

Latest results on CPV and B anomalies

C. Langenbruch¹

on behalf of the ATLAS, CMS, and LHCb collaborations

¹Heidelberg University

QCD at LHC 2026

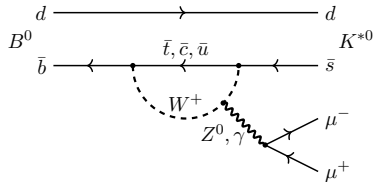
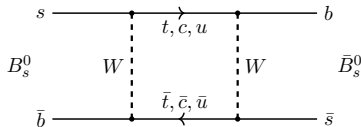
Oxford, September 30th 2026



New Physics searches with precision flavour

- New Physics particles can enter loop processes as virtual particles
- Particularly sensitive: Flavour Changing Neutral Currents

$B_s^0 - \bar{B}_s^0$ mixing (box diagram) $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (penguin diagram)

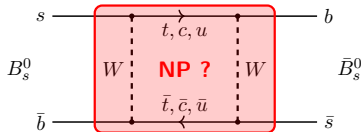


- Compare SM predictions with precision flavour measurements
→ Indirect search for New Physics
- Higher mass scales $\mathcal{O}(100 \text{ TeV})$ accessible than with direct searches
- Pattern of deviations can hint at structure of New Physics

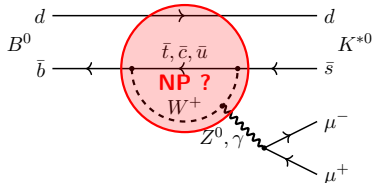
New Physics searches with precision flavour

- New Physics particles can enter loop processes as virtual particles
- Particularly sensitive: Flavour Changing Neutral Currents

$B_s^0 - \bar{B}_s^0$ mixing (box diagram) $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (penguin diagram)



NP can induce new CPV phases



NP can affect $\mathcal{B}$, angular distributions

- Compare SM predictions with precision flavour measurements
→ Indirect search for New Physics
- Higher mass scales $\mathcal{O}(100 \text{ TeV})$ accessible than with direct searches
- Pattern of deviations can hint at structure of New Physics

CP Violation

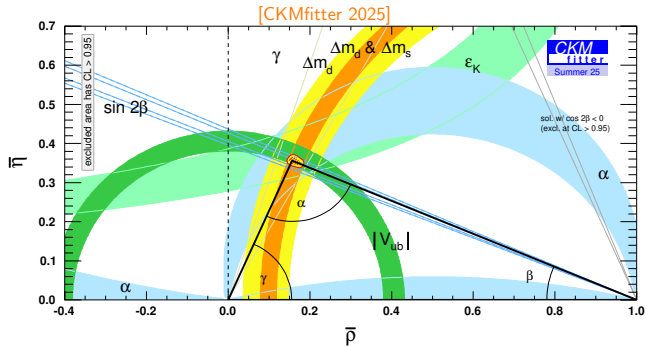
~~CP~~ Violation

- Hunt for CPV phases induced by NP



NP searches with precision CP violation measurements

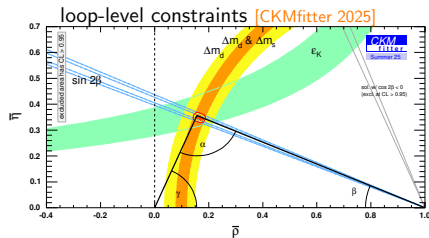
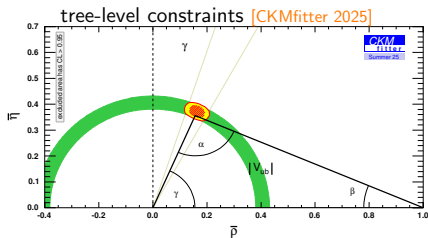
- CKM matrix the only source of CP violation in the SM
- Unitarity condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ triangle in complex plane



- Compare tree-level constraints with loop-level constraints
 - No NP
 - Possible NP
- Tree: $|V_{ub}|$ from $b \rightarrow ul\nu_l$, γ from $B \rightarrow DK$
- Loop: $B_{(s)}^0$ -mixing, $\Delta m_{(s)}$, mixing phase $\beta_{(s)}$

NP searches with precision CP violation measurements

- CKM matrix the only source of CP violation in the SM
- Unitarity condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ triangle in complex plane



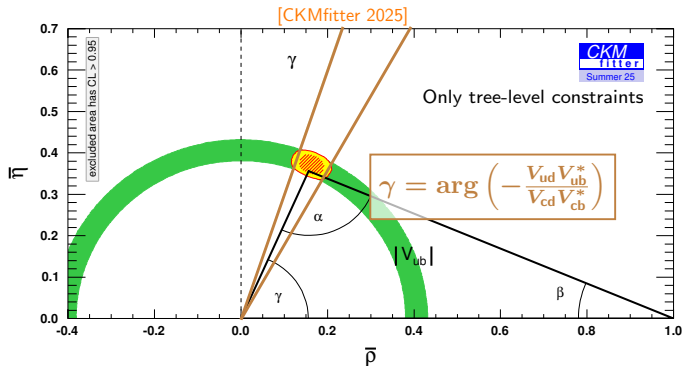
- Compare tree-level constraints with loop-level constraints

No NP
Possible NP
- Tree: $|V_{ub}|$ from $b \rightarrow u \ell \nu_\ell$, γ from $B \rightarrow DK$
- Loop: $B_{(s)}^0$ -mixing, $\Delta m_{(s)}$, mixing phase $\beta_{(s)}$



The CKM angle γ

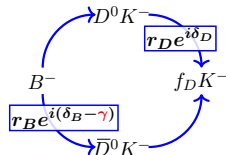
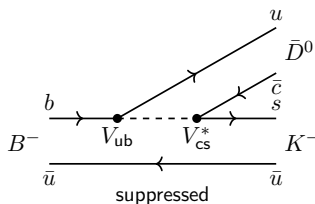
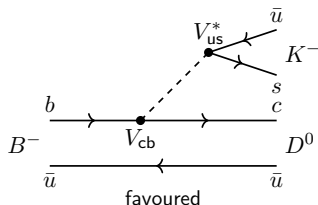
- γ only known to around $\pm 3^\circ$
- Only angle that can be determined using only tree-level processes



- CKM picture dominated by loop measurements
- Improve tree-level precision to search for deviations in loops



Determining γ from $B^- \rightarrow \bar{D}^0 K^-$ tree-level decays



To access the relative phase γ need final state f_D common to D^0 and $\bar{D}^0$

- ADS using flavour-specific states $\bar{D}^0 \rightarrow K^+ \pi^-$

[Atwood, Dunietz, Soni, PRL 78 (1997) 3257]

- GLW using CP eigenstates $\bar{D}^0 \rightarrow h^+ h^-$ with $h = \pi, K$

[Gronau, London, Wyler, PLB 265 (1991) 172, PLB 253 (1991) 483]

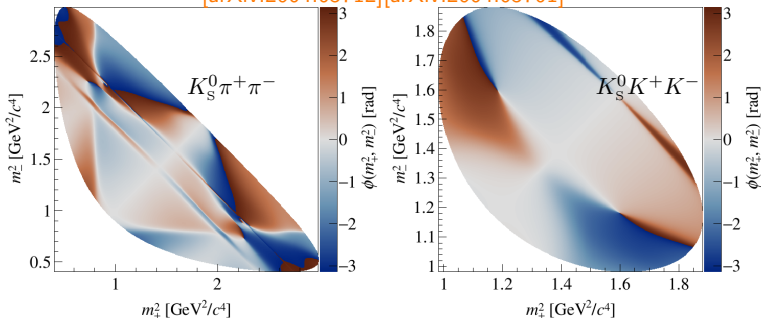
- GGSZ using Dalitz analysis of 3-body decays $\bar{D}^0 \rightarrow K_S^0 h^+ h^-$

[Giri, Grossmann, Soffer, Zupan, PRD 68 (2003) 054018]



New results from $B^- \rightarrow \bar{D}^0(\rightarrow K_S^0 h'^+ h'^-) h^-$ decays

[arXiv:2604.05712][arXiv:2604.05701]

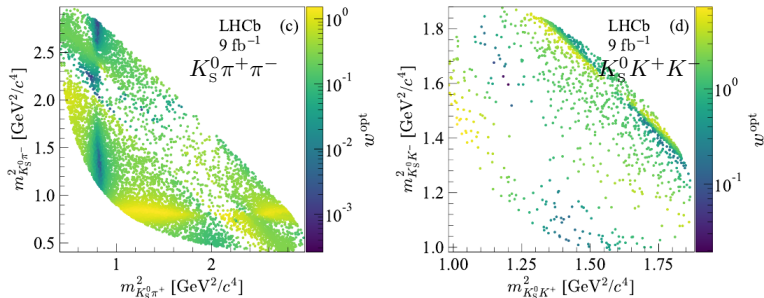


- New model-ind. unbinned approach [EPJC 78 (2018) 121] using sim. fit of
 - 8 fb^{-1} BESIII data (2010–2011 and 2021–2022)
 - 9 fb^{-1} of LHCb data (2011–2018)
- Strong phase difference $\phi = \delta_D - \delta_{\bar{D}}$ varies over Dalitz plot
- Most precise single measurement of γ : $(71.3 \pm 5.0)^\circ$
 [arXiv:2604.05712] [arXiv:2604.05701]



New results from $B^- \rightarrow \bar{D}^0 (\rightarrow K_S^0 h'^+ h'^-) h^-$ decays

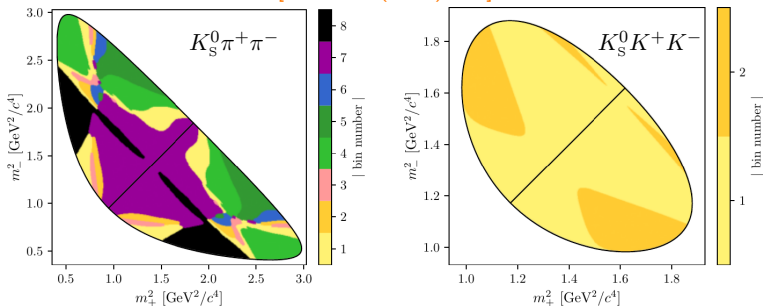
[arXiv:2604.05712][arXiv:2604.05701]



- New model-ind. unbinned approach [EPJC 78 (2018) 121] using sim. fit of
 - 8 fb $^{-1}$ BESIII data (2010–2011 and 2021–2022)
 - 9 fb $^{-1}$ of LHCb data (2011–2018)
- Strong phase difference $\phi = \delta_D - \delta_{\bar{D}}$ varies over Dalitz plot
- Most precise single measurement of γ : $(71.3 \pm 5.0)^\circ$
 [arXiv:2604.05712] [arXiv:2604.05701]

Binned results from $B^- \rightarrow \bar{D}^0 (\rightarrow K_S^0 h'^+ h'^-) h^-$ decays

[JHEP 08 (2026) 037]



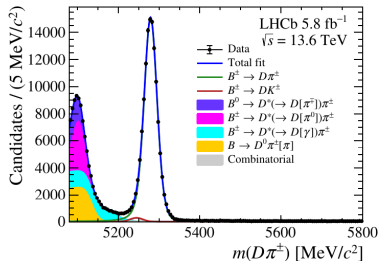
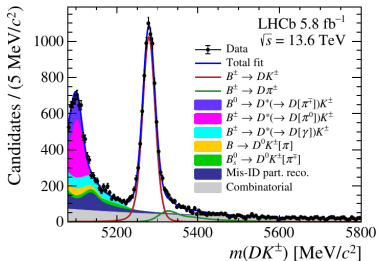
- Model-ind. binned approach using 5.8 fb^{-1} of Run 3 data [JHEP 08 (2026) 037]
- Higher yields than in Run 2 due to Run 3 full software trigger
- $\gamma = (68.1 \pm 6.7)^\circ$ in good agreement with unbinned and world average



Binned results from $B^- \rightarrow \bar{D}^0 (\rightarrow K_S^0 h'^+ h'^-) h^-$ decays



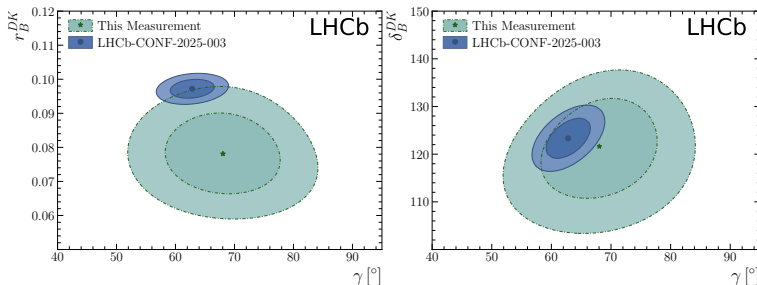
[JHEP 08 (2026) 037]



- Model-ind. binned approach using 5.8 fb^{-1} of Run 3 data [JHEP 08 (2026) 037]
- Higher yields than in Run 2 due to Run 3 full software trigger
- $\gamma = (68.1 \pm 6.7)^\circ$ in good agreement with unbinned and world average

Binned results from $B^- \rightarrow \bar{D}^0(\rightarrow K_S^0 h'^+ h'^-) h^-$ decays

[JHEP 08 (2026) 037]

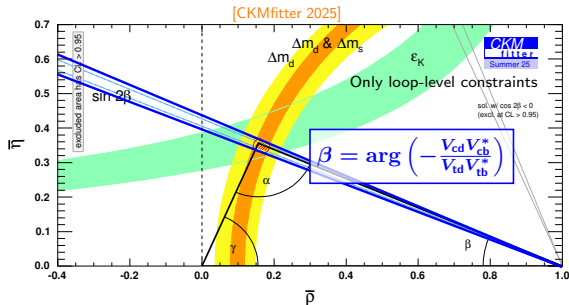


- Model-ind. binned approach using 5.8 fb^{-1} of Run 3 data [JHEP 08 (2026) 037]
- Higher yields than in Run 2 due to Run 3 full software trigger
- $\gamma = (68.1 \pm 6.7)^\circ$ in good agreement with unbinned and world average



