Rare $b$ Decays and Tests of LFU at LHCb

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A Forward Spectrometer

- Optimized for beauty and charm physics at large pseudorapidity (2<\(\eta<5\))
  - **Trigger**: \(\sim 90\%\) efficient for di-muon channels, \(\sim 30\%\) for all-hadronic
  - **Tracking**: \(\sigma_p/p\ 0.4\%–0.6\%\ (p\ from\ 5\ to\ 100\ GeV),\ \sigma_{IP} < 20\ \mu m\)
  - **Vertexing**: \(\sigma_{\tau}\ \sim 45\ \text{fs}\)
  - **PID**: 97% \(\mu\) ID for 1–3\% \(\pi\rightarrow\mu\) misID
Analyses presented today based on the Run 1 dataset

Due to luminosity levelling, same running conditions throughout fills

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Why Rare b Decays?

> $b \to sll$ decays proceed via **FCNC transitions** that only occur at loop order (and beyond) in SM

![FCNC transitions](image)

> New particles can contribute to loop or tree level enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles

![New particles](image)

> Goal

  » **Make precise measurements of rare FCNC decays as precision tests of the SM**

  » **Make null tests of the SM, e.g. look for LFV or LNV decays that are essentially forbidden in the SM**
Differential branching fractions of $B^0 \rightarrow K(\ast)^0 \mu \mu$, $B^+ \rightarrow K(\ast)^+ \mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B^+ \rightarrow \pi^+ \mu \mu$ and $\Lambda_b \rightarrow \Lambda \mu \mu$ decays

» Large hadronic uncertainties in theory predictions

Angular analyses of $B \rightarrow K(\ast)\mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B^0 \rightarrow K^0 ee$ and $\Lambda_b \rightarrow \Lambda \mu \mu$

» Define observables with small theory uncertainties

Test of Lepton Flavour Universality in $B^+ \rightarrow K^+ ll$

» Cancellation of hadronic uncertainties in theory predictions
Results **consistently lower than SM predictions** despite large theory uncertainties from form-factors.

- **Differential Branching Fractions**
  - $B^+ \rightarrow K^+ \mu^+ \mu^-$
  - $B^0 \rightarrow K^0 \mu^+ \mu^-$

![Graphs showing differential branching fractions](image-url)
Results consistently lower than SM predictions despite large theory uncertainties from form-factors.

Differential Branching Fractions

- **B^0 \rightarrow K^{*0} \mu \mu**
- **B^+ \rightarrow \pi^+ \mu \mu**
- **B_s \rightarrow \phi \mu \mu**
- **B_0 \rightarrow K^* \mu \mu**
- **\Lambda_b \rightarrow \Lambda \mu \mu**
Angular Analyses

- Four-body final states

- System described by three angles (helicity basis) and the di-lepton invariant mass squared, $q^2$

- Complex angular distribution that provides many observables sensitive to different types of NP

- Each observable depends on different Wilson coefficients (underlying short-distance physics) and form-factors (hadronic matrix elements)
Angular Analyses

First **full angular analysis** of $B^0 \rightarrow K^* \mu \mu$: full set of CP-averaged angular terms and correlations as well as full set of CP-asymmetries

Can construct **form-factor independent ratios of observables**

New Belle result consistent with LHCb

[Descotes-Genon et al, JHEP 05 (2013) 137]
Angular Analyses

- Results consistent with SM predictions

\[ B^0 \rightarrow K^{*0}ee \]

- \( F_L = 0.16 \pm 0.06 \pm 0.03 \)
- \( A_{T}^{Re} = 0.10 \pm 0.18 \pm 0.05 \)
- \( A_{T}^{(2)} = -0.23 \pm 0.23 \pm 0.05 \)
- \( A_{T}^{Im} = 0.14 \pm 0.22 \pm 0.05 \)

\[ JHEP 04 (2015) 064 \]

- Low-\( q^2 \): 0.0004–1 GeV\(^2\)
- Challenging due to Bremsstrahlung
- Sensitive to photon polarisation

- \( \Lambda_b \): gives access to different combinations of Wilson coefficients

\[ JHEP 09 (2015) 179 \]

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Several attempts to interpret results by performing global fits to \( b \to s \) data (e.g. \( \text{arXiv:1503.06199, arXiv:1510.04239 and arXiv:1512.07157} \))

Take into account \( \sim 80 \) observables from 6 experiments including \( b \to \mu\mu \), \( b \to s\ell\ell \) and \( b \to s\gamma \) transitions

All global fits require an additional contribution with respect to the SM to accommodate the data, with a preference for NP in \( C_9 \) at \( \sim 4\sigma \)

> Or is this a problem with our understanding of QCD? (e.g. are we correctly estimating the contribution for charm loops?)
Tests of LFU

▷ Ratio of branching fractions of $B^+ \rightarrow K^+ \mu\mu$ to $B^+ \rightarrow K^+ ee$ expected to be unity in the SM (theoretical uncertainty of $O(10^{-3})$)

▷ Observation of LFU violations would be a clear sign of NP

▷ Extremely challenging due to Bremsstrahlung and different trigger / tracking performances between muons and electrons

▷ Measured relative to $B^+ \rightarrow K^+ J/\psi(\Upsilon)$ in order to reduce systematics

