Lepton Flavour Universality

XII Latin American Symposium of High Energy Physics

Lima, 26 November 2018

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Plan

- summary of present hints of Violation of Lepton Flavour Universality in semi-leptonic B-decays

detailed discussion of processes and experimental perspective → Bernardo Adeva's talk

- compatibility of New Physics explanations with existing constraints EWPTs, LFU/LFV, collider physics

Lepton Flavour Universality in the SM

basic property of SM*

[including the extension to accommodate neutrino masses]
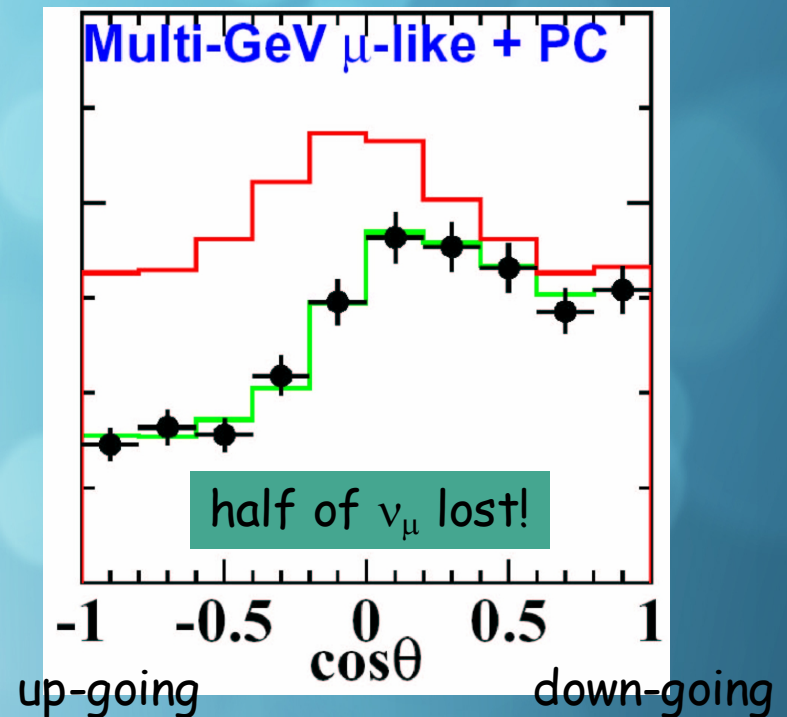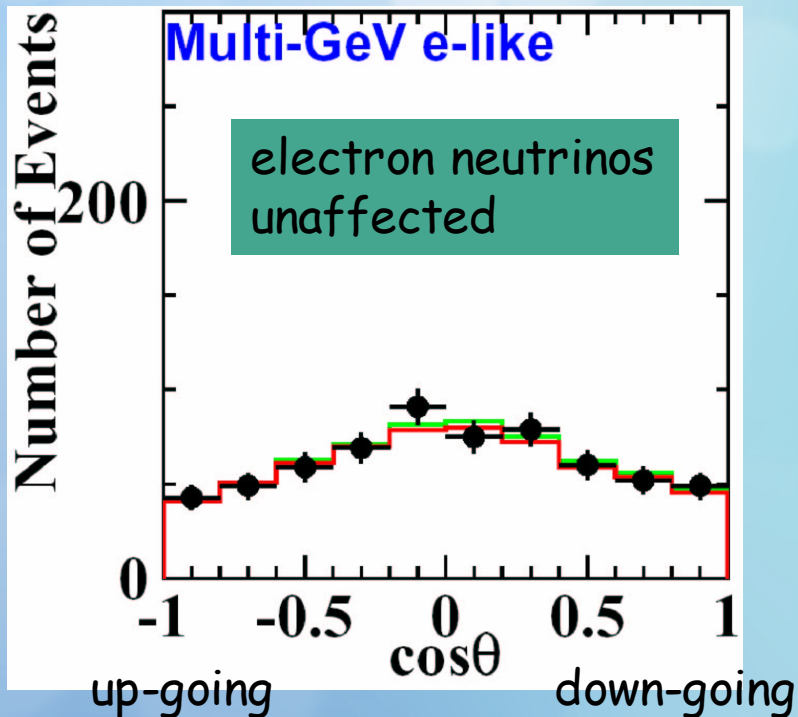
neglecting mass terms and Yukawa interactions → lepton interactions are fully described by g, g'

we cannot distinguish e, μ and τ (and the corresponding neutrinos)

of course, LFU is largely broken by $\mathcal{L}_Y + \delta\mathcal{L}_\nu$ e.g. in neutrino oscillations

Multi-GeV e-like

electron neutrinos unaffected

Number of Events

200

0

-1   -0.5   0   0.5   1
cosθ

up-going   down-going

Multi-GeV μ-like + PC

half of ν_μ lost!

-1   -0.5   0   0.5   1
cosθ

up-going   down-going

For the processes discussed here, to an excellent approximation

$m_\nu = 0$ and $U_{PMNS} = 1$

➡️ 1. no LFV in charged lepton transitions

2. LFUV controlled by m_e, m_μ, m_τ

1. Very well verified: no exception

$\mu \to e$

	Present upper bound	
$BR(\mu^+ \to e^+\gamma)$	4.2×10^{-13}	[MEG]
$BR(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}	[SINDRUM]
$CR(\mu^- Ti \to e^- Ti)$	4.3×10^{-12}	[SINDRUM II]
$CR(\mu^- Au \to e^- Au)$	7.0×10^{-13}	[SINDRUM II]

$\tau \to e$ $\tau \to \mu$

	Present upper bound
$BR(\tau \to e\gamma)$	3.3×10^{-8}
$BR(\tau \to \mu\gamma)$	4.4×10^{-8}

	Present upper bound
$BR(\tau \to 3e)$	2.7×10^{-8}
$BR(\tau \to 3\mu)$	2.1×10^{-8}

bounds on the scale of New Physics

Λ_{NP} (TeV) ($|c| = 1$)	
6.3×10^4	$\mu \to e\gamma$
6.5×10^2	$\tau \to e\gamma$
6.1×10^2	$\tau \to \mu\gamma$

Λ_{NP} (TeV) ($|c| = 1$)	
207	$\mu \to 3e$
10.4	$\tau \to 3e$
11.3	$\tau \to 3\mu$
174	$\mu \to 3e$

➡️

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

introduce different couplings of W to e, μ and τ

$$g_e \qquad g_\mu \qquad g_\tau$$

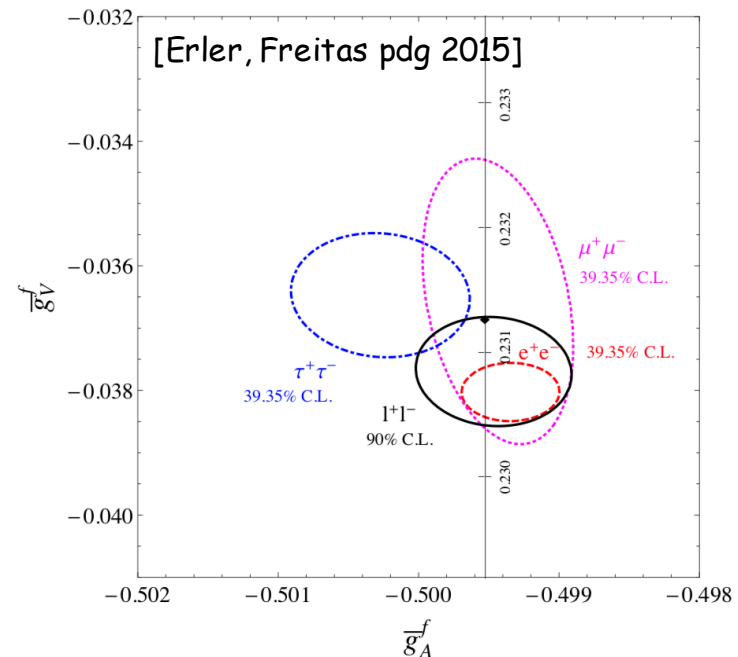| E≈1 GeV	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$|g_\mu/g_e|$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$|g_\tau/g_\mu|$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$|g_\tau/g_e|$	1.0030 (15)	1.031 (13)			[A.Pich, 1310.7922]

Z couplings to charged leptons

E≈100 GeV

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

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

[Erler, Freitas pdg 2015]

