New physics in $\tau \to \mu$ transition

Olcyr Sumensari

hep-ph/1808.08179, 1911.XXXXX

In collaboration with

A. Angelescu, D. Bečirević and D. Faroughy

C. Cornella and P. Paradisi

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INFN

Università degli Studi di Padova

Outline

- **L**epton **F**lavor **V**iolation (LFV) is forbidden in the SM.

  $\Rightarrow$ Nonzero m_{ν_i} imply LFV, but with unobservable rates.

  $\Rightarrow$ These are very **clean probes** of new physics!

- **Renewed interest** by recently found **conflict** between theory and experiment in flavor observables (related to leptons).

  $\Rightarrow$ Should we expect LFV around the corner? [Glashow et al. '14]

- **Promising exp. prospects**: Belle-II, LHCb and future facilities.

  See talks by Cogan, Monteil and Trabelsi

This talk: (i) B-anomalies predictions to $b \to s\mu\tau$ (and $b \to s\tau\tau$)

(ii) From $(g-2)_\ell$ to LFV in τ-decays

Implications of B-anomalies to LFV

[Angelescu, Bečirević, Faroughy, **OS**. 1808.08179]

B-physics anomalies see talks by Abhishek et al., Crivellin, Moris et al. and Stangl

Several discrepancies [$\approx 2-3\sigma$] appeared recently in B-meson decays:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B\to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}\mu\mu)}{\mathcal{B}(B\to K^{(*)}ee)}\Bigg|_{q^2\in[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} \qquad \& \qquad R_{K^{(*)}}^{\mathrm{exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

$\Rightarrow$ Violation of **L**epton **F**lavor **U**niversality (LFU)?

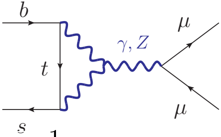
$\Rightarrow$ Theoretically clean observables!

$\Rightarrow$ Large effects in $b\to s\mu\tau$ are predicted by (few) viable solutions.

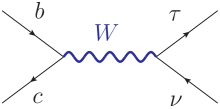
see also [Glashow et al. '14]

Viable new physics scenarios

EFT interpretations: See back-up



$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda_{R_K}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$



$$\mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda_{R_D}^2} (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

with $\Lambda_{R_K} \approx 30$ TeV $\Lambda_{R_D} \approx 3$ TeV

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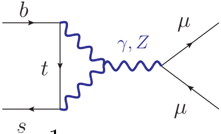

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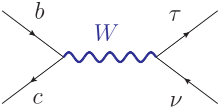

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Challenges for New Physics: (mainly driven by $R_{D^{(*)}}$)

- Flavor observables: e.g. Δm_{B_s} and $B \to K\nu\bar{\nu}$
- Radiative constraints: e.g. $\tau \to \mu\nu\bar{\nu}$ and $Z \to \ell\ell$ [Feruglio et al., '16]
- High-p_T LHC bounds [Greljo et al. '15, Faroughy et al., '16]

⇒ Scalar and vector **leptoquarks (LQ)** are the **best candidates** so far.

(with predominant couplings to 3rd generation)

Which leptoquark?

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

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- Only U_1 can do the job, but UV completion needed.

  ⇒ Viable TeV models proposed (with more than one mediator!)

  [Di Luzio et al. '17, Bordone et al. '17, Assad et al. '17, Blanke et al. '17. . .].

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- Two scalar LQs are also viable:
  $\Rightarrow$ S_1 and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 [Becirevic et al. '18].

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  $\Rightarrow$ S_1 and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 [Becirevic et al. '18].

This talk: Closing the U_1 window with $b \to s\mu\tau$ and/or $b \to s\tau\tau$.

Example: $U_1 = (3, 1, 2/3)$

[Angelescu, Bečirević, Faroughy, **OS**. 1808.08179]

Setup

$U_1 = (3, 1, 2/3)$

$$\mathcal{L} = x_L^{ij}\ \bar{Q}_i \gamma_\mu U_1^\mu L_j + x_R^{ij}\ \bar{d}_{Ri} \gamma_\mu U_1^\mu \ell_{Rj} + \text{h.c.}\,,$$

- $b \to c\tau\bar{\nu}$:

$$\mathcal{L}_\text{eff} \supset -\frac{\left(x_L^{b\tau}\right)^* \left(V x_L\right)^{c\tau}}{m_{U_1}^2} (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

