Flavour anomalies in $b \rightarrow s\ell\ell$ decays

A review

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Standard Model

- **Successful recipe:**
  - 3 generations of quarks + leptons
  - only differing in mass
  - weak, strong & EM force
  - “gauge” bosons: $\gamma$, $W^\pm$, $Z^0$, $g$
  - Higgs boson $\rightarrow$ masses

- **Problems!**
  - what is dark matter?
  - origin of flavour structure?
  - origin of neutrino masses?
  - where did antimatter go?

“New Physics” out there?
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“New Physics” out there?
$\mathcal{L}_{SM} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$
Under the hood

\[ \mathcal{L}_{SM} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} \]

\[ \mathcal{L}_{\text{gauge}} = \sum_{i=1}^{3} \sum_{\psi} \bar{\psi}^i i \gamma \cdot D \psi^i - \frac{1}{4} \left[ G^a \cdot G^a + \vec{W} \cdot \vec{W} + B \cdot B \right], \]

with \( \gamma \cdot D = \gamma^\mu D^\mu \) and \( D^\mu = \partial^\mu - i g s T^a G^a_{\mu} - i g T^a W^a_{\mu} - i g' Y B^a_{\mu}. \)

\[ \psi^i = Q^i_L, u^i_R, d^i_R, L^i_L, e^i_R; \quad Q^i_L = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}; \quad L^i_L = \begin{pmatrix} \nu^i_L \\ e^i_L \end{pmatrix}. \]
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Fields \( \psi \) exist in 3 copies (families): \( i = 1, 2, 3 \) is the flavour index. Gauge interactions are the same for all families: flavour symmetry.
Under the hood

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\[ \mathcal{L}_{\text{Higgs}} = \mathcal{L}_H + \mathcal{L}_{\text{Yukawa}} \]

\[ \mathcal{L}_H = D_\mu H^\dagger D_\mu H + \frac{\lambda}{4} \left( H^\dagger H - \frac{v^2}{2} \right)^2 \]

\[ \mathcal{L}_{\text{Yukawa}} = \bar{Q}_L^i Y_{d}^{ij} d_R^j H + \bar{Q}_L^i Y_{u}^{ij} u_R^j H_c + \bar{L}_L^i Y_{e}^{ij} e_R^j H \]

\[ \mathcal{L}_{\text{Yukawa}} \text{ distinguishes} \] the three families.

Flavour physics is the study of different generations of fermions.
Lepton flavour in the Standard Model

Lepton generations differ **only in mass**.

- **Flavour symmetry** of $L_{\text{gauge}}$: amplitudes of processes with $e, \mu, \tau$ are identical (except phase space effects)

  This is called **Lepton Flavour Universality (LFU)**.

- e.g. the decay $W \to \ell \nu$:

- LFU well established in the decay of light mesons, e.g. $\pi \to \ell \nu, K \to \pi \ell \ell, J/\psi \to \ell \ell$

- **Lepton Flavour (LF)** is conserved (for massless $\nu$): no $\ell_1 \leftrightarrow \ell_2$

  - stringent limits on LF violating decays:

    $\mu \to e\gamma \times, K \to \pi e\mu \times$  

    ($\mathcal{B} \lesssim 10^{-13}$) [Eur.Phys.J.C76(2016)8,434]  

    ($\mathcal{B} \lesssim 10^{-11}$) [Phys.Rev.D72(2005)012005]

- **LFU or LF** → **unknown physics** not accounted for

  - some SM extensions include particles that can cause LFU and/or LF (e.g. LQ, $Z'$)
Lepton flavour in $b$ decays

- **Charged current decays (CC):** “$\beta$ decays” of $B$ hadrons.
  - tree level, large $B \sim$ few %
  - strong and weak part factorize $\Rightarrow$ clean SM predictions

- **Neutral current decays (NC):** “penguins” and “boxes”
  - Flavour-Changing Neutral Currents, can only occur in loops: $B \sim 10^{-7} \div 10^{-6}$
  - new particles can enhance SM-suppressed amplitudes
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- **Charged current decays (CC):** “$\beta$ decays” of $B$ hadrons.
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  - hints of $\text{LFU}$ in $b \to c\ell\nu$, $\ell = \mu, \tau$

