Probing for New Physics with $b \to s\ell\ell$ Transitions at LHCb
EPS 2025

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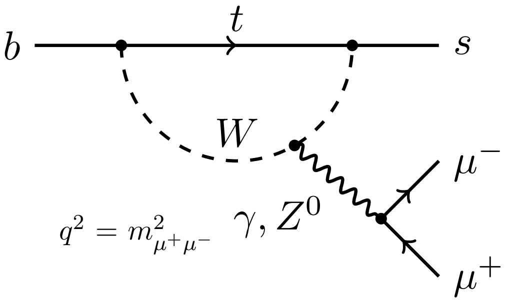
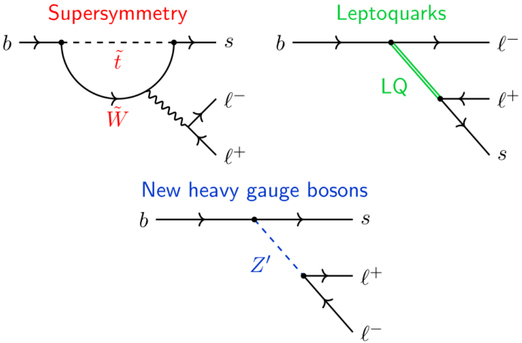
LHCb

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

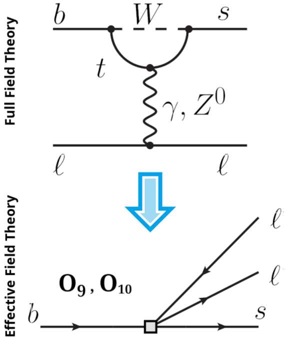
Search for New Physics with $b \to s\ell\ell$

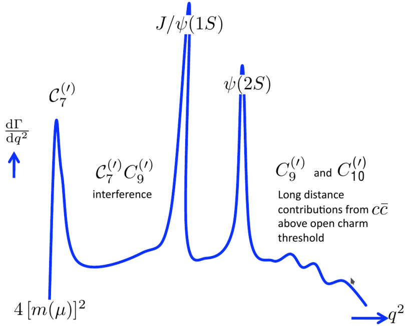




- b hadron decays via flavour changing neutral current (FCNC)
- High sensitivity to New Physics due to high suppression in SM
- Heavy NP particles can contribute significantly to observables, like branching fractions, angular observables and rates

Effective field theories for $b \to s\ell\ell$





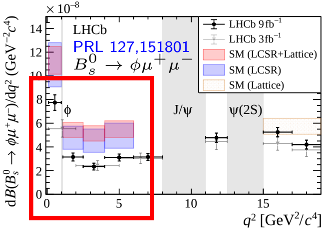
Effective couplings in $b \to s\ell^+\ell^-$ transitions

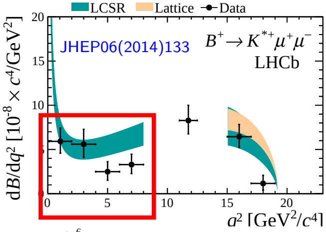
	Wilson coefficient	Operator
γ-penguin	$C_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$C_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$C_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$C_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$C_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

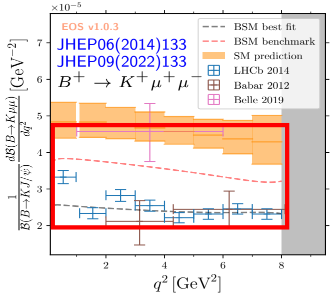
- Model-independent description of FCNC transitions in effective theory
- Physics encoded in effective couplings Wilson Coefficients and local operators

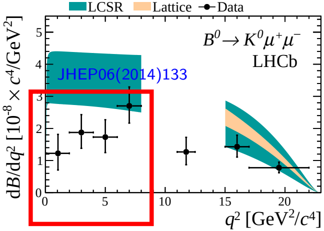
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i f^i_{CKM}\, \boxed{\mathcal{C}_i}\, \boxed{\mathcal{O}_i}$$