- $b \to s\mu\mu$:

$$\mathcal{L}_\text{eff} \supset -\frac{\left(x_L\right)^{s\mu} \left(x_L^{b\mu}\right)^*}{m_{U_1}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}$$

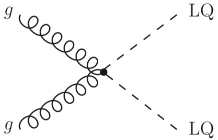
- Other observables: $\tau \to \mu\phi$, $B \to \tau\bar{\nu}$, $D_{(s)} \to \mu\bar{\nu}$, $D_s \to \tau\bar{\nu}$, $K \to \mu\bar{\nu}/K \to e\bar{\nu}$, $\tau \to K\bar{\nu}$ and $B \to D^{(*)}\mu\bar{\nu}/B \to D^{(*)}e\bar{\nu}$.

LHC constraints

$U_1 = (3, 1, 2/3)$

- LQ pair-production via QCD:

[CMS-PAS-EXO-17-003]

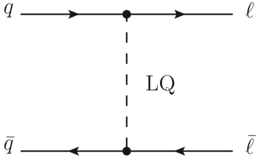


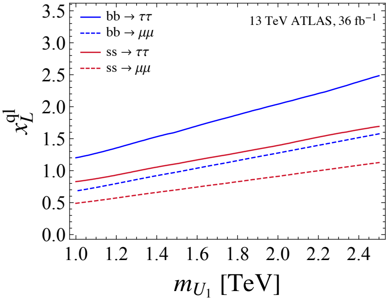
$m_{U_1} \gtrsim 1.5$ TeV

[*assuming* $\mathcal{B}(U_1 \to b\tau) \approx 0.5$]

- Di-lepton tails at high-pT:

[ATLAS. 1707.02424,1709.07242]

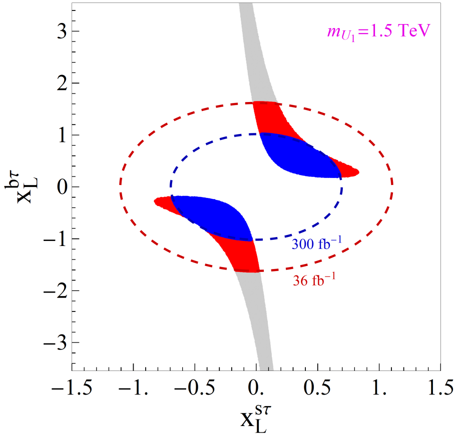




[Angelescu, Becirevic, Faroughy, OS. '18]

[see also Faroughy et al. '15]

Combining low and high-energy constraints



$$\mathcal{L}_{U_1} \supset x_L^{ij}\, \bar{Q}_i \gamma_\mu U_1^\mu L_j + \text{h.c.}$$

$R_{D^{(*)}}$ depends on:

$$g_{V_L} = \frac{v^2}{2m_{U_1}^2} (x_L^{b\tau})^* \left(x_L^{b\tau} + \frac{V_{cs}}{V_{cb}} x_L^{s\tau} \right)$$

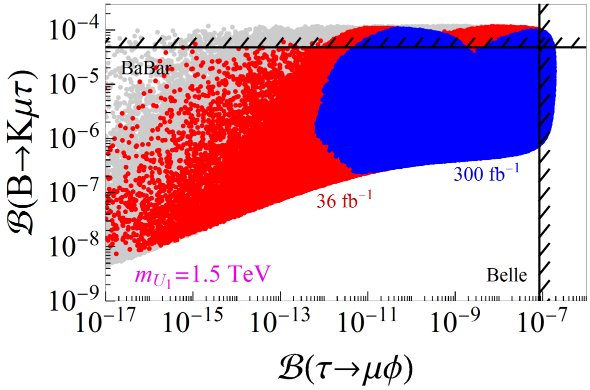
Same couplings probed by $\underline{pp \to \tau\tau}$:

36 fb^{-1} (blue) and 300 fb^{-1} (red).

$\Rightarrow$ Upper limit on $|x_L^{b\tau}|$ implies a nonzero lower limit on $|x_L^{s\tau}|$!

Notable predictions

- High-p_T constraints set a model independent lower bound $\mathcal{B}(B \to K\mu\tau) \gtrsim \text{few} \times 10^{-7}$ (to be improved with more data!)



- BaBar: $\mathcal{B}(B \to K\mu\tau) < 4.8 \times 10^{-5}$ (90% CL.). Can we do better?

