B-anomalies related to leptons and LFV: new directions in model building

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La Biodola, Isola d' Elba

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Based on:
- F.F., P. Paradisi and A. Pattori 1606.00524 and 1705.00929 [FPP]
- C. Cornella, F.F., P. Paradisi, 1803.00945

Hints of violation of LFU in semileptonic B decays

NC b -> s [1-loop in SM]

[LHCb, 1705.05802
SM at 2.4-2.5σ]

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

$$R_{K}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K \mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K e\bar{e})_{\rm exp}}\right|_{q^2\in[1,6]\,{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036\ ,$$

[LHCb, 1406.6482
SM at 2.6σ]

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

CC b -> c [tree-level in SM]

[P.Owen, F. Simonetto]

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

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

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

- theoretical uncertainties largely drop in these ratios and R≈1 is expected

[Bordone, Isidori, Pattori, 1605.07633]

$$R_{J/\Psi}^{\rm exp} = \frac{\mathcal{B}(B_c \to J/\Psi \tau\bar{\nu})}{\mathcal{B}(B_c \to J/\Psi \ell\bar{\nu})} = 0.71(17)(18)$$

[LHCb 2017]

general context and implications

in the SM [m_ν = 0 and U_{PMNS} = 1 in this talk]

1. no (measurable) LFV in charged lepton transitions
2. LFUV controlled by m_e , m_μ , m_τ

1. Very well verified, e.g.

$\mathrm{BR}(\mu^+ \to e^+\gamma)$	4.2×10^{-13}	[MEG]
$\mathrm{BR}(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}	[SINDRUM]

⇒ $\Lambda > 10^5$ TeV
$\Lambda > 10^2$ TeV

2. Well verified in a large energy range, at per mille level

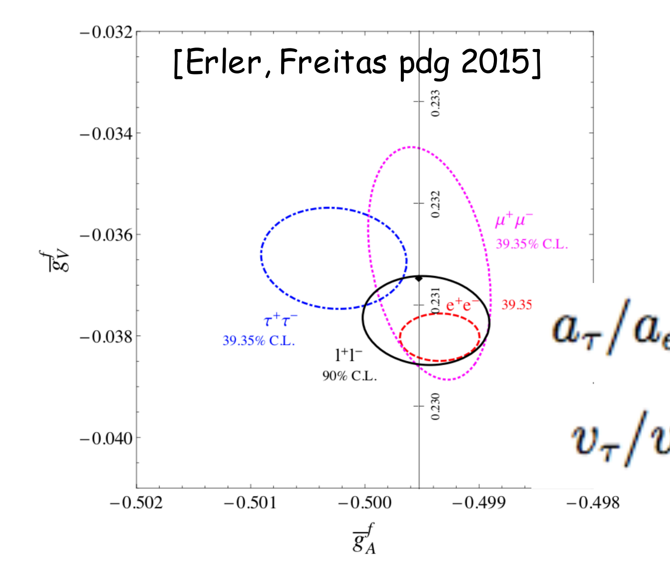
leptonic tau/muon decays E≈1 GeV

$$R_\tau^{\tau/e} = 1.0060 \pm 0.0030$$
$$R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030$$

but also in many leptonic and semileptonic light pseudoscalar decays

[A.Pich, 1310.7922]

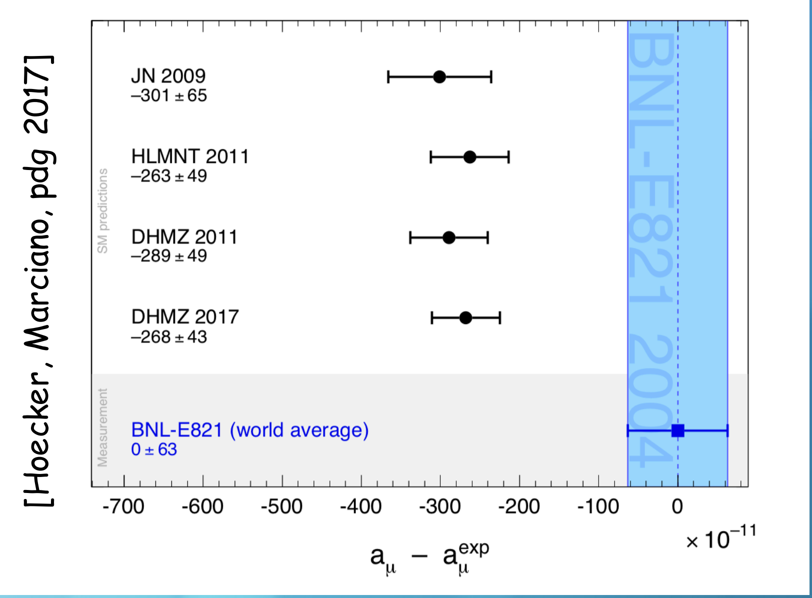
Z couplings to charged leptons E≈100 GeV



$$a_\tau/a_e = 1.0019\ (15)$$
$$v_\tau/v_e = 0.959\ (29)$$

the muon (g-2):
a long-standing exception ?

[waiting to be confirm by
Fermilab Muon (g-2)]



any violations of 1. and/or 2. → physics beyond the SM

LFV in charged leptons and LFUV are closely related in most SM extensions, though this is not a strict rule.

back to R_{D,D^*} R_{K,K^*}

- can they be made compatible with the existing tests of LFV and LFU?
- any specific LFV/LFUV process to especially monitor?

