Lepton Flavour Universality in B decays



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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

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

Flavor Physics for Non-Experts 45'

Several aspects of flavour physics, including the recent experimental ``anomalies" in leptonic decays, are critically reviewed and future developments discussed.

Speaker: Guido Martinelli (University of Rome La Sapienza)



Lepton Flavour Universality in the SM

basic property of SM*

neglecting mass terms and Yukawa interactions

lepton interactions are fully described by

 $\mathcal{L}_{Y}+\delta\mathcal{L}_{V}$

g, g'

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

of course, LFU is largely broken by e.g. in neutrino oscillations





For the processes discussed here, to an excellent approximation

 $m_v = 0$ 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

$\mu \rightarrow e$

	Present upper bound	
$BR(\mu^+ \to e^+ \gamma)$	4.2 $\times 10^{-13}$ [MEG]	
$BR(\mu^+ \to e^+ e^+ e^-)$	1.0×10^{-12} [SINDRUM]	
$CR(\mu^-Ti \to e^-Ti)$	4.3×10^{-12} [SINDRUM II]	bounds on the scale of
$CR(\mu^-Au \to e^-Au)$	7.0×10^{-13} [SINDRUM II]	New Physics
		TNEW FILYSICS

$\tau \rightarrow e$ $\tau \rightarrow \mu$

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

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

f

Λ_{NP} (TeV) ($ c =1$)	
$6.3 imes 10^4$	$\mu \to e\gamma$
$6.5 imes 10^2$	$\tau \to e\gamma$
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	$\mu \rightarrow 3e$

2. Well verified in a large energy range, at per mille level						
introduce	e different o	ouplings of N	V to e, µ and	т g _e	$g_\mu \ g_ au$	
E≈1 GeV	$\Gamma_{\tau \to \mu} / \Gamma_{\tau \to e}$	$\Gamma_{\pi \to \mu} / \Gamma_{\pi \to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K \to \pi \mu} / \Gamma_{K \to \pi e}$	$\Gamma_{W o \mu} / \Gamma_W$	$V \rightarrow e$
$ g_{\mu}/g_{e} $	1.0018(14)	1.0021(16)	0.9978(20)	1.0010(25)	0.996 (10	0)
	$\Gamma_{\tau \to e} / \Gamma_{\mu \to e}$	$\Gamma_{\tau \to \pi} / \Gamma_{\pi \to \mu}$	$\Gamma_{\tau \to K} / \Gamma_{K \to \mu}$	$\Gamma_{W \to \tau} / \Gamma_{W \to \mu}$		
$ g_ au/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_{ au}/g_{e} $	1.0030(15)	1.031(13)			[A.Pich, 1310.7	'922]
			-0.032	Erler, Freitas pdg 20)15] - ^{££} ?	
Z couplin E≈100 Ge	igs to charge eV	d leptons	-0.034 -0.036		$= \frac{6}{50} \qquad \mu^+ \mu^-$ 39.35% C.L. $= \frac{15}{50} e^+ e^-$ 39.35% C.L.	
$a_{ au}/$	$a_e = 1.0019$	(15)	-0.038	39.35% CL. 1+1- 90% CL.	1	
$v_{ au}$	$/v_{e} = 0.959$	(29)	-0.040	2 -0.501 -0.500	-0.499 -0.49	98
				\overline{g}_A^f		



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]

$$\begin{split} R_{D^*}^{\tau/\ell} &= \frac{\mathcal{B}(B \to D^* \tau \overline{\nu})_{\exp} / \mathcal{B}(B \to D^* \tau \overline{\nu})_{\mathrm{SM}}}{\mathcal{B}(B \to D^* \ell \overline{\nu})_{\exp} / \mathcal{B}(B \to D^* \ell \overline{\nu})_{\mathrm{SM}}} = 1.23 \pm 0.07 \ , \\ R_D^{\tau/\ell} &= \frac{\mathcal{B}(B \to D \tau \overline{\nu})_{\exp} / \mathcal{B}(B \to D \tau \overline{\nu})_{\mathrm{SM}}}{\mathcal{B}(B \to D \ell \overline{\nu})_{\exp} / \mathcal{B}(B \to D \ell \overline{\nu})_{\mathrm{SM}}} = 1.34 \pm 0.17 \ , \end{split}$$

