Rare decays at LHCb

Marc-Olivier Bettler (CERN) on behalf of LHCb
After Run 1 at the LHC, the **SM seems healthier than ever**. Its postulated key component, the Higgs boson, was discovered, while **no new off-shell particles** were.

However, the **shortcomings of the SM have not disappeared**. The SM has no explanation for the nature of dark matter. The level of the imbalance between matter and antimatter is still not accounted for in the SM.

Looking **for new phenomena**, one searches for deviations from the SM predictions. While a few anomalies have arisen during Run1 ... ... only a very limited **few remain, notably in rare decays**.
Tensions for some observables ...

\[ R(D^{(*)}) = \frac{\mathcal{B}(B^0 \rightarrow D^{(*)} - \tau^+ \nu_{\tau})}{\mathcal{B}(B^0 \rightarrow D^{(*)} - \mu^+ \nu_{\mu})} \]

\[ R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)} \]

Angular observables, mainly \[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

Branching fraction, eg in \[ B^0_s \rightarrow \phi \mu^+ \mu^- \]

[see talk on LFU by M.-H. Schune]
Model-independent approach via OPE (Wilson Coefficients)

Global fits to 80+, 100+ observables 
\( C_9^{NP} \sim -1 \) (3.7 to 4.7\( \sigma \))

How to explain this?
- Underestimated QCD
- New Physics
(not mutually exclusive!)
[see talk of S. Neshatpour and J. Virto]

In this talk:
- constraining charm loop contributions
- \( \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \) and lifetime
- search for \( B_s^0 \rightarrow \tau^+ \tau^- \)
- search for \( K_s^0 \rightarrow \mu^+ \mu^- \)
- probing \( \Sigma^+ \rightarrow p \mu^+ \mu^- \)

[JHEP06 (2016) 092]
[EPJC 75 (2015) 382]
New physics
Z', leptoquark

Hadronic SM effect
large long-distance effect from resonances

or ?
and ?
to what extent ?

\[ C_9 + C_9^{NP} \]

\[ C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{res}(q^2) \]

experimental input to the discussion
[LHCb-PAPER-2016-045]
Probing the effect of resonances

- Analyse the $m(\mu\mu)$ spectrum of $B^+ \rightarrow K^+ \mu^+ \mu^-$ modeling all resonances.
- The differential decay rate depends on Wilson coefficients:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{128 \pi^5} |k|/\beta \left\{ \frac{2}{3} |k|^2 \beta^2 C_{10,0}(q^2)^2 + \frac{4m_\mu^2 (m_B^2 - m_K^2)}{q^2 m_B^2} C_{10,0}(q^2)^2 \right\} + |k|^2 \left[ 1 - \frac{1}{3} \beta^2 \right] \left( C_{9,0}(q^2) + 2C_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right)^2 \right\},$$

C7 fixed to SM value

Parametrise the effects of 9 resonances on $C_9$

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

relative phase to $C_9$ Breit-Wigner/Flatte

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\psi(2S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
<td>$\psi(3770)$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$\psi(4040)$</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>$\psi(4160)$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\psi(4415)$</td>
</tr>
</tbody>
</table>

Phase: neg. neg.
Four degenerate $J/\psi$ and $\psi(2S)$ phase sign choices:
Modeling all resonances, the observed **BF is lower than the SM**, in agreement with previous analysis (same data)

\[
B(B^+ \to K^+ \mu^+ \mu^-) = (4.29 \pm 0.07 \text{ (stat)} \pm 0.21 \text{ (syst)}) \times 10^{-7} \quad \text{old}
\]

\[
B(B^+ \to K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \text{ (stat)} \pm 0.23 \text{ (syst)}) \times 10^{-7} \quad \text{new}
\]

- Two fits to the Wilson coefficients:
  - \(C_9\) only (fixing \(C_{10}\) to SM): \(C_9 < \text{SM}\), as in global fits
  - \(C_9\) and \(C_{10}\): \(C_9 > \text{SM}\) and \(C_{10} < \text{SM}\)

- The effect of charm loops is limited and **cannot account for the low value of the BF with SM Wilson coefficients**.

- Similar work is ongoing for the \(B^0 \to K^{*0} \mu\mu\) channel
Purely Leptonic decays

[LHCb-PAPER-2017-001]
[LHCb-PAPER-2017-003]
Very accurate SM predictions [PRL 96 (2006) 241802]

\[ \mathcal{B}(B^0 \to \mu^+ \mu^-)^{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10} \]
\[ \mathcal{B}(B_s^0 \to \mu^+ \mu^-)^{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9} \]

Current situation
Improvements

- 3 fb$^{-1}$ of Run1 + 1.4 fb$^{-1}$ of Run2
- new signal isolation
- new BDT: 50% better back. rejection
- improved PID: 50% less B$\to$h$^+$h$^-$

First single-experiment observation of the $B_s$ mode!

\[
\mathcal{B}(B^0_s \to \mu^+ \mu^-) = (3.0 \pm 0.6 \text{ (stat)} ^{+0.3}_{-0.2} \text{ (syst)}) \times 10^{-9} \quad (7.8\sigma)
\]

\[
\mathcal{B}(B^0 \to \mu^+ \mu^-) = (1.5 \pm 1.2 \text{ (stat)} ^{+0.2}_{-0.1} \text{ (syst)}) \times 10^{-10} \quad (1.6\sigma)
\]

Limit derived on the $B^0$ (CLs method)

\[
\mathcal{B}(B^0 \to \mu^+ \mu^-) < 3.4 \times 10^{-10} \quad @ 95\% \ C.L.
\]
In the SM, only the heavy mass eigenstate decays to $\mu\mu$.

