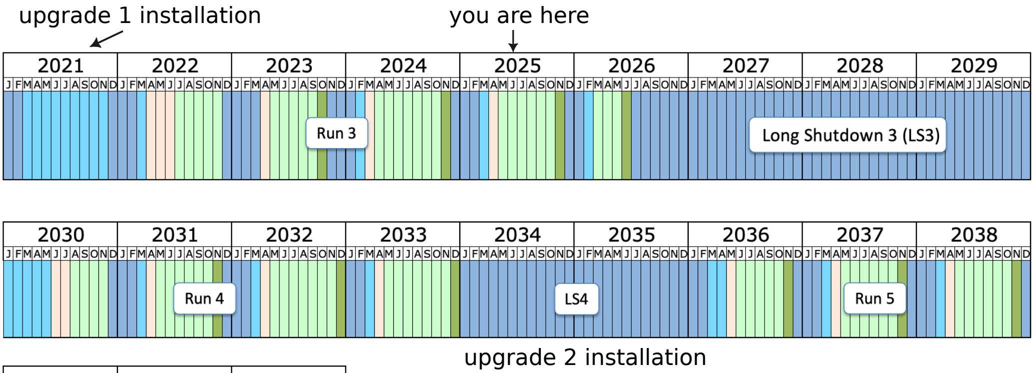
Flavour physics at LHCb: status and future prospects

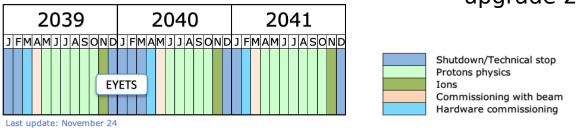
MITP: Flavour for new physics at present and future colliders

Mark Smith, on behalf of the LHCb collaboration

17 June 2025

Status and plans

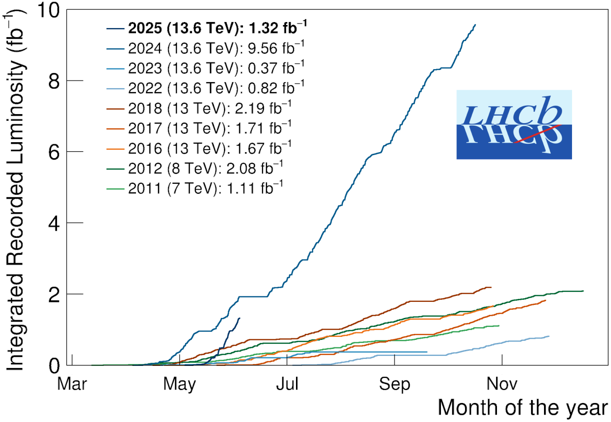




LHCb v1:

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

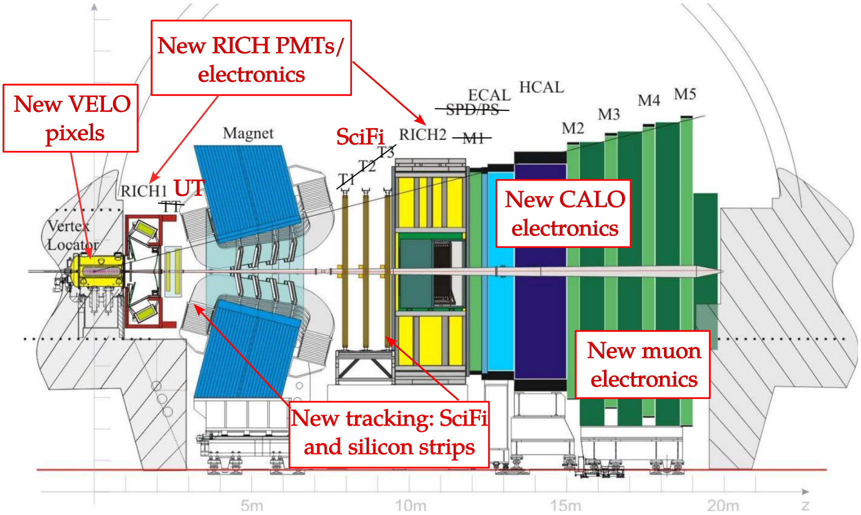
Status



- $3\,\mathrm{fb}^{-1}$ at $7/8\,\mathrm{TeV}$ in Run 1
- $6\,\mathrm{fb}^{-1}$ at $13\,\mathrm{TeV}$ in Run 2
  - b-hadron cross-section roughly doubled
- Aiming for $\int\mathcal{L}\sim 50\,\mathrm{fb}^{-1}$ by end of Run 4
  - Collected entire Run 1+2 data set again in 2024

