Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay at LHCb arXiv:2512.18053, accepted by PRL

LHC EFT WG meeting

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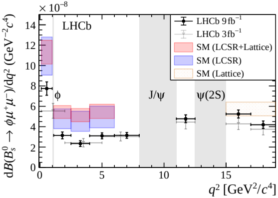
IMPERIAL

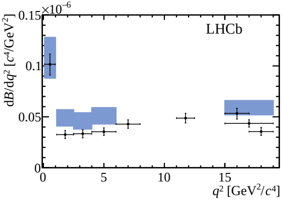
Flavour anomalies

- Recent results in $b \to s\ell\ell$ and $b \to c\ell\nu$ have presented discrepancies with respect to the SM
- These include branching fractions, ratio of branching fractions, and angular observables

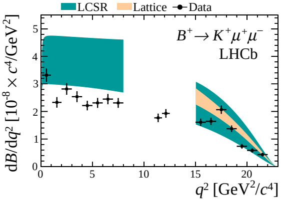
$B_s^0 \to \phi\mu^+\mu$
PRL 127, 151801 (2021)



$B^0 \to K\ ^0\mu^+\mu$
JHEP 04 (2017) 142

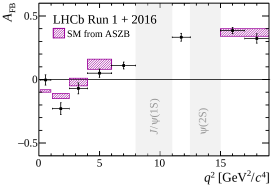


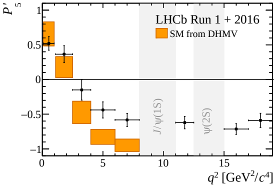
$B^+ \to K^+\mu^+\mu$
JHEP 06 (2014) 133



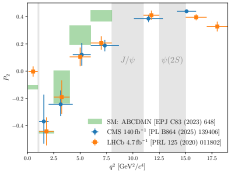
Flavour anomalies – $B^0 \to K^{*0}\mu^+\mu^-$

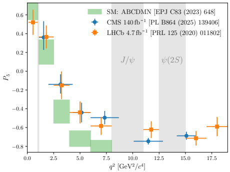
- Previous angular analysis of $B^0 \to K\;^{0}\mu^+\mu$ at LHCb presents discrepancies with respect to the SM [PRL 125, 011802 (2020)]





- Measurements from other experiments agree well with LHCb (e.g. CMS) [PLB 864 (2025) 139406]

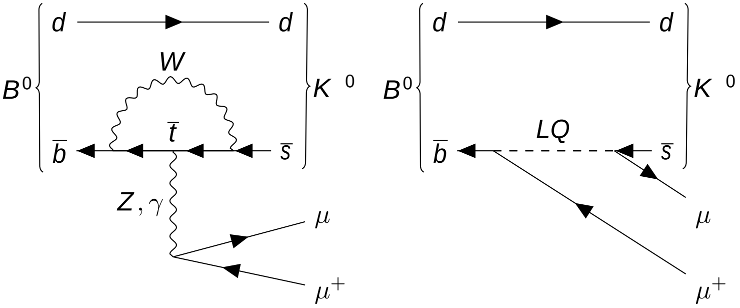




- This talk: **updated angular analysis of $B^0 \to K\;^{0}\mu^+\mu$ at LHCb**

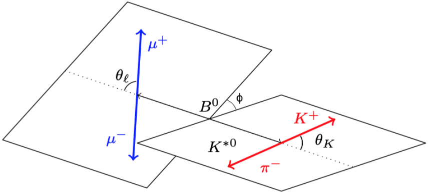
$B^0 \to K^{*0}\mu^+\mu^-$

- The decay $B^0 \to K\ ^0\mu^+\mu$ requires a $b \to s$ Flavour Changing Neutral Current, thus it is suppressed in the Standard Model
- Due to the SM suppression, this decay is highly sensitive to **New Physics**
- Left: SM, Right: NP model with Leptoquark.



Angular analysis

- Measure the **decay rate** of $B^0 \to K\ ^0(\to K^+\pi\ )\mu^+\mu$ as a function of three angles (θ_l, θ_K and ϕ), the invariant mass of the dimuon system squared, $q^2 = m^2_{\mu^+\mu}$, and the invariant mass of the kaon-pion system, $m_{K\pi}$



- The $K\pi$ system can be in an S-wave configuration, or a P-wave configuration

- An angular analysis gives rise to a large number of observables

- Due to the SM suppression, the $B^0 \to K\ ^0\mu^+\mu$ decay is highly sensitive to **New Physics**. It can also be used to deduce the **nature** of New Physics models

This measurement [arXiv:2512.10853]

- **Measure angular observables and differential branching fraction to** $B^0 \to K\ ^0\mu^+\mu$ **in bins of** q^2
- **This is with twice the dataset used in the previous binned angular analysis!**
- Compared to the previous angular analysis:
  - Measure the di erential branching fraction
  - Include the e ect of lepton masses, allowing one to test for scalar and tensor contributions
  - Measure the full set of CP-asymmetries in addition to the CP-averaged observables
  - Present the full suite of S-wave and P-/S- interference observables
  - Use a ner binning scheme in addition to the nominal binning scheme

