Imperial College London

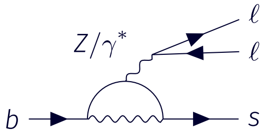
$b \to s\ell\ell$ decays at LHCb

Moriond EW

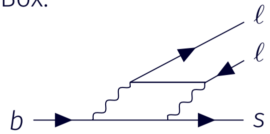
Mark Smith, on behalf of the LHCb collaboration

27 March 2024

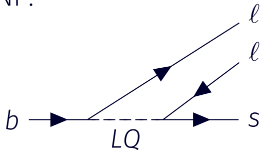
Penguin:



Box:



NP:



Small SM amplitude $\rightarrow$ excellent place to search for NP!

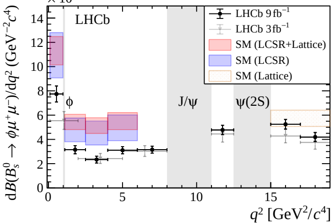
- Lepton Flavour Universality $\frac{\mathcal{B}(H_b \to F\mu^+\mu^-)}{\mathcal{B}(H_b \to Fe^+e^-)}$
- (Differential) BFs $\frac{\mathrm{d}\Gamma(H_b \to F\ell\ell)}{\mathrm{d}\,q^2}$
- Angular analyses P_5', A_{FB} etc

multifarious possibilities

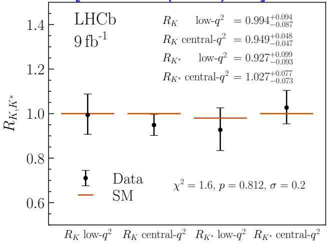
B^+, B^0, B_s^0, Λ_b $\longrightarrow$ K^+, K^0, K^{*+}, K^{*0}, ϕ, $f_2'(1525)$, pK^-, none + e^+e^-, $\mu^+\mu^-$, $(\tau^+\tau^-)$

LHCb results

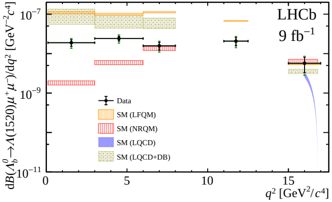
[PRL 127 (2021) 15]



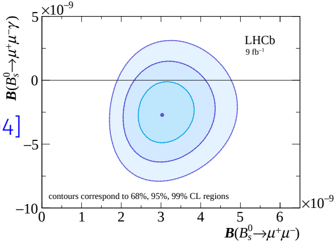
[PRL 131 (2023) 05]

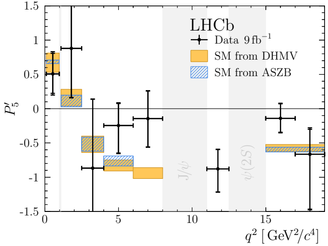


[PRL 131 (2023) 15]



[PRL 128 (2022) 04]

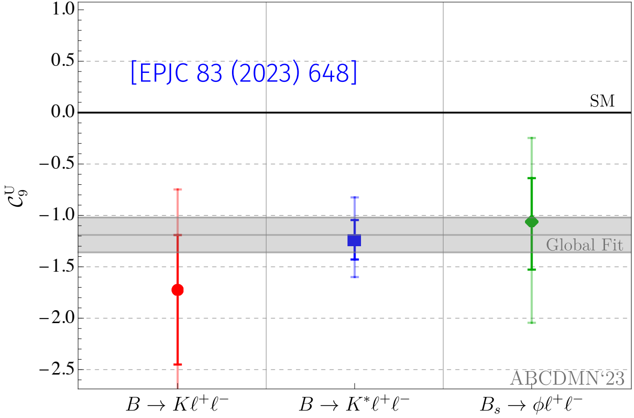




[PRL 126 (2021) 16]

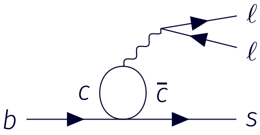
$B^+ \to K^{*+}\mu^+\mu^-$

E.g. fit for C_9^U, assuming SM for other WCs:



Is this all NP?

- Could be due to long-distance charm-loop:



$$C_9^{\text{eff}} = C_9^{SM} + C_9^{c\bar{c}} + C_9^{NP}$$

- Difficult to calculate

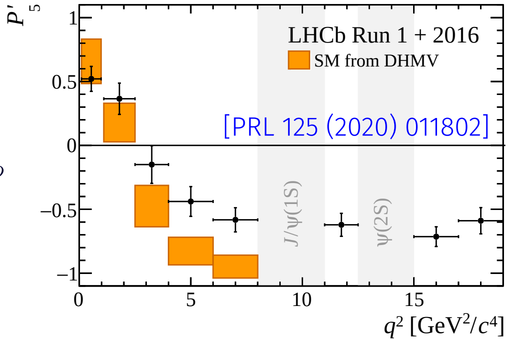
Can we measure the long-distance contribution?