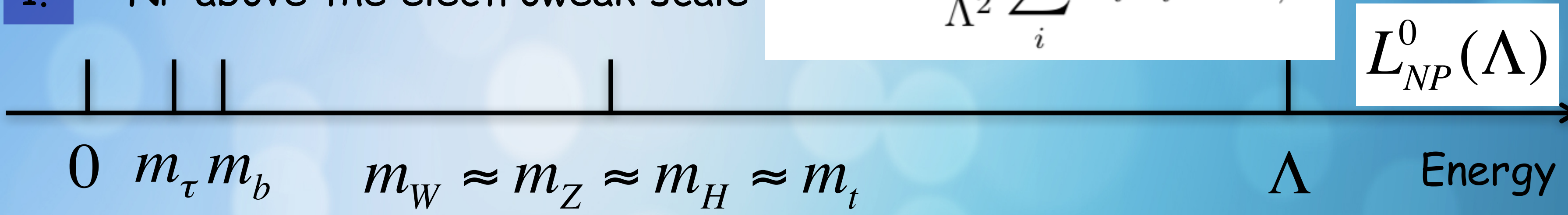
we need a concrete framework to answer that. Here

- define a benchmark scenario
- discuss deviations from the benchmark

Benchmark framework: assumptions

1. NP above the electroweak scale

$$\mathcal{L}^{NP} = \frac{1}{\Lambda^2}\sum_i C_i O_i + \ldots ,$$



2. NP mainly affects the third generation

couplings to lighter generations [e.g. muons, c-quark, ….] ⟷ misalignment between mass and interaction bases

6 sub-leading operators

$$\mathcal{L}^0_{NP}(\Lambda) = \frac{1}{\Lambda^2}\left(C_1\, \bar{q}'_{3L}\gamma^\mu q'_{3L}\; \bar{\ell}'_{3L}\gamma_\mu \ell'_{3L} + C_3\, \bar{q}'_{3L}\gamma^\mu \tau^a q'_{3L}\; \bar{\ell}'_{3L}\gamma_\mu \tau^a \ell'_{3L}\right) + \ldots$$

(V-A) pattern in NC supported by global fits

Hiller and Schmaltz 1408.1627;
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].

not the only possibility:

- V lepton current (O_9 operator) by itself provides a good fit
- right quark helicities disfavored after R_{K^*} measurement
- scalar operators are constrained by B leptonic decays-
- tensor operator at Λ gives rise to scalar operators at low-scale

Benchmark framework: assumptions

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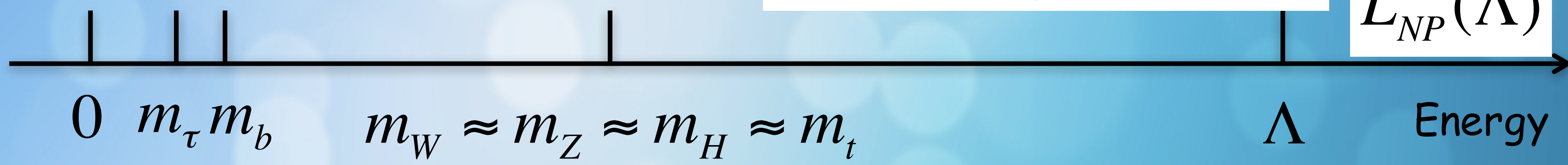
$L^0_{NP}(\Lambda)$



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(V-A) pattern in NC supported by global fits

→ g_{V_L} Olcyr Sumensari

→ $C_9^{NP} = -\,C_{10}^{NP}$ Nazila Mahmoudi

not the only possibility:

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$\mathcal{L}^0_{NP}(\Lambda)$ can address both NC and CC anomalies

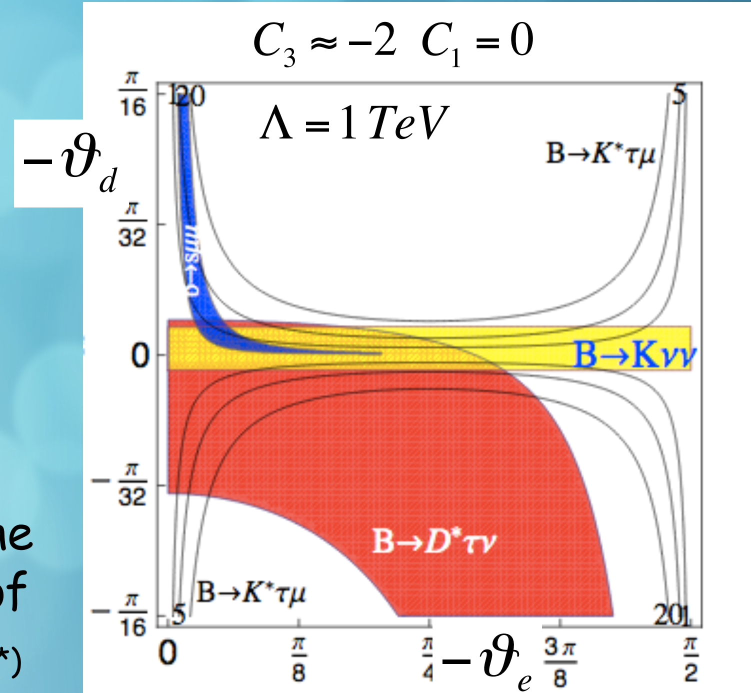
$$\mathcal{L}^0_{NP}(\Lambda) = \frac{\lambda^e_{kl}}{\Lambda^2}\,[(C_1+C_3)\;\lambda^u_{ij}\;\bar{u}_{Li}\gamma^\mu u_{Lj}\;\bar{\nu}_{Lk}\gamma_\mu\nu_{Ll} + (C_1-C_3)\;\lambda^u_{ij}\;\bar{u}_{Li}\gamma^\mu u_{Lj}\;\bar{e}_{Lk}\gamma_\mu e_{Ll} +$$
$$(C_1-C_3)\;\lambda^d_{ij}\;\bar{d}_{Li}\gamma^\mu d_{Lj}\;\bar{\nu}_{Lk}\gamma_\mu\nu_{Ll} + (C_1+C_3)\;\lambda^d_{ij}\;\bar{d}_{Li}\gamma^\mu d_{Lj}\;\bar{e}_{Lk}\gamma_\mu e_{Ll} +$$
$$2C_3\;\left(\lambda^{ud}_{ij}\;\bar{u}_{Li}\gamma^\mu d_{Lj}\;\bar{e}_{Lk}\gamma_\mu\nu_{Ll} + h.c.\right)\,]\;.$$

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

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

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

[Calibbi, Crivellin, Ota, 1506.02661]



4 parameters $\dfrac{C_1}{\Lambda^2}, \dfrac{C_3}{\Lambda^2}, \vartheta_d, \vartheta_e$

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

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

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

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

(ϑ_d x ϑ_e^2) provides the needed suppression of $R_{K(*)}$ compared to $R_{D(*)}$

Constraints (tree-level)

