

"Eres libre de tomar las opciones que quieras, pero eres prisionero de sus consecuencias."

Pablo Neruda

Lepton Flavour Universality in B decays

[on the importance of EW corrections for B-anomalies]

January 9th 2018

7th International Conference on
High Energy Physics in the LHC Era
Universidad Técnica Federico Santa María
Valparaiso, Chile

Ferruccio Feruglio
Universita' di Padova

Based on:

- F., P. Paradisi and A. Pattori 1606.00524 and 1705.00929
- C. Cornella, F., P. Paradisi, in preparation

Plan

- Hints of LFU violation and New Physics above the ew scale
- Electroweak corrections from the NP scale Λ down to scales $\leq m_b$
- Impact on LFU-violating and LFV transitions
- Discussion

Main message

- relevance of EW corrections when addressing B-anomalies
- simultaneous explanation of both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies through V-A interactions challenged by electroweak RGE effects

Hints of violation of LFU in semileptonic B decays

NC $b \rightarrow s$ [1-loop in SM]

[LHCb, 1705.05802
SM at 2.4-2.5 σ]

$$R_{K^*}^{\mu/e} = \frac{\mathcal{B}(B \rightarrow K^* \mu \bar{\mu})_{\text{exp}}}{\mathcal{B}(B \rightarrow K^* e \bar{e})_{\text{exp}}} \Big|_{q^2 \in [1.1, 6] \text{ GeV}} = 0.69 \pm_{-0.07}^{+0.11} (\text{stat}) \pm 0.05 (\text{syst})$$

$$R_K^{\mu/e} = \frac{\mathcal{B}(B \rightarrow K \mu \bar{\mu})_{\text{exp}}}{\mathcal{B}(B \rightarrow K e \bar{e})_{\text{exp}}} \Big|_{q^2 \in [1, 6] \text{ GeV}} = 0.745_{-0.074}^{+0.090} \pm 0.036 ,$$

[LHCb, 1406.6482
SM at 2.6 σ]

- allowing NP, global fits to $b \rightarrow s$ transitions are consistent.
- solutions have a pull ~ 4 -5 σ w.r.t. the SM and prefer NP in muon channel.

CC $b \rightarrow c$ [tree-level in SM]

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \rightarrow D^* \tau \bar{\nu})_{\text{exp}} / \mathcal{B}(B \rightarrow D^* \tau \bar{\nu})_{\text{SM}}}{\mathcal{B}(B \rightarrow D^* \ell \bar{\nu})_{\text{exp}} / \mathcal{B}(B \rightarrow D^* \ell \bar{\nu})_{\text{SM}}} = 1.23 \pm 0.07 ,$$

$$R_D^{\tau/\ell} = \frac{\mathcal{B}(B \rightarrow D \tau \bar{\nu})_{\text{exp}} / \mathcal{B}(B \rightarrow D \tau \bar{\nu})_{\text{SM}}}{\mathcal{B}(B \rightarrow D \ell \bar{\nu})_{\text{exp}} / \mathcal{B}(B \rightarrow D \ell \bar{\nu})_{\text{SM}}} = 1.34 \pm 0.17 ,$$

[HFAG averages
of Babar, Belle and
LHCb, 1612.07233
SM at 3.9 σ]

- theoretical uncertainties largely drop in these ratios and $R \approx 1$ is expected

[Bordone, Isidori, Pattori, 1605.07633]

$R \neq 1$



violation of LFU and New Physics

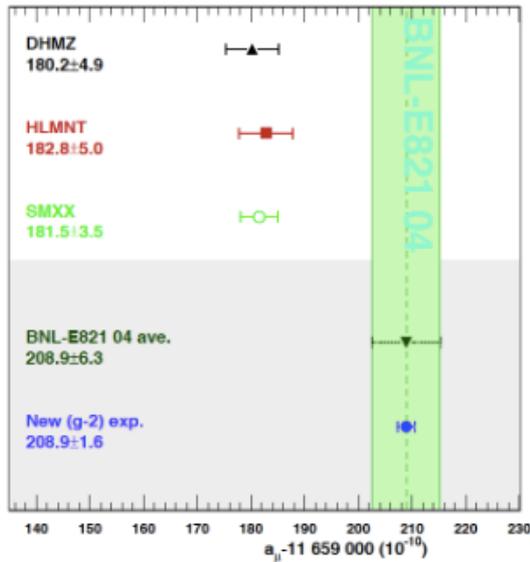
- no conclusive NP signal from individual measurements
- significant discrepancy from the SM predictions comes from average and/or global fits

other hints of LFU violation

e-μ universality

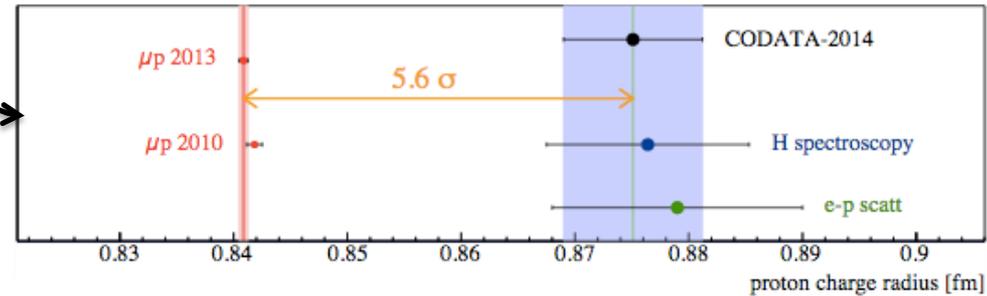
muon (g-2)

T. Blum et al. (arXiv:1311.2198)



W leptonic decays

proton radius



[arXiv:1706.00696]

τ-e and τ-μ universality

$$\frac{2\mathcal{B}(W^+ \rightarrow \tau^+ \nu_\tau)}{\mathcal{B}(W^+ \rightarrow e^+ \nu_e) + \mathcal{B}(W^+ \rightarrow \mu^+ \nu_\mu)} = 1.067 \pm 0.029 .$$

Global Fit

- $B \rightarrow K^{(*)} \ell^+ \ell^-$

$$\mathcal{O}_9 = \frac{\alpha}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma_\mu \ell)$$

$$\mathcal{O}_{10} = \frac{\alpha}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$\mathcal{O}'_9 = \frac{\alpha}{4\pi} (\bar{s}_R \gamma_\mu b_R) (\bar{\ell} \gamma_\mu \ell)$$

$$\mathcal{O}'_{10} = \frac{\alpha}{4\pi} (\bar{s}_R \gamma_\mu b_R) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$\mathcal{O}_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$\mathcal{O}'_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_R \sigma^{\mu\nu} b_L) F_{\mu\nu}$$



▷ $C_9^{NP} \neq 0$

▷ $C_9^{NP} = -C_{10}^{NP} \neq 0$



▷ R_K

▷ P'_5 (et al.)

