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

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On behalf of the LHCb collaboration

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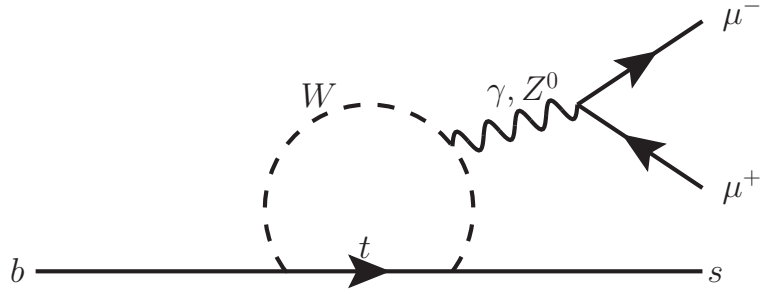
FPCP - Lyon, France

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

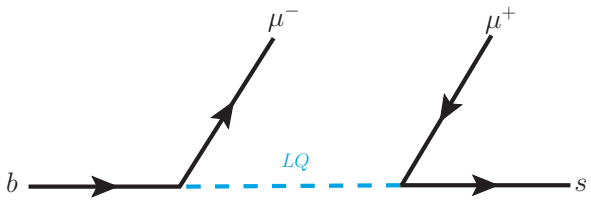
SM:



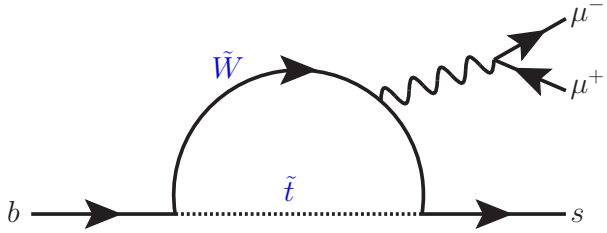
- $b \to s\mu^+\mu^-$ transitions occur via **FCNC** $\to$ **cannot occur at tree level in SM**

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

Possible NP contributions:



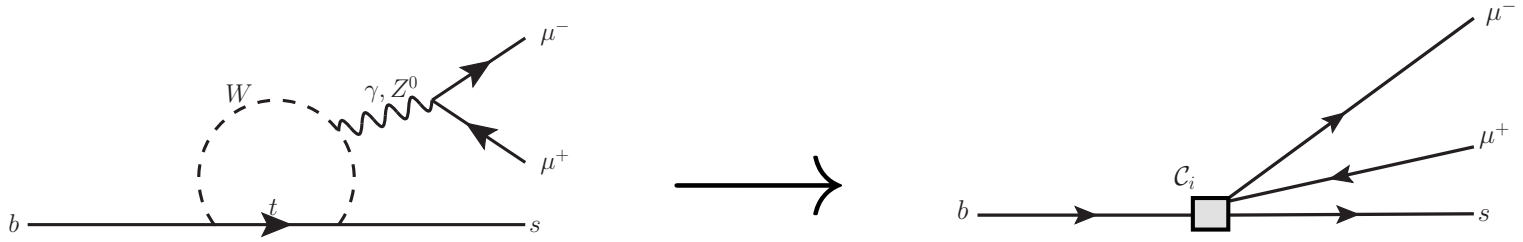
Leptoquarks (tree-level)



Supersymmetry (loop-level)

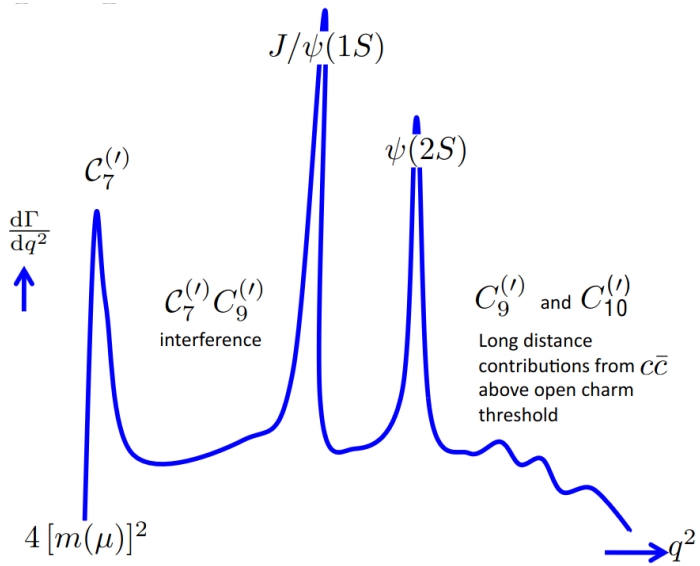
Heavy Quark Effective Field Theory (HQEFT) for $b \to s\mu^+\mu^-$ decays

