Rare decays at LHCb

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Why rare decays?

Forbidden at a tree level in the Standard Model (SM) and proceed via loop processes, involving FCNC

Non-standard effects can contribute at the same or even higher levels than the SM

Any non-standard contributions will be visible

Gives an access to higher scales with respect to the direct searches

Provide us with an other door to enter the building of the New Physics

Through studies of various observables like branching fractions, angular variables, asymmetries etc.
Latest results from LHCb

Search for the new rare decays:
\[ B_{d,s} \rightarrow \pi^+\pi^-\mu^+\mu^- \]
\[ B_{d,s} \rightarrow \mu^+\mu^- \]

Studies of the angular distributions:
\[ B_d \rightarrow K^{*0}\mu^+\mu^- \]
\[ B_s \rightarrow \phi\mu^+\mu^- \]
\[ B_d \rightarrow K^{*0}e^+e^- \]
Search for new rare decays
$B_{d,s} \rightarrow \pi^+\pi\mu^+\mu^- \, \text{decays}$

**Introduction**


FCNC loop processes suppressed by the GIM mechanism and the small values of the CKM elements.

Expected to be dominated by the resonant $B_d \rightarrow \rho^0\mu^+\mu^-$ and $B_s \rightarrow f_0(980)\mu^+\mu^-$ decays.

Expected branching fractions within the SM vary from $10^{-7}$ to $10^{-9}$


Predictions suffer from the calculation of the hadronic matrix elements and limited knowledge of the $f_0(980)$ quark content.

The non-SM effects may contribute to the branching fraction:

- Universal extra dimension \[\text{[JHEP 02 (2012) 021]}\]
**Signal observation**


**Event selection:** loose cut-based preselection + Boosted Decision Tree (BDT)

Use the $B_{d,s} \rightarrow J/\psi \pi^+ \pi^-$ channels as the control channel

$\phi \rightarrow \mu^+ \mu^-$, $J/\psi \rightarrow \mu^+ \mu^-$ and $\psi(2S) \rightarrow \mu^+ \mu^-$ contributions are vetoed

Use $B_d \rightarrow J/\psi K^{*0}$ channel for normalization:

$$R_q \equiv \frac{\mathcal{B}(B_{s}^{0} \rightarrow \pi^+ \pi^- \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^{*}(892)^{0} (\rightarrow K^+ \pi^-))}$$

**Resulting ratios:**

$$R_s = (1.67 \pm 0.29 \text{(stat)} \pm 0.13 \text{(syst)}) \times 10^{-3}$$

$$R_d = (0.41 \pm 0.10 \text{(stat)} \pm 0.03 \text{(syst)}) \times 10^{-3}$$

Which leads to:

$$\mathcal{B}(B_{s}^{0} \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (8.6 \pm 1.5 \text{(stat)} \pm 0.7 \text{(syst)} \pm 0.7 \text{(norm)}) \times 10^{-8} \text{ and}$$

$$\mathcal{B}(B^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (2.11 \pm 0.51 \text{(stat)} \pm 0.15 \text{(syst)} \pm 0.16 \text{(norm)}) \times 10^{-8}.$$
Neglecting the other contributions except for the dominant resonant decays

\[ \mathcal{B}(B_{s}^{0} \rightarrow f_{0}(980) \rightarrow \pi^{+}\pi^{-}) \mu^{+}\mu^{-} = (8.3 \pm 1.7) \times 10^{-8} \]
\[ \mathcal{B}(B^{0} \rightarrow \rho^{0}(770) \mu^{+}\mu^{-}) = (1.98 \pm 0.53) \times 10^{-8} \]

In agreement with SM predictions from
Quark model [arXiv:hep-ph/9609503]

Disfavours the QCD sum rules calculations from [Phys. Rev. D80 (2009) 016009]
Extremely rare and very well predicted within the Standard Model

\[ BR(B_s \rightarrow \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9} \]

\[ BR(B_d \rightarrow \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10} \]

Many non-standard models can contribute (additional Higgs bosons etc.)

\[ B_s \rightarrow \mu^+\mu^- \] decay was seen by both CMS and LHCb

Each experiment at the 4\(\sigma\) level

But both did not achieve enough accuracy to claim the observation


Now the results are combined
$B_{d,s} \rightarrow \mu^+\mu^-$ decays

Signals

Similar strategies in both experiments:
- cut-based + BDT event selection
- normalization by the $B^+ \rightarrow J/\psi K^+$ channel
- split events into categories according to the experiment and BDT output (angle and datataking period in case of CMS)

The simultaneous fit to the data in all categories with branching fractions considered as the free parameters of the fit

Fit results

$B_d \rightarrow \mu^+\mu^-$:
$BR = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

3.0σ significance

$B_s \rightarrow \mu^+\mu^-$:
$BR = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

6.2σ significance

First observation!