 $\tau \leftrightarrow \mu/e$

[HFAG averages of Babar, Belle and LHCb, 1612.07233 SM at 3.90]

$$R_{J/\Psi}^{\exp} = \frac{\mathcal{B}(B_c \to J/\Psi \tau \bar{\nu})}{\mathcal{B}(B_c \to J/\Psi \ell \bar{\nu})} = 0.71(17)(18)$$
[LHCb 2017

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.





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

needs confirmation from Belle II and LHCb (run 2)



- 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 $\mathcal{L}_{eff} = -\frac{4G_F V_{cb}}{\sqrt{2}} \left[(1 + \epsilon_L) \bar{\tau} \gamma_\mu P_L \nu_\tau \cdot \bar{c} \gamma^\mu P_L b + \epsilon_R \bar{\tau} \gamma_\mu P_L \nu_\tau \cdot \bar{c} \gamma^\mu P_R b \right] + \epsilon_S \bar{\tau} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_L b + \epsilon_S \bar{\tau} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_R b \right] + h.c.$ CC $+ \epsilon_T \bar{\tau} \sigma_{\mu\nu} P_L \nu_\tau \cdot \bar{c} \sigma^{\mu\nu} P_L b + \epsilon_S \bar{\tau} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_R b + \epsilon_S \bar{\tau} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_R b + h.c.$ simplest solution:has large renormalization
into scalar operators
[Gonzalez-Alonso, Camalich,
Mimouni 1706.00410] $\epsilon_L = 0.18 \pm 0.04$
[Freytsis, Ligeti, Ruderman 1506.08896][Alonso, Grinstein, Camalich 1611.06676]

NC

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

 $O_9^{\ell} = (\bar{s}\gamma_{\mu}P_Lb)(\bar{\ell}\gamma^{\mu}\ell), \quad O_9^{\prime\,\ell} = (\bar{s}\gamma_{\mu}P_Rb)(\bar{\ell}\gamma^{\mu}\ell),$ $O_{10}^{\ell} = (\bar{s}\gamma_{\mu}P_Lb)(\bar{\ell}\gamma^{\mu}\gamma_5\ell), O_{10}^{\prime\,\ell} = (\bar{s}\gamma_{\mu}P_Rb)(\bar{\ell}\gamma^{\mu}\gamma_5\ell)$

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 ~50 w.r.t. the SM and prefer NP in muon channel

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

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

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



open questions

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

any specific LFV/LFUV process to especially monitor?

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

$$-\frac{4G_F V_{cb}}{\sqrt{2}} \epsilon_L \left(\overline{c}_L \gamma_\mu b_L\right) \left(\overline{\tau}_L \gamma^\mu v_{\tau L}\right) -\frac{8G_F V_{tb} V_{ts}^*}{\sqrt{2} 16\pi^2} \frac{e^2}{16\pi^2} C \left(\overline{s}_L \gamma_\mu b_L\right) \left(\overline{\mu}_L \gamma^\mu \mu_L\right) C \equiv C_{9\mu}^{NP} = -C_{10\mu}^{NP}$$
2. NP above the electroweak scale
$$\mathcal{L}^{NP} = \frac{1}{\Lambda^2} \sum_i C_i O_i + \dots, \qquad L_{NP}^0 \left(\Lambda\right)$$
0 $m_\tau m_b$ $m_W \approx m_Z \approx m_H \approx m_t$ Λ Energy
3. NP dominantly affects the third generation couplings to lighter generations [e.g. muons, c-quark,] = misalignment between mass and interaction bases
$$\mathcal{L}_{NP}^0 \left(\Lambda\right) = \frac{1}{\Lambda^2} \left(C_1 \ \overline{q}'_{3L} \gamma^\mu q'_{3L} \ \overline{\ell}'_{3L} \gamma_\mu \ell'_{3L} + C_3 \ \overline{q}'_{3L} \gamma^\mu \tau^a q'_{3L} \ \overline{\ell}'_{3L} \gamma_\mu \tau^a \ell'_{3L}\right) + \dots$$