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



Full Theory

Effective Theory

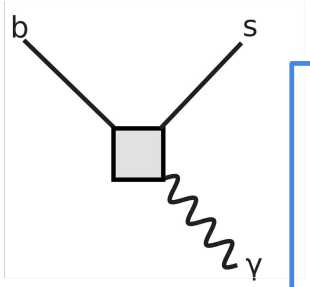


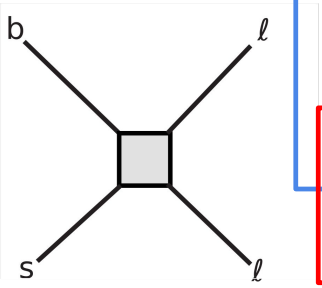
- Perform measurements in different $q^2 \equiv m^2_{\mu\mu}$ regions to probe different Wilson Coefficients

Effective Hamiltonian

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

- Wilson Coefficients (Effective Coupling)
- Local operators





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

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

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

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

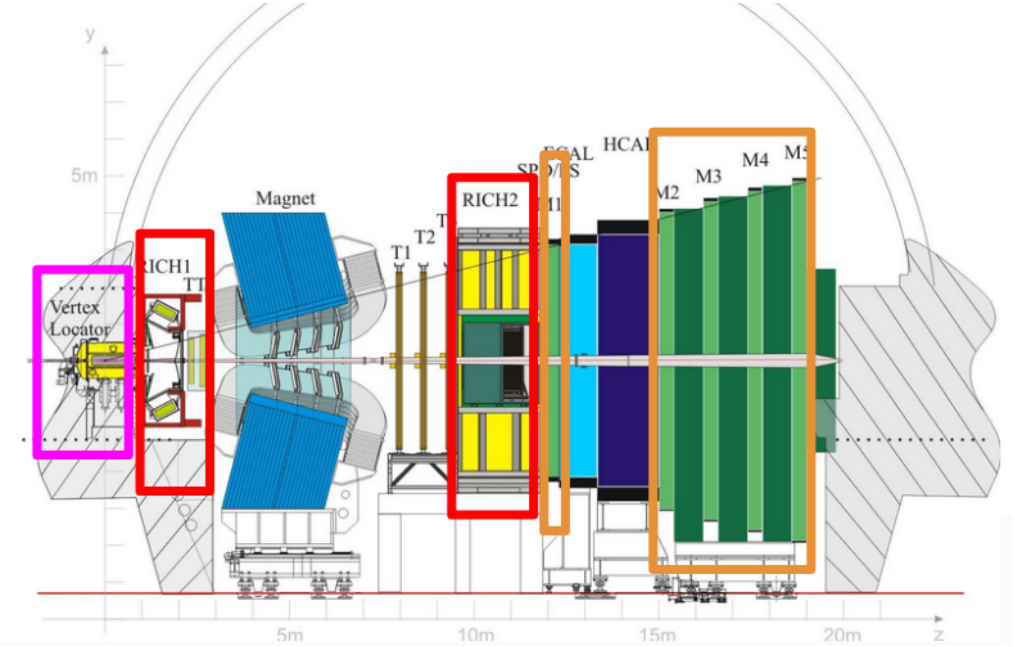
$B \to K^{*0}\gamma$

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

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

b-hadron physics at LHCb

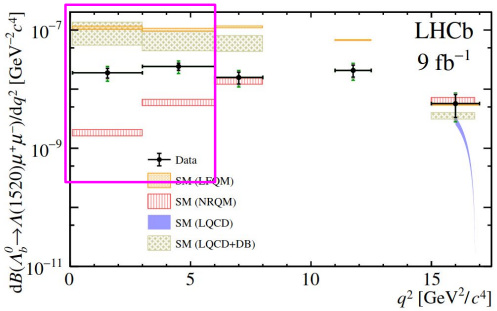
Optimised for b-hadron physics
Forward spectrometer (where most $b\bar{b}$ is produced)



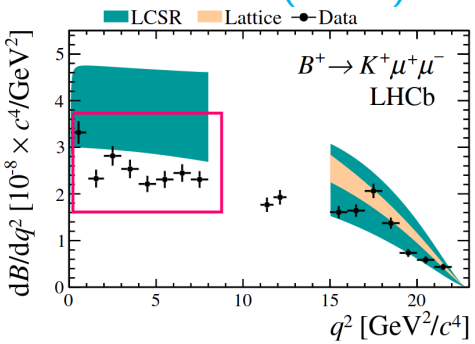
- Vertex Locator
  - Separate b and c hadron production and decay vertices at high precision
- Ring Imaging Cherenkov (RICH) Detectors
  - PID of K, p, π
  - High K PID efficiency: $\sim 95\%$
  - Low hadron mis-ID: 5% ($\pi \to K$)
- Muon System
  - High μ PID efficiency: $\sim 97\%$
  - Low hadron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

