THE $B_s \rightarrow \mu \mu$ DECAY, LFV AND LFU AT THE LHCb EXPERIMENT
• **Rare decays**: processes suppressed in the SM that can happen only at loop level
  - **Flavour Changing Neutral Currents**
    - forbidden at tree level in the SM (e.g. $b \rightarrow s$ or $b \rightarrow d$ transitions)
    - branching fractions typically $\sim 10^{-6}$ or less

- **New Physics** can enter in the loops
  - Very sensitive to new physics effects
    - NP can enter at the same level as SM
  - No evidence in direct searches so far
    - loops can probe high energy scales
Effective Hamiltonian

Effective Hamiltonian for $b \rightarrow d$ and $b \rightarrow s$ in terms of Operator Expansion.

With possible **left-handed** and **right-handed** components:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{\alpha_e}{4\pi} \sum_{i=1}^{10} \left[ C_i O_i + C'_i O'_i \right]$$

 Relevant operators:

- $O_{S,P}$: purely leptonic decay
- $O_7$: radiative penguin
- $O_{9,10}$: semileptonic decays
  
  ($Z$ penguin and $W$-box)

[arXiv:1501.03309]
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Suppressed $C' \sim m_s/m_b \ C$
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$$
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  (Z penguin and W-box)

Nothing different than what was done for the Fermi theory of EW interactions.

[arXiv:1501.03309]
\[ B(B_{d/s} \rightarrow \mu^+ \mu^-) \]

- Highly suppressed in the SM FCNC + CKM + helicity
- Possible tree level BSM contributions → very sensitive
- Ratio between \( B_s \) and \( B^0 \) highly constrains MFV
- Leptonic decay (no hadronic uncertainties) → Very well predicted

\[
\begin{align*}
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &= (3.66 \pm 0.23) \times 10^{-9} \\
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &= (1.06 \pm 0.09) \times 10^{-10}
\end{align*}
\]

CMS + LHCb Run I combination:
\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \]
Compatible with SM at the level of 2σ
B(\(B_{d/s}\rightarrow\mu^+\mu^-\)): adding Run II

- Includes the re-analysis of Run I data
- New improved isolation variables based on MVAs help rejecting backgrounds
- Two normalisation channels \(B^0\rightarrow K\pi\) and \(B^0\rightarrow (J/\psi\rightarrow \mu^+\mu^-)K\)
  - Using \(f_s/f_d = 0.259 \pm 0.015\) [LHCb-CONF-2013-011]
  - Scaled to 13 TeV using the ratio \(B_s\rightarrow J/\psi \phi / B^0\rightarrow J/\psi K\)

[LHCb-PAPER-2017-001]
$B(B_{d/s} \rightarrow \mu^+\mu^-)$: backgrounds

Decays with mis-ID

- $B \rightarrow h^+h'^-$
- $B^0 \rightarrow \pi^-\mu^+\nu_\mu$
- $B^0_{s} \rightarrow K^-\mu^+\nu_\mu$
- $\Lambda^0_{b} \rightarrow p\mu^-\bar{\nu}_\mu$

- Less then 5 expected events in total, mostly at low masses
- $B\rightarrow hh$, peaking under the signal, reduced by a factor of 2 wrt previous analysis

Decays with 2 real muons

- $B_{c}^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\mu^+\nu_\mu$
- $B^{0(+)} \rightarrow \pi^0(+)\mu^+\mu^-$

[LHCB-PAPER-2017-001]
**B(B_{d/s} \rightarrow \mu^+\mu^-): mass fits**

- BDT calibrated to have flat response on signal → Reduce uncertainty in efficiency estimation

- Simultaneous fit in 8 bins of BDT output.

- Systematics on nuisance parameters and background model

---

[LHCB-PAPER-2017-001]
$\mathcal{B}(B_{d/s} \rightarrow \mu^+ \mu^-)$: the peak

$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.8 \pm 0.6) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.6^{+1.1}_{-0.9}) \times 10^{-10}$

As no evidence for $B^0$ a limit is set: $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \cdot 10^{-10}$ @ 95% CL

LHCb alone!
B(B_{d/s} \rightarrow \mu^+\mu^-): a 30 years long story

- First limit set by CLEO in 1985.
- First observation by a single experiment in 2017 by LHCb
- Strongly constrains the phase-space for BSM. Particularly SUSY.

