Recent results of $b \to sll$

22nd Conference on Flavor Physics and CP Violation

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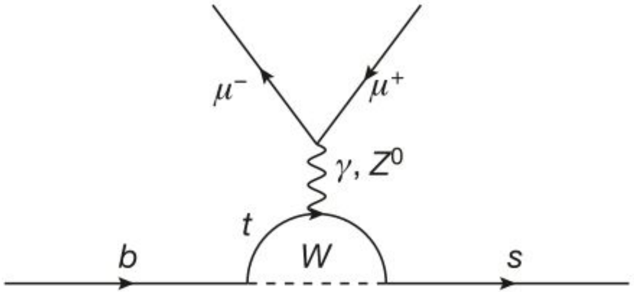
Outline

- Introduction
- Lepton flavor universality
- Branching fraction measurements
- Angular analysis
- Amplitude analysis
- Global analysis
- Summary

Introduction



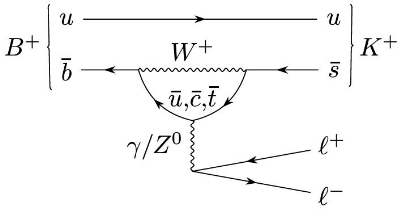
[Nature 546 (2017) 221-226]

- Standard Model (SM) is known to be incomplete
  - dominance of matter over antimatter
  - dark matter content of the Universe

- One of the goals of experimental particle physics is to discover new particles and their interactions: New Physics (NP)

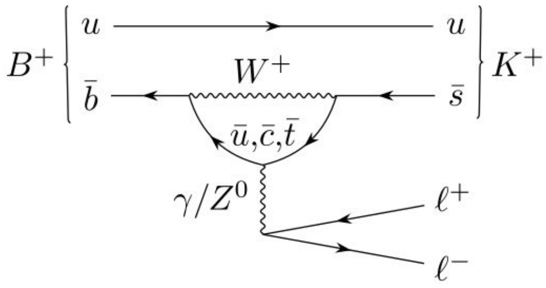
- Study the flavor changing neutral current (FCNC) transitions $b\to s l^+ l^-$
  - forbidden in SM at tree level
  - proceeds through high order electroweak loop diagrams
  - heavy new particles may enter these diagrams
    - large deviations from the SM predictions of decay rate and its dynamics
  - $b\to s l^+ l^-$ sensitive to NP

- Such decays have been studied extensively in B-meson sector
  - testing lepton flavor universality
  - branching fractions
  - angular distributions



[arXiv:2401.07090]

[Nat. Phys. 18 (2022) 277-282]



Lepton flavor universality

- All leptons in SM (e, μ and τ) have the same interaction strength
- Ratio of branching fractions (R_K) of $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ in SM is predicted to be unity with high precision
  - small masses of both e and μ as compared to b quark
- To reduce systematic uncertainties and precise modelling of e and μ reconstruction efficiencies: measured as double ratios

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}\ (B\to He^+e^-)}{dq^2} dq^2}$$

$B = B^+$, B^0, B_s or Λ_b
$H = K^+$ or K^{*0}

[Nat. Phys. 18 (2022) 277-282]

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \Big/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$

- R_{K*} 2.2-2.4σ and 2.4-2.5σ deviation in q^2: 0.045-1.1 and 1.1-6.0 GeV^2/c^4 [JHEP 08 (2017) 055]
- R_K 2.5σ below SM [PRL 122 (2019) 191801]
- Using $\Lambda_b \to pK^-l^+l^-$ decays R_{pK} measurement consistent with SM (1σ) [JHEP 05 (2020) 040]

Results

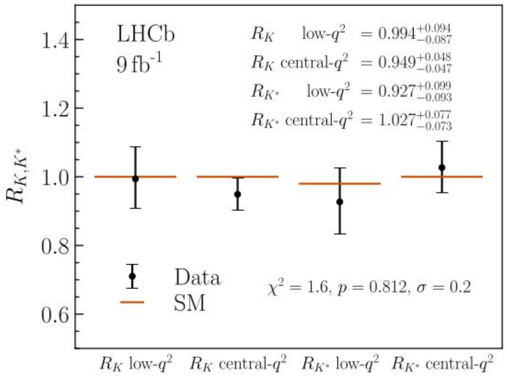
- In q^2 1-6.0 GeV^2/c^4
  - $R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$ 3.1σ below SM prediction [*Nat. Phys. 18 (2022) 277-282*]
  - evidence for violation of lepton universality
  - $R_K = 0.78^{+0.46+0.09}_{-0.23-0.05}$ within 1σ of SM prediction [arXiv:2401.07090]
- In q^2 1.1-6.0 GeV^2/c^4 $R_{K^0_S} = 0.66^{+0.20+0.02}_{-0.14-0.04}$ 1.5σ
- In q^2 0.045-6.0 GeV^2/c^4 $R_{K^{*+}} = 0.70^{+0.18+0.03}_{-0.13-0.04}$ 1.4σ

central values exhibit the same deficit of muonic decays relative to electronic decays [PRL 128 (2022) 191802]

- Simultaneous test of muon-electron universality in low-q^2 0.1-1.1 GeV^2/c^4 and central-q^2 1.1-6.0 GeV^2/c^4

$$\text{low-}q^2 \begin{cases} R_K = 0.994^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst}), \\ R_{K^*} = 0.927^{+0.093}_{-0.087}(\text{stat})^{+0.036}_{-0.035}(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst}), \\ R_{K^*} = 1.027^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.026}(\text{syst}). \end{cases}$$



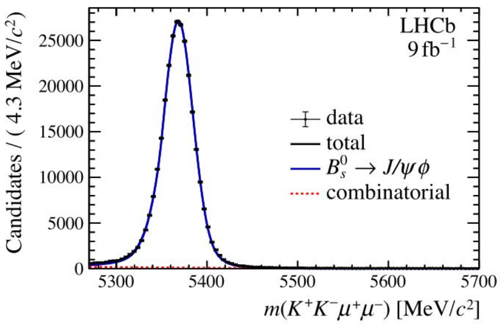
$B_s \to \phi \mu^+ \mu^-$ and $B_s \to f_2'(1525) \mu^+ \mu^-$ decays

