Lepton Flavour Universality

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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
- F.F., P. Paradisi, O. Sumensari 1806.10155

Plan

- Lepton Flavour Universality: an Introduction

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

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

Lepton Flavour Universality in the SM

- $\mathcal{L} = \mathcal{L}_{SM} + \delta\mathcal{L}_\nu$

$$\mathcal{L}_{SM} = -\frac{1}{4}FF + i\bar{\psi}\gamma^\mu D_\mu\psi$$ gauge

$$-(D_\mu\varphi)^\dagger D^\mu\varphi - V(\varphi^\dagger\varphi)$$ symmetry breaking

$$-\bar{\psi}\mathcal{Y}\varphi\psi + h.c.$$ flavour

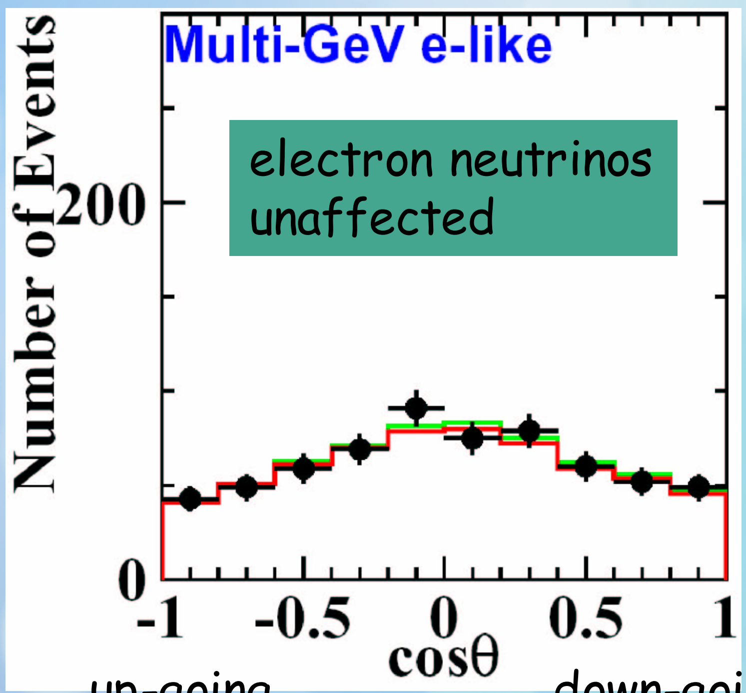
- set $\mathcal{Y} = 0$ and $\delta\mathcal{L}_\nu = 0$ to get $\mathcal{L}^0_{SM}$ → lepton interactions are fully described by g, g'

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

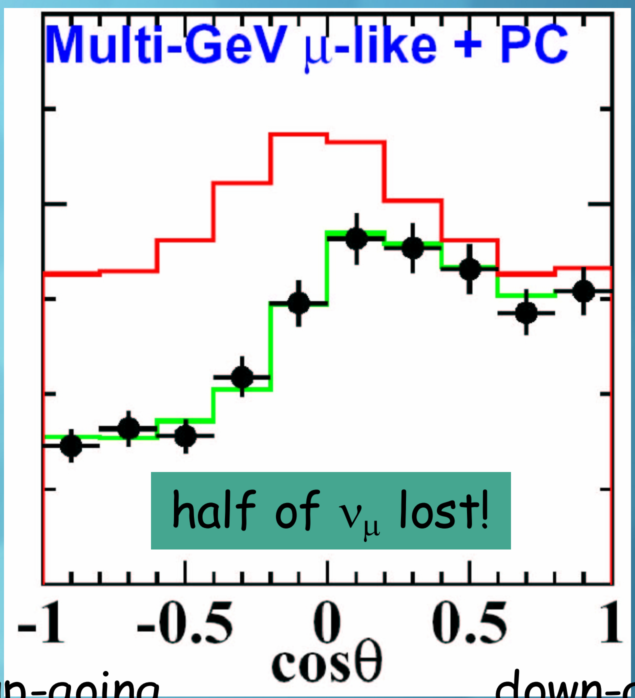
$\mathcal{L}^0_{SM}$ invariant under $\underbrace{SU(3)}_{\ell_L} \times \underbrace{SU(3)}_{e_R} \times \cdots$

of course, LFU is largely broken by $\mathcal{L}_Y + \delta\mathcal{L}_\nu$ in the real world

e.g. in neutrino oscillations



up-going down-going



up-going down-going

for the processes discussed here,
to an excellent approximation

$m_\nu = 0$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L \gamma^\mu \underbrace{U_{PMNS} \nu_L}_{\nu_L'} + h.c.$$

ν_L' and ν_L are equivalent when $m_\nu = 0$

effectively, $U_{PMNS} = 1$

two theorems in this limit

1. no LFV in charged lepton transitions
2. LFU violation 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) ($\lvert c\rvert = 1$)	
6.3×10^4	$\mu \to e\gamma$
6.5×10^2	$\tau \to e\gamma$
6.1×10^2	$\tau \to \mu\gamma$

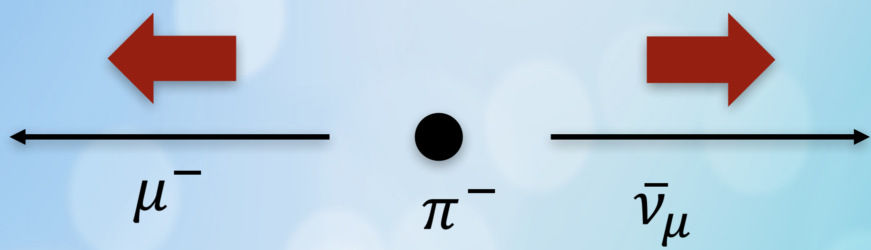
Λ_{NP} (TeV) ($\lvert c\rvert = 1$)	
207	$\mu \to 3e$
10.4	$\tau \to 3e$
11.3	$\tau \to 3\mu$
174	$\mu \to 3e$

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

an example: charged pion decay

$\pi^- \to e^- \bar{\nu}_e$ and $\pi^- \to \mu^- \bar{\nu}_\mu$ have very different rates

CC interaction is V-A: only left-handed electrons and muons are involved



angular momentum conservation requires helicity > 0 for electrons and muons

$$e_L = e(h = -1/2) + \frac{m_e}{E} e(h = +1/2) \qquad \mathcal{A}(\pi^- \to e^- \bar{\nu}_e) \propto f_\pi \frac{m_e}{m_\pi}$$

radiative corrections

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_e)} = \frac{m_e^2}{m_\mu^2} \frac{\left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} (1 + \cdots) = 1.235 \times 10^{-4}$$

hadronic uncertainty cancel in the ratio

cfr. Exp $= (1.230 \pm 0.004) \times 10^{-4}$

allowing for different couplings of W to e, μ

$$g_\mu / g_e = 1.0021 \pm 0.0016$$

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

introduce different couplings of W to e, μ and τ $g_e \quad g_\mu \quad g_\tau$

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

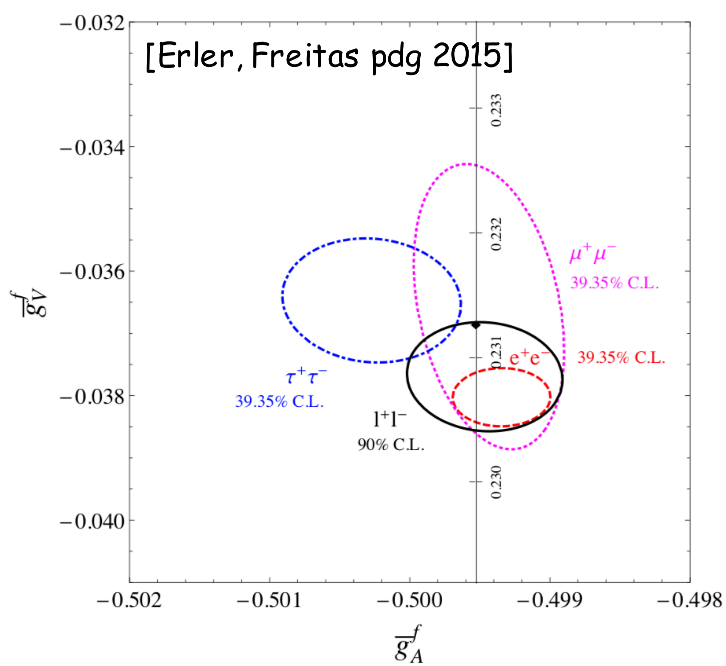
[A.Pich, 1310.7922]