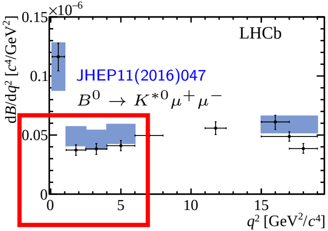
$b \to s\ell\ell$ anomalies: Branching fractions









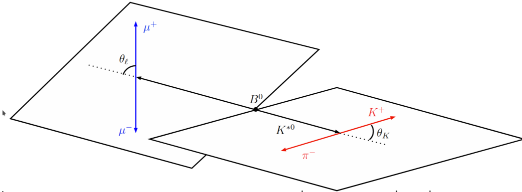


- Branching fractions found to be consistently below the SM expectation in $b \to s\ell\ell$
- Significant theory uncertainty from local + non-local hadronic form factors

$b \to s\ell\ell$ anomalies: Angular analysis of $B \to V(\to h^+h^-)\ell^+\ell^-$

- Decay rate parameterized in three angles and q^2
- Measurement of angular observables in bins of q^2

$q^2 = (\text{inv. dimuon mass})^2$



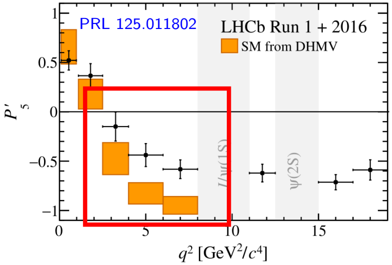
$$\frac{1}{N}\frac{d^4\Gamma + \bar{\Gamma}}{d\vec{\Omega}\, dq^2} = \frac{9}{32\pi}\sum_i S_i f_i(\theta_l, \theta_K, \phi)$$

Spherical harmonics

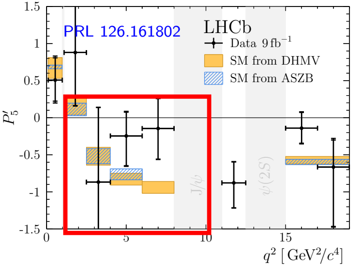
- Optimized P_i observables
  - Less form factor dependent
  - Remaining theory uncertainty from charm-loops