And the story goes on:
- Still important to observe B^0, as the ratio between B_s and B^0 highly constrains MFV models.
- Effective lifetime (see next slides)
Effective lifetime

- $B_s$ light and heavy eigenstates are characterised by a sizeable $\Delta \Gamma$
- In the Standard Model only the heavy state can decay into $\mu^+\mu^-$

\[
A_{\Delta \Gamma}^{\ell^+\ell^-} = \frac{\Gamma_{B_s,H \rightarrow \ell^+\ell^-} - \Gamma_{B_s,L \rightarrow \ell^+\ell^-}}{\Gamma_{B_s,H \rightarrow \ell^+\ell^-} + \Gamma_{B_s,L \rightarrow \ell^+\ell^-}} \overset{SM}{=} 1
\]

Can assume values in $[-1, 1]$ BSM!

- Effective lifetime to measure $A_{\Delta \Gamma}$

\[
\tau_{\ell^+\ell^-} = \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow \ell^+\ell^-) \rangle dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow \ell^+\ell^-) \rangle dt}
\]

\[
\tau_{\ell^+\ell^-} = \frac{\tau_{B_s}}{1 - y_s^2} \left[ \frac{1 + 2A_{\Delta \Gamma}^{\ell^+\ell^-} y_s + y_s^2}{1 + A_{\Delta \Gamma}^{\ell^+\ell^-} y_s} \right]
\]
• Similar selection as for the BR analysis but with looser PID to favour efficiency upon purity.
• Only one BDT bin: > 0.5
• Background subtracted using the sPlot technique.
• Acceptance modelled using simulation.

\[ \tau(B^0 \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44_{\text{stat}} \pm 0.05_{\text{syst}} \text{ ps} \]

• Toys used to calculate compatibility with \( A_{\Delta\Gamma} = 1/-1 \)
• Compatible with 1 (-1) at 1\( \sigma \) (1.4\( \sigma \)) level.
**$B_s \rightarrow \tau^+ \tau^-$**

- Can be used to study LFU when combined with $B_s \rightarrow \mu \mu$
- Less helicity suppression $\rightarrow$ higher BR $\sim 10^{-7}$ vs $10^{-9}$
- Reconstructed using $\tau \rightarrow 3\pi \nu$. Challenging due the neutrinos.
- Normalised with respect to $B^0 \rightarrow D^+(K^-\pi^+\pi^+)D^-(K^-K^+\pi^+)$
- As there is no peak the MVA output is fitted

![Graphs showing neural network output and mass distribution](image)

Assuming $B_s$ dominates: $\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 2.4(3.0) \times 10^{-3}$ at 90(95)% C.L.

[LHCB-CONF-2016-011]
Using full Run I: 3 fb⁻¹.
Limits improved by a factor \(\sim 6 \times 10^{-4}\) for \(B_s (B^0)\) wrt previous LHCb results. 

\[
\mathcal{B}(B_s^0 \to \mu^+ \mu^- \mu^+ \mu^-) < 2.5 \times 10^{-9}, \\
\mathcal{B}(B^0 \to \mu^+ \mu^- \mu^+ \mu^-) < 6.9 \times 10^{-10}, \\
\mathcal{B}(B_s^0 \to S(\to \mu^+ \mu^-)P(\to \mu^+ \mu^-)) < 2.2 \times 10^{-9}, \\
\mathcal{B}(B^0 \to S(\to \mu^+ \mu^-)P(\to \mu^+ \mu^-)) < 6.0 \times 10^{-10}.
\]

• Can proceed via scalar and pseudo scalar sgoldino decays.
• SUSY BR up to \(\sim 10^{-4}\)
• Related to the \(\Sigma \to \tau \mu \mu\) excess observed by HyperCP

[PRL 94 (2005) 021801]

