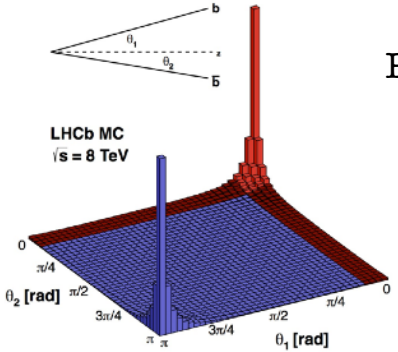
Recent results from the LHCb experiment

T. Blake

2025 CAP congress

Forward spectrometer at the LHC ($2 < \eta < 5$)

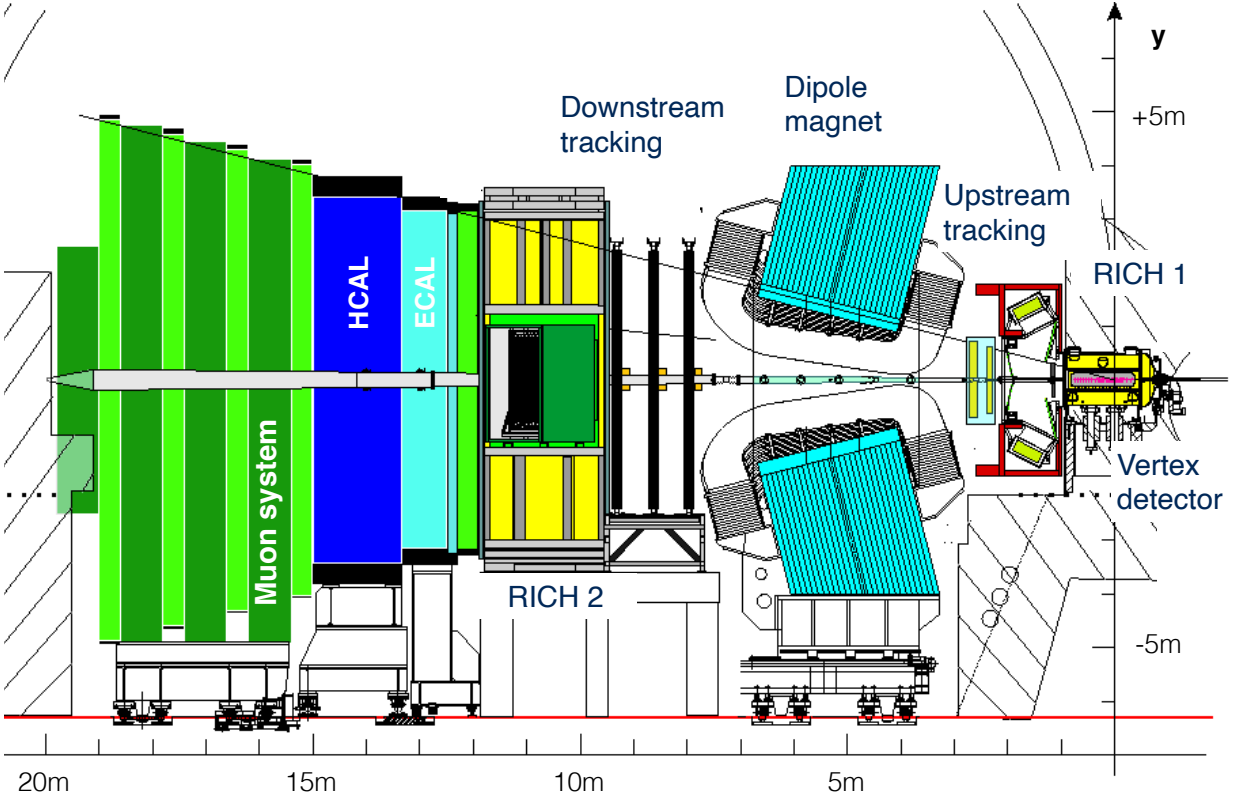


PYTHIA simulation of b-hadron production: b and $\bar{b}$ quarks are typically produced at small angles to the beam line

LHCb detector

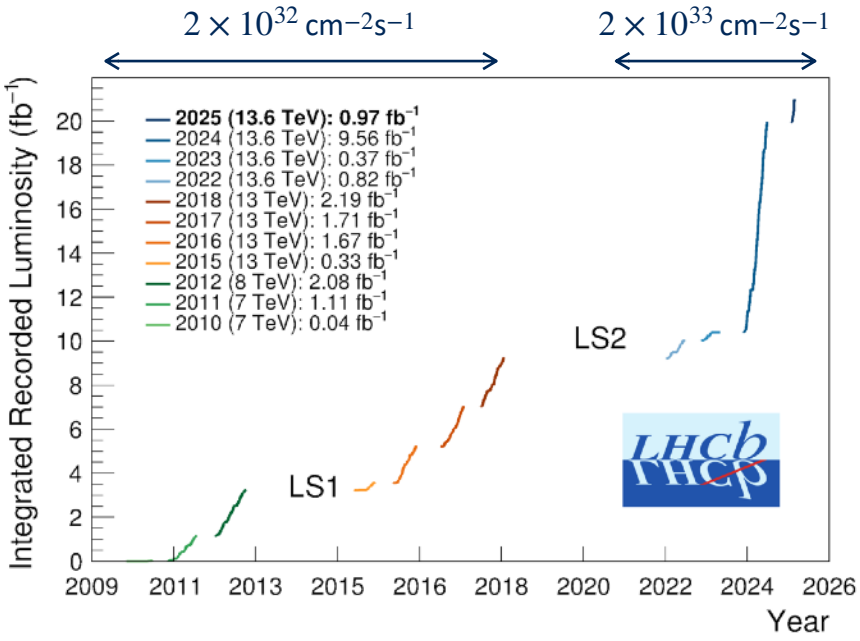
- Long lever arm for tracking ($\delta p/p$ of 0.5–1%)
- Excellent decay time resolution (of 45fs).
- Good particle identification:

$$\epsilon(e \to e) \sim 90\,\%\,, \epsilon(\pi \to e) \sim 5\,\%$$
$$\epsilon(K \to K) \sim 95\,\%\,, \epsilon(\pi \to K) \sim 5\,\%$$
$$\epsilon(\mu \to \mu) \sim 97\,\%\,, \epsilon(\pi \to \mu) \sim 1\,\%$$



Data taking

- LHCb has been taking data since 2010:
  - Majority of published results are based on data from 2010—2018.
- Major upgrade carried out in LS2 to enable the detector to run at higher instantaneous luminosity and the full be read out at 40MHz.



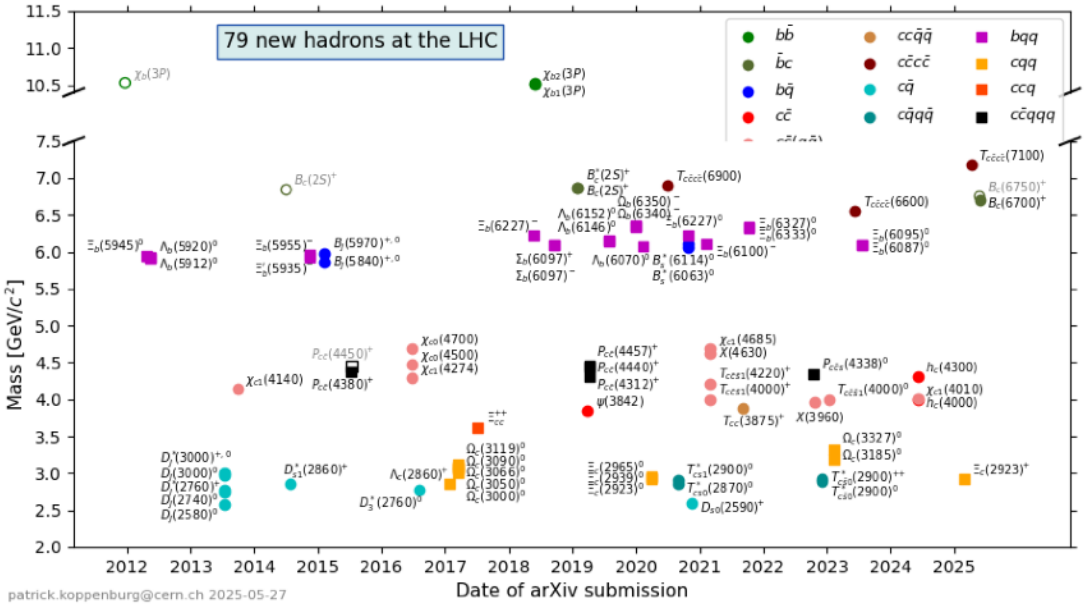
- To do this many sub-detectors were upgraded:
  - Silicon strip vertex detector replaced by a silicon pixel detector, straw drift tubes replaced by a fibre tracker.