Differential decay rate

$$\frac{d^5\Gamma}{dq^2\, d\vec{\Omega}\, dm_{K\pi}} \frac{1}{\Gamma+\bar{\Gamma}} = (1-F_S)\frac{9}{64\pi}\sum_i (S_i - A_i)\, f_i(\vec{\Omega})\, |BW_P(m_{K\pi})|^2$$
$$+ \frac{1}{8\pi}\sum_{1ac,2ac} (\tilde{S}_i - \tilde{A}_i)\, f_i(\vec{\Omega})\, |BW_S(m_{K\pi})|^2$$
$$+ \frac{1}{8\pi}\sum_{1bc,S1-S5} \mathrm{Re}/\mathrm{Im}\left[(\tilde{S}_i - \tilde{A}_i)\, f_i(\vec{\Omega})\, BW_S(m_{K\pi})\, BW_P^*(m_{K\pi})\right]$$

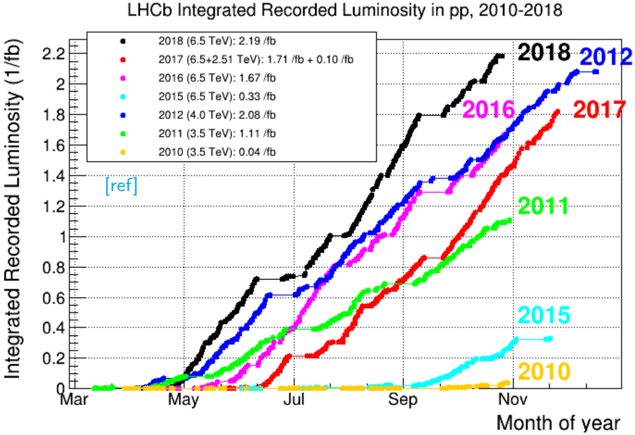
where

$$F_S = 2\tilde{S}^c_{1a} - \frac{2}{3}\tilde{S}^c_{2a}$$

- Fit differential rate to data, extract S_i (or optimised $P_i^{(0)}$), $\tilde{S}_i$, A_i, $\tilde{A}_i$
  - $S_i, \tilde{S}_i$ are CP-averages, and $A_i, \tilde{A}_i$ are CP-asymmetries
  - S_i, A_i are P-wave observables, and $\tilde{S}_i, \tilde{A}_i$ are S-wave / interference observables
- $m_{K\pi}$ is explicitly included in the angular rate, allowing for **S-wave** and **interference** observables to be precisely determined [JHEP 12 (2021) 085]

Data sample

- Perform this measurement on 2011, 2012, 2016, 2017, 2018 data collected by the LHCb experiment (8.4 fb ^{1})



- **New for this analysis: including 2017 and 2018 data**

Analysis strategy

- Perform a dedicated selection to obtain $B^0 \to K\ ^0\mu^+\mu$ candidates

- Model detector and selection effects with an acceptance function
  - $\varepsilon(\ \ , q^2, m_{K\pi}) = \sum_{ijmnp} c_{ijmnp} L_i(\cos\theta_\ell) L_j(\cos\theta_K) L_m(\phi) L_n(q^2) L_p(m_{K\pi})$

- Normalise branching fraction to $B^0 \to J/\psi\, K^+\pi$
  - There are exotic states in the $J/\psi\, \pi$ spectrum

  - Thus estimate the fraction in $B(B^0\ \ !\ \ J/\psi\, K^+\pi\ \ )$ from the Belle amplitudes [PRD 90, 112009 (2014)] and estimating the fraction in our $m_{K\pi}$ window

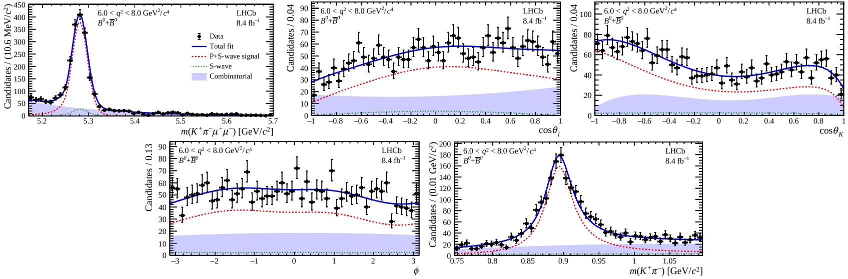
- Systematic uncertainties are assessed coherently across all q^2 bins
  - **Full covariance matrix for all observables across all q^2 bins is provided**

q^2 and $m_{K\pi}$ regions

- Use the same q^2 binning scheme as in the previous analysis
  - Exclude ϕ, J/ψ and $\psi(2S)$ resonances
  - Eight q^2 bins, each of width 1.5 2 GeV^2/c^4
  - Two wide q^2 bins
- **New for this analysis:** 16 narrow q^2 bins (half the nominal q^2 size)
  - Allows for greater resolution in the q^2 dependence of the angular observables
- Select $0.7459 < m_{K\pi} < 1.0959\ \mathrm{GeV}/c^2$
  - Larger $m_{K\pi}$ region than previous iteration of this analysis
  - Allows for greater precision in S-wave and interference observables

Fit strategy

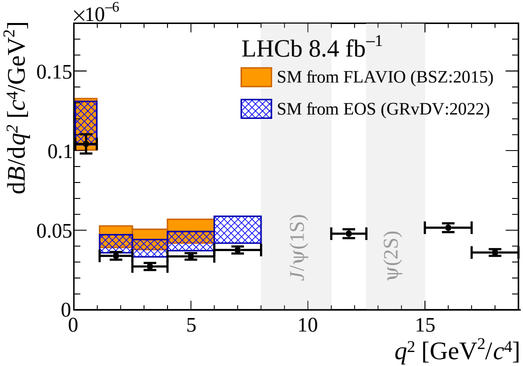
- Extract the angular observables and branching fraction via an extended unbinned maximum likelihood fit in bins of q^2
  - Use $m_{K\pi\mu\mu}$ for signal-background separation
  - Measure the three decay angles and $m_{K\pi}$ to obtain the angular observables
  - Split the data in B^0 and B^0 and t simultaneously
- Below: example fit projections ($6.0 < q^2 < 8.0\ \mathrm{GeV}^2/c^4$)