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

$B \to V\ell^+\ell^-$ - 3 decay angles (Ω), $q^2 = m^2_{\ell\ell}$, $k^2 = m^2_{K\pi}$

- Final state of $K^+\pi^-\mu^+\mu^-$
  - P-wave K^{*0} and S-wave $K^+\pi^-$ must be accounted for

$$\frac{d^4\Gamma_P}{dq^2 d\Omega} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K$$
$$+(J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+J_5\sin 2\theta_K\sin\theta_\ell\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_l$$
$$+J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$+J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



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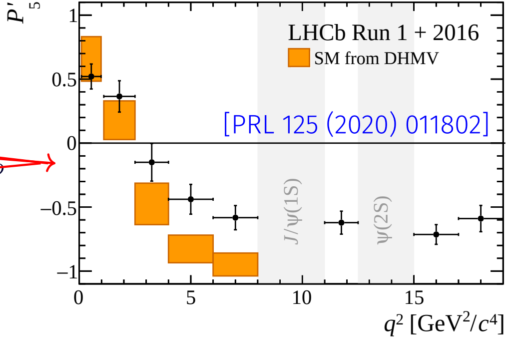
$$+ (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+ J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ J_5\sin 2\theta_K\sin\theta_\ell\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_l$$
$$+ J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi$$
$$\left. + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\right]$$



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

$B \to V\ell^+\ell^-$ - 3 decay angles (Ω), $q^2 = m^2_{\ell\ell}$, $k^2 = m^2_{K\pi}$

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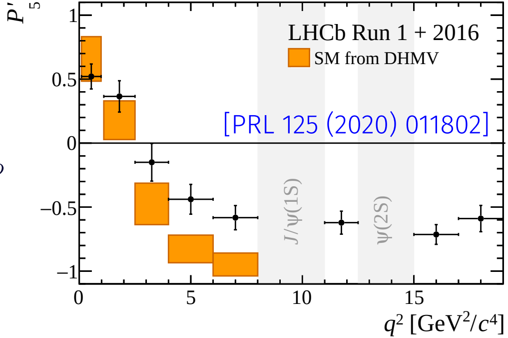
$$\frac{d^4\Gamma_P}{dq^2 d\Omega} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell + J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi + J_{6s}\sin^2\theta_K\cos\theta_l + J_7\sin 2\theta_K\sin\theta_\ell\sin\phi + J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



The *observables*, J_i are constructed from q^2 dependent *amplitudes*. E.g.:

$$J_5 \sim \left[\Re(\mathcal{A}_0^L\mathcal{A}_\perp^L*) - \Re(\mathcal{A}_0^R\mathcal{A}_\perp^{R*})\right]$$

Unbinned amplitudes

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \Big\{ \big[\underbrace{(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')}_{\text{WCs}} \big] \overbrace{\mathcal{F}_\lambda(q^2)}^{\text{FFs}} + \frac{2 m_b M_B}{q^2} \big[\underbrace{(C_7 \pm C_7')}_{\text{WCs}} \overbrace{\mathcal{F}_\lambda^T(q^2)}^{\text{FFs}} - 16\pi^2 \frac{M_B}{m_b} \underbrace{\mathcal{H}_\lambda(q^2)}_{\text{non-local}} \big] \Big\}$$

- C_9, C_9', C_{10}, C_{10}' are fit parameters. C_7, C_7' fixed to SM.
- Local FFs $F_\lambda^{(T)}(q^2)$ constrained to lattice + LCSR determinations [JHEP 01 (2019) 150], [PoS (LATTICE2014) 372]
- Non-local function follows [JHEP 09 (2022) 133]