[JHEP 03 (2017) 001]
LFU and LFV

Lepton Flavour Universality (LFU): equality of lepton couplings in the SM

- Signature: comparisons between e/μ/τ channels
- Especially interesting for channels sensitive to NP: rare decays!
- Usually exploiting ratios as hadronic uncertainties cancel

b PENGUINS (b → s FCNC): B → K/K*/φ ℓℓ, Λ_b → Λ/Λ*ℓℓ
TREE LEVEL LQ EMISSION: B → D^*ℓν
CHARM PENGUINS (c → u FCNC): D → hℓℓ, Λ_c → pℓℓ
Lepton Flavour Universality (LFU): equality of lepton couplings in the SM
- Signature: comparisons between e/μ/τ channels
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Lepton Flavour Violation (LFV): non-conservation of lepton number
- Signature: searches for forbidden decays in the SM (eμ/μτ/et)
- Neutrino oscillations already allow these decays with very small BR

\[
\begin{align*}
\text{b PENGUINS (b} \rightarrow & \text{s FCNC): } B \rightarrow K/K^*/\phi \ell \ell, \quad \Lambda_b \rightarrow \Lambda/\Lambda^* \ell \ell \\
\text{TREE LEVEL LQ EMISSION: } B & \rightarrow D^* \ell \nu \\
\text{CHARM PENGUINS (c} \rightarrow & \text{u FCNC): } D \rightarrow h \ell \ell, \quad \Lambda_c \rightarrow p \ell \ell
\end{align*}
\]
Anomalies

A few individually small anomalies found in $b\to s\ell\ell$ decays
- BR of $B\to K/K^*/\phi\ell\ell$ all found slightly lower SM (1-2 $\sigma$)
- Angular analyses of $B\to K^*/\phi\ell\ell$ (1-3 $\sigma$)

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.29 \pm 0.07 \text{ (stat)} \pm 0.21 \text{ (syst)}) \times 10^{-7},$$
$$\mathcal{B}(B^0 \to K^0\mu^+\mu^-) = (3.27 \pm 0.34 \text{ (stat)} \pm 0.17 \text{ (syst)}) \times 10^{-7},$$
$$\mathcal{B}(B^{*+} \to K^*\mu^+\mu^-) = (9.24 \pm 0.93 \text{ (stat)} \pm 0.67 \text{ (syst)}) \times 10^{-7}.$$
A few individually small anomalies found in $b \to s \ell \ell$ decays

- BR of $B \to K^*/\phi \, \ell \ell$ all found slightly lower SM (1-2 $\sigma$)
- Angular analyses of $B \to K^*/\phi \, \ell \ell$ (1-3 $\sigma$)

A scenario a new physics contribution $C_9^{NP} = -1$ is favoured.

Model independent global fits performed using inputs from several decays including $B_s \to \mu \mu$. 

LHCb, JHEP 02 (2016) 104
LFV at LHCb: $B^0_{(s)}/D^0 \rightarrow e\mu$

- $B^0 \rightarrow e\mu$ on 1 fb$^{-1}$: update to 3 fb$^{-1}$ coming soon!
- $B^0 \rightarrow K\mu$ coming soon as well.
- $D^0 \rightarrow e\mu$ analysed on full Run I: 3 fb$^{-1}$

Using $D^{*+} \rightarrow D^0 \pi^+$ to limit combinatorics

$D^0 \rightarrow \pi\pi$ main background (BR $\sim 10^{-3}$)
- Rejected by PID cuts
- Fit in 2D $m(e\mu)$ vs $|m(D^0) - m(D^{*+})|$

No signal observed so limits are set.

\begin{align*}
B(D^0 \rightarrow e\mu) &< 1.3 \times 10^{-8} \ @ \ 90\% \ CL \\
B(B^0 \rightarrow e\mu) &< 2.8 \times 10^{-9} \ @ \ 90\% \ CL \\
B(B_s \rightarrow e\mu) &< 1.1 \times 10^{-9} \ @ \ 90\% \ CL
\end{align*}

LHCb, PRL 108 (2012) 231801

LHCb, PLB 754 (2016) 167
LFV at LHCb: $\tau \rightarrow \mu\mu\mu$

- Possible contribution from doubly charged Higgs
- Using full Run 1 (3fb$^{-1}$)

- Events studied in a 3D binned space:
  - Invariant mass of $\tau$ candidate
  - Output of a MVA based on topological information: vertex quality, displacement
  - Output of a MVA based on PID

\[ \mathcal{B}(\tau \rightarrow \mu\mu\mu) < 4.6 \times 10^{-8} \text{ at 90\% CL} \]

Compatible with best limit from Belle.
• Testing LFU in $B \to D^* \ell \nu$ decays: tree level lepto-quark exchange.