Upgrade 1

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



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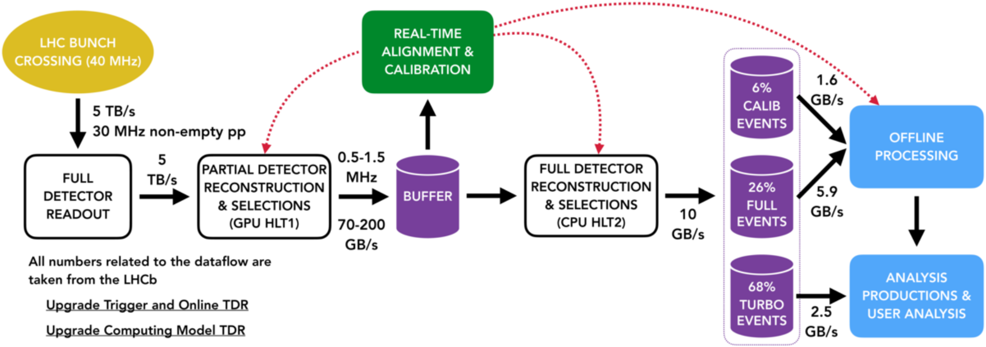
- Trigger changes:
  - Removed L0 hardware trigger
  - Upgrades to software triggers HLT1 (GPU) and HLT2.

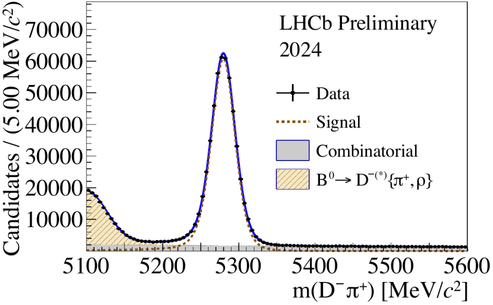


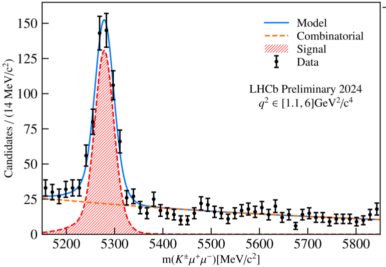
Upgrade 1

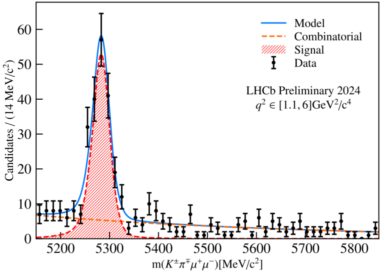
[LHCb-FIGURE-2024-022]
[LHCb-FIGURE-2024-021]

Excellent performance in 2024:

- Good momentum resolution $\rightarrow$ invariant mass resolution
- Low background rates





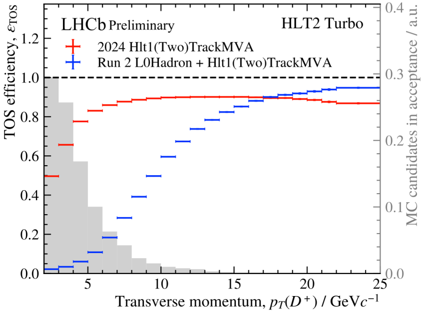


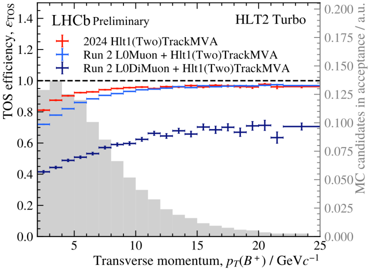
Upgrade 1

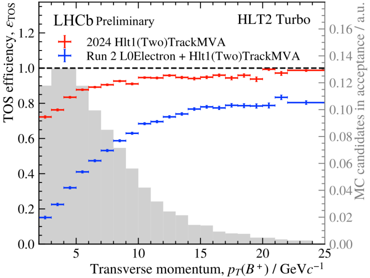
[LHCb-FIGURE-2024-030]

Clear benefit from L0 removal:

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





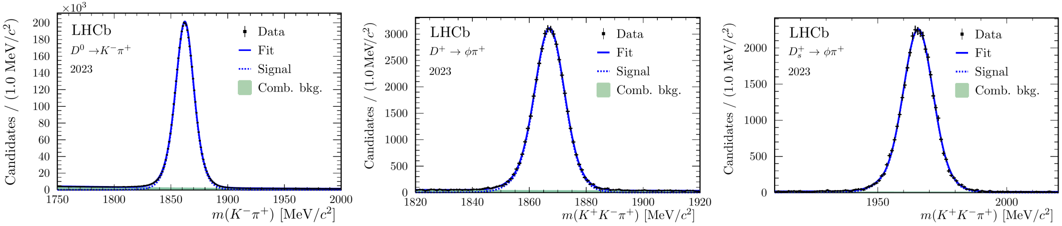


First Run 3 analysis

[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



First Run 3 analysis

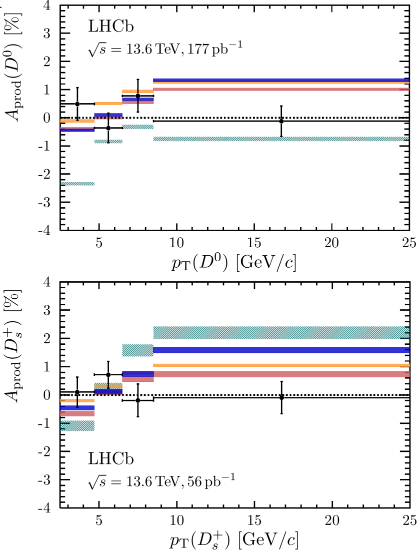
[arXiv:2505.14494]

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:

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



Physics programme

The LHCb physics programme is diverse:

- Production and spectroscopy
- Ions and fixed target
- Electroweak
- Tree-level semileptonic decays
- Rare penguin decays (electroweak and gluonic)
- “Very-rare” decays
- Charm
- CPV and CKM
- and more ...