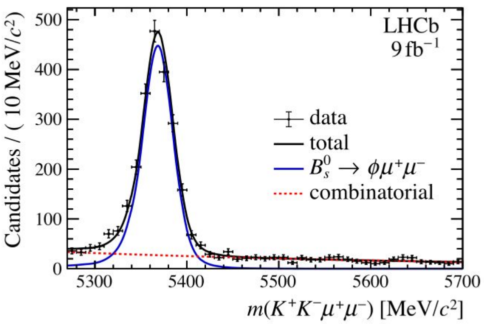
$B_s \to \phi\mu^+\mu^-$ differential branching fractions

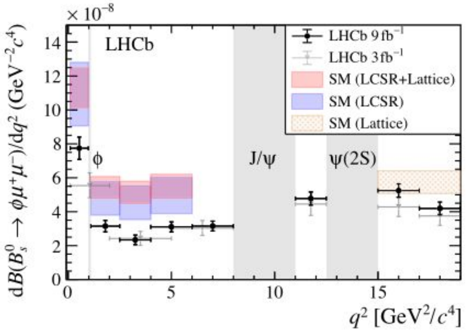
[PRL 127 (2021) 151801] $\sqrt{s}$=7, 8 and 13 TeV, $\mathcal{L}$=9fb^{-1}

- Significant discrepancies have been reported in the branching fraction measurements
  - In q^2: 1.0-6.0 GeV^2/c^4 lies >3σ below SM predictions [JHEP 09 (2015) 179]

- Narrow width of ϕ allows for a clean selection with low level of backgrounds







- In q^2: 1.1-6.0 GeV^2/c^4 3.6σ deviation from the SM prediction based on LCSR and lattice QCD

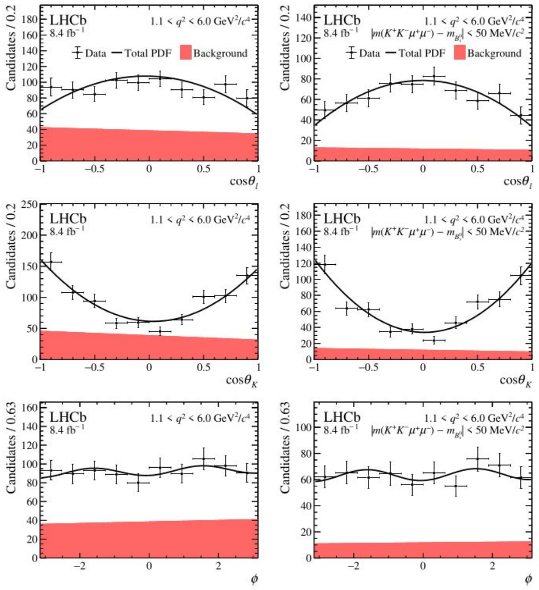
$B_s \to \phi \mu^+ \mu^-$ angular analysis

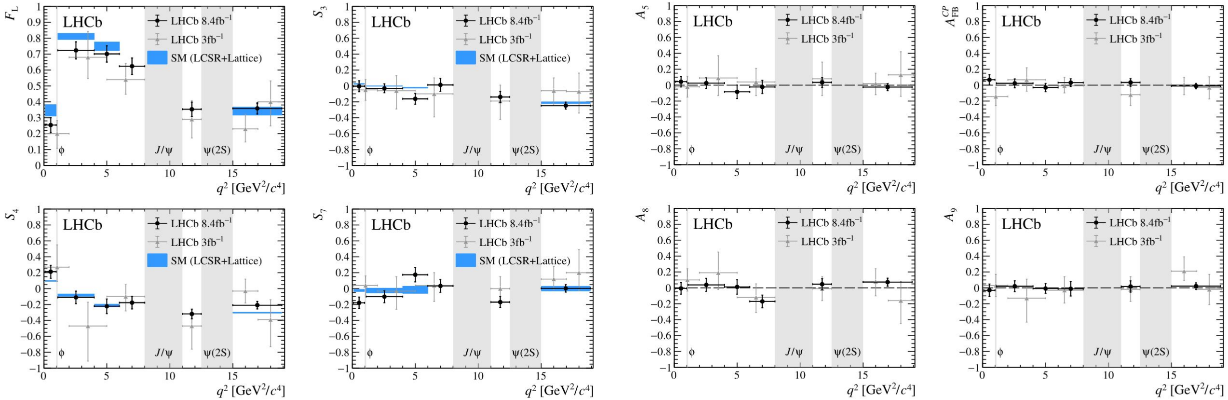
[JHEP 11 (2021) 043] $\sqrt{s}$=7, 8 and 13 TeV, $\mathcal{L}$=8.4fb^{-1}

Flavor-symmetric final state, untagged CP-averaged angular decay rate

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K(1+\frac{1}{3}\cos 2\theta_l)$$
$$+ F_{\mathrm{L}}\cos^2\theta_K(1-\cos 2\theta_l) + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + A_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+ \frac{4}{3}A_{\mathrm{FB}}^{CP}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+ A_8\sin 2\theta_K\sin 2\theta_l\sin\phi + A_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- Two-fold increase in sensitivity (compared to earlier measurement)
- Results are compatible with SM predictions



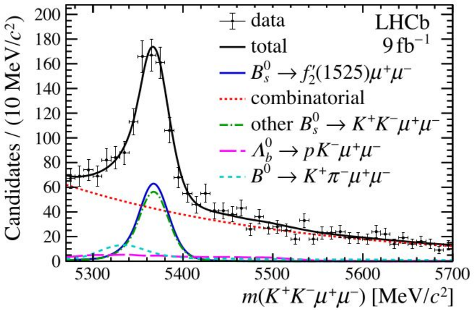


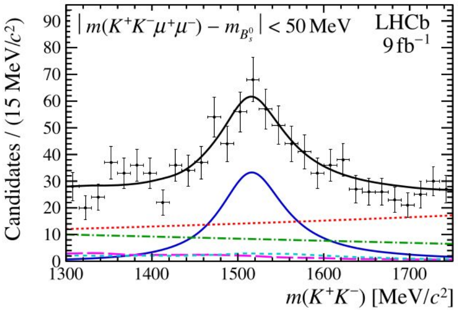
$B_s \rightarrow f'_2(1525)\mu^+\mu^-$ decays