S. Descotes-Genon, L. Hofer, J. Matias, J. Virto (2015)



$$(\bar{s}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma_\mu \ell_L)$$

⇒ left-handed current

Altmannshofer, Stangl and Straub, 1704.05435;

Celis, Fuentes Martin, Vicente and Virto, 1704.05672;

Capdevila, Crivellin, Descotes-Genon, Matias and Virto, 1704.05340;

D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre and Urbano, 1704.05438;

Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini and Valli 1704.05447;

G. Hiller and I. Nisandzic, 1704.05444 [hep-ph].

Are the NC and CC anomalies related?

both NC and CC anomalies can be explained by NP occurring (above the EW scale) purely in V-A combinations

$$(\bar{s}_L \gamma_\mu b_L) (\bar{\mu}_L \gamma^\mu \mu_L)$$

$$(\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_{\tau L})$$

not the only possibility:

- V lepton current (O_9 operator) by itself provides a good fit
- tensor operator vanish at LO when $SU(2) \times U(1)$ is enforced
- scalar operators are constrained by B leptonic decays
- right quark helicities disfavored after R_{K^*} measurement

the two operators are related by

- $SU(2)_L$ gauge invariance
- transformations in flavour space

This suggests to start from operators

- (V-A)
- $SU(2) \times U(1)$ -invariant
- involving only the 3rd generation [U(2), U(1), ...]

$$O_{ql}^{(1,3)} = (\bar{q}'_{3L} \gamma_\mu A q'_{3L}) (\bar{\ell}'_{3L} \gamma^\mu A \ell'_{3L}) \quad A = (1, \sigma^a)$$

couplings to lighter generations



misalignment between mass and interaction bases

- welcome since small mixing angles can suppress the contribution to $R_{K^{(*)}}$ compared to $R_{D^{(*)}}$, as in the SM

Starting point

$$L_{NP}^0(\Lambda) = \frac{C_1}{\Lambda^2} O_{ql}^{(1)} + \frac{C_3}{\Lambda^2} O_{ql}^{(3)} =$$

$$\mathcal{L}_{NP}^0(\Lambda) = \frac{\lambda_{kl}^e}{\Lambda^2} [(C_1 + C_3) \lambda_{ij}^u \bar{u}_{Li} \gamma^\mu u_{Lj} \bar{\nu}_{Lk} \gamma_\mu \nu_{Ll} + (C_1 - C_3) \lambda_{ij}^u \bar{u}_{Li} \gamma^\mu u_{Lj} \bar{e}_{Lk} \gamma_\mu e_{Ll} + (C_1 - C_3) \lambda_{ij}^d \bar{d}_{Li} \gamma^\mu d_{Lj} \bar{\nu}_{Lk} \gamma_\mu \nu_{Ll} + (C_1 + C_3) \lambda_{ij}^d \bar{d}_{Li} \gamma^\mu d_{Lj} \bar{e}_{Lk} \gamma_\mu e_{Ll} + 2C_3 (\lambda_{ij}^{ud} \bar{u}_{Li} \gamma^\mu d_{Lj} \bar{e}_{Lk} \gamma_\mu \nu_{Ll} + h.c.)] \quad (\text{limit of massless neutrinos})$$

mixing among generation
encoded in matrices $\lambda^{e,d,u}$

$$\lambda^u = V_{CKM}^+ \lambda^d V_{CKM}$$

$$\lambda^{d,e} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & \vartheta_{d,e}^2 & \vartheta_{d,e} \\ 0 & \vartheta_{d,e} & 1 \end{pmatrix}$$

[Calibbi, Crivellin, Ota, 1506.02661]

4 parameters

$$\frac{C_1}{\Lambda^2}, \frac{C_3}{\Lambda^2}, \vartheta_d, \vartheta_e$$

$-\vartheta_d$

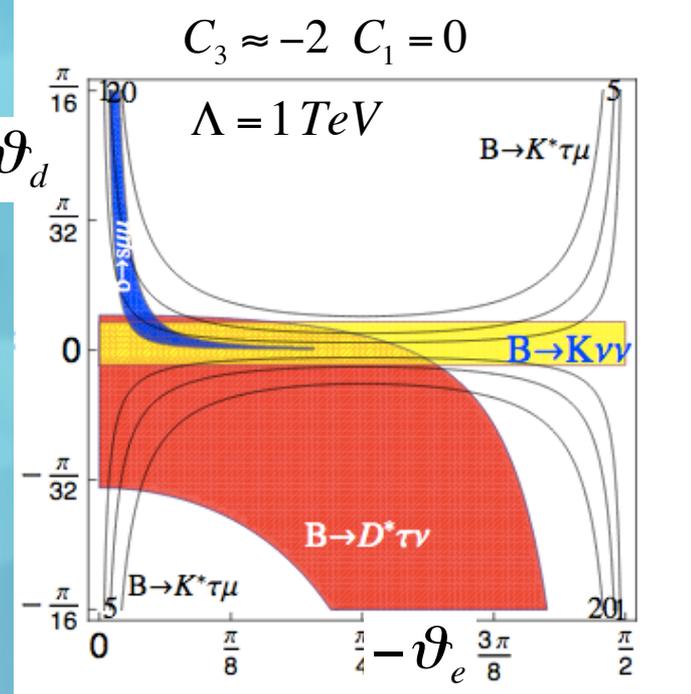
both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ can be explained

$$\Lambda \approx 1 \text{ TeV} \quad C_3, C_1 = O(1)$$

$$\vartheta_d = O(0.01) \approx V_{cb}$$

$$\vartheta_e = O(0.3) \approx U_{ij}^{PMNS}$$

$(\vartheta_d \times \vartheta_e^2)$ provides the needed suppression of $R_{K^{(*)}}$ compared to $R_{D^{(*)}}$



Constraints (tree-level)

