Angular analyses and branching fraction measurements of $b$-hadron FCNC decays

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on behalf of the LHCb collaboration

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Introduction to Flavour Changing Neutral Currents

Branching fraction measurements:
- Differential branching fraction of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ using 9 fb$^{-1}$ (new on arxiv)
- First observation of $B_s^0 \rightarrow f_2(1525) \mu^+ \mu^-$ using 9 fb$^{-1}$ (new on arxiv)
- Branching fraction measurement of $B(s) \rightarrow \mu^+ \mu^-$ using 9 fb$^{-1}$

Angular Analyses:
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ using 4.7 fb$^{-1}$
- $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ using 9 fb$^{-1}$
- $B^0 \rightarrow K^{*0} e^+ e^-$ using 9 fb$^{-1}$
- $B_s^0 \rightarrow \phi \mu^+ \mu^-$ using 8.4 fb$^{-1}$ (shown for the first time)

Summary
\( b \rightarrow s \ell^+ \ell^- \) transitions are Flavour Changing Neutral Currents (FCNC)

- Only allowed at loop-level in SM (penguin and box diagrams)

\[ \mathcal{B} \approx 10^{-9} \]

\[ \mathcal{B} \approx 10^{-7} \]

\[ \mathcal{B} \approx 10^{-5} \]

⇒ Sensitive to New Physics

- \( b \rightarrow s \ell^+ \ell^- \) transitions in tension with SM (flavour anomalies)
Integrate out heavy degrees of freedom in $b \to s\ell^+\ell^-$ decays and replace with effective couplings, denoted as Wilson Coefficients $C_i$.

Rare $b \to s\ell^+\ell^-$ decays most sensitive to $C_{7,9,10}$.
Observables in $b \rightarrow s \ell^+ \ell^-$ transitions

- Complementary information from different observables
- Flavour anomalies observed coherently for all observables

**Branching fractions**

- $C_7^{(t)}$, $C_9^{(t)}$, and $C_{10}^{(t)}$
- Interference
- Long-distance contributions from $c\bar{c}$ above open charm threshold

**Angular observables**

- $J/\psi (1S)$
- $\psi (2S)$
- $B_c^-$
- $K^-$
- $\phi$, $\theta$, $\theta_K$
- $b \rightarrow t, c, u$
- $s$
- $W$, $Z^0$, $\gamma$
- $\mu/e$
- $\ell^+ \ell^-$ final states

- Conceptually “simple”
- Reduced dependence on form factors
- Probes structure of potential NP
- Compare $\mu^+ \mu^-$ and $e^+ e^-$ final states
- Theoretically clean

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Branching fraction measurements
Typical branching fraction measurement strategy

- Cleanly select signal decay by using kinematic, particle identification and tracking information to reject background candidates
- Perform measurement of differential branching fraction $\mathcal{B}$ according to
  \[ \frac{d\mathcal{B}(\text{signal})}{dq^2} = \frac{\mathcal{B}(\text{norm})}{q^2_{\text{max}} - q^2_{\text{min}}} \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}} \]
- Relative to normalisation mode
  - Cancellation of systematic uncertainties
  - Additionally used as control mode to e.g. correct simulated events
- Determine event yields in maximum likelihood fits to data
- Determination of efficiencies from corrected simulation
Measurement of $\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-)$

$$\frac{d\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-)}{dq^2} = \mathcal{B}(B^0_s \rightarrow J/\psi \phi) \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}}$$

- Updated analysis using full LHCb data set (9 fb$^{-1}$)
- Candidates after full selection
- Accumulation of candidates around known $B^0_s$ mass
- Signal visible as vertical band

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Measurement of $\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-)$

$$\frac{d\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-)}{dq^2} = \frac{\mathcal{B}(B^0_s \rightarrow J/\psi \phi)}{q^2_{\text{max}} - q^2_{\text{min}}} \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}}$$

- Model signal with Crystal Ball function (param. from $J/\psi$ mode)
- Combinatorial background described by exponential function