- **Neutral current decays (NC):** “penguins” and “boxes”
  - Flavour-Changing Neutral Currents, can only occur in loops: $B \sim 10^{-7} \div 10^{-6}$
  - new particles can enhance SM-suppressed amplitudes
  - anomalies in $b \to s\ell\ell$ transitions, $\ell = e, \mu$, including $3\sigma$ evidence of $\text{LFU}$ at LHCb
\( b \rightarrow s\ell\ell \) as a test for the SM

- new physics diagrams can modify measured observables

- model-independent approach: build Fermi-like effective theory with point-like interaction thanks to \( m_b \ll m_W \)

\[
\mathcal{L} \propto \sum_i C_i O_i, \quad C_i = C_i^{\text{SM}} + C_i^{\text{NP}}
\]

“Wilson coefficients”

- SM operators for \( b \rightarrow s\ell^+\ell^- \):

\[
O_7 = \left( \bar{b} \sigma_{\mu\nu} P_R s \right) F^{\mu\nu} \quad \text{(photon, not Fermi-like!)}
\]

\[
O_9 = \left( \bar{b} \gamma_\mu P_L s \right) \left( \bar{\ell} \gamma^\mu \ell \right)
\]

\[
O_{10} = \left( \bar{b} \gamma_\mu P_L s \right) \left( \bar{\ell} \gamma^\mu \gamma^5 \ell \right)
\]
$b \to s\ell\ell$ as a test for the SM

- new physics diagrams can modify measured observables
- model-independent approach: build Fermi-like effective theory with point-like interaction thanks to $m_b \ll m_W$

$$\mathcal{L} \propto \sum_i C_i \mathcal{O}_i, \quad C_i \equiv C_i^{\text{SM}} + C_i^{\text{NP}} \quad \text{“Wilson coefficients”}$$

- SM operators for $b \to s\ell^+\ell^-$:

$$\mathcal{O}_7 = (\bar{b} \sigma_{\mu\nu} P_R s) F^{\mu\nu} \quad \text{(photon, not Fermi-like!)}$$

$$\mathcal{O}_9 = (\bar{b} \gamma_{\mu} P_L s) (\bar{\ell} \gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{b} \gamma_{\mu} P_L s) (\bar{\ell} \gamma^\mu \gamma^5 \ell)$$
\( b \rightarrow s\ell\ell \) as a test for the SM

- **new physics** diagrams can modify measured observables
- **model-independent** approach: build Fermi-like *effective theory* with point-like interaction thanks to \( m_b \ll m_W \)

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- **SM operators** for \( b \rightarrow s\ell^+\ell^- \):
  
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  \[
  \mathcal{O}_{10} = (\bar{b} \gamma_\mu P_L s) (\bar{\ell} \gamma^\mu \gamma^5 \ell)
  \]
Over the past decade, LHCb observed a coherent set of tensions with respect to the SM predictions:

1. **Branching Fractions**
   \[ B \rightarrow K(\ast)\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^-, \Lambda_b \rightarrow \Lambda\mu^+\mu^- \]
   suffer from uncertainties related to the hadronic matrix element

2. **Angular observables**
   \[ B \rightarrow K(\ast)\mu^+\mu^-, \Lambda_b \rightarrow \Lambda\mu^+\mu^- \]
   profit from cancellation of most form factors

3. **Ratios of branching fractions involving \( \mu/e \)**
   \[ B^0 \rightarrow K^{*0}\ell^+\ell^-, B^+ \rightarrow K^+\ell^+\ell^- \]
   all theoretical uncertainties cancel
$b \rightarrow s\ell\ell$ branching fractions

- exclude $c\bar{c}$ resonances (different physics)
- deficit of decays to muons found in $B^0,+ \rightarrow K^0,+ \mu^+ \mu^-$, $B^0,+ \rightarrow K^{*0},+ \mu^+ \mu^-$, $\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$, $B_s^0 \rightarrow \phi \mu^+ \mu^-$
  - recent result suggests decays to electrons are SM-like
- new analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ in agreement with Run 1, and $3.6\sigma$ tension with the SM
$b \rightarrow s\ell\ell$ angular observables

- use angular observables to measure Wilson coefficients
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - local tension in $P'_5$ confirmed by 2016 data
  - global tension of 3.3$\sigma$ with SM
- $B^+ \rightarrow K^{*+} \mu^+ \mu^-$: global 3.1$\sigma$ tension with SM
- $B^+_s \rightarrow \phi \mu^+ \mu^-$ consistent with SM at 1.9$\sigma$
- coherent trends pointing at $\text{Re}(\Delta C_9) \approx -1$

