Rare B and strange decays

Siim Tolk
on behalf of the LHCb collaboration

Moriond EW
2017
Serious tensions in **Lepton Flavour Universality** tests

![Graph showing R(D) and R(D*) values with contours](image)

- **Tree level** (3'rd/2'nd generation)

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

  - SM compatibility: 3.9σ
  - New Physics competing with SM at tree level?

- **Loop level** (2'nd/1'st generation)

  \[ \mathcal{R}(K) \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)} \]

  - SM compatibility 2.6σ
  - New Physics at loop level?

- Could be a manifestation of the same NP (~TeV leptoquarks)

Rare decays in the Standard Model (SM)

Tree level CC

\[ M_{CC} \sim G_F V_{ij} U_{kl}^* \]

The SM FCNC

\[ M_{FCNC} \sim G_F \frac{\alpha}{4\pi} \sum_k V_{ki} V_{kj}^* \frac{m_k^2}{M_W^2} \]

- **GIM, loop, CKM, ...**
- (branching fractions \( \leq 10^{-6} \))
- \( \ldots + \) **helicity** \( (m_\mu / M_B)^2 \approx 10^{-4} \)
  (branching fractions \( \leq 10^{-9} \))

- involve flavour changing up-up or down-down type quark transitions (FCNC)
- In SM: **suppressed by multiple mechanisms:**
  only allowed at loop level (GIM), must involve an **off-diagonal CKM element** and (possibly) **helicity** suppressed:
Rare decays are sensitive to heavy New Physics (NP)

### NP at tree level

\[
\mathcal{M}_{FCNC} \sim G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left( C^{SM} + \frac{4\pi}{\alpha} \frac{1}{V_{tb} V_{ts}^*} \frac{g_{sb}^2 g_{ll}^2}{M^2} \right) \times (s \otimes \bar{ll})
\]

\[\sim 200^2\quad \text{M}_{NP} \sim 10^2\text{ TeV}\]

### NP at loop level

- B_{s} \rightarrow \mu^+ \mu^- sensitive to Z’s up to 160TeV or new scalars up to 1000TeV

JHEP 1411 (2014) 121

- In B_{s} \rightarrow \mu^+ \mu^- (pseudo)scalars can bypass the helicity suppression
- Two Higgs Doublet model effects \sim \tan(\beta)^3

- Indirect NP signs are expected to precede the direct evidence.
The theoretical description of the rare hadron decays

- processes over a wide energy range:
  
  $0.2 \text{GeV} \cdots 4 \text{GeV} \cdots 80 \text{GeV} \cdots \sim 100 \text{ TeV}$

- described by the effective field theory and operator product expansion:
  
  $A(B \to f) = \langle f | H_{\text{eff}} | B \rangle = \frac{G_F}{\sqrt{2}} \sum_i \lambda_{CKM} C_i(\mu_b) \langle f | Q_i(\mu_b) | B \rangle$

  **Wilson coefficients** Hadronic matrix el.
  (perturbative) (include non-perturbative QCD)

**Leptonic modes**

$\langle ll | j_{ll} \cdot j_{qq} | B_q \rangle = \langle ll | j_{ll} | 0 \rangle \cdot f_{Bq}$

Lattice QCD

**Semi-leptonic modes:**

$\langle llM | j_{ll} \cdot j_{qq} | B \rangle = \langle ll | j_{ll} | 0 \rangle \cdot F(q^2) + C_{\text{non-fact}}$ corrections

Lattice QCD (large $q^2$)

Light Cone Sum Rules (small $q^2$)
The **operators** relevant for the rare B decays:

- **Electromagnetic penguin**
  \[ Q_7^{(')} = \frac{e}{16 \pi^2} m_b (\bar{s} \sigma_{\mu \nu} P_{R(L)} b) F^{\mu \nu} \]

- **Semi-leptonic vector current**
  \[ Q_9^{(')} = \frac{e^2}{16 \pi^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell) \]

- **Semi-leptonic A-V current**
  \[ Q_{10}^{(')} = \frac{e^2}{16 \pi^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell) \]

- **Scalar**
  \[ Q_S^{(')} = \frac{e^2}{16 \pi^2} (\bar{s} L(R)b_R(L)) (\bar{\ell} \ell) \]

- **Pseudo-scalar**
  \[ Q_P^{(')} = \frac{e^2}{16 \pi^2} (\bar{s} L(R)b_R(L)) (\bar{\ell} \gamma_5 \ell) \]

*four quark operators \( Q_1 \ldots 6 \) only contribute through operator mixing.

