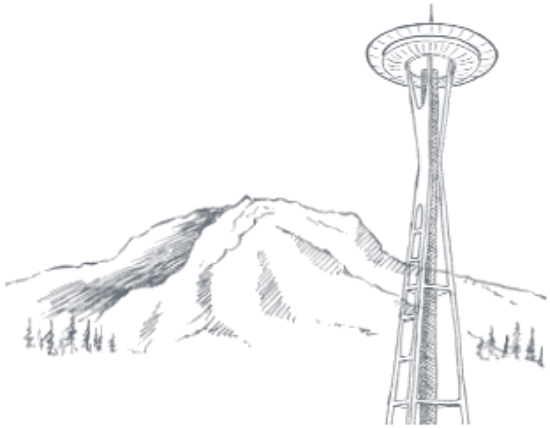
CLFV in heavy quark decays - interplay between LFV and LFUV

Peter Stangl AEC & ITP University of Bern



Community Summer Study

SN WMASS

July 17-26 2022, Seattle

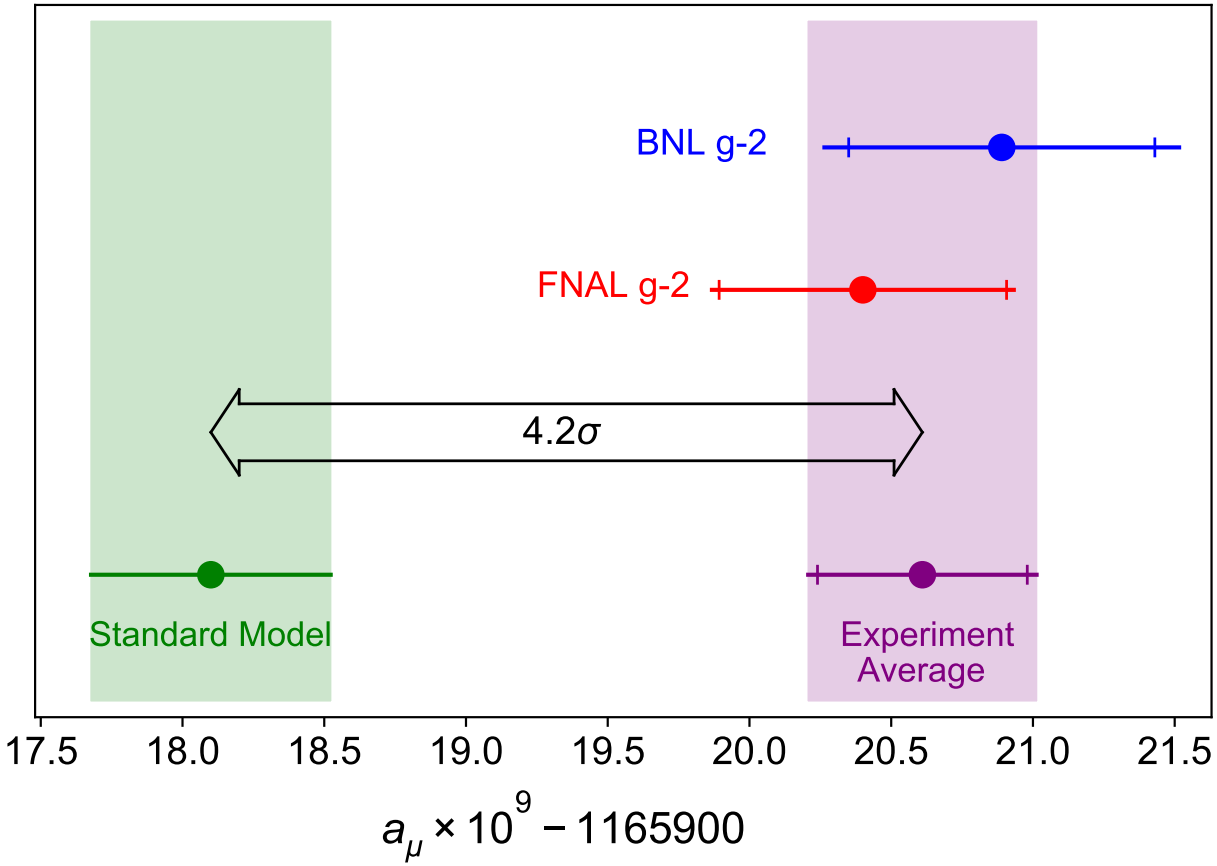
Experimental hints for Lepton Flavor Universality Violation (LFUV)

Muon $(g-2)$

Muon $(g-2)$

Measurements of anomalous magnetic moment of the muon, $(g-2)_\mu$, at BNL and FNAL show combined deviation from SM prediction* by 4.2σ.