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

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Lepton flavour universality tests in $b \to s \ell\ell$

- Ratios of the form

$$R_{Xs} = \frac{\mathcal{B}(B \to X_s \mu^+\mu^-)}{\mathcal{B}(B \to X_s e^+e^-)}$$

are equal to unity in the SM and free from QCD uncertainties that potentially affect BFs and angular observables

$\rightarrow$ e.g. $\mathcal{O}(10^{-4})$ uncertainty on $R_K$

- up to $\mathcal{O}(1\%)$ QED corrections

$\rightarrow$ extremely powerful tools to look for deviations from the SM!
Electrons vs muons

- while $\mu^\pm$ fly through, $e^\pm$ lose energy in the detector
- most $e^\pm$ emit a Bremsstrahlung photon before the magnet → $brem$ recovery
- high occupancy in calorimeter $\Rightarrow$ high L0 thresholds
- $e^\pm$ also suffer from worse PID and tracking efficiency

$B^+ \rightarrow K^+ \mu^+ \mu^-$

$B^+ \rightarrow K^+ e^+ e^-$
\( R_{X_s} \) at LHCb

- the \( X_s \ell^+\ell^- \) final state can also result from a \( B \rightarrow X_s J/\psi \) decay → measure \( R_{X_s} \) in a \( q^2 \) range that excludes \( c\bar{c} \) resonances

- \( B \rightarrow X_s J/\psi \left( \rightarrow \ell^+\ell^- \right) \) share similar topology as \( B \rightarrow X_s \ell^+\ell^- \) → reduce systematics related to \( e/\mu \) differences

- \( R_{X_s} \) is measured as a double ratio:

\[
R_{X_s} \equiv \frac{\mathcal{B}(B \rightarrow X_s \ell^+\ell^-)}{\mathcal{B}(B \rightarrow X_s e^+e^-)} / r_{J/\psi} \\
\equiv \frac{\mathcal{B}(B \rightarrow X_s \ell^+\ell^-)}{\mathcal{B}(B \rightarrow X_s J/\psi \left( \rightarrow \ell^+\ell^- \right))} \frac{\mathcal{B}(B \rightarrow X_s J/\psi \left( \rightarrow e^+e^- \right))}{\mathcal{B}(B \rightarrow X_s e^+e^-)}
\]

- Note: \( J/\psi \rightarrow \ell\ell \) decays are lepton universal (\( r_{J/\psi} = 1_{(SM)} \))
**$R_K$ and $R_{K^*}$ results**

- All LHCb measurements are below 1:
  - $R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low $q^2$ (2.2σ below SM)
  - $R_{K^*} = 0.66^{+0.11}_{-0.07} \pm 0.05$ at central $q^2$ (2.4σ below SM)
  - **New!** $R_K = 0.846^{+0.044}_{-0.041}$ at central $q^2$ (3.1σ below SM)

- $B$ factories have less precise but compatible results

- More $R_X$ measurements upcoming with other $b \to s\ell\ell$-mediated decays

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\[ \text{[LHCb $R_{K^*}$ 3 fb}^{-1}: \text{JHEP08(2017)055]} \quad \text{[LHCb $R_K$ 3 fb}^{-1}: \text{PRL113(2014)151601]} \quad \text{[LHCb 5 fb}^{-1}: \text{PRL122(2019)191801]} \quad \text{[LHCb 9 fb}^{-1}: \text{hep-ex/2103.11769]} \\
\text{[Belle 605 fb}^{-1}: \text{R_{K^*}} (\ast) \quad \text{PRL103(2009)171801}; 711 \text{ fb}^{-1}: \text{hep-ex/1904.02440, R_K}: \text{EPS-HEP 2019]} \quad \text{[BaBar: PRD86(2012)032012]} \]
Flavour anomalies: interpretations

- deviations from $\tau/\mu$ LU in $b \rightarrow c\ell\nu$ tree decays, combined $\sim 3\sigma$
- deviations from $\mu/e$ LU in $b \rightarrow s\ell\ell$ loops, global fit $> 4\sigma$
- no deviations observed in $\pi, K$ decays nor in EW observables

Anomalies motivate searches for new mediators with enhanced couplings to heavier generations of quarks and leptons

- New mediators could be leptoquarks, $Z'$, ... with mass in LHC reach?
Flavour anomalies: interpretations

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[Complementarity!]

