B decay anomalies at LHCb

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(On behalf of the LHCb collaboration)
Outline

- Introduction
- The LHCb experiment
- Branching fraction measurements in $b \rightarrow s \ell \ell$
- Angular analyses
- Lepton Flavour Universality tests
- Conclusions
Introduction

- $b \rightarrow s, d$ quark transitions are Flavor Changing Neutral Currents (FCNCs), → in the SM they only can occur through loops (penguin and box diagrams) → very sensitive to new physics

Experimentally → leptons/photons with high transverse momenta
Theoretically → observables can be calculated by using effective theories

In this talk I will focus on $b \rightarrow s \ell\ell$ transitions
**Introduction**

- The amplitude of a hadron decay process can be described using OPE:

\[
A(M \rightarrow F) = \langle F|\mathcal{H}_{\text{eff}}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) \langle F|O_i(\mu)|M\rangle
\]

- CKM couplings
- Wilson Coefficients \((\mu = \text{scale})\)
- Hadronic Matrix Elements

→ a series of **effective vertices** multiplied by effective coupling constants \(C_i\).

\[
O_7 \quad O_8 \quad O_{9,10} \quad O_{1...6}
\]

Electroweak scale \(\sim 1/M_w\)
New Physics scale \(\sim 1/M_{NP}\)

\[
C_i = C_i^{SM} + C_i^{NP}
\]

\[
C'_i = C'_i^{SM} + C'_i^{NP}
\]

Primed \(C'_i\) → right handed currents: suppressed in SM
Introduction

- $b \rightarrow s \ell^+\ell^-$ is mainly sensitive to $C_7$, $C_9$ and $C_{10}$ Wilson coefficients

Observables that can be affected:

- **Differential branching fractions**
  $(B^0 \rightarrow K^{(*)0}\mu^+\mu^-, B^+ \rightarrow K^{(*)+}\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^-, B^+ \rightarrow \pi^+\mu^+\mu^- \text{ and } \Lambda_b \rightarrow \Lambda\mu^+\mu^-)$
  → Affected by hadronic uncertainties in the theory predictions

- **Angular distributions**
  $(B^0 \rightarrow K^{(*)0}\mu^+\mu^-, B_s \rightarrow \phi\mu^+\mu^- B^0 \rightarrow K^{0*}\mu^+\mu^- \text{ and } \Lambda_b \rightarrow \Lambda\mu^+\mu^-)$
  → Observables with smaller theory uncertainties

- **Ratios testing Lepton Flavour Universality**
  $(B^+ \rightarrow K^+\ell^+\ell^- \text{ and } B^0 \rightarrow K^{0*}\ell^+\ell^-)$
  → Hadronic uncertainties in theory predictions cancel in ratios
The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion:

- $\sim 300\,\mu b$ @ $\sqrt{s}=7\,\text{TeV}$
- $\sim 600\,\mu b$ @ $\sqrt{s}=13\,\text{TeV}$

The LHCb idea: to build a single-arm forward spectrometer:
- $\sim 4\%$ of the solid angle ($2<\eta<5$),
- $\sim 30\%$ of the $b$ hadron production

The $b$ quarks hadronize in $B$, $B_s$, $B^{(*)}$, $b$-baryons...
→ average $B$ meson momentum $\sim 80\,\text{GeV}$

Letter of Intent, 1995

[Letter of Intent, 1995]
The LHCb experiment

Excellent tracking and particle identification

[INT.J.MOD.PHYS A30 (2015) 1530022]
[JINST 3 (2008) S08005]
Very good performance: 3 fb\(^{-1}\) in Run1, more than 5 fb\(^{-1}\) in Run2
Analysis of $b \rightarrow s \ell \ell$ events

- $b$-hadron mass is reconstructed from final hadron decays and two energetic leptons
- Background events suppressed by requiring displaced vertices
- The decay width is expressed in terms of $q^2 = \text{invariant mass of the dilepton system}$ (differential BR, ratios of BRs) and decay angles (angular analysis)
- Tree level decays involving $J/\psi$ and $\psi(2S)$ resonances are used as control samples and the $q^2$ regions are generally removed from the analyses of $b \rightarrow s \ell \ell$ decays

Ex: $B \rightarrow K^* \mu^- \mu^+$

[JHEP02(2016)104]

Region of analysis:
Decays involving electrons:

- LHCb is far better with muons than electrons
- *Trigger*, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by *e bremsstrahlung* → need energy recovery
- Mass shape modelled according to the number of *bremsstrahlung* recovered

Data-MC for the number of γ recovered by trigger category
Analysis of $b \rightarrow s \ell \ell$ events

B mass versus $q^2$ for $B^+ \rightarrow K^+ \ell^+ \ell^-$

[Graphs showing $q^2$ versus $m(K^+\ell^+\ell^-)$ for $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$, with peaks at $\psi(2S)$ and $J/\psi$.]