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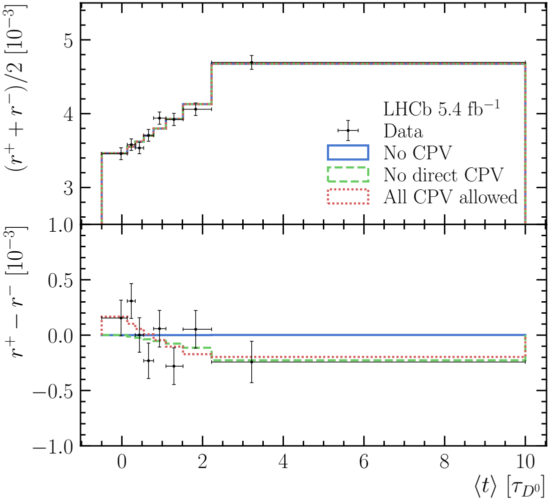
Charm mixing and *CP* violation

[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 $D^0 \to K^+\pi^-$ / $D^0 \to K^-\pi^+$



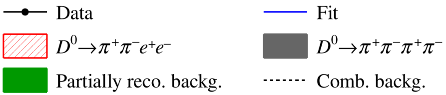
No evidence for *CP*-violation in mixing or $D \to K\pi$ decay

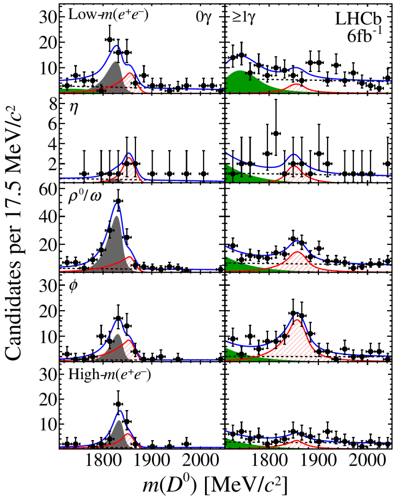
Charm rare decays

[PRD 111 (2025) L091101]

Study the $c \to u$ FCNC decays

- $D^0 \to h^+ h^- e^+ e^-$
  - $6\,\text{fb}^{-1}$ Run 2 data
  - Search for $\pi^+\pi^-$ and K^+K^- final states in bins of $m(e^+e^-)$
  - First observation of $D^0 \to \pi^+\pi^- e^+ e^-$, no sign of $D^0 \to K^+K^- e^+ e^-$
  - Consistent with corresponding muon decays and LFU



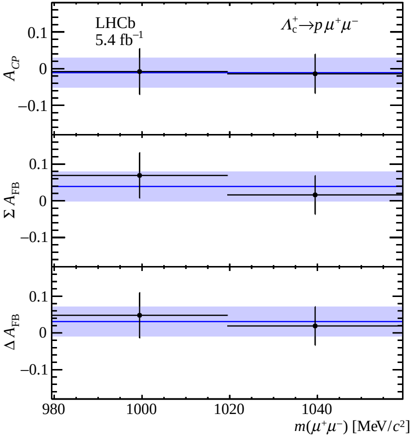


Charm rare decays

[PRD 111 (2025) L091102]

Study the $c \to u$ FCNC decays

- CP-violation in $\Lambda_c^+ \to p\mu^+\mu^-$
  - 5.4 fb^{-1} of Run 2 data
  - Look for direct CP violation in region of $m(\mu^+\mu^-)$ around the ϕ
  - Hope the interference of LD resonance, and SD enhances observable CPV
  - No CP-violation found

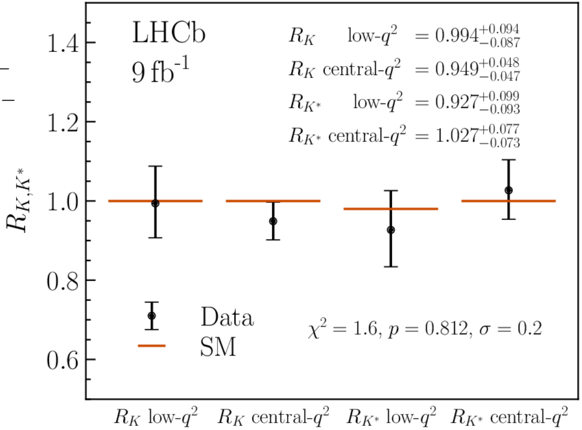


Rare decays - LFU

[PRL 131 (2023) 051803]
[PRD 108 (2023) 032002]

$$R_X = \frac{\frac{d\mathcal{B}}{dq^2}(H_b \to X\mu^+\mu^-)}{\frac{d\mathcal{B}}{dq^2}(H_b \to Xe^+e^-)}$$