Programme of measurements

- Measurements of CP violation and searches for rare and forbidden decays of *b*- and *c*-hadrons.
  - Exploiting the large cross-sections for heavy flavour production at the LHC.
- Measurements of new hadrons and multi-quark states.
- Measurements of electroweak production in the forward region.
- Studies of quark-gluon plasma in heavy ion collisions and measurements of proton or heavy-ion collisions with injected gasses (Ne, Ar and He).

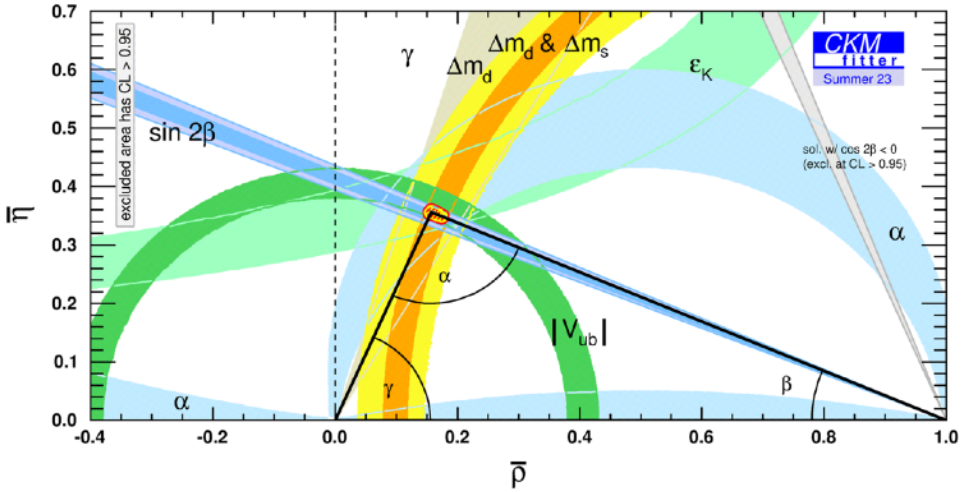
Hadron spectroscopy

- Large number of new hadrons discovered at the LHC (70 of 79 by LHCb):
  - 55 conventional mesons or baryons.
  - 24 exotic hadrons, e.g. multi-quark states.
- Many states were discovered through amplitude analyses of heavy-quark hadron decays.



Standard Model flavour structure

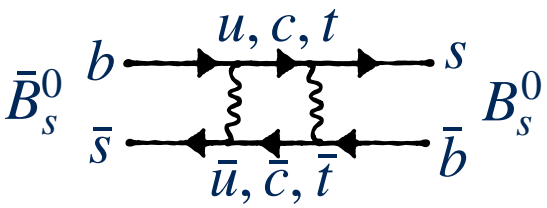
- The Yukawa mass mechanism results in a misalignment of the mass and weak eigenstates.
- Represented by the Cabibo-Kobayashi-Maskawa quark-mixing matrix, which appears in weak interactions.
- CKM matrix is hierarchical, off-diagonal elements are small.
- Single complex phase in the CKM matrix is the sole source of CP violation in the SM.



Constraints on the CKM matrix can be represented by triangles in the complex plane.

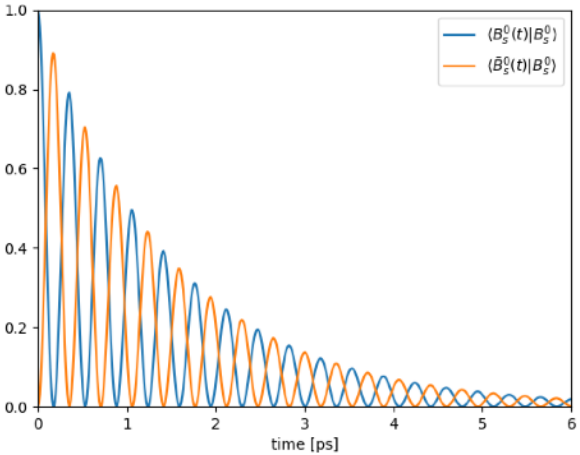
$$1 + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

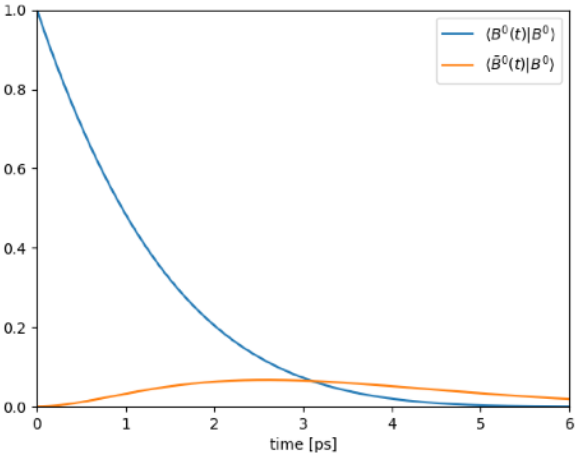
Neutral meson mixing



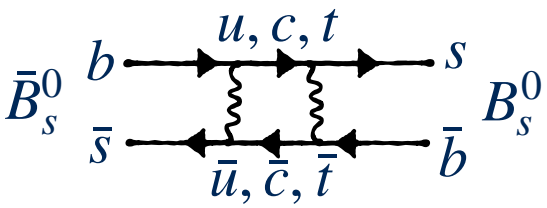
- In neutral meson system mass eigenstates are not flavour eigenstates and instead correspond to combinations $|B_{L,H}\rangle = p\,|B^0\rangle \pm q\,|\bar{B}^0\rangle$.
- Observe oscillation between $B^0_{(s)}$ and $\bar{B}^0_{(s)}$:

Oscillation frequency is about 40x faster for the B_s system than the B^0





Neutral meson mixing



- In neutral meson system mass eigenstates are not flavour eigenstates and instead correspond to combinations $|B_{L,H}\rangle = p\,|B^0\rangle \pm q\,|\bar{B}^0\rangle$.
- Time dependent decay rates of B_s^0 and $\bar{B}_s^0$ mesons to a common final-state depend on mass and width difference of $|B_{L,H}\rangle$:

$$\frac{d\Gamma[B_s^0 \to f]}{dt} \propto e^{-\Gamma_s t}\left[\cosh(\tfrac{1}{2}\Delta\Gamma_s t) + A_f^{\Delta\Gamma_s}\sinh(\tfrac{1}{2}\Delta\Gamma_s t) + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

$$\frac{d\Gamma[\bar{B}_s^0 \to f]}{dt} \propto \left|\frac{p}{q}\right|^2 e^{-\Gamma_s t}\left[\underbrace{\cosh(\tfrac{1}{2}\Delta\Gamma_s t) + A_f^{\Delta\Gamma_s}\sinh(\tfrac{1}{2}\Delta\Gamma_s t)} - \underbrace{C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)}\right]$$

Time evolution due to the width difference of mass eigenstates

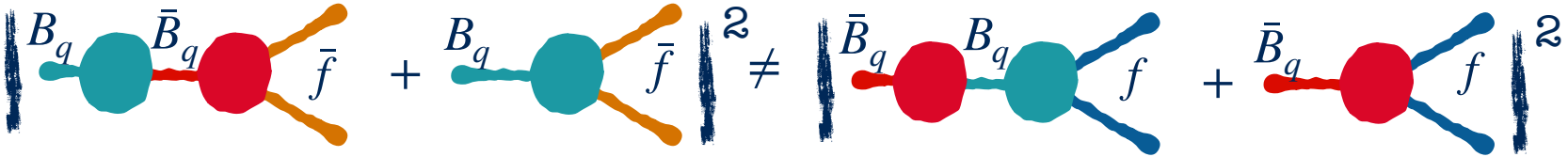
Time evolution due to the mass difference of mass eigenstates

