Rare Decays at LHCb

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On behalf of the LHCb collaboration

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B^+ \rightarrow K^+ \mu \mu, \ \text{Phys. Rev. Lett.} \ 111 \ (2013) \ 151801, \ [\text{arXiv:1308.1340}] \\
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B_{s/d} \rightarrow \mu \mu, \ \text{Phys. Rev. Lett.} \ 111 \ (2013) \ 101805, \ [\text{arXiv:1307.5024}] \\
B_{s/d} \rightarrow \mu \epsilon, \ \text{Phys. Rev. Lett.} \ 111 \ (2013) \ 141801, \ [\text{arXiv:1307.4889}] \\
\Lambda_b \rightarrow \Lambda \mu \mu, \ \text{Phys. Lett.} \ B725 \ (2013) \ 25, \ [\text{arXiv:1306.2577}] \\
D \rightarrow \mu \mu, \ \text{Phys. Lett.} \ B725 \ (2013) \ 15, \ [\text{arXiv:1305.5059}] \\
B_s \rightarrow \phi \mu \mu, \ \text{JHEP} \ 1307 \ (2013) \ 084, \ [\text{arXiv:1305.2168}] \\
B \rightarrow K^* \mu \mu, \ \text{JHEP} \ 1308 \ (2013) \ 131, \ [\text{arXiv:1304.6325}] \\
\tau \rightarrow 3 \mu, \ \tau \rightarrow \mu \mu, \ \text{Phys. Lett.} \ B724 \ (2013), \ [\text{arXiv:1304.4518}] \\
B \rightarrow K^* \epsilon \epsilon, \ \text{JHEP} \ 05 \ (2013) \ 159, \ [\text{arXiv:1304.3035}] \\
B \rightarrow 4 \mu, \ \text{Phys. Rev. Lett.} \ 110 \ (2013) \ 211801, \ [\text{arXiv:1303.1092}] \\
B \rightarrow K^* \mu \mu, \ \text{Phys. Rev. Lett.} \ 110 \ (2013) \ 031801, \ [\text{arXiv:1210.4492}] \\
B^+ \rightarrow \pi^+ \mu \mu, \ \text{JHEP} \ 12 \ (2012) \ 125, \ [\text{arXiv:1210.2645}] \\
K_s \rightarrow \mu \mu, \ \text{JHEP} \ 01 \ (2013) \ 090, \ [\text{arXiv:1209.4029}] \\
B \rightarrow K^* \mu \mu, \ \text{JHEP} \ 07 \ (2012) \ 133, \ [\text{arXiv:1205.3422}] \\
B \rightarrow K^* \gamma / B_s \rightarrow \phi \gamma, \ \text{Nucl. Phys.} \ B \ 867 \ (2012) \ 118, \ [\text{arXiv:1209.0313}] \\
B^+ \rightarrow \chi \mu \mu, \ \text{Phys. Rev.} \ D \ 85 \ (2012) \ 112004, \ [\text{arXiv:1201.5600}]
Outline

- Rare B decays
- The LHCb experiment
- Leptonic decays: $B_{s/d} \to \mu^+\mu^-$
- Lepton Flavour Violation: $B_{s/d} \to e^+\mu^-$
- Semi(di)leptonic decays: $B_d \to K^{*0}\mu^+\mu^-$
- Radiative decays: $B^+ \to K^+\pi^-\pi^+\gamma$
- Conclusions
Rare B decays

- $b \rightarrow s$ transitions are **Flavor Changing Neutral Currents (FCNCs)**, forbidden in the Standard Model (SM) at tree level → they go through loops (*penguin and box diagrams*)

- **Leptonic**, **semileptonic** and **radiative $b \rightarrow s$ decays** are of particular interest since the SM rates (and other observables) can be calculated with high precision using effective theories (in terms of the Wilson coefficients)

- Rare (and very rare) processes: $\text{BR}_{\text{SM}} \sim 10^{-5} – 10^{-10}$, but experimentally accessible by flavour experiments (*B- factories & LHCb*) → Experimental signature: high $P_T$ leptons/photons

- Excellent probe for physics beyond the SM → sensitivity to **new heavy particles** in the loops

\[ H^-, \chi^-, \tilde{g}, \chi^0 \ldots \]
The LHCb experiment
The LHCb experiment

- LHC: Large $b\bar{b}$ cross section in pp collisions (gluon fusion)
  ($\sim 250 \mu$b – 500 $\mu$b @ $\sqrt{s}=7$ – 14 TeV):

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

- Very good performance: $3$ fb$^{-1}$ accumulated in Run1
The LHCb experiment
The LHCb experiment