**New Physics** can
- alter the SM operator contributions (Wilson coefficients)
- enter through new operators (right-handed Q’s, \( Q_{S,P} \))
Electromagnetic and semi-leptonic Wilson coefficients: $C_7$, $C_9$ and $C_{10}$
Wilson coefficients are measured in global $b \rightarrow s l^+ l^- (\gamma)$ analysis

- No evidence for right-handed FCNC ($C_i' = 0$) and $C_{(7,9,10)}$ signs $[-,+,-]$ agree with the predictions (pre LHC discussion)
- There are tensions w.r.t SM (up to $4\sigma$)
- Tensions are driven by $B^0 \rightarrow K^* \mu^+ \mu^-$ angular observables and by several exclusive $b \rightarrow s l^+ l^-$ branching fraction measurements; supported by $R(K)$.
- Tensions are relieved by (NP effects?):

$$ [(C_9)_s^\mu]^{NP} \approx -1.1 \quad \text{Or} \quad [(C_9)_s^\mu]^{NP} = -[(C_{10})_s^\mu]^{NP} \approx -0.5 $$

Descotes-Genon, Hofer, Matias, Virto [JHEP 06 (2016) 092]
Hurth, Mahmoudi, Neshatpour [arXiv:1603.00865]
**Z’, leptoquarks,…**

Possible **NP**

\[ \mu^- \quad Z' \quad \mu^+ \]

\[ b \quad \quad \quad s \]

**Hadronic SM effects**

**SM c\bar{c} loop**

\[ \gamma \quad \ell^- \quad \ell^+ \]

\[ c \quad \quad \quad \bar{c} \]

\[ Z', \text{ leptoquarks,…} \]

\[ C_9 + C_9^{NP} \]

or

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

Large long-distance charm resonance effects far from the resonances on the \(q^2\) plane.

**NEW!**

**Measure the resonance effects in \(C_9\) in an inclusive analysis:**

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \quad + \quad B^+ \rightarrow K^+ X_{c\bar{c}} (\rightarrow \mu^+ \mu^-) \]
Measuring resonance effects in $C_9$

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

The differential decay rate depends on the Wilson coefficients:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |k|/\beta \left\{ \frac{2}{3} |k|^2 \beta^2 (C_{10} + (q^2))^2 + \frac{4m_\mu(m_\mu^2 - m_\chi^2)}{q^2m_B^2} (C_{10} + (q^2))^2 \right\} + \frac{1}{3} \beta^2 \left\{ C_9 f_+(q^2) + 2C_7 \left( \frac{m_\mu + m_{\chi}}{m_B + m_\chi} \right) f_I(q^2) \right\}^2,$$

fix $C_7$ to the SM value (small)

Phase: neg. neg.

Parametrise resonance effects:

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

relative Breit-Wigner/ phase to $C_9$ Flatté $\Phi(3770)$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\psi(2S)$</th>
<th>$\psi(3770)$</th>
<th>$\psi(4040)$</th>
<th>$\psi(4160)$</th>
<th>$\psi(4415)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
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<tr>
<td>$\omega(782)$</td>
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<td>$\phi(1020)$</td>
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<td>$J/\psi$</td>
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</table>
Measuring resonance effects in $C_9$

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

The short-distance branching fraction agrees with the previous (exclusive) result:

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

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

**NEW!** [arXiv:1612.06764] submitted to EPJC

Measuring resonance effects in $C_9$

The main conclusion: contributions from $J/\psi$ and $\psi(2S)$ are contained around their (narrow) resonances.

Inclusive $B^0 \rightarrow K^* \mu^+ \mu^-$ analysis will follow
Scalar and pseudoscalar Willson coefficients:

$C_S$ and $C_P$
Coefficients $C_{10}$, $C_S$ and $C_P$ in fully leptonic $B$ decays

\[ B^0_{(s)} \rightarrow \ell^+ \ell^- \]

\[ Q_{10}^{(s)} = \frac{e^2}{16\pi^2} (\bar{s}_\gamma \mu P_L(R)b)(\bar{\ell} \gamma^\mu \gamma^5 \ell) \]
\[ Q_S^{(s)} = \frac{e^2}{16\pi^2} (\bar{s}_L(R)b_R(L))(\bar{\ell}\ell) \]
\[ Q_P^{(s)} = \frac{e^2}{16\pi^2} (\bar{s}_L(R)b_R(L))(\bar{\ell} \gamma^5 \ell) \]

- Only $C_{10}$ contributes in the Standard Model
- NP sensitivity in $C_S$ and $C_P$ is larger than in $C_{10}$ (no helicity suppression)
  (K* mumu sensitivity to $C_S$ is lower than initially expected)
- Very precise Standard Model predictions (limited by CKM and B decay constant):

\[ \mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.59 \pm 0.18) \times 10^{-9} \]

Rel. Unc. from 6.4% -> 5%

updated in arXiv:1702.05498
How long does it take to find a three-in-a-billion decay?