Results

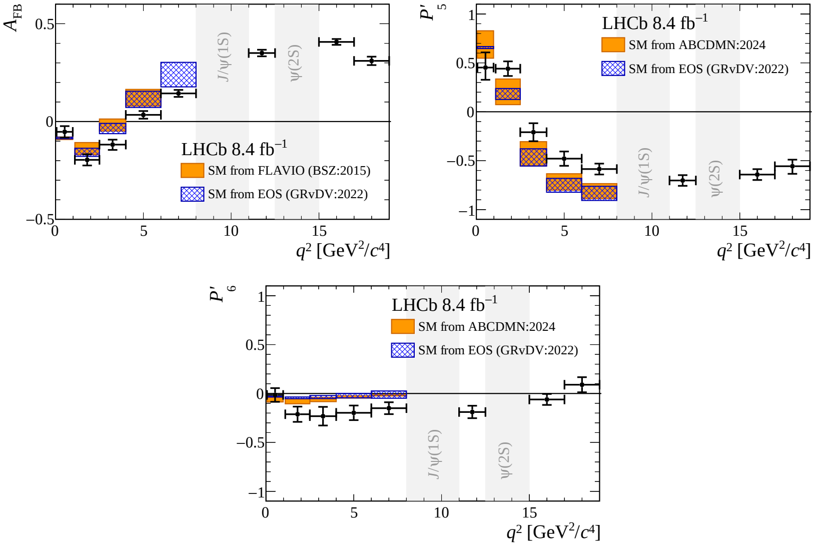
- Following slides show results from this analysis with the following SM predictions
  - BSZ: arXiv:1810.08132, JHEP 08 (2016) 098
  - GRvDV: EPJC 82 (2022) 569, JHEP 09 (2022) 133
  - ABCDMN: EPJC 83 (2023) 648

Results – Branching fraction



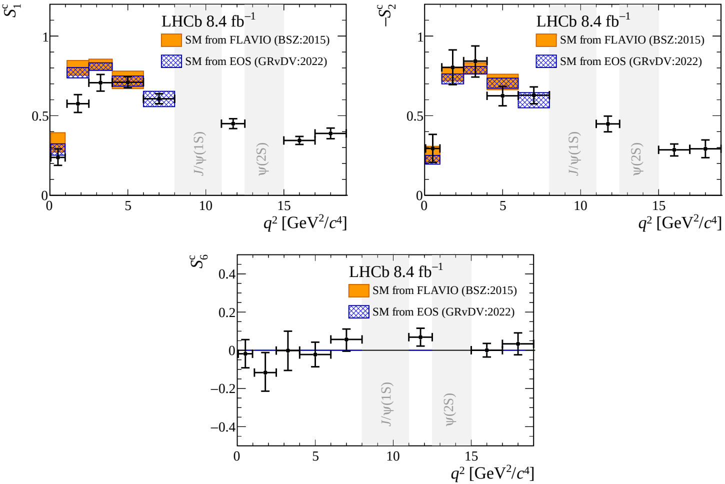
- $\frac{d\mathcal{B}}{dq^2}$ shows a coherent undershooting with respect to the theory prediction
- Experimental results are dominated by the normalisation branching fraction uncertainty
- Theoretical uncertainties are large

Results – CP-averaged observables



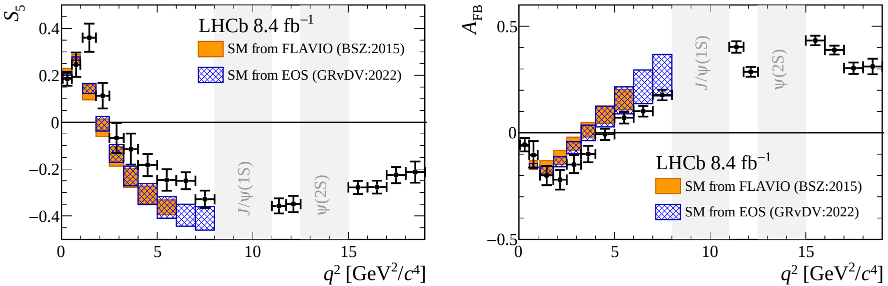
- Some local discrepancies with respect to the SM, e.g. A_{FB}, P'_5, P'_6

Results – CP-averaged observables – massive leptons



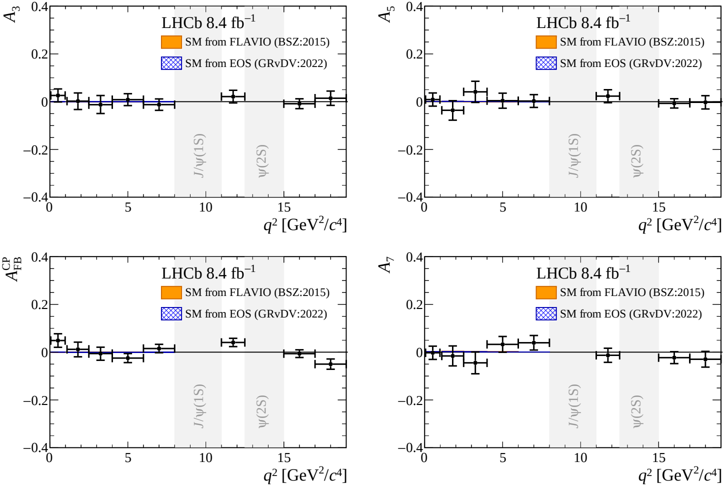
- Under massless leptons and no scalars, $S_1^c = -S_2^c$ and $S_6^c = 0$
- Relaxing this assumption unlocks sensitivity to all new physics scenarios!