$N_{\text{norm}} = 282\,440 \pm 570$

- data
- total
- $B^0_s \rightarrow J/\psi \phi$
- combinatorial

LHCb 9 fb$^{-1}$
Measurement of $\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)$

$$\frac{d\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0 \to J/\psi \phi)}{q^2_{\text{max}} - q^2_{\text{min}}} \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}}$$

$\phi \rightarrow 0\pi$ candidates

$B_{\text{combinatorial}}$:

- Model signal with Crystal Ball function (param. from $J/\psi$ mode)
- Combinatorial background described by exponential function

$N_{\text{signal}} = 2006 \pm 53$

[arxiv:2105:14007] new on arXiv
Result for $\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)$

Branching fraction in good agreement with Run 1 analysis

Tension with SM in $q^2$ bin $[1.1, 6.0] \text{ GeV}^2/c^4$ at $3.6 \sigma$ ($1.8 \sigma$ with LCSR alone)

$d\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)/dq^2 = (2.88 \pm 0.21) \times 10^{-8}/(\text{ GeV}^2/c^4)$ for $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$

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First observation of $B_s^0 \rightarrow f'_2(1525)\mu^+\mu^-$

- $f'_2$ meson is a spin-2 $K^+K^-$ resonance
- $f'_2(1525)$ heavier and wider (width $\approx 86$ MeV) than $\phi$ meson
- Tighter selection to combat increase in background
- Fit $m_{B_s^0}$ and $m_{K^+K^-}$ to separate signal from other $B_s^0 \rightarrow K^+K^-\mu^+\mu^-$

![Graph 1](#)

- $B(B_s^0 \rightarrow f'_2(1525)\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.08 \pm 0.06) \times 10^{-7}$
- First observation with 9 $\sigma$ significance

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Measurement of $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$

- Long history of searches for $B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$

- Updated measurement with full LHCb data set (9 fb$^{-1}$)

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Branching fraction of $B_{(s)}^0 \to \mu^+ \mu^-$

- Two normalisation channels: $B^+ \to J/\psi K^+, B^0 \to K^+ \pi^-$
- Analysis performed in 5 bins of BDT classifier
- Simultaneous fit to all bins and data sets
- Measured branching fraction for $B_s^0 \to \mu^+ \mu^-$:
  $\mathcal{B}(B_s^0 \to \mu^+ \mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$ ($10\sigma$)
- Measurement consistent with SM [JHEP10(2019)232]:
  $\mathcal{B}(B_s^0 \to \mu^+ \mu^-) = 3.66 \pm 0.14 \times 10^{-9}$
- Set limits on $B^0 \to \mu^+ \mu^-$ and $B_s^0 \to \mu^+ \mu^-\gamma$:
  - $\mathcal{B}(B^0 \to \mu^+ \mu^-) < 2.6 \times 10^{-10}$ at 95% CL
  - $\mathcal{B}(B_s^0 \to \mu^+ \mu^-\gamma)_{m_{\mu\mu} > 4.9 \text{ GeV}/c^2} < 2.0 \times 10^{-9}$ at 95% CL
Effective lifetime of $B_s^0 \rightarrow \mu^+\mu^-$

- In SM only heavy mass eigenstate contributes to $B_s^0 \rightarrow \mu^+\mu^-$
- Test for possible NP contribution from light $B_s^0$ mass eigenstate ($A_{\Delta\Gamma}^{\mu\mu} = -1$)
- Fit dimuon mass distribution to statistically subtract background contribution
- Subsequent fit to $B_s^0 \rightarrow \mu^+\mu^-$ decay time finds: $\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03$ ps
- Consistent with lifetime of heavy (light) mass eigenstate at 1.5 (2.2) $\sigma$

[Preprint: LHCb-PAPER-2021-007 (in prep.)]