$R_K^{\mu/e}$ $R_{K^*}^{\mu/e}$	$(C_1+C_3)\vartheta_d\vartheta_e^2$		
$R_D^{\tau/\ell}$ $R_{D^*}^{\tau/\ell}$	C_3		
process	parameters	size	exp. bound
$R_{B_s\mu\mu}=\dfrac{\mathcal{B}(B_s\to\mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B_s\to\mu\bar{\mu})_{\rm SM}}$	$(C_1+C_3)\vartheta_d\vartheta_e^2$	$O(0.1)$	$\mathcal{B}(B_s\to\mu\bar{\mu})_{\rm exp}=2.8^{+0.7}_{-0.6}\times10^{-9}$ $\mathcal{B}(B_s\to\mu\bar{\mu})_{\rm SM}=3.65(23)\times10^{-9}$
$R_{B\tau\nu}^{\tau/\mu}=\dfrac{\mathcal{B}(B\to\tau\nu)_{\rm exp}/\mathcal{B}(B\to\tau\nu)_{\rm SM}}{\mathcal{B}(B\to\mu\nu)_{\rm exp}/\mathcal{B}(B\to\mu\nu)_{\rm SM}}$	C_3	$O(0.1)$	Belle II ?
$R_{K^{(*)}}^{\nu\nu}=\dfrac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})_{\rm SM}}$	$(C_1-C_3)\vartheta_d$	$O(1)$	$R_{K^*}^{\nu\nu}<4.4$ $R_K^{\nu\nu}<4.3$
$\mathcal{B}(B\to K\tau\mu)$ $\mathcal{B}(B\to\tau^\pm\mu^\mp)\approx\mathcal{B}(B\to K\tau^\pm\mu^\mp)$, $\mathcal{B}(B\to K^*\tau^\pm\mu^\mp)\approx2\times\mathcal{B}(B\to K\tau^\pm\mu^\mp)$	[Glashow, Guadagnoli, Lane 1411.0565] $\left\|(C_1+C_3)\vartheta_d\vartheta_e\right\|^2$	$O(10^{-6\div7})$	$\mathcal{B}(B\to K\tau\mu)\le4.8\times10^{-5}$
$\mu^+\mu^-$ and $\tau^+\tau^-$ Production at LHC	(C_1+C_3)		[Greljo, Marzocca 1704.09015] Admir Greljo talk

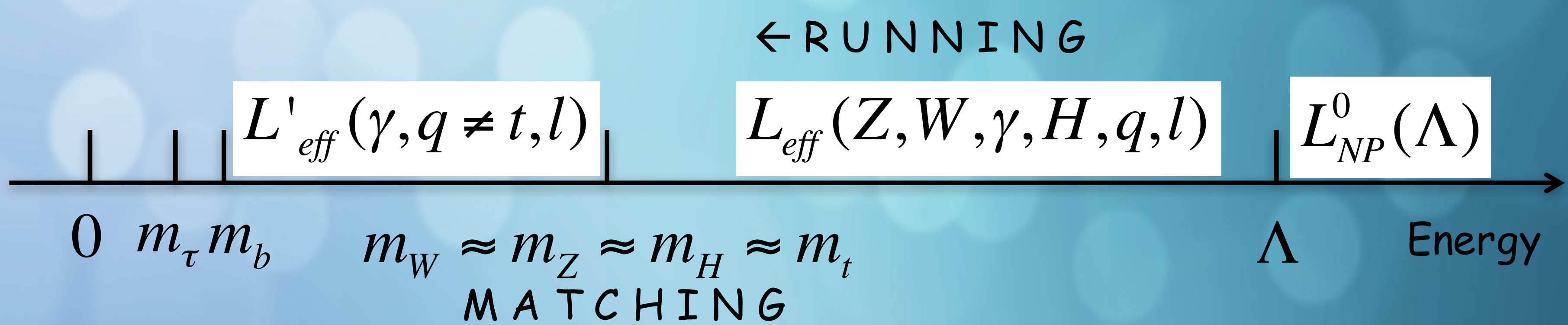
Constraints from quantum effects [FPP]

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

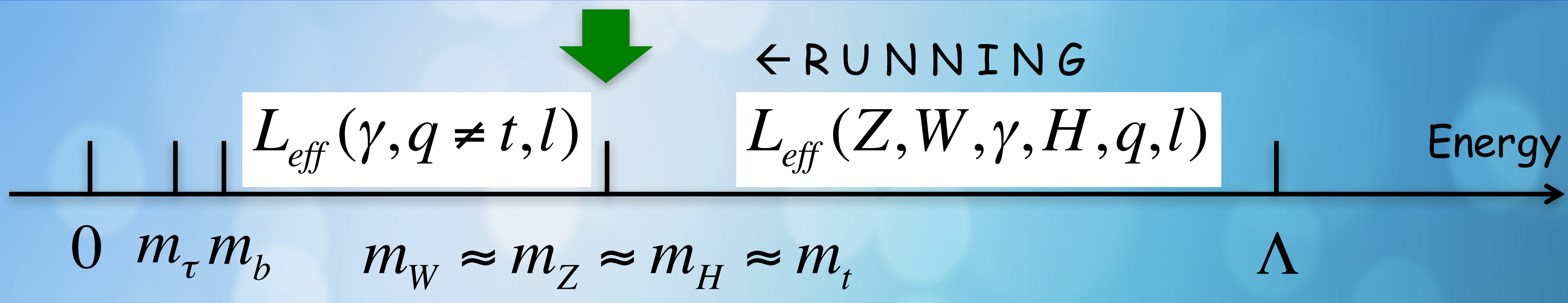
- How can quantum corrections ~ $\alpha/4\pi \sim 10^{-3}$ be relevant?