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

$$\begin{aligned} \mathcal{L}_{NP}^{0}(\Lambda) &= \frac{\lambda_{kl}^{e}}{\Lambda^{2}} \left[\left(C_{1} + C_{3} \right) \lambda_{ij}^{u} \ \bar{u}_{Li} \gamma^{\mu} u_{Lj} \ \bar{\nu}_{Lk} \gamma_{\mu} \nu_{Ll} + \left(C_{1} - C_{3} \right) \lambda_{ij}^{u} \ \bar{u}_{Li} \gamma^{\mu} u_{Lj} \ \bar{e}_{Lk} \gamma_{\mu} e_{Ll} + \\ \left(C_{1} - C_{3} \right) \lambda_{ij}^{d} \ \bar{d}_{Li} \gamma^{\mu} d_{Lj} \ \bar{\nu}_{Lk} \gamma_{\mu} \nu_{Ll} + \left(C_{1} + C_{3} \right) \lambda_{ij}^{d} \ \bar{d}_{Li} \gamma^{\mu} d_{Lj} \ \bar{e}_{Lk} \gamma_{\mu} e_{Ll} + \\ 2C_{3} \left(\lambda_{ij}^{ud} \ \bar{u}_{Li} \gamma^{\mu} d_{Lj} \ \bar{e}_{Lk} \gamma_{\mu} \nu_{Ll} + h.c. \right) \right] . \end{aligned}$$



Constraints (tree-level)

$R_K^{\mu/e}$ $R_{K^*}^{\mu/e}$	$(C_1 + C_3)\vartheta_d \vartheta_e^2$		
$R_D^{ au/\ell}$ $R_{D^*}^{ au/\ell}$	<i>C</i> ₃		
process	parameters	size	exp. bound
$R_{B_s\mu\mu} = rac{\mathcal{B}(B_s o \mu \bar{\mu})_{ m exp}}{\mathcal{B}(B_s o \mu \bar{\mu})_{ m SM}}$	$(C_1 + C_3)\vartheta_d \vartheta_e^2$	<i>O</i> (0.1)	$\begin{aligned} \mathcal{B}(B_s \to \mu \bar{\mu})_{\rm exp} &= 2.8^{+0.7}_{-0.6} \times 10^{-9} \\ \mathcal{B}(B_s \to \mu \bar{\mu})_{\rm SM} &= 3.65(23) \times 10^{-9} \end{aligned}$
$R_{B\tau\nu}^{\tau/\mu} = \frac{\mathcal{B}(B \to \tau\nu)_{\rm exp}}{\mathcal{B}(B \to \mu\nu)_{\rm exp}} / \mathcal{B}(B \to \mu\nu)_{\rm SM}$	C ₃	<i>O</i> (0.1)	Belle II ?
$R_{K^{(*)}}^{\nu\nu} = \frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})_{\rm SM}}$	$(C_1 - C_3)\vartheta_d$	O (1)	$R_{K^*}^{\nu\nu} < 4.4 R_K^{\nu\nu} < 4.3$
$\mathcal{B}(B \to K \pi \mu)$	[Glashow, Guadagnoli, Lane 1411.0565]		
$\mathcal{B}(B \to \tau^{\pm} \mu^{\mp}) \approx \mathcal{B}(B \to K \tau^{\pm} \mu^{\mp}),$ $\mathcal{B}(B \to K^* \tau^{\pm} \mu^{\mp}) \approx 2 \times \mathcal{B}(B \to K \tau^{\pm} \mu^{\mp})$	$\left (C_1 + C_3) \vartheta_d \vartheta_e \right ^2$	$O(10^{-6+7})$	$\mathcal{B}(B \to K \tau \mu) \leq 4.8 \times 10^{-5}$
μ+μ- and τ+τ- Production at LHC	$(C_1 + C_3)$		[Greljo, Marzocca 1704.09015]