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Angular analyses
Decay described by $q^2$ and three decay angles, $\vec{\Omega} = (\cos \theta_K, \cos \theta_\ell, \phi)$

Differential decay rate given as

$$\frac{d^4\Gamma}{dq^2 d^3\vec{\Omega}} = \sum_i J_i(q^2) f_i(\vec{\Omega})$$

- Angular coefficients $J_i$ and functions $f_i$ identical for different $b \rightarrow s \ell^+ \ell^-$ transitions
- Accessible angular observables $J_i \pm \bar{J}_i$ differ for self-tagging and untagged decays

Parameterise efficiency in decay angles and $q^2$ using corrected simulation

Simultaneously fit reconstructed $B$ mass and $\vec{\Omega}$ to extract angular observables
- Fitting mass component improves separation of signal and background
Angular analyses of $B_{u/d} \to K^* \mu^+ \mu^-$

- Known decay flavour (self-tagging) as e.g. $K^*^0 \to K^+ \pi^-$
- Access to $CP$-averaged observables $F_L, A_{FB}, S_i$
  - Access to clean observables $P'_i$
- Separate S-wave from P-wave with fit to $m_{K\pi}$
- Exemplary plots from $B^0 \to K^*^0 \mu^+ \mu^-$

LHCb 2016

$4.0 < q^2 < 6.0 \text{ GeV}^2/c^4$

$\cos \theta_{l}$

$\cos \theta_{k}$

$\phi$

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Results in $B_{u/d} \rightarrow K^* \mu^+ \mu^-$ decays

- Results in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ using 4.7 fb$^{-1}$:
  - Simultaneous fit to $\bar{\Omega}$, $m_{B^0}$ and $m_{K^+\pi^-}$
  - Local tension with SM up to 2.9 $\sigma$ in $P_5'$
  - Global tension determined by varying $Re(C_9)$: 3.3 $\sigma$

- Results in $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ using 9 fb$^{-1}$:
  - Two step approach:
    - S-wave fraction fit in 2 dimensions ($m_{B^+}$ and $m_{K^0_S\pi^+}$)
    - 4-dimensional fit to $\bar{\Omega}$ and $m_{B^+}$
  - Local tension with SM up to 3.0 $\sigma$ in $P_2(\sim A_{FB})$
  - Global tension determined by varying $Re(C_9)$: 3.1 $\sigma$
Angular analysis of $B^0 \rightarrow K^{*0} e^+ e^-$ at very low $q^2$

- Probe photon polarisation in very low $q^2$ region [0.0008, 0.257] GeV$^2$/c$^4$
- S-wave fraction assumed to be negligible
- 4-dimensional fit to $\vec{\Omega}$ and $m_{B^0}$
- Results consistent with SM
- Strongest constraint on photon polarisation

[JHEP 12 (2020) 081]
Angular analysis of $B^0 \rightarrow K^{*0}e^+e^-$ at very low $q^2$

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- S-wave fraction assumed to be negligible
- 4-dimensional fit to $\vec{\Omega}$ and $m_{B^0}$
- Results consistent with SM
- Strongest constraint on photon polarisation

[flavio v2.0.0]

- Constraints at 2σ
- $B(B \rightarrow X_s\gamma)$
- $B^0 \rightarrow K^0_S\pi^0\gamma$
- $B^0 \rightarrow \phi\gamma$
- $B^0 \rightarrow K^{*0}e^+e^-$
- Global

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Candidates / 0.08
LHCb]

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Candidates / 0.1
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LHCb]

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Re(C′/C_7)]

[−1.
0 −0.5 0.0 0.5 1.0
Im(C′/C_7)]

[flavio v2.0.0]

[Constraints at 2σ]

[Re(C′/C_7)]

[Im(C′/C_7)]

[JHEP 12 (2020) 081]

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Updated angular analysis using 8.4 fb\(^{-1}\) of LHCb data, more than 4-fold increase in yields

Latest addition to analyses related to flavour anomalies

Decay of \(B^0_s \to \phi \to K^+ K^- \mu^+ \mu^-\) flavour-symmetric \(\Rightarrow\) untagged decay

Untagged angular decay rate described by \(q^2\) and the angles \(\vec{\Omega}\):