The CKM angle β

- β is the best determined angle ($\pm 0.5^\circ$) in the B^0 CKM-triangle
- Important constraint in global CKM fits

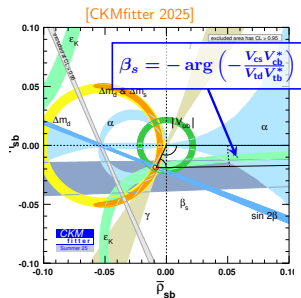
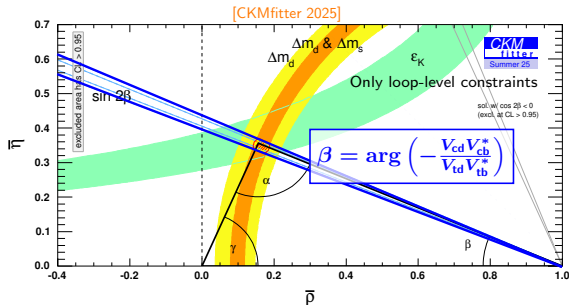


- Measured using the golden mode $B^0 \rightarrow J/\psi K_S^0$
- CPV in interference between mixing and decay
- β_s the corresponding angle in the B_s^0 CKM-triangle



The CKM angle $\beta_{(s)}$

- β is the best determined angle ($\pm 0.5^\circ$) in the B^0 CKM-triangle
- Important constraint in global CKM fits

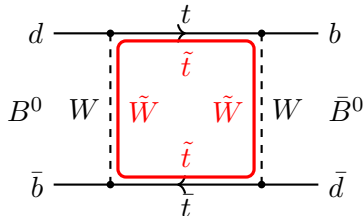


- Measured using the golden mode $B^0 \rightarrow J/\psi K_S^0$
- CPV in interference between mixing and decay
- β_s the corresponding angle in the B_s^0 CKM-triangle



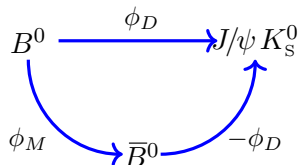
Determining the CP violating phase β with $B^0 \rightarrow J/\psi K_S^0$

SM (NP) Box-diagram



$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{NP}} = \mathcal{A}_{\text{SM}} \times |\Delta| e^{i\phi_{\text{NP}}}$$

CPV in interference between mixing and decay



$$\phi_M = \phi_M^{\text{SM}} + \phi_{\text{NP}}$$

- Measure $2\beta = \phi_M - 2\phi_D$ in interference between decay and mixing
- Time-dependent CP-asymmetry

$$A_{\text{CP}}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f_{\text{CP}}, t) - \Gamma(B^0 \rightarrow f_{\text{CP}}, t)}{\Gamma(\bar{B}^0 \rightarrow f_{\text{CP}}, t) + \Gamma(B^0 \rightarrow f_{\text{CP}}, t)} = -\eta_f \sin 2\beta \sin(\Delta m t)$$

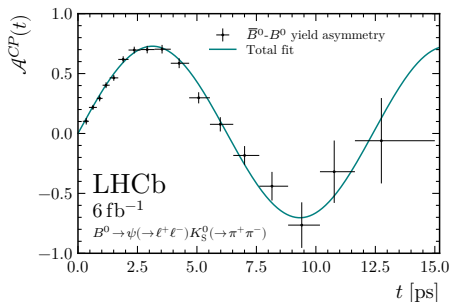
Final state CP-eigenvalue $\eta_{J/\psi K_S^0} = -1$

CPV phase

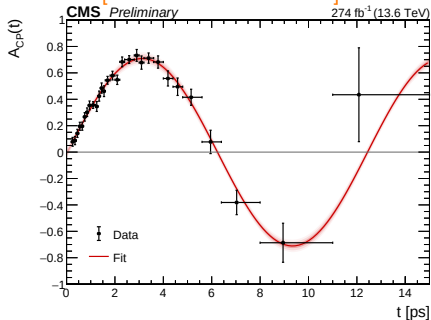
Mixing frequency

Determining the CP violating phase β with $B^0 \rightarrow J/\psi K_S^0$

[PRL 132 (2024) 021801]



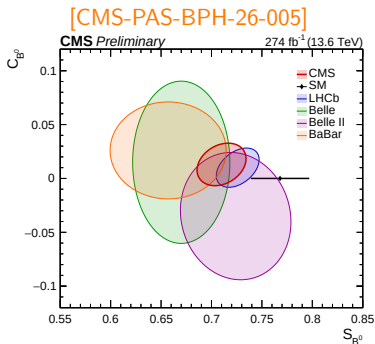
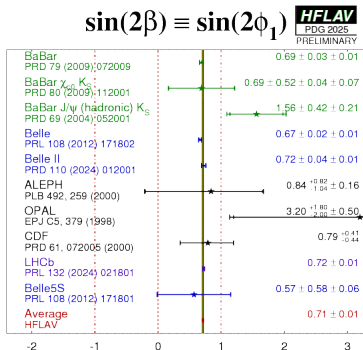
[CMS-PAS-BPH-26-005]



- LHCb [PRL 132 (2024) 021801] $\sin(2\beta) = 0.717 \pm 0.013 \pm 0.008$
- CMS preliminary [CMS-PAS-BPH-26-005] $\sin(2\beta) = 0.710 \pm 0.013 \pm 0.009$
- In good agreement with each other and world average
- LHC results have overtaken B -factories



Determining the CP violating phase β with $B^0 \rightarrow J/\psi K_S^0$

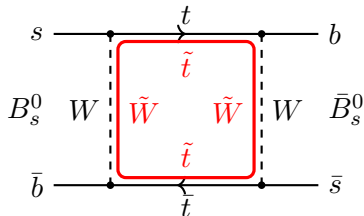


- LHCb [PRL 132 (2024) 021801] $\sin(2\beta) = 0.717 \pm 0.013 \pm 0.008$
- CMS preliminary [CMS-PAS-BPH-26-005] $\sin(2\beta) = 0.710 \pm 0.013 \pm 0.009$
- In good agreement with each other and world average
- LHC results have overtaken B -factories



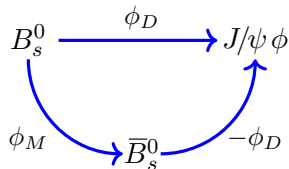
Determining the CP violating phase ϕ_s with $B_s^0 \rightarrow J/\psi \phi$

SM (NP) Box-diagram



$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{NP}} = \mathcal{A}_{\text{SM}} \times |\Delta| e^{i\phi_{\text{NP}}}$$

CPV in interference between mixing and decay



$$\phi_M = \phi_M^{\text{SM}} + \phi_{\text{NP}}$$

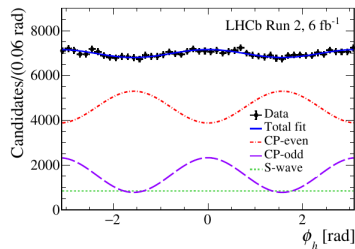
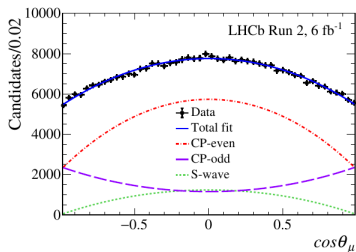
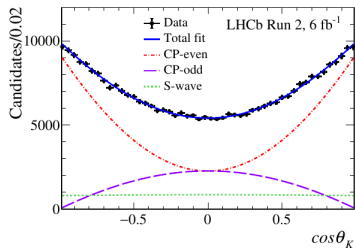
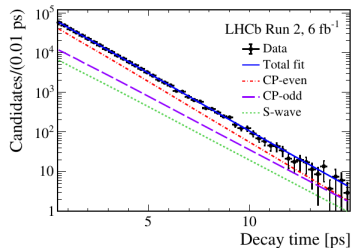
- Measure $\phi_s = \phi_M - 2\phi_D$ in interference between decay and mixing
- In SM precise constraint $\phi_s^{\text{SMfit}} = -0.03778^{+0.00065}_{-0.00053} \text{ rad}$ [CKM fitter]
- Time-dependent CP-asymmetry

$$A_{\text{CP}}(t) = \frac{\Gamma(\bar{B}_s^0 \rightarrow f_{\text{CP}}, t) - \Gamma(B_s^0 \rightarrow f_{\text{CP}}, t)}{\Gamma(\bar{B}_s^0 \rightarrow f_{\text{CP}}, t) + \Gamma(B_s^0 \rightarrow f_{\text{CP}}, t)} = \eta_f \sin \phi_s \sin(\Delta m_s t)$$

CP-eigenvalue of final state

CPV phase

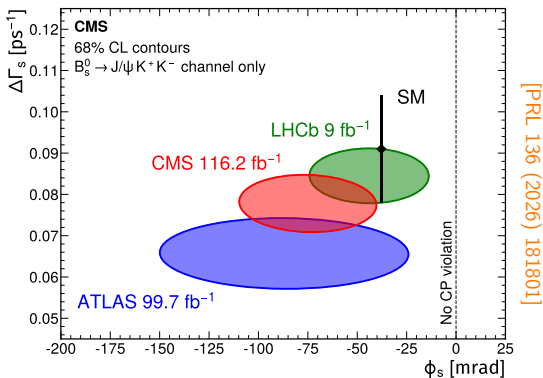
Mixing frequency

 B_s^0 -mixing phase β_s with $B_s^0 \rightarrow J/\psi \phi$ 

[PRL 132 (2024) 051802]

- Need to separate CP-even decay amplitudes $A_{0,\parallel}$ from CP-odd amplitude $A_\perp$ (and spin 0 S-wave A_S) via time-dependent angular analysis

B_s^0 -mixing phase β_s with $B_s^0 \rightarrow J/\psi \phi$



- LHCb $B_s^0 \rightarrow J/\psi \phi$ [PRL 132 (2024) 051802]
 $\phi_s = -0.039 \pm 0.022 \pm 0.006$ rad
 $\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024$ ps⁻¹
- CMS $B_s^0 \rightarrow J/\psi \phi$ [PRL 136 (2026) 181801]
 $\phi_s = -0.075 \pm 0.023$ rad
 $\Delta\Gamma_s = 0.0778 \pm 0.0046$ ps⁻¹
- Results in good agreement with each other and with SM expectation from global fit $\phi_s^{\text{SMfit}} = -0.03778^{+0.00065}_{-0.00053}$ rad [CKM fitter]
- Recently constrained penguin pollution with $B^0 \rightarrow J/\psi \rho^0$ [PRL 137 (2026) 031803]

Rare Decays

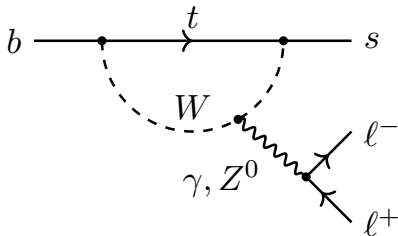
- A persistent set of intriguing flavour anomalies



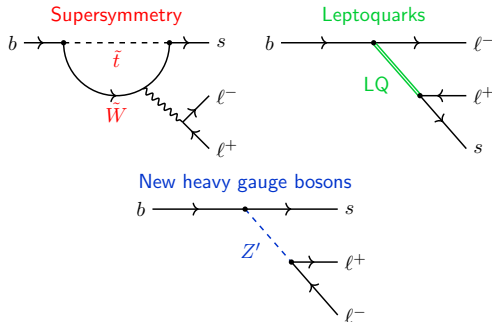


Rare $b \rightarrow s \ell^+ \ell^-$ decays as sensitive probes for NP

$b \rightarrow s \ell \ell$ decays in the SM



Possible contributions from NP

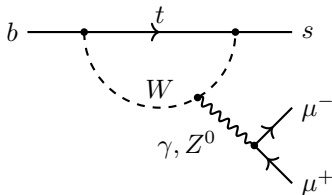


- Rare semileptonic decays heavily (loop-)suppressed in the SM
- New heavy particles can significantly contribute and affect $b \rightarrow s \ell^+ \ell^-$ decays
- Many observables accessible that allow to probe nature of potential NP:
Decay rates, Angular observables, Asymmetries in rates

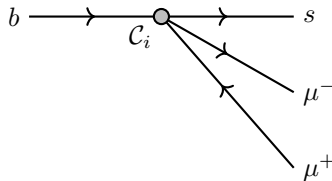


Rare $b \rightarrow s \ell^+ \ell^-$ decays in effective field theory

Full theory



Effective description



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

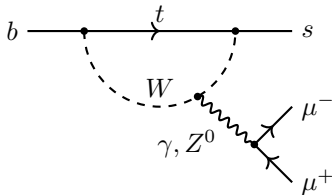
Effective coupling, *Wilson coefficient*

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
- $b \rightarrow s \ell \ell$ decays probe several $\mathcal{O}_i^{(\text{NP})}$

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

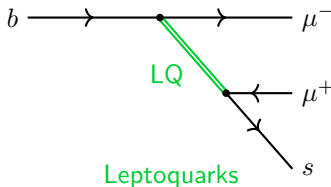
Rare decays in the SM



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

weak trans. CKM suppression loop suppression

Possible NP contribution



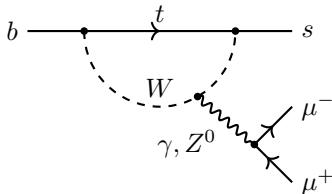
$$\mathcal{A}^{\text{NP}} \propto \frac{\kappa}{\Lambda_{\text{NP}}^2} \mathcal{O}_i$$

Leptoquarks

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

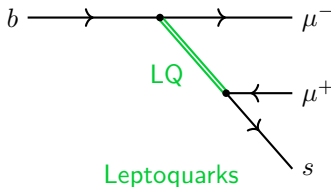
Rare $b \rightarrow s \ell^+ \ell^-$ decays in effective field theory

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



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

- 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
- $b \rightarrow s \ell \ell$ decays probe several $\mathcal{O}_i^{(\text{NP})}$

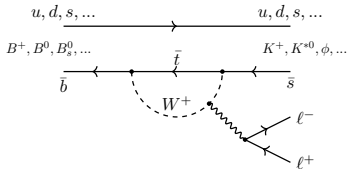
	Wilson coefficient	Operator
γ -penguin ¹	$C_7^{(\ell)}$	$\frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$C_9^{(\ell)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \ell)$
	$C_{10}^{(\ell)}$	$\frac{e^2}{g^2} (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{\ell}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

$b \rightarrow s \gamma$ $B_s^0 \rightarrow \mu^+ \mu^-$
 $b \rightarrow s \ell \ell$

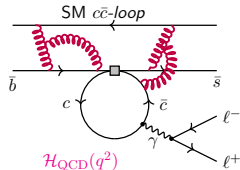
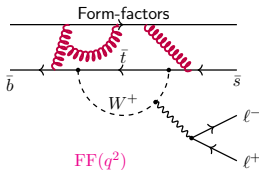


Observables in rare $b \rightarrow s\ell\ell$ decays and their cleanliness

Quarks bound in hadrons, e.g.