Results – CP-averaged observables – half-sized q^2 bins



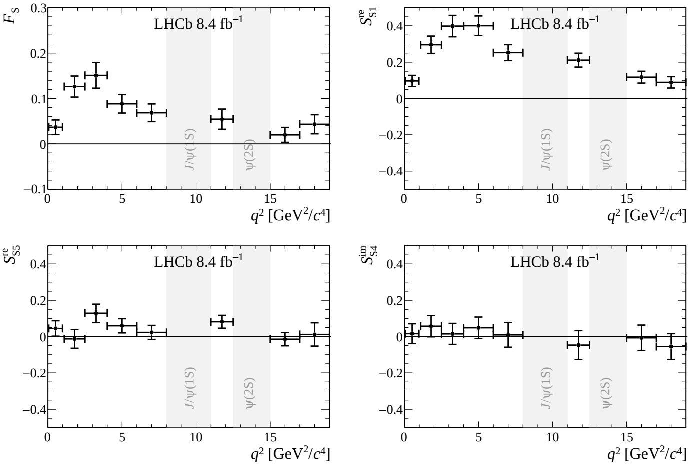
- Half-sized q^2 bins offer greater resolution in the q^2-dependence of the angular observables
- These are consistent with the normal sized bins

Results – CP-asymmetries



- No significant CP-asymmetry

Results – S-wave and interference observables



- New determination of F_S (fraction of S-wave) and first publication of interference observables, split into real and imaginary parts

EFT Interpretation

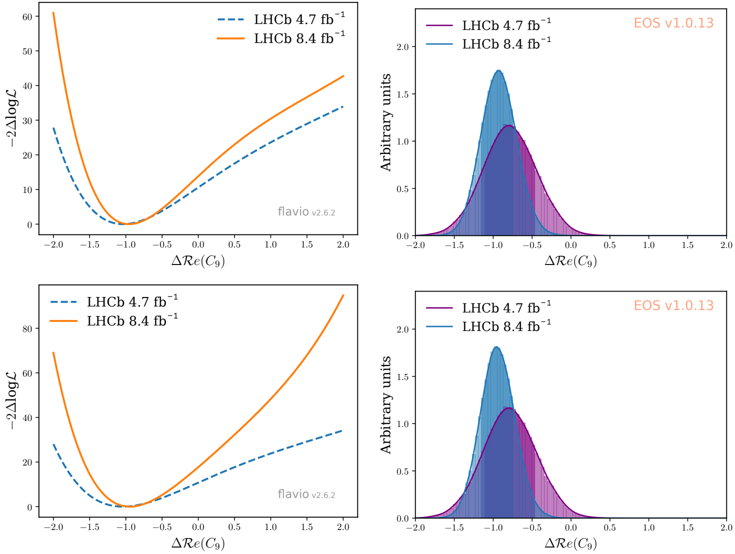
- Describe this decay in the Weak Effect Theory framework [JHEP 0901:019,2009], with vector and axial-vector couplings C_9 and C_{10}

$$O_9^{(0)} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu), \qquad O_{10}^{(0)} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- Perform fits using the flavio and EOS software packages, using results in the following regions
  - $0.06 < q^2 < 0.98$ GeV$^2/c^4$, $1.1 < q^2 < 2.5$ GeV$^2/c^4$, $2.5 < q^2 < 4.0$ GeV$^2/c^4$, $4.0 < q^2 < 6.0$ GeV$^2/c^4$, $15 < q^2 < 19$ GeV$^2/c^4$
- Consider two New Physics scenarios:
  - Re(C_9)
  - Re(C_9) and Re(C_{10})
- Consider two configurations
  - Angular observables
  - Angular observables and branching fraction
- Note: treatment of non-local issues is still of significant debate in the theory community
  - Thus exclude the $6.0 < q^2 < 8$ GeV$^2/c^4$ bin for these ts

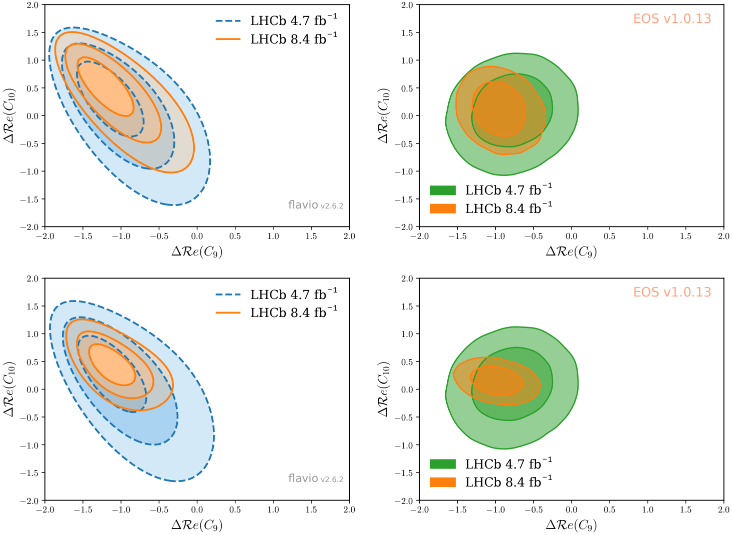
EFT Interpretation: $\Delta\mathrm{Re}(C_9)$