  - 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: $\log(\Lambda^2/m_W^2) \sim 5\text{-}7$

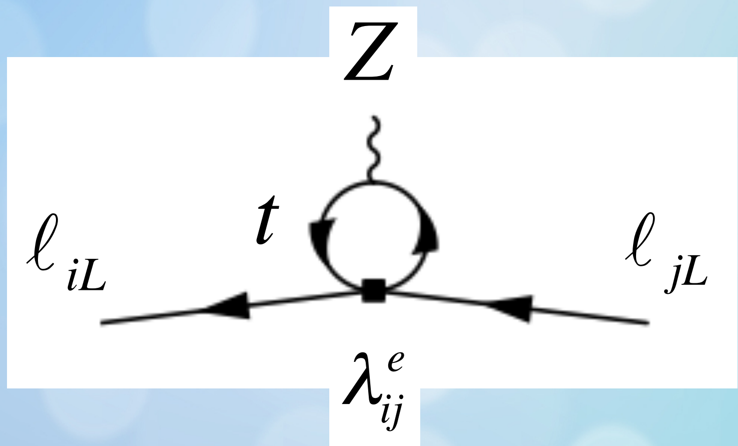
in the present framework - (V-A) semileptonic operators - corrections are dominated by electroweak interactions. They can be estimated by a well-known running and matching procedure. Here, Leading Log effects only



1st: the electroweak scale



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



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

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

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

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

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

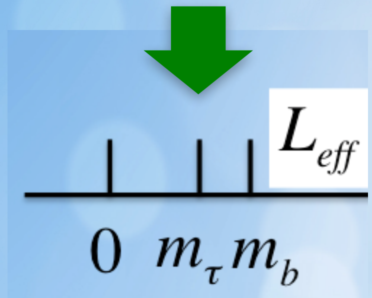
$$N_\nu = 2.9840 \pm 0.0082$$

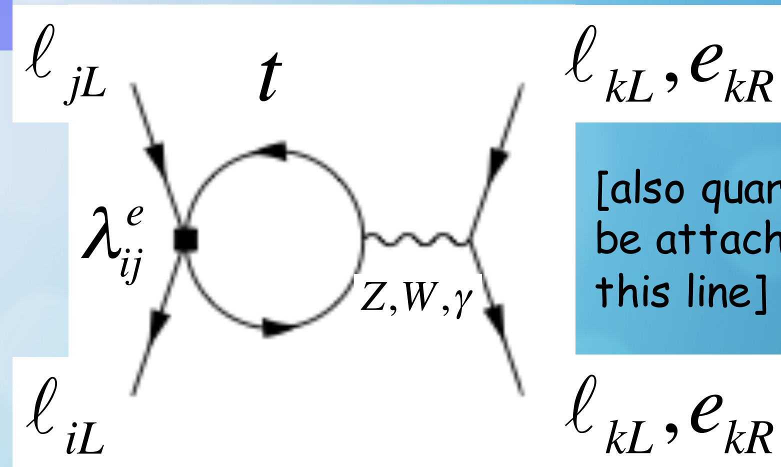
$$\mathcal{B}(Z \to \mu^\pm \tau^\mp) \approx 10^{-7}$$

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

2. generation of a purely leptonic effective Lagrangian at the scale ≤ m_b

2nd: m_τ

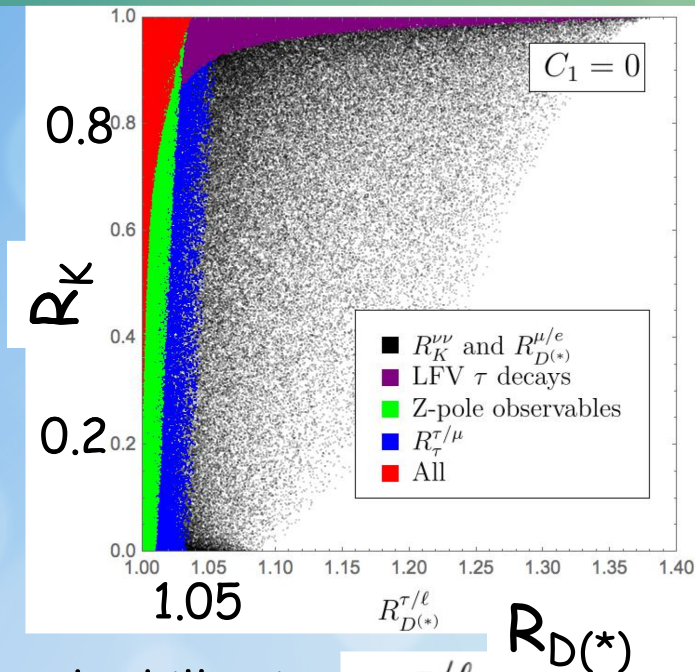


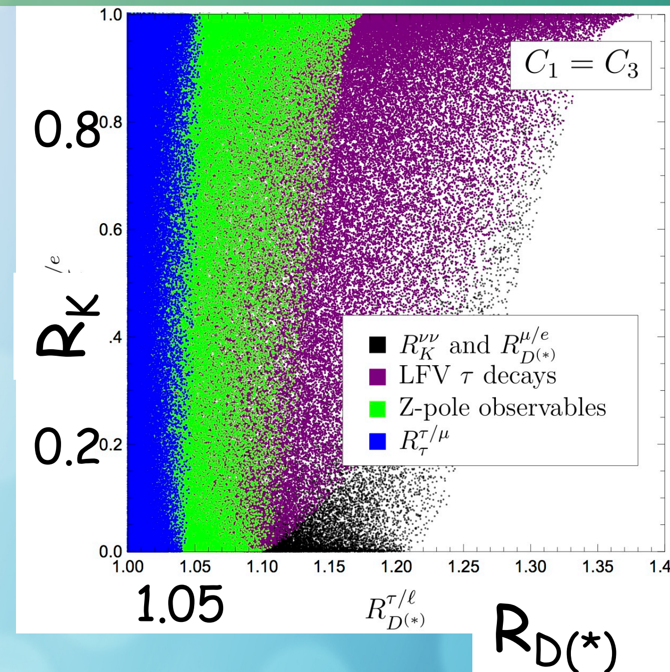


[also quarks can be attached to this line]