Measuring CP violating effects

- CP violation can show up in three ways:
  - In decay

  - In mixing

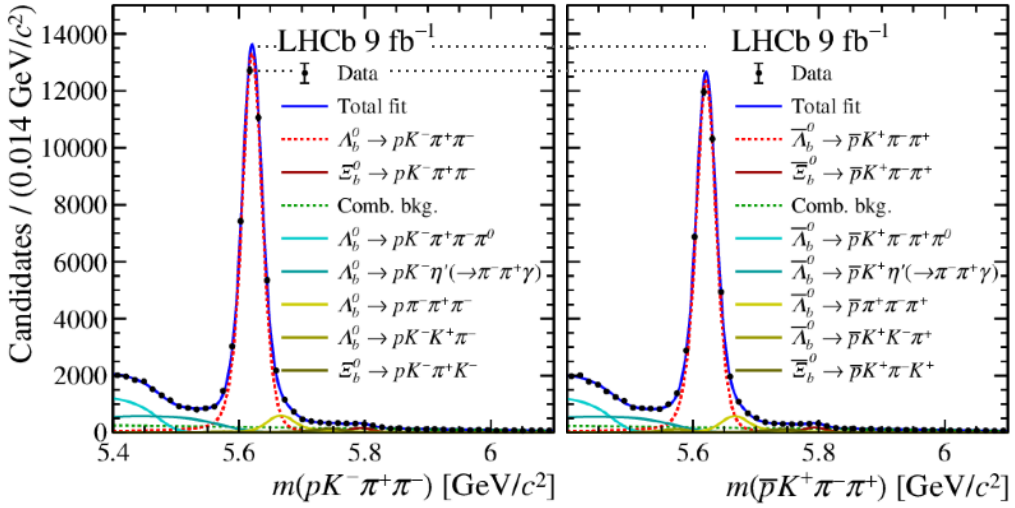
  - In the interference between mixing and decay



Observation of CP violation in *b*-baryon decays

- To measure CP violation in decay need contributions to the decay with different weak and strong phases.
- First observation of CP violation in a baryon decay using $\Lambda_b \to pK^-\pi^+\pi^-$ and $\Lambda_b \to \bar{p}K^+\pi^+\pi^-$.
- LHCb measures:

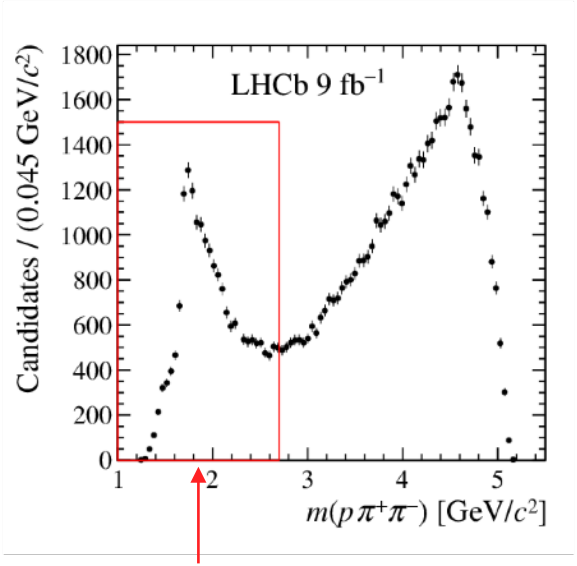
$$A_{CP} = \frac{\Gamma[\Lambda_b \to pK^-\pi^+\pi^-] - \Gamma[\bar{\Lambda}_b \to \bar{p}K^+\pi^+\pi^-]}{\Gamma[\Lambda_b \to pK^-\pi^+\pi^-] + \Gamma[\bar{\Lambda}_b \to \bar{p}K^+\pi^+\pi^-]}$$
$$= 2.45 \pm 0.46 \pm 0.10\,\%$$

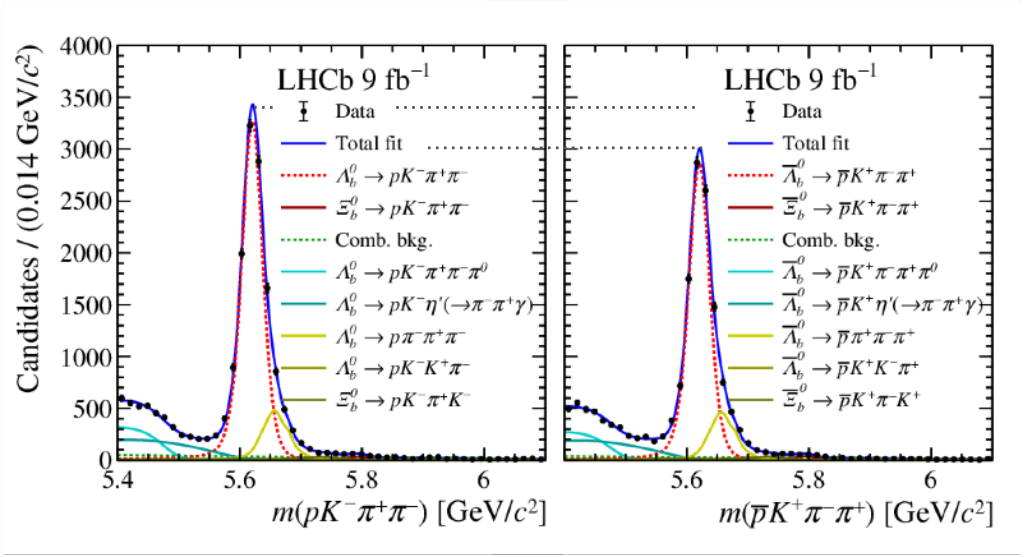


[LHCb-PAPER-2024-054
Submitted to Nature]

Observation of CP violation in *b*-baryon decays

- Asymmetry is largest at small $p\pi^+\pi^-$ masses:



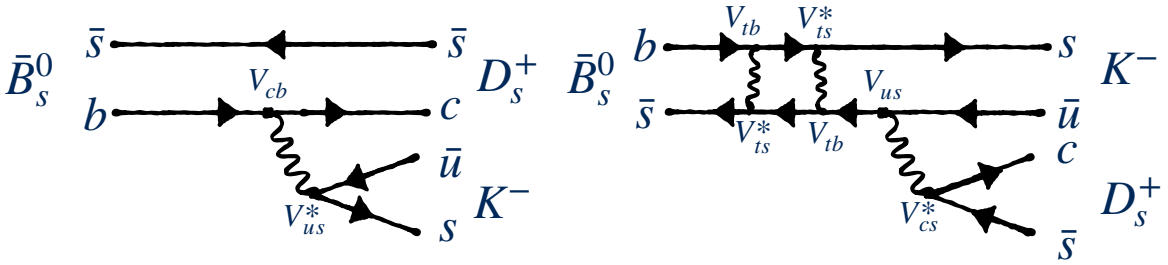


Multiple interfering contributions

[LHCb-PAPER-2024-054
Submitted to Nature]

CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

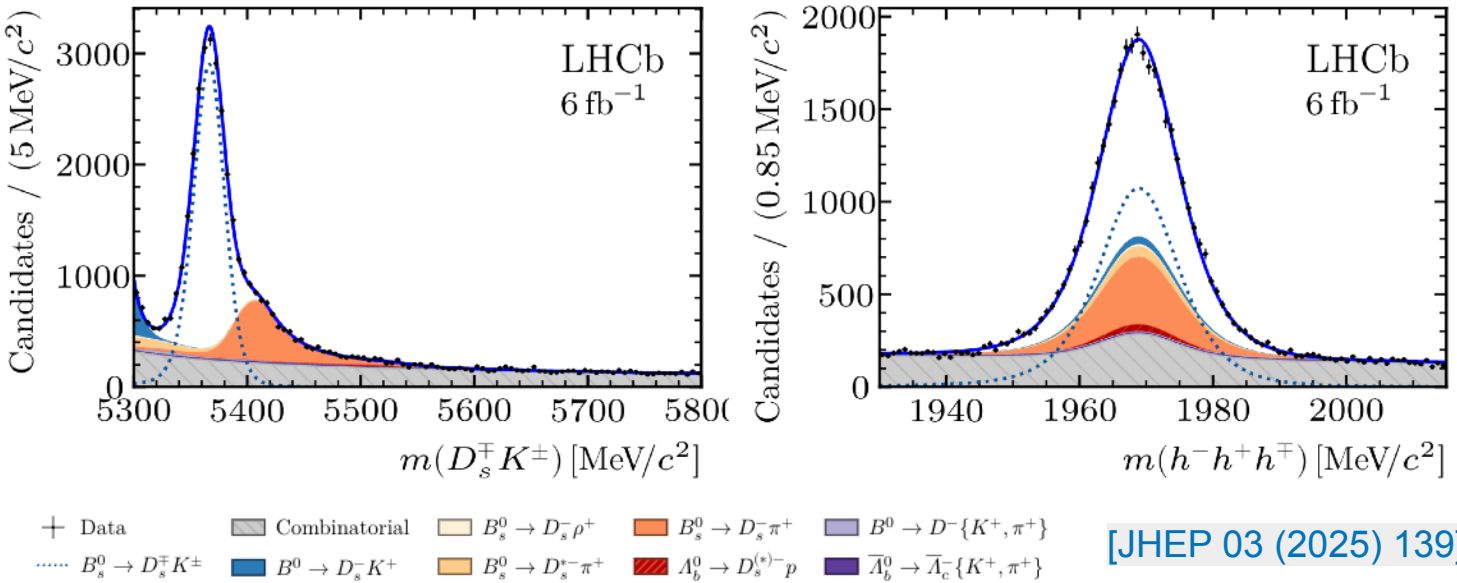
- Exploit interference between mixing and decay to measure relative weak phase between contributing diagrams ($\gamma - 2\beta_s$):



  - γ is an angle of the unitary triangle
  - β_s is the B_s mixing phase ($2\beta_s = 0.031 \pm 0.018$ rad [PRL 132 (2024) 051802])
- We can determine C, S and $A^{\Delta\Gamma}$ and infer γ from known β_s for $f \equiv D_s^- K^+$ and $\bar{f} \equiv D_s^+ K^-$

CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

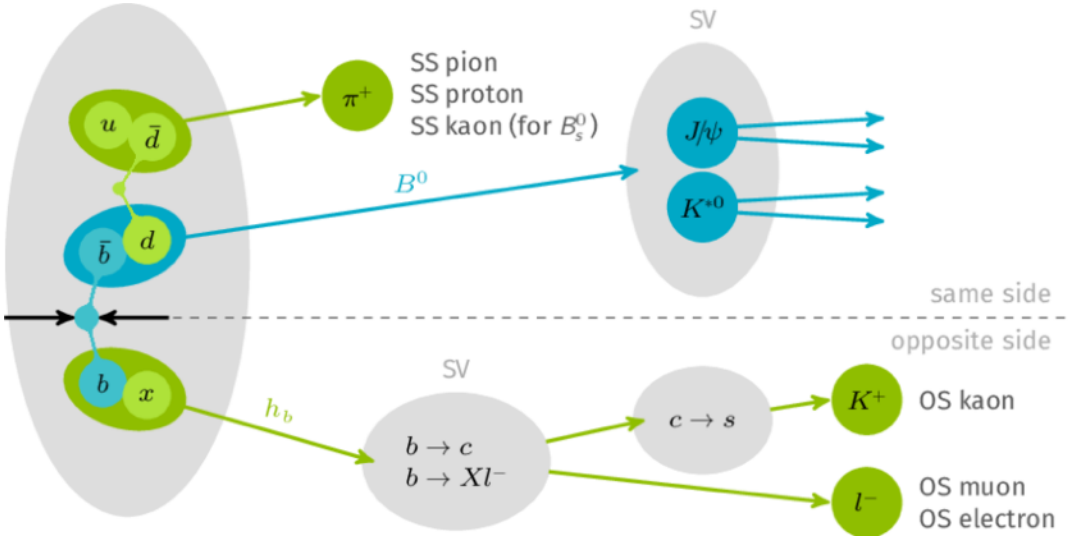
- Separate signal from experimental backgrounds using the B_s^0 and D_s^- masses:



[JHEP 03 (2025) 139]

Flavour tagging

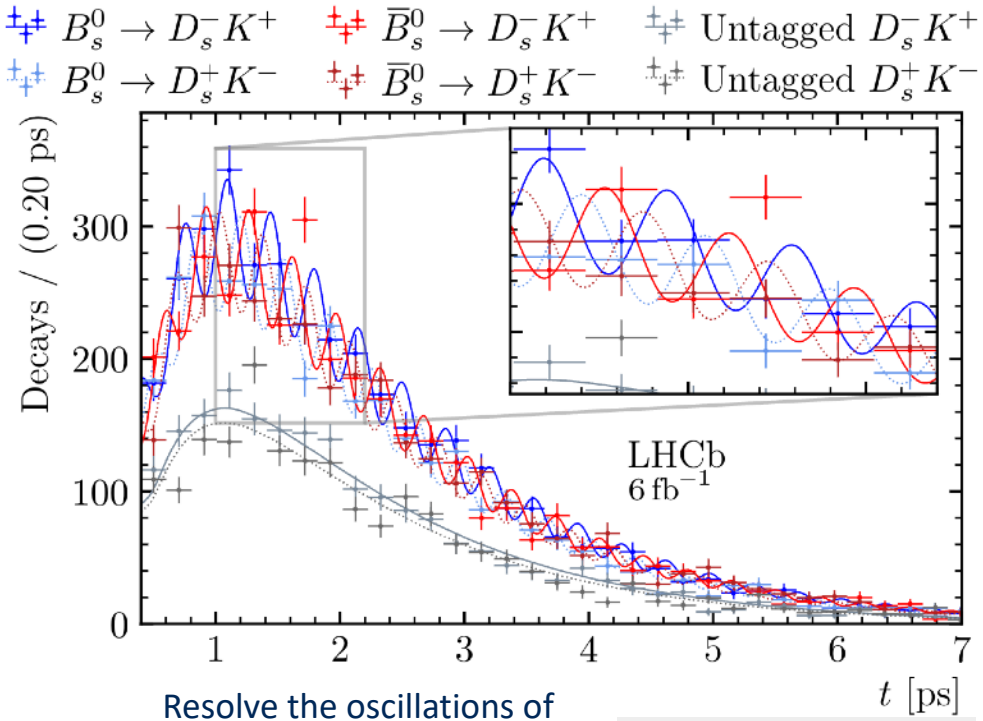
- Need to determine the flavour of the B_s^0 or $\bar{B}_s^0$ at production.
  - Use information from the decay of the other *b*-hadron and the hadronisation of the B_s^0 meson.
  - Achieve an effective tagging power of 6%



CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

- Splitting by the final-state and by the initial flavour tag shows the fast oscillation of B_s^0 system.
- Fit the decay-time distributions to determine:

$$C_f = 0.791 \pm 0.061 \pm 0.022$$
$$S_f = -0.571 \pm 0.084 \pm 0.023$$
$$S_{\bar{f}} = -0.503 \pm 0.084 \pm 0.025$$
$$A_f^{\Delta\Gamma} = -0.051 \pm 0.134 \pm 0.058$$
$$A_{\bar{f}}^{\Delta\Gamma} = -0.303 \pm 0.125 \pm 0.055$$



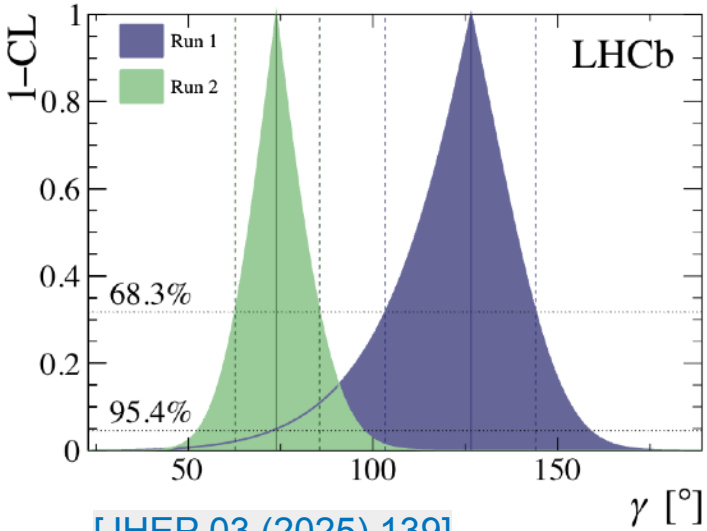
Resolve the oscillations of the B_s system