- Well predicted as hadronic uncertainties cancel
- Prediction is not unity in the SM uniquely due to the different lepton mass

$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*-} \tau^- \bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*-} \mu^- \bar{\nu}_\mu)} = 0.252 \pm 0.003$$  
[PRD85 (2012) 094025]

• Reconstructed using $\tau \to \mu \nu$: similar final state between the two channels
• Main backgrounds from part-reco B decays: $B \to D^{**} \mu \nu, B \to (D \to X\mu)D^*$
R(D*): fitting without a peak

- Missing neutrino → no narrow peak to fit
- Template fit in three variables: missing mass ($m_{\text{miss}}$), $E_\mu$, $q^2$
  - ✔ Simulated samples for signal and physics background
  - ✔ Background from $\mu$ mis-ID and combinatorial from data

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Compatible with SM at 2.1$\sigma$ level

[LHCb, PRL 115 (2015) 111803]
R(D*) combination

- Combination with other experiments yields $3.9\sigma$ from SM
- Independent measurement using $\tau \rightarrow 3\pi \nu$ coming soon from LHCb.
  ➡ Different trigger, topology, backgrounds, …
Testing LFU in loops

- LFU tested via rare decays sensitive to new particles in the loops

\[ R_H = \frac{\int m_b \frac{d\mathcal{B}(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int m_b \frac{d\mathcal{B}(B \rightarrow H e^+ e^-)}{dq^2} dq^2} \]

- Universality: \( R_H \sim 1 \) with \( O((m_\mu/m_b)^2) \) corrections
- Hadronic uncertainties cancel in the ratio
- Different ratios are sensitive to different combinations of Wilson Coefficients

\[ R_{X_s} = 0.987 \pm 0.006, \quad R_K = 1.0000 \pm 0.0001, \quad R_{K^*0} = 0.991 \pm 0.002, \]

\[ C + C': \quad K, K^*_\perp, ... \]
\[ C - C': \quad K_0(1430), K^*_0, ... \]
The $R_K$ measurement

Challenging due to electrons: bremsstrahlung and low trigger efficiency.

Measured as a double ratio normalising by $B^0 \rightarrow (J/\psi \rightarrow \ell\ell)K$ to cancel systematics.

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

LHCb: 2.6σ FROM THE SM

No smoking gun but clear motivation to continue explore such ratios.
Given also other $b \rightarrow s \mu \mu$ anomalies.
Prospects for more LFU/LFV @LHCb

- $R_{K^*}$: long awaited; it should come in the next few weeks.
Prospects for more LFU/LFV @LHCb

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• $\Lambda_b$ decays:
  • Progress on the theory side (e.g. improved form factor calculation)
  • Different spin and hadronic physics allows independent verifications
  • Experimental precision start to be comparable to B decays.
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• Charm decays:
  • In most cases LHCb sensitivity is still far from SM values.
  • $\Lambda_c \rightarrow p\ell\ell$ might be feasible with the full Run II statistics.
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Links with LFV → Important to build a consistent picture \[ \text{[arXiv: 1609.08895v2]} \]

\[
\begin{align*}
B(B \rightarrow K\mu^\pm e^\mp) &\sim 3 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23}\right)^2, \\
B(B \rightarrow K(e^\pm, \mu^\pm)\tau^\mp) &\sim 2 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23}\right)^2, \\
\frac{B(B_s \rightarrow \mu^+\mu^-)}{B(B_s \rightarrow \mu^+\mu^-)_{\text{SM}}} &\sim 0.01 \left(\frac{1 - R_K}{0.23}\right)^2, \\
\frac{B(B_s \rightarrow \tau^+ (e^-, \mu^-))}{B(B_s \rightarrow \mu^+\mu^-)_{\text{SM}}} &\sim 4 \left(\frac{1 - R_K}{0.23}\right)^2.
\end{align*}
\]
SUMMARY AND CONCLUSIONS

• Rare decays offer a rich environment to test the Standard Model and probe new physics models
  ✓ The observation of a SM-like $B_s \rightarrow \mu^+\mu^-$ strongly constrains BSM

• LFU and LFV studies can provide clear signatures of new physics.
  ✓ Hints of anomalies make very interesting to continue these studies.

