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

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on behalf of the LHCb collaboration

Conference on Flavour Physics and CP violation 2021

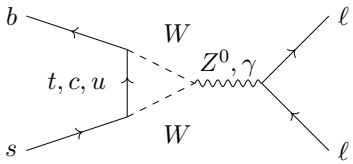
Shanghai, June 7, 2021

Outline

- Introduction to Flavour Changing Neutral Currents
- Branching fraction measurements:
  - Differential branching fraction of $B_s^0 \to \phi\mu^+\mu^-$ using $9\,\text{fb}^{-1}$ (new on arxiv)
  - First observation of $B_s^0 \to f_2'(1525)\mu^+\mu^-$ using $9\,\text{fb}^{-1}$ (new on arxiv)
  - Branching fraction measurement of $B_{(s)} \to \mu^+\mu^-$ using $9\,\text{fb}^{-1}$
- Angular Analyses:
  - $B^0 \to K^{*0}\mu^+\mu^-$ using $4.7\,\text{fb}^{-1}$
  - $B^+ \to K^{*+}\mu^+\mu^-$ using $9\,\text{fb}^{-1}$
  - $B^0 \to K^{*0}e^+e^-$ using $9\,\text{fb}^{-1}$
  - $B_s^0 \to \phi\mu^+\mu^-$ using $8.4\,\text{fb}^{-1}$ (shown for the first time)
- Summary

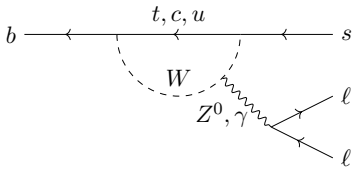
- $b \to s\ell^+\ell^-$ transitions are Flavour Changing Neutral Currents (FCNC)
- Only allowed at loop-level in SM (penguin and box diagrams)

leptonic



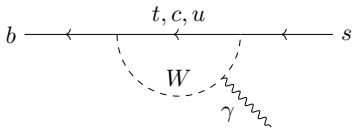
$\mathcal{B} \approx 10^{-9}$

semileptonic



$\mathcal{B} \approx 10^{-7}$

radiative

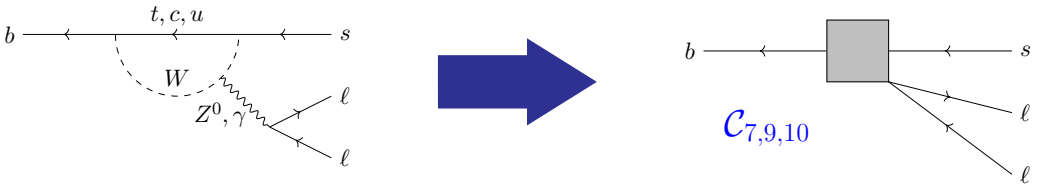


$\mathcal{B} \approx 10^{-5}$

$\Rightarrow$ Sensitive to New Physics

- $b \to s\ell^+\ell^-$ 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 $\mathcal{C}_i$

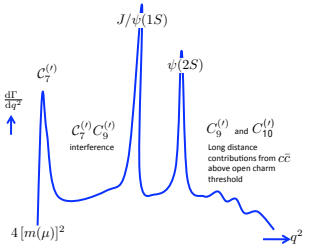


- Rare $b \to s\ell^+\ell^-$ decays most sensitive to $\mathcal{C}_{7,9,10}$

Observables in $b \to s\ell^+\ell^-$ transitions

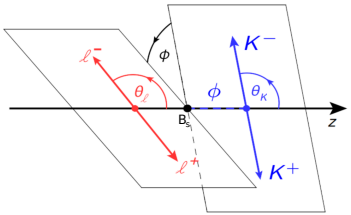
- Complementary information from different observables
- Flavour anomalies observered coherently for all observables

