

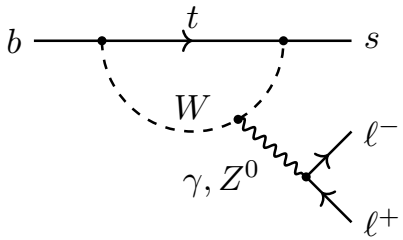
Anomalies in the Rare Decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$



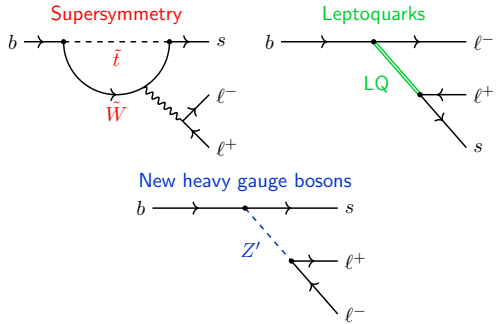
C. Langenbruch¹
¹Heidelberg University



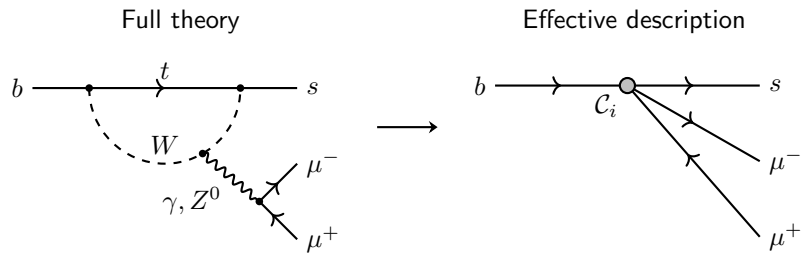
Oxford EPP seminar
June 2nd 2026

Rare $b \rightarrow sl^+l^-$ decays as sensitive probes for NP $b \rightarrow sl\ell$ decays in the SM

Possible contributions from NP



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

Rare $b \rightarrow sl^+l^-$ decays in effective field theory

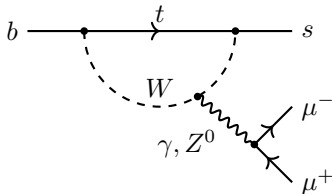
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i$$

Effective coupling, *Wilson coefficient* \rightarrow 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
- $b \rightarrow sll$ decays probe several $\mathcal{O}_i^{(\text{NP})}$

Rare $b \rightarrow sl^+l^-$ decays in effective field theory

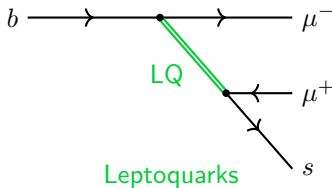
Rare decays in the SM



$$\mathcal{A}^{\text{SM}} \propto \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i c_i \mathcal{O}_i$$

weak trans. CKM suppression loop suppression

Possible NP contribution



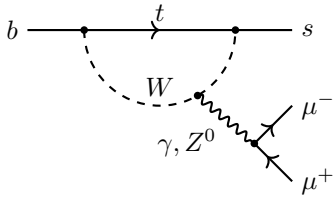
$$\mathcal{A}^{\text{NP}} \propto \frac{\kappa}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

Leptoquarks

- Model-independent description in effective field theory
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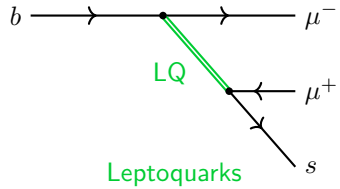
Rare $b \rightarrow sl^+l^-$ decays in effective field theory

Rare decays in the SM



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

Possible NP contribution

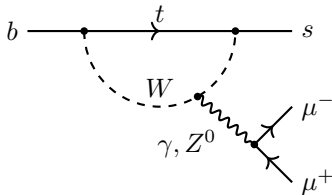


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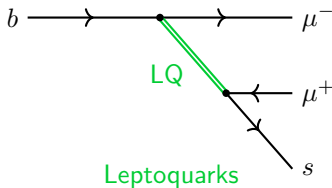
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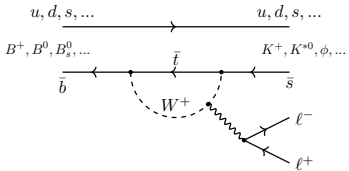
	Wilson coefficient	Operator
γ -penguin ¹	$C_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$C_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \mu)$
	$C_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\mu} \gamma^\mu \gamma_5 \mu)$
scalar	$C_S^{(\prime)}$	$\frac{e^2}{16\beta^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \mu)$
pseudoscalar	$C_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b) (\bar{\mu} \gamma_5 \mu)$

$$\left. \begin{array}{l} b \rightarrow s \gamma \\ b \rightarrow s l l \end{array} \right\} \mathcal{B}_s^0 \rightarrow \mu^+ \mu^-$$

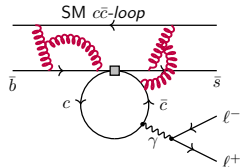
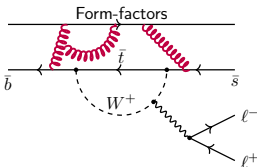


Observables in rare $b \rightarrow sll$ decays and their cleanliness

Quarks bound in hadrons, e.g.



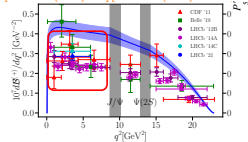
Hadronic uncertainties



$b \rightarrow sll$ Observables

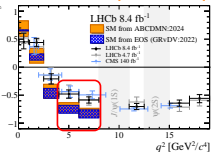
Increasing precision of SM prediction

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



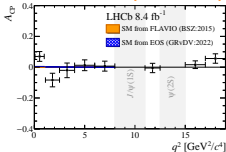
Branching fractions
affected by form-factors
and $c\bar{c}$ -loop

[arXiv:2512.18053]

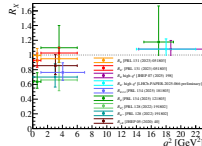


Angular observables
affected by $c\bar{c}$ -loop

[arXiv:2512.18053]

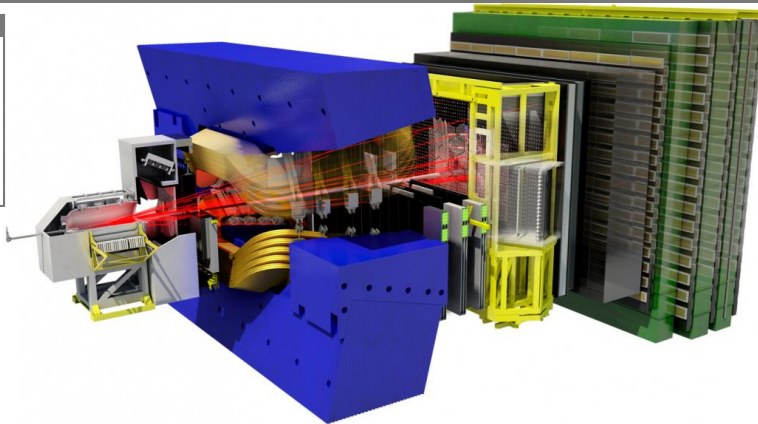
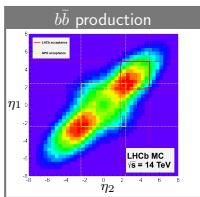


CP-asymmetries
clean



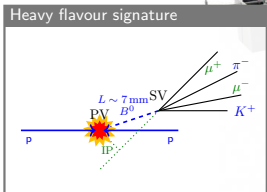
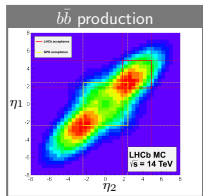
Lepton Universality Tests
clean

The LHCb detector: Optimized for heavy flavour

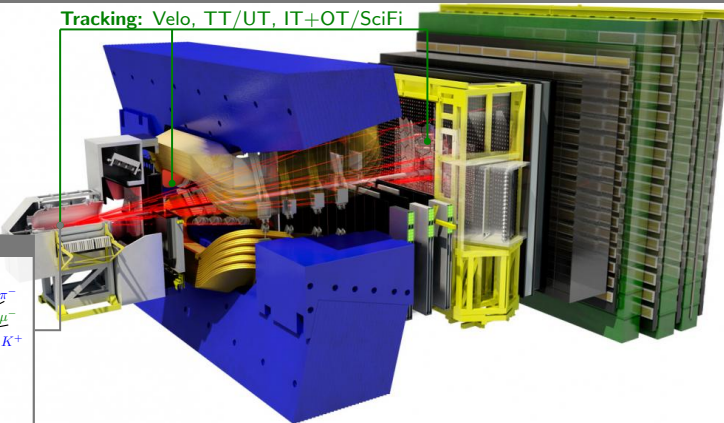


- Large $\sigma_{b\bar{b}}$: $(495 \pm 52) \mu\text{b}$ at 13 TeV [JHEP 10 (2015) 172] predominantly in forward direction \Rightarrow single-arm forward spectrometer with unique $2 < \eta < 5$ coverage [LJMP A30 (2015) 1530022] [JINST 19 (2024) P05065]
- Excellent IP resolution $\sim 20 \mu\text{m}$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

The LHCb detector: Optimized for heavy flavour

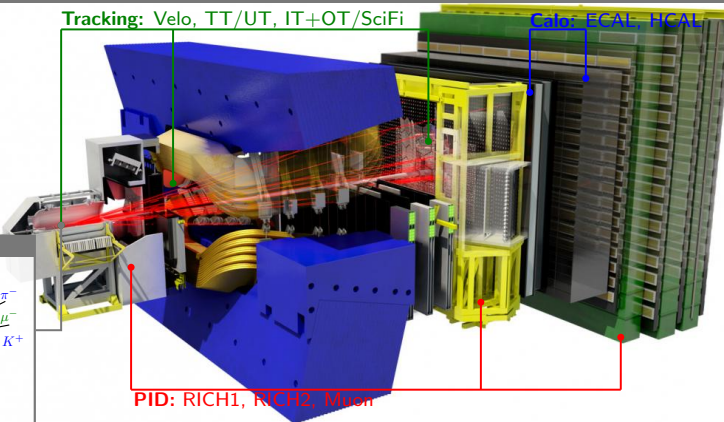
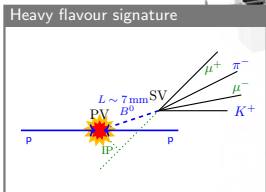
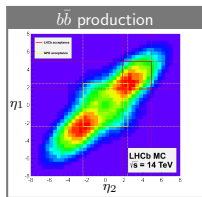


