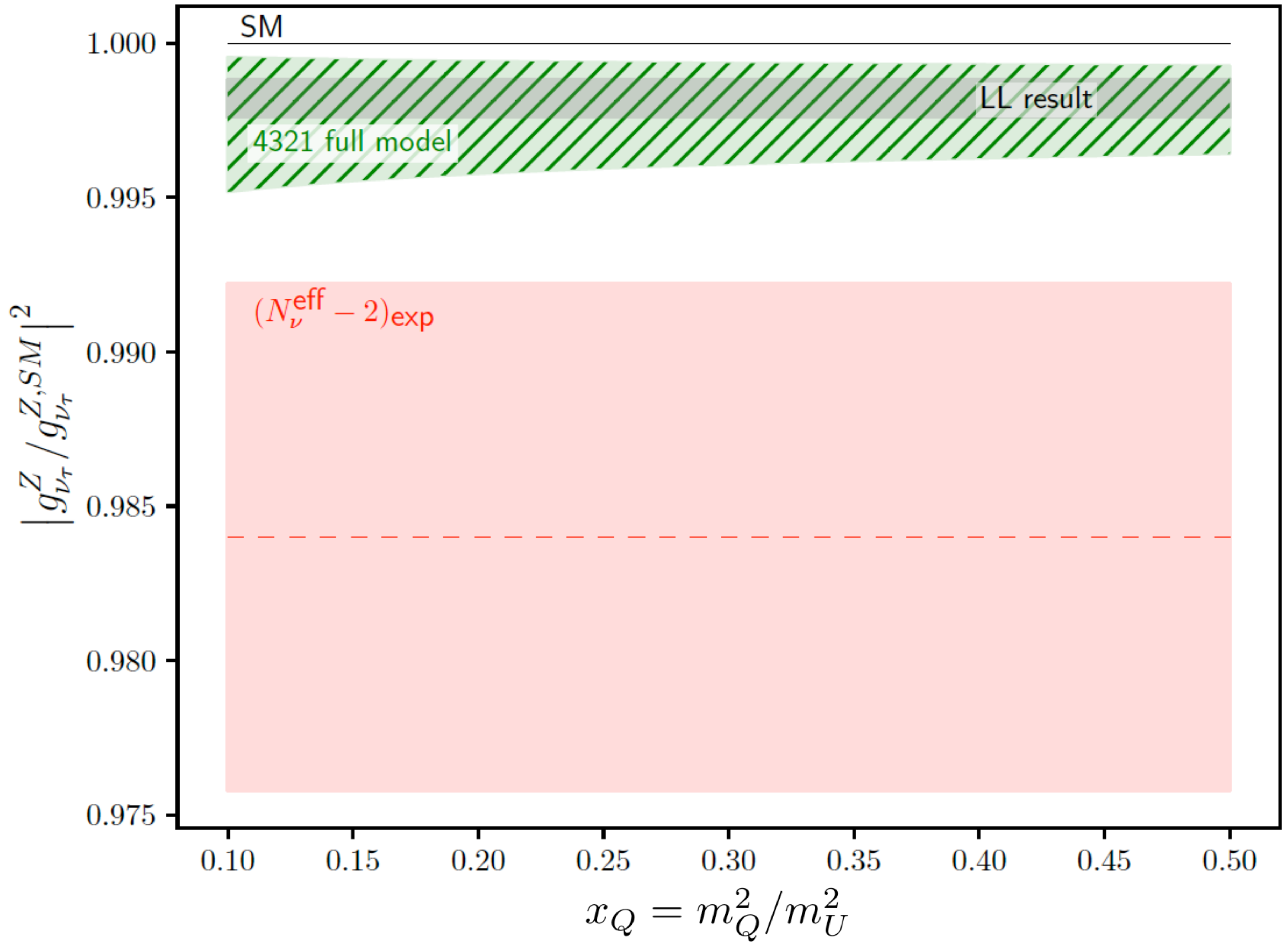
$$[O^{(1)}_{H\ell}]_{\alpha\beta} = (\bar{\ell}_\alpha\gamma_\mu\ell_\beta)(H^\dagger i\overleftrightarrow{D^\mu}H)\,,$$
$$[O^{(3)}_{H\ell}]_{\alpha\beta} = (\bar{\ell}_\alpha\gamma_\mu\sigma^I\ell_\beta)(H^\dagger i\overleftrightarrow{D^\mu}\sigma^I H)$$

