Precision analyses of $b \to s\mu^+\mu^-$ decays

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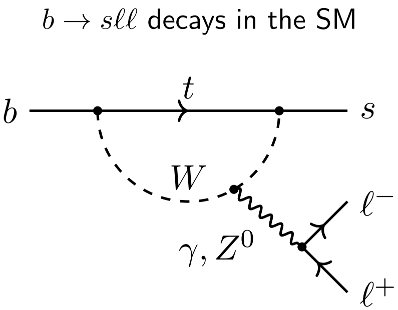
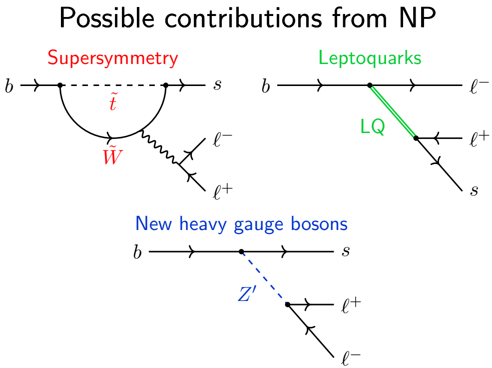
MITP WS: Flavourful Opportunities in Semileptonic B Decays

July 7nd 2026

Rare $b\to s\ell^+\ell^-$ decays as sensitive probes for NP

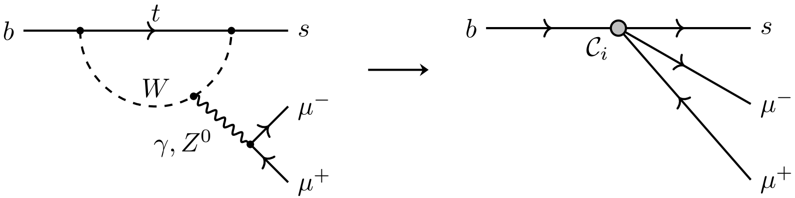




- Rare semileptonic decays heavily (loop-)suppressed in the SM
- New heavy particles can significantly contribute and affect $b\to s\ell^+\ell^-$ decays
- Many observables accessible that allow to probe nature of potential NP: Decay rates, Angular observables, Asymmetries in rates

Rare $b \to s\ell^+\ell^-$ decays in effective field theory

Full theory Effective description



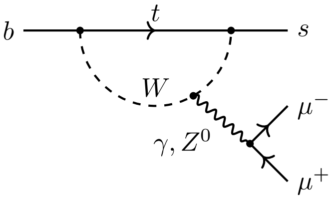
$$\mathcal{H}_{\text{eff}} = \frac{4G_{\text{F}}}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Effective coupling, *Wilson coefficient* Local operator with specific Lorentz structure

- Model-independent description in effective field theory
- Strong suppression in the SM, could be lifted for NP
- Λ_{NP} up to $\mathcal{O}(100\,\text{TeV})$ reachable
- $b \to s\ell\ell$ decays probe several $\mathcal{O}_i^{(\text{NP})}$

Rare $b \to s\ell^+\ell^-$ decays in effective field theory

Rare decays in the SM



$$\mathcal{A}^{\mathrm{SM}} \propto \frac{4G_{\mathrm{F}}}{\sqrt{2}} V_{\mathrm{tb}} V_{\mathrm{ts}}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

weak trans. CKM suppression loop suppression

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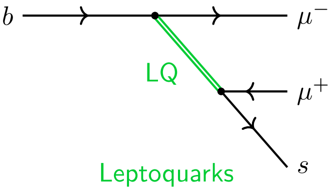
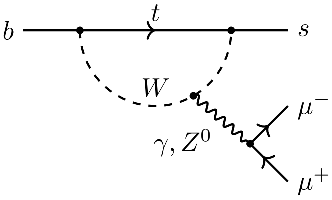
Possible NP contribution



$$\mathcal{A}^{\mathrm{NP}} \propto \frac{\kappa}{\Lambda_{\mathrm{NP}}^2} \mathcal{O}_i$$

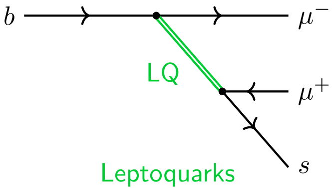
Rare $b \to s\ell^+\ell^-$ decays in effective field theory

Rare decays in the SM



$$\mathcal{A}^{\rm SM} \propto \frac{1}{(35\ \rm TeV)^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Possible NP contribution

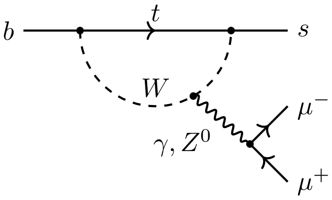


$$\mathcal{A}^{\rm NP} \propto \frac{\kappa}{\Lambda_{\rm NP}^2} \mathcal{O}_i$$

- Model-independent description in effective field theory
- Strong suppression in the SM, could be lifted for NP
- $\Lambda_{\rm NP}$ up to $\mathcal{O}(100\,\rm TeV)$ reachable
- $b \to s\ell\ell$ decays probe several $\mathcal{O}_i^{\rm (NP)}$

Rare $b \to s\ell^+\ell^-$ decays in effective field theory

Rare decays in the SM



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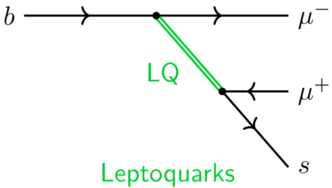

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Wilson coefficient		Operator
γ-penguin[1]	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

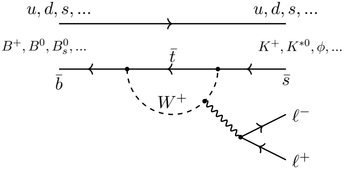
$b \to s\gamma$

$b \to s\ell\ell$

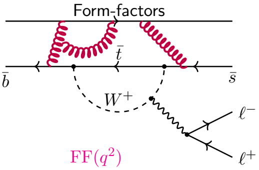
$B_s^0 \to \mu^+\mu^-$

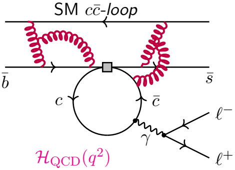
Observables in rare $b \to s\ell\ell$ decays and their cleanliness

Quarks bound in hadrons, *e.g.*



Hadronic uncertainties

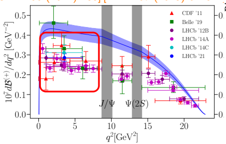




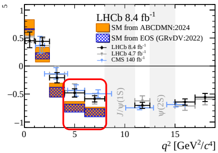
$b \to s\ell\ell$ Observables

Increasing precision of SM prediction

[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



[arXiv:2512.18053]



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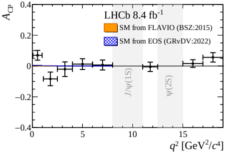
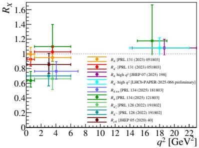




Branching fractions
affected by form-factors and $c\bar{c}$-loop

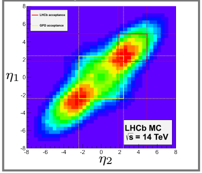
Angular observables
affected by $c\bar{c}$-loop

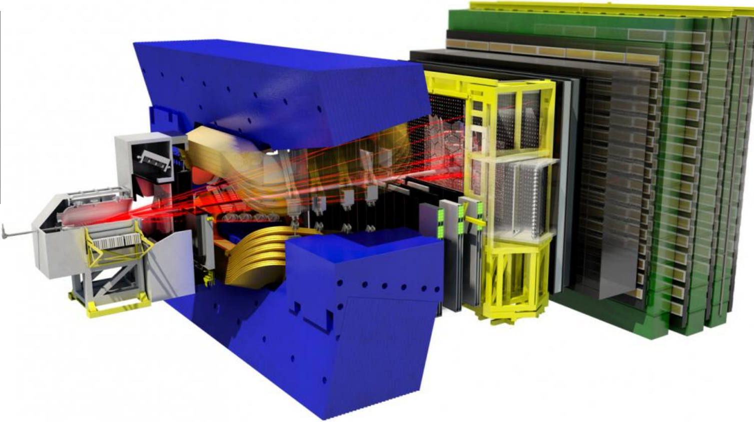
CP-asymmetries
clean

Lepton Universality Tests
clean

The LHCb detector: Optimized for heavy flavour

$b\bar{b}$ production





- Large $\sigma_{b\bar{b}}$: $(495 \pm 52)\,\mu\mathrm{b}$ at $13\,\mathrm{TeV}$ [JHEP 10 (2015) 172] predominantly in forward direction
  $\Rightarrow$ single-arm forward spectrometer with unique $2 < \eta < 5$ coverage [IJMP A30 (2015) 1530022] [JINST 19 (2024) P05065]
- Excellent IP resolution $\sim 20\,\mu\mathrm{m}$ to identify B decay vertices, $\Delta p/p = 0.5 - 1\%$
- Particle identification: $\epsilon_{K\to K} \sim 95\%$, $\epsilon_{\pi\to K} \sim 5\%$ and $\epsilon_{\mu\to\mu} \sim 97\%$, $\epsilon_{\pi\to\mu} \sim 1-3\%$
- Low trigger thresholds $\to$ high ϵ_{sig}, Full software trigger in Run 3 at $40\,\mathrm{MHz}$

The LHCb detector: Optimized for heavy flavour

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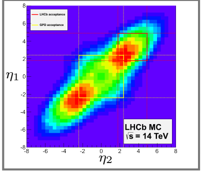
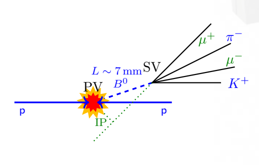
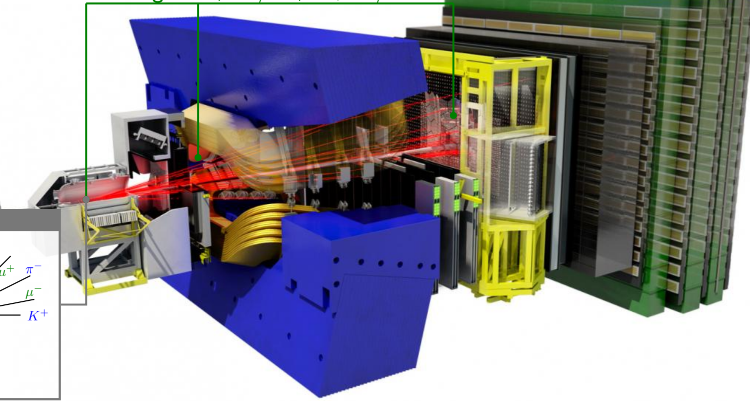


Heavy flavour signature



Tracking: Velo, TT/UT, IT+OT/SciFi



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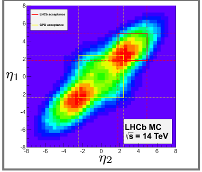

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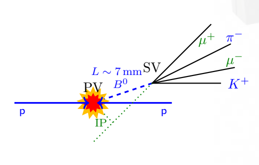