Deviations from SM in $b \to s\mu^+\mu^-$ decays at LHCb (Branching Fraction Measurements)

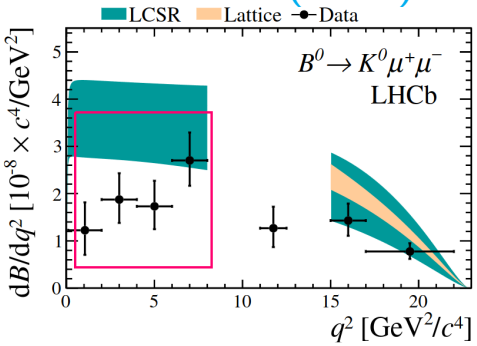
arxiv: 2302.08262



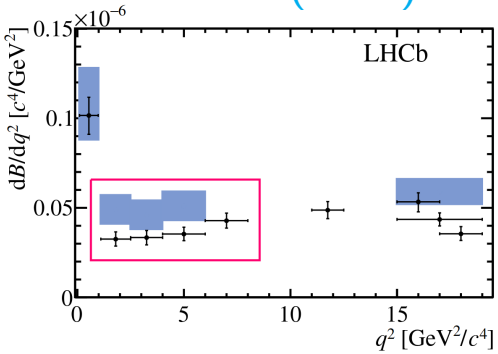
JHEP 06 (2014) 133



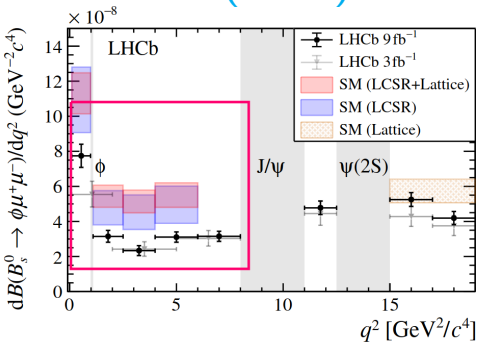
JHEP 06 (2014) 133



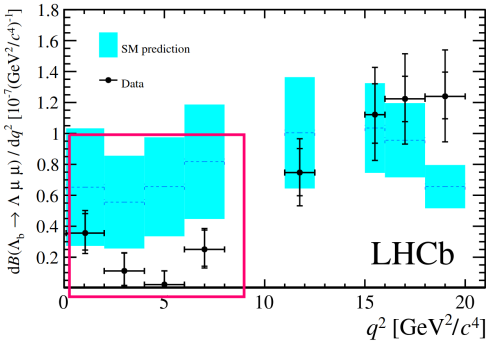
JHEP 04 (2017) 142



JHEP 09 (2018) 145



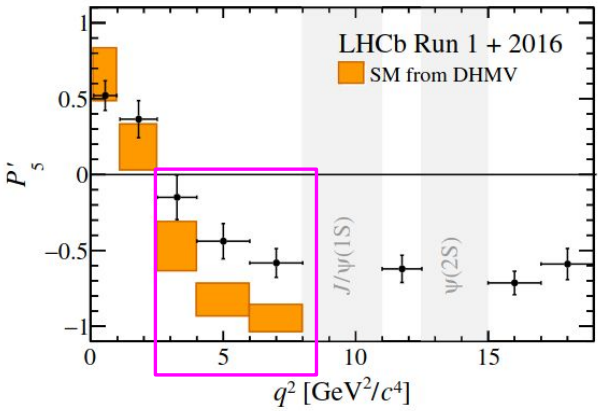
Phys. Lett. B 753 (2016) 424



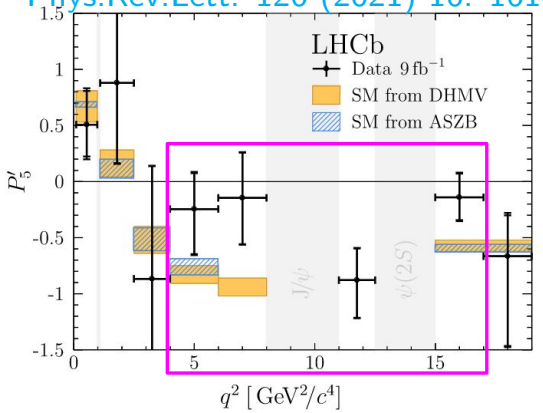
- Measurements **below SM** by 1-3σ levels
- Sizeable hadronic uncertainties ($\sim 20 - 30\%$) in SM calculations
  $\to$ **need for improved theory predictions**