$$\delta g^Z_{\nu_\ell}(\mu) = -\frac{v^2}{2}\left\{[C^{(1)}_{H\ell}]_{\ell\ell}(\mu) - [C^{(3)}_{H\ell}]_{\ell\ell}(\mu)\right\}$$
$$\delta g^Z_{\ell_L}(\mu) = -\frac{v^2}{2}\left\{[C^{(1)}_{H\ell}]_{\ell\ell}(\mu) + [C^{(3)}_{H\ell}]_{\ell\ell}(\mu)\right\}$$

$$\delta g^Z_{\ell_L}\big|_{Y_-=0} = 0\,, \qquad \left.\frac{\delta g^Z_{\nu_\ell}}{g^{Z,\text{SM}}_{\nu_\ell}}\right|_{Y_-=0} = \left.\frac{\delta g^W_\ell}{g^{W,\text{SM}}_\ell}\right|_{Y_-=0}$$

$$\left|\frac{g^Z_{\nu_\tau}}{g^{Z,\text{SM}}_{\nu_\tau}}\right|^2_{N^{\text{eff}}_\nu} = N^{\text{eff}}_\nu - 2$$

$$(N^{\text{eff}}_\nu - 2)_{\text{exp}} = 0.9840 \pm 0.0082$$



Summary & Outlook

- A general EFT approach implies that the $b \to c\tau\nu$ anomaly implies a decrease of the effective W-boson coupling to τ leptons in the few per-mil range.
- The inclusion of vector-like fermions, motivated by B-physics data, can lead to sizeable modifications of the EFT results.
- The same contributions lead to a modification of the Z-boson couplings to neutrinos
- Need for $\mathcal{O}(10^{-4})$ LFU tests to exclude/confirm the model

THANK YOU!

BACKUP

What is Lepton Flavour Universality (LFU)?

In the SM:

- $\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}$ ⟶ LFU: Interactions of $e,\ \mu,\ \tau$ with $\gamma,\ W,\ Z$

  $+\mathscr{L}_{\text{Higgs+Yukawa}}$ ⟶ LFUV: Interactions of $e,\ \mu,\ \tau$ with H

- LFU breaking is small: $y_\tau \sim 10^{-2}$

Beyond the SM:

- New Physics may distinguish different lepton species

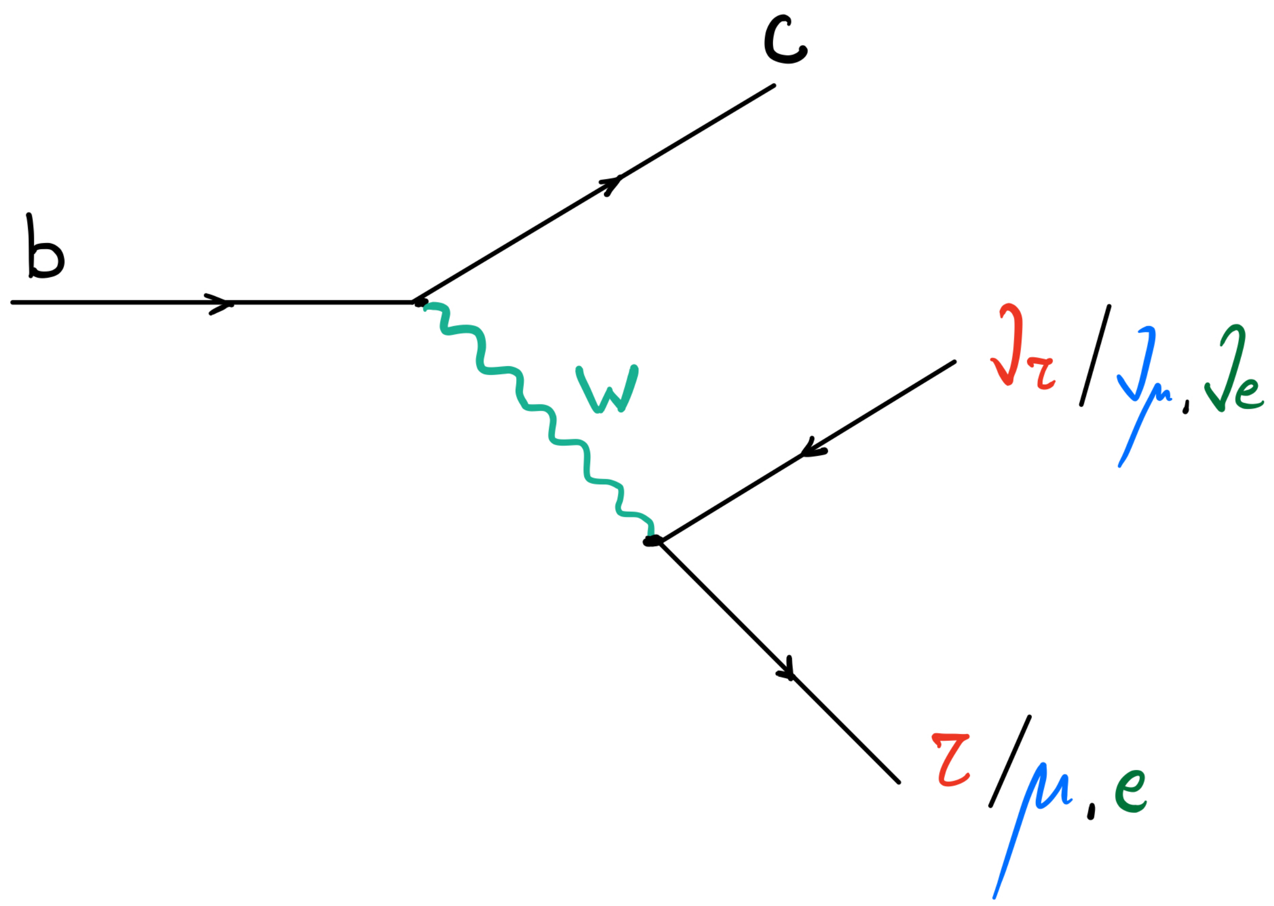
Hints of LFUV:

