Latest results in rare decays at LHCb

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Overview

Confront with Standard Model (SM) predictions
Look for hints of new physics (NP)

Highly suppressed in SM

\[ B_{s(d)} \rightarrow \mu^+ \mu^- \]

BR

\[ b \rightarrow s \text{ FCNC processes} \]

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

\[ A_{CP} \ (\ldots) \]

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \]

\[ A_{FB} \text{ angular} \]

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

\[ \text{BR (aim: angular)} \]

\[ \text{BR (searches)} \]

\[ D_{(s)^+} \rightarrow \pi^+ \mu^+ \mu^- \text{ and } D_{(s)^+} \rightarrow \pi^- \mu^+ \mu^+ \]

\[ c \rightarrow u \text{ FCNC} \quad \text{LFV} \]

Charm decays
Why rare decays with LHCb?

- Large $b\bar{b}$ cross section $\sigma(pp \rightarrow b\bar{b}X) @ 7\text{TeV} = 284\pm53\mu\text{b}$ [LHCb, PLB 694 209]
  - $c\bar{c}$ cross section ~20 times larger
- Large acceptance for $b$ hadron decays
- Efficient and flexible trigger (particularly $\mu$ trigger for analyses presented here)
- Good particle ID, tracking and reconstruction
- Dipole magnet polarity regularly flipped
First evidence of the decay $B_s^0 \rightarrow \mu^+ \mu^-$


Comparing to the previous results:
- sample x 2
- refined analysis

Performed with 1.0 fb$^{-1}$ from 2011 (7 TeV) and 1.1 fb$^{-1}$ from 2012 (8 TeV)
**$B^0_{d,s} \rightarrow \mu^+\mu^-$**

- **Double suppression:**
  FCNC and helicity

- **Precise SM prediction:**
  - $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$
  - $\text{BR}(B_d \rightarrow \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$
  

- **Possible new particles in the loops. For example (2HDM)**

- **In LHCb:**
  - maximize sensitivity by classifying events according to two variables:
    - $m_{\mu\mu}$
    - Boosted Decision Tree (BDT) combining geometrical and kinematic information
  - Data driven calibration of BDT for signal from $B_{d,s} \rightarrow h^+h'^-$ events
$B^0_{d,s} \rightarrow \mu^+\mu^-$

- Excess $\rightarrow$ extract yields from a simultaneous fit of $m(\mu\mu)$ in different BDT bins
- BR normalized using $B^0_s \rightarrow h^+h'^-$ and $B^+ \rightarrow K^+J/\psi$

$BR(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}\text{ (stat.)} \pm 0.2\text{ (syst.)}) \times 10^{-9}$

Probability of background-only fluctuations: $5 \times 10^{-4} \equiv 3.5 \sigma$ (first evidence!)

(In agreement with the SM expectation)

$BR(B^0_d \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$ @95% C.L (single exp. world-best!)

Probability of background-only fluctuations: $11\% \equiv 1.2 \sigma$
b→s FCNC processes: B→K(∗)ℓℓ

- Measurement of the CP Asymmetry in B^0→K^{*0}μ^+μ^-

- Differential branching fraction and angular analysis of the B^+→K^+μ^+μ^- decay
  arXiv:1209.4284 [hep-ex], JHEP 02 (2013) 105

- Measurement of the B^0→K^{*0}e^+e^- branching fraction at low dilepton mass
  LHCb-PAPER-2013-005, publication in preparation

All performed with 1.0 fb^{-1} from 2011 (7 TeV)
**B→K(*)ℓℓ: b→s FCNC processes**

- Within the SM, these processes proceed via loop diagrams like

- New physics entering the virtual parts, could largely alter observables

- Effective Hamiltonian: \( \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \sum_{i=1}^{10} (C_i^{SM} + \Delta C_i^{NP}) O_i \)

Wilson coefficients (short-dist. interactions) Operators (long-dist. interactions)
$B^0 \rightarrow K^{(*)0} \mu^+ \mu^-$: results already shown (1.0 fb$^{-1}$)

- **Isospin asymmetry** [JHEP07 (2012) 133]

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

- **Angular analysis** [LHCb-CONF-2012-008]

Other observables: $S3$, $S9$, $A_{FB}$ zero crossing point. So far all agree with the SM