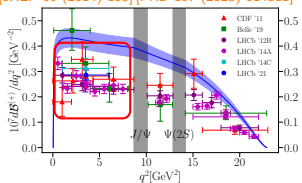
Hadronic uncertainties



$b \rightarrow s\ell\ell$ Observables

Increasing precision of SM prediction

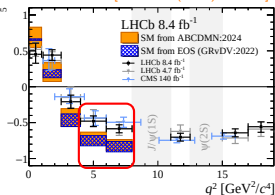
[JHEP 06 (2014) 133] [PRD 107 (2023) 014511]



Branching fractions

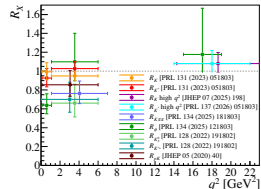
affected by form-factors
and $c\bar{c}$ -loop

[PRL 137 (2026) 021802]



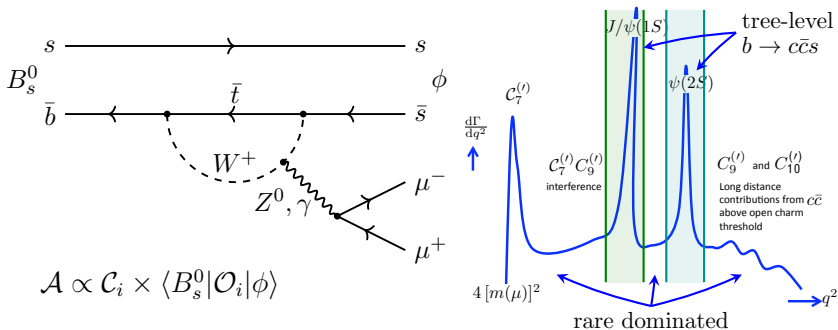
Angular observables

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



Lepton Universality Tests
clean

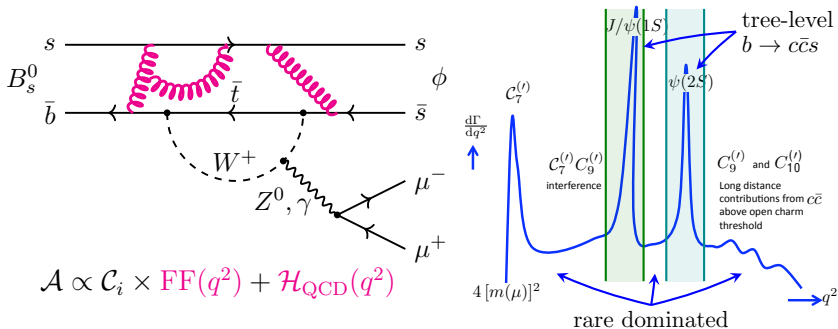
Branching fraction of $B_s^0 \rightarrow \phi \mu^+ \mu^-$



- 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 $B_s^0 \rightarrow J/\psi \phi$
- Measurements of norm. mode $\mathcal{B}(B \rightarrow J/\psi X)$ from Belle 2 would be useful
- SM predictions directly affected by significant **form factor** uncertainties

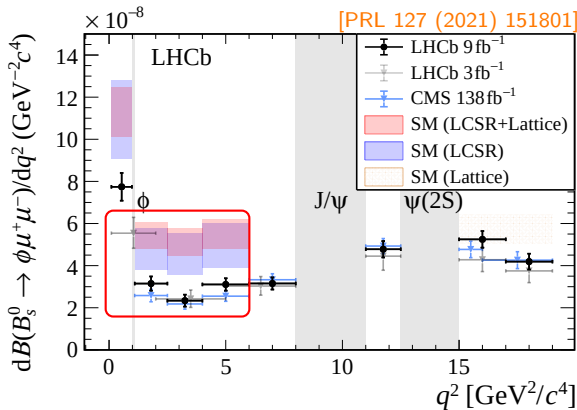
Low q^2 : LCSR [PRD 71 (2005) 014029] [JHEP 08 (2016) 98] [PRD 75 (2007) 054013] [JHEP 09 (2010) 089] High q^2 : Lattice [PRD 89 (2014) 094501] [PRD 88 (2013) 054509]

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



- 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 $B_s^0 \rightarrow J/\psi \phi$
- Measurements of norm. mode $\mathcal{B}(B \rightarrow J/\psi X)$ 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\]](#)

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

SM LCSR

[JHEP 08 (2016) 098]

[EPJC 75 (2015) 8]

SM LCSR+Lattice

[PRL 112 (2014) 212003]

[PoS Lattice 2014 372]



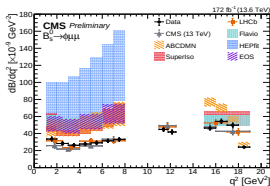
- LHCb measurement using full Run 1+2 sample [PRL 127 (2021) 151801]
- Tension with SM at **3.6 σ (LCSR+Lattice)** and **1.8 σ (LCSR only)**
- Recent confirmation from **CMS** [CMS-PAS-BPH-23-003]



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

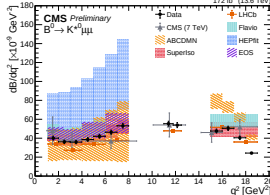
$$B_s^0 \rightarrow \phi \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

PRL 127 (2021) 151801



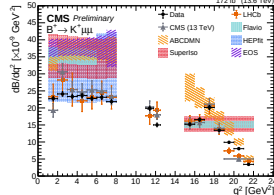
$$B^0 \rightarrow K^{*0} \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

JHEP 11 (2016) 047



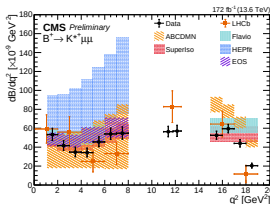
$$B^+ \rightarrow K^+ \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

JHEP 06 (2014) 133



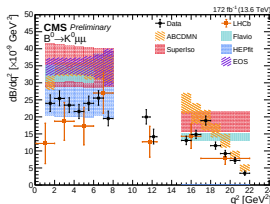
$$B^0 \rightarrow K^{*+} \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

JHEP 06 (2014) 133



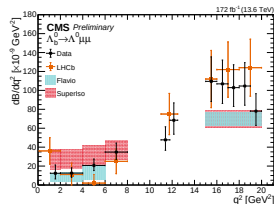
$$B^0 \rightarrow K^0 \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

JHEP 06 (2014) 133



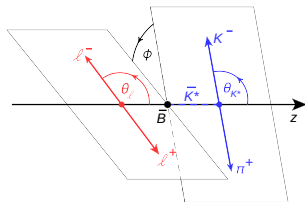
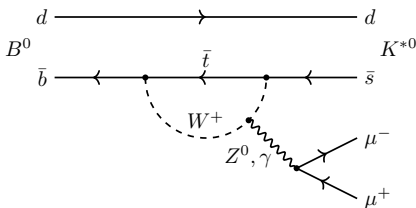
$$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^- \quad [\text{CMS-PAS-BPH-24-005}]$$

JHEP 06 (2015) 115



- Data consistently below SM predictions, tensions at $1-3\sigma$ level but significant hadronic uncertainties from form-factors and charm-loop
- Nb. [CMS-PAS-BPH-24-005] does not subtract S-wave component in vector modes
- Recent $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)$ update $(6.3 \pm 1.3) \times 10^{-4} \rightarrow (3.34 \pm 0.31) \times 10^{-4}$ [arXiv:2509.12805]

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

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

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

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

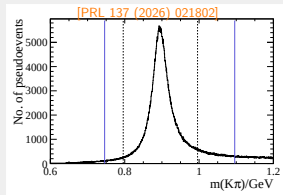
Example: $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}} \quad \left[\text{S. Descotes-Genon et al., JHEP, 05 (2013) 137} \right]$



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

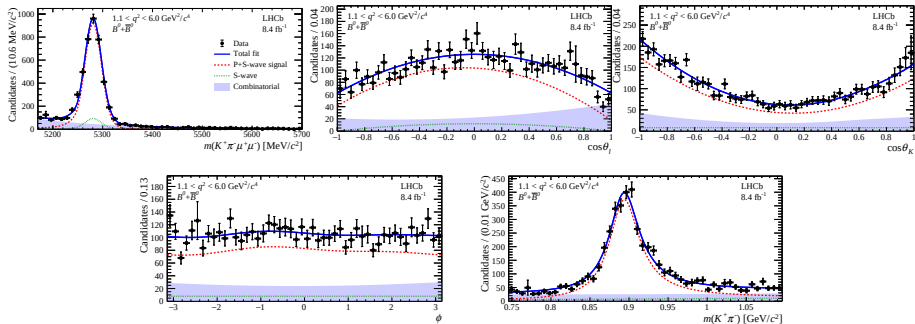
- No longer assume massless leptons throughout
- Branching fraction extracted without model assumptions

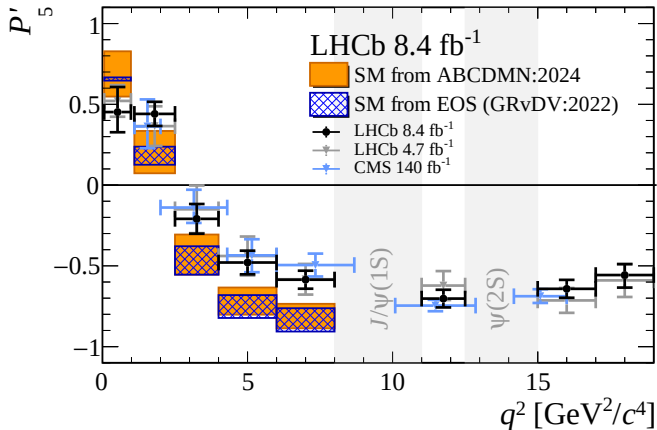
Example fit projection



- 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]

[PRL 137 (2026) 021802]



Results: P'_5 

[PRL 137 (2026) 021802]

ABCDMN:

[EPJC 83 (2023) 648]

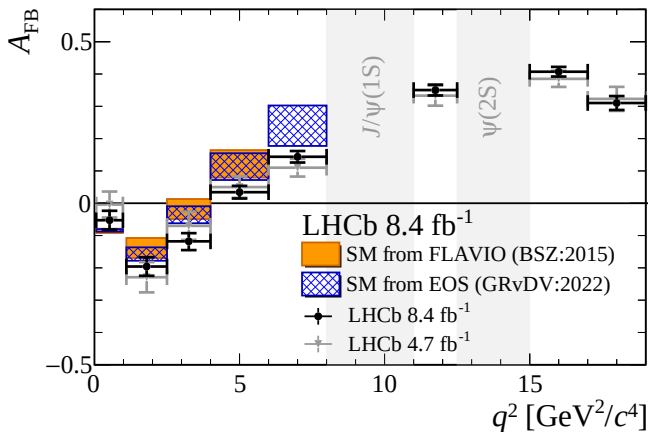
GRvDV:

[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] GeV² for EOS (ABCDMN)

Results: A_{FB} 

[PRL 137 (2026) 021802]

BSZ:

[arXiv:1810.08132]

[JHEP 08 (2016) 098]

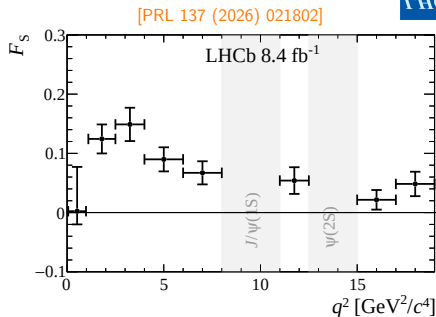
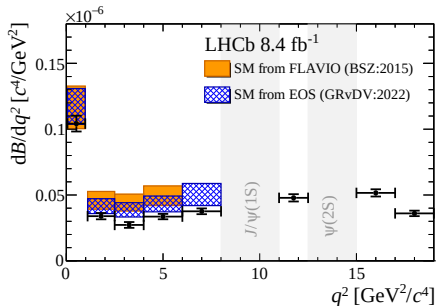
GRvDV:

[EPJC 82 (2022) 569]

[JHEP 09 (2022) 133]

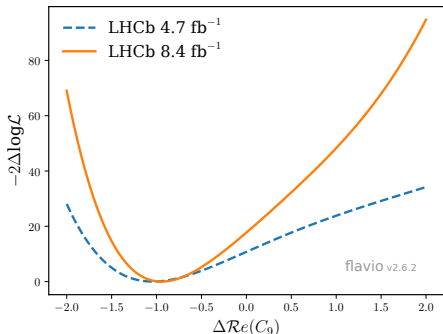
- Tensions now also more pronounced in A_{FB}
- Local deviations 2.5 (2.2) and 1.9 (1.7) σ in $[2.5, 4]$ and $[4, 6]$ GeV^2 for EOS (Flavio)

P-wave branching fraction and S-wave fraction



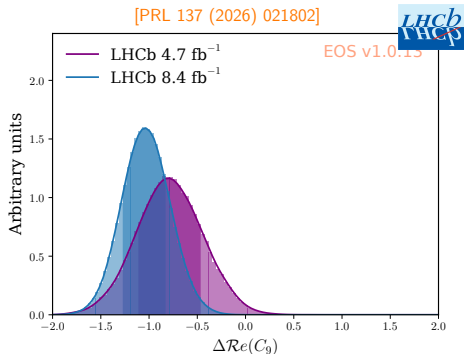
- Branching fraction lower than SM prediction, consistent with other $b \rightarrow s \mu^+ \mu^-$ decays
- No predictions available for F_S and other S-wave/interference observables