The Muon $g-2$ Collaboration, arXiv:hep-ex/0602035
The Muon $g-2$ Collaboration, arXiv:2104.03281



*: no full consensus on hadronic vacuum polarisation contribution, lattice QCD study of BMW Collaboration finds only 1.6σ deviation

BMW Collaboration, arXiv:2002.12347

The $b \to c\ell\nu$ anomalies

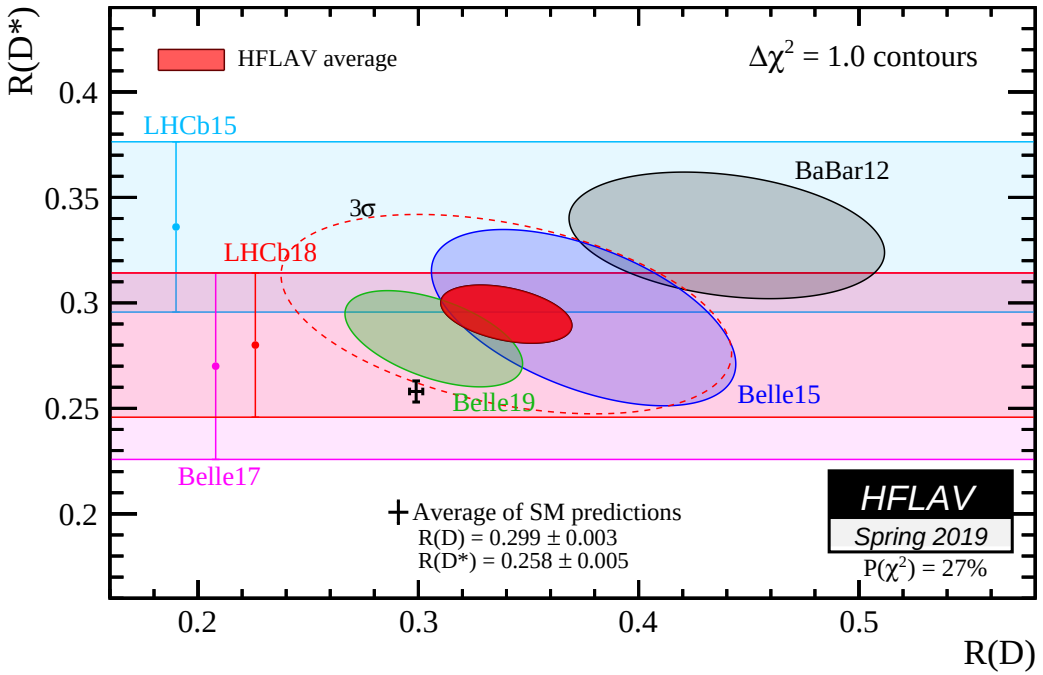
Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3-4σ.

BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$$

$$\ell \in \{e, \mu\}$$



HFLAV, hflav.web.cern.ch

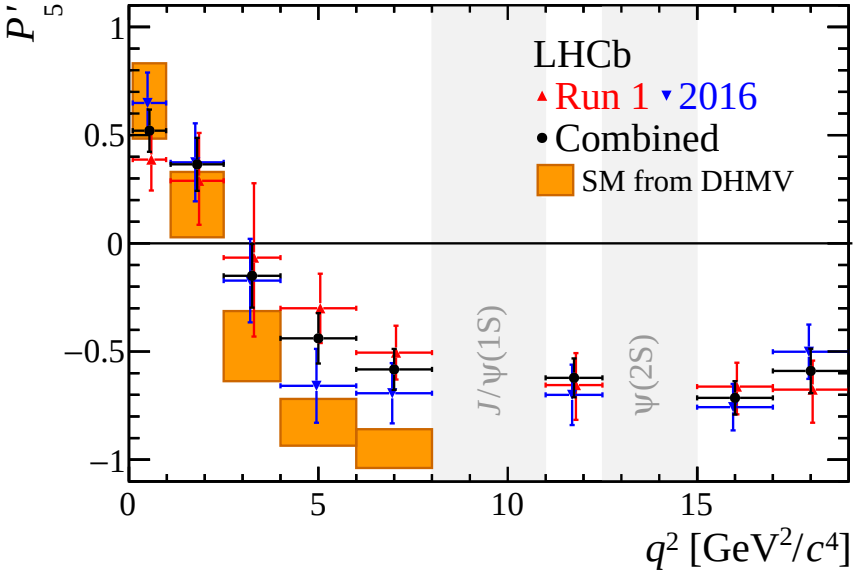
The $b \to s\ell\ell$ anomalies

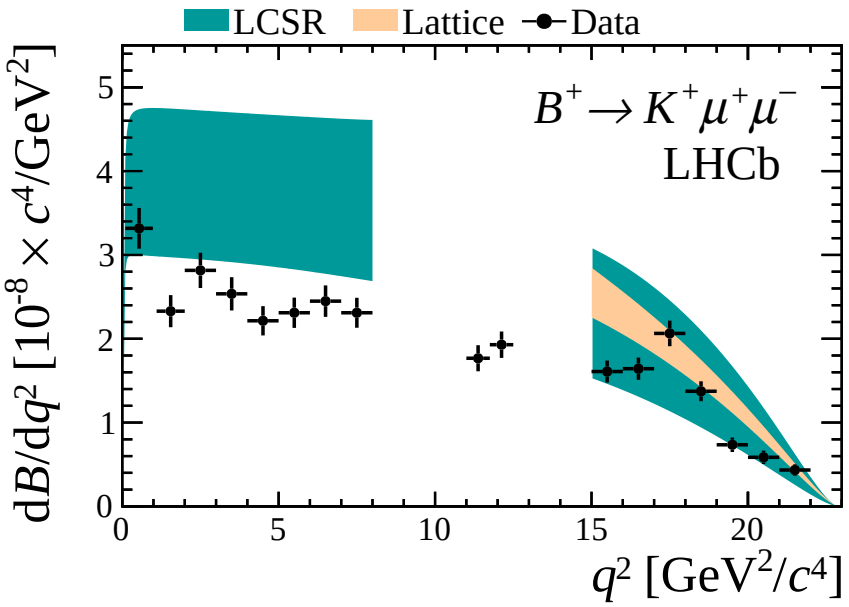
$b \to s\,\mu^+\mu^-$ anomaly

Several LHCb measurements deviate from Standard model (SM) predictions* by 2-3σ:

- Angular observables in $B \to K^*\mu^+\mu^-$. LHCb, arXiv:2003.04831, arXiv:2012.13241
- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$.

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731, arXiv:2105.14007





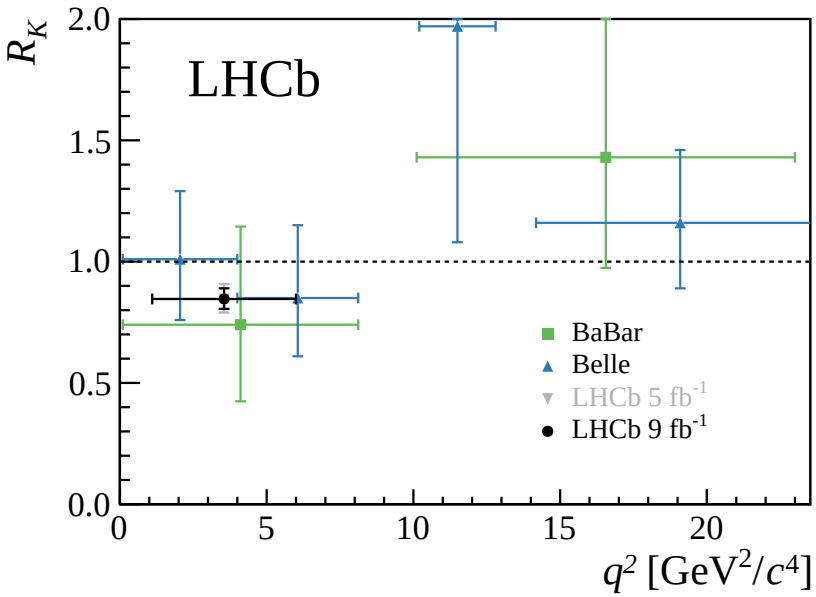
*: based on hadronic assumptions on which there is no theory consensus yet

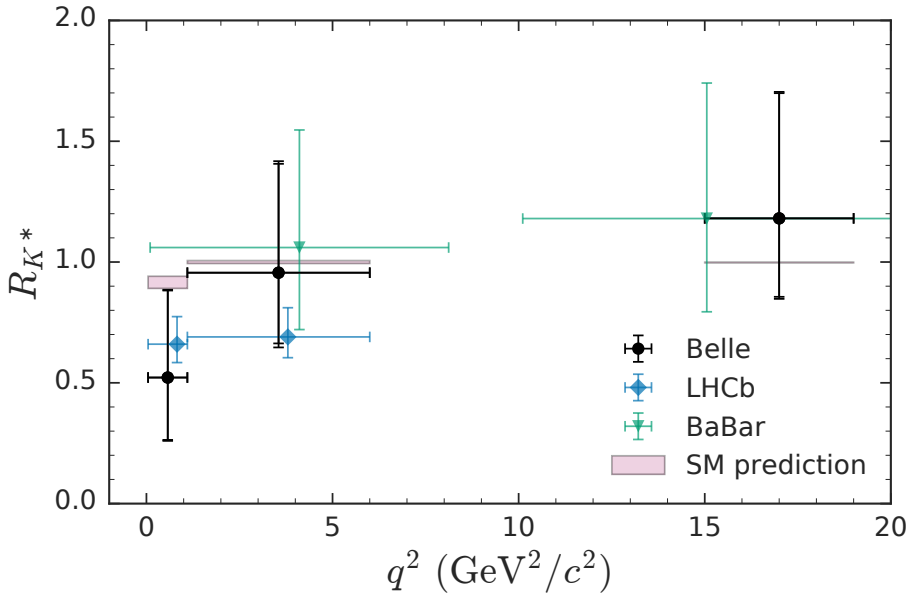
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavor universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$, $R_K^{[1,6]}$ show deviations from SM by 2.3, 2.5, and 3.1σ.