[PRL 127 (2021) 151801] $\sqrt{s}$=7, 8 and 13 TeV, $\mathcal{L}$=9fb^{-1}

- Other resonances $f_2(1270)$, $f_0(1500)$, between $\phi(1020)$ and $f'_2(1525)$, have branching fraction of 5% or less into K^+K^- final state
  - $f'_2(1525)$ next best candidate after $\phi(1020)$
- First observation of b→sll involving a spin-2 meson
- Reported with a statistical significance of 9σ (Wilks' theorem)
- Branching fraction in agreement with SM predictions

$$\frac{\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \frac{\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(f_2' \to K^+K^-)} \times \frac{N_{f_2'\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{f_2'\mu^+\mu^-}},$$





$$\frac{\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = (1.55 \pm 0.19 \pm 0.06 \pm 0.06) \times 10^{-4},$$

$$\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}.$$

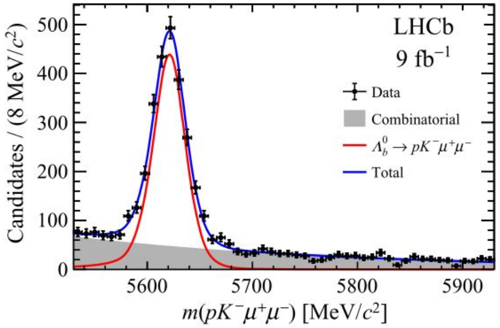
$\Lambda_b \rightarrow \Lambda(1520)\mu^+\mu^-$ decays

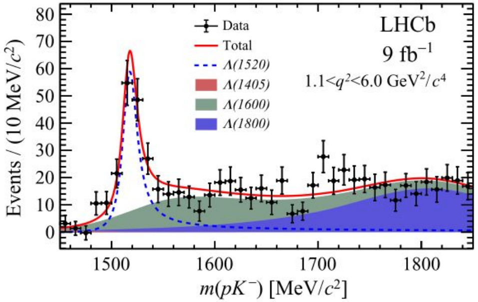
$\Lambda_b \to \Lambda(1520)\mu^+\mu^-$ decays

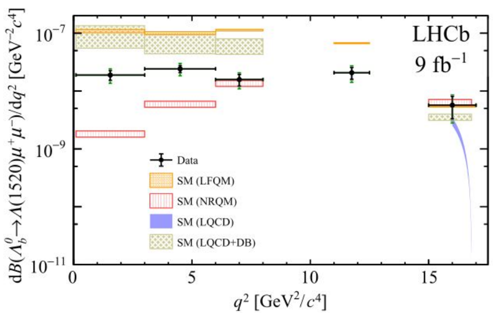
[PRL 131 (2023) 151801] $\sqrt{s}$=7, 8 and 13 TeV, $\mathcal{L}$=9fb^{-1}

- $\Lambda_b \to \Lambda\mu^+\mu^+$ have been observed by the LHCb Collaboration [JHEP 06 (2015) 115]
- Excited Λ(1520) has J^P=(3/2)$^-$ while the ground state Λ has J^P=(1/2)
    - providing complimentary information to NP
- First measurement of the differential branching fraction of the $\Lambda_b \to \Lambda\mu^+\mu^+$ decays

$$\left\{\frac{d\mathcal{B}[\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-]}{dq^2}\right\}_{q^2_{\rm min}}^{q^2_{\rm max}} = \frac{1}{(q^2_{\rm max} - q^2_{\rm min})} \frac{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi)\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}[\Lambda(1520) \to pK^-]} \frac{N_{\Lambda(1520)\mu^+\mu^-}}{N_{pK^-J/\psi}} \frac{\varepsilon_{pK^-J/\psi}}{\varepsilon_{\Lambda(1520)\mu^+\mu^-}}$$







$B \to K l^+ l^-$ decays

B→Kl⁺l⁻ decays

- **CMS Collaboration:** in 2018, deployed novel trigger
  - Enabled collection of unbiased 10^{10} b hadron decays
  - B-parking dataset
- Measurement below the SM predictions [arXiv:2401.07090]
  - In q^2 1.1-6.0 GeV^2/c^4, $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (12.42 \pm 0.68) \times 10^{-8}$
- **LHCb Collaboration:** branching fraction results from R_K analysis. In q^2 1.1-6.0 GeV^2/c^4
  - $\mathcal{B}(B^+ \to K^+e^+e^-) = (28.6^{+1.5}_{-1.4} \pm 1.3) \times 10^{-9}$ [Nat. Phys. 18, 277-282 (2022)]
  - Combining R_K with dB($B^+ \to K^+\mu^+\mu^-$)/dq^2 [JHEP 06 (2014) 133]

    $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (11.86 \pm 0.68) \times 10^{-8}$
- In q^2 1.1-6.0 GeV^2/c^4, [PRL 128 (2022) 191802]

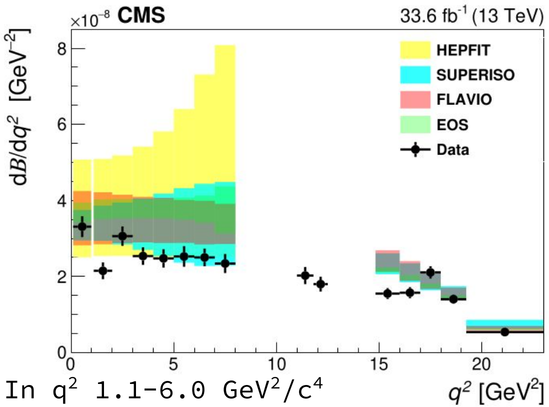
  $\mathcal{B}(B^0 \to K^0 e^+e^-) = (2.6 \pm 0.6 \pm 0.1) \times 10^{-8}$

