Measurements of $b \to s\mu^+\mu^-$ transitions at LHCb

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On behalf of the LHCb collaboration

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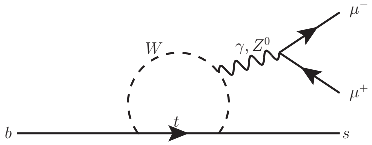
BEACH - Charleston, South Carolina

$b \to s\mu^+\mu^-$ decays as a probe for New Physics

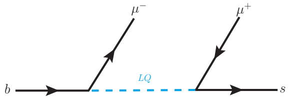
SM:



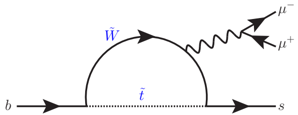
- $b \to s\mu^+\mu^-$ transitions occur via **FCNC**
  $\to$ **cannot occur at tree level in SM**

- New particles:
  - ◇ enhance/suppress decay rates
  - ◇ modify angular distribution of final state particles
  - ◇ introduce new sources of CP violation

Possible NP contributions:



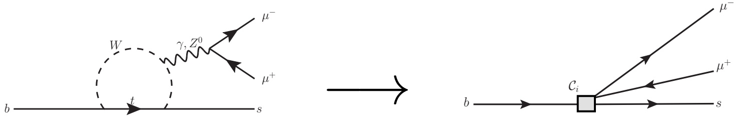
Leptoquarks (tree-level)



Supersymmetry (loop-level)

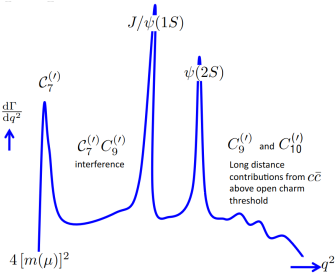
Heavy Quark Effective Field Theory (HQEFT) for $b \to s\mu^+\mu^-$ decays

- Search for BSM physics in a **model independent** way
- Integrate out interesting heavy physics (at m_W):



Full Theory

Effective Theory

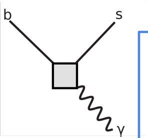


- Perform measurements in different $q^2 \equiv m^2_{\mu\mu}$ regions to probe different Wilson Coefficients

Effective Hamiltonian

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i^{(\prime)} \mathcal{O}_i^{(\prime)}$$

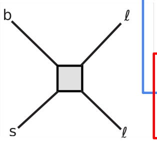
- Wilson Coefficients (Effective Coupling)
- Local operators



$\mathcal{O}_7 \sim m_b \, (\bar{s}_L \sigma_{\mu\nu} b_R) \, F_{\mu\nu}$

$B \to K^{*0}\gamma$

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



$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$ $\longrightarrow$ vector-like contribution

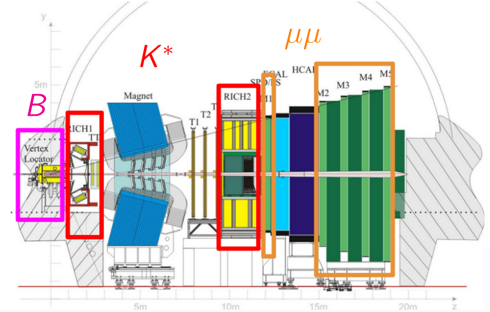
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$

$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$

$B \to \mu^+\mu^-$

b-hadron physics at LHCb

Optimised for b-hadron physics
Forward spectrometer (where most $b\bar{b}$ is produced)

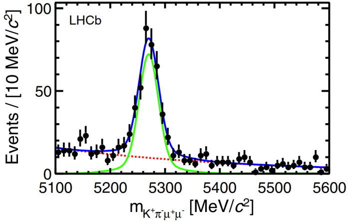


- Vertex Locator
  - ◇ Separate b and c hadron production and decay vertices at high precision
- Ring Imaging Cherenkov (RICH) Detectors
  - ◇ PID of K, p, π
  - ◇ High K PID efficiency: $\sim 95\%$
  - ◇ Low hadron mis-ID: 5% ($\pi \to K$)
- Muon System
  - ◇ High μ PID efficiency: $\sim 97\%$
  - ◇ Low hadron mis-ID: $1 - 3\%$ ($\pi \to \mu$)

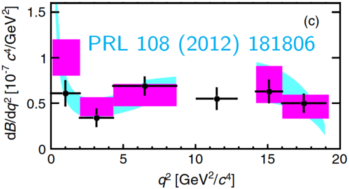
JINST 3 (2008) S08005
International Journal of Modern Physics A Vol. 30, No. 7 (2015) 1530022

Deviations from SM in $b \to s\mu^+\mu^-$ decays at LHCb

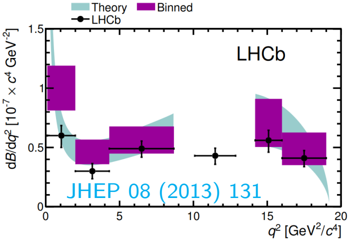
$B \to K^*\mu\mu$ observed at LHCb with first data (2010)