LHCb, arXiv:1705.05802, arXiv:2103.11769
Belle, arXiv:1904.02440, arXiv:1908.01848

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$





“Cleanliness” of $b \to s\ell\ell$ observables in the SM

	parametric uncertainties	local hadr. matrix elements	non-local hadr. matrix elements
$\mathcal{B}(B \to M\ell\ell)$	✗	✗	✗
angular observables	✓	✗	✗
$\overline{\mathcal{B}}(B_s \to \ell\ell)$	✗	✓	✓ (N/A)
LFU observables	✓	✓	✓

LFU observables are very clean in SM!

LFU is approximate **accidental symmetry** of SM!

Experimental observation of LFU violation would be **clear sign of new physics**!

Accidental Symmetries of the SM

Accidental Symmetries of the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{SM}-\text{Yuk}} + \mathcal{L}_{\text{Yuk}}$$

- $\mathcal{L}_{\text{SM}-\text{Yuk}}$ has **accidental global symmetry $U(3)^5$**:

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

- $U(3)^5$ is broken by $\mathcal{L}_{\text{Yuk}} = -\bar{q}\, V^\dagger\, \hat{Y}_u\, \tilde{H}\, u - \bar{q}\, \hat{Y}_d\, H\, d - \bar{l}\, \hat{Y}_e\, H\, e$
  - quark masses $\hat{m}_{u,d} \propto \hat{Y}_{u,d}$ and CKM matrix $V^\dagger$ break
    $U(3)_q \times U(3)_u \times U(3)_d \to U(1)_B$
    $\Rightarrow$ **Baryon number** conserved in $\mathcal{L}_{\text{SM}}$
  - lepton masses $\hat{m}_e \propto \hat{Y}_e$ break
    $U(3)_l \times U(3)_e \to U(1)_e \times U(1)_\mu \times U(1)_\tau$
    $\Rightarrow$ **Individual lepton numbers** conserved in $\mathcal{L}_{\text{SM}}$

A closer look at the lepton sector

Lepton sector in $\mathcal{L}_{\mathrm{SM-Yuk}}$ has accidental global symmetry $U(3)_\ell \times U(3)_e$

- **Lepton Flavor Universality (LFU)**:
  unbroken $\boldsymbol{U(3)_L}$ subgroup of $U(3)_\ell \times U(3)_e$
  - would be exact if $\hat{Y}_e \propto \mathbb{1}$
  - $\hat{Y}_e \ll$ gauge couplings:
    $\Rightarrow$ **LFU is good approximate symmetry** of $\mathcal{L}_{\mathrm{SM}}$, only broken by small $\hat{Y}_e$

- **Lepton Flavor**:
  unbroken $\boldsymbol{U(1)_e \times U(1)_\mu \times U(1)_\tau}$ subgroup of $\boldsymbol{U(3)_L}$
  - exact in $\mathcal{L}_{\mathrm{SM}}$ since $\hat{Y}_e$ is diagonal
  - Including neutrino masses in general breaks $U(1)_e \times U(1)_\mu \times U(1)_\tau \to U(1)_L$ or $\emptyset$ but proportional to tiny neutrino masses
    $\Rightarrow$ **Lepton Flavor is extremely good approximate symmetry** of $\mathcal{L}_{\mathrm{SM}+\nu}$

- $U(3)_\ell \times U(3)_e \quad \supset \quad U(3)_L \quad \supset \quad U(1)_e \times \mathrm{U}(1)_\mu \times U(1)_\tau$
  - **Lepton Flavor Violation (LFV)** $\quad \Rightarrow \quad$ **LFU violation (LFUV)**

    $$\cancel{U(1)_e} \times \cancel{U(1)_\mu} \times \cancel{U(1)_\tau} \quad \Rightarrow \quad \cancel{U(3)_L}$$

  - **Does LFUV imply LVF?** $\to$ not necessarily, **model-dependent!**

Interplay between LFUV and LFV in new physics models

Models with flavor misalignment

Models with flavor misalignment

Glashow, Guadagnoli, Lane, arXiv:1411.0565

- Idea: explain $b \to s\ell\ell$ anomalies with purely "third-generation" coupling and generate couplings to s quark and muon by flavor rotations
- This is possible if UV flavor basis that defines the "third-generation" is different from the mass basis
- Consider effective "third-generation" new physics (NP) interaction

$$\mathcal{H}_{NP} = \frac{C}{\Lambda^2} \left(\bar{b}'_L \gamma^\lambda b'_L\right) \left(\bar{\tau}'_L \gamma_\lambda \tau'_L\right)$$

- Express flavor-basis "third-generation" fields in terms of the mass-basis fields and unitary matrices $U^{d,\ell}_{L3i}$

$$d'_{L3} \equiv b'_L = \sum_{i=1}^{3} U^d_{L3i}\, d_{Li}\,, \quad \ell'_{L3} \equiv \tau'_L = \sum_{i=1}^{3} U^\ell_{L3i}\, \ell_{Li}$$

- If unitary matrices $U^{d,\ell}_{L3i}$ are not diagonal, UV flavor basis and mass basis are misaligned and flavor violating couplings can be generated in the mass basis