• As we deal with rare decays most results are still statistically limited…
  ✓ Many analyses are working to include Run II
  ✓ New modes will be analysed: $\Lambda_b$ and charm

… stay tuned!
Analysis strategy

• Three $q^2$ regions considered:
  ‣ Low-$q^2$: $0.0004 < q^2 < 1.1$ dominated by the photon pole
  ‣ Central-$q^2$: $1.1 < q^2 < 6$ most interesting to observe new physics
  ‣ High-$q^2$: $q^2 > 15\text{GeV}^2/c^4$

• Normalisation channels
  ✓ $J/\psi \rightarrow \mu\mu/\text{ee}$

• Control samples for ee channels:
  ✓ $B \rightarrow K^*(\gamma \rightarrow \text{ee})$
  ✓ $B \rightarrow K^*(\psi(2S) \rightarrow \text{ee})$

\[ q^2 = m_{\ell\ell}^2 \]
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\[ q^2 = m_{\ell \ell}^2 \]
Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for $b\to d$ and $b\to s$ transitions

$$\mathcal{H}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} \left[ \lambda_q^t \sum C_i(\mu) \mathcal{O}_i(\mu) + \lambda_q^u \sum C_i(\mu)(\mathcal{O}_i(\mu) - \mathcal{O}_i^u(\mu)) \right]$$

Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for $b \rightarrow d$ and $b \rightarrow s$ transitions

Short distance physics encoded in the Wilson Coefficients

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[ \lambda_q^t \sum C_i(\mu)O_i(\mu) + \lambda_q^u \sum C_i(\mu)(O_i(\mu) - O_i^u(\mu)) \right]$$

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**Short distance**

physics encoded in
the Wilson Coefficients

**Long-distance**

described by a finite
set of operators

Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for $b \rightarrow d$ and $b \rightarrow s$ transitions

**Short distance**
physics encoded in the Wilson Coefficients

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[ \lambda_q^t \sum C_i(\mu) O_i(\mu) + \lambda_q^u \sum C_i(\mu) (O_i(\mu) - O_i^u(\mu)) \right]$$

**CKM factors:**
$$\lambda_{q'}^q = V_{q'b} V_{q'q}^\ast$$

For $b \rightarrow s$ transitions $V_{us} << V_{ts}$

⇒ the second term can be neglected

**Long-distance**
described by a finite set of operators

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Effective Hamiltonian for $b \rightarrow d$ and $b \rightarrow s$ transitions

**Short distance**
physics encoded in the Wilson Coefficients

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[ \chi_q^t \sum \mathcal{C}_i(\mu) \mathcal{O}_i(\mu) \right]$$

Contributions to $b \rightarrow s \ell^+ \ell^-$:
- ✓ $O_7$: radiative penguin
- ✓ $O_{9,10}$: semileptonic decays
  (Z penguin and W-box)

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Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for $b \to d$ and $b \to s$ transitions

**Short distance**

physics encoded in the Wilson Coefficients

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \left[ \lambda_q \sum C_i(\mu) O_i(\mu) \right]$$

Contributions to $b \to s \ell^+ \ell^-$:

✓ $O_7$: radiative penguin
✓ $O_{9,10}$: semileptonic decays
($\bar{Z}$ penguin and W-box)

**Long-distance**

described by a finite set of operators

Left-handed and right-handed

$$C_i O_i + C'_i O'_i$$

In the SM: $C' \sim m_s/m_b \ C$

In the SM: $C' \sim m_s/m_b \ C$
Calculating exclusive decay amplitudes

The decay amplitude of an exclusive decay $A(M \rightarrow F)$ is given by:

$$A(M \rightarrow F) = \langle M | \mathcal{H}_{eff} | F \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) \langle M | \mathcal{O}_i(\mu) | F \rangle$$
Calculating exclusive decay amplitudes