Interpretation in terms of Wilson coefficients



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

Significance 4.1σ

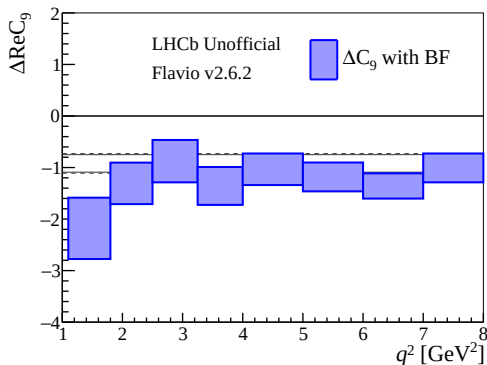


$$\Delta\text{Re}C_9 = -0.94^{+0.22}_{-0.22}$$

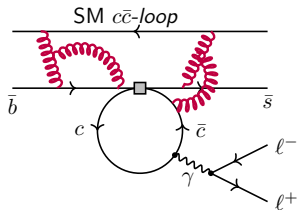
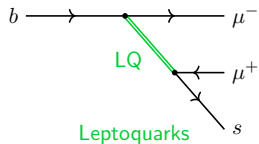
Significance 4.0σ

- 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
- $\text{Im}C_i$ consistent with zero [PRL 137 (2026) 061801]

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



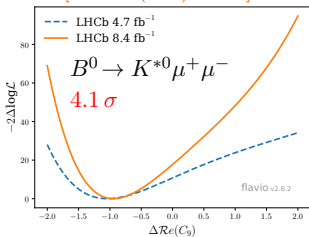
Possible NP contribution



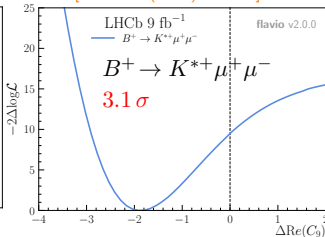
- Shift in $\mathcal{Re}C_9$ quite consistent across q^2 bins
- Open question: NP or underestimated hadronic contributions (charm-loop)?
 - If shift due to heavy NP $\rightarrow q^2$ -independent
 - If shift due to charm-loop $\rightarrow$ might expect rise towards J/ψ -region
- Data taken during LHC Run 3 crucial to clarify

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

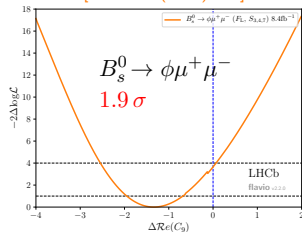
[PRL 137 (2026) 021802]



[PRL 126 (2021) 161802]



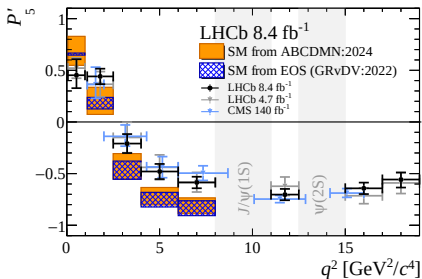
[JHEP 11 (2021) 043]



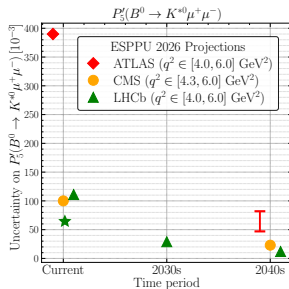
- Use flavio [arXiv:1810.08132] to determine tension with SM hypothesis
- Variation of vector coupling $\text{Re}(C_9)$ results in improved description of data
- Consistent trend for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [PRL 137 (2026) 021802], $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ [PRL 126 (2021) 161802] and $B_s^0 \rightarrow \phi \mu^+ \mu^-$ [JHEP 11 (2021) 043] angular observables



Summary and Conclusions

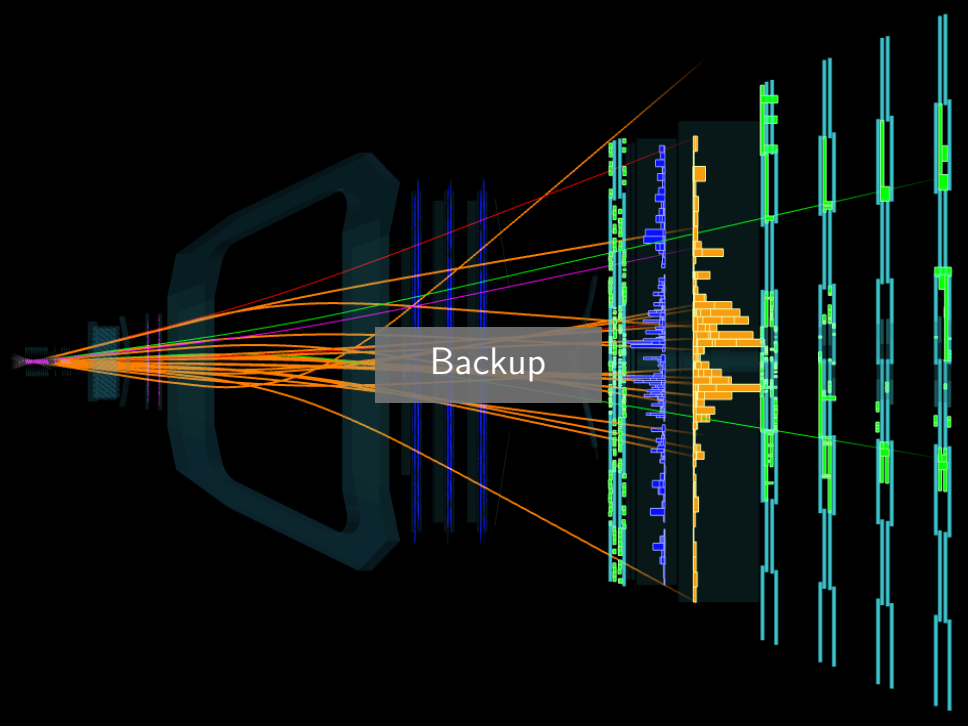


[PRL 137 (2026) 021802]



[arXiv:2503.24346][Figures]

- Precision measurements find no evidence of CP violation beyond the SM
 - Did not cover CPV in charm, b -baryon decays
- Intriguing pattern of flavour anomalies in Rare Decays:
 - Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ with Run 1 and 2 data reveals tension with SM predictions with increased significance [PRL 137 (2026) 021802]
 - Tensions in $b \rightarrow s \mu^+ \mu^-$ angular observables consistent with low $\mathcal{B}$
- Analysis of Run 3 data in full swing
- Current and future data samples will allow for measurements with unprecedented precision

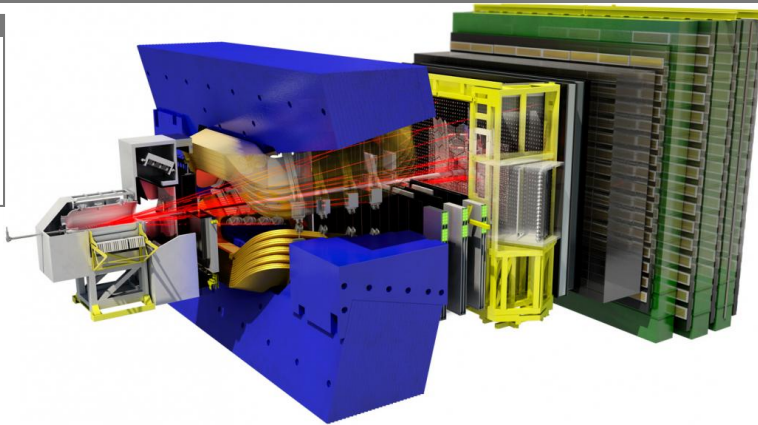
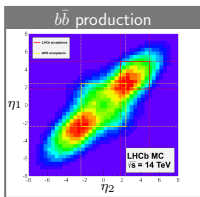


The diagram illustrates a neural network architecture. On the left, a large, dark blue, funnel-shaped structure represents the input layer. From this structure, numerous orange lines radiate outwards, connecting to a series of vertical bars on the right. These bars are colored in a gradient from blue to green. The word "Backup" is written in white text on a dark gray rectangular background, positioned in the center of the diagram. The overall background is black.

Backup



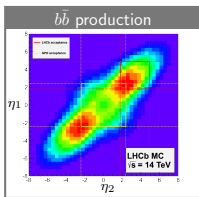
The LHCb detector: Optimized for heavy flavour



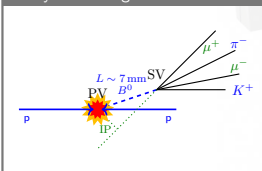
- Large $\sigma_{b\bar{b}}$: $(495 \pm 52) \mu\text{b}$ at 13 TeV [JHEP 10 (2015) 172] predominantly in forward direction
 $\Rightarrow$ single-arm forward spectrometer with unique $2 < \eta < 5$ coverage [JHEP A30 (2015) 1530022] [JINST 19 (2024) P05065]
- Excellent IP resolution $\sim 20 \mu\text{m}$ 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



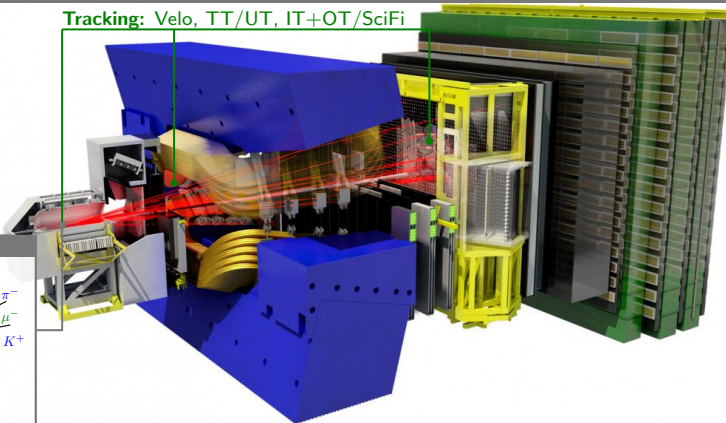
The LHCb detector: Optimized for heavy flavour



Heavy flavour signature



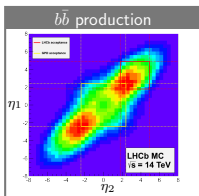
Tracking: Velo, TT/UT, IT+OT/SciFi



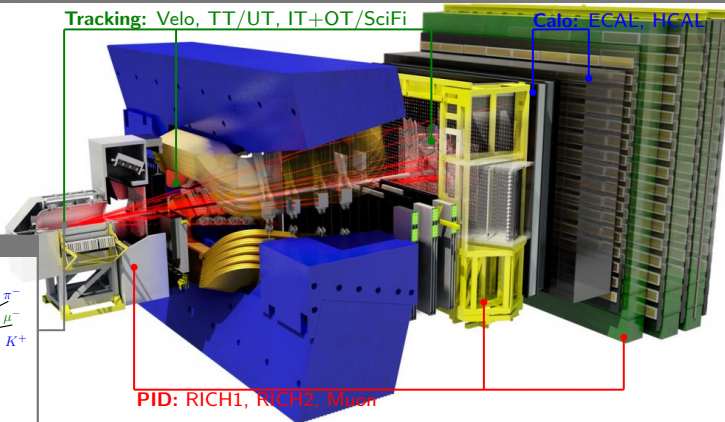
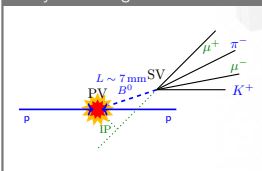
- Large $\sigma_{b\bar{b}}$: $(495 \pm 52) \mu\text{b}$ at 13 TeV [JHEP 10 (2015) 172] predominantly in forward direction
 $\Rightarrow$ single-arm forward spectrometer with unique $2 < \eta < 5$ coverage [JHEP A30 (2015) 1530022] [JINST 19 (2024) P05065]
- Excellent IP resolution $\sim 20 \mu\text{m}$ 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



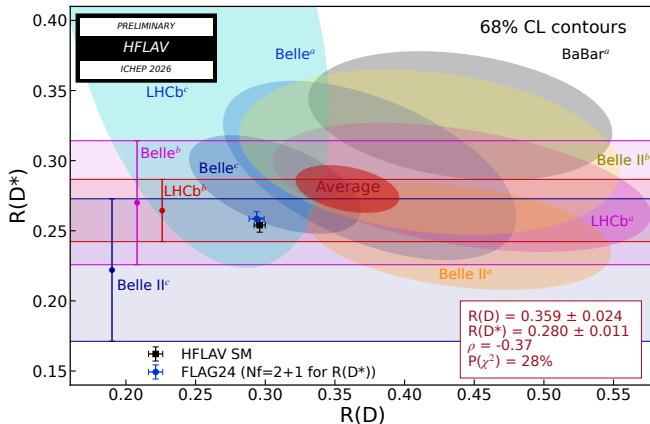
Heavy flavour signature



- 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 [JHEP 03 (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



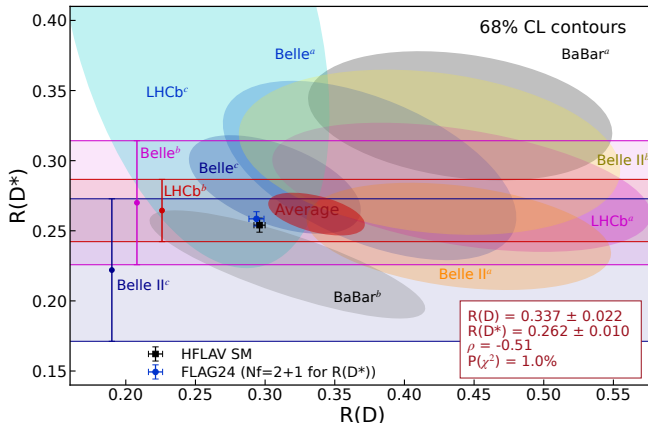
LFU tests using $b \rightarrow c\tau^- \bar{\nu}_\tau$ and $b \rightarrow c\mu^- \bar{\nu}_\mu$ decays