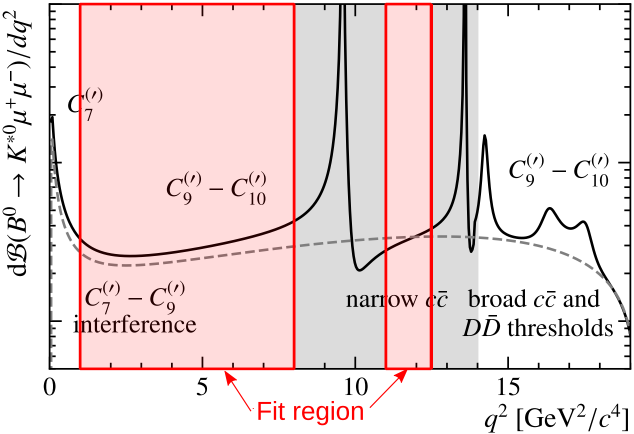
$$\mathcal{H}_\lambda(z) = \frac{1 - z z_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z), \qquad \hat{\mathcal{H}}_\lambda(z) = \phi_\lambda^{-1}(z) \sum_k a_{\lambda,k} z^k$$

  - Option to use theory predictions at $q^2 < 0$ [JHEP 02 (2021) 088]
  - Experimental inputs for magnitudes and phases at resonances [PRD 90 (2014) 112009], [PRD 76 (2007) 031102], [PRD 88 (2013) 074026], [PRD 88 (2016) 052002], [EPJC 72 (2012) 2118]
- Include k^2 dependence: $\mathcal{A}_\lambda^{L,R} \to \mathcal{A}_\lambda^{L,R} \times f(k^2)$
  - $f(k^2)$ is a relativistic Breit-Wigner for P-wave, LASS for S-wave

Plan

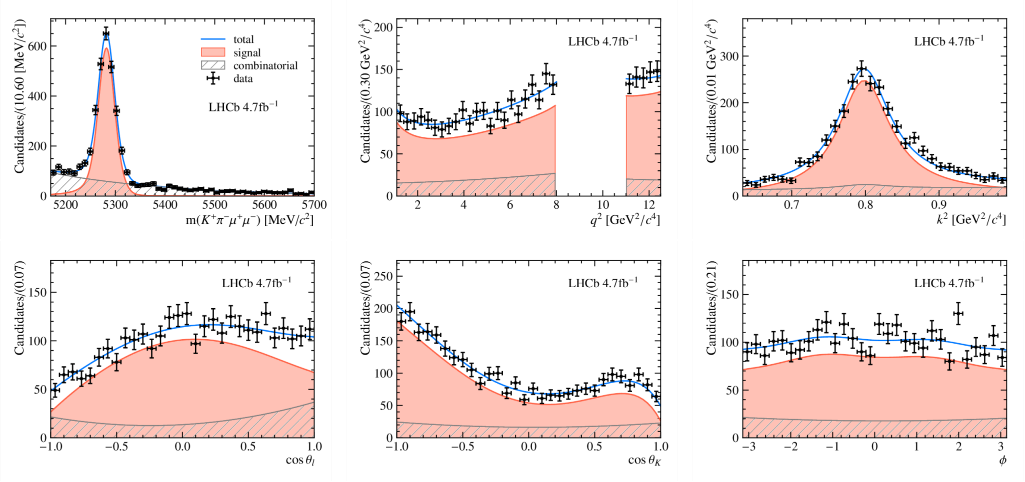
Fit for the non-local contributions in the data:

- $4.7\,\text{fb}^{-1}$ of data: Run 1 + 2016
  - Same data as published binned angular analysis [PRL 125 (2020) 011802]
- Unbinned fit in q^2 for the *amplitude* parameters: FFs, WCs etc
  - 6D fit: 3 decay angles, q^2, k^2 and $m(K\pi\mu\mu)$
  - BF relative to $B^0 \to J/\psi K^+\pi^-$ for absolute WC magnitude
- Two versions of the fit: with or without $q^2 < 0$ non-local predictions



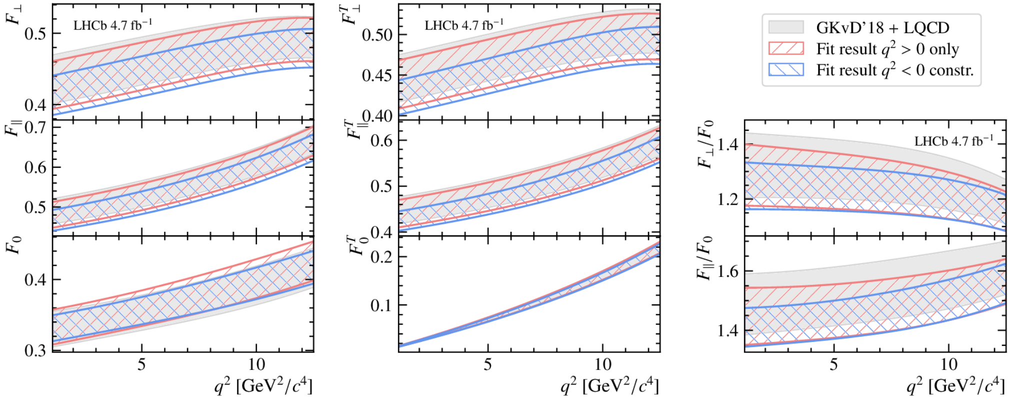
- Model dependent analysis
- Maximum sensitivity to non-local effects

