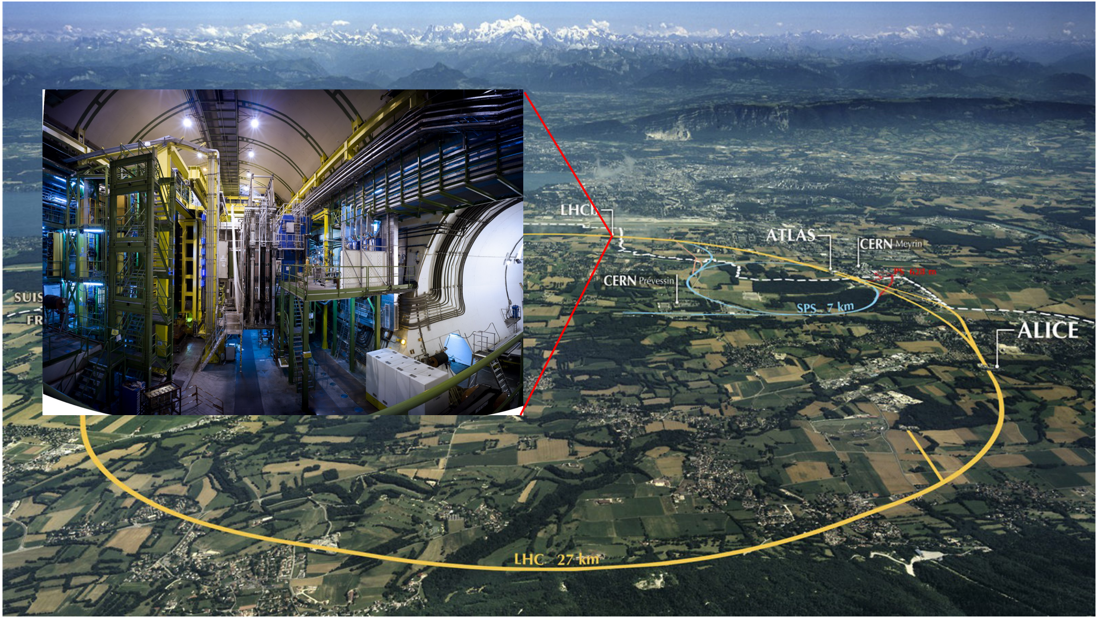
CP violation and CKM measurements at LHCb