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \left[ \frac{d^3\Gamma + \bar{\Gamma}}{d\vec{\Omega}} \right] = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K (1 + \frac{1}{3} \cos 2\theta_l) + F_L \cos^2 \theta_K (1 - \cos 2\theta_l) \right. \\
+ S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi \\
+ A_5 \sin 2\theta_K \sin \theta_l \cos \phi + \frac{4}{3} A_{FB}^{CP} \sin^2 \theta_K \cos \theta_l \\
+ S_7 \sin 2\theta_K \sin \theta_l \sin \phi + A_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + A_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \\
\left. \right] \]

\(S_i\) CP-averages \quad \(A_i\) CP-asymmetries

Minimal S-wave pollution due to narrow \(K^+ K^-\) window
NEW: Fit strategy for $B_s^0 \rightarrow \phi \mu^+ \mu^-$

[PREPARE-2021-022] (in prep.)

- Simultaneous fit in 4-dimensions to $\tilde{\Omega}$ and $m_{B_s^0}$
- Signal modelled by Crystal Ball function in mass and untagged decay rate in angles
- Combinatorial background described by exponential function in mass and Chebyshev polynomial of order 1 in angles

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NEW: \( CP \)-averaged angular observables in \( B^0_s \rightarrow \phi \mu^+ \mu^- \)

- Precision for angular observables significantly improved with respect to 3 \( fb^{-1} \) LHCb analysis
- Compatible with SM prediction
- Global compatibility determined by varying \( Re(C_9) \): 1.9 \( \sigma \)
NEW: $CP$-asymmetries in $B_s^0 \rightarrow \phi \mu^+ \mu^-$

- Precision for angular observables significantly improved with respect to 3 fb$^{-1}$ LHCb analysis
- Overall good compatibility with SM prediction
- $T$-odd $CP$ asymmetries $A_{8,9}$ close to zero in SM, can be large in presence of NP contribution

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NEW: Global fits using $CP$-averaged angular observables

- Global compatibility with SM tested using flavio by scanning over $\Re e(C_9)$
- Fit $CP$ averages $(F_L, S_{3,4,7})$ in narrow bins below $6 \text{GeV}^2/c^4$ in $q^2$
  and wide bin $(15 < q^2 < 18.9) \text{GeV}^2/c^4$ (not sensitive to potential charm loop effects)

Preferred value for $\Re e(C_9)$ agrees with the SM value at 1.9 $\sigma$ level
NEW: Global fits using $CP$-averaged angular observables

- Global compatibility with SM tested using \textit{flavio} by scanning over $\mathcal{R}e(C_9)$
- Fit $CP$ averages ($F_L$, $S_{3,4,7}$) in narrow bins below $6 \text{ GeV}^2/c^4$ in $q^2$ and wide bin $(15 < q^2 < 18.9) \text{ GeV}^2/c^4$ (not sensitive to potential charm loop effects)

Preferred value for $\mathcal{R}e(C_9)$ agrees with the SM value at $1.9 \sigma$ level

Similar trend as found in $B \to K^*\mu^+\mu^-$

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Discussed current status of LHCb $b \rightarrow s \ell^+ \ell^-$ measurements:

- Fully leptonic $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decays compatible with SM
- Branching fraction of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ in 3.6 $\sigma$ tension with SM (new on arxiv!)
- First observation of $B_s^0 \rightarrow f_2'(1520) \mu^+ \mu^-$ with significance of 9 $\sigma$ (new on arxiv!)
- Angular analyses of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ in tension with SM at 3.3 $\sigma$ and 3.1 $\sigma$
- Most stringent constraint on photon polarisation from $B^0 \rightarrow K^{*0} e^+ e^-$ (consistent with SM)

Presented angular analysis of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ with 8.4 fb$^{-1}$ for the first time:

- Most precise measurement of angular observables to date
- $CP$-averages compatible with SM at 1.9 $\sigma$
- $CP$-asymmetries compatible with zero