Colliders bounds

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

enhancement expected in ${\bf T}^{\!\!+} \, {\bf T}^{\!\!-}$ production at high p_T through $b \overline{b} \to \tau^+ \tau^-$

signals depend on the mediator type

colorless mediator: Z'

ŝ-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

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

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 $% \mathcal{T}_{\mathrm{S}}$

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

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

← R U N N I N G

$$| L'_{eff}(\gamma, q \neq t, l) |$$

$$L_{eff}(Z,W,\gamma,H,q,l) = L^0_{NP}(\Lambda)$$

[FPP]

 $\begin{array}{ccc} 0 & m_{\tau} m_{b} & m_{W} \approx m_{Z} \approx m_{H} \approx m_{t} \\ & & \mathsf{MATCHING} \end{array}$

1st: the electroweak scale

$$\leftarrow RUNNING$$

$$L_{eff}(\gamma, q \neq t, l)$$

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

$$M_{W} \approx m_{Z} \approx m_{H} \approx m_{t}$$

$$\Lambda$$

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



$$\begin{aligned} \frac{a_{\tau}}{a_e} &\approx 1 - 0.004 \frac{(C_1 - 0.8 C_3)}{\Lambda^2 (\text{TeV}^2)} \\ \frac{v_{\tau}}{v_e} &\approx 1 - 0.05 \frac{(C_1 - 0.8 C_3)}{\Lambda^2 (\text{TeV}^2)} \\ a_{\tau}/a_e &= 1.0019 \ (15) \\ v_{\tau}/v_e &= 0.959 \ (29) \end{aligned}$$
$$\mathcal{B}(Z \to \mu^{\pm} \tau^{\mp}) &\approx 10^{-7} \\ \mathcal{B}(Z \to \mu^{\pm} \tau^{\mp})_{\text{exp}} &\leq 1.2 \times 10^{-5} \end{aligned}$$

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



Putting everything together



A more general setup C. Cornella, F.F., P. Paradisi, 1803.00945

$$\mathcal{L}_{\rm NP}^{_0} = \frac{1}{\Lambda^2} (C_1[Q_{lq}^{_{(1)}}]_{_{3333}} + C_3[Q_{lq}^{_{(3)}}]_{_{3333}} + C_4[Q_{ld}]_{_{3333}} + C_5[Q_{ed}]_{_{3333}} + C_6[Q_{qe}]_{_{3333}})$$

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

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

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

an example

1

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

$$O^{\scriptscriptstyle 9} = rac{e^2}{16\pi^2} (ar{s}_{\scriptscriptstyle L} \gamma_\mu b_{\scriptscriptstyle L}) (ar{e}_i \gamma^\mu e_i)$$

we find

$$\frac{v_{\tau}}{v_{e}} = 1 - \frac{0.05 \lambda_{33}^{e}}{\Lambda^{2}} (2 C_{1} + 0.2 C_{3} + 0.02 (2 C_{1} + C_{3}))$$
 directly correlated to

$$\frac{a_{\tau}}{a_{e}} = 1 + 0.007 \lambda_{33}^{e} \frac{C_{3}}{\Lambda^{2}}$$
 directly correlated to

$$R_{\tau}^{\tau/\ell} \text{ and } R_{D(*)}$$
forces $\delta R_{D(*)}^{\tau/\ell}$ 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 U₁=(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