- Ratios of tree-level decays $R_D = \frac{\mathcal{B}(\bar{B} \rightarrow D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D\mu^- \bar{\nu}_\mu)}$ and $R_{D^*} = \frac{\mathcal{B}(\bar{B} \rightarrow D^*\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^*\mu^- \bar{\nu}_\mu)}$
- Tension corresponds to $\sim 3.7\sigma$
- Tension reduces to $\sim 2\sigma$ when including BaBar preliminary



LFU tests using $b \rightarrow c\tau^- \bar{\nu}_\tau$ and $b \rightarrow c\mu^- \bar{\nu}_\mu$ decays

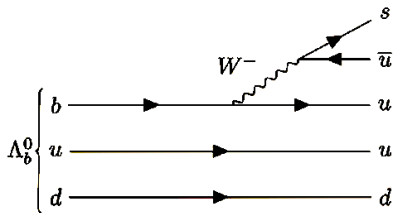


- Ratios of tree-level decays $R_D = \frac{\mathcal{B}(\bar{B} \rightarrow D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D\mu^- \bar{\nu}_\mu)}$ and $R_{D^*} = \frac{\mathcal{B}(\bar{B} \rightarrow D^*\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^*\mu^- \bar{\nu}_\mu)}$
- Tension corresponds to $\sim 3.7\sigma$
- Tension reduces to $\sim 2\sigma$ when including BaBar preliminary

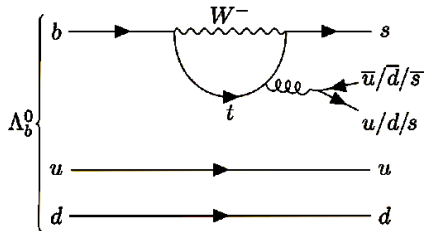


Observation of CPV in baryon decays [Nature 643 (2025) 1223]

Tree

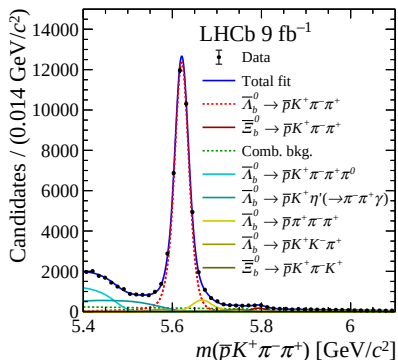
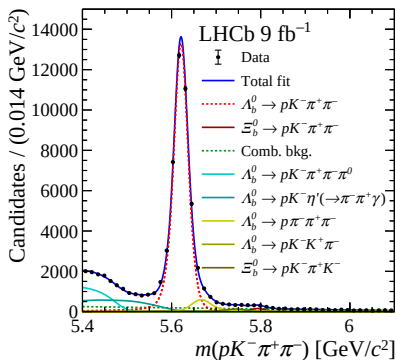


Loop



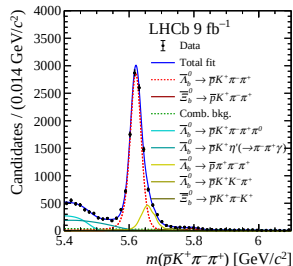
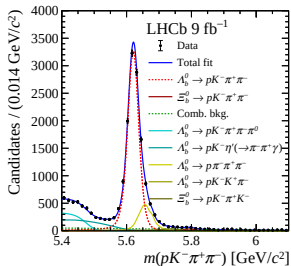
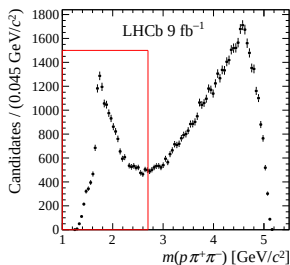
- Target decay $\Lambda_b^0 \rightarrow p K^- \pi^+ \pi^-$, interference between tree- and loop-level
- Control mode $\Lambda_b^0 \rightarrow \Lambda_c^+ (\rightarrow p K^- \pi^+) \pi^-$
- Global asymmetry $A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$
- Significance of 5.2σ

Observation of CPV in baryon decays [Nature 643 (2025) 1223]



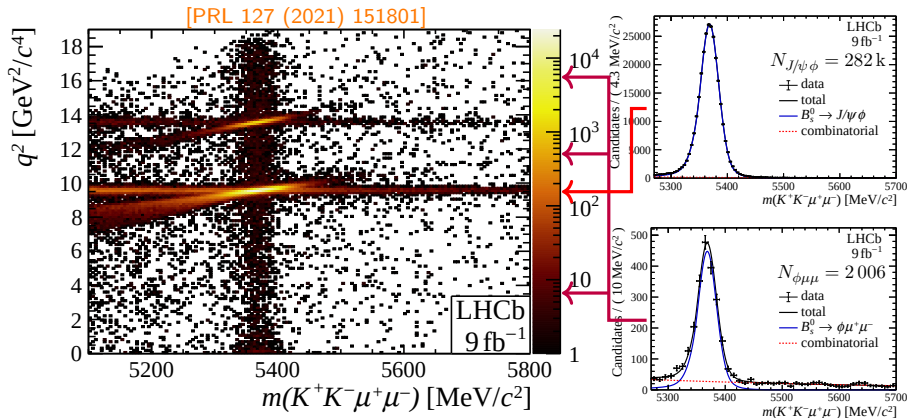
- Target decay $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, interference between tree- and loop-level
- Control mode $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi^-$
- Global asymmetry $A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$
- Significance of 5.2σ

Observation of CPV in baryon decays II [Nature 643 (2025) 1223]



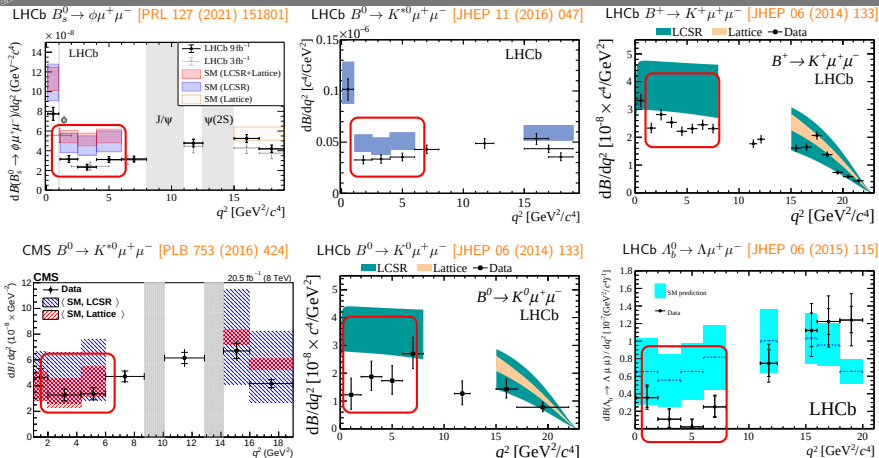
- Largest local asymmetry for $\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$, $m(p\pi^+\pi^-) < 2.7 \text{ GeV}/c^2$
- $A_{CP} = (5.4 \pm 0.9 \pm 0.1)\%$
- Significance 6.0σ

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



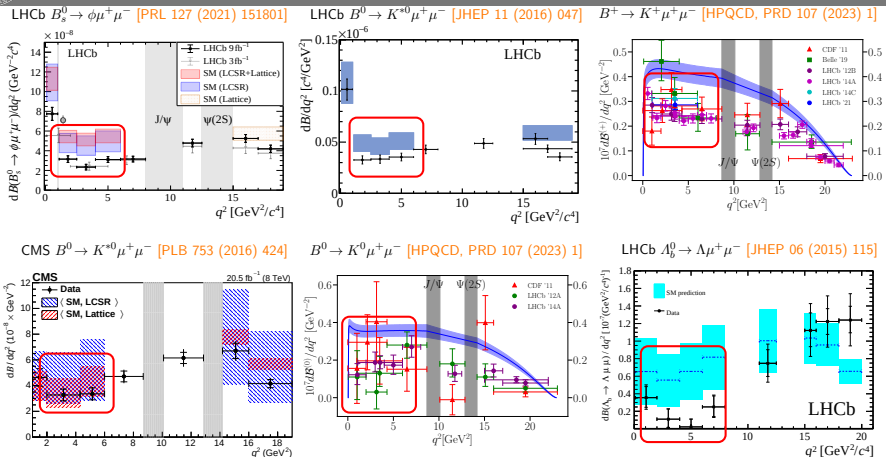
- BDT to suppress combinatorial background
Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto q^2 range $[8, 11] \cup [12.5, 15]$ GeV $^2/c^4$ containing tree level decays $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow \psi(2S)\phi$ (important control modes)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

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



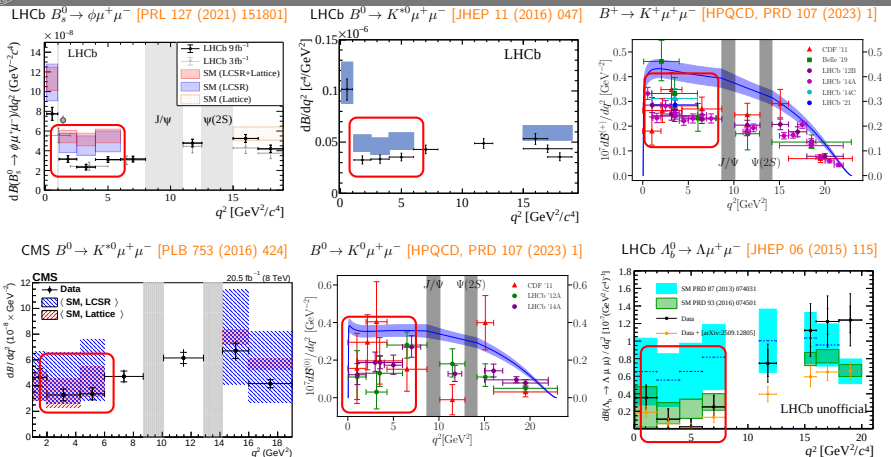
- Data consistently below SM predictions, tensions at $1-3\sigma$ level but significant hadronic uncertainties from form-factors and charm-loop
- Important results from Lattice QCD [HPQCD, PRD 107 (2023) 1]
- $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda)$ update $(6.3 \pm 1.3) \times 10^{-4}$ to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

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]
- $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi\Lambda)$ 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

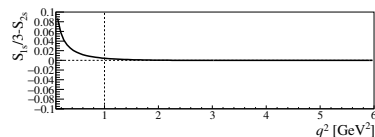
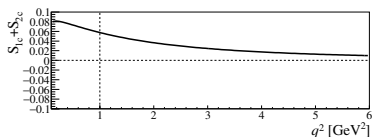
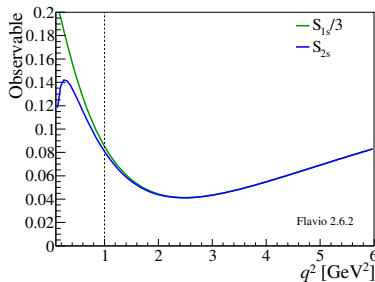
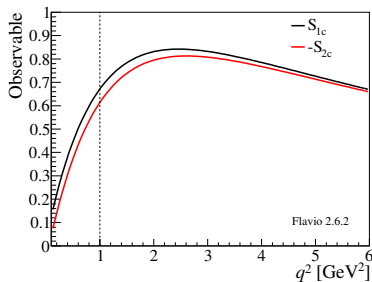
Consistently low $\mathcal{B}$ found for $b \rightarrow s \mu^+ \mu^-$ decays



- 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]
- $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)$ 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

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”)





