The University of Manchester

Chris Parkes presents

an LHCb

Flavour Physics at the start of a new era

13th December 2023

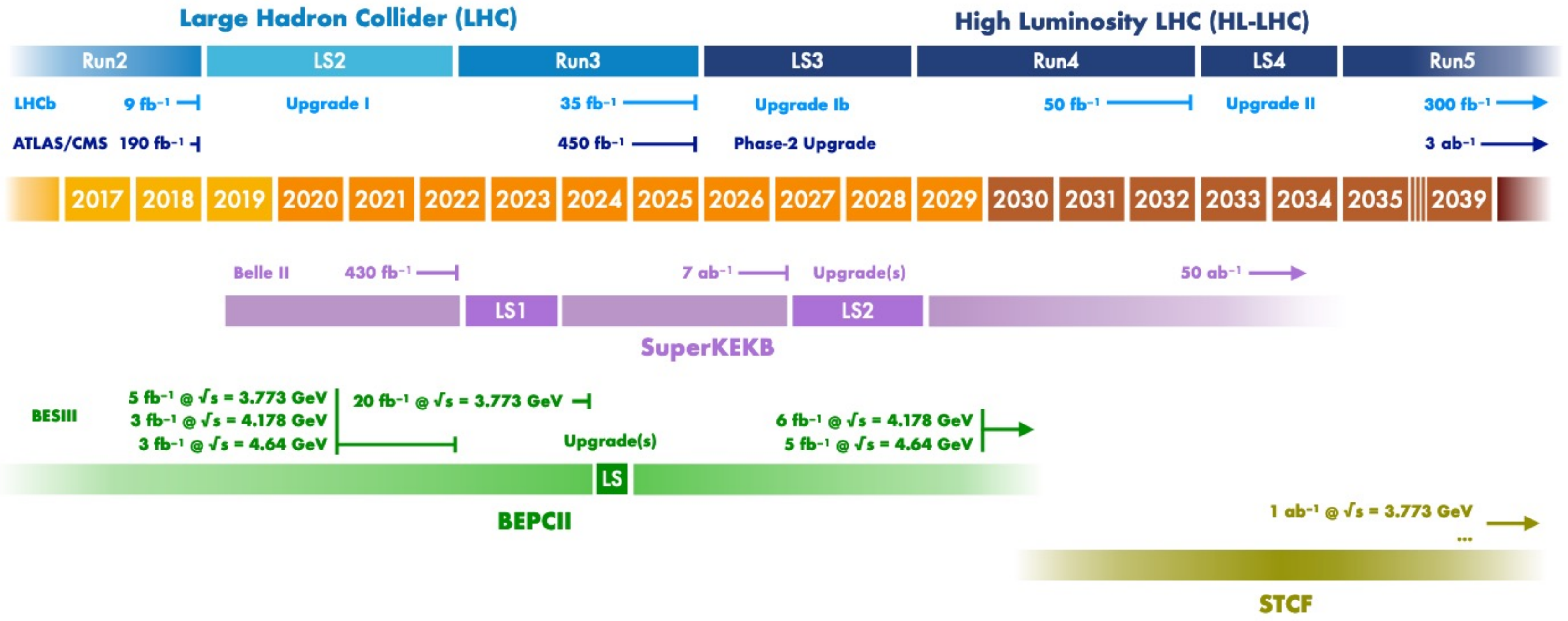
MANCHESTER 1824

The University of Manchester

Chris Parkes

Part I: Experiment Outlook (other than LHCb)