The decay amplitude of an exclusive decay $A(M \rightarrow F)$ expectation value of $H_{eff}$ given the initial and final states

$$A(M \rightarrow F) = \langle M | H_{eff} | F \rangle = \frac{G_F}{\sqrt{2}} \sum V_{CKM}^i C_i(\mu) \langle M | O_i(\mu) | F \rangle$$

Perturbative contribution

Wilson Coefficients
Calculating exclusive decay amplitudes

The decay amplitude of an exclusive decay $\rightarrow$ expectation value of $H_{\text{eff}}$ given the initial and final states

$$A(M \rightarrow F) = \langle M | H_{\text{eff}} | F \rangle = \frac{G_F}{\sqrt{2}} \sum V_{CKM}^i C_i(\mu) \langle M | O_i(\mu) | F \rangle$$

**Perturbative contribution**

**Wilson Coefficients**

**Form factors**: describing the hadronic physics.

Need to be obtained with non perturbative methods e.g. Lattice QCD

**Form factors = main source of uncertainty** in theory predictions
CMS + LHCb Run I combination:
\[ \mathcal{B}(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \]
6.2σ significance, compatible with SM

- Highly suppressed in the SM FCNC + CKM + helicity
- Possible tree level BSM contributions → very sensitive
- Ratio between \( B_{s} \) and \( B^{0} \) highly constrains MFV
- Leptonic decay (no hadronic uncertainties) → Very well predicted

[Nature 522, 68-72]
[EPJ C76 (2016) 9, 513]
Isospin asymmetry in $B \to \mathcal{K}^{(*)}\mu\mu$

✓ Observables in semileptonic decays: asymmetries

✓ Isospin asymmetry: same quark level transition but different spectator quark

$$A_I = \frac{\mathcal{B}(B^0 \to \mathcal{K}^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+)\mathcal{B}(B^+ \to \mathcal{K}^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to \mathcal{K}^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+)\mathcal{B}(B^+ \to \mathcal{K}^{(*)+}\mu^+\mu^-)}$$

Two ratios are measured for $K$ and $K^*$

B$^0$ over B$^+$ lifetimes ratio ~ $O(1\%)$ in SM

✓ CP asymmetry: tiny in the SM due to small CKM factors

BSM models can introduce new sources of CP violation

JHEP 06 (2014) 133,
Asymmetries measurements

✓ Isospin asymmetries:

![Graphs showing LHCb measurements of B → K^*μ^+μ^− and B → K μ^+μ^- asymmetries vs. q^2 (GeV^2/c^4).]

✓ CP asymmetries

<table>
<thead>
<tr>
<th>B^0 → K^+μ^+μ^-</th>
<th>B^0 → K^*0μ^+μ^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{CP}</td>
<td></td>
</tr>
<tr>
<td>1.1–6 [GeV^2/c^4]</td>
<td>15.0–22.0 GeV^2/c^4</td>
</tr>
<tr>
<td>A_I</td>
<td></td>
</tr>
<tr>
<td>0.004 ± 0.028</td>
<td>−0.005 ± 0.030</td>
</tr>
<tr>
<td>−0.10_{−0.09}^{+0.08} ± 0.02</td>
<td>−0.09 ± 0.08 ± 0.02</td>
</tr>
</tbody>
</table>

Both compatible with SM within 1-2σ
BO → K*0\(\mu\mu\) angular analysis

- Angular distributions described by 3 angles: θ_\(l\), θ_\(K\), \(\phi\)
- Distributions depend on:
  - √ Wilson coefficients: sensitive to NP :-)
  - √ and form factors :-(
- Measure variables with reduced form factor uncertainties ([JHEP, 05, 2013, 137])

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

\(F_L = \) fraction of longitudinally polarised dimuons

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

JHEP 08 (2013) 131, [arXiv:1304.6325]

L. PESCATORE - DIS WORKSHOP
\[ P_{(4,5,6,8)}' = \frac{S_{(4,5,7,8)}}{\sqrt{F_L(1 - F_L)}} \]

Angular distributions described by 3 angles: \( \theta_l, \theta_K, \phi \)

