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

Quirks in Quark Flavour Physics 2024

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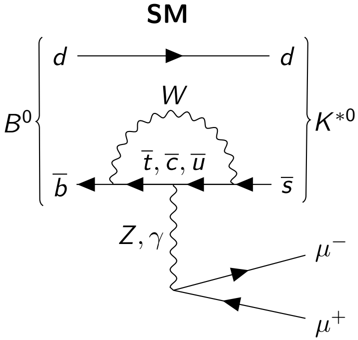
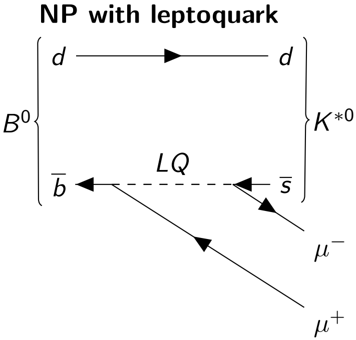
June 18, 2024

Motivation

- The decay $B^0 \to K^{*0}\mu^+\mu^-$ requires a $b \to s$ Flavour Changing Neutral Current, thus is suppressed in the SM.
- Due to the SM suppression and the coupling to 3rd generation, this decay is highly sensitive to New Physics (NP).
- These processes are sensitive to contributions towards $\mathcal{O}(10)$TeV, which is inaccessible by current LHC direct searches.

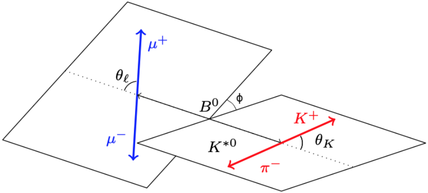




- Latest published binned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ at LHCb shows discrepancies with respect to the SM [PRL 125.011802 (2020)].

Angular analysis

- The decay rate of $B^0 \to K^{*0}\mu^+\mu^-$, where $K^{*0} \to K^+\pi^-$, is described by the three angles θ_l, θ_K and ϕ and the invariant mass of the dimuon system squared, $q^2 = m^2_{\mu^+\mu^-}$.



- Differential decay rate is given by [JHEP 01 (2009) 019]

$$\frac{\mathrm{d}^4\Gamma[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}\cos\theta_l \mathrm{d}\cos\theta_K \mathrm{d}\phi \mathrm{d}q^2} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\Omega),$$

where

- J_i are q^2-dependent angular observables. These are written in terms of bilinear combinations of the complex decay amplitudes.

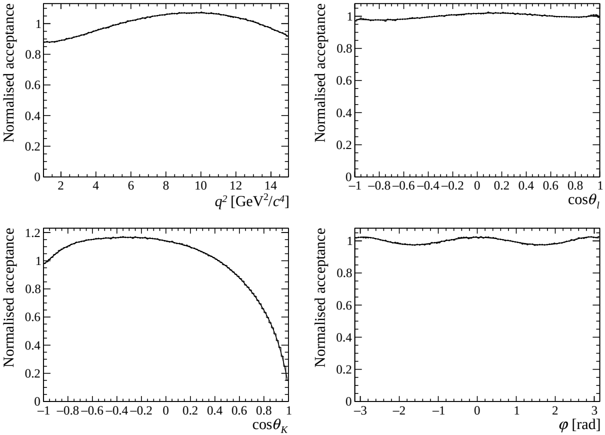
- f_i are combinations of spherical harmonics involving θ_l, θ_K and ϕ.

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

- Binned analysis
  - Binned angular observables
  - Run 1 + 2016 shows discrepanceis wrt the SM [PRL 125.011802 (2020)]
  - Upcoming Run 1 + Run 2 analysis in progress
  - See **Eluned's talk** for more information
- Ansatz analysis
  - Unbinned analysis in q^2, using Legendre polynomials to describe the amplitudes
  - Upcoming Run 1 + Run 2 analysis in progress
  - **This talk**
- z-expansion analysis
  - Recently published [PRD.109.052009] [PRL.132.131801] analysis unbinned in q^2, using the same dataset as the Run 1 + 2016 binned analysis
  - Fit $C_9^{(\prime)}$, $C_{10}^{(\prime)}$, polynomials are used to describe the non-local contributions
  - **This talk**
- Dispersion model analysis
  - Analysis unbinned in q^2, using the full Run 1 + Run 2 datasets [arXiv:2405.17347]
  - Fit $C_9^{(\prime)}$, $C_{10}^{(\prime)}$, C_9^{τ}, non-local phases and magnitudes
  - **Eluned's talk**