- $b \to s\ell\ell$
- $b \to c\tau\nu$

transitions

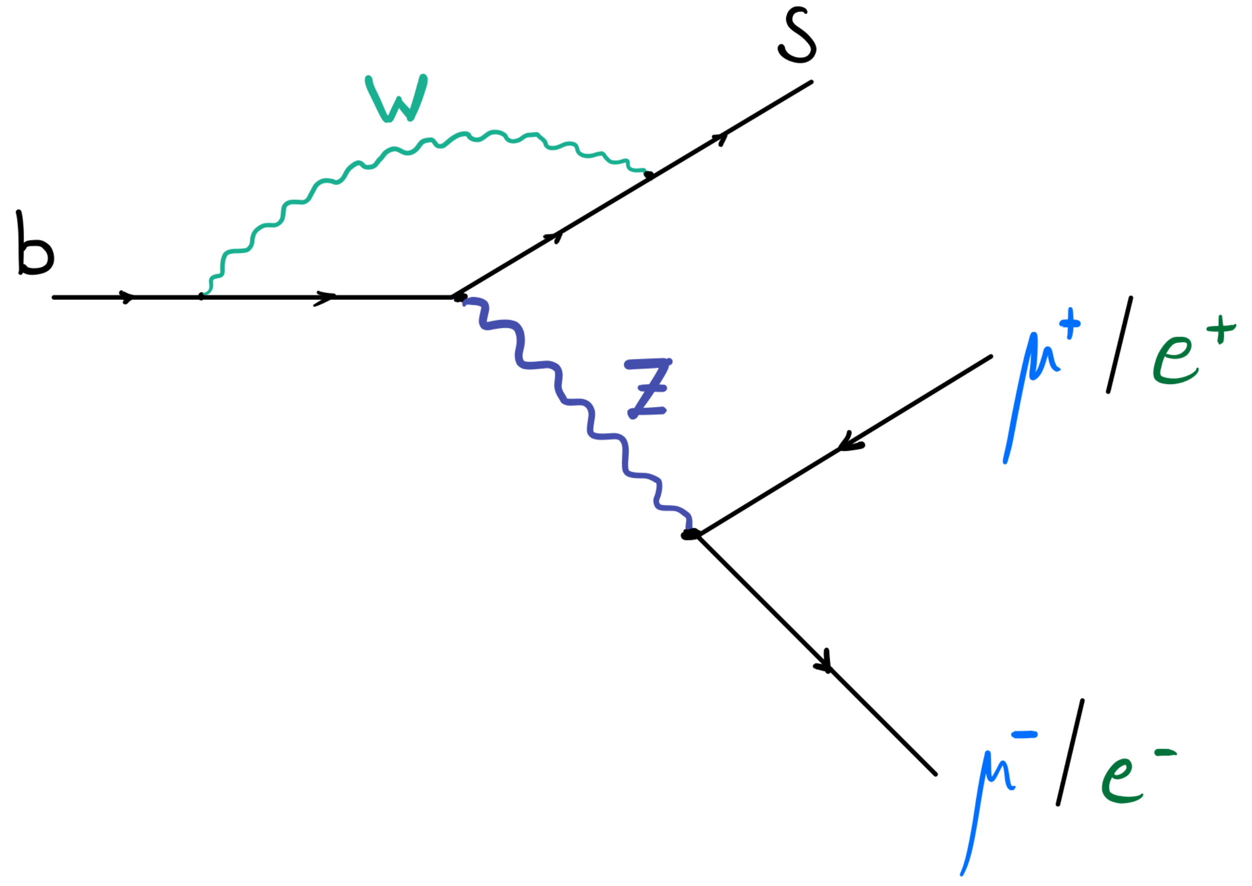
B-anomalies: a quick review

- $\tau\,/\,\mu$ and $\tau\,/\,e$ $\sim 3\sigma$ deviation in $b \to c\tau\nu$ charged current