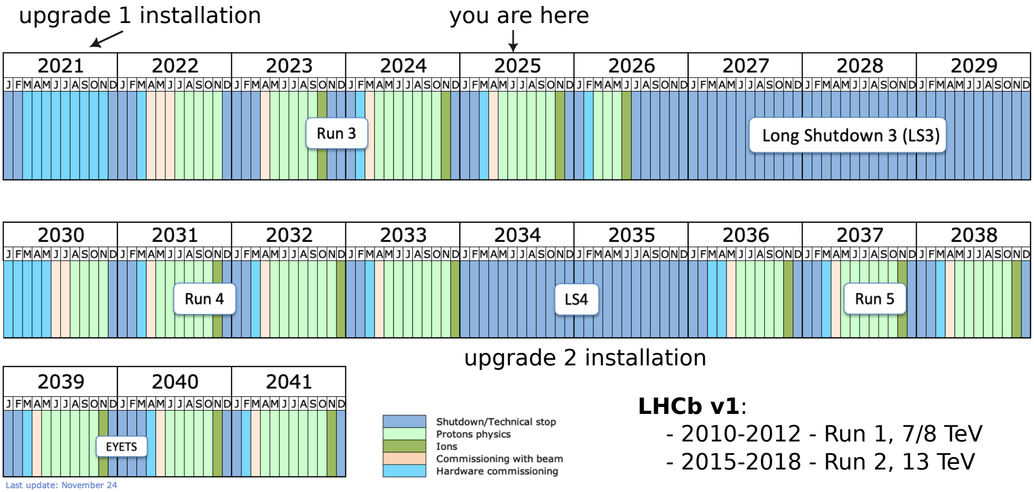
PASCOS, Durham

Mark Smith, on behalf of the LHCb collaboration

23 July 2025

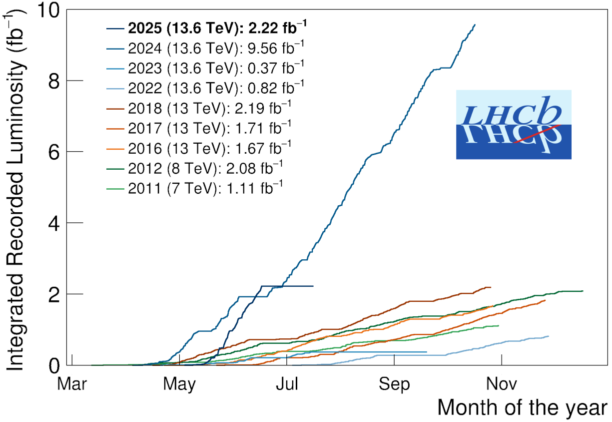

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
LHC 27 km

Status and plans



LHCb v1:
- 2010-2012 - Run 1, 7/8 TeV
- 2015-2018 - Run 2, 13 TeV

Status



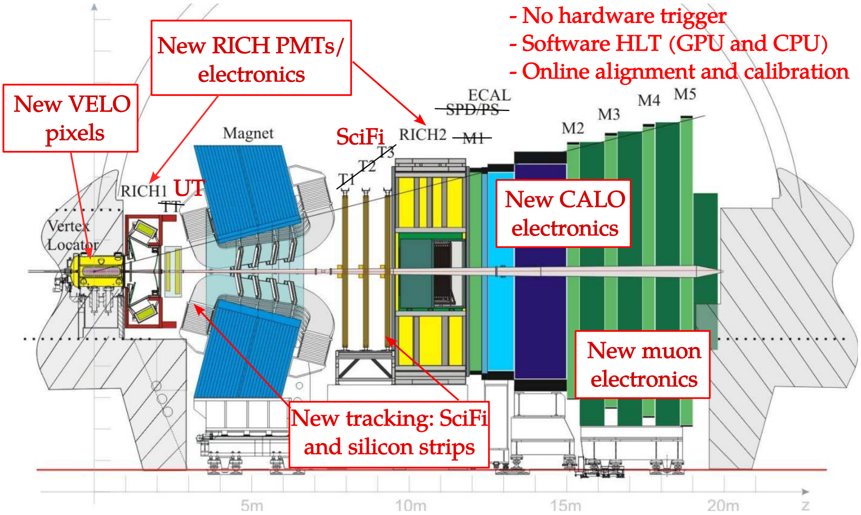
- $3\,\text{fb}^{-1}$ at $7/8\,\text{TeV}$ in Run 1
- $6\,\text{fb}^{-1}$ at $13\,\text{TeV}$ in Run 2
  - *b*-hadron cross-section roughly doubled
- Already double data set in Run 3!
  - $11.8\,\text{fb}^{-1}$ in 2024 and 2025 (so far)
- Aiming for $\int \mathcal{L} \sim 50\,\text{fb}^{-1}$ by end of Run 4
  - Collected entire Run 1+2 data set again in 2024

Upgrade 1

[JINST 19 (2024) P06065]

$$\mathcal{L}^{\text{Run 2}} \sim 0.4 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1} \to \mathcal{L}^{\text{Run 3}} \sim 2 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$$

- No hardware trigger
- Software HLT (GPU and CPU)
- Online alignment and calibration

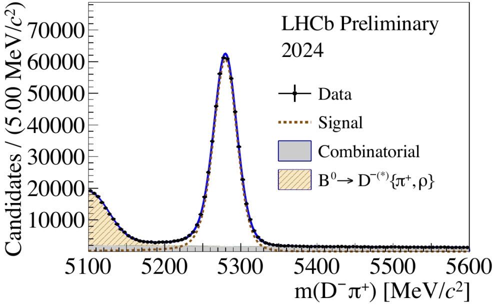


Upgrade 1

[LHCb-FIGURE-2024-030]
[LHCb-FIGURE-2024-021]

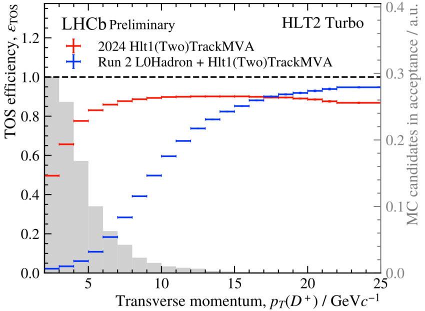
Excellent performance in 2024:

- Good momentum resolution → invariant mass resolution
- Low background rates



Clear benefit from hardware trigger removal:

- Improved `HLT1` efficiency at low p_T
- Low p_T objects can be retained in more complex `HLT2` selections



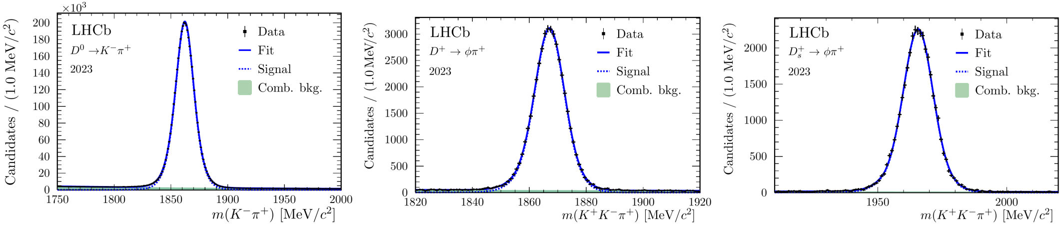
First Run 3 analysis

[arXiv:2505.14494]

Measurement of charm meson production asymmetries:

- Double-differential in $\eta - p_{\mathrm{T}}(D)$
- For D^0, D^+, and D_s^+
- Using a mix of 2022 and 2023 data
  - First measurement at $\sqrt{s} = 13.6\,\mathrm{TeV}$
  - Without UT, 2023 with VELO retracted
  - Small samples: $15\,\mathrm{pb}^{-1}$ (D^+), $41\,\mathrm{pb}^{-1}$ (D_s^+), $177\,\mathrm{pb}^{-1}$ (D^0)
- Nuisance asymmetries determined with data control modes $\rightarrow$ no simulation

[See Francesco's presentation for details]



First Run 3 analysis

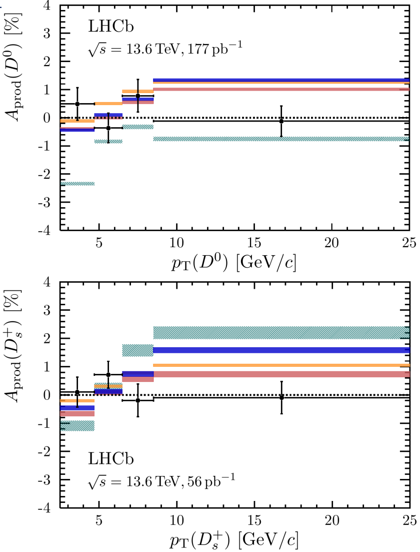
[arXiv:2505.14494]