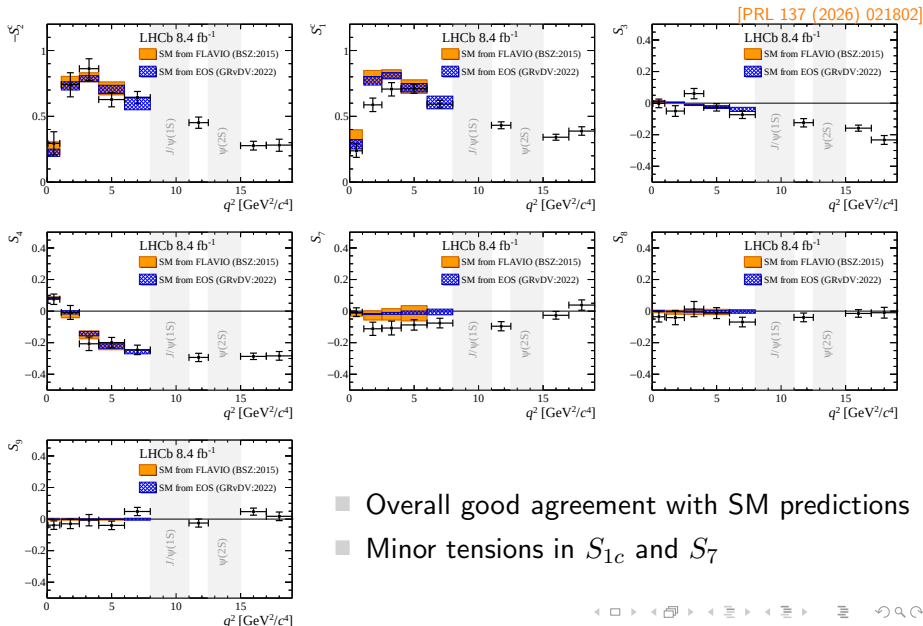
Observables and fit configurations

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

$$\frac{N_{\text{obs}}(N_{\text{obs}}^{q^2 < 1 \text{ GeV}^2})}{21}$$

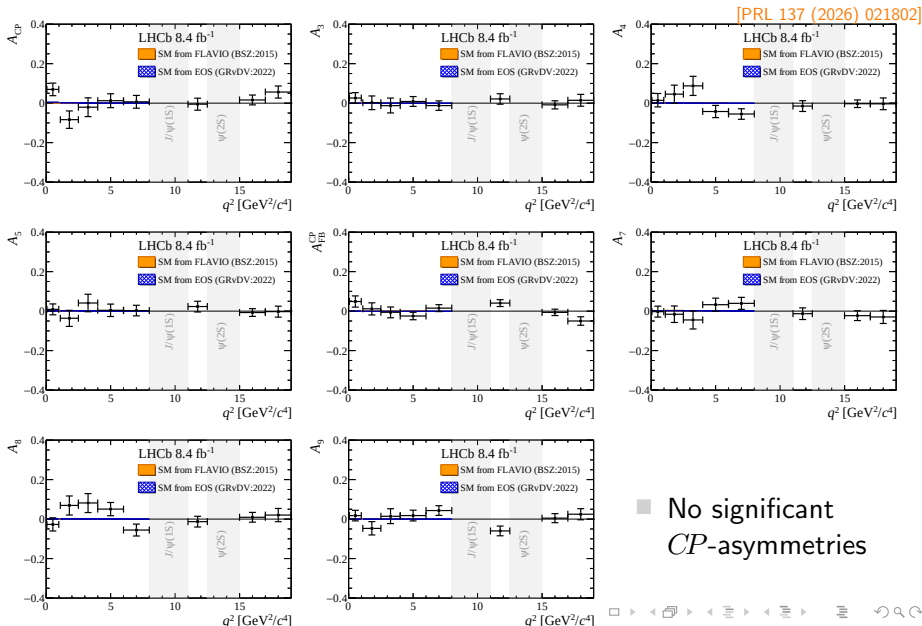
- 1 CP -averages only, S_i basis, partially massive¹ 21 (26)
Default for S_i basis
- 2 CP -averages only, $P_i^{(\prime)}$ basis, partially massive 21 (26)
Default for P_i basis
- 3 Fully massive model, CP -averages only, S_i basis 26
For effect of massive leptons
- 4 CP -averages + CP -asymmetries, S_i basis, massless leptons¹ 40 (52)
For CP -asymmetries
- 5 CP -averages only, $P_i^{(\prime)}$ basis, massless leptons 20
For comparison with [PRL 125 (2020) 011802]
- 6 CP -averages only, S_i basis, partially massive, narrow q^2 bins 21 (26)
For better q^2 resolution

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

Results: Remaining CP -symmetries (config 1)

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

CP -asymmetries (config 4)

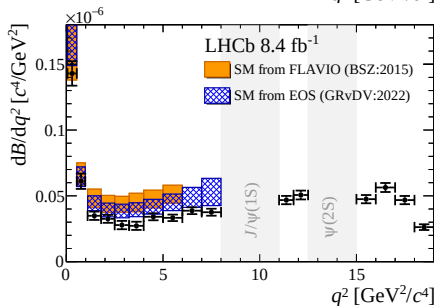
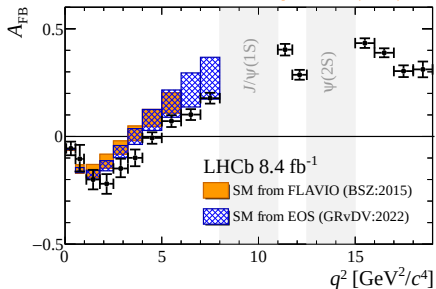
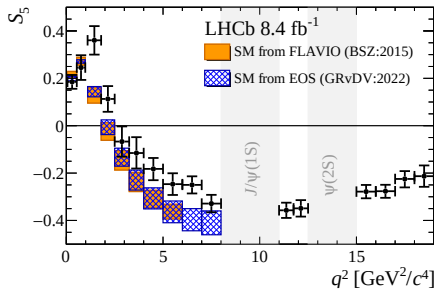


■ No significant
 CP -asymmetries



Narrow q^2 bins (config 6)

[PRL 137 (2026) 021802]



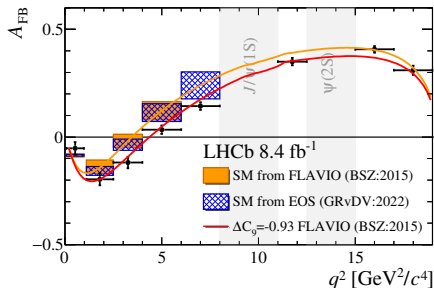
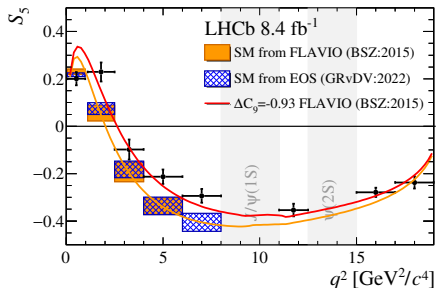
- Tradeoff between statistical uncertainty/better q^2 resolution
- In excellent agreement with regular-sized q^2 bins



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



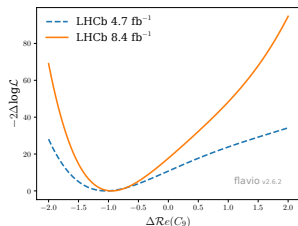
[PRL 137 (2026) 021802]



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



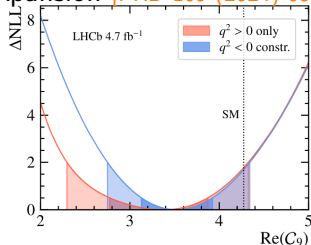
Comparison with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ unbinned results



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

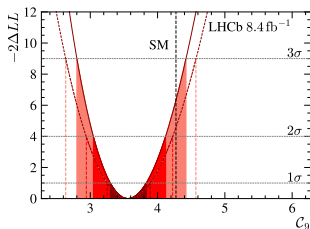
- Unbinned parameterize **charm loop**:
 $C_9^{\text{eff}} = C_9 + \mathcal{H}_{0,\parallel,\perp}(q^2)$
- Shifts in C_9 consistent
- Fewer parameters in binned analysis, smaller uncertainties

z-Expansion [PRD 109 (2024) 052009]



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

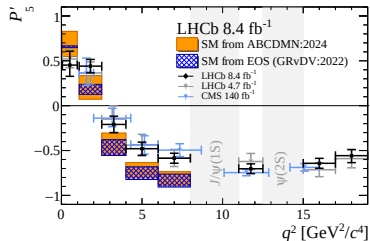
Amplitude model [JHEP 09 (2024) 026]



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

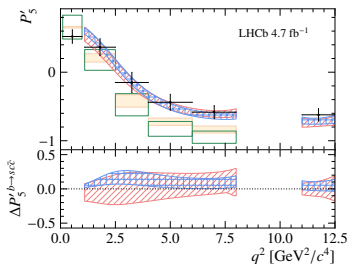


Comparison with $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ unbinned results

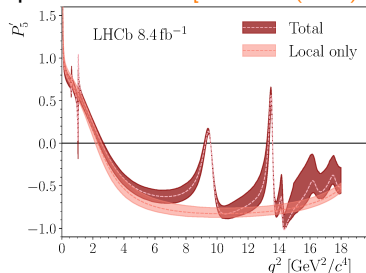


■ Excellent agreement of angular observables

z-Expansion [PRD 109 (2024) 052009]

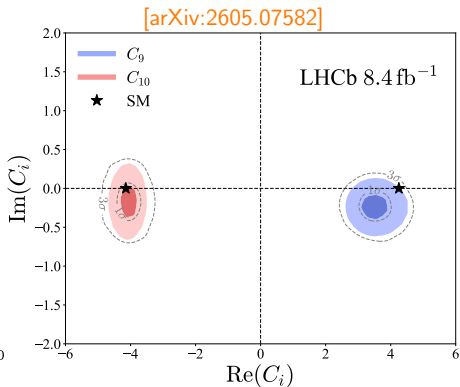
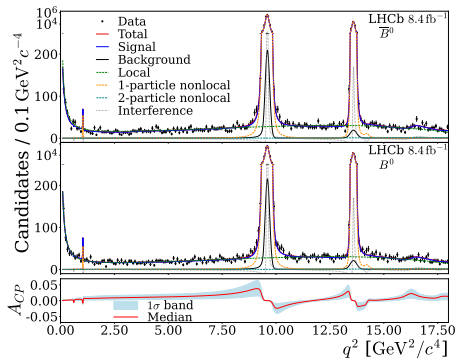


Amplitude model [JHEP 09 (2024) 026]





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



- Recent unbinned CPV measurement of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ using 8.4 fb⁻¹ [arXiv:2605.07582]
- No significant CP-asymmetries found

Systematic uncertainties

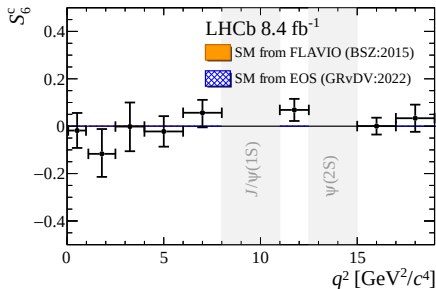
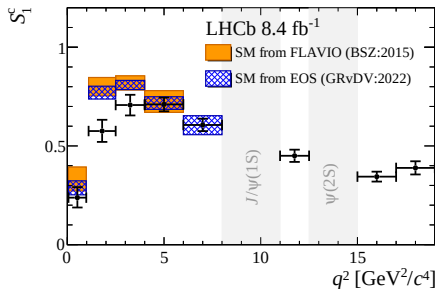
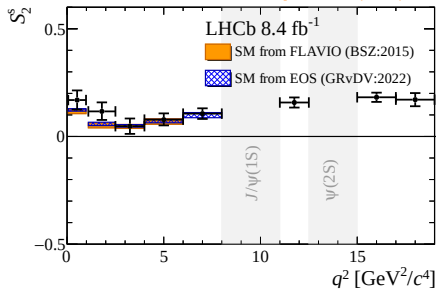
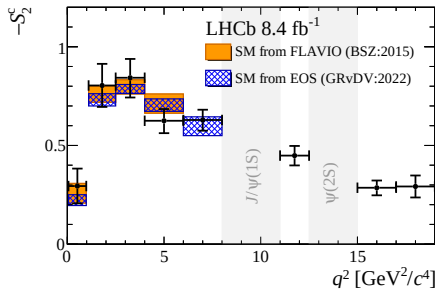
[PRL 137 (2026) 021802]

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
Neyman construction nuisance	< 0.010	< 0.010	< 0.075	< 0.025	< 0.025	< 0.000



Massive leptons (config 3)

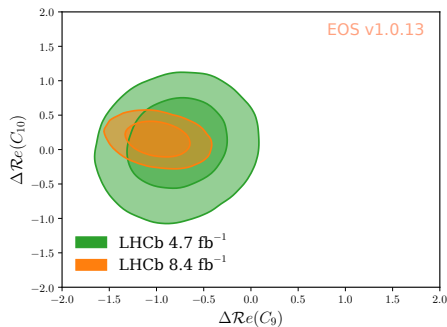
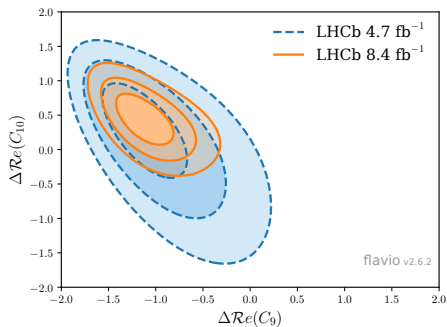
[PRL 137 (2026) 021802]





Interpretation in terms of Wilson coefficients

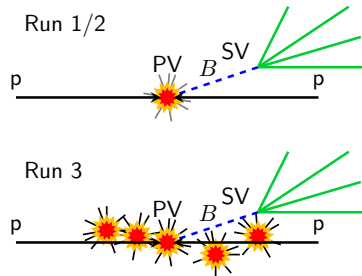
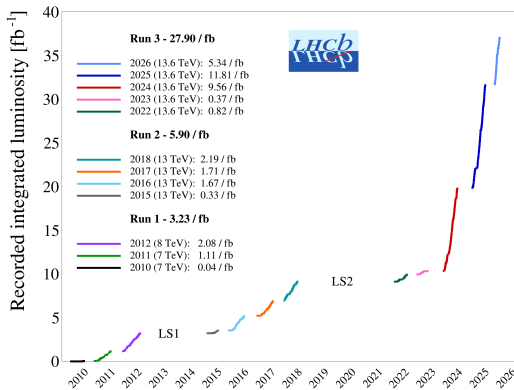
[PRL 137 (2026) 021802]



- Tension most pronounced in $\mathcal{R}e C_9$
- $\mathcal{R}e C_{10}$ in agreement with SM prediction

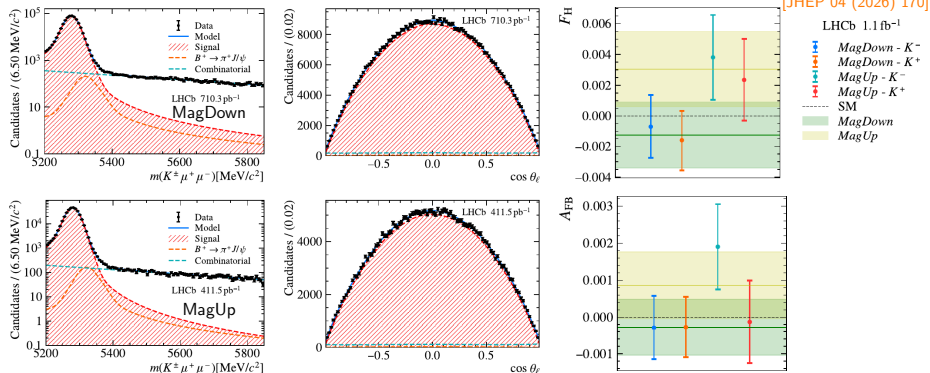
Current and future data samples

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

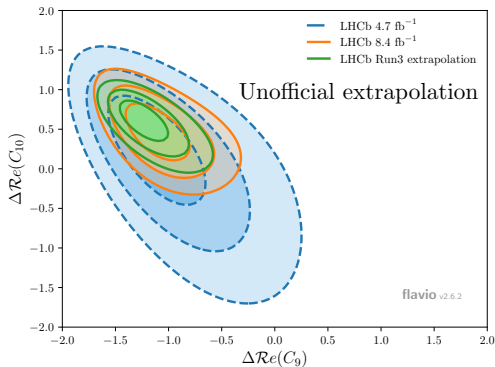
Angular analysis of $B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-)$



