B decay anomalies at LHCb

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On behalf of the LHCb collaboration
Outline

- Introduction
- The LHCb experiment
- Rare B decays
- Semileptonic B decays
- Conclusions
Introduction

- The amplitude of a hadron decay process can be described using Effective Field Theories: Operator Product Expansion (OPE)

\[ A(M \to F) = \langle F | \mathcal{H}_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^{i} C_i(\mu) \langle F | O_i(\mu) | M \rangle \]

→ a series of effective vertices multiplied by effective coupling constants \( C_i \).

Electroweak scale \( \sim 1/M_W \)
New Physics scale \( \sim 1/M_{NP} \)

\[ C_i = C_i^{SM} + C_i^{NP} \]
\[ C'_i = C'^{SM}_i + C'^{NP}_i \]

Primed \( C'_i \) → right handed currents: suppressed in SM
The LHCb experiment
• The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion
  ~ 300 $\mu$b @ $\sqrt{s}$=7 TeV
  ~ 600 $\mu$b @ $\sqrt{s}$=13 TeV

  [PRL 118 (2017) 052002]

  The $b$ quarks hadronize in $B$, $B_s$, $B^*_s$, $b$-baryons...
  $\rightarrow$ average $B$ meson momentum ~ 80 GeV

• The LHCb idea: to build a single-arm forward spectrometer:
  ~ 4% of the solid angle ($2 < \eta < 5$),
  ~30% of the $b$ hadron production

  [INT.J.MOD.PHYS.A 30 (2015) 1530022]
  [JINST 3 (2008) S08005]
The LHCb experiment

Smaller number of primary vertices as compared to ATLAS and CMS
Analysis with Run2 data only includes 2015 and 2016 data

Run1 (2011 and 2012) = 3fb\(^{-1}\)
Run2 (2015 and 2016) = 2fb\(^{-1}\)
Run2 (2017 and 2018) = 4fb\(^{-1}\)
Rare B decays

Himalayan quail (India), last seen in 1876.
Rare B decays

- $b \to s,d$ quark transitions are Flavor Changing Neutral Currents (FCNCs),
  → in the SM they only can occur through loops (*penguin and box diagrams*),
  excellent probe for physics beyond the SM

**leptonic**

- $\bar{b} \to \ell^+ \ell^{-}$
- $B R \sim 10^{-9}$

**semileptonic**

- $b \to W^{-}\ell^+$
- $B R \sim 10^{-7}$

**radiative**

- $b \to s \gamma$
- $B R \sim 10^{-5}$

**Experimentally** → leptons/photons with high transverse momenta

**Theoretically** → observables can be calculated in terms of Wilson coefficients

**Ex:**

$$\Gamma\left( B_s^0 \to \mu^+ \mu^- \right) \sim \frac{G_F^2 \alpha^2}{64\pi^3} m_{B_s}^2 f_{B_s}^2 |V_{tb} V_{ts}|^2 \left| 2m_\mu C_{10} \right|^2$$

- Hadronic uncertainties in decay constants or form factors
Rare B decays: $B_s \rightarrow \mu^+\mu^-$

- Very rare decay:
  FCNC and helicity suppressed
  $BR_{SM} = 3.57(17) \times 10^{-9}$

- Searched for over the last 30 years, observed by LHCb and CMS

- Updated analysis by LHCb, including Run2 data
  [PRL 118 (2017) 191801]

- $B_s \rightarrow \tau^+\tau^-$ also searched for at LHCb:
  $BR(B_s^0 \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95%
  [PRL 118 (2017) 251802]

$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6_{-0.2}^{+0.3}) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95%

→ Agreement with the SM
→ Theoretical uncertainties ($f_{B(s)}$, $V_{CKM}$) well below statistical uncertainty
Rare B decays: $B_s \rightarrow \mu^+\mu^-$

We are here!
(almost touching $B \rightarrow \mu^+\mu^-$)
Rare B decays: $B \rightarrow K^{(*)}\mu^+\mu^-$