Z couplings to charged leptons

E≈100 GeV

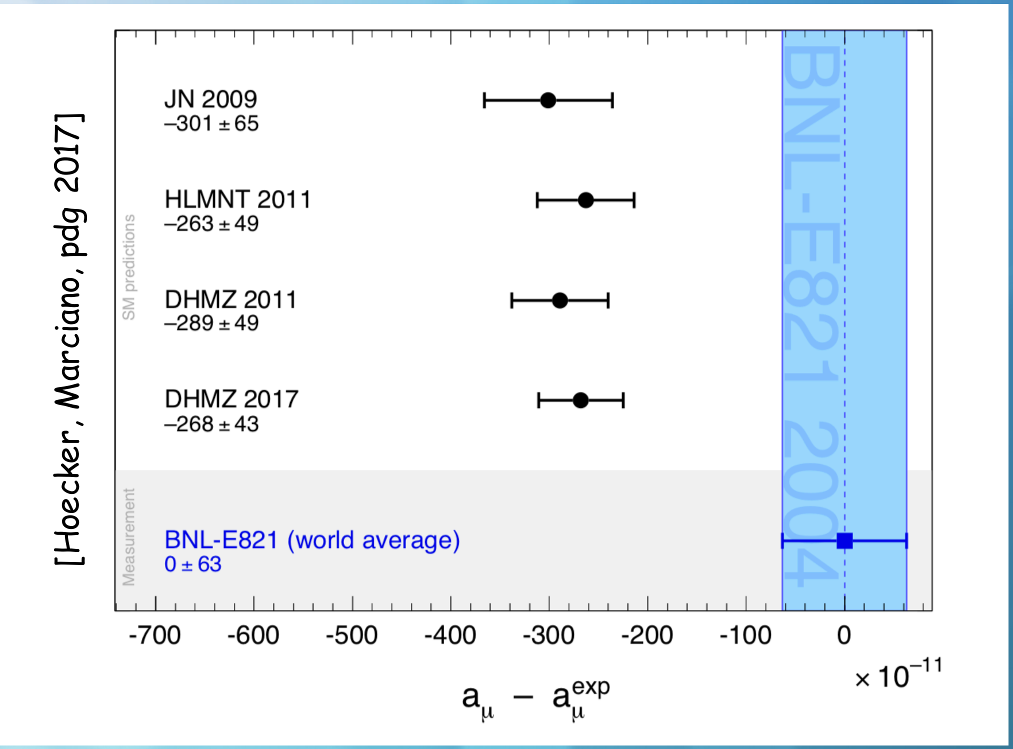
$$a_\tau/a_e = 1.0019\ (15)$$

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



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

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



troubles at the horizon for the electron (g-2) ?

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

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = [-87 \pm 28\,(\mathrm{exp}) \pm 23\,(\alpha) \pm 2\,(\mathrm{theory})] \times 10^{-14},$$

[H.Davoudiasl and W.Marciano 1806.10252]

any violations of 1. and/or 2. → physics beyond the SM* [including the extension to accommodate neutrino masses]

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

Lesson: tests of LFU require
- precise measurements
- good control of theoretical uncertainties (hadronic, perturbation theory,...)

many tests of LFU in decays of pseudoscalar mesons, charged lepton, W and Z bosons

in this talk: semileptonic decays of B mesons like

BaBar
Belle
LHCb
Belle II

$$B \to D\,\ell\bar{\nu}$$
$$B \to D^*\,\ell\bar{\nu}$$

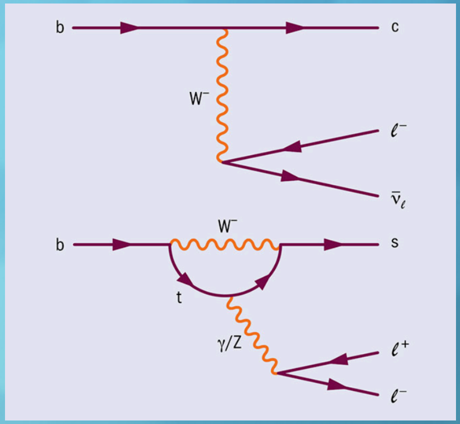
CC transitions $b \to c$

Tree-level

$$B \to K\,\ell\bar{\ell}$$
$$B \to K^*\ell\bar{\ell}$$

NC transitions $b \to s$

1-loop



Strategy:
- focus on ``safe quantities" to minimize SM uncertainties, e.g. ratios between reactions differing only in the LF
- small, residual uncertainties remain yet these ratios are believed to be well understood in the SM

What are data telling us?

Hints of violation of LFU in semileptonic B decays

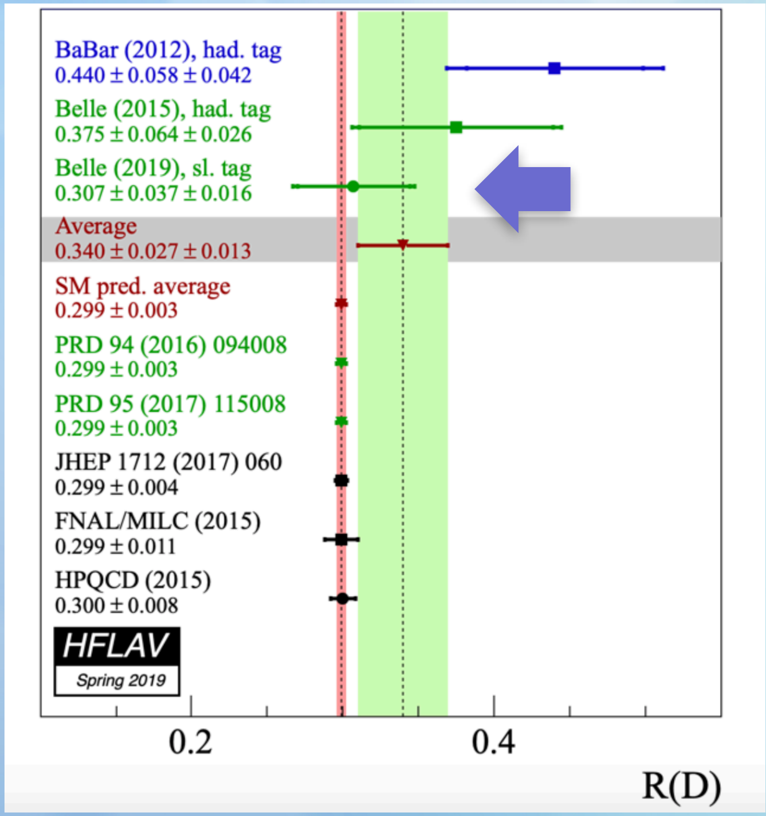
CC b -> c [tree-level in SM]

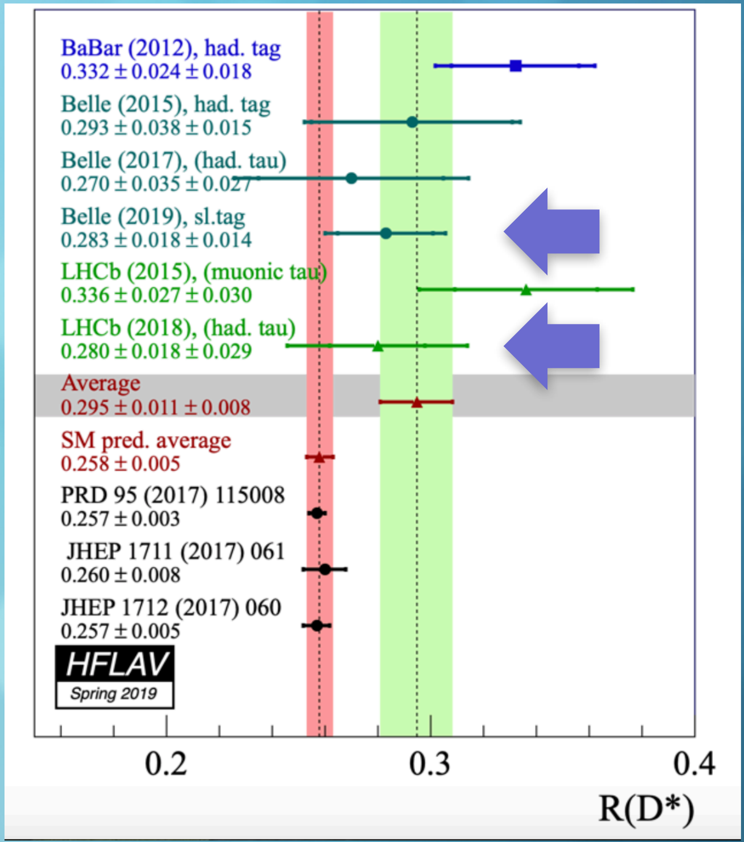
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

$\tau \leftrightarrow \mu/e$

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

[LHCb 2017]