$R_\tau^{\tau/e} = \frac{\mathcal{B}(\tau\to\mu\nu\bar\nu)_{\rm exp}/\mathcal{B}(\tau\to\mu\nu\bar\nu)_{\rm SM}}{\mathcal{B}(\mu\to e\nu\bar\nu)_{\rm exp}/\mathcal{B}(\mu\to e\nu\bar\nu)_{\rm SM}}$ $R_\tau^{\tau/\mu} = \frac{\mathcal{B}(\tau\to e\nu\bar\nu)_{\rm exp}/\mathcal{B}(\tau\to e\nu\bar\nu)_{\rm SM}}{\mathcal{B}(\mu\to e\nu\bar\nu)_{\rm exp}/\mathcal{B}(\mu\to e\nu\bar\nu)_{\rm SM}}$	$\approx 1 + \frac{0.008\, C_3}{\Lambda^2({\rm TeV}^2)}$	$R_\tau^{\tau/e} = 1.0060 \pm 0.0030$ $R_\tau^{\tau/\mu} = 1.0022 \pm 0.0030$ [A.Pich, 1310.7922]
$\mathcal{B}(\tau\to 3\mu)$	$\approx 5\times 10^{-8}\frac{(C_1 - C_3)^2}{\Lambda^4({\rm TeV}^4)}\left(\frac{\vartheta_e}{0.3}\right)^2$	Lusiani talk $\mathcal{B}(\tau\to 3\mu) \le 1.2\times 10^{-8}$ [HFAG, 1412.7515]
$\mathcal{B}(\tau\to \mu\rho)$	$\approx 5\times 10^{-8}\frac{(C_1 - 1.3\,C_3)^2}{\Lambda^4({\rm TeV}^4)}\left(\frac{\vartheta_e}{0.3}\right)^2$	$\mathcal{B}(\tau\to \mu\rho) \le 1.5\times 10^{-8}$
$\mathcal{B}(\tau\to \mu\pi)$	$\approx 8\times 10^{-8}\frac{(C_1 - C_3)^2}{\Lambda^4({\rm TeV}^4)}\left(\frac{\vartheta_e}{0.3}\right)^2$	$\mathcal{B}(\tau\to \mu\pi) \le 2.7\times 10^{-8}$ [HFAG, 1412.7515]

Putting everything together



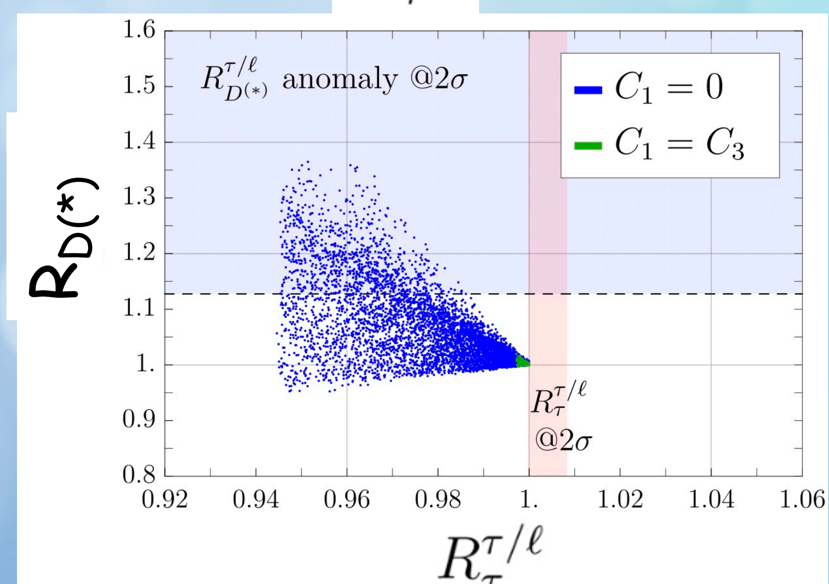


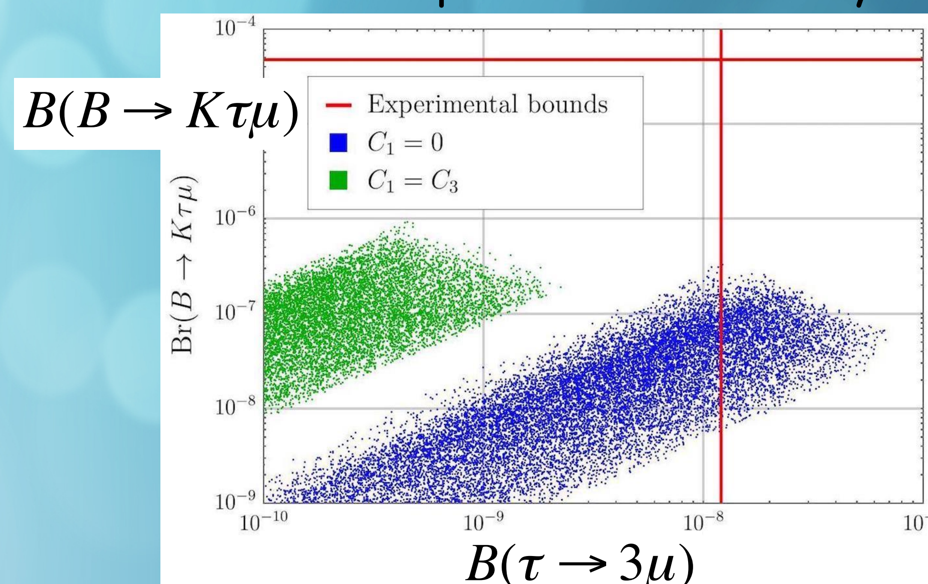
$$\left|\frac{C_{1,3}}{\Lambda^2}\right| \leq 4\, TeV^{-2}$$

$$\left|\vartheta_{d,e}\right| \leq 0.5$$

the killer is $R_\tau^{\tau/\ell}$!