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 T⁺ T⁻ 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

$$\frac{a_{\tau}}{a_{e}} \quad \frac{v_{\tau}}{v_{e}}$$

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

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

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

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

•
$$B \to K^{(*)}\ell^+\ell^-$$

$$\mathcal{O}_{9} = \frac{\alpha}{4\pi} (\bar{s}_{L} \gamma_{\mu} b_{L}) (\bar{\ell} \gamma_{\mu} \ell) \qquad \mathcal{O}_{9}' = \frac{\alpha}{4\pi} (\bar{s}_{R} \gamma_{\mu} b_{R}) (\bar{\ell} \gamma_{\mu} \ell) \qquad \mathcal{O}_{7\gamma} = \frac{e}{4\pi^{2}} m_{b} (\bar{s}_{L} \sigma^{\mu\nu} b_{R}) F_{\mu\nu} \\ \mathcal{O}_{10} = \frac{\alpha}{4\pi} (\bar{s}_{L} \gamma_{\mu} b_{L}) (\bar{\ell} \gamma_{\mu} \gamma_{5} \ell) \qquad \mathcal{O}_{10}' = \frac{\alpha}{4\pi} (\bar{s}_{R} \gamma_{\mu} b_{R}) (\bar{\ell} \gamma_{\mu} \gamma_{5} \ell) \qquad \mathcal{O}_{7\gamma}' = \frac{e}{4\pi^{2}} m_{b} (\bar{s}_{R} \sigma^{\mu\nu} b_{L}) F_{\mu\nu}$$

 $\downarrow \downarrow$

$$> C_{9}^{NP} \neq 0$$

$$> C_{9}^{NP} = -C_{10}^{NP} \neq 0$$

$$> P'_{5} \text{ (et al.)}$$

$$S. \text{ Descotes-Genon, L. Hofer, } J. \text{ Matias, J. Virto (2015)}$$

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

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^{μ}_{10}	+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^e_{10}	-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^{\primee}	+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 $R_{K_{r}}R_{K^{*}}$, angular variables in B -> K^{*} $\mu^{+} \mu^{-}$, differential BR in B -> K^{*} $\mu^{+} \mu^{-}$, B -> $\phi \mu^{+} \mu^{-}$

Global Fit

 $[R_{K}]_{[1,6]} \simeq 1.00(1) + 0.230(\mathcal{C}_{9\mu-e}^{\rm NP} + \mathcal{C}_{9\mu-e}') - 0.233(2)(\mathcal{C}_{10\mu-e}^{\rm NP} + \mathcal{C}_{10\mu-e}'),$ $[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)\mathcal{C}_{9\mu-e}^{\rm NP} - 0.10(2)\mathcal{C}_{9\mu-e}' - 0.11(2)\mathcal{C}_{10\mu-e}^{\rm NP} + 0.11(2)\mathcal{C}_{10\mu-e}' + 0.55(6)\mathcal{C}_{7}^{\rm NP},$ $[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)\mathcal{C}_{9\mu-e}^{\rm NP} - 0.19(1)\mathcal{C}_{9\mu-e}' - 0.27(1)\mathcal{C}_{10\mu-e}^{\rm NP} + 0.21(1)\mathcal{C}_{10\mu-e}'.$