Top: Angular observables, bottom: angular observables and branching fraction



EFT Interpretation: $\Delta\mathrm{Re}(C_9)$ and $\Delta\mathrm{Re}(C_{10})$

Top: Angular observables, bottom: angular observables and branching fraction



EFT Interpretation

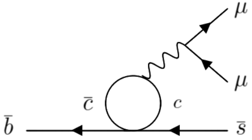
- Table below shows discrepancies with respect to the SM [arXiv:2512.10853]

	Angular observables	Angular observables and branching fraction
$\Delta\mathrm{Re}(C_9)$, flavio	3.6	4.1
$\Delta\mathrm{Re}(C_9)$, EOS	3.8	4.0

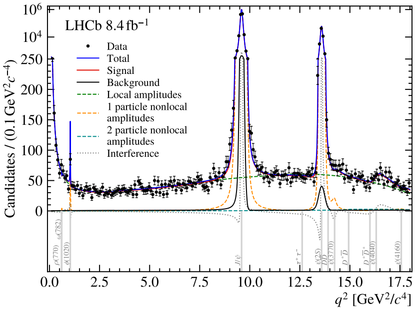
- Plenty more to be done with these results!
  - **CP-asymmetries** allows the **imaginary** parts of the Wilson coe cients to be deduced
  - Can also constrain the potential scalar contributions
  - Fits with the narrower q^2 bins con guration can also be investigated
- In this Wilson coefficient extraction, the uncertainties are now dominated by the theory nuisance parameters

- Analyses of this decay mode, unbinned in q^2, have been performed, where C_9 and C_{10} are measured directly from data [PRD 109 (2024) 052009], [PRL 132 (2024) 131801], [JHEP 09 (2024) 026]

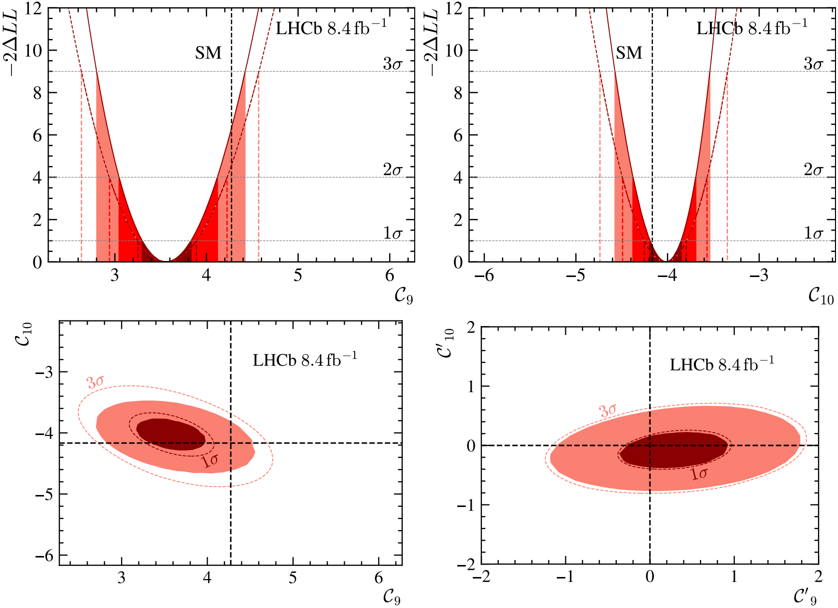
- Are long-distance e ects fully accounted for in the predictions?



  - Under intense theory debate
  -) Fit these contributions directly from data

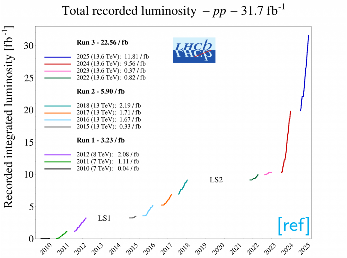


Unbinned analyses – results from [JHEP 09 (2024) 026]



Summary

- The binned and unbinned analyses point towards shifts in $\mathrm{Re}(C_9)$ with respect to the SM
- More information yet to be extracted from the results from the binned analysis
- Upgraded detector is performing extremely well, with each year of data corresponding to more than Run 1 and Run 2 combined!



- New suite of unbinned analyses being performed, e.g.[JHEP 06 (2015) 084, PRD 112 (2025), 016007]
- Exciting times ahead!

Back up

Differential rate - P-wave

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_l, \theta_K \ \ , \phi)\,,$$

where

$$\begin{aligned} I(q^2, \theta_\ell, \theta_K, \phi) = & I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell \\ & + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \\ & + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\ & + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi \\ & + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \end{aligned}$$