Branching fractions



- Conceptually "simple"
- Significant hadronic uncertainties

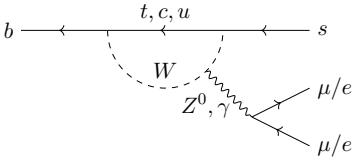
Angular observables



- Reduced dependence on form factors
- Probes structure of potential NP

Lepton universality

see Shun Watanuki's talk



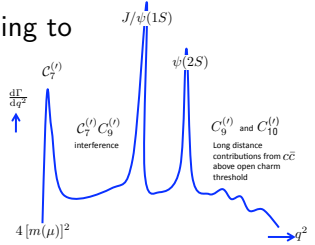
- Compare $\mu^+\mu^-$ and e^+e^- final states
- Theoretically clean

Branching fraction measurements

- 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

$$\frac{\mathrm{d}\mathcal{B}(\text{signal})}{\mathrm{d}q^2} = \frac{\mathcal{B}(\text{norm})}{{q^2}_{\text{max}} - {q^2}_{\text{min}}} \times \frac{N_{\text{signal}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{signal}}}$$

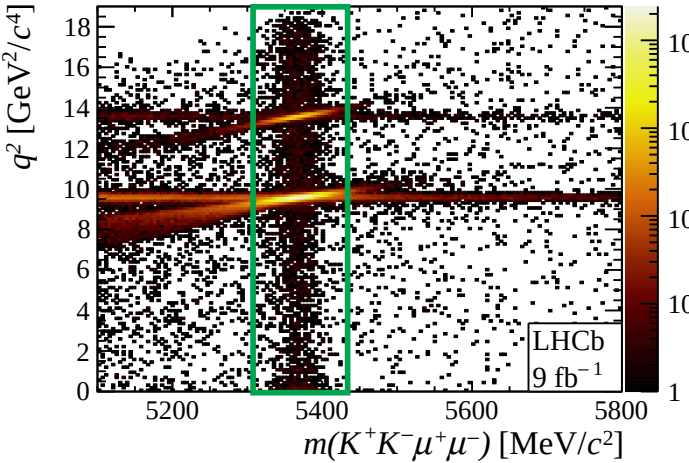
- Relative to normalisation mode
  - Cancellation of systematic uncertainties
  - Additionally used as control mode to e.g. correct simulated events
- Determine event yields in maximum likelihood fits to data
- Determination of efficiencies from corrected simulation



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

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

[arxiv:2105:14007]
new on arXiv



- Updated analysis using full LHCb data set ($9\,\mathrm{fb}^{-1}$)
- Candidates after full selection
- Accumulation of candidates around known B_s^0 mass

$\Rightarrow$ Signal visible as vertical band

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

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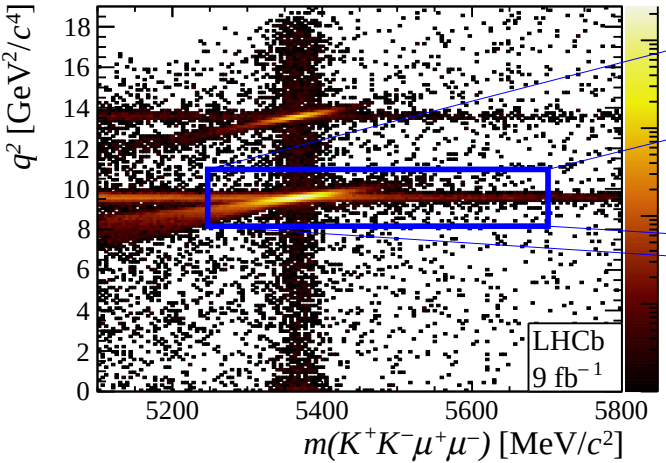

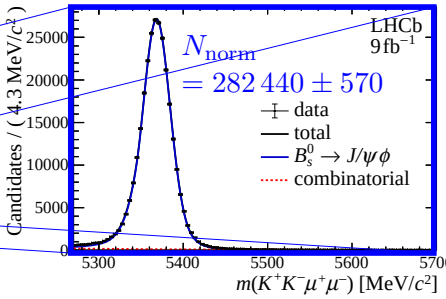

- Model signal with Crystal Ball function (param. from J/ψ mode)
- Combinatorial background described by exponential function