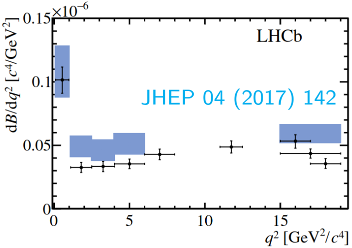
Soon after (2012) BF and angular analysis



2013



2017



$\rightarrow$ Many years of hard work to understand this channel

Deviations from SM in $b \to s\mu^+\mu^-$ decays at LHCb

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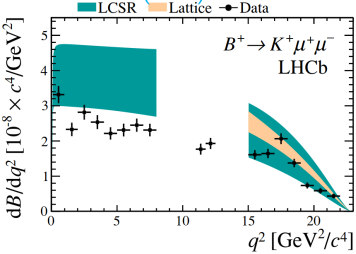

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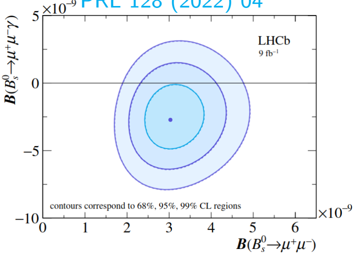
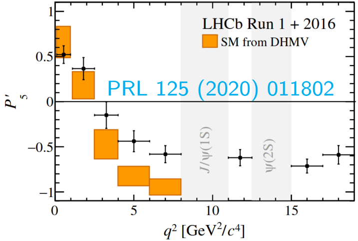
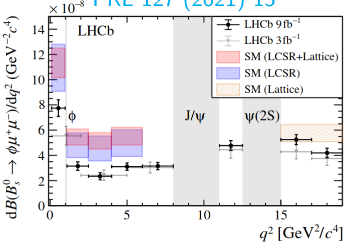




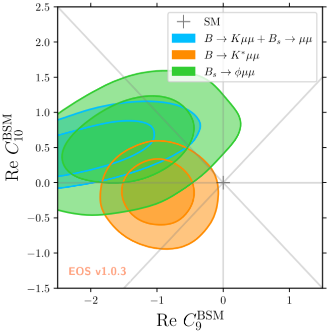
PRL 127 (2021) 15



Deviations from SM in $b \to s\mu^+\mu^-$ decays at LHCb

global fit of WCs (binned analyses):

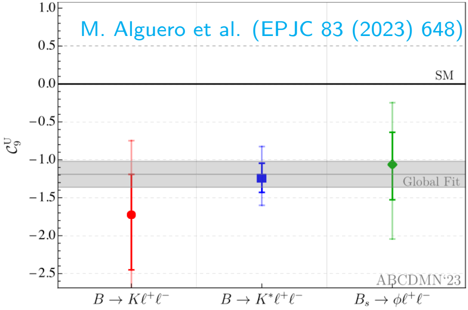
N. Gubernari et al. JHEP 09 (2022) 133



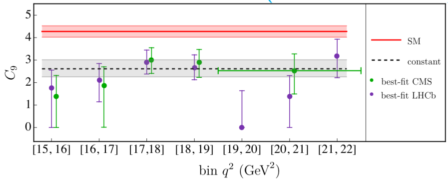
- Measurements deviate from the SM at the level of $\sim 3\sigma$
- NP contribution to a **single WC C_9** is sufficient to explain the tensions between theory and experiment
- C_9 is the effective $b \to s\ell\ell$ vector coupling (C_{10} is the axial vector coupling)

Global Fits of C_9

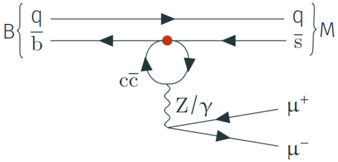
Fit for C_9 (No LFV), assuming SM for other WCs:



M. Bordone et al. (arXiv: 2401.18007)



Deviation due to NP in long-distance charm loop?



- $C_9^{eff} = C_9^{SM} + C_9^{c\bar{c}}(q^2) + C_9^{NP}$
- $C_9^{c\bar{c}}(q^2)$ requires theory input (A. Khodjamirian et al. JHEP 09 (2010) 089, N. Gubernari et al. JHEP 02 (2021) 088, N. Gubernari et al. JHEP 09 (2022) 133)

BSM physics would appear as a shift in the Wilson Coefficients
→ **diluted** by long-distance contributions

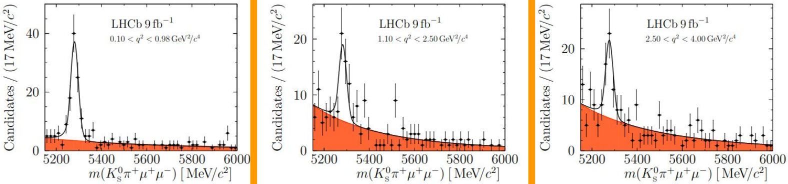
Different Types of Analyses

	Binned Fit	**Amplitude Analysis**	**Z-Expansion**	**Dispersion Relation**
Measurable Quantities	Binned angular observables (e.g. P_5', A_{FB})	$A^{L,R}(q^2)$	$C_9^{(\prime)}$, $C_{10}^{(\prime)}$, non-local polynomial	$C_9^{(\prime)}$, $C_{10}^{(\prime)}$, C_9^{τ}, non-local phases and magnitudes
Type	Binned	Unbinned	Unbinned	Unbinned