Model with flavor misalignment

Glashow, Guadagnoli, Lane, arXiv:1411.0565

- Expressing NP interaction with mass-basis fields yields contribution to $b \to s\mu\mu$

$$\mathcal{H}_{NP} \supset \frac{C}{\Lambda^2} U^{d*}_{L33} U^{d}_{L32} |U^{\ell}_{L32}|^2 \left(\bar{b}_L \gamma^\lambda s_L\right) \left(\bar{\mu}_L \gamma_\lambda \mu_L\right)$$

- Explanation of $b \to s\ell\ell$ anomalies requires non-zero values for U^d_{L33}, U^d_{L32}, U^ℓ_{L32}
- LFV interactions are generated as well and depend also on entries of unitary matrices $U^{d,\ell}_{L3i}$
- **LFV decays** can be **predicted** in terms of $U^{d,\ell}_{L3i}$ and measured processes, e.g.

$$\mathcal{B}(B^+ \to K^+ \mu^\pm e^\mp) \approx 0.05 \left|\frac{U^\ell_{L31}}{U^\ell_{L32}}\right|^2 \mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$$

$$\mathcal{B}(B^+ \to K^+ \mu^\pm \tau^\mp) \approx 0.05 \left|\frac{U^\ell_{L33}}{U^\ell_{L32}}\right|^2 \mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$$

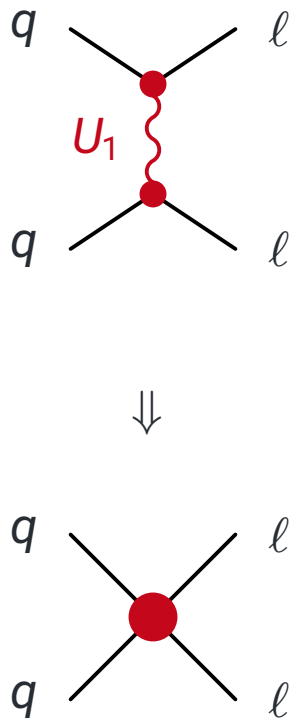
- Without a strict flavor alignment, **LFUV and LFV appear together** and can be related to each other

Combined explanation: The U_1 vector leptoquark

Simplified U_1-leptoquark model

- ***U_1* vector leptoquark** $(\mathbf{3},\mathbf{1})_{2/3}$ couples quarks and leptons

$$\mathcal{L}_{U_1} \supset g_{lq}^{ji} \left(\bar{q}^i \gamma^\mu l^j\right) U_\mu + \text{h.c.}$$



- Generates **semi-leptonic operators at tree-level**
  - $b \to s\ell\ell$ anomalies can be explained by

$$C_9^{\ell_i\ell_j} = -C_{10}^{\ell_i\ell_j} \propto -\frac{g_{lq}^{j2}\, g_{lq}^{i3*}}{2M_U^2}$$

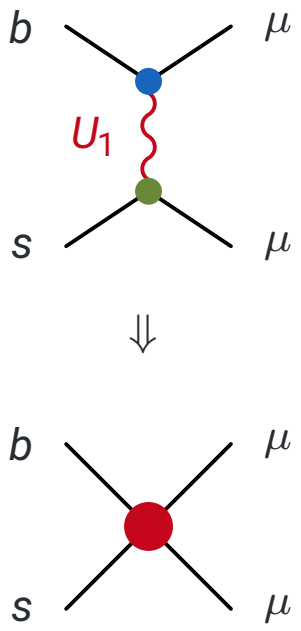
  - $b \to c\ell\nu$ anomalies can be explained by

$$C_V^{\ell_i\ell_j} \propto -\sum_k V_{2k} \frac{g_{lq}^{jk}\, g_{lq}^{i3*}}{M_U^2}$$

Simplified U_1-leptoquark model

Explaining $\boldsymbol{b \to s\ell\ell}$ **and** $\boldsymbol{b \to c\ell\nu}$ anomalies requires couplings to $\boldsymbol{\mu}$ **and** $\boldsymbol{\tau}$
$\Rightarrow$ **lepton flavor violation!**

$b \to s\mu\mu$	$b \to c\tau\nu_\tau$
g_{lq}^{23}	g_{lq}^{33}
g_{lq}^{22}	g_{lq}^{32}



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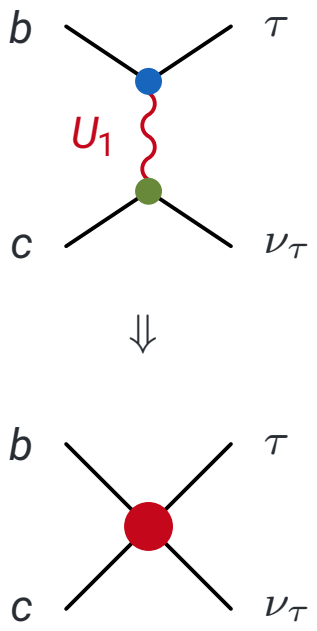