Angular coefficients

$$I_1^s = \frac{(2+\beta_\mu^2)}{4}\left[|\mathcal{A}_?^L|^2 + |\mathcal{A}_k^L|^2 + (L \to R)\right] + \frac{4m_\mu^2}{q^2}\mathrm{Re}\left(\mathcal{A}_?^L\mathcal{A}_?^R \ + \mathcal{A}_k^L\mathcal{A}_k^R \ \right)$$

$$I_1^c = |\mathcal{A}_0^L|^2 + |\mathcal{A}_0^R|^2 + \frac{4m_\mu^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(\mathcal{A}_0^L\mathcal{A}_0^R \ )\right] + \beta_\mu^2|A_S|^2$$

$$I_2^s = \frac{\beta_\mu^2}{4}\left[|\mathcal{A}_?^L|^2 + |\mathcal{A}_k^L|^2 + (L \to R)\right]$$

$$I_2^c = -\beta_\mu^2\left[|\mathcal{A}_0^L|^2 + (L \to R)\right]$$

$$I_3 = \frac{1}{2}\beta_\mu^2\left[|\mathcal{A}_?^L|^2 - |\mathcal{A}_k^L|^2 + (L \to R)\right]$$

$$I_4 = \frac{1}{\sqrt{2}}\beta_\mu^2\left[\mathrm{Re}(\mathcal{A}_0^L\mathcal{A}_k^L \ ) + (L \to R)\right]$$

$$I_5 = \sqrt{2}\beta_\mu\left[\mathrm{Re}(\mathcal{A}_0^L\mathcal{A}_?^L \ ) - (L \to R) - \frac{m_\mu}{\sqrt{q^2}}\mathrm{Re}(\mathcal{A}_k^L A_S + \mathcal{A}_k^R A_S)\right]$$

Angular coefficients

$$I_6^s = 2\beta_\mu \left[\mathrm{Re}(\mathcal{A}_k^L \mathcal{A}_?^L\ ) - (L \to R)\right]$$

$$I_6^c = 4\beta_\mu \frac{m_\mu}{\sqrt{q^2}}\,\mathrm{Re}\left[\mathcal{A}_0^L A_S + (L \to R)\right]$$

$$I_7 = \sqrt{2}\beta_\mu \left[\mathrm{Im}(\mathcal{A}_0^L \mathcal{A}_k^L\ ) - (L \to R) + \frac{m_\mu}{\sqrt{q^2}}\,\mathrm{Im}(\mathcal{A}_?^L A_S + \mathcal{A}_?^R A_S)\right]$$

$$I_8 = \frac{1}{\sqrt{2}}\beta_\mu^2 \left[\mathrm{Im}(\mathcal{A}_0^L \mathcal{A}_?^L\ ) + (L \to R)\right]$$

$$I_9 = \beta_\mu^2 \left[\mathrm{Im}(\mathcal{A}_k^L\ \mathcal{A}_?^L) + (L \to R)\right]$$

where $\beta_\mu = \sqrt{1 - 4m_\mu^2/q^2}$

Transversity amplitudes

$$A_{\perp L,R} = N\sqrt{2}\lambda^{1/2}\left[\left[(C_9^{e} + C_9^{e\prime}) \quad (C_{10}^{e} + C_{10}^{e\prime})\right]\frac{V(q^2)}{m_B + m_K} + \frac{2m_b}{q^2}(C_7^{e} + C_7^{e\prime})T_1(q^2)\right]$$

$$A_{\parallel L,R} = \quad N\sqrt{2}(m_B^2 \quad m_K^2)\left[\left[(C_9^{e} \quad C_9^{e\prime}) \quad (C_{10}^{e} \quad C_{10}^{e\prime})\right]\frac{A_1(q^2)}{m_B \quad m_K} + \frac{2m_b}{q^2}(C_7^{e} \quad C_7^{e\prime})T_2(q^2)\right]$$

Transversity amplitudes

$$A_{0L,R} = \quad \frac{N}{2m_K \quad \sqrt{q^2}} \Big\{ \Big[(C_9^{e} \qquad C_9^{e\ 0}) \quad (C_{10}^{e} \qquad C_{10}^{e\ 0}) \Big]$$

$$\Big[(m_B^2 \quad m_K^2 \qquad q^2)(m_B + m_K \quad) A_1(q^2) \quad \lambda \frac{A_2(q^2)}{m_B + m_K} \Big]$$

$$+ 2m_b (C_7^{e} \qquad C_7^{e\ 0}) \Big[(m_B^2 + 3m_K^2 \qquad q^2) T_2(q^2) \quad \frac{\lambda}{m_B^2 \quad m_K^2} T_3(q^2) \Big] \Big\}$$

$$A_t = \frac{N}{\sqrt{q^2}} \lambda^{1/2} \Big[2(C_{10}^{e} \qquad C_{10}^{e\ 0}) + \frac{q^2}{m_\mu}(C_P \quad C_P^0) \Big] A_0(q^2)$$

$$A_S = \quad 2N\lambda^{1/2}(C_S \quad C_S^0) A_0(q^2),$$

where

$$N = V_{tb} V_{ts} \left[\frac{G_F^2 \alpha^2}{3 \quad 2^{10} \pi^5 m_B^3} q^2 \lambda^{1/2} \beta_\mu \right]^{1/2},$$

with $\lambda = m_B^4 + m_K^4 \quad + q^4 - 2(m_B^2 m_K^2 \quad + m_K^2 \ q^2 + m_B^2 q^2)$ and $\beta_\mu = \sqrt{1 - 4m_\mu^2/q^2}$.