R_K : $B^+ \to K^+\ell^+\ell^-$
R_{K^*} : $B^0 \to K^{*0}\ell^+\ell^-$



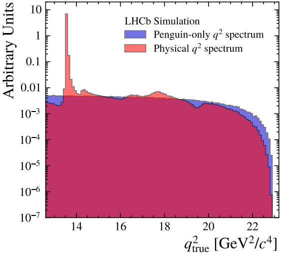
Rare decays - LFU

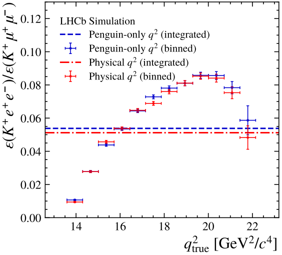
[arXiv:2505.03483]

Measure R_K at $q^2 > 14.3\,\mathrm{GeV}^2$, $9\,\mathrm{fb}^{-1}$, Run 1+2

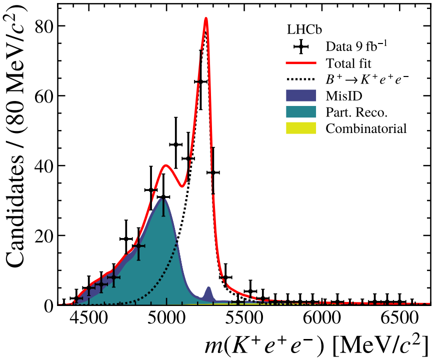
- Challenges of electron reconstruction and truncated phase-space
- Many wide $c\bar{c}$ resonances at high q^2
  - Weight the μ mode data to match the selection efficiencies as a function of q^2_{true}

$$R_K(q^2 > 14.3\,\mathrm{GeV}^2) = 1.079^{+0.106+0.044}_{-0.092-0.040}$$





R_K : $B^+ \to K^+\ell^+\ell^-$

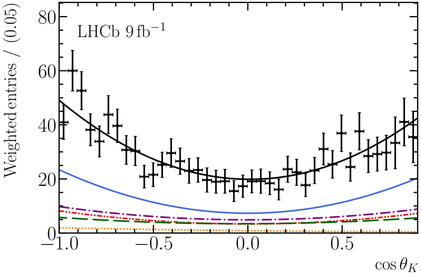


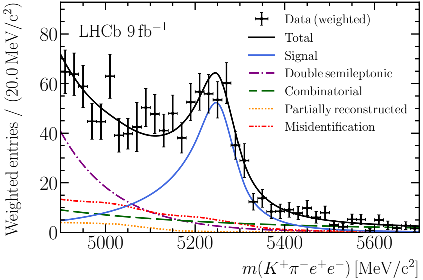
Rare decays - e^+e^- angular analysis

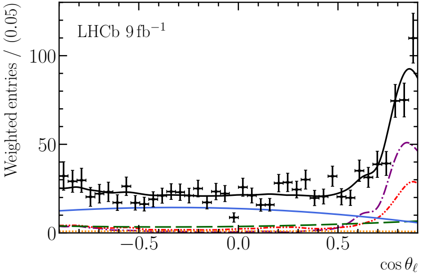
[arXiv:2502.10291]

Angular analysis of $B^0 \to K^{*0}e^+e^-$

- $9\,\text{fb}^{-1}$ Run 1+2 data set
- One region $1.1 < q^2 < 6\,\text{GeV}^2$
- Access to the angular Q_i observables
  - Difference between e^+e^- and $\mu^+\mu^-$



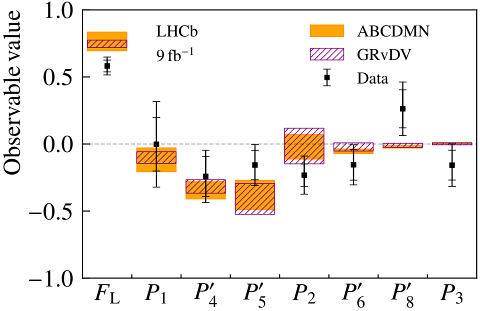


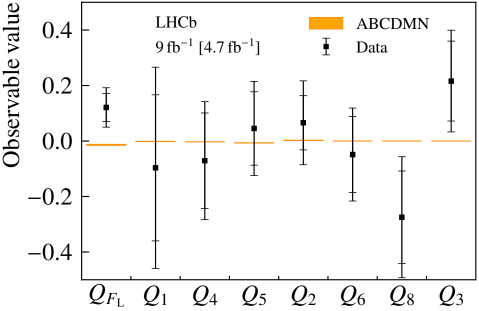


Rare decays - e^+e^- angular analysis [arXiv:2502.10291]

Angular analysis of $B^0 \to K^{*0}e^+e^-$

- Q_i observables consistent with zero
    - Muon and electron modes compatible
- Electron mode results compatible with SM