Commonalities

- Selections, for example
  - Particle identification selections
  - Veto peaking backgrounds
  - Train BDTs to remove combinatorial background
- Acceptance



Amplitude ansatz

- Perform an unbinned measurement of the q^2-dependent amplitudes which is as model independent as possible
- Method is described in JHEP06(2015)084
- Apply the ansatz

$$\mathcal{A} = \sum_i \alpha_i L_i(q^2) \quad (1)$$

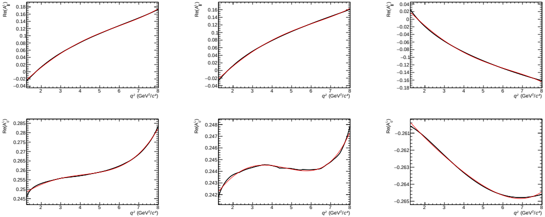
  to the amplitudes, where L_i are Legendre polynomials of order i
- Use four parameters for the amplitudes and fit in the $1.1 < q^2 < 8$ GeV$^2/c^4$ region
- Due to symmetries in the PDF, define which amplitude basis to work in
- Work in the basis where

$$Im(\mathcal{A}_\perp^R) = Im(\mathcal{A}_0^L) = Re(\mathcal{A}_0^R) = Im(\mathcal{A}_0^R) = 0$$

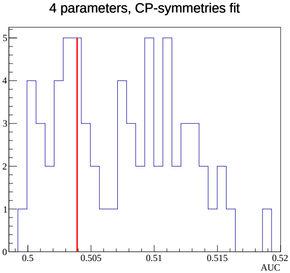
- Fit m_B, $\cos\theta_\ell$, $\cos\theta_K$, ϕ and q^2
- Integrate over $m_{K\pi}$

Amplitude ansatz

- The ansatz used for the amplitudes can be described by a variety of models

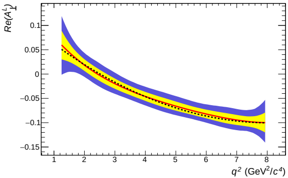


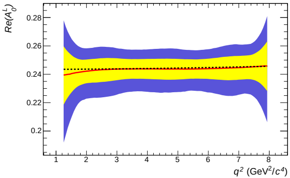
- It is also validated via goodness-of-fits to the data



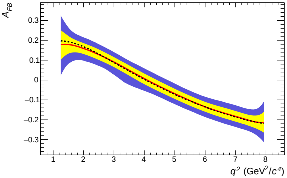
Amplitude ansatz - pseudoexperiment studies

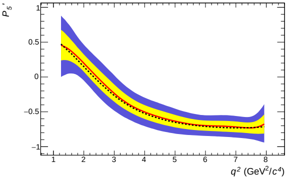
- From amplitude components (signal fit parameters) compute the q^2-dependent amplitudes $\mathcal{A} = \sum_i \alpha_i L_i(q^{2'})$





- These can be used to compute the observables

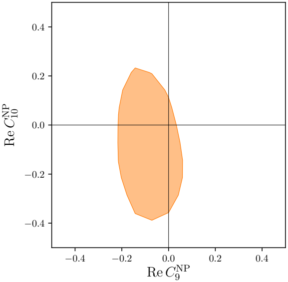




Black = true value, red = median, yellow and blue = 1σ and 2σ bands.