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

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[arxiv:2105:14007]
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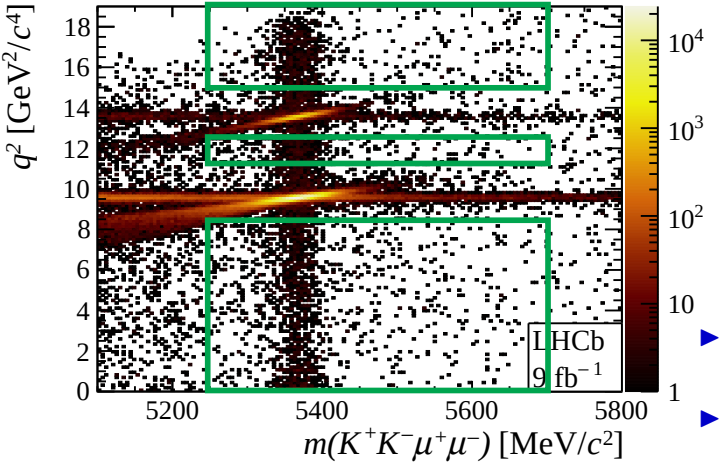
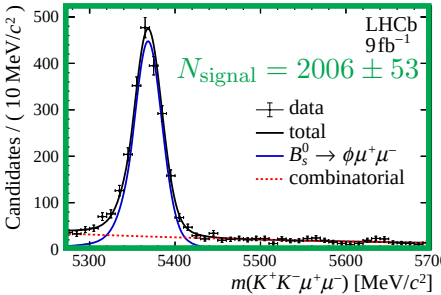
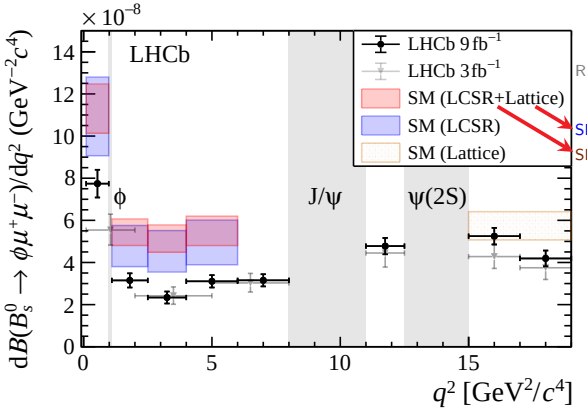




- Model signal with Crystal Ball function (param. from J/ψ mode)
- Combinatorial background described by exponential function

Result for $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$



[arxiv:2105:14007]
new on arXiv

Run 1 result: [JHEP 09 (2015) 179], [arxiv:2103.06810]

SM LCSR: [JHEP 08 (2016) 098], [EPJ C 75 (2015) 382], [arXiv:1810.08132]

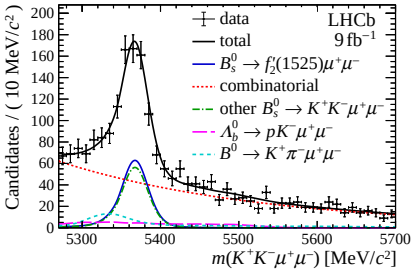
SM Lattice: [PRL 112 (2014) 212003], [PoS LATTICE2014 (2015) 372]

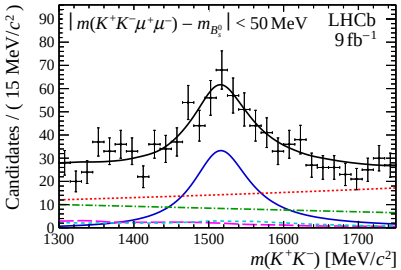
- Branching fraction in good agreement with Run 1 analysis
- Tension with SM in q^2 bin $[1.1, 6.0]\,\mathrm{GeV}^2/c^4$ at $3.6\,\sigma$ ($1.8\,\sigma$ with LCSR alone)
  $\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/\mathrm{d}q^2 = (2.88 \pm 0.21) \times 10^{-8}/(\,\mathrm{GeV}^2/c^4)$ for $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$