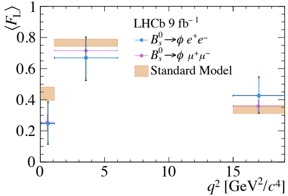




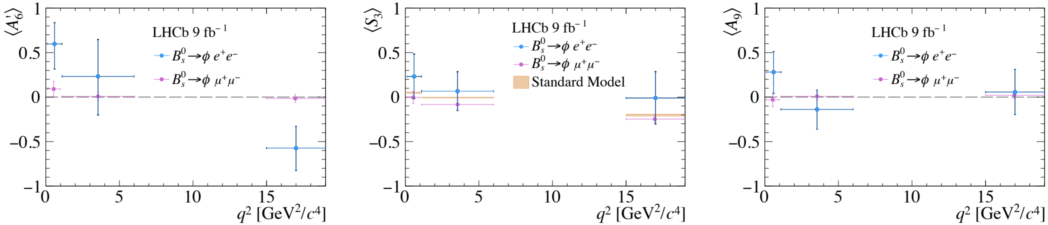
Rare decays - e^+e^- angular analysis [arXiv:2504.06346]

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

- $9\,\text{fb}^{-1}$ Run 1+2 data set
- No flavour tagging - CP-averaged and time-integrated
- Limited stats - fit 1D angular distributions
  - Reduced set of observables



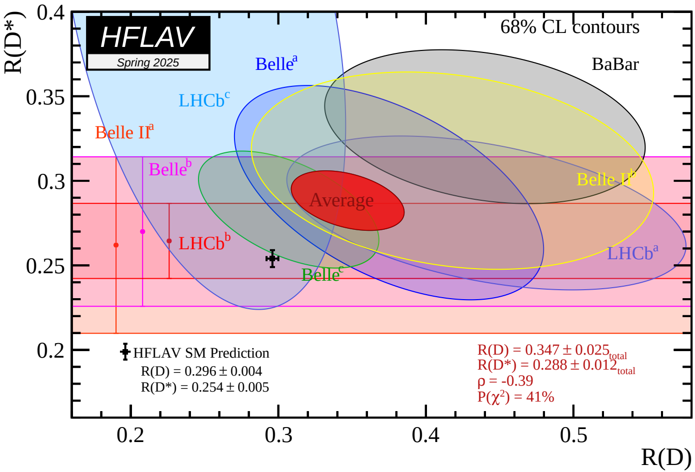
- Consistent with muon mode and SM



SL - the LFU anomaly that lived

[arXiv:2411.18639]

$$R(X) = \frac{\mathcal{B}(H_b \to X\tau\nu)}{\mathcal{B}(H_b \to X\mu\nu)}$$

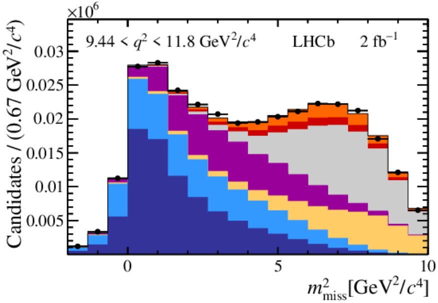


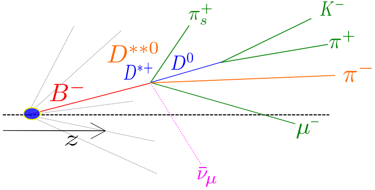
$R(D^+) - R(D^{*+})$ [PRL 134 (2025) 061801]

Similarities with $R(D^0) - R(D^*)$ analysis (Run 1, $3\,\text{fb}^{-1}$) [PRL 131 (2023) 111802]

- $2\,\text{fb}^{-1}$ of 2015+2016 13 TeV data
- $\tau \to \mu\nu\nu$ final state
  - Same signal and normalisation
- Do not reconstruct $D^{*+} \to D^+\pi^0$
- Extract signal yield via a 3D template fit of:
  - $m^2_{\text{miss}} = (P_B - P_{D^+} - P_\mu)^2$
  - E^2_μ - μ energy in the B rest frame
  - $q^2 = (P_B - P_{D^+})^2$
- Estimate the B momentum

$$p_z(B) \approx p_z^{\text{vis}} \frac{m_B^{\text{PDG}}}{m_B^{\text{vis}}}$$





$R(D^{+}) - R(D^{*+})$ **[PRL 134 (2025) 061801]**

What is new?

- Fast simulation - "tracker only"
  - Do not simulate RICH photons, CALO showers, muon stations
  - Factor 8 speed up in production, 40% reduction in disk usage
  - Must emulate the trigger response
  - PID treatments already well established in LHCb [LHCb-PUB-2016-021]
- Form-factor weighting
  - Form-factor variations allowed for by the HAMMER tool [EPJC 80 (2020) 883]
  - Variations incorporated into the fit minimisation - [JINST 17 (2022) T04006]
    - Constrain BGL parameters for $B \to D^{*+}$ and $B \to D^{+}$ [EPJC 82 (2022) 1141][PRD 94 (2016) 094008]
    - Constrain principle background, $B \to D^{**}$ FFs too [PRD 95 (2017) 014022]
  - Nevertheless the FFs are among the dominant uncertainties - not much discrimination from the data

$R(D^+) - R(D^{*+})$

[PRL 134 (2025) 061801]

Table 1: Summary of systematic uncertainties on the $R(D^+)$ and $R(D^{*+})$ measurements. Systematic uncertainties associated with the efficiency are not shown as they are negligible.

Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

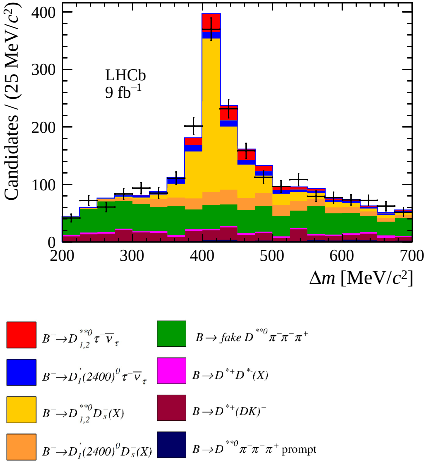
$B \to D^{**}\tau\nu$

[arXiv:2501.14943]

First evidence of $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$ at 3.5 σ

- All LHCb Run 1+2 data
- Hadronic $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays
  - A reconstructible τ^+ decay vertex
  - Background suppression
  - Exclusively select τ^+ decays
- Extract signal with a 3D template fit:
  - Double-charm BDT score
  - q^2
  - $\Delta m = m(D^{*+}\pi^-) - m(D^{*+})$

$$R(D^{**0}_{1,2}) = 0.13 \pm 0.03(\mathrm{stat}) \pm 0.01(\mathrm{syst}) \pm 0.02(\mathrm{ext})$$



SL LFU status summary

LHCb can access all H_b hadrons decaying to various H_c states, with $\tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$ and $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays

Mode	Run 1, $3\,\text{fb}^{-1}$ at $7/8\,\text{TeV}$ muonic	Run 1, $3\,\text{fb}^{-1}$ at $7/8\,\text{TeV}$ hadronic	Run 2, $6\,\text{fb}^{-1}$ at $13\,\text{TeV}$ muonic	Run 2, $6\,\text{fb}^{-1}$ at $13\,\text{TeV}$ hadronic
$R(D)$	✔	✗	2016, $R(D^+)$	✗
$R(D^*)$	✔	✔	2016, $R(D^+)$	✗
$R(D^{**})$	✗	✔	✗	✔
$R(\Lambda_c)$	✗	✔	✗	✗
$R(\Lambda_c^*)$	✗	✗	✗	✗
$R(J/\psi)$	✔	✗	✗	✗
$R(D_s)$	✗	✗	✗	✗
$R(D_s^*)$	✗	✗	✗	✗
$R(\pi)$	✗	✗	✗	✗
$R(\pi\pi)$	✗	✗	✗	✗
$R(p)$	✗	✗	✗	✗
$R(p\bar{p})$	✗	✗	✗	✗

SL analyses are hard

The elephant in the room

"Where is the latest result for my favourite measurement? Why is it taking so long?"

- Seven years later we are *still* analysing Run 2 data
  - This includes some long-overdue "high-profile" results that have the potential to significantly influence the flavour community (i.e. $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis)
- Victims of our success - enormous data sets
  - Just manipulating/processing/fitting data takes time
  - High stats $\to$ small $\sigma_{\rm syst}$. We have to work harder
- We want to improve analyses - more complexity

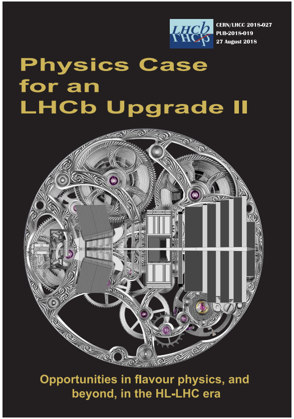
Prospects

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

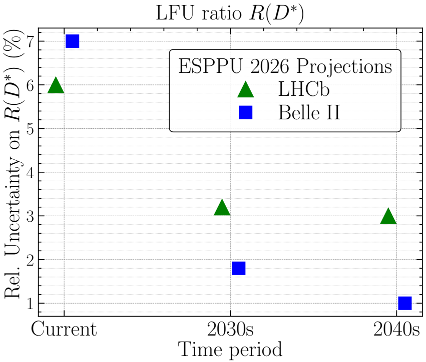
[LHCb-PUB-2018-027]

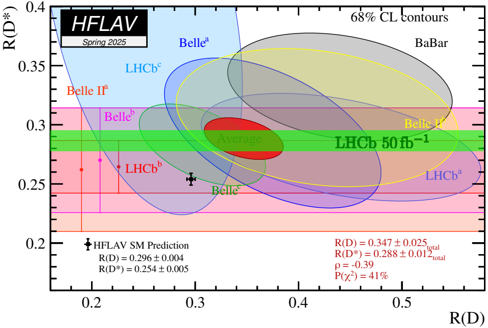


[LHCb-TDR-026]
[LHCb-TDR-023]

Prospects for SL decays

[arXiv:2411.18639]
[arXiv:2503.24346]