Applications of the ansatz results

- Aim to present amplitude components with uncertainties and correlations.
- This would allow one to generate pseudoexperiments and fit that pseudoexperiment with any choice of model
- **A model-independent parameterisation of the LHCb dataset which can be used to generate synthetic datasets and fit back with any choice of model!**
- e.g. fit the Wilson coefficients to a pseudoexperiment by using flavio.



z-expansion

- Standard Model description of local amplitudes
  - Wilson coefficients

  - Form factors
- Parametric form (polynomials) used to describe the non-local contributions

- Amplitude is written as

$$\mathcal{A}_\lambda^{L,R} = N_\lambda([(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}[(C_7 \pm C_7')\mathcal{F}_T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)]) \quad (2)$$

where the z-expansion [JHEP09(2022)133] is used for the non-local contributions $\mathcal{H}_\lambda(q^2)$, i.e.

$$\mathcal{H}_\lambda(q^2) = \frac{1 - z z_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z_{\psi(2S)}}{z - z_{\psi(2S)}} \phi_\lambda^{-1}(z) \sum_k \alpha_k z^k \quad (3)$$

z-expansion fit details

$$\mathcal{A}_\lambda^{L,R} = N_\lambda([(C_9 \pm C_9') \mp (C_{10} \pm C_{10}')]\mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2}[(C_7 \pm C_7')\mathcal{F}_T(q^2) - 16\pi^2 \frac{M_B}{m_b}\mathcal{H}_\lambda(q^2)])$$

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- C_9, C_9', C_{10}, C_{10}' float in the fit
- C_7 and C_7' are fixed to the SM
- Form factors $\mathcal{F}$ are constrained to theory predictions from LCSR+Lattice [JHEP01(2019)150] [PoSLATTICE2014 (2015)372]

z-expansion fit details

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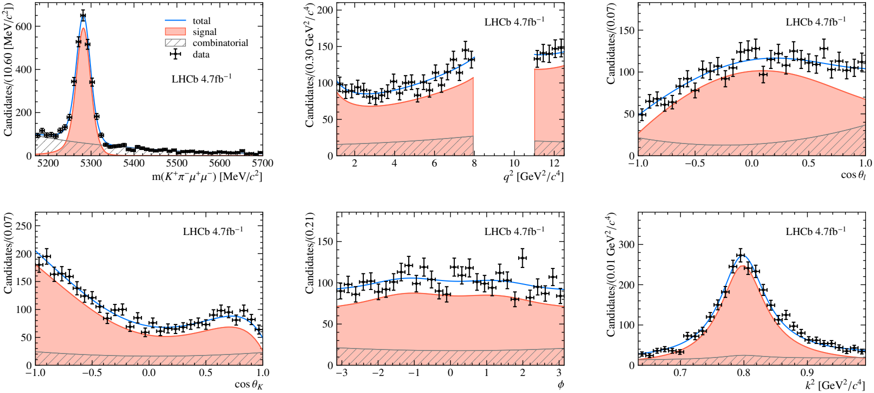
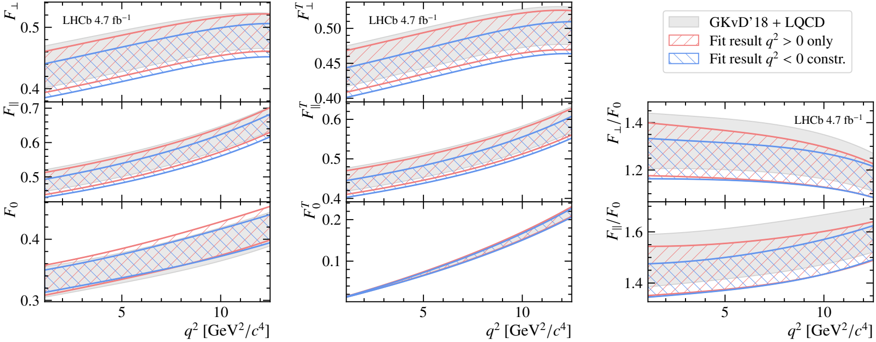
- Two fit configurations:
  - With $q^2 < 0$ predictions using predictions from [JHEP02(2021)088]
  - Without $q^2 < 0$ predictions
- Use experimental inputs to the magnitudes and phases from [PRD.90.112009] [PRD.76.031102] [PRD.88.074026] [PRD.88.052002] [EPJC72,2118(2012)]
- Also include $m_{K\pi} = k^2$ dependence

Fit projections [PRD.109.052009] [PRL.132.131801]

