CLFV in heavy quark decays - interplay between LFV and LFUV

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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 4.2\(\sigma\).

* no full consensus on hadronic vacuum polarisation contribution, lattice QCD study of BMW Collaboration finds only 1.6\(\sigma\) deviation

\[ a_\mu \times 10^9 = 1165900 \]
The $b \rightarrow c\ell\nu$ anomalies
Hints for LFU violation in $b \rightarrow c \ell \nu$ decays

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

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

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


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The $b \rightarrow s \ell \ell$ anomalies
$b \rightarrow s \mu^+ \mu^-$ anomaly

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

- Angular observables in $B \rightarrow K^* \mu^+ \mu^-$.  
- Branching ratios of $B \rightarrow K \mu^+ \mu^-, B \rightarrow K^* \mu^+ \mu^-$, and $B_s \rightarrow \phi \mu^+ \mu^-$.  

*: based on hadronic assumptions on which there is no theory consensus yet
Hints for LFU violation in $b \rightarrow s \ell^+ \ell^-$ 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 3.1$\sigma$.

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

### "Cleanliness" of $b \rightarrow s \ell \ell$ observables in the SM

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<tr>
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<th>Parametric uncertainties</th>
<th>Local hadr. matrix elements</th>
<th>Non-local hadr. matrix elements</th>
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<td>$\mathcal{B}(B \rightarrow M \ell \ell)$</td>
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<td>Angular observables</td>
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<td>$\overline{\mathcal{B}}(B_s \rightarrow \ell \ell)$</td>
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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

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

- \( \mathcal{L}_{\text{SM-Yuk}} \) 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
    \[ U(3)_q \times U(3)_u \times U(3)_d \rightarrow U(1)_B \]
    ⇒ **Baryon number** conserved in \( \mathcal{L}_{\text{SM}} \)

  - lepton masses \( \hat{m}_e \propto \hat{Y}_e \) break
    \[ U(3)_l \times U(3)_e \rightarrow U(1)_e \times U(1)_\mu \times U(1)_\tau \]
    ⇒ **Individual lepton numbers** conserved in \( \mathcal{L}_{\text{SM}} \)
A closer look at the lepton sector

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

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

- **Lepton Flavor:**
  - unbroken $U(1)_e \times U(1)_\mu \times U(1)_\tau$ subgroup of $U(3)_L$
  - exact in $\mathcal{L}_\text{SM}$ since $\hat{\mathcal{Y}}_e$ 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 $\mathcal{L}_{\text{SM+}\nu}$

- $U(3)_\ell \times U(3)_e \supset U(3)_L \supset U(1)_e \times U(1)_\mu \times U(1)_\tau$

- **Lepton Flavor Violation (LFV)**
  - $\Rightarrow$ **LFU violation (LFUV)**
    - $U(1)_e \times U(1)_\mu \times U(1)_\tau \Rightarrow U(3)_L$

- **Does LFUV imply LVF?** $\Rightarrow$ not necessarily, **model-dependent!**
Interplay between LFUV and LFV in new physics models
Models with flavor misalignment
Models with flavor misalignment

- Idea: explain $b \rightarrow s\ell\ell$ 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

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

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

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

- If unitary matrices $U_{L3i}^{d,\ell}$ 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

Expressing NP interaction with mass-basis fields yields contribution to

\[ b \rightarrow s \mu\mu \]

\[ \mathcal{H}_{NP} \supset \frac{C}{\Lambda^2} U_{L33}^d U_{L32}^d U_{L32}^\ell |s_L|^2 (\bar{b}_L \gamma^\lambda s_L) (\bar{\mu}_L \gamma^\lambda \mu_L) \]

Explanation of \( b \rightarrow s\ell\ell \) anomalies requires non-zero values for \( U_{L33}^d, U_{L32}^d, U_{L32}^\ell \)

LFV interactions are generated as well and depend also on entries of unitary matrices \( U_{L3i}^{d,\ell} \)

**LFV decays** can be **predicted** in terms of \( U_{L3i}^{d,\ell} \) and measured processes, e.g.

\[
\mathcal{B}(B^+ \rightarrow K^+ \mu^\pm e^\mp) \approx 0.05 \left| \frac{U_{L31}^\ell}{U_{L32}^\ell} \right|^2 \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) \\
\mathcal{B}(B^+ \rightarrow K^+ \mu^\pm \tau^\mp) \approx 0.05 \left| \frac{U_{L33}^\ell}{U_{L32}^\ell} \right|^2 \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)
\]

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** $(3, 1)_{2/3}$ couples quarks and leptons
  \[ \mathcal{L}_{U_1} \supset g_{lq}^{ii} \left( \bar{q}^i \gamma^\mu \ell^j \right) U_{\mu} + \text{h.c.} \]