$$P_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

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

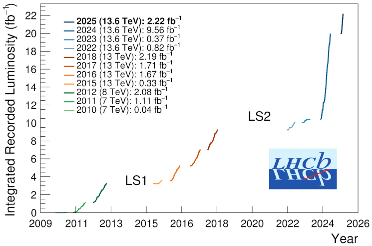


$B^+ \to K^{*+}\mu^+\mu^-$

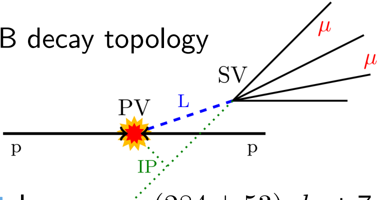


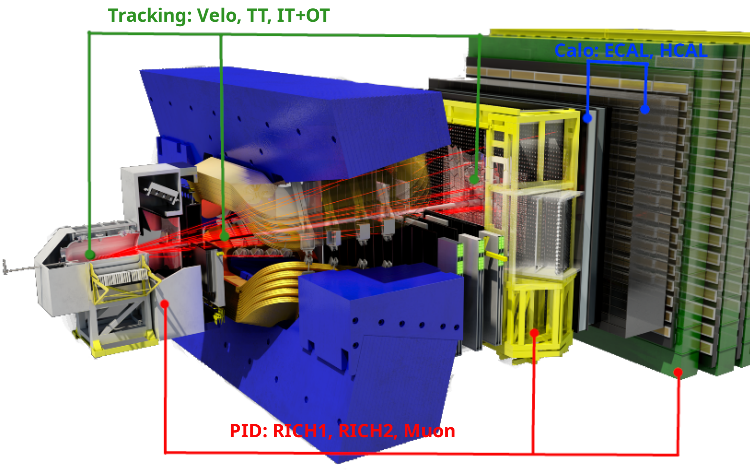
The LHCb experiment

Run 1: $3\,\text{fb}^{-1}$, Run 2: $6\ \text{fb}^{-1}$



B decay topology

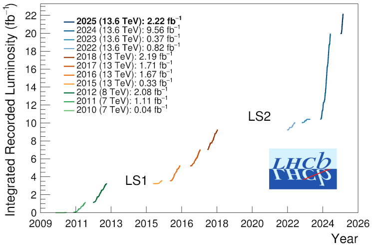


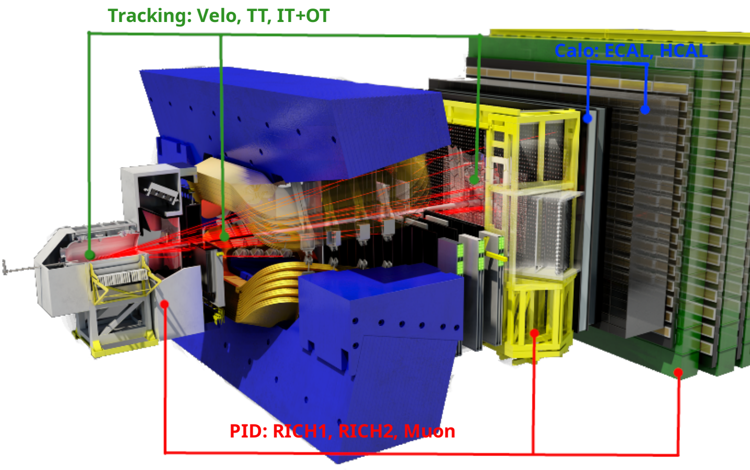


- Large $\sigma_{b\bar{b}}$: $(284 \pm 53)\mu b$ at 7 TeV and $(495 \pm 52)\mu b$ at 13 TeV
- Excellent IP resolutions $\approx 20\mu m$ to identify B decays. $\Delta p/p = 0.5 - 1\%$

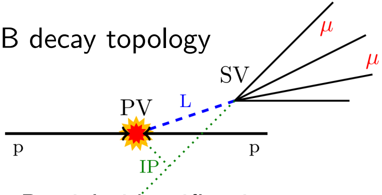
The LHCb experiment

Run 1: $3\,\mathrm{fb}^{-1}$, Run 2: $6\ \mathrm{fb}^{-1}$





B decay topology



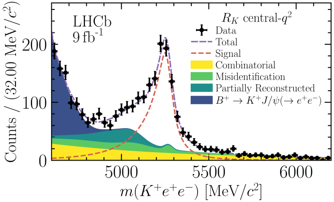
- Particle identification: $\epsilon_{K\to K} \approx 95\%, \epsilon_{\pi\to K} \approx 5\%$ and $\epsilon_{\mu\to\mu} \approx 97\%, \epsilon_{\pi\to\mu} \approx 1-3\%$
- Trigger thresholds: $p_T(\mu) > 1.8\,\mathrm{GeV}, E_T(e) > 3.0\,\mathrm{GeV}$

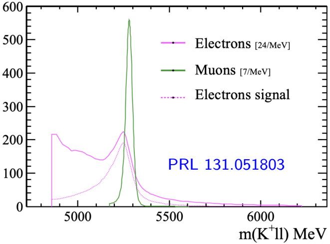
Angular Analysis of $B \to V(\to h^+h^-)e^+e^-$