EFT Interpretation

- Can interpret these results in an EFT framework
- Perform an operator-product expansion, where the light degrees of freedom are described by the operators $\mathcal{O}_i$ and the heavy degrees of freedom are described by the Wilson coefficients C_i
- These Wilson coefficients are treated as generalised couplings, where these can capture effects from New Physics with energy scale $> \mu$, as described in [JHEP 0901:019,2009]
- Write the effective Hamiltonian for $b \to s\mu^+\mu$ transitions as

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\left(\lambda_t \mathcal{H}_{\text{eff}}^{(t)} + \lambda_u \mathcal{H}_{\text{eff}}^{(u)}\right)$$

with the CKM combination $\lambda_i = V_{ib}V_{is}$ and

$$\begin{aligned}
\mathcal{H}_{\text{eff}}^{(t)} &= C_1\mathcal{O}_1^c + C_2\mathcal{O}_2^c + \sum_{i=3}^{6} C_i\mathcal{O}_i + \sum_{i=7,8,9,10,P,S} \left(C_i\mathcal{O}_i + C_i^{\prime}\mathcal{O}_i^{\prime}\right), \\
\mathcal{H}_{\text{eff}}^{(u)} &= C_1(\mathcal{O}_1^c - \mathcal{O}_1^u) + C_2(\mathcal{O}_2^c - \mathcal{O}_2^u).
\end{aligned}$$

EFT Interpretation

where the operators are written as [JHEP 0901:019,2009]

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad \mathcal{O}_7' = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a}, \qquad \mathcal{O}_8' = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu), \qquad \mathcal{O}_9' = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu), \qquad \mathcal{O}_{10}' = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu),$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\mu), \qquad \mathcal{O}_S' = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\mu),$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\gamma_5 \mu), \qquad \mathcal{O}_P' = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\gamma_5 \mu),$$

Fit configurations

(i) Partially massive model, S_i basis, with CP-asymmetries fixed to zero

(ii) Partially massive model, $P_i^{(0)}$ basis, with CP-asymmetries fixed to zero

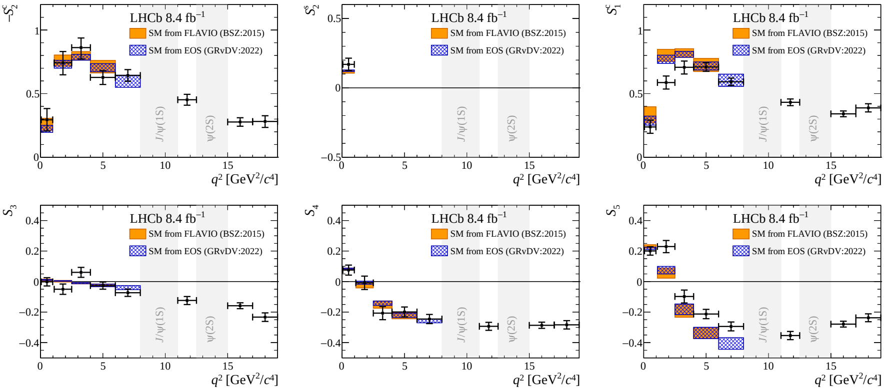
(iii) Fully massive model, S_i basis, with CP-asymmetries fixed to zero

(iv) Massless model, S_i basis, with both CP-averaged and CP-asymmetry observables floated

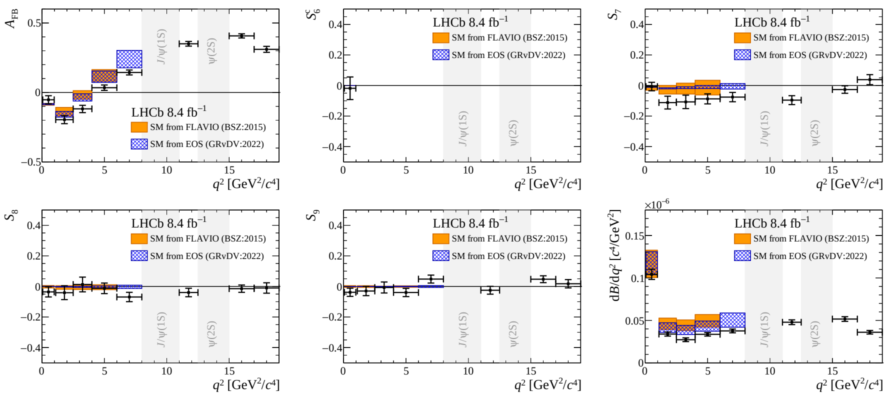
(v) Massless model, applied also in the $q^2 < 1.0\ \text{GeV}^2/c^4$ region, $P_i^{(0)}$ basis, with CP-asymmetries fixed to zero

(vi) Partially massive model, S_i basis, with CP-asymmetries fixed to zero and q^2 bins with widths half the size of those in the other configurations

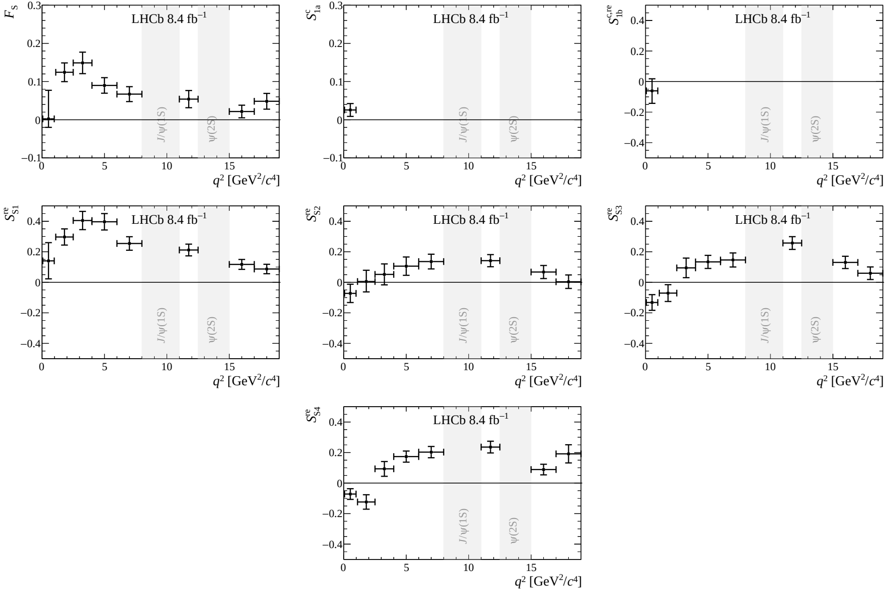
Results: fit configuration (i)