[JHEP 03 (2025) 139]

CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

- From decay-time distribution parameters can determine γ along with nuisance parameters due to the unknown decay amplitude ratio and strong phase.
- Use a modified frequentist approach in GammaCombo [JHEP 12 (2016) 087] to obtain

$$\gamma = (74 \pm 12)^{\circ}$$



[JHEP 03 (2025) 139]

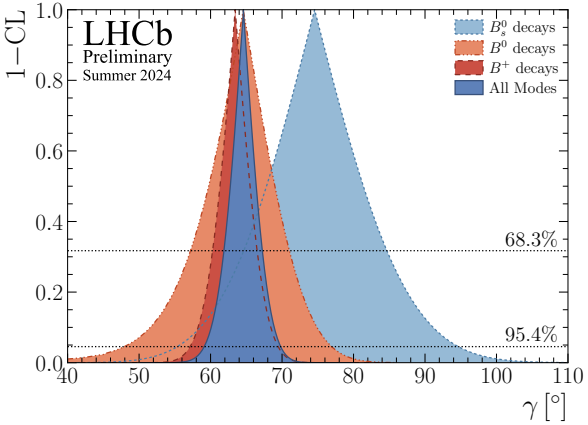
LHCb measurements of γ

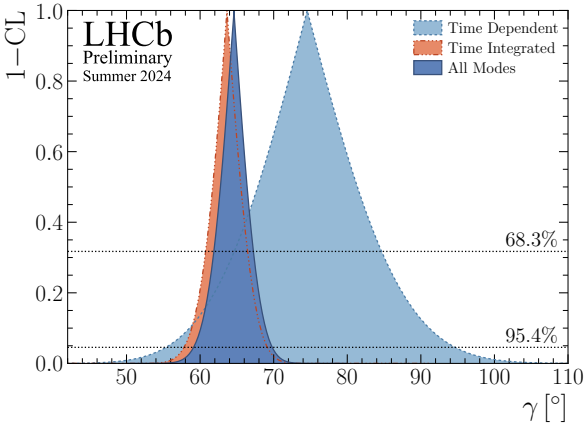
[LHCb-CONF-2024-004]

- Most recent LHCb combination of measurements of γ yields:

$$\gamma = (64.6 \pm 2.8)^\circ$$

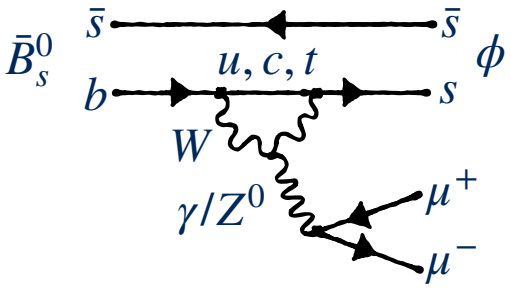
- Determined in a simultaneous analysis of parameters relevant to CP violation and mixing in the charm sector.

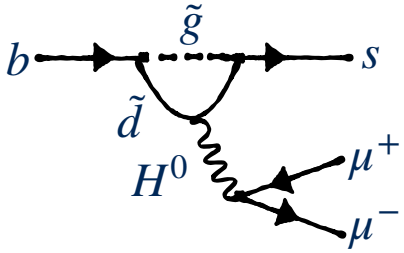




Rare decays of *b* hadrons

- Rare flavour-changing neutral current decay processes can be highly sensitive to contributions from new particles.
- New contributions can enhance or suppress the decay rate and modify the angular distribution of final-state particles.

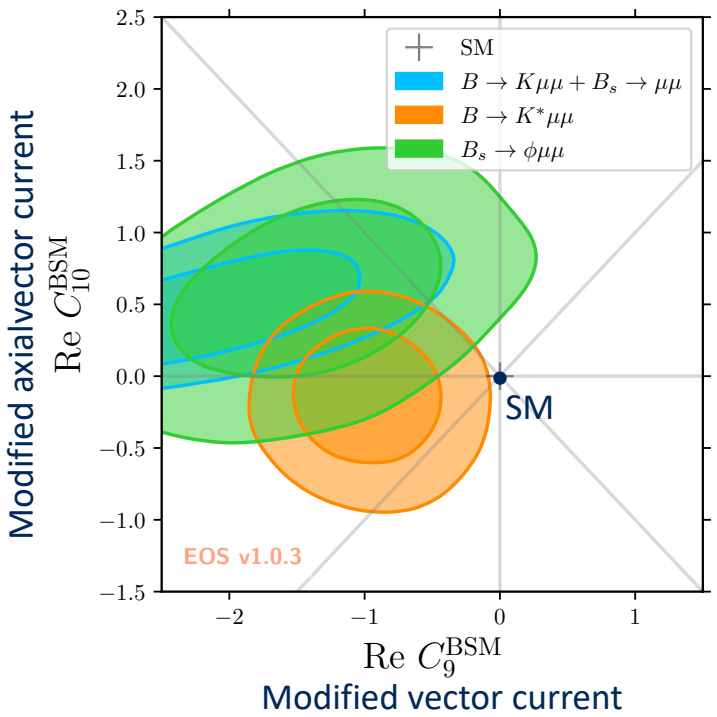




Rare decays of *b* hadrons

- Can interpret measurements of $b \to s$ transition processes in an effective field theory formalism.
- Fit data from experiments (ATLAS, BaBar, Belle, CDF, CMS and LHCb) to look for deviations from the SM.
- See tension between data and SM expectations (new contribution or just a problem with SM calculations?)

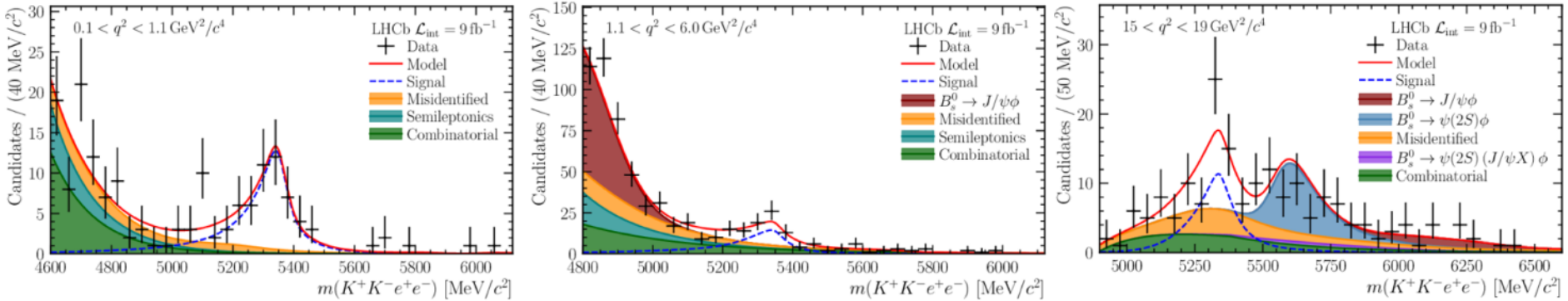
N. Gubernari et al.
[JHEP 09 (2022) 133]



Lepton flavour universality in $B_s^0 \to \phi l^+ l^-$ decays

- Expect $B_s^0 \to \phi e^+ e^-$ and $B_s^0 \to \phi \mu^+ \mu^-$ decays to have same rate:
  - Differ only by phase space in SM due to universality of lepton couplings.
  - In SM extensions couplings could be modified.
- Experimentally more challenging to reconstruct/select $B_s^0 \to \phi e^+ e^-$ decays in LHCb due to Bremsstrahlung losses from electrons.