Contingent on several factors

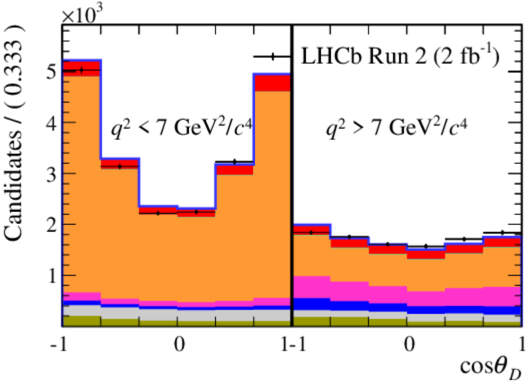
- More precise FF calculations
- Better understanding of $B \to D^{**}$ feed-down background
- Control of experimental uncertainties (large data control samples)
- Producing and refining large samples of simulation

SL angular analyses

LHCb is exploring SL angular analyses:

- Already D^{*+} polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$ [PRD 110 (2024) 092007]
  - Run 1 + 2016, $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$
  - Reconstruct $\cos\theta_D$ in two q^2 regions
  - Competitive precision (compare to Belle [arXiv:1903.03102])

LHCb: $F_L^{D^*} = 0.41 \pm 0.06 \pm 0.03$
Belle: $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$

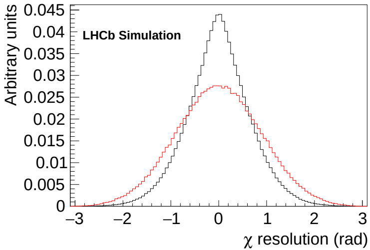


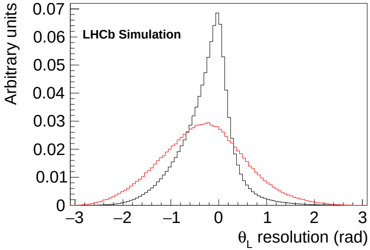
SL angular analyses

[LHCb-PUB-2018-027]

There is scope for more advanced angular analyses:

- Already demonstrated angular reconstruction for $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$
- Possibility for the $\tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$ decays
  - Even with the "B-frame approximation" the angular resolution is not disastrous
  - Black: $B^0 \to D^{*-}\mu^+\nu_\mu$, red: $B^0 \to D^{*-}\tau^+\nu_\tau$
- Incorporating HAMMER into fits allows us to do more
  - Extract the WCs directly [CERN-THESIS-2022-105], Mitreska
  - Initial studies are targeting $B^0 \to D^{*-}\mu^+\nu_\mu$
  - Not so good for model-independence, re-analysis





Events to expect

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

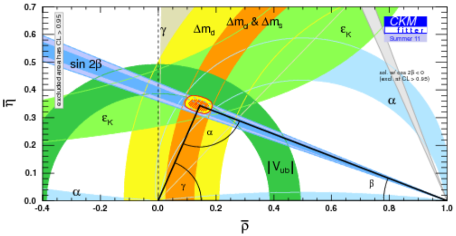
Experiment	*BABAR*	Belle	Belle II	LHCb			
				Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2008	2010	2031	2012	2018	2031	2041
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times10^5$	5.6×10^5	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

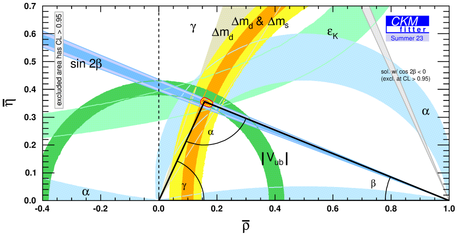
What it means - unitarity triangle

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

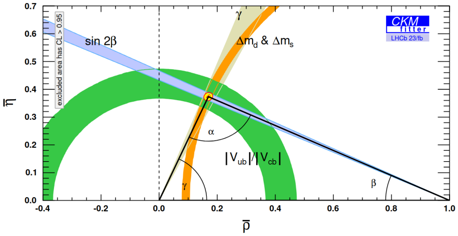
2011



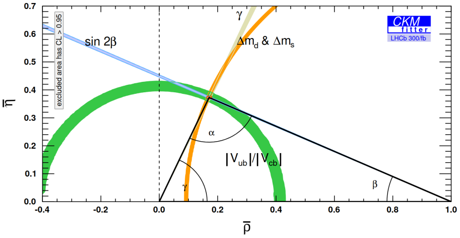
2023



Run 3 (LHCb only)



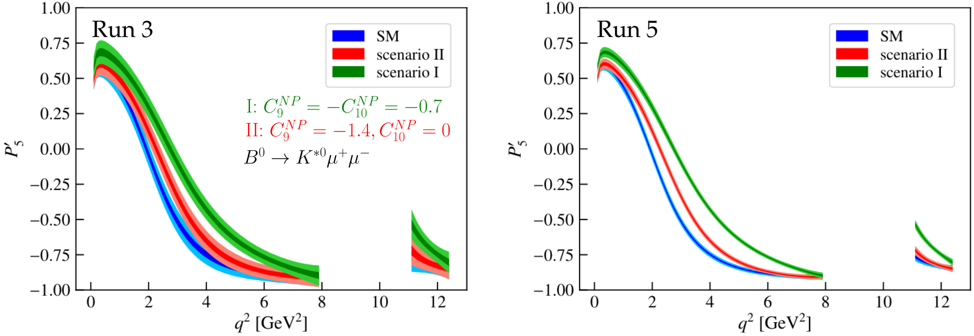
Run 5 (LHCb only)