Which LFV decay?

[Becirevic, **OS**, Zukanovich. '16]

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big)$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell') \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell')$$

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- For $C_9^{\mu\tau} = -C_{10}^{\mu\tau}$: see also [Glashow et al. '14]

$$\frac{\mathcal{B}(B_s \to \mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 0.8\,, \qquad \frac{\mathcal{B}(B \to K^*\mu\tau)}{\mathcal{B}(B \to K\mu\tau)} \simeq 1.8$$

- For $C_S^{\mu\tau}$ and $C_P^{\mu\tau}$:

$$\mathcal{B}(B_s \to \mu\tau) \gg \mathcal{B}(B \to K^*\mu\tau)$$

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- For $C_S^{\mu\tau}$ and $C_P^{\mu\tau}$:

$$\mathcal{B}(B_s \to \mu\tau) \gg \mathcal{B}(B \to K^*\mu\tau)$$

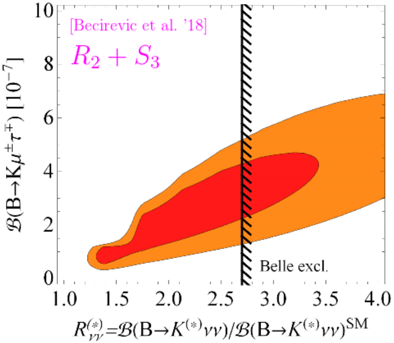
- LHCb [NEW '19]: $\mathcal{B}(B_s \to \mu\tau)^{\text{exp}} < 4.2 \times 10^{-5}$

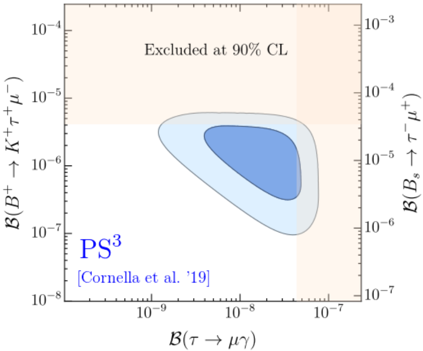
  $\Rightarrow$ Best constraint on (pseudo)scalar operators!

Take-home: different observables are complementary.

Large effects in $b \to s\mu\tau$ are a common prediction of minimal solutions to the B-anomalies:

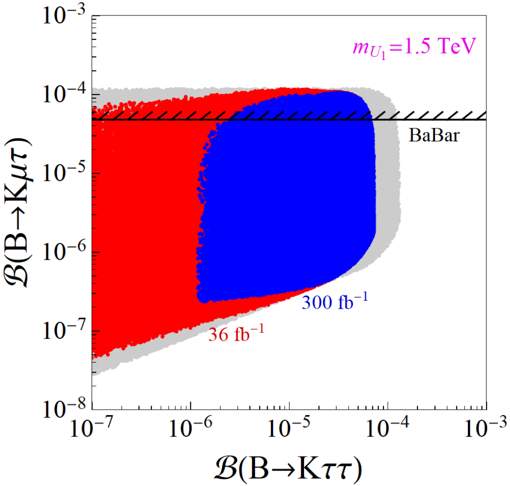
see also [Glashow et al. '14]





How about $b \to s\tau\tau$?

see e.g. [Buttazzo et al. '17, Capdevila et al. '17]



$\Rightarrow$ Large enhancement of e.g. $\mathcal{B}(B \to K\tau\tau)^{\mathrm{SM}}_{[15,22]} = 1.20(12) \times 10^{-7}$

$\Rightarrow$ Can it be tested experimentally?

How to probe $b \to s\tau\tau$?

e.g. $C_9^{\tau\tau} = -C_{10}^{\tau\tau}$

- Existing direct limits:

$$\mathcal{B}(B \to K\tau\tau)^{\rm exp} < 2.2 \times 10^{-3} \quad \text{[BaBar. '17]}$$

$$\mathcal{B}(B_s \to \tau\tau)^{\rm exp} < 6.8 \times 10^{-3} \quad \text{[LHCb. '17]}$$

still far from SM predictions ($\approx 10^{-7}$). Perhaps at FCC-ee? See talk by Monteil

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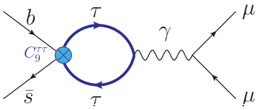
- New idea: deformation of $B \to K\mu\mu$ q^2-spectrum



$$\mathcal{B}(B \to K\tau\tau) \lesssim 2.3 \times 10^{-3} \quad \text{[preliminary]}$$