Differential decay width: $d\Gamma/dq^2$

Each $q^2$ region probes different processes

$q^2 = (p_{\ell^+} + p_{\ell^-})^2$

charmonium resonances

$\psi(2S)$

$J/\psi(1S)$

photon pole

$\gamma$

$O_7$ $O_{9,10}$

SM values ($\mu = m_b$):

$C_7 \sim -0.33$

$C_9 \sim 4.27$

$C_{10} \sim -4.17$

(Everything else small or negligible)

$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

(Primed $C'_i$ → right handed currents: suppressed in SM)
Rare B decays: $B^0 \rightarrow K^* \mu^+ \mu^-$

$B$ mass versus $q^2$ for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$J/\psi (2S)$

$\psi (2S)$

$J/\psi$

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

[JHEP 08 (2017) 055]
Rare B decays: $B \rightarrow K^{(*)}\mu^+\mu^-$

- Differential decay width as function of $q^2 = m_{\mu\mu}^2$ at LHCb, using 3fb$^{-1}$

$\Lambda_b \rightarrow \Lambda\mu^+\mu^-$

$\rightarrow$ Smaller branching fractions than the SM predictions

PRD 71 (2005) 014015 (LCSR)
PRL 111 (2013) 162002 (LQCD)
JHEP 06 (2014) 133
PRD 89 (2014) 094501 (LQCD)
JHEP 08 (2016) 098 (LCSR)
JHEP 06(2015)115
PRD93 (2016) 074501
Rare B decays: $B \rightarrow K^{(*)} \mu^+ \mu^-$

- Angular distribution in $B \rightarrow K^* \ell^- \ell^+$: $q^2$ and three angles

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

→ In the lepton massless limit there are **eight** independent observables:

$F_L =$ fraction of the longitudinal polarization of the $K^*$
$S_6 = 4/3 \ A_{FB}$, the forward-backward asymmetry of the dimuon system
$S_{3,4,5,7,8,9}$ are the remaining CP-averaged observables
Rare B decays: $B \rightarrow K^{(*)} \mu^+ \mu^-$

- These observables are also affected by hadronic uncertainties
- A new set of “optimized observables”, with form factor cancellations can be defined: [Descotes-Genon et al, JHEP 05 (2013) 137]

\[ P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L (1 - F_L)}} \]

- These observables are functions of $q^2$ and the Wilson coefficients $C_i$

Example: $P'_5$

3σ local deviation
Rare B decays: $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

→ Results from LHCb in the $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ decay channel

$$\frac{d^5 \Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i}^{34} K_i(q^2) f_i(\vec{\Omega})$$

5 angles and 1 normal vector $\vec{n}$

Depends on many observables ($K_i$)

Obtained from method of moments

$$15 < q^2 < 20 \text{ GeV}^2$$

In general compatible with SM predictions

[Boër et al., JHEP 01 (2015) 155],

Run1 + Run2 data: 5fb$^{-1}$

[LHCb, JHEP 09 (2018) 146]
Rare B decays: $R_K$

- In the SM all leptons are expected to behave in the same way

Test of lepton universality:

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 1.000 + O(m_\mu^2/m_b^2)$$

- Precise theory prediction due to cancellation of hadronic form factor uncertainties

- Challenge: bremsstrahlung by electrons

- Experimentally, we perform a double ratio to cancel systematic uncertainties
Rare B decays: $R_K$

B mass versus $q^2$ for $B^+ \to K^+ \ell^+\ell^-$
Rare B decays: $R_K$

B mass versus $q^2$ for $B^+ \rightarrow K^+ \ell^+ \ell^-$

$B^+ \rightarrow K^+ \mu^+ \mu^-$  $m(B^+)$

$B^+ \rightarrow K^+ e^+ e^-$  $m(B^+)$

$\psi(2S)$  $J/\psi$

$B^+ \rightarrow K^+ \mu^+ \mu^-$  $m(K^+ \mu^+ \mu^-)$

$B^+ \rightarrow K^+ e^+ e^-$  $m(K^+ e^+ e^-)$

[PRL 113 (2014) 151601]
Rare B decays: $R_K$

Results with Run1 data: [LHCb, PRL 113 (2014) 151601]