Summary

[Greljo, 2017]
Conclusions and prospects

- Intriguing anomalies in $B$ decays
- Good prospects for resolution in a short time scale
  - New decays being studied
  - Belle II run started, waiting for first results
  - CMS collected $10^{10} B$ decays; measurement systematics orthogonal to LHCb
  - LHCb upgrades will greatly improve sensitivity
- The importance of flavour physics within the experimental strategy in HEP cannot be overestimated!

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**Angular analyses prospects**

- Systematic uncertainties will likely be $\leq 0.01$ (many will scale as $\sqrt{N}$)
  - e.g. control angular distribution of the background with data, etc.
- Understanding the angular acceptance will need of large MC samples
- Rescaling the existing measurement with the same binning to $300 \text{fb}^{-1}$ with a syst. of 0.01
- We could also reduce binning size to learn more about the shape of the distribution (input on $\frac{d\Gamma}{dq^2}$ to subdivide dataset within the existing bins)

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**LFU prospects**

- For ratios of $B$'s (e.g. $R_K$, $R_{K^*0}$) we could reach 1-2% precision
  - For comparison Belle 2 expects to reach a precision of 4-5% with a 50 $\text{ab}^{-1}$ dataset
  - Angular analyses with electrons have orthogonal systematics with respect to $R_X$’s and these can also be kept under control
  - Expect good sensitivity to differences in the angular distributions for electron/muon final states
Swiss involvement in the flavour anomalies

Swiss groups paving the way! See e.g. this year’s SPS/OPG talks:

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<th>Speaker</th>
<th>Institute</th>
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<tr>
<td>E. Graverini</td>
<td>EPFL</td>
<td>Flavour anomalies in $b \to s\ell\ell$ decays: a review</td>
<td>now</td>
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<td>A. Buonaura</td>
<td>UZH</td>
<td>Lepton flavour universality tests in charged-current $b$-quark decays</td>
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<td>V. Denysenko</td>
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<td>M. Ferrillo</td>
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<td>F. Riti</td>
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<td>S. Bouchiba</td>
<td>EPFL</td>
<td>Study of a very rare decay with multiple leptons in the final state at the LHCb experiment</td>
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<td>M. Andersson</td>
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<td>Measuring $B(B^0 \to K^{*0}\tau^+\tau^-)$ via the double-loop process $B^0 \to K^{*0}\tau^+\tau^- (\to \mu^+\mu^-)$</td>
<td>31/08 18:30</td>
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<td>P. Owen</td>
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<td>Review of the flavour anomalies at LHCb</td>
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</table>
Spare slides
Electrons vs muons

- while $\mu^\pm$ fly through, $e^\pm$ lose energy in the detector
- most $e^\pm$ emit a Bremsstrahlung photon before the magnet
  - degraded momentum resolution
- *bremsstrahlung recovery*:
  - look for $\gamma$ cluster compatible with initial $e^\pm$ direction ($E_T > 75$ MeV)
  - add cluster energy back to electron and refit track
Electrons vs muons

- high occupancy in calorimeter $\implies$ high L0 thresholds
  - add independently-triggered samples to pool of $e^+ e^-$:
    - **ETOS**: $e^\pm$ from $B$ candidate
    - **HTOS**: $K^\pm$ from $B$ candidate
    - **TIS**: rest of the event
- electrons suffer also from worse PID and tracking efficiency

**need to control $e/\mu$ differences!**
$R_K$ at LHCb

$R_K = 0.846^{+0.042}_{-0.039} \text{(stat)}^{+0.013}_{-0.012} \text{(syst)}$

- main systematics: fit model, size of calibration samples
- $p$-value in SM hypothesis: $0.0010 \rightarrow 3.1\sigma$ evidence of LFU violation in $B \rightarrow K\ell\ell$ decays
- $R_{K^{*0}} = 0.69^{+0.11}_{-0.07} \text{(stat)} \pm 0.05 \text{(syst)}$ has 2.4–2.5$\sigma$ significance

[BaBar $0.1 < q^2 < 8.12 \text{ GeV}^2/c^4$ [PRD86032012]]

[Belle $1.0 < q^2 < 6.0 \text{ GeV}^2/c^4$ [JHEP03(2021)105]]

[LHCb 5 fb$^{-1}$ $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ [PRL122191801]]

[LHCb 9 fb$^{-1}$ $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ [LHCb-PAPER-2021-004]]

[hep-ex:2103.11769]
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