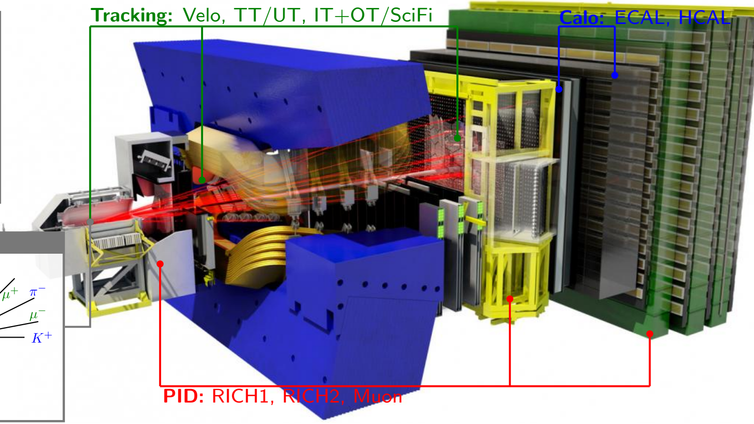

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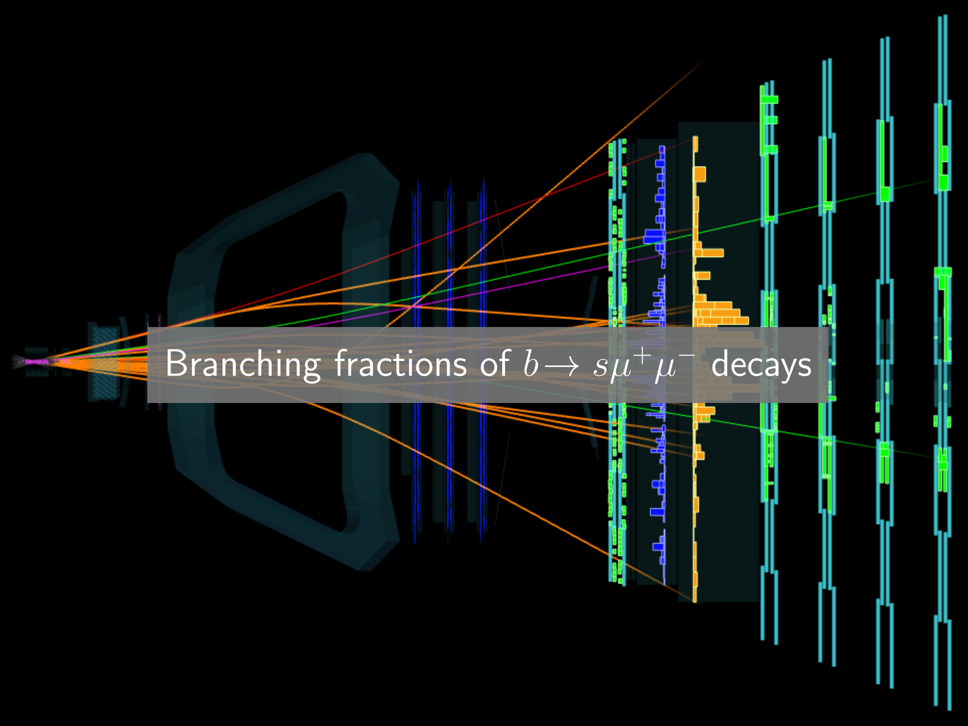
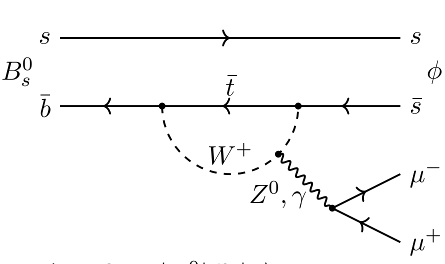
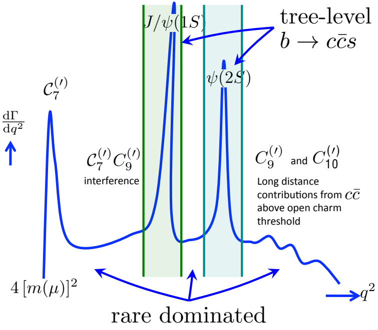
Branching fractions of $b \to s\mu^+\mu^-$ decays



Branching fraction of $B_s^0 \to \phi\mu^+\mu^-$

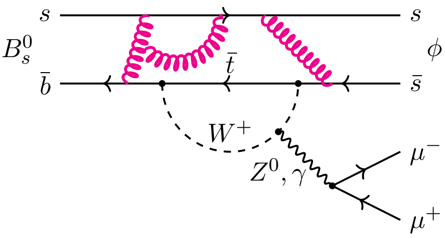


$\mathcal{A} \propto \mathcal{C}_i \times \langle B_s^0|\mathcal{O}_i|\phi\rangle$

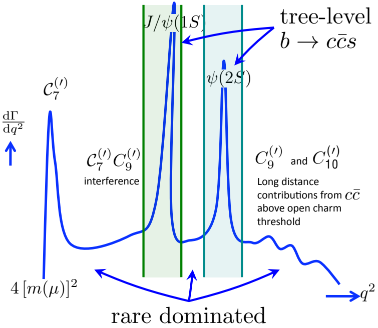


- Branching fraction of semileptonic $b \to s\mu^+\mu^-$ decays can be affected by NP
- Central: $q^2 = m(\ell^+\ell^-)^2$, different operators contribute depending on q^2
- At $q^2 = m^2_{J/\psi}$ important tree-level $b \to c\bar{c}s$ normalisation mode $B_s^0 \to J/\psi\,\phi$
- Measurements of norm. mode $\mathcal{B}(B \to J/\psi\,X)$ from Belle 2 would be useful
- SM predictions directly affected by significant form factor uncertainties
  Low q^2: LCSRs [PRD 71 (2005) 014029] [JHEP 08 (2016) 98] [PRD 75 (2007) 054013] [JHEP 09 (2010) 089] High q^2: Lattice [PRD 89 (2014) 094501] [PRD 88 (2013) 054509]

Branching fraction of $B_s^0 \to \phi\mu^+\mu^-$



$\mathcal{A} \propto \mathcal{C}_i \times \mathrm{FF}(q^2) + \mathcal{H}_{\mathrm{QCD}}(q^2)$



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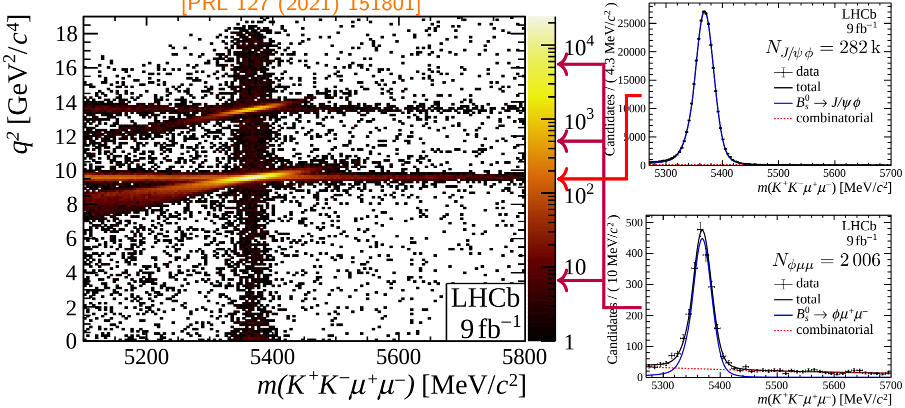
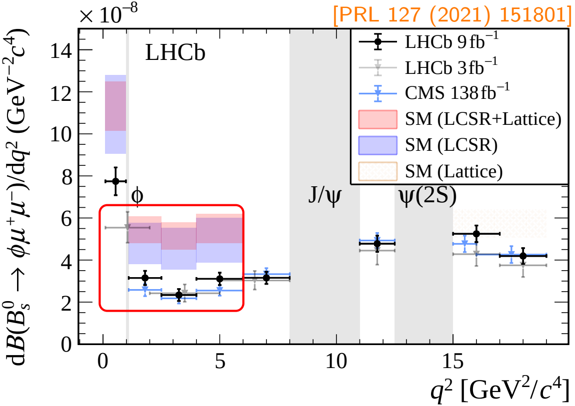
$B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$ with LHCb

[PRL 127 (2021) 151801]



- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto q^2 range $[8, 11] \cup [12.5, 15]\,\mathrm{GeV}^2/c^4$ containing tree level decays $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to \psi(2S)\phi$ (important control modes)
- Signal clearly visible as vertical band after the full selection

$B_s^0 \to \phi\mu^+\mu^-$ branching fraction

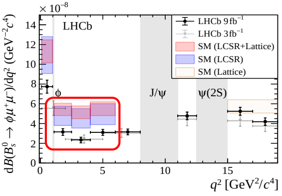


SM LCSR
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 8]
SM LCSR+Lattice
[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

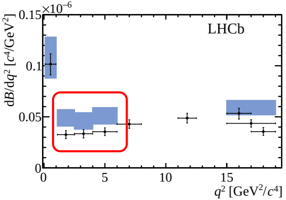
- LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- Tension with SM at $3.6\,\sigma$ (LCSR+Lattice) and $1.8\,\sigma$ (LCSR only)
- Recent confirmation from CMS [CMS-PAS-BPH-23-003]

Consistently low $\mathcal{B}$ found for $b \to s\mu^+\mu^-$ decays

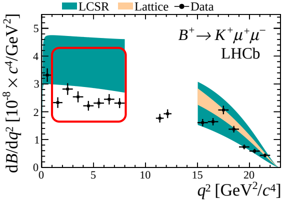
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



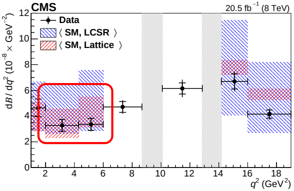
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



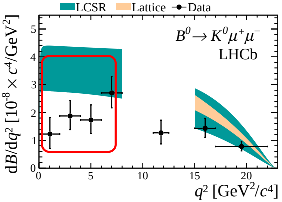
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



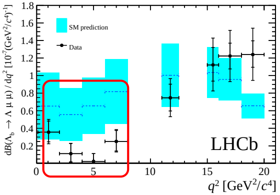
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



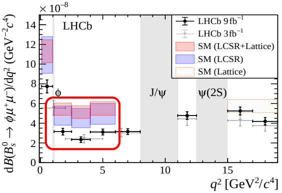
LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



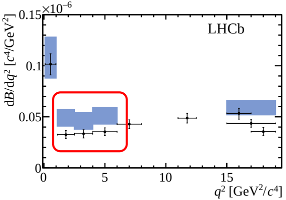
- Data consistently below SM predictions, tensions at $1\text{–}3\sigma$ level
  but significant hadronic uncertainties from form-factors and charm-loop
- Important results from Lattice QCD [HPQCD, PRD 107 (2023) 1]
- $\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)$ update $(6.3 \pm 1.3) \times 10^{-4}$ to $(3.34 \pm 0.31) \times 10^{-4}$ [arXiv:2509.12805]
  Nb. [PRD 101 (2020) 035023] derived $(3.7 \pm 1.0) \times 10^{-4}$ using f_{Λ_b} from TeVatron only

Consistently low $\mathcal{B}$ found for $b \to s\mu^+\mu^-$ decays

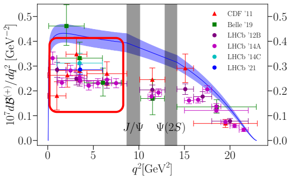
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



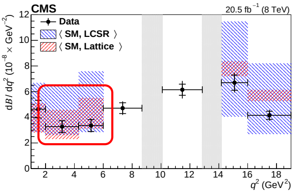
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



$B^+ \to K^+\mu^+\mu^-$ [HPQCD, PRD 107 (2023) 1]



CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



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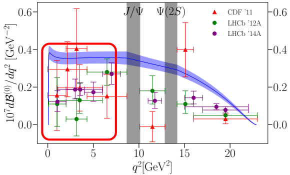
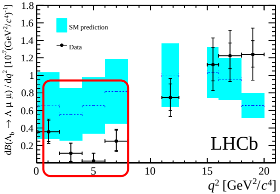


LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



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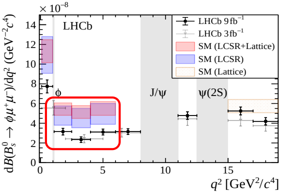
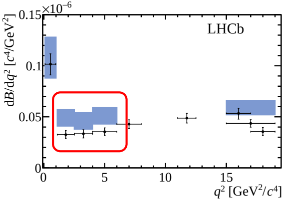
- Important results from Lattice QCD [HPQCD, PRD 107 (2023) 1]
- $\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)$ update $(6.3 \pm 1.3) \times 10^{-4}$ to $(3.34 \pm 0.31) \times 10^{-4}$ [arXiv:2509.12805]
  Nb. [PRD 101 (2020) 035023] derived $(3.7 \pm 1.0) \times 10^{-4}$ using f_{Λ_b} from TeVatron only

Consistently low $\mathcal{B}$ found for $b \to s\mu^+\mu^-$ decays

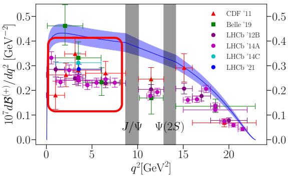
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