▷ Observed a $2.6\sigma$ deviation from SM

▷ Consistent with decay rate if NP does not couple to electrons

▷ Pursuing other $R$–like measurements (e.g see talk by S.Klaver on $R(D^*)$)

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Rare b decays place strong constraints on many NP models allowing to probe energy scales higher than direct searches

A large number of analyses have been performed using Run 1 data

While there is no significant evidence for NP from a single measurement, a clear tension with the SM have been seen in global fits to rare decay observables

Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb⁻¹ expected in LHCb) in Run 2
Di-Lepton Mass

Photon pole enhancement (doesn’t exist for $B \to P\ell\ell$ decays)

$\frac{d\Gamma}{dq^2}$

$C_7^{(1)} C_9^{(1)}$ interference

removed from analysis

$c\bar{c}$ above open charm threshold

$C_9^{(1)}$ and $C_{10}^{(1)}$

$J/\psi(1S)$

$b \to c\bar{c}s$ tree level (!)

$\psi(2S)$

$q^2$

dimuon mass squared

$4[m(\mu)]^2$
Differential Branching Fractions

\[\frac{dB}{dq^2} \quad [10^{-7} \text{ GeV}^{-2}]\]

\(\Lambda_b \rightarrow \Lambda \mu\mu\)

\[\frac{d\sigma}{dq^2} \quad 10^{-2} \text{ GeV}^{-2} \cdot \text{cm}^{-2}\]

\(\Lambda_b \rightarrow \Lambda \mu\mu\)

\[F_S, \%\]

\(B^0 \rightarrow K^*0\mu\mu\)

\[q^2 \quad [\text{GeV}^2 / c^4]\]

\[LHCb, \text{ CMS (7, 8 TeV)}\]

\[\text{BaBar, Belle, CDF}\]

\[\text{SM prediction}\]

\[\text{Data}\]

\[\text{JHEP 06 (2015) 115}\]

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arXiv:1507.08126

arXiv:1606.04731
Angular Analyses

LHCb

$0.10 < q^2 < 0.98 \text{ GeV}^2/c^4$

Candidates / 5.3 MeV/c$^2$

$m(K^+ \pi^- \mu^+ \mu^-) [\text{MeV}/c^2]$
First **full angular analysis** of $B^0 \rightarrow K^* \mu\mu$: full set of CP-averaged angular terms and correlations as well as full set of CP-asymmetries

Can construct **form-factor independent ratios** of observables

New Belle result consistent with LHCb

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Tests of LFU

- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

![Graphs showing data from LHCb experiment](image)

LHCb [PRL113 (2014) 151601]

- Partially reconstructed decays

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Theoretical Framework

- In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by the low-energy theory (QED) plus a single operator with an effective coupling constant.

\[ \mathcal{L}_{\text{EW}} \rightarrow \mathcal{L}_{\text{QED}} + \frac{G_F}{\sqrt{2}} (\bar{ud})(e\bar{\nu}) \]

- Can write a Hamiltonian for the effective theory as

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) O_i(\mu), \]

- Wilson coefficient (integrating out scales above \( \mu \))
- Local operator with different Lorentz structure (vector, axial vector current etc)
Operators

SM operators

\[ \mathcal{O}_7 = \frac{m_b}{e} \bar{s}\sigma^{\mu\nu} P_R b F_{\mu\nu}, \]
\[ \mathcal{O}_8 = g_s \frac{m_b}{e^2} \bar{s}\sigma^{\mu\nu} P_R T^a b G^a_{\mu\nu}, \]
\[ \mathcal{O}_9 = \bar{s}\gamma_\mu P_L b \bar{\ell}\gamma_\mu \ell, \]
\[ \mathcal{O}_{10} = \bar{s}\gamma_\mu P_L b \bar{\ell}\gamma_\mu\gamma_5 \ell, \]

Beyond SM operators

\[ \mathcal{O}_7' = \frac{m_b}{e} \bar{s}\sigma^{\mu\nu} P_L b F_{\mu\nu}, \]
\[ \mathcal{O}_8' = g_s \frac{m_b}{e^2} \bar{s}\sigma^{\mu\nu} P_L T^a b G^a_{\mu\nu}, \]
\[ \mathcal{O}_9' = \bar{s}\gamma_\mu P_R b \bar{\ell}\gamma_\mu \ell, \]
\[ \mathcal{O}_{10}' = \bar{s}\gamma_\mu P_R b \bar{\ell}\gamma_\mu\gamma_5 \ell. \]

 photon penguin

vector and axial-vector currents

right handed currents
(suppressed in SM)
Angular Analyses

- Complex angular distribution:

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \bigg|_P = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \right.
\]

\[
\left. + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi + \right.
\]

\[
\left. + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]

The observables depend on form-factors for the \( B \to K^* \) transition plus the underlying short distance physics (Wilson coefficients).
Interpretation of Global Fits

Optimist's view point

Vector-like contribution could come from new tree level contribution from a $Z'$ with a mass of a few TeV

Pessimist's view point

Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two
Interpretation of Global Fits

• This is the physics we are interested in.

• We also get long-distance hadronic contributions. Included in the SM but are the predictions correct?

Short distance part integrates out (as a Wilson coefficient)