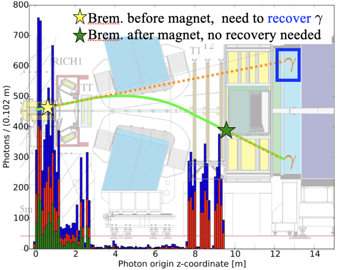
Analysis of $B \to V(\to h^+h^-)e^+e^-$

- $B^0 \to K^{*0}\mu\mu$ angular analysis displayed tension with SM (3.3σ),[PRL 125.011802]
- LHCb results indicate that LFU is respected [PRL 131.051803]
- LFU test in angular observables provides additional sensitivity

PRD 108.032002 PRL 131.051803







Experimental challenges for electron modes

1. Lower e trigger efficiencies due to higher thresholds
2. Degraded momentum resolution due to Bremsstrahlung
3. Background modeling more critical compared to muons

Angular analysis of the decay $B_s \to \phi e^+ e^-$

LHCb-PAPER-2025-006

Analysis strategy: Angular analysis of the decay $B_s \to \phi e^+ e^-$

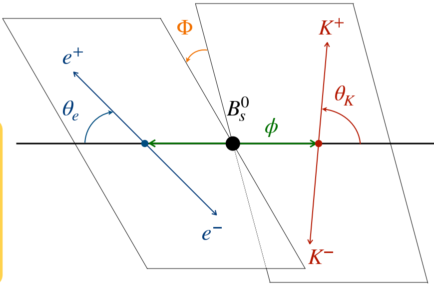
LHCb-PAPER-2025-006

- Extraction of the angular observables F_L,A_6,S_3 and A_9 in three q^2 bins
- Full LHCb Run 1 and Run 2 data sample ($\mathcal{L}_{int} = 9\,\text{fb}^{-1}$)

$$\frac{d^4[\Gamma(t)+\bar{\Gamma}(t)]}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} = \sum_i \left[J_i(q^2,t)+\bar{J}_i(q^2,t)\right] f_i(\cos\theta_K,\cos\theta_\ell,\phi)$$

- Signal statistics small due to electrons in final state
  - Measurement performed decay-time integrated
  - Two fits on folded angular distributions

$$\frac{1}{N}\frac{d^2[\Gamma+\bar{\Gamma}]}{dq^2 d\cos\theta_K d\cos\theta_\ell} = \frac{9}{16}\Big[\frac{3}{4}(1-F_L)sin^2(\theta_K)(1+\frac{1}{3}cos(2\theta_l)) + F_L cos^2(\theta_K)(1-2cos(2\theta_\ell)) + A_6 sin^2(\theta_K)cos(\theta_\ell)\Big]$$



Analysis strategy: Angular analysis of the decay $B_s \to \phi e^+ e^-$

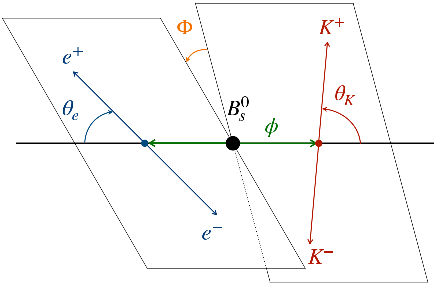
LHCb-PAPER-2025-006

- Extraction of the angular observables F_L, A_6, S_3 and A_9 in three q^2 bins
- Full LHCb Run 1 and Run 2 data sample ($\mathcal{L}_{int} = 9\,\text{fb}^{-1}$)

$$\frac{d^4[\Gamma(t) + \bar{\Gamma}(t)]}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} = \sum_i \left[J_i(q^2, t) + \bar{J}_i(q^2, t)\right] f_i(\cos\theta_K, \cos\theta_\ell, \phi)$$

- Signal statistics small due to electrons in final state
  - Measurement performed decay-time integrated
  - Multiple fits on reduced angular distributions