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

Dimension six operators

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

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

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

$$\begin{split} \Delta g_{\nu L}^{ij} &= \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \big(\frac{1}{3} g_1^2 C_1 - g_2^2 C_3 + 3y_t^2 \lambda_{33}^u (C_1 + C_3) \big) \lambda_{ij}^e \\ \Delta g_{eL}^{ij} &= \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \big(\frac{1}{3} g_1^2 C_1 + g_2^2 C_3 + 3y_t^2 \lambda_{33}^u (C_1 - C_3) \big) \lambda_{ij}^e \\ \Delta g_{uL}^{ij} &= -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{1}{3} \big(g_1^2 C_1 + g_2^2 C_3 \big) \lambda_{ij}^u \\ \Delta g_{dL}^{ij} &= -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{1}{3} \big(g_1^2 C_1 - g_2^2 C_3 \big) \lambda_{ij}^d \\ \Delta g_{fR}^{ij} &= 0 \qquad (f = \nu, e, u, d) \\ \Delta g_{\ell}^{ij} &= \frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} (-2g_2^2 C_3 + 6y_t^2 \lambda_{33}^u C_3) \lambda_{ij}^e \\ \Delta g_{q}^{ij} &= -\frac{v^2}{\Lambda^2} \frac{L}{16\pi^2} \frac{2}{3} g_2^2 C_3 \lambda_{ij}^{ud} \qquad L = \log \end{split}$$

Effective Lagrangian - ew scale

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

Q_i	ξ_i
$\left(ar{ u}_{iL}\gamma_{\mu} u_{jL} ight)\left(ar{ u}_{kL}\gamma^{\mu} u_{nL} ight)$	$\lambda^e_{ij}\delta_{kn}\left[-6y_t^2\lambda^u_{33}(C_1+C_3) ight]$
$\left(ar{ u}_{iL} \gamma_\mu u_{jL} ight) \left(ar{e}_{kL} \gamma^\mu e_{nL} ight)$	$\lambda_{ij}^e\delta_{kn}\left[rac{4}{3}e^2(C_1+3C_3)-12\left(-rac{1}{2}+s_ heta^2 ight)y_t^2\lambda_{33}^u(C_1+C_3) ight]$
	$+ \delta_{ij}\lambda^e_{kn}[-6y_t^2\lambda^u_{33}(C_1-C_3)]$
$\left(ar{ u}_{iL}\gamma_{\mu} u_{jL} ight)\left(ar{e}_{kR}\gamma^{\mu}e_{nR} ight)$	$\lambda^e_{ij}\delta_{kn}\left[rac{4}{3}e^2(C_1+3C_3)-12s^2_ hetay^2_t\lambda^u_{33}(C_1+C_3) ight]$
$(ar{e}_{iL}\gamma_\mu e_{jL})~(ar{e}_{kL}\gamma^\mu e_{nL})$	$\lambda_{ij}^e\delta_{kn}\left[rac{4}{3}e^2(C_1-3C_3)-12(-rac{1}{2}+s_ heta^2)y_t^2\lambda_{33}^u(C_1-C_3) ight]$
$(ar{e}_{iL}\gamma_{\mu}e_{jL})~(ar{e}_{kR}\gamma^{\mu}e_{nR})$	$\lambda^e_{ij}\delta_{kn}\left[rac{4}{3}e^2(C_1-3C_3)-12s^2_ hetay^2_t\lambda^u_{33}(C_1-C_3) ight]$
$\left(ar{ u}_{iL} \gamma_\mu e_{jL} ight) \left(ar{e}_{kL} \gamma^\mu u_{nL} ight)$	$(\lambda^e_{ij}\delta_{kn}+\delta_{ij}\lambda^e_{kn})\left[-12y^2_t\lambda^u_{33}C_3 ight]$