Precise tracking
Good mass and Impact Parameter (IP) resolution
Good vertex resolution
The LHCb experiment

Excellent particle identification
$\pi/K$ separation over 2-100 GeV
Powerful $\mu$ identification

Calorimeter system
Trigger
Photon reconstruction
Leptonic decays: \( B_{s/d} \rightarrow \mu^+\mu^- \)

- FCNC + helicity suppressed → **Very Rare decay**:

**Standard Model prediction:**

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = (3.35 \pm 0.28) \times 10^{-9}
\]
\[
B(B^0 \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}
\]

- First evidence by LHCb in 2012 [LHCb, PRL110 (2013)021801] (2fb\(^{-1}\))
  → Now updated with 3fb\(^{-1}\)

**FIRST EVIDENCE** (3.5\(\sigma\))
**Leptonic decays: B_{s/d} \rightarrow \mu^+ \mu^-**

[LHCb, PRL 111 (2013) 101805] (3fb^{-1})

- Reconstruct opposite charged muons making a good vertex and separated from the PV, with m_{\mu\mu} in the range [4.9-6] GeV/c^2
- Data control channels and normalization using the B^+ \rightarrow J/\Psi \ K^+ (J/\Psi \rightarrow \mu^+ \mu^-) and B_d \rightarrow K \pi (\pi\pi, KK) decays with similar selection
- Signal and background discrimination based on the invariant mass and Boosted Decision Tree (BDT), using kinematic and topological properties (trained with MC signal and bb\rightarrow \mu\mu X background)

- Blind analysis: don’t look the data in m(B_{d/s})\pm60 MeV/c^2 until the end of the analysis
Leptonic decays: $B_{s/d} \rightarrow \mu^+ \mu^-$

- Signal shape derived from $B_{d/s} \rightarrow K \pi$ data and dimuon resonances (same topology as the signal):

- Background from dimuon mass sidebands:

→ BDT output (defined to be flat for signal and peaked at 0 for background):
Leptonic decays: $B_{s/d} \rightarrow \mu^+\mu^-$

- Two different normalization channels used:
  
  $B^+ \rightarrow J/\psi K^+$
  
  $B_d \rightarrow K\pi$

  ~1.1M events
  
  ~38k events

Similar trigger, one additional track

Same topology, different trigger

$$\mathcal{B}(B_{(s)}^0 \rightarrow \mu^+\mu^-) = \frac{\mathcal{B}_{\text{norm}} \epsilon_{\text{norm}} f_{\text{norm}}}{N_{\text{norm}} \epsilon_{\text{sig}} f_{d(s)}} \times N_{B_{(s)}^0 \rightarrow \mu^+\mu^-}$$

$\epsilon_{\text{sig}}$ and $\epsilon_{\text{norm}} = \epsilon_{\text{trigger}} \times \epsilon_{\text{selection}} \times \epsilon_{\text{reconstruction}}$

$f_{\text{norm}}$ and $f_{d(s)} = $ production fractions @ LHCb [LHCb-CONF-2013-011]

→ The 2 normalization channels give compatible results

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Leptonic decays: $B_s/d \rightarrow \mu^+ \mu^-$

- Results:

\[
\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} \text{ (stat)} ^{+0.3}_{-0.1} \text{ (syst)}) \times 10^{-9}
\]

\[
\text{BR}(B^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1} \text{ (stat)} ^{+0.6}_{-0.4} \text{ (syst)}) \times 10^{-10}
\]

@ 95% C.L: $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 7.4 \times 10^{-10}$

Significance: 4.0 $\sigma$

Significance: 2.0 $\sigma$
Leptonic decays: $B_{s/d} \rightarrow \mu^+\mu^-$

- Combination with CMS: [CMS PAS BPH-13-007]

- New Physics constraints:

[D.M. Straub, arXiv:1205.6094]
Lepton Flavour Violation: $B_{s/d} \rightarrow e^+ \mu^-$

[Michał Kazana, PRL 111 (2013) 141801] (1fb$^{-1}$)

- Forbidden in the Standard Model
- Constrain New Physics models: Pati-Salam -LeptoQuarks (LQ)- model, 2HDM (Type III) ...

\[ \begin{align*}
  b & \quad e(\mu) \\
  B_s & \quad LQ \\
  s & \quad \mu(e)
\end{align*} \]

- Similar analysis method to $B_{s/d} \rightarrow \mu^+ \mu^-$: normalization and control channels $B_{s/d} \rightarrow K\pi$ (KK, $\pi\pi$)

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**Graph 1:**
- Probability scale
- Data points showing distributions for Signal and Background