$R_K^{\mu/e} \quad R_{K^*}^{\mu/e}$	$(C_1 + C_3) \vartheta_d \vartheta_e^2$		
$R_D^{\tau/\ell} \quad R_{D^*}^{\tau/\ell}$	C_3		
process	parameters	size	exp. bound
$R_{B_s \mu\mu} = \frac{\mathcal{B}(B_s \rightarrow \mu\bar{\mu})_{\text{exp}}}{\mathcal{B}(B_s \rightarrow \mu\bar{\mu})_{\text{SM}}}$	$(C_1 + C_3) \vartheta_d \vartheta_e^2$	$O(0.1)$	$\mathcal{B}(B_s \rightarrow \mu\bar{\mu})_{\text{exp}} = 2.8_{-0.6}^{+0.7} \times 10^{-9}$ $\mathcal{B}(B_s \rightarrow \mu\bar{\mu})_{\text{SM}} = 3.65(23) \times 10^{-9}$
$R_{B\tau\nu}^{\tau/\mu} = \frac{\mathcal{B}(B \rightarrow \tau\nu)_{\text{exp}}/\mathcal{B}(B \rightarrow \tau\nu)_{\text{SM}}}{\mathcal{B}(B \rightarrow \mu\nu)_{\text{exp}}/\mathcal{B}(B \rightarrow \mu\nu)_{\text{SM}}}$	C_3	$O(0.1)$	Belle II ?
$R_{K^{(*)}}^{\nu\nu} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \rightarrow K^{(*)}\nu\bar{\nu})_{\text{SM}}}$	$(C_1 - C_3) \vartheta_d$	$O(1)$	$R_{K^*}^{\nu\nu} < 4.4$ $R_K^{\nu\nu} < 4.3$
$\mathcal{B}(B \rightarrow K\tau\mu)$ $\mathcal{B}(B \rightarrow \tau^\pm\mu^\mp) \approx \mathcal{B}(B \rightarrow K\tau^\pm\mu^\mp),$ $\mathcal{B}(B \rightarrow K^*\tau^\pm\mu^\mp) \approx 2 \times \mathcal{B}(B \rightarrow K\tau^\pm\mu^\mp)$	$ (C_1 + C_3) \vartheta_d \vartheta_e ^2$	$O(10^{-6\div 7})$	$\mathcal{B}(B \rightarrow K\tau\mu) \leq 4.8 \times 10^{-5}$
$\mu^+\mu^-$ and $\tau^+\tau^-$ Production at LHC	$(C_1 + C_3)$		[Greljo, Marzocca 1704.09015]

Constraints from quantum effects

$$L_{NP}(m_b) = L_{NP}^0(\Lambda) + \text{quantum corrections}$$

How can quantum corrections $\sim \alpha/4\pi \sim 10^{-3}$ be relevant?



they generate terms that are absent in $L_{NP}^0(\Lambda)$ and new processes are affected

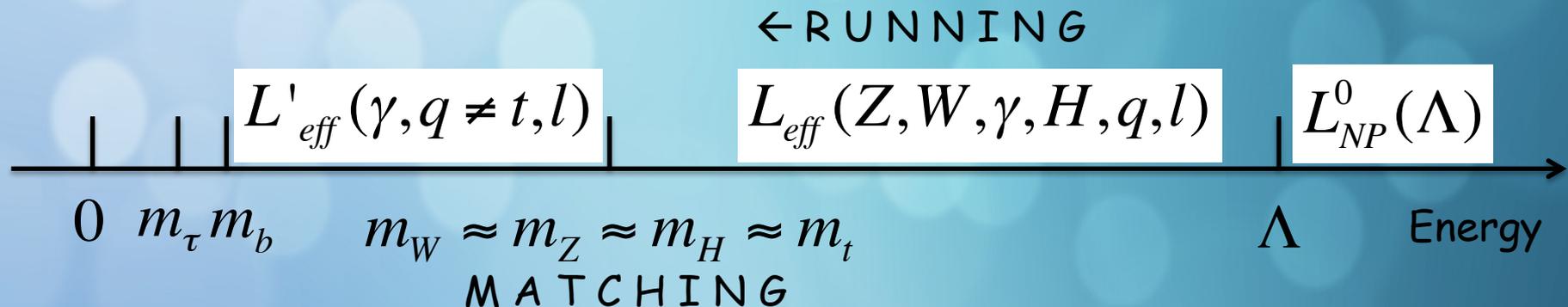


their order of magnitude is similar to accuracy in EWPT and in other tests of LFU

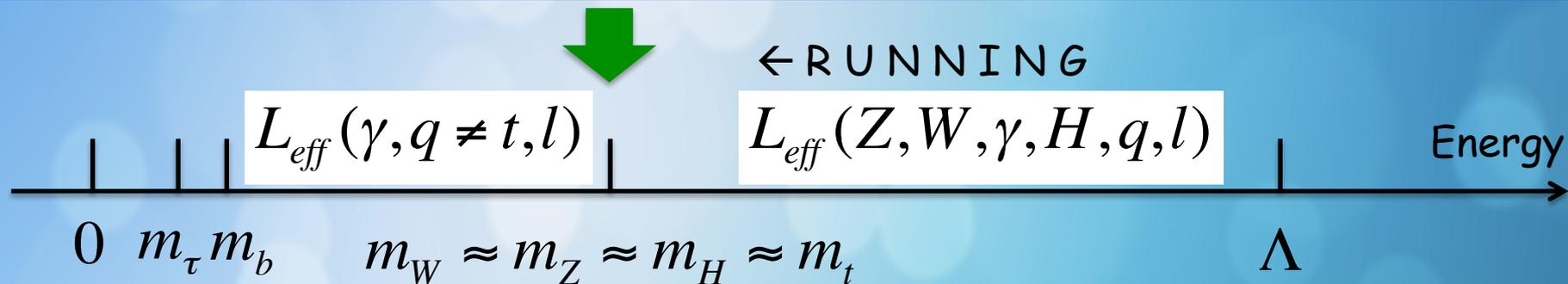


they are enhanced by logs: $\log(\Lambda^2/m_W^2) \sim 5-7$

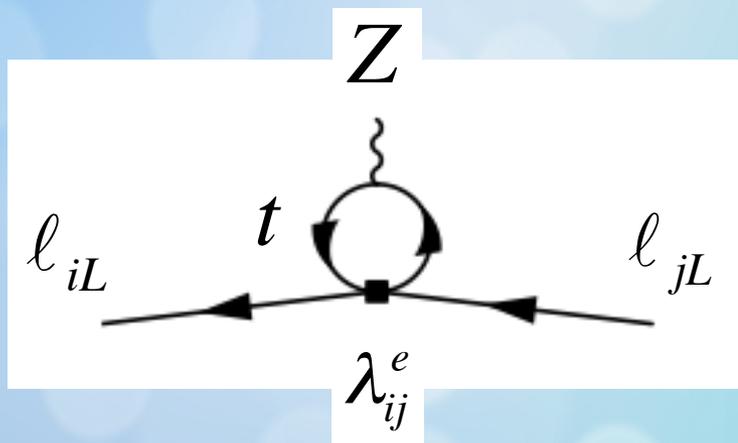
in the present framework - (V-A) semileptonic operators - corrections are dominated by electroweak interactions. They can be estimated by a well-known running and matching procedure. Here, Leading Log effects only