  and in q^2 0.045-6.0 GeV^2/c^4,

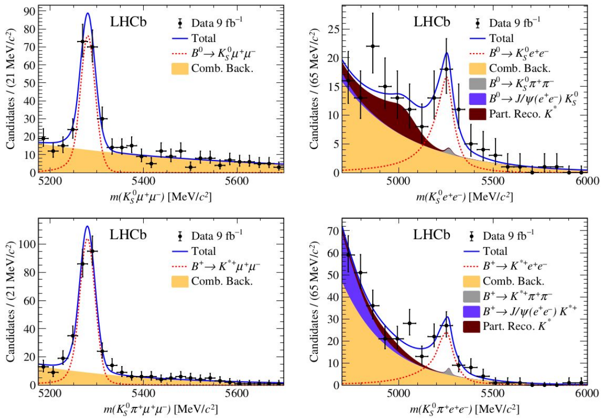
  $\mathcal{B}(B^+ \to K^{*+}e^+e^-) = (9.2^{+1.9}_{-1.8}(\text{stat})^{+0.8}_{-0.6}(\text{syst})) \times 10^{-8}$

  First observation for $B^0 \to K^0_s e^+e^-$ with 5.3σ

√s=13 TeV, $\mathcal{L}$=33.6fb^{-1}



√s=7, 8 and 13 TeV, $\mathcal{L}$=9fb^{-1}



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

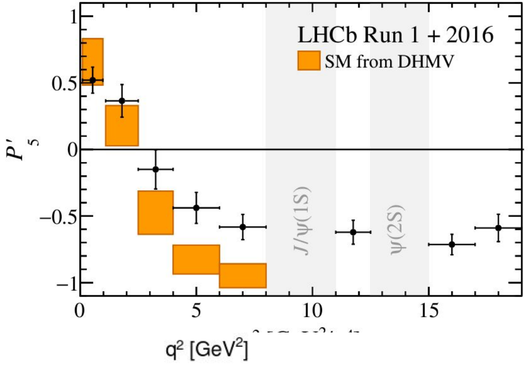
- Isospin partner decay of $B \to K^* \mu^+ \mu^-$ where tension with the SM predictions in the angular observables have been observed [PRL 125 (2020) 011802, JHEP 10 (2018) 047]

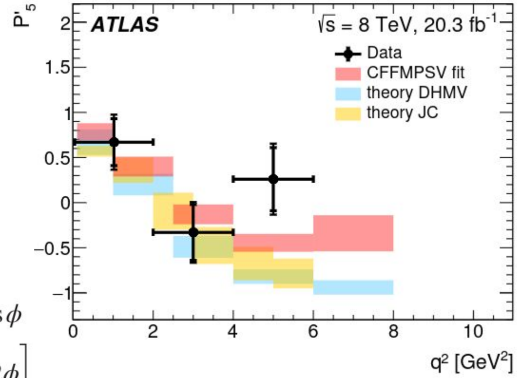
- $B \to K^{*+} \mu^+ \mu^-$ decay:
  - First measurement of the complete set of angular observables
  - K meson reconstructed through the decay chain $K^{*+} \to K_s \pi^+$ with $K_s \to \pi^+ \pi^-$

- $B \to K^{*+} \mu^+ \mu^-$ decay rate with $K_s \pi^+$ in both P-wave and S-wave configuration

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\bigg|_P = \frac{9}{32\pi}\bigg[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\bigg]$$

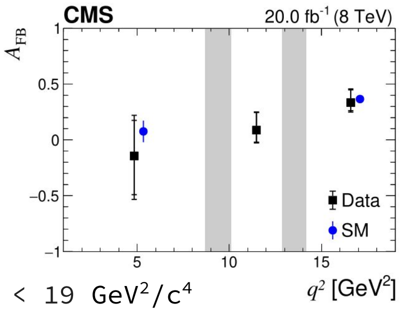
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\bigg|_{P+S} = (1-F_S)\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}}\bigg|_P + \frac{3}{16\pi}F_S\sin^2\theta_l + \frac{9}{32\pi}(S_{11} + S_{13}\cos 2\theta_l)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_l + S_{15}\sin\theta_l)\sin\theta_K\cos\phi + \frac{9}{32\pi}(S_{16}\sin\theta_l + S_{17}\sin 2\theta_l)\sin\theta_K\sin\phi,$$

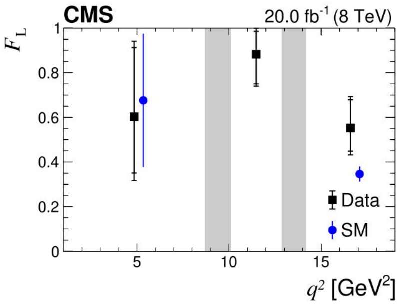




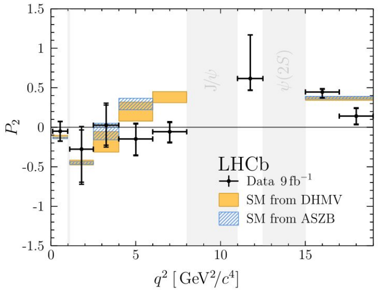
Results

- CMS Collaboration at $\sqrt{s}$=8 TeV, $\mathcal{L}$=20fb^{-1} [JHEP 04 (2021) 124]
  - $1 < q^2 < 8.68$, $10.09 < q^2 < 12.86$, and $14.18 < q^2 < 19$ GeV^2/c^4
  - A_{FB} and F_L are found to be consistent with the SM prediction

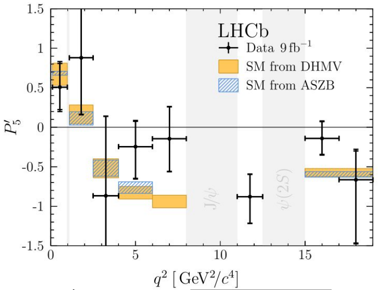




- LHCb Collaboration at $\sqrt{s}$=7, 8 and 13 TeV, $\mathcal{L}$=9fb^{-1} [PRL 126 (2021) 161802] (full set of angular observables)
  - Results confirm the global tension with respect to SM predictions as reported in $B^0 \to K^{*0}\mu^+\mu^-$
  - Largest local discrepancy for P_2 in 6.0-8.0 GeV^2/c^4, 3.0σ with respect to the SM