First observation of $B^0_s \to f'_2(1525)\mu^+\mu^-$

[arxiv:2105:14007]
new on arXiv

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

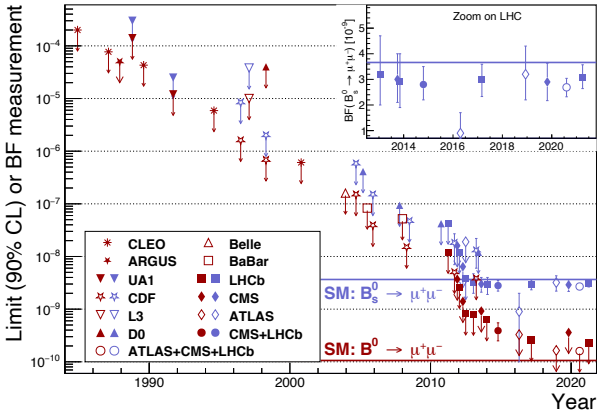




- $\mathcal{B}(B^0_s \to f'_2(1525)\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.08 \pm 0.06) \times 10^{-7}$
- First observation with $9\,\sigma$ significance

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

- Long history of searches for $B^0_{(s)} \to \mu^+\mu^-$

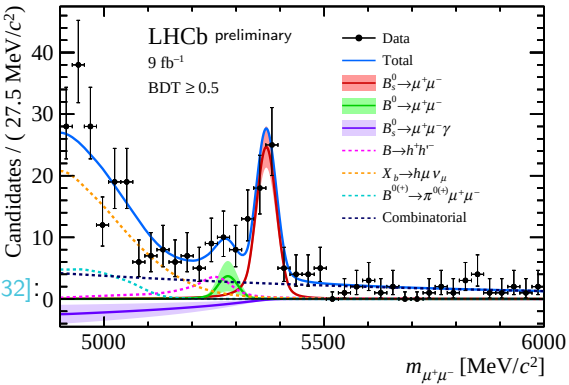


- Updated measurement with full LHCb data set ($9\,\text{fb}^{-1}$)

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

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

- 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

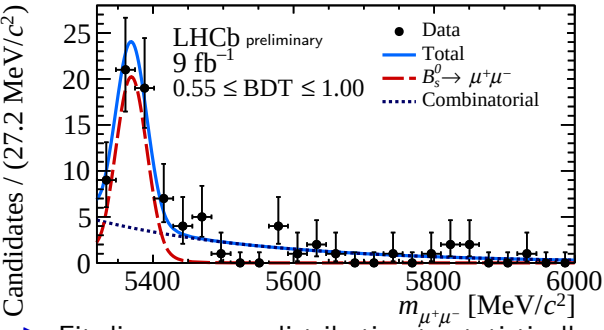


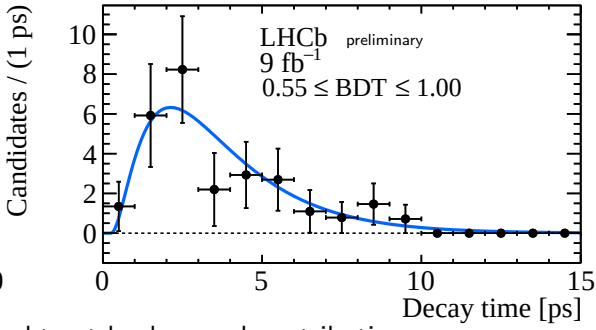
- Measured branching fraction for $B^0_s \to \mu^+\mu^-$:
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$ $(10\,\sigma)$
- Measurement consistent with SM[JHEP10(2019)232]:
  $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.66 \pm 0.14 \times 10^{-9}$

- Set limits on $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$:
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 95% CL
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ at 95% CL

Effective lifetime of $B_s^0 \to \mu^+\mu^-$

- In SM only heavy mass eigenstate contributes to $B_s^0 \to \mu^+\mu^-$ [LHCb-PAPER-2021-007] (in prep.)
- Test for possible NP contribution from light B_s^0 mass eigenstate ($A_{\Delta\Gamma}^{\mu\mu} = -1$)