Model Independent $\longleftrightarrow$ Model Dependent

Binned Strategy

- Extraction of a limited set of observables in **bins of q^2**



PRL 126 (2021) 161802

Integrate decay rate over each q^2 bin

Measure $\langle P_5' \rangle$

P_5' = function of angular coefficients, designed to reduce the dependency on the hadronic $B \to K$ form-factors at leading order

Explore Additional Strategies

Increase in data and theory developments allow:

- New approach to determine $B \to K^* \mu\mu$ amplitudes as **continuous distributions in q^2**

◇ Able to exploit relations between observables that are inaccessible in binned fits to observables

◇ Able to exploit q^2 shape information via unbinned fits

◇ Eliminates the need to correct theory predictions for q^2 averaging effects

Increases sensitivity to NP!

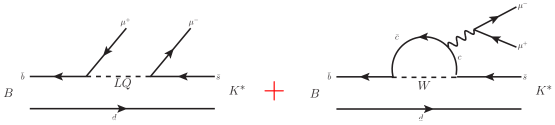
Direct measurements of Wilson Coefficients

- Unbinned fits allow for direct extraction of Wilson Coefficients

An example: $B \to K^* \mu\mu$ (Dispersion Relation)

Short distance contributions
(Sensitive to NP)

non-local contributions
(Resonances and DD rescattering contributions)



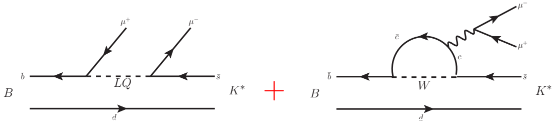
- Able to simultaneously extract C_9, C_9', C_{10} and C_{10}'

Direct measurements of Wilson Coefficients (Form Factors)

An example: $B \to K^* \mu\mu$ (Dispersion Relation)

Short distance contributions
(Sensitive to NP)

non-local contributions
(Resonances and DD rescattering contributions)



- q^2 spectrum has theory uncertainties both **local** and **non-local** contributions:

  Local:
  - ◇ Form-factors well described by:
    Lattice QCD (Phys. Rev. D 107 (2023) 014510, Phys. Rev. D 93, 025026 (2016))
    Light Cone Sum rules (JHEP 01 (2019) 150)

  Non-Local:
  - ◇ Far from resonances: estimations are made using perturbative bounds (Nucl.Phys.B612:25-58,2001, JHEP 1009 (2010) 089, JHEP 08 (2016) 098)

$B \to K^{*}\mu\mu$ differential decay rate

$$\frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = f(q^2, C_9^{\text{eff}}, C_9^{\prime}, C_{10}, C_{10}^{\prime}, F_i(q^2))$$

$$\Longrightarrow \text{Final fit model} \sim \mathcal{R}(q^2) \otimes \epsilon(q^2, \cos\theta_\ell, \cos\theta_k, \phi) \frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}}$$

- Local Form Factors
- Wilson Coefficients
- Resolution function
- Efficiency function

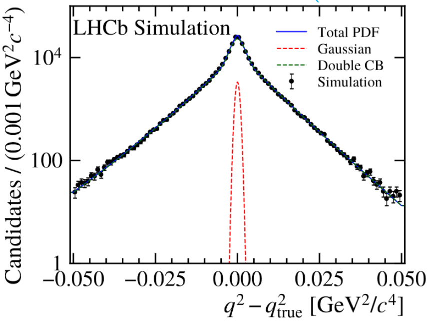
$B \to K^*\mu\mu$ differential decay rate

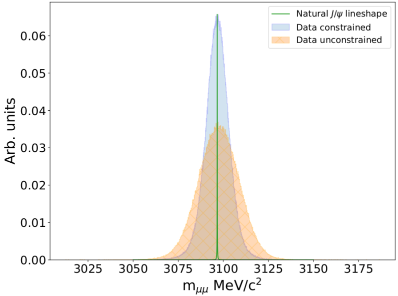
$$\frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = f(q^2, C_9^{\rm eff}, C_9^{'}, C_{10}, C_{10}^{'}, F_i(q^2))$$

- Form Factors
- Wilson Coefficients

$\Longrightarrow$ Final fit model $\sim \mathcal{R}(q^2) \otimes \epsilon(q^2, \cos\theta_\ell, \cos\theta_k, \phi) \frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}}$

LHCb-PAPER-2024-011 (arXiv: 2405.17347)