Tracking: Velo, TT/UT, IT+OT/SciFi

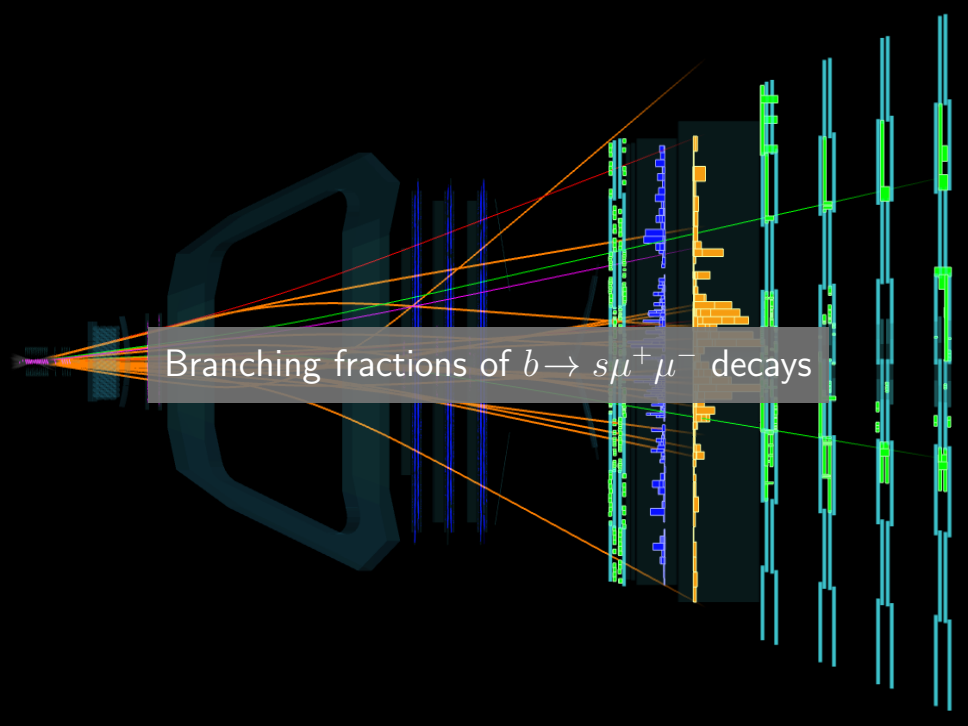


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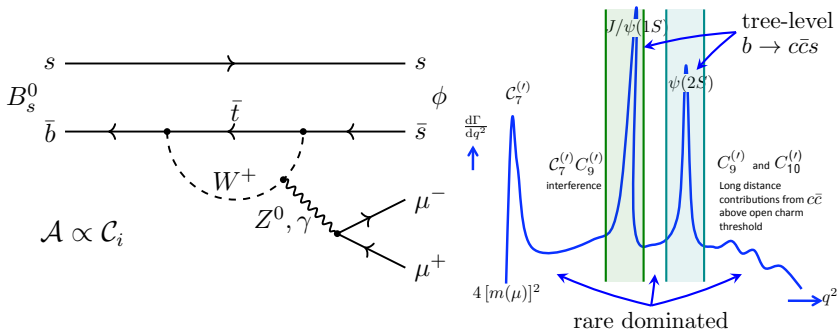
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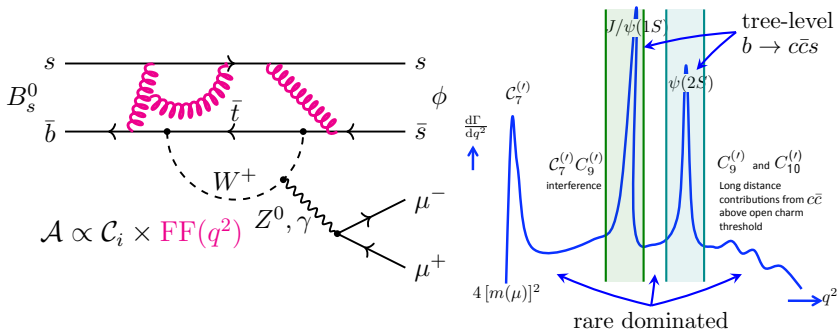


Branching fractions of $b \rightarrow s \mu^+ \mu^-$ decays

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

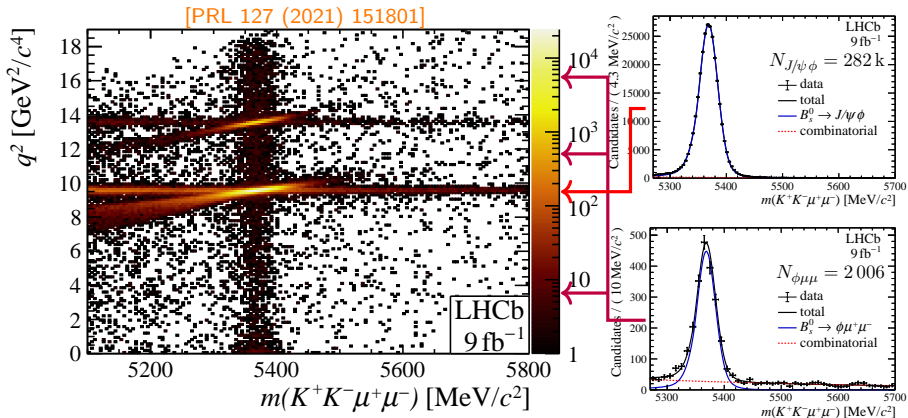
- Branching fraction of semileptonic $b \rightarrow s \mu^+ \mu^-$ decays can be affected by NP
- Central: $q^2 = m(\ell^+ \ell^-)^2$, different operators contribute depending on q^2
- At $q^2 = m_{J/\psi}^2$ important tree-level $b \rightarrow c\bar{c}s$ normalisation mode $B_s^0 \rightarrow J/\psi \phi$
- 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\]](#)

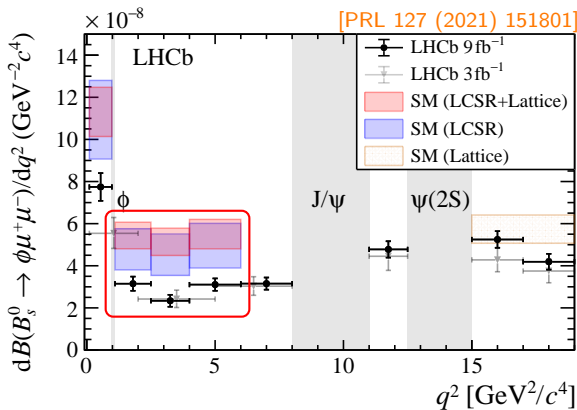
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$B_s^0 \rightarrow \phi[\rightarrow K^+K^-]\mu^+\mu^-$ with LHCb

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

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

SM LCSR

[JHEP 08 (2016) 098]

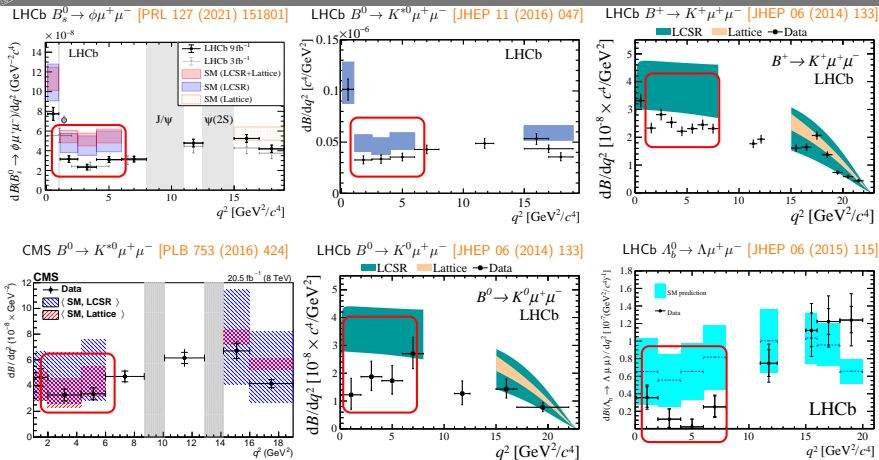
[EPJC 75 (2015) 8]

SM LCSR+Lattice

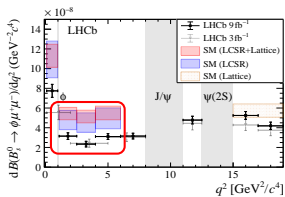
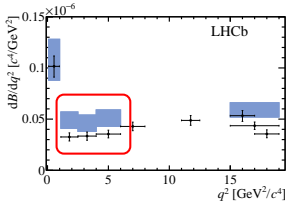
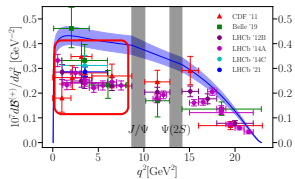
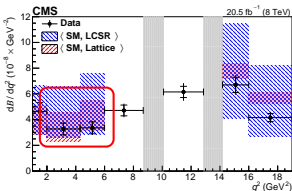
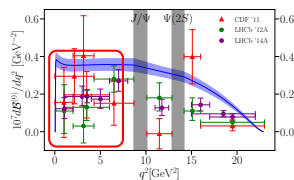
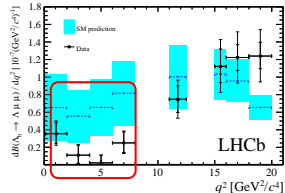
[PRL 112 (2014) 212003]

[PoS Lattice 2014 372]

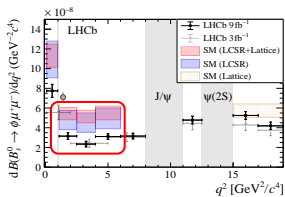
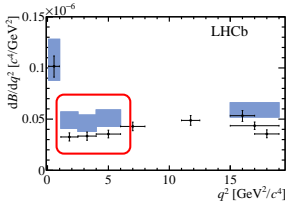
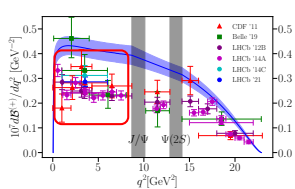
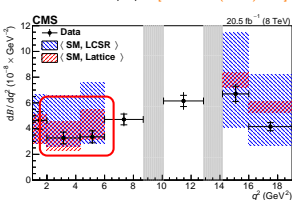
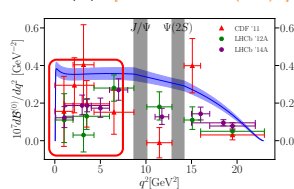
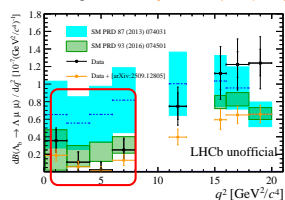
- Recent LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- $d\mathcal{B}(B_s^0 \rightarrow \phi \mu^+ \mu^-, 1.1 < q^2 < 6 \text{ GeV}^2/c^4) = (2.88 \pm 0.21)^{-8} \text{ GeV}^2/c^4$
- Tension with SM at **3.6 σ (LCSR+Lattice)** and **1.8 σ (LCSR only)**