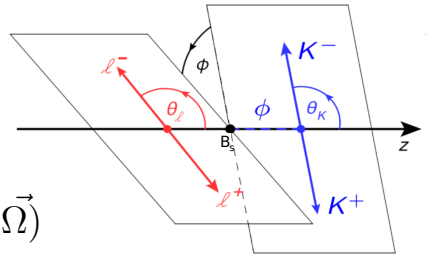


- Fit dimuon mass distribution to statistically subtract background contribution
- Subsequent fit to $B_s^0 \to \mu^+\mu^-$ decay time finds: $\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\text{ps}$
- Consistent with lifetime of heavy (light) mass eigenstate at $1.5\ (2.2)\,\sigma$

Angular analyses

Typical $B \to V\ell\ell$ angular analysis strategy

- Decay described by q^2 and three decay angles, $\vec{\Omega} = (\cos\theta_K, \cos\theta_l, \phi)$



- Differential decay rate given as

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

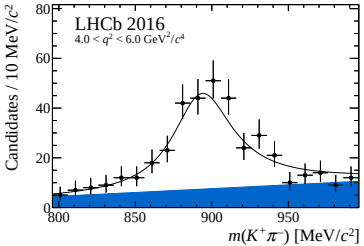
  - Angular coefficients J_i and functions f_i identical for different $b \to s\ell^+\ell^-$ transitions
  - Accessible angular observables $J_i \pm \overline{J}_i$ differ for self-tagging and untagged decays

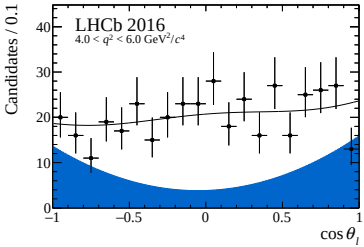
- Parameterise efficiency in decay angles and q^2 using corrected simulation
- Simultaneously fit reconstructed B mass and $\vec{\Omega}$ to extract angular observables
  - Fitting mass component improves separation of signal and background

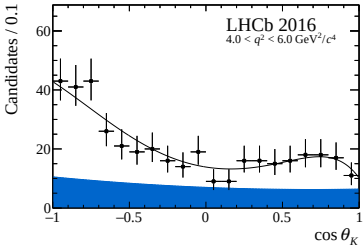
Angular analyses of $B_{u/d} \to K^* \mu^+ \mu^-$

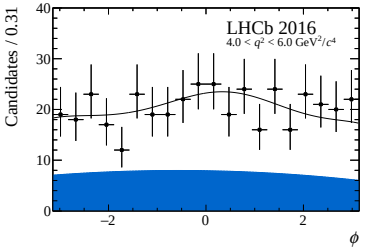
[PRL 125 (2020) 011802]

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



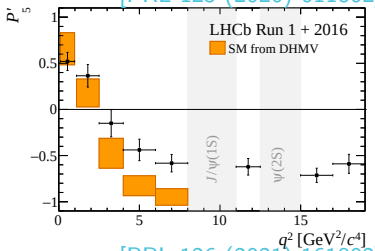






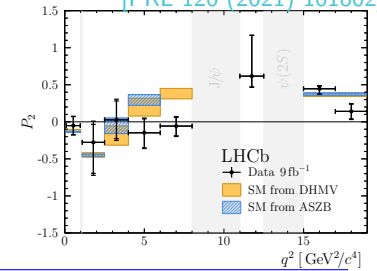
[PRL 125 (2020) 011802]

- Results in $B^0 \to K^{*0} \mu^+ \mu^-$ using $4.7\,\text{fb}^{-1}$:
  - Simultaneous fit to $\vec{\Omega}$, m_{B^0} and $m_{K^+\pi^-}$
  - Local tension with SM up to $2.9\,\sigma$ in P_5'
  - Global tension determined by varying $\mathcal{R}e(\mathcal{C}_9)$: $3.3\,\sigma$



