Overview

- Short overview of $b \rightarrow s$ and $b \rightarrow c$ data
- LFV in $B$ decays: general arguments
- LFV in Kaon decays?
- Status of searches
Collider Data

- No direct evidence of BSM at colliders
- A coherent set of discrepancies in B decays

$\textbf{1}\quad b \to s \mu\mu\quad \text{BR data} < \text{SM}$

Challenge: $B \to \text{light meson f.f.'s}$
$b \rightarrow s \mu \mu$ BR data $< SM$
Collider Data

- No direct evidence of BSM at colliders
- A coherent set of discrepancies in B decays

1. \( b \to s \, \mu\mu \) BR data < SM
   Challenge: \( B \to \) light meson f.f.'s

2. \( B \to K^* \, \mu\mu \) angular data
   Challenge: charm loops

3. \( b \to s \, \mu\mu / b \to s \, ee \) ratios
   Challenge: (mostly) stats

4. \( b \to c \, \tau\nu / b \to c \, \ell\nu \) ratios
   Challenge: stats + syst

D. Guadagnoli, 20th Lomonosov Conference
Minimal TH considerations

(before any fit)
**EFT considerations**

1. **Quite remarkably, most data hint at shifts to just 2 eff. couplings**

   \[
   H(\bar{b} \rightarrow \bar{s} \mu \mu) = -\frac{4 G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{em}}{4 \pi} \left[ \bar{b}_L \gamma^\lambda s_L \cdot \left( C_9^{(\mu)} \bar{\mu} \gamma_\lambda \mu + C_{10}^{(\mu)} \bar{\mu} \gamma_\lambda \gamma_5 \mu \right) \right] + \text{RH-quark ops.} + \text{dipoles} + \text{scalar & tensor ops.}
   \]

   Effects are (mostly) here

2. **Also remarkably, two scenarios stand out:**

   \[
   dC_9^{(\mu)} \text{ alone}
   \]

   \[
   dC_9^{(\mu)} = -dC_{10}^{(\mu)} \quad \text{[Hiller-Schmaltz, 2014]}
   \]

   This op. combination can be written in terms of SU(2)_L invariants
   \[
   \text{[Alonso, Grinstein, M.Camalich, 2014]}
   \]

   Well-suited to UV-complete models
More on $dC_9^{(\mu)}$ vs. $dC_9^{(\mu)} = -dC_{10}^{(\mu)}$

How to resolve between the two scenarios?

Accurate $B_s \rightarrow \mu\mu$ measurement

- present single-measurement error $\approx 20\%$
- $exp$ combi may soon be able to confirm or exclude deviations of $C_{10}$ of $O(10\%)$
More TH considerations

3 Pattern of Lepton Universality Violation in \( b \to s \)

The observed new-physics hierarchy:

\[
\text{effects in } ee \ll \text{effects in } \mu\mu \ll (\text{allowed}) \text{ effects in } \tau\tau
\]

suggestive of NP coupled dominantly to 3\textsuperscript{rd} gen. SM fermions

[Glashow et al., 2015]

4 ... which in turn makes it natural to link \( b \to s \) and \( b \to c \) data

[Bhattacharyya et al., 2015]

Data now allow to disprove some, and to make more precise some other of these considerations
### 1-Wilson-coeff. picture

[Carvunis et al., 2102.13390]

[See Altmannshofer-Stangl, 2103.13370, for a comprehensive discussion including CPV]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pre-Moriond 2021</th>
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<th>Post-Moriond 2021</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Best-fit</td>
<td>Pull</td>
<td>p-value</td>
<td>Best-fit</td>
<td>Pull</td>
<td>p-value</td>
</tr>
<tr>
<td>$C_7$</td>
<td>IR</td>
<td>$-0.0079$</td>
<td>$0.58 \sigma$</td>
<td>$0.11%$</td>
<td>$-0.0079$</td>
<td>$0.57 \sigma$</td>
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<tr>
<td></td>
<td>C</td>
<td>$-0.0045 - 0.056 i$</td>
<td>$0.61 \sigma$</td>
<td>$0.11%$</td>
<td>$-0.0044 - 0.056 i$</td>
<td>$0.61 \sigma$</td>
</tr>
<tr>
<td>$C_9$</td>
<td>IR</td>
<td>$-0.97$</td>
<td>$6.4 \sigma$</td>
<td>$10.0%$</td>
<td>$-0.93$</td>
<td>$6.7 \sigma$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$-0.98 - 0.22 i$</td>
<td>$6.1 \sigma$</td>
<td>$9.4%$</td>
<td>$-0.93 - 0.25 i$</td>
<td>$6.4 \sigma$</td>
</tr>
<tr>
<td>$C_{10}$</td>
<td>IR</td>
<td>$0.72$</td>
<td>$5.8 \sigma$</td>
<td>$6.1%$</td>
<td>$0.68$</td>
<td>$6.0 \sigma$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$0.80 + 0.74 i$</td>
<td>$5.6 \sigma$</td>
<td>$6.0%$</td>
<td>$0.76 + 0.75 i$</td>
<td>$5.8 \sigma$</td>
</tr>
<tr>
<td>$C_{LL}$</td>
<td>IR</td>
<td>$-1.1$</td>
<td>$6.9 \sigma$</td>
<td>$18.0%$</td>
<td>$-0.96$</td>
<td>$7.0 \sigma$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$-1.2 - 1.5 i$</td>
<td>$6.7 \sigma$</td>
<td>$18.0%$</td>
<td>$-1.1 - 1.4 i$</td>
<td>$6.8 \sigma$</td>
</tr>
</tbody>
</table>
- Two scenarios stand out: $C_9$ alone or $C_9 = -C_{10}$ (μμ-channel only)
- $C_{10}$ alone also ok, but angular $B \rightarrow K^* \mu \mu$ anomaly unresolved
Why LFV