$B_{(s)} \rightarrow \mu^+ \mu^-$


~30 years!
Combined CMS and LHCb Run 1 analysis

LHCb

MisID

Peaking bkg shape pars.

Mass and signal shape parameters

Combined CMS and LHCb Run 1 analysis

CMS

Shared

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

\[ f_s/f_d \]

\[ BR(B^+ \rightarrow J/\psi K^+) \]

And common BR values for exclusive backgrounds
First observation in Run 1

\[ B_s \rightarrow \mu^+ \mu^- \]

The combined significances (w.r.t. the null hypothesis, using Wilk’s theorem)
- \[ 6.2\sigma \text{ obs.} \] (expected 7.2\sigma in SM)
- \[ 3.2\sigma \text{ obs.} \] (expected 0.8\sigma in SM)

*Cross-checked with Feldman-Cousins: 3.0\sigma (official significance)

The fitted central values
- \[ \mathcal{B} \mathcal{R}(B_s \rightarrow \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \]
- \[ \mathcal{B} \mathcal{R}(B_d \rightarrow \mu^+ \mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10} \]

The first observation of \( B_s \rightarrow \mu \mu \) decay and the first evidence of \( B_d \rightarrow \mu \mu \) (unexpected!)
**First observation in Run 1**

\[ B(s) \rightarrow \mu^+ \mu^- \]

The fitted central values are:

- \( \mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9} (2\sigma) \)
- \( \mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} (95\% CL) \)

Cross-checked with Feldman-Cousins:

- \( 3.0\sigma \) (official significance)

**The first observation** of \( B_s \rightarrow \mu \mu \) decay and **the first evidence** of \( B_d \rightarrow \mu \mu \) (unexpected!)
First results from Run 2 (LHCb Run1 + Run2)

\[ B_s \rightarrow \mu^+ \mu^- \]

LHCb Run1 data (3fb^{-1}) + 2015 (0.33fb^{-1}) + 2016 (1.4fb^{-1})

- Several improvements compared to the old analysis:
  - better di-hadron background rejection (50%)
  - exclusive background estimates validated on data
  - new isolation variables with improved geometry

- The most precise results up to date; the first single experiment \( B_s \rightarrow \mu \mu \) observation

\[ \mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \]
\[ \mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \]

\( B_s \rightarrow \mu \mu \ (7.8\sigma) \) and \( B_d \rightarrow \mu \mu \ (1.6\sigma) \)

see M. Mulder’s talk @ YSF4

NEW!

arXiv:1703.05747
Submitted to PRL
First interpretations of the Run 2 $B_s \rightarrow \mu^+\mu^-$ results

- Fit for $C_S = -C_P$ (MFV NP e.g. MSSM)

- Ambiguity can be solved by measuring the mass-eigenstate-rate asymmetry:

$$A_{\Delta\Gamma} = \frac{\Gamma(B_s^H \rightarrow \mu^+\mu^-) - \Gamma(B_s^L \rightarrow \mu^+\mu^-)}{\Gamma(B_s^H \rightarrow \mu^+\mu^-) + \Gamma(B_s^L \rightarrow \mu^+\mu^-)}$$

Range: NP [-1 ..... +1] SM
First **effective \( B_s \rightarrow \mu^+\mu^- \) lifetime** measurement

\[
B_s \rightarrow \mu^+\mu^-
\]

**Mass-eigenstate-rate asymmetry** can be determined from the \( B_s \rightarrow \mu\mu \) effective lifetime:

\[
\tau(B_s \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ps}
\]

(stat) (syst)

**Compatible with the SM:** \( \tau(B_s \rightarrow \mu^+\mu^-)^{SM} = (1.615 \pm 0.010) \text{ps} \)

**Proof of concept measurement** (no attempt to extract \( A_{\Delta\Gamma} \) yet)

**Result consistent with the \( A_{\Delta\Gamma} = +1(-1) \) at 1.0\( \sigma \) (1.4\( \sigma \))

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**arXiv:1703.05747**

Submitted to PRL
Other di-lepton decays
Other **di-lepton decays** searches

\[ B(s) \rightarrow \tau^+ \tau^- \]