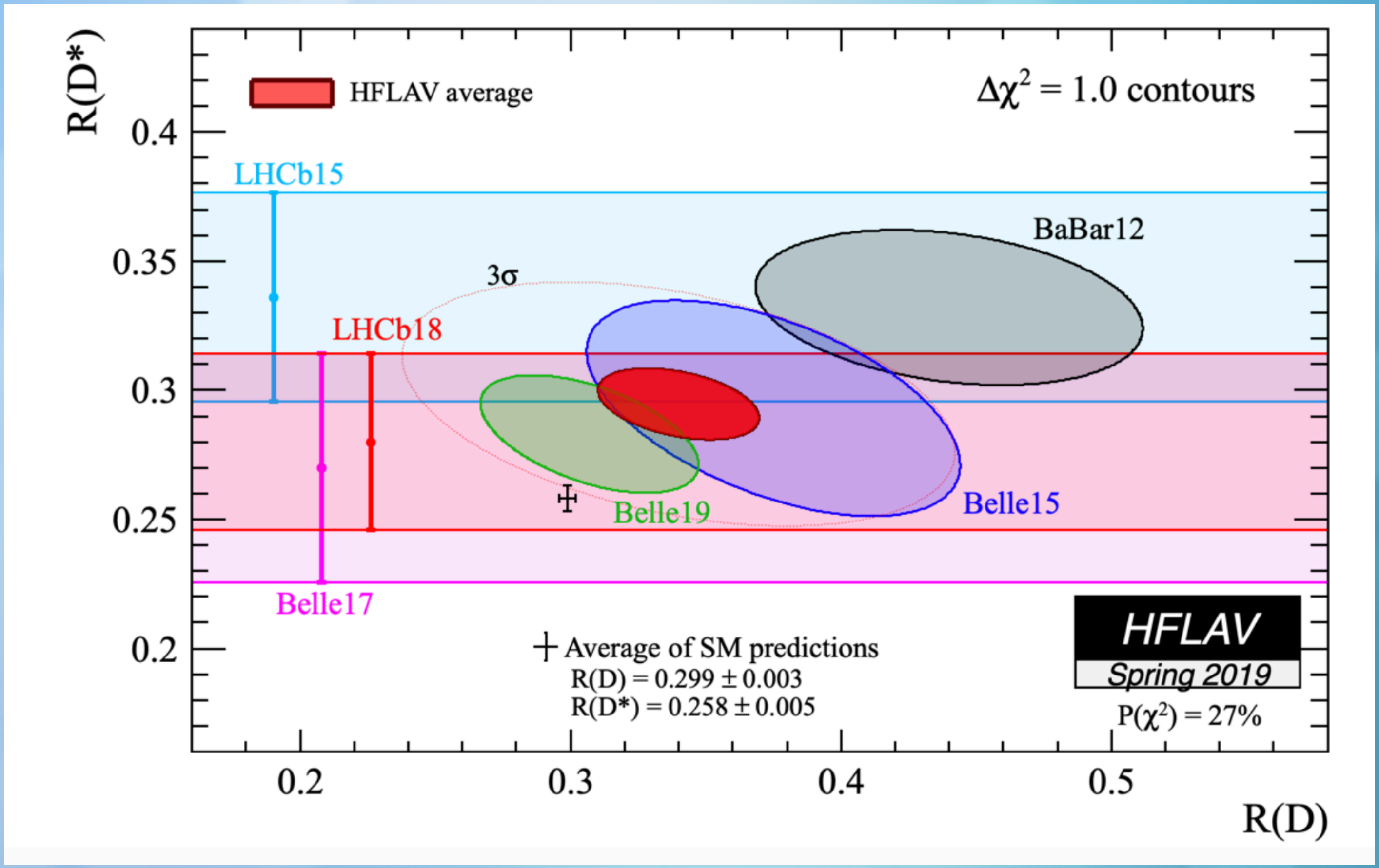
SM accuracy:
few percent

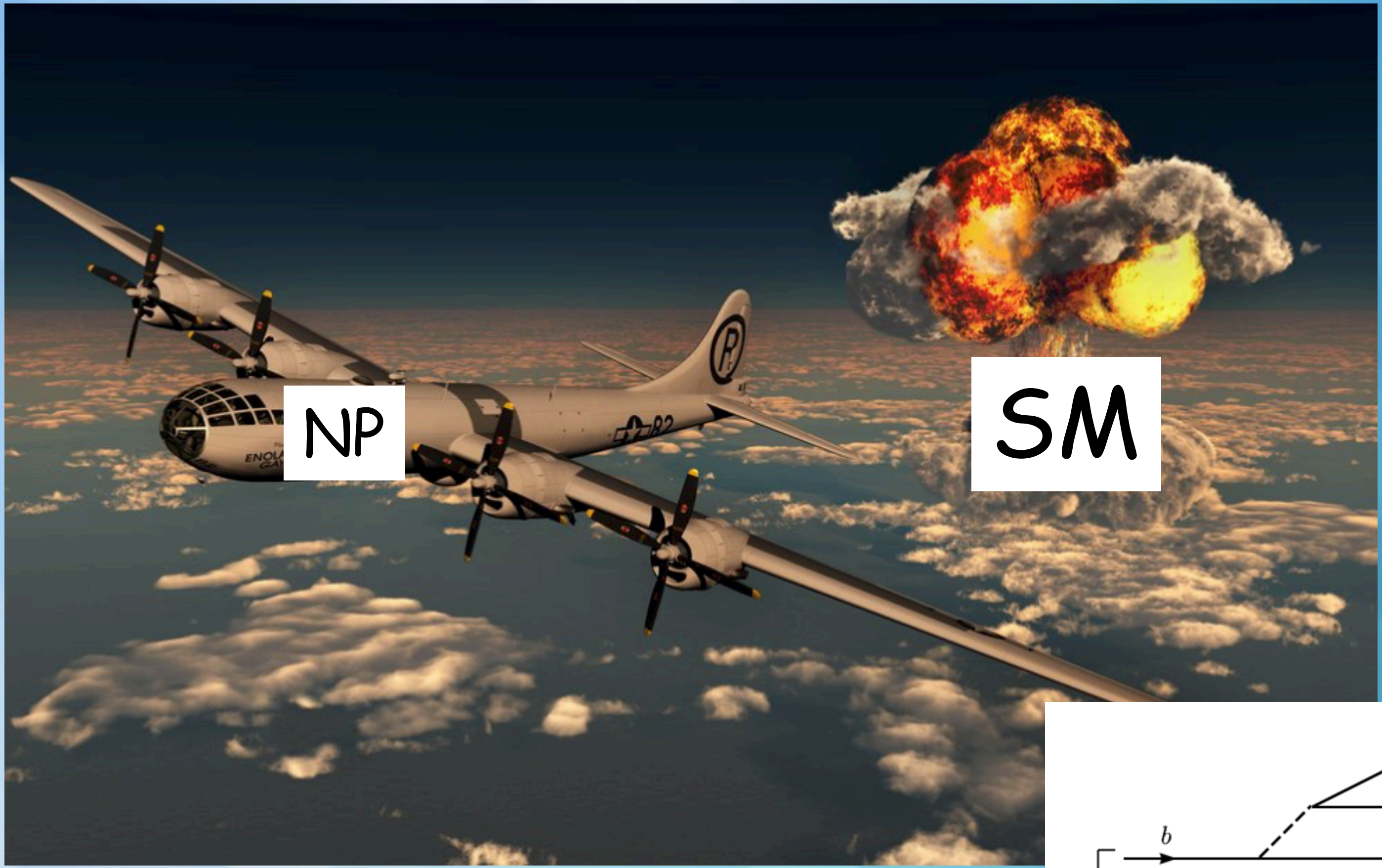
$$R_D^{\tau/\ell} = 0.300 \pm 0.008$$

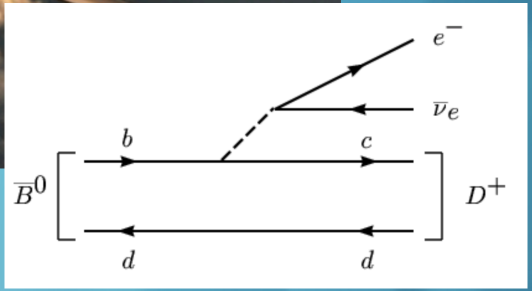
$$R_{D^*}^{\tau/\ell} = 0.260 \pm 0.008$$

$R_D^{\tau/\ell}$: 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

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

$\mu \leftrightarrow e$

[LHCb, 1705.05802
SM at 2.4-2.5σ]

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

$$R_{K}^{\mu/e} = \frac{\mathcal{B}(B \to K \mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K e\bar{e})_{\rm exp}}\bigg|_{q^2\in[1,6]\rm GeV} = 0.846\,^{+0.060+0.016}_{-0.054-0.014}$$

[LHCb, 1903.09252
SM at 2.5σ]

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

[Bordone, Isidori, Pattori, 1605.07633]

Which type of New Physics ?