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

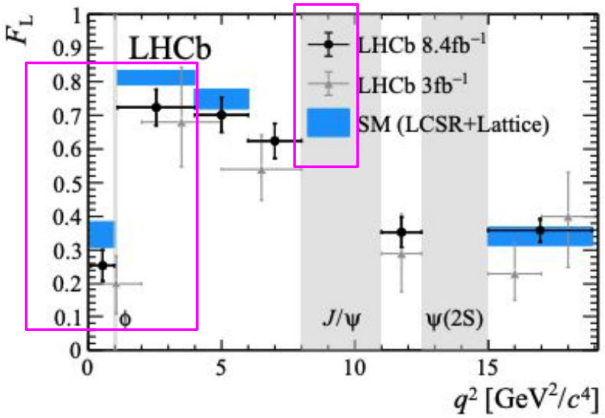
Phys.Rev.Lett. 125(2020) 1,011802



Phys.Rev.Lett. 126 (2021) 16. 161802



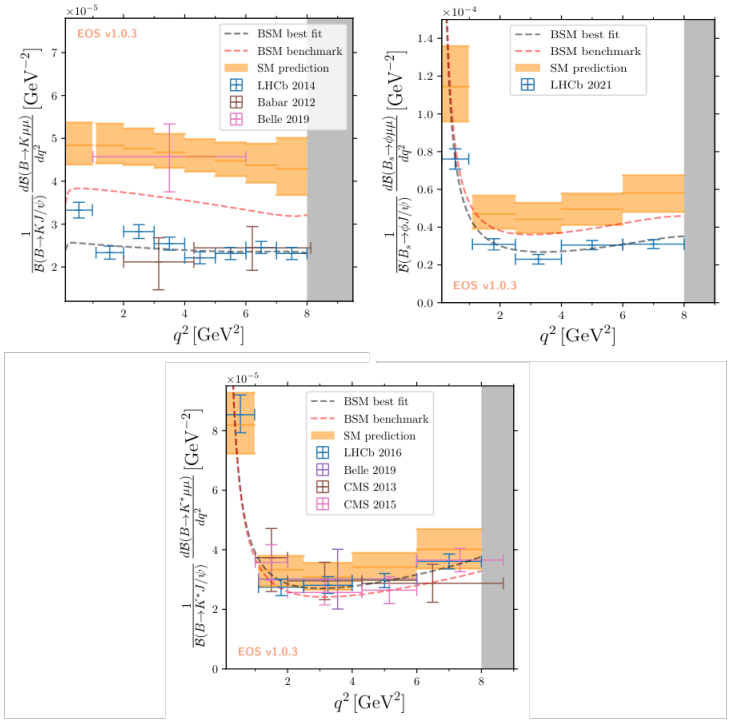
LHCb Coll. JHEP 09 (2015) 179



- Measurements in tension with SM predictions (1-3σ levels)
- Sizeable hadronic uncertainties ($\sim 20 - 30\%$) in SM calculations $\to$ **need for improved theory predictions**

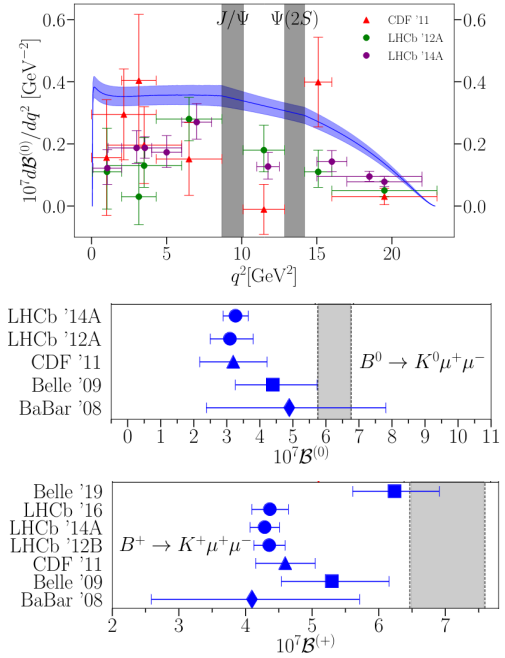
Improved Theory Predictions at Low q^2 (Branching Fraction Measurements)

