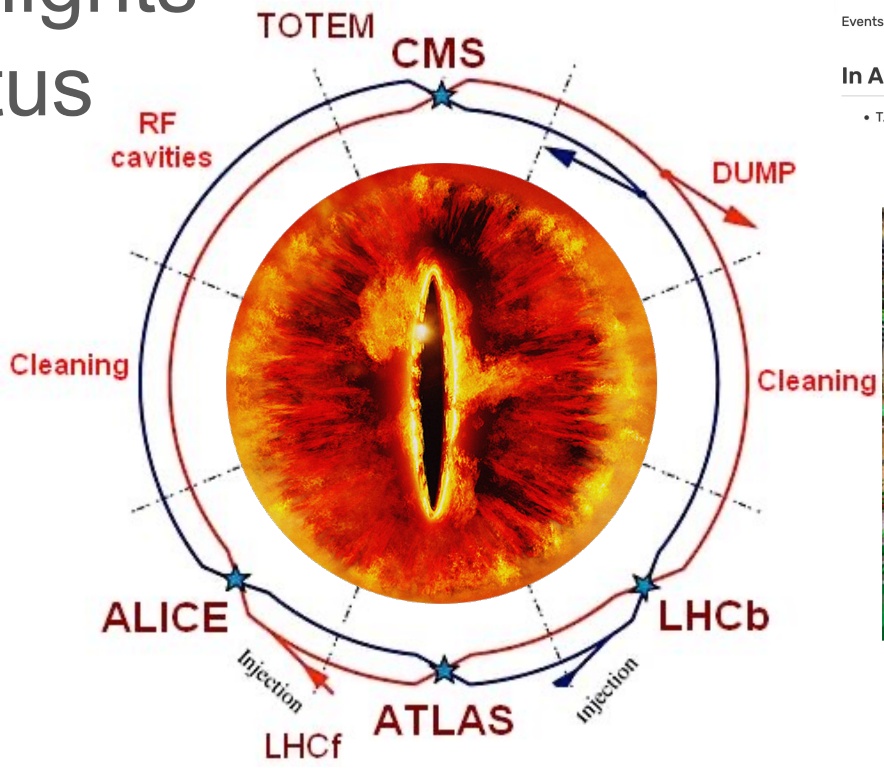
MANCHESTER 1824
The University of Manchester

Original	Upgrade I	Upgrade II
2009-2018	2022-2032	2033-

LHCb - There and Back Again:
My Three Years as an LHC Ring Bearer

- Recent Physics Highlights
- LHCb Upgrade I Status
- LHCb Upgrade II Opportunities



22 November

Events that occurred on 22 November.

In Arda

- T.A. 3018:
  - Frodo and Samwise rest in Rivendell and prepare for their quest to destroy The One Ring.

22nd November

UNIVERSITY OF LIVERPOOL
Chris Parkes

2020-2023: Three special years…

With its challenges….

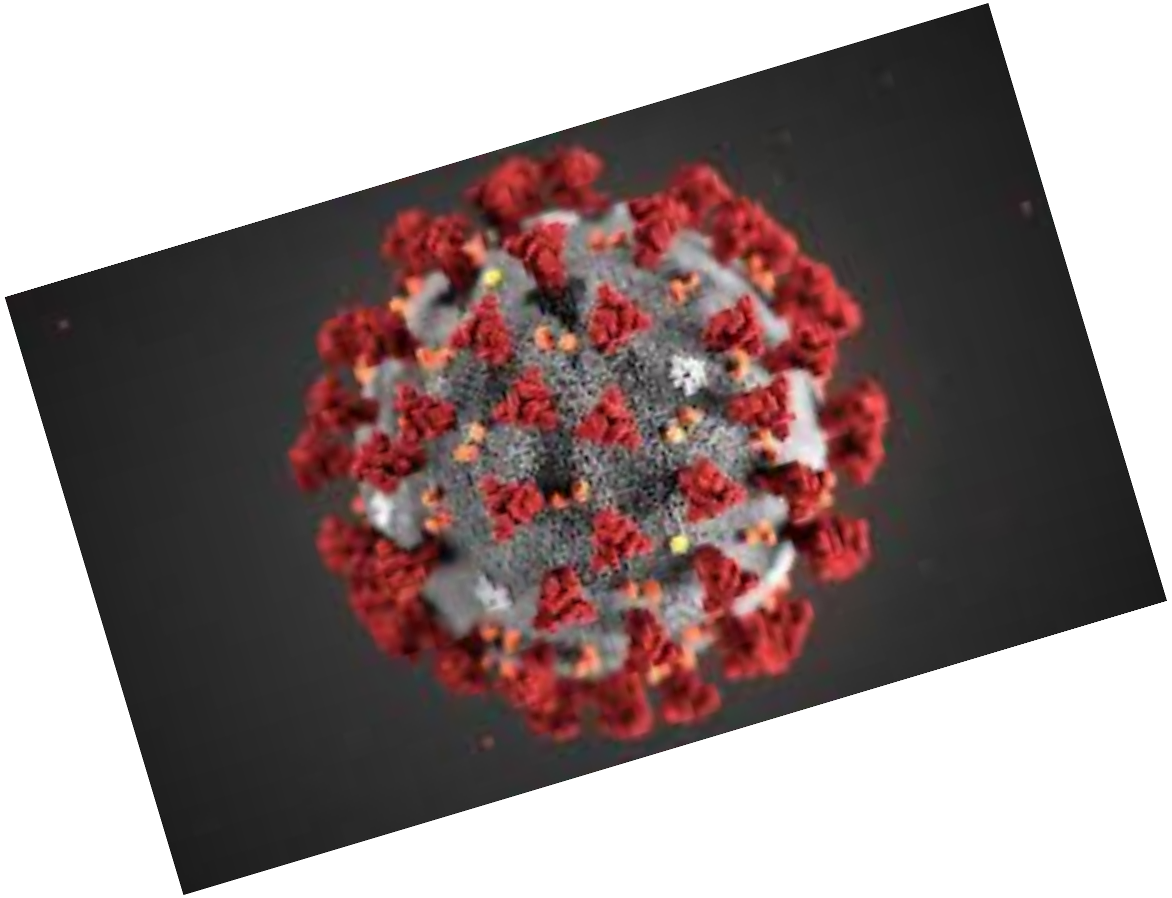
LHCb Upgrade

- 5 major new detector systems to install
- New electronics for all 7 major systems
- New software-only trigger system

Most major CERN detector project since start of LHC

2020-2023: Three special years…

With its challenges….



Started in covid lockdown of 2020:

- Daily crisis meetings

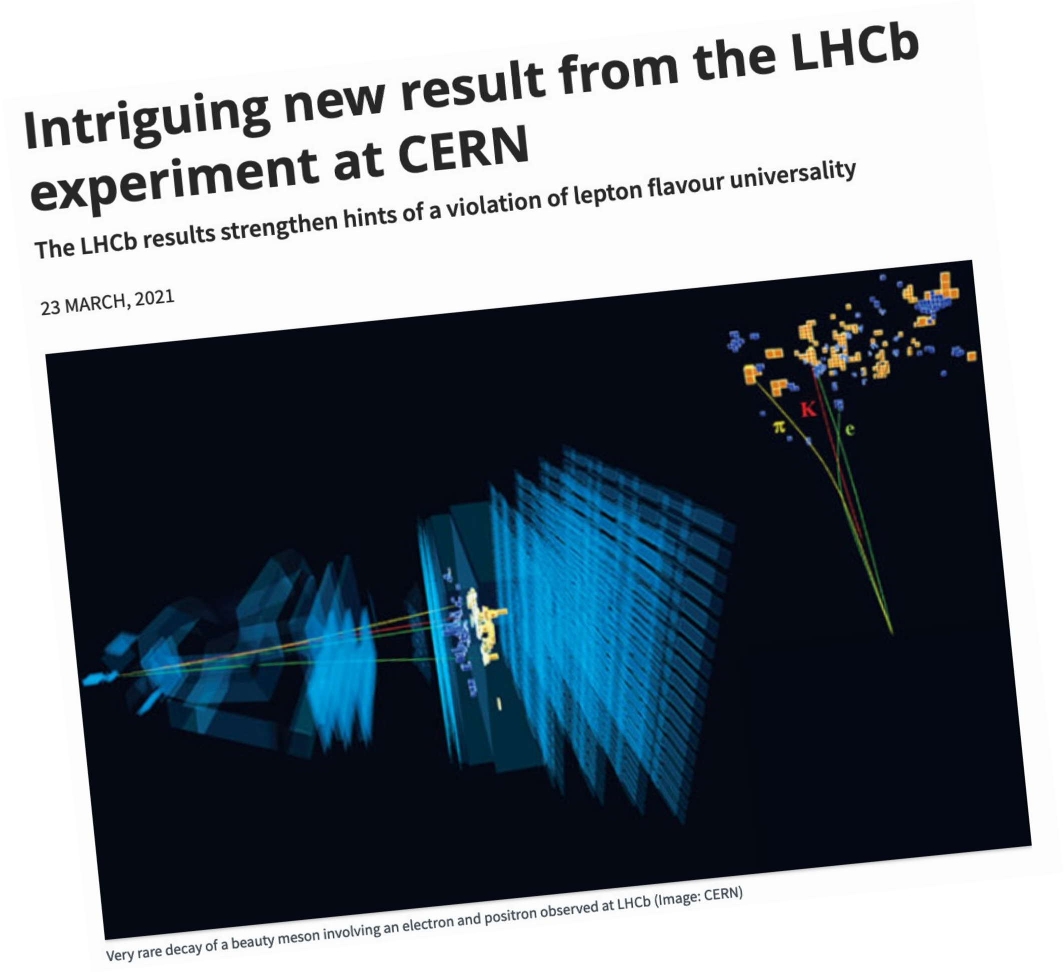
Personal tragedies of collaborators

Throughout two years:

- Logistics of construction, transport & installation of new experiment across 20 countries

2020-2023: Three special years…

With its challenges….



Intriguing pattern of "B anomalies" over past decade (and g-2 muon)
- attempts to create a coherent theoretical picture

March 2021 LHCb result (R_K) at 3.1σ from SM

December 2022 LHCb results ($R_{K,}$ $R_{K^*,}$ 4 bins q^2) compatible with SM

2020-2023: Three special years…

With its challenges….

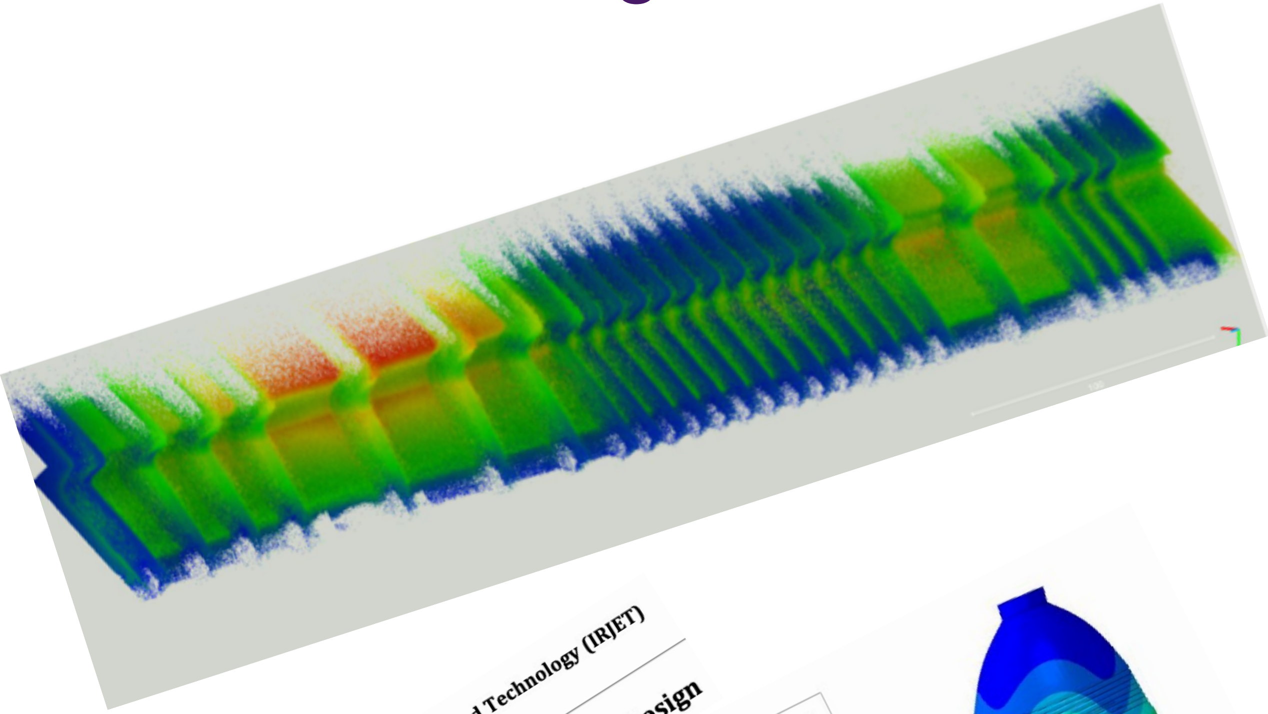
LHCb Collaboration

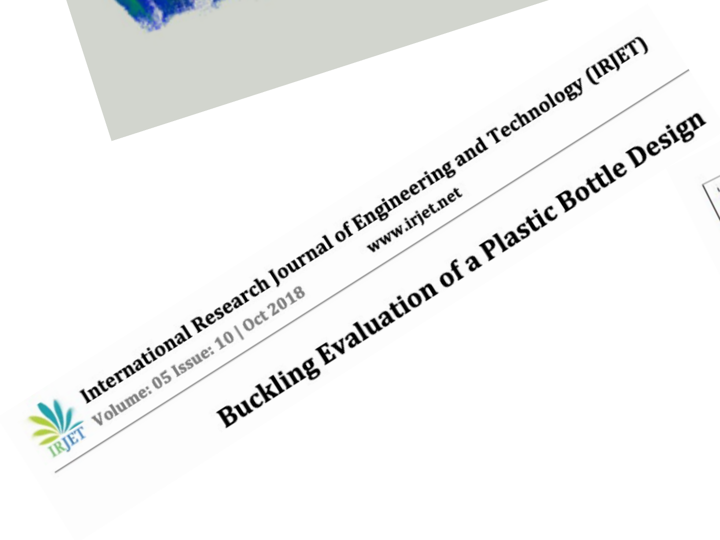
- Four institutes in Ukraine
    - Three damaged by Russian bombs
    - Members sheltering in underground stations, family members killed
    - Males under 65 unable to leave country
    - Major responsibilities for luminometer and radiation monitoring system
- Eleven institutes in Russia (10% collaboration)
    - Many colleagues openly against the war
    - Difficult decisions whether to return to family or move / stay outside Russia
    - Major responsibilities for calorimeters and muon systems

- Paper publication suspended for 1 year to reach author list agreement
    - Results continued to be released on arXiv

2020-2023: Three special years…

With its challenges….





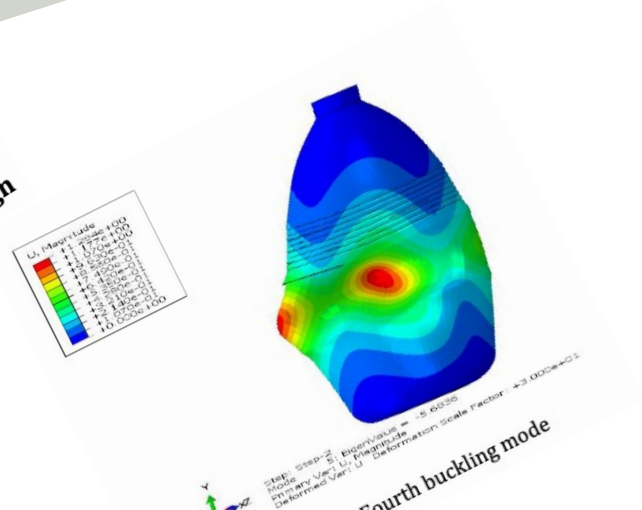


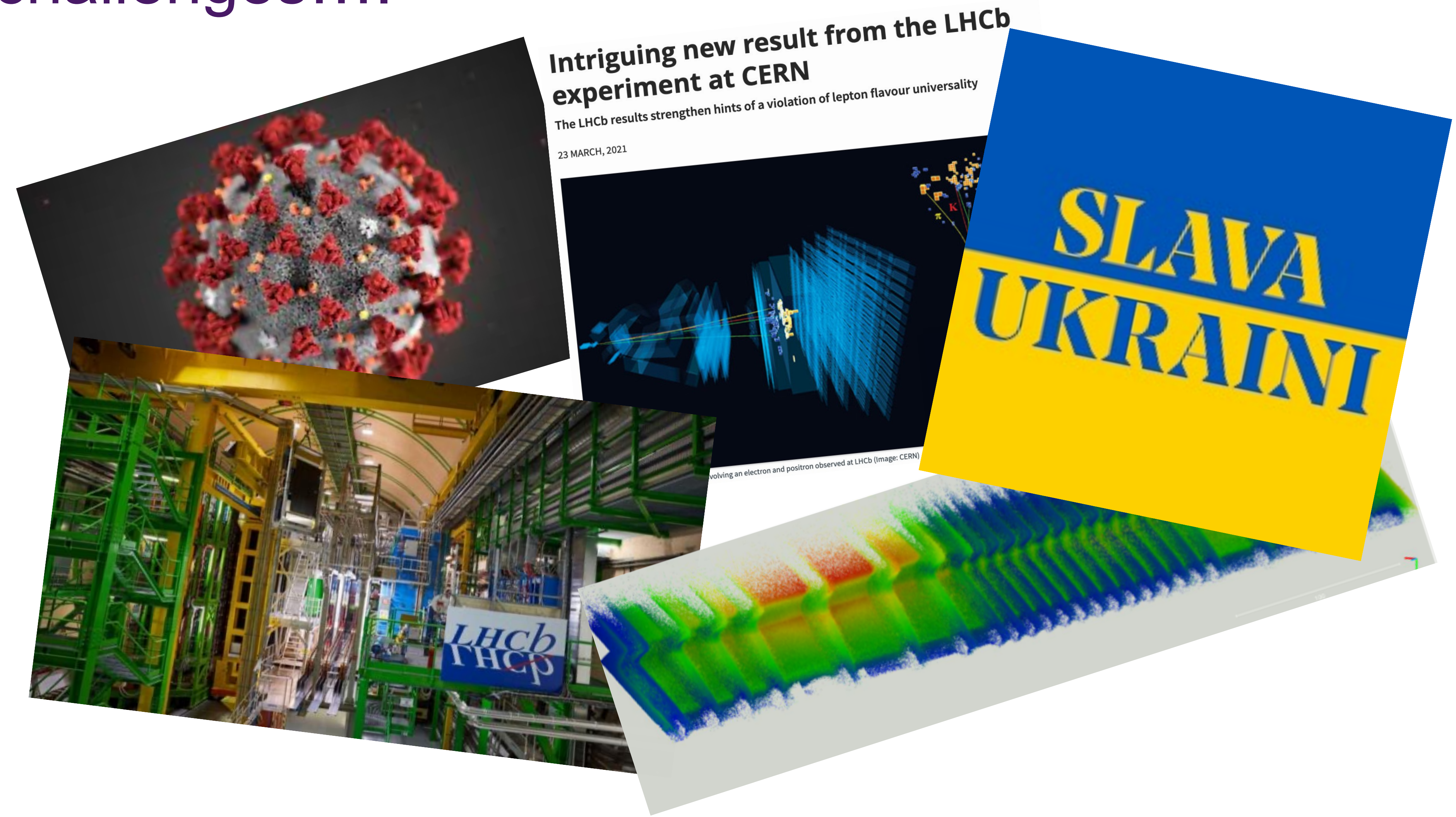
Fig-10: Fourth buckling mode

January 2023

- Malfunction of LHC vacuum safety system
- Primary LHC vacuum and vertex detector modules separated by thin foil
- 200mbar pressure differential across 250µm of aluminum
  - 400kg, thickness of a few sheets of paper

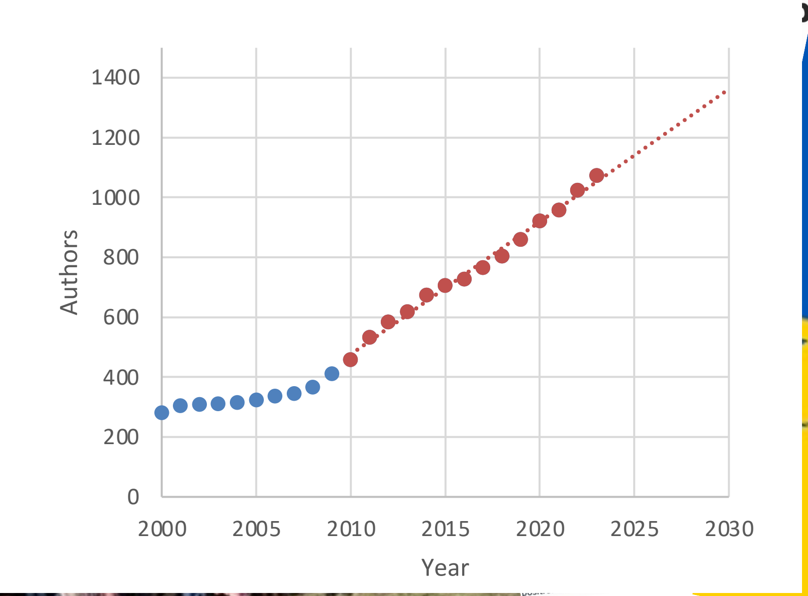
2020-2023: Three special years…

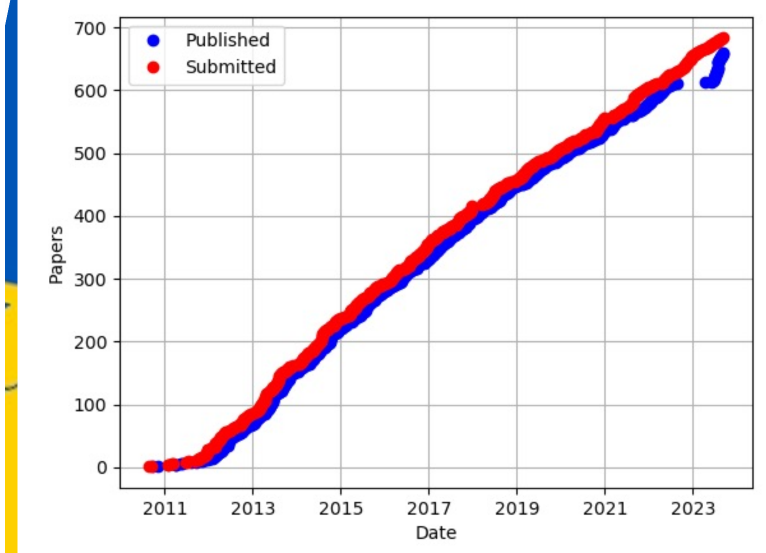
With its challenges….



2020-2023: Three special years…

And its successes….