1st: the electroweak scale



1. modifications of the W,Z couplings to fermions by non-universal terms



$$\frac{a_\tau}{a_e} \approx 1 - 0.004 \frac{(C_1 - 0.8 C_3)}{\Lambda^2(\text{TeV}^2)}$$

$$\frac{v_\tau}{v_e} \approx 1 - 0.05 \frac{(C_1 - 0.8 C_3)}{\Lambda^2(\text{TeV}^2)}$$

$$a_\tau/a_e = 1.0019 \quad (15)$$

$$v_\tau/v_e = 0.959 \quad (29)$$

$$N_\nu \approx 3 + 0.008 \frac{(C_1 + 0.8 C_3)}{\Lambda^2(\text{TeV}^2)}$$

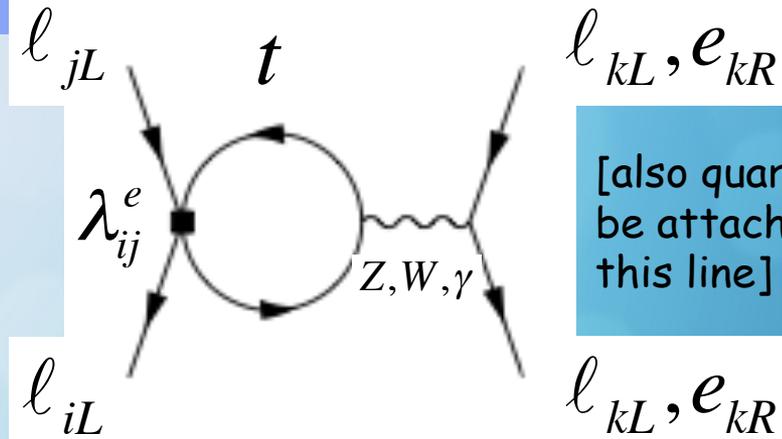
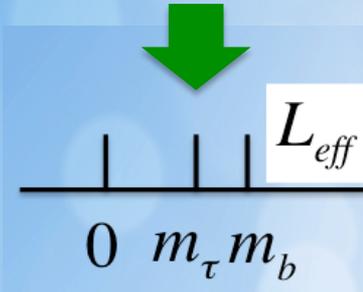
$$N_\nu = 2.9840 \pm 0.0082$$

$$\mathcal{B}(Z \rightarrow \mu^\pm \tau^\mp) \approx 10^{-7}$$

$$\mathcal{B}(Z \rightarrow \mu^\pm \tau^\mp)_{\text{exp}} \leq 1.2 \times 10^{-5}$$

2. generation of a purely leptonic effective Lagrangian at the scale $\leq m_b$

2nd: m_τ



[also quarks can be attached to this line]

$$R_\tau^{\tau/e} = \frac{\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})_{\text{exp}}/\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})_{\text{SM}}}{\mathcal{B}(\mu \rightarrow e\nu\bar{\nu})_{\text{exp}}/\mathcal{B}(\mu \rightarrow e\nu\bar{\nu})_{\text{SM}}}$$

$$R_\tau^{\tau/\mu} = \frac{\mathcal{B}(\tau \rightarrow e\nu\bar{\nu})_{\text{exp}}/\mathcal{B}(\tau \rightarrow e\nu\bar{\nu})_{\text{SM}}}{\mathcal{B}(\mu \rightarrow e\nu\bar{\nu})_{\text{exp}}/\mathcal{B}(\mu \rightarrow e\nu\bar{\nu})_{\text{SM}}}$$

$$\approx 1 + \frac{0.008 C_3}{\Lambda^2(\text{TeV}^2)}$$

$$R_\tau^{\tau/e} = 1.0060 \pm 0.0030$$

$$R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030$$

[A.Pich, 1310.7922]

$$\mathcal{B}(\tau \rightarrow 3\mu)$$

$$\approx 5 \times 10^{-8} \frac{(C_1 - C_3)^2}{\Lambda^4(\text{TeV}^4)} \left(\frac{\mathcal{V}_e}{0.3}\right)^2$$

$$\mathcal{B}(\tau \rightarrow 3\mu) \leq 1.2 \times 10^{-8}$$

[HFAG, 1412.7515]

$$\mathcal{B}(\tau \rightarrow \mu\rho)$$

$$\approx 5 \times 10^{-8} \frac{(C_1 - 1.3C_3)^2}{\Lambda^4(\text{TeV}^4)} \left(\frac{\mathcal{V}_e}{0.3}\right)^2$$

$$\mathcal{B}(\tau \rightarrow \mu\rho) \leq 1.5 \times 10^{-8}$$

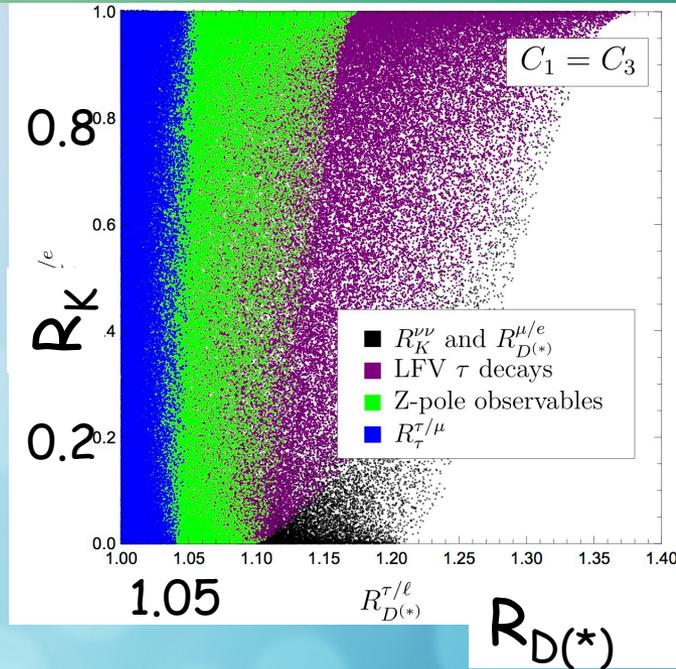
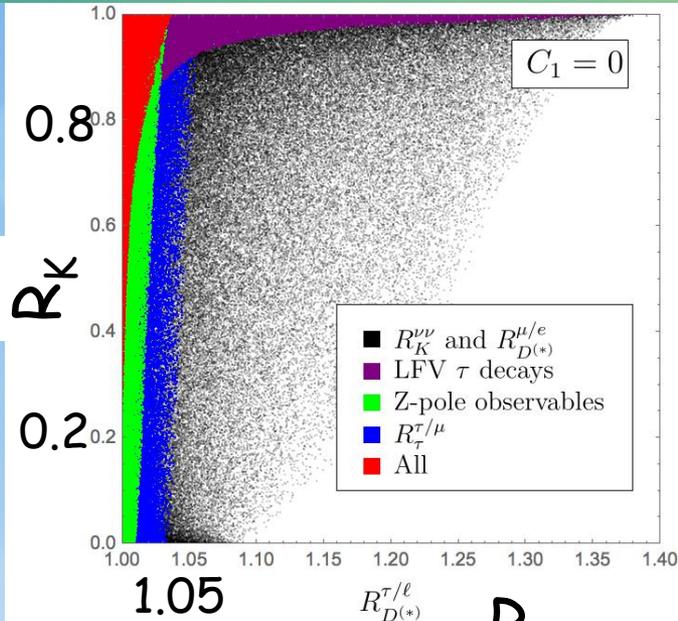
$$\mathcal{B}(\tau \rightarrow \mu\pi)$$