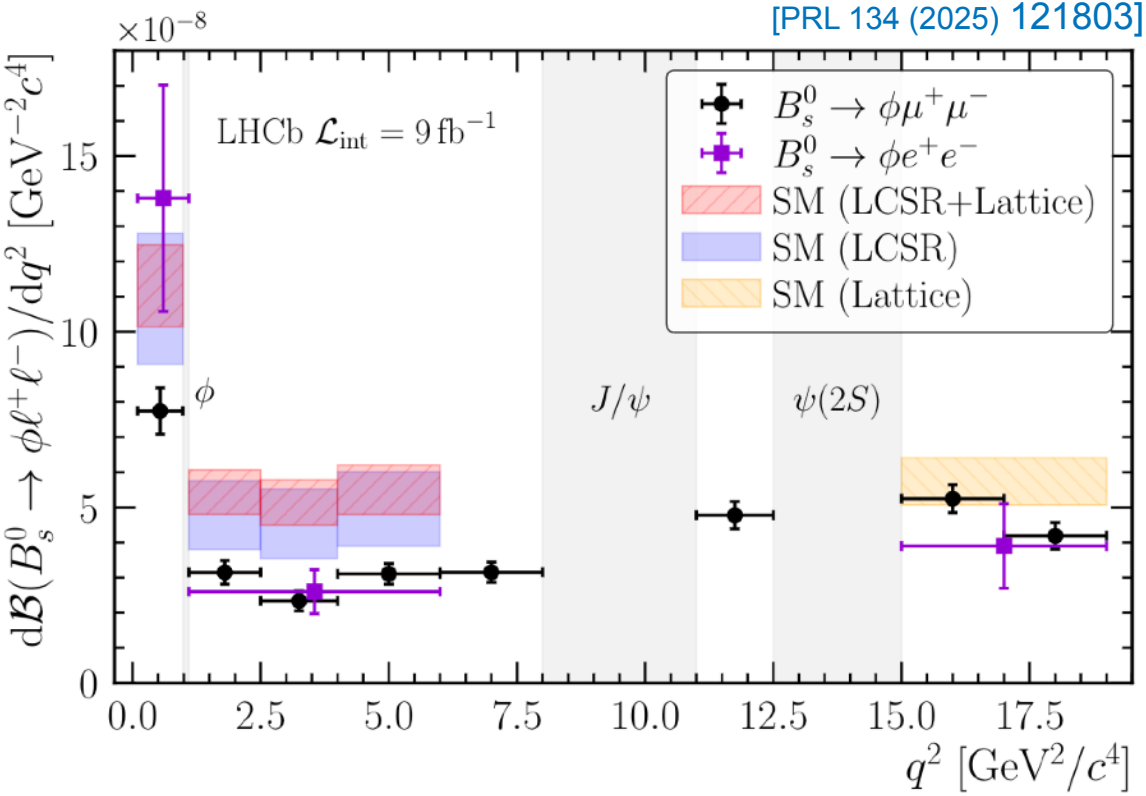
[PRL 134 (2025) 121803]



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

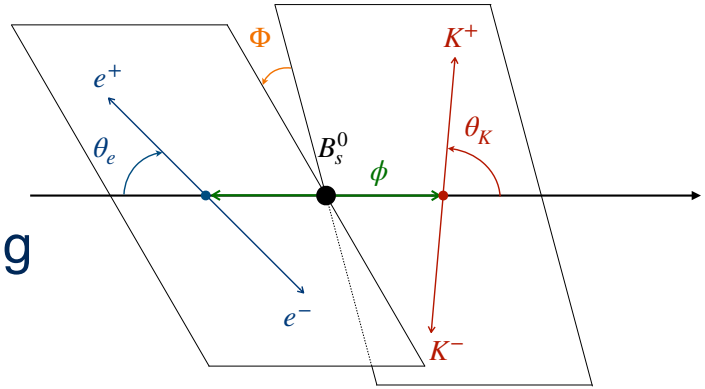
[PRL 134 (2025) 121803]

- No evidence for non-universal couplings in the rates of $B_s^0 \to \phi e^+ e^-$ and $B_s^0 \to \phi \mu^+ \mu^-$ decays.
- Measurements are consistently below SM predictions.



Angular distribution of $B_s^0 \to \phi e^+ e^-$ decays

- Decay can be parameterised by three angles and dielectron mass squared (q^2).
- Obtain simplified distribution by integrating over Φ and decay time:

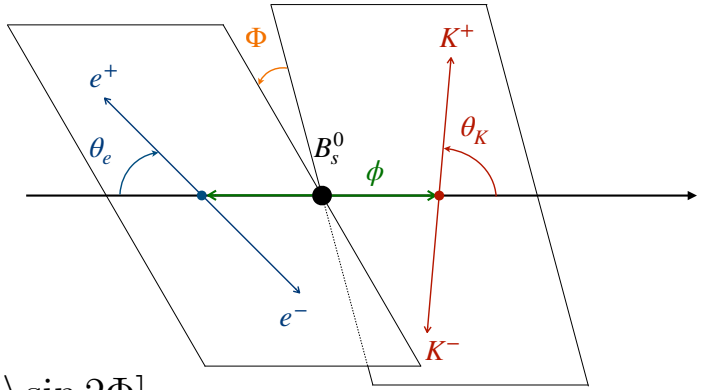


$$\frac{1}{\mathrm{d}[\Gamma+\tilde{\Gamma}]/\mathrm{d}q^2}\frac{\mathrm{d}^3[\Gamma+\tilde{\Gamma}]}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_K\,\mathrm{d}\cos\theta_e} = \frac{9}{16}\Big[\frac{3}{4}(1-\langle F_\mathrm{L}\rangle)\sin^2\theta_K(1+\tfrac{1}{3}\cos 2\theta_e)$$
$$+\langle F_\mathrm{L}\rangle\cos^2\theta_K(1-\cos 2\theta_e)$$
$$+\langle A_6\rangle\sin^2\theta_K\cos\theta_e\Big]\,.$$

Time integrated observables
(differ from t=0 due to $\Delta\Gamma_s$)

Angular distribution of $B_s^0 \to \phi e^+ e^-$ decays

- Decay can be parameterised by three angles and dielectron mass squared (q^2).
- Integrating over $\cos\theta_K$ and $\cos\theta_e$:

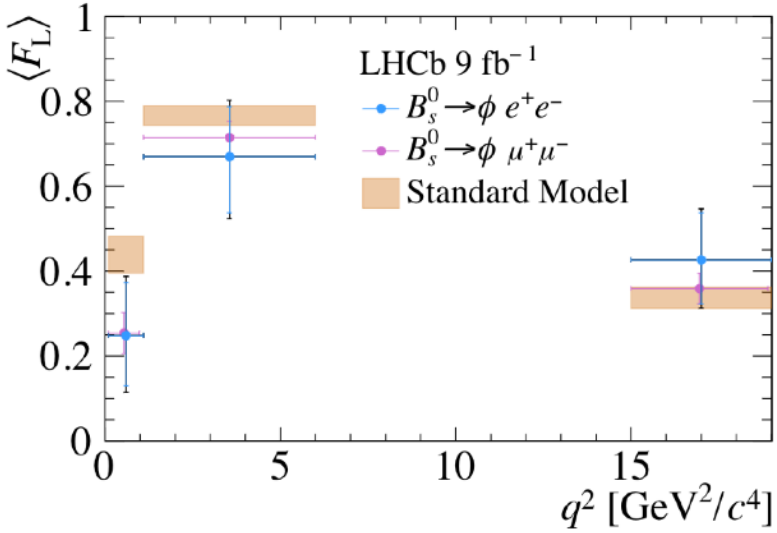


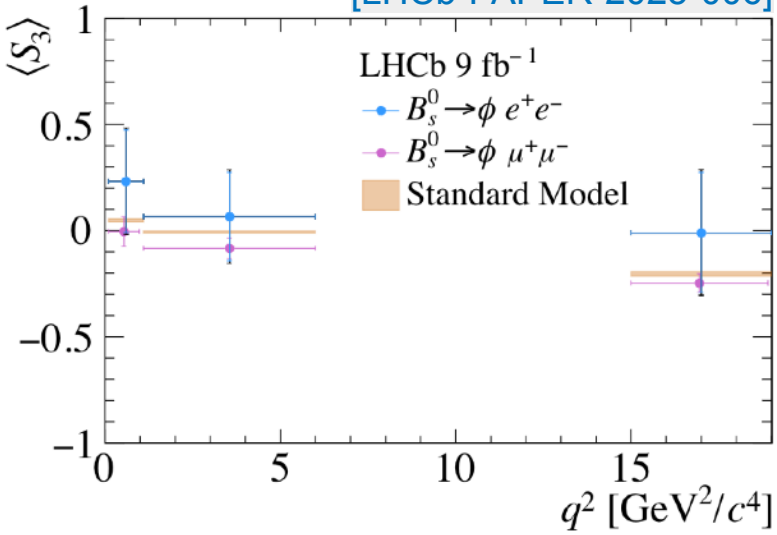
$$\frac{1}{\mathrm{d}[\Gamma+\tilde{\Gamma}]/\mathrm{d}q^2}\frac{\mathrm{d}^2[\Gamma+\tilde{\Gamma}]}{\mathrm{d}q^2\,\mathrm{d}\Phi} = \frac{1}{2\pi}\left[1+\langle S_3\rangle\cos 2\Phi + \langle A_9\rangle \sin 2\Phi\right] .$$

- Determine observables by performing unbinned maximum-likelihood fits to mass and angular distributions in bins of q^2.