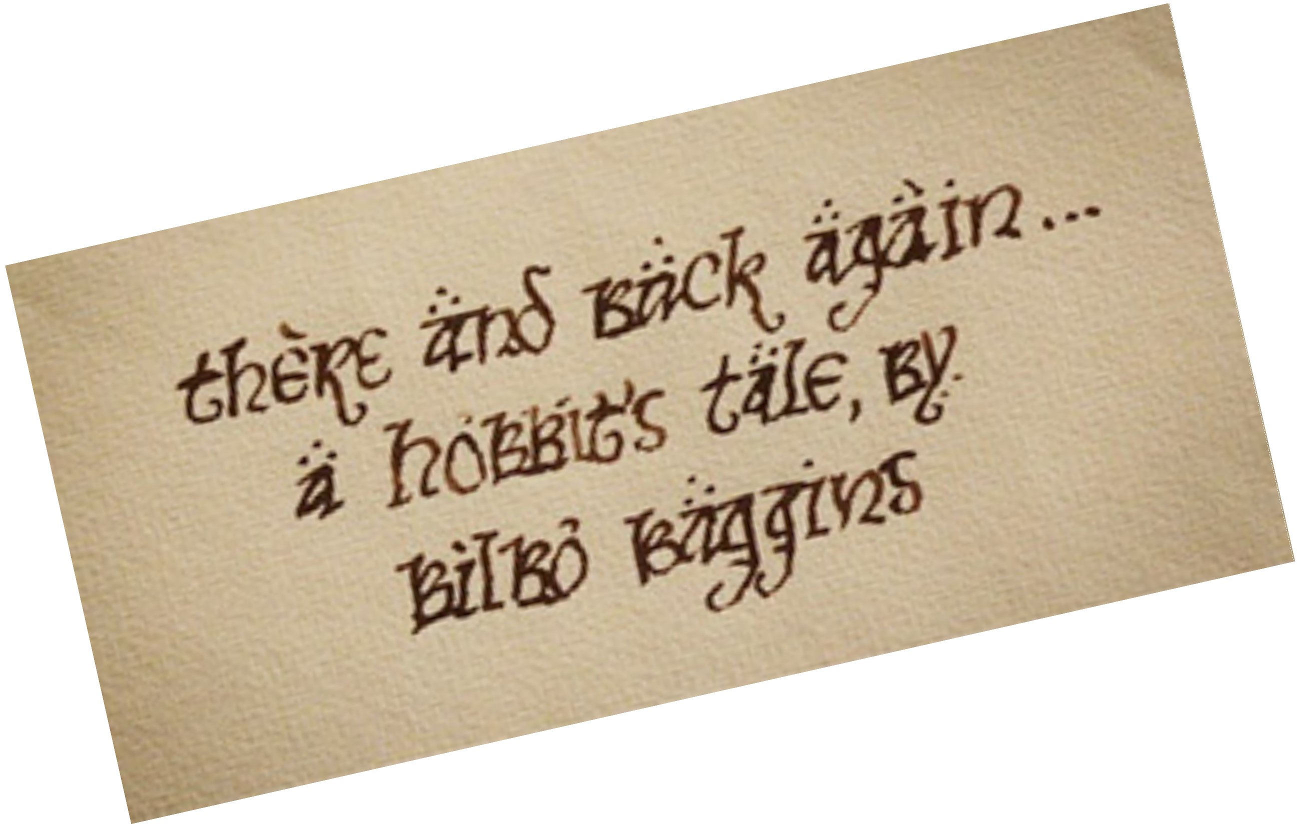




1100 authors, 98 institutes, 22 countries

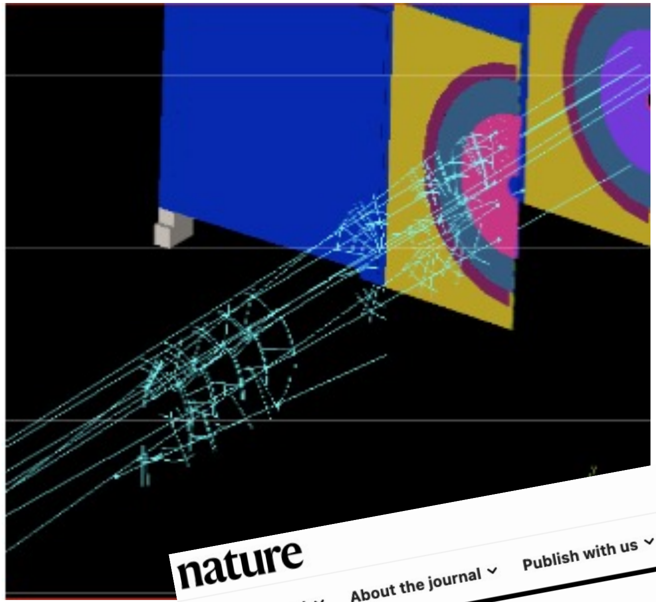
697 submitted papers

LHCb Original – LHC Run 1&2



Original

2009-2018

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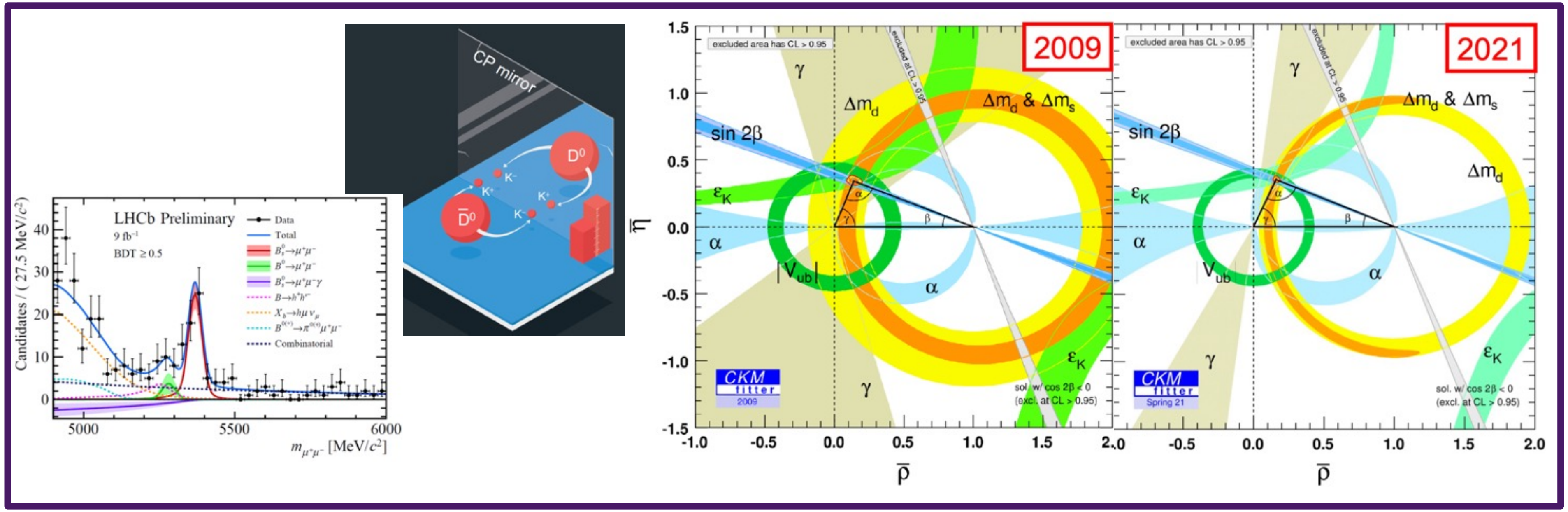
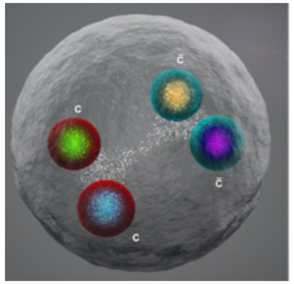
Published: 25 August 2008
Double first for Large Hadron Collider
Matthew Chalmers
Nature (2008) | Cite this article

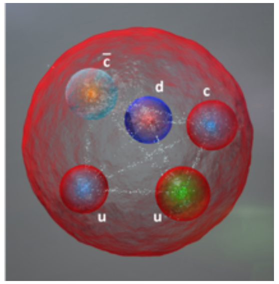
Celebrating “LHCb-original"!

LHCb was originally designed for CP violation and b & c-hadron rare decays…



… but it achieved much more: exotic spectroscopy, heavy ions, fixed target programme, EW precision physics, dark sector searches…





Today recent results on

CP violation in B decays and D^0 mixing, Lepton Flavour Universality, Spectroscopy, breadth of programme

Sin(2β) – full LHCb data

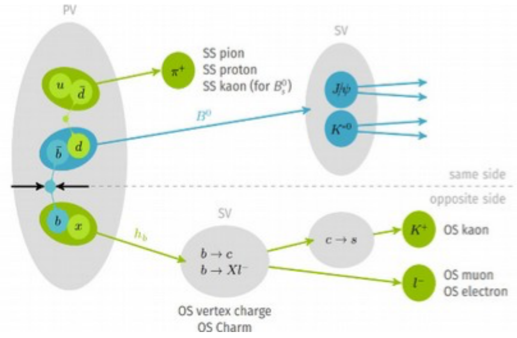
LHCP '23

LHCb-PAPER-2023-013

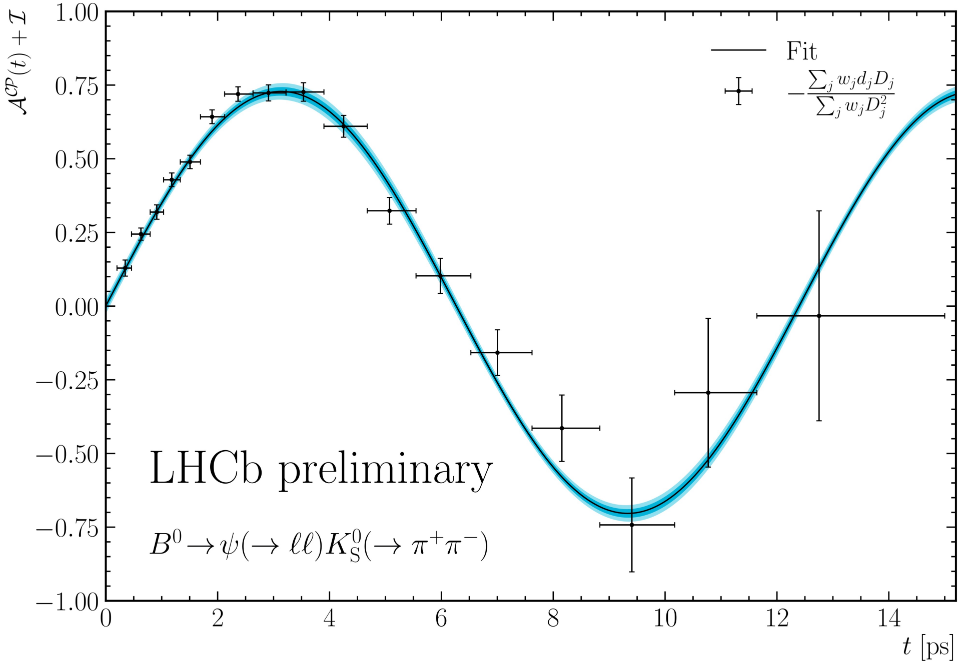
- obtained by the "golden mode" $B^0 \rightarrow J/\psi K^0$

CP violation in interference between decay and mixing $P(B \rightarrow f_{CP}) = P(B \rightarrow \bar{B} \rightarrow f_{CP})$

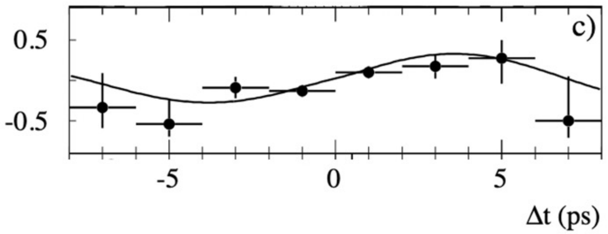
Flavour Tagging

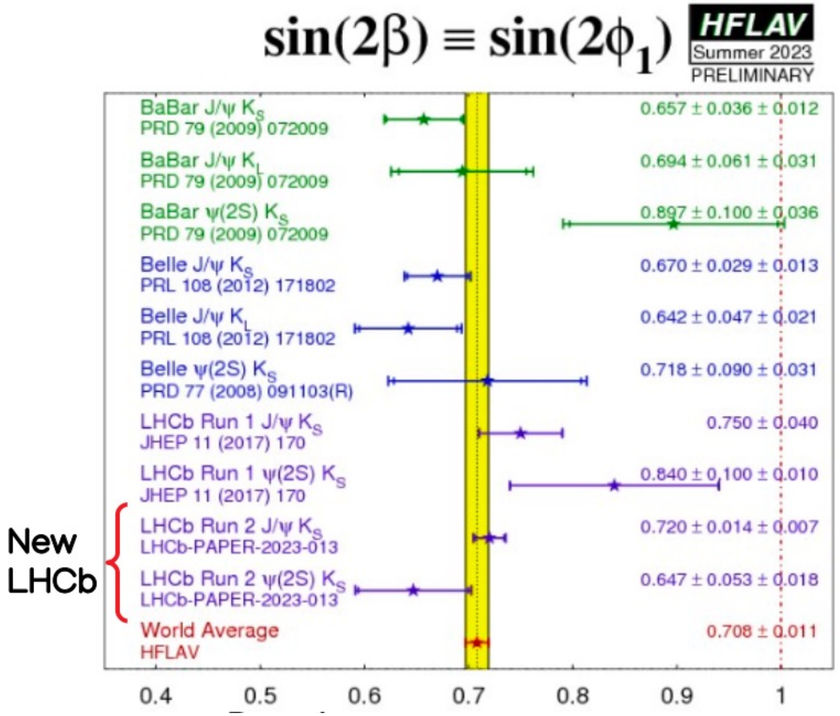


$A_{CP}(t) = \sin(2\beta)\sin(\Delta m_d t)$



Belle 2001





- Original mode of Babar/Belle discovery 2001
  - Confirming SM interpretation of CP violation, Nobel Prize 2008
  - Factor 2 better than prev. world best (Belle), compatible result

CP Violating Phase ϕ_s – full data

FPCP '23

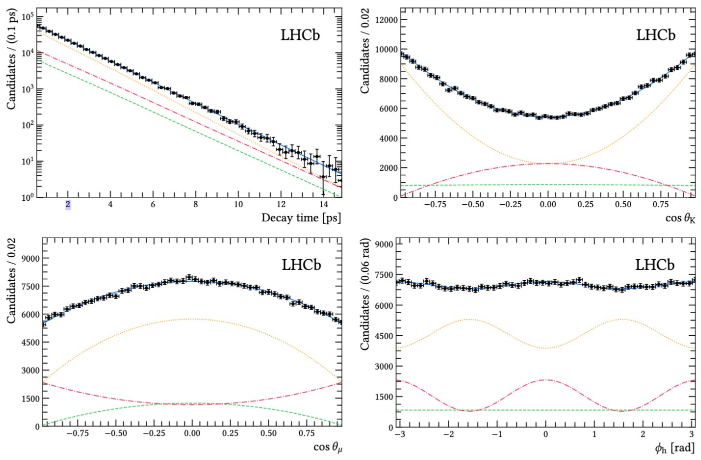
LHCb-PAPER-2023-013

- Obtained by the "golden mode" $B^0 \to J/\psi K^+K^-$
  - Similar role to β but for B_s system – not accessible Belle

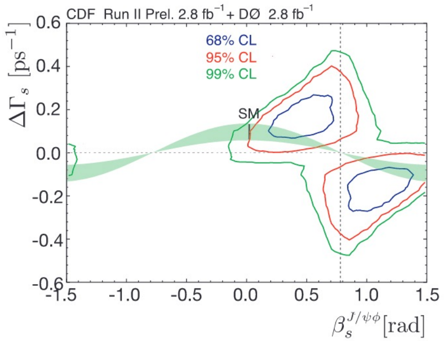
CP violation in interference between decay and mixing $P(B \to f) = P(B \to \bar{B} \to f)$

Time-dependent and angular analysis – separate CP even and odd components

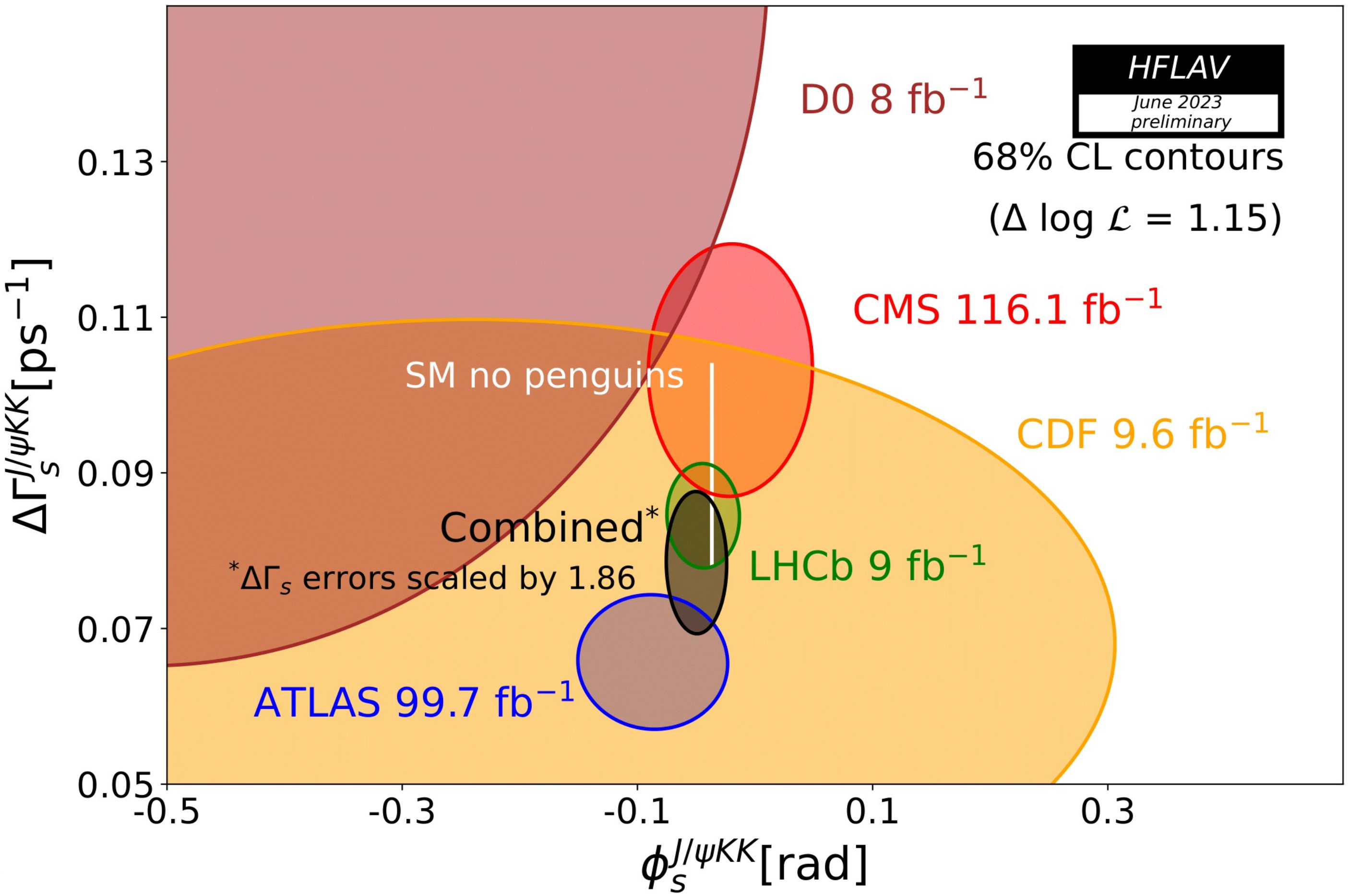
CP-even
CP-odd
S-wave



New physics sensitive
Was tension with SM
At time of start of LHC
D0 public note 5928



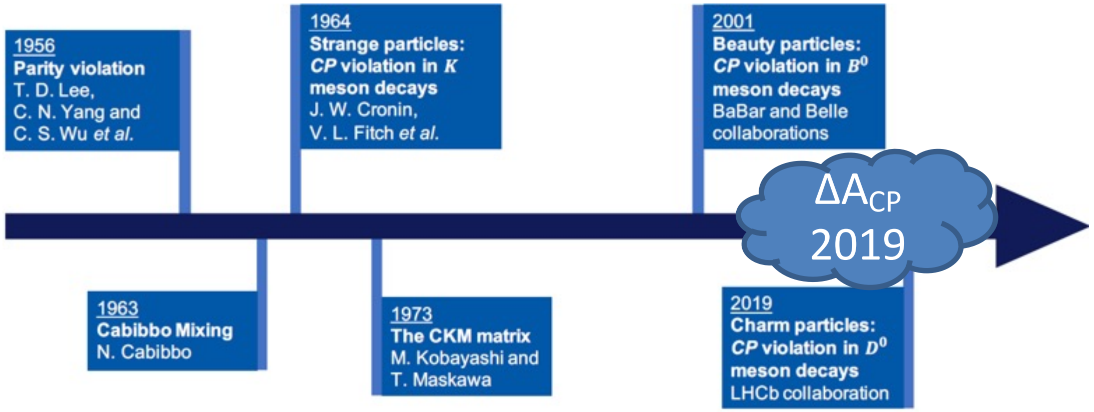
Run2: LHCb ϕ_s = -0.039±0.022±0.006 rad

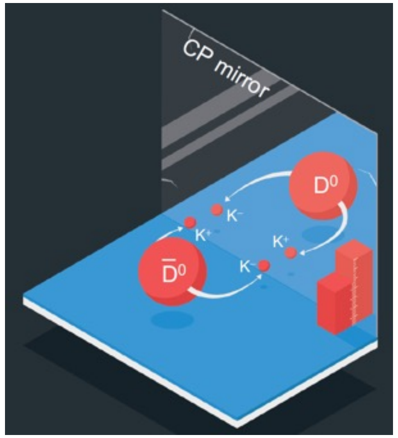


First evidence Charm CP Violation in specific decay

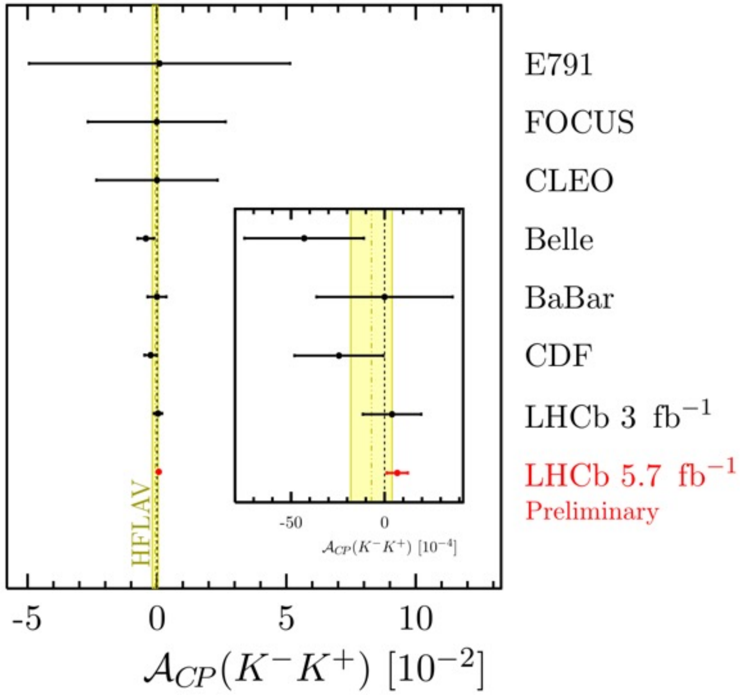
ICHEP '22

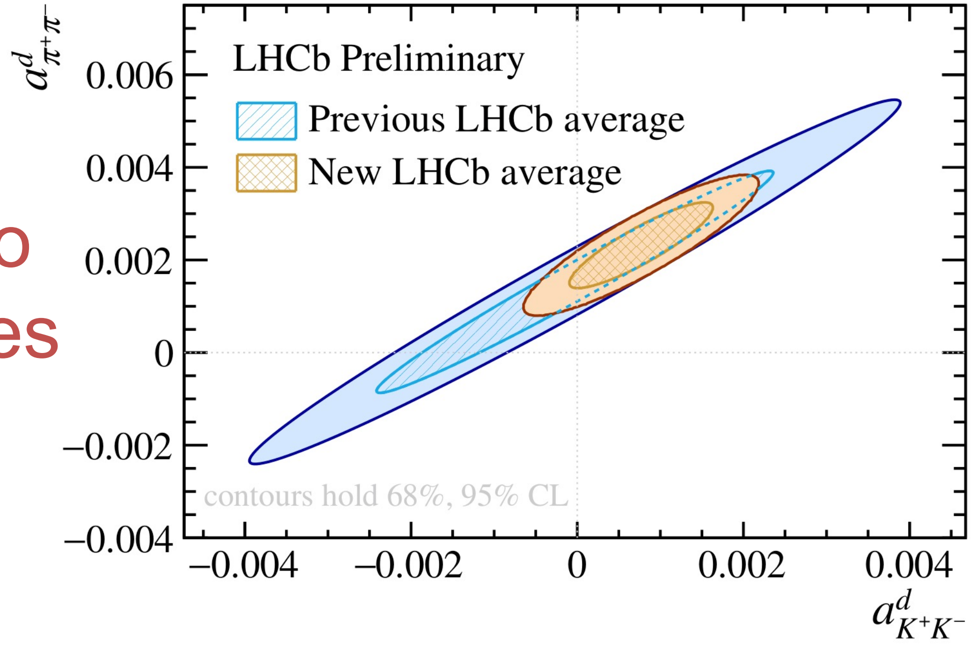
LHCb-PAPER-2022-024





- Direct CP Discovery 2019
- ΔA_{CP} difference KK,ππ
- Cancel systematics
  - Production, detection asymmetries
- Upper end of SM prediction – separate into individual symmetries
  - Control channels to correct asymmetries
  - 3.8σ asymmetry evidence in KK