Comparatively precise results, even with a small sample - **Gain in selection efficiency!**

$$A_{\text{prod}}(D^0) = (0.07 \pm 0.26(\text{stat}) \pm 0.10(\text{syst}))\%,$$
$$A_{\text{prod}}(D^+) = (-0.33 \pm 0.29(\text{stat}) \pm 0.14(\text{syst}))\%,$$
$$A_{\text{prod}}(D_s^+) = (0.18 \pm 0.26(\text{stat}) \pm 0.08(\text{syst}))\%$$

compared to $1\,\text{fb}^{-1}$ $7\,\text{TeV}$ (2011) results:

$$A_{\text{prod}}(D^+) = (-0.96 \pm 0.26(\text{stat}) \pm 0.18(\text{syst}))\%,$$
$$A_{\text{prod}}(D_s^+) = (-0.33 \pm 0.22(\text{stat}) \pm 0.10(\text{syst}))\%$$



Cabibbo - Kobayashi - Maskawa matrix

Governs quark flavour changing interactions. It is a 3×3 matrix - 3 real parameters, 1 phase.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

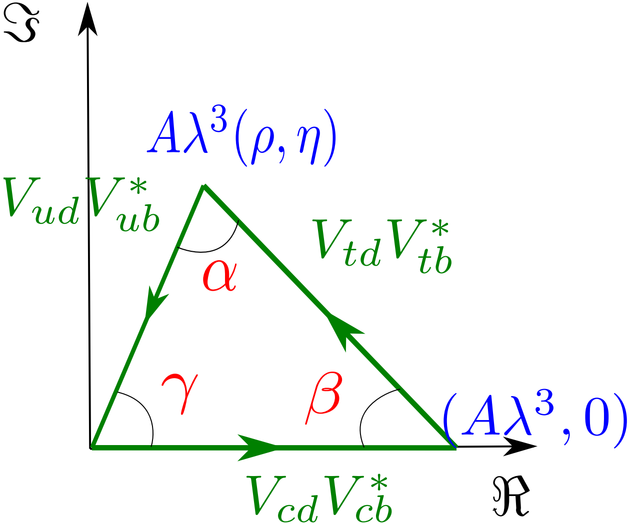
If we impose unitarity, $V^\dagger V = I$

$$\sum_k V_{ik}^* V_{jk} = 0$$

For CP violation only consider three triangles with complex parts in (V_{td}, V_{ub}):

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5)\eta = 0$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = \mathcal{O}(\lambda^4)\eta + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0$$
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = \mathcal{O}(\lambda^3)\eta + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3)\eta = 0$$

Unitarity triangle



$$\sin 2\alpha = \Im\left(\frac{V_{tb}^* V_{td} V_{ud}^* V_{ub}}{V_{tb} V_{td}^* V_{ud} V_{ub}^*}\right)$$

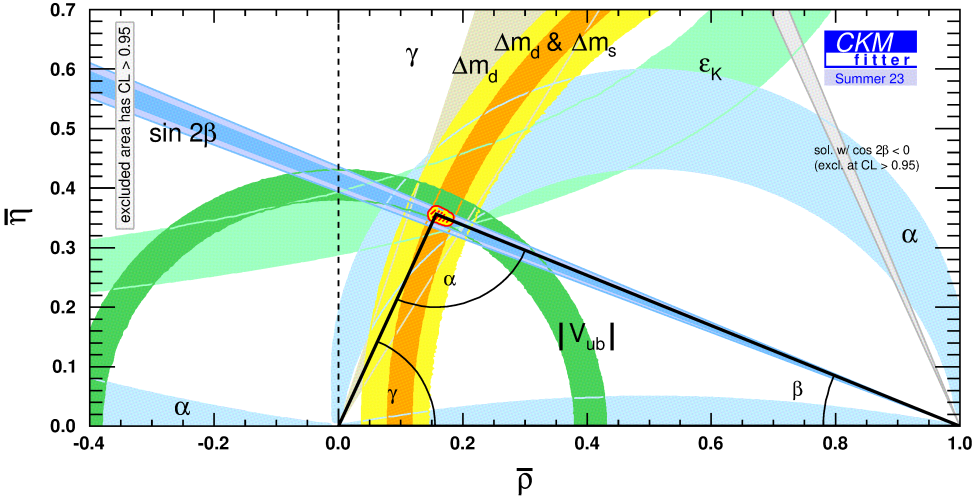
$$\sin 2\gamma = \Im\left(\frac{V_{cb}^* V_{cd} V_{ud}^* V_{ub}}{V_{cb} V_{cd}^* V_{ud} V_{ub}^*}\right)$$

$$\sin 2\beta = \Im\left(\frac{V_{cb}^* V_{cd} V_{td}^* V_{tb}}{V_{cb} V_{cd}^* V_{td} V_{tb}^*}\right)$$

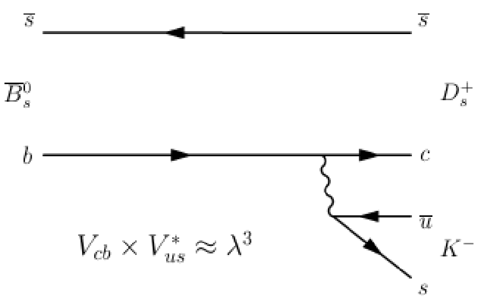
- Is the triangle a triangle?
- Are different determinations consistent?