$$\approx 8 \times 10^{-8} \frac{(C_1 - C_3)^2}{\Lambda^4(\text{TeV}^4)} \left(\frac{\mathcal{V}_e}{0.3}\right)^2$$

$$\mathcal{B}(\tau \rightarrow \mu\pi) \leq 2.7 \times 10^{-8}$$

[HFAG, 1412.7515]

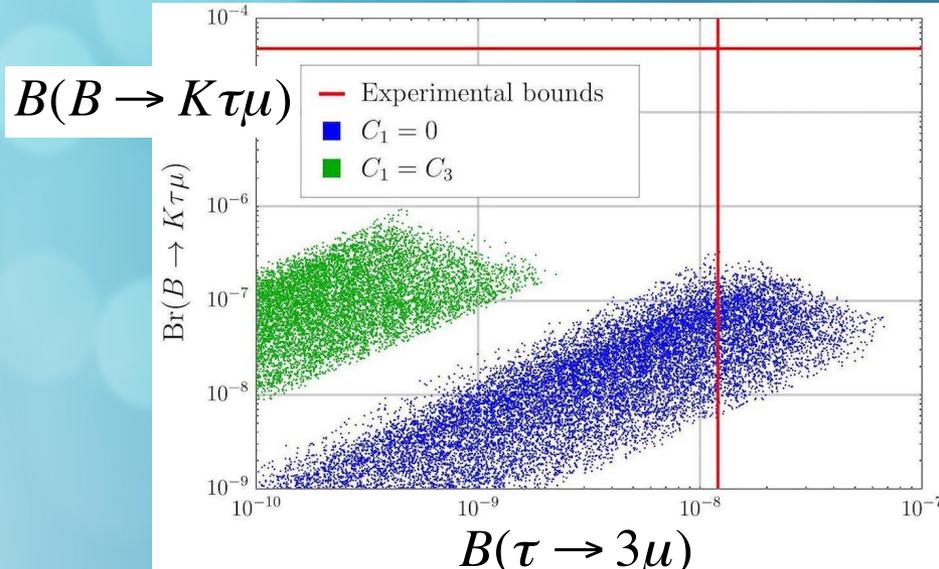
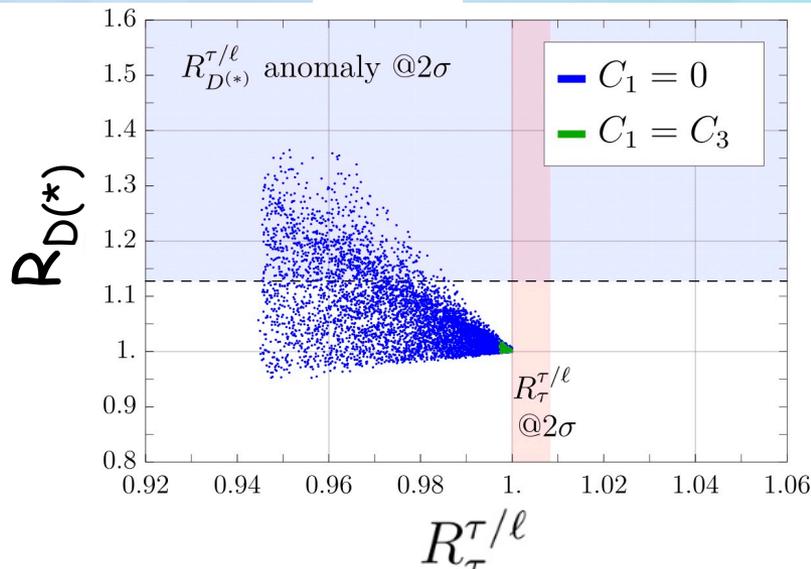
Putting everything together



$$\left| \frac{C_{1,3}}{\Lambda^2} \right| \leq 4 \text{ TeV}^{-2}$$

$$\left| \mathcal{G}_{d,e} \right| \leq 0.5$$

LFV better probed in tau decays



A more general setup

[Cornella, F. Paradisi
in preparation]

$$\mathcal{L}_{\text{NP}}^0 = \frac{1}{\Lambda^2} (C_1 [Q_{lq}^{(1)}]_{3333} + C_3 [Q_{lq}^{(3)}]_{3333} + C_4 [Q_{ld}]_{3333} + C_5 [Q_{ed}]_{3333} + C_6 [Q_{qe}]_{3333})$$

$$[Q_{lq}^{(1)}]_{3333} = (\bar{\ell}'_{3L} \gamma^\mu \ell'_{3L}) (\bar{q}'_{3L} \gamma^\mu q'_{3L})$$

$$[Q_{lq}^{(3)}]_{3333} = (\bar{\ell}'_{3L} \gamma^\mu \tau^a \ell'_{3L}) (\bar{q}'_{3L} \gamma^\mu \tau^a q'_{3L})$$

$$[Q_{ld}]_{3333} = (\bar{\ell}'_{3L} \gamma^\mu \ell'_{3L}) (\bar{d}'_{3R} \gamma^\mu d'_{3R})$$

$$[Q_{ed}]_{3333} = (\bar{e}'_{3R} \gamma^\mu e'_{3R}) (\bar{d}'_{3R} \gamma^\mu d'_{3R})$$

$$[Q_{qe}]_{3333} = (\bar{q}'_{3L} \gamma^\mu q'_{3L}) (\bar{e}'_{3R} \gamma^\mu e'_{3R})$$

most general set of
SU(2)×U(1) - invariant
semileptonic operators
involving the 3rd generation

the main effects are 1.
and 2., as before

an example

$$C_1 + C_3 = C_6$$

$$C_4 = C_5 = 0.$$



$$O^9 = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L) (\bar{e}_i \gamma^\mu e_i)$$

we find

$$\frac{v_\tau}{v_e} = 1 - \frac{0.05 \lambda_{33}^e}{\Lambda^2} (2 C_1 + 0.2 C_3 + 0.02 (2 C_1 + C_3))$$

$$\frac{a_\tau}{a_e} = 1 + 0.007 \lambda_{33}^e \frac{C_3}{\Lambda^2}$$

directly correlated to

$$R_\tau^{\tau/\ell}$$

and

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

forces $\delta R_{D^{(*)}}^{\tau/\ell}$ to be $\lesssim 0.02$.