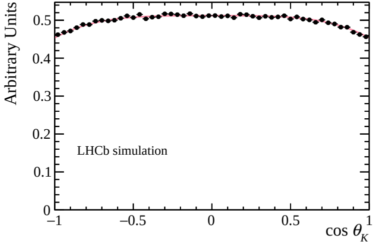
$$\frac{1}{N}\frac{d^2[\Gamma + \bar{\Gamma}]}{dq^2 d\Phi} = \frac{1}{2\pi}[1 + S_3 cos(2\Phi) + A_9 sin(2\Phi)]$$



Analysis strategy: Angular analysis of the decay $B_s \to \phi e^+ e^-$

- Narrow $\phi(1020)$ resonance allows for clean selection
- Angles + q^2 distorted by reconstruction and selection

$$\epsilon = \sum_{k,l,m,n,o} c_{klmno} P(cos(\theta_l), k) P(cos(\theta_K), l) P(q^2, n) cos(m\Phi)$$



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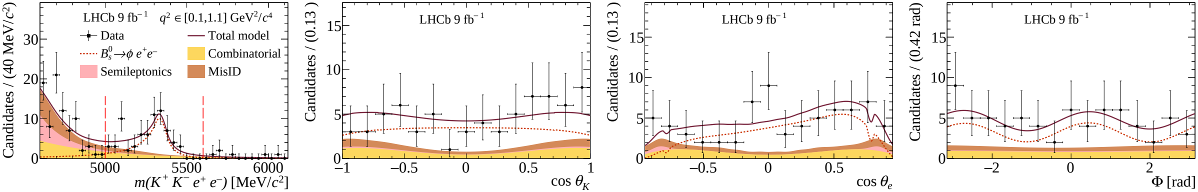
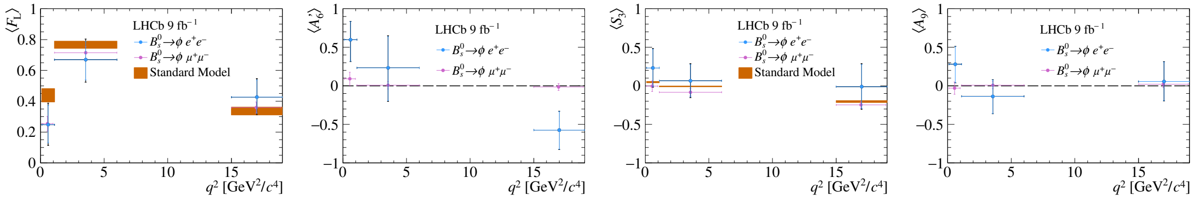
- Decay-time acceptance parameterized from simulation
- Residual backgrounds modeled using shapes from corrected simulation



Results: Angular analysis of the decay $B_s \to \phi e^+ e^-$

LHCb-PAPER-2025-006

- Observable coverage corrected using the Feldman-Cousin method [PRD 57.3873]
- Results found to be in good agreement with the SM prediction [arXiv: 1810.08132]
- Good agreement with angular observables extracted from $B_s \to \phi\mu^+\mu^-$ [JHEP11(2021)043]
- Improvement of sensitivity expected with larger data samples in future



Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

JHEP06(2025)140

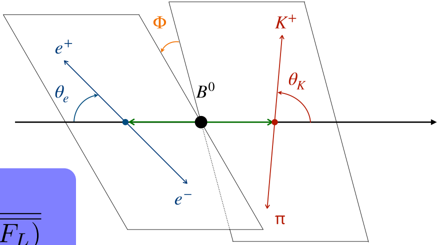
Analysis strategy: Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

JHEP06(2025)140

- Extraction of the angular observables in the q^2 bin from 1.1-6.0 GeV^2/c^4
- Full LHCb Run 1 and Run 2 data sample ($\mathcal{L}_{int} = 9\,\mathrm{fb}^{-1}$)

$$\frac{1}{N}\frac{d^4[\Gamma+\bar{\Gamma}]}{dq^2 d\cos\theta_K d\cos\theta_\ell d\phi} = \sum_i S_i f_i(\cos\theta_K, \cos\theta_\ell, \phi)$$