- *Tree* level in SM

- $\mu\,/\,e$ $\sim 4\sigma$ deviation in $b \to s\ell\ell$ neutral current



- *Loop* level in SM

Combined explanation ingredients

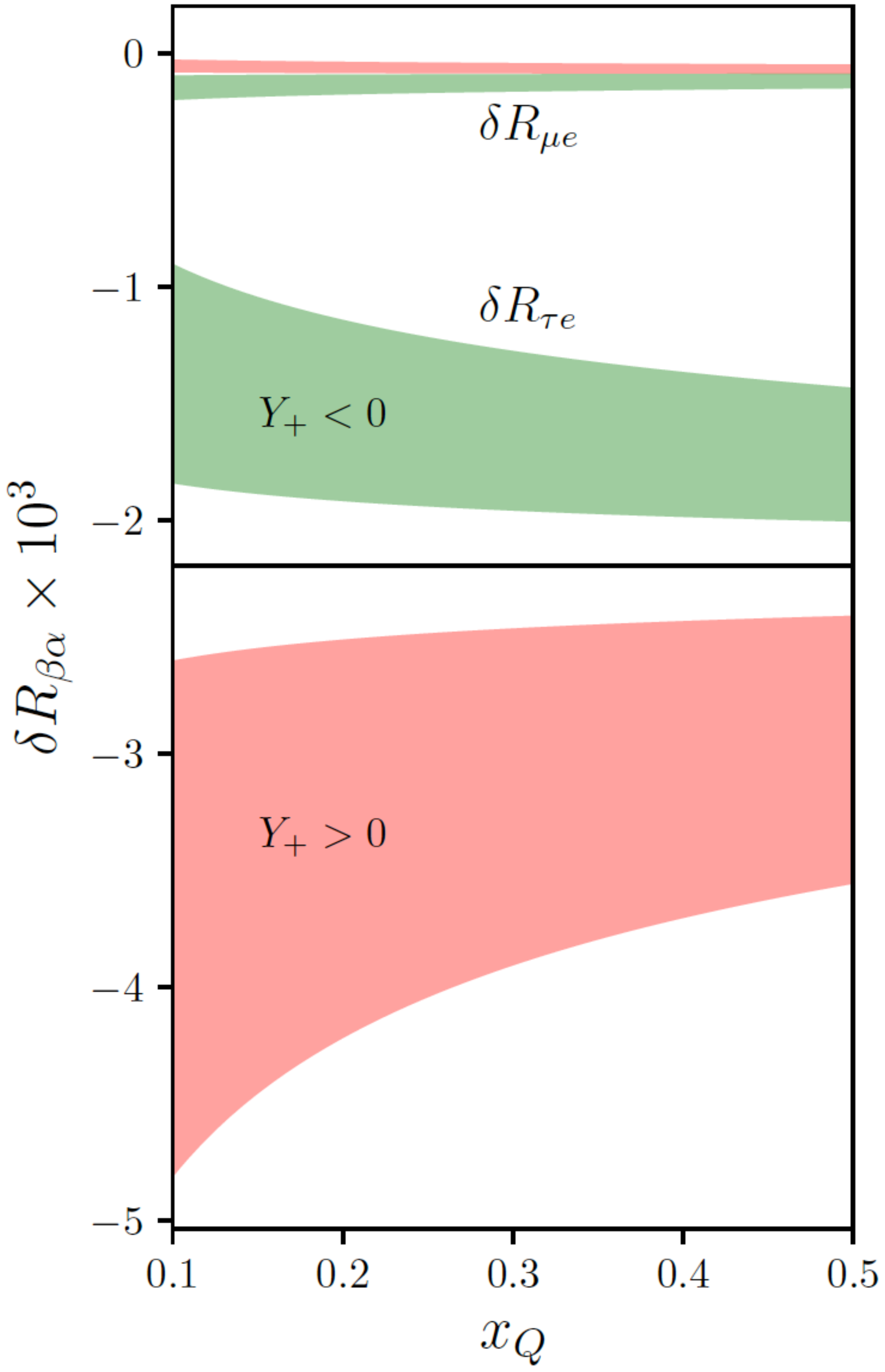
1. Approximate $U(2)^5$ *flavour symmetry*