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

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

Q_i	$\delta \xi_i$
$(ar{ u}_{iL}\gamma_{\mu} u_{jL})~(ar{ u}_{kL}\gamma^{\mu} u_{nL})$	0
$\left(ar{ u}_{iL}\gamma_{\mu} u_{jL} ight)\left(ar{e}_{k}\gamma^{\mu}e_{n} ight)$	$\lambda_{ij}^{e}\delta_{kn}\cdot \tfrac{4}{3}e^{2}\left[(C_{1}+3C_{3})-2(C_{1}+C_{3})(\hat{\lambda}_{33}^{u}\log\tfrac{m_{t}}{\mu}+\hat{\lambda}_{22}^{u}\log\tfrac{m_{c}}{\mu})\right.$
	$+(C_1-C_3)\hat{\lambda}^d_{33}\lograc{m_b}{\mu}\Big]$
$(ar{e}_{iL}\gamma_{\mu}e_{jL})~(ar{e}_k\gamma^{\mu}e_n)$	$\lambda_{ij}^e \delta_{kn} \cdot rac{4}{3} e^2 \left[(C_1 - 3C_3) - 2(C_1 - C_3) (\hat{\lambda}_{33}^u \log rac{m_t}{\mu} + \hat{\lambda}_{22}^u \log rac{m_c}{\mu}) ight]$
	$+(C_1+C_3)\hat{\lambda}^d_{33}\lograc{m_b}{\mu}\Big]$

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

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

Field	Spin	Quantum Numbers	Operator	C_1	C_3
A_{μ}	1	(1, 1, 0)	$ar q_L' \gamma^\mu q_L' \; ar \ell_L' \gamma_\mu \ell_L'$	-1	0
A^a_μ	1	(1, 3, 0)	$ar q_L' \gamma^\mu au^a q_L' \; ar \ell_L' \gamma_\mu au^a \ell_L'$	0	-1
U_{μ}	1	(3, 1, +2/3)	$ar q_L' \gamma^\mu \ell_L' \;ar \ell_L' \gamma_\mu q_L'$	$-\frac{1}{2}$	$-\frac{1}{2}$
U^a_μ	1	(3, 3, +2/3)	$ar q_L' \gamma^\mu au^a \ell_L' \; ar \ell_L' \gamma_\mu au^a q_L'$	$-\frac{3}{2}$	$+\frac{1}{2}$
S	0	(3, 1, -1/3)	$ar{q}_L' i \sigma^2 {\ell'}_L^c \ \overline{i \sigma^2 {\ell'}_L^c} q_L'$	$+\frac{1}{4}$	$-\frac{1}{4}$
S^a	0	(3, 3, -1/3)	$ar{q}_L^\prime au^a i \sigma^2 {\ell^\prime}_L^c \ \overline{i \sigma^2 {\ell^\prime}_L^c} au^a q_L^\prime$	$+\frac{3}{4}$	$+\frac{1}{4}$

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.



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



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)
- $m_U \ge 100$ TeV unless flavour pattern is cleverly arranged

 $R_{D}^{\tau/\ell} R_{D^{*}}^{\tau/\ell} \text{ alone can be explained in present framework}$ $e.g. \ \vartheta_{d} \approx 1, \ \vartheta_{e} \ll \alpha_{em}, \ \Lambda \approx 5 \text{ TeV} \text{ loop effects decouple as } v^{2}/\Lambda^{2}$ $R_{K}^{\mu/e} R_{K^{*}}^{\mu/e} \text{ alone can be explained in present framework}$ $e.g. \ \vartheta_{d} \approx 1, \ \vartheta_{e} \approx 1, \ \Lambda \approx 30 \text{ TeV} \text{ loop effects decouple as } v^{2}/\Lambda^{2}$

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

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

[not automatically p-decay free]

contributions to dipole transitions can be chirally enhanced

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

[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



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

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

[NC anomaly requires special care: no contribution to $b \rightarrow s\ell^+\ell^-$ from tree-level S₁ exchange; C₉=+C₁₀ from R₂ 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

$$\frac{BR(\tau \to \mu\gamma)}{(\delta a_{\mu})^{2}} \ge \frac{9 \times 10^{-7}}{(+3 \times 10^{-9})^{2}} \left(\frac{g_{33}^{L}}{g_{32}^{L}}\right)^{2}$$
$$BR(Z \to \tau^{\pm}\mu^{\mp}) \approx \frac{10^{-8} (g_{33}^{L}g_{32}^{L})^{2}}{M_{L0}^{4} (TeV)}$$



[Crivellin, Muller, Ota, 1703.09226]