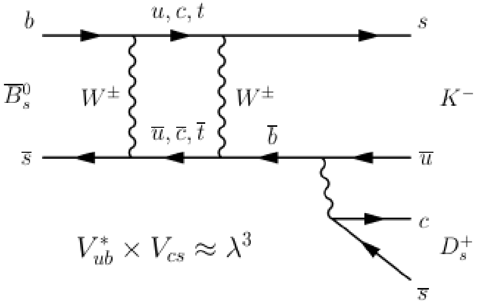
Unitarity triangle

[EPJC 41 (2005) 1]



Measure γ: $B_s^0 \to D_s^{\mp} K^{\pm}$ [JHEP 03 (2025) 139]





- *CP*-violation in interference between mixing and decay
- Similar decay amplitudes:

$$r_{D_sK} = \frac{|A(\overline{B}_s^0 \to D_s^+ K^-)|}{|A(B_s^0 \to D_s^+ K^-)|} \approx 0.4$$

- A strong phase difference between decay amplitudes δ
- Two weak phases: γ from V_{ub}^* and β_s from B_s^0 mixing

Measure γ: $B_s^0 \to D_s^{\mp} K^{\pm}$ [JHEP 03 (2025) 139]

$$\frac{\mathrm{d}\Gamma_{B_s^0\to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f\cos\left(\Delta m_s t\right) - S_f\sin\left(\Delta m_s t\right)\right],$$

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

where $\left|\frac{p}{q}\right| = 1$ (no CPV in B_s^0 mixing), $|\lambda_f| = \left|\frac{1}{\lambda_{\bar{f}}}\right|$ (no CPV in this decay) and

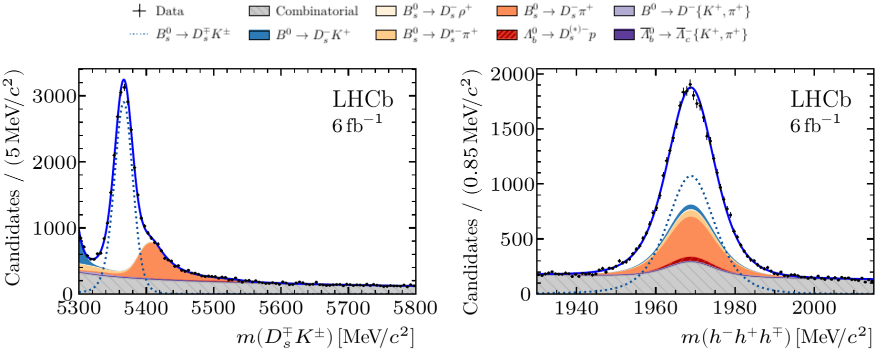
$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2},$$

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}.$$

Measure γ: $B_s^0 \to D_s^\mp K^\pm$ [JHEP 03 (2025) 139]

- Full Run 2 LHCb data set: $6\,\text{fb}^{-1}$
  - Follows on from Run 1 analysis [JHEP 03 (2018) 059]
- Reconstruct D_s^- in 5 final states: $K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^-$, $\phi\pi^-$. $K^{*0}K^-$, $K^-K^+\pi^-$
- Fit bkg subtracted decay time distributions of B_s^0 and $\bar{B}_s^0$ to the same final state
  - 2D fit (mD_s^-K) and $m(h^+h^-h^+)$ and calculate sWeights

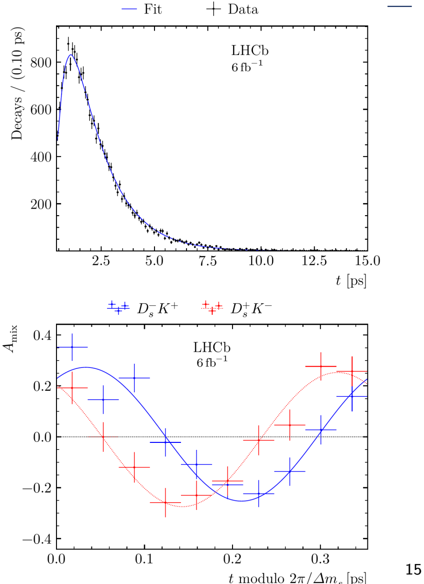


Measure γ: $B_s^0 \to D_s^{\mp} K^{\pm}$

[JHEP 03 (2025) 139]

Fit the decay-time distribution and extract *CPV* observables

- Tag the initial B_s^0 flavour [JINST 11 (2016) 05] [JINST 10 (2015) 10] [EPJC 72 (2012) 2022]
  - Tagging power of $(6.10 \pm 0.15)\%$
- Correct for the detector and selection decay-time acceptance
  - Determined from $B_s^0 \to D_s^- \pi^+$ data and corrected to $B_s^0 \to D_s^- K^+$ with simulation
- Model decay-time resolution and bias using per-event vertex fit uncertainty
  - Calibrated with sample of $D_s^- K^+$, where both D_s^- and K^+ originate from the PV



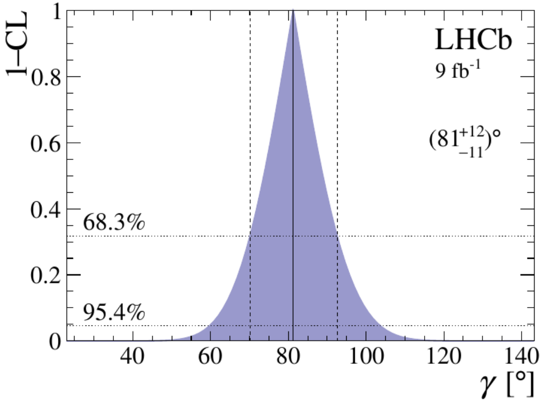
Measure γ: $B_s^0 \to D_s^{\mp} K^{\pm}$ [JHEP 03 (2025) 139]