**More abundant than muon mode**

\[ \mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) \overset{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8} \]

**Only existing limit is on \( B_0 \) mode:**

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

**Implications from LFU tests:** \( R_K, R(D^{(*)}) \) ➽ \( O(10^3) \) boost to the BF?

**LHCb analyses Run 1 data (3fb^{-1})** for the **hadronic \( \tau \)-modes**

\[ \mathcal{B}(\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\mp \bar{\nu}_\tau) = (9.31 \pm 0.05)\% \]

..and select the intermediate resonances:

\[ \tau^- \rightarrow a_1^- (1260) \nu_\tau \rightarrow \rho^0 (770) \pi^- \nu_\tau \]

**Results with an updated \( \tau \rightarrow 3\text{body decay model} \):**

\[
\begin{align*}
\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) &< 2.1 \times 10^{-3} \quad @ \, 95\% \, \text{C.L} \\
\mathcal{B}(B_s \rightarrow \tau^+ \tau^-) &< 6.8 \times 10^{-3} \quad @ \, 95\% \, \text{C.L}
\end{align*}
\]

(assuming one of the other \( B \) mode)

**NEW! Updated results**
Other di-lepton decays searches

\[ K_S \rightarrow \mu^+ \mu^- \]

- Not measured yet... SM expectation:
  \[ \mathcal{B}(K_S \rightarrow \mu^+ \mu^-)^{SM} = (5.0 \pm 1.5) \times 10^{-12} \]

- LHCb 1 fb\(^{-1}\) analysis improves previous limit by \(\sim 30\) times:
  \[ \mathcal{B}(K_S \rightarrow \mu^+ \mu^-) < 6.9 \times 10^{-9} @ 95\% CL \]

- LHCb 2 fb\(^{-1}\) analysis:
  \[ \mathcal{B}(K_S \rightarrow \mu^+ \mu^-) < 6.9 \times 10^{-9} @ 95\% CL \]

**Update:** KAON2016 result has been revised with a new signal classifier and trigger selection. Paper with improve will follow (soon)
(Pseudo)scalar resonance searches

► In 2005 HyperCP: Measured $\Sigma^+ \rightarrow p\mu^+\mu^-$
  
PRL 94 (2005) 021801

  $\mathcal{B}(\Sigma^+ \rightarrow p^+\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$

► ..which agrees to the SM predictions
  

► ...could the di-muon mass be pointing to a new intermediate $P \rightarrow \mu^+\mu^-$ resonance at 214 MeV/c$^2$?
The decay is confirmed:
13 candidates (4\sigma) in LHCb Run 1 data

No evidence for a di-muon resonance

example fit around 214MeV
(fit: 1.6(1.9) candidates)

Branching ratio results will follow in a paper (precision at HyperCP level)
Indirect $P(S)$-resonance searches in LHCb

Very low non-resonant SM predictions: $3.5 \times 10^{-11}$


Sensitive to intermediate resonances (MSSM sgoldsino’s, $P(S) \rightarrow \mu^+ \mu^-$)

New analysis includes many improvements to the analysis (normalisation, multivariate selection) and an additional 2fb$^{-1}$ of Run 1 data.

New improved upper limits with the full 3fb$^{-1}$ Run 1 data:

<table>
<thead>
<tr>
<th>Mode</th>
<th>1 fb$^{-1}$</th>
<th>3 fb$^{-1}$</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$</td>
<td>$&lt; 1.6 \times 10^{-8}$</td>
<td>$&lt; 2.5 \times 10^{-9}$</td>
<td>6.4</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$</td>
<td>$&lt; 6.6 \times 10^{-9}$</td>
<td>$&lt; 6.9 \times 10^{-10}$</td>
<td>9.5</td>
</tr>
<tr>
<td>$B^0 \rightarrow S(\mu^+ \mu^-)P(\mu^+ \mu^-)$</td>
<td>$&lt; 1.6 \times 10^{-8}$</td>
<td>$&lt; 2.2 \times 10^{-9}$</td>
<td>7.3</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow S(\mu^+ \mu^-)P(\mu^+ \mu^-)$</td>
<td>$&lt; 6.3 \times 10^{-9}$</td>
<td>$&lt; 6.0 \times 10^{-10}$</td>
<td>10.5</td>
</tr>
</tbody>
</table>

(for the S/P scenario, assume short lived $m(S)$ of 2.6GeV and $m(P)$ of 214.3MeV)
Summary

➽ Tensions in semi-leptonic Wilson coefficients are well established by several independent global (b-sl⁺l⁻) fits.
   ➽ resonance contributions to C₉ not likely to be the cause: effects contained to the narrow resonance regions (inclusive B⁺→K⁺µ⁺µ⁻ analysis).