- Initial B flavor tagged via charge of final state K
  $\Rightarrow$ Access to full set of observables: F_L, S_3, S_4, S_5, A_{FB}, S_7, S_8, S_9
- Also extracting observables in the optimized P basis



$$P_1 = \frac{2S_3}{1-F_L} \quad P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L} \quad P_3 = \frac{-S_9}{1-F_L} \quad P_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

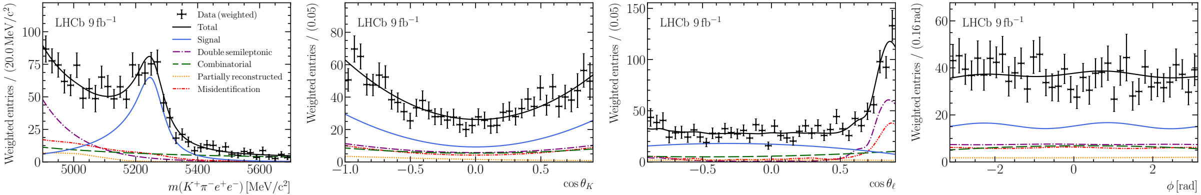
Analysis strategy: Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

- Select events in $m(K\pi)$ window around K^{*0} mass
- Distortion of angles and q^2 again modeled from corrected simulation

$$\epsilon = \sum_{k,l,m,n,o} c_{klmno} P(cos(\theta_l), k) P(cos(\theta_K), l) P(q^2, n) F(\Phi, m)$$

- Background components parameterized in the fit
  - Double semi-leptonic and mis-ID backgrounds modeled from data
  - Partially reconstructed backgrounds modeled from simulation

JHEP06(2025)140



Results: Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

- Considerable systematic uncertainty from background model (up to the level of σ_{stat})
- Most precise measurement of angular observables in central-q^2 to date [PRL 118.111801]
- Results in agreement with the SM predictions (largest discrepancy $\approx 2\sigma$ in F_L and A_{FB})

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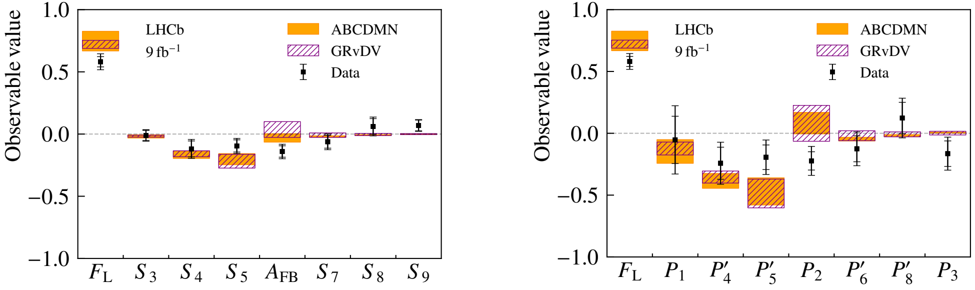

Results: Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

- Test of lepton flavor universality performed
- Good agreement with observables from $B^0 \to K^{*0}\mu^+\mu^-$ mode [PRL 125.011802]
  - No sign of lepton-flavor-violating effects

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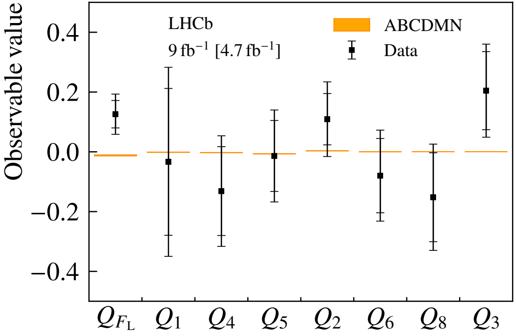