Run 2 results:

$$r_{D_sK} = 0.327^{+0.039}_{-0.037}$$
$$\delta = (346.9^{+6.8}_{-6.6})^\circ$$
$$\gamma = (74 \pm 12)^\circ$$

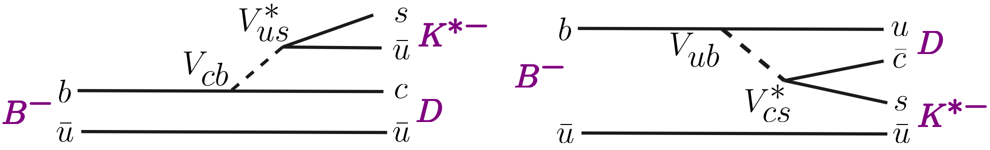
Combined with Run 1 analysis:

$$r_{D_sK} = 0.318^{+0.034}_{-0.033}$$
$$\delta = (347.6 \pm 6.3)^\circ$$
$$\gamma = (74^{+12}_{-11})^\circ$$



Measure γ: $B^- \to DK^{*-}$

[JHEP 02 (2025) 113]



- Weak phase of γ between the two diagrams
- Strong phase of δ between the two diagrams
- Amplitude ratio $r_{DK^*} \sim 0.13$ [PRD 91 (2015) 073007]
- Measure interference between amplitudes with common final states of the D
    - (quasi-) CP eigenstates: K^+K^-, $\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$
    - Self-conjugate $K_S K^+K^-$, $K_S\pi^+\pi^-$
    - Non self-conjugate decays:
        - OS kaon wrt B^-: $K^+ \pi^-$, $K^+ \pi^- \pi^+\pi^-$. Cabibbo suppressed
        - SS kaon wrt B^-: $K^- \pi^+$, $K^- \pi^+ \pi^+\pi^-$. Cabibbo favoured

Measure γ: $B^- \to DK^{*-}$ [JHEP 02 (2025) 113]

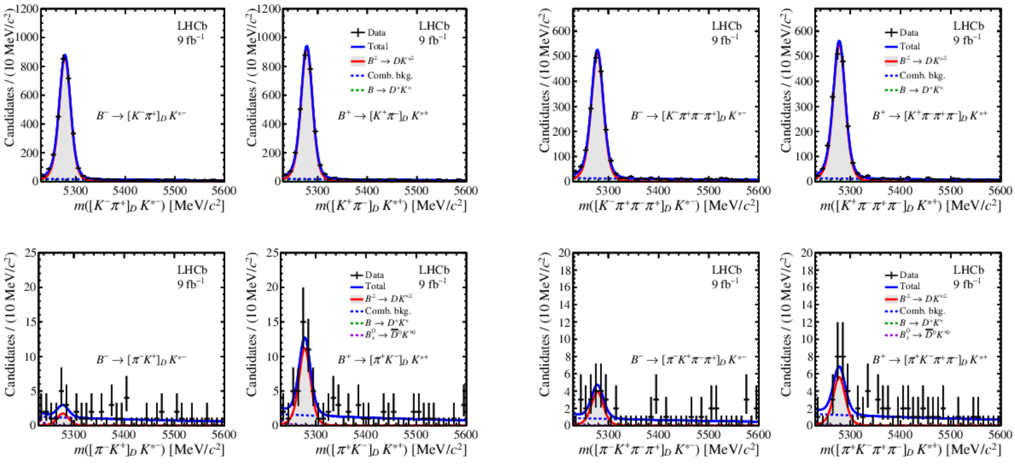
Full LHCb Run 1 + Run 2 data set: $9\,\text{fb}^{-1}$

- Extract yields from invariant mass fits
  - Separate for B^+ and B^-
- Correct asymmetries for known production ([JHEP 04 (2021) 081]) and detection asymmetries ([PRD 95 (2017) 052005])
- Extract γ from asymmetries

D decay mode	B^-	B^+
$K\pi$	2656 ± 55	2844 ± 57
KK	366 ± 20	274 ± 18
$\pi\pi$	121 ± 13	63 ± 10
πK	5 ± 4	35 ± 7
$K\pi\pi\pi$	1665 ± 44	1783 ± 45
$\pi\pi\pi\pi$	160 ± 14	149 ± 14
$\pi K\pi\pi$	13 ± 5	18 ± 5
$K^0_S\pi\pi$	279 ± 18	268 ± 18
$K^0_S KK$	29 ± 6	40 ± 7

Measure γ: $B^- \to DK^{*-}$

[JHEP 02 (2025) 113]



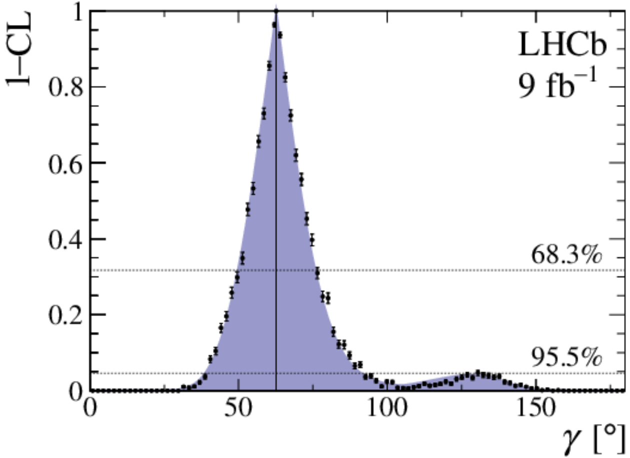
First observation of the suppressed modes $B^\pm \to [\pi^\pm K^\mp]_D K^{*\pm}$ and $B^\pm \to [\pi^\pm K^\mp \pi^+\pi^-]_D K^{*\pm}$