$\mathcal{R}(q^2)$ to account for smearing of reco. q^2 w.r.t. q^2_{true}

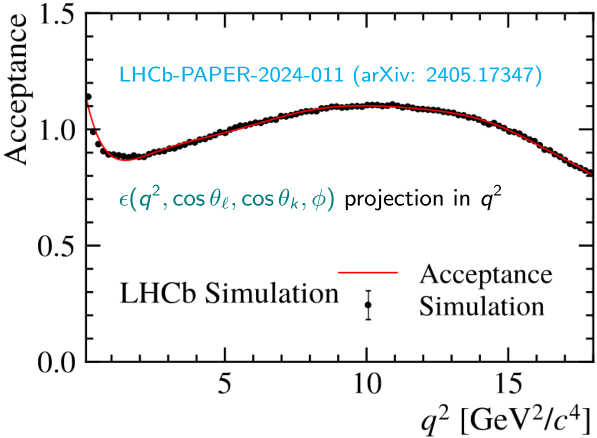
Improve mass resolution by performing a kinematic fit with $m_{PDG}(B)$ as a constraint

$B \to K^*\mu\mu$ differential decay rate

$$\frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = f(q^2, C_9^{\text{eff}}, C_9', C_{10}, C_{10}', F_i(q^2))$$

- Form Factors
- Wilson Coefficients

$$\Longrightarrow \text{Final fit model} \sim \mathcal{R}(q^2) \otimes \underline{\epsilon(q^2, \cos\theta_\ell, \cos\theta_k, \phi)} \frac{d\Gamma}{dq^2 d\vec{\Omega} dm^2_{K\pi}}$$



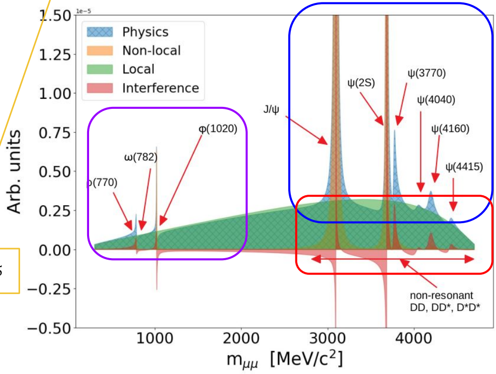
Structure of $C_9^{\mu,\text{eff}}$ in $B \to K^*\mu\mu$ differential decay rate

e.g. Cornella et al., EPJC 80 (2020) 12. 1095

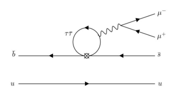
$$C_9^{\mu,\text{eff}}(q^2) = C_9^{\mu} + Y_{c\bar{c}}^{(0)} + \Delta Y_{c\bar{c}}^{1\text{P}}(q^2) + \Delta Y_{D\bar{D}}^{2\text{P}}(q^2) + Y_{\text{light}}^{1\text{P}}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

Short distance ~ 4.23 (SM)

≈-0.10 ± 0.05



Dimuon mass spectrum courtesy of Lakshan Ram Madhan Mohan



Fit for C_9^{τ}

$R(D^{0(*)})$ hints that $b \to s\ell\ell$ tensions are potentially due to tau loop contribution
PRL 131 (2023) 111802

Needs unbinned approach to probe!

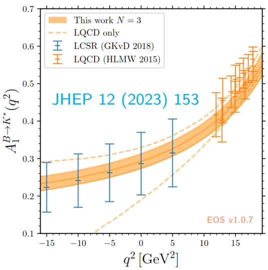
- Rely on once-subtracted dispersion relation that includes $D\bar{D} \to \mu\mu$ and $\tau\tau \to \mu\mu$ amplitudes
- $Y_{c\bar{c}}^{(0)}$ subtraction term to ensure convergence at large q^2

Variants of unbinned fits $B \to K^*\mu\mu$

Analysis performed using **z-expansion and dispersion relation**

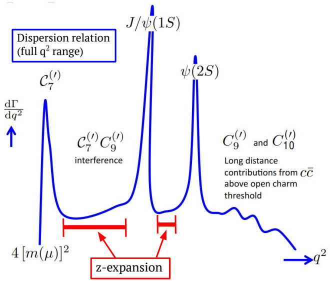
Similarities

- Standard experimental treatment (e.g. acceptance correction, background reduction using ML and cuts/selections, etc.)
- Local form factors (well described by lattice QCD and LCSR)



Differences

- Modelling of the non-local contributions
- q^2 range
- Dataset
  - Dispersion relation: Full Run 1+2
  - z-expansion: Run 1 + 2016



$B \to K^*\mu\mu$: z-expansion

(based off EPJC 78 (2018) 451, JHEP 02 (2021) 088, JHEP 09 (2022) 133)

$$\mathrm{A}_\lambda^{L,R} = \left\{ N_\lambda \left[(C_9 \pm C_9') \mp (C_{10} \pm C_{10}') \right] \mathcal{F}_\lambda\left(q^2\right) + \frac{2m_b M_B}{q^2} \left[(C_7 \pm C_7') \mathcal{F}_\lambda^T\left(q^2\right) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda\left(q^2\right) \right] \right\}$$