If we observe LUV, then, in general we should expect observable LFV as well.

Exceptions require that the specific LUV dynamics has some ad hoc symmetry that prevents LFV.
Model zero

- All $b \rightarrow s$ data are explained at one stroke if one assumes
  - $(V - A)_q \times (V - A)_\ell$ structure
  - with Wilson-coeff. shift much larger for $\mu\mu$ than for $ee$

- Such pattern can be obtained from a purely 3$^{rd}$-generation interaction of the kind [Glashow et al., 1411.0565]

\[
H_{NP} = G \left( \bar{b}'_L \gamma^\lambda b'_L \right) \left( \bar{\tau}'_L \gamma^\lambda \tau'_L \right)
\]

with $G = 1/\Lambda_{NP}^2 \ll G_F$
• **Note:** primed fields in $H_{NP} = G \left( \bar{b}'_L \gamma^\lambda b'_L \right) \left( \bar{\tau}'_L \gamma^\lambda \tau'_L \right)$

- Above the EWSB scale, fields are in the “gauge” basis, not the mass eigenbasis

- Mass-basis unitary transformations induces LUV and LFV effects

- $b'_L \equiv (d'_L)_3 = \left| U^d_L \right|_{3i} (d_L)_i$

- $\tau'_L \equiv (\ell'_L)_3 = \left| U^\ell_L \right|_{3i} (\ell_L)_i$

• One can then parametrically relate measured LUV ($R_{K(*)}$) to LFV decays such as $B \rightarrow (K) \tau\mu$

$$BR\left( B^+ \rightarrow K^+ \ell^+_1 \ell_2^+ \right) \simeq 2 \left( \frac{\sqrt{R_K}-1}{R_K} \right)^2 \cdot \text{func.}(U^\ell_L \text{ ratios}) \cdot BR\left( B^+ \rightarrow K^+ \mu \mu \right) = 2\%$$

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$BRs \sim 10^{-8}$ expected, for generic choices of $U$ matrices

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• **Note:** primed fields in \( H_{NP} = G \left( \bar{b}'_L \gamma^\lambda b'_L \right) \left( \bar{\tau}'_L \gamma^\lambda \tau'_L \right) \)

- Above the EWSB scale, fields are in the “gauge” basis, not the mass eigenbasis
- Mass-basis unitary transformations induces LUV and LFV effects

\[
b'_L = (d'_L)_3 = \begin{pmatrix} U^{d}_L \end{pmatrix}_{3i} (d_L)_i
\]
\[
\tau'_L = (\ell'_L)_3 = \begin{pmatrix} U^{\ell}_L \end{pmatrix}_{3i} (\ell_L)_i
\]

• One can then parametrically relate measured LUV (\( R_{K^{(*)}} \)) to LFV decays such as \( B \to (K) \tau \mu \) \[\text{[Glashow et al., 1411.0565]}\]

\[
BR(B^+ \to K^+ \ell^+_1 \ell^-_2) \approx 2 \left( \frac{\sqrt{R_K} - 1}{R_K} \right)^2 \cdot \text{func.} \left( U^{\ell}_L \right) \cdot BR(B^+ \to K^+ \mu \mu) = 2\% \\
= 4 \times 10^{-7}
\]

\( BRs \sim 10^{-8} \) expected, for generic choices of \( U \) matrices
Actually certain LFV decays represent strong constraints.

Given, at the UV matching scale

\[ \mathcal{L}_{NP}^0(\Lambda) = \frac{1}{\Lambda^2} \left( C_1 \bar{d} \gamma^\mu d L \bar{\ell} \gamma_\mu \ell L + C_3 \bar{d} \gamma^\mu \tau^a d L \bar{\ell} \gamma_\mu \tau^a \ell L \right) \]

close the quark loop & attach a gauge boson → two further leptons
Explicit UV-complete constructions (ex. the U1 vector leptoquark) generally predict B-decay LFV while fulfilling leptonic-LFV limits.