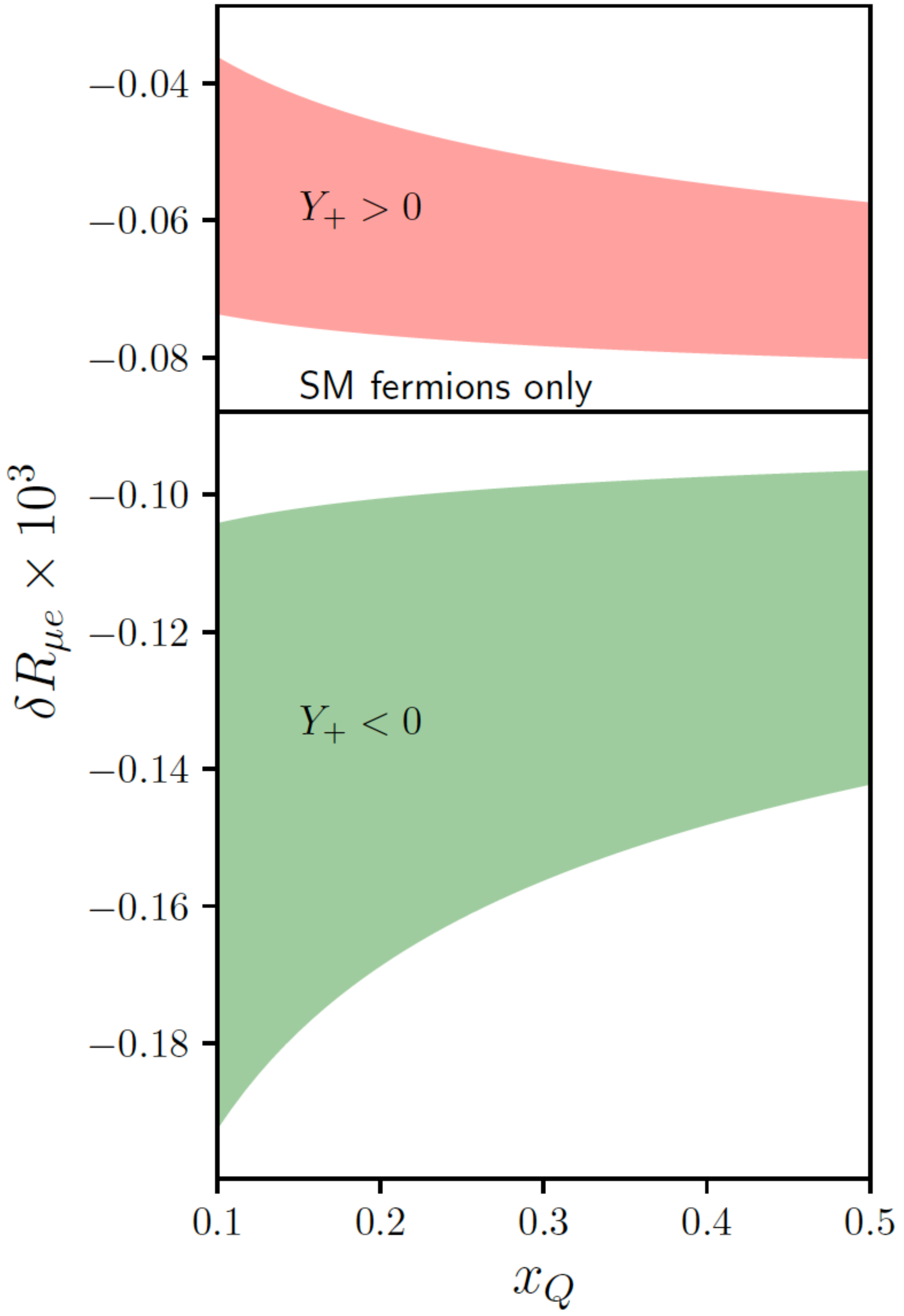
   [R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone and D. M. Straub, arXiv:1105.2296]