B anomalies: R(K) & R(K*)

LHCb-PAPER-2022-045/046

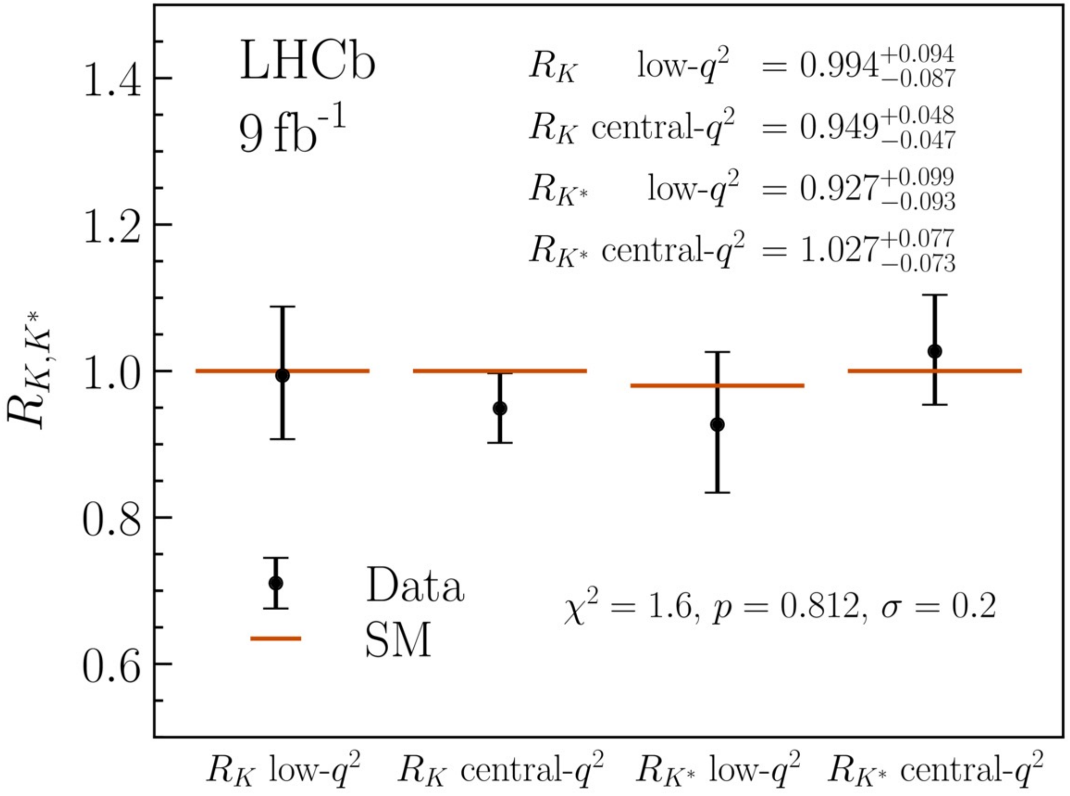
December '22

- "B anomalies" – several results in tension with standard model (SM)
- Included lepton flavour universality ratios in **rare b→sll processes**

- 2021 LHCb paper reported 3.1σ from SM in one q^2 bin in R_K generating much interest

$$R_H \equiv \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2} .$$

- Coherent measurement of four values (R_K, R_{K^*} each in two q^2 bins) with full Run1+2 data sample for all
  - new treatment of hadronic misidentified background to electrons
  - All results in good agreement with SM



B anomalies: R(D) & R(D*)

LHCb-PAPER-2022-039

LHCb-PAPER-2023-052

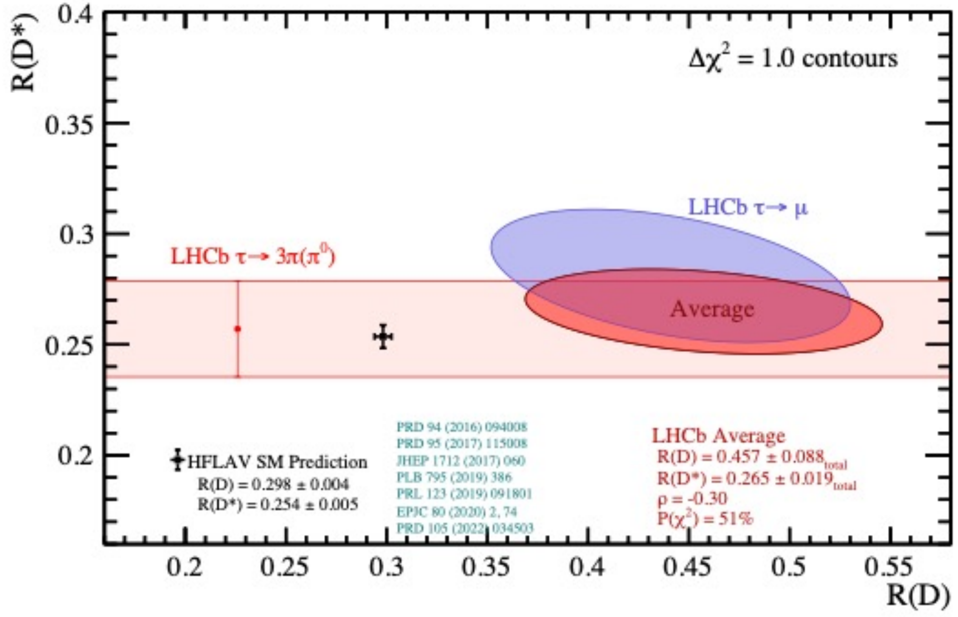
La Thuile '23

- "B anomalies" – several results in tension with standard model (SM)
- Including lepton flavour universality ratios in **semi-leptonic b→clν processes**
- Undetected ν considered difficult at LHC, previously results dominated by Belle/Babar
- LHCb results with muonic and hadronic decay of tau

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\overline{B} \to D^* \tau^- \overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^* \mu^- \overline{\nu}_\mu)$$

$$\mathcal{R}(D^0) \equiv \mathcal{B}(B^- \to D^0 \tau^- \overline{\nu}_\tau)/\mathcal{B}(B^- \to D^0 \mu^- \overline{\nu}_\mu)$$

  - LHCb results compatible with SM and with previous results
  - world average remains 3σ from SM



Red band – LHCb hadronic tau result

Blue elipse – LHCb muonic result, October '22

- LHCb now major contributor in this area
- Future results with full Run1&2 will give significant improvement in precision

B anomalies: R(D) & R(D*)

LHCb-PAPER-2022-039

LHCb-PAPER-2023-052

La Thuile '23

- "B anomalies" – several results in tension with standard model (SM)
- Including lepton flavour universality ratios in **semi-leptonic b→clν processes**
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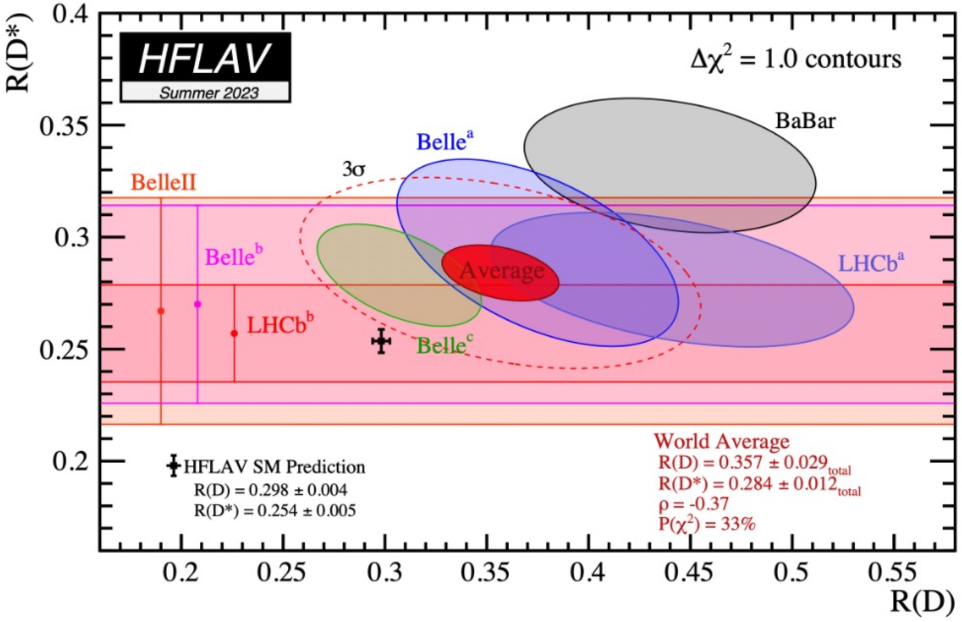
  - LHCb results compatible with SM and with previous results
  - world average remains 3σ from SM



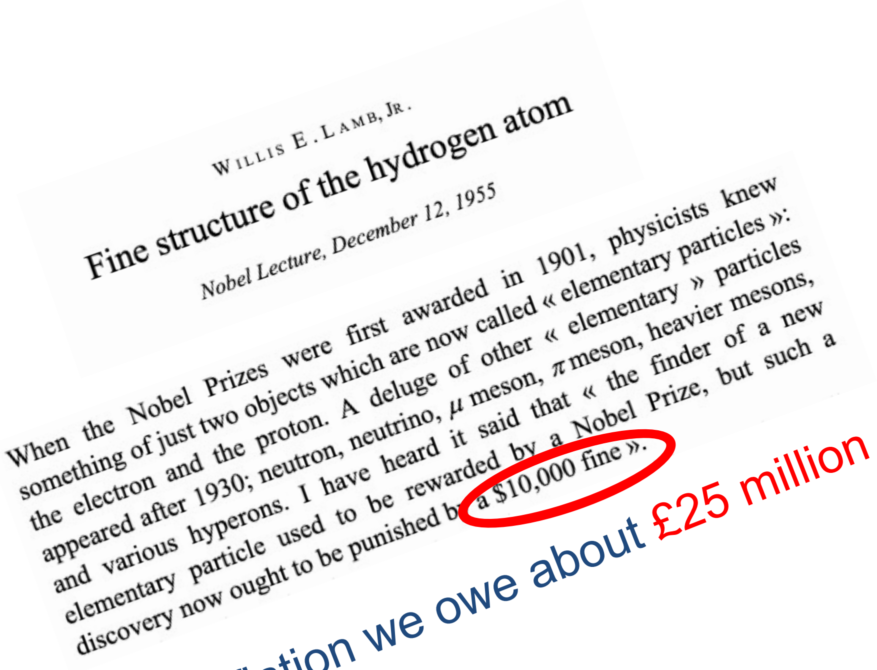
Hot topic – lots of activity !

- LHCb now major contributor in this area
- Future results with full Run1&2 will give significant improvement in precision

Hadrons

- **More than 70 particles discovered at LHC**
- **64 at LHCb**

Including 23 exotic hadrons
Tetraquarks & Pentaquarks



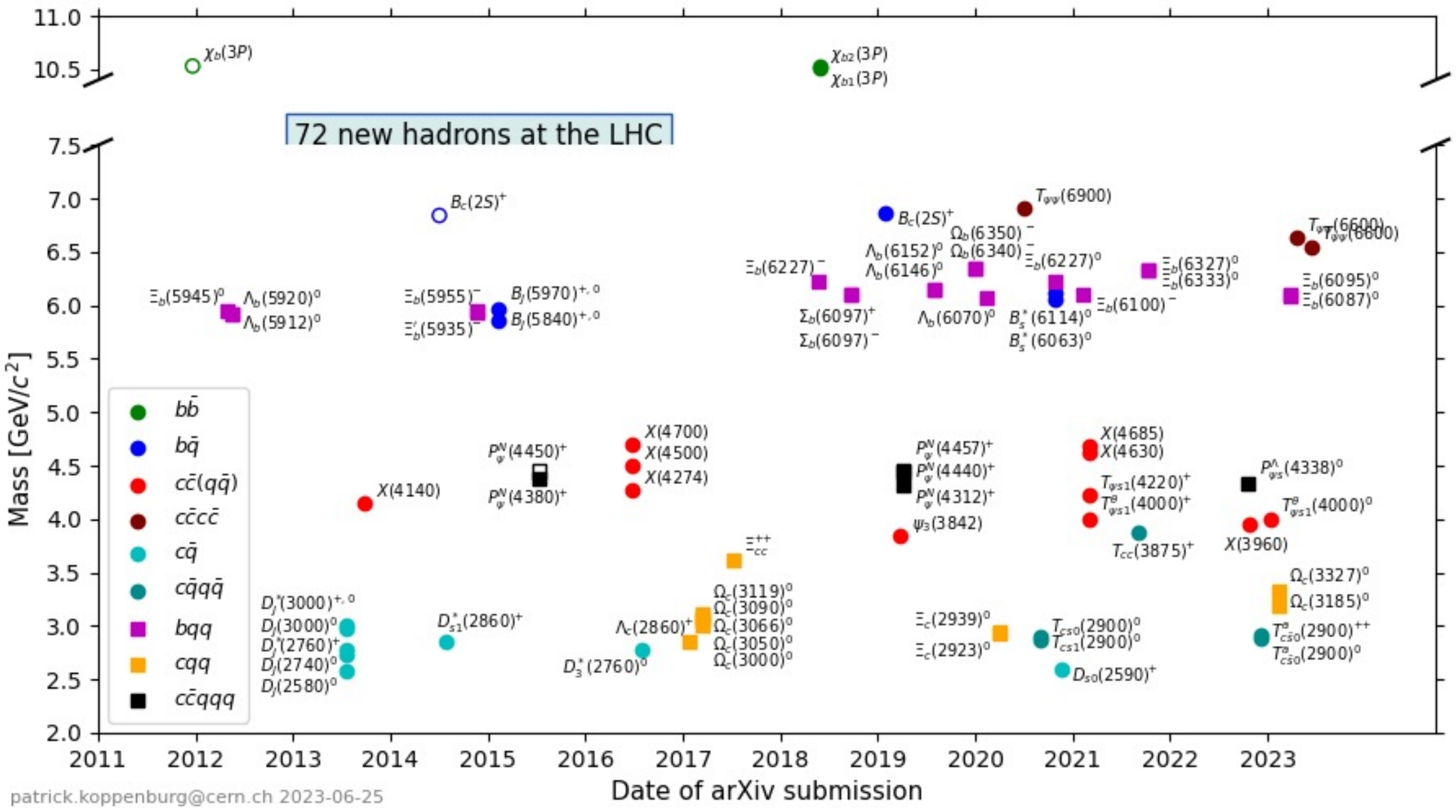
WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

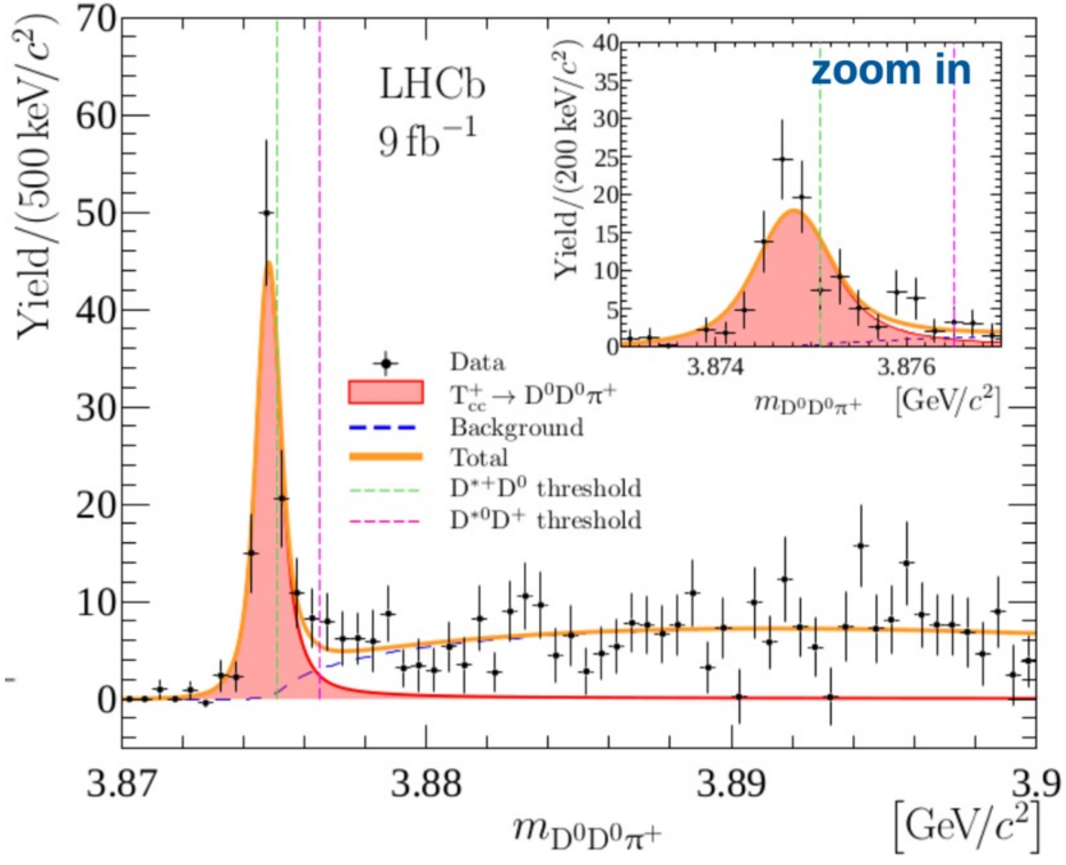
Nobel Lecture, December 12, 1955

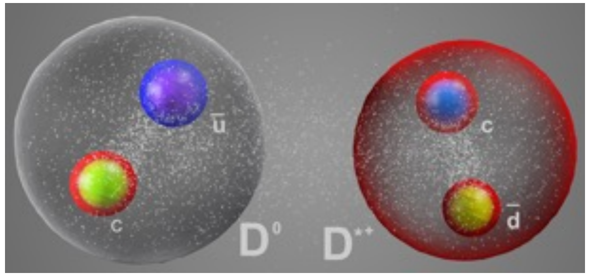
When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».

With inflation we owe about £25 million



- *Doubly Charming* Tetraquark Discovery: T_{cc}^{+} in $D^0 D^0 \pi^+$ consistent with $cc\overline{u}\overline{d}$





Very narrow state, slightly below $D^{*+}D^0$ threshold

$$\delta m_{BW} = -273 \pm 61 \pm 5 \,^{+11}_{-14}\,\mathrm{keV}/c^2\,,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43 \,^{+18}_{-38}\,\mathrm{keV}\,,$$

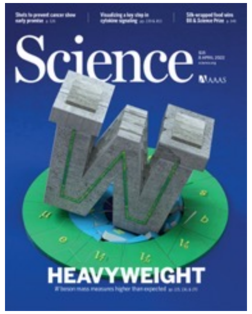
Increased interest for T_{bc} , T_{bb} as possible first long-lived, weakly decaying, states!

Need Upgrade statistics

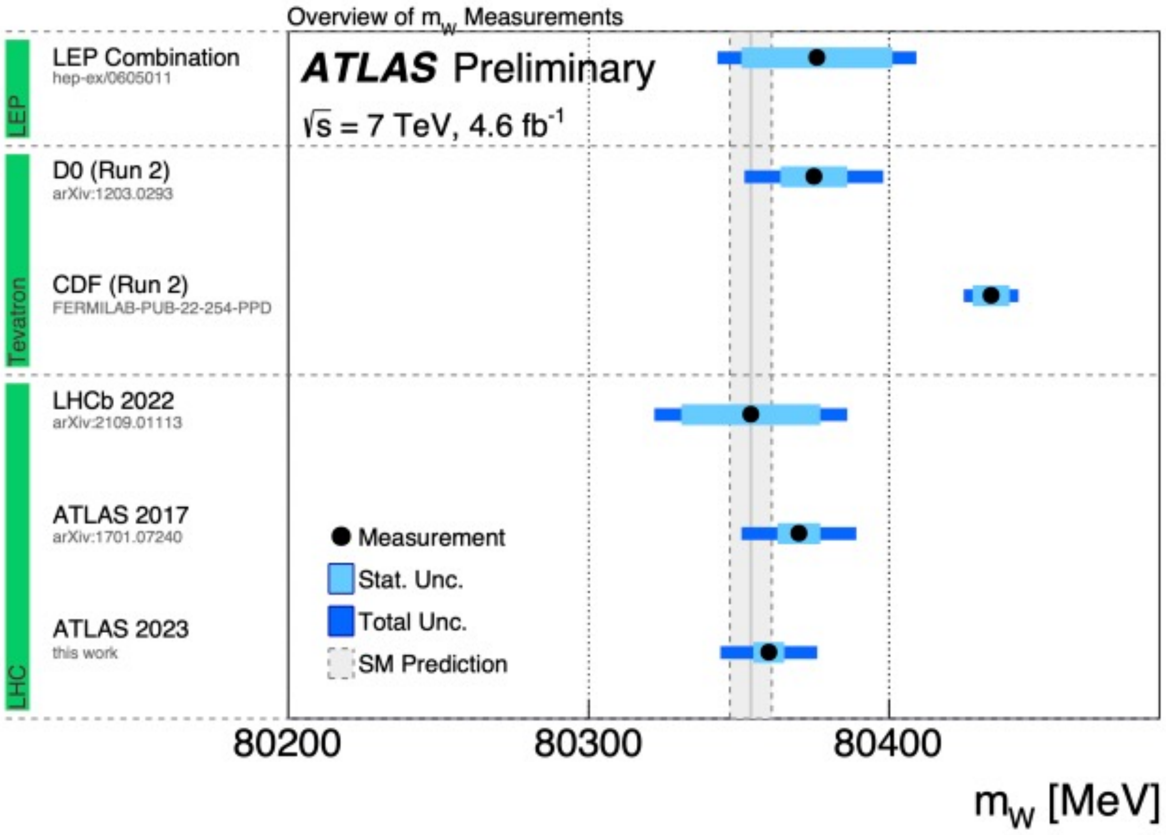
Breadth of LHCb Physics: Electroweak

EPS '21

JHEP 01 (2022) 36



- LHCb results in Precision Electroweak
- W mass – hot topic with '22 CDF result
- Pathfinder LHCb result with 2016 data only