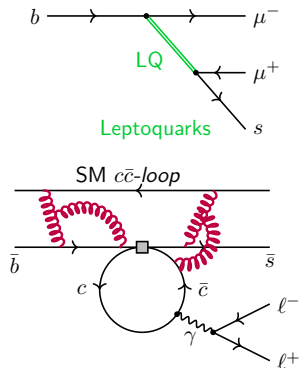
- Differential angular fit of $\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4}(1 - F_H) + \frac{1}{2}F_H + A_{\text{FB}} \cos \theta_\ell$
- Using 1 fb^{-1} of Run 3 data from 2024 good agreement with SM pred. of 0:
 $A_{\text{FB}} = 0.00019 \pm 0.00048_{\text{stat}} \pm 0.00033_{\text{syst}}$,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



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



Possible NP contribution



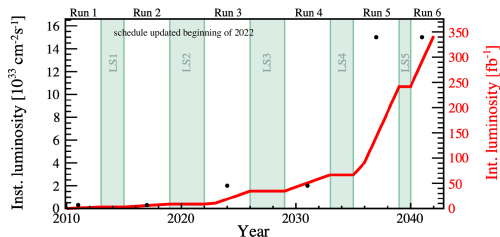
- Run 3 data allows for measurement with unprecedented precision, assuming equal central values tension would increase to $\gtrsim 5\sigma$
- Clarification of anomalies requires synergistic work between theory/exp.
 - Finer q^2 binning and closer focus on J/ψ interference region
 - Observables sensitive 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 [\[arXiv:1808.08865\]](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
$\sigma(\mathcal{C}'_{10})$	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/2012.01012),
 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/2012.01012)
- NP reach in Upgrade II increases by more than factor 2 wrt. Run 1+2
- Λ_{NP} reach beyond 100 TeV



Projections I [arXiv:2503.24346]

Experiment Assumed data sample	ATLAS 3000 fb ⁻¹	CMS 3000 fb ⁻¹	LHCb 300 fb ⁻¹	Belle II 50 ab ⁻¹
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_γ [mrad]	(4–9)	3	3	—
CP violation in loop-dominated decays				
$S(B^0 \rightarrow \eta' K_S^0)$	—	—	—	0.015
$\phi_\eta(B_s^0 \rightarrow \phi\phi)$ [mrad]	—	—	9	—
$\phi_\eta(B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$ [mrad]	—	—	8	—
CP violation in $B_{(s)}^0$-$\bar{B}_{(s)}^0$ mixing				
$a_{\text{sl}}^{\text{th}}$	—	—	3	—
a_{sl}^{d}	—	—	2	6.2
CP violation in the charm sector				
$\Delta A_{\text{CP}} [10^{-5}]$	—	—	3.3	60
$A_{\text{CP}}(D^{+,\bar{0}} \rightarrow \pi^{+,\bar{0}} \pi^0) [10^{-5}]$	—	—	100, —	130, 70
$A_{\Gamma}(KK, \pi\pi) [10^{-5}]$	—	—	1.2	—
$\Delta x(D^0 \rightarrow K_S^0 \pi^+ \pi^-) [10^{-5}]$	—	—	1.6	40
Semileptonic B decays				
$ V_{ub} $	—	—	1%	1.2%
$ V_{cb} $	—	—	—	1.0%
$R(D), R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%
Leptonic B decays				
$S(B_s^0 \rightarrow \mu^+ \mu^-) [10^{-9}]$	(0.33–0.40)	0.22	0.16	—
$S(B^0 \rightarrow \mu^+ \mu^-) [10^{-10}]$	(0.32–0.48)	0.12	0.12	—
$\tau_{\text{sl}}(B_s^0 \rightarrow \mu^+ \mu^-)$ [ps]	$^{+(0.07-0.11)}_{-(0.05-0.08)}$	0.05	0.05	—
$S(B_s^0 \rightarrow \mu^+ \mu^-)$	—	—	0.2	—
$S(B^+ \rightarrow \tau^+ \nu_\tau)$	—	—	—	6%
$S(B^+ \rightarrow \mu^+ \nu_\mu)$	—	—	—	5%
Flavour-changing neutral current $b \rightarrow s \ell \ell$ decays				
$P_5^{\text{f}}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]$ [†]	(47–82)	23	12	—
$S(B^{+,\bar{0}} \rightarrow K^{+,\bar{0}} \nu \bar{\nu})$	—	—	—	8%, 23%
$S(B^{+,\bar{0}} \rightarrow K^{+,\bar{0}} \tau^+ \tau^-) [10^{-6}]$	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current $b \rightarrow s \gamma$ decays				
$S(B \rightarrow X_s \gamma; E_\gamma > 1.6 \text{ GeV})$	—	—	—	(4.7–8.8)%
$S(B^0 \rightarrow K_S^0 \pi^0 \gamma)$	—	—	—	0.04
$S(B_s^0 \rightarrow \phi \gamma)$	—	—	0.025	—
$A_{\Gamma}^{(2)}(B^0 \rightarrow K^{*0} e^+ e^-; \text{very low } q^2)$	—	—	0.016	0.08
$\alpha_\gamma(A_h^0 \rightarrow A^0 \gamma)$	—	—	0.038	—
Lepton flavour violation in τ decays				
$S(\tau^+ \rightarrow \mu^+ \gamma) [10^{-8}]$	—	—	—	< 0.7
$S(\tau^+ \rightarrow \mu^+ \mu^+ \mu^-) [10^{-8}]$	< (0.13–0.64)	< 0.39	< 0.26	< (0.02–0.17)

[†] The sensitivity for the P_5^{f} variable is quoted for the range $q^2 \in [4.0, 6.0] \text{ GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0] \text{ GeV}^2$ for CMS.

Projections II [arXiv:1808.08865]

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
<u>EW Penguins</u>					
$R_K (1 < q^2 < 6 \text{ GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	—
$R_{K^*} (1 < q^2 < 6 \text{ GeV}^2 c^4)$	0.1 [275]	0.031	0.032	0.008	—
R_ϕ, R_{pK}, R_π	—	0.08, 0.06, 0.18	—	0.02, 0.02, 0.05	—
<u>CKM tests</u>					
γ , with $B_s^0 \rightarrow D_s^+ K^-$	$(\begin{smallmatrix} +17 \\ -22 \end{smallmatrix})^\circ$ [136]	4°	—	1°	—
γ , all modes	$(\begin{smallmatrix} +5.0 \\ -5.8 \end{smallmatrix})^\circ$ [167]	1.5°	1.5°	0.35°	—
$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	—
ϕ_s , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [44]	14 mrad	—	4 mrad	22 mrad [610]
ϕ_s , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [49]	35 mrad	—	9 mrad	—
ϕ_s^{SSS} , with $B_s^0 \rightarrow \phi \phi$	154 mrad [94]	39 mrad	—	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	—	3×10^{-4}	—
$ V_{ub} / V_{cb} $	6% [201]	3%	1%	1%	—
<u>$B_s^0, B^0 \rightarrow \mu^+ \mu^-$</u>					
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	90% [264]	34%	—	10%	21% [612]
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [264]	8%	—	2%	—
$S_{\mu\mu}$	—	—	—	0.2	—
<u>$b \rightarrow c \ell^- \bar{\nu}_\ell$ LUV studies</u>					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	—
$R(J/\psi)$	0.24 [220]	0.071	—	0.02	—
<u>Charm</u>					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	—
$A_\Gamma (\approx x \sin \phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	—
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	—
$x \sin \phi$ from multibody decays	—	$(K3\pi) 4.0 \times 10^{-5}$	$(K_S^0 \pi\pi) 1.2 \times 10^{-4}$	$(K3\pi) 8.0 \times 10^{-6}$	—

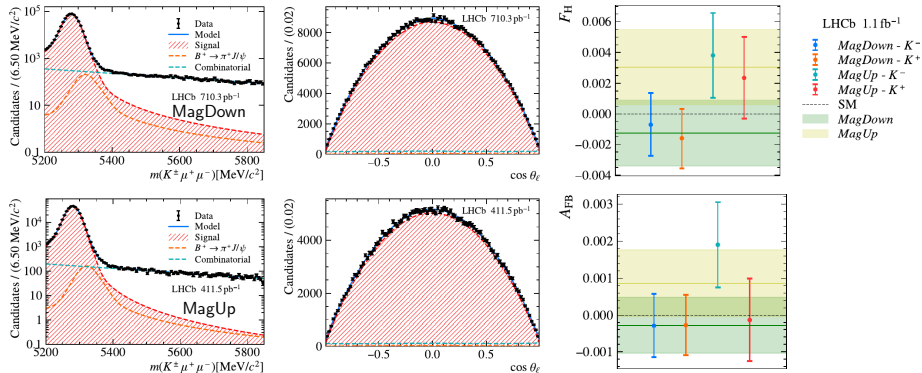
 $B^+ \rightarrow J/\psi K^+$ systematics

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

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

LHCb-PAPER-2025-040, in preparation



- Differential angular fit of

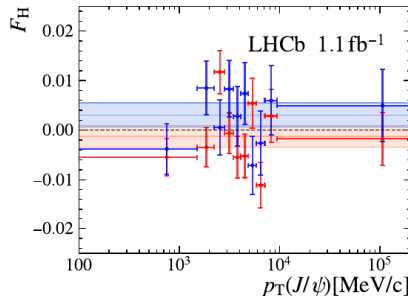
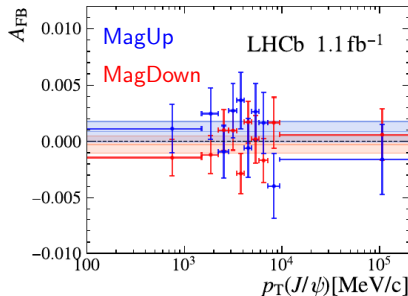
$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4}(1 - F_H) + \frac{1}{2}F_H + A_{FB} \cos \theta_\ell$$

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

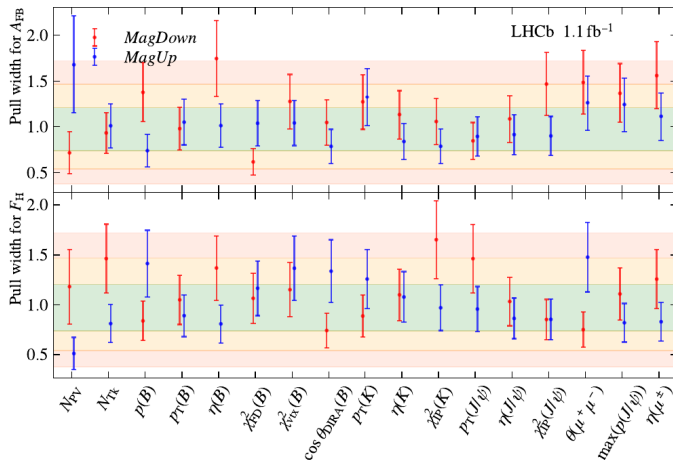
LHCb-PAPER-2025-040, in preparation



- 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!

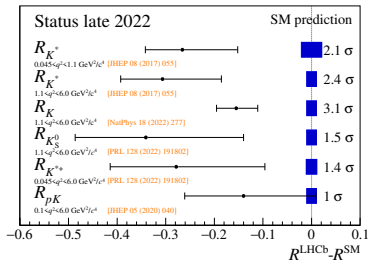
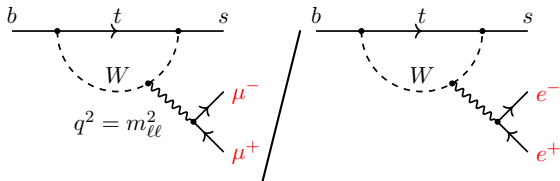
Stability of results from $B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-)$

LHCb-PAPER-2025-040, in preparation



- 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!