**Graph 2:**
- $m_{e\mu}$ vs. BDT
- Blind region highlighted
- Data points distributed across the graph
Lepton Flavour Violation: $B_{s/d} \to e^+\mu^-$

- Results:

$\mathcal{B}(B^0_s \to e^+\mu^-) < 1.1 (1.4) \times 10^{-8}$

$\mathcal{B}(B^0 \to e^+\mu^-) < 2.8 (3.7) \times 10^{-9}$

→ Largely improves (~ /20) CDF limits [PRL102(2009)201801]
Lepton Flavour Violation: $B_{s/d} \rightarrow e^+\mu^-$

- New Physics constraints: Pati-Salam Model (coupling different generations)

$$M_{LQ}(B^0_s \rightarrow e^\pm \mu^{\mp}) > 107 \ (101) \ \text{TeV}/c^2$$
$$M_{LQ}(B^0 \rightarrow e^\pm \mu^{\mp}) > 135 \ (126) \ \text{TeV}/c^2$$

[Pat and A. Salam PRD10(1974)275].

- Direct searches at LEP/TeVatron/DESY/LHC (first generation) [PDG’13] (not directly comparable)
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- New Physics amplitudes can modify branching fractions, angular observables, CP and isospin asymmetries ...

- The differential decay width depends on three angles $\theta_\ell$, $\theta_K$, $\phi$ and $q^2=m_{\mu\mu}^2$

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

- $F_L$ and $S_i$ are observables which are functions of the Wilson coefficients (sensitive to NP) and form factors (long distance effects, non-perturbative methods)

- A new set of observables, $P'_{i=4,5,6,8} = S_{i=4,5,7,8}/\sqrt{F_L(1-F_L)}$ can be defined, being less sensitive to the hadronic form-factors uncertainties

[S. Descotes-Genon, T. Hurth, J. Matias, J. Virto, JHEP 05 (2013) 137]
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- Select at least one high $P_T$ muon (> 1.5GeV/c) and one hadron displaced from PV
- Candidates are retained in the $K^*(\rightarrow K^+\pi^-)$ invariant mass range
- Signal selected with a BDT using kinematic, topological and PID info; trained with resonant $B \rightarrow J/\psi K^*$ data (signal) and data from sidebands (background), and keeping flat the angular acceptance
- $B \rightarrow J/\psi K^*$ data as control channel for Data/MC efficiencies
- $\Psi$(2S) and $J/\Psi$ resonance regions vetoed
- Analysis performed in six bins of $q^2$ and in the region $1<q^2<6$ GeV$^2$

[JHEP 1308 (2013) 131]
[LHCb, PRL08 (2013) 117]
(1fb$^{-1}$)
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

$\rightarrow$ peaking backgrounds reduced to a negligible level
In the SM, $A_{FB}$ changes sign as function of $q^2$. The zero crossing-point is free of hadronic uncertainties:

→ First measurement of the zero-crossing point in $A_{FB}$: $q_0^2 = 4.9 \pm 0.9$ GeV²/c⁴
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- In terms of the new observables $P'_i$:

  - Agreement with the SM for $P'_4$, $P'_6$, $P'_8$
  - Local discrepancy of $3.7\sigma$ is observed in the interval $4.30 < q^2 < 8.68 \text{ GeV}^2/c^4$ for $P'_5$
  - Integrating over the region $1.0 < q^2 < 6.0 \text{ GeV}^2/c^4$, the observed discrepancy is $2.5\sigma$

$\rightarrow C_9$ Wilson coefficient?  (update with 3fb$^{-1}$ in progress)

Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- Comparison with other experiments:

[ATLAS-CONF-2013-038]
[CMS PAS BPH-11-009]
Semi(di)leptonic Decays: $B_d \rightarrow K^* \mu^+ \mu^-$

- Other (non angular) observables:

  **CP asymmetry:**

  \[
  A_{CP} = \frac{\Gamma(B^0 \rightarrow \overline{K}^{*0} \mu^+ \mu^-) - \Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow \overline{K}^{*0} \mu^+ \mu^-) + \Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}
  \]

Corrected for production/detection asymmetry using $B \rightarrow J/\psi K^*$ data →

\[
A_{CP} (B^0 \rightarrow K^{*0} \mu^+ \mu^-) = -0.072 \pm 0.040 \pm 0.005
\]

[**LHCb, PRL. 110 (2013)031801**] (1fb⁻¹)
Radiative Decays: $B^+ \to K^+ \pi^- \pi^+ \gamma$

- Radiative $b \to s$ decays are also FCNC, with a photon in the final state.
- Branching fractions and CP asymmetries can be largely affected by New Physics contributions.
- In the SM, the photon from $b$ decays is predominantly left handed, with small corrections of order $m_s/m_b \sim 2\%$.