Measure γ: $B^- \to DK^{*-}$ [JHEP 02 (2025) 113]

Combine *CP* asymmetries with external inputs:

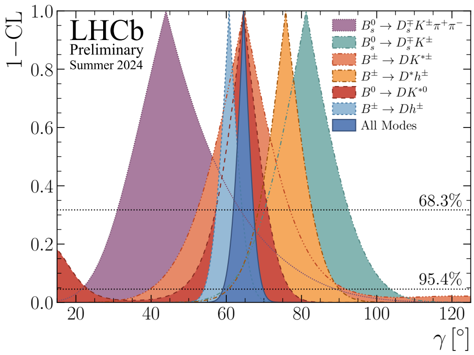
- *D* decay parameters [LHCb-CONF-2022-003], [JHEP 05 (2021) 164]
- *CP* even fraction of $D \to \pi^+\pi^-\pi^+\pi^-$ [PRD 106 (2022) 092004]

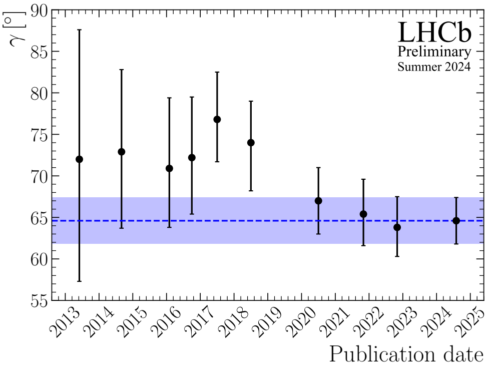
$$\gamma = (63 \pm 13)^\circ$$
$$r_{DK^*} = 0.103 \pm 0.010$$
$$\delta_{DK^*} = (47^{+14}_{-12})^\circ$$



LHCb γ combination

[LHCb-CONF-2024-004]





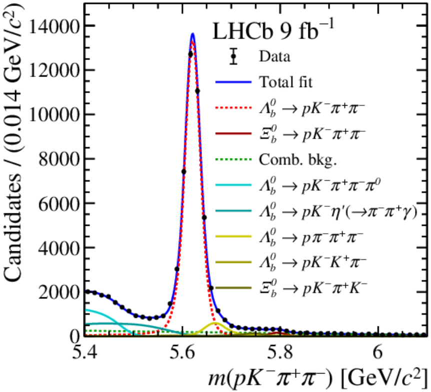
$$\gamma_{\text{LHCb}} = (64.6 \pm 2.8)^{\circ}$$

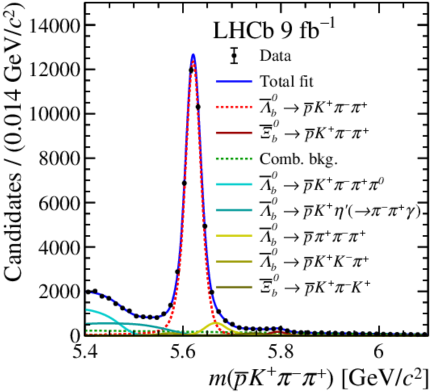
$\gamma_{\text{UTfit}} = (64.9 \pm 1.4)^{\circ}$ [JHEP 10 (2006) 081]

$\gamma_{\text{CKMfitter}} = (66.0^{+0.7}_{-1.9})^{\circ}$ [Eur. Phys. J. C41, 1-131 (2005)]

First observation of CPV in baryons [Nature (2025)]

- CP violation is well established in meson decays
  - Sizeable asymmetries observed in $B \to hh'$ or multibody B decays
  - Changing strong phases around resonances enhances observable CP violation in particular phase-space regions
- CP violation in baryons only observed recently; $\Lambda_b \to pK^-\pi^+\pi^-$





First observation of CPV in baryons [Nature (2025)]

$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

- $5.2\,\sigma$ significance - First observation!

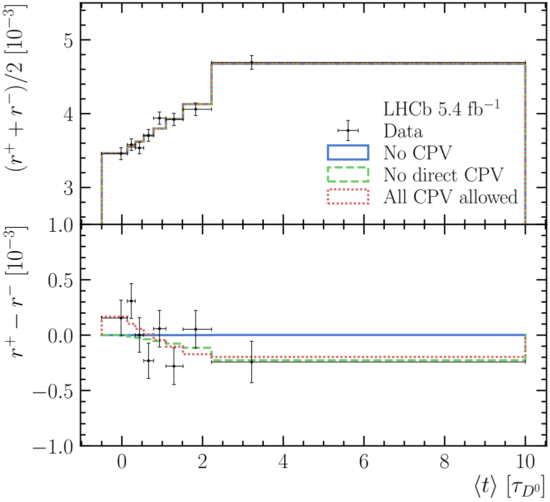
- Split final state into resonance regions for CPV enhancement
  - $N^{*+} \to p\pi^+\pi^-$, $N^{*0} \to p\pi^-$
  - $\Lambda \to pK^-$
  - $K^{*-} \to K^-\pi^+\pi^-$, $\overline{K}^{*0} \to K^-\pi^+$, $\rho \to \pi^+\pi^-$