LHCb had already the most precise measurements! Stay tuned for future results
CP asymmetry is predicted to be $O(10^{-3})$ in SM. Could be significantly enhanced in NP models (modifying the mixture of vector and axial vector components in the operator basis)

[Phys.Rev.Lett 110, 031801 (2013)]

[Other curves: representative values of NP parameters]

CP Asymmetry in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Motivation

$A_{CP}(q^2) = \frac{\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-) - \Gamma(B^0 \rightarrow K^{0} \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-) + \Gamma(B^0 \rightarrow K^{0} \mu^+ \mu^-)}$

$m^2(\mu\mu) \uparrow$

$A_{CP}$

$q^2$ (GeV$^2$)

$A_{CP} (\%)$

$q^2$ (GeV$^2$)

Eli Ben-Haim

Moriond QCD and High Energy Interactions, March 12th 2013
Self tagging according to the charge of the kaon in $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$

Average data over two magnet polarities to cancel detector effects

Correct the observed asymmetry $A_{raw}$ for production ($A_P$) and detection ($A_D$) asymmetries with $B^0 \rightarrow K^{*0} J/\psi$

$$A_{CP}(B^0 \rightarrow K^{*0} \mu^+\mu^-) = A_{RAW} - A_D - \kappa A_P \approx A_{RAW} - A_{RAW}^{K^{*0} J/\psi}$$

CP asymmetry extracted from simultaneous unbinned likelihood fit to the $B^0$ mass in $B^0 \rightarrow K^{*0} J/\psi$ and $B^0 \rightarrow K^{*0} \mu^+\mu^-$ in bins of $q^2$ and per magnet polarity
CP Asymmetry in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Results

- Result integrated over the full $q^2$ range:

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

- Consistent with SM within 1.8σ
- Most precise measurement to date

(Same bins as in angular analysis)
Differential BF of $B^+ \rightarrow K^+ \mu^+ \mu^-$

- The measurement is performed in 7 $q^2$ bins $0.05 < q^2 < 22$ GeV$^2$
- A large $B^+ \rightarrow K^+ J/\psi$ sample is used to extract the signal shape, train a BDT and as a normalization sample

Result is consistently below the SM in low $q^2$. Agrees with and more precise with results from other experiments

Integrated BF in full $q^2$ range:

$$BR(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.36 \pm 0.15 \pm 0.18) \times 10^{-7}$$

More precise than the current world average
Angular analysis of $B^+ \rightarrow K^+ \mu^+ \mu^-$

- Differential decay rate:
  \[
  \frac{1}{\Gamma} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{d\cos \theta_l} = \frac{3}{4} (1 - F_H)(1 - \cos^2 \theta_l) + \frac{1}{2} F_H + A_{FB} \cos \theta_l
  \]

- SM predictions for the parameters: $A_{FB} = 0$, $F_H$ nearly 0. Deviations indicate NP. Sensitive to scenarios with (pseudo-)scalar or tensor-like couplings.

- $F_H$ and $A_{FB}$ measured in the same 7 bins of $q^2$ by likelihood fit to $m_{K\mu\mu}$ and $\cos \theta_l$.

- Results are consistent with the SM expectation.
**Motivation**: first step on the way to an angular analysis, like in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Comparing to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $B^0 \rightarrow K^{*0} e^+ e^-$ has pros and cons:

- Negligible lepton mass $\Rightarrow$ simpler formalism
- Lower $q^2$ $\Rightarrow$ increased sensitivity to photon polarization (left handed in SM)
- Complementary, since more sensitive to $C7'$ than $C9'$
- More difficult to trigger
- Bremsstrahlung $\Rightarrow$ deteriorated resolution

**Analysis**

- $q^2$ range: $0.03 < \sqrt{q^2} = m(e^+e^-) < 1$ GeV/c$^2$ (below: high background, multiple scattering)
- BDT, trained with signal MC
- $B^0 \rightarrow K^{*0} J/\psi$ is used to control the signal shape and as a normalization sample
- Maximum likelihood fit to the $B^0$ candidate invariant mass, in two categories:
  - Events where one of the signal electrons triggered at hardware level ($L0Electron$)
  - Events that were triggered by other particle, not from the signal B ($L0TIS$)
Results

In agreement with SM expectation (arXiv:1212.2263[hep-ph])

Signal significance of 4.6\(\sigma\) including systematics

It is planned to perform a full angular analysis with all the available LHCb data
Rare charm decays