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

- Data consistently below SM predictions, tensions at $1-3\sigma$ level but significant hadronic uncertainties from form-factors and charm-loop
- Important results from Lattice QCD [HPQCD, PRD 107 (2023) 1]
- $\mathcal{B}(A_b^0 \rightarrow J/\psi \Lambda)$ 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

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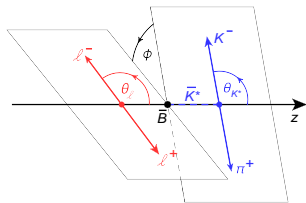
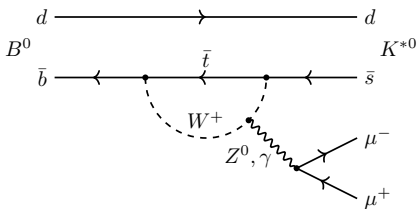
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The background features a dark blue, stylized particle detector structure. Overlaid on this are several data plots: a blue histogram, an orange histogram, and a green histogram, all connected by thin lines to various parts of the detector. The text is centered in a semi-transparent grey box.

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

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

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

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

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

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

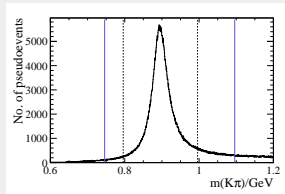
- In full generality 52 observables per q^2 bin
- Perform ratios of observables where **form factors** cancel at leading order

Example: $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}} \quad \left[\text{S. Descotes-Genon et al., JHEP, 05 (2013) 137} \right]$

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

More data

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



More observables

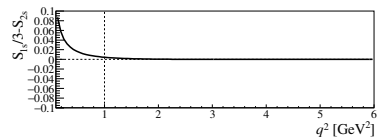
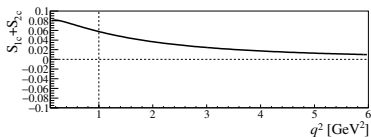
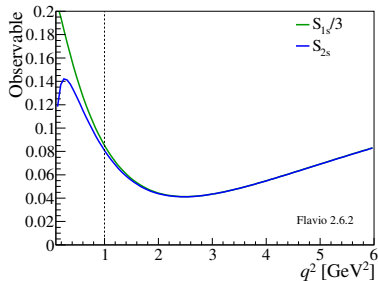
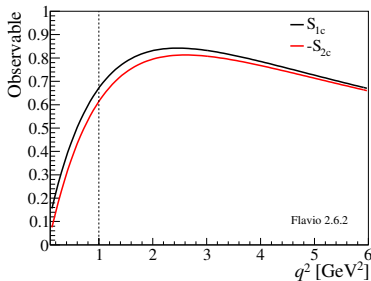
- P-wave, S-wave+interference observables, as well as CP -asymmetries
- Provide branching fraction measurement and full set of correlations
- In addition to nominal $\sim 2 \text{ GeV}^2$ wide bins use finer $\sim 1 \text{ GeV}^2$ binning

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 $q^2 < 1 \text{ GeV}^2$, assume $S_{1s} = 3S_{2s}$ at $q^2 > 1 \text{ GeV}^2$ ("partially massive")





Observables and fit configurations

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

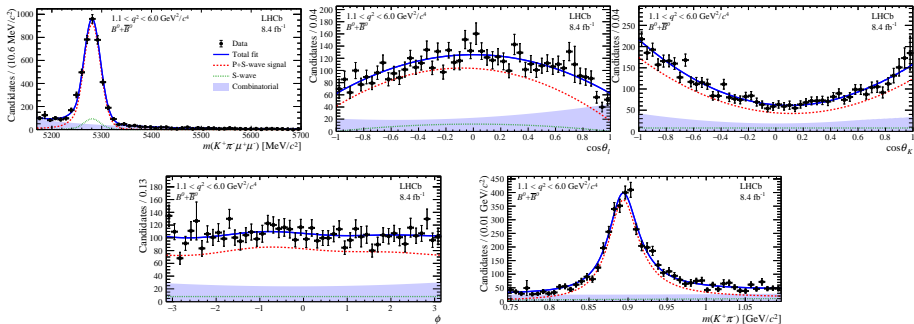
	$N_{\text{obs}}(N_{\text{obs}}^{q^2 < 1 \text{ GeV}^2})$
1 CP -averages only, S_i basis, partially massive ¹ Default for S_i basis	21 (26)
2 CP -averages only, $P_i^{(\prime)}$ basis, partially massive Default for P_i basis	21 (26)
3 Fully massive model, CP -averages only, S_i basis For effect of massive 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)

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

Example fit projection

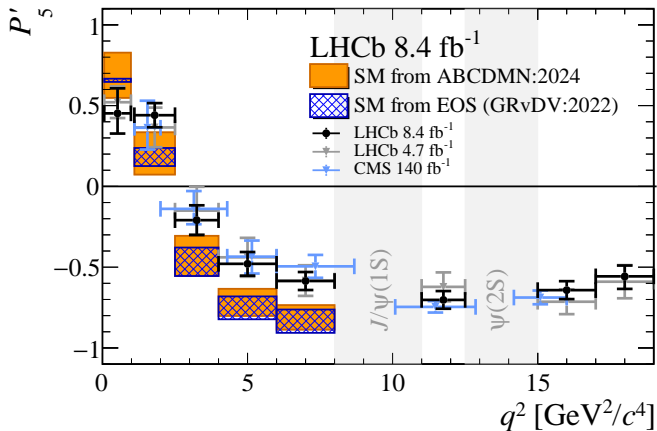
[arXiv:2512.18053]

- Fit projections of the five dimensions for $1.1 < q^2 < 6 \text{ GeV}^2$
- 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)

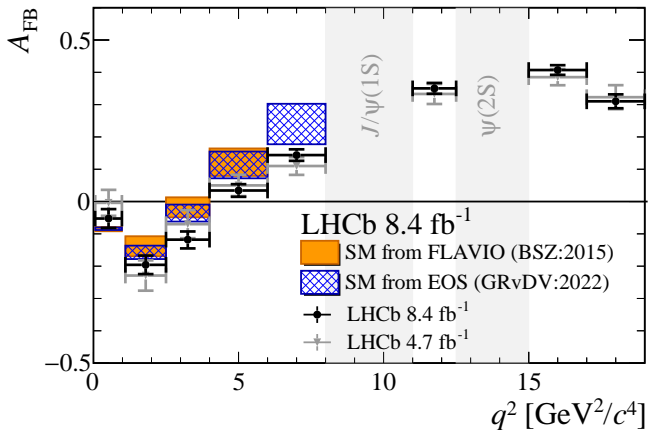
[arXiv:2512.18053]



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)[\[arXiv:2512.18053\]](https://arxiv.org/abs/2512.18053)

BSZ:

[\[arXiv:1810.08132\]](https://arxiv.org/abs/1810.08132)[\[JHEP 08 \(2016\) 098\]](https://arxiv.org/abs/1810.08132)

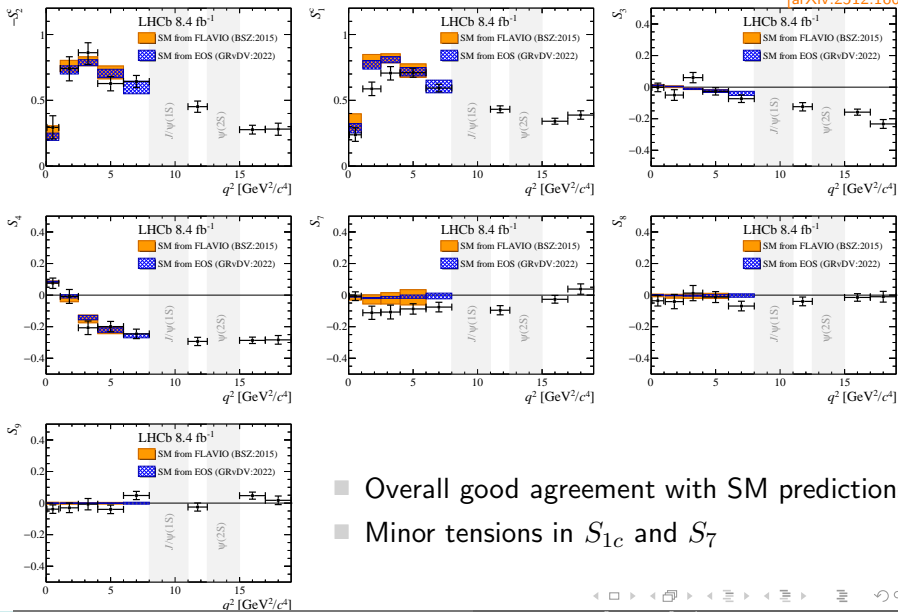
GRvDV:

[\[EPJC 82 \(2022\) 569\]](https://arxiv.org/abs/2202.0569)[\[JHEP 09 \(2022\) 133\]](https://arxiv.org/abs/2202.0569)

- 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)

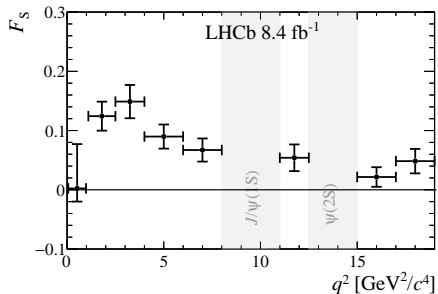
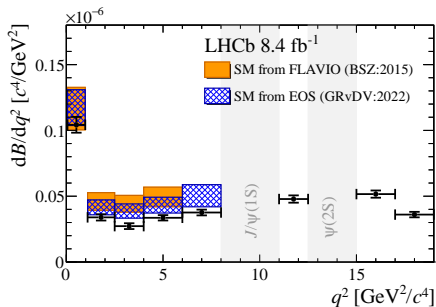
[arXiv:2512.18053]