→ The photon polarization is then sensitive to the spin structure of the New Physics.
→ It is largely affected in New Physics Models (particularly in Left-Right Symmetric Models).

The photon polarization parameter $\lambda_{\gamma}$

$$\lambda_{\gamma} \equiv \frac{|C_R|^2 - |C_L|^2}{|C_R|^2 + |C_L|^2}$$

expected to be $-1 (\bar{B})$ or $+1 (B)$ with corrections of $(m_s/m_b)^2$.

(C_{R, L} right and left amplitudes)

Can be extracted by studying the three body decay of a $K_j (J^P)$ resonant state in $B \to K_{\text{res}} \gamma$ radiative decays.

Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

- For a radiative $B \rightarrow K_{\text{res}} \gamma$, with the $K_{\text{res}}$ a three body decay $K_{\text{res}} \rightarrow P_1 P_2 P_3$

$$d\Gamma (\overline{B} \rightarrow \overline{K}_{\text{res}} \gamma \rightarrow P_1 P_2 P_3 \gamma) \propto \frac{1}{d\cos \theta}$$

with $s_{ij} = (p_i + p_j)^2$; $s = (p_1 + p_2 + p_3)^2$

is the sum of the helicity amplitudes

The **Up-down asymmetry** $A_{\text{UD}}$

$$A_{\text{up-down}} = \int_0^1 d\cos \theta \frac{d\Gamma}{d\cos \theta} - \int_{-1}^0 d\cos \theta \frac{d\Gamma}{d\cos \theta} \propto \lambda_{\gamma}$$

Allows to extract the photon polarization information

→ Need to count the number of events with photon emitted above/below the $\vec{p}_1 \vec{p}_2$-plane and subtract them.

- There are two known $K_1(1^+)$ states, decaying into $K\pi\pi$ final state via $K^*\pi$ and $\rho K$ modes: the $K_1(1270)$ and $K_1(1400)$ resonances, from where the $\lambda_{\gamma}$ can be measured.
Radiative Decays: \( B^+ \rightarrow K^+\pi^-\pi^+\gamma \)

[LHCb-CONF -2013-009] (2fb\(^{-1}\))

- Use the full mass range to measure \( A_{CP} \)

\[
A_{CP} = \frac{N(K^-\pi^+\pi^-\gamma) - N(K^+\pi^-\pi^+\gamma)}{N(K^-\pi^+\pi^-\gamma) + N(K^+\pi^-\pi^+\gamma)}
\]

- Avoid the interference mass regions to measure \( A_{UD} \)

\[
A_{UD} = \frac{N(K\pi^+\pi^-\gamma)_{\cos\theta > 0} - (K\pi^+\pi^-\gamma)_{\cos\theta < 0}}{N(K\pi^+\pi^-\gamma)_{\cos\theta > 0} + (K\pi^+\pi^-\gamma)_{\cos\theta < 0}}
\]

Individual resonances cannot be resolved without angular analysis, then:

- Reconstruct a kaon resonance from three charged tracks: two pions of opposite sign and a kaon, plus a high \( E_T \) photon.

Background substracted \( K\pi\pi \) spectrum showing the expected resonant contributions.

(since there are effects from several contributions, results are difficult to interpret in terms of photon polarization)
Radiative Decays: $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

Corrections to raw $A_{CP}$:

\[
A_{raw}^{CP} = -0.022 \pm 0.015
\]

$A_D$ and $A_P \quad 0.013 \pm 0.008$

$\Delta A_{raw}^{CP} \quad 0.002 \pm 0.001$

Fit model \quad $0.000 \pm 0.002$

$A_{CP} = -0.007 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)}$
Contributions to the $A_{ud}$ uncertainties very small ($\sim$1-3‰)

\[
A_{ud}^+ = -0.084 \pm 0.026 \text{ (stat) } ^{0.004}_{-0.003} \text{ (syst)}
\]
\[
A_{ud}^- = -0.086 \pm 0.025 \text{ (stat) } \pm 0.002 \text{ (syst)}
\]

$A_{ud} = -0.085 \pm 0.019 \text{ (stat) } \pm 0.003 \text{ (syst)}$

Proportional to photon polarization (first evidence at 4.6$\sigma$)
Conclusions:

- LHCb has performed very well in Run1: $3\text{fb}^{-1}$
- Rare B decays are probes for Physics Beyond SM
- Many new measurements on Rare Decays at LHCb:
  - $B$, charm, tau sectors
  - Leptonic, Semi(di)leptonic, Radiative decays
- Only a few have been covered here!

- Few discrepancy with SM predictions to be followed
- Completing the analyses with the full statistics
Thank you!