Significances are calculated according to Feldman–Cousins procedure
$B_{d,s} \rightarrow \mu^+\mu^- \text{ decays}$

**Likelihood profiles**

Measured ratio of branching fractions:

$$R = 0.14^{+0.08}_{-0.06}$$

Compatible with the SM prediction of $R=0.0295$ at a level of $2.3\sigma$.
Angular analyses in semileptonic decays
\( B_d \rightarrow K^{*0} \mu^+ \mu^- \) decay

Introduction

Can be described with \( m_{\ell\ell}^2 = q^2 \) and three angles:

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\
+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_i \\
- F_L \cos^2 \theta_K \cos 2\theta_i + S_3 \sin^2 \theta_K \sin^2 \theta_i \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_i \cos \phi + S_5 \sin 2\theta_K \sin \theta_i \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_i + S_7 \sin 2\theta_K \sin \theta_i \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_i \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_i \sin 2\phi \right]
\]

Angular observables are less affected by the form-factors uncertainties and thus are of particular interest.

LHCb measurement with 1fb\(^{-1}\) of data has shown some tension with the SM in

\[
P'_5 = S_5 / \sqrt{F_L(1 - F_L)}
\]
$B_d \rightarrow K^{*0}\mu^+\mu^-$ decay

Signal

Event selection: loose cut-based preselection + BDT

$\psi$(2S) mode – excluded

$J/\psi$ mode – excluded for the signal selection

Used for the control channel

Event yield: $2398 \pm 57$
$B_d \rightarrow K^{*0} \mu^+\mu^-$ decay

Angular distributions

$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

The $K\pi$ invariant mass included in the fit

In order to constrain the S-wave contribution to the $K\pi$ system

Angular acceptance corrections are accounted for

Modelled by Legendre polynomials

Corresponding functions are included in the fit

Cross-check with the control $B_d \rightarrow J/\psi K^{*0}$ channel is made

Found to be in agreement with the dedicated analysis

[PRD 88, 052002 (2013)]

The uncertainties are determined with the Feldman-Cousins method

\[ B_d \rightarrow K^{*0}\mu^+\mu^- \text{ decay} \]

**Results**

Data points are systematically below (< 1σ) the SM prediction. Measured zero-crossing point position \( q^2_0 = (3.7^{+0.8}_{-1.1}) \text{ GeV}^2/c^4 \) is in agreement with the SM predictions of ~4 GeV\(^2/c^4\):

- [JHEP 01 (2012) 107]

Some tension in the low \( q^2 \) region accounts for the known correlation between the different form-factors. Light-cone sum rules predictions at low \( q^2 \):

- [arXiv:1503.05534]

Lattice determinations at high \( q^2 \):

- [arXiv:1501.00367]
$B_d \rightarrow K^{*0}\mu^+\mu^-$ decay

Results

Analysis with 1 fb$^{-1}$
Analysis with 3 fb$^{-1}$ (current)

Theoretical predictions
[JHEP 1412 (2014) 125]

Local tension 2.9σ in two bins:
- $4.0 < q^2 < 6.0$ GeV$^2$/c$^4$
- $6.0 < q^2 < 8.0$ GeV$^2$/c$^4$

Combining these deviations gives local tension of 3.7σ
(naive $\chi^2$ combination of the two bins)
$B_d \rightarrow K^{*0}e^+e^-$ decay

Introduction

Dominating SM contributions

Relative contribution of the diagrams depends on the $q^2$ value

- The photon coupling process dominates in the very low $q^2$ region (below 1 GeV$^2$/c$^4$)

- Provides the possibility of photon helicity measurement in $b \rightarrow s$ transition
The angles are defined quite in the same way as for the $B_d \rightarrow K^{*0} \mu^+\mu^-$ decays.

The formalism, neglecting the electron mass and the S-wave $K^+\pi^-$ contribution:

\[
\frac{1}{d(\Gamma + \tilde{\Gamma})/dq^2 dq^2 d\cos \theta_\ell d\cos \theta_K d\phi} = \frac{9}{16\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \left( \frac{1}{4} (1 - F_L) \sin^2 \theta_K - F_L \cos^2 \theta_K \right) \cos 2\theta_\ell + \frac{1}{2} (1 - F_L) A_T^{(2)} \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + (1 - F_L) A_T^{Re} \sin^2 \theta_K \cos \theta_\ell + \frac{1}{2} (1 - F_L) A_T^{Im} \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right].
\]

The values measured:

- $F_L$ – longitudinal polarization

- $A_T^{(Re)} = \frac{4}{3} A_{FB} / (1 - F_L)$

- $A_T^{(2)} = \frac{1}{2} S_3 / (1 - F_L)$

- $A_T = \frac{1}{2} S_9 / (1 - F_L)$
\[ B_d \rightarrow K^{*0}e^+e^- \text{ decay} \]

**Fit to the angular observables**

[JHEP 04 (2015) 064]

Event selection: cut-based preselection and BDT selection

Events are selected in the effective \(0.002 < q^2 < 1.12 \text{ GeV}^2/c^4\) range

Angular acceptances are modelled by the 4\(^{th}\) order Legendre polynomials

124 signal events

Fit results:

Corrected by the contribution from the \(B_d \rightarrow K^{*0}\gamma\) with converted photon

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

Consistent with the SM predictions:

[arXiv:1412.3183]

The \(A_T^{(2)}\) compatible with zero is also expected in the left-handed polarization of the SM
**$B_s \rightarrow \phi \mu^+\mu^-$ decay**

*Introduction*

Non-standard effects can contribute both in the branching fraction and angular observables.