Angular observables in $B_s^0 \to \phi e^+ e^-$

[LHCb-PAPER-2025-006]

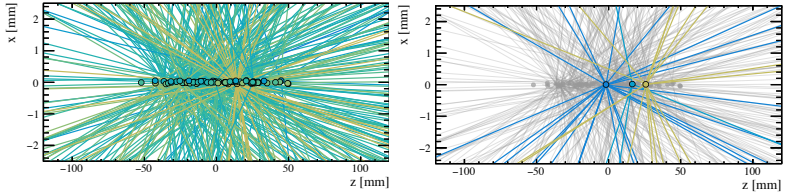




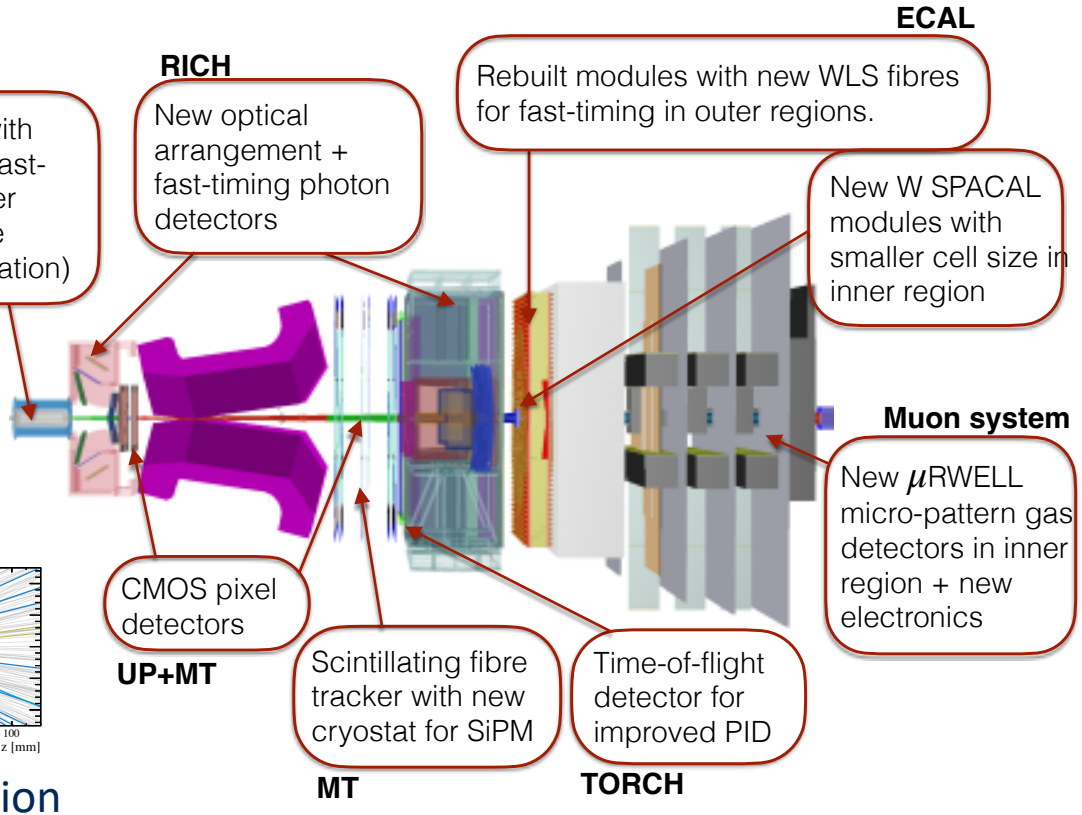
- Observables are consistent with SM predictions and between $B_s^0 \to \phi e^+ e^-$ and $B_s^0 \to \phi \mu^+ \mu^-$ decays.

LHCb Upgrade II

- Second upgrade planned for LS4, aiming to reach 1×10^{34} cm^{-2}s^{-1}.
- Range of interesting technological challenges.
- Fast timing is key:

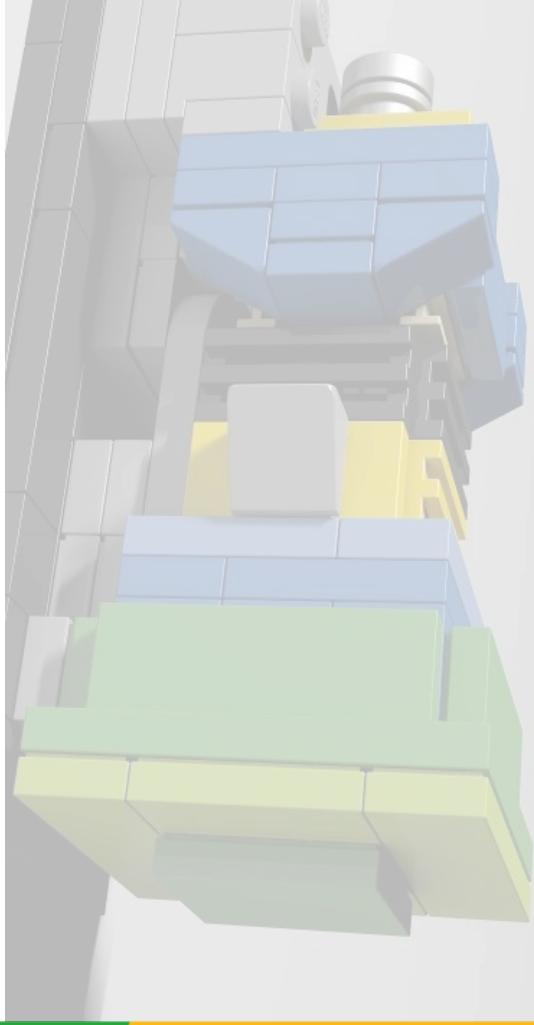


Impact of 30ps gate in PV reconstruction



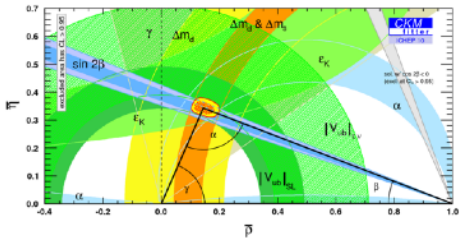
Summary

- Data from 2010—2018 has enabled world leading measurements of a wide range of *b*- and *c*-hadron decay processes.
- A large data set has already been acquired with the upgraded detector. Expect new results with this data set soon.
- A future upgrade to operate at even higher instantaneous luminosities is planned.



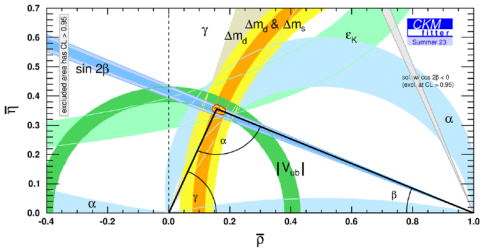
Opportunities in flavour physics

2010



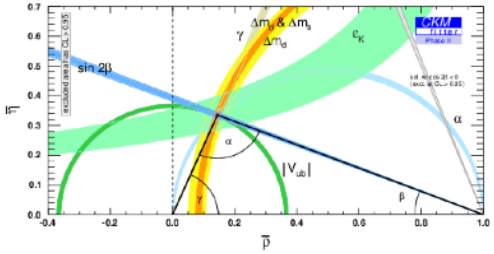
Data from 2010—2018 and updated results from BaBar/Belle.