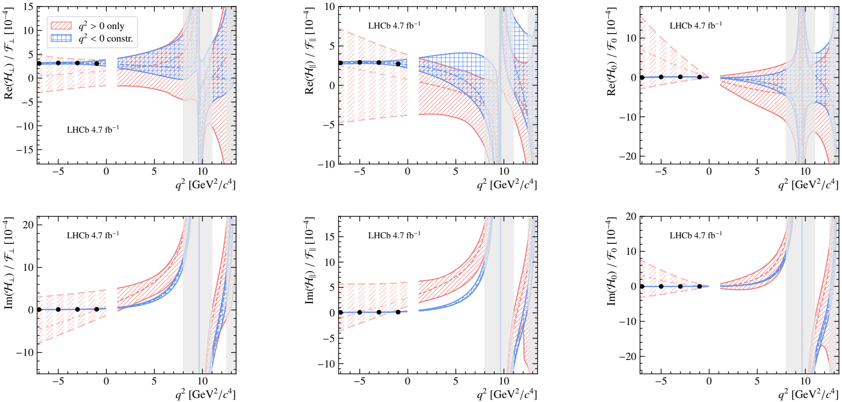


- Results in the two fit configurations are shown (with and without theory constraints)
- As seen on the right, the $\mathcal{F}_{\parallel,\perp}/\mathcal{F}_0$ ratios slightly pull at lower values

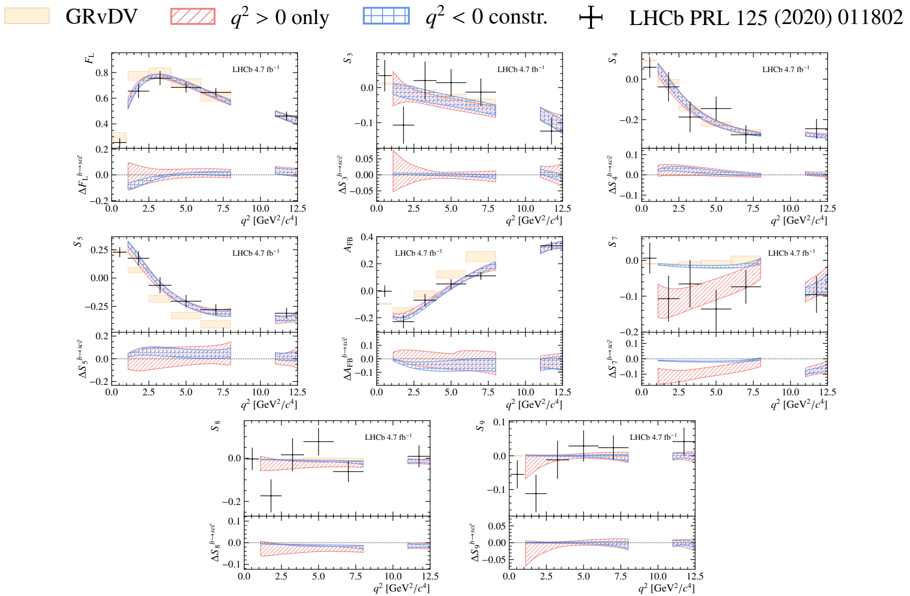


Non-local form factors [PRD.109.052009] [PRL.132.131801]

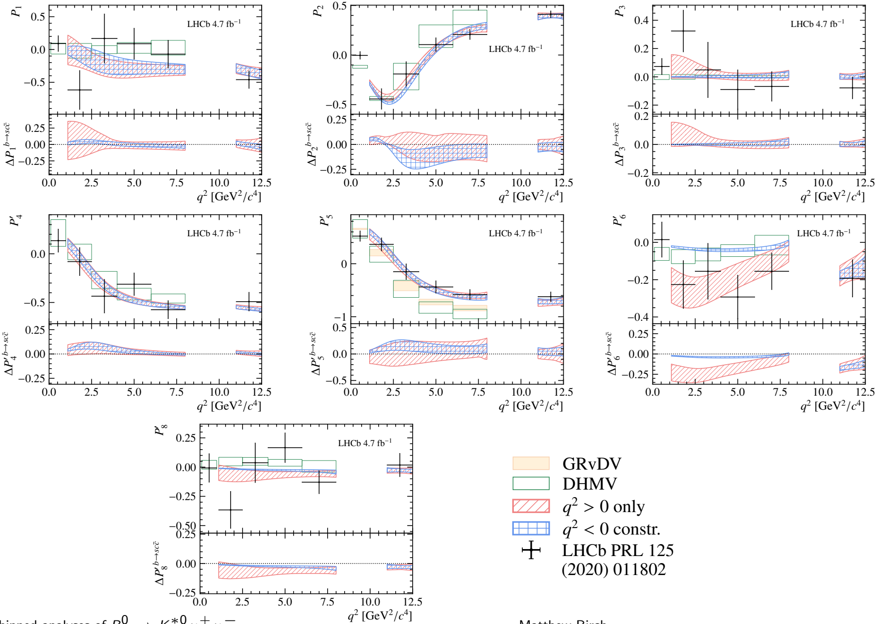
- In general, good agreement between the two fit configurations
- Some discrepancies in the imaginary parts, e.g. in $Im(\mathcal{H}_{\parallel})$