- Kaons
- Charm
- Beauty



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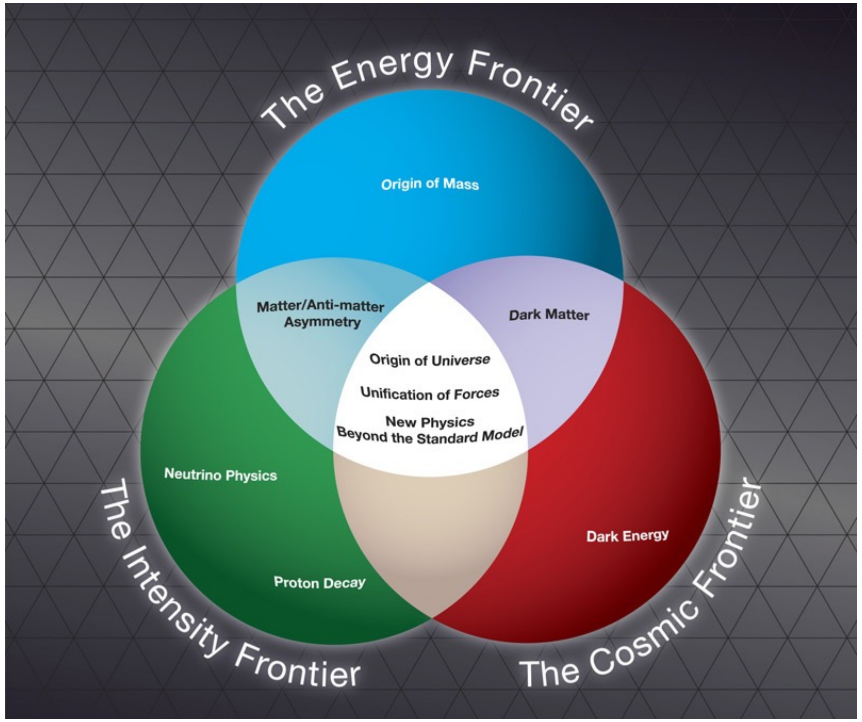
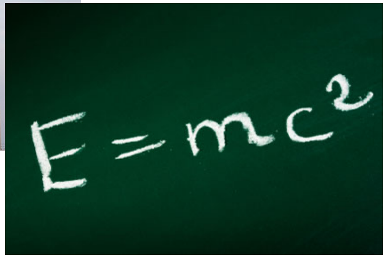
>2045

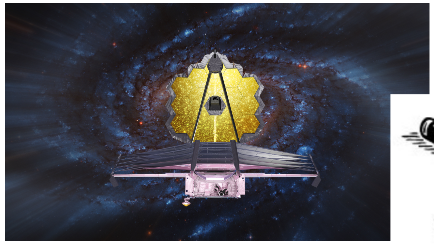
Flavour Physics



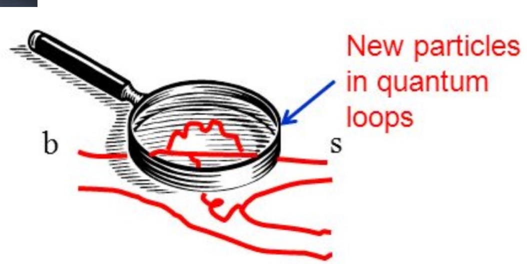
https://science.osti.gov/hep/About/Vision-for-HEP



- **Energy**
- Directly produce new particles and observe from their decays.



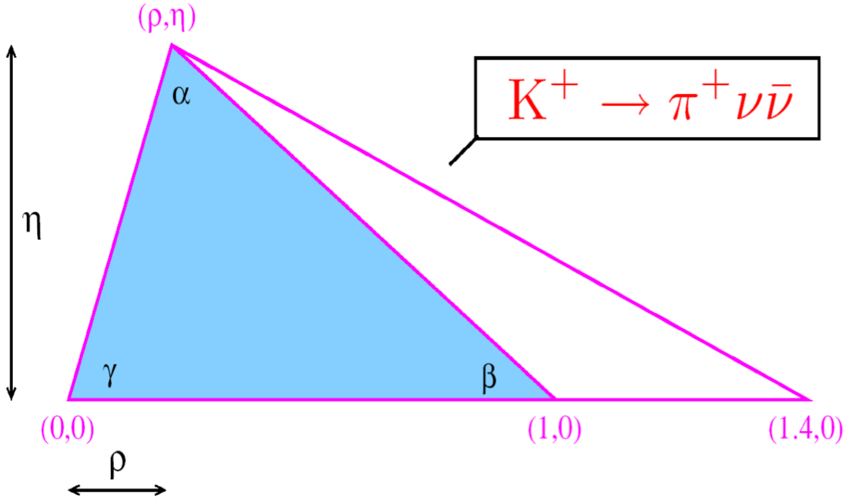
"Quantum Imprints"