➽ The LHCb Run1+2 B⁰(s)→µ⁺µ⁻ analysis shows a SM like Bₛ→µ⁺µ⁻ at 7.8σ; B_d→µ⁺µ⁻ excess is not confirmed.

➽ (Pseudo)scalar contributions ambiguities can be solved by an effective B⁰ₛ→µ⁺µ⁻ lifetime measurement. First (statistics limited) results available.

➽ No large NP effects seen in other rare leptonic modes: B⁰(s)→τ⁺τ⁻, B⁰(s)→µ⁺µ⁻µ⁺µ⁻ or Kₛ→µ⁺µ⁻. LHCb sets new strong new limits.

➽ Σ⁺→pµ⁺µ⁻ confirmed, alas no sign of a pseudoscalar di-muon resonance.

➽ Serious tensions in (several) LFU tests:
   R(D(*) (third/second generation) ~ 3.9σ
   R(K) (second/first generation) ~ 2.6σ

See all the LHCb results
The Wilson coefficients are measured in global $b \rightarrow s l^+ l^-$ analysis:

- No evidence for right-handed FCNC ($C'_i = 0$) and $C_{(7,9,10)}$ signs $[-,+,-]$ agree with the predictions (pre LHC discussion).
- There are tensions w.r.t SM (up to $4\sigma$).
- Tensions are driven by $B_0 \rightarrow K^* \mu^+ \mu^-$ angular observables and by several exclusive $b \rightarrow s l^+ l^-$ branching fraction measurements; supported by $R(K)$.
- Tensions are relieved by (NP effects?): $\left[ (C_9)_{\mu s}^{NP} \right] \approx 1$ and $\left[ (C_{10})_{\mu s}^{NP} \right] = \left[ (C_{10})_{\mu s}^{NP} \right] = 0.5$.

Note the different setup:
- no $K^* mm$, excl. $b \rightarrow s l^+ l^-$
- fit both $C_9, C_{10}$.
- no constraint on $C_9 = -C_{10}$

A (simpler) global fit including $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ shows a mild opposite effect on $C_9$: Excellent review: [arXiv:1606.00916]
Measuring resonance effects in $C_9$

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

Four degenerate Jpsi and psi2S phase sign choices:

- Phase: neg. neg.
- Phase: pos. neg.
- Phase: neg. pos.
- Phase: pos. pos.
Coefficients $C_{10}, C_S$ and $C_P$ in fully leptonic B decays

$B_{(s)} \rightarrow \mu^+ \mu^-$

- Only $C_{10}$ contributes in the Standard Model
- NP sensitivity in $C_S$ and $C_P$ is larger than in $C_{10}$ (no helicity suppression)
  (K$^*$mumu sensitivity to $C_S$ is lower than initially expected)

$$\frac{BR(B_q \rightarrow \ell^+ \ell^-)}{BR(B_q \rightarrow \ell^+ \ell^-)_{SM}} = \frac{|S|^2 \left(1 - \frac{4m_{\ell}^2}{m_{B_q}^2}\right) + |P|^2}{|C_{10}^S|^2}$$  

- SM: $S=0$
- SM: $P=1$

- Very precise Standard Model predictions (limited by CKM and B decay constant):

$$B(B_s \rightarrow \mu^+ \mu^-) = (3.59 \pm 0.18) \times 10^{-9}$$

Rel. Unc. from 6.4% -> 5%

updated in arXiv:1702.05498
The measured $B^0 \rightarrow K^+\pi^-$ effective lifetime is $1.52 \pm 0.03$ ps, where the uncertainty is statistical only. The statistical unc. in assigned as a systematic to the effective $B_s \rightarrow \mu\mu$ lifetime measurement.
MSSM with MFV (present)

\[ B_s \rightarrow \mu^+ \mu^- \]