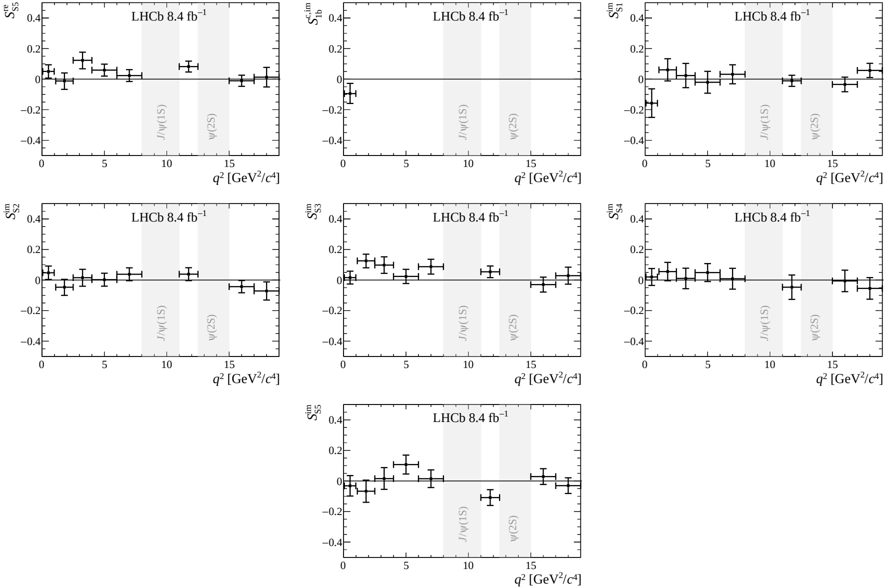
Results: fit configuration (i)



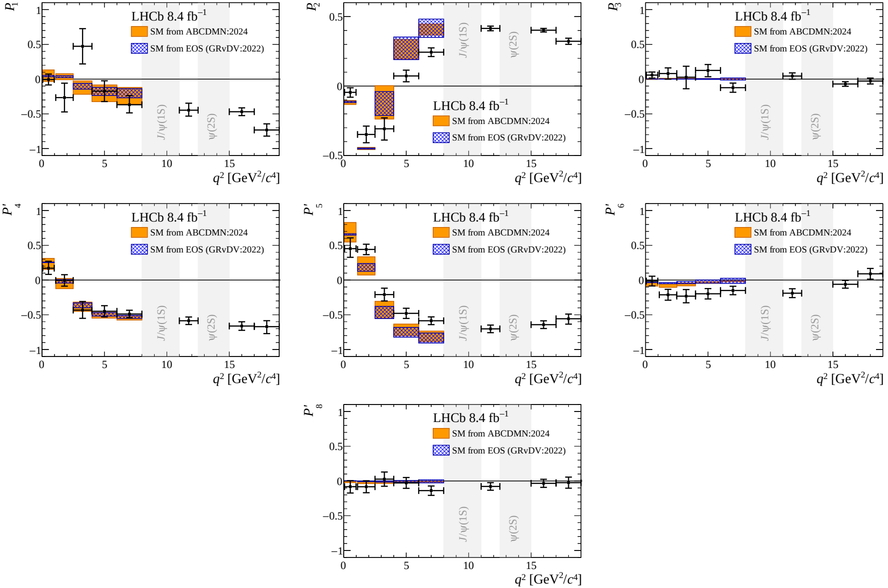
Results: fit configuration (i)



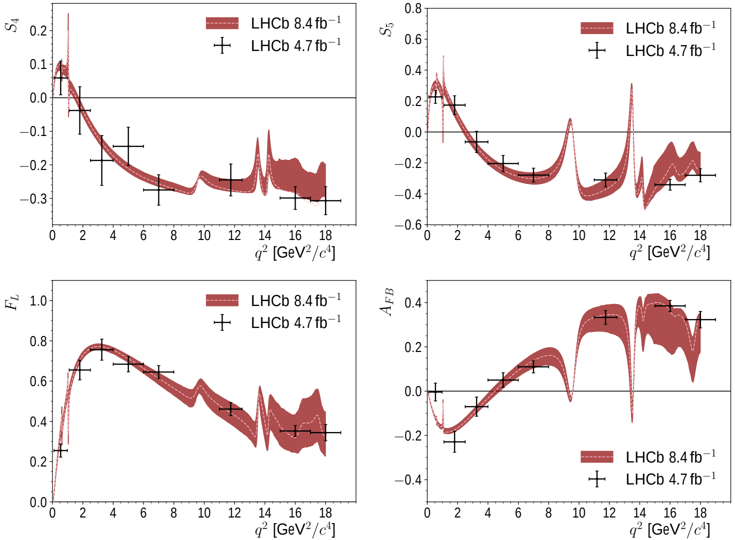
Results: fit configuration (i)



Results: fit configuration (ii)



Comparison between unbinned analysis [JHEP 09 (2024) 026] and binned angular analysis [PRL 125, 011802 (2020)]



Comparison between unbinned analysis [JHEP 09 (2024) 026] and binned angular analysis [PRL 125, 011802 (2020)]