LFV better probed in tau decays





A more general setup

C. Cornella, F.F., P. Paradisi, 1803.00945

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

$$[Q^{(1)}_{lq}]_{3333} = (\bar{\ell}'_{3L}\gamma^\mu \ell'_{3L})(\bar{q}'_{3L}\gamma^\mu q'_{3L})$$
$$[Q^{(3)}_{lq}]_{3333} = (\bar{\ell}'_{3L}\gamma^\mu \tau^a \ell'_{3L})(\bar{q}'_{3L}\gamma^\mu \tau^a q'_{3L})$$
$$[Q_{ld}]_{3333} = (\bar{\ell}'_{3L}\gamma^\mu \ell'_{3L})(\bar{d}'_{3R}\gamma d'_{3R})$$
$$[Q_{ed}]_{3333} = (\bar{e}'_{3R}\gamma^\mu e'_{3R})(\bar{d}'_{3R}\gamma d'_{3R})$$
$$[Q_{qe}]_{3333} = (\bar{q}'_{3L}\gamma q'_{3L})(\bar{e}'_{3R}\gamma^\mu e'_{3R})$$

most general set of (current)^2 SU(2)xU(1) – invariant semileptonic operators involving the 3rd generation

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

an example

$$C_1 + C_3 = C_6 \qquad C_4 = C_5 = 0\,.$$

⇒

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

we find

$$\frac{v_\tau}{v_e} = 1 - \frac{0.05\,\lambda^e_{33}}{\Lambda^2}\left(2\,C_1 + 0.2\,C_3 + 0.02\,(2\,C_1 + C_3)\right)$$
$$\frac{a_\tau}{a_e} = 1 + 0.007\,\lambda^e_{33}\frac{C_3}{\Lambda^2}$$

directly correlated to $R^{\tau/\ell}_\tau$ and $R_{D(*)}$

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

Discussion

- cancellation/suppression of log effects by contributions of additional operators and/or finite correction terms not captured by this approach

- different flavour pattern in $O_{lq}^{(1,3)}$ can help in softening the bounds, e.g. in recent UV complete models with the vector LQ U_1=(3,1,+2/3)

  [Buttazzo, Greljo, Isidori, Marzocca, 1706.07808, Di Luzio, Greljo, Nardecchia 1708.08450, Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368, Barbieri, Tesi 1712.06844,...]

  couplings to 2nd lepton generation not dominated by mixing to 3rd one

- $R_D^{\tau/\ell}$ $R_{D^*}^{\tau/\ell}$ alone can be explained in present framework

  e.g. $\vartheta_d \approx 1$, $\vartheta_e \ll \alpha_{em}$, $\Lambda \approx 5$ TeV → loop effects decouple as v^2/Λ^2

- $R_K^{\mu/e}$ $R_{K^*}^{\mu/e}$ alone can be explained in present framework

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Discussion

- cancellation/suppression of log effects by contributions of additional operators and/or finite correction terms not captured by this approach

- vector LQ $U_1=(3,1,+2/3)$

  - $O_{lq}^{(1,3)}$ operators with $C_1=+C_3$ if $g_{ql}^L \neq 0$ $g_{ql}^R = 0$
  - automatically free from p-decay
  - realizes the minimal lepton-quark unification within the Pati-Salam SU(4)
  - $m_U \geq 100$ TeV unless flavour pattern is cleverly arranged

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any relation to the muon (g-2) ?

- among all possible 1-particle extensions of the SM a special property enjoyed by scalar LQ that couples to quarks of BOTH chiralities

$S_1 = (\bar{3}, 1, +1/3)$ $\qquad\qquad$ $R_2 = (3, 2, +7/6)$

[not automatically p-decay free]

- contributions to dipole transitions can be chirally enhanced

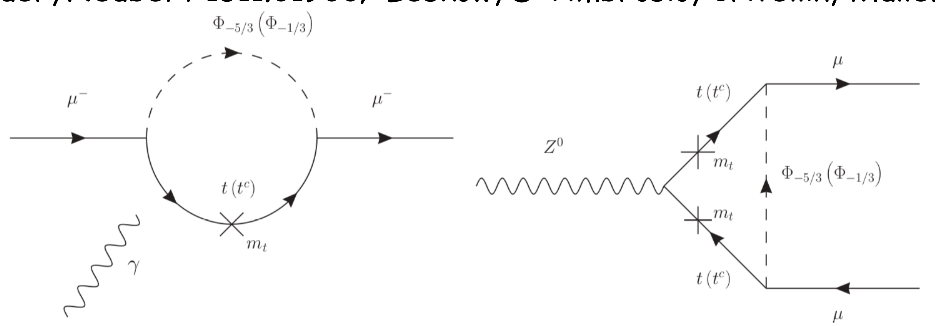
δa_ℓ	$\Gamma(\ell \to \ell' \gamma)$
$\frac{1}{16\pi^2} \frac{m_\ell m_{top}}{M_{LQ}^2} g_{t\ell}^L g_{t\ell}^R$	$\frac{\alpha_{em}}{256\pi^4} \frac{m_\ell^3 m_{top}^2}{M_{LQ}^4} \lvert g_{t\ell}^{L(R)} g_{t\ell'}^{R(L)} \rvert^2$

[Djouadi, Kohler, Spira, Tutas, 1990
Chakraverty, Choudhury, Datta 0102180
Cheung 0102238
Biggio, Bordone 1411.6799]

δa_μ of correct size for $M_{LQ} \approx 1$ TeV in a weak coupling regime

- 1-to-1 correlation to (chirally enhanced) deviations in Z-coupling to leptons

Bauer, Neubert 1511.01900; Leskow, D' Ambrosio, Crivellin, Muller 1612.06858]



$$\delta BR(Z \to \ell^+ \ell^-) \approx \frac{1}{16\pi^2} \frac{m_{top}^2}{M_{LQ}^2} \lvert g_{t\ell}^L \rvert^2$$

many models addressing B-anomalies include S_1 or R_2 in their spectrum

[NC anomaly requires special care: no contribution to $b \to s\ell^+\ell^-$ from tree-level S_1 exchange; C_9=+C_{10} from R_2 exchange]

Bauer, Neubert 1511.01900	S_1
Chen, Nomura, Okada 160704857	$R_2 + S_3$
Caio, Gargalionis, Schmidt, Volkas 1704.05849	S_1
Becirevic, Sumensari, 1704.05835	R_2
Chauhan, Kindra,Narang, 1706.04598	R_2
Crivellin, Muller, Ota, 1703.09226	$S_1 + S_3$
…	