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

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

[Hoecker, Marciano, pdg 2017]
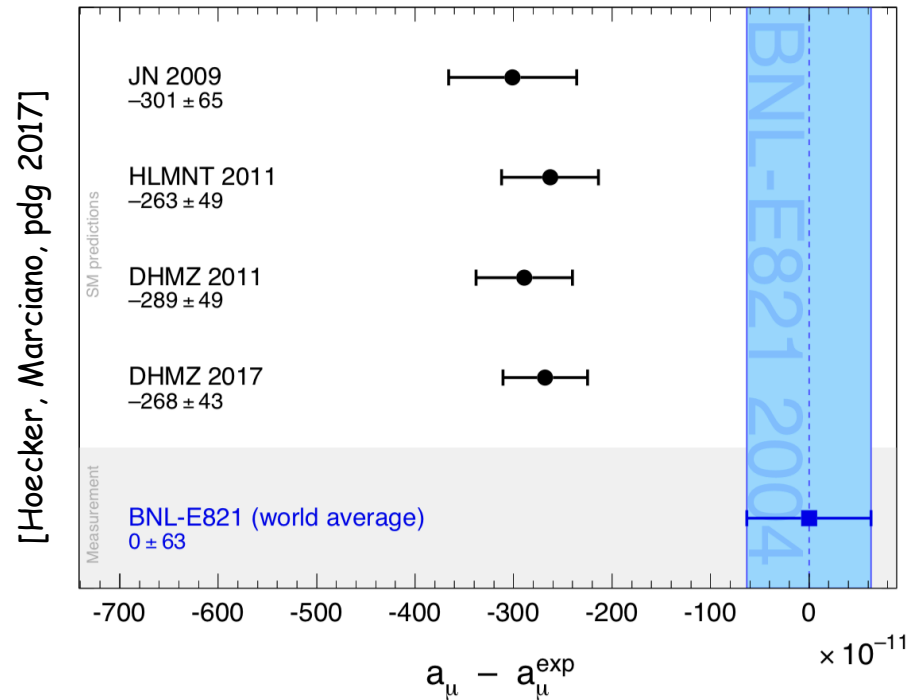
troubles at the horizon for the electron (g-2) ?

$$\alpha^{-1}(\mathrm{Cs}) = 137.035999046(27).$$

➡️

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}}$$
$$= [-87 \pm 28\,(\mathrm{exp}) \pm 23\,(\alpha) \pm 2\,(\mathrm{theory})]$$
$$\times 10^{-14}, \text{ [H.Davoudiasl and W.Marciano 1806.10252]}$$

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.

Hints of violation of LFU in semileptonic B decays

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

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

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

$\tau \leftrightarrow \mu/e$

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

$$R_{J/\Psi}^{\mathrm{exp}} = \frac{\mathcal{B}(B_c \to J/\Psi\tau\overline{\nu})}{\mathcal{B}(B_c \to J/\Psi\ell\overline{\nu})} = 0.71(17)(18)$$ [LHCb 2017]
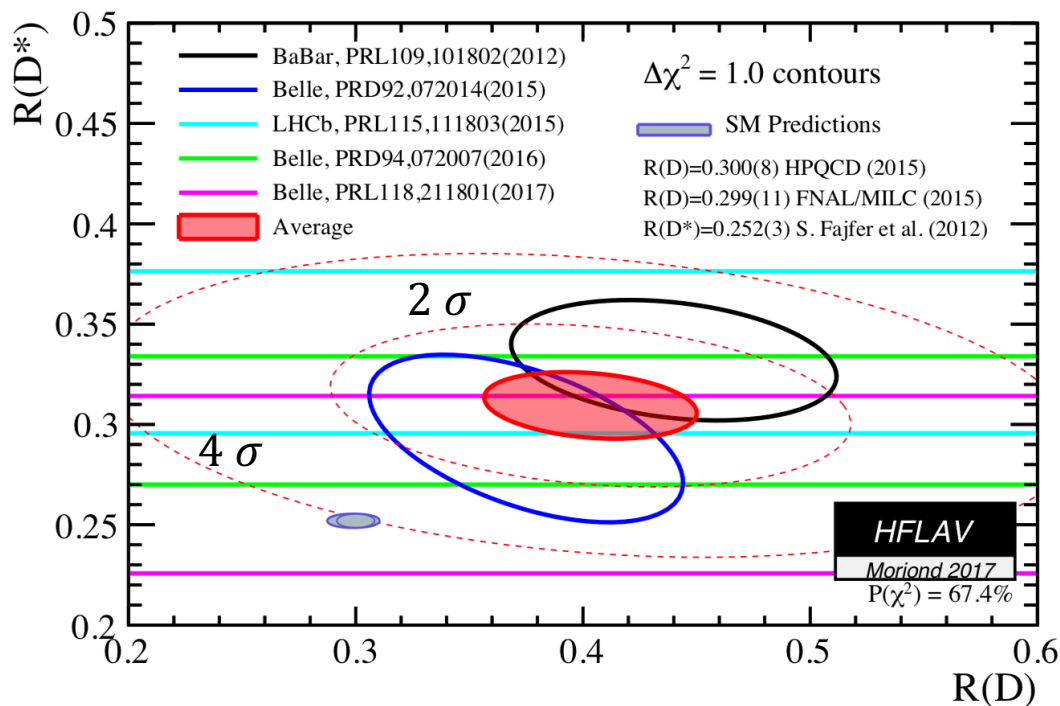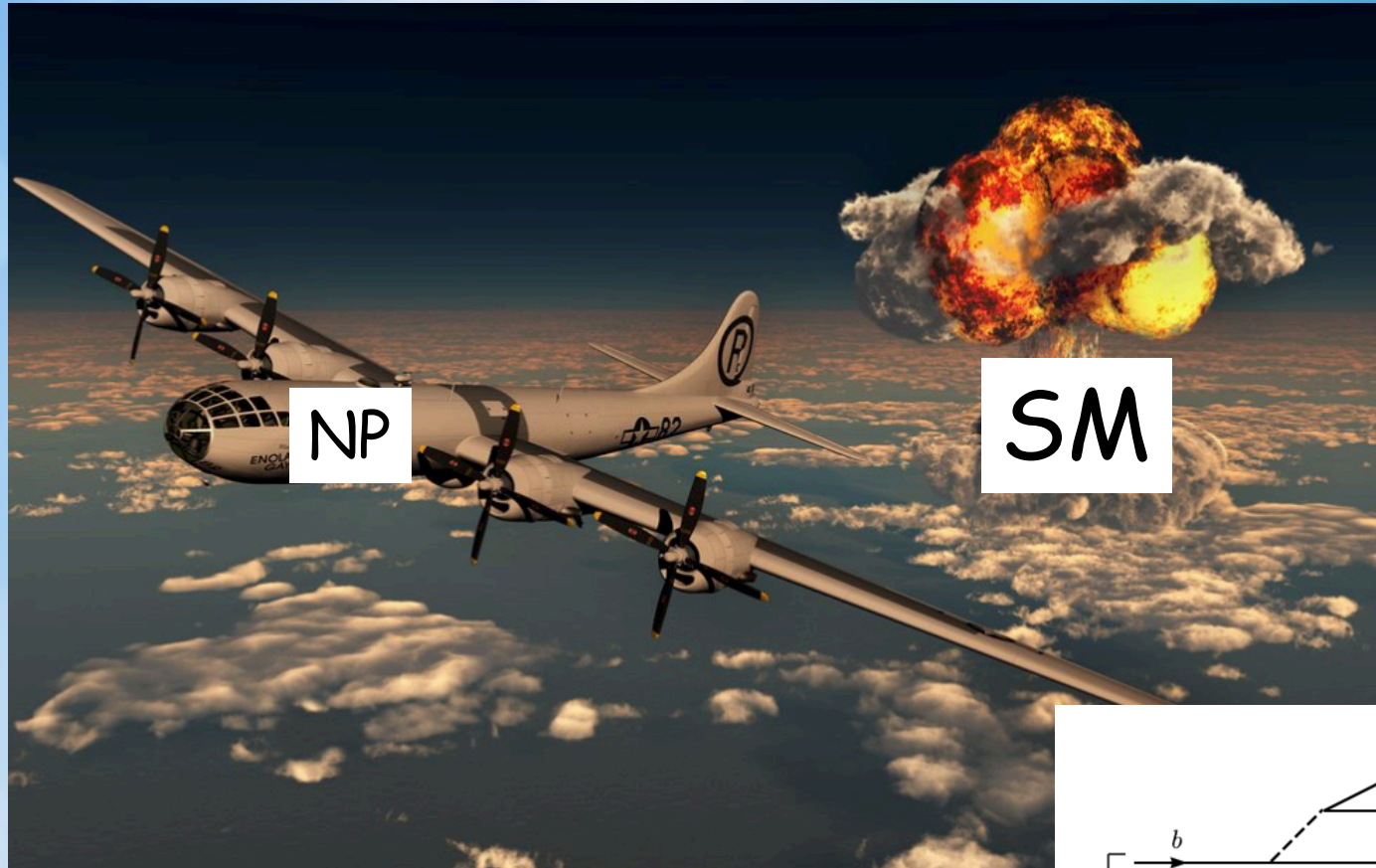
SM accuracy:
few percent

$$R_{D}^{\tau/\ell} = 0.300 \pm 0.008$$
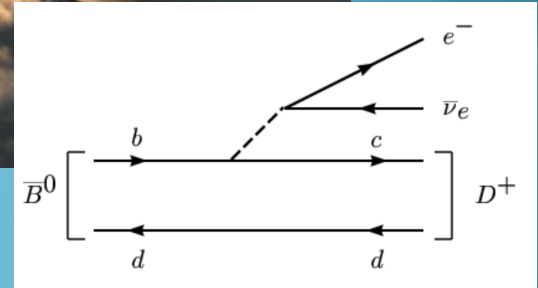
$$R_{D^*}^{\tau/\ell} = 0.260 \pm 0.008$$

$R_{D}^{\tau/\ell}$: 1+1 FFs,
lattice extrapolation also away from zero recoil

$R_{D^*}^{\tau/\ell}$: 3+1 FFs,
only zero recoil results from lattice unknown scalar FF.