The decay is not flavour-specific.

Angular observables are **CP-averages** and **CP-asymmetries**.

\[
\frac{1}{d\Gamma/dq^2 \ d\cos\theta_l \ d\cos\theta_K \ d\Phi} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l \\
+ S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\Phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \Phi \\
+ A_5 \sin 2\theta_K \sin \theta_l \cos \Phi + A_6 \sin^2 \theta_K \cos \theta_l \\
+ S_7 \sin 2\theta_K \sin \theta_l \sin \Phi + A_8 \sin 2\theta_K \sin 2\theta_l \sin \Phi \\
+ A_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\Phi \right].
\]
$B_s \rightarrow \phi\mu^+\mu^-$ decay

**Signal**

Event selection: loose cut-based preselection + BDT

\(\psi(2S)\) mode – excluded

\(J/\psi\) mode – excluded for the signal selection

Used for normalization channel

Differential branching fraction measured in each \(q^2\) bin:

\[
\frac{d\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)}{dq^2} = \frac{1}{q_{\text{max}} - q_{\text{min}}} \cdot \frac{N_{\phi\mu\mu}}{N_{J/\psi\phi}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu\mu}} \cdot \mathcal{B}(B_s^0 \rightarrow J/\psi\phi) \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)
\]

Event yield 432 ± 24
$B_s \rightarrow \phi \mu^+ \mu^-$ decay

Differential branching fraction

The resulting total relative and absolute branching fraction:

$$\frac{B(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{B(B_s^0 \rightarrow J/\psi \phi)} = (7.41^{+0.42}_{-0.36} \pm 0.20 \pm 0.21) \times 10^{-4},$$

$$B(B_s^0 \rightarrow \phi \mu^+ \mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7}.$$

3.3σ tension with the SM prediction (averaging between the two bins)

[arXiv:1506.08777]

SM predictions:
[arXiv:1503.05534]
[arXiv:1411.3161]

Form factors calculated:
light-cone sum rule calculations at low $q^2$
lattice QCD calculations at high $q^2$

No predictions available near the charmonium resonances

Compatible with the previous LHCb measurement [JHEP 07 (2013) 084]
$B_s \rightarrow \phi \mu^+ \mu^- \text{ decay}$

Angular variables

SM predictions from:
- [arXiv:1503.05534]
- [arXiv:1411.3161]

Form factors calculated:
- Light-cone sum rule calculations at low $q^2$
- Lattice QCD calculations at high $q^2$

Measurement results are in agreement with the SM predictions
$B_s \rightarrow \phi \mu^+ \mu^-$ decay

Angular variables contd.

No theoretical predictions available
The values are expected to be close to zero in the SM

Comparable with zero as expected from the SM predictions
Conclusions

Rare decays provide us with an excellent probe for the new physics

General agreement with the Standard Model is seen

Some tension with the SM is observed in several channels

And they are not described by the most expected models

We're looking forward for the data of Run II, more precision and new exciting measurements!

Thank you for your attention!
Backup
The LHCb detector

See details in talk by Ivan Polyakov

[JINST 3 (2008) S08005]

VELO – microstrip vertex detector;
TT, T1-T3 – tracking system;
RICH1, RICH2 – ring imaging Cherenkov detectors;
SPD, PS, ECAL, HCAL - calorimeter system;
M1-M5 – muon system;

3 fb⁻¹ of data has been taken during 2011-2012 datataking period
  1 fb⁻¹ at \( \sqrt{s} = 7 \) TeV centre of mass energy
  2 fb⁻¹ at \( \sqrt{s} = 8 \) TeV centre of mass energy

Performance:

B-meson lifetime resolution ~45 fs
Track momentum resolution \( \delta P/P < 0.4-0.6\% \)
p/π/K separation accuracy > 90%
Photon energy resolution ~2%
h/e⁻ separation efficiency ~90% for ~5 % e⁻→h mis-id probability
Muon identification efficiency ~97% for 1-3 % π→μ mis-id probability
Trigger efficiency ~90 % for dimuon channels
~30% for multi-body hadronic final states

Angular coverage: 300 mrad
2 < \( \eta \) < 5
$$B_d \rightarrow K^{*0}e^+e^-\text{ decay}$$

**Brehmsstrahlung and converted photons**

Brehmsstrahlung recovery

$$B_d \rightarrow K^{*0}e^+e^-$$

**p_T(\gamma) > 75 \text{ MeV/c}**

Selection requirement

Hits the same ECAL cell

→ correct energy measurement

$$m(e^+e^-) > 20 \text{ MeV/c}^2$$

$$\sigma_z(e^+e^-) < 30 \text{ mm}$$

Removes ~99% of such contamination

The remaining contribution is taken as a correction
$B_d \rightarrow K^{*0} \mu^+\mu^-$ decay

Theoretical discussions

Minimal flavour violation: arXiv:1312.5267