CC

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{cb}}{\sqrt{2}}\Big[\Big(1+\epsilon_L\Big)\bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_L b + \epsilon_R \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_R b + \epsilon_T\,\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau \cdot \bar{c}\sigma^{\mu\nu}P_L b + \epsilon_{S_L}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_L b + \epsilon_{S_R}\bar{\tau}P_L\nu_\tau \cdot \bar{c}P_R b\Big] + \rm h.c.$$

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

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

disfavored by B_c
lifetime

[Alonso, Grinstein, Camalich 1611.06676]

simplest solution:

ϵ_L=0.07±0.02

[Shi, Geng, Grinstein, Jäger, Camalich, 1905.08498]

NC

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

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

[Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli 1903.09632
Alok, Dighe, Gaugal, Kumar 1903.09017
Aebisher, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub 1903.10434
Arbey, Hurth, Mahmoudi, Martinez Santos, Neshatpour 1904.08399
Kumar, Kowalska, Sessolo 1906.08596]

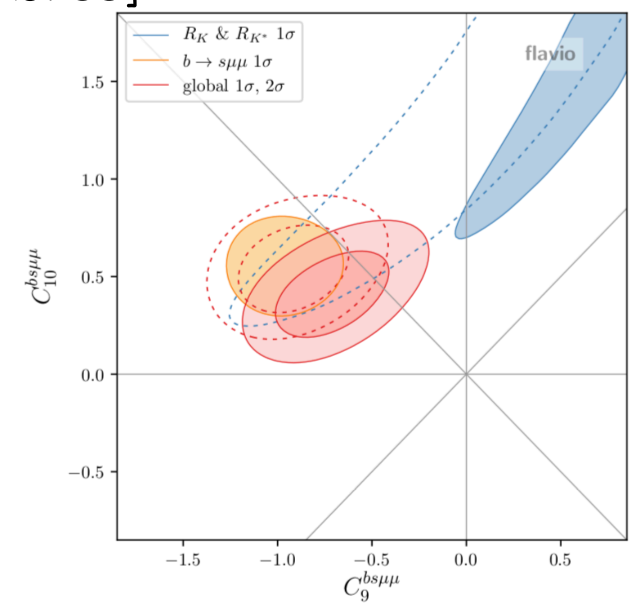
C coefficients from global fits to b -> s transitions,
including angular distributions and differential rates

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

[AAGRSS]

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10,\ -0.79]$	$[-1.26,\ -0.63]$	5.8σ
$C_9'^{bs\mu\mu}$	$+0.09$	$[-0.07,\ +0.24]$	$[-0.23,\ +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59,\ +0.87]$	$[+0.46,\ +1.01]$	5.6σ
$C_{10}'^{bs\mu\mu}$	-0.19	$[-0.30,\ -0.07]$	$[-0.41,\ +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05,\ +0.35]$	$[-0.09,\ +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62,\ -0.45]$	$[-0.70,\ -0.36]$	6.5σ

[AAGRSS]



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

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

[Aebisher, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub 1903.10434 = AAGRSS]

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?
- 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

$$-\frac{4G_F V_{cb}}{\sqrt{2}}\epsilon_L \left(\bar{c}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma^\mu \nu_{\tau L}\right) \qquad -\frac{8G_F V_{tb}V_{ts}^*}{\sqrt{2}}\frac{e^2}{16\pi^2}\, C \left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{\mu}_L\gamma^\mu \mu_L\right)$$

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

2. NP above the electroweak scale

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

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

$0 \quad m_\tau \, m_b \quad m_W \approx m_Z \approx m_H \approx m_t \quad \Lambda \quad$ Energy

3. NP dominantly affects the third generation

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

6 sub-leading operators

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

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

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

$b_L \xleftrightarrow{\vartheta_d} s_L$

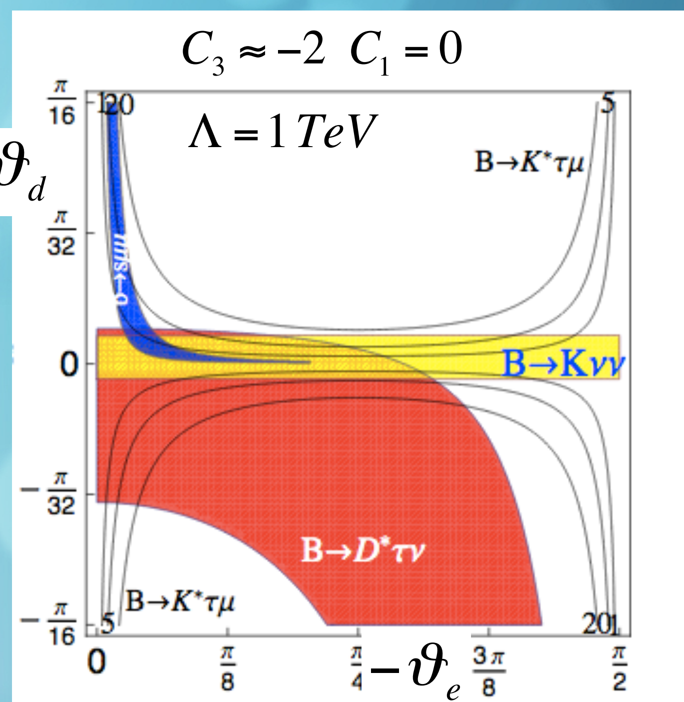
$\tau_L \xleftrightarrow{\vartheta_e} \mu_L$

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

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

(ϑ_d x ϑ_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

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

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

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

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

Colliders bounds

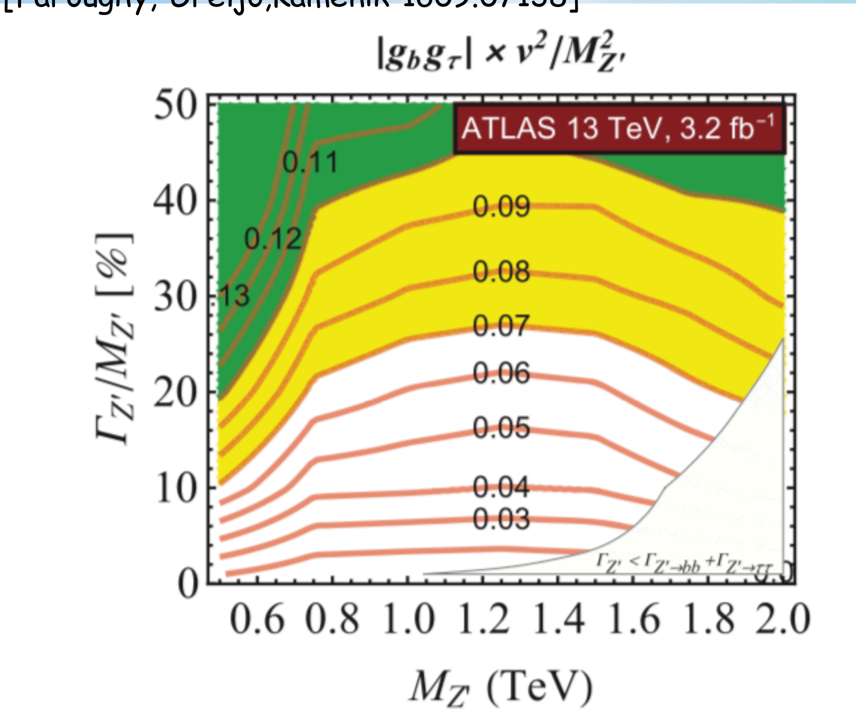
$\frac{1}{\Lambda^2}(C_1 + C_3)\overline{b_L}\gamma^\mu b_L\,\bar{\tau}_L\,\gamma^\mu\tau_L$ → enhancement expected in $\tau^+\tau^-$ production at high p_T through $b\bar{b} \to \tau^+\tau^-$

signals depend on the mediator type

colorless mediator: Z′

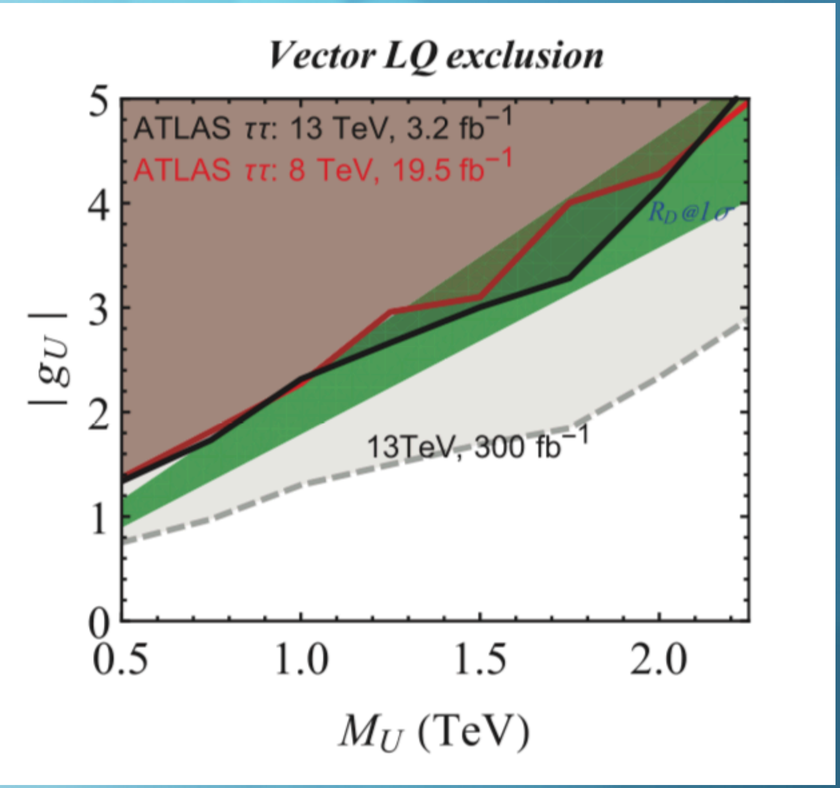
$\hat{s}$-channel resonance
dependence on resonance width