[PRL 113 (2014) 151601]
Branching fractions

Differential branching fraction: \( \frac{d\Gamma}{dq^2} \)
Each \( q^2 \) region probes different processes

\[ B \rightarrow K^* \ell^- \ell^+ \]

\[ q^2 = (p_{\ell^+} + p_{\ell^-})^2 \]

Charmonium resonances

\[ J/\psi (1S) \]
\[ \psi (2S) \]

SM values (\( \mu = m_b \)):
- \( C_7 \sim -0.33 \)
- \( C_9 \sim 4.27 \)
- \( C_{10} \sim -4.17 \)

(Everything else small or negligible)
Branching fractions

In a $q^2$ range, the differential branching fraction can be obtained:

$$\frac{d\mathcal{B}}{dq^2} = \frac{R_{\epsilon}}{(q^2_{\text{max}} - q^2_{\text{min}})} \frac{(1 - F_S^{J/\psi K^*0}) n_{J/\psi K^*0}}{(1 - F_S^{J/\psi K K^*0}) n_{J/\psi K}} \mathcal{B}(B^0 \rightarrow J/\psi K^*0) \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$$

→ Normalized to the $J/\psi$ mode
→ $n_{\text{channel}}$ is the yield for the signal and normalization decay modes
→ $R_{\epsilon}$ is the ratio of efficiencies for signal and normalization decay modes
→ $F_S$ is the fraction of a S-Wave interfering with the P-wave (for signal and normalization), in a specific $m_{K\pi}$ range (use LASS parameterization to describe the S-wave)

→ S-wave contribution found to be small, < 10%
Branching fractions

- Differential decay width as function of $q^2 = m_{\mu\mu}^2$ at LHCb, using $3\text{fb}^{-1}$

$\Lambda_b \rightarrow \Lambda \mu^+\mu^-$

$\rightarrow$ Smaller branching fractions than the SM predictions
Branching fractions

- Also measured by other experiments in the $B \rightarrow K^* \ell^+\ell^-$ channel:

$\rightarrow$ Smaller branching fractions than the SM predictions?

$\rightarrow$ Results dominated by statistical uncertainties (including the BR of the normalization channels)

$\rightarrow$ Caveat: theory affected by hadronic uncertainties (LQCD + LCSR)

$\rightarrow$ And what about the charm resonances contribution?
Understanding effects from charm at LHCb:

- Phase difference between short- and long-distance amplitudes in the $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay [LHCb, EPJC(2017)77]

$\frac{d\Gamma}{dm_{\mu\mu}}$ is a function of form factors and $C_i$

- $C_i^{\text{eff}}$ expressed as a sum of relativistic Breit-Wigner amplitudes: magnitudes and phases extracted from data

- Form factors from FNAL & MILC [PRD 93(2016)025026]

$C^{\text{eff}}_9 = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2)$

→ Small effect of hadronic resonances in Wilson coefficients
Angular analyses

- Angular distribution in $B \to K^* \ell^- \ell^+$: $q^2$ and three angles

$$
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \\
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\
+ S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
$$

→ In the lepton massless limit there are **eight** independent observables:

- $F_L$ = fraction of the longitudinal polarization of the $K^*$
- $S_6 = 4/3 \ A_{FB}$, the forward-backward asymmetry of the dimuon system
- $S_{3,4,5,7,8,9}$ are the remaining CP-averaged observables
Angular analyses

LHCb
[JHEP02(2016)104]

CMS
[PLB 753 (2016) 424]

ATLAS
[arXiv:1805.04000]

SM predictions based on
[Altmannshofer & Straub, EPJC 75 (2015) 382]
[LCSR f.f. from Bharucha, Straub & Zwicky, JHEP 08 (2016) 98]
Angular analyses

- These observables are also affected by hadronic uncertainties.
- A new set of "optimized observables", with form factor cancellations can be defined: [Descotes-Genon et al, JHEP 05 (2013) 137]

\[ P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L (1 - F_L)}} \]

- These observable are functions of \( q^2 \) and the Wilson coefficients \( C_i \)

Example: \( P'_5 \)

3σ local deviation
Angular analyses

→ **New**: results from LHCb in the $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decay channel

$$\frac{d^5\Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i=1}^{34} K_i(q^2) f_i(\Omega)$$

5 angles and 1 normal vector $\vec{n}$

Depends on many observables ($K_i$)

Obtained from *method of moments*

$$15 < q^2 < 20 \text{ GeV}^2$$

\[\text{In general compatible with SM predictions}\]

[Boër et al, JHEP 01 (2015) 155],
Angular analyses

• What about electrons? (sensitive to $C_{\gamma}^{(l)}$)

Angular observables of the $B^0 \rightarrow K^* e^+ e^-$ at LHCb in the low $q^2 < 1\text{GeV}^2$