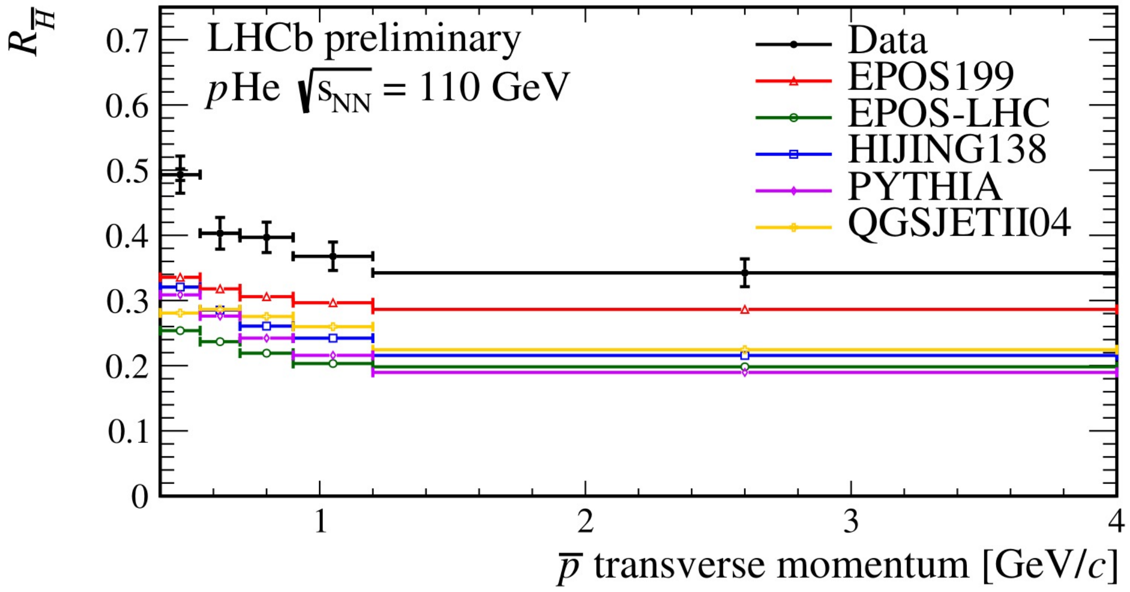
- LHCb results combined with ATLAS reduce sensitivity to the parton distribution functions. PDFs.
- In LHCb W bosons are produced in collisions of high- with low-x partons
- ATLAS mainly collisions of mid-x partons produce the W bosons observed

Breadth of LHCb: Understanding Dark Matter in Space

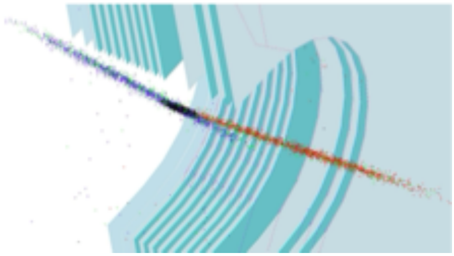
LHCb-PAPER-2021-031/032

QM ‘22

- Astrophysics tells us that dark matter exists
- Space based experiments try to detect it by measuring anti-protons
  - need to know how many anti-protons to expect from standard physics
  - protons collide with He in space and can produce anti-protons
- LHCb has unique programme measuring protons with gas



- Ratio of *detached* to *prompt* anti-protons
  - Predictions have under-estimated this ratio



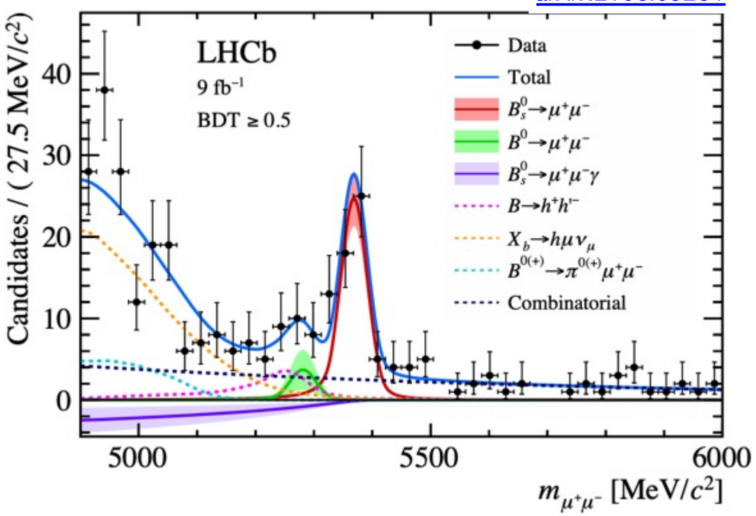
LHCb Highlights

Original 2009-2018

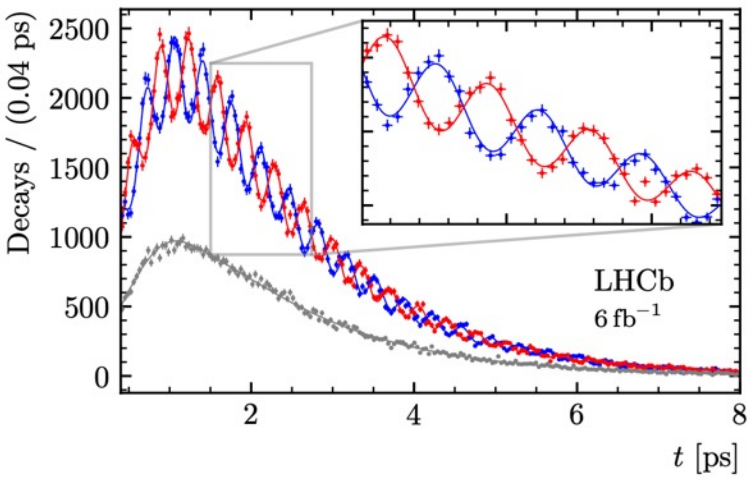
- Future plans build on the success of the experiment during Run 1 & 2

$B_s^0 \to \mu\mu$

arXiv:2108.09284



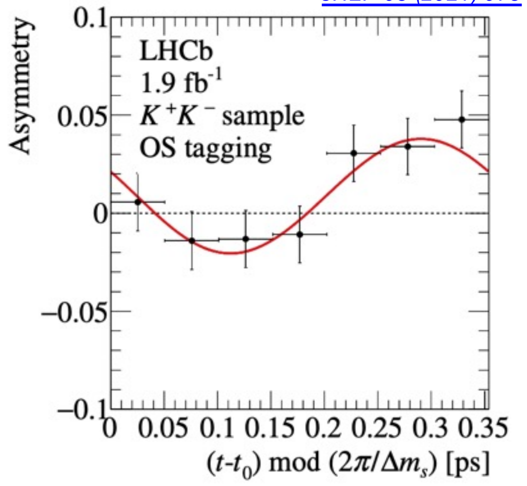
arXiv:2104.04421



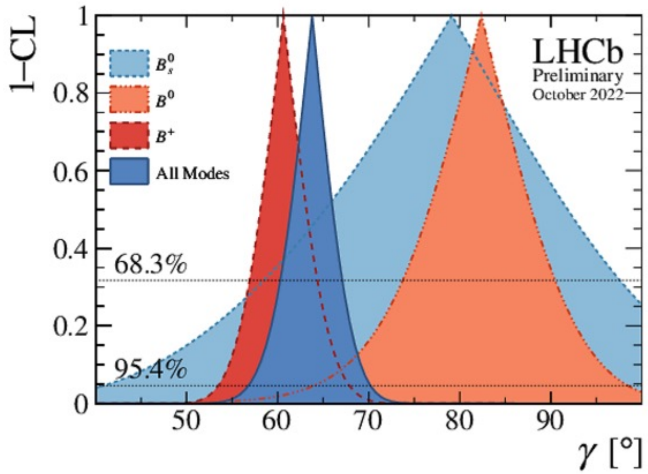
Δm_s

Time-dependent CPV in B_s

JHEP 03 (2021) 075



LHCb-CONF- 2022-003



CKM angle γ

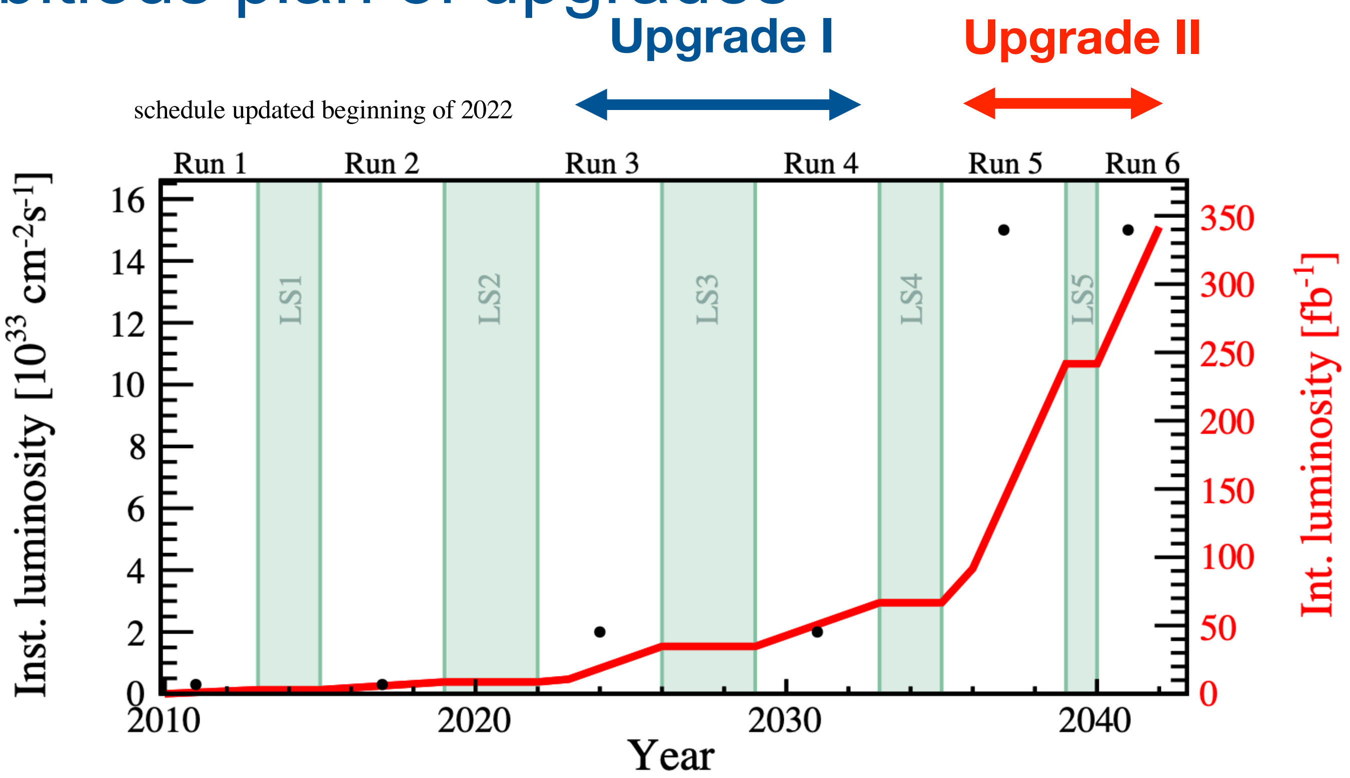
$(63.8^{+3.5}_{-3.7})^\circ$

LHCb Upgrades

- Physics programme limited by detector, NOT by LHC
- Hence, clear case for an ambitious plan of upgrades

Upgrade I started now!

- *L_{peak} = 2x10^{33} cm^{-2} s^{-1}*
- *L_{int} = 50 fb^{-1} during Run 3 & 4*
- *Healthy competition with Belle II if reach 50 ab^{-1}*



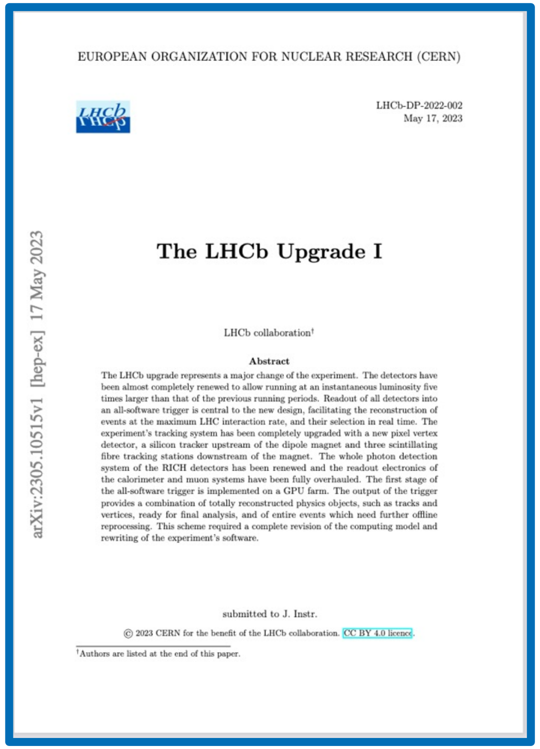
Upgrade II

- *L_{peak} = 1.5x10^{34} cm^{-2} s^{-1}*
- *L_{int} = ~300 fb^{-1} during Run 5 & 6, Install in LS4 (2033)*
- *Some smaller detector consolidation and enhancements in LS3 (2026)*
- *Potentially the only general purpose flavour physics facility in world on this timescale*

LHCb Upgrade I

Upgrade I

2022-2032



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

LHCb-DP-2022-002
May 17, 2023

arXiv:2305.10515v1 [hep-ex] 17 May 2023

The LHCb Upgrade I

LHCb collaboration†

Abstract

The LHCb upgrade represents a major change of the experiment. The detectors have been almost completely renewed to allow running at an instantaneous luminosity five times larger than that of the previous running periods. Readout of all detectors into an all-software trigger is central to the new design, facilitating the reconstruction of events at the maximum LHC interaction rate, and their selection in real time. The experiment's tracking system has been completely upgraded with a new pixel vertex detector, a silicon tracker upstream of the dipole magnet and three scintillating fibre tracking stations downstream of the magnet. The whole photon detection system of the RICH detectors has been renewed and the readout electronics of the calorimeter and muon systems have been fully overhauled. The first stage of the all-software trigger is implemented on a GPU farm. The output of the trigger provides a combination of totally reconstructed physics objects, such as tracks and vertices, ready for final analysis, and of entire events which need further offline reprocessing. This scheme required a complete revision of the computing model and rewriting of the experiment's software.

submitted to J. Instr.

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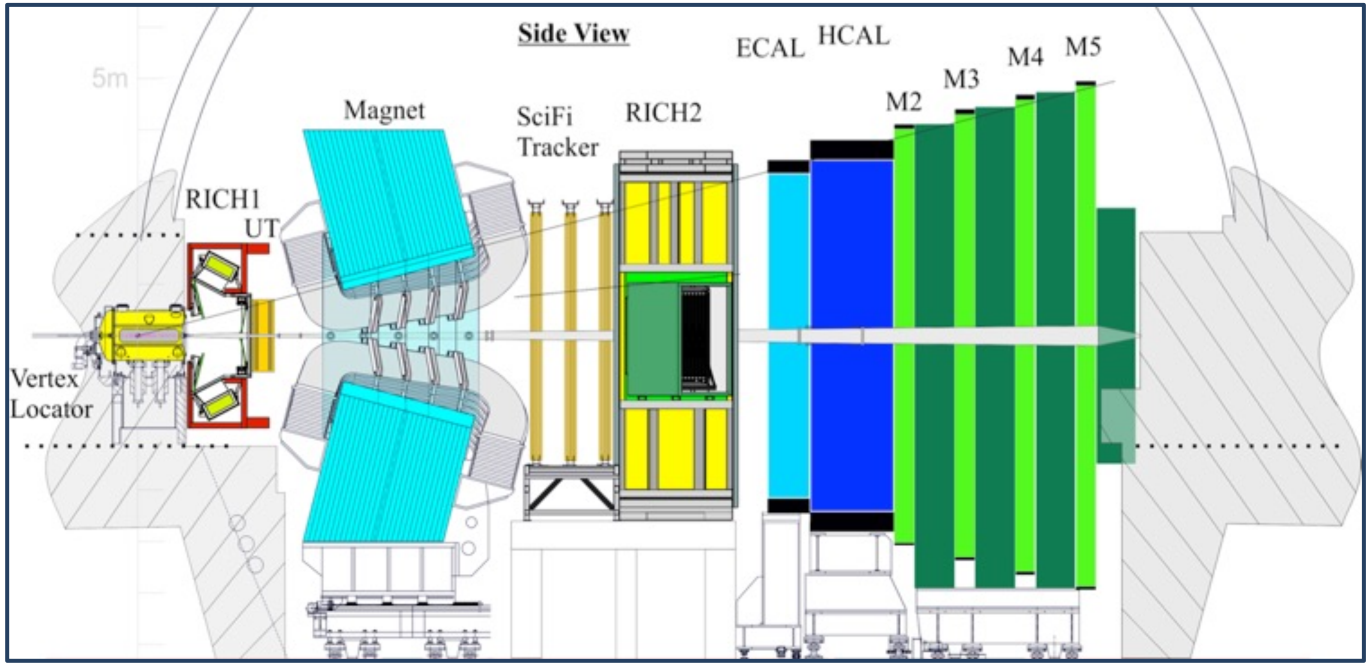
†Authors are listed at the end of this paper.

https://arxiv.org/abs/2305.10515

Accepted by JINST

Upgrade I

- All sub-detectors read out at 40 MHz for a **fully software trigger**



- Target $L_{peak} = 2 \times 10^{33}$ cm^{-2} s^{-1}, pile-up ~5

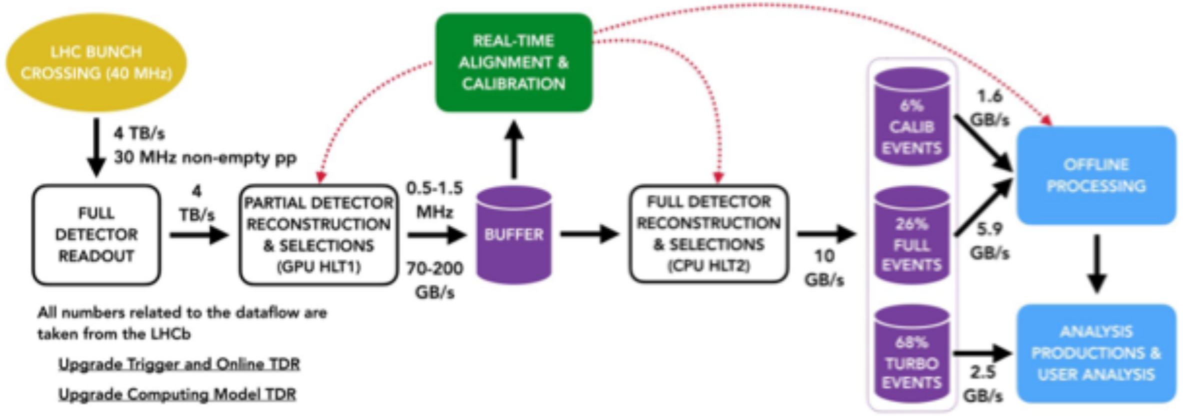
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Major project installed for operation in Run 3

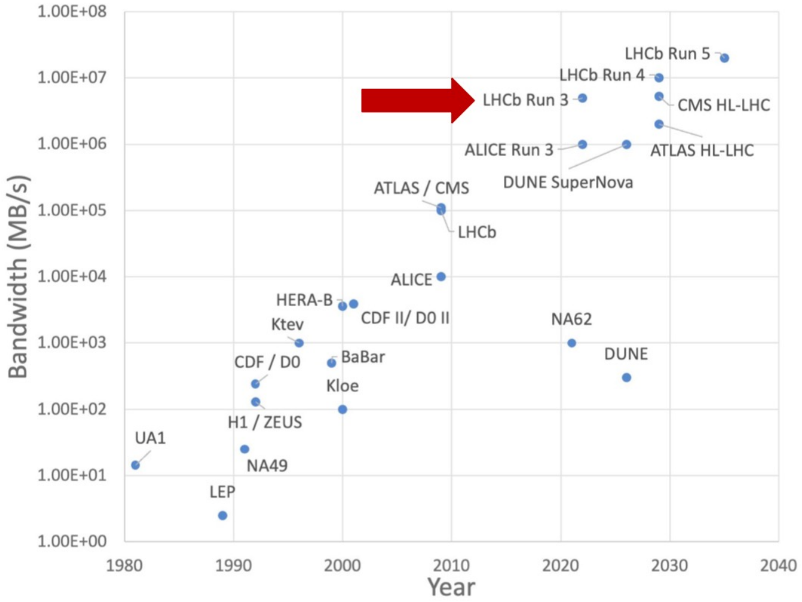
LHCb Upgrade I: Trigger Revolution

CERN-LHCC-2014-016
CERN-LHCC-2020-006

- All sub-detectors read out at 40 MHz for a **fully software trigger**
- Factor of ~ 10 increase expected in hadronic yields at Run 3



- 30 MHz of inelastic collisions will be reduced to ~1MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**
  - – ~ 400 cards
- Highest throughput of any HEP experiment
  - Up to 4 TB/s data rate through Event Builder network.
  - – O(4%) of internet traffic in 2022



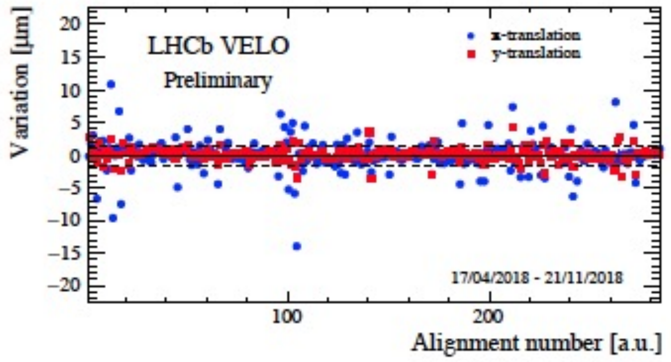
A. Cerri, LHCP 2022

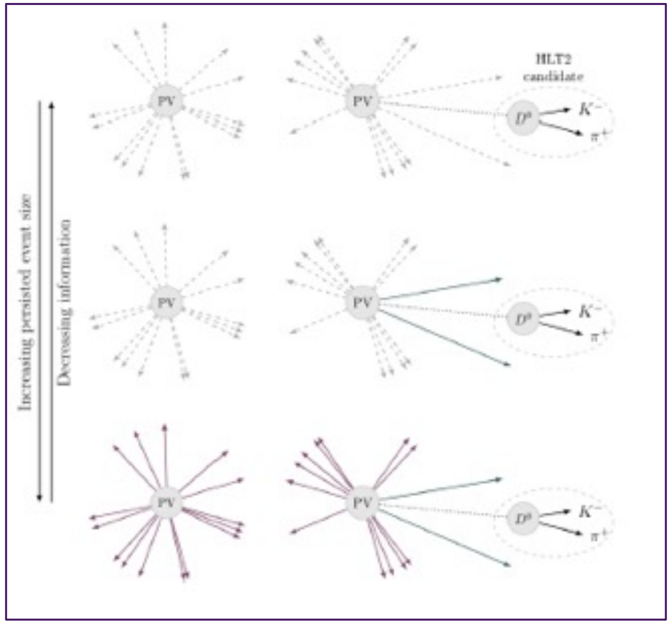
Real Time Analysis - Turbo

CERN-LHCC-2018-014
CERN-LHCC-2018-007

- Online Align and Calib means…
- Optimal quality reconstruction online in trigger
  - No need for re-reconstruction
  - No need to keep raw data
- Benefits:
  - Expansion of physics programme
  - Large reduction in computing resources (raw data 200kB, triggered objects 15kB)
- Risks:
  - Reprocessing not possible in case of errors

e.g. VELO alignment performed online in 7mins in Run2





- Selective persistence

  Only signal decay tracks….

  those in cone around...