New Physics in Cabibbo-favoured, tree-level decay!

violates all expectations:
New Physics in loop-driven, Cabibbo-suppressed and/or chiral-suppressed transitions, like $b \to s\,\gamma$, $B_s \to \mu^+\mu^-$, ... or EDM,...

needs confirmation from Belle II and LHCb (run 2)

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

$\mu \leftrightarrow e$

[LHCb, 1705.05802
SM at 2.4-2.5σ]

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

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

[LHCb, 1406.6482
SM at 2.6σ]

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

[Bordone, Isidori, Pattori, 1605.07633]

Which type of New Physics ?

does not match
d=6 G_{SM} invariant operators

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{cb}}{\sqrt{2}}\left[\left(1+\epsilon_L\right)\bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_L b + \boxed{\epsilon_R \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_R b} \right.$$

CC

$$\left. + \boxed{\epsilon_T\, \bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau \cdot \bar{c}\sigma^{\mu\nu}P_L b} + \boxed{\epsilon_{S_L}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_L b + \epsilon_{S_R}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_R b} \right] + \text{h.c.}$$

has large renormalization
into scalar operators
[Gonzalez-Alonso, Camalich,
Mimouni 1706.00410]

disfavored by B_c
lifetime

simplest solution:

ϵ_L =0.18±0.04

[Freytsis, Ligeti, Ruderman 1506.08896]

[Alonso, Grinstein, Camalich 1611.06676]

$$\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{i,\ell} (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) + \text{h.c.}$$

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \quad O_9'^\ell = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \; O_{10}'^\ell = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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, 1704.0
Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini and Valli 1704.05447
G. Hiller and I. Nisandzic, 1704.05444 [hep-ph].

C coefficients from global fits to b -> s transitions,
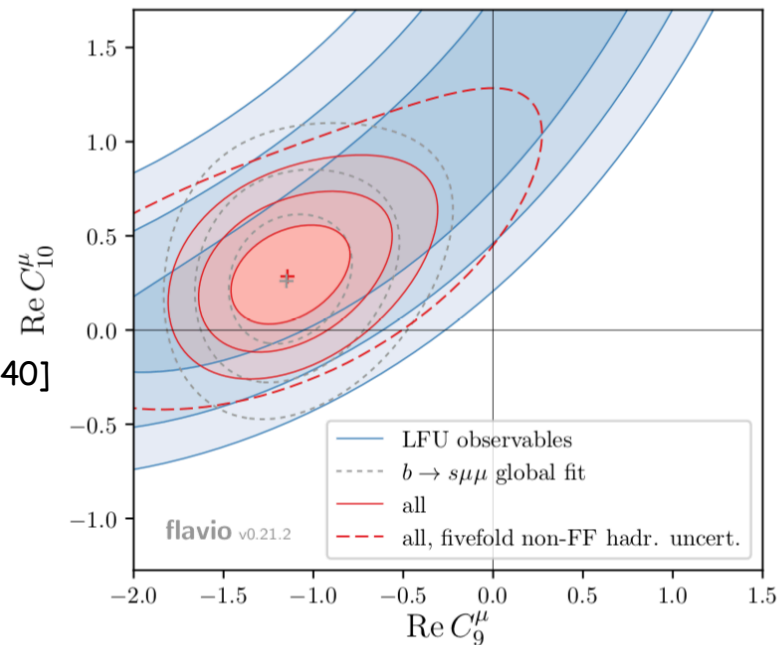including angular distributions and differential rates

solutions have a pull ~5σ w.r.t. the SM
and prefer NP in muon channel

1D Hyp.	Best fit	1 σ	2 σ
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.11	$[-1.28, -0.94]$	$[-1.45, -0.75]$
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.62	$[-0.75, -0.49]$	$[-0.88, -0.37]$

[Capdevila, Crivellin, Descotes-Genon, Matias and Virto, 1704.05340]

`All' includes R_K, R_{K^*},
angular variables in B -> K* μ⁺ μ⁻ ,
differential BR in B -> K* μ⁺ μ⁻ , B -> φ μ⁺ μ⁻

[Altmannshofer, Stangl and Straub, 1704.05435]

LFU observables
$b \to s\mu\mu$ global fit
all
all, fivefold non-FF hadr. uncert.

flavio v0.21.2

open questions

can R_{D,D^*} R_{K,K^*} be made compatible with the existing tests of LFV and LFU?

what are the most relevant correlated processes in a New Physics scenario?

is the implied New Physics compatible with collider bounds?

we need a concrete framework to answer that. Here

- define a benchmark scenario

- discuss deviations from the benchmark

Benchmark framework: assumptions

1. NP mainly occurs in four-fermion V-A operators

$$-\frac{4G_F V_{cb}}{\sqrt{2}}\epsilon_L \left(\overline{c}_L \gamma_\mu b_L\right)\left(\overline{\tau}_L \gamma^\mu \nu_{\tau L}\right)$$

$$-\frac{8G_F V_{tb}V_{ts}^*}{\sqrt{2}}\frac{e^2}{16\pi^2} C \left(\overline{s}_L \gamma_\mu b_L\right)\left(\overline{\mu}_L \gamma^\mu \mu_L\right)$$

$$C \equiv C_{9\mu}^{NP} = -C_{10\mu}^{NP}$$

2. NP above the electroweak scale $\quad \mathcal{L}^{NP} = \frac{1}{\Lambda^2}\sum_i C_i O_i + \dots,$

$$L_{NP}^0(\Lambda)$$

$$0 \quad m_\tau \, m_b \qquad m_W \approx m_Z \approx m_H \approx m_t \qquad\qquad \Lambda \qquad \text{Energy}$$
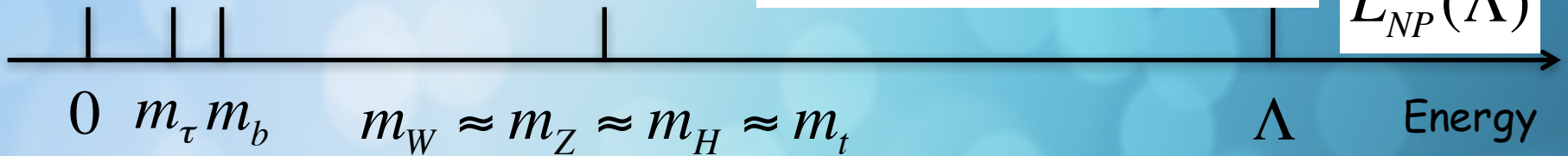
3. NP dominantly affects the third generation

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

6 sub-leading operators

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

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

b_L ϑ_d s_L

τ_L ϑ_e μ_L

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

$\dfrac{2C_3}{\Lambda^2} V_{cb}$ $\left(\bar{c}_L \gamma_\mu b_L\right)\left(\bar{\tau}_L \gamma^\mu \nu_{\tau L}\right)$

$\dfrac{(C_1 + C_3)}{\Lambda^2} \vartheta_d \vartheta_e^2$ $\left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{\mu}_L \gamma^\mu \mu_L\right)$

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

[Calibbi, Crivellin, Ota, 1506.02661]

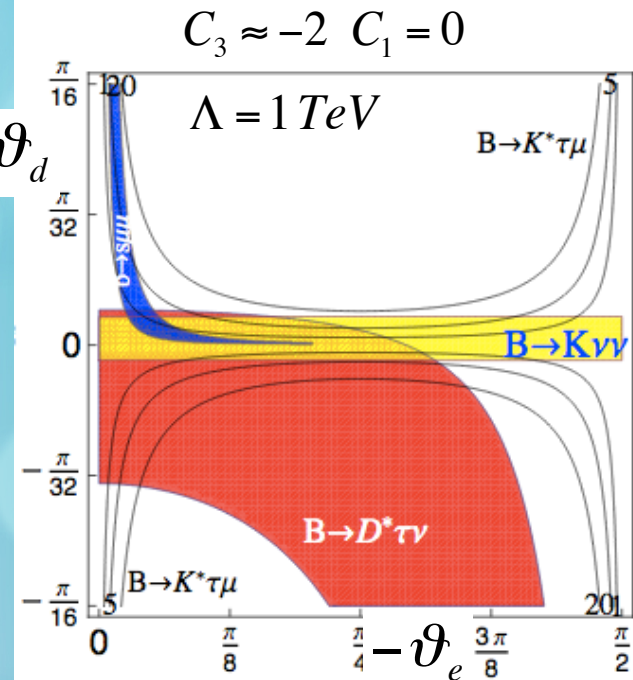both $R_{K(*)}$ and $R_{D(*)}$ can be explained