- **Intensity**
- Precision measurements and compare with theory

Kaon Physics

With thanks to Cristina Lazzeroni for info. on following slides



arXiv:1408.0728

Can we reach the Zeptouniverse with rare K and $B_{s,d}$ decays?

arXiv:2210.04765

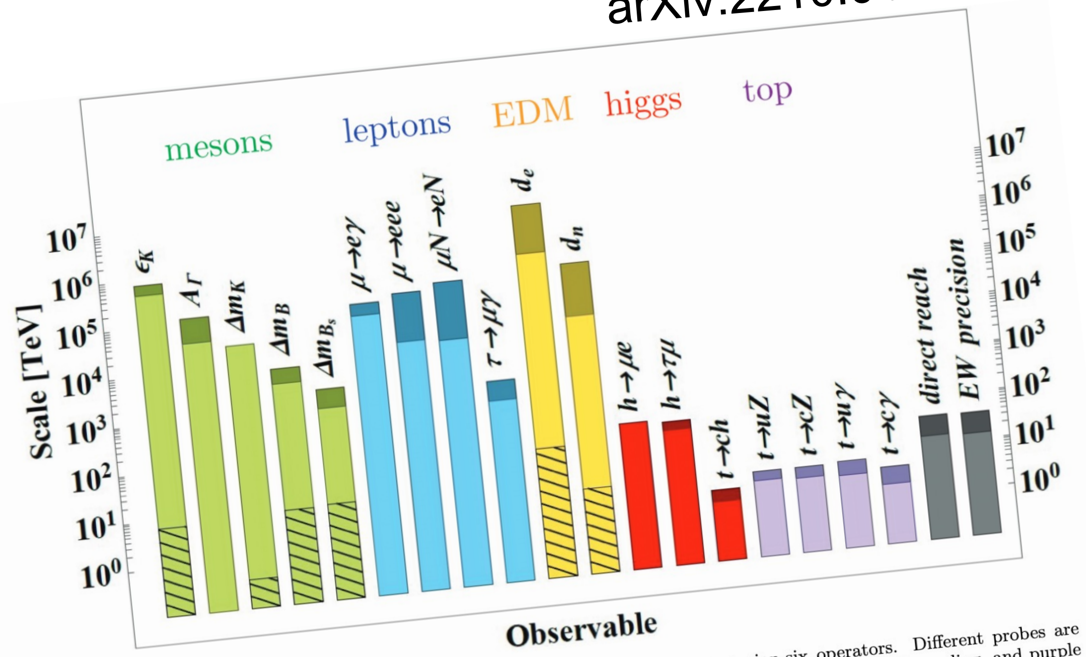
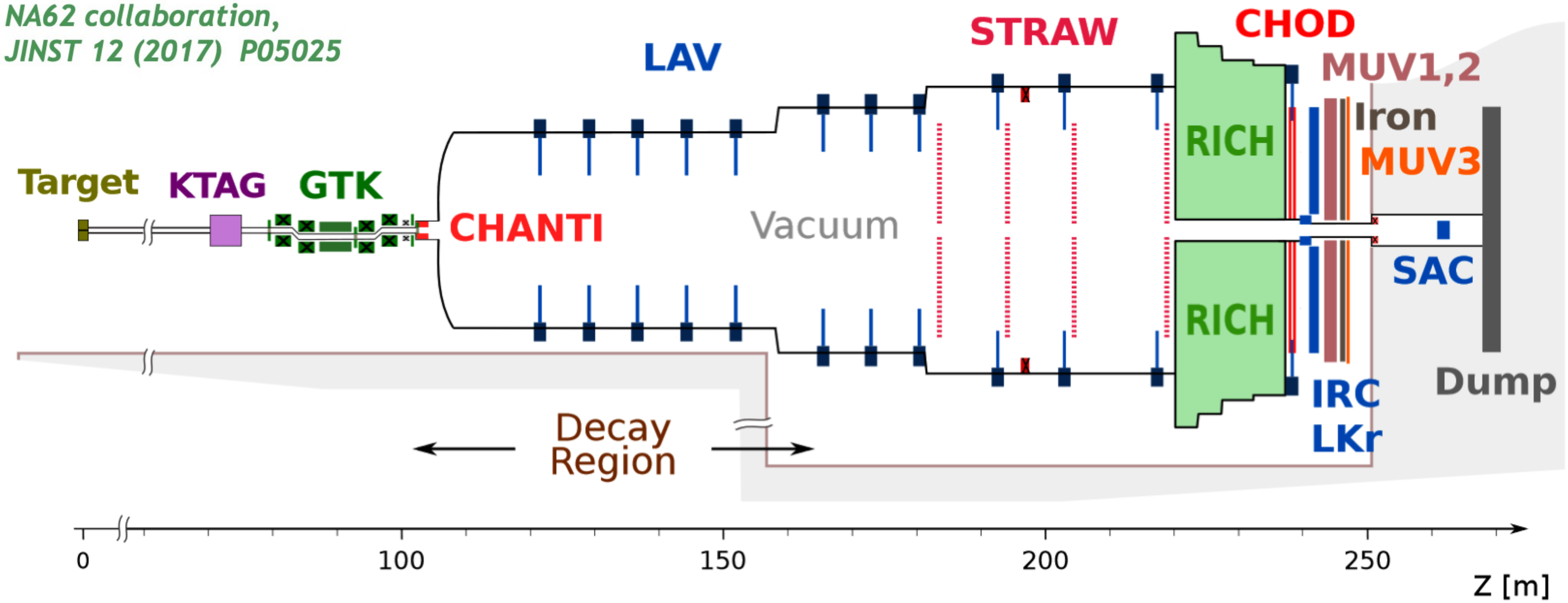