[M. König, LHCb Implications '19]

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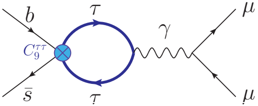

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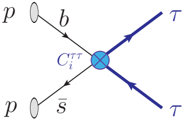
- Also promising: $pp \to \tau\tau$ at high-p_T



$$\mathcal{B}(B \to K\tau\tau) \lesssim 1.1 \times 10^{-3} \qquad (36.1\ \text{fb}^{-1})$$
$$\mathcal{B}(B \to K\tau\tau) \lesssim 1.4 \times 10^{-5} \qquad (3\ \text{ab}^{-1})$$

[Angelescu, Faroughy, **OS**. To appear]

but more model dependent (EFT validity?)

Take-home: Different approaches are complementary!

Other directions: from $(g-2)_{e,\mu}$ to LFV

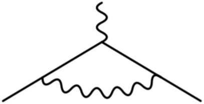
[Cornella, Paradisi, **OS**. 1911.XXXXX]

$(g-2)_\ell$ as a probe of new physics

See talk by Knecht

- Long-standing discrepancy $[\approx 3.6\,\sigma]$ in $(g-2)_\mu$:

$$a_\mu^{\text{exp}} = 116592089(63) \times 10^{-11}$$
$$a_\mu^{\text{SM}} = 116591820(36) \times 10^{-11}$$



[Brookhaven, '06]
[Keshavarzi et al., '18], [Davier et al. '19]

$\Rightarrow$ Signal of new bosons coupled to muons?

Perhaps a leptoquark? [Cheung, '01], [Coluccio, '16], [Dorsner, Fajfer, **OS**. '19]

$\Rightarrow$ New results by *Muon* $g-2$ at Fermilab coming soon!

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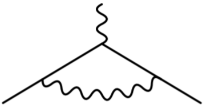

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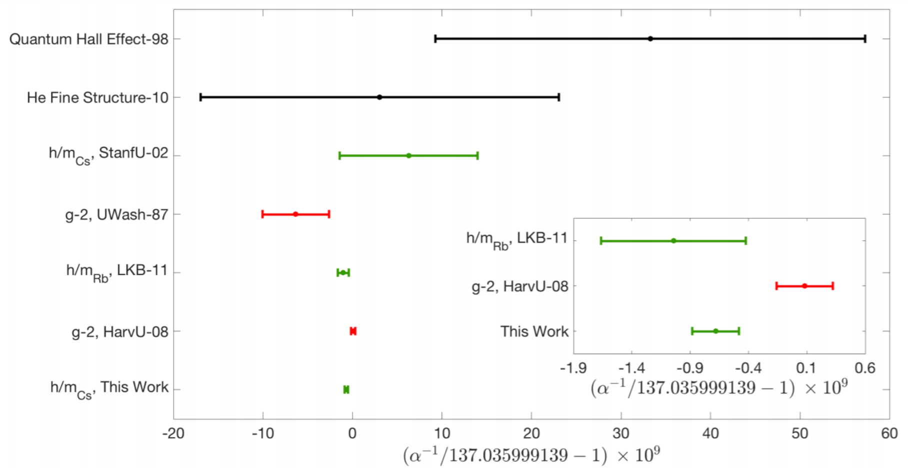
- New determination of α [Cs. '18] shows a [2.4σ] discrepancy in $(g-2)_e$:

$$a_e^{\rm exp} = 1159652180 7.3(2.8) \times 10^{-13}$$
$$a_e^{\rm SM} = 1159652181 6.1(2.3)_{\delta_\alpha}(0.2)_{\rm th} \times 10^{-13}$$

(with the opposite sign!)

$\Rightarrow$ Work in progress to further reduce the error in $(g-2)_e^{\rm exp}$ and $\delta\alpha$.