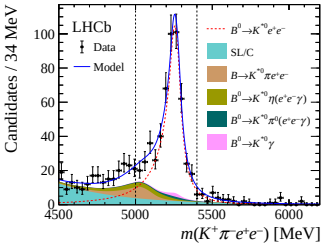
[PRL 126 (2021) 161802]

- Results in $B^+ \to K^{*+} \mu^+ \mu^-$ using $9\,\text{fb}^{-1}$:
  - Two step approach:
    - S-wave fraction fit in 2 dimensions (m_{B^+} and $m_{K^0_S \pi^+}$)
    - 4-dimensional fit to $\vec{\Omega}$ and m_{B^+}
  - Local tension with SM up to $3.0\,\sigma$ in $P_2 (\sim A_{\text{FB}})$
  - Global tension determined by varying $\mathcal{R}e(\mathcal{C}_9)$: $3.1\,\sigma$

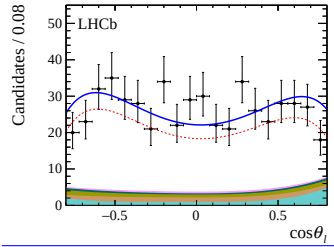


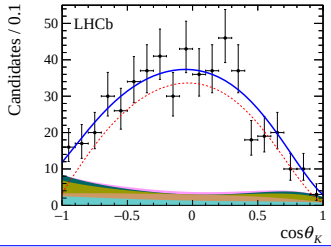
Angular analysis of $B^0 \to K^{*0} e^+ e^-$ at very low q^2

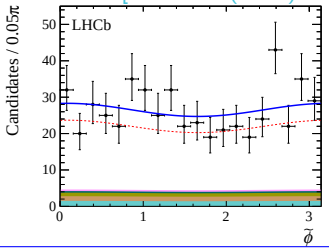
- Probe photon polarisation in very low q^2 region $[0.0008, 0.257]\,\mathrm{GeV}^2/c^4$
- S-wave fraction assumed to be negligible
- 4-dimensional fit to $\vec{\Omega}$ and m_{B^0}
- Results consistent with SM
- Strongest constraint on photon polarisation



[JHEP 12 (2020) 081]







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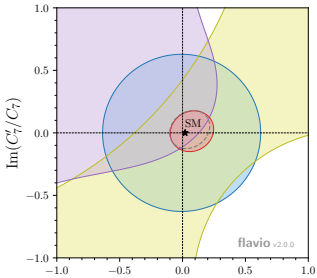
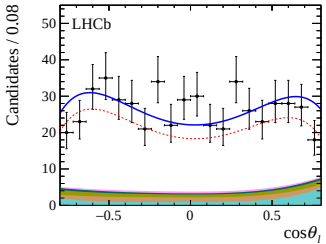
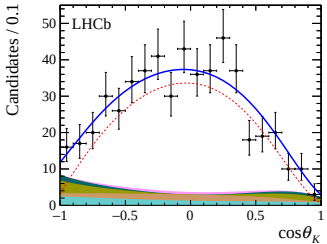
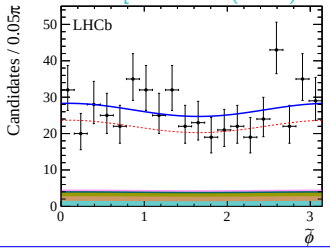


[JHEP 12 (2020) 081]







NEW: Angular analysis of $B_s^0 \to \phi\mu^+\mu^-$

[LHCb-PAPER-2021-022] (in prep.)

- 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 $B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$ flavour-symmetric $\Rightarrow$ untagged decay
- Untagged angular decay rate described by $\boldsymbol{q^2}$ and the angles $\vec{\Omega}$:

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

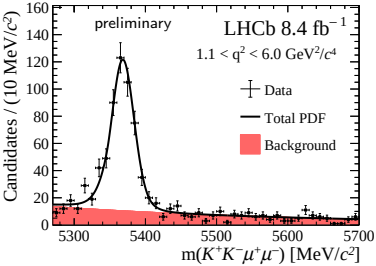
S_i CP-averages $\qquad$ A_i CP-asymmetries