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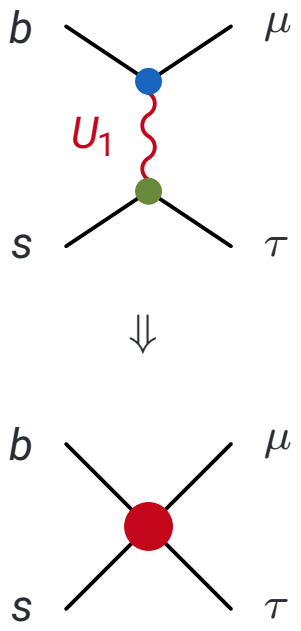
$\Rightarrow$ **lepton flavor violation!**

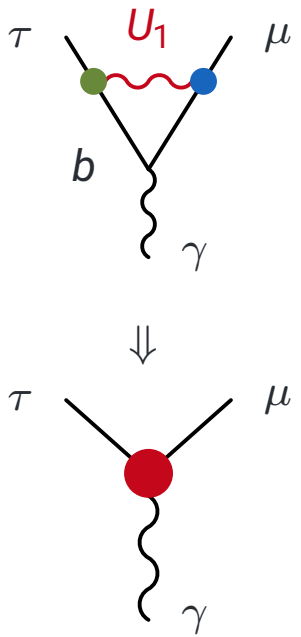
$\boldsymbol{b \to s\mu^-\tau^+}$	$b \to s\mu\mu$	$b \to c\tau\nu_\tau$
	$\boldsymbol{g_{lq}^{23}}$	g_{lq}^{33}
	g_{lq}^{22}	$\boldsymbol{g_{lq}^{32}}$



Simplified U_1-leptoquark model

Explaining $\boldsymbol{b \to s\ell\ell}$ **and** $\boldsymbol{b \to c\ell\nu}$ anomalies requires couplings to $\boldsymbol{\mu}$ **and** $\boldsymbol{\tau}$
$\Rightarrow$ **lepton flavor violation!**

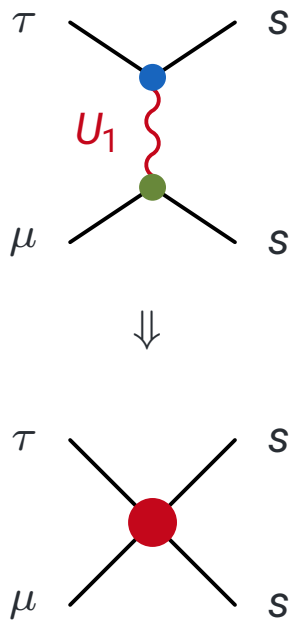
$b \to s\mu^-\tau^+$	$b \to s\mu\mu$	$b \to c\tau\nu_\tau$
$\boldsymbol{\tau \to \mu\gamma}$	$\boldsymbol{g_{lq}^{23}}$	$\boldsymbol{g_{lq}^{33}}$
	g_{lq}^{22}	g_{lq}^{32}



Simplified U_1-leptoquark model

Explaining $\boldsymbol{b \to s\ell\ell}$ **and** $\boldsymbol{b \to c\ell\nu}$ anomalies requires couplings to $\boldsymbol{\mu}$ **and** $\boldsymbol{\tau}$
$\Rightarrow$ **lepton flavor violation!**

$b \to s\mu^-\tau^+$	$b \to s\mu\mu$	$b \to c\tau\nu_\tau$
$\tau \to \mu\gamma$	g_{lq}^{23}	g_{lq}^{33}
$\boldsymbol{\tau \to \mu\bar{s}s, \mu\gamma}$	$\boldsymbol{g_{lq}^{22}}$	$\boldsymbol{g_{lq}^{32}}$