$(g-2)_e$ no longer gives the best value of α



[Parker et al. Science '18]

- In a broad class of BSM models: [Giudice et al. '12]

$$\frac{\Delta a_\mu}{\Delta a_e} = \left(\frac{m_\mu}{m_e}\right)^2 \qquad \text{(naive scaling)}$$

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- Current deviation in muons would suggest:

$$\boxed{\Delta a_\mu^{\text{exp}} = (2.7 \pm 0.7) \times 10^{-9}} \quad \Rightarrow \quad \Delta a_e^{\text{naive}} = (7 \pm 2) \times 10^{-14}$$

much smaller, and with the opposite sign, than

$$\boxed{\Delta a_e^{\text{exp}} = (-87 \pm 36) \times 10^{-14}}$$

- In a broad class of BSM models: [Giudice et al. '12]

$$\frac{\Delta a_\mu}{\Delta a_e} = \left(\frac{m_\mu}{m_e}\right)^2 \qquad \text{(naive scaling)}$$

- Current deviation in muons would suggest:

$$\boxed{\Delta a_\mu^{\text{exp}} = (2.7 \pm 0.7) \times 10^{-9}} \qquad \Rightarrow \qquad \Delta a_e^{\text{naive}} = (7 \pm 2) \times 10^{-14}$$

much smaller, and with the opposite sign, than

$$\boxed{\Delta a_e^{\text{exp}} = (-87 \pm 36) \times 10^{-14}}$$

- There exist scenarios that violate the "naive scaling".

$\Rightarrow$ They can lead to large contributions to LFV or LFU breaking.

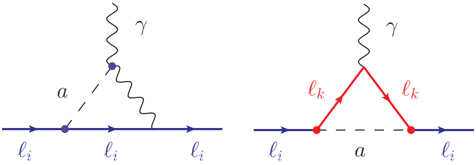
$\Rightarrow$ Example: light pseudoscalar with $a\gamma\gamma$ and $a\bar{\ell}\gamma_5\ell'$ couplings.

[Cornella, Paradisi, **OS**. To appear]

see also [Davoudiasl '18], [Crivellin et al. '18], [Bauer et al. '19]

Light pseudoscalars for $(g-2)_e$ and $(g-2)_\mu$

$$\mathcal{L}_{\text{eff}}^{d\leq 5} \supset c_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\widetilde{F}^{\mu\nu} + a_{ij}^{\ell}\frac{\partial_\mu a}{\Lambda}\bar{\ell}_i\gamma^\mu\gamma_5\ell_j + \dots$$



$$\Delta a_{\ell_i} = (\Delta a_{\ell_i})_{\text{LFC}} + (\Delta a_{\ell_i})_{\text{LFV}}$$

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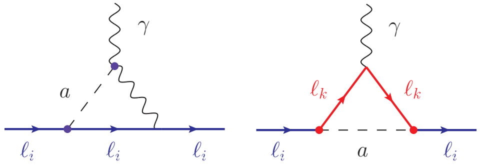

$$\Delta a_{\ell_i} = (\Delta a_{\ell_i})_{\text{LFC}} + (\Delta a_{\ell_i})_{\text{LFV}}$$

- Barr-Zee diagram (left) can account for $(g-2)_\mu$: [Marciano et al. '16]

$$(\Delta a_\mu)_{\text{LFC}} \propto \frac{m_\mu^2}{\Lambda^2}\, a_{\mu\mu}^{\ell}\, a_{\gamma\gamma}\, \log\frac{\Lambda}{m_a} + \dots$$

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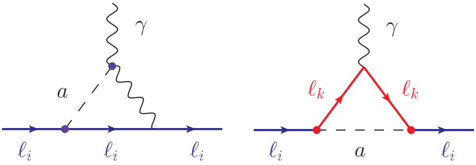

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- LFV contributions to $(g-2)_e$ are chirality-enhanced:

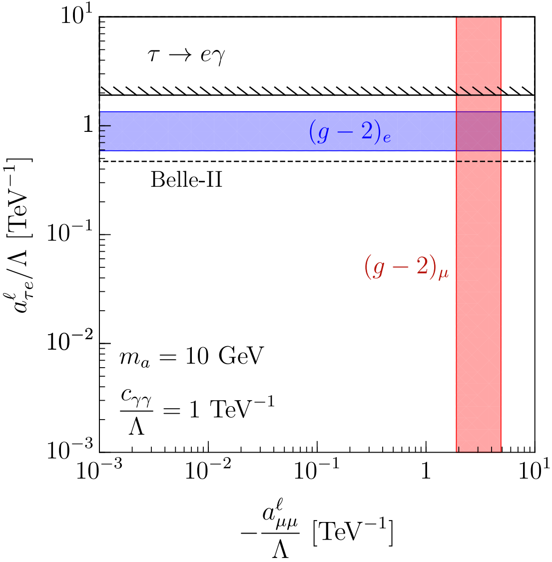
$$(\Delta a_e)_{\text{LFV}} \propto \frac{m_\tau m_e}{\Lambda^2}\,|a_{e\tau}^{\ell}|^2$$