[Faroughy, Greljo,Kamenik 1609.07138]



colorful mediator: LQ

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

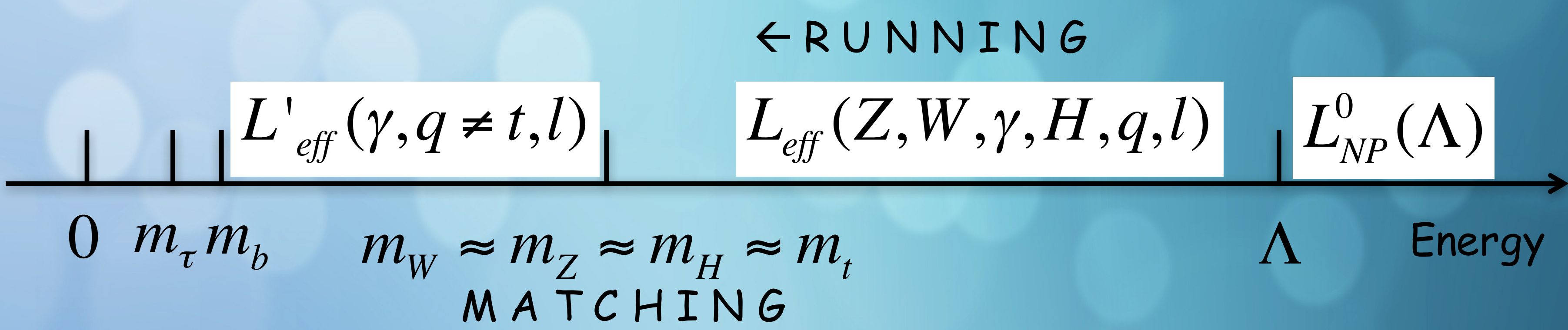


Constraints from quantum effects [FPP]

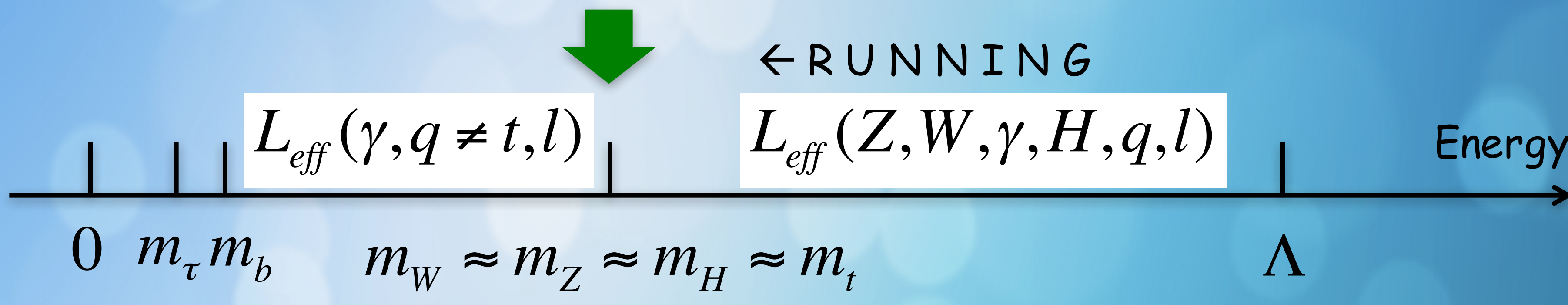
$$L_{NP}(m_b) = L_{NP}^0(\Lambda) + \text{quantum corrections}$$

- How can quantum corrections ~ $\alpha/4\pi$ ~ 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: $\log(\Lambda^2/m_W^2)$ ~ 5-7

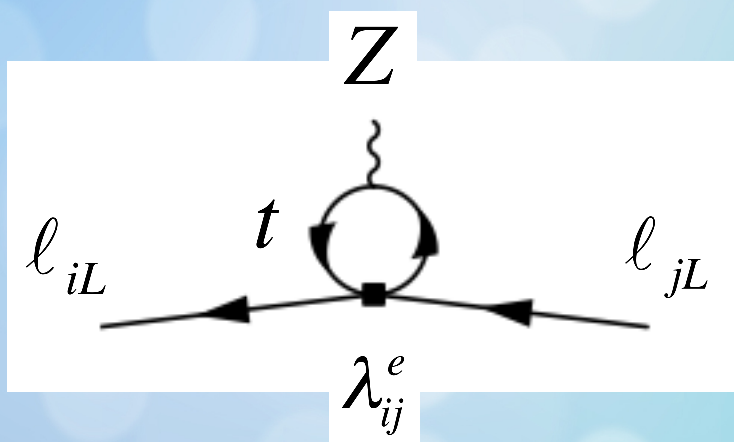
in the present framework - (V-A) semileptonic operators - corrections are dominated by electroweak interactions. They can be estimated by a well-known running and matching procedure. Here, Leading Log effects only



1st: the electroweak scale



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



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

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

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

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

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

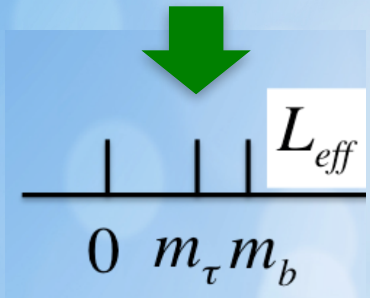
$$N_\nu = 2.9840 \pm 0.0082$$

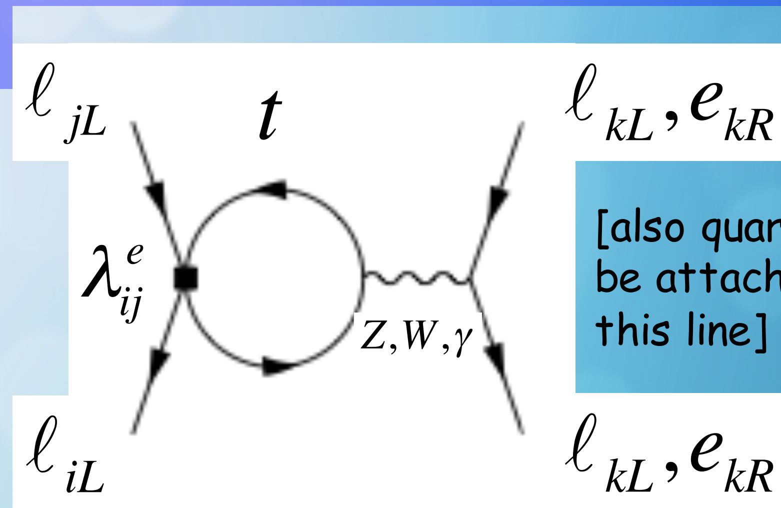
$$\mathcal{B}(Z \to \mu^\pm \tau^\mp) \approx 10^{-7}$$

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

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

2nd: m_τ

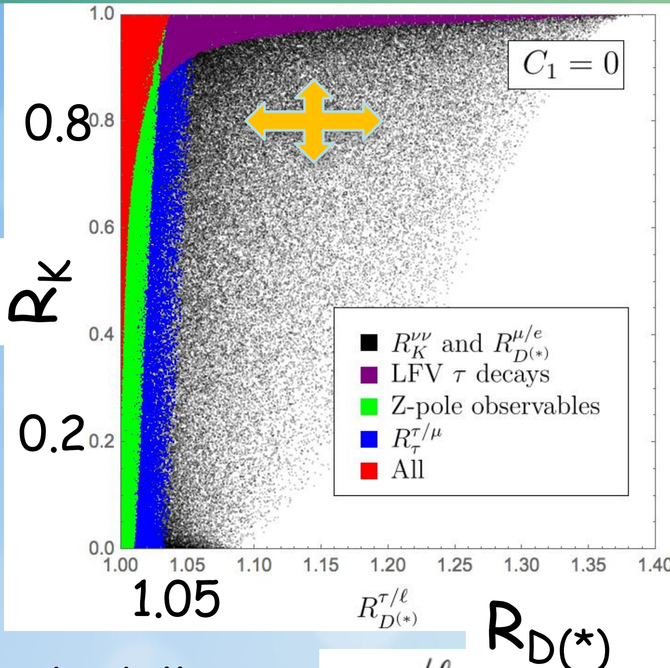


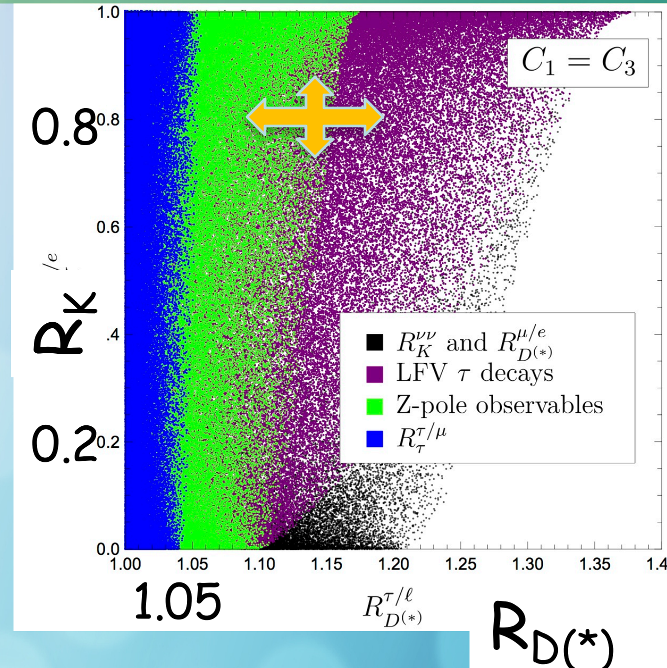


[also quarks can be attached to this line]