- Distributions depend on:
  - ✔ Wilson coefficients: sensitive to NP :-) 
  - ✔ and form factors :-)

- Measure variables with reduced form factor uncertainties (JHEP, 05, 2013, 137)

\[
\frac{1}{d\Gamma/dq^2} d\cos \theta_l d\cos \theta_K d\phi dq^2 = \frac{9}{32\pi} \left[ \frac{1}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi \\
+ S_5 \sin 2\theta_K \sin \theta_l \cos \phi + S_6 \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]
Many observables found to be in agreement with the SM predictions

BUT

LOCAL $3.7\sigma$ DEVIATION ON $P^5$ FOUND ON 2011 DATA AND CONFIRMED ON 2012.
$P'_5$: ATLAS AND CMS JOIN THE CLUB
Global fits

- Global fits including information from many results combining many observables.
  [S. Descotes-Genon et al. PRD 88, 074002] [Altmannshofer et al. arxiv:1411.3161] [Beaujean et al. EPJC 74 2897]

- A consistent picture can be built
- Possible explanation with Z’ bosons.

A SHIFT OF $C_9$ BY $-1$ IS FAVOURED WITH RESPECT TO THE SM
Global fits

- Global fits including information from many results combining many observables.
  [S. Descotes-Genon et al. PRD 88, 074002] [Altmannshofer et al. arxiv:1411.3161] [Beaujean et al. EPJC 74 2897]
  
  - Or for pessimist theorists… charm loops
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- Global fits including information from many results combining many observables.
  
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- Or for pessimist theorists... charm loops
- If it is NP → it should be $q^2$ independent

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Best fit</th>
<th>$1\sigma$</th>
<th>$3\sigma$</th>
<th>Pull$_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^\text{NP}_9$</td>
<td>$-1.13$</td>
<td>$[-1.33, -0.91]$</td>
<td>$[-1.72, -0.42]$</td>
<td>4.6</td>
</tr>
</tbody>
</table>

bin-wise fit to $B \rightarrow K^*\mu^+\mu^-$ data

global fit to $88 b \rightarrow s\mu^+\mu^-$ observables

global fit to $B \rightarrow K^*\mu^+\mu^-$ data only

[Altmannshofer & Straub, 1503.06199]
Dealing with electrons

The ee channels are the challenge in this analysis:

- **Bremsstrahlung** affects the e momentum → energy recovered looking at calorimeter hits

- Low trigger efficiency
  → Trigger by the electron, hadron and other particles in the event
  → Final result comes from likelihoods combination

![Graphs and diagrams related to electron analysis](image-url)
The LHCb detector

Forward geometry optimised for for $b$ and $c$ decays.

Fully instrumented in $2 < \eta < 5$

Cleanest LHC events: $<\text{Pile-Up}> \sim 2$ in Run I

$3\text{fb}^{-1}$ collected: $1\text{fb}^{-1}$ in 2011 at TeV and $2\text{fb}^{-1}$ in 2012 at 8TeV
B mesons travel ~1 cm into the detector. VeLo is essential to reconstruct secondary vertices of B and D hadrons.
The LHCb detector

RICH

RICH I: before magnet for $1 < p < 70$ GeV/c
RICH II: before magnet for $20 < p < 200$ GeV/c

Provide particle ID

Essential to distinguish kinematically similar decays with different final states
Calorimeters

- PD for charged pions rejection
- SPD for neutral pions rejection
- ECAL fully contains electrons
- HCAL for hadrons ID

Example of e/h discrimination

Scintillator Pad Detector (SPD)

Pre-Shower Detector
The LHCb detector

Muon detector

5 tracking station separated by iron layers
Drift tubes in the outer region
GEM in the inner region due to higher track density

Each station has 95% efficiency.
Provides good triggering.
Only 10 GeV/c muons pass through.
The LHCb detector

Magnet
Power: 4 Tm
Polarity periodically reversed to reduce systematics

Tracking system
TT → before magnet
OT → after magnet
Precision:
0.4% at 5 GeV/c
1% at 200 GeV/c

Silicon strip and drift chambers