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

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

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

$C_3 \approx -2 \quad C_1 = 0$

$\Lambda = 1\,TeV$

$-\vartheta_d$

B→K*τμ

B→Kνγ

B→D*τν

B→K*τμ

$-\vartheta_e$

Constraints (tree-level)

process	parameters	size	exp. bound
$R_K^{\mu/e}$ $R_{K^*}^{\mu/e}$	$(C_1 + C_3)\vartheta_d \vartheta_e^2$		
$R_D^{\tau/\ell}$ $R_{D^*}^{\tau/\ell}$	C_3		
$R_{B_s\mu\mu} = \dfrac{\mathcal{B}(B_s \to \mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B_s \to \mu\bar{\mu})_{\rm SM}}$	$(C_1 + C_3)\vartheta_d \vartheta_e^2$	$O(0.1)$	$\mathcal{B}(B_s \to \mu\bar{\mu})_{\rm exp} = 2.8^{+0.7}_{-0.6} \times 10^{-9}$ $\mathcal{B}(B_s \to \mu\bar{\mu})_{\rm SM} = 3.65(23) \times 10^{-9}$
$R_{B\tau\nu}^{\tau/\mu} = \dfrac{\mathcal{B}(B \to \tau\nu)_{\rm exp}/\mathcal{B}(B \to \tau\nu)_{\rm SM}}{\mathcal{B}(B \to \mu\nu)_{\rm exp}/\mathcal{B}(B \to \mu\nu)_{\rm SM}}$	C_3	$O(0.1)$	Belle II ?
$R_{K^{(*)}}^{\nu\nu} = \dfrac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}}$	$(C_1 - C_3)\vartheta_d$	$O(1)$	$R_{K^*}^{\nu\nu} < 4.4$ $R_K^{\nu\nu} < 4.3$
$\mathcal{B}(B \to K\tau\mu)$ $\mathcal{B}(B \to \tau^\pm\mu^\mp) \approx \mathcal{B}(B \to K\tau^\pm\mu^\mp),$ $\mathcal{B}(B \to K^*\tau^\pm\mu^\mp) \approx 2 \times \mathcal{B}(B \to K\tau^\pm\mu^\mp)$	[Glashow, Guadagnoli, Lane 1411.0565] $\left|(C_1 + C_3)\vartheta_d \vartheta_e\right|^2$	$O(10^{-6\div 7})$	$\mathcal{B}(B \to K\tau\mu) \leq 4.8 \times 10^{-5}$
$\mu^+\mu^-$ and $\tau^+\tau^-$ Production at LHC	$(C_1 + C_3)$		[Greljo, Marzocca 1704.09015]

$$\frac{1}{\Lambda^2}(C_1 + C_3)\overline{b_L}\gamma^\mu b_L \,\overline{\tau_L}\,\gamma^\mu \tau_L$$

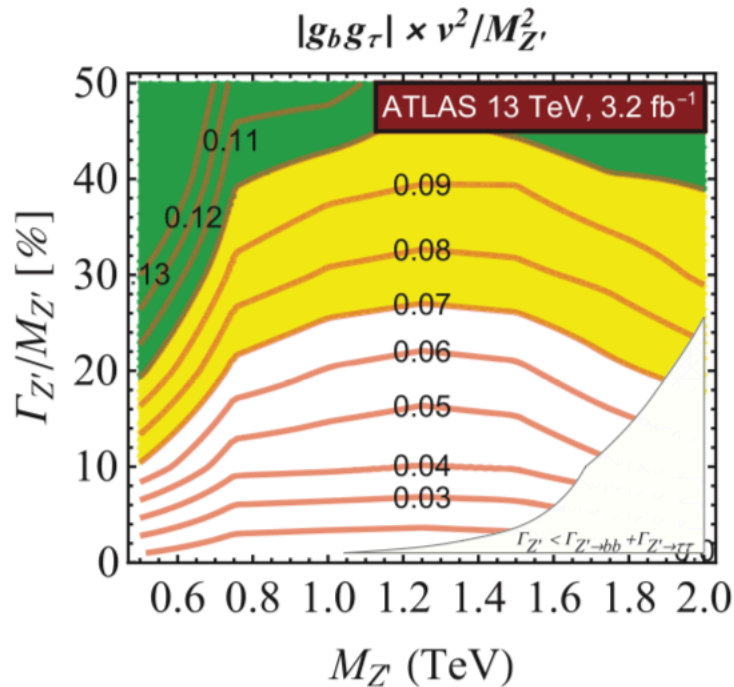⟹ enhancement expected in τ⁺ τ⁻ production at high p_T through $b\bar{b} \to \tau^+\tau^-$

signals depend on the mediator type

colorless mediator: Z'
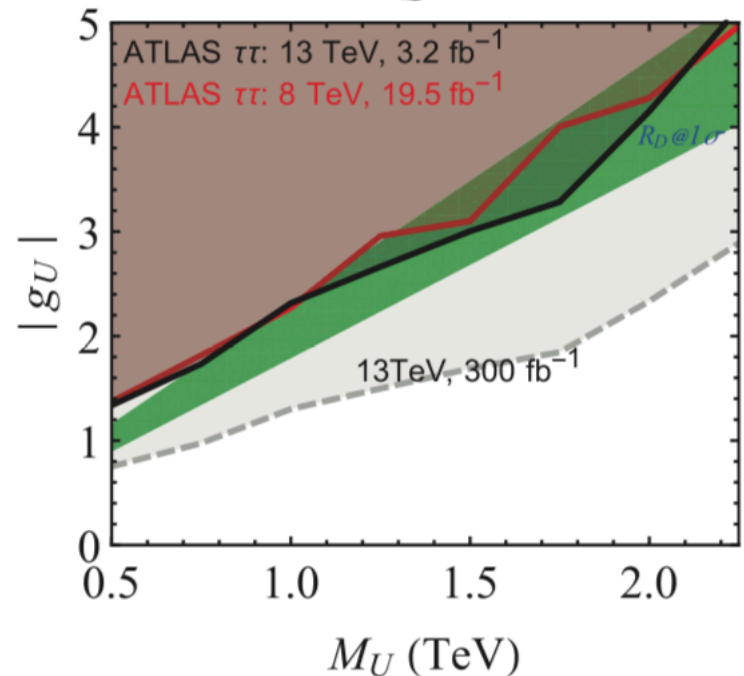
$\hat{s}$-channel resonance
dependence on resonance
width

[Faroughy, Greljo, Kamenik 1609.07138]

colorful mediator: LQ

$\hat{t}/\hat{u}$-exchange
no width dependence

Constraints from quantum effects

[F.F., P. Paradisi and A. Pattori 1606.00524 and 1705.00929]

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

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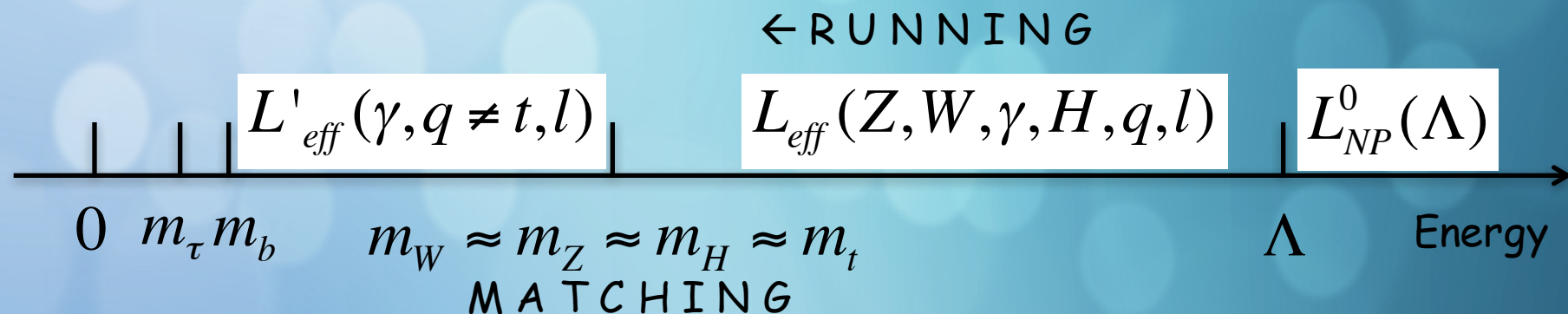
➡ their order of magnitude is similar to accuracy in EWPT and in other tests of LFU

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

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

$\leftarrow$ R U N N I N G

$$L'_{eff}(\gamma, q \neq t, l) \qquad L_{eff}(Z, W, \gamma, H, q, l) \qquad L_{NP}^0(\Lambda)$$

$$0 \quad m_\tau m_b \qquad m_W \approx m_Z \approx m_H \approx m_t \qquad \Lambda \qquad \text{Energy}$$

M A T C H I N G

1st: the electroweak scale

←R U N N I N G

$$L_{eff}(\gamma, q \neq t, l) \qquad L_{eff}(Z, W, \gamma, H, q, l)$$

Energy

$$0 \quad m_\tau \, m_b \qquad m_W \approx m_Z \approx m_H \approx m_t \qquad \Lambda$$
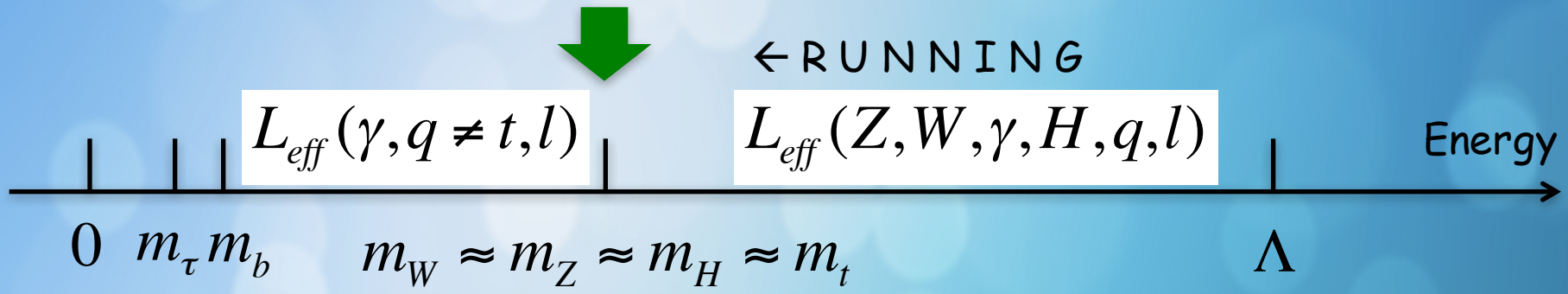
1. modifications of the W,Z couplings to fermions by non-universal terms