Decay topology	Mass region (GeV/c^2)	A_{CP}
$\Lambda_b \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

CPV in charm

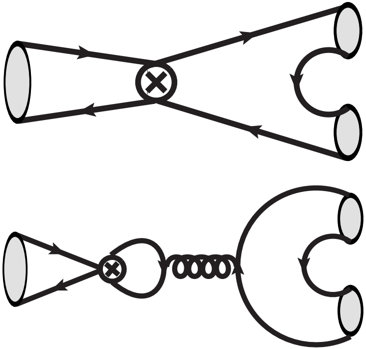
[JHEP 03 (2025) 149]

- Direct *CP* violation in charm well established
  - ΔA_{CP} non-zero with $> 5\,\sigma$ [PRL 122 (2019) 211803]
  - 3.8σ evidence in a single channel ($D^0 \to \pi^+\pi^-$) [PRL 131 (2023) 091802] [LHCb-CONF-2024-004]
- Search for *CP*-violation in mixing with "double-tagged" wrong-sign decays
  - $B \to D^{*+}\mu^-\overline{\nu}_\mu X$, $D^{*+} \to D^0\pi^+$, $D^0 \to K\pi$
  - Measure time-dependent ratio of $D^0 \to K^+\pi^-$ / $D^0 \to K^-\pi^+$

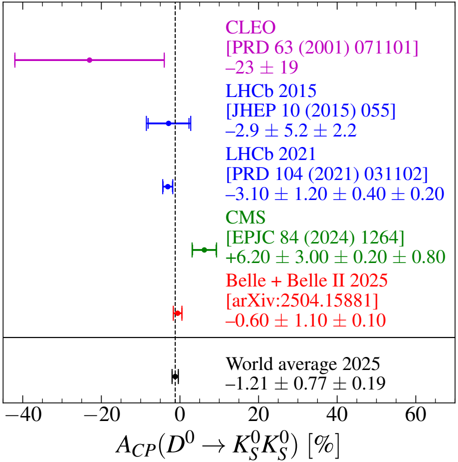


No evidence for *CP*-violation in mixing or $D \to K\pi$ decay

CPV in charm: $D^0 \to K^0_S K^0_S$



CharmFitter - [JHEP 03 (2022) 162]



- Branching fraction is small: $(1.41 \pm 0.05) \times 10^{-4}$ [PDG]
- SM *CP* violation $A_{CP} <\sim 1\%$ [PRD 92 (2015) 054036][PRD 111 (2025) 035023]

CPV in charm: $D^0 \to K_S^0 K_S^0$

LHCB-PAPER-2025-036
(in preparation)

Previous LHCb effort with Run 2 data ($6\,\mathrm{fb}^{-1}$): [PRD 104 (2021) L031102]

$$A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

New update with 2024 data set: $6.2\,\mathrm{fb}^{-1}$

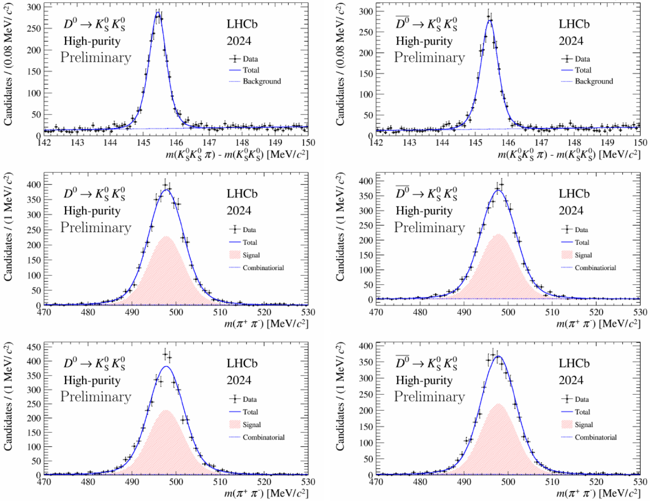
- Analyse “easiest” K_S^0 candidates decaying in VELO
  - Best mass resolution
  - K_S^0 decaying downstream will be included in follow up analysis
- Improved online selection:
  - Previously required energy in CALO and some basic track features
  - Now we reconstruct the event online $\to$ select K_S^0 candidates in the initial selection stage!

CPV in charm

LHCB-PAPER-2025-036 (in preparation)

Method:

- Tag D^0 flavour with $D^{*+} \to D^0\pi^+$
- Multivariate analysis for bkg suppression → split data into two purity bins
- 3D fit of $\Delta m = m(K^0_S K^0_S \pi^+) - m(K^0_S K^0_S)$; $m(\pi^+\pi^-)_1$; $m(\pi^+\pi^-)_2$ to extract signal yields
- Use similar $D^0 \to K^0_S \pi^+\pi^-$ control mode to correct production and detection asymmetries



CPV in charm

LHCB-PAPER-2025-036 (in preparation)

Data block	Yield	$\mathcal{A}^{CP}$ [%]
1	2915 ± 85	0.3 ± 2.4
2	1385 ± 55	-0.3 ± 3.4
3	1639 ± 56	0.8 ± 3.2
4	1534 ± 75	5.5 ± 3.4
5	3149 ± 94	0.0 ± 2.4
6	2544 ± 77	4.6 ± 2.6
7	1599 ± 67	1.7 ± 3.3
8	911 ± 54	5.6 ± 4.3