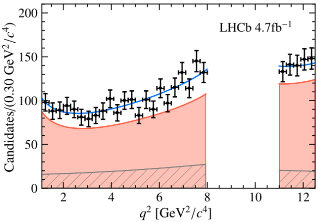
- Form Factors
- Wilson Coefficients
- Non-local hadronic matrix elements ('charm loop')

- Add information to constrain non-local parameters:
  1. External inputs coming from J/ψ and $\psi(2S)$ measurements
  2. Theory points in $q^2 < 0$

     $\rightarrow$ have two configurations: with and without $q^2 < 0$ constraint

$B \to K^*\mu\mu$: Fit Result

z-expansion



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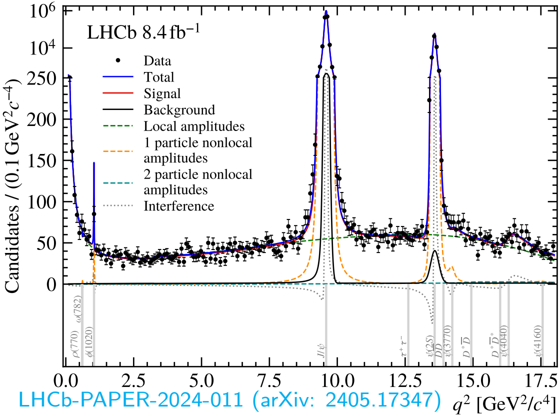
- 6D fit:
  - q^2 (above)
  - $m(K\pi\mu\mu)$
  - k^2
  - 3 decay angles

dispersion relation

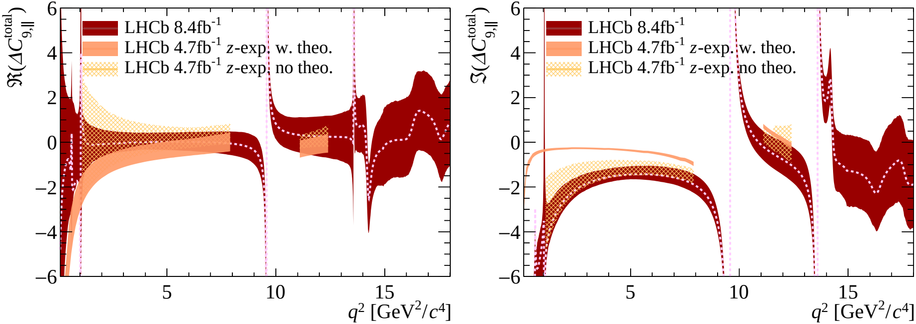


LHCb-PAPER-2024-011 (arXiv: 2405.17347)

- 4D + 1D (fit m_B first) fit:
  - q^2 (above)
  - 3 decay angles

Results: Non-Local

LHCb-PAPER-2024-011 (arXiv: 2405.17347)



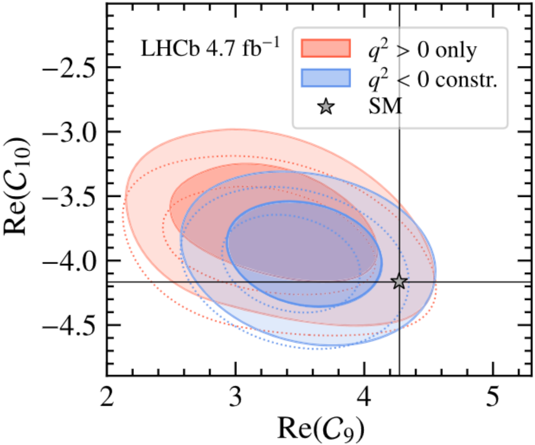
z-expansion:

- Real part (left plot): good agreement between analysis with and without $q^2 < 0$ constraint
- Imaginary part (right plot): some discrepancy between analysis with and without $q^2 < 0$ constraint

Good agreement between the two analyses

Results: 2D profiles of Wilson Coefficients

z-expansion PRL 132 (2024) 131801



$C_9^{\text{w/o constr.}} = 3.34^{+0.53}_{-0.57}$ (1.9σ)

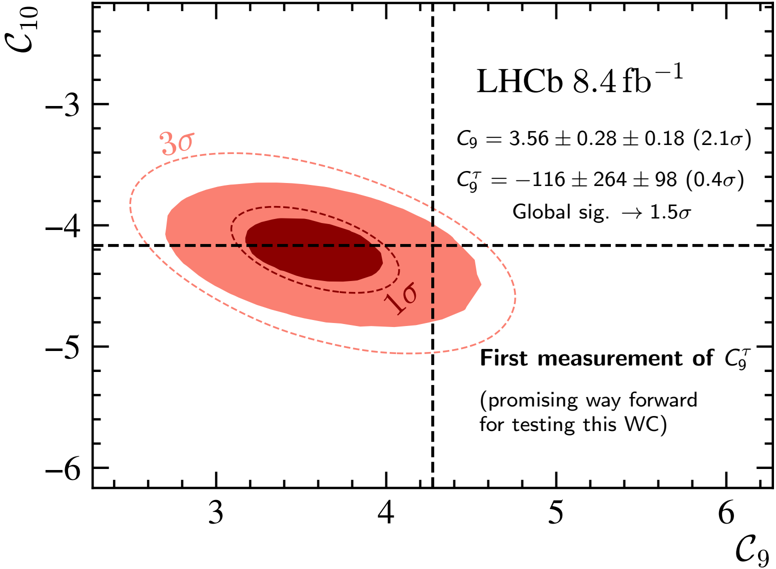
$C_9^{\text{w constr.}} = 3.59^{+0.33}_{-0.46}$ (1.8σ)