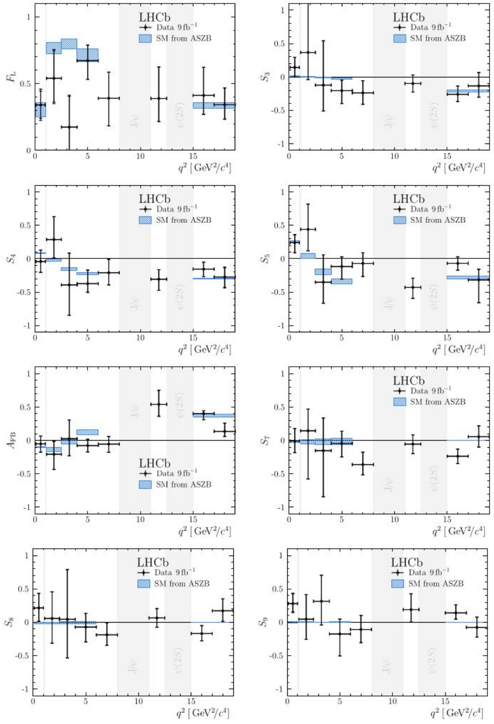
$$P_2 = \frac{2}{3}A_{FB}/(1-F_L)$$



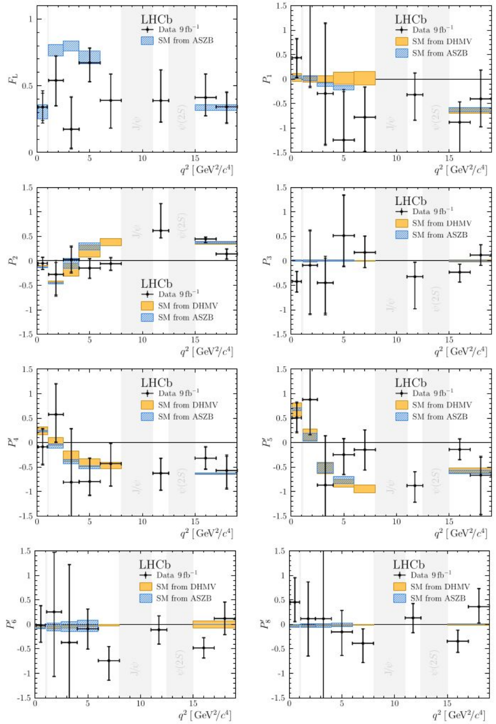
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

Results

[PRL 126 (2021) 161802]



CP averaged observables F_L, A_{FB} and S_3-S_9 versus q^2



Optimized observables P_1 to P'_8 versus q^2

Short and long-distance contributions in $B^0 \to K^{*0} \mu^+ \mu^-$

[PRD 109 (2024) 052009, PRL **132** (2024) 131801]

Amplitude analysis

Decay amplitudes

Wilson coefficients — Local form factors — non-local form factors

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}\left\{\left[(\mathcal{C}_9 \pm \mathcal{C}_9') \mp (\mathcal{C}_{10} \pm \mathcal{C}_{10}')\right]\mathcal{F}_\lambda(q^2,k^2) + \frac{2m_b M_B}{q^2}\left[(\mathcal{C}_7 \pm \mathcal{C}_7')\mathcal{F}_\lambda^T(q^2,k^2) - 16\pi^2\frac{M_B}{m_b}\mathcal{H}_\lambda(q^2,k^2)\right]\right\}$$

λ : polarization of K^{*0} meson
L,R: left & right-hand chirality
N: normalization factors

C_7^{SM}=-0.337, C_9^{SM}=4.27, C_{10}^{SM}=-4.17 and $C'^{SM}_{7,9,10}$≃0 at μ_b=4.2 GeV^{2}c^{-4}
Local form factors evaluated using LCSR and LQCD techniques

- Non-local contributions from $b \to c\bar{c}s$ operators [JHEP 09 (2022) 133]
  - isolate ψ_n (J/ψ or ψ(2S)) poles
  - polynomial expansion in terms of conformal variable $z(q^2)$
- K dependence included in the model $A_\lambda^{L,R} \to A_\lambda^{L,R} \times f(k^2)$
  - Relativistic Breit-Wigner for P-wave
  - LASS parameterization for S-wave
- Decay rate including P-wave and S-wave amplitudes
  - I_i^S : pure S-wave angular coefficients
  - $\tilde{I}_i^S$: interference terms between S and P-wave amplitudes

$$q^2 \mapsto z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

$$\mathcal{H}_\lambda(z) = \frac{1 - z z_{J/\psi}}{z - z_{J/\psi}}\frac{1 - z z_{\psi(2S)}}{z - z_{\psi(2S)}}\hat{\mathcal{H}}_\lambda(z)$$

$$\hat{\mathcal{H}}_\lambda(z) = \phi_\lambda^{-1}(z)\sum_k \alpha_{\lambda,k} z^k$$

$$\begin{aligned}\frac{32\pi}{9}\frac{d^5\Gamma}{dq^2dk^2d\vec{\Omega}} = \frac{32\pi}{9}\frac{d^5\Gamma^P}{dq^2dk^2d\vec{\Omega}} &+ (I_{1c}^S + I_{2c}^S\cos 2\theta_\ell) \\ &+ (\tilde{I}_{1c} + \tilde{I}_{2c}\cos 2\theta_\ell)\cos\theta_K \\ &+ (\tilde{I}_4\sin 2\theta_\ell + \tilde{I}_5\sin\theta_\ell)\sin\theta_K\cos\phi \\ &+ (\tilde{I}_7\sin\theta_\ell + \tilde{I}_8\sin 2\theta_\ell)\sin\theta_K\sin\phi,\end{aligned}$$

Analysis overview

- The absolute scale of the Wilson coefficients set by the branching fraction of the decay