A search for $D_{(s)}^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$ and $D_{(s)}^{+} \rightarrow \pi^{-}\mu^{+}\mu^{+}$ decays

To be submitted to Phys. Lett. B

Preliminary

All performed with 1.0 fb$^{-1}$ from 2011 (7 TeV)
**Search for** $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ **and** $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^+$ **decays**

**Motivations**

- $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^- : c \rightarrow u$ FCNC process
  - **Essentially 2-family only** … no virtual top quark, thus **strong GIM suppression** $(\text{BR}_{\text{SM}} \sim 1 - 3 \times 10^{-9})$
  - **Probes the coupling of up-type quarks** in EW penguins

> Will only detail this analysis in the following

- $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^+ :$ **Lepton-number violating**
  - Forbidden in the SM
  - May occur by, e.g., Majorana neutrinos
Search for $D_{(s)}^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-}$ decays

Analysis

5 regions of the dimuon spectrum studied simultaneously

- $D_{(s)}^{+} \rightarrow \pi^{+} \phi(\mu^{+}\mu^{-})$ used as Standard Candles
  - Normalization mode: minimize $\sigma(\text{syst})$ since the final state is the same as the signal
  - Signal proxy: optimize the selection (BDT+ muon ID) and control signal shape

LHCb preliminary
Search for $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ decays

Analysis

5 regions of the dimuon spectrum studied simultaneously

LHCb preliminary

Low $m(\mu\mu)$

High $m(\mu\mu)$

FCNC, NP?

$\eta$

$\rho/\omega$

$\phi$

FCNC, NP?

LHCb preliminary

Signal

Comb. background

Peaking backgrounds:

$D_{(s)}^+ \rightarrow \pi^+ \pi^+ \pi^-$

- Shapes from data, by loosening muon ID
- Yields vary in the fit
Search for $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ decays

Analysis

5 regions of the dimuon spectrum studied simultaneously

LHCb preliminary

- Shapes from data, by loosening muon ID
- Yields vary in the fit
Search for $D_{(s)}^+\rightarrow \pi^+\mu^+\mu^-$ and $D_{(s)}^+\rightarrow \pi^+\mu^+\mu^+$ decays

Results

- $D_{(s)}^+\rightarrow \pi^+\mu^+\mu^-$: Upper limits $\times 10^{-8}$ @ 90% (95%) C.L.

<table>
<thead>
<tr>
<th>Region</th>
<th>$B(D^+\rightarrow \pi^+\mu^+\mu^-)$</th>
<th>$B(D_S^+\rightarrow \pi^+\mu^+\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $m(\mu\mu)$</td>
<td>2.0 (2.5)</td>
<td>6.9 (7.7)</td>
</tr>
<tr>
<td>High $m(\mu\mu)$</td>
<td>2.6 (2.9)</td>
<td>16.0 (18.6)</td>
</tr>
<tr>
<td>Total $^{(1)}$</td>
<td>7.3 (8.3)</td>
<td>41.0 (47.7)</td>
</tr>
</tbody>
</table>

Preliminary

(1) Total non resonant BF, extrapolated from the high $M(\mu\mu)$ region (phase space model)
- Limits of the order of a few $10^{-8}$ ($10^{-7}$) for $D^+$ ($D_S$) decays
- **50 to 100 times better than previous measurements** ($D_0$, Babar)
  - Still above largest theory predictions ($\sim 10^{-8}$)

- $D_{(s)}^+\rightarrow \pi^+\mu^+\mu^+$: (the analysis uses a similar approach to $D_{(s)}^+\rightarrow \pi^+\mu^+\mu^-$)
  - No sign of LFV
  - Limits of the order of a few $10^{-8}$ ($10^{-7}$) for $D^+$ ($D_S$) decays
  - **100 times better than previous measurement** (Babar)
Summary and Conclusions

- This was just a selection of a few LHCb results in rare decays
- LHCb continues to produce exciting physics results, adding more information and using more sophisticated analysis techniques to improve the precision of measurements in rare b and c hadron decays
- All measurements presented here agree with the standard model predictions
- Larger samples are needed to tell whether or not there could be indications for NP. Some of the analyses shown here have interesting perspectives with more data
- We are analyzing our full sample of ~3 fb\(^{-1}\)… Stay tuned