→ Virtual $\gamma$ decaying in an observable $\ell^- \ell^+$ pair
→ Requires to go very low in the $q^2$ region

![Diagram of $B^0 \rightarrow K^* e^+ e^-$ decay]

[Adapted from Jäger and Camalich arXiv:1412.3183]

→ Compatible with the SM predictions*

[Adapted from JHEP04(2015)064] $(3\text{fb}^{-1})$

*leading order estimation, 5% accuracy for SM value
Lepton Flavour Universality

• In the SM all leptons are expected to behave in the same way:

\[ R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1.000 + O(m_{\mu}^2/m_b^2) \text{ (SM)} \]

• Experimentally, use the \( B^+ \rightarrow K^+ J/\psi(\rightarrow e^+ e^-) \) and \( B^+ \rightarrow K^+ J/\psi(\rightarrow \mu^+ \mu^-) \) to perform a double ratio

• Precise theory prediction due to cancellation of hadronic form factor uncertainties

\[ 1 \text{ GeV} < q^2 < 6 \text{ GeV} \]

\[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \]

→ Consistent, but lower, than the SM at 2.6σ
Lepton Flavour Universality

• Measurement in the $B \to K^* \mu^+ \mu^-$ channel, $R_{K^*}$:

$$R_{K^*} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}$$

• Precise theoretical calculations due to the cancellation of form factors

• Double ratio using $J/\psi$ modes to cancel systematics:

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to \mu^+ \mu^-))}$$

• Several trigger categories with different efficiencies

• Blinded analysis, many checks performed before unblinding:

\[
\begin{align*}
\rightarrow r_{J/\psi} &= \frac{B(B \to K^* J/\psi (\to \mu^+ \mu^-))}{B(B \to K^* J/\psi (\to e^+ e^-))} = 1.04 (0.05) \\
\rightarrow R_{\psi(2S)} &= \text{muon/electron ratio for } B(B \to K^* \psi(2s))/B(B \to K^* J/\psi) = 1 (0.02) \\
\rightarrow B(B \to K^* \mu^+ \mu^-) \checkmark ; B(B \to K^* \gamma (\to e^+ e^-)) \checkmark
\end{align*}
\]
Lepton Flavour Universality

- Computed in two bins of $q^2$
  - [0.045, 1.1 GeV$^2$] avoiding the photon pole
  - [1.1, 6.0 GeV$^2$] avoiding the radiative tail of $J/\psi$ modes

- Decay mode with muons:

LHCb, JHEP08(2017)055
• Decay mode with electrons: exploiting kinematics in case of unrecovered bremsstrahlung photons

LHCb, JHEP08(2017)055

- 89 events
- 111 events
Lepton Flavour Universality

- Results:

\[ R_{K^*0} = 0.66 \pm 0.11 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)} \]

Low \( q^2 \) [0.045-1.1 GeV\(^2\)]:

- SM\( _\downarrow \) = 0.922(22)

Central \( q^2 \) [1.1-6 GeV\(^2\)]:

- SM\( _\downarrow \) = 1.000(6)

\[ R_{K^*0} = 0.69 \pm 0.11 \pm 0.07 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

\[ \rightarrow \text{Consistent, but lower than the SM at 2.1-2.3}\sigma \text{ (low } q^2 \text{) and 2.4-2.5}\sigma \text{ (central } q^2 \text{)} \]
New Physics hypothesis preferred over SM by more than 4 - 5σ
Main effect on the $c_{9\mu}$ coefficient: $4.27^{SM} - 1.1^{NP}$

Triggered models with $Z'$, leptoquarks (LQ), and composite Higgs

Interpretation

- Global fits (some cases with more than 100 observables)
Conclusions

• Measurements on rare $b \rightarrow s \ell\ell$ decays present a consistent pattern of anomalies in some observables, observed by several experiments:

  * **Differential branching fractions:** $B^0 \rightarrow K(\ast)\mu^+\mu^-$, $B^+ \rightarrow K(\ast)^+\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$, and $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$
  
  * **Angular analyses:** $B^0 \rightarrow K(\ast)\mu^+\mu^-$, $B^0 \rightarrow K^0 e^+e^-$ and $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$
  
  * **Test of Lepton Flavour Universality:** $B^+ \rightarrow K^+\ell^+\ell^-$ and $B^0 \rightarrow K^0\ell^+\ell^-$

• Particular interest is in ratios testing LFV since they are not affected by hadronic uncertainties.

• These deviations from SM predictions point to new physics in the Wilson coefficient $C_{9\mu}$, affecting differently to lepton families.

  → **Difficult to be explained by just experimental effects.**

  → **Difficult to be explained by just QCD effects...**

• Most of results here are from Run1 and are limited by statistics... measurements on Run2 data ongoing!
Thanks !