- Total signal yield: $15,676 \pm 229$
- Compare to 8,102 from full Run 2 data
  - Of which 5,444 match the requirements of this analysis (decay in VELO, originate in PV)
- **Record luminosity quicker in Run 3**
- **Record more signal per fb^{-1}**

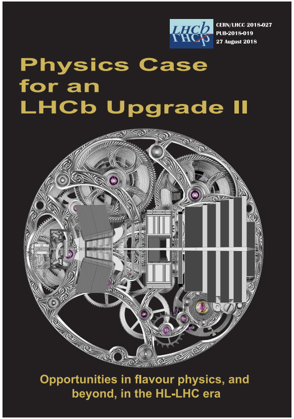
$$A_{CP}(D^0 \to K^0_{\mathrm{S}} K^0_{\mathrm{S}})_{\mathrm{LHCb\,2025}} = (1.86 \pm 1.04 \pm 0.38)\%$$

Upgrade II

$\mathcal{L}^{\mathrm{U1}} \sim 2 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \rightarrow \mathcal{L}^{\mathrm{U2}} \sim 1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

- For installation in LS4 (2034-2035)
  - Take advantage of HL-LHC
- Aiming for $\int \mathcal{L} \sim 300\,\mathrm{fb}^{-1}$
  - Reminder from Upgrade 1: $\int \mathcal{L} \sim 50\,\mathrm{fb}^{-1}$
- New detector technologies required
  - High granularity, radiation hard
  - Timing
  - TDRs due in 2026

[LHCb-PUB-2018-027]



[LHCb-TDR-026]
[LHCb-TDR-023]

Events to expect

From [RevModPhys 94 (2022) 015003](based on [PTEP 12 (2019) 123C01], [EPJC 74 (2014) 3026], [LHCb-PUB-2019-001])

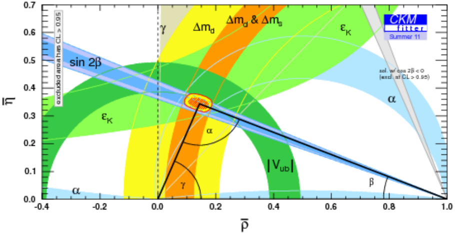
Experiment	*BABAR*	Belle	Belle II	LHCb			
				Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2008	2010	2031	2012	2018	2031	2041
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times 10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(40/4)\times 10^3$	3	6	40	300
B^0 mesons [10^9]	0.47	0.77	40	100	350	2,500	19,000
B^+ mesons [10^9]	0.47	0.77	40	100	350	2,500	19,000
B_s mesons [10^9]	-	0.01	0.5	24	84	610	4,600
Λ_b baryons [10^9]	-	-	-	51	180	1,300	9,800
B_c mesons [10^9]	-	-	-	0.8	4.4	19	150

Large samples of all hadron species

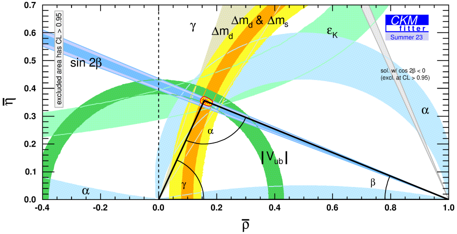
What it means - unitarity triangle

[EPJC 41 (2005) 1]
[LHCb-PUB-2018-027]

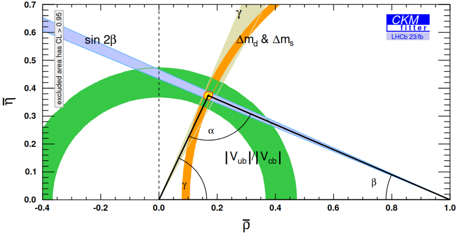
2011



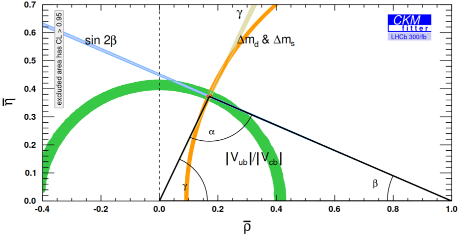
2023



Run 3 (LHCb only)



Run 5 (LHCb only)



Charm physics

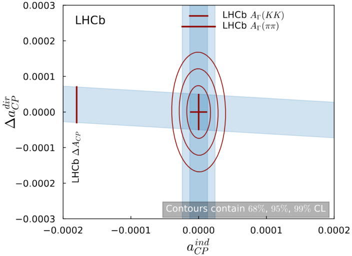
[LHCb-PUB-2018-027]

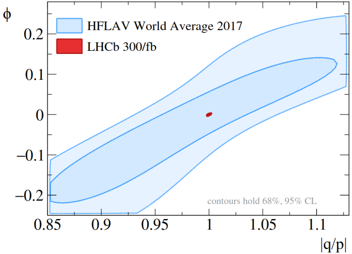
Enormous $D^{*+} \to D^0\pi^+$ tagged charm yields. i.e for time-dependent CP-violation A_Γ:

Table 6.4: Extrapolated signal yields, and statistical precision on indirect CP violation from A_Γ.

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

$\mathcal{O}(10^{-5})$ precision, testing the SM





Conclusion

- LHCb is in the midst of Run 3 data taking
  - The detector and data acquisition is in excellent shape, with an abundant harvest
  - The first physics analyses of Run 3 are appearing
- Run 1+2 analyses are being finalised
  - Some high profile results still expected
- The second upgrade is already being planned
  - Significant technical challenges - design choices being made
  - Expect that systematics will continue to be controlled
  - **Fully exploit the statistical power of HL-LHC for flavour**

The End