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

Putting everything together



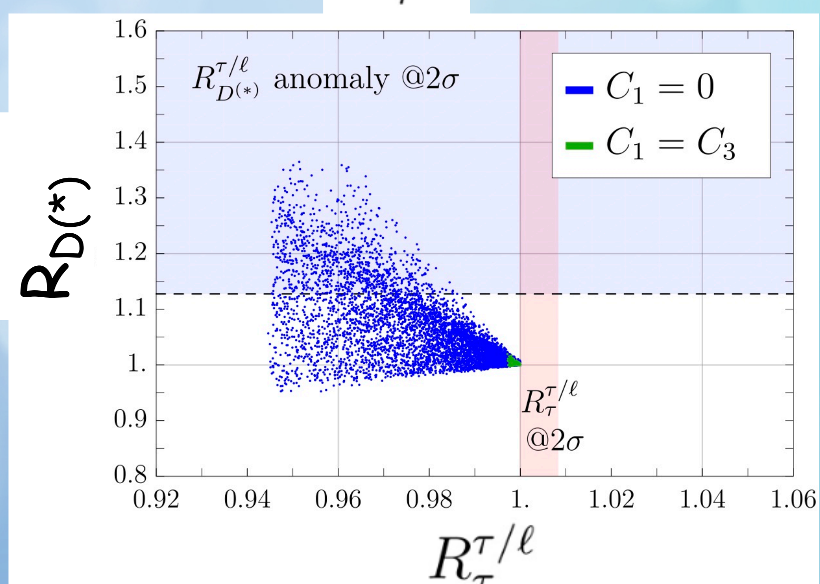


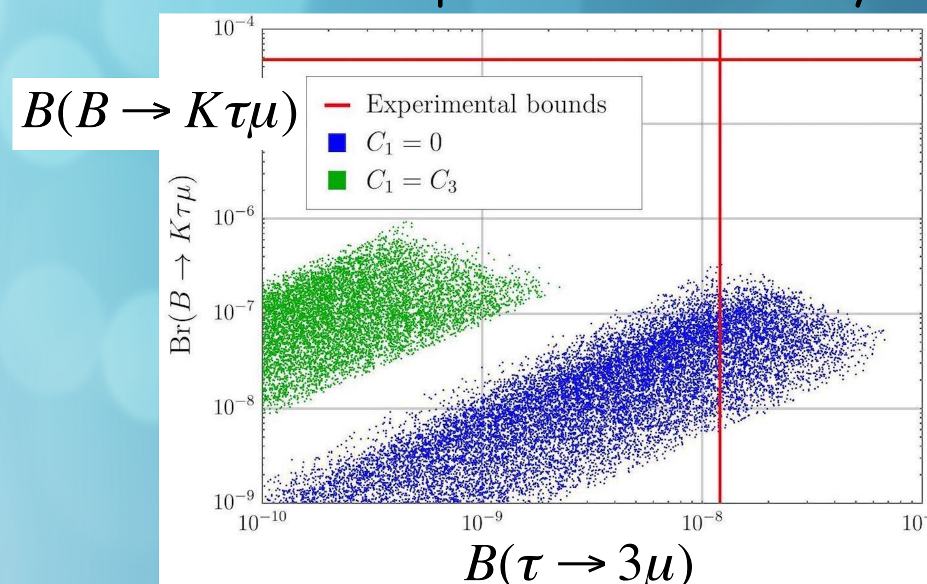
$$\left|\frac{C_{1,3}}{\Lambda^2}\right| \leq 4\, TeV^{-2}$$

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

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

LFV better probed in tau decays





A more general setup

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

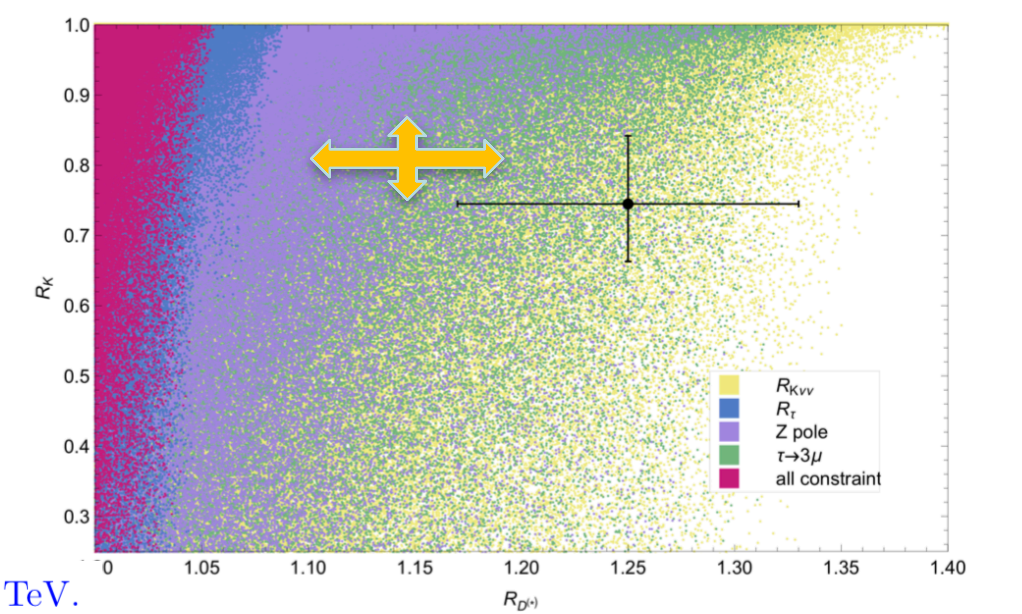
$$\mathcal{L}^0_{\rm NP} = \frac{1}{\Lambda^2}(C_1[Q^{(1)}_{lq}]_{3333} + C_3[Q^{(3)}_{lq}]_{3333} + C_4[Q_{ld}]_{3333} + C_5[Q_{ed}]_{3333} + C_6[Q_{qe}]_{3333})$$

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

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

constraints from Z pole and $\tau \to 3\mu$ less severe but simultaneous explanation of both CC and NC anomalies still prevented by $R_\tau^{\tau/\ell}$



$C_{1-6} \in \{-3, 3\}$, $\lambda^{d,e}_{23}$ and $\Gamma^{d,e}_{23} \in \{-0.3, 0.3\}$, and $\Lambda = 1$ TeV.

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

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

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

watch $\tau \to 3\mu$

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

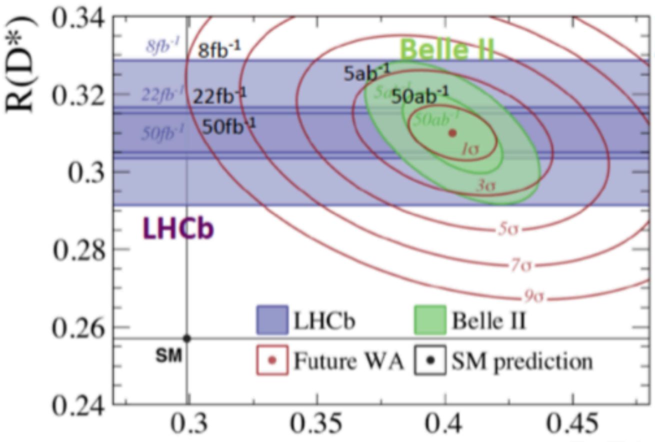
$$R_\tau^{\tau/\mu} = \frac{\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp}/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}$$

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

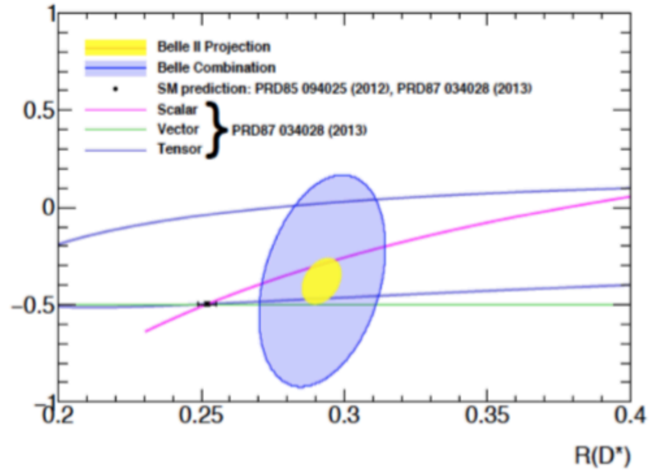
Back-up slides

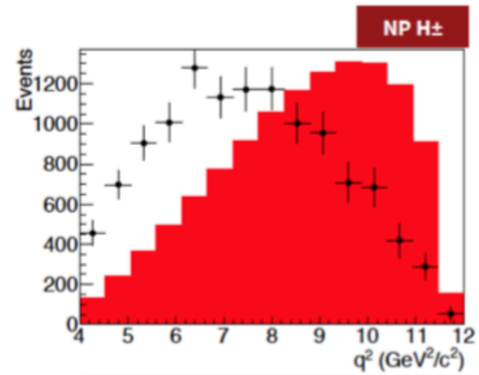
Belle II sensitivity

- Lepton universality violation may be established even with $5ab^{-1}$ (2020).
- High statistics data will provide more detailed information, such as τ polarization, q^2 distribution, to discriminate type of NP.



arXiv:1709.10308





50 ab-1 projection of the subtracted q^2 spectrum in $B \to D^* \tau \nu$ (HT)

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

Will soon hit the systematic limit !

