Electroweak penguin decays at LHCb

Małgorzata Pikies
Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Poland
on behalf of LHCb Collaboration

Lake Louise Winter Institute
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The LHCb experiment

Momentum resolution:
\[ \frac{\delta p}{p} = 0.4 \% \text{ at } 5 \text{ GeV to } 0.6 \% \text{ at } 100 \text{ GeV} \]

Impact parameter resolution:
\[ \sigma_{IP} \sim 20 \mu m \]

Primary vertex resolution:
13 \mu m in x and y, and 71 \mu m in z

Decay time resolution:
\[ \sigma_\tau \sim 50 \text{ fs} \]

Excellent particle identification

- Single arm forward spectrometer
- Dedicated to heavy flavour physics
- Looks for indirect evidence of new physics in CP violation and rare decays

Rare Decays

- Mediated by electroweak Flavour Changing Neutral Current (FCNC) processes in the Standard Model (SM)
- They are suppressed in the SM, so more sensitive to New Physics
- There are many precise SM predictions

\[ H_{\text{eff}} = - \frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu)O_i(\mu) + C'_i(\mu)O'_i(\mu)] \]

- \( i = 1, 2 \) Tree
- \( i = 3 - 6, 8 \) Gluon penguin
- \( i = 7 \) Photon penguin
- \( i = 9, 10 \) Electroweak penguin
- \( i = S \) Higgs (scalar) penguin
- \( i = P \) Pseudoscalar penguin

- New particles in the loop level processes could significantly change observables
- The pattern of deviations can guide towards NP
Recent LHCb measurements

Branching fractions:

\[ \Lambda_b \to \pi p \mu^+ \mu^- \text{ arXiv:1701.08705} \]
\[ B^0 \to K^{*0} \mu^+ \mu^- \text{ JHEP 1611 (2016) 047} \]
\[ B^\pm \to \pi^\pm \mu^- \mu^+ \text{ JHEP 10 (2015) 034} \]
\[ B^0_s \to \phi \mu^+ \mu^- \text{ JHEP 09 (2015) 179} \]
\[ \Lambda_b \to \Lambda \mu^+ \mu^- \text{ JHEP 06 (2015) 115} \]
\[ B^0_s \to \pi^+ \pi^- \mu^+ \mu^- \text{ Phys.Lett B743 (2015) 46} \]
\[ B^+ \to K^+ \pi^+ \pi^- \mu^+ \mu^- \text{ JHEP 10 (2014) 064} \]
\[ B^+ \to \phi K^+ \mu^+ \mu^- \text{ JHEP 10 (2014) 064} \]
\[ B^0 \to K^{*0} e^+ e^- \text{ JHEP 05 (2013) 159} \]

CP asymmetry:
\[ B^\pm \to \pi^\pm \mu^- \mu^+ \text{ JHEP 10 (2015) 034} \]

Isospin asymmetry:
\[ B \to K \mu^- \mu^+ \text{ JHEP 06 (2014) 133} \]

Phase difference:
\[ B^+ \to K^+ \mu^+ \mu^- \text{ JHEP 11 (2016) 047} \]

Lepton Universality:
\[ B^\pm \to K^\pm l^- l^+ \text{ Phys.Rev.Lett.113, 151601(2014)} \]

Angular:
\[ B^0 \to K^+ \pi^- \mu^+ \mu^- \text{ JHEP 12 (2016) 065} \]
\[ B^0 \to K^{*0} \mu^- \mu^+ \text{ JHEP 02 (2016) 104} \]
\[ B^0_s \to \phi \mu^+ \mu^- \text{ JHEP 09 (2015) 179} \]
\[ \Lambda_b \to \Lambda \mu^+ \mu^- \text{ JHEP 06 (2015) 115} \]
\[ B^0 \to K^{*0} e^- e^+ \text{ JHEP 04 (2015) 064} \]
The first observation of the $\Lambda_b^0 \rightarrow \pi^- p \mu^+ \mu^-$ decay.

Statistical significance corresponding to $5.5 \sigma$.

Normalized to $\Lambda_b^0 \rightarrow J/\psi \pi^- p$. Chin. Phys. C40 (2016) 011001

The expected branching fraction is of $\mathcal{O}(10^{-8})$.

This is the first observation of a $b \rightarrow d$ transition in a baryonic decay.

$$B(\Lambda_b^0 \rightarrow \pi^- p \mu^+ \mu^-) = (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$$
Deviations from the SM in the $b \to s \ell \ell$ transitions could be explained by the short-distance contributions from non-SM particles.

They also could indicate a problem with SM predictions.

Contributions from $B \to X_{c \bar{c}}(\to \mu \mu)K$ could mimic vector-like new physics effects.