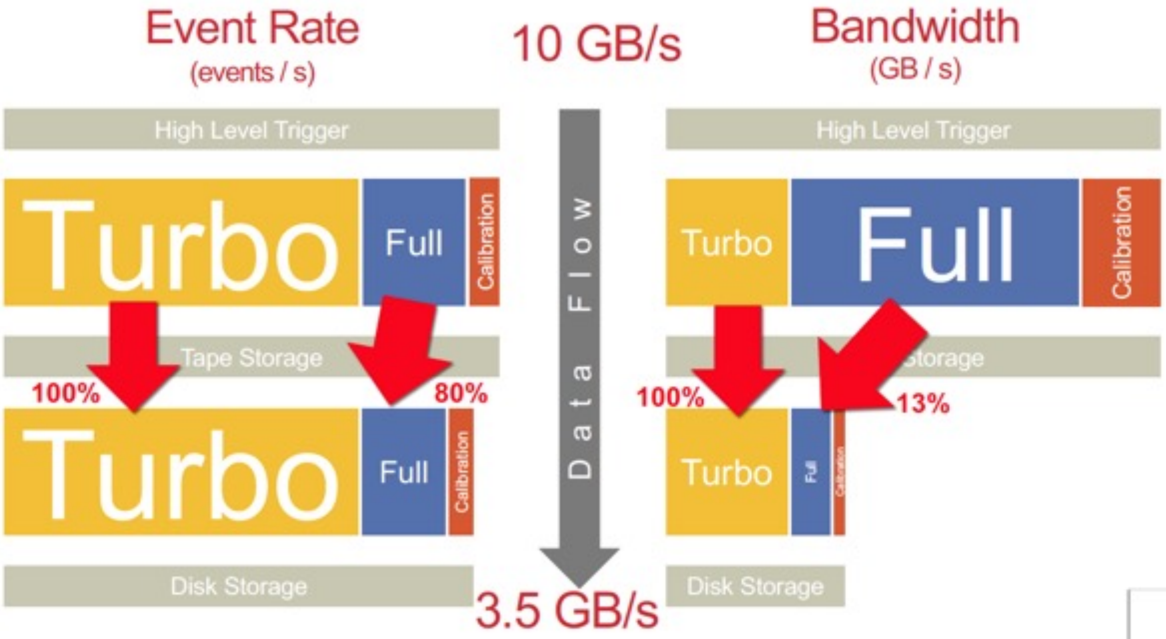
  those from same PV....

  All tracks in event….

  All ECAL clusters....

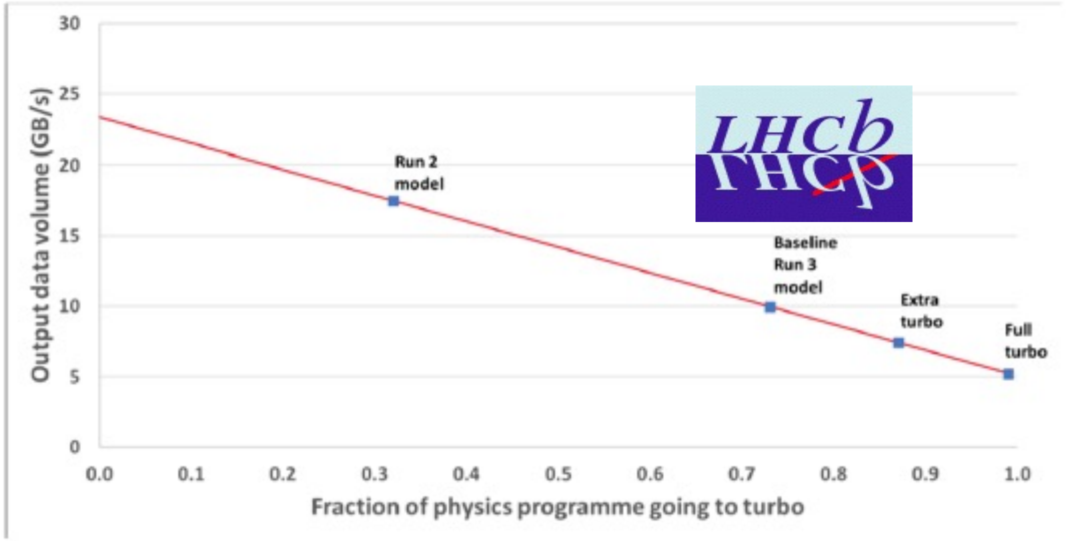
Real Time Analysis - Computing Resources

CERN-LHCC-2018-014
CERN-LHCC-2018-007



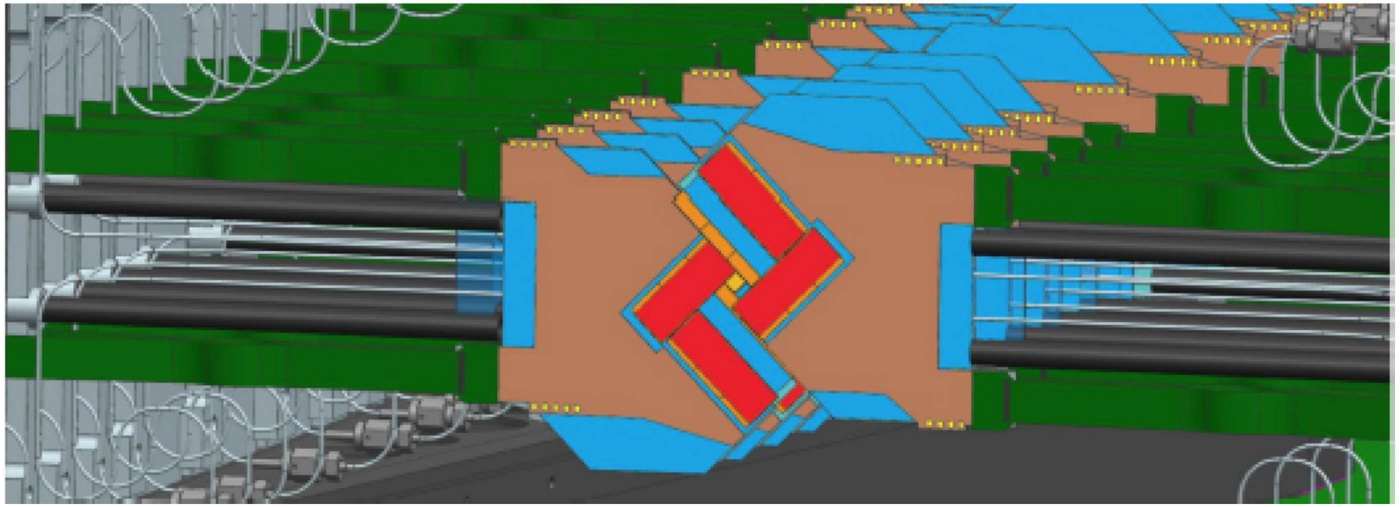
- Efficient use of computing resources
- Focus on bandwidth not event rate
- Minimise expensive disk resource

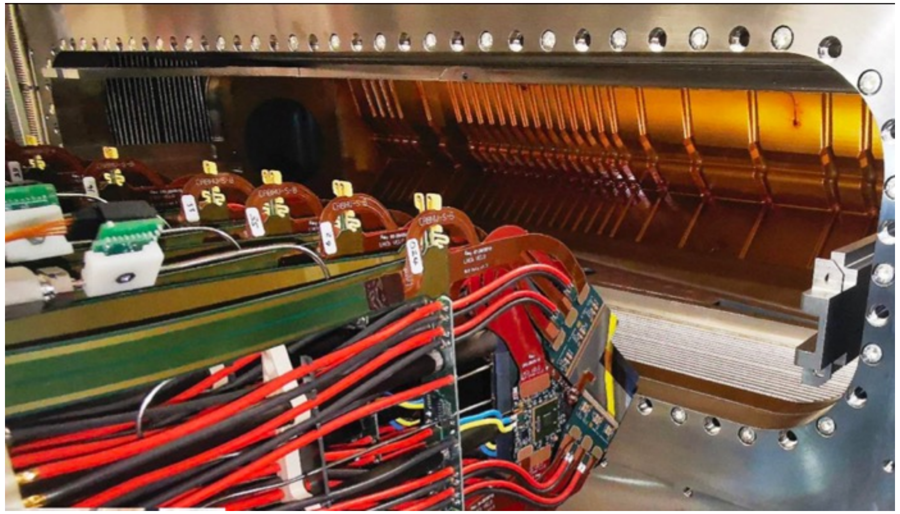
- Real time analysis already extensively used in Run 2
- >70% of events in Upgrade I will use real time analysis

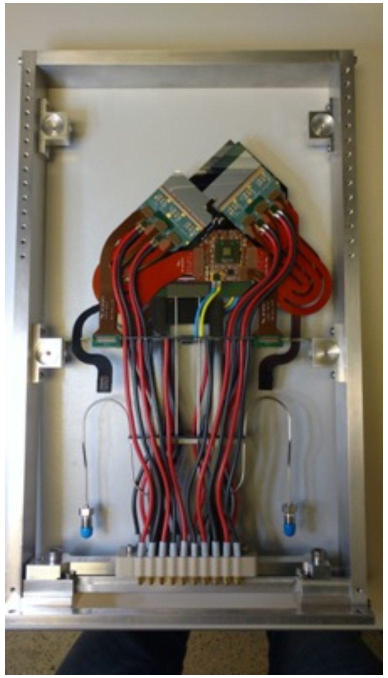


LHCb Upgrade I: VELO

CERN-LHCC-2013-021



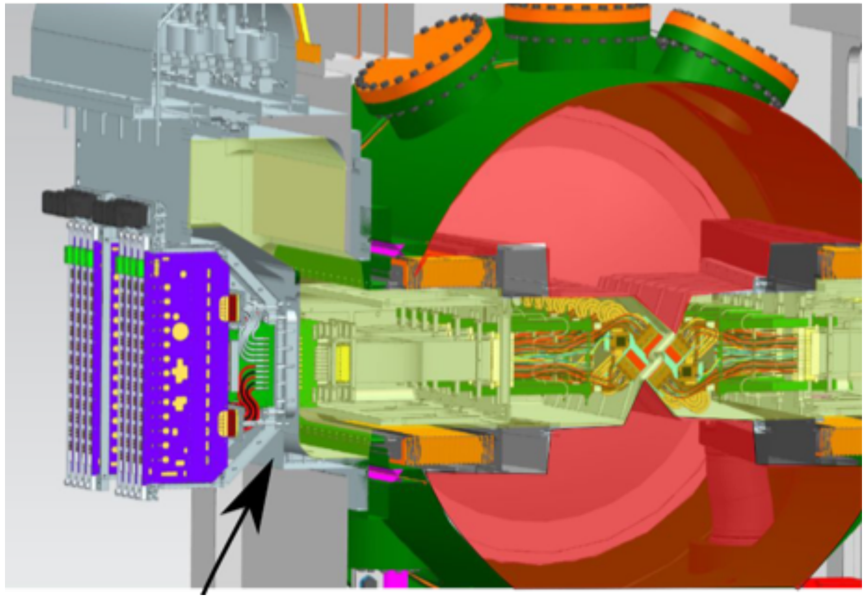




- Hybrid Pixel Detectors (55µm pitch)
- Close to the LHC beam (5.1 mm)
  - retracted/reinserted each fill
- Innovative silicon microchannel substrate
  - Bi-phase CO_2 cooling
- DAQ capable of handling 40TB/s
- **Installation completed May 2022**

LHC Vacuum Volume Incident in VELO

RF Foil, 150-250μm thick, separates primary and secondary vacuum volumes

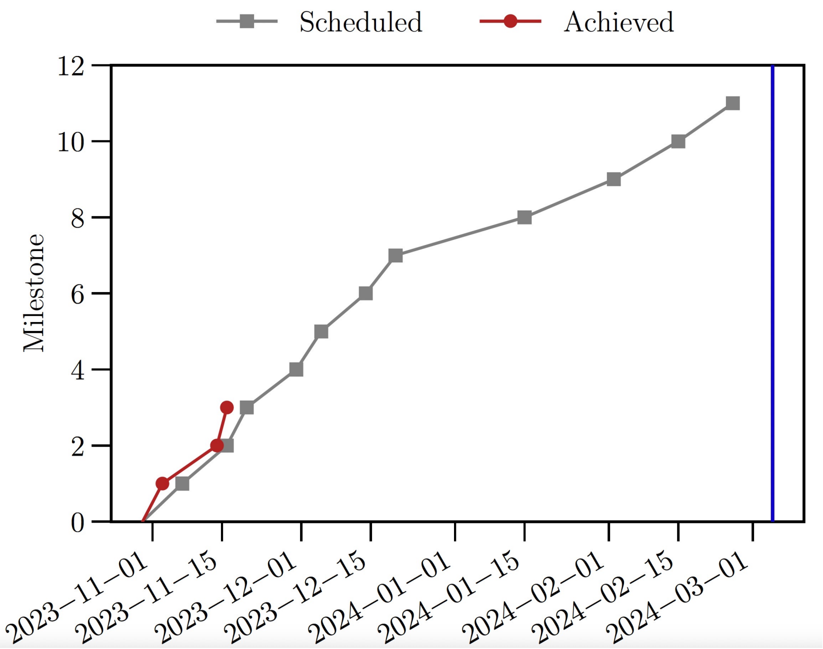


- On 10th January 2023 incident occurred due to a failure of the LHC vacuum system at the VELO.

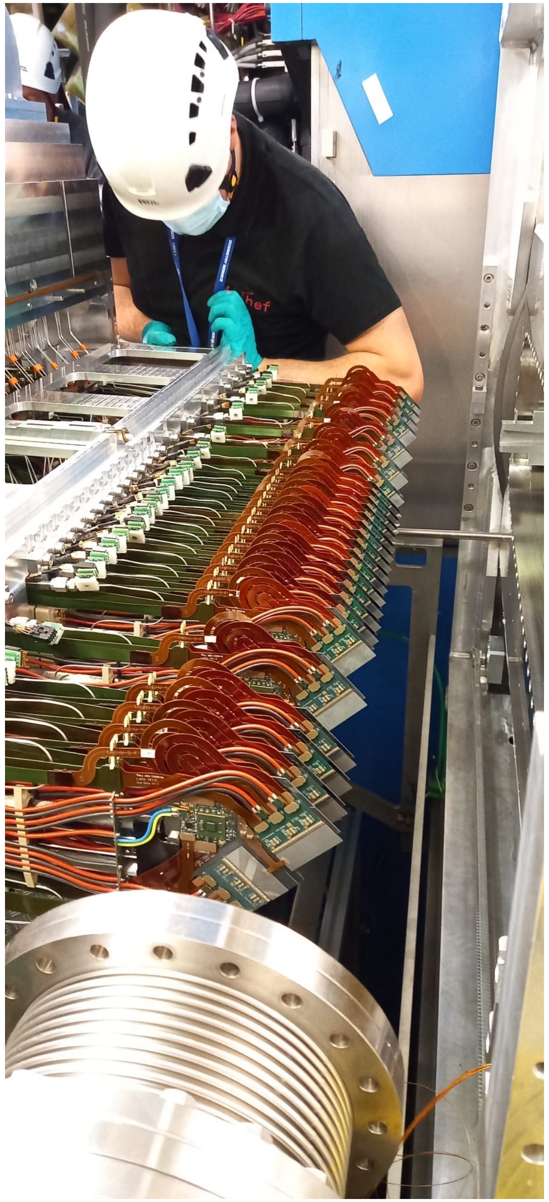
- **Detector modules & cooling are not damaged**
- The system was returned to a safe situation

- **RF foil has undergone plastic deformation**
- Replacement in current shutdown would have significantly affected overall LHC programme
- Replace in the shutdown now at the end of 2023
  - schedule: 13 weeks + contingency 3 weeks
- LHCb physics programme in ‘23 affected as VELO could not be fully closed but opportunities remain

VELO RF Foil Replacement



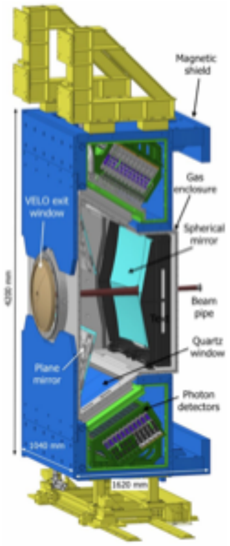
- Detector halves & RF foil are removed in last week by Liverpool team
- Replacement work is proceeding on schedule

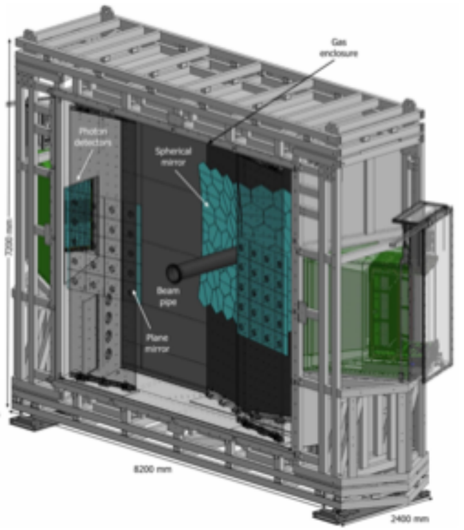


LHCb Upgrade I: RICH 1 & 2

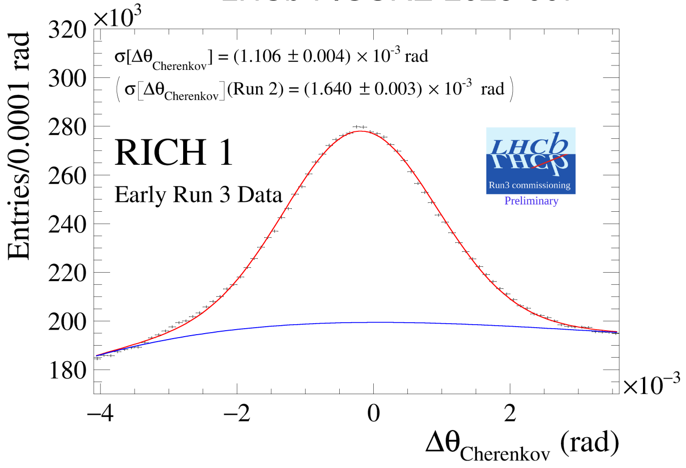
CERN-LHCC-2013-022

- Unique particle identification system, key for success of physics programme
- RICH1&2: new photodetector MaPMTs with Increased granularity and 40MHz readout
- RICH1: new design with new optical system with increased focal length, to halve occupancy
- **Installation successfully completed Feb. '22**

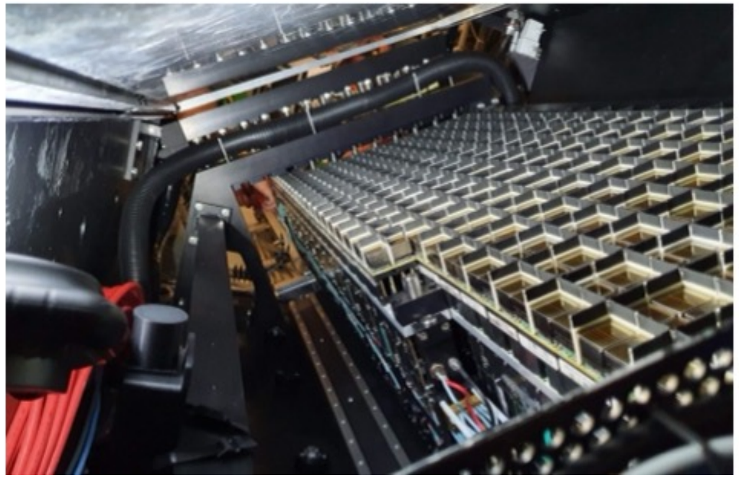




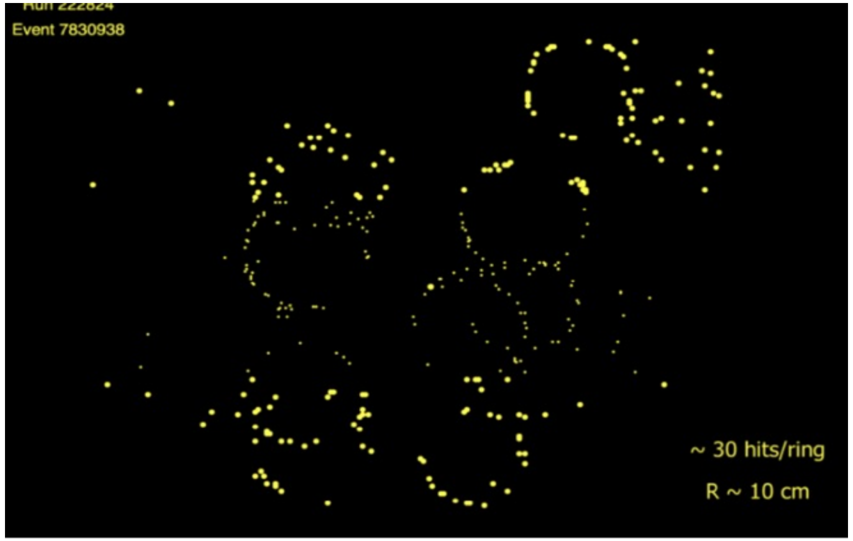
LHCb-FIGURE-2023-007



RICH1: MaPMTs installation



RICH2: first rings, LHC October '21 test

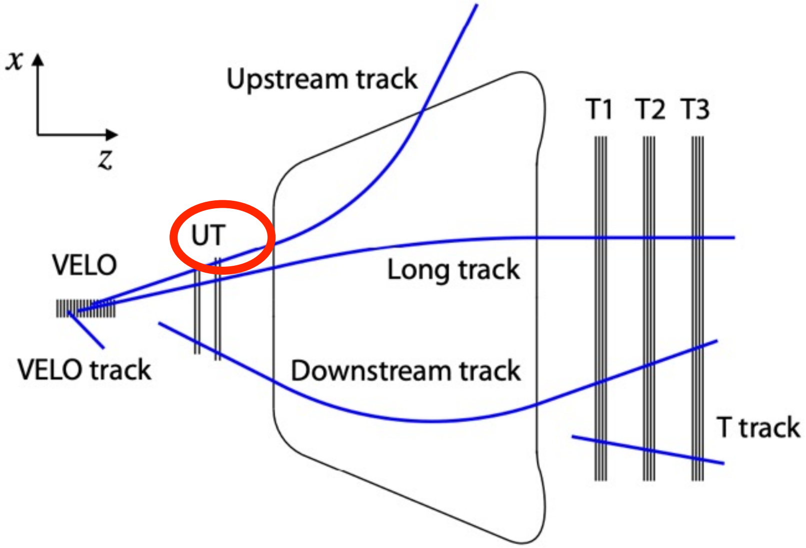


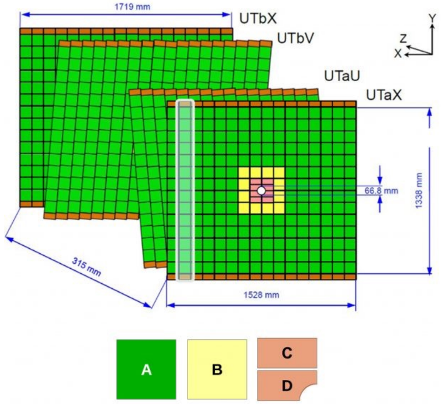
LHCb Upgrade I: Upstream Tracker

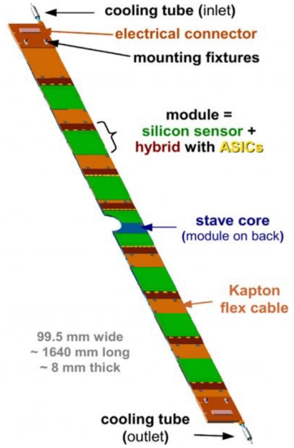
CERN-LHCC-2014-001

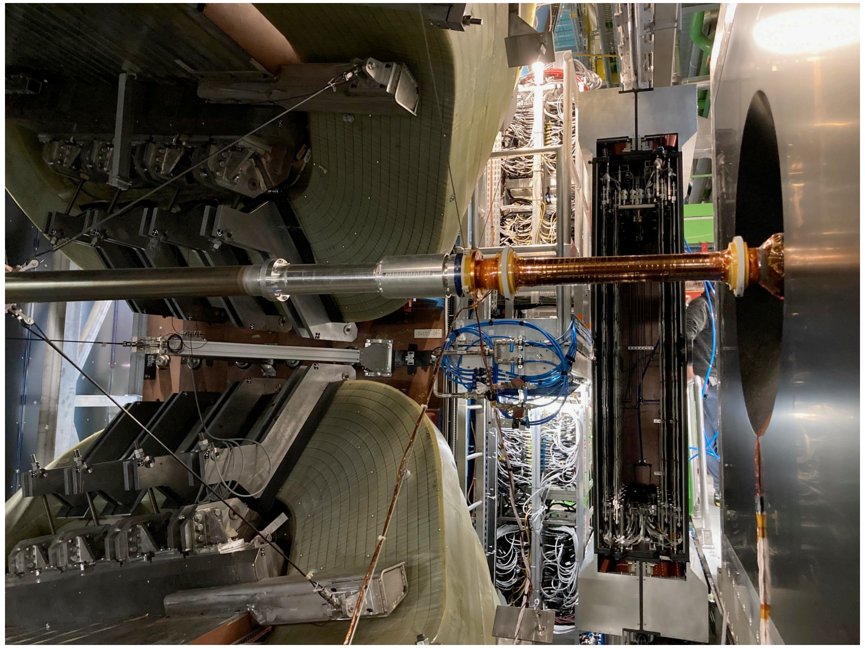
- 68 staves with silicon strips and integrated cooling, arranged in 4 planes
  - fast pT determination for track extrapolation