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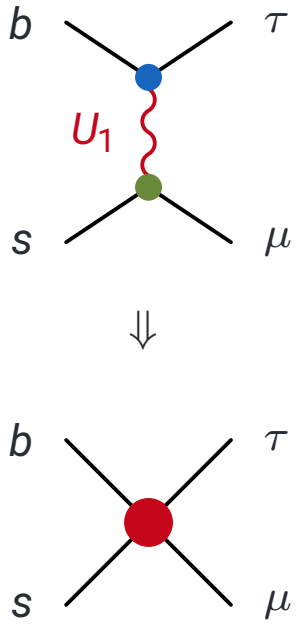
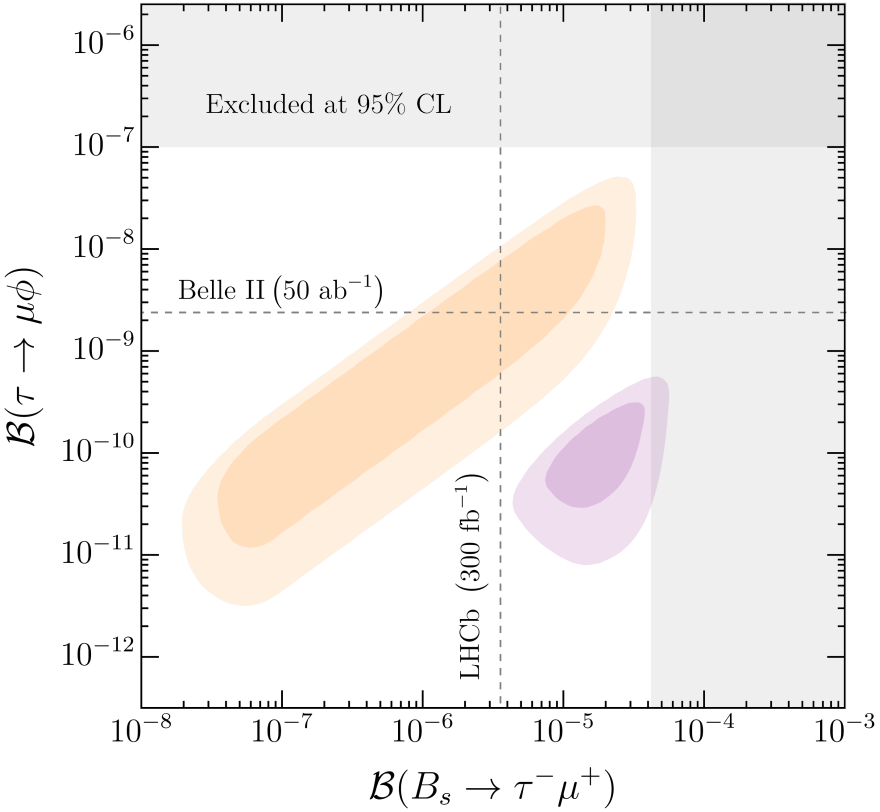
$b \to s\mu^-\tau^+$	$b \to s\mu\mu$	$b \to c\tau\nu_\tau$
$\tau \to \mu\gamma$	g_{lq}^{23}	$\boldsymbol{g_{lq}^{33}}$
$\tau \to \mu\bar{s}s, \mu\gamma$	$\boldsymbol{g_{lq}^{22}}$	g_{lq}^{32}
$\boldsymbol{b \to s\tau^-\mu^+}$		

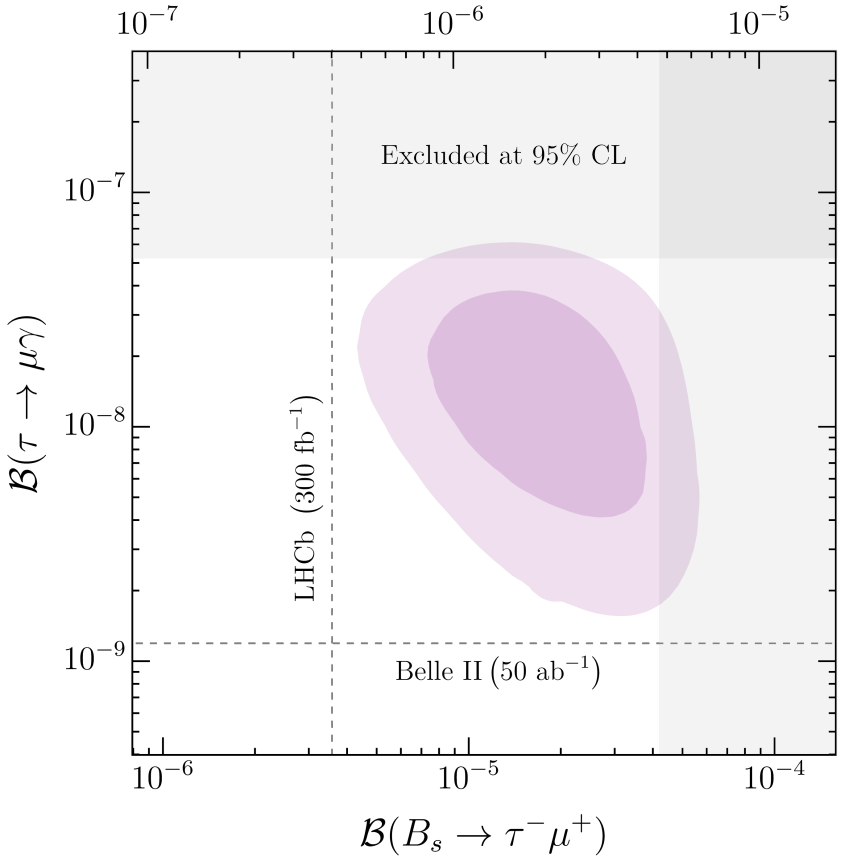


Simplified U_1-leptoquark model - LFV predictions

Comparison of LFV predictions in two versions of the model:

- only left-handed leptoquark couplings
- including a right-handed leptoquark coupling





Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, arXiv:2103.16558

Leptoquarks without LFV

Leptoquarks without LFV

Model setup:

- Effect in $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ can be generated at tree level by scalar leptoquark $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ Hiller, Schmaltz, arXiv:1408.1627
- Generic S_3 couples to all lepton generations $\Rightarrow$ **Lepton Flavour Violation**
- Generic S_3 has di-quark couplings $\Rightarrow$ **proton decay**
- **Strong experimental constraints** on LFV and proton decay