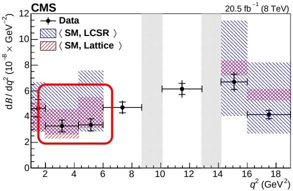
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



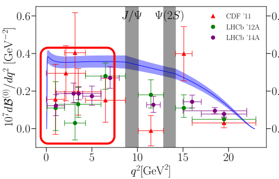
$B^+ \to K^+\mu^+\mu^-$ [HPQCD, PRD 107 (2023) 1]



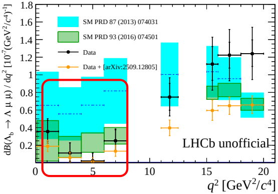
CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



$B^0 \to K^0\mu^+\mu^-$ [HPQCD, PRD 107 (2023) 1]



LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



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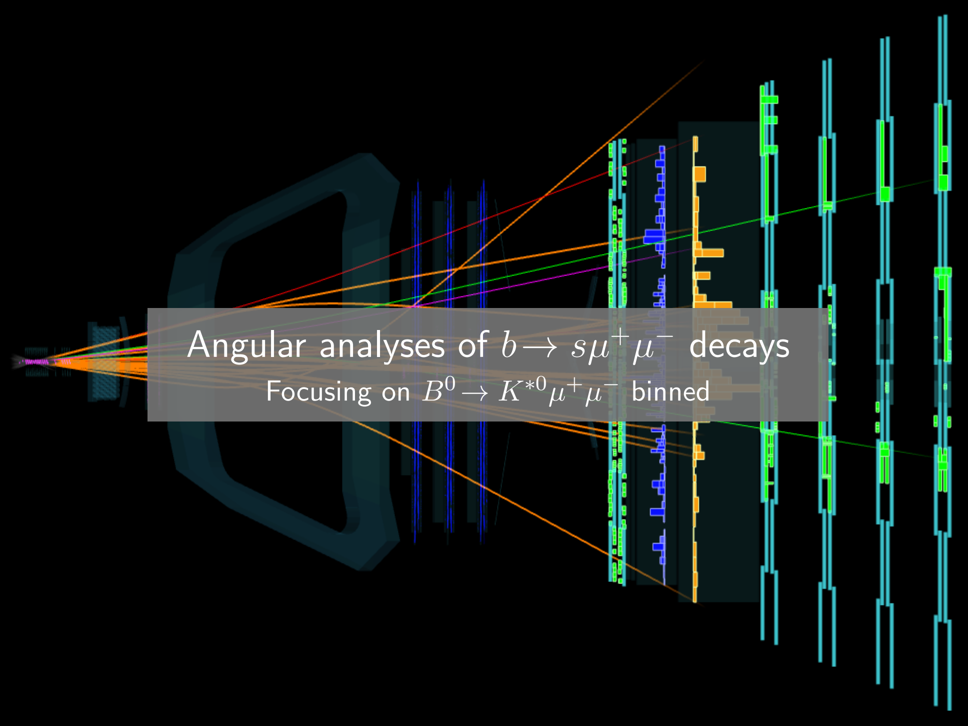
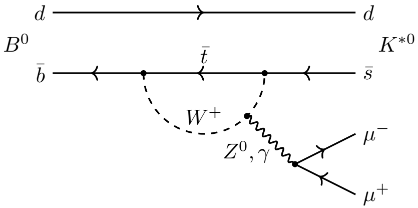
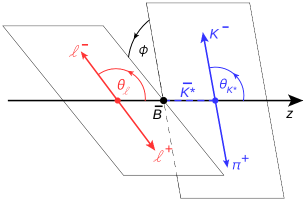


Angular analyses of $b \to s\mu^+\mu^-$ decays

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

Angular analysis of $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$





- Described by 5 DoF: helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$, $q^2 = m^2_{\mu\mu}$ and $m_{K\pi}$
- Fit of 5D PDF to determine CP-symmetries S_i and CP-asymmetries A_i

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^5\overleftrightarrow{\Gamma}}{\mathrm{d}q^2\mathrm{d}m_{K\pi}\mathrm{d}\vec{\Omega}} = (1-\hat{F}_S)\frac{9}{64\pi}\sum_i (S_i \pm A_i) f_i(\vec{\Omega})|\mathcal{BW}_P(m_{K\pi})|^2 \quad \text{P-wave}$$

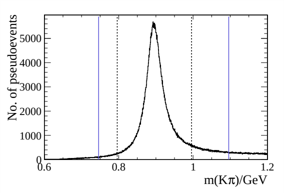
$$+\frac{1}{8\pi}\sum_j (\tilde{S}_j \pm \tilde{A}_j) f_j(\vec{\Omega}) F(m_{K\pi}) \quad \text{S-wave+interference}$$

- In full generality 52 observables per q^2 bin
- Perform ratios of observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

Legacy Run 1+2 $B^0 \to K^{*0}\mu^+\mu^-$ analysis

More data

- Full Run 1+2 data: $4.7\,\mathrm{fb}^{-1} \to 8.4\,\mathrm{fb}^{-1}$
  Signal yield: $\sim 4600 \to 12\,400$
- Larger $m_{K\pi}$ mass window and more optimised selection



More observables

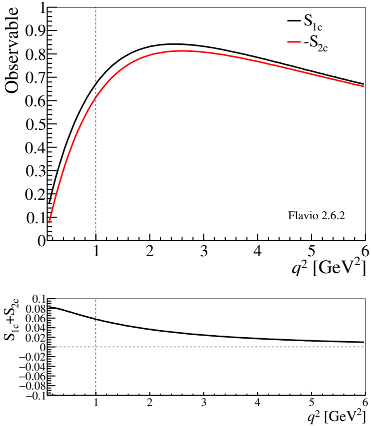
- P-wave, S-wave+interference observables, as well as CP-asymmetries
- Provide branching fraction measurement and full set of correlations
- In addition to nominal $\sim 2\,\mathrm{GeV}^2$ wide bins use finer $\sim 1\,\mathrm{GeV}^2$ binning

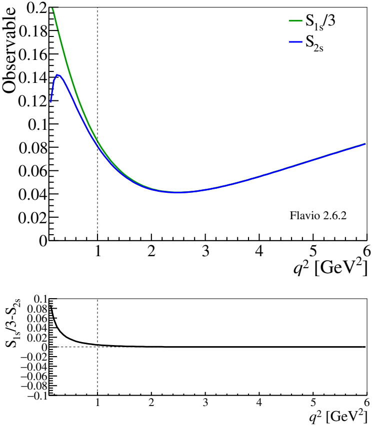
Fewer assumptions

- No longer assume massless leptons throughout
- Branching fraction extracted without model assumptions

Massive leptons

- 11 independent CP-averaged angular observables
- Reduce to 8 when assuming no scalars, tensors and massless leptons
  $S_{1c} = -S_{2c}$ ✗ $S_{1s} = 3S_{2s}$ ✓ $S_{6c} = 0$ ✓
- Nominal: Fully massive $q^2 < 1\ \mathrm{GeV}^2$, assume $S_{1s} = 3S_{2s}$ at $q^2 > 1\ \mathrm{GeV}^2$ ("partially massive")





Observables and fit configurations

Tradeoff: N_{obs}/fewer assumptions $\Leftrightarrow$ better stat. behaviour/precision

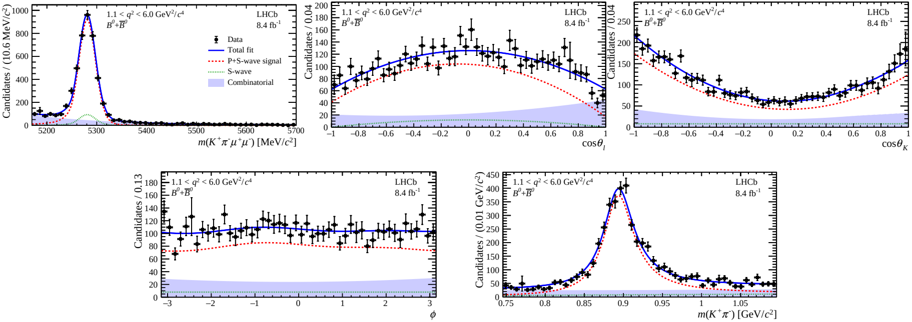
	$N_{\text{obs}}(N_{\text{obs}}^{q^2<1\,\text{GeV}^2})$
1. CP-averages only, S_i basis, partially massive[1] Default for S_i basis	$21\,(26)$
2. CP-averages only, $P_i^{(\prime)}$ basis, partially massive Default for P_i basis	$21\,(26)$
3. Fully massive model, CP-averages only, S_i basis For effect of massive leptons	26
4. CP-averages + CP-asymmetries, S_i basis, massless leptons[1] For CP-asymmetries	$40\,(52)$
5. CP-averages only, $P_i^{(\prime)}$ basis, massless leptons For comparison with [PRL 125 (2020) 011802]	20
6. CP-averages only, S_i basis, partially massive, narrow q^2 bins For better q^2 resolution	$21\,(26)$

[1] Fully massive $q^2 < 1\,\text{GeV}^2$

Example fit projection

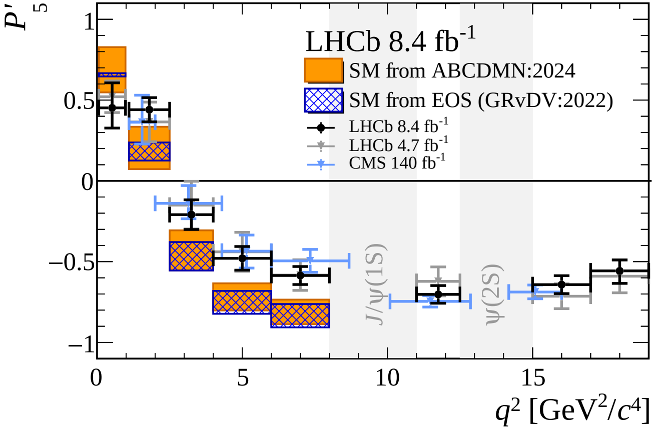
[arXiv:2512.18053]

- Fit projections of the five dimensions for $1.1 < q^2 < 6\,\mathrm{GeV}^2$
- Goodness of fit checked in 5D using BDT [arXiv:1612.07186] and Point-to-point dissimilarity test [JINST 5 (2010) P09004]



Results: P_5' (config 2)

[arXiv:2512.18053]



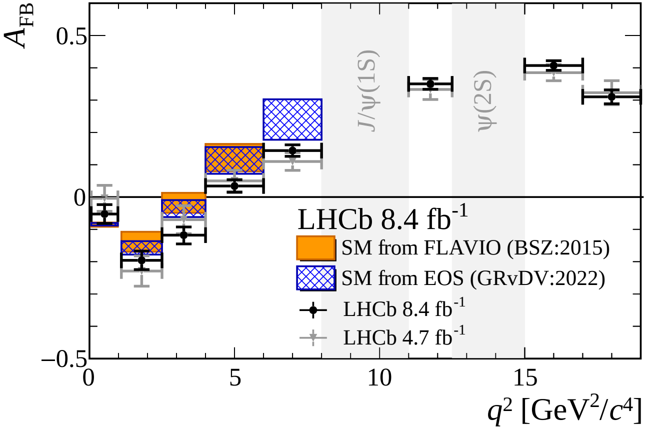
ABCDMN:
[EPJC 83 (2023) 648]

GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]

- P_5' in excellent agreement with both CMS and previous LHCb
- Local deviations 2.6 (2.1) and 2.7 (2.4) σ in $[4, 6]$ and $[6, 8]$ GeV^2 for EOS (ABCDMN)

Results: A_{FB} (config 1)

[arXiv:2512.18053]