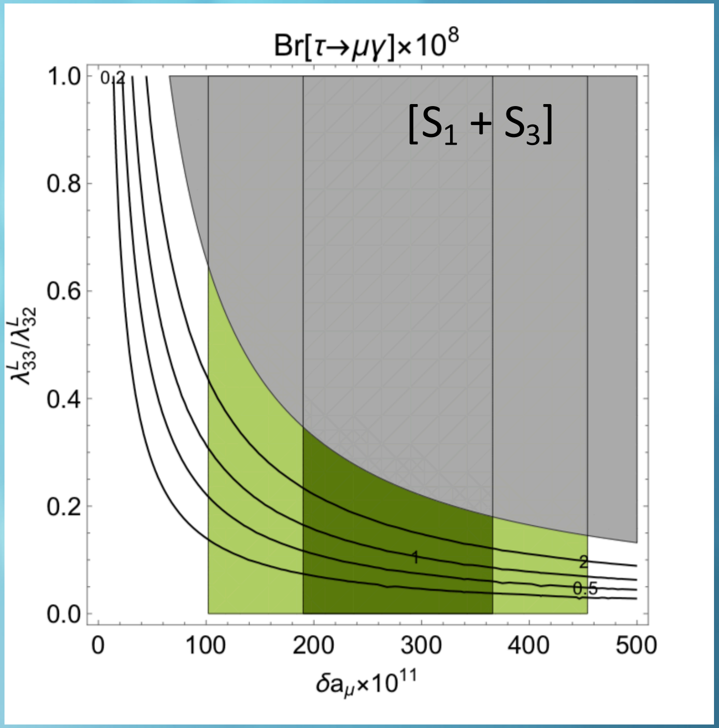
if LQ couples mainly to top and 2nd lepton generation

$$\delta a_\mu \approx +3\times 10^{-9} \Rightarrow \delta BR(Z\to \mu^+\mu^-) \approx 10^{-4}$$

If LQ couples also to top and 3rd lepton generation

$$\frac{BR(\tau\to\mu\gamma)}{(\delta a_\mu)^2} \geq \frac{9\times 10^{-7}}{(+3\times 10^{-9})^2}\left(\frac{g^L_{33}}{g^L_{32}}\right)^2$$

$$BR(Z\to\tau^\pm\mu^\mp) \approx \frac{10^{-8}(g^L_{33}g^L_{32})^2}{M^4_{LQ}(TeV)}$$



[Crivellin, Muller, Ota, 1703.09226]

conclusion

- simultaneous explanation of $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies appealing
  it calls for a "low" New Physics scale $\Lambda \approx 1$ TeV, at least in simplest scheme

- in this context the inclusion of quantum corrections $\approx O(v^2/\Lambda^2)$ is crucial to asses the viability of proposed solutions

- in the reference case discussed here (NP in 3rd generation V-A currents) purely leptonic LFUV/LFV transitions are generated and strong constraints arise

$$\frac{a_\tau}{a_e} \qquad \frac{v_\tau}{v_e}$$

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

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

watch $\tau \to 3\mu$

- Bounds from EWPT and/or tau physics can be softened by
  - more elaborate flavor patterns in NP and/or
  - some conspiracy by UV physics

Back-up slides

Global Fit

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

$$\mathcal{O}_9 = \frac{\alpha}{4\pi}(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}'_9 = \frac{\alpha}{4\pi}(\bar{s}_R \gamma_\mu b_R)(\bar{\ell}\gamma_\mu \ell) \qquad \mathcal{O}_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$\mathcal{O}_{10} = \frac{\alpha}{4\pi}(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \qquad \mathcal{O}'_{10} = \frac{\alpha}{4\pi}(\bar{s}_R \gamma_\mu b_R)(\bar{\ell}\gamma_\mu \gamma_5 \ell) \qquad \mathcal{O}'_{7\gamma} = \frac{e}{4\pi^2} m_b (\bar{s}_R \sigma^{\mu\nu} b_L) F_{\mu\nu}$$

$\Downarrow$

- ▹ $C_9^{NP} \neq 0$
- ▹ $C_9^{NP} = -C_{10}^{NP} \neq 0$

} good fits of: ▹ R_K
▹ P'_5 (et al.)

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

$\Downarrow$

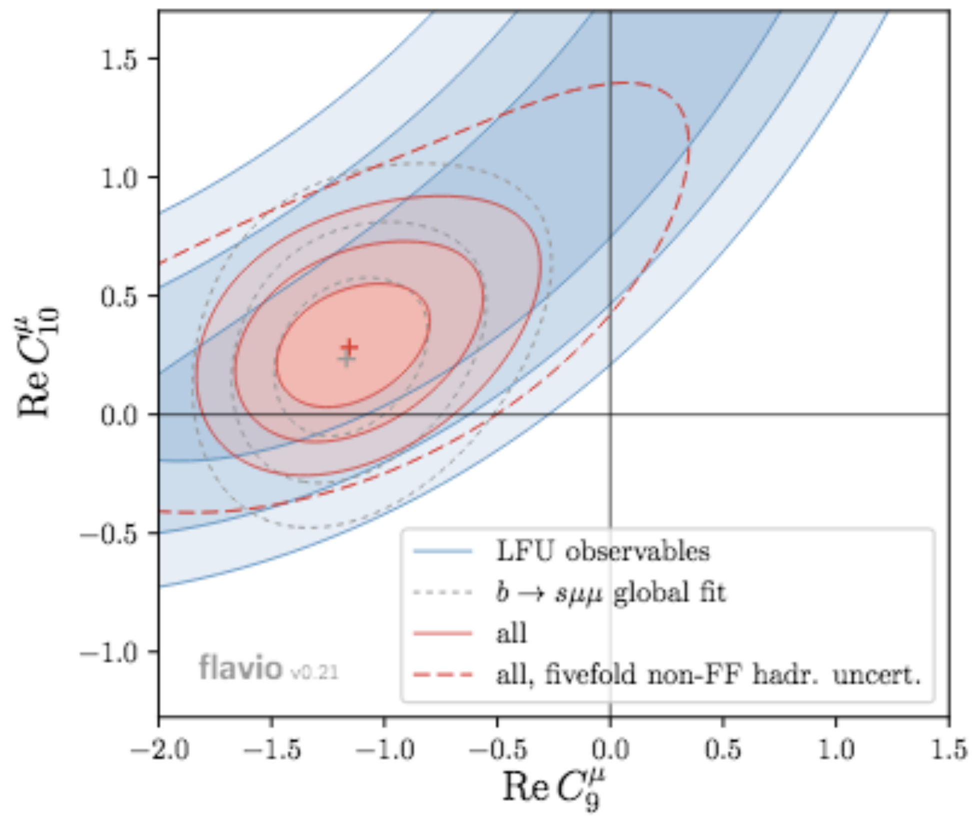
$(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma_\mu \ell_L)$ $\Rightarrow$ left-handed current