$B^+ \rightarrow K^+ e^+ e^-$

1 GeV < $q^2$ < 6 GeV

$R_K = 0.745^{+0.090}_{-0.074}$ (stat) ± 0.036 (syst)

→ Consistent, but lower, than the SM at 2.6σ
Rare B decays: $R_K$

**New results (Moriond 2019):**

Including partial sample of Run2 (2fb$^{-1}$)

[LHCb, *PRL* 122 (2019) 191801]

With improved reconstruction and re-optimized analysed strategy

$R_K = 0.846^{+0.060}_{-0.054}\text{(stat.)}^{+0.016}_{-0.014}\text{(syst.)}$

$1.1\text{ GeV} < q^2 < 6\text{ GeV}$

→ Still consistent, lower, than the SM at $2.5\sigma$

Not confirmed, not ruled out...
Rare B decays: $R_{K^*}$

- Measurement in the $B \to K^* \mu^+ \mu^-$ channel, $R_{K^*}$:

$$R_{K^*0} = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}$$

- Computed in two bins of $q^2$
  - [0.045, 1.1 GeV$^2$] avoiding the photon pole
  - [1.1, 6.0 GeV$^2$] avoiding the radiative tail of $J/\psi$ modes

$0.045 \text{ GeV} < q^2 < 1.1 \text{ GeV}$  
$1.1 \text{ GeV} < q^2 < 6 \text{ GeV}$
Rare B decays: $R_{K^*}$

- Results: [LHCb, JHEP 08 (2017) 055]

$R_{K^*0}$ vs $q^2$ [GeV$^2$/c$^4$]

- Low $q^2$ [0.045-1.1 GeV$^2$]: $SM\downarrow = 0.922(22)$
  
  \[
  R_{K^*0} = 0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)}
  \]

- Central $q^2$: [1.1-6 GeV$^2$]: $SM\downarrow = 1.000(6)$
  
  \[
  R_{K^*0} = 0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)}
  \]

→ Consistent, but lower than the SM at 2.1-2.3σ (low $q^2$) and 2.4-2.5σ (central $q^2$)
Rare B decays: $B_s \rightarrow \phi \gamma$

**New results (Moriond 2019):** [arXiv:1905.06284, accepted by PRL]

- Time dependent distribution for $B_s \rightarrow \phi \gamma$ is sensitive to the photon polarization (photon is left-handed polarized in $b \rightarrow s$ transitions)

\[
\Gamma_{B_s,\bar{B}_s}(t) = B_0 e^{-\Gamma t} \left[ \cosh\left( \frac{\Delta \Gamma}{2} t \right) - A^4 \sinh\left( \frac{\Delta \Gamma}{2} t \right) \mp C \cos(\Delta m t) \mp S \sin(\Delta m t) \right]
\]

\[S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11\]
\[C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11\]
\[A_{\phi\gamma}^{\Delta} = -0.67^{+0.37}_{-0.41} \pm 0.17\]

→ Compatible with SM at 1.3, 0.3, 1.7σ
Rare B decays: $B_s \rightarrow \phi \gamma$

First measurement in the $B_s$ system for radiative decays!