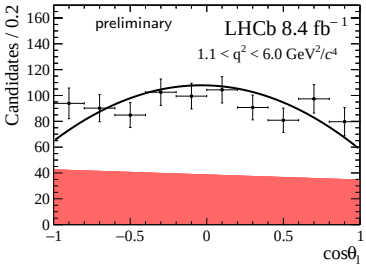
- Minimal S-wave pollution due to narrow K^+K^- window

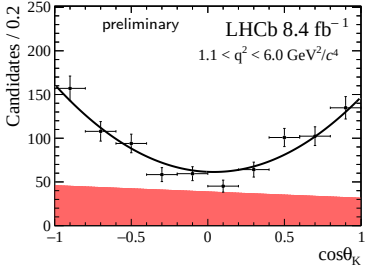
NEW: Fit strategy for $B_s^0 \to \phi\mu^+\mu^-$

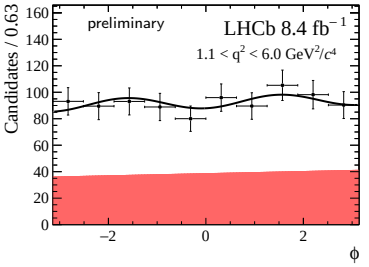
[LHCb-PAPER-2021-022] (in prep.)

- Simultaneous fit in 4-dimensions to $\vec{\Omega}$ 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





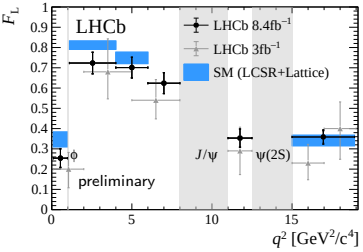


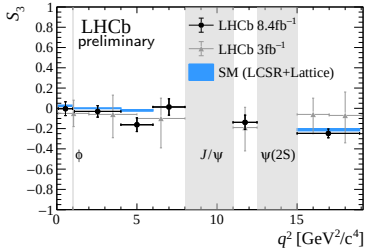


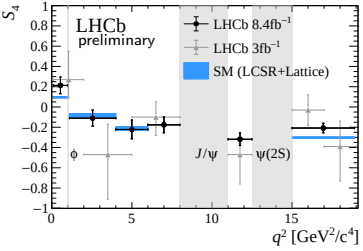
NEW: CP-averaged angular observables in $B_s^0 \to \phi\mu^+\mu^-$

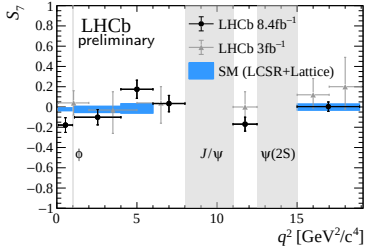
[LHCb-PAPER-2021-022] (in prep.)

- Precision for angular observables significantly improved with respect to $3\,\text{fb}^{-1}$ LHCb analysis
- Compatible with SM prediction
- Global compatibility determined by varying $\mathcal{R}e(\mathcal{C}_9)$: $1.9\,\sigma$





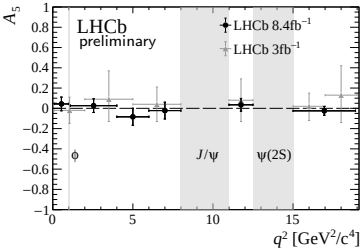


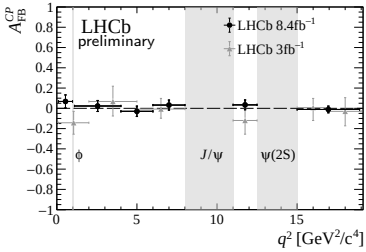


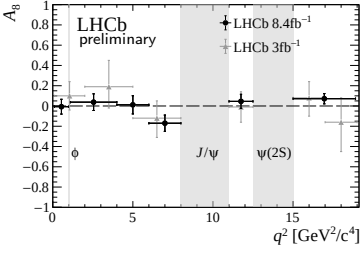
NEW: CP-asymmetries in $B_s^0 \to \phi\mu^+\mu^-$

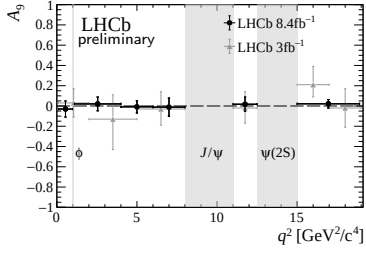
[LHCb-PAPER-2021-022] (in prep.)