JHEP 09 (2022) 133



Use of novel parameterisation of non-local QCD form factors

Phys. Rev. D 107 (2023) 014511

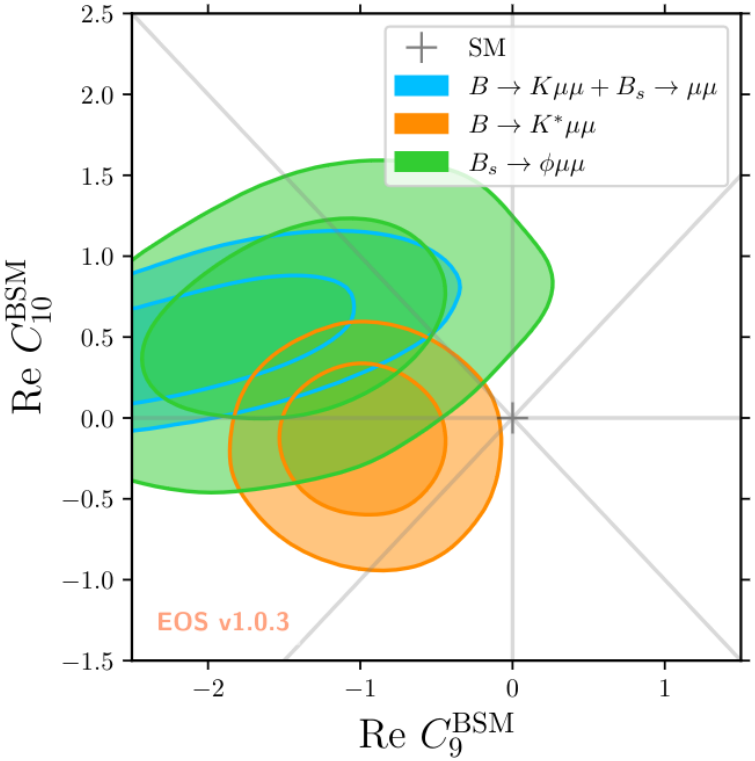


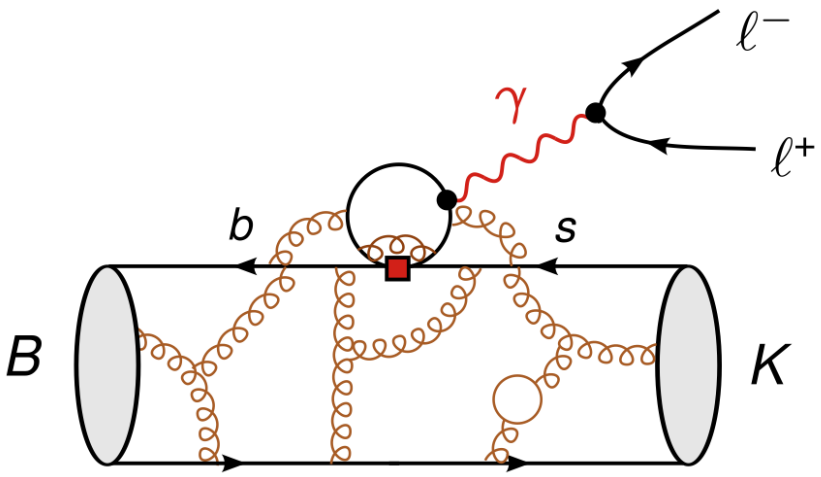
Use of form factors from $N_f = 2 + 1 + 1$ lattice QCD

- Tensions between SM and experiment are still observed in most cases (agreement in $B \to K^*\mu\mu$)

Theory Explanations for the $B \to K^* \mu\mu$ anomaly

JHEP 09 (2022) 133

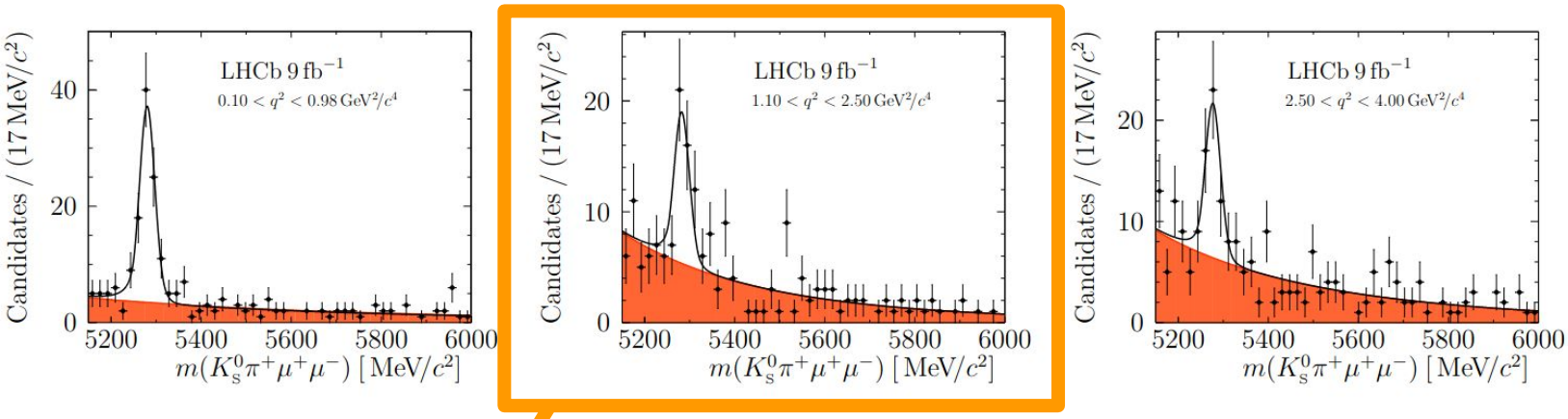




- Hadronic contributions could be severely underestimated (e.g. $B^0 \to D^* D_s \to K^{*0}\mu\mu$: Phys.Rev.Lett. 125(2020) 1,011802)
- Results can be explained by an apparent shift in C_9 (charm loop)