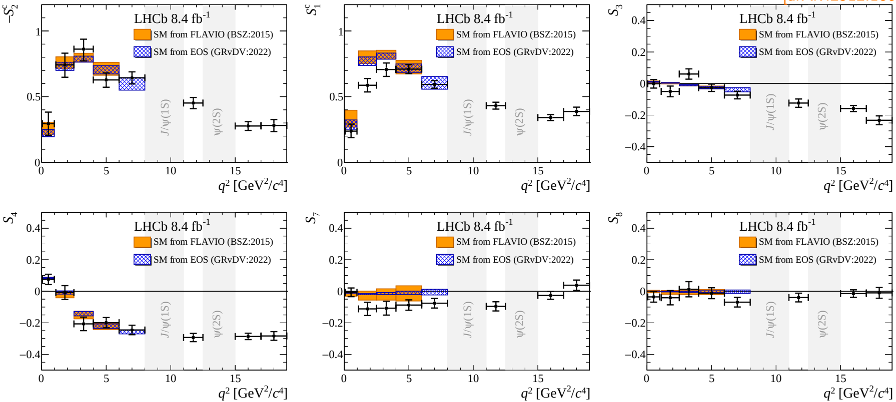
BSZ:
[arXiv:1810.08132]
[JHEP 08 (2016) 098]

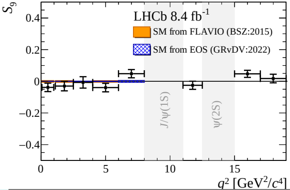
GRvDV:
[EPJC 82 (2022) 569]
[JHEP 09 (2022) 133]

- Tensions now also more pronounced in A_{FB}
- Local deviations 2.5 (2.2) and 1.9 (1.7) σ in $[2.5, 4]$ and $[4, 6]$ GeV^2 for EOS (Flavio)

Results: Remaining CP-symmetries (config 1)

[arXiv:2512.18053]

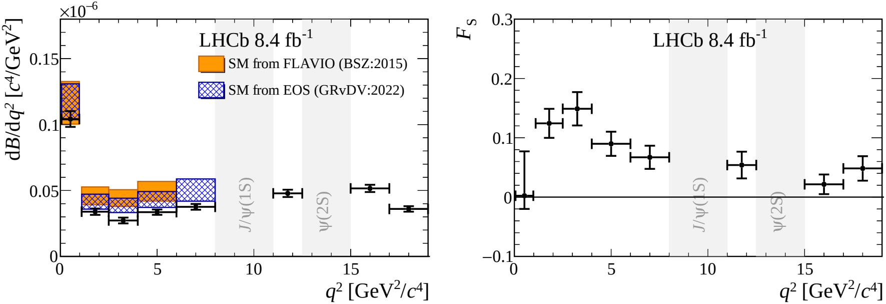




- Overall good agreement with SM predictions
- Minor tensions in S_{1c} and S_7

P-wave branching fraction and S-wave fraction

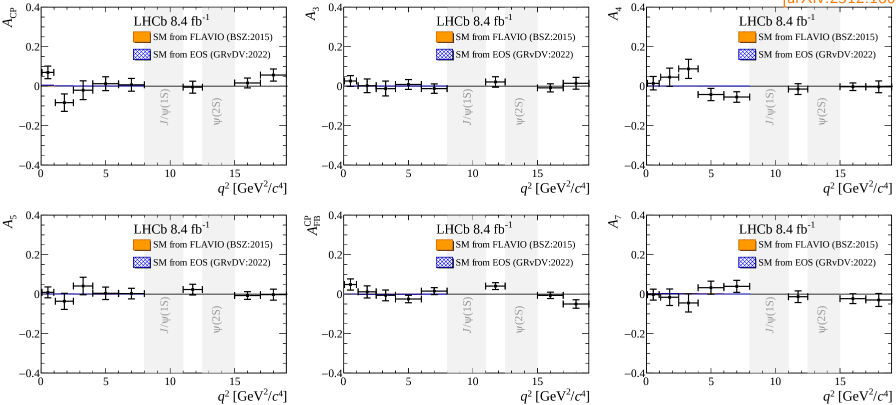
[arXiv:2512.18053]

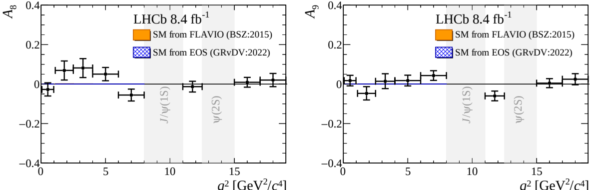


- Branching fraction lower than SM prediction, consistent with other $b \to s\mu^+\mu^-$ decays
- No predictions available for F_S and other S-wave/interference observables

CP-asymmetries (config 4)

[arXiv:2512.18053]

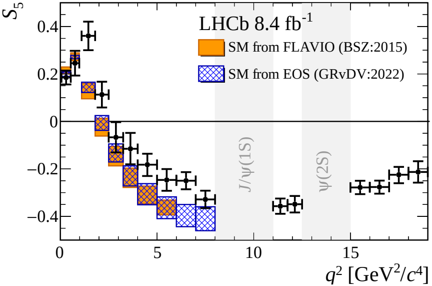


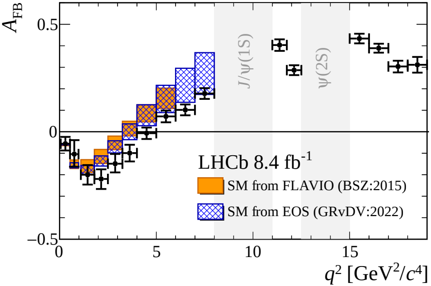


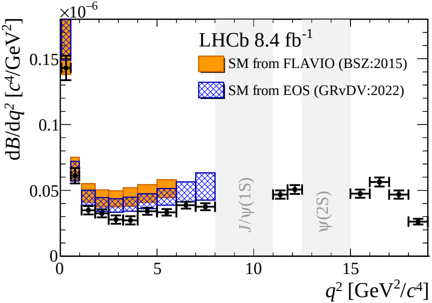
- No significant CP-asymmetries

Narrow q^2 bins (config 6)

[arXiv:2512.18053]



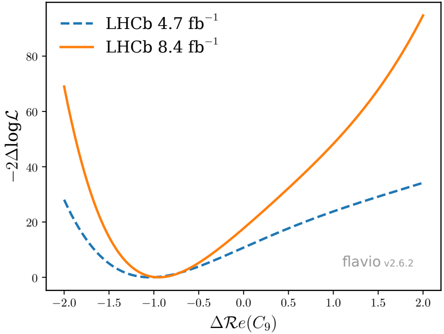




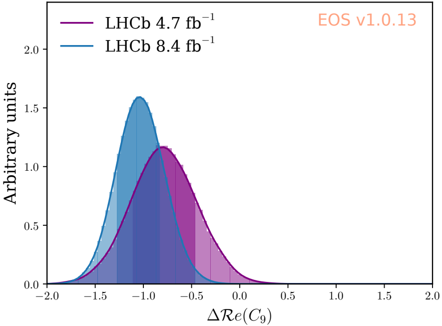
- Tradeoff between statistical uncertainty/better q^2 resolution
- In excellent agreement with regular-sized q^2 bins

Interpretation in terms of Wilson coefficients

[arXiv:2512.18053]



$$\Delta\mathcal{R}eC_9 = -0.93^{+0.18}_{-0.16}$$
Significance $4.1\,\sigma$

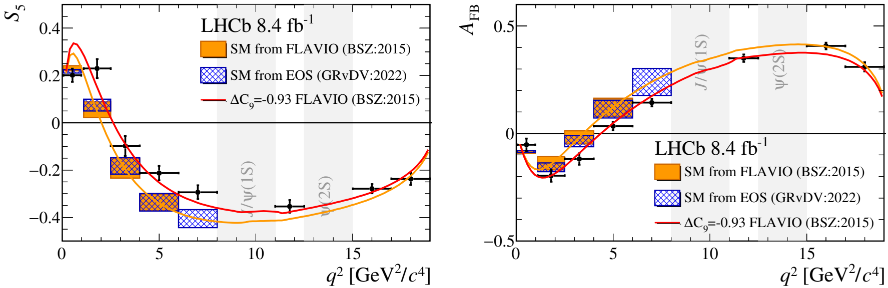


$$\Delta\mathcal{R}eC_9 = -0.94^{+0.22}_{-0.22}$$
Significance $4.0\,\sigma$

- Combine angular obs. and branching fraction up to $8\ \mathrm{GeV}^2$
- Use two different theory packages with different approaches
  e.g. different (non-local) FFs, very consistent results

Improved description of data with $\Delta\mathcal{R}eC_9 = -0.93$

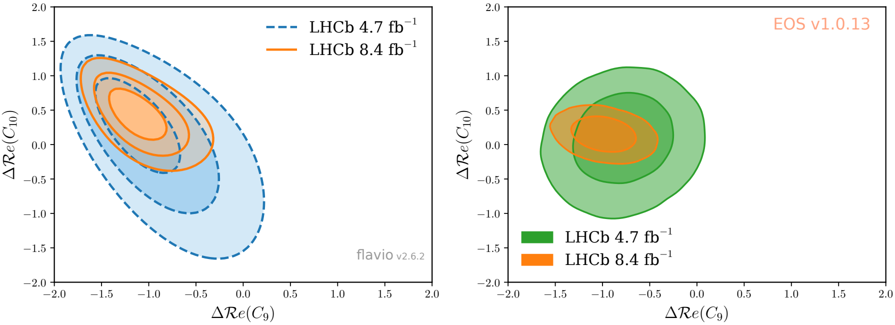
[arXiv:2512.18053]



- For illustration overlaid central value for $\Delta\mathcal{R}eC_9 = -0.93$
- Clearly improved description of the data

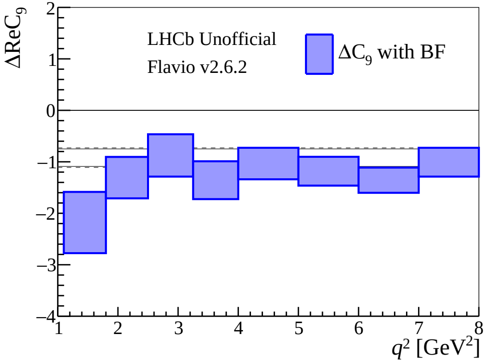
Interpretation in terms of Wilson coefficients

[arXiv:2512.18053]

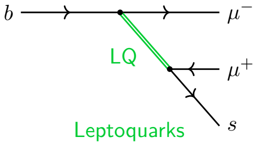


- Tension most pronounced in $\mathcal{R}eC_9$
- $\mathcal{R}eC_{10}$ in agreement with SM prediction

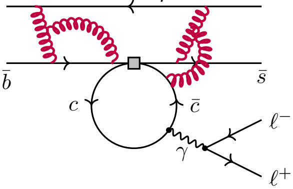
Dependence of shift of $\mathcal{R}eC_9$ on q^2



Possible NP contribution

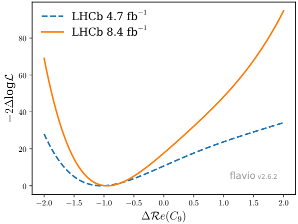


SM $c\bar{c}$-loop



- Shift in $\mathcal{R}eC_9$ quite consistent across q^2 bins
- Open question: NP or underestimated hadronic contributions (charm-loop)?
  If shift due to heavy NP $\to$ q^2-independent
  If shift due to charm-loop $\to$ might expect rise towards J/ψ-region
- Data taken during Run 3 ($> 27\,\mathrm{fb}^{-1}$!) crucial to clarify
- More on global fits and interpretation in Peter's talks

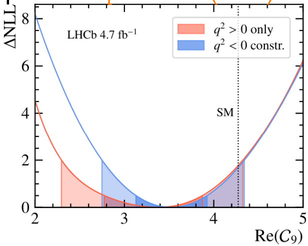
Comparison with $B^0 \to K^{*0}\mu^+\mu^-$ unbinned results



$$\Delta\mathcal{R}eC_9 = -0.93^{+0.18}_{-0.16}$$

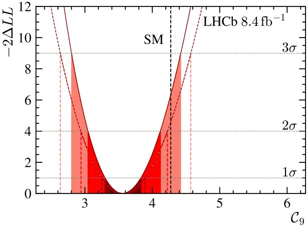
- Unbinned paramerize charm loop: $C_9^{\text{eff}} = C_9 + \mathcal{H}_{0,\|,\perp}(q^2)$
- Shifts in C_9 consistent
- Fewer parameters in binned analysis, smaller uncertainties

z-Expansion [PRD 109 (2024) 052009]