- Precision for angular observables significantly improved with respect to $3\,\text{fb}^{-1}$ 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





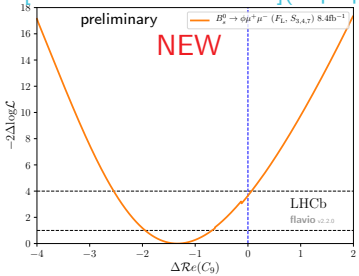




NEW: Global fits using CP-averaged angular observables

- Global compatibility with SM tested using `flavio` by scanning over $\mathcal{R}e(\mathcal{C}_9)$
- Fit CP averages ($F_{\rm L}$, $S_{3,4,7}$) 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)

[LHCb-PAPER-2021-022](in prep.)



- Preferred value for $\mathcal{R}e(\mathcal{C}_9)$ agrees with the SM value at $1.9\,\sigma$ level

NEW: Global fits using CP-averaged angular observables

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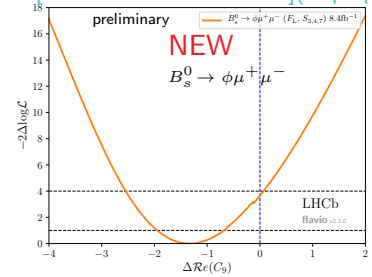
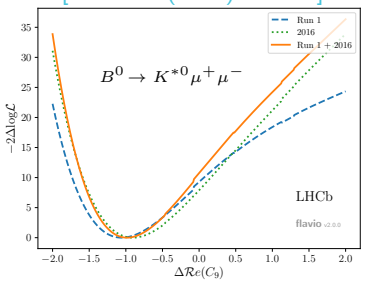
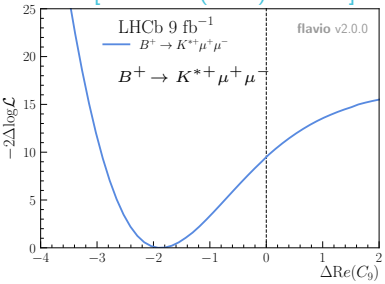
[LHCb-PAPER-2021-022](in prep.)



[PRL 125 (2020) 011802]



[PRL 126 (2021) 161802]



- Preferred value for $\mathcal{R}e(\mathcal{C}_9)$ agrees with the SM value at $1.9\,\sigma$ level
- Similar trend as found in $B \to K^*\mu^+\mu^-$

Summary

- Discussed current status of LHCb $b \to s\ell^+\ell^-$ measurements:
  - Fully leptonic $B^0_{(s)} \to \mu^+\mu^-$ decays **compatible** with SM
  - Branching fraction of $B^0_s \to \phi\mu^+\mu^-$ in $\mathbf{3.6\,\sigma}$ **tension** with SM (new on arxiv!)
  - **First observation** of $B^0_s \to f_2'(1520)\mu^+\mu^-$ with significance of $\mathbf{9\,\sigma}$ (new on arxiv!)
  - Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ in **tension** with SM at $\mathbf{3.3\,\sigma}$ and $\mathbf{3.1\,\sigma}$
  - Most stringent constraint on photon polarisation from $B^0 \to K^{*0}e^+e^-$ (**consistent** with SM)
- Presented angular analysis of $\boldsymbol{B^0_s \to \phi\mu^+\mu^-}$ with $8.4\,\text{fb}^{-1}$ for the first time:
  - Most precise measurement of angular observables to date
  - CP-averages **compatible** with SM at $\mathbf{1.9\,\sigma}$
  - CP-asymmetries compatible with zero