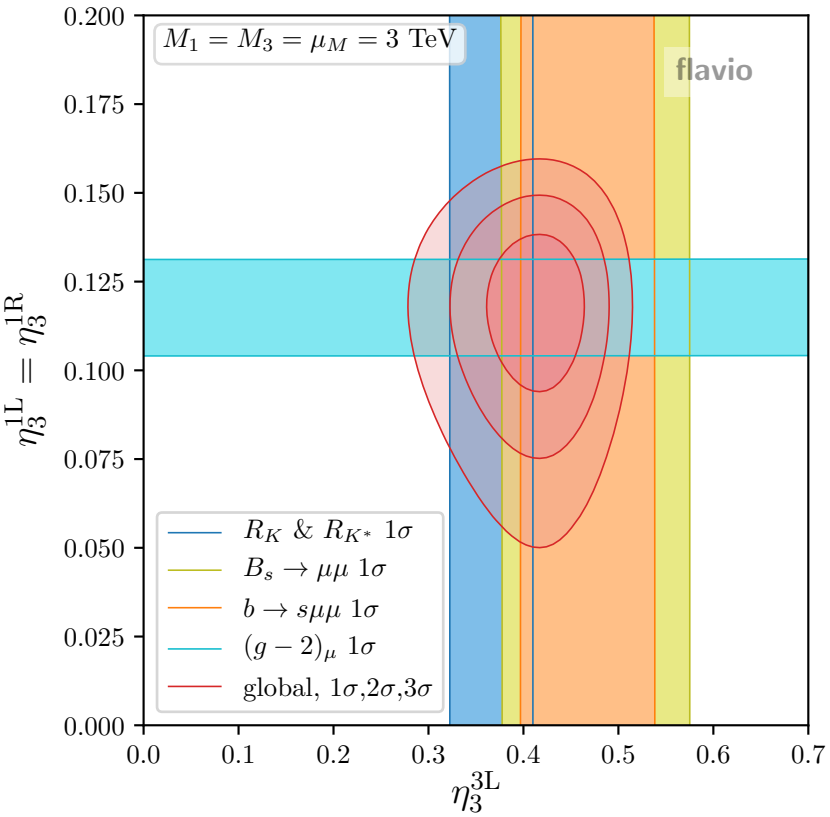
Idea:

- Charge S_3 and muon under **new U(1) gauge symmetry** such that
  - S_3 cannot couple to two quarks $\Rightarrow$ prevents proton decay
  - Muon is only lepton that couples to S_3 $\Rightarrow$ prevents LFV Hambye, Heeck, arXiv:1712.04871 Davighi, Kirk, Nardecchia, arXiv:2007.15016
- Second leptoquark $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ charged under **same U(1)** gauge symmetry receives same protection (only coupling to muons, no LFV, no proton decay) $\Rightarrow$ "**Muoquark**" models **explaining $\mathbf{R_{K^{(*)}}}$** and $(\mathbf{g-2})_\mu$ Greljo, PS, Thomsen, arXiv:2103.13991

A model for muon anomalies

Greljo, PS, Thomsen, arXiv:2103.13991

- $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ and $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ **muoquarks** charged under new $U(1)_X$



$$\eta_i^{3L} = (V_{td},\ V_{ts},\ 1)\,\eta_3^{3L}$$
$$\eta_i^{1L} = (V_{td},\ V_{ts},\ 1)\,\eta_3^{1L}$$
$$\eta_i^{1R} = (0,\ 0,\ 1)\,\eta_3^{1R}$$

- All new Yukawa couplings involve muons:

$$\mathcal{L} \supset \eta_i^{3L}\,\overline{q}_L^{c\,i}\ell_L^2\,S_3 + \eta_i^{1L}\overline{q}_L^{c\,i}\ell_L^2 S_1 + \eta_i^{1R}\overline{u}_R^{c\,i}\mu_R S_1$$

- One-loop matching to SM effective field theory (SMEFT)

  Gherardi, Marzocca, Venturini, arXiv:2003.12525

- Interface to **smelli** - the **SME**FT **L**ike**LI**hood Python package

  Aebischer, Kumar, PS, Straub, arXiv:1810.07698

- Likelihood in space of model parameters

- Excellent fit to data with best fit point at $(\eta_3^{3L}, \eta_3^{1L} = \eta_3^{1R}) \simeq (0.42, 0.12)$ and $\Delta\chi^2 \simeq 56$ compared to SM point $(0, 0)$

- Compatible with all measurements included in smelli (>400 observables)

Conclusions

Conclusions

- Discrepancies in B meson decays **hint** at **Lepton Flavor Universality Violation**.
- There is **no experimental indication** for **Lepton Flavor Violation**.
- **LFV implies LFUV** but whether LFUV implies LFV is model dependent.
- In models with flavor misalignment, LFUV and LFV generically appear together and are related to each other.
- In a U_1 leptoquark model that explains both $b \to s$ and $b \to c$ anomalies, LFV is unavoidable.
- Interactions of leptoquarks can be protected by a gauge symmetry such that the approximate symmetries of the SM are preserved and no LFV couplings appear.
- Searches for LFV decays are extremely useful to distinguish different models and scenarios that explain the hints for LFUV in B decays.

Backup slides