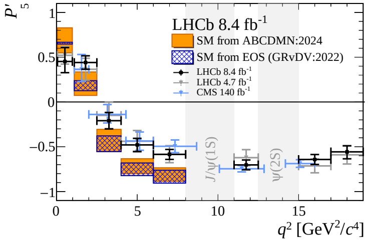
$$\Delta\mathcal{R}eC_9 = -0.93^{+0.53}_{-0.57}$$

Amplitude model [JHEP 09 (2024) 026]



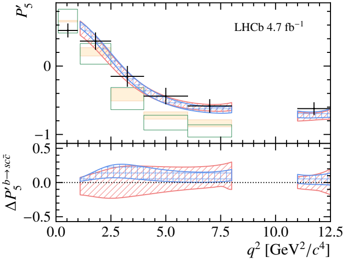
$$\Delta\mathcal{R}eC_9 = -0.71 \pm 0.33$$

Comparison with $B^0 \to K^{*0}\mu^+\mu^-$ unbinned results

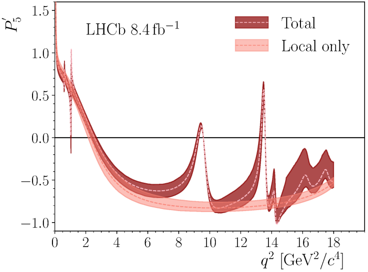


- Excellent agreement of angular observables

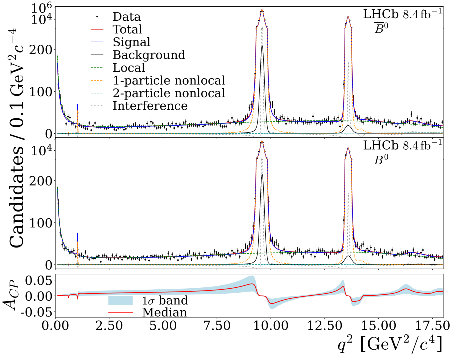
z-Expansion [PRD 109 (2024) 052009]



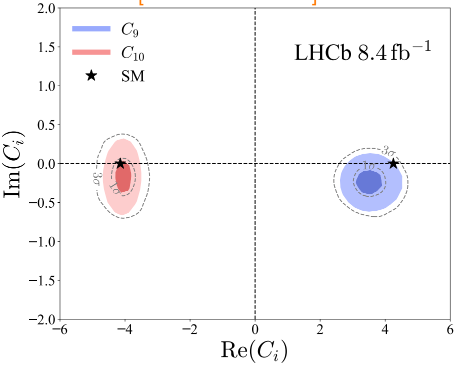
Amplitude model [JHEP 09 (2024) 026]



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



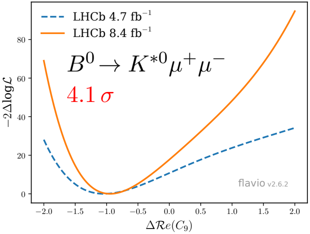
[arXiv:2605.07582]



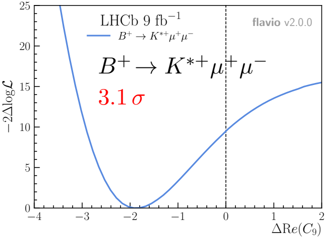
- Recent unbinned CPV measurement of $B^0 \to K^{*0}\mu^+\mu^-$ using 8.4 fb^{-1} [arXiv:2605.07582]
- No significant CP-asymmetries found
- More Details on unbinned approaches in talk by Ulrik next week

Consistency with other $b \to s\mu^+\mu^-$ angular analyses

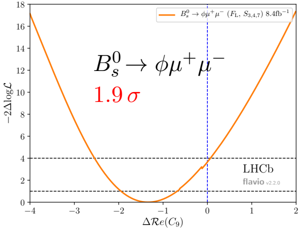
[arXiv:2512.18053]



[PRL 126 (2021) 161802]

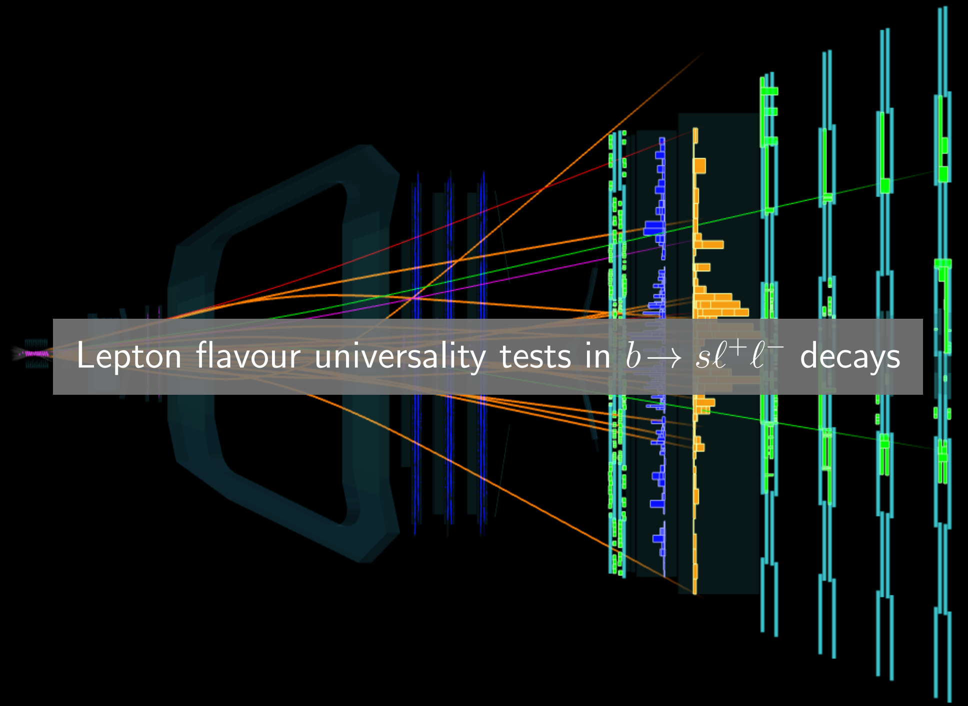


[JHEP 11 (2021) 043]

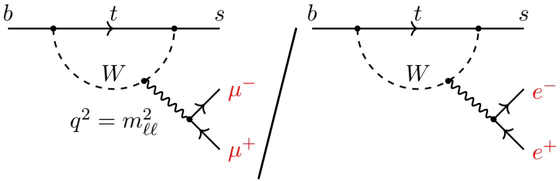


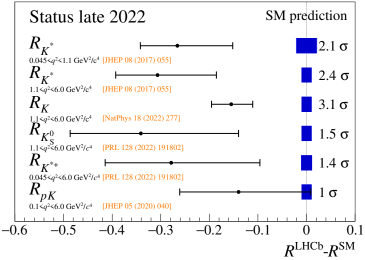
- Use `flavio` [arXiv:1810.08132] to determine tension with SM hypothesis
- Variation of vector coupling $\mathcal{R}e(\mathcal{C}_9)$ results in improved description of data
- Consistent trend for $B^0 \to K^{*0}\mu^+\mu^-$ [arXiv:2512.18053], $B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802] and $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 11 (2021) 043] angular observables

Lepton flavour universality tests in $b \to s\ell^+\ell^-$ decays



Lepton universality in rare $b \to s\ell^+\ell^-$ decays



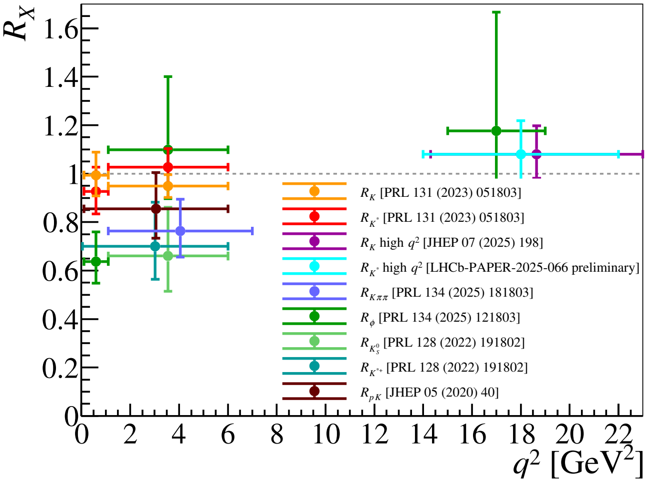


- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \to s\ell^+\ell^-$ decays:

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

- Exactly unity in SM, differences only through lepton mass effects
- QED corrections $\mathcal{O}(1\,\%)$ [EPJC 76 (2016) 440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio

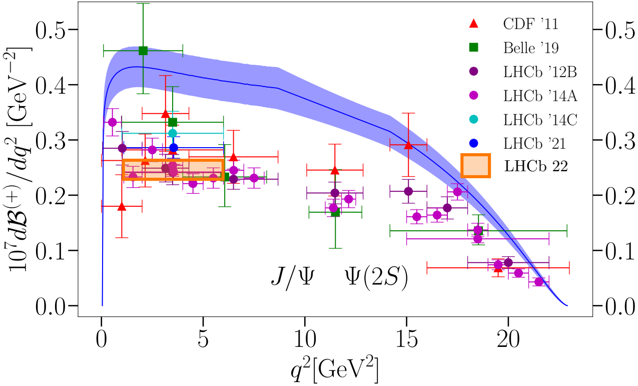
Summary LFU tests in rare $b \to s\ell^+\ell^-$ decays



- Tests of LFU in $b \to s\ell^+\ell^-$ in excellent agreement with the SM
- Measurements statistically dominated
- Run 3: More data ✓ Better trigger ✓ Busier calorimetry ✗

One remark on $B^+ \to K^+e^+e^-$ branching fraction

[PRD 107 (2023) 1] with [arXiv:2212.09152]

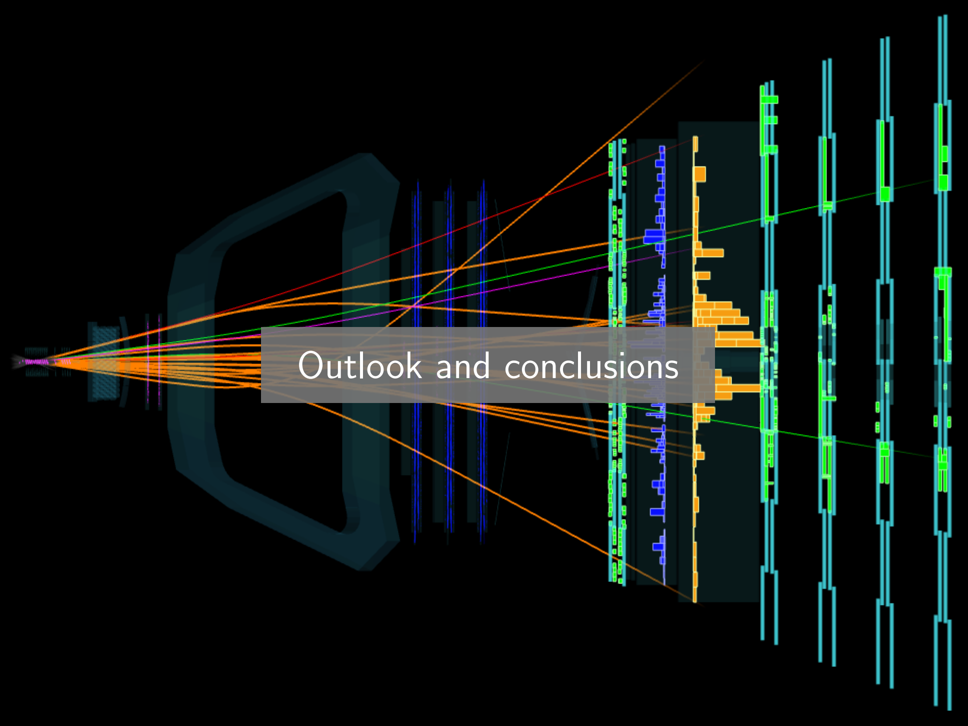


- Scaling R_{K,K^*} with measured muon $\mathcal{B}$ yields [JHEP 06 (2014) 133]