    → reduce ghost track, and improve trigger bandwidth
  - long-lived particles decaying after VELO (K_S, Λ)
- **Installation successfully completed March '23, now commissioning,**





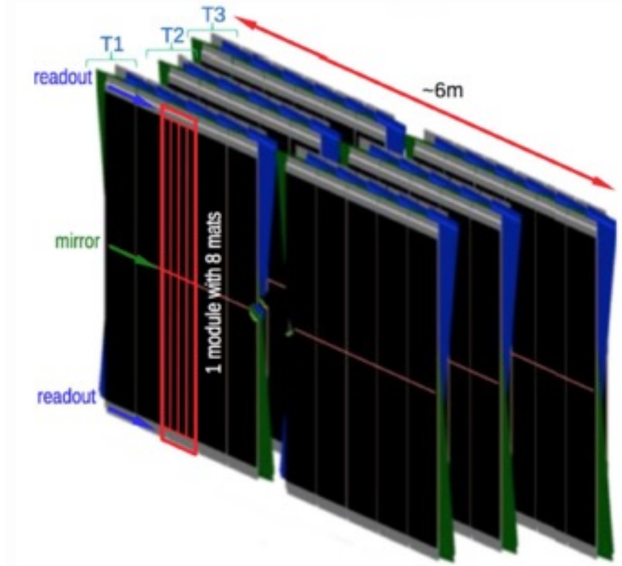


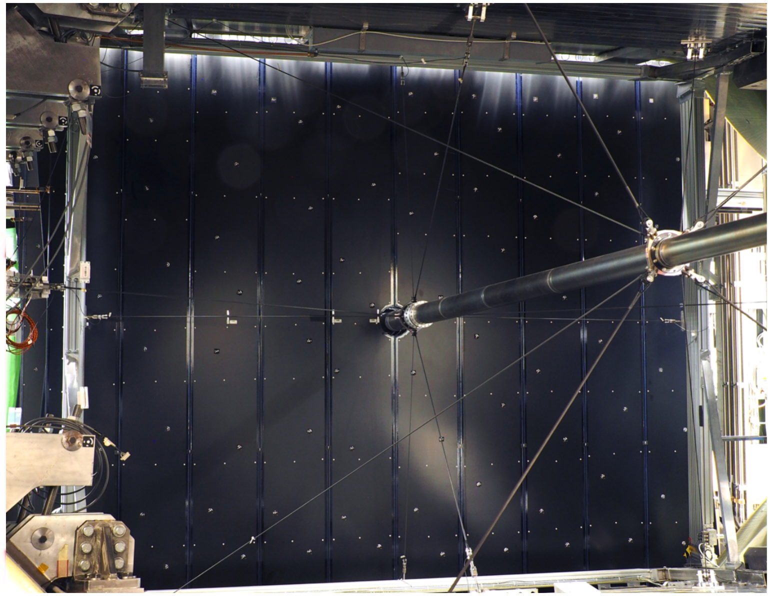


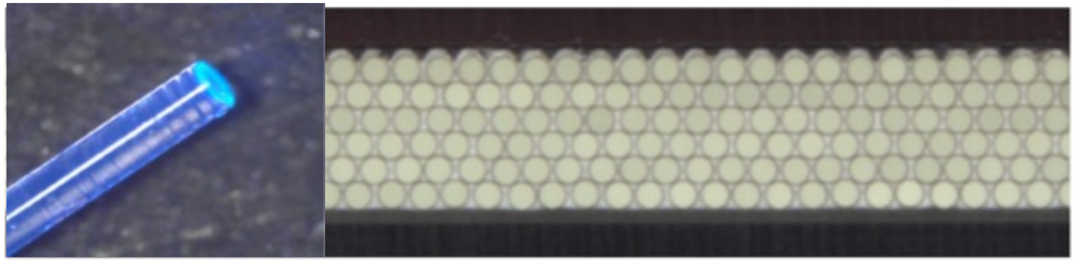
LHCb Upgrade I: SciFi

CERN-LHCC-2014-001

- Large scale tracking stations after magnet
- Scintillating Fibres
  - 250μm diameter, 2.5m long
- Signal readout by SiPMs
  - Operate at -40 C
- 12 layers of mats
- 6 layers of fibres in each mat
  - 12,000 km of fibre !
- **Installation completed March '22**

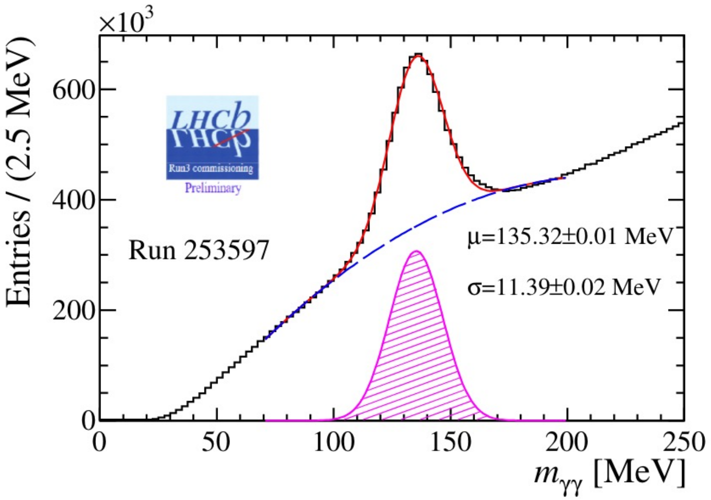


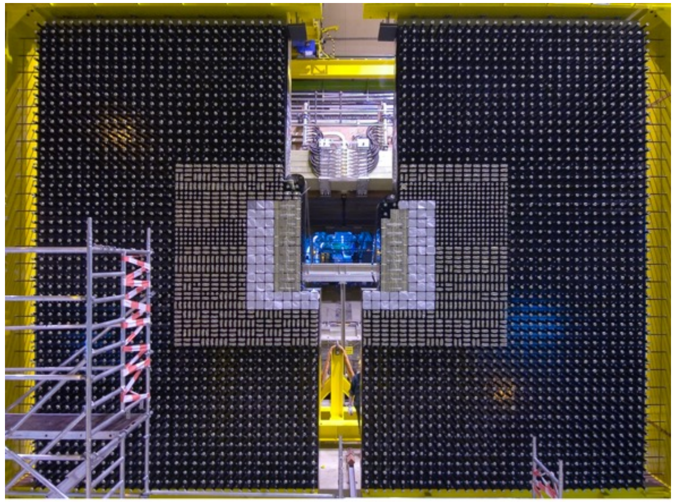




LHCb Upgrade I: CALO & Muon

- New Electronics readout
- Existing detectors able to stand increased luminosity of Run3
  - Inner ECAL upgrade for LS3

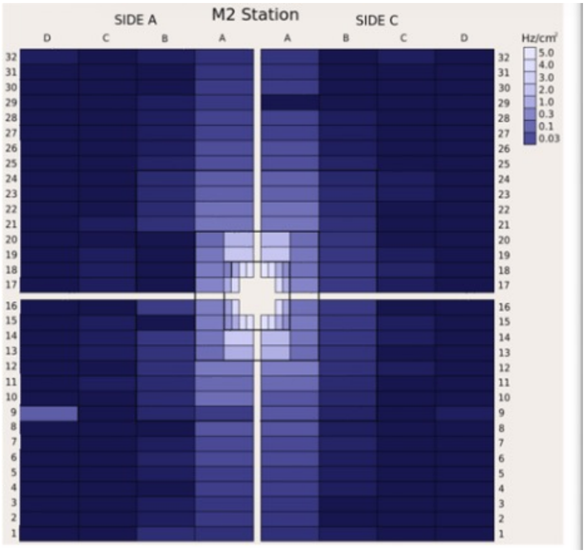


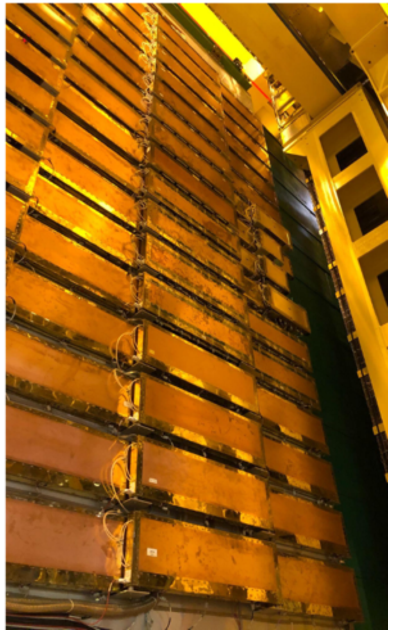


- **Shashlik Calorimeters**
  - PMT gains reduced
  - New front-end electronics

  with improved S/N and 40MHz readout
- **Muon stations**
  - 4 walls equipped with MWPCs, and interleaved with iron filters
  - 40Mz readout electronics

Occupancy Muon station 2

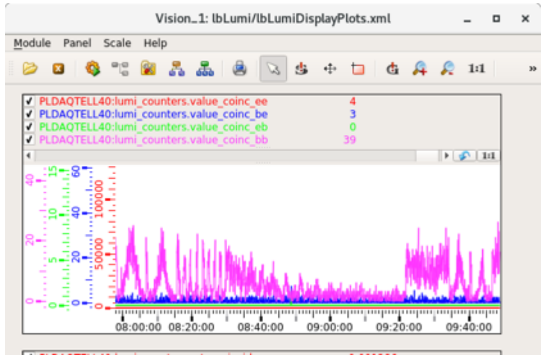


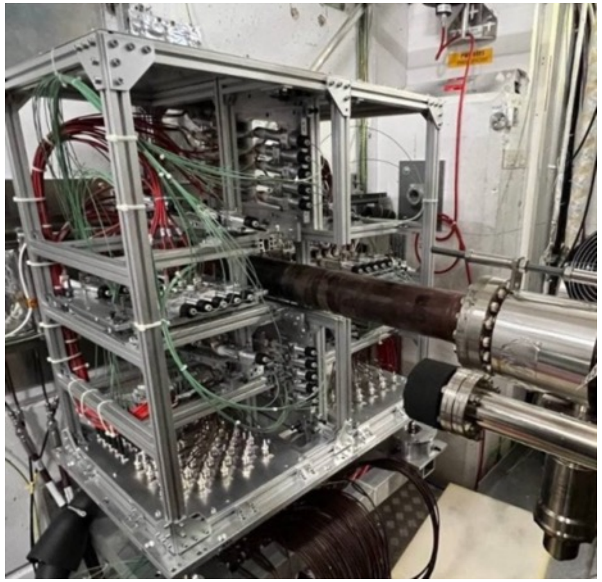


LHCb Upgrade I: PLUME & SMOG

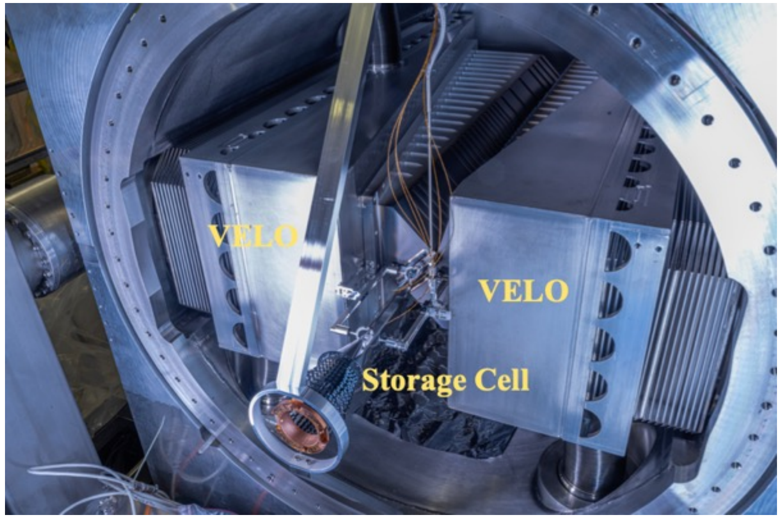
CERN-LHCC-2021-002
CERN-LHCC-2019-005

- Systems at the entrance of the VELO are ready to operate

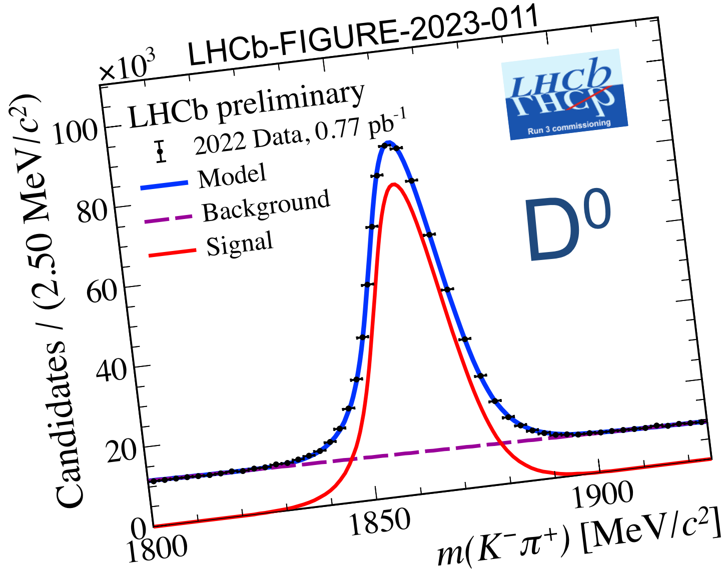


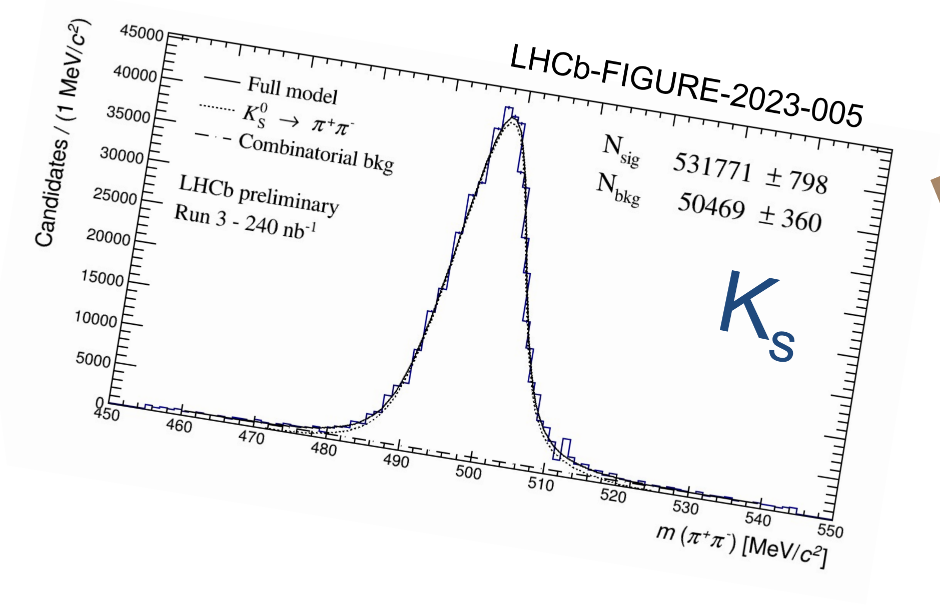


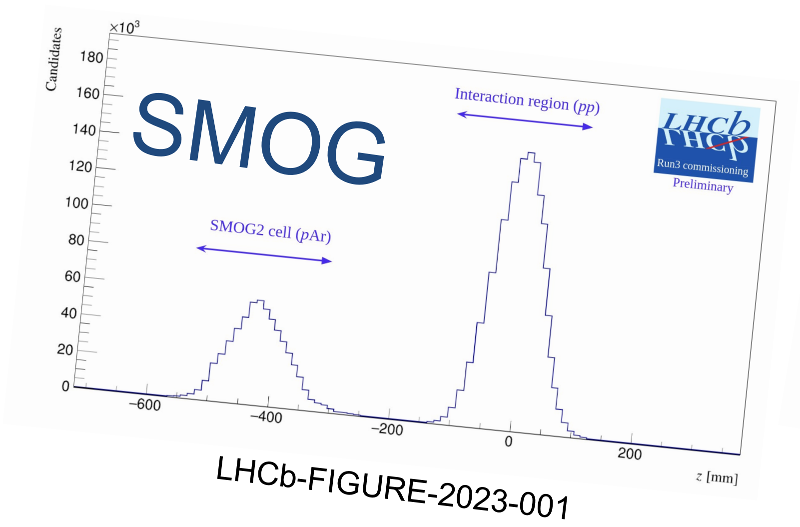
- **PLUME luminometer**
  - quartz tablets + PMTs
  - online+offline per-bunch luminosity measurement
  - **in Global data taking**
- **SMOG2 gas target**
  - New storage cell for the gas upstream of the nominal IP
  - Gas density increased by up to two orders of magnitude → much higher luminosity
  - Gas targets: He, Ne, Ar + possibly H_2, D_2, N_2, Kr, Xe
  - **Installed & tested**
  - **Simultaneous p-p and p-gas data taking possible!**

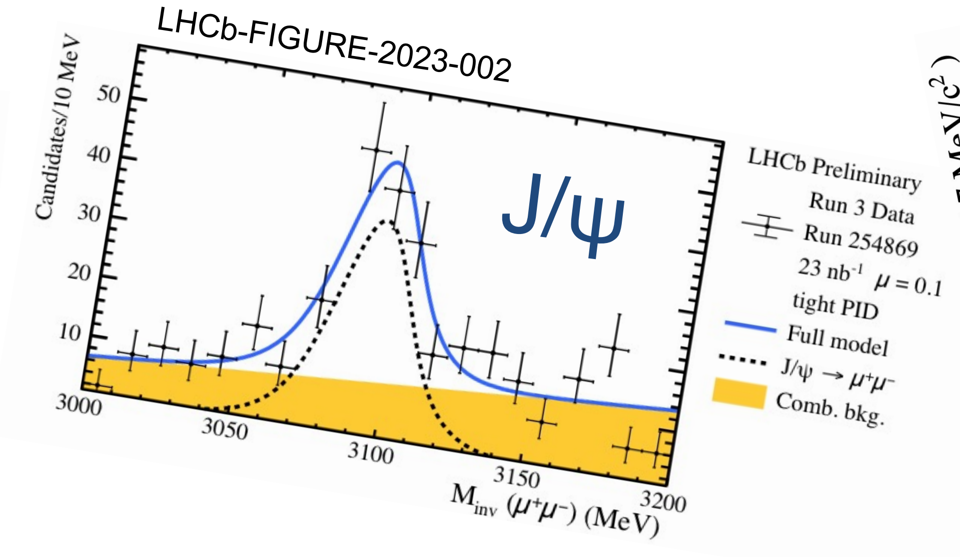


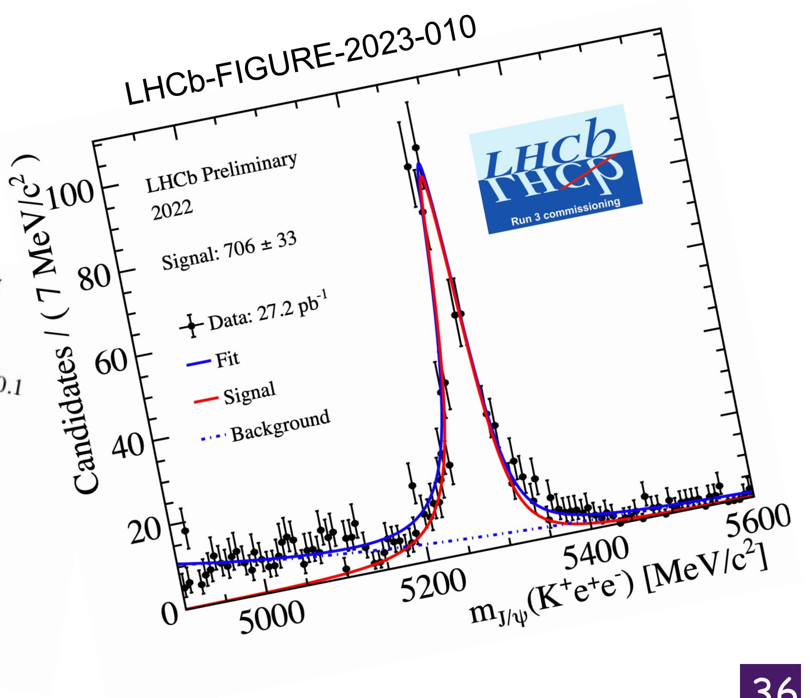
Some first plots…..









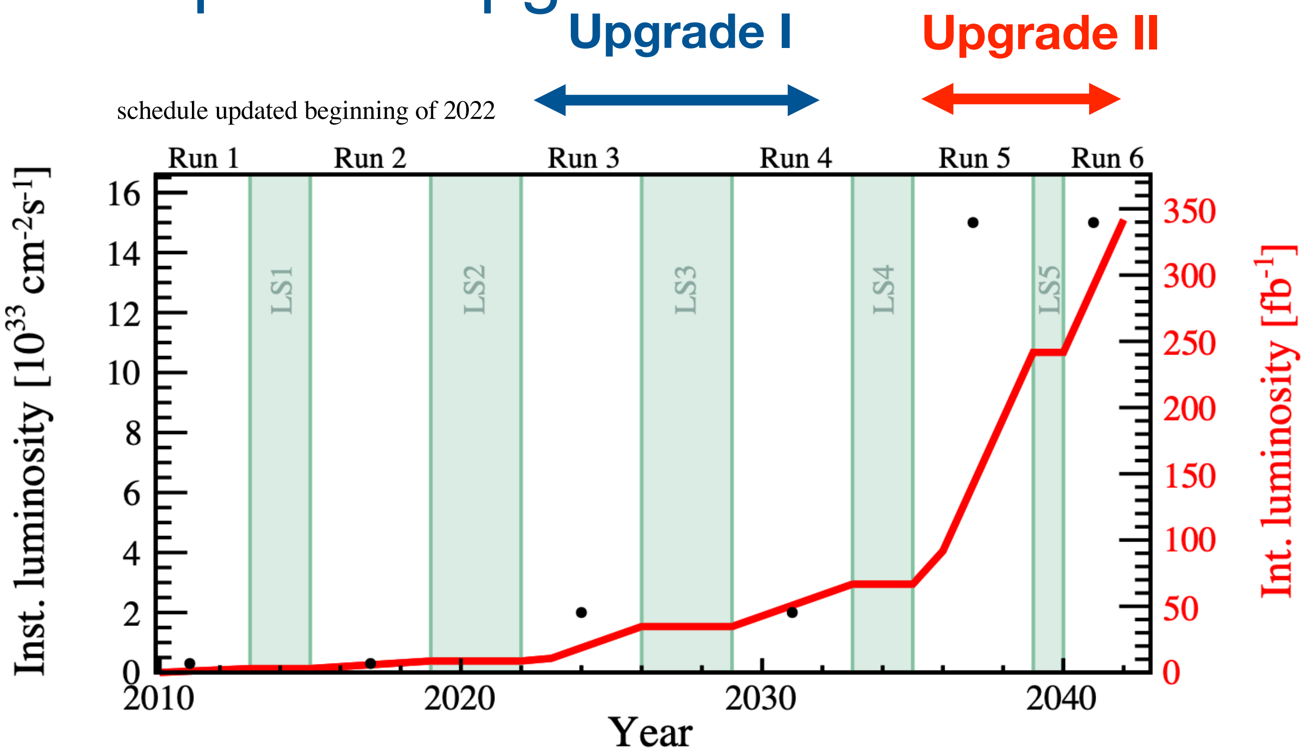


LHCb Upgrades

- Physics programme limited by detector, NOT by LHC
- Hence, clear case for an ambitious plan of upgrades

Upgrade I starting now!