[arXiv:1905.06284, accepted by PRL]
Rare B decays: $\Lambda_b \rightarrow \Lambda\gamma$


- First observation of a radiative decay of a $b$-baryon: $\Lambda_b \rightarrow \Lambda\gamma$
  - Very challenging: no vertex from the photon and long living $\Lambda$

$$\frac{N(\Lambda_b^0 \rightarrow \Lambda\gamma)}{N(B^0 \rightarrow K^{*0}\gamma)} = \frac{f_{\Lambda_b^0} \cdot B(\Lambda_b^0 \rightarrow \Lambda\gamma) \cdot B(\Lambda \rightarrow p\pi^-)}{f_{B^0} \cdot B(B^0 \rightarrow K^{*0}\gamma) \cdot B(K^{*0} \rightarrow K^+\pi^-) \cdot e(\Lambda_b^0 \rightarrow \Lambda\gamma)}$$

$$B(\Lambda_b^0 \rightarrow \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

- In agreement with the SM: (6–100)$\times 10^{-7}$

Run2 data: $1.7\text{fb}^{-1}$
Rare B decays: $\Lambda_b \rightarrow \Lambda \gamma$

- Possibility for direct measurement of photon polarization ($\alpha_\gamma$) in $b$-baryon decays ($\Lambda_b, \Xi_b \ldots$) (non-zero spin of the initial- and final-state particles)

[Sinha et al, arXiv:1902.04870, accepted by EPJC]

$$\Gamma_{\Lambda_b}(\theta_p) = \frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Lambda \cos \theta_p \right)$$

For $\Xi_b$ there is an additional angle:

$$\Gamma_{\Xi_b}(\theta_\Lambda, \theta_p) = \frac{1}{4} \left( 1 - \alpha_\gamma \alpha_\Xi \cos \theta_\Lambda + \alpha_\Lambda \cos \theta_p \left( \alpha_\Xi - \alpha_\gamma \cos \theta_\Lambda \right) \right)$$
Rare B decays

Global fits (some cases with more than 100 observables)

New Physics hypothesis preferred over SM by > 5σ
Main effect on the $C_{9\mu}$ coefficient: $\sim 4.27^{SM} -1.0^{NP}$ & Contribution of RH currents?

Triggered models with $Z'$, leptoquarks (LQ), new fermions and scalars....
Semileptonic $B$ decays
Semileptonic B decays: $R_D, R_{D^*}$

- Another test of lepton universality (now at tree level):

  Ratio of semi-tauonic and semi-muonic branching fractions:

  $$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*-}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*-}\mu^-\bar{\nu}_\mu)}$$

  Sensitive to charged Higgs bosons and leptoquarks

SM predictions very precise: $(V_{cb}$ and form factors (partially) cancel)

- $R(D)_{SM} = 0.299 \pm 0.003$
- $R(D^*)_{SM} = 0.252 \pm 0.003$

Based on HQET form factors:

[H. Na et al., PRD 92 (2015) 054510]
and experimental measurements (HFLAV)

[D.Bigi, Gambino, PRD 94 (2016) 094008]
Semileptonic B decays

**BaBar** measured an excess of $B^0 \rightarrow D^{(*)}\tau^-\nu_\tau$ \(3\sigma\) away from SM! \([\text{PRD 88 (2013) 072012}]\)

\([\text{Nature 546 (2017) 227}]\)

LHCb:

- $R(D^*) \quad \begin{cases} \bar{B}^0 \rightarrow D^{**}\tau^-\nu_\tau, \text{ with } \tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau \quad [\text{PRL 115 (2015) 111803}] \\ B^0 \rightarrow D^{*-}\tau^+\nu, \text{ with } \tau^+ \rightarrow \pi^+\pi^+\pi^0\nu_\tau \quad [\text{PRL 120 (2018) 171802}] \end{cases}$

- $R(J/\psi) \quad B^+_c \rightarrow J/\psi^-\tau^+\nu, \text{ with } \tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau \quad [\text{PRL 120 (2018) 121801}]$

- **Using** $\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$

Information from the missing mass squared $m_{\text{miss}}^2 = (P_B - P_{D^* - P_\mu})^2$ and muon energy

- **Using** $\tau^+ \rightarrow \pi^+\pi^-\pi^+\nu_\tau$

Information from the position of the pions. Normalized to $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+$

\([\text{PRL 120 (2018) 121801}]\)
Semileptonic B decays

New results (Moriond 2019) from Belle:

- Global picture of $R_D$ and $R_{D^*}$

→ New results from Belle: $4\sigma \rightarrow 3\sigma$ deviation from SM
Conclusions

• Several deviations from the Standard Model in the flavour sector have been found by LHCb (and other experiments)

• Measurements of branching fractions, angular analyses and test of lepton flavour universality show a consistent pattern in global fits, pointing to new physics in the Wilson coefficient $C_{9\mu}$.