- More observables (distributions) !
  - P(τ), P(D*)
  - $d\Gamma/dq^2$, $d\Gamma/dp_{D(*)}$, $d\Gamma/dp_e$, …
- More modes !
  - $B \to \pi \tau \nu$,
  - $B_s \to D_s \tau \nu$ (at 5S runs) , …

(Semi-)leptonic				
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	(Semi)	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	LEPTONIC	7%	Belle II
$R(B \to D\tau\nu)$	***	LFUV	3%	Belle II
$R(B \to D^*\tau\nu)$	***		2%	Belle II/LHCb

Tau				
$\tau \to \mu\gamma$ $[10^{-10}]$	***		< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	TAU	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***		< 3	Belle II/LHCb

Chengping Shen shencp@fudan.edu.

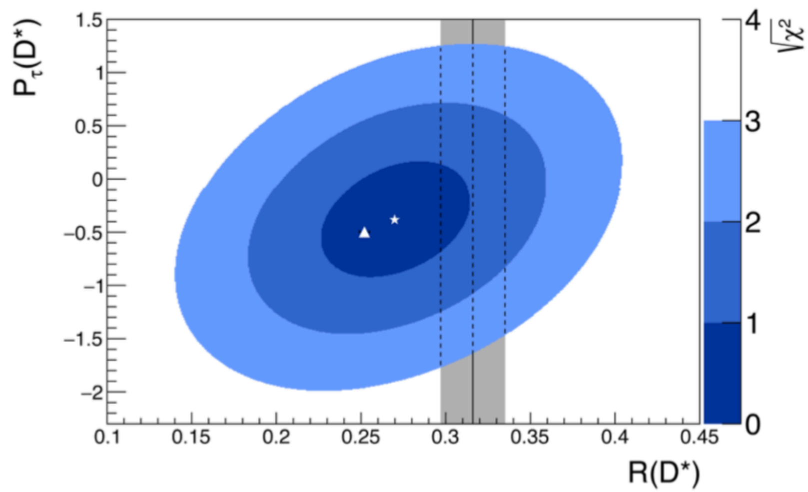
- Leptonic:

	SM pred	Exp
$\frac{\Gamma(B^-\to\mu^-\bar{\nu})}{\Gamma(B^-\to\tau^-\bar{\nu})}$	$(4.45 \pm 0.01) \cdot 10^{-3}$	$(5.92 \pm 2.83) \cdot 10^{-3}$

- Semileptonic:
  - For the comparison between e and μ, only $b \to c\ell\nu$, averaging naively results from Babar and Belle

	Exp		Exp
$\frac{\Gamma(B\to D\mu\nu)}{\Gamma(B\to De\nu)}$	0.98 ± 0.07	$\frac{\Gamma(B\to D^*\mu\nu)}{\Gamma(B\to D^*e\nu)}$	1.03 ± 0.05

both expected to be 1 up to a good accuracy



τ polarisation in $B \to D^* \tau \nu$

- Belle with $\tau \to X\nu$, $X = \rho$ (or π)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\left[1 + \alpha_X P_\tau \cos\theta_\tau\right]$$

θ_τ angle $(\vec{p}_X, -\vec{p}_{\tau\nu})$

- Large stat unc, SM compatible, $P_\tau > 0.5$ excluded at 90% CL

D^* polarisation in $B \to D^* \tau \nu$

- Angular analysis: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}\left[2F_L\cos^2\theta_{D^*} + (1 - F_L)\sin^2\theta_{D^*}\right]$
- Belle: $F_L = 0.60 \pm 0.08 \pm 0.04$, agree with SM at 1.7 σ

scalar and tensor operators

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

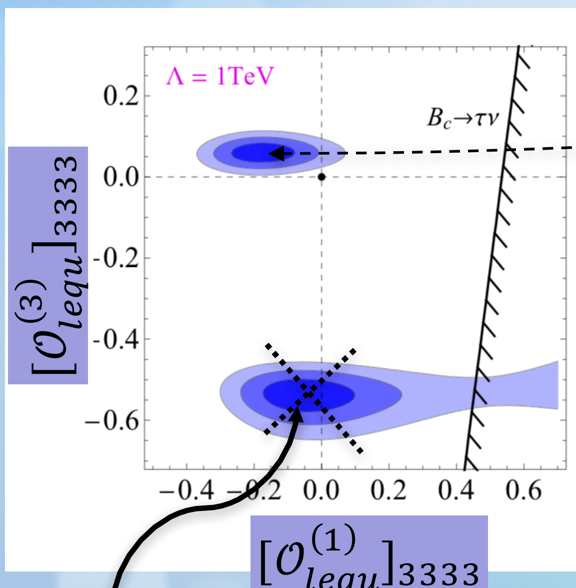
$$[\mathcal{O}^{(1)}_{\ell equ}]_{prst} = (\overline{L'}^a_p e'_{rR})\varepsilon_{ab}(\overline{Q'}^b_s u'_{tR})\,,$$

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

disfavoured by bounds on B_c^- lifetime
[Alonso, Grinstein, Camalich 1611.06676]

can only contribute to CC anomaly

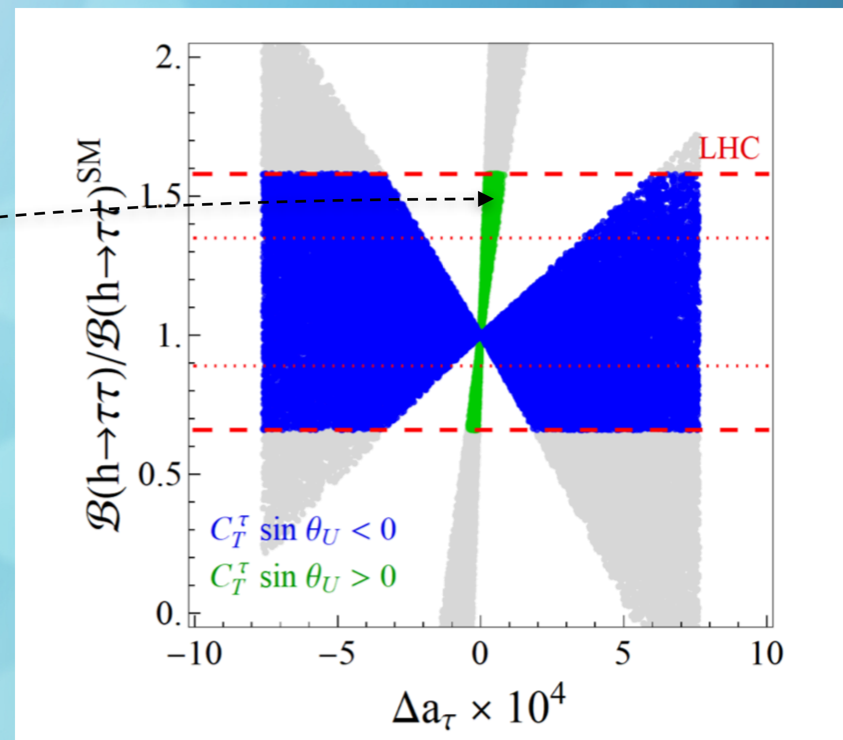
solutions by a weighted combination



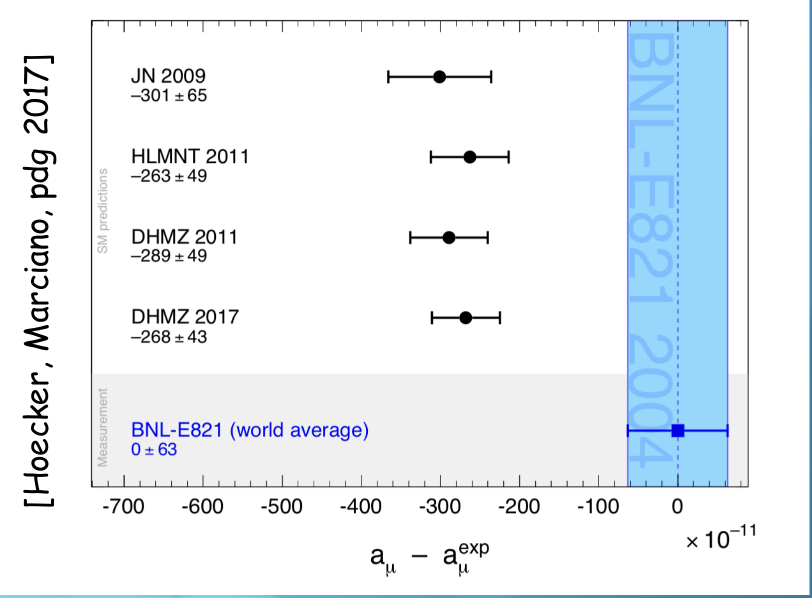
excluded by new Belle data
[Straub talk, GGI 1.10.2018]

$F_L(B \to D^*\tau\nu) = 0.60 \pm 0.08 \pm 0.03$

[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]



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

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

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

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

$\Downarrow$

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

} good fits of: ▹ R_K
▹ P'_5 (et al.)