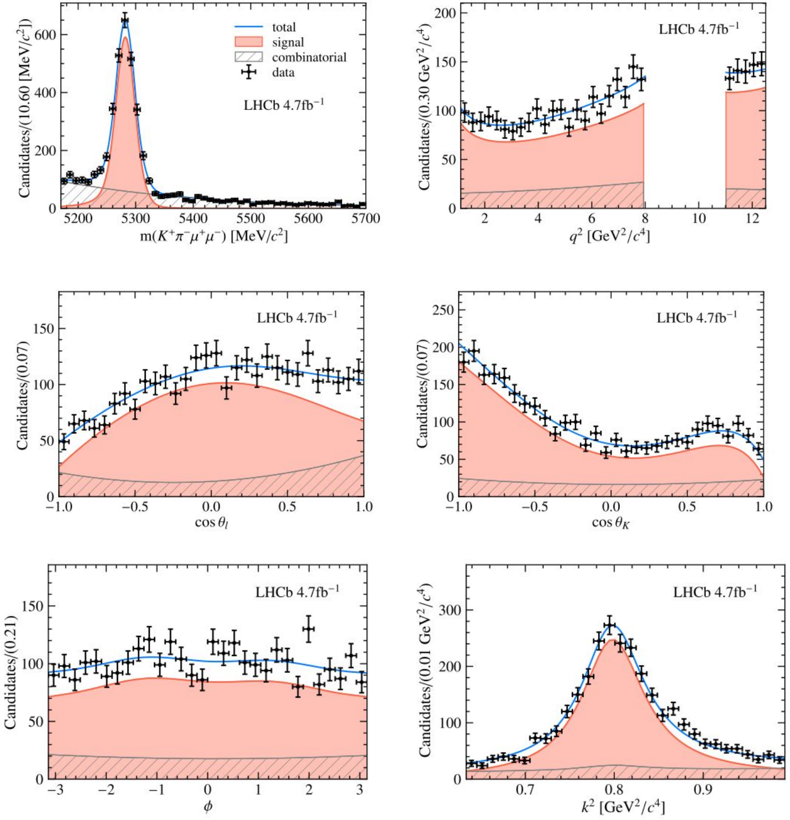
$$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) = \frac{\tau_B}{\hbar}\int_{q^2_{\rm min}}^{q^2_{\rm max}}\int_{k^2_{\rm min}}^{k^2_{\rm max}} \frac{{\rm d}^2\Gamma}{{\rm d}q^2{\rm d}k^2}{\rm d}q^2{\rm d}k^2,$$

- Extended unbinned maximum likelihood fit to q^2, k^2, $\cos\theta_l$, $\cos\theta_K$, Φ and $m(K\pi\mu\mu)$
  - C_9, C'_9, C_{10} and C'_{10} fit parameters
  - C_7 and C'_7 fixed from SM

- The signal yield is normalized to $B^0 \to J/\psi K\pi$

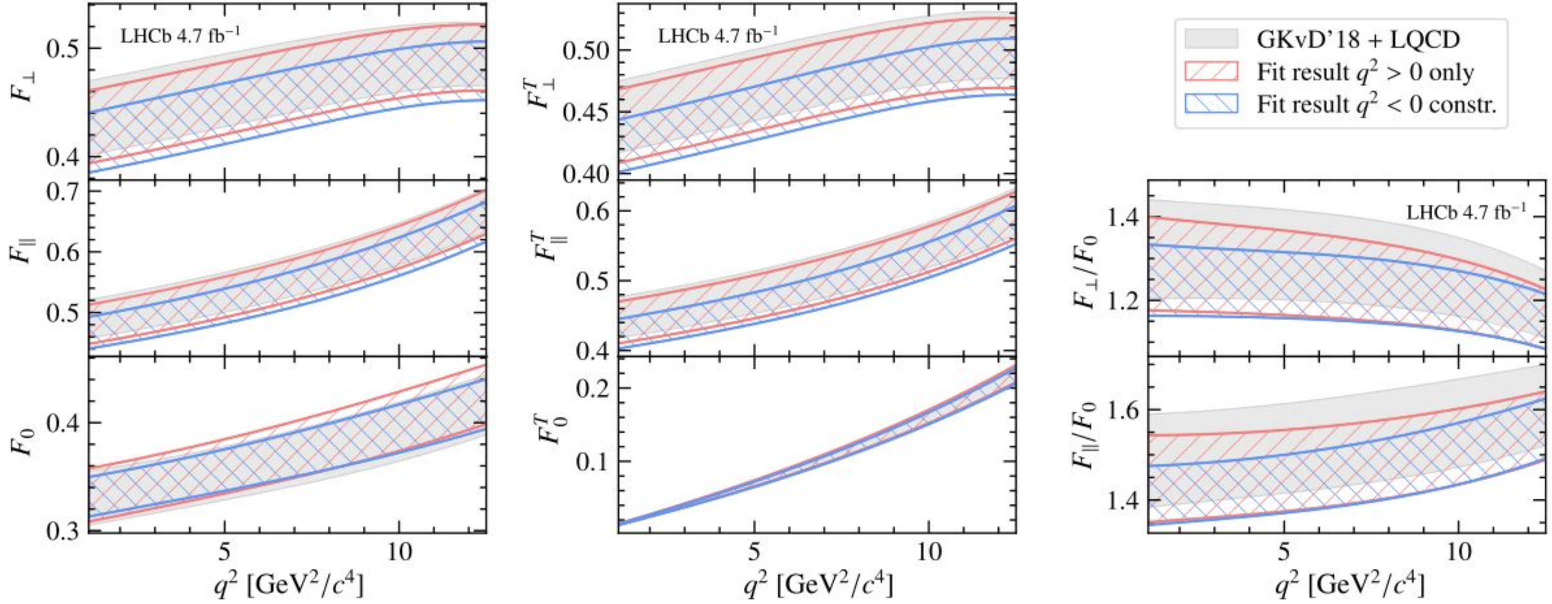
$$N_{\rm sig} = N_{J/\psi K\pi} \times \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)\times\frac{2}{3}}{\mathcal{B}(B^0 \to J/\psi K^+\pi^-)\times f^{J/\psi K\pi}\times\mathcal{B}(J/\psi \to \mu^+\mu^-)} \times R_\varepsilon$$