Discussion

log effects discussed here can be cancelled/suppressed by finite terms, not captured by this approach

the starting point adopted here can be generalized by allowing more $SU(2) \times U(1)$ invariant operators at the scale Λ , making it possible cancellation/suppression of log effects

different generation pattern in $O_{lq}^{(1,3)}$ can help in evading the bounds most of flavour schemes adopted in model building - $U(1)_{FN}$, $U(2)$, Partial Compositeness - prefer NP coupled mainly to third generation.

$$R_D^{\tau/\ell} \quad R_{D^*}^{\tau/\ell}$$

alone can be explained in present framework

e.g. $\vartheta_d \approx 1, \vartheta_e \ll \alpha_{em}, \Lambda \approx 5 \text{ TeV}$



loop effects decouple as v^2/Λ^2

$$R_K^{\mu/e} \quad R_{K^*}^{\mu/e}$$

alone can be explained in present framework

e.g. $\vartheta_d \approx 1, \vartheta_e \approx 1, \Lambda \approx 30 \text{ TeV}$



loop effects decouple as v^2/Λ^2

conclusion

- B anomalies extensively studied in literature
simultaneous $R_{K^{(*)}}$ and $R_{D^{(*)}}$ explanation is appealing
- the estimate of quantum corrections is crucial to assess the viability of proposed solutions
- in the example discussed here (NP in 3rd generation V-A currents) purely leptonic LFUV/LFV transitions are generated and strong constraints arise
- this is not a no-go theorem:
 - ways out are possible but require some conspiracy by UV physics.

Back-up slides

Global Fit

- $B \rightarrow K^{(*)} \ell^+ \ell^-$

$$\mathcal{O}_9 = \frac{\alpha}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma_\mu \ell)$$

$$\mathcal{O}_{10} = \frac{\alpha}{4\pi} (\bar{s}_L \gamma_\mu b_L) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$\mathcal{O}'_9 = \frac{\alpha}{4\pi} (\bar{s}_R \gamma_\mu b_R) (\bar{\ell} \gamma_\mu \ell)$$

$$\mathcal{O}'_{10} = \frac{\alpha}{4\pi} (\bar{s}_R \gamma_\mu b_R) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$\mathcal{O}_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$\mathcal{O}'_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_R \sigma^{\mu\nu} b_L) F_{\mu\nu}$$



▷ $C_9^{NP} \neq 0$

▷ $C_9^{NP} = -C_{10}^{NP} \neq 0$



▷ R_K

▷ P'_5 (et al.)

S. Descotes-Genon, L. Hofer, J. Matias, J. Virto (2015)



$$(\bar{s}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma_\mu \ell_L)$$

⇒ left-handed current

Altmannshofer, Stangl and Straub, 1704.05435;

Celis, Fuentes Martin, Vicente and Virto, 1704.05672;

Capdevila, Crivellin, Descotes-Genon, Matias and Virto, 1704.05340;

D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre and Urbano, 1704.05438;

Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini and Valli 1704.05447;

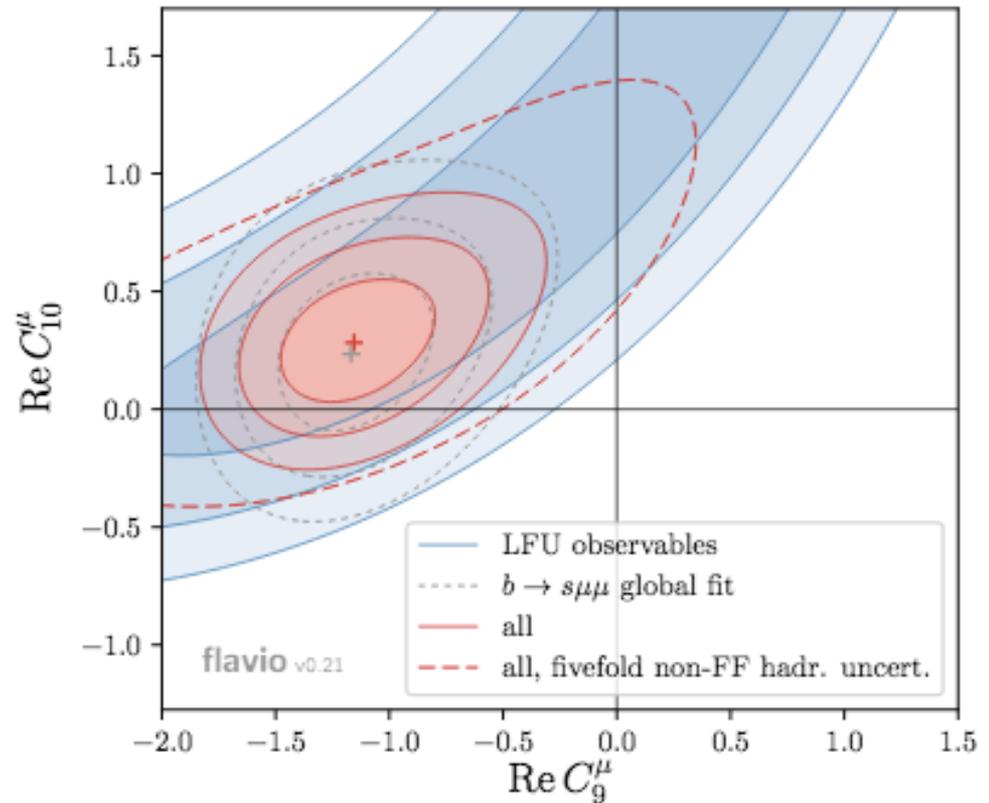
G. Hiller and I. Nisandzic, 1704.05444 [hep-ph].