- *$L_{peak} = 2x10^{33}\ cm^{-2}\ s^{-1}$*
- *$L_{int} = 50\ fb^{-1}$ during Run 3 & 4*
- *Healthy competition with Belle II at 50 ab^{-1}*



Upgrade II

- *$L_{peak} = 1.5x10^{34}\ cm^{-2}\ s^{-1}$*
- *L_{int} = ~300 fb^{-1} during Run 5 & 6, Install in LS4 (2033)*
- *Some smaller detector consolidation and enhancements in LS3 (2026)*
- *Potentially the only general purpose flavour physics facility in world on this timescale*

Upgrade II

Upgrade II

2033-

SM destroyed in fiery pit

Upgrade II: steps so far

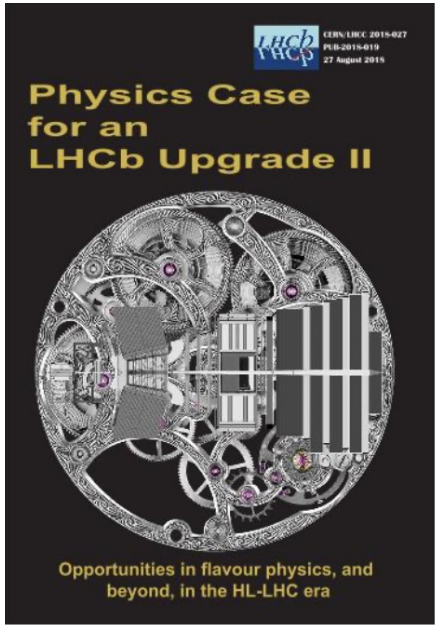
Upgrade II

2033-

Expression of Interest

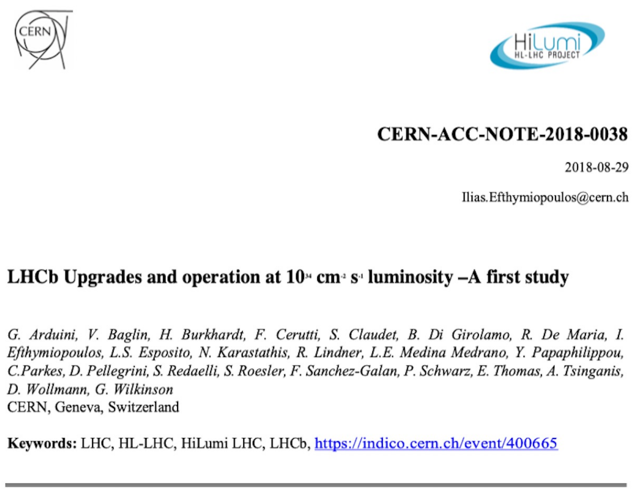
[LHCC-2017-003]

Physics case



[LHCC-2018-027]

Accelerator study



CERN-ACC-NOTE-2018-0038

2018-08-29

Ilias.Efthymiopoulos@cern.ch

LHCb Upgrades and operation at 10^{34} cm^{-2} s^{-1} luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665

[CERN-ACC-2018-038]

[LHCC-2021-012]

CERN Research Board September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

Approved March 2022
R&D programme followed by sub-system TDRs

European Strategy Update 2020 ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

Physics Case: performance table

Upgrade I will not saturate precision in many key observables

⇒ Upgrade II will fully realise the flavour-physics potential of the HL-LHC

Key observables in flavour physics

LHCC-2018-027

updated for FTDR

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	(50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_{T}^{Im} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

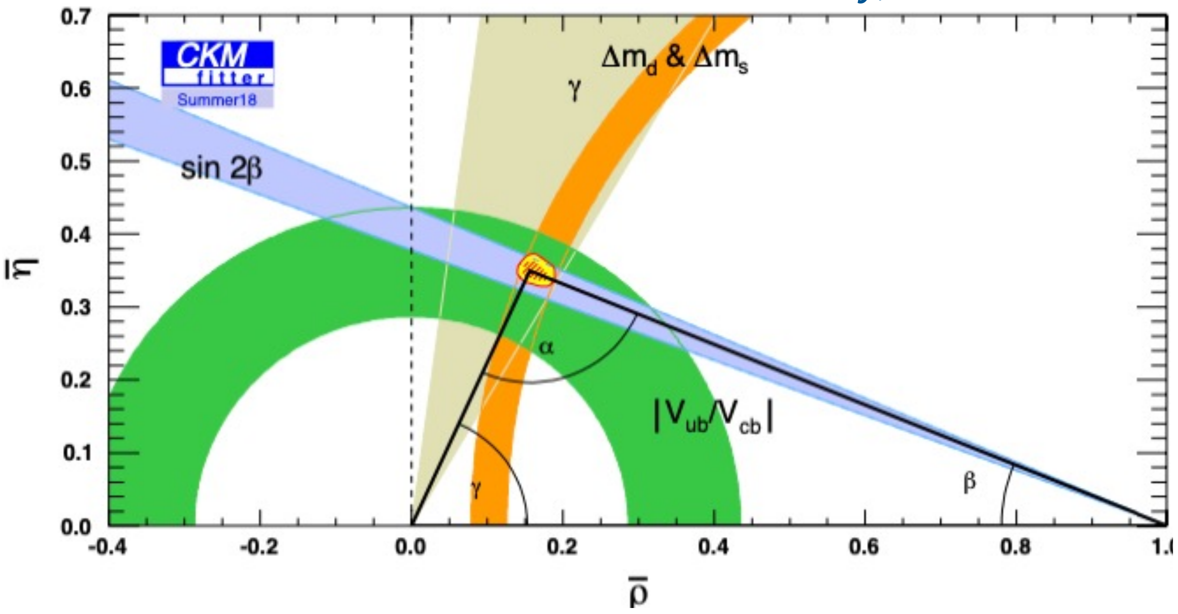
- Full range of beauty & charm mesons & baryons accessible
- Strong results with π^0, photons, missing particles reconstruction
- Beyond Flavour: LHCb as general purpose detector in forward region
- Spectrocopy, EW precision, dark sector and exotic searches, heavy ions and fixed target physics

Constraining the Unitarity Triangle

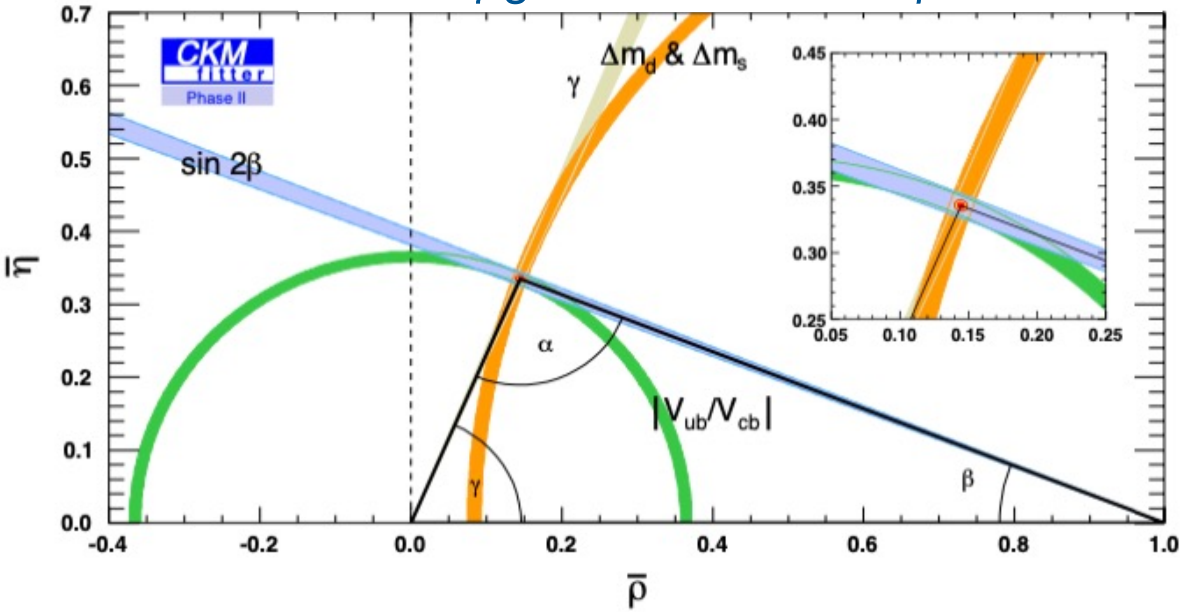
- *Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes*
- *Either NP is very heavy of it has a highly non trivial structure*

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement

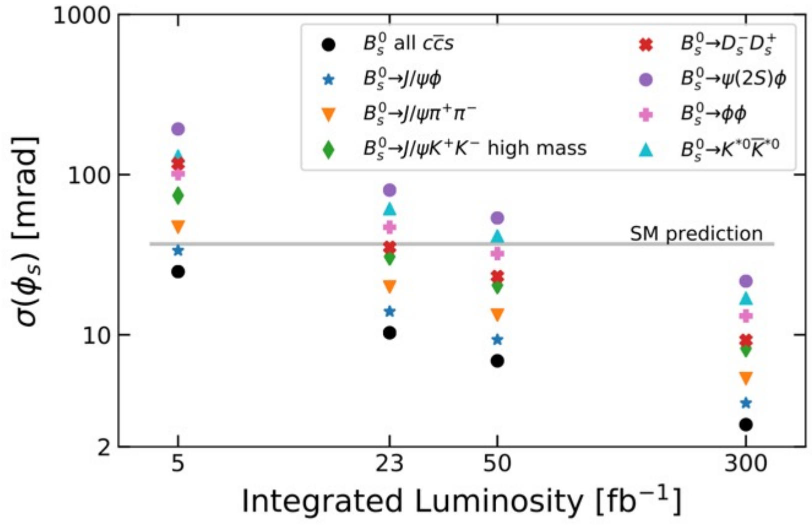


Arguably the greatest likelihood of a further paradigm shifting discovery at the HL-LHC lies with flavour physics

Beauty and Charm CPV Examples

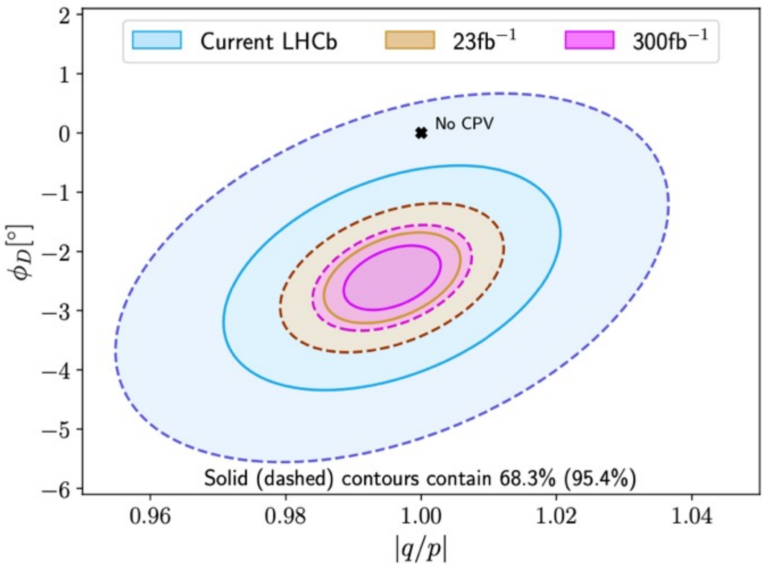
CP violating phase ϕ_s

- Sensitive to new physics – small and well predicted in SM
- Upgrade II sensitivity below SM prediction in multiple channels



CP violation in charm

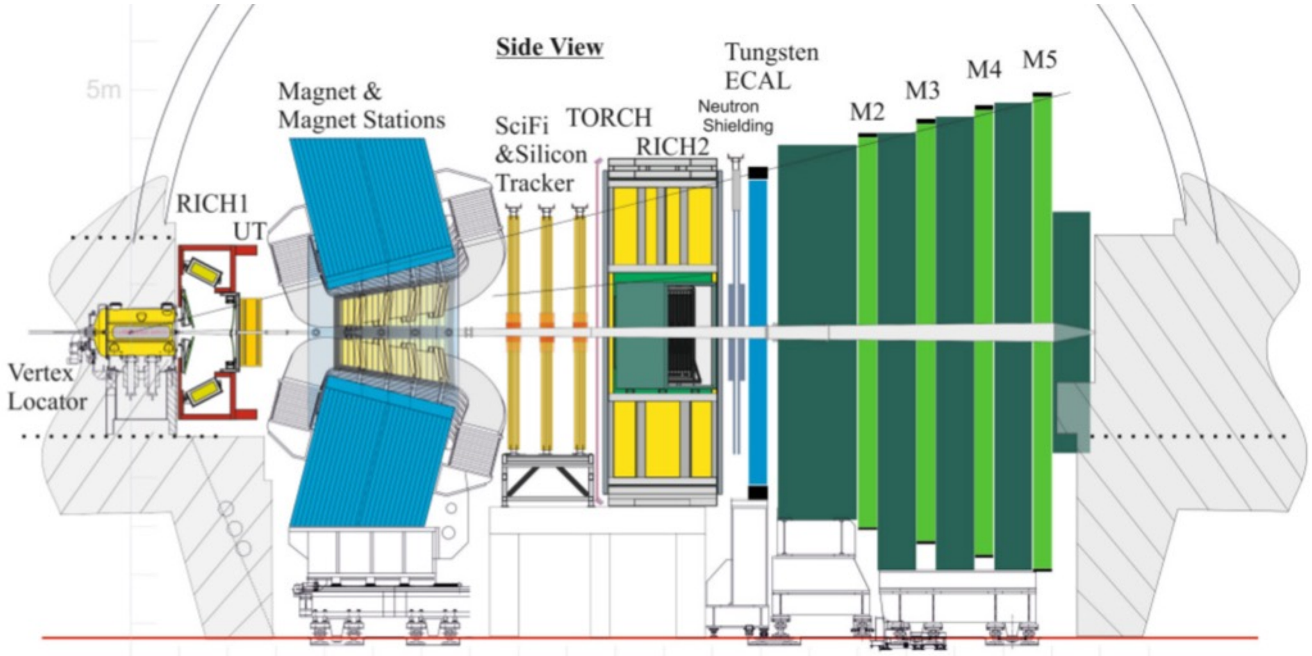
- LHCb Upgrade II is the only planned facility with a realistic possibility to observe CPV in charm mixing *(at >5σ if present central values are assumed)*



Broad programme – Ions, Fixed Target, EW, Dark Sector….

The detector challenge

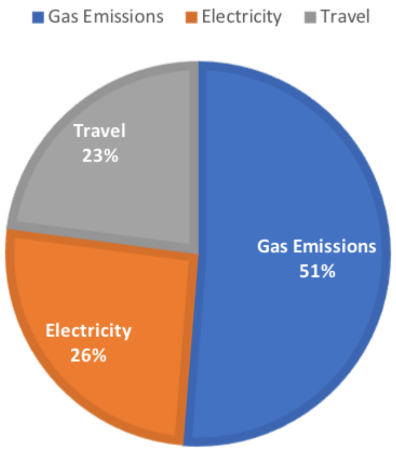
Targeting same performance as in Run 3, but with pile-up ~40!



Same spectrometer footprint, innovative technology for detector and data processing

Key ingredients:

- granularity
- fast timing (few tens of ps)
- radiation hardness

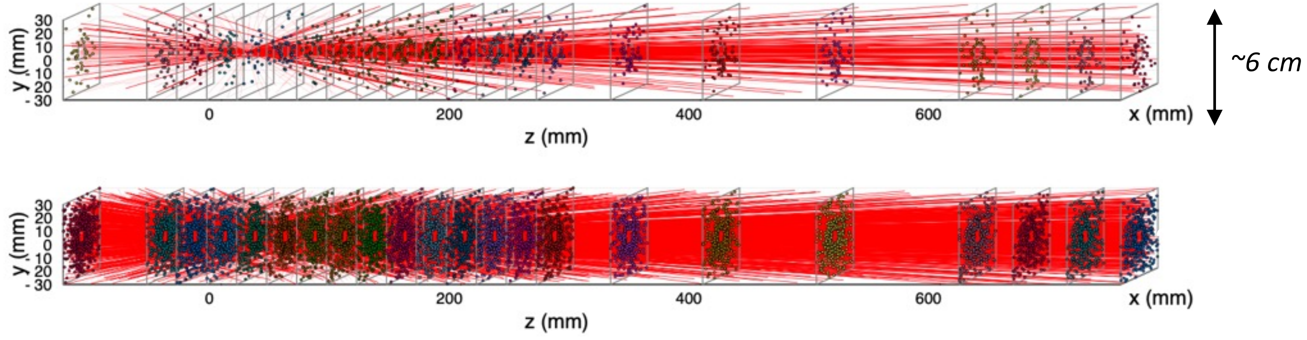


Environmental impact discussed for the first time in a TDR

VErtex LOcator (VELO)

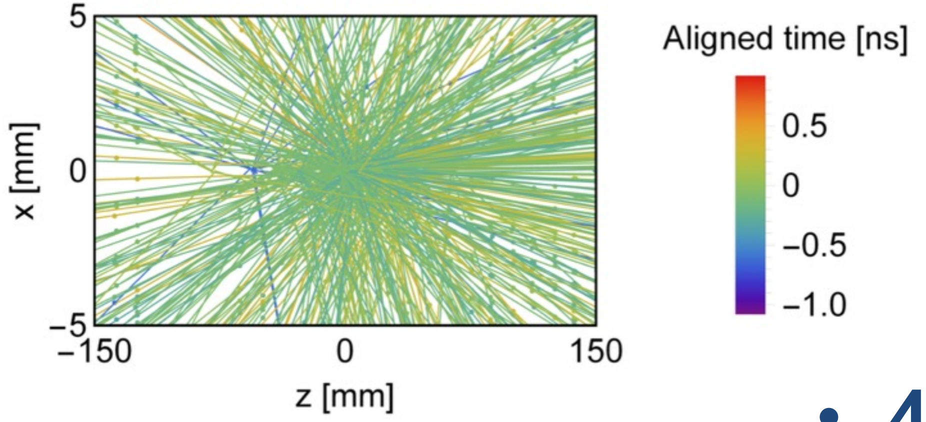
Run 3: pile-up ~6

Upgrade II: pile-up ~42

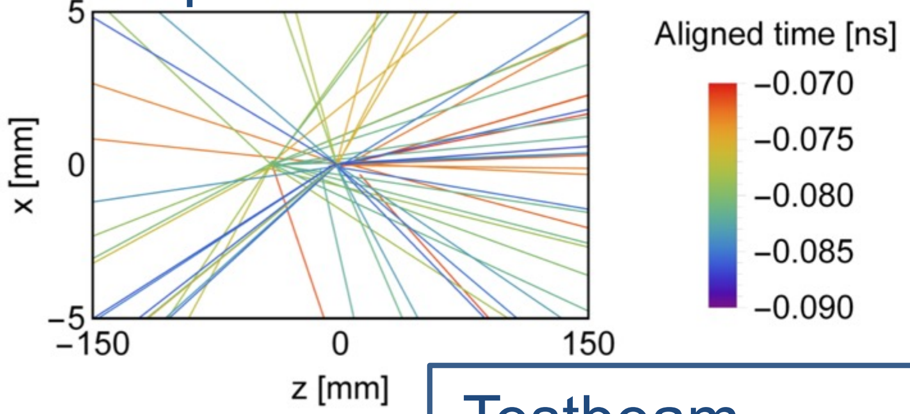


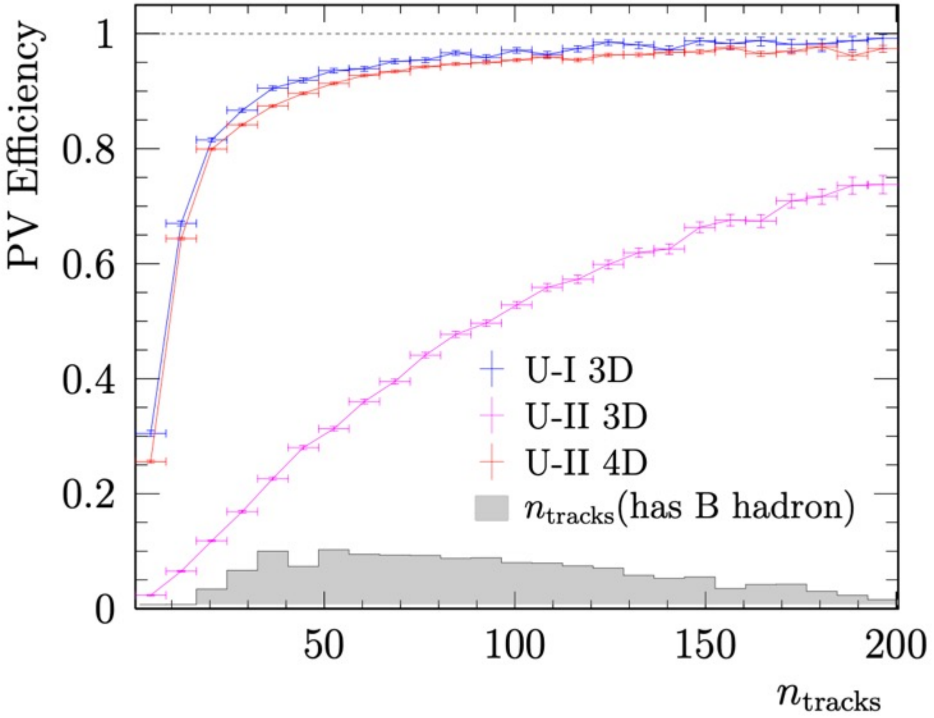
4D Vertexing: Precision Timing

42 interactions

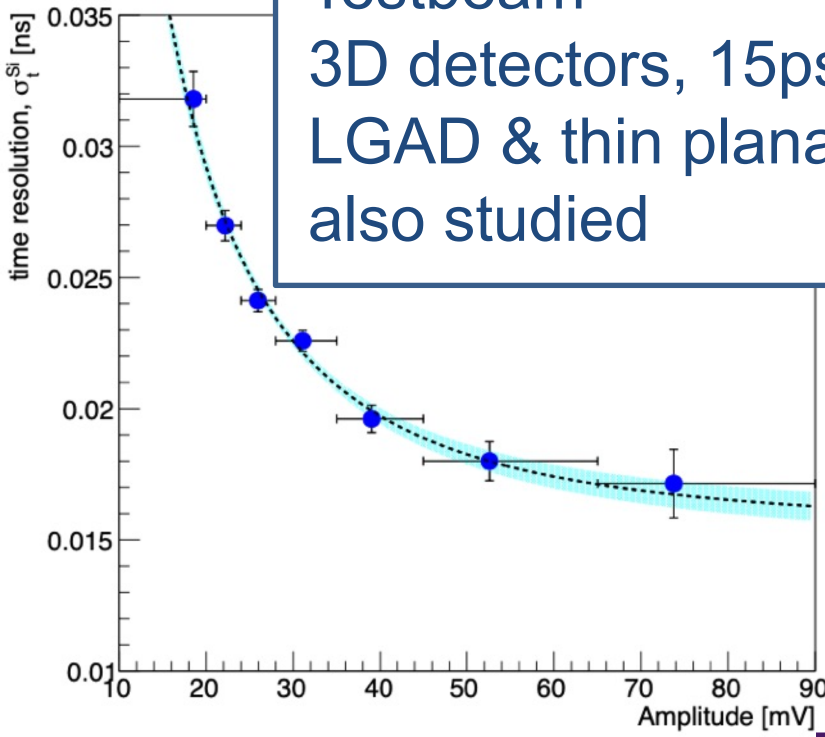


20ps time window





- **4D tracking**
- Ensures similar performance to U1 at U2
  - ~ 50ps, 50μm²
- Extreme lifetime fluence
  - $6{\times}10^{16} n_{eq}/cm^2$