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

P-wave branching fraction and S-wave fraction

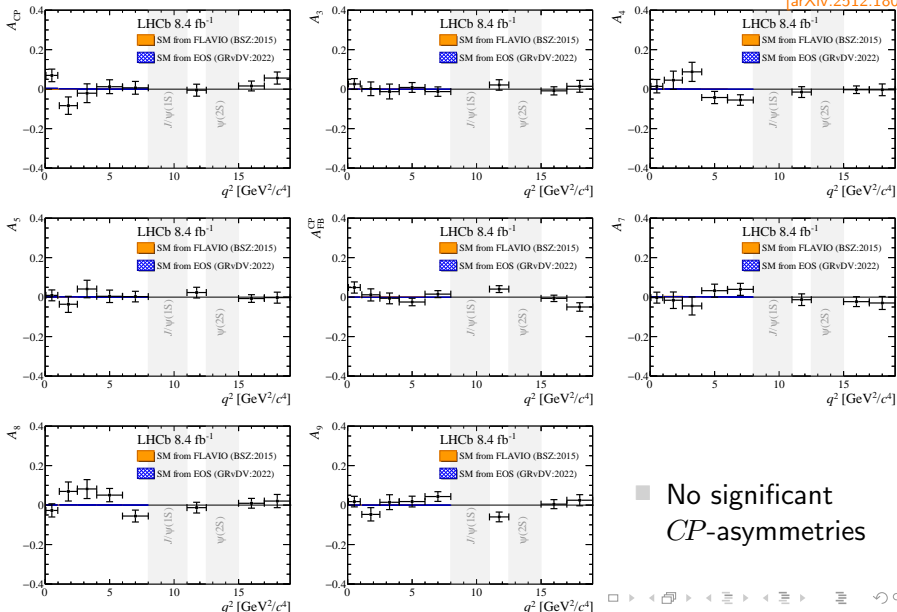
[arXiv:2512.18053]



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

CP -asymmetries (config 4)

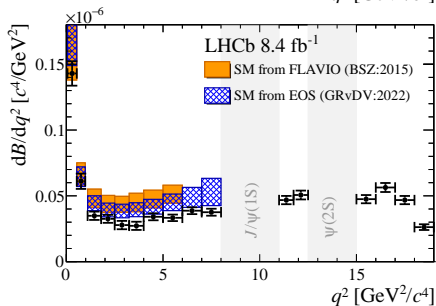
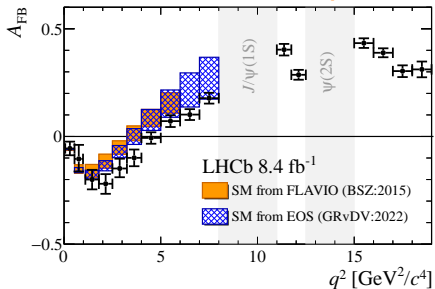
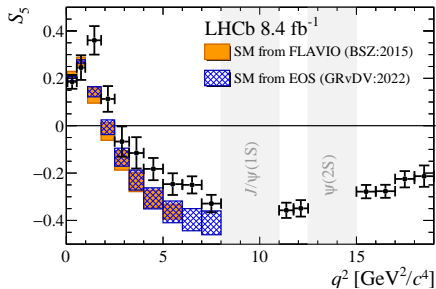
[arXiv:2512.18053]



■ No significant CP -asymmetries

Narrow q^2 bins (config 6)

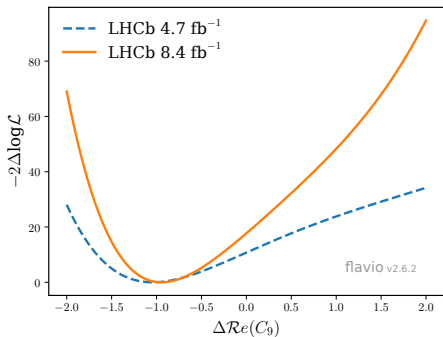
[arXiv:2512.18053]



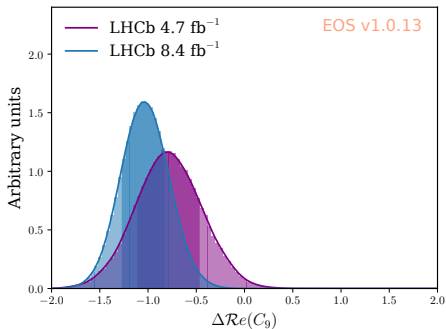
- Tradeoff between statistical uncertainty/better q^2 resolution
- In excellent agreement with regular-sized q^2 bins

Interpretation in terms of Wilson coefficients

[arXiv:2512.18053]



$$\Delta \mathcal{R}e C_9 = -0.93^{+0.18}_{-0.16}$$

Significance 4.1σ 

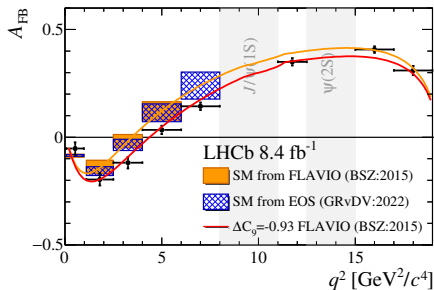
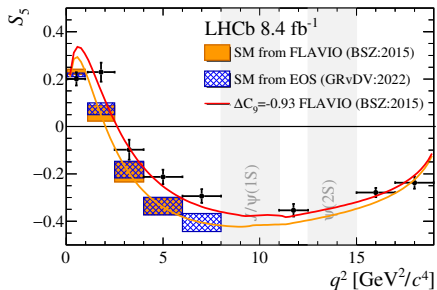
$$\Delta \mathcal{R}e C_9 = -0.94^{+0.22}_{-0.22}$$

Significance 4.0σ

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

Improved description of data with $\Delta \mathcal{R}e C_9 = -0.93$

[arXiv:2512.18053]

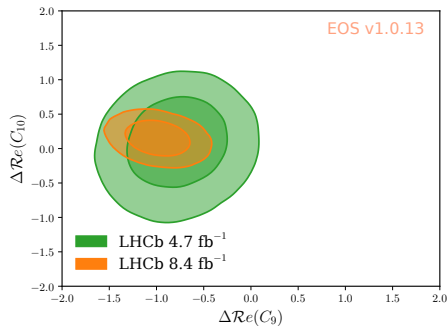
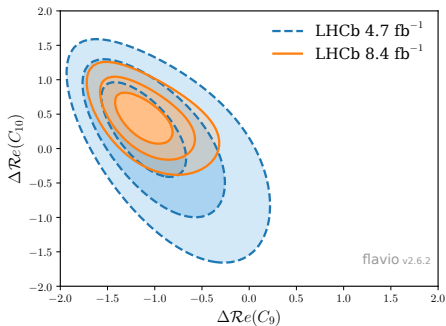


- For illustration overlaid central value for $\Delta \mathcal{R}e C_9 = -0.93$
- Clearly improved description of the data

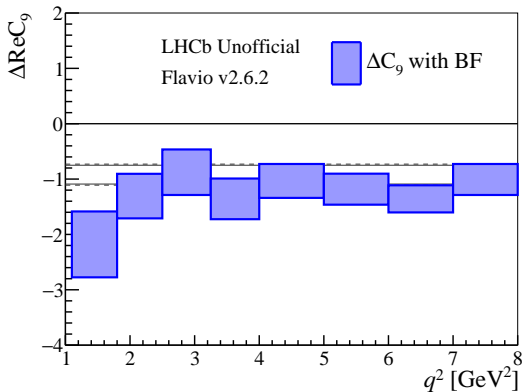


Interpretation in terms of Wilson coefficients

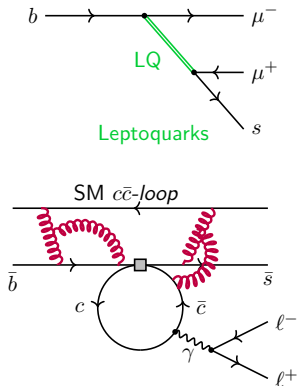
[arXiv:2512.18053]



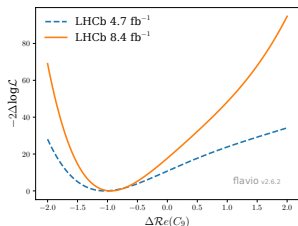
- Tension most pronounced in $\text{Re}C_9$
- $\text{Re}C_{10}$ in agreement with SM prediction

Dependence of shift of $\text{Re}C_9$ on q^2 

Possible NP contribution



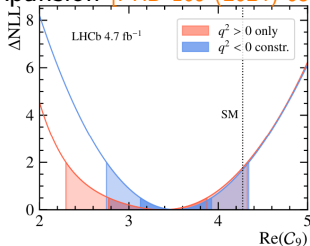
- Shift in $\text{Re}C_9$ quite consistent across q^2 bins
- Open question: NP or underestimated hadronic contributions (charm-loop)?
 - If shift due to heavy NP $\rightarrow q^2$ -independent
 - If shift due to charm-loop \rightarrow might expect rise towards J/ψ -region

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

$$\Delta \text{Re} C_9 = -0.93^{+0.18}_{-0.16}$$

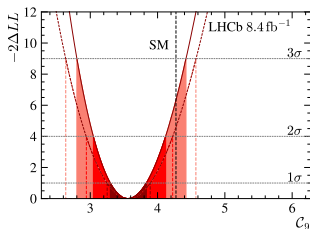
- Unbinned parameterize **charm loop**:
 $C_9^{\text{eff}} = C_9 + \mathcal{H}_{0,\parallel,\perp}(q^2)$
- Shifts in C_9 consistent
- Fewer parameters in binned analysis, smaller uncertainties

z-Expansion [PRD 109 (2024) 052009]

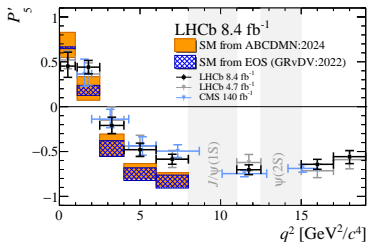


$$\Delta \text{Re} C_9 = -0.93^{+0.53}_{-0.57}$$

Amplitude model [JHEP 09 (2024) 026]

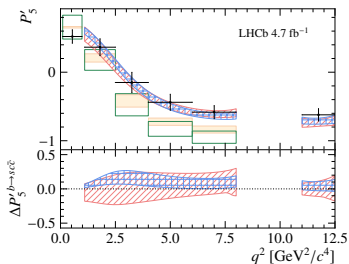


$$\Delta \text{Re} C_9 = -0.71 \pm 0.33$$

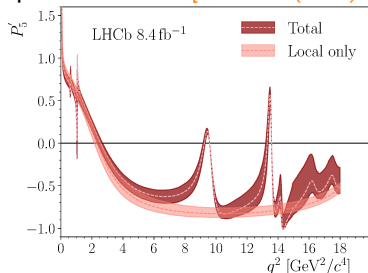
Comparison with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ unbinned results