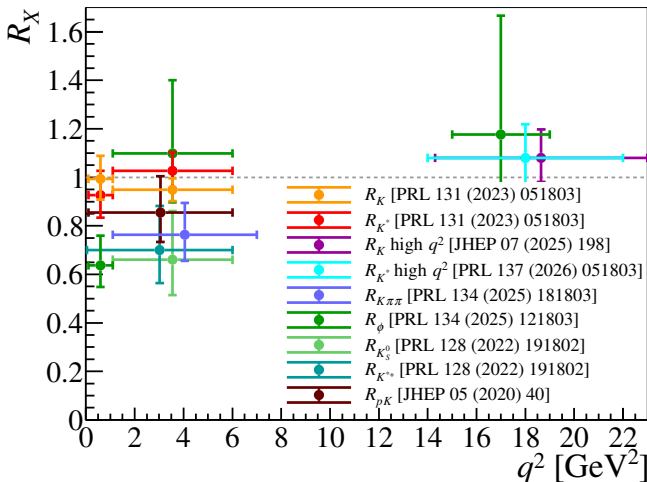
Lepton universality in rare $b \rightarrow s \ell^+ \ell^-$ decays



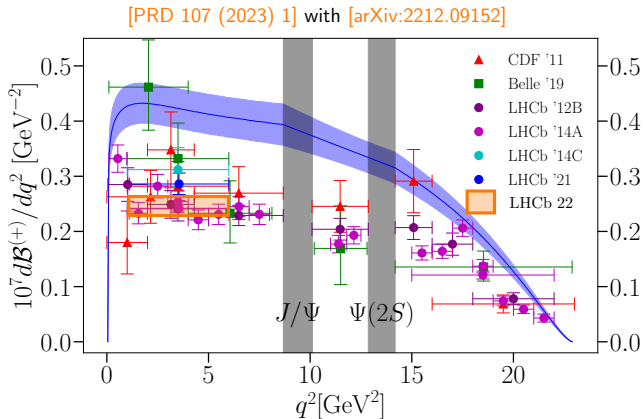
- Lepton flavour universality central property of SM
- Testable using ratios of branching fractions of rare $b \rightarrow s \ell^+ \ell^-$ decays:

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

- 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

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

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

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

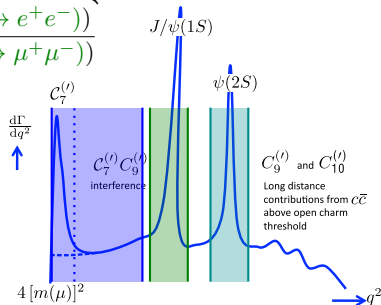
- Scaling R_{K,K^*} with measured muon $\mathcal{B}$ yields [JHEP 06 (2014) 133]
 $d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)/dq^2 = (25.5^{+1.3}_{-1.2} \pm 1.1) \times 10^{-9} \text{ GeV}^{-2}$
- Electron $\mathcal{B}$ consistent with muons, also below SM prediction

Analysis strategy: Double ratio (Example: R_K)

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

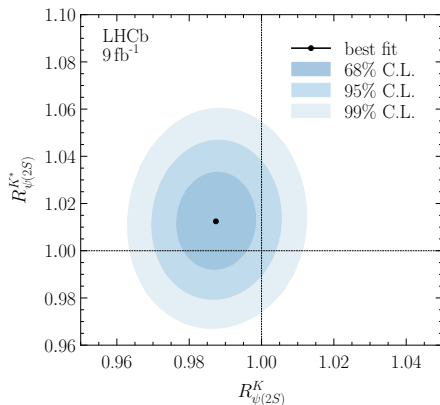
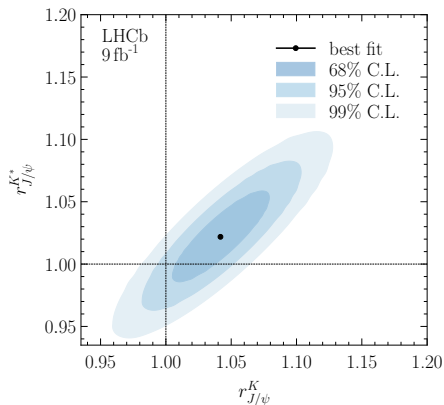
$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \times \overbrace{\frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}}^{r_{J/\psi}^{-1} = 1 \text{ [PRD 88 (2013) 3]}}$$

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



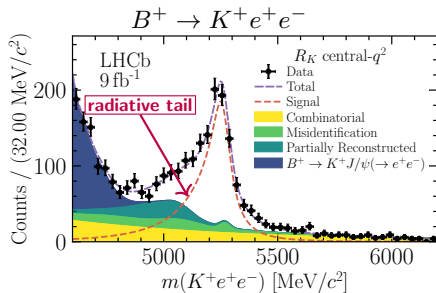
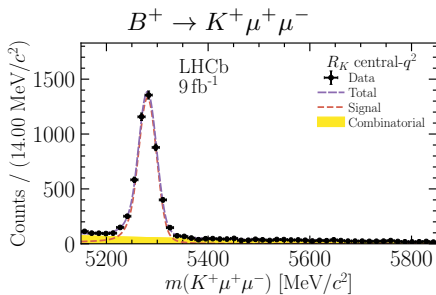
- Important cross-checks: $r_{J/\psi} = \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}$ and

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

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



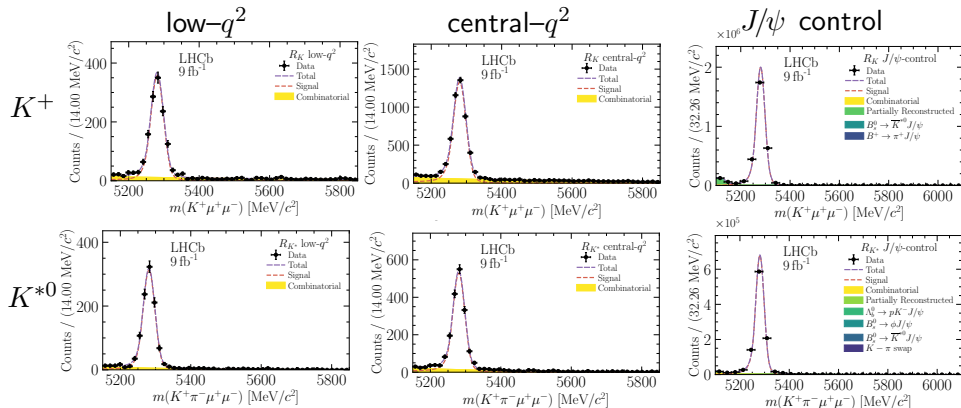
[arXiv:2212.09152] [arXiv:2212.09153]

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

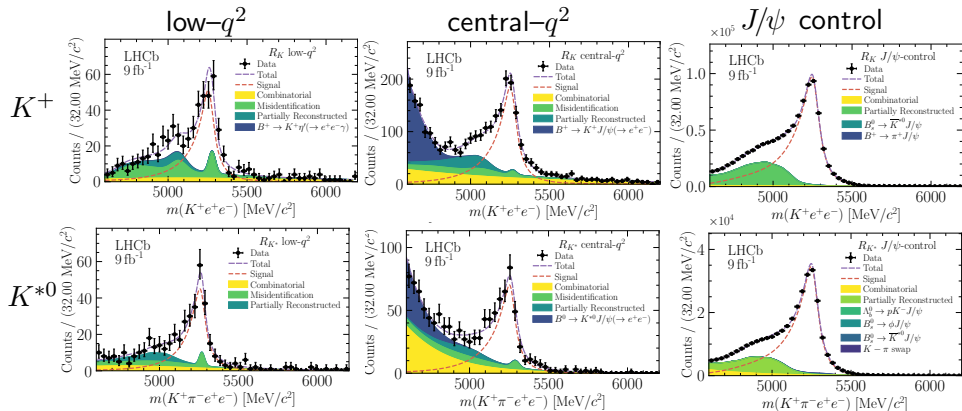


- Muon mode is very clean!
- Muon branching fraction compatible with published results

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



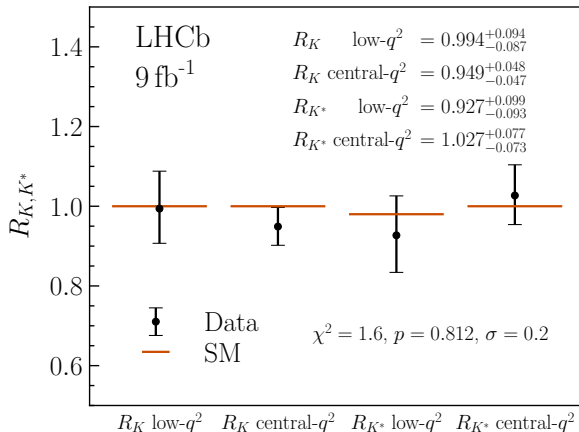
Electron mode fits



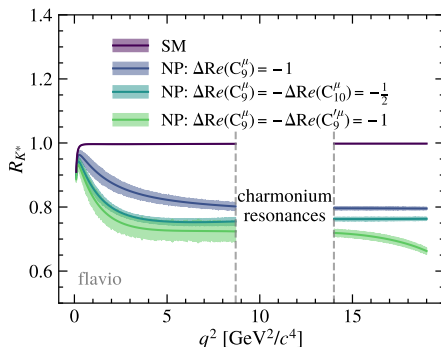
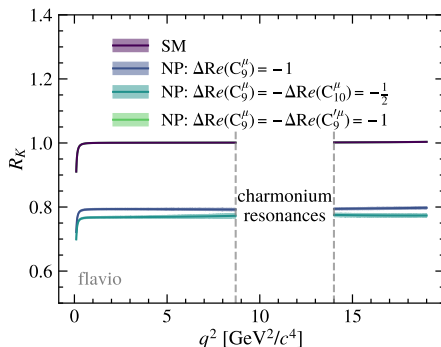
- Good fit quality when including all components
- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bkg. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

 R_K and R_{K^*} results

[arXiv:2212.09152] [arXiv:2212.09153]

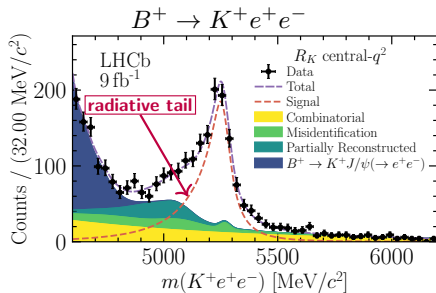
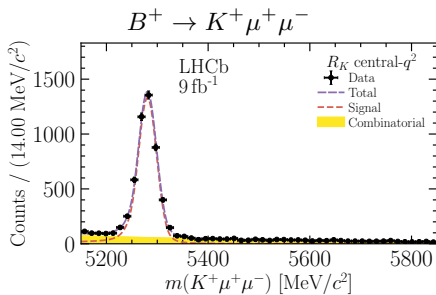


- Most precise test of LFU in $b \rightarrow s \ell^+ \ell^-$ transitions
- Compatible with the SM at 0.2σ using simple χ^2 test

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 : $q^2 \in [0.1, 1.0]$ GeV²/c⁴
 - central- q^2 : $q^2 \in [1.1, 6.0]$ GeV²/c⁴

Experimental challenges for electron modes at LHCb



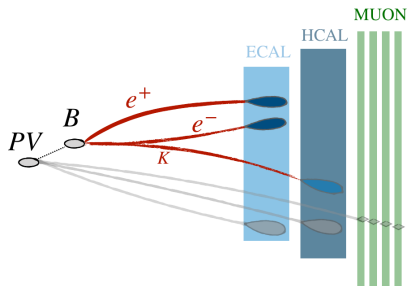
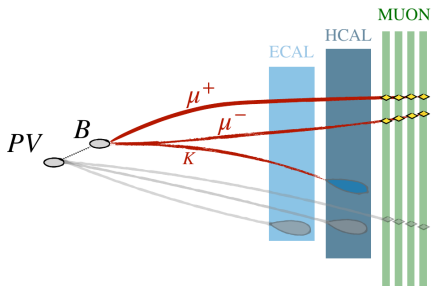
[arXiv:2212.09152] [arXiv:2212.09153]

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

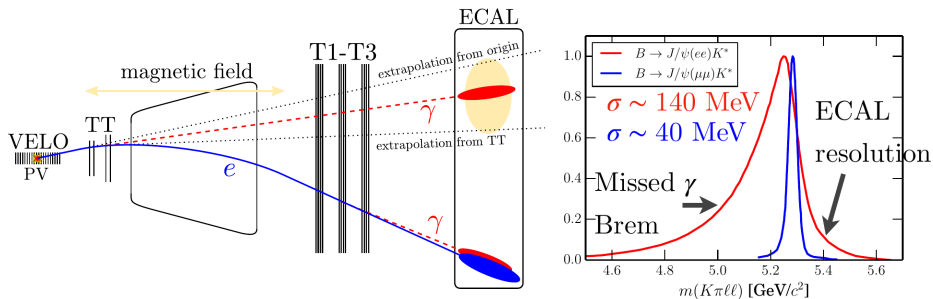


Experimental challenge: 1. Electron trigger



- 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

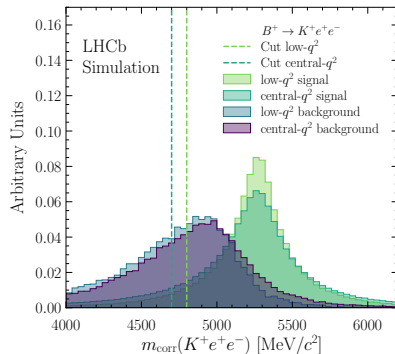
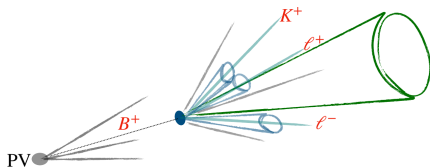
Experimental challenge: 2. Bremsstrahlung



- 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
→ higher background pollution and more sensitive to bkg. modeling

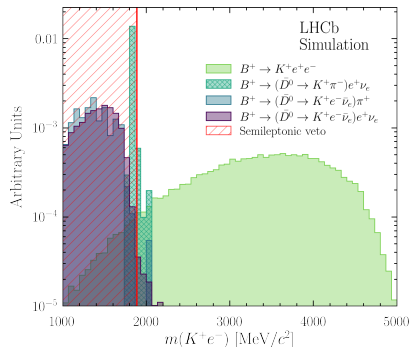
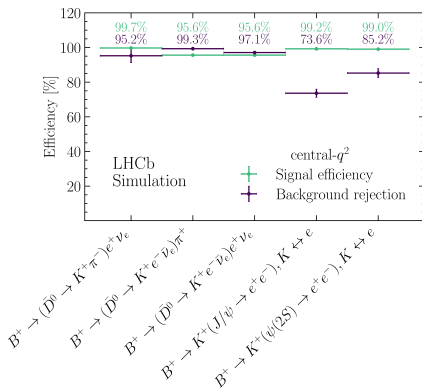


Experimental challenge: 3. Background suppression



- 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

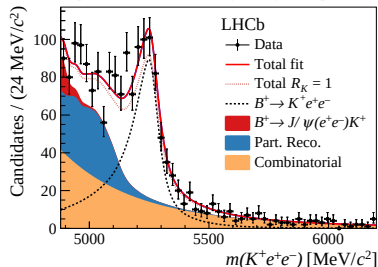
Experimental challenge: 3. Background suppression



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

Difference to previous R_K analysis

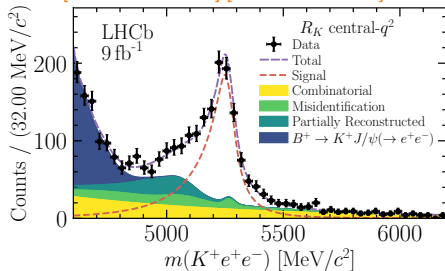
[Nature Phys. 18 (2022) 277]



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

[Nature Phys. 18 (2022) 277]

[arXiv:2212.09152] [arXiv:2212.09153]



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

[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 $+0.038$