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

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 $B \to K^* \mu^+ \mu^-$, differential BR in $B \to K^* \mu^+ \mu^-$, $B \to \varphi \mu^+ \mu^-$

Global Fit

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

$$[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.10(2)\mathcal{C}'_{9\mu-e} - 0.11(2)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.11(2)\mathcal{C}'_{10\mu-e} + 0.55(6)\mathcal{C}^{\rm NP}_7,$$

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

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

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

$$g_{fL,R} = g^{SM}_{fL,R} + \Delta g_{fL,R} \qquad\qquad g_{\ell,q} = g^{SM}_{\ell,q} + \Delta g_{\ell,q}$$

$$\Delta g^{ij}_{\nu L} = \frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\left(\frac{1}{3}g_1^2 C_1 - g_2^2 C_3 + 3y_t^2\lambda^u_{33}(C_1 + C_3)\right)\lambda^e_{ij}$$

$$\Delta g^{ij}_{eL} = \frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\left(\frac{1}{3}g_1^2 C_1 + g_2^2 C_3 + 3y_t^2\lambda^u_{33}(C_1 - C_3)\right)\lambda^e_{ij}$$

$$\Delta g^{ij}_{uL} = -\frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\frac{1}{3}\left(g_1^2 C_1 + g_2^2 C_3\right)\lambda^u_{ij}$$

$$\Delta g^{ij}_{dL} = -\frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\frac{1}{3}\left(g_1^2 C_1 - g_2^2 C_3\right)\lambda^d_{ij}$$

$$\Delta g^{ij}_{fR} = 0 \qquad (f = \nu, e, u, d)$$

$$\Delta g^{ij}_{\ell} = \frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\left(-2g_2^2 C_3 + 6y_t^2\lambda^u_{33}C_3\right)\lambda^e_{ij}$$

$$\Delta g^{ij}_{q} = -\frac{v^2}{\Lambda^2}\frac{L}{16\pi^2}\frac{2}{3}g_2^2 C_3 \lambda^{ud}_{ij} \quad . \qquad\qquad L = \log\frac{\Lambda}{\mu}$$

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

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
$(\bar\nu_{iL}\gamma_\mu\nu_{jL})\,(\bar e_k\gamma^\mu e_n)$	$\lambda^e_{ij}\,\delta_{kn}\cdot\frac{4}{3}e^2\Big[(C_1+3C_3)-2(C_1+C_3)(\hat\lambda^u_{33}\log\frac{m_t}{\mu}+\hat\lambda^u_{22}\log\frac{m_c}{\mu})$ $+(C_1-C_3)\hat\lambda^d_{33}\log\frac{m_b}{\mu}\Big]$
$(\bar e_{iL}\gamma_\mu e_{jL})\,(\bar e_k\gamma^\mu e_n)$	$\lambda^e_{ij}\,\delta_{kn}\cdot\frac{4}{3}e^2\Big[(C_1-3C_3)-2(C_1-C_3)(\hat\lambda^u_{33}\log\frac{m_t}{\mu}+\hat\lambda^u_{22}\log\frac{m_c}{\mu})$ $+(C_1+C_3)\hat\lambda^d_{33}\log\frac{m_b}{\mu}\Big]$

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 $\hat\lambda^{u,d}_{ii}=\lambda^{u,d}_{ii}/\log\frac{m_{EW}}{\mu}$.

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^a_μ	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^a_μ	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	$(3,3,-1/3)$	$\bar{q}'_L\tau^a i\sigma^2\ell'^c_L\ \overline{i\sigma^2\ell'^c_L}\tau^a q'_L$	$+\frac{3}{4}$	$+\frac{1}{4}$

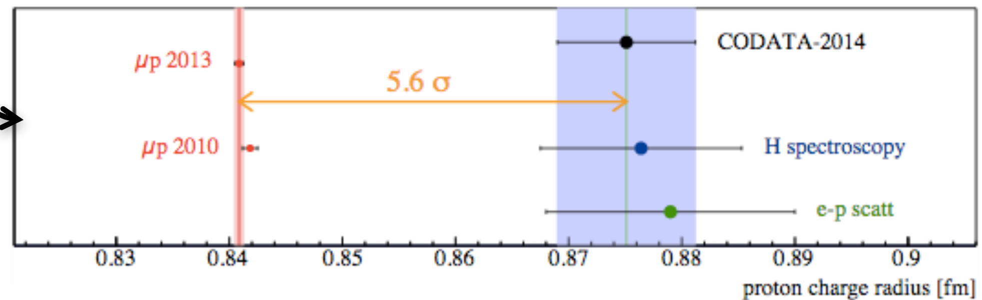
Table 11: Spin zero and spin one mediators contributing, at tree-level, to the Lagrangian $\mathcal{L}^0_{NP}(\Lambda)$ of eq. (7). Also shown are the operators they give rise to and the contribution to the coefficients C_1 and C_3 of the Lagrangian $\mathcal{L}^0_{NP}(\Lambda)$, when a single fermion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

- 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

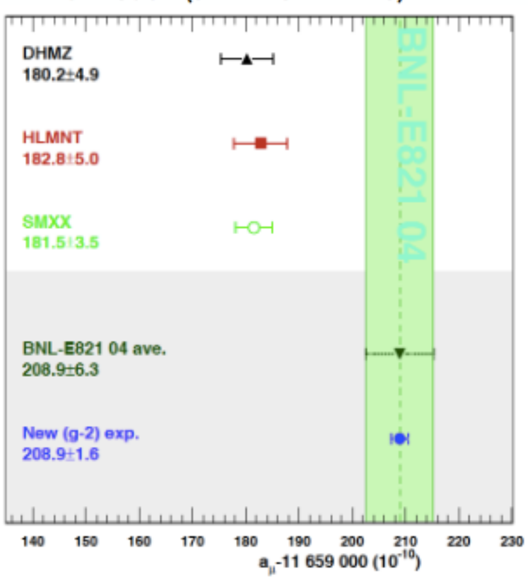
proton radius



[arXiv:1706.00696]

muon (g-2)

T. Blum et al. (arXiv:1311.2198)



τ-e and τ-μ universality

W leptonic decays

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