Global sig. $\rightarrow$ 1.3 (1.4)σ

- minimal difference between with and without $q^2 < 0$ constraint

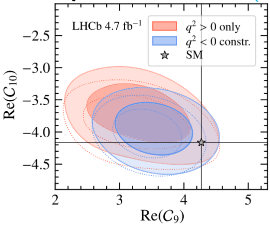
Results: 2D profiles of Wilson Coefficients

dispersion relation LHCb-PAPER-2024-011 (arXiv: 2405.17347)



Results: 2D profiles of Wilson Coefficients

z-expansion PRL 132 (2024) 131801



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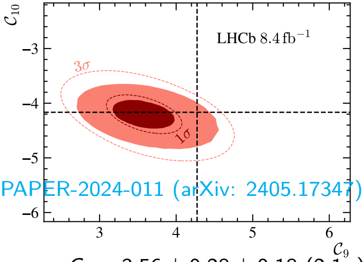
dispersion relation



LHCb-PAPER-2024-011 (arXiv: 2405.17347)

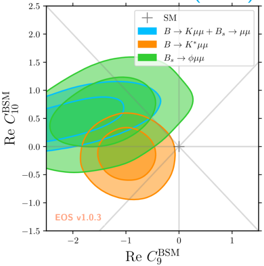
$\mathcal{C}_9 = 3.56 \pm 0.28 \pm 0.18$ (2.1σ)

$\mathcal{C}_9^{\tau} = -116 \pm 264 \pm 98$ (0.4σ)

Global sig. $\rightarrow 1.5\sigma$

global fit (binned data)

N. Gubernari et al. JHEP 09 (2022) 133



Both results consistent with global fit

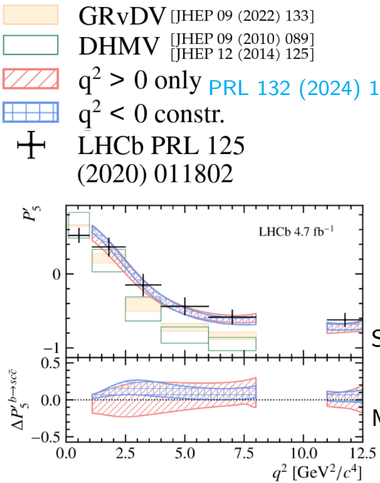
Data prefers a shift in C_9 from the SM

First measurement of $\mathcal{C}_9^{\tau}$

(promising way forward for testing this WC)

Results: Effects of non-local contributions to angular observables P_5'

z-expansion



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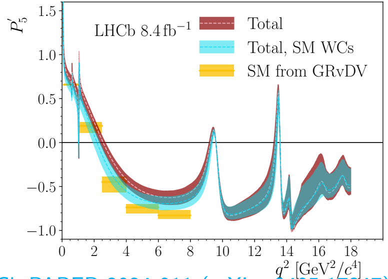
dispersion relation



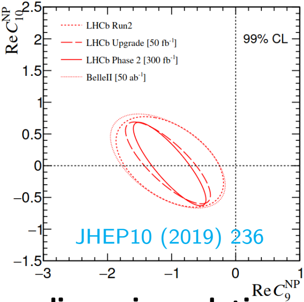
LHCb-PAPER-2024-011 (arXiv: 2405.17347)

Small shifts (similar size to previous analyses) for both analyses

Many more angular observables calculated (See Backup)

Expected Sensitivity at High-Luminosity LHC

z-expansion



within next 10 years, plan to collect **x30** the current dataset

dispersion relation

- Run 4 (starting 2029) $\times 5$ integrated luminosity: $\sim \frac{1}{2}$ current stat. uncertainty
- Run 5 (starting 2035) $\times 30$ integrated luminosity: $\sim \frac{1}{5}$ current stat. uncertainty

Most dominant systematic is the knowledge of $B \to J/\psi K^*$ BF
(sets scale of the decay rate in the LH fit)
$\to$ Need improved measurement of $B \to J/\psi K^*$ BF from Belle II

Summary and Future Prospects

- First unbinned amplitude analyses of $B \to K^* \mu\mu$
  - Results highly compatible between 2 analyses
  - Data prefers a shift in C_9 (~ -0.7) from SM (even with freedom of non-local components)

- Finally we are less dependent on charm loop theory inputs

- Tensions between SM theory and experiment **persist**, independent of recent status of LFU violation