Global Fit

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	[-2.15, -1.13]	[-2.90, -0.73]	4.2 σ
C_{10}^μ	+1.23	[+0.90, +1.60]	[+0.60, +2.04]	4.3 σ
C_9^e	+1.58	[+1.17, +2.03]	[+0.79, +2.53]	4.4 σ
C_{10}^e	-1.30	[-1.68, -0.95]	[-2.12, -0.64]	4.4 σ
$C_9^\mu = -C_{10}^\mu$	-0.64	[-0.81, -0.48]	[-1.00, -0.32]	4.2 σ
$C_9^e = -C_{10}^e$	+0.78	[+0.56, +1.02]	[+0.37, +1.31]	4.3 σ
$C_9^{\prime\mu}$	-0.00	[-0.26, +0.25]	[-0.52, +0.51]	0.0 σ
$C_{10}^{\prime\mu}$	+0.02	[-0.22, +0.26]	[-0.45, +0.49]	0.1 σ
$C_9^{\prime e}$	+0.01	[-0.27, +0.31]	[-0.55, +0.62]	0.0 σ
$C_{10}^{\prime e}$	-0.03	[-0.28, +0.22]	[-0.55, +0.46]	0.1 σ

TABLE I. Best-fit values and pulls for scenarios with NP in one individual Wilson coefficient.

[Altmannshofer, Stangl and Straub, 1704.05435]



'All' includes R_K , R_{K^*} , angular variables in $B \rightarrow K^* \mu^+ \mu^-$, differential BR in $B \rightarrow K^* \mu^+ \mu^-$, $B \rightarrow \phi \mu^+ \mu^-$

Global Fit

$$[R_K]_{[1,6]} \simeq 1.00(1) + 0.230(C_{9\mu-e}^{\text{NP}} + C'_{9\mu-e}) - 0.233(2)(C_{10\mu-e}^{\text{NP}} + C'_{10\mu-e}),$$

$$[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)C_{9\mu-e}^{\text{NP}} - 0.10(2)C'_{9\mu-e} - 0.11(2)C_{10\mu-e}^{\text{NP}} + 0.11(2)C'_{10\mu-e} + 0.55(6)C_7^{\text{NP}},$$

$$[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)C_{9\mu-e}^{\text{NP}} - 0.19(1)C'_{9\mu-e} - 0.27(1)C_{10\mu-e}^{\text{NP}} + 0.21(1)C'_{10\mu-e}.$$

[Celis, Fuentes Martin, Vicente and Virto, 1704.05672]

Dimension six operators

Semileptonic operators:	Leptonic operators:
$[O_{\ell q}^{(1)}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL}) (\bar{q}'_{sL} \gamma^\mu q'_{tL})$	$[O_{\ell\ell}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL}) (\bar{\ell}'_{sL} \gamma^\mu \ell'_{tL})$
$[O_{\ell q}^{(3)}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \tau^a \ell'_{rL}) (\bar{q}'_{sL} \gamma^\mu \tau^a q'_{tL})$	$[O_{\ell e}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL}) (\bar{e}'_{sR} \gamma^\mu e'_{tR})$
$[O_{\ell u}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL}) (\bar{u}'_{sR} \gamma^\mu u'_{tR})$	
$[O_{\ell d}]_{prst} = (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL}) (\bar{d}'_{sR} \gamma^\mu d'_{tR})$	
$[O_{qe}]_{prst} = (\bar{q}'_{pL} \gamma_\mu q'_{rL}) (\bar{e}'_{sR} \gamma^\mu e'_{tR})$	
Vector operators:	Hadronic operators:
$[O_{H\ell}^{(1)}]_{pr} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{\ell}'_{pL} \gamma_\mu \ell'_{rL})$	$[O_{qq}^{(1)}]_{prst} = (\bar{q}'_{pL} \gamma_\mu q'_{rL}) (\bar{q}'_{sL} \gamma^\mu q'_{tL})$
$[O_{H\ell}^{(3)}]_{pr} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^a \varphi) (\bar{\ell}'_{pL} \gamma_\mu \tau^a \ell'_{rL})$	$[O_{qq}^{(3)}]_{prst} = (\bar{q}'_{pL} \gamma_\mu \tau^a q'_{rL}) (\bar{q}'_{sL} \gamma^\mu \tau^a q'_{tL})$
$[O_{Hq}^{(1)}]_{pr} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}'_{pL} \gamma_\mu q'_{rL})$	$[O_{qu}^{(1)}]_{prst} = (\bar{q}'_{pL} \gamma_\mu q'_{rL}) (\bar{u}'_{sR} \gamma^\mu u'_{tR})$
$[O_{Hq}^{(3)}]_{pr} = (\varphi^\dagger i \overleftrightarrow{D}_\mu^a \varphi) (\bar{q}'_{pL} \gamma_\mu \tau^a q'_{rL})$	$[O_{qd}^{(1)}]_{prst} = (\bar{q}'_{pL} \gamma_\mu q'_{rL}) (\bar{d}'_{sR} \gamma^\mu d'_{tR})$

Table 1: Minimal set of gauge-invariant operators involved in the RGE flow considered in this paper. Fields are in the interaction basis to maintain explicit $SU(2) \times U(1)$ gauge invariance. Our notation and conventions are as in [26].

Effective Lagrangian - ew scale

$$g_{fL,R} = g_{fL,R}^{SM} + \Delta g_{fL,R} \quad g_{\ell,q} = g_{\ell,q}^{SM} + \Delta g_{\ell,q}$$

$$\Delta g_{\nu L}^{ij} = \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \left(\frac{1}{3} g_1^2 C_1 - g_2^2 C_3 + 3y_t^2 \lambda_{33}^u (C_1 + C_3) \right) \lambda_{ij}^e$$

$$\Delta g_{eL}^{ij} = \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \left(\frac{1}{3} g_1^2 C_1 + g_2^2 C_3 + 3y_t^2 \lambda_{33}^u (C_1 - C_3) \right) \lambda_{ij}^e$$

$$\Delta g_{uL}^{ij} = -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{1}{3} (g_1^2 C_1 + g_2^2 C_3) \lambda_{ij}^u$$

$$\Delta g_{dL}^{ij} = -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{1}{3} (g_1^2 C_1 - g_2^2 C_3) \lambda_{ij}^d$$

$$\Delta g_{fR}^{ij} = 0 \quad (f = \nu, e, u, d)$$

$$\Delta g_{\ell}^{ij} = \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} (-2g_2^2 C_3 + 6y_t^2 \lambda_{33}^u C_3) \lambda_{ij}^e$$

$$\Delta g_q^{ij} = -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{2}{3} g_2^2 C_3 \lambda_{ij}^{ud} \quad .$$

$$L = \log \frac{\Lambda}{\mu}$$

Effective Lagrangian - ew scale

$$\mathcal{L}_{eff}^{EW} = \mathcal{L}'_{SM} + \mathcal{L}_{NP}^0 + \frac{1}{16\pi^2\Lambda^2} \log \frac{\Lambda}{m_{EW}} \sum_i \xi_i Q_i$$