2011, 2012 and 2016 dataset, $\mathcal{L}$=4.7 fb^{-1}

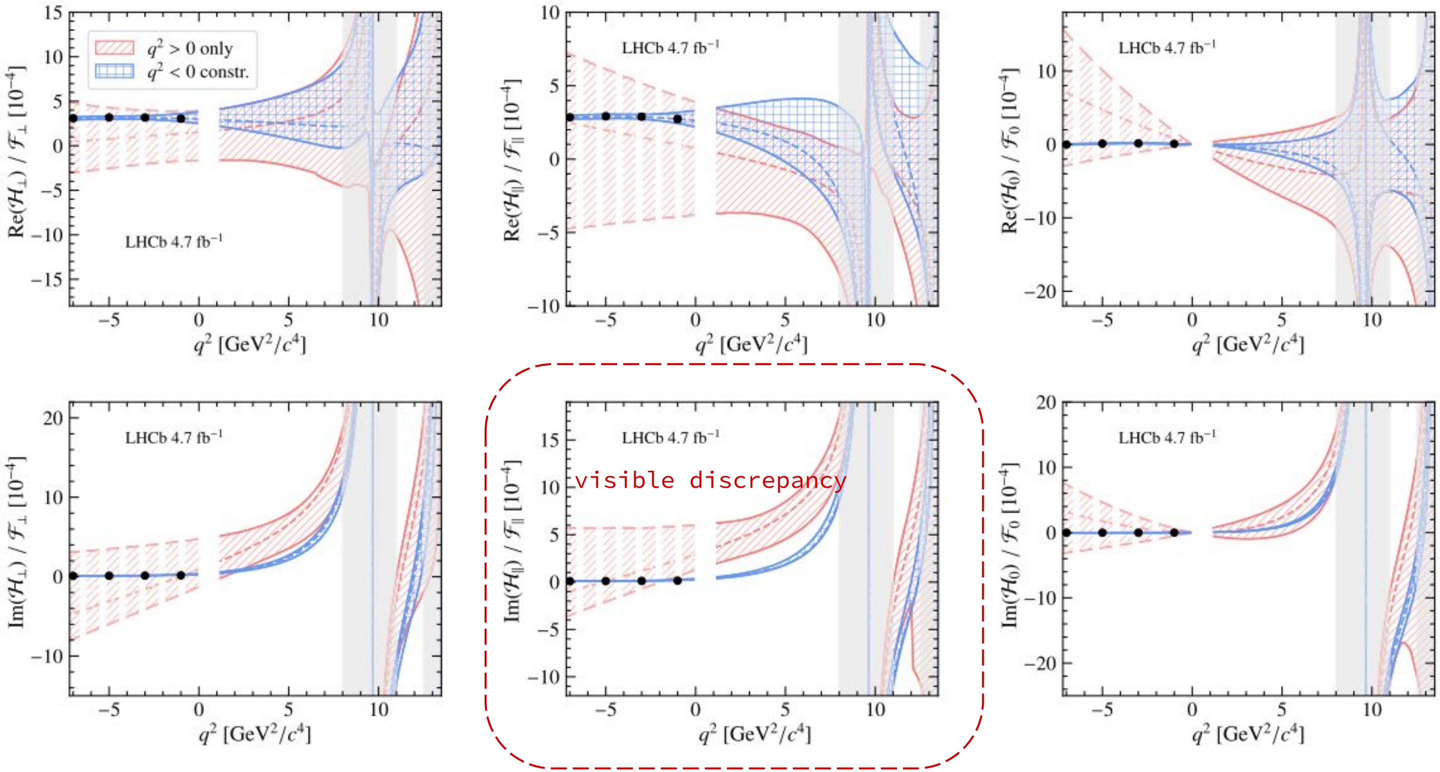


Results: local form factors

- The ratio takes lower values with respect to the theoretical predictions

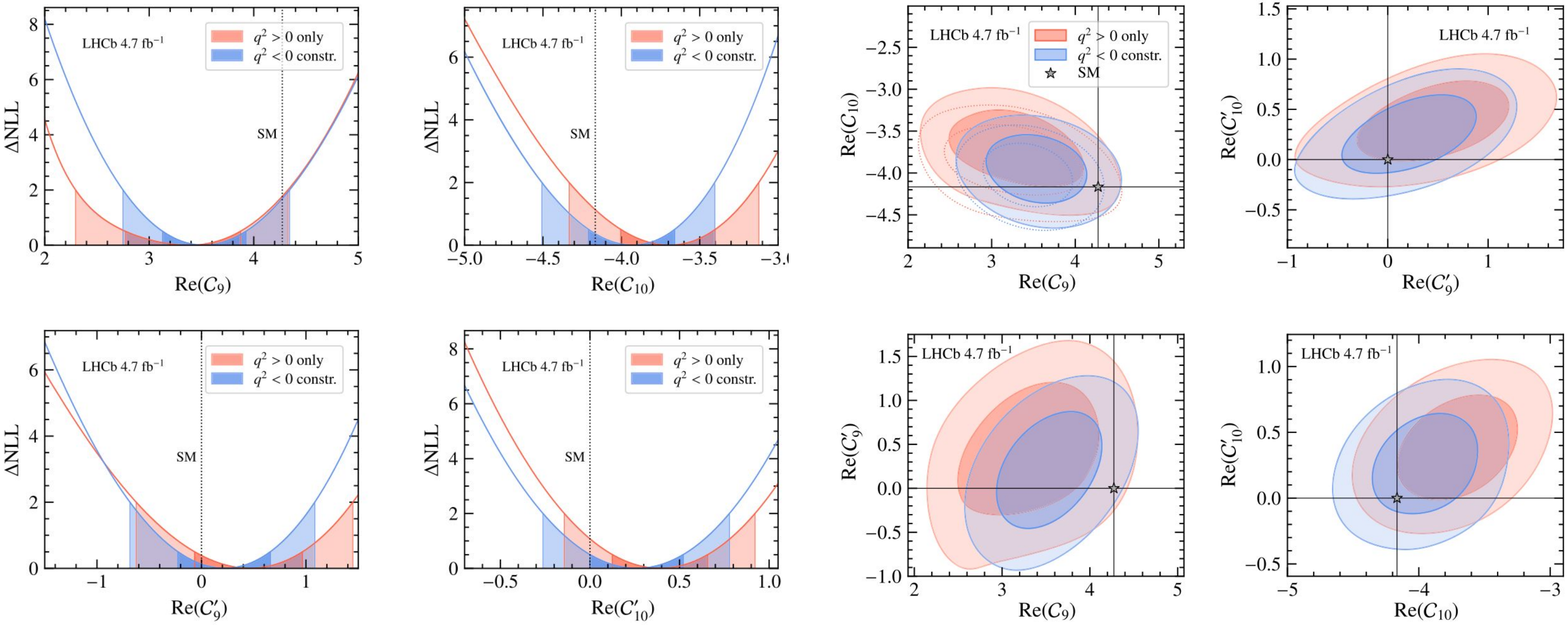


Results: non-local form factors



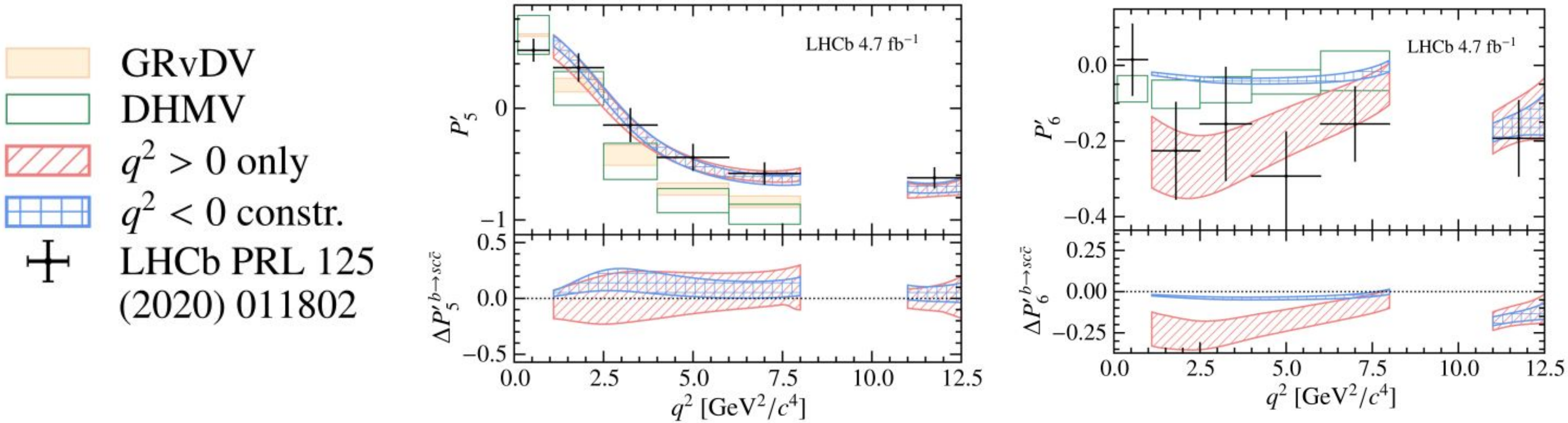
Results: Wilson coefficients

$$\Delta\mathcal{C}_9 = -0.93^{+0.53}_{-0.57}(-0.68^{+0.33}_{-0.46}),$$
$$\Delta\mathcal{C}_{10} = 0.48^{+0.29}_{-0.31}(0.24^{+0.27}_{-0.28}),$$
$$\Delta\mathcal{C}'_9 = 0.48^{+0.49}_{-0.55}(0.26^{+0.40}_{-0.48}),$$
$$\Delta\mathcal{C}'_{10} = 0.38^{+0.28}_{-0.25}(0.27^{+0.25}_{-0.27}),$$



Results: P'_5 and P'_6

- Non-local hadronic contributions are responsible for the positive shift In P'_5
- A good agreement observed between the angular observables obtained with the binned analysis [PRL 125 (2020) 011802]
- Discrepancy in P due to imaginary part of nonlocal $H_\lambda(q^2)$



Global fits

Recent results

[EPJC (2023) 83:648]

- Updated form factors resulting in reduction of uncertainties
- Using the latest experimental results from LHCb and CMS Collaborations
- Changes observed in the SM predictions:
  - R_K and R_{K*} are in excellent agreement with the SM
    - Previous deviations due to statistical fluctuations and systematic effects from e modes