Even if the BF is SM, the effective lifetime provides a probe to search for NP.

The effective lifetime can be expressed in terms of $A_{\Delta\Gamma}^{\mu^+\mu^-}$.

For the first time, measurement of the effective lifetime.

$$\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ ps}$$

consistent with the SM $A_{\Delta\Gamma}^{\mu^+\mu^-} = 1 \ (1\sigma)$ and with $A_{\Delta\Gamma}^{\mu^+\mu^-} = -1 \ (1.4\sigma)$ the most extreme value for NP.
Theoretically, as clean as the muonic mode. Experimentally much more challenging. Will make for a very clean LFU test with muonic mode in the future.

More abundant than the muon mode

\[ \mathcal{B}(B^0 \to \tau^+\tau^-)^{\text{SM}} = (2.22 \pm 0.19) \times 10^{-8} \]
\[ \mathcal{B}(B_s^0 \to \tau^+\tau^-)^{\text{SM}} = (7.73 \pm 0.49) \times 10^{-7} \]

Only existing limit on the $B^0$ mode

\[ \mathcal{B}(B^0 \to \tau^+\tau^-) < 4.1 \times 10^{-3} \quad @ \ 90\% \ C.L. \]

Babar, [PRL 96 (2006) 241802]

Analysis of Run1 data, in hadronic tau decay via the resonances

\[ \tau^- \to a_1(1260)^- \nu_\tau, \ a_1(1260)^- \to \rho(770)^0 \pi^- \]
\[ \mathcal{B}(\tau^\pm \to \pi^\pm \pi^\mp \pi^\pm \bar{\nu}_\tau) = (9.31 \pm 0.05)\% \]

World best limits set for each mode (assuming no contributions from the other):

\[ \mathcal{B}(B^0 \to \tau^+\tau^-) < 1.8 \times 10^{-3} \quad @ \ 95\%CL \]
\[ \mathcal{B}(B_s \to \tau^+\tau^-) < 6.0 \times 10^{-3} \quad @ \ 95\%CL \]
Rare strange decays

[LHCb-CONF-2016-012]
[LHCb-CONF-2016-013]
The suppression of the $K^0_L \rightarrow \mu^+ \mu^-$ decay is a corner stone of the SM: the GIM mechanism was brought up to explain it.

$K^0_S \rightarrow \mu^+ \mu^-$ is still unobserved and its SM prediction is

$$B(K^0_S \rightarrow \mu^+ \mu^-) = (5.1 \pm 1.5) \times 10^{-12}$$

Even though, by construction, the branching fraction of the $K^0_L$ mode is SM, different physics is at play for the $K^0_S$ mode and its BF can be NP-enhanced.

LHCb opened the Kaon physics at the LHC in 2013.

[JHEP 01 (2004) 009]
[JHEP 01 (2013) 090]
New analysis on the remaining 2fb\(^{-1}\) of Run1 data

The analysis heavily relies on the mass resolution to distinguish signal from the very abundant \(K^0_S \to \pi^+\pi^-\).

Combinatorial background and \(K^0_S \to \pi^+\pi^-\) suppressed via dedicated MVAs.

A lot of work goes into improving the trigger efficiency for such soft decays, still the bottleneck.

No signal found:

\[
\text{BF}(K^0_S \to \mu^+\mu^-) < 6.9 \times 10^{-9} \text{ at 95\% CL}
\]

This preliminary result will be updated (and improved) soon.
An evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$ was found by the HyperCP experiment with 3 events in absence of background. Branching fraction measured as $(8.6_{-5.4}^{+6.6} \pm 5.5) \cdot 10^{-8}$ compatible with SM. [PRD 72 (2005) 074003] [PRL 94 021801 (2005)]

The interest lies in the fact that the 3 observed signal events have the same dimuon mass:

suggesting a decay through a resonance $\Sigma^+ \rightarrow pX^0 (\rightarrow \mu^+\mu^-)$?
Preliminary result, as normalisation was possible only for part of the analyzed data. Will be updated soon with BF measurement.

- Evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$ with ~13 candidates (4$\sigma$)

- No enhancement at $m(\mu\mu) = 214.3$ MeV, 1.6 ± 1.9 events
Rare decays continue to deliver

Rare decays remain the source of tensions with the SM both in LFU tests and in global fits to Wilson coefficients.

LHCb provides experimental input to the discussion about the effect of the narrow charm resonance in global interpretation.

LHCb observes the $B^0_s \to \mu^+\mu^-$ decay with $7.8\sigma$ using part of run2 data. The excess in $B^0 \to \mu^+\mu^-$, from the previous combination with CMS, is not confirmed.

World best limits on tauonic modes have been set.

First measurement of promising observable, the effective lifetime $B^0_s \to \mu^+\mu^-$

LHCb expands the study of rare strange decays with $K^0_s \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$

Many other recent results not covered here: [link]
Backup