Current Strategy

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



Integrate decay rate over each q^2 bin

Measure $\langle P_5' \rangle$

Example: Angular analysis $B^0 \to K^{*0}\mu^+\mu^-$
(Phys. Rev. Lett. 126, 161802 (2021), JHEP 1308 (2013) 131, JHEP 06 (2015) 084)

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

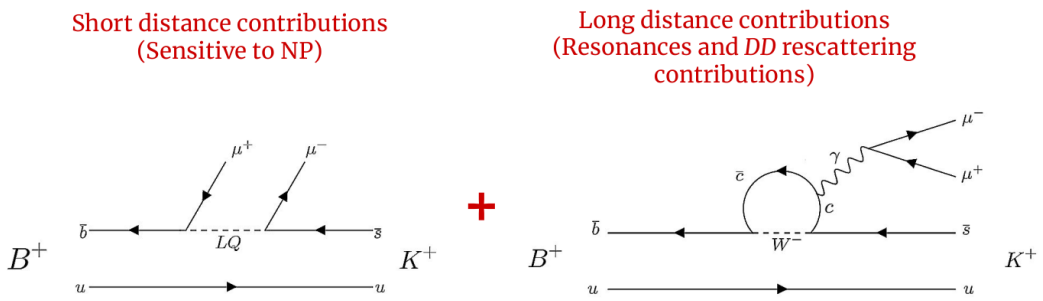
Increases sensitivity to NP!

- more work is still required to fully account for $B \to D^* D_s \to K^{(*)} \mu\mu$ rescattering amplitudes

Direct measurements of Wilson Coefficients

- Unbinned fits allow for direct extraction of Wilson Coefficients

An example: $B^+ \to K^+\mu^+\mu^-$

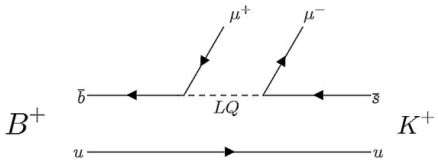


- Able to simultaneously extract C_9 and C_{10}

Direct measurements of Wilson Coefficients (Form Factors)

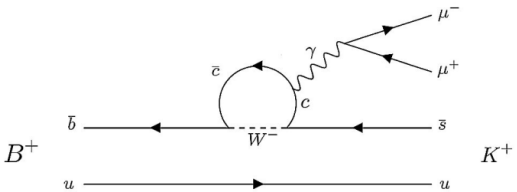
An example: $B^+ \to K^+\mu^+\mu^-$

Short distance contributions
(Sensitive to NP)



+

Long distance 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)

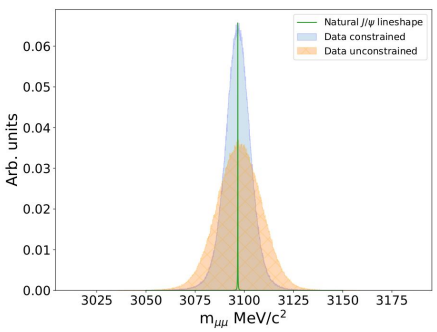
  Non-Local:
  - ◇ Far from resonances: estimations are made using perturbative bounds (Nucl.Phys.B612:25-58,2001, JHEP 1009 (2010) 089)

$B^+ \to K^+\mu^+\mu^-$ decay rate as a function of q^2

Obtain a model of the decay rate as a function of q^2:

$$\frac{d\Gamma}{dq^2} = \frac{\alpha_{\rm em}^2 G_F^2 \left|V_{tb}V_{ts}^*\right|^2}{128\pi^5}\kappa\left(q^2\right)\beta\left(q^2\right)\left\{\frac{2}{3}\kappa^2\left(q^2\right)\beta^2\left(q^2\right)\left|\mathcal{C}_{10}^{\mu} f_+\left(q^2\right)\right|^2 + \frac{m_\mu^2\left(m_B^2-m_K^2\right)^2}{q^2 m_B^2}\left|\mathcal{C}_{10}^{\mu} f_0\left(q^2\right)\right|^2 + \kappa^2\left(q^2\right)\left[1-\frac{1}{3}\beta^2\left(q^2\right)\right]\left|\mathcal{C}_9^{\mu,\rm eff} f_+\left(q^2\right) + 2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K} f_T\left(q^2\right)\right|^2\right\} \otimes \boxed{\mathcal{R}(q^2)}$$