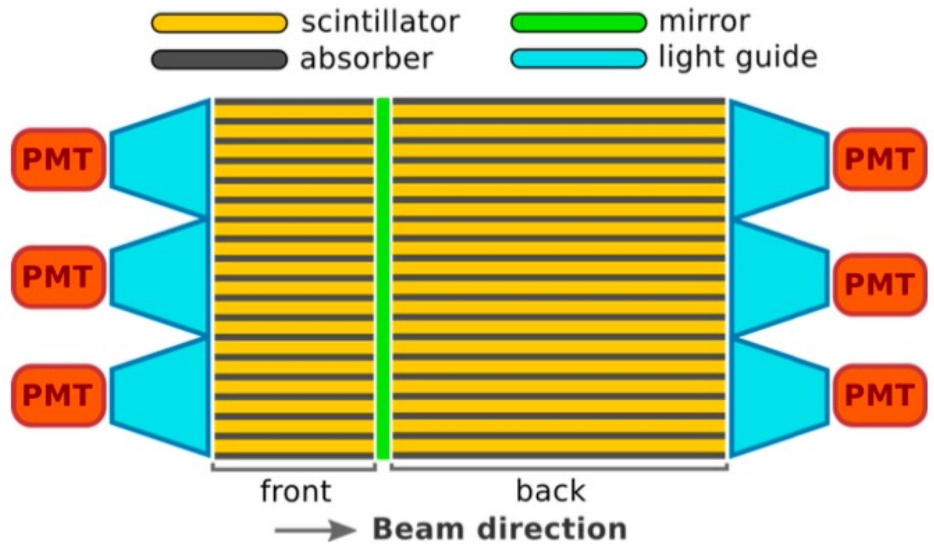


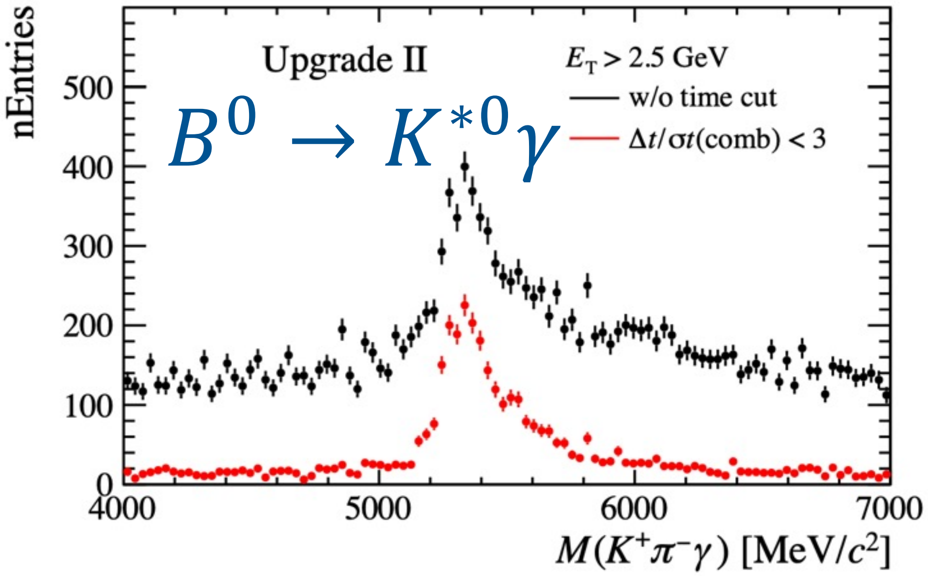
Testbeam
3D detectors, 15ps
LGAD & thin planar also studied

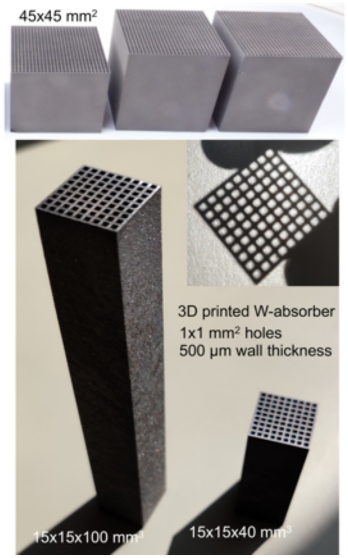
JINST 15 (2020) P09029

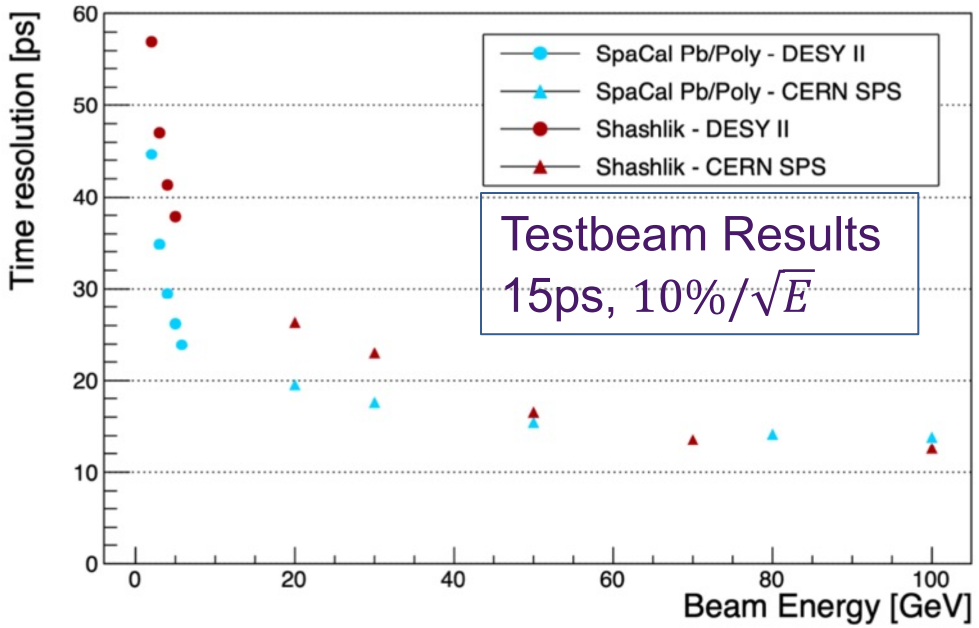
5D Calorimetry: Precision timing

- Goal: achieve energy resolution and reconstruction eff. ~ to Run1&2
  - pile-up, radiation up to 1MGy
- Requires: granularity, precision timing
- Different technologies in different regions
- Crystal fibres R&D for highest fluence regions
- Extensive R&D



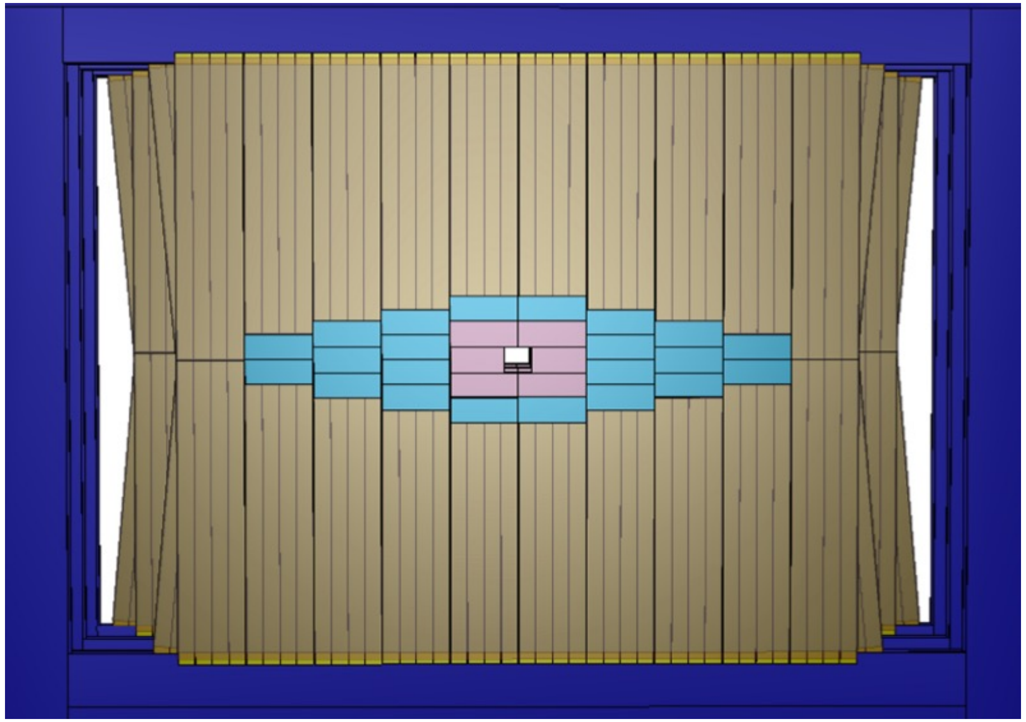


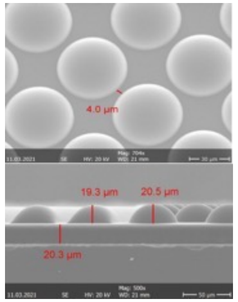


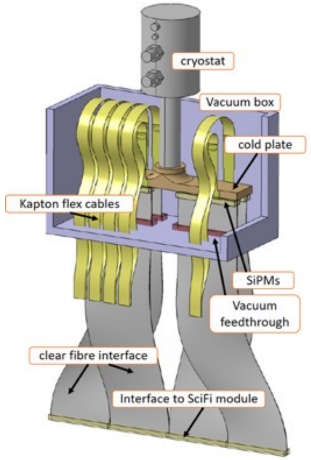


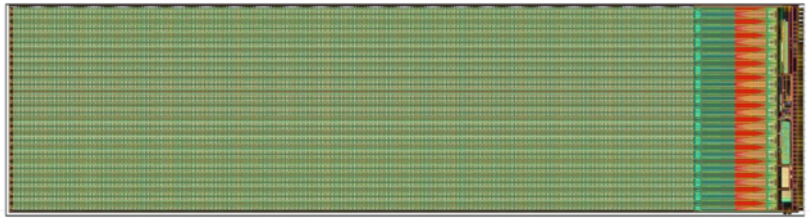
Tracker: Rad Hard MAPs, first of kind at LHC

- UT – before magnet
- Mighty tracker – SciFi+CMOS – after magnet
- Monolithic Active Pixel Sensors $(50\times150\mu m^2)$
  - Radiation requirements in UT $3\times10^{15} n_{eq}/cm^2$
  - low-cost commercial process, low material budget
- Scintillating fibres in outer region
  - radiation-hard fibres, cryogenic cooling, micro-lens enhanced SiPMs

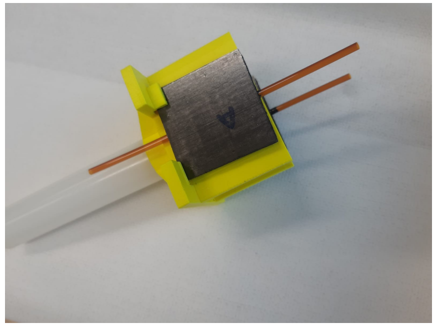








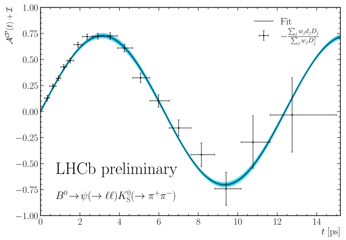
MightyPix1 1/4 scale chip fabricated



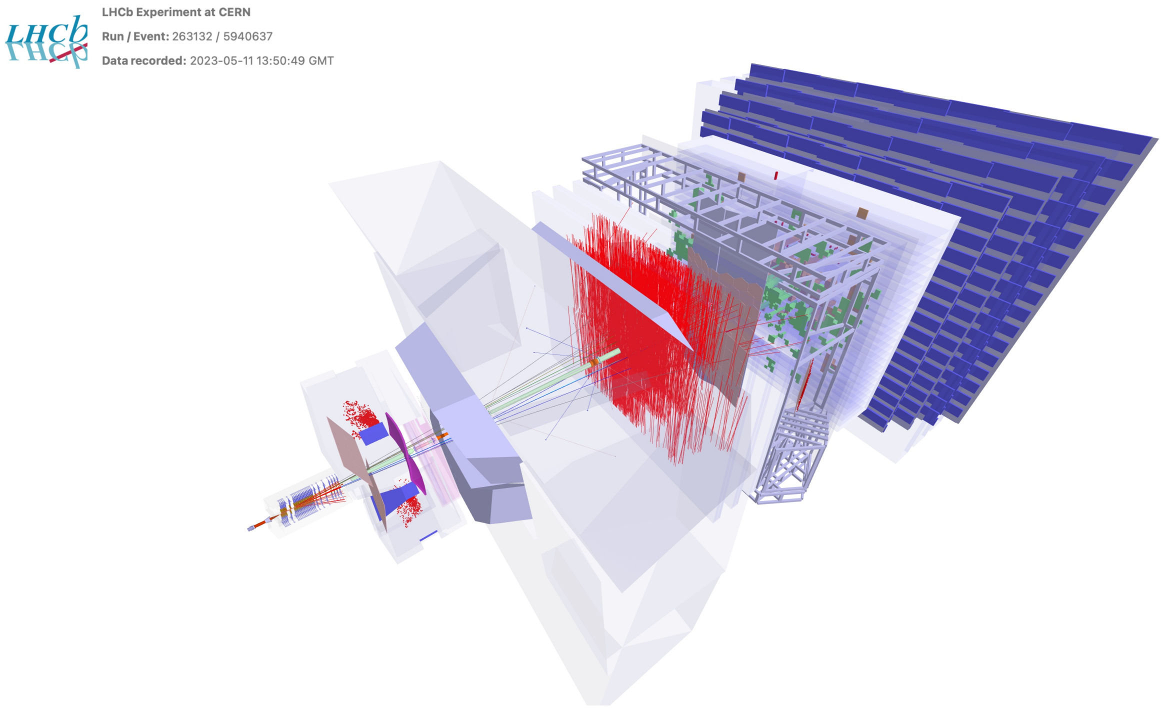
Summary

Original	Upgrade I	Upgrade II
2009-2018	2022-2032	2033-

- LHCb physics
  - > 650 papers so far, many more to come from Run 2 analysis
  - New: sin(2β), ϕ_s



- LHCb Upgrade I
  - Largest CERN particle physics project since LHC completion
  - Despite pandemic completed on-budget and in time for Run 3



- LHCb Upgrade II
  - project taking shape: Framework TDR approved, R&D setting path to future

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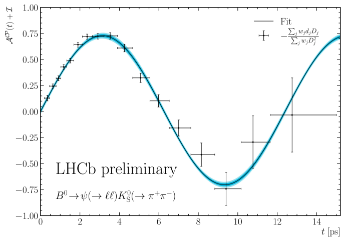

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  - Largest CERN particle physics project since LHC completion
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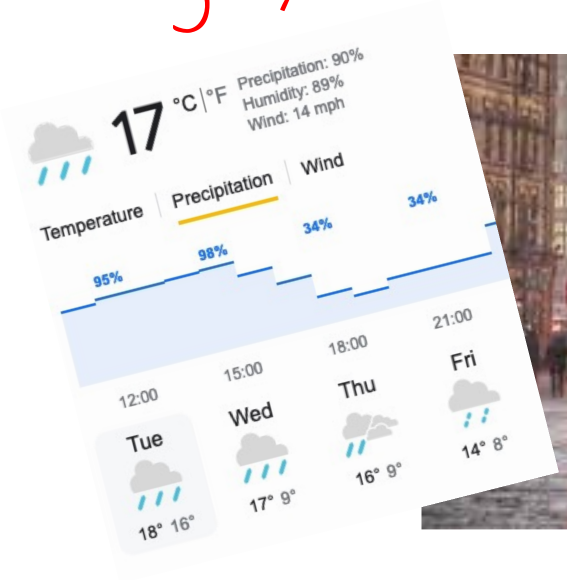
Good to be back in the grayhavens of NW !



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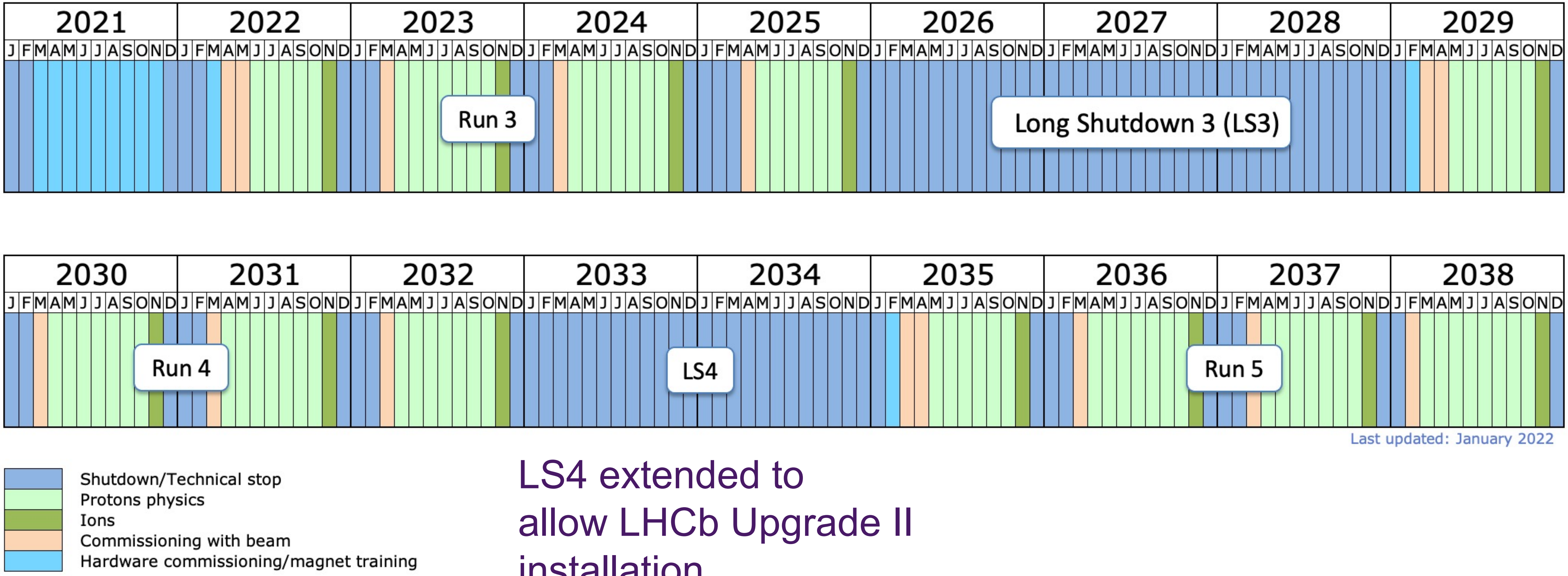
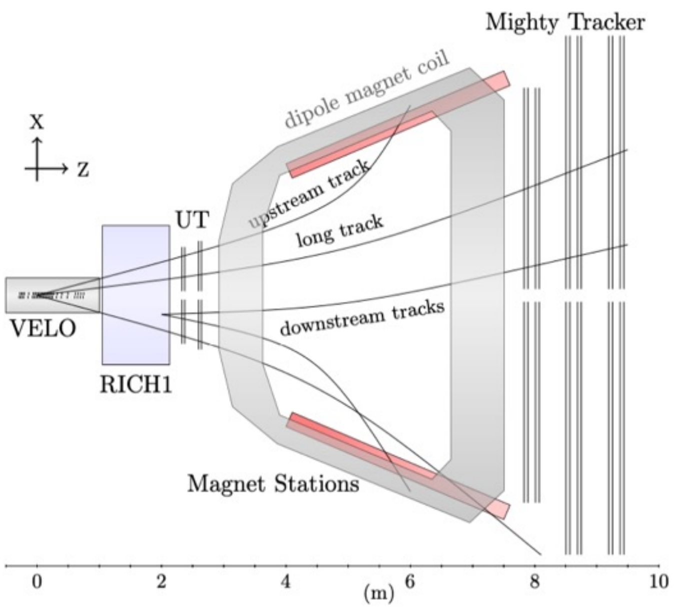
Backup

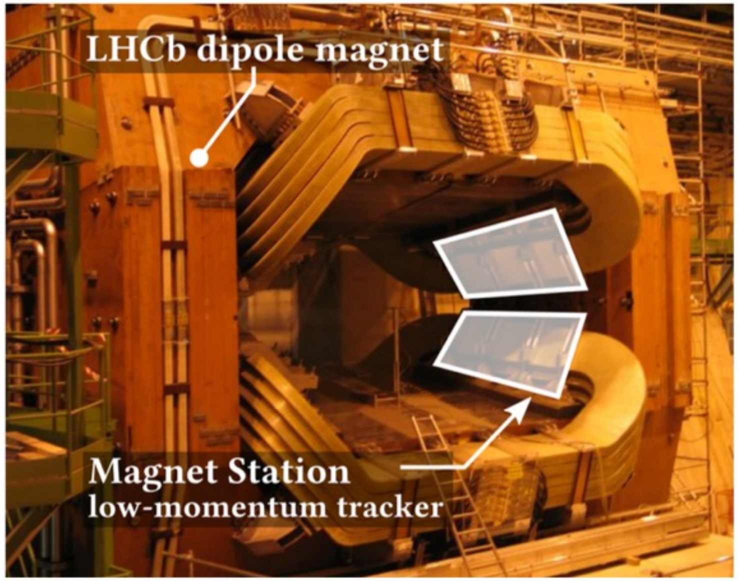
LHC Schedule

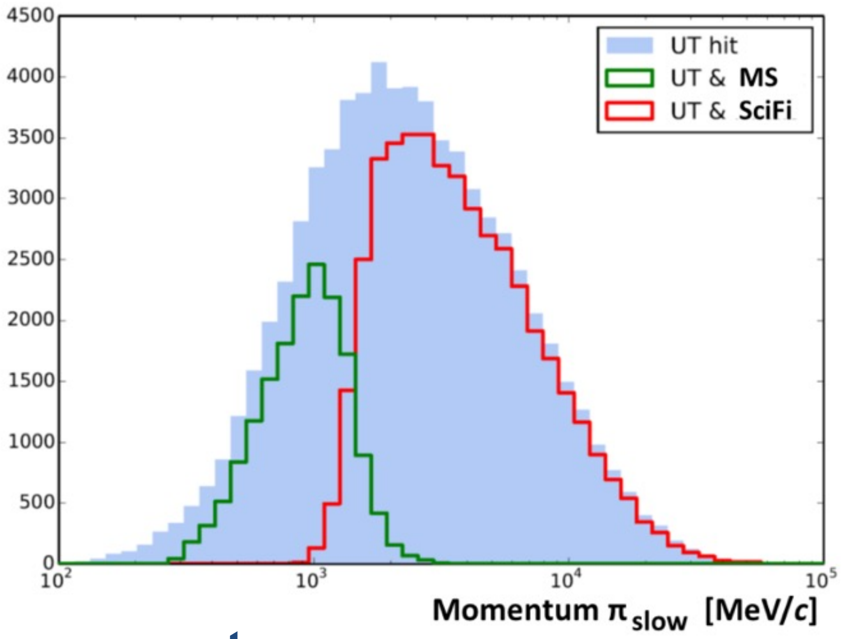


LS4 extended to allow LHCb Upgrade II installation

Magnet Stations: expanding physics potential







- Low momentum particles swept out by magnet
- Instrument walls of magnet with scintillating bars
- Obtain sub-% momentum measurement
- Significant increase of acceptance for low momentum

e.g. factor of ~2 gain in prompt D^{*+} with slow π