**FIG. 5.** Current constraints in the \( m_A - \tan \beta \) plane in the MSSM scenario discussed in the text. The dark and light green shaded regions are *allowed* by the \( \text{BR}(B_s \rightarrow \mu^+ \mu^-) \) measurements at the 1\( \sigma \) and 2\( \sigma \) level. The black hatched region is *excluded* by direct searches for \( \tau^+ \tau^- \) resonances. Throughout the plot the light Higgs mass is \( m_h = 125 \text{ GeV} \).
\[ B_s \rightarrow \mu^+\mu^- \]

\[ \sigma_{\text{exp}}(B_s \rightarrow \mu^+\mu^-) = 0.19, \quad \sigma_{\text{exp}}(A_{\Delta\tau}) = 0.8, \quad \text{for } 50 \text{ fb}^{-1} \quad (\text{"Run 4"}), \]
\[ \sigma_{\text{exp}}(B_s \rightarrow \mu^+\mu^-) = 0.08, \quad \sigma_{\text{exp}}(A_{\Delta\tau}) = 0.3, \quad \text{for } 300 \text{ fb}^{-1} \quad (\text{"Run 5"}). \]

FIG. 6. Expected sensitivities in the $m_A$ - $\tan\beta$ plane in the MSSM scenario discussed in the text. Left: integrated luminosities of 50 fb$^{-1}$ at LHCb and 300 fb$^{-1}$ at CMS and ATLAS. Right: integrated luminosities of 300 fb$^{-1}$ at LHCb and 3000 fb$^{-1}$ at CMS and ATLAS. The dark and light green shaded regions will be allowed by the expected $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ sensitivity at the 1$\sigma$ and 2$\sigma$ level, assuming the SM rate. The black hatched region could be excluded by direct searches for $\tau^+\tau^-$ resonances assuming no non-standard signal. The blue hatched region can be covered by measurements of the mass-eigenstate rate asymmetry $A_{\Delta\tau}$. In both plots the light Higgs mass is $m_h = 125$ GeV.
**Leptoquarks**

\[ B(s) \rightarrow \mu^+ \mu^- \]

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**FIG. 7.** The currently allowed parameter regions in the mass vs. coupling plane for the LQs \( U_1 \) (left) and \( V_2 \) (right) in the scenarios (43) and (44). Inside the dark and light green bands, the present value of the experimental branching ratio (13) is reproduced at 1 and 2\( \sigma \), respectively. The black //-hatched regions show the exclusions from present direct searches. The more densely hatched region corresponds to minimal LQ production, while the more coarsely hatched region is for YM-like production.
Lower than predicted differential $b$-sll branching fractions:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ \mu^-$</td>
<td>$8.5 \pm 0.3 \pm 0.4$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0 \mu^+ \mu^-$</td>
<td>$6.7 \pm 1.1 \pm 0.4$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+} \mu^+ \mu^-$</td>
<td>$15.8^{+3.2}_{-2.9} \pm 1.1$</td>
</tr>
</tbody>
</table>
Individual B decays to leptons

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

- Measured BF lower than predicted by SM (though predictions have large uncertainties)
  
  **LHCb**: arXiv:1606.04731, **CMS**: PLB 753 (2016) 424
  

- Angular distributions sensitive to NP effects
- 3 angles and di-lepton mass squared mapped to **optimised variables** to reduced form factor dependencies
- Significant local tension in one of the variables

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

- Very challenging (statistics, resolution, trigger)
- Simplified angular analysis performed (in agreement with SM)
  
  **LHCb**: LHCb-PAPER-2014-066,
  
  **SM**: PRD 93 (2016) 014028

Global fit at 3.4\(\sigma\) from SM predictions
Individual B decays to leptons

\[ B_s \rightarrow \phi \mu^+ \mu^- \]

- Narrow $\phi$ resonance simplifies selection
- Lower BF than predicted in the SM
- Only CP averaged angular observables accessible (e.g. no $P'_5$), latter in agreement

LHCb: JHEP 09 (2015) 179,
PRD 89 (2014) 094501

\[ B_s \rightarrow \mu^+ \mu^- \]

Similar (lower BF) trend seen in other $b \rightarrow s \mu^+ \mu^-$ processes
 Compatibility with the SM $1.2\sigma$ for $B_s$ (and $2.2\sigma$ for $B^0$)

Nature 522, 68-72 (04 June 2015)
Historical success of the effective approach

- Effective approach has historically played a crucial role in understanding the underlying theory from both direct and indirect measurements:
  - **1933**: First model for the weak decays. Same coupling for the beta decay and muon decay suggested **underlying structure (V-A)**
  - **1960's**: Predicting **charm** to make **GIM** work and explain missing FCNC.
  - **1970's**: Predict lower bounds on **Z and W masses** from muon lifetime (motivate SPS)
  - **2010's**: **Lepton Flavour Universality Violation? Z'? Leptoquarks?**