- Continue with the robust approach of binned measurements

  $\to$ However, in order to take advantage of:

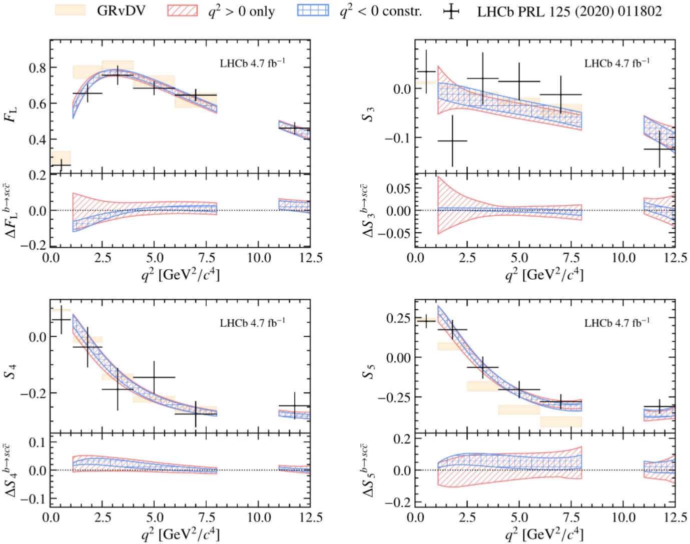
  - the increase in datasets
  - sensitivity to the tau loop (motivated by $R(D^{0(*)})$)

  we employ the **new unbinned approach**

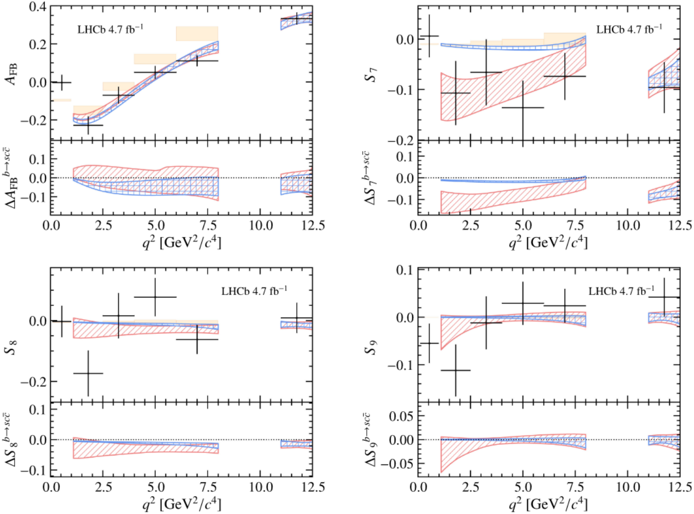
This is just the start!!

Backup

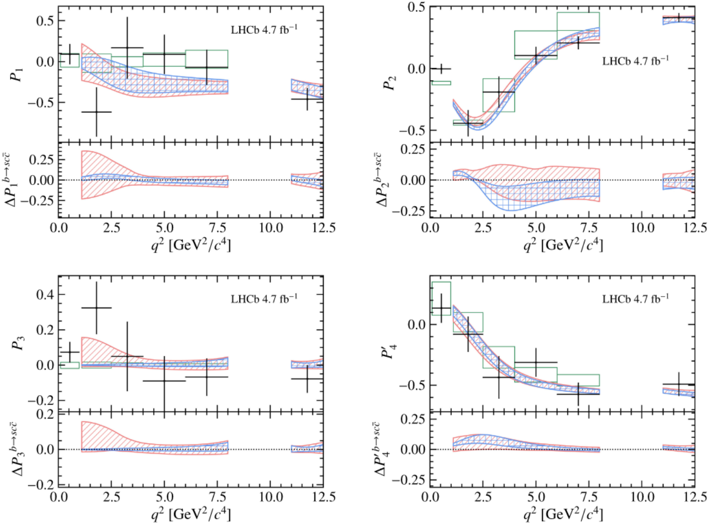
$B \to K^*\mu\mu$: z-expansion
Angular Observables



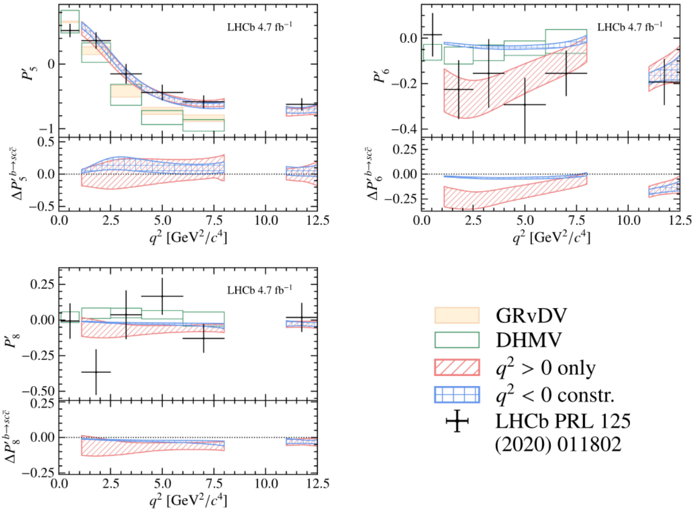
$B \to K^*\mu\mu$: z-expansion
Angular Observables