2. $U_1 \sim (3,1)_{2/3}$ *vector leptoquark*

   [D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, arXiv:1706.07808]

$\delta R_{\tau e}$ and $\delta R_{\mu e}$





Loop functions

$$B_0(x_Q) = \log x_Q/(1-x_Q)$$

$$B_1(x_Q) = \frac{1 - x_Q + \log x_Q}{(1-x_Q)^2}$$

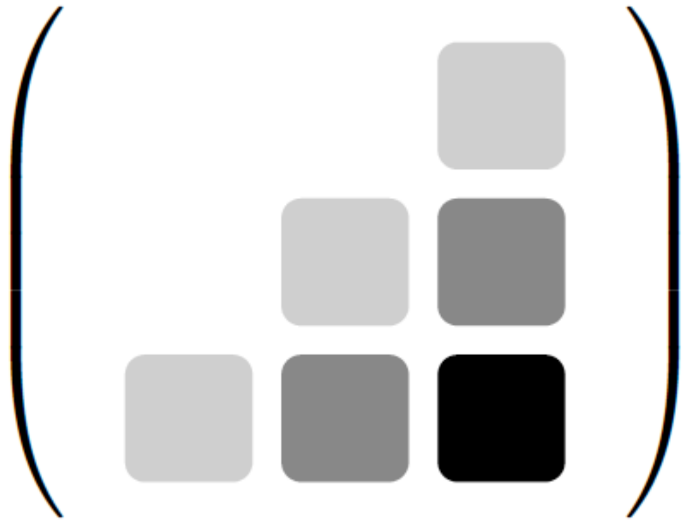
$$B_2(x_Q) = \frac{x_Q - x_Q^2 + x_Q^2 \log x_Q}{4(1-x_Q)^2}$$

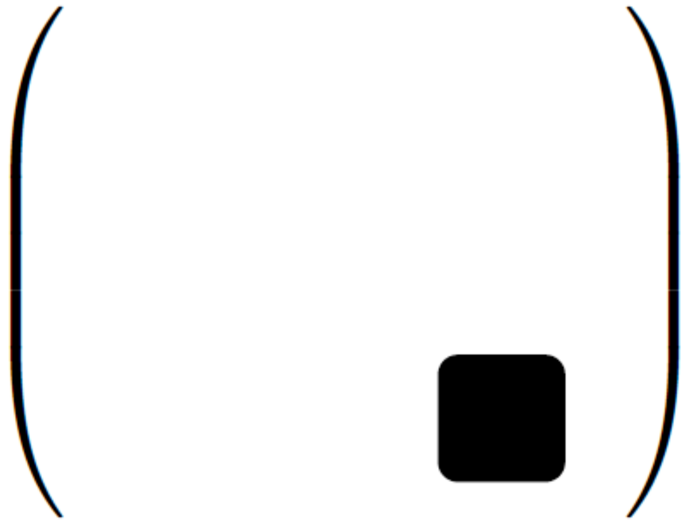
$$F(x_Q, x_Q^R) = B_1(x_Q) - B_2(x_Q) - \tan^2\beta B_2(x_Q^R)$$

Simplified U_1

$$U_1 \sim \left(\mathbf{3}, \mathbf{1}, \tfrac{2}{3}\right) \quad \mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha}(\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_L^{i\alpha}(\bar{d}_R^i \gamma_\mu e_R^\alpha)\right]$$