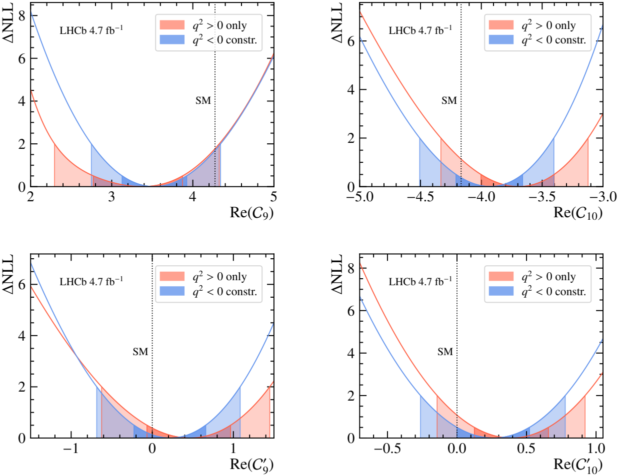
Angular observables - S basis [PRD.109.052009] [PRL.132.131801]



Angular observables - P basis [PRD.109.052009] [PRL.132.131801]



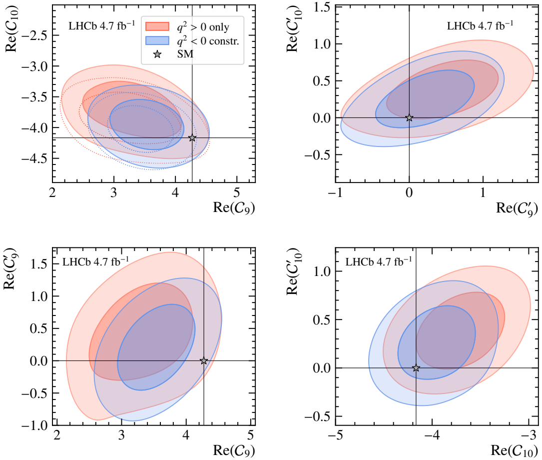
- 1D profiles:



- Look at C_9 and C_{10} alone - compatibility wrt the SM is $1.8 - 1.9\sigma$

Wilson coefficients [PRD.109.052009] [PRL.132.131801]

- 2D profiles:



- Global compatibility wrt the SM has been computed and is at the level of $1.3 - 1.4\sigma$

Summary

- Upcoming binned angular analysis
  - More data than previous analysis, now fitting both the CP-symmetries and the CP-asymmetries.
  - Run 1 + Run 2 analysis is in collaboration-wide review
- Ansatz analysis
  - Unbinned analysis in q^2, using Legendre polynomials to describe the amplitudes
  - Run 1 + Run 2 analysis is in collaboration-wide review
- z-expansion analysis
  - Recently published [PRD.109.052009] [PRL.132.131801] analyses shows shifts of $1.8 - 1.9\sigma$ when considering C_9 only
- Dispersion model analysis
  - Analysis unbinned in q^2, using the full Run 1 + Run 2 datasets [arXiv:2405.17347] presents 2.1σ shift of C_9, and the world's first direct measurement of $C_{9\tau}$
- Last CMS binned analysis of $B^0 \to K^{*0}\mu^+\mu^-$ also presents tensions with the SM
- **Very exciting times ahead!**