$$\mathcal{Q}_i = P_i^{\mu} - P_i^{e}$$

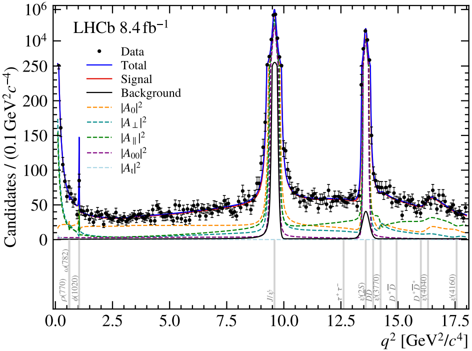
Analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

JHEP09(2024)026

Analysis strategy: Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays

- Binned $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis displayed tension with SM (3.3σ) [PRL 125.011802]
- Size of non-local contributions still debated
- Approach: Model-dependent unbinned analysis that parametrizes non-local effects
- Recent unbinned amplitude analysis performed by LHCb in partial q^2 range [PRL 132.131801]

- New: Fit full q^2 range including J/ψ and $\psi(2S)$
  Local and non-local amplitudes measured



JHEP09(2024)026

Analysis strategy: Decay rate parameterization

- Decay described by three decay angles $\cos\theta_\ell$, $\cos\theta_K$, $\phi + q^2$
- 4-dimensional differential decay rate used as signal model

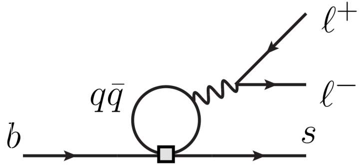
$$\frac{d^4\overleftrightarrow{\Gamma}(B^0 \to K\pi\mu\mu)}{dq^2 d\vec{\Omega}} = \frac{9}{32}\sum_i \overleftrightarrow{J}_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi) G_i$$

J_i : Angular coefficients | *f_i : Spherical harmonics* | *G_i : $m(K\pi)$ line shape*

- Angular coefficients dependent on $C_9^{(\prime)}, C_{10}^{(\prime)}$ and local form factors
- Effective WC $C_9^\lambda = C_9 + Y_{q\bar{q},\lambda}(q^2)$ absorbs non-local effects

1. Non-local diagrams (e.g. charm-loops)
2. Vector resonances: $\rho(770), w(782), \phi(1020), J/\psi, \psi(2S),$ $\psi(3770), \psi(4040), \psi(4160)$
3. Open charm pairs: $(D\bar{D}, D^\star\bar{D}, D^\star\bar{D}^\star)$

Quark loop contributions



JHEP09(2024)026

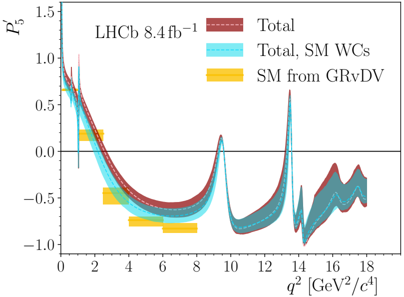
Results: Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays

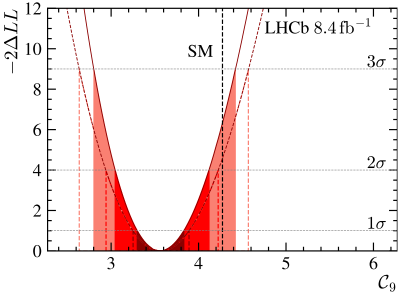
JHEP09(2024)026

- Wilson Coefficients $C_9^{(\prime)}, C_{10}^{(\prime)}$: C_9 in tension with SM at 2.1σ
- Non-local contributions relevant, but cannot fully explain tension
- First parameterization of $b \to s\tau\tau(\to \gamma^* \to \mu\mu)$ rescattering
- Results sensitive to form factor constraints
  - Improved theory predictions required