Q_i	ξ_i
$(\bar{\nu}_{iL}\gamma_\mu\nu_{jL})(\bar{\nu}_{kL}\gamma^\mu\nu_{nL})$	$\lambda_{ij}^e \delta_{kn} [-6y_t^2\lambda_{33}^u(C_1 + C_3)]$
$(\bar{\nu}_{iL}\gamma_\mu\nu_{jL})(\bar{e}_{kL}\gamma^\mu e_{nL})$	$\lambda_{ij}^e \delta_{kn} [\frac{4}{3}e^2(C_1 + 3C_3) - 12(-\frac{1}{2} + s_\theta^2)y_t^2\lambda_{33}^u(C_1 + C_3)]$ $+ \delta_{ij} \lambda_{kn}^e [-6y_t^2\lambda_{33}^u(C_1 - C_3)]$
$(\bar{\nu}_{iL}\gamma_\mu\nu_{jL})(\bar{e}_{kR}\gamma^\mu e_{nR})$	$\lambda_{ij}^e \delta_{kn} [\frac{4}{3}e^2(C_1 + 3C_3) - 12s_\theta^2 y_t^2\lambda_{33}^u(C_1 + C_3)]$
$(\bar{e}_{iL}\gamma_\mu e_{jL})(\bar{e}_{kL}\gamma^\mu e_{nL})$	$\lambda_{ij}^e \delta_{kn} [\frac{4}{3}e^2(C_1 - 3C_3) - 12(-\frac{1}{2} + s_\theta^2)y_t^2\lambda_{33}^u(C_1 - C_3)]$
$(\bar{e}_{iL}\gamma_\mu e_{jL})(\bar{e}_{kR}\gamma^\mu e_{nR})$	$\lambda_{ij}^e \delta_{kn} [\frac{4}{3}e^2(C_1 - 3C_3) - 12s_\theta^2 y_t^2\lambda_{33}^u(C_1 - C_3)]$
$(\bar{\nu}_{iL}\gamma_\mu e_{jL})(\bar{e}_{kL}\gamma^\mu\nu_{nL})$	$(\lambda_{ij}^e \delta_{kn} + \delta_{ij} \lambda_{kn}^e) [-12y_t^2\lambda_{33}^u C_3]$

Table 2: Operators Q_i and coefficients ξ_i for the purely leptonic part of the effective Lagrangian \mathcal{L}_{eff}^{EW} . We set $\sin^2 \theta_W \equiv s_\theta^2$.

Effective Lagrangian at low energy

$$\delta\mathcal{L}_{eff}^{QED} = \frac{1}{16\pi^2\Lambda^2} \log \frac{m_{EW}}{\mu} \sum_i \delta\xi_i Q_i$$

Q_i	$\delta\xi_i$
$(\bar{\nu}_{iL}\gamma_\mu\nu_{jL}) (\bar{\nu}_{kL}\gamma^\mu\nu_{nL})$	0
$(\bar{\nu}_{iL}\gamma_\mu\nu_{jL}) (\bar{e}_k\gamma^\mu e_n)$	$\lambda_{ij}^e \delta_{kn} \cdot \frac{4}{3}e^2 \left[(C_1 + 3C_3) - 2(C_1 + C_3)(\hat{\lambda}_{33}^u \log \frac{m_t}{\mu} + \hat{\lambda}_{22}^u \log \frac{m_c}{\mu}) + (C_1 - C_3)\hat{\lambda}_{33}^d \log \frac{m_b}{\mu} \right]$
$(\bar{e}_{iL}\gamma_\mu e_{jL}) (\bar{e}_k\gamma^\mu e_n)$	$\lambda_{ij}^e \delta_{kn} \cdot \frac{4}{3}e^2 \left[(C_1 - 3C_3) - 2(C_1 - C_3)(\hat{\lambda}_{33}^u \log \frac{m_t}{\mu} + \hat{\lambda}_{22}^u \log \frac{m_c}{\mu}) + (C_1 + C_3)\hat{\lambda}_{33}^d \log \frac{m_b}{\mu} \right]$

Table 6: Operators Q_i and coefficients $\delta\xi_i$ for the purely leptonic part of the effective Lagrangian $\delta\mathcal{L}_{eff}^{QED}$. We set $\hat{\lambda}_{ii}^{u,d} = \lambda_{ii}^{u,d} / \log \frac{m_{EW}}{\mu}$.

tree-level mediators of $O_{lq}^{(1,3)}$

Field	Spin	Quantum Numbers	Operator	C_1	C_3
A_μ	1	(1, 1, 0)	$\bar{q}'_L \gamma^\mu q'_L \bar{\ell}'_L \gamma_\mu \ell'_L$	-1	0
A_μ^a	1	(1, 3, 0)	$\bar{q}'_L \gamma^\mu \tau^a q'_L \bar{\ell}'_L \gamma_\mu \tau^a \ell'_L$	0	-1
U_μ	1	(3, 1, +2/3)	$\bar{q}'_L \gamma^\mu \ell'_L \bar{\ell}'_L \gamma_\mu q'_L$	$-\frac{1}{2}$	$-\frac{1}{2}$
U_μ^a	1	(3, 3, +2/3)	$\bar{q}'_L \gamma^\mu \tau^a \ell'_L \bar{\ell}'_L \gamma_\mu \tau^a q'_L$	$-\frac{3}{2}$	$+\frac{1}{2}$
S	0	(3, 1, -1/3)	$\bar{q}'_L i\sigma^2 \ell'^c_L \overline{i\sigma^2 \ell'^c_L} q'_L$	$+\frac{1}{4}$	$-\frac{1}{4}$
S^a	0	(3, 3, -1/3)	$\bar{q}'_L \tau^a i\sigma^2 \ell'^c_L \overline{i\sigma^2 \ell'^c_L} \tau^a q'_L$	$+\frac{3}{4}$	$+\frac{1}{4}$

Table 11: Spin zero and spin one mediators contributing, at tree-level, to the Lagrangian $\mathcal{L}_{NP}^0(\Lambda)$ of eq. (7). Also shown are the operators they give rise to and the contribution to the coefficients C_1 and C_3 of the Lagrangian $\mathcal{L}_{NP}^0(\Lambda)$, when a single fermion generation is involved.