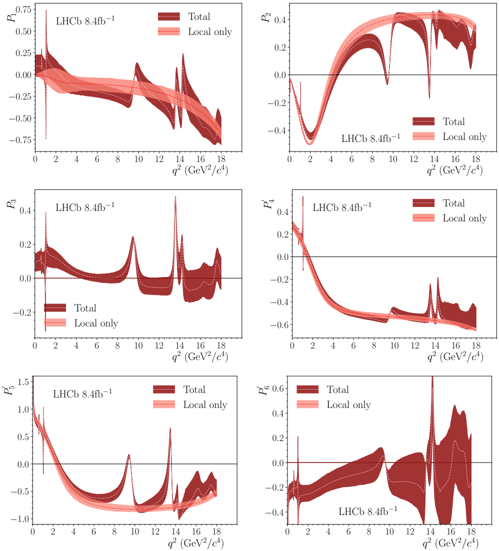
$B \to K^*\mu\mu$: z-expansion
Angular Observables



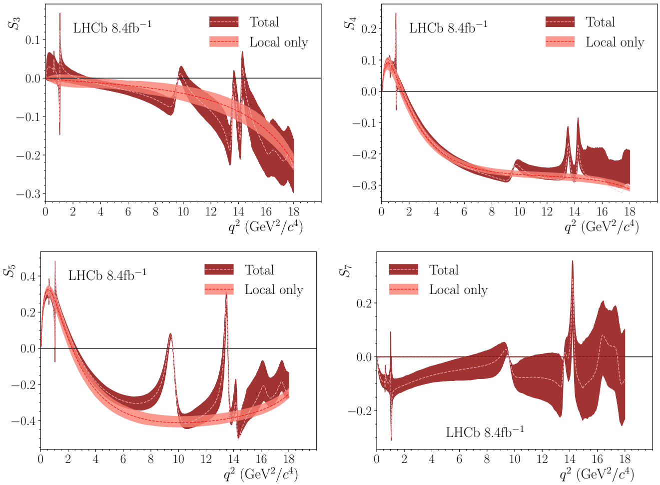
$B \to K^*\mu\mu$: z-expansion
Angular Observables



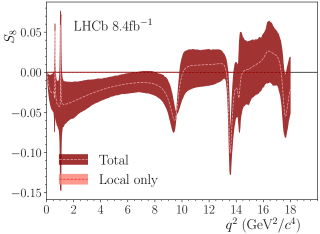
$B \to K^* \mu\mu$: Dispersion Relation Angular Observables

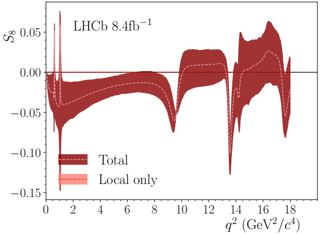


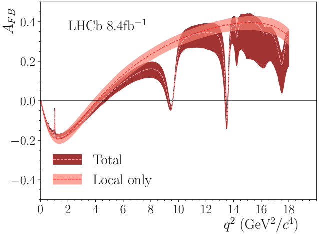
$B \to K^*\mu\mu$: Dispersion Relation Angular Observables

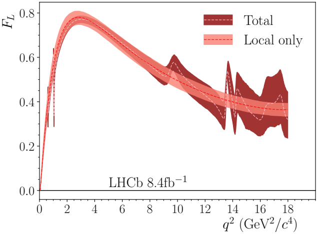


$B \to K^*\mu\mu$: Dispersion Relation Angular Observables

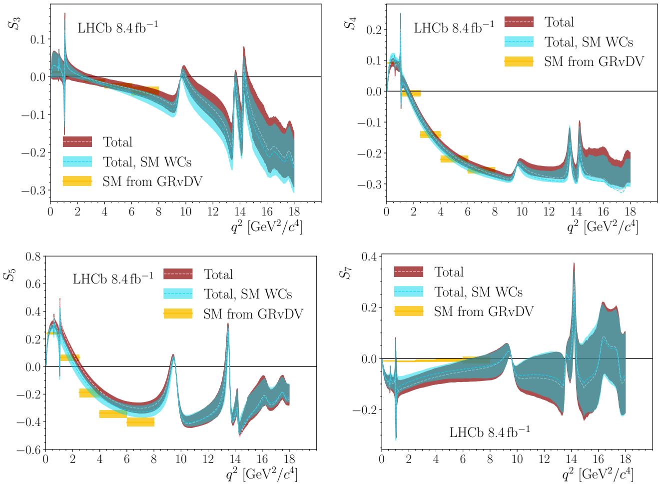








$B \to K^* \mu\mu$: Dispersion Relation Angular Observables



$B \to K^*\mu\mu$: Dispersion Relation Angular Observables