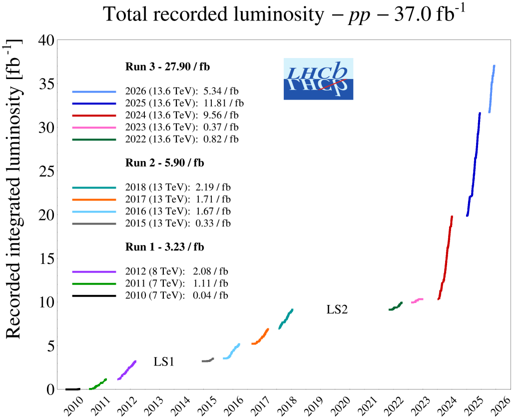
$$\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)/\mathrm{d}q^2 = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

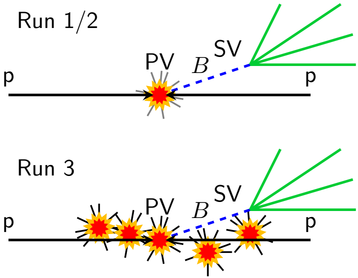
- Electron $\mathcal{B}$ consistent with muons, also below SM prediction

Outlook and conclusions



Current and future data samples

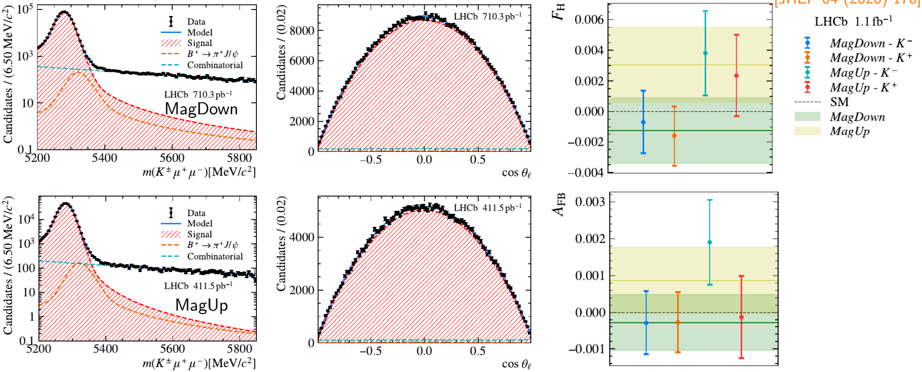




- LHCb has taken more than $27\,\mathrm{fb}^{-1}$ in Run 3 (compare $\sim 9\,\mathrm{fb}^{-1}$ in Run 1–2)
- A huge Run 3 data sample available for analysis, good understanding of data from [Upgrade I] detector required

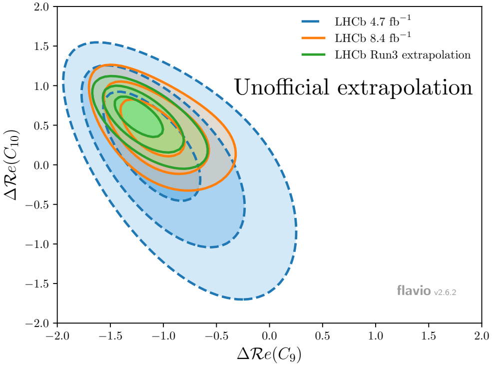
Angular analysis of $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$

[JHEP 04 (2026) 170]

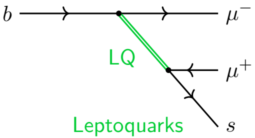


- Differential angular fit of $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}}) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell$
- Using $1\,\mathrm{fb}^{-1}$ of Run 3 data from 2024 good agreement with SM pred. of 0:
  $A_{\mathrm{FB}} = 0.00019 \pm 0.00048_{\mathrm{stat}} \pm 0.00033_{\mathrm{syst}},\ F_{\mathrm{H}} = 0.0005 \pm 0.0011_{\mathrm{stat}} \pm 0.0014_{\mathrm{syst}}$
- Consistent results for MagnetUp/Down and Kaon charge
- Measured angular dist. across 17 different variables, no syst. deviations gives great confidence in quality of data!

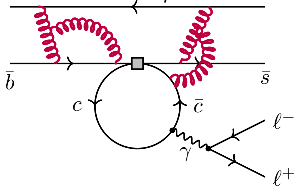
$B^0 \to K^{*0}\mu^+\mu^-$ in Run 3



Possible NP contribution



SM $c\bar{c}$-*loop*

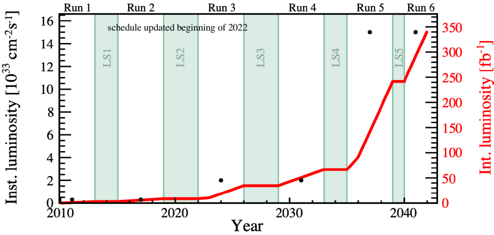


- Run 3 data allows for measurement with unprecedented precision, assuming equal central values tension would increase to $\gtrsim 5\,\sigma$
- Clarification of anomalies requires synergistic work between theory/exp.
  - Finer q^2 binning and closer focus on J/ψ interference region
  - Observables sensitive to strong phases $S_{7/8}$ [arXiv:2603.27753]
  - Clean observables such as A_{CP}

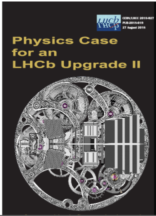
Prospects beyond Run 3/4: the Upgrade II

Prospects from [arXiv:1808.08865]

$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis			
$\int \mathcal{L}\mathrm{d}t$	$3\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$\sigma^{\mathrm{stat}}(S_i)$	≤ 0.058	≤ 0.016	≤ 0.004
$\sigma(\mathcal{C}'_{10})$	0.31	0.15	0.06
$\Lambda_{\mathrm{NP}}^{\mathrm{tree\ generic}}\,[\mathrm{TeV}]$	50	75	115

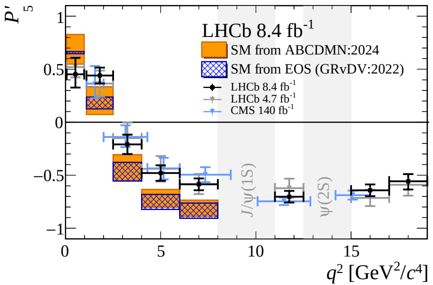


- At the end of Run 4 expect to have collected around $50\,\mathrm{fb}^{-1}$
- Upgrade 2 will increase $\int \mathcal{L}\mathrm{d}t$ to $300\,\mathrm{fb}^{-1}$
  Framework TDR [CERN-LHCC-2021-012],
  Physics case [CERN-LHCC-2018-027],
  CERN Yellow report [arxiv:1812.07638],
  Scoping document [CERN-LHCC-2024-010]
- NP reach in Upgrade II increases by more than factor 2 wrt. Run 1+2
- Λ_{NP} reach beyond $100\,\mathrm{TeV}$

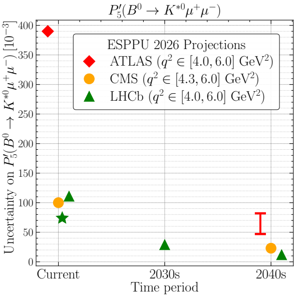


Summary and Conclusions

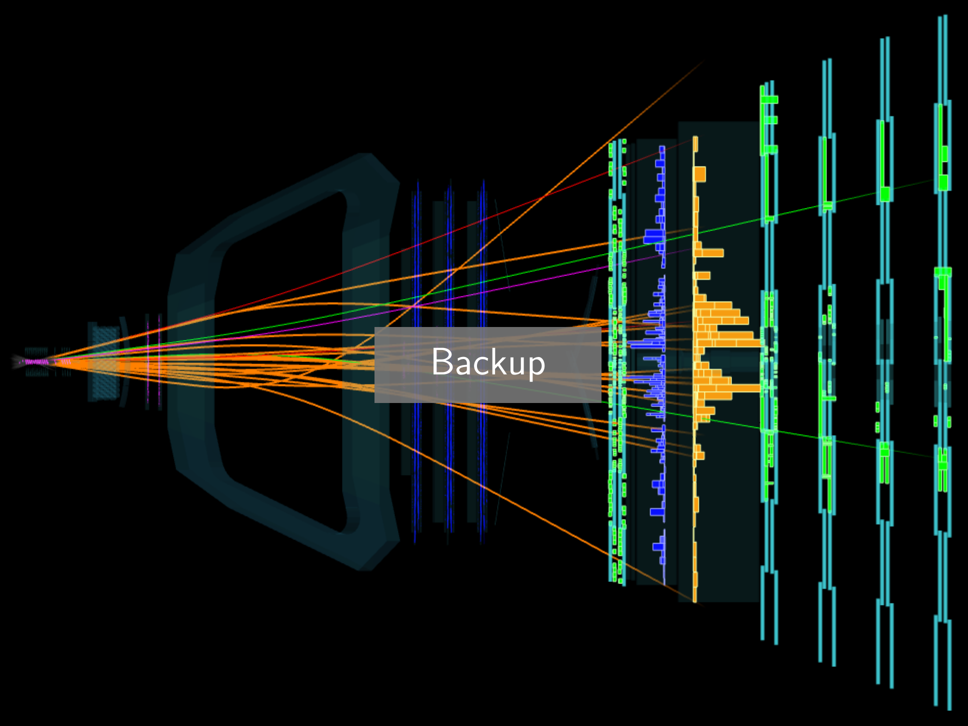
[arXiv:2512.18053]



[arXiv:2503.24346][Figures]



- Legacy analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with Run 1 and 2 data: Tension remains with increased significance [arXiv:2512.18053]
- Tensions in $b \to s\mu^+\mu^-$ angular observables consistent with low decay rates
- Analysis of Run 3 data in full swing
- Current and future data samples will allow for measurements with unprecedented precision



Backup

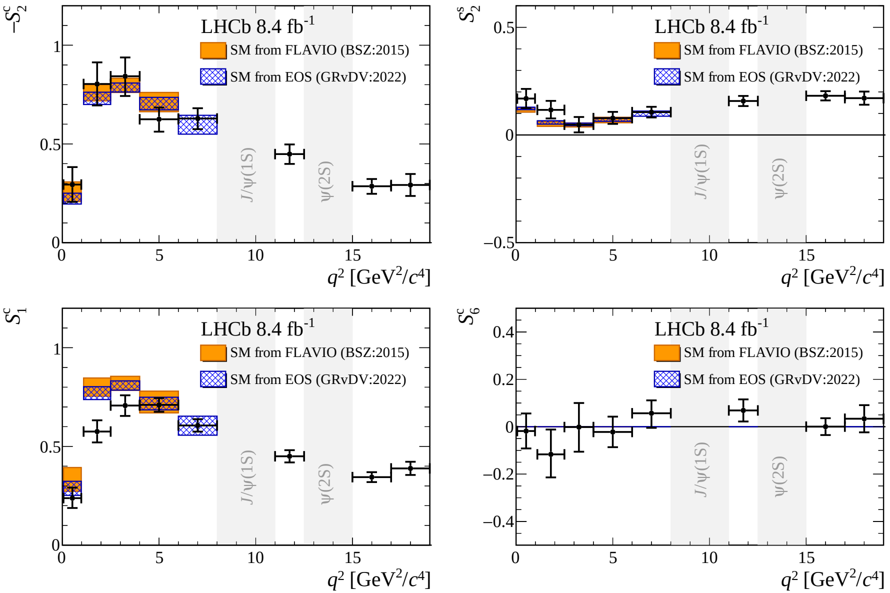
Systematic uncertainties

[arXiv:2512.18053]