Minimally broken $U(2)$ structure:

$\beta_L \sim$ 

$\beta_R \sim$ 

Data well described with

$$\beta_L^{b\tau} = 1$$
$$\beta_R^{b\tau} \sim \mathcal{O}(1)$$
$$\beta_L^{s\tau}, \beta_L^{b\mu} \sim \mathcal{O}(0.1)$$
$$\beta_L^{s\mu}, \beta_L^{d\tau} \sim \mathcal{O}(0.01)$$

Benchmarks:

- $\beta_R^{b\tau} = 0$
- $|\beta_R^{b\tau}| = |\beta_L^{b\tau}| = 1$

Scenario		$\Delta\chi^2$	Parameter	best fit	1σ
no RH currents ($\beta_R^{b\tau}=0$)	min. $U(2)^5$ breaking ($\beta_L^{d\tau}=V_{td}^*/V_{ts}^*\,\beta_L^{s\tau}$)	58.6	C_U	0.010	$[0.007, 0.017]$
			$\beta_L^{b\mu}$	-0.15	$[-0.26, -0.02]$
			$\beta_L^{s\tau}$	0.19	$[0.10, 0.25]$
			$\beta_L^{s\mu}$	0.014	$[0.004, 0.14]$
	$\beta_L^{d\tau}$ free	59.5	C_U	0.011	$[0.007, 0.018]$
			$\beta_L^{b\mu}$	-0.14	$[-0.25, -0.02]$
			$\beta_L^{s\tau}$	0.19	$[0.11, 0.24]$
			$\beta_L^{s\mu}$	0.013	$[0.005, 0.125]$
			$\lvert V_{ts}^*/V_{td}^*\,\beta_L^{d\tau}\rvert$	0.11	$[0.04, 0.24]$
			$\arg\left(V_{ts}^*/V_{td}^*\,\beta_L^{d\tau}\right)$	$0.4\,\pi$	$[0.0, 0.5]\,\pi$
max. RH currents ($\beta_R^{b\tau}=-1$)	min. $U(2)^5$ breaking ($\beta_L^{d\tau}=V_{td}^*/V_{ts}^*\,\beta_L^{s\tau}$)	54.0	C_U	0.004	$[0.002, 0.006]$
			$\beta_L^{b\mu}$	-0.21	$[-0.26, -0.16]$
			$\beta_L^{s\tau}$	0.21	$[0.12, 0.26]$
			$\beta_L^{s\mu}$	0.03	$[0.01, 0.04]$
	$\beta_L^{d\tau}$ free	56.7	C_U	0.005	$[0.004, 0.007]$
			$\beta_L^{b\mu}$	-0.21	$[-0.25, -0.14]$
			$\beta_L^{s\tau}$	0.21	$[0.15, 0.26]$
			$\beta_L^{s\mu}$	0.02	$[0.01, 0.07]$
			$\lvert V_{ts}^*/V_{td}^*\,\beta_L^{d\tau}\rvert$	0.24	$[0.13, 0.34]$
			$\arg\left(V_{ts}^*/V_{td}^*\,\beta_L^{d\tau}\right)$	$-0.6\,\pi$	$[-0.7, -0.5]\,\pi$

β

$$U_1 \sim \left(\mathbf{3}, \mathbf{1}, \tfrac{2}{3}\right) \quad \mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_L^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right]$$

Minimally broken $U(2)$ structure:

$$\beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{d\tau} \\ 0 & \beta_L^{s\mu} & \beta_L^{s\tau} \\ 0 & \beta_L^{b\mu} & \beta_L^{b\tau} \end{pmatrix} \qquad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{b\tau} \end{pmatrix}$$

- $\beta_{L,R}^{b\tau} + \beta_L^{s\tau} \longrightarrow R_D, R_{D^*}, b \to s\tau\tau$
- $\beta_L^{b\mu} + \beta_L^{s\mu} \longrightarrow R_K, R_{K^*}$
- $\beta_{L,R}^{b\tau} + \beta_L^{s\mu} \longrightarrow b \to s\tau\mu$
- $\beta_{L,R}^{b\tau} + \beta_L^{s\tau} \longrightarrow \tau \to \mu\gamma$ (loop)