- Excellent agreement of angular observables

z-Expansion [PRD 109 (2024) 052009]

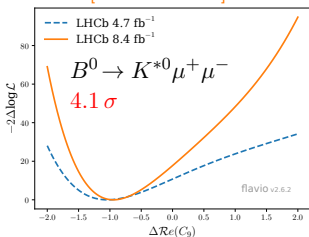


Amplitude model [JHEP 09 (2024) 026]

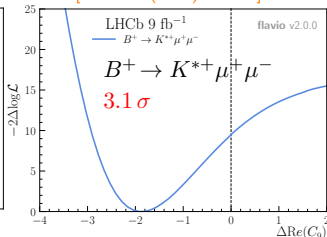


Consistency with other $b \rightarrow s \mu^+ \mu^-$ angular analyses

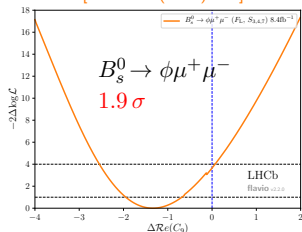
[arXiv:2512.18053]



[PRL 126 (2021) 161802]



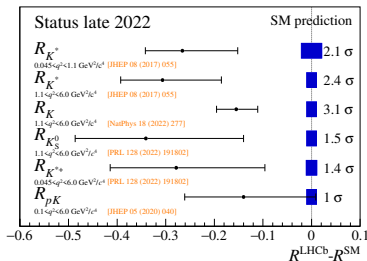
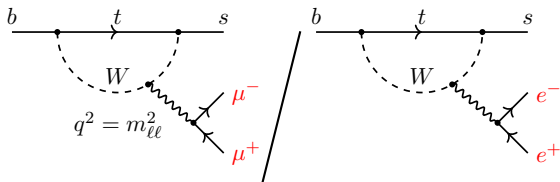
[JHEP 11 (2021) 043]



- Use flavio [arXiv:1810.08132] to determine tension with SM hypothesis
- Variation of vector coupling $\text{Re}(C_9)$ results in improved description of data
- Consistent trend for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [arXiv:2512.18053], $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ [PRL 126 (2021) 161802] and $B_s^0 \rightarrow \phi \mu^+ \mu^-$ [JHEP 11 (2021) 043] angular observables



Lepton flavour universality tests in $b \rightarrow sl^+l^-$ decays

Lepton universality in rare $b \rightarrow sl^+l^-$ decays

- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \rightarrow sl^+l^-$ decays:

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

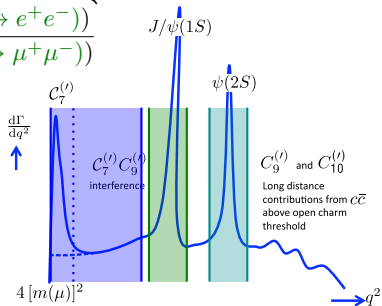
- Exactly unity in SM, differences only through lepton mass effects
- QED corrections $\mathcal{O}(1\%)$ [EPJC 76 (2016) 440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio

Analysis strategy: Double ratio (Example: R_K)

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

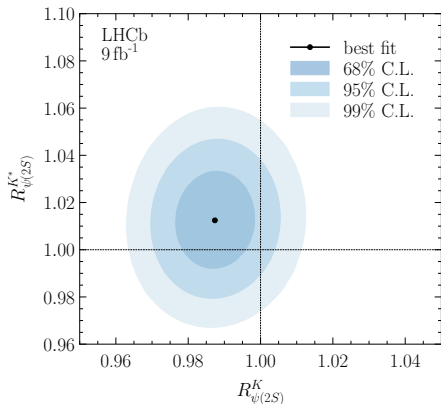
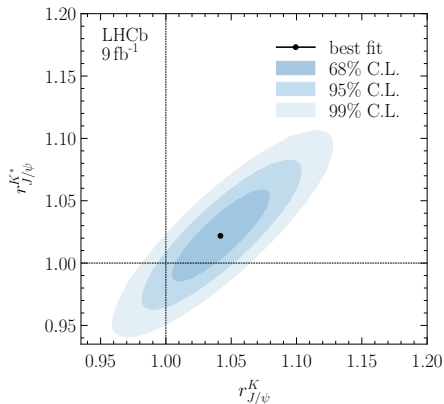
$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \times \overbrace{\frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}}^{r_{J/\psi}^{-1} = 1 \text{ [PRD 88 (2013) 3]}}$$

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



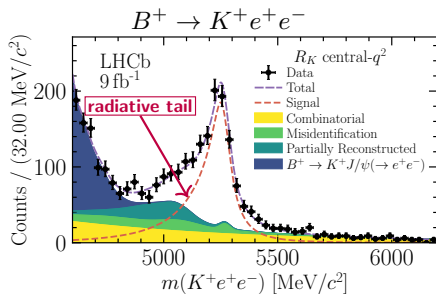
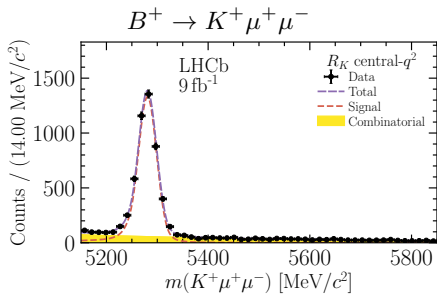
- Important cross-checks: $r_{J/\psi} = \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}$ and

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

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

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

Experimental challenges for electron modes at LHCb

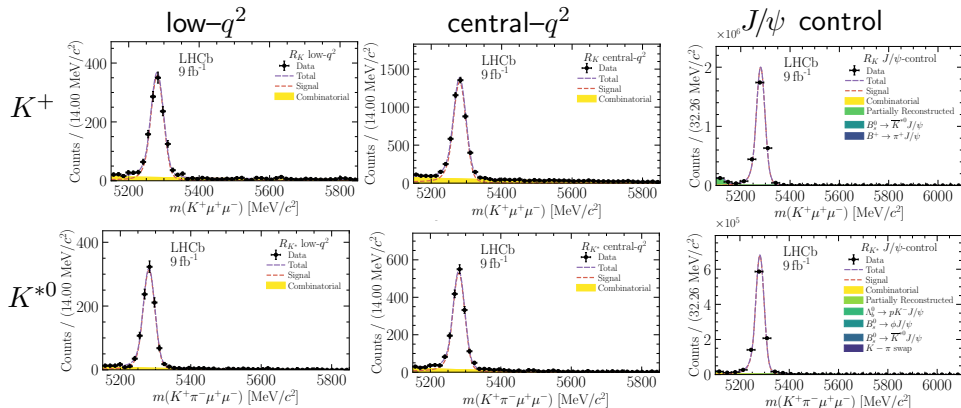


[arXiv:2212.09152] [arXiv:2212.09153]

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

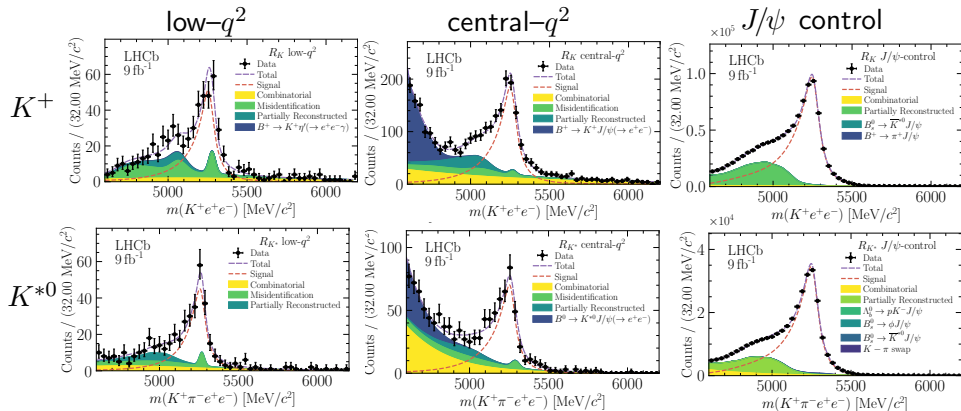
Muon mode fits



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

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

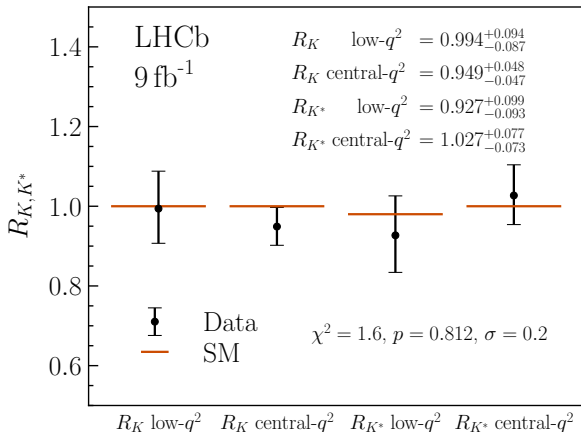
Electron mode fits



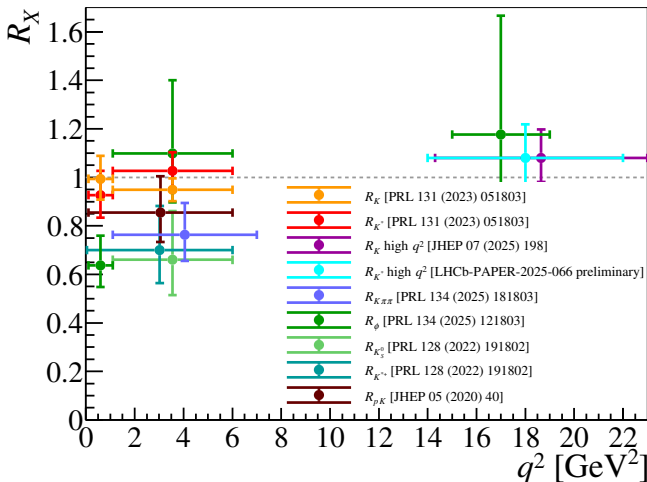
- Good fit quality when including all components
- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bkg. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