Source	S_2^c	$A_{\rm FB}, S_1^c - S_9$	$P_1 - P_8$	$F_{\rm S}, S_{1a}^c$	$S_{1b}^{c,re/im}, S_{S1}^{re/im} - S_{S5}^{re/im}$	$dB/dq^2 \times 10^7$
S-wave $m(K\pi)$ model	< 0.010	< 0.010	< 0.010	< 0.010	< 0.070	< 0.010
Acceptance stat. uncertainty	< 0.010	< 0.010	< 0.050	< 0.010	< 0.020	< 0.010
Angular background model	< 0.025	< 0.010	< 0.025	< 0.010	< 0.020	< 0.010
Peaking backgrounds	< 0.025	< 0.010	< 0.025	< 0.020	< 0.020	< 0.010
$m(K^+\pi^-)$ background model	< 0.010	< 0.010	< 0.020	< 0.020	< 0.010	< 0.020
Ghost tracks	< 0.010	< 0.010	< 0.020	< 0.010	< 0.010	< 0.010
Trigger efficiency	< 0.010	< 0.010	< 0.020	< 0.010	< 0.010	< 0.015
$B^+ \to K^+\mu\mu$ background veto	< 0.010	< 0.010	< 0.010	< 0.010	< 0.020	< 0.010
q^2 dependent angular model	< 0.010	< 0.010	< 0.010	< 0.010	< 0.020	< 0.010
Peaking background in control mode	< 0.000	< 0.000	< 0.000	< 0.000	< 0.000	< 0.015
Detection asymmetry	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Production asymmetry	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Acceptance variation with q^2	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
B^0 kinematic data-simulation differences	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Kaon momentum distribution	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Pion momentum distribution	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
PID calibration stat. uncertainty	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
PID calibration KDE	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Punzi effect in weighted fits	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Momentum resolution	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Asymmetry of tracking efficiency	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Tracking efficiency	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
D-wave contribution	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Final-state radiation	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Hadron range parameter	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
B^0 decay time	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
$m(K^+\pi^-) - m(K^+\pi^-\mu^+\mu^-)$ correlation	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Neyman construction nuisance	< 0.010	< 0.010	< 0.075	< 0.025	< 0.025	< 0.000

Massive leptons (config 3)

[arXiv:2512.18053]



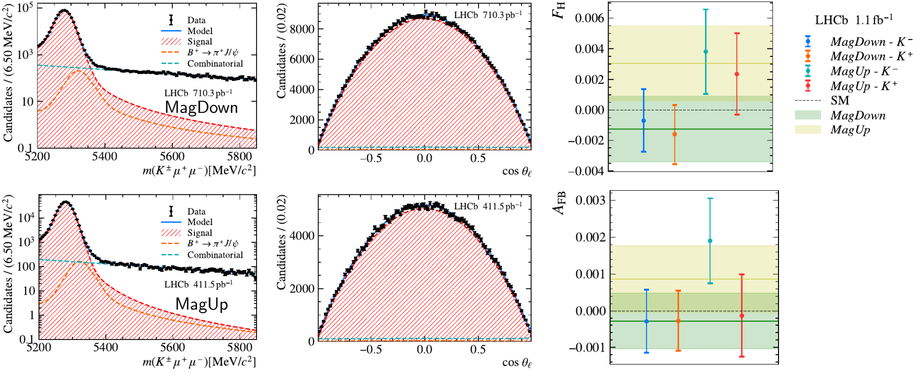
$B^+ \to J/\psi\, K^+$ systematics

LHCb-PAPER-2025-040, in preparation

Systematic source	*MagDown*		*MagUp*	
	A_{FB}	F_{H}	A_{FB}	F_{H}
Simulation sample size	44	103	39	104
Alternative scheme for $w_{\mathrm{kin.\&mult.}}$	3	114	4	90
Simulation corrections	14	30	12	24
Truth-matching	7	28	2	51
Signal mass model	1	25	1	17
Choice of hyperparameters in $w_{\mathrm{kin.\&mult.}}$	1	19	1	17
Multiple candidates removal	0	5	7	20
Orders of combinatorial	4	8	4	10
Tracking corrections	1	6	1	7
Uncertainty on PID corrections	1	2	0	1
Higher order efficiency	0	1	1	1
Total systematic uncertainty	47	162	42	153
Total statistical uncertainty	59	141	80	191

Angular analysis of $B^+ \to K^+ J/\psi (\to \mu^+\mu^-)$

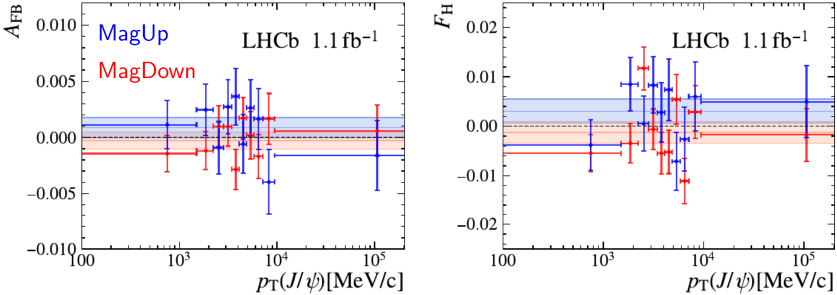
LHCb-PAPER-2025-040, in preparation



- Differential angular fit of
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}}) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell$$
- Using $1\,\mathrm{fb}^{-1}$ of 2024 data excellent agreement with SM prediction of 0:
$$A_{\mathrm{FB}} = 0.00019 \pm 0.00048_{\mathrm{stat}} \pm 0.00033_{\mathrm{syst}},\ F_{\mathrm{H}} = 0.0005 \pm 0.0011_{\mathrm{stat}} \pm 0.0014_{\mathrm{syst}}$$
- Consistent results for MagnetUp/Down and Kaon charge

Stability of results from $B^+ \to K^+ J/\psi\,(\to \mu^+\mu^-)$

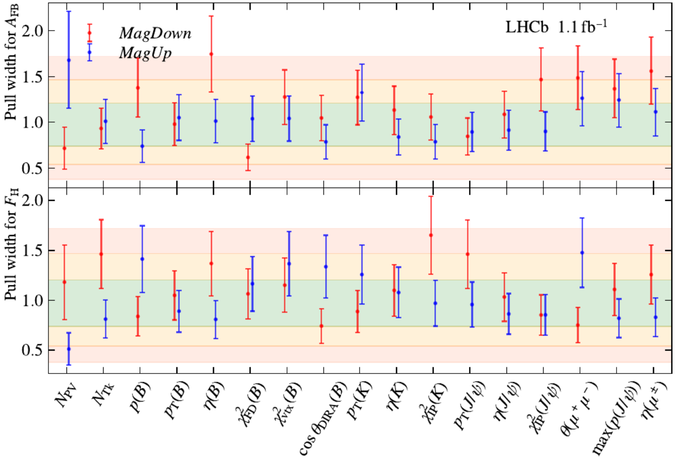
LHCb-PAPER-2025-040, in preparation



- No systematic deviations observed in angular obs. depending on $p_{\rm T}(J/\psi)$
- Measured angular dist. across 17 different variables, no syst. deviations gives great confidence in quality of data!

Stability of results from $B^+ \to K^+ J/\psi (\to \mu^+\mu^-)$

LHCb-PAPER-2025-040, in preparation



Check both linear coeff. and pull:
$p(O|_i^m) = \frac{O|_i^m - O|_{\text{int}}^m}{\sigma(O|_i^m)}$

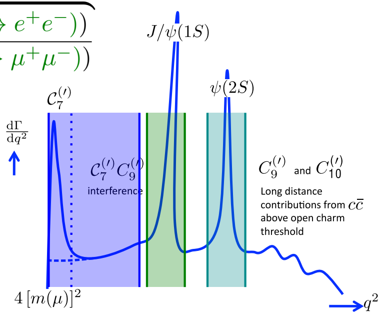
- No systematic deviations observed in angular obs. depending on $p_T(J/\psi)$
- Measured angular dist. across 17 different variables, no syst. deviations gives great confidence in quality of data!

Analysis strategy: Double ratio (Example: R_K)

- Analysis strategy: Double ratio of rare modes $B^+ \to K^+\ell^+\ell^-$ with resonant decays $B^+ \to K^+ J/\psi(\to \ell^+\ell^-)$:

$$R_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+e^+e^-)} \times \overbrace{\frac{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+\to K^+J/\psi(\to \mu^+\mu^-))}}^{r^{-1}_{J/\psi}=1 \text{ [PRD 88 (2013) 3]}}$$

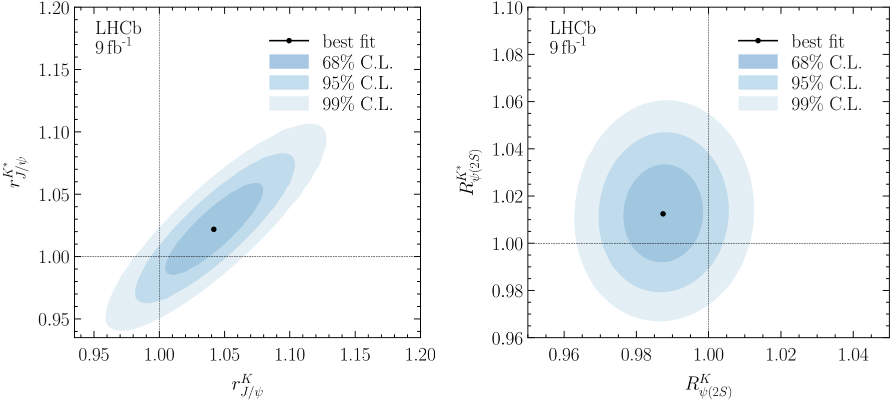
- Electron and Muon reconstruction very different at LHCb
- Efficiencies from corrected simulation
- Double ratio cancels most experimental systematic effects in efficiency ratios



- Important cross-checks: $r_{J/\psi} = \frac{\mathcal{B}(B^+\to K^+J/\psi(\to \boxed{\mu^+\mu^-}))}{\mathcal{B}(B^+\to K^+J/\psi(\to \boxed{e^+e^-}))}$ and

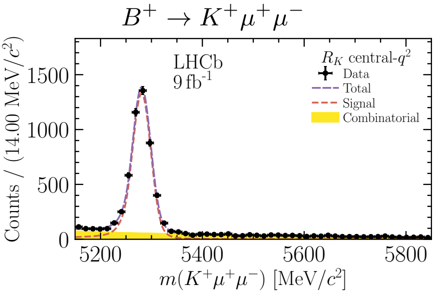
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+\to K^+\psi(2S)(\to\mu^+\mu^-))}{\mathcal{B}(B^+\to K^+\psi(2S)(\to e^+e^-))} \times \frac{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+\to K^+J/\psi(\to\mu^+\mu^-))}$$

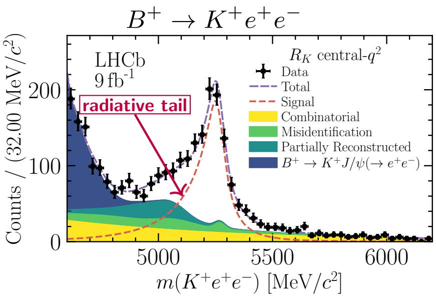
Crosschecks $r_{J/\psi}$ and $R_{\psi(2S)}$



- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$

Experimental challenges for electron modes at LHCb



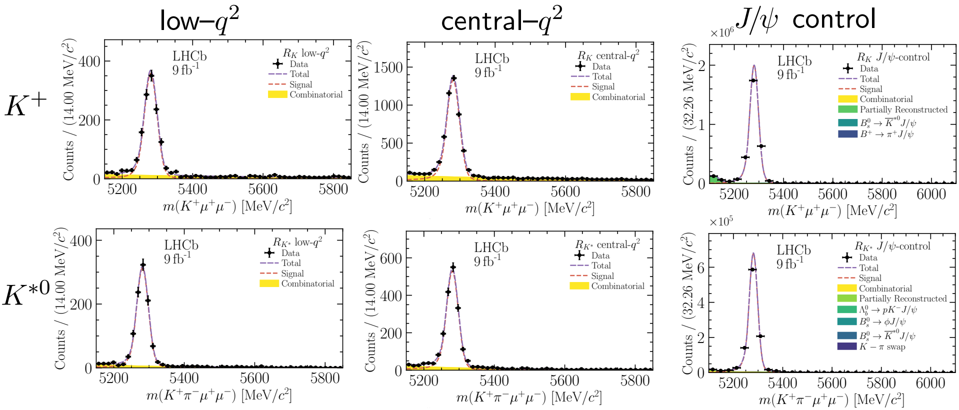


[arXiv:2212.09152] [arXiv:2212.09153]