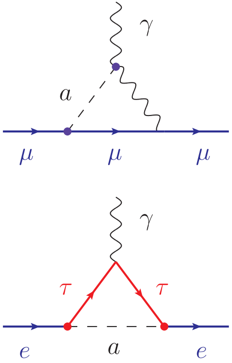
$\Rightarrow$ Both anomalies can be explained with reasonable couplings.

Predictions for Belle-II

[Cornella, Paradisi, **OS**. To appear]

See also [Bauer et al. '19]



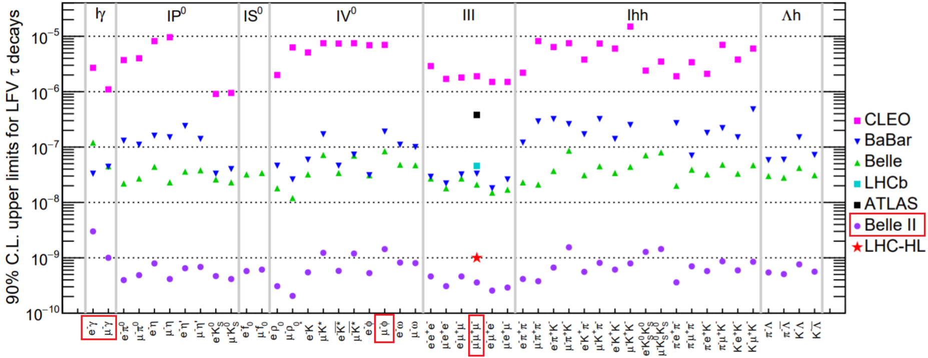


$\Rightarrow \mathcal{B}(\tau \to e\gamma) \approx 10^{-9}$ to be tested at Belle-II!

[Kuo et al. '18]

LFV τ decays

See talks by Cogan and Trabelsi



"Opportunities in Flavour Physics at the HL-LHC and HE-LHC", [1812.07638]

Summary and perspectives

- Flavor anomalies are still there, but the experimental situation after Moriond '19 is (perhaps) less convincing.

  Needs clarification from LHCb and Belle-II!

- There is a pronounced complementarity of flavor physics constraints with those obtained from the direct searches at the LHC.

  Minimal scenarios ⇒ lower bound $\mathcal{B}(B \to K\mu\tau) \gtrsim \mathcal{O}(10^{-7})$

- Simultaneous explanations of the $(g-2)_e$ and $(g-2)_\mu$ require a sizable violation of naive scaling.

  Solutions with light pseudoscalar can lead to large $\mathcal{B}(\tau \to e\gamma)$

- Building a concrete model to simultaneously explain $R_{K^{(*)}}$ and $R_{D^{(*)}}$ remains challenging.

  Data-driven model building!

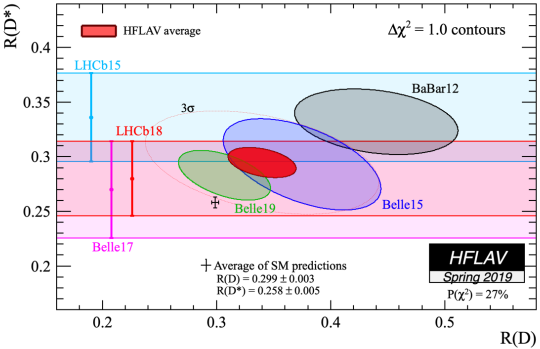
Thank you!

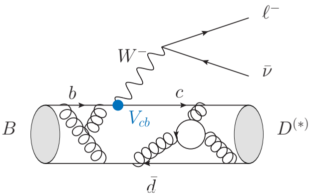
Back-up

(i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Experiment $[\approx 3.1\sigma]$

See talk G. Pardinas





- R_D and R_{D^*}: $[\approx 2\sigma]$ and $[\approx 3\sigma]$; dominated by BaBar.
- LHCb confirmed tendency $R_{J/\psi}^{\text{exp}} > R_{J/\psi}^{\text{SM}}$, i.e. $B_c \to J/\psi \ell\bar{\nu}$,

$\Rightarrow$ **Needs clarification** from **Belle-II & LHCb (run-2)** data!