  - More precise branching fractions in low-q^2 for $B \to K l^+ l^-$ modes $\mathcal{O}(30\%) \to \mathcal{O}(10\%)$
    - Increase in tension $\mathcal{B}(B \to K\mu^+\mu^-)$ with experimental results upto 4σ
  - Uncertainties in branching fractions of $B \to K^* l^+ l^-$ reduced by half
    - Compatible with experimental results
  - Optimized observables:
    - Central values shift towards experimental values
    - Uncertainties remain unchanged
    - Reduction in tension for $P_5'(B^0 \to K^{*0}\mu^+\mu^-)$ from $2.7\sigma(2.9\sigma)$ to $1.9\sigma(1.9\sigma)$ in q^2 4-6(6-8) GeV^2/c^4

Summary

- Recent results from $b \to sl^+l^-$ transitions were presented for:
  - Lepton Universality
  - Branching fractions
  - Angular analysis
- LFU ratios are in excellent agreement with the SM
  - Earlier tension due to e modes
- Tension in the branching fractions remain
  - $B(B \to K\mu^+\mu^-)$ due to form factors based on lattice QCD ~4σ
  - $B(B_s \to \phi\mu^+\mu^-)$ in low-q^2 >3σ
- Tension on P decreases to ~2σ
  - updated form factors from LCSR
- First unbinned amplitude analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$
- Future measurements in b→sll to may provide additional support to the deviations observed

BackUp