- Generates **semi-leptonic operators at tree-level**
  - $b \rightarrow s\ell\ell$ anomalies can be explained by
    \[ C_9^{\ell_i \ell_j} = -C_{10}^{\ell_i \ell_j} \propto -\frac{g_{lq}^{i^2} g_{lq}^{i^3*}}{2M_U^2} \]
  - $b \rightarrow c\ell\nu$ anomalies can be explained by
    \[ C_V^{\ell_i \ell_j} \propto -\sum_k V_{2k}^{i^j} \frac{g_{lq}^{j^k} g_{lq}^{j^3*}}{M_U^2} \]
Simplified $U_1$-leptoquark model

Explaining $b \rightarrow s \ell\ell$ and $b \rightarrow c\ell\nu$ anomalies requires couplings to $\mu$ and $\tau$ 

$\Rightarrow$ lepton flavor violation!
Simplified $U_1$-leptoquark model

Explaining $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies requires couplings to $\mu$ and $\tau$ ⇒ lepton flavor violation!

![Diagram showing $b \to s\mu\mu$ and $b \to c\tau\nu\tau$ with couplings $g_{lq}^{23}$, $g_{lq}^{33}$, $g_{lq}^{22}$, and $g_{lq}^{32}$]
Simplified $U_1$-leptoquark model

Explaining $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies requires couplings to $\mu$ and $\tau$ ⇒ lepton flavor violation!

\[ b \to s\mu^-\tau^+ \quad b \to s\mu\mu \quad b \to c\tau\nu_\tau \]

\[ g_{lq}^{23} \quad g_{lq}^{33} \quad g_{lq}^{22} \quad g_{lq}^{32} \]

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Simplified $U_1$-leptoquark model

Explaining $b \rightarrow s \ell \ell$ and $b \rightarrow c \ell \nu$ anomalies requires couplings to $\mu$ and $\tau$ ⇒ lepton flavor violation!

$b \rightarrow s \mu^- \tau^+$; $b \rightarrow s \mu \mu$; $b \rightarrow c \tau \nu_{\tau}$

$\tau \rightarrow \mu \gamma$

$g_{lq}^{23}$; $g_{lq}^{33}$

$g_{lq}^{22}$; $g_{lq}^{32}$
Simplified $U_1$-leptoquark model

Explaining $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$ anomalies requires couplings to $\mu$ and $\tau$ ⇒ lepton flavor violation!

\[
\begin{align*}
    b & \rightarrow s\mu^-\tau^+ & b & \rightarrow s\mu\mu & b & \rightarrow c\tau\nu_	au \\
    \tau & \rightarrow \mu\gamma & g_{lq}^{23} & g_{lq}^{33} \\
    \tau & \rightarrow \mu\bar{S}S, \mu\gamma & g_{lq}^{22} & g_{lq}^{32}
\end{align*}
\]
Simplified $U_1$-leptoquark model

Explaining $b \rightarrow s \ell \ell$ and $b \rightarrow c \ell \nu$ anomalies requires couplings to $\mu$ and $\tau$ ⇒ lepton flavor violation!

\[
\begin{align*}
\tau &\rightarrow \mu \gamma \\
\tau &\rightarrow \mu \bar{s}s, \mu \gamma \\
\tau &\rightarrow s \tau^- \mu^+ \\
b &\rightarrow s \mu^- \tau^+ \\
b &\rightarrow s \mu \mu \\
b &\rightarrow c \tau \nu_	au \\
g_{\ell q}^{23} &\quad g_{\ell q}^{33} \\
g_{\ell q}^{22} &\quad g_{\ell q}^{32}
\end{align*}
\]
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

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 $S_3 \sim (\bar{3}, 3, 1/3)$

- 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

- Second leptoquark $S_1 \sim (\bar{3}, 1, 1/3)$ charged under **same $U(1)$ gauge symmetry**
  - receives same protection (only coupling to muons, no LFV, no proton decay)
  - $\Rightarrow$ **“Muoquark” models explaining $R_K^\ast$ and $(g - 2)_\mu$**

Hiller, Schmaltz, arXiv:1408.1627

Hambye, Heeck, arXiv:1712.04871


Greljo, PS, Thomsen, arXiv:2103.13991
A model for muon anomalies

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

- All new Yukawa couplings involve muons:

$$\mathcal{L} \supset \eta_i^{3L} \bar{q}^c_i \ell^2_L S_3 + \eta_i^{1L} \bar{q}^c_i \ell^2_L S_1 + \eta_i^{1R} \bar{u}^c_i \mu_R S_1$$

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

- Interface to smelli - the SMEFT LikeLIhood Python package

- Likelihood in space of model parameters

- Excellent fit to data with best fit point at $(\eta_3^{3L}, \eta_3^{1L}) \simeq (0.42, 0.12)$ 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 $b \rightarrow s$ and $b \rightarrow c$ 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