(i) $R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})$

Theory (tree-level in SM) *See talks by Peñuelas, Jung and Melic*

- R_D: lattice QCD at $q^2 \neq q^2_{\max}$ $(w > 1)$ available for both leading (vector) and subleading (scalar) form factors [MILC 2015, HPQCD 2015]

$$\langle D(k)|\bar{c}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2} f_0(q^2)$$

with $f_+(0) = f_0(0)$.

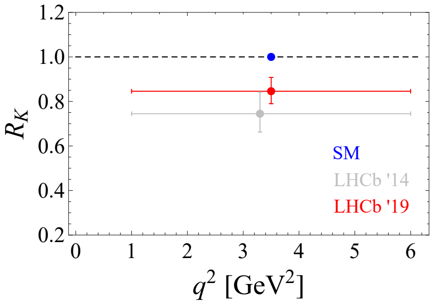
- R_{D^*}: lattice QCD at $q^2 \neq q^2_{\max}$ not available, scalar form factor $[A_0(q^2)]$ never computed on the lattice

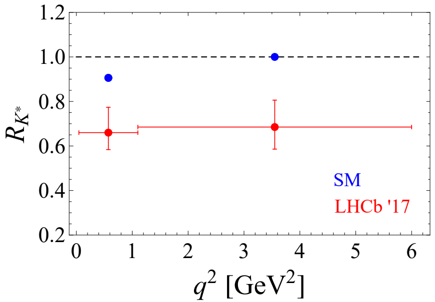
*Use **decay angular distributions** measured at B-factories to fit the **leading form factor** $[A_1(q^2)]$ and extract **two others as ratios** wrt $A_1(q^2)$. All other ratios from HQET (NLO in $1/m_{c,b}$) [Bernlochner et al 2017] but with more generous error bars (truncation errors?)*

[Preliminary LQCD results by Fermilab/MILC!]

(ii) $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu\mu)/\mathcal{B}(B \to K^{(*)}ee)$

Experiment $[\approx 4\sigma]$ *See talk by Lisovskyi*





$\Rightarrow$ **Needs confirmation from Belle-II!**

Theory (loop induced in SM) [Kruger, Hiller. '03]

- Hadronic uncertainties cancel to a large extent.
  $\Rightarrow$ Clean observables! [*working below the narrow $c\bar{c}$ resonances*]
- QED corrections important, $R_{K^{(*)}} = 1.00(1)$. [Bordone et al. '16]

i) Effective theory for $b \to c\tau\bar{\nu}$

R_D & R_{D^*}

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \Big[(1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R)(\bar{\ell}_L \gamma^\mu \nu_L)$$
$$+ g_{S_R} (\bar{c}_L b_R)(\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L)(\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\ell}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}$$

General messages:

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance:

  $\Rightarrow$ g_{V_R} is LFU at dimension 6 ($W \bar{c}_R b_R$ vertex).

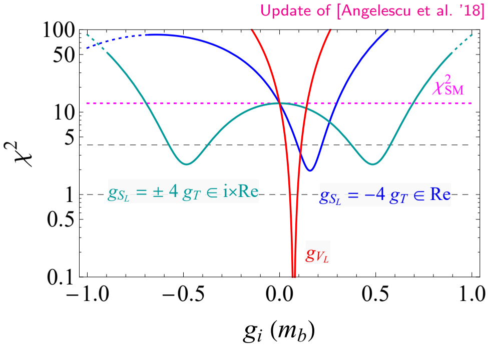
  $\Rightarrow$ Four coefficients left: g_{V_L}, g_{S_L}, g_{S_R} and g_T.

- Several viable solutions to $R_{D^{(*)}}$: [Freytsis et al. 2015]
  - e.g. $g_{V_L} \in (0.05, 0.09)$, but not only!

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

see also [Murgui et al. '19, Shi et al. '19, Blanke et al. '19]

Which Lorentz structure to pick?



Viable solutions (at $\mu \approx 1$ TeV):

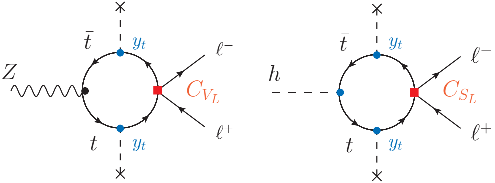
$\Rightarrow$ g_{V_L} and $g_{S_L} = \pm 4\, g_T$

See talk by Peñuelas

More exp. information is needed:

$\Rightarrow$ e.g. $B \to D^*(D\pi)\tau\bar{\nu}$ angular observables

[Becirevic et al. '19], [Murgui et al. '19]...