Measurement of the phase difference between short-distance and long-distance amplitudes:

- the full di-muon mass spectrum, candidates with 40 MeV/$c^2$ of $B^+$ mass,
- sum of relativistic Breit–Wigner amplitudes as a long-distance contributions,
- $C_7$ fixed to SM, hadronic form factors $f_+$ constrained Phys. Rev. D 93, 025026 (2016), magnitudes, phases, $C_9$ and $C_{10}$ floated.
$B^+ \rightarrow K^+ \mu^+ \mu^-$ the phase difference

- $J/\psi$ phase is compatible with $\pm \frac{\pi}{2}$, interference with short distance contribution far from pole is small.
- Fit to Wilson coefficients: $|C_{10}| < |C_{10}^{SM}|$ and $|C_9| > |C_9^{SM}|$, or if $|C_{10}| = |C_{10}^{SM}|$ then $|C_9| < |C_9^{SM}|$.
- The best $C_9$, $C_{10}$ fit-point deviates at the level of $3.0 \sigma$ from SM.
- These results are consistent with the results reported previously in global analyses.

$$B(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 (\text{stat}) \pm 0.23 (\text{syst})) \times 10^{-7}$$
First (P-wave only) measurement of the differential branching fraction of the $B^0 \to K^* (892)^0 \mu^+ \mu^-$ decay.

Precise theoretical predictions in the $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$.

The first measurement of the S-wave fraction in the range $796 < m(K^+ \pi^-) < 996$ MeV/c$^2$, $F_s = 0.101 \pm 0.017$ (stat) $\pm 0.009$ (syst).

The differential branching fraction is determined to be

$$\frac{d\mathcal{B}}{dq^2} = (0.392)^{+0.020}_{-0.019} \text{(stat)} \pm 0.010 \text{(syst)} \pm 0.027 \text{(norm)} \times 10^{-7} c^4/\text{GeV}^2$$

- in agreement with SM predictions.

\[ B^0 \rightarrow K^*0(\rightarrow K^+\pi^-)\mu^+\mu^- \text{ angular} \]

Described by:
- three helicity angles (\(\theta_1, \theta_K, \phi\)),
- the di-lepton invariant mass squared \(q^2\).

The CP-averaged angular decay distribution:

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K 
+ F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_1 
- F_L \cos^2 \theta_K \cos 2\theta_1 + S_3 \sin^2 \theta_K \sin^2 \theta_1 \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_1 \cos \phi + S_5 \sin 2\theta_K \sin \theta_1 \cos \phi 
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \phi + S_7 \sin 2\theta_K \sin \theta_1 \sin \phi 
+ S_8 \sin 2\theta_K \sin 2\theta_1 \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_1 \sin 2\phi \right]
\]

A_{FB}, F_L, S_j - functions of Wilson coefficients

Additional sets of observables, for which the leading form-factor uncertainties cancel, e.g.:

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

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$B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$ angular

**Signal candidates:**

$5170 < m(K^+\pi^-\mu^+\mu^-) < 5700$ MeV/c$^2$

**K*0 candidates:**

$796 < m(K^+\pi^-) < 996$ MeV/c$^2$

Combinatorial background is reduced using a boosted decision tree:

- trained fully on data
- $B^0 \rightarrow J/\psi K^{*0}$ as a signal
- background sample: data
  $5350 < m(K^+\pi^-\mu^+\mu^-) < 7000$ MeV/c$^2$

- variables used for training
  - PID - kinematics and geometric quantities - isolations

**Signal yield:** 2398 ± 57
The first full angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ decay (Run 1):

- tension in $P'_5$
- $3.4\,\sigma$ global deviations from the SM
- the SM central value for $\text{Re}(C_9)$ is 4.27, best fit-point corresponds to the $\Delta\text{Re}(C_9) = -1.04 \pm 0.25$

![Graph showing $P'_5$ vs. $q^2$]
\[ \Lambda_b \rightarrow \Lambda(p\pi^-)\mu^+\mu^- \]

- Normalized to \( \Lambda_b \rightarrow \Lambda J/\psi \).
- No evidence for signal in \( 2 < q^2 < 8 \text{ GeV}^2/c^4 \).
- More statistics needed.

JHEP06(2015)115
\( B_s^0 \rightarrow \phi(\rightarrow K^+K^-)\mu^+\mu^- \)

- Similar to \( B^0 \rightarrow K^{*0}\mu^+\mu^- \), experimentally very clean (narrow \( \phi \) resonance).
- Final state not self-tagging - less observables are accessible.
- Angular distributions - good agreement with SM.
- Branching fraction - differs from SM by \( 3.3 \sigma \) at low \( q^2 \)

\[ F_L \]

\[ d\beta(B^0_s \rightarrow \phi\mu\mu) dq^2 [10^{-8} GeV^2/c^4] \]

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M. PIKIES

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Rare decays are a powerful tool for searching for BSM effects. Intresting tensions with SM predictions emerged in the rare decays: $B^0 \rightarrow K^* \mu^+ \mu^-$ angular observables, $B_s^0 \rightarrow \phi \mu^+ \mu^-$ brancing fraction. Motivates further work both in theory and experiment. Many more analyses in the pipeline.
Thank you for your attention :)