Z

t

ℓ_{iL} $\qquad$ ℓ_{jL}

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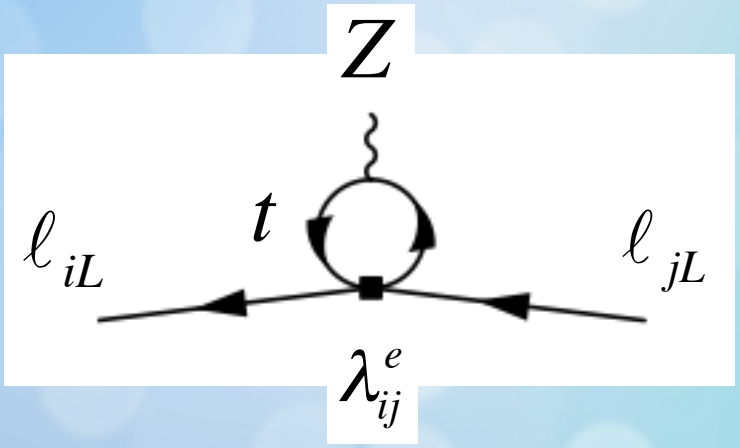
$$\frac{a_\tau}{a_e} \approx 1 - 0.004 \, \frac{(C_1 - 0.8\, C_3)}{\Lambda^2 (\mathrm{TeV}^2)}$$

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

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

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

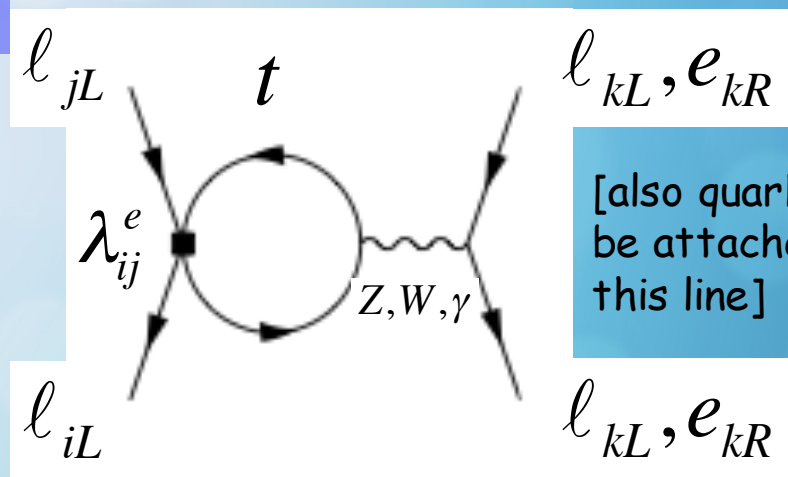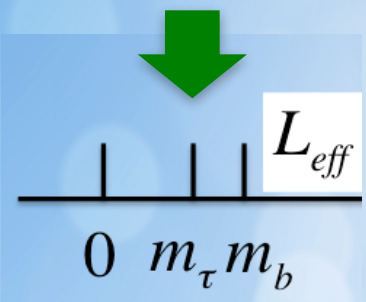$$N_\nu \approx 3 + 0.008 \, \frac{(C_1 + 0.8\, C_3)}{\Lambda^2 (\mathrm{TeV}^2)}$$

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

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

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

2nd: m_τ

L_{eff}

$0 \quad m_\tau m_b$

ℓ_{jL} t ℓ_{kL}, e_{kR}

λ^e_{ij} Z, W, γ

ℓ_{iL} ℓ_{kL}, e_{kR}

[also quarks can be attached to this line]

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

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

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

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

[A.Pich, 1310.7922]

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

$$\approx 5 \times 10^{-8} \frac{(C_1 - C_3)^2}{\Lambda^4(\mathrm{TeV}^4)} \left(\frac{\vartheta_e}{0.3}\right)^2$$

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

[HFAG, 1412.7515]

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

$$\approx 5 \times 10^{-8} \frac{(C_1 - 1.3\, C_3)^2}{\Lambda^4(\mathrm{TeV}^4)} \left(\frac{\vartheta_e}{0.3}\right)^2$$

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

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

$$\approx 8 \times 10^{-8} \frac{(C_1 - C_3)^2}{\Lambda^4(\mathrm{TeV}^4)} \left(\frac{\vartheta_e}{0.3}\right)^2$$

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

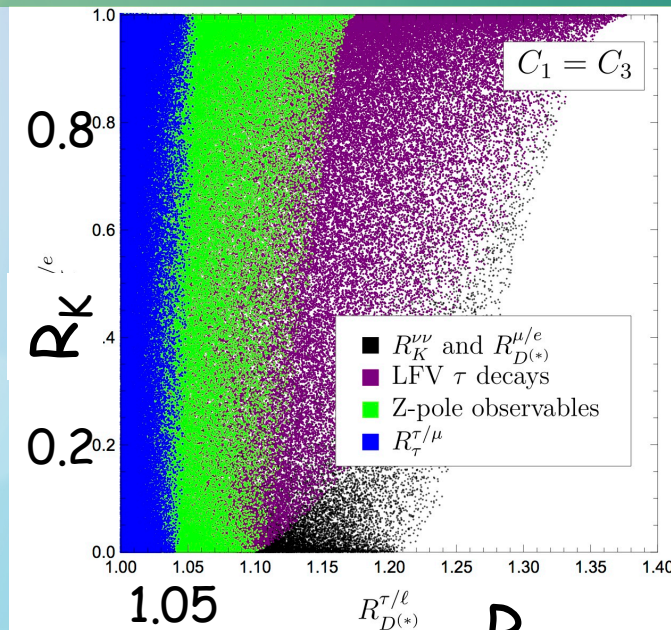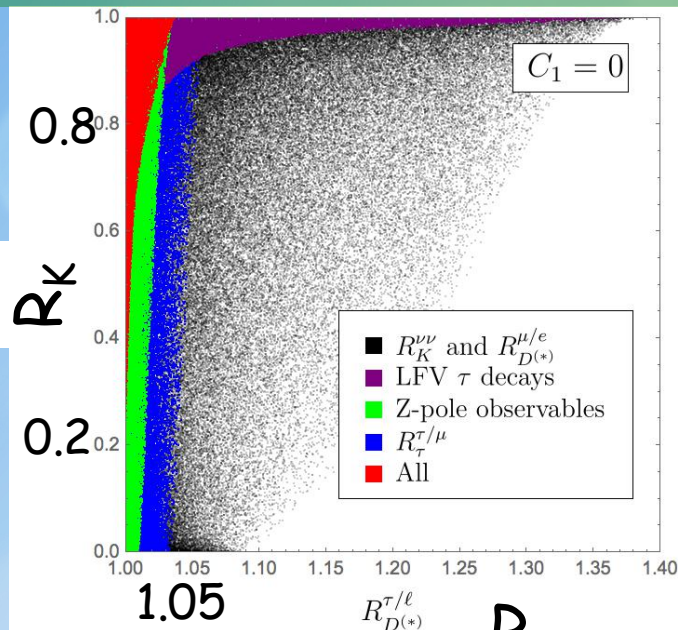[HFAG, 1412.7515]