2023



Adding projected sensitivity of Belle 2 and LHCb upgrades

end of HL-LHC



- Huge opportunity for flavour physics with Belle II and the LHCb upgrade I and II.
- Will lead to a step change in precision on flavour observables.

CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

- Splitting by the final-state and by the initial flavour tag shows the fast oscillations of B_s^0 system.
- Fit the decay-time distributions to determine:

$$C_f = 0.791 \pm 0.061 \pm 0.022$$
$$S_f = -0.571 \pm 0.084 \pm 0.023$$
$$S_{\bar{f}} = -0.503 \pm 0.084 \pm 0.025$$
$$A_f^{\Delta\Gamma} = -0.051 \pm 0.134 \pm 0.058$$

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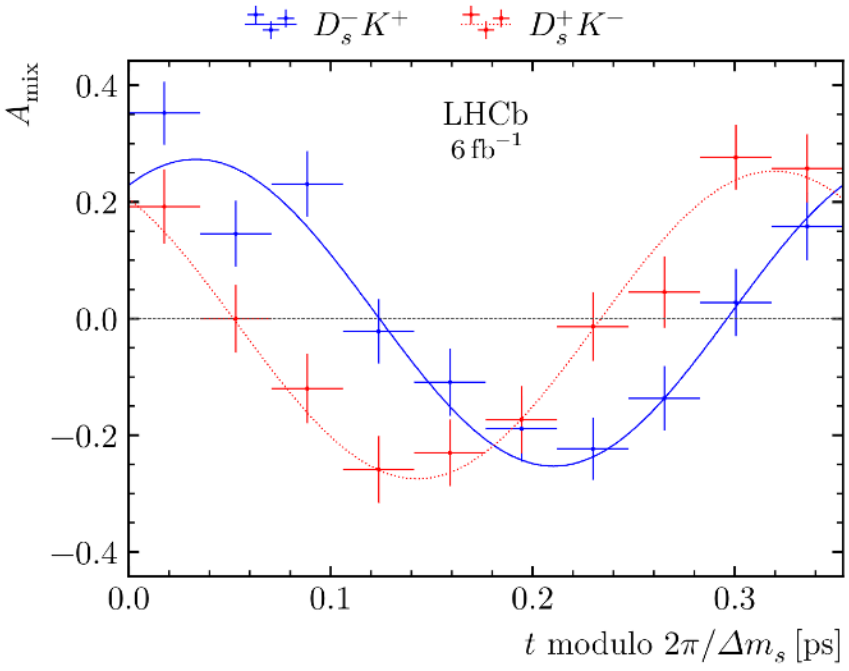

Resolve the oscillations of the B_s system

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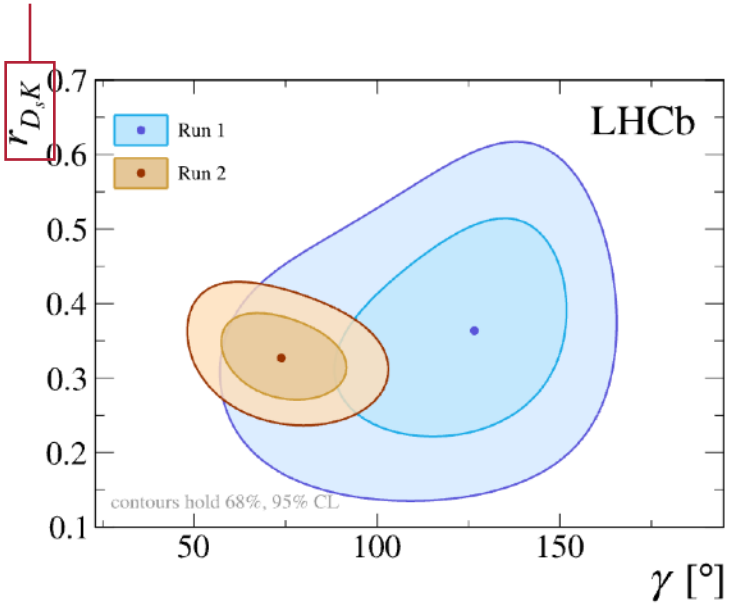
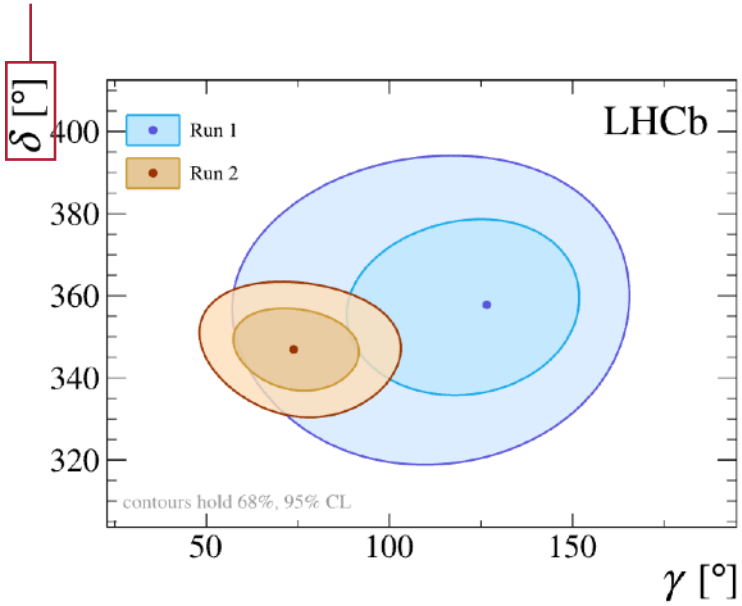
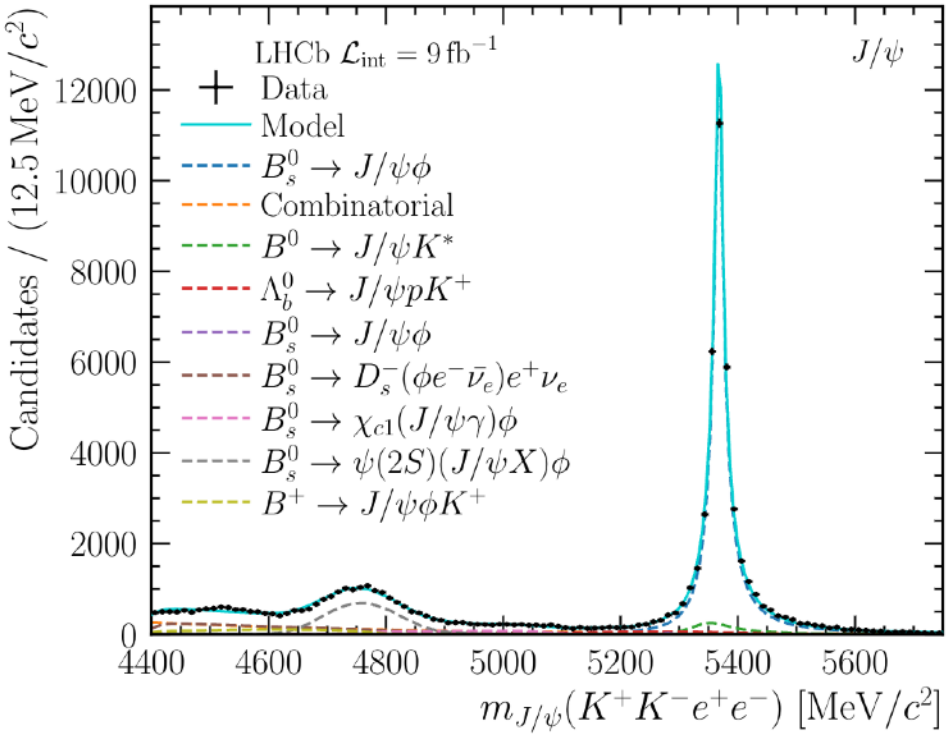
CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

Amplitude ratio between
$A(\bar{B}_s^0 \to D_s^- K^+)$ and $A(B_s^0 \to D_s^- K^+)$



Strong phase difference between
$A(\bar{B}_s^0 \to D_s^- K^+)$ and $A(B_s^0 \to D_s^- K^+)$



Backgrounds in $B_s^0 \to J/\psi\phi$ decays

- Mass constraint in $B_s^0 \to J/\psi\phi$ decays allows background components to be studied in detail.
- Background appears well understood.