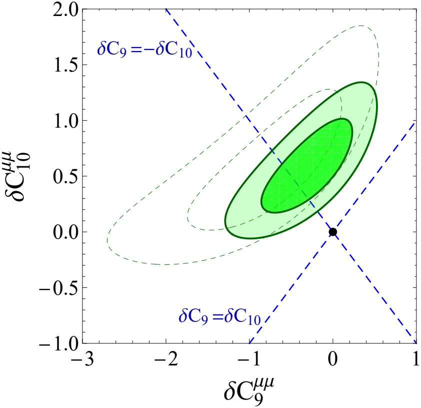
Electroweak observables can also be a useful handle!

[Feruglio et al. '17]

[Feruglio, Paradisi, **OS**. '18]

ii) Effective theory for $b \to s\ell\ell$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[C_9(\mu)\, (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) + C_{10}(\mu)\, (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma^5 \ell) \Big] + \dots$$



Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$.

- Only vector (axial) coefficients can accommodate data.
- $C_9 = -C_{10}$ allowed – predicted by left-handed operator!

See talk by Guadagnoli

Interesting: Conclusion corroborated by global $b \to s\ell\ell$ fit!

cf. e.g. [Capdevilla et al. '19], [Aebischer et al. '19], [Arbey et al.]...

UV completion: $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

Pati-salam unification: [Pati, Salam. '74]

- $\mathcal{G}_{\rm PS} = SU(4) \times SU(2)_L \times SU(2)_R$ contains U_1 as gauge boson.
- Main difficulty: flavor universal $\Rightarrow$ $m_{U_1} \gtrsim 100$ TeV from FCNC.

Viable scenario for B-anomalies: [Di Luzio et al. '17]

- $SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \to \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$
- Flavor violation from (ad-hoc) mixing with vector-like fermions.
- Main feature: $U_1 + Z' + g'$ at the TeV scale.

Rich LHC pheno, cf. [Baker et al. '19], [Di Luzio et al. '18]

Step beyond: $[\mathrm{PS}]^3 = [SU(4) \times SU(2)_L \times SU(2)_R]^3$ [Bordone et al. '17]

- Hierarchical LQ couplings fixed by symmetry breaking pattern.
- Explanation of fermion masses and mixing (flavor puzzle)!

Limits on LQ pair-production

[Angelescu, Becirevic, Faroughy, **OS**. 1808.08179]

Decays	LQs	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$ / Ref.
$jj\,\tau\bar{\tau}$	S_1, R_2, S_3, U_1, U_3	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	R_2, S_3, U_1, U_3	850 (550) GeV	1550 (1290) GeV	12.9 fb^{-1} [49]
$t\bar{t}\,\tau\bar{\tau}$	S_1, R_2, S_3, U_3	900 (560) GeV	1440 (1220) GeV	35.9 fb^{-1} [50]
$jj\,\mu\bar{\mu}$	S_1, R_2, S_3, U_1, U_3	1530 (1275) GeV	2110 (1860) GeV	35.9 fb^{-1} [51]
$b\bar{b}\,\mu\bar{\mu}$	R_2, U_1, U_3	1400 (1160) GeV	1900 (1700) GeV	36.1 fb^{-1} [52]
$t\bar{t}\,\mu\bar{\mu}$	S_1, R_2, S_3, U_3	1420 (950) GeV	1780 (1560) GeV	36.1 fb^{-1} [53, 54]
$jj\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	980 (640) GeV	1790 (1500) GeV	35.9 fb^{-1} [55]
$b\bar{b}\,\nu\bar{\nu}$	S_1, R_2, S_3, U_3	1100 (800) GeV	1810 (1540) GeV	35.9 fb^{-1} [55]
$t\bar{t}\,\nu\bar{\nu}$	R_2, S_3, U_1, U_3	1020 (820) GeV	1780 (1530) GeV	35.9 fb^{-1} [55]

$(g-2)_e$ and $(g-2)_\mu$ from flavor-conserving ALP couplings

[Cornella, Paradisi, **OS**. To appear]