• New results of $R_K$ doesn’t confirm or rule out the scenario: need more data!

• New inputs from radiative decays will help to constrain NP patterns
Thanks!
Prospects

arXiv:1808.08865v4 [hep-ex]

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<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb⁻¹</th>
<th>23 fb⁻¹</th>
<th>50 fb⁻¹</th>
<th>300 fb⁻¹</th>
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<td>$B^+ \to K^+ e^+ e^-$</td>
<td>254 ± 29</td>
<td>1120</td>
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<td>7500</td>
<td>46000</td>
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<td>$B^0 \to K^{*0} e^+ e^-$</td>
<td>111 ± 14</td>
<td>490</td>
<td>1400</td>
<td>3300</td>
<td>20000</td>
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<td>$B^0_s \to \phi e^+ e^-$</td>
<td>80</td>
<td>230</td>
<td>530</td>
<td>3300</td>
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<td>$A^0_\phi \to pK e^+ e^-$</td>
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<td>360</td>
<td>820</td>
<td>5000</td>
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<tr>
<td>$B^+ \to \pi^+ e^+ e^-$</td>
<td>20</td>
<td>70</td>
<td>150</td>
<td>900</td>
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$R_X$ precision

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<tr>
<th>$R_K$</th>
<th>0.745 ± 0.090 ± 0.036</th>
<th>0.043</th>
<th>0.025</th>
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<td>$R_{K^*0}$</td>
<td>0.69 ± 0.11 ± 0.05</td>
<td>0.052</td>
<td>0.031</td>
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<td>$R_\phi$</td>
<td>0.130</td>
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<td>$R_{pK}$</td>
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<td>$R_\pi$</td>
<td>0.302</td>
<td>0.176</td>
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LHCb

<table>
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<th>±10.0</th>
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<th>±90</th>
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$R_K$ [%]  
$R(D^+)$ [%]  
$R(B_{s} \to \mu^+ \mu^-)$ [%]  
$R(B_{s}^0 \to \mu^+ \mu^-)$ [%]
Rare B decays: $B \rightarrow K^* e^+ e^-$

- What about electrons? (sensitive to $C_7^{(*)}$)

  Angular observables of the $B^0 \rightarrow K^* e^- e^+$ at LHCb in the low $q^2 < 1\text{GeV}^2$
  
  → Virtual $\gamma$ decaying in an observable $\ell^- \ell^+$ pair
  
  → Requires to go very low in the $q^2$ region

  [JHEP04(2015)064] $(3\text{fb}^{-1})$

  > Compatible with the SM predictions*

  [Adapted from Jäger and Camalich arXiv:1412.3183]

  *leading order estimation, 5% accuracy for SM value
Rare B decays: $R_{K^{(*)}}$

Quick note on experimental issues:

- LHCb is far better with muons than electrons
- Trigger, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by $e$ bremsstrahlung → need energy recovery
- Mass shape modelled according to the number of bremsstrahlung recovered
Rare B decays: $B \rightarrow K^{(*)} \mu^+ \mu^-$

LHCb
[JHEP02(2016)104]

CMS
[PLB 753 (2016) 424]

ATLAS
[arXiv:1805.04000]

SM predictions based on
[Altmannshofer & Straub, EPJC 75 (2015) 382]
[LCSR f.f. from Bharucha, Straub & Zwicky, JHEP 08 (2016) 98]
Rare B decays: \( B \to K^{(*)}\mu^+\mu^- \)