- Form Factors
- Wilson Coefficients



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

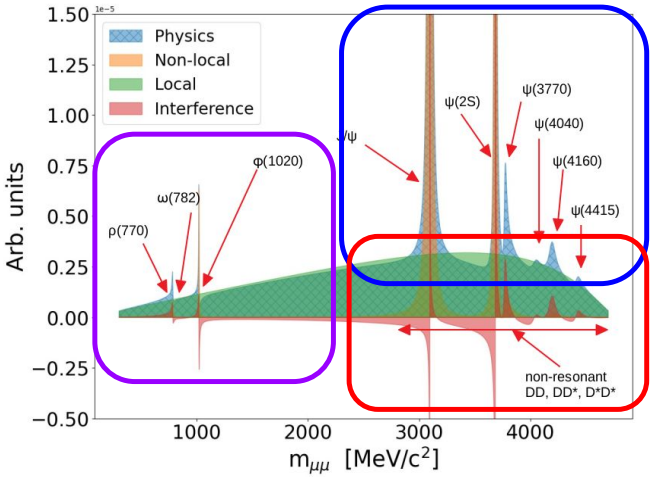
Structure of $C_9^{\mu,\text{eff}}$ in $B^+ \to K^+\mu^+\mu^-$ decay rate as a function of q^2

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

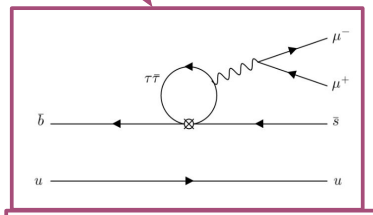
$$\mathcal{C}_9^{\mu,\text{eff}}(q^2) = \mathcal{C}_9^{\mu} + Y_{c\bar{c}}^{(0)} + \Delta Y_{c\bar{c}}^{1\text{P}}(q^2) + \Delta Y_{D\bar{D}}^{2\text{P}}(q^2) + Y_{\text{light}}^{1\text{P}}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

Short distance ~ 4.23 (SM)

≈-0.10 ± 0.05



Dimuon mass spectrum courtesy of Lakshan Ram Madhan Mohan



arxiv: 2302.02886

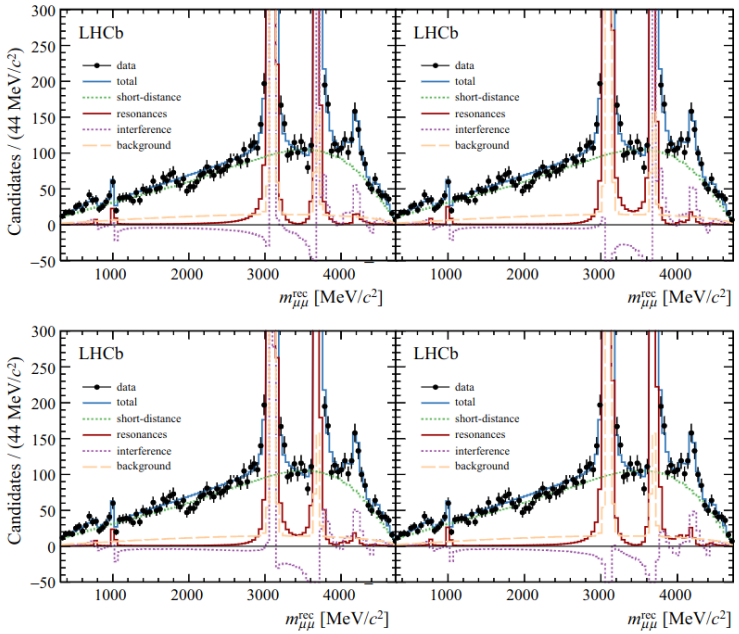
$R(D^{0(*)})$ hints that $b \to s\ell\ell$ tensions are potentially due to tau loop contribution

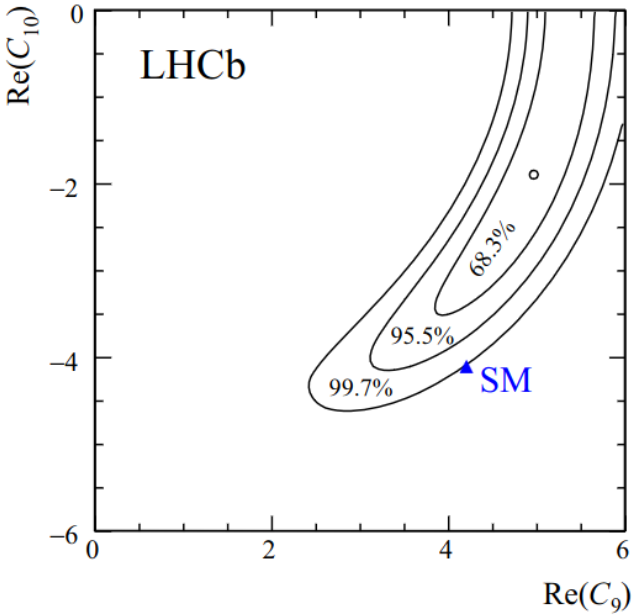
Needs unbinned approach to probe!