Putting everything together

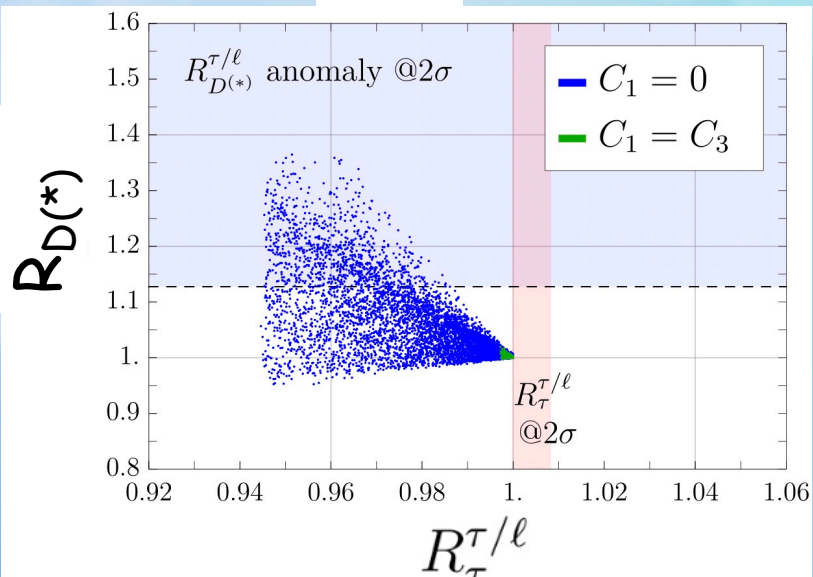$$\left| \frac{C_{1,3}}{\Lambda^2} \right| \leq 4\, TeV^{-2}$$
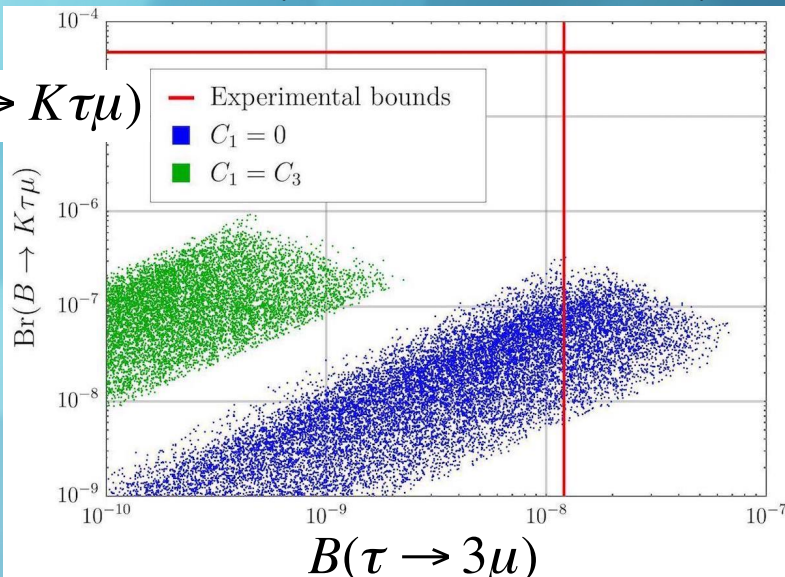
$$\left| \vartheta_{d,e} \right| \leq 0.5$$

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

LFV better probed in tau decays

$B(B \to K\tau\mu)$

A more general setup

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

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

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

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

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

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

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

constraints from Z pole
and $\tau \to 3\mu$ less severe
but simultaneous explanation
of both CC and NC anomalies
still prevented by $R_\tau^{\tau/\ell}$
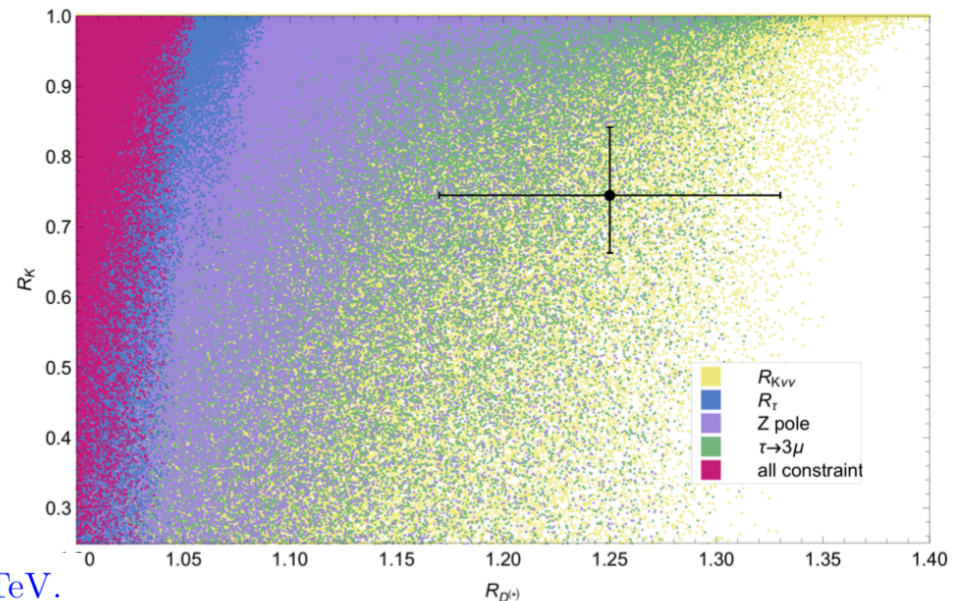
$C_{1-6} \in \{-3, 3\}$, $\lambda_{23}^{d,e}$ and $\Gamma_{23}^{d,e} \in \{-0.3, 0.3\}$, and $\Lambda = 1\,\text{TeV}$.

scalar and tensor operators

$$[\mathcal{O}_{\ell eqd}]_{prst} = (\overline{L'_p}^a e'_{rR})(\overline{d'_{sR}} Q'^a_t),$$

$$[\mathcal{O}^{(1)}_{\ell equ}]_{prst} = (\overline{L'_p}^a e'_{rR})\varepsilon_{ab}(\overline{Q'_s}^b u'_{tR}),$$

$$[\mathcal{O}^{(3)}_{\ell equ}]_{prst} = (\overline{L'_p}^a \sigma_{\mu\nu} e'_{rR})\varepsilon_{ab}(\overline{Q'_s}^b \sigma^{\mu\nu} u'_{Rt}).$$

disfavoured by bounds on B_c^- lifetime

[Alonso, Grinstein, Camalich 1611.06676]

can only contribute to CC anomaly

solutions by a weighted combination

excluded by new Belle data
[Straub talk, GGI 1.10.2018]

$F_L(B \to D^* \tau \nu) = 0.60 \pm 0.08 \pm 0.03$
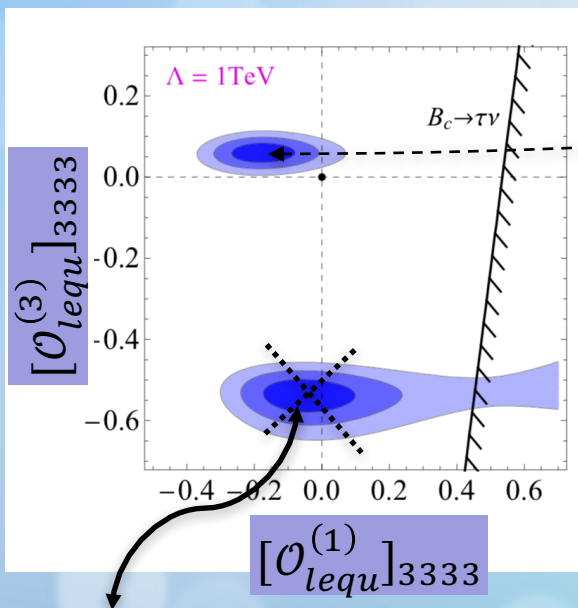
[CKM 2018]
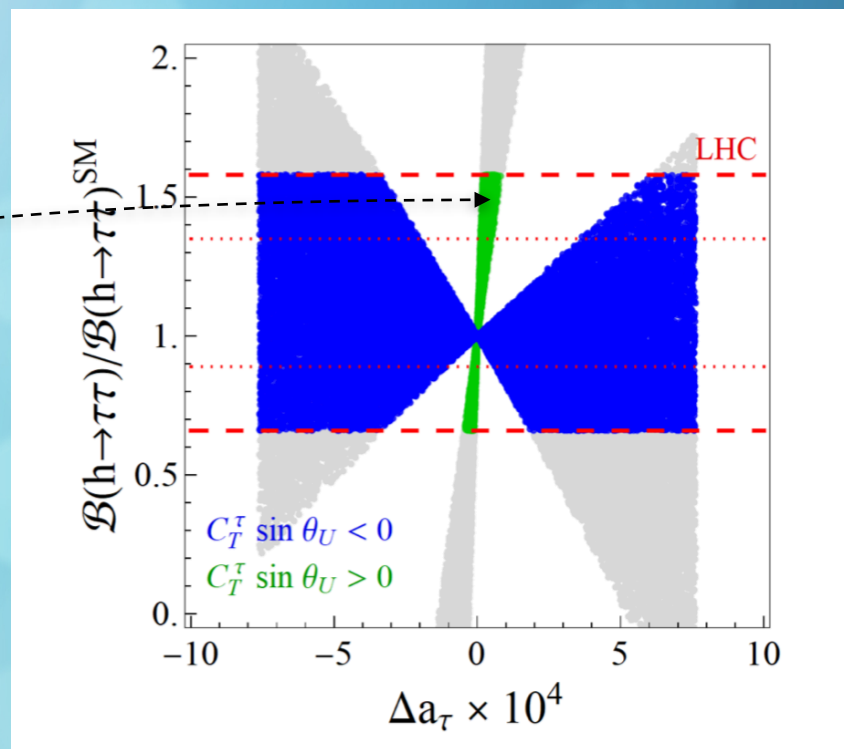
chirally enhanced (m_t/m_τ) contributions to $h \to \tau\tau$ and $(g-2)_\tau$ from EW RGE effects [FPS, 1806.10155]

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

   e.g. $\vartheta_d \approx 1$, $\vartheta_e \approx 1$, $\Lambda \approx 30$ TeV ➡ loop effects decouple as v^2/Λ^2

Discussion

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

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

  - $O_{lq}^{(1,3)}$ operators with $C_1=+C_3$ if $g_{ql}^L \neq 0$ $\quad$ $g_{ql}^R = 0$
  - 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