**Understanding effects from charm at LHCb:**

- Phase difference between short- and long-distance amplitudes in the \( B^+ \to K^+\mu^+\mu^- \) decay \[ \text{LHCb, [EPJ C(2017) 77]} \]

\[ \frac{d\Gamma}{dm_{\mu\mu}} \] is a function of form factors and \( C_i \)

\( C_i^{\text{eff}} \) expressed as a sum of relativistic Breit-Wigner amplitudes: magnitudes and phases extracted from data

- Form factors from FNAL & MILC [PRD 93(2016)025026]

\[ C_i^{\text{eff}} = C_i + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2) \]

→ Small effect of hadronic resonances in Wilson coefficients
Rare B decays: $B \rightarrow K^{(*)}\mu^+\mu^-$

- Also measured by CMS in the $B \rightarrow K^*\mu^+\mu^-$ channel [PLB 753 (2016) 424]
- 20.5 fb$^{-1}$, 1430 signal decays

$\rightarrow$ Smaller branching fractions than the SM predictions?
$\rightarrow$ Compatible with other experiments, competitive accuracy with LHCb

$\rightarrow$ Results dominated by statistical uncertainties (including the BR of the normalization channels)
$\rightarrow$ Caveat: theory affected by hadronic uncertainties (LQCD + LCSR)
Recent measurements by CMS in the $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay channel [arXiv:1806.00636], submitted to PRD

$$\frac{1}{\Gamma_\ell} \frac{d\Gamma_\ell}{d\cos \theta_\ell} = \frac{3}{4} (1 - F_H)(1 - \cos^2 \theta_\ell) + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$$

$A_{FB}$ = Forward-backward asymmetry of the dimuon system

$F_H$ = contribution from the pseudoscalar, scalar and tensor amplitudes to the decay width

→ Consistent with SM predictions
Semileptonic B decays: $R_D, R_{D^*}$

BaBar measured an excess of $B^0 \rightarrow D^{(*)}\tau^-\nu_\tau$ (3σ away from SM!) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

Belle:

$R(D), R(D^*)$

- $B^0 \rightarrow D^{(*)+}\tau^-\nu_\tau$, with $\tau^- \rightarrow \ell^-\nu_\ell\nu_\tau$ [PRD92 (2015) 072014]
- $B^0 \rightarrow D^{*+}\tau^-\nu_\tau$, with $\tau^- \rightarrow \ell^-\nu_\ell\nu_\tau$ [PRD94 (2016) 072007]
- $B^0 \rightarrow D^{*+}\tau^-\nu_\tau$ and $\tau^-$ polarization [PRL118 (2017) 211801]

(remaining energy of e.m. calorimeter clusters)
Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

Recent results by CMS and ATLAS in the $B^0 \to K^*\mu^+\mu^-$ decay channel


(CMS and ATLAS fit simultaneously only a subset of the amplitude parameters)
Rare B decays: $B_s \rightarrow \mu^+ \mu^-$

- Result from ATLAS:
  ATLAS-CONF-2018-046

Run II data (2015+2016):
26.3 fb$^{-1}$ at 13 TeV

Combined with the Run I result:
[ATLAS, EPJ C76 (2016) 513]

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$

→ Measurements in agreement with the SM
→ Theoretical uncertainties ($f_{B(s)}$, $V_{CKM}$) well below statistical uncertainty
The LHCb experiment

LHCb, ATLAS & CMS

2<\eta<5 \quad \sigma_P \sim 0.5-1\% \quad \sigma_{IP} \sim 15-50 \mu m

Good PID (fake < 3%)

|\eta|<2.4 \quad \sigma_{P_T} \sim 0.7-1.5\% \quad \sigma_{IP} \sim 25-100\mu m

Very good PID (fake < 0.1%)

|\eta|<2.5 \quad \sigma_{P_T} \sim 1.3-3.8\% \quad \sigma_{IP} \sim 25-100\mu m