Electroweak penguins

[LHCb-PUB-2018-027]

- $\sim 400,000$ reconstructed $B^0 \to K^{*0}\mu^+\mu^-$ decays with Upgrade 2
  - Clear separation of SM and NP
  - If $C_{10}^{NP} \neq 0$, discrimination with Run 3
- More data leads to $b \to d$ penguins
  - Possibility of angular analysis of $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$



Charm physics

[LHCb-PUB-2018-027]

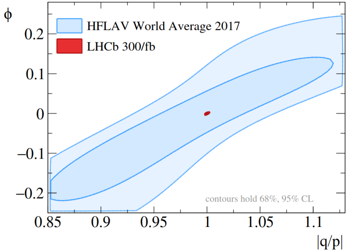
Enormous $D^{*+} \to D^0\pi^+$ tagged charm yields. i.e for time-dependent *CP*-violation A_Γ:

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

- Search for direct *CP* violation in more modes
- High yield means rare decay searches
  - Including LFV modes
  - Angular analyses if possible (i.e. $D^0 \to h^+h^-\mu^+\mu^-$



Open data

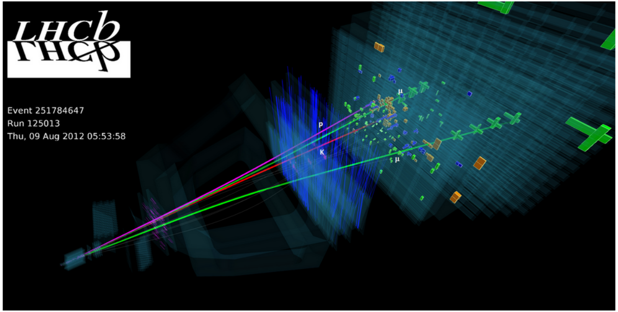
LHCb is releasing its data for your entertainment!

LHCb releases the entire Run I dataset

2023-12-20 by LHCb Collaboration

News

Today the LHCb collaboration completes the release of the data collected throughout the Run I of the Large Hadron Collider at CERN. The sample made available amounts to approximately 800 terabytes (TB) of data. These data, collected by the LHCb experiment in 2011 and 2012, contains information obtained from proton-proton collisions. The format made available provides pre-filtered data, suitable for a wide range of physics studies. The image below displays an event recorded during 2012.

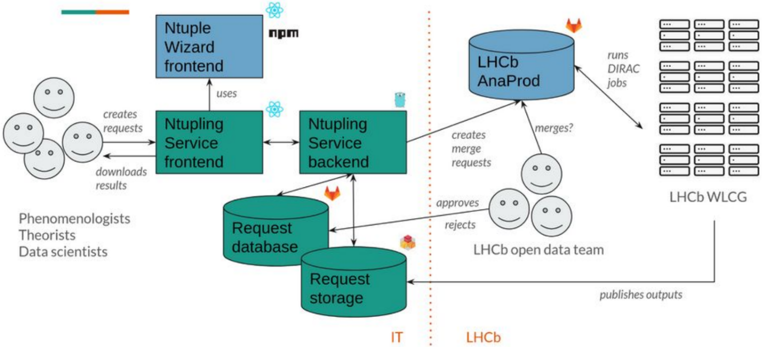


Run 1 is available on the [CERN open data portal]

Open data

Some helpful tools have been created for you:

- The NTupleWizard [CSFBS 7 (2023) 6]
  - Front-end interface for you to specify the data sets and configure the variables you want
- The NTuple service
  - Combines the NTupleWizard with the open data portal and the LHCb data production infrastructure



More information at [First LHCb Open Data and Ntuple Wizard Workshop]

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 analysis of Run 3 has appeared
- 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

Challenge - simulation

Simulation is already a limiting factor for several analyses:

- Analyses of partially reconstructed final states usually use template fits $\rightarrow$ large simulation samples needed
  - i.e. $R(D) - R(D^*)$
- More complex analyses need to map the efficiency in a multidimensional space $\rightarrow$ large simulation samples needed
  - i.e. $B^0 \rightarrow K^{*0}\mu^+\mu^-$ is in 5 dimensions
  - Multibody hadronic final states want efficiency maps over the Dalitz variables
- Solutions afoot!
  - We saw tracker-only used for the first time
    - Now the requisite techniques have been established
  - ReDecay [EPJC 78 (2018) 1009]
    - Simulate an entire event
    - Keep everything the same, except for the signal B - rerun the B decay N times
    - $\sim 10 - 20\times$ speedup
    - Used regularly in LHCb (i.e. [PRD 111 (2025) L091102])
- Parametric simulation [EPJ Web Conf. 295 (2024) 03040]
  - In development