R_K and R_{K^*} results

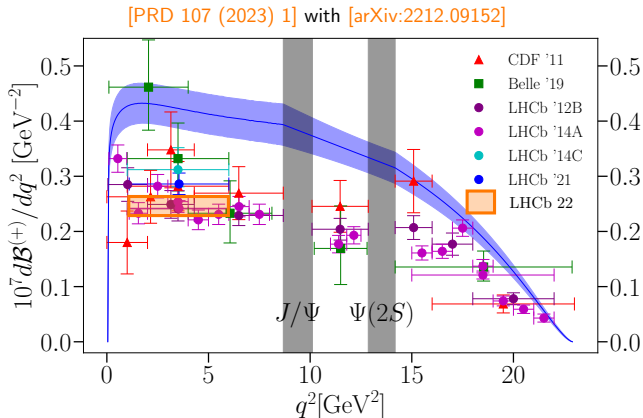
[arXiv:2212.09152] [arXiv:2212.09153]



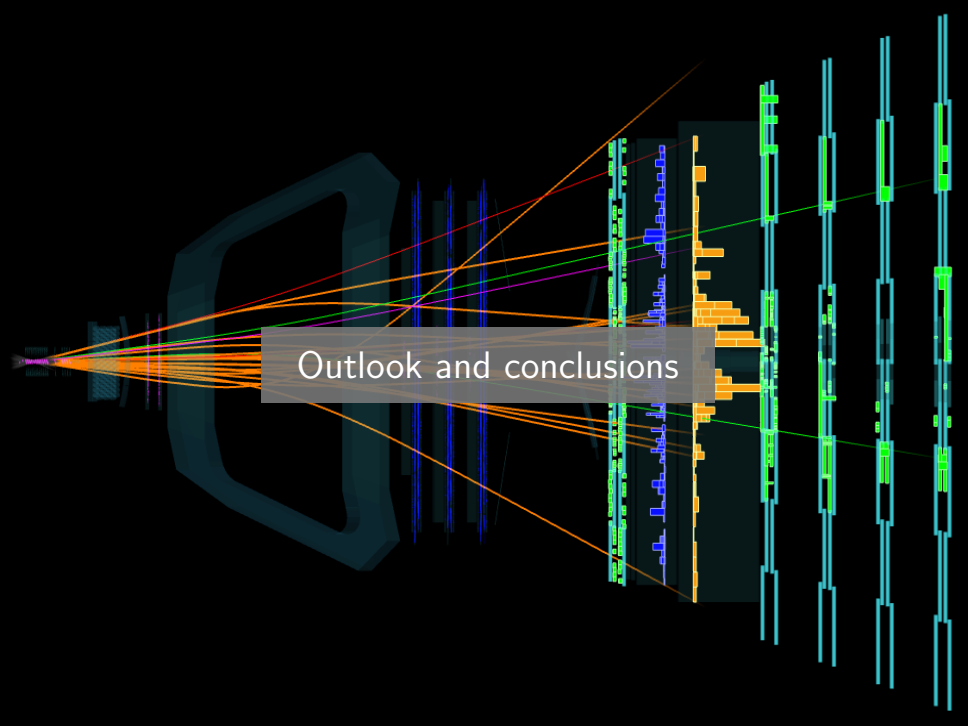
- Most precise test of LFU in $b \rightarrow s \ell^+ \ell^-$ transitions
- Compatible with the SM at 0.2σ using simple χ^2 test

Summary LFU tests in rare $b \rightarrow sl^+l^-$ decays

- Enormous experimental effort since 2022
- Good agreement with SM

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

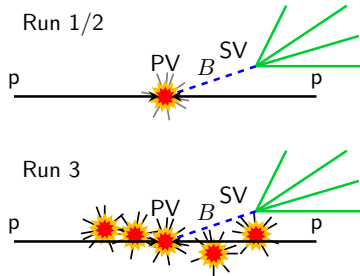
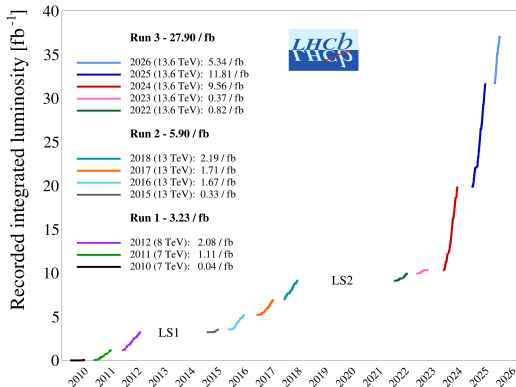
- Scaling R_{K,K^*} with measured muon \mathcal{B} yields [JHEP 06 (2014) 133]
 $d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) / dq^2 = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9} \text{ GeV}^{-2}$
- Electron \mathcal{B} consistent with muons, also below SM prediction



Outlook and conclusions

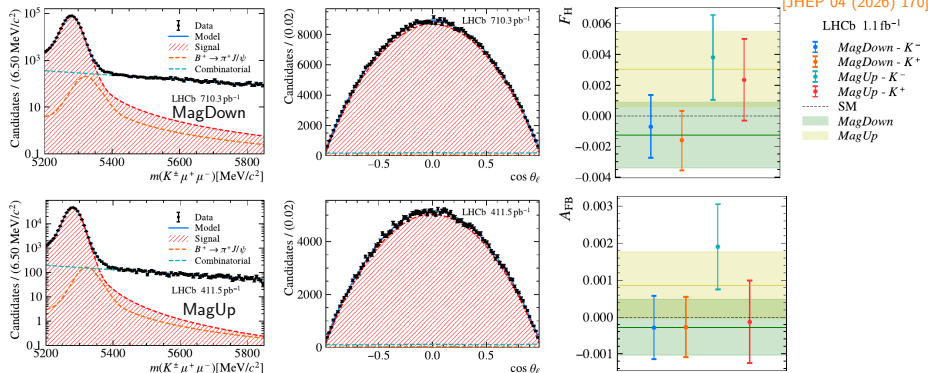
Current and future data samples

Total recorded luminosity – pp – 37.0 fb^{-1}

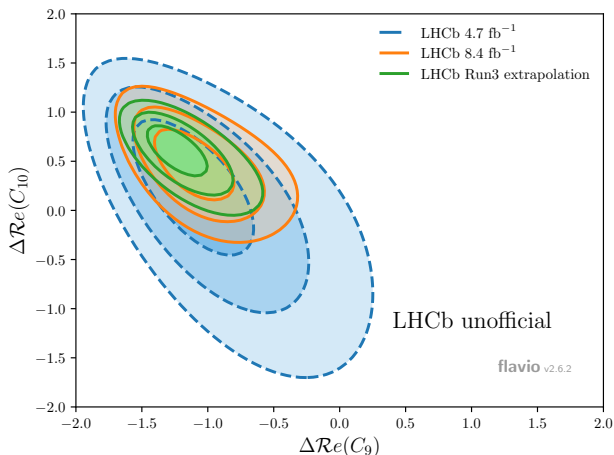


- LHCb has taken more than 27 fb^{-1} in Run 3 (compare $\sim 9 \text{ fb}^{-1}$ in Run 1–2)
- A huge Run 3 data sample available for analysis, good understanding of data from [Upgrade I] detector required

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



- Differential angular fit of $\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4}(1 - F_H) + \frac{1}{2}F_H + A_{FB} \cos \theta_\ell$
- Using 1 fb^{-1} of Run 3 data from 2024 good agreement with SM pred. of 0:
 $A_{FB} = 0.00019 \pm 0.00048_{\text{stat}} \pm 0.00033_{\text{syst}}$, $F_H = 0.0005 \pm 0.0011_{\text{stat}} \pm 0.0014_{\text{syst}}$
- 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!

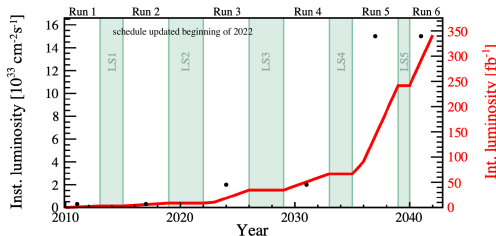
Run 3 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ extrapolation

- Assuming equal central values tension in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ goes $\gtrsim 5\sigma$
- Work on update of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ using Run 3 data ongoing

Prospects beyond Run 3/4: the Upgrade II

 Prospects from [\[arXiv:1808.08865\]](https://arxiv.org/abs/1808.08865)
 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis

$\int \mathcal{L} dt$	3 fb^{-1}	23 fb^{-1}	300 fb^{-1}
$\sigma^{\text{stat}}(S_i)$	≤ 0.058	≤ 0.016	≤ 0.004
$\sigma(C'_{10})$	0.31	0.15	0.06
$\Lambda_{\text{NP}}^{\text{tree generic}} [\text{TeV}]$	50	75	115



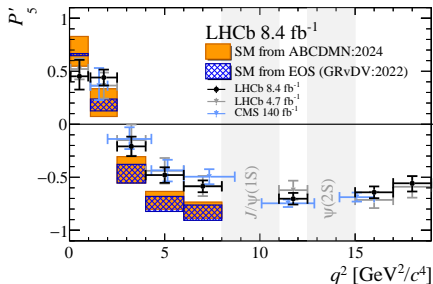
- At the end of Run 4 expect to have collected around 50 fb^{-1}
- Upgrade 2 will increase $\int \mathcal{L} dt$ to 300 fb^{-1}
 Framework TDR [\[CERN-LHCC-2021-012\]](https://arxiv.org/abs/2012.01513),
 Physics case [\[CERN-LHCC-2018-027\]](https://arxiv.org/abs/1812.07638),
 CERN Yellow report [\[arxiv:1812.07638\]](https://arxiv.org/abs/1812.07638),
 Scoping document [\[CERN-LHCC-2024-010\]](https://arxiv.org/abs/2012.01513)
- NP reach in Upgrade II increases by more than factor 2 wrt. Run 1+2
- Λ_{NP} reach beyond 100 TeV