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

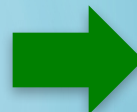 e.g. $\vartheta_d \approx 1$, $\vartheta_e \ll \alpha_{em}$, $\Lambda \approx 5$ TeV $\quad$ ➡ $\quad$ loop effects decouple as v^2/Λ^2

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

  e.g. $\vartheta_d \approx 1$, $\vartheta_e \approx 1$, $\Lambda \approx 30$ TeV $\quad$ ➡ $\quad$ loop effects decouple as v^2/Λ^2

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

- colliders bound strongly restricts consistent explanations
  due to the enhancement expected in $\tau^+ \tau^-$ production

- 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

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

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

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

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

NC anomaly and Z'

$$\mathcal{L} \supset - Z'_\alpha \left[g_{bb}^L \, \bar{b}\gamma^\alpha P_L b + g_{bs}^L \left(\bar{b}\gamma^\alpha P_L s + \bar{s}\gamma^\alpha P_L b \right) \right.$$
$$\left. + g_{\mu\mu}^L \left(\bar{\mu}\gamma^\alpha P_L \mu + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu \right) + g_{\mu\mu}^R \, \bar{\mu}\gamma^\alpha P_R \mu \right]$$

$$C_9^{\mathrm{NP}} = \frac{g_{bs}^L \, g_{\mu\mu}^V}{\mathcal{N} m_{Z'}^2}, \quad C_{10}^{\mathrm{NP}} = \frac{g_{bs}^L \, g_{\mu\mu}^A}{\mathcal{N} m_{Z'}^2},$$

$m_{Z'}$ = 500 GeV

- C_9^{NP} = −1.11 (blue dashed)
- B_s mixing (black dotted)
- Muon g−2 (yellow)
- Neutrino Trident (red)
- LFU in Z decays (red dashed)
- $B \to K^{(*)}\nu\nu$ (cyan)

strongest bound from

Δm_{B_s}

$$\frac{M_{12}}{M_{12}^{\mathrm{SM}}} = 1 + \frac{\left(g_{bs}^L\right)^2}{m_{Z'}^2} \left(\frac{g_2^2}{16\pi^2 v^2} (V_{tb}V_{ts}^*)^2 S_0 \right)^{-1}$$

trident production

The ratio between the total $\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$ cross section and its SM prediction is given by [31]

$$\frac{\sigma}{\sigma^{\mathrm{SM}}} = \frac{1 + \left[1 + 4s_W^2 + 2(g_{\mu\mu}^V)^2 \frac{v^2}{m_{Z'}^2} \right]^2}{1 + (1 + 4s_W^2)^2}, \quad (14)$$
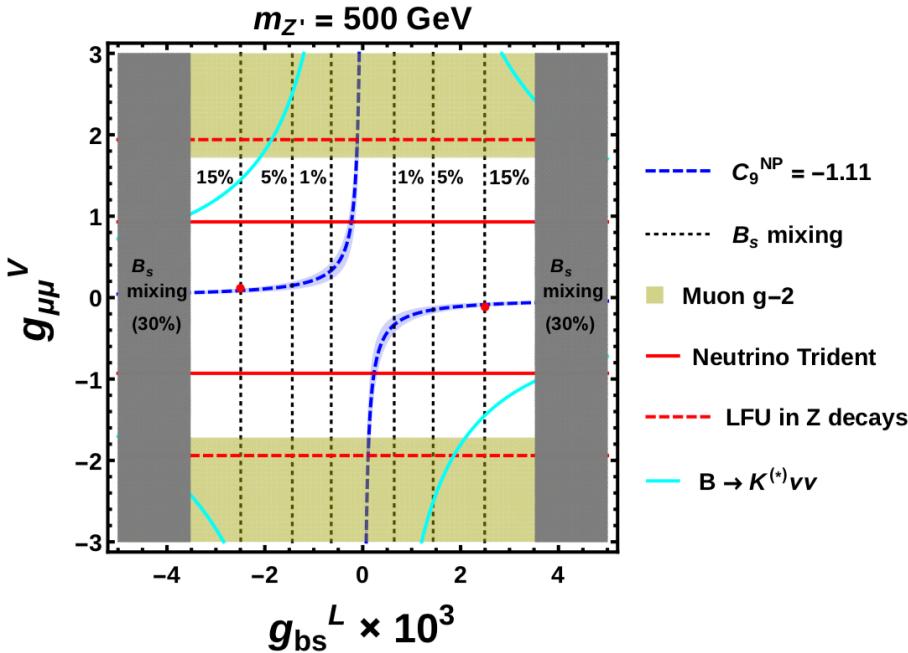
Kohda, Modak, Soffer 1803.07492

$\sigma(pp \to Z' + X)B(Z' \to \mu^+\mu^-) < 9 \, fb \quad (95\% \, CL)$
ATLAS $\quad 36 \, fb^{-1} \quad 13 \, TeV$

$$\sqrt{|g_{bs}^L|^2 + 0.21|g_{bb}^L|^2} < 0.011 \quad (m_{Z'} = 500 \text{ GeV})$$

➡ **non-universal Z' can explain NC anomaly**

NC +CC anomalies and Z'+W'

additional couplings needed

CC anomaly ➡ $$(V_{cs}g_{bs} + V_{cb}g_{bb})g_{\tau\tau} \approx 0.1$$ $[M_{W'} = 1\,TeV]$

$g_{bs} < 0.001$ from Δm_{B_s}

g_{bb} small from collider bounds
    on dimuon production

$g_{\tau\tau} < 0.1$ from leptonic τ decays

$R_{D^{(*)}}$ can be only marginally modified

[Greljio, Isidori, Marzocca 1506.01705]
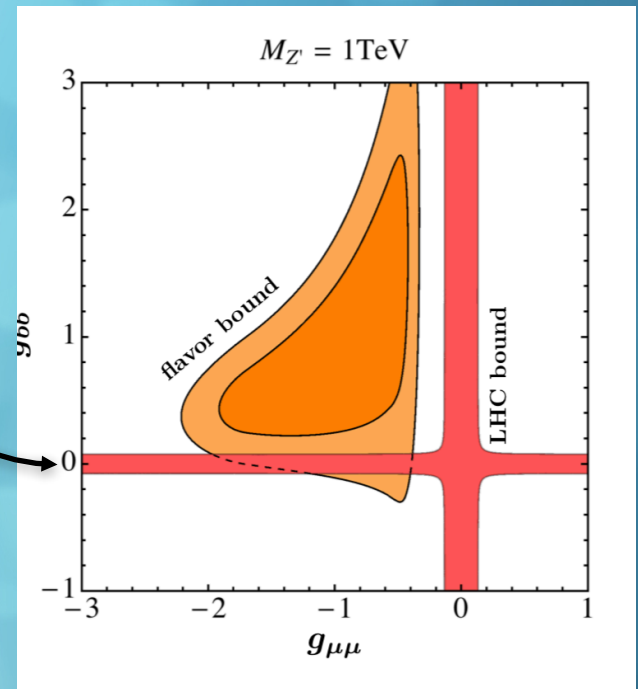
[Kumar, London, Watanabe 1806.07403]

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

[waiting to be confirm by
Fermilab Muon (g-2)]
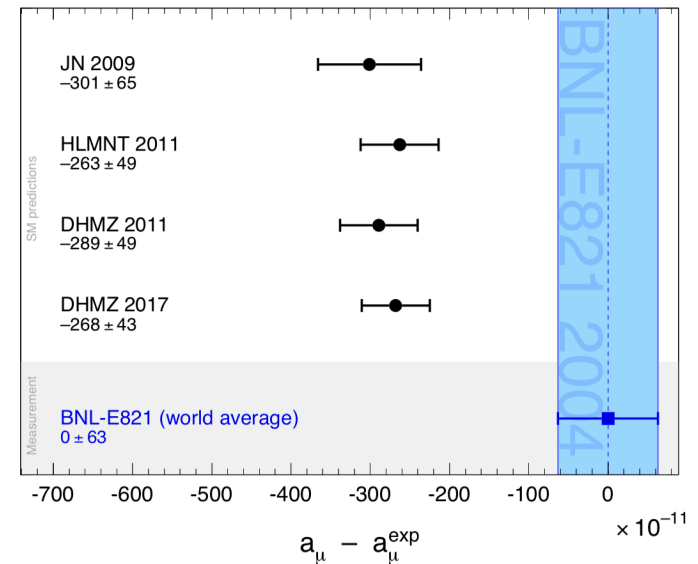
any violations
of 1. and/or 2. ➡ physics
beyond the SM

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

Global Fit

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

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

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

$$\Downarrow$$

$$\triangleright \; C_9^{NP} \neq 0$$

$$\triangleright \; \boxed{C_9^{NP} = -C_{10}^{NP} \neq 0}$$

$\Bigg\}$ good fits of: $\triangleright R_K$

$\triangleright P'_5$ (et al.)