Fit projections



Local FFs, $\mathcal{F}_\lambda^{(T)}$

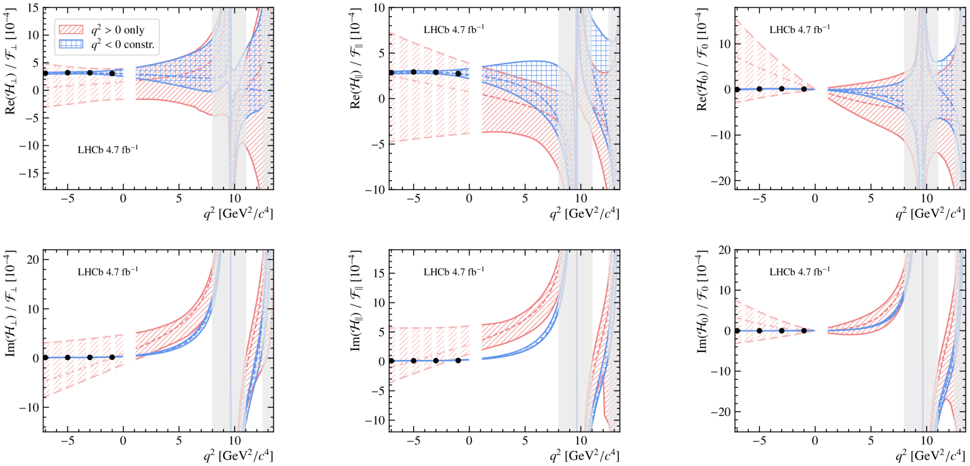
- Data slightly pulls down the ratios $\frac{\mathcal{F}_\perp}{\mathcal{F}_0}$ and $\frac{\mathcal{F}_\parallel}{\mathcal{F}_0}$
  - Apparent for fits without and with $q^2 < 0$ constraints



Non-local FFs, $\mathcal{H}_\lambda$

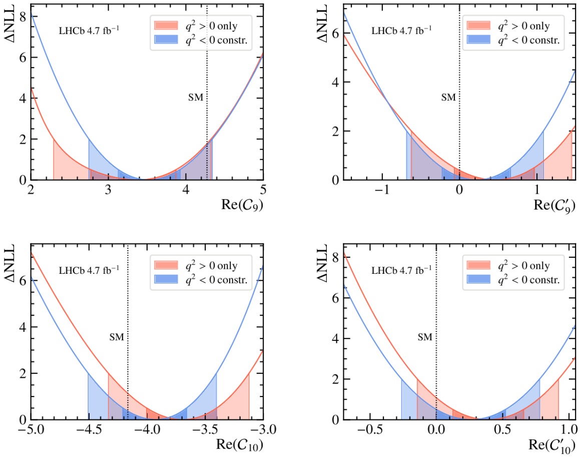
[arXiv:2312.09102]
[arXiv:2312.09115]

- In general good agreement between fits without and with $q^2 < 0$ constraints
  - Slight discrepancy in the imaginary parts



Wilson coefficients

1D profiles:

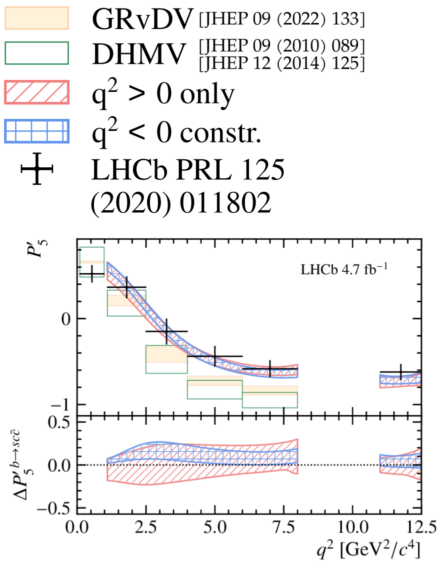


WC	deviation from SM	
	$q^2 > 0$ only	$q^2 < 0$ constraint
C_9	$1.9\,\sigma$	$1.8\,\sigma$
C_{10}	$1.5\,\sigma$	$0.9\,\sigma$
C_9'	$0.9\,\sigma$	$0.5\,\sigma$
C_{10}'	$1.5\,\sigma$	$1.0\,\sigma$