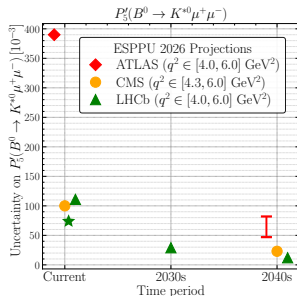


Summary and Conclusions

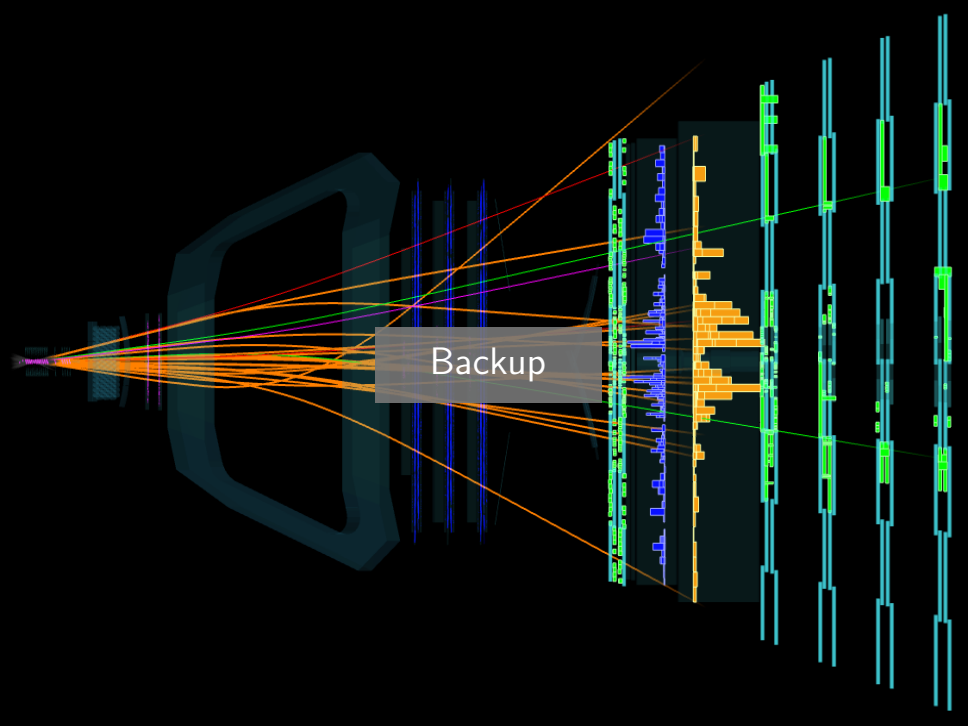
[arXiv:2512.18053]



[arXiv:2503.24346][Figures]



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



Backup

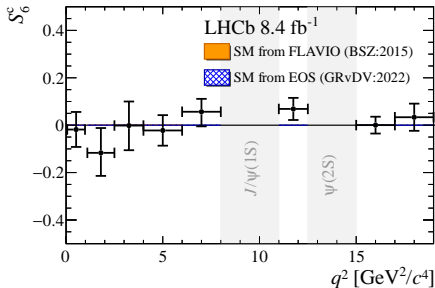
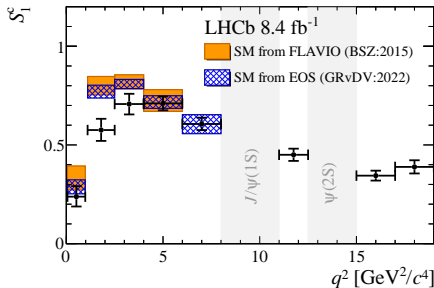
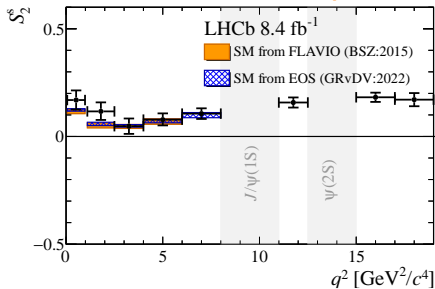
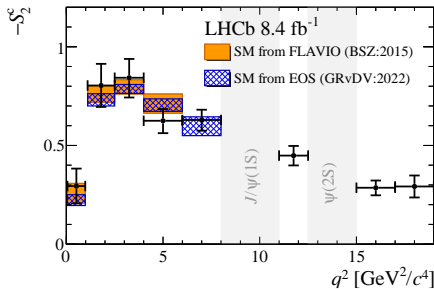
Systematic uncertainties

[arXiv:2512.18053]

Source	S_2^c	$A_{FB}, S_1^c - S_9$	$P_1 - P_8$	F_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
$B^+ \rightarrow K^+\mu\mu$ 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
Neuman construction nuisance	< 0.010	< 0.010	< 0.075	< 0.025	< 0.025	< 0.000

Massive leptons (config 3)

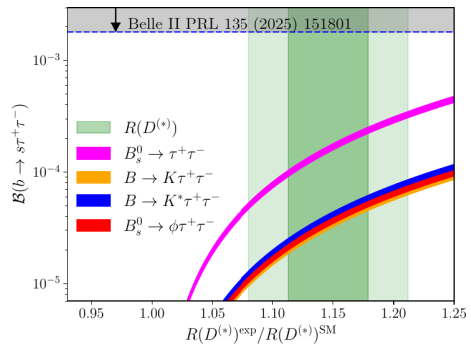
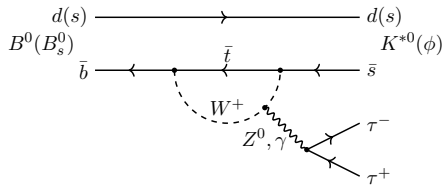
[arXiv:2512.18053]



Massive leptons (config 3)

LHCb-PAPER-2025-040, in preparation

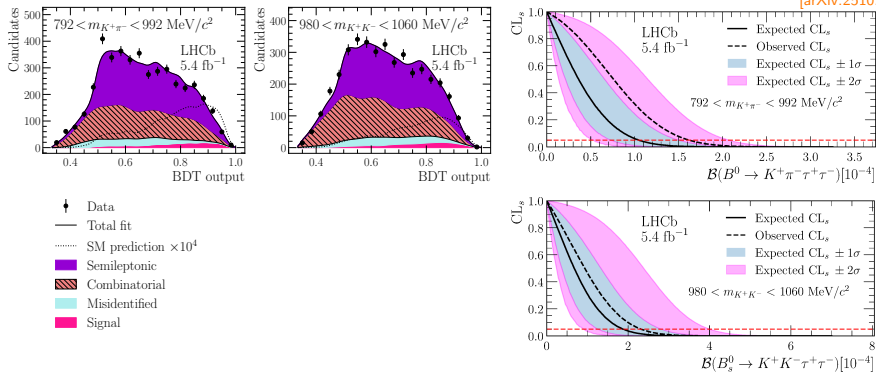
Systematic source	<i>MagDown</i>		<i>MagUp</i>	
	A_{FB}	F_{H}	A_{FB}	F_{H}
Simulation sample size	44	103	39	104
Alternative scheme for $w_{\text{kin.}\&\text{mult.}}$	3	114	4	90
Simulation corrections	14	30	12	24
Truth-matching	7	28	2	51
Signal mass model	1	25	1	17
Choice of hyperparameters in $w_{\text{kin.}\&\text{mult.}}$	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

Search for $B \rightarrow K^+ \pi^- (K^+ K^-) \tau^+ \tau^-$ 

- SM prediction at the order of 10^{-7} [PRL 120 (2018) 181802]
- Could have large NP effects in $b \rightarrow s \tau^+ \tau^-$ decays [PRL 120 (2018) 181802]
- Most stringent limit from Belle II $\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) < 1.8 \times 10^{-3}$ [PRL 135 (2025) 151801] and preliminary $\mathcal{B}(B^+ \rightarrow K^+ \tau^+ \tau^-) < 8.7 \times 10^{-4}$ at 90%
- New search using $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ decays [arXiv:2510.13716]

Exclusion limits for $B \rightarrow K^+ \pi^- (K^+ K^-) \tau^+ \tau^-$

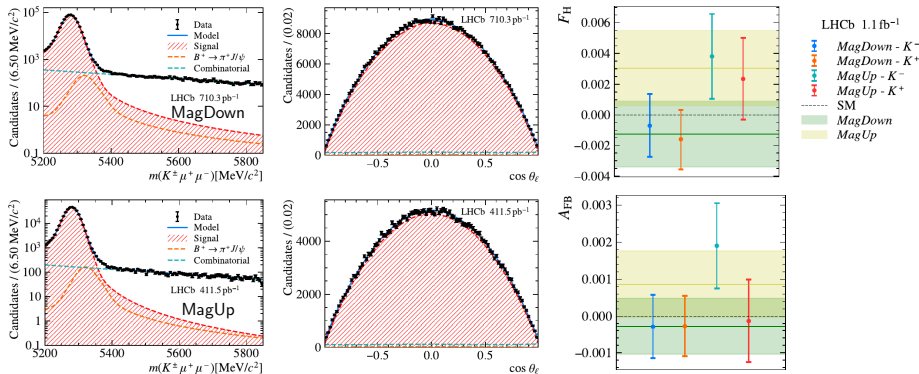
[arXiv:2510.13716]



- B mass cannot be fully reconstructed, instead fit BDT output
- Obtained upper limits using 5.4 fb^{-1} Run 2 data:
 $\mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \tau^-) < 2.8 \times 10^{-4} (2.5 \times 10^{-4})$ at 95% (90%) CL
 $\mathcal{B}(B_s^0 \rightarrow \phi \tau^+ \tau^-) < 4.7 \times 10^{-4} (4.1 \times 10^{-4})$ at 95% (90%) CL
- Can be interpreted as limit on Δ^2 under assumption $\Delta = \Delta C_9^{\tau\tau} = -\Delta C_{10}^{\tau\tau}$:
 $\Delta^2 < 2.9 \times 10^4 (2.5 \times 10^4)$ at 95% (90%)

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

LHCb-PAPER-2025-040, in preparation



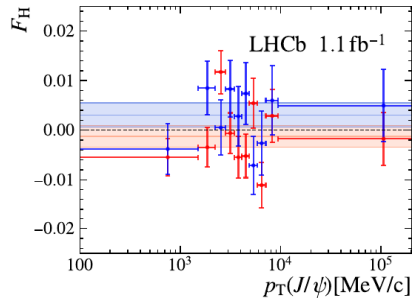
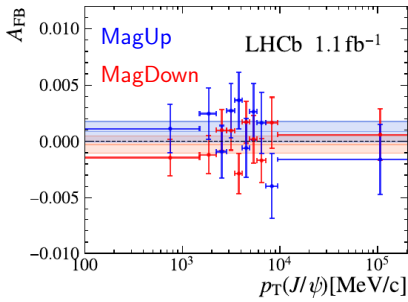
- Differential angular fit of

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4} (1 - F_H) + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$$

- Using 1 fb⁻¹ of 2024 data excellent agreement with SM prediction of 0:
 $A_{FB} = 0.00019 \pm 0.00048_{\text{stat}} \pm 0.00033_{\text{sys}}$, $F_H = 0.0005 \pm 0.0011_{\text{stat}} \pm 0.0014_{\text{sys}}$
- Consistent results for MagnetUp/Down and Kaon charge

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

LHCb-PAPER-2025-040, in preparation

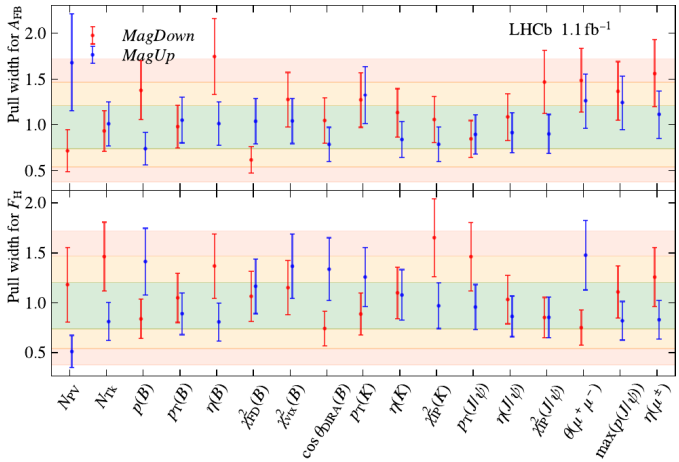


- No systematic deviations observed in angular obs. depending on $p_T(J/\psi)$
- Measured angular dist. across 17 different variables, no syst. deviations gives great confidence in quality of data!