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

$\Downarrow$

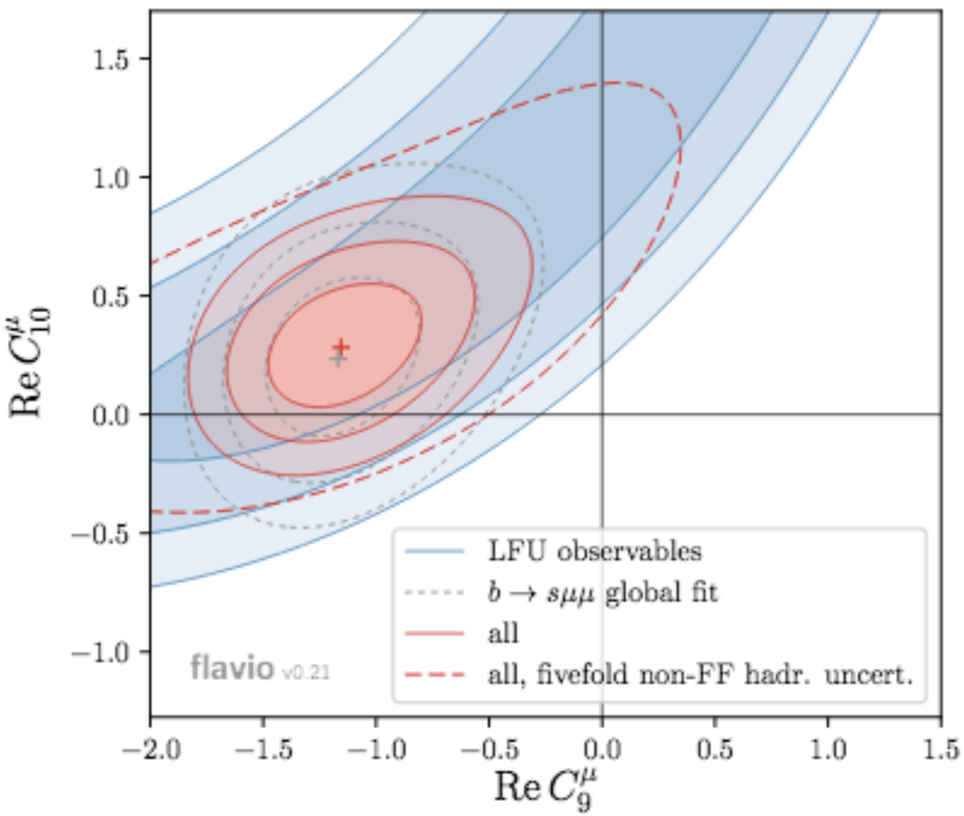
$(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma_\mu \ell_L)$ $\quad \Rightarrow$ left-handed current

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
$C_9'^\mu$	-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 $B \to K^* \mu^+ \mu^-$, 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

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

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

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

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

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

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

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

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

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

Effective Lagrangian – ew scale

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

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.

A more general setup

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

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

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

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

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

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

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

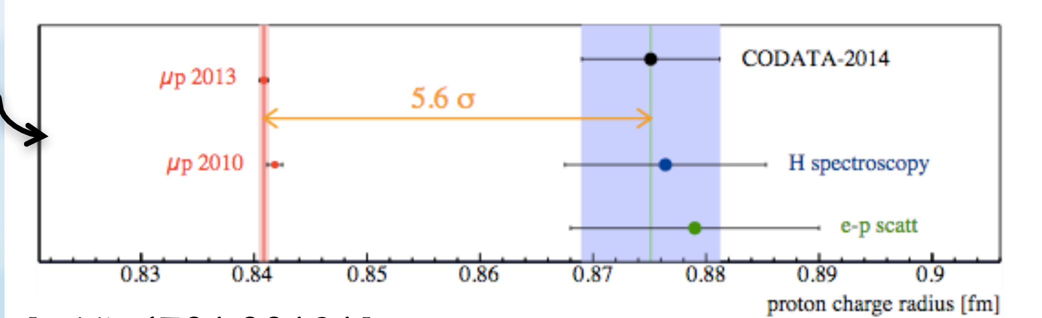
forces $\delta R^{\tau/\ell}_{D^{(*)}}$ to be $\lesssim 0.02.$

- 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

e-μ universality

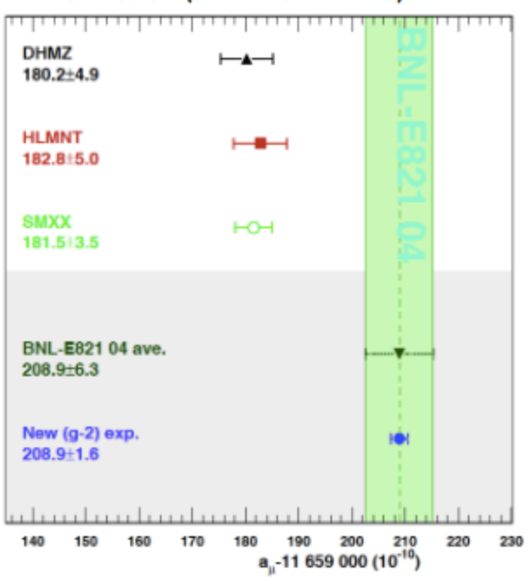
proton radius



[arXiv:1706.00696]

muon (g-2)

T. Blum et al. (arXiv:1311.2198)



τ-e and τ-μ universality

W leptonic decays

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

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

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

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

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

[not automatically p-decay free]

- contributions to dipole transitions can be chirally enhanced

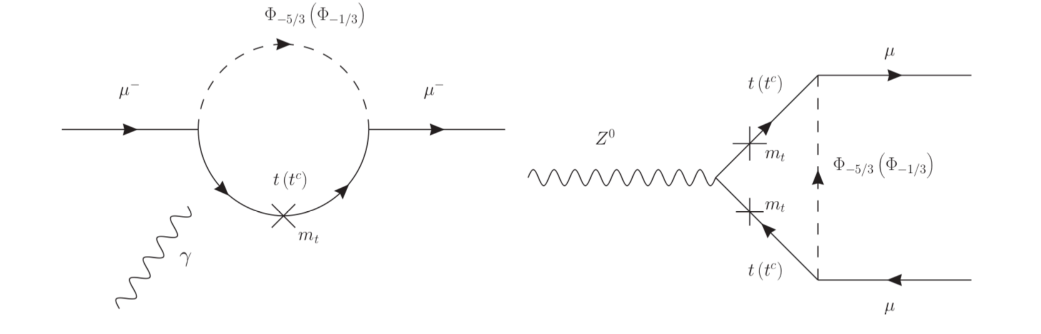
δa_ℓ	$\Gamma(\ell \to \ell' \gamma)$
$\frac{1}{16\pi^2} \frac{m_\ell m_{top}}{M_{LQ}^2} g_{t\ell}^L g_{t\ell}^R$	$\frac{\alpha_{em}}{256\pi^4} \frac{m_\ell^3 m_{top}^2}{M_{LQ}^4} \lvert g_{t\ell}^{L(R)} g_{t\ell'}^{R(L)} \rvert^2$

[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	$S_1 + S_3$
...	

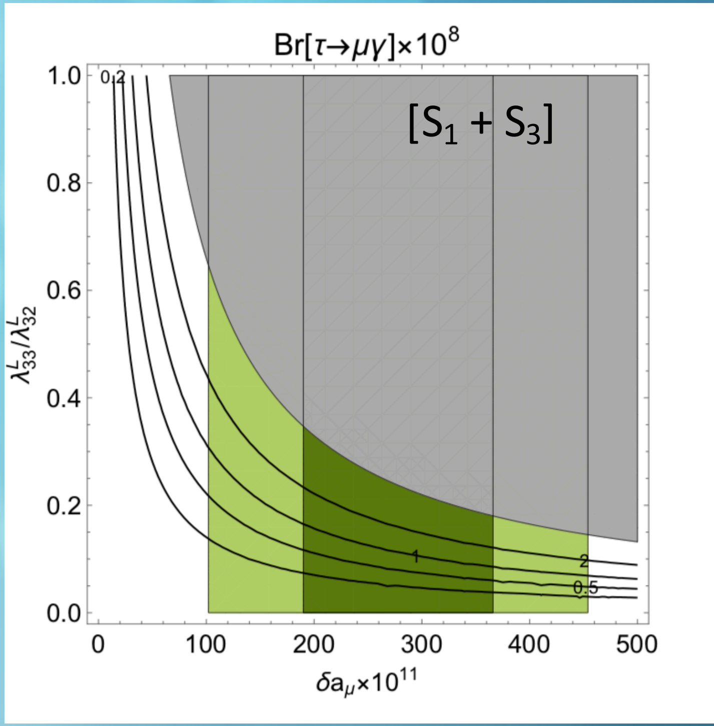
if LQ couples mainly to top and 2nd lepton generation

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

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]