- 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

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

(Example of earlier isobar naive approach which ignores 2 particle states)





Run 1 Analysis (EPJC (2017) 77: 161)

- Degeneracy of J/ψ and ψ_{2S} phases lead to 4 equivalent solutions
- Run 2 analysis (following the dispersion relation) currently in WG review

Extension to $B \to K^* \mu\mu$

(based off EPJC (2018) 78: 453)

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

- Form Factors
- Wilson Coefficients
- Non-local hadronic matrix elements

Two approaches pursued at LHCb (currently ongoing):

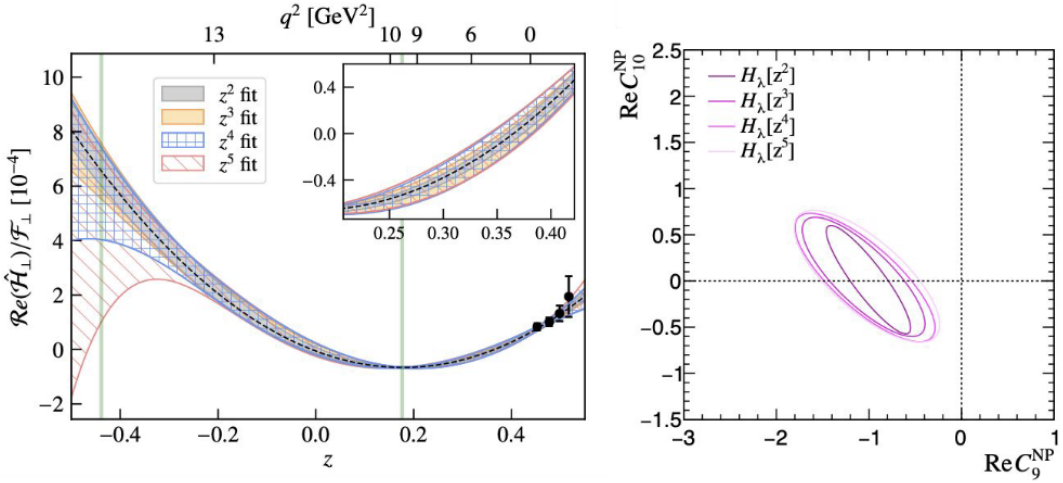
1. Expand $\mathcal{H}_\lambda (q^2)$ as a polynomial in $z(q^2)$[1] and fitting simultaneously (Chrzaszcz et al., JHEP 10 (2019) 236) with:
   - External inputs coming from J/ψ and ψ_{2S} measurements
   - Theory points in negative q^2 region
2. Include all known contributions to C_9 (combine approaches of Egede et al., EPJC 78 (2018) 6, 453 and Cornella et al., EPJC 80 (2020) 12, 1095)
   $\to$ fit to full q^2 spectrum

[1] Conformal mapping of q^2 to the unit circle

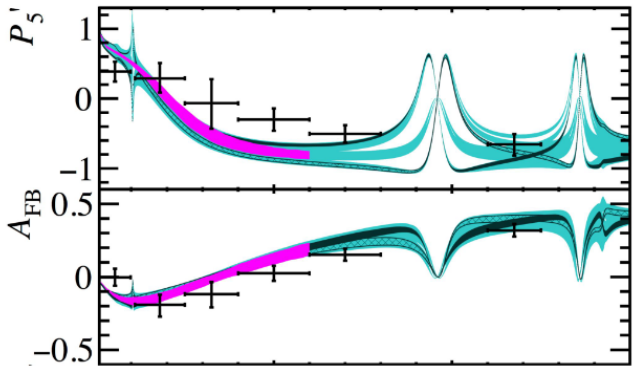
Extension to $B \to K^* \mu\mu$

(based off EPJC (2018) 78: 453)

- Sensitivity studies with pseudo-experiments



Left: Fits to z-expansion of $\mathcal{H}_\lambda\left(q^2\right)$ with negative q^2 theory inputs.
Right: 2D sensitivity scans for Wilson Coefficients.
(approach 1)



Angular observables as a function of q^2
(approach 2)

Future Prospects

- Tensions between SM theory and experiment **persist**, independent of recent status of LFU violation
- Model of the strong phase with q^2 allows for extra sensitivity of the imaginary parts of the Wilson Coefficients
  $\rightarrow$ work ongoing
- Continue with the robust approach of binned measurements

  $\rightarrow$ 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**