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

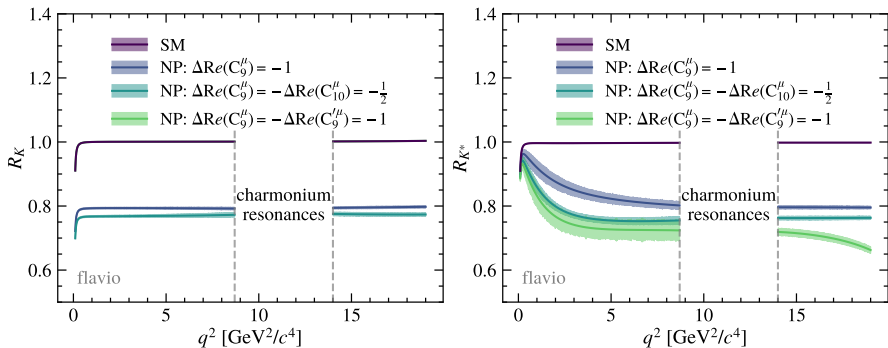
LHCb-PAPER-2025-040, in preparation



Check both linear coeff. and pull:

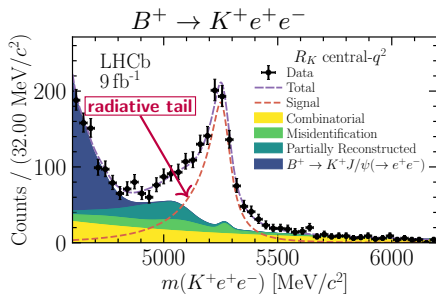
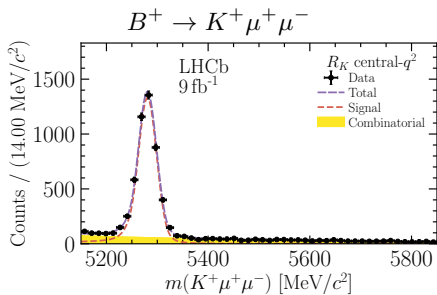
$$p(O_i^m) = \frac{O_i^m - O_{int}^m}{\sigma(O_i^m)}$$

- 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!

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 fb^{-1} Run 1+2 data
 - low- q^2 : $q^2 \in [0.1, 1.0] \text{ GeV}^2/c^4$
 - central- q^2 : $q^2 \in [1.1, 6.0] \text{ GeV}^2/c^4$

Experimental challenges for electron modes at LHCb

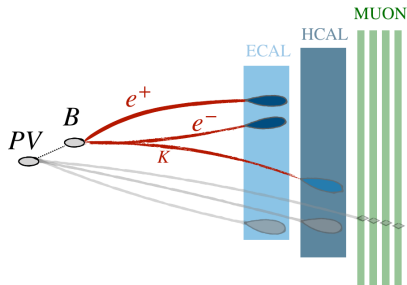
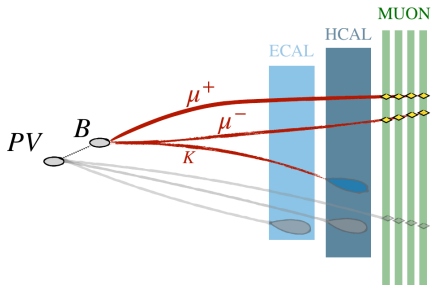


[arXiv:2212.09152] [arXiv:2212.09153]

Experimental Challenges for electron modes:

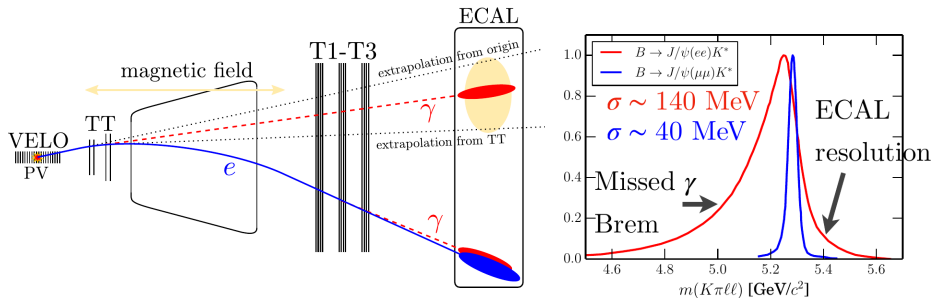
- 1 Low e trigger efficiencies due to higher thresholds compared to muons
- 2 Electrons strongly emit **Bremsstrahlung** traversing material
Brem- γ recovery has limited efficiency and degrades mass resolution
- 3 Contribution from several background sources, bkg. modeling critical

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 GeV/ c) compared to electrons (2.5–3.0 GeV) \rightarrow 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

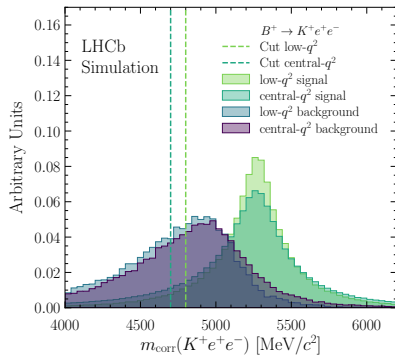
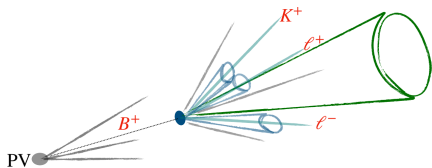
Experimental challenge: 2. Bremsstrahlung



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

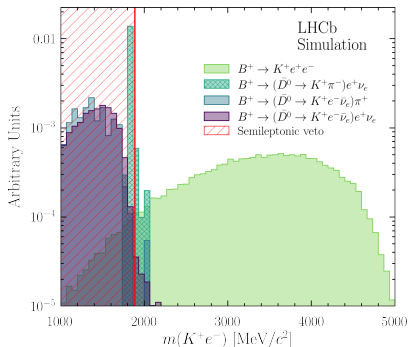
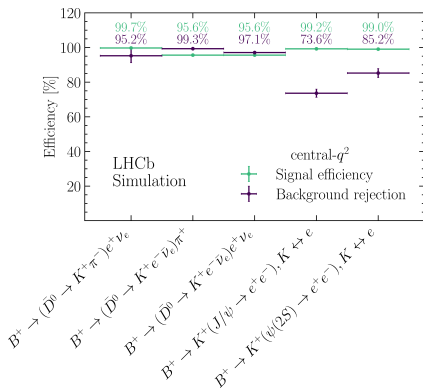


Experimental challenge: 3. Background suppression

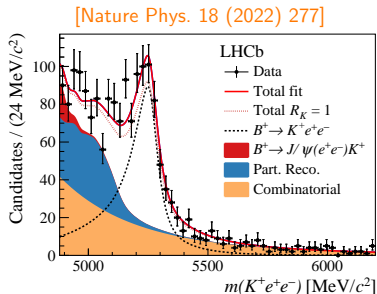


- Combinatorial backgrounds: suppressed using multivariate classifier using kinematic and vertex quality information
- Partially reconstructed:
 - 1 MVA using track/vertex isolation
 - 2 Corrected mass exploiting PV/SV
- Specific backgrounds: vetos combining PID and kinematic criteria

Experimental challenge: 3. Background suppression



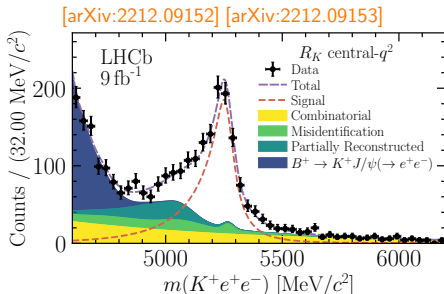
- Combinatorial backgrounds: suppressed using multivariate classifier using kinematic and vertex quality information
- Partially reconstructed:
 - 1 MVA using track/vertex isolation
 - 2 Corrected mass exploiting PV/SV
- Specific backgrounds: vetos combining PID and kinematic criteria

Difference to previous R_K analysis

$$R_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

[Nature Phys. 18 (2022) 277]

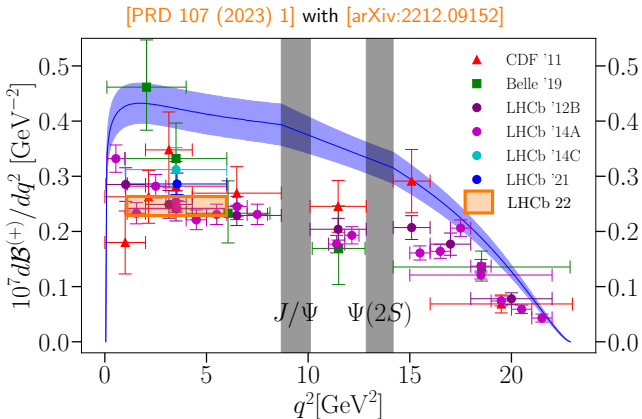
→



$$R_K = 0.949^{+0.042+0.022}_{-0.041-0.022}$$

[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

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

- Scaling R_{K,K^*} with measured muon \mathcal{B} yields [JHEP 06 (2014) 133]
 $d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) / dq^2 = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9} \text{ GeV}^{-2}$
- Electron \mathcal{B} consistent with muons, also below SM prediction