Wilson Coefficient fit results	
C_9	$3.56 \pm 0.28 \pm 0.18$
C_{10}	$-4.02 \pm 0.18 \pm 0.16$
C_9'	$0.28 \pm 0.41 \pm 0.12$
C_{10}'	$-0.09 \pm 0.21 \pm 0.06$
$C_{9\tau}$	$(-1.2 \pm 2.6 \pm 1.0) \times 10^2$

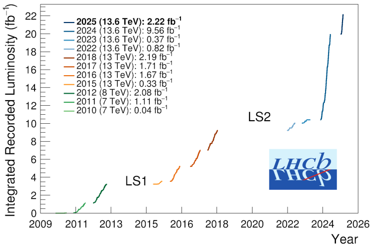
Wilson Coefficient	SM
C_9	4.27
C_{10}	−4.17
C_9'	0.0
C_{10}'	0.0
$C_{9\tau}$	4.27





Conclusion and Outlook

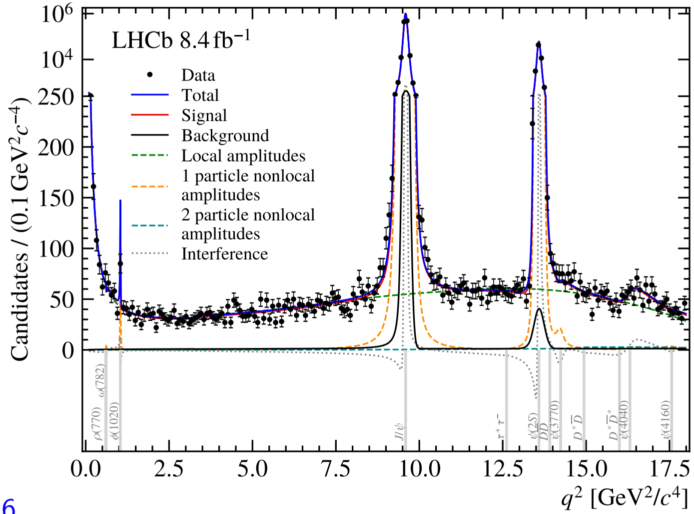
- Flavor anomalies in $b \to s\ell\ell$ angular observables and rates persist
- Angular observables in $B \to V(\to h^+h^-)e^+e^-$ in good agreement with muon modes
  - More data required to improve sensitivity
- Model-dependent measurement of local and non-local amplitudes in $B^0 \to K^{*0}\mu\mu$
  - Non-local contributions can't fully explain tension with SM
  - Binned angular analysis update coming very soon



- LHCb Run 3 data taking is ongoing
- Already collected more than 13 fb^{-1} in Run 3
- Significant improvement in precision expected for $b \to s\ell\ell$ observables
- Increased sensitivity to more suppressed $b \to dll$ transitions

Backup

Results: Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays



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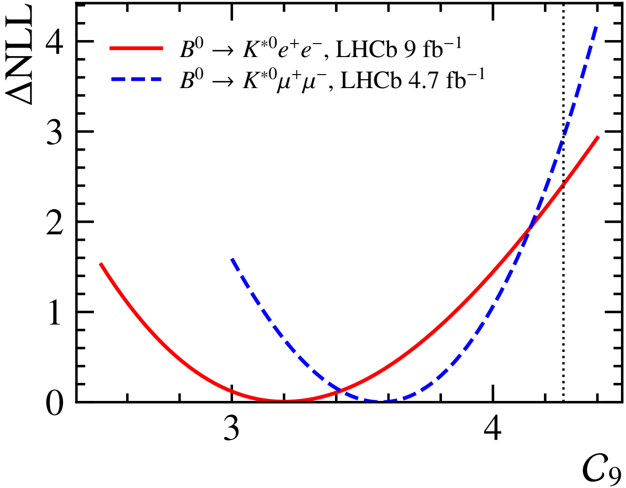
Results: Amplitude analysis of $B^0 \to K^{*0}ee$ decays



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