For all 4 WCs the best fit point is 1.3 (1.4) σ from the SM without (with) $q^2 < 0$ constraint

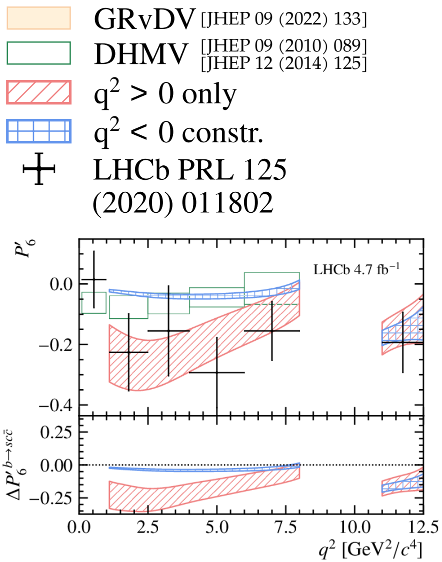
Comparison with binned results

- In general good agreement with binned results
  - Minimal difference between fit with or without $q^2 < 0$ constraint
- Calculate effect of non-local contribution to observables, i.e. $\Delta P_5'^{b\to sc\bar{c}}$
  - The shifts are small



- In general good agreement with binned results
  - Minimal difference between fit with or without $q^2 < 0$ constraint
- Calculate effect of non-local contribution to observables, i.e. $\Delta P_5'^{b\to sc\bar{c}}$
  - The shifts are small
- Slight discrepancy in P_6' (or S_7)
  - Driven by the imaginary part of the non-local $\mathcal{H}_\lambda(q^2)$

$$S_7 \sim \Im[\mathcal{A}_0^L \mathcal{A}_\parallel^{L*} - \mathcal{A}_0^R \mathcal{A}_\parallel^{R*}]$$



Conclusion

First unbinned amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$

- Complementary information to the previous binned analysis
  - Determination from data of non-local contribution with and without theory constraint
- Even with freedom of non-local component the data prefers a shift in C_9 from the SM

Much data in hand, more analysis possibilities to study $B^0 \to K^{*0}\mu^+\mu^-$:

- Binned 'model-independent' analysis with full Run 1+2 data [JHEP 12 (2021) 085]
- Unbinned analysis - fit WCs with a model including resonances [EPJC 80 (2020) 12,1095], [EPJC 78 (2018) 6,453]
- Ansatz analysis - fit the q^2-dependent amplitudes [JHEP 06 (2015) 084]

More data to be collected:

- $7\,\text{fb}^{-1}$ in 2024 $\to$ double the data set!

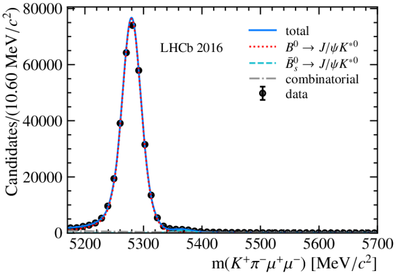
BACKUP

Branching fraction

[arXiv:2312.09102]
[arXiv:2312.09115]

Angular analysis alone can only tell you the relative sizes of the amplitudes (WCs) $\rightarrow$ Fit the BF to set the scale

- Note: BF is measured relative to $B^0 \rightarrow J/\psi K^+\pi^-$, with $0.795 < m_{K\pi} < 0.995\,\mathrm{GeV}$, not $B^0 \rightarrow J/\psi K^{*0}$
  - $B^0 \rightarrow J/\psi K^{*0}$ included significant S-wave and $J/\psi \pi^-$ exotic contributions
  - Estimate fraction of $B^0 \rightarrow J/\psi K^+\pi^-$ in the $100\,\mathrm{MeV}$ window from Belle analysis [PRD 90 (2014) 112009]



$$f_{\pm 100\,\mathrm{MeV}}(B^0 \rightarrow J/\psi K^+\pi^-) = 0.644 \pm 0.010$$

The systematic from $f_{\pm 100\,\mathrm{MeV}}(B^0 \rightarrow J/\psi K^+\pi^-)$ can be reduced with new measurements

2D profiles

[arXiv:2312.09102]
[arXiv:2312.09115]