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

$$\Downarrow$$

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

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
$C_9'^\mu$	-0.00	$[-0.26, +0.25]$	$[-0.52, +0.51]$	0.0σ
$C_{10}'^\mu$	$+0.02$	$[-0.22, +0.26]$	$[-0.45, +0.49]$	0.1σ
$C_9'^e$	$+0.01$	$[-0.27, +0.31]$	$[-0.55, +0.62]$	0.0σ
$C_{10}'^e$	-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]
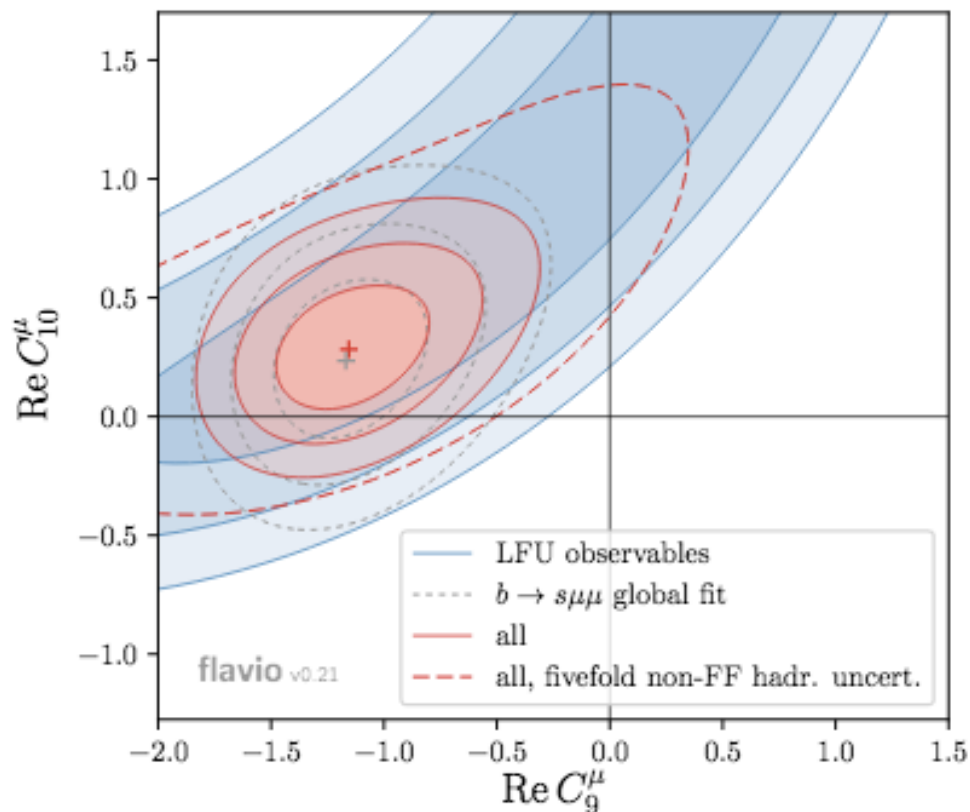
`All' includes R_K, R_{K*}, angular variables in B -> K^* μ^+ μ^- , differential BR in B -> K^* μ^+ μ^- , B -> φ μ^+ μ^-

Global Fit

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

directly correlated to

$$R_\tau^{\tau/\ell} \quad \text{and} \quad R_{D(*)}$$

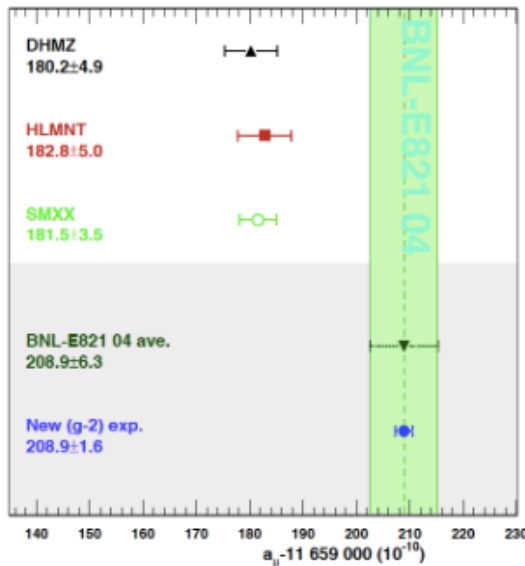forces $\delta R_{D^{(*)}}^{\tau/\ell}$ to be $\lesssim 0.02.$

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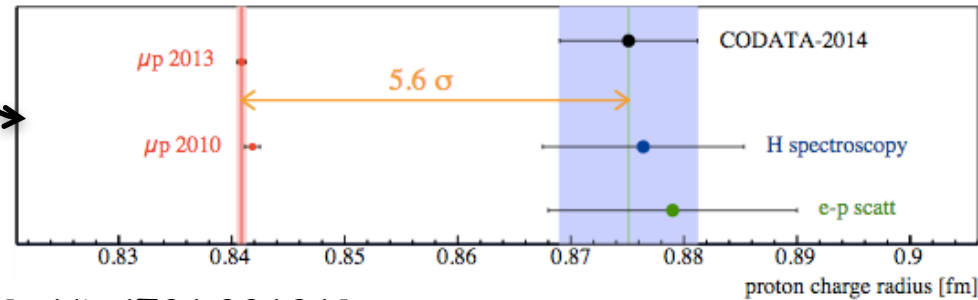
other hints of LFU violation

proton radius

e-µ universality

[arXiv:1706.00696]

muon (g-2)

τ-e and τ-µ universality

W leptonic decays

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

Discussion

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

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

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

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

  e.g. $\vartheta_d \approx 1, \vartheta_e \ll \alpha_{em}, \Lambda \approx 5$ TeV $\quad\Longrightarrow\quad$ loop effects decouple as v^2/Λ^2
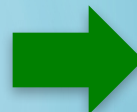
- $R_K^{\mu/e} \quad R_{K*}^{\mu/e}$ alone can be explained in present framework

  e.g. $\vartheta_d \approx 1, \vartheta_e \approx 1, \Lambda \approx 30$ TeV $\quad\Longrightarrow\quad$ loop effects decouple as v^2/Λ^2

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

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

$$R_2 = (3, 2, +7/6)$$

[not automatically p-decay free]

- contributions to dipole transitions can be chirally enhanced

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

[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]
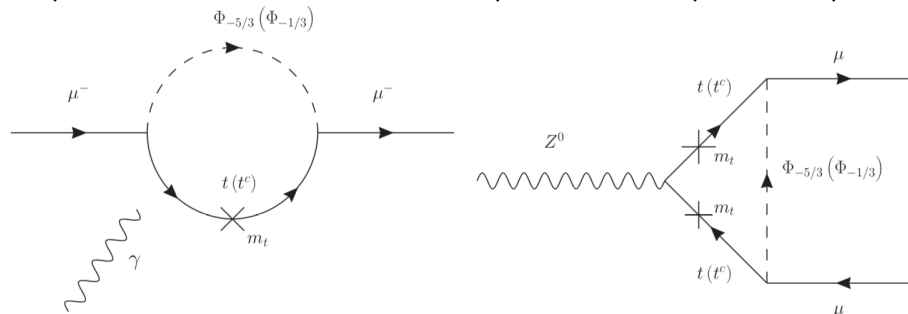
$$\delta BR(Z \to \ell^+\ell^-) \approx \frac{1}{16\pi^2}\frac{m_{top}^2}{M_{LQ}^2}\left|g_{t\ell}^L\right|^2$$

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
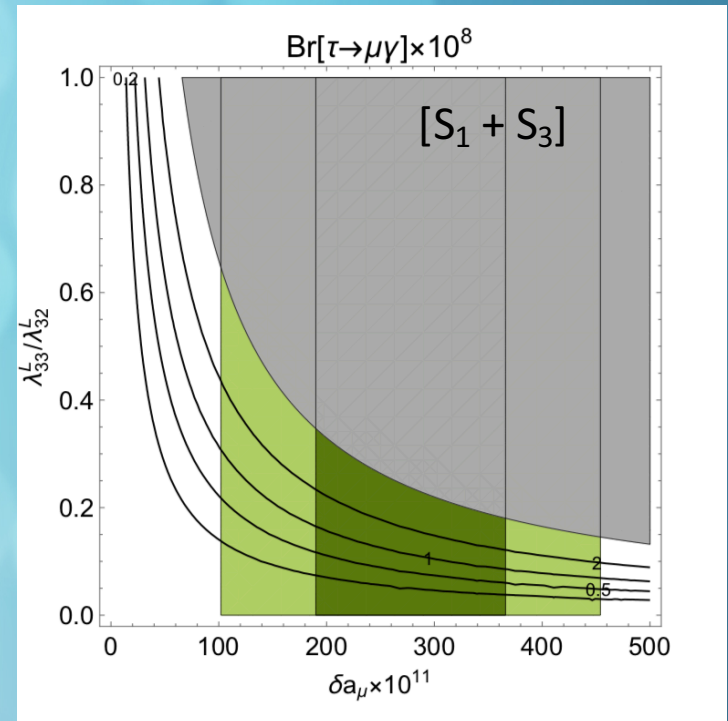Chauhan, Kindra,Narang, 1706.04598 R_2
Crivellin, Muller, Ota, 1703.09226 $S_1 + S_3$
...

if LQ couples mainly to top and 2nd lepton generation

$$\delta a_\mu \approx +3 \times 10^{-9}$$

$$\delta BR(Z \to \mu^+\mu^-) \approx 10^{-4}$$

If LQ couples also to top and 3rd lepton generation

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

$$BR(Z \to \tau^\pm\mu^\mp) \approx \frac{10^{-8}(g_{33}^L g_{32}^L)^2}{M_{LQ}^4 (TeV)}$$

[Crivellin, Muller, Ota, 1703.09226]