Experimental Challenges for electron modes:

1. Low e trigger efficiencies due to higher thresholds compared to muons
2. Electrons strongly emit Bremsstrahlung traversing material
   Brem-γ recovery has limited efficiency and degrades mass resolution
3. Contribution from several background sources, bkg. modeling critical

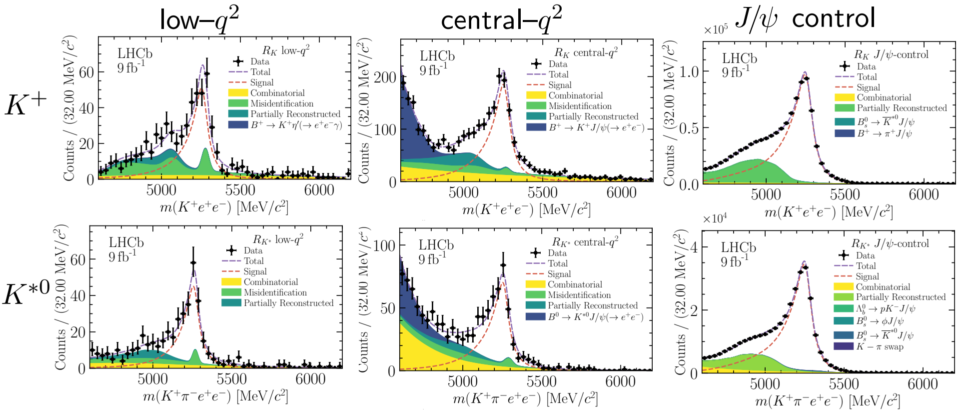
Muon mode fits



- Muon mode is very clean!
- Muon branching fraction compatible with published results

[JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

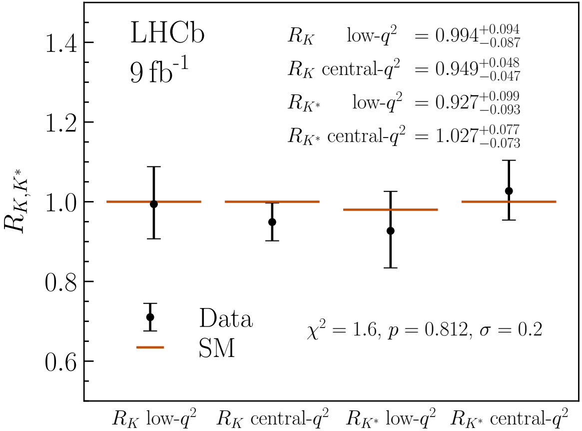
Electron mode fits



- Good fit quality when including all components
- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bgk. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

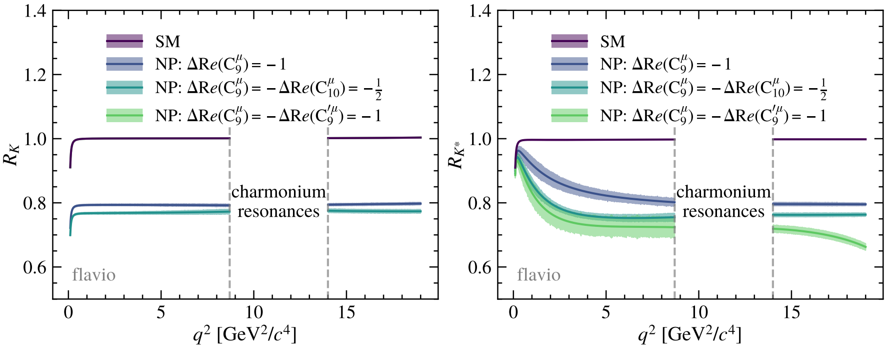
R_K and R_{K^*} results

[arXiv:2212.09152] [arXiv:2212.09153]



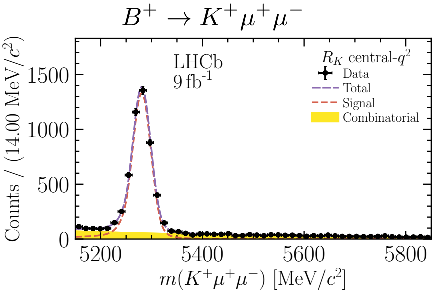
- Most precise test of LFU in $b \to s\ell^+\ell^-$ transitions
- Compatible with the SM at $0.2\,\sigma$ using simple χ^2 test

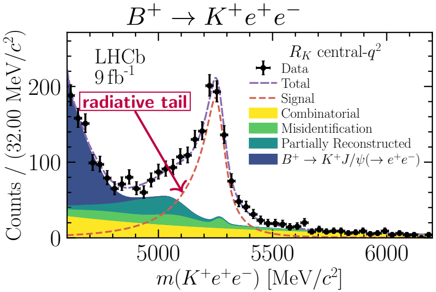
R_K and R_{K^*} in different NP scenarios



- Example NP models assuming NP only in muons
- Some ability to disentangle different scenarios with R_K and R_{K^*}
- Simultaneous R_K and R_{K^*} determination with $9\,\mathrm{fb}^{-1}$ Run 1+2 data
  - low–q^2: $q^2 \in [0.1, 1.0]\,\mathrm{GeV}^2/c^4$
  - central–q^2: $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$

Experimental challenges for electron modes at LHCb





[arXiv:2212.09152] [arXiv:2212.09153]

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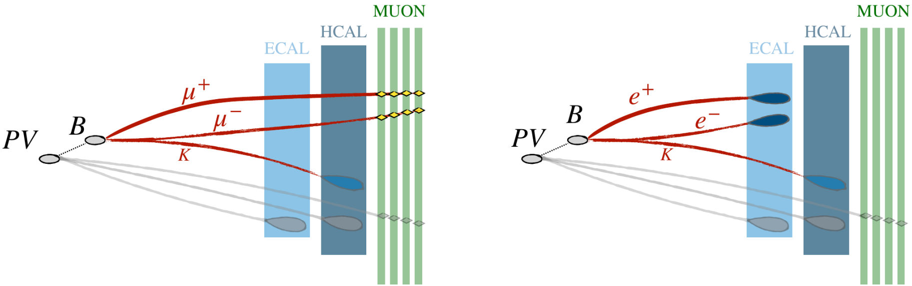
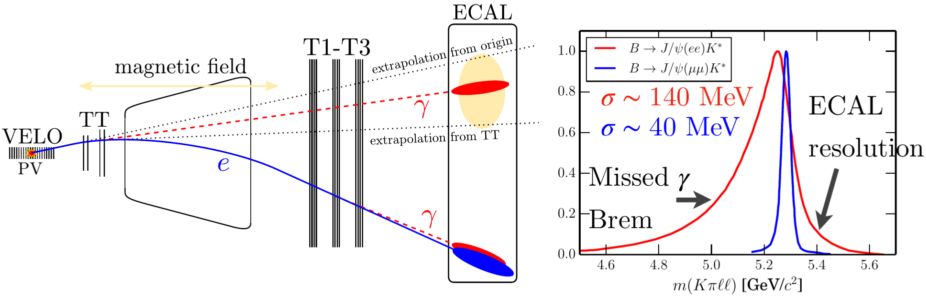
2. Electrons strongly emit Bremsstrahlung traversing material
   Brem-γ recovery has limited efficiency and degrades mass resolution
3. Contribution from several background sources, bkg. modeling critical

Experimental challenge: 1. Electron trigger



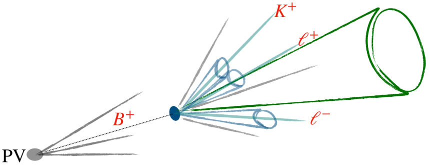
- Trigger signatures for muon and electron modes very different
- Lower L0 p_T thresholds for muons (1.5–$1.8\,\mathrm{GeV}/c$) compared to electrons (2.5–$3.0\,\mathrm{GeV}$) $\to$ challenging for e^+e^- modes
- Combine exclusive trigger categories to improve ϵ for electron modes:
  1. Trigger on rest of event (independent of signal)
  2. Trigger on e/μ from signal

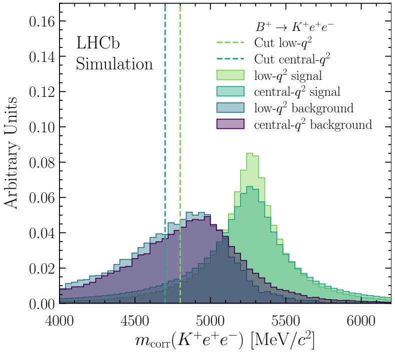
Experimental challenge: 2. Bremsstrahlung



- Correct electron momentum by adding matching photons ($E_{\mathrm{T}} > 75\,\mathrm{MeV}/c^2$) reconstructed in the ECAL
- Bremsstrahlung recovery $\sim 50\%$ efficient, well simulated
- Bremsstrahlung reconstruction impacts momentum resolution $\to$ higher background pollution and more sensitive to bkg. modeling

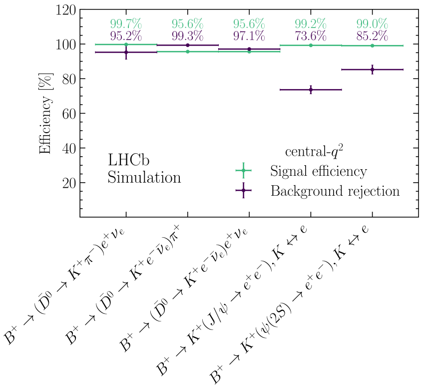
Experimental challenge: 3. Background suppression

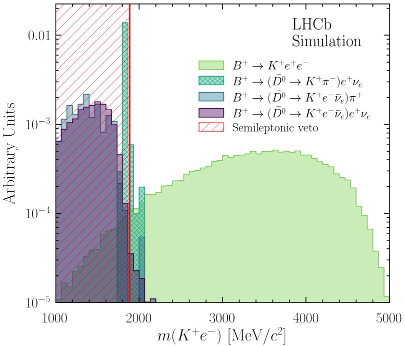




- Combinatorial backgrounds: suppressed using multivariate classifier using kinematic and vertex quality information
- Partially reconstructed:
  1. MVA using track/vertex isolation
  2. Corrected mass exploiting PV/SV
- Specific backgrounds: vetos combining PID and kinematic criteria

Experimental challenge: 3. Background suppression





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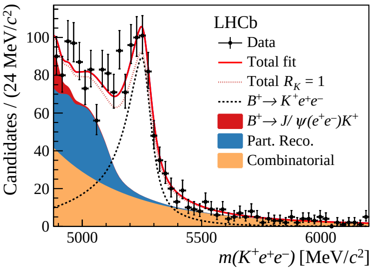
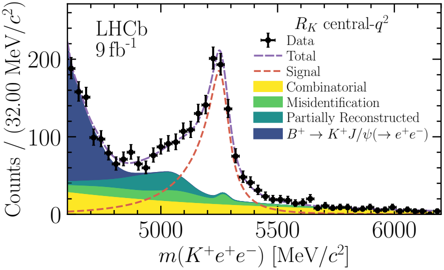
Difference to previous R_K analysis

[Nature Phys. 18 (2022) 277]



[arXiv:2212.09152] [arXiv:2212.09153]



$$R_K = 0.846^{+0.042}_{-0.039}{}^{+0.013}_{-0.012} \quad \rightarrow \quad R_K = 0.949^{+0.042}_{-0.041}{}^{+0.022}_{-0.022}$$

[Nature Phys. 18 (2022) 277] [arXiv:2212.09152] [arXiv:2212.09153]

- Different selection allows for statistical scatter of ± 0.033
- Shift of ~ 0.1 due to pollution by residual misidentified backgrounds present and not accounted for in [Nature Phys. 18 (2022) 277]
  - Tighter particle identification cuts: Shift of $+0.064$
  - Explicit inclusion of residual misid. backgrounds: Shift of $+0.038$