Example: models based on the so-called (Pati-Salam)\(^3\)

General prediction: large \(\tau \rightarrow \mu\) effective coupling due to assumed \(U(2)^5\) flavor symmetry and its breaking pattern.

\[
\begin{align*}
\mathcal{B}(B_s \rightarrow \tau^+ \mu^-) &\approx 2 \times 10^{-4} \left( \frac{\Delta R_K}{0.3} \right)^2 \left( \frac{0.1}{s_\tau} \right)^2, \\
\mathcal{B}(B \rightarrow K^* \tau^+ \mu^-) &\approx 1.5 \times 10^{-6} \left( \frac{\Delta R_K}{0.3} \right)^2 \left( \frac{0.1}{s_\tau} \right)^2, \\
\mathcal{B}(B^+ \rightarrow K^+ \tau^+ \mu^-) &\approx 2 \times 10^{-5} \left( \frac{\Delta R_K}{0.3} \right)^2 \left( \frac{0.1}{s_\tau} \right)^2,
\end{align*}
\]
to compare e.g. with
\[
\text{BR}(B^+ \rightarrow K^+ \mu^- \tau^+) < 3.9 \times 10^{-5}
\]

[Bordone, Cornella, Fuentes-M, Isidori, ‘18]

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LFV in Kaon decays?
The putative new dynamics in B decays may yield correlated effects in suitable K decays.

Especially interesting examples include

\[ K \to \pi \nu \bar{\nu} \quad K \to (\pi)\mu e \]

It turns out that B-physics machines can offer complementary info on these decays w.r.t. Kaon machines, because of

- the large amounts of Kaons produced
- the excellent decay-reconstruction capabilities (e.g. for \( K_s \))
The new physics for B decays can usually be described by

\[ \mathcal{L}_{\text{eff}} \supset \frac{C_{ijkl}^{(a)}}{\Lambda^2} \mathcal{O}_{ijkl}^{(a)} \]

- two-quark \( \{ i, j \} \)
- two-lepton \( \{ k, l \} \)

New scale \( \Lambda \) may be fixed by size of observed discrepancies (typically \( \Lambda = \text{few to 10 x few TeV} \)) [Di Luzio, Nardecchia, 1706.01868]

The \( C \) couplings encode flavor structure. If dynamics tree-level:

- for new colorless massive bosons
  \[ C_{ijkl} \sim \lambda_{ij}^{(q)} \lambda_{kl}^{(\ell)} \]

- for leptoquarks
  \[ C_{ijkl} \sim \lambda_{il}^{(q\ell)} (\lambda_{jk}^{(q\ell)})^* \]

In many motivated scenarios, the \( \lambda \)'s entering B decays and those entering K decays are highly correlated

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LHCb may well improve existing limits on $K_L \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu e$

[Borsato et al., 1808.02006][Alves Jr. et al., 1808.03477]

Example

**TH assumptions**

- $(V-A) \times (V-A)$, $SU(2)_L$-invariant $qq\ell\ell$ Hamiltonian adopted in [Buttazzo et al., 1706.07808] to explain $B$ anomalies

- CKM-like ansatz for the $\lambda^{(q)}$ coupling

- Agnostic on the $\lambda^{(\ell)}$ coupling
Status
of LFV searches
Since the connection “measured LUV ↔ measurable LFV” was pointed out, many exp searches have been performed see e.g. [P. de Simone, EPJ WoC 2020]

All modes involve two leptons with different flavours

Muons are the easiest

Best searches: $\mu e$ and $\mu \tau$

Sensitivity relies on background control:
- combinatorial; semi-lept. or resonant ($c\bar{c}$) with mis-ID;

Challenges to “close the kinematics”
- electrons radiate
- taus decay, involving missing energy
Many recent stringent searches

\[ B^+ \rightarrow K^+ \mu^\pm e^\mp \]  
\[ B(B^+ \rightarrow K^+ \mu^- e^+) < 7.0 (9.5) \times 10^{-9} \quad B(B^+ \rightarrow K^+ \mu^+ e^-) < 6.4 (8.8) \times 10^{-9} \]  
\[ B(B^+ \rightarrow K^+ \mu^- \tau^+) < 3.9 \times 10^{-5} \]  
\[ B(B^+ \rightarrow K^+ \mu^- \tau^-) < 3.9 \times 10^{-5} \]  
\[ B(B^0 \rightarrow e^\pm \mu^\mp) \]  
\[ B(B^0 \rightarrow e^\pm \mu^\mp) < 5.4 (6.3) \times 10^{-9} \quad B(B^0 \rightarrow e^\pm \mu^\mp) < 1.0 (1.3) \times 10^{-9} \]  
\[ B(B^0 \rightarrow \tau^\pm \mu^\mp) \]  
\[ B(B^0 \rightarrow \tau^\pm \mu^\mp) < 4.2 \times 10^{-5} \quad B(B^0 \rightarrow \tau^\pm \mu^\mp) < 1.4 \times 10^{-5} \]  

Notes: some limits are 90%, some other 95% CL; previous limits are from BaBar
Conclusions

- As of Moriond 2021, B anomalies hold their ground
  One clear hint: beyond-SM LUV

- LUV and LFV are two sides of the same broken symmetry
  i.e. to prevent LFV requires an additional ad hoc assumption
  Generally, models explaining the B anomalies also predict LFV

- By general arguments, from the measured LUV one can expect
  LFV BRs ~ $10^{-8}$ (e.g. in $B \rightarrow K \tau\mu$)

- Using EFT-driven arguments,
  K physics offers potential complementary probes