FIG. 1. Reach in new physics of present and future facilities, from generic dimension-six operators. Different probes are identified by color coding: green is for mesons, blue for leptons, yellow for EDMs, red for Higgs flavored coupling, and purple for the top quark. The grey columns illustrate the reach of direct searches and electroweak precision studies. The coupling coefficients of these operators are taken to be of $\mathcal{O}(1)$ in the solid color columns or suppressed by MFV factors (hatch-filled surfaces). Light colors correspond to present data, and dark colors correspond to mid-term prospects in the time scale of the HL-LHC [17, 18].

- Small number of kaon decay modes
- Simple final states
- Ease of producing intense kaon beams
- Can probe unprecedented mass scales

Kaons - NA62 at CERN. Detector

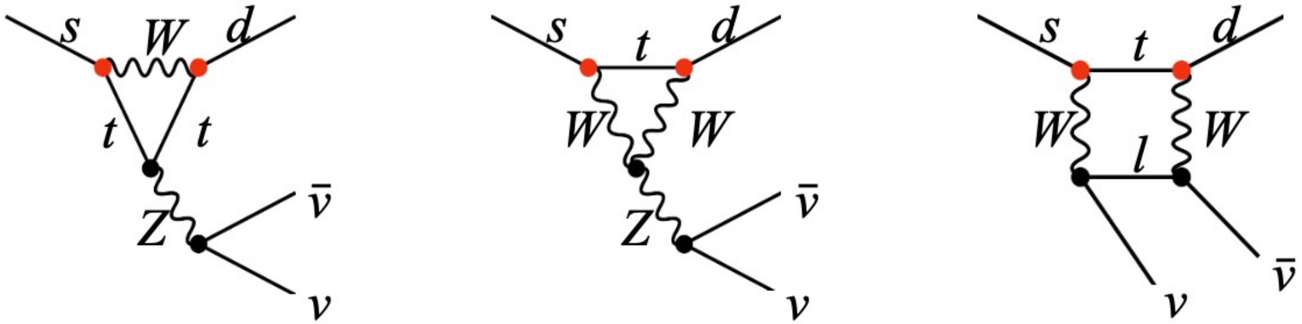


- K decay volume – hence 300m long !
- Kaons: KTAG – Cherenkov kaon tagger, GTK – silicon tracker
- Decay products – Straw tracker, RICH, Calorimeters

Kaons - NA62 at CERN. Physics Results & Aims

Ultra-rare Kaon Decays $K \rightarrow \pi\nu\bar{\nu}$

JHEP 06 (2021) 093

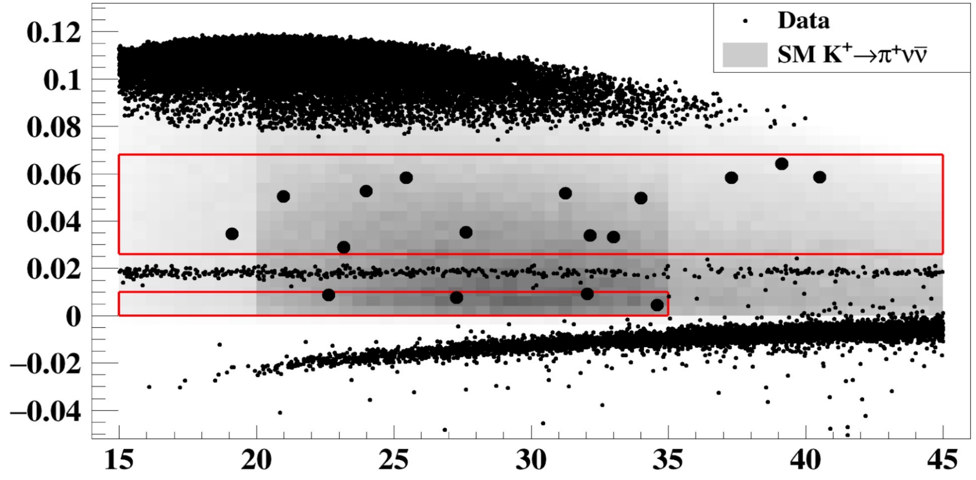


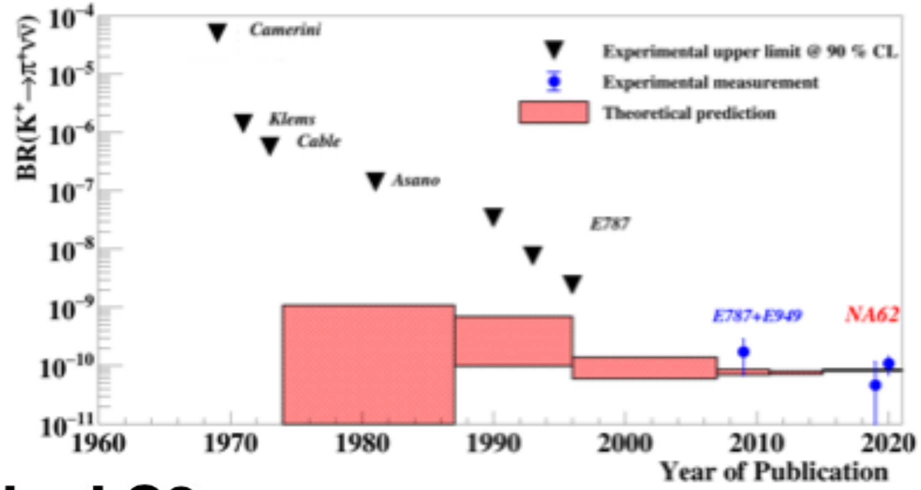
A high-order process with highest CKM suppression:

$A \sim (m_t/m_W)^2 |V^*_{ts}V_{td}| \sim \lambda^5$

Extremely rare decays, rates very precisely predicted in SM
"Free" from hadronic uncertainties. Exceptional SM precision

$\mathrm{BR}(K^+ \rightarrow \pi^+\nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \mathrm{stat}} \pm 0.3_{\mathrm{syst}})\times 10^{-11}$ 3.5σ significance from first results



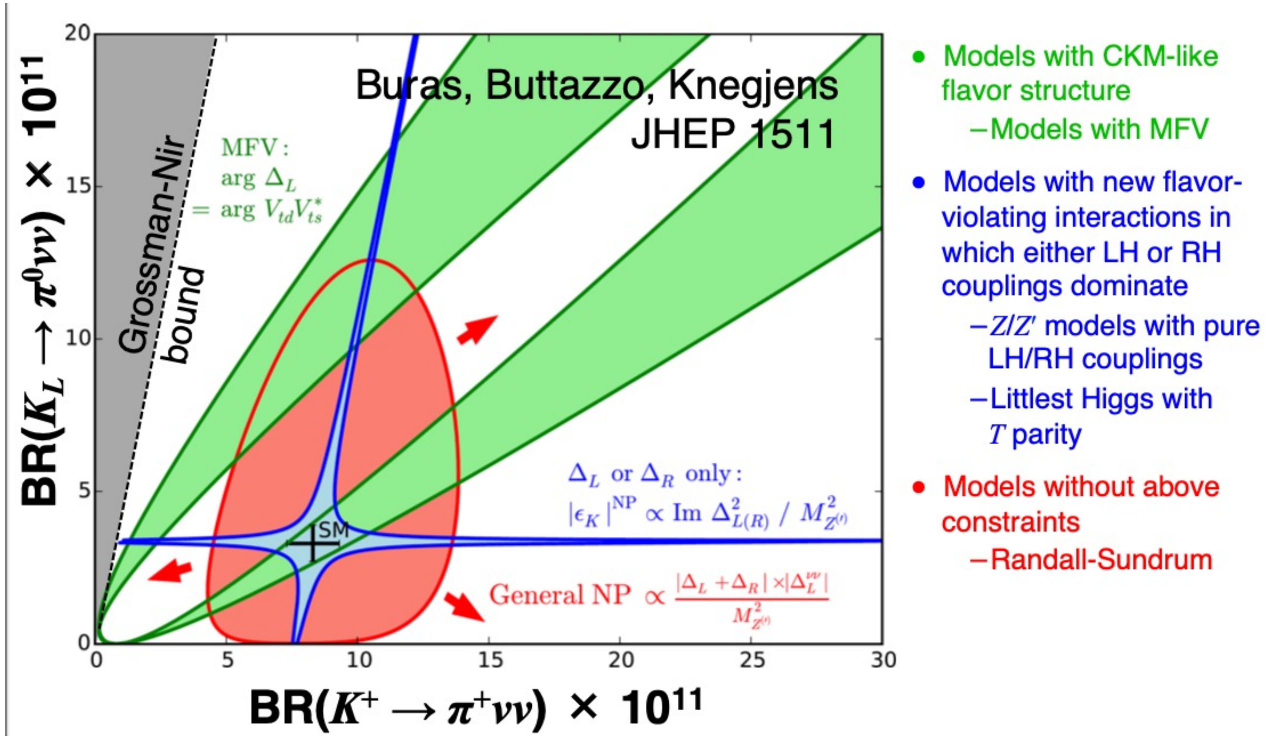


Measure $\mathrm{BR}(K^+ \rightarrow \pi^+\nu\nu)$ to O(10%) by LS3 (2026)

HIKE – Future Kaon Physics Programme at CERN

arXiv:2211.16586

- CERN approving an upgrade to an SPS beamline (ECN3) – ~5 times intensity
- One of the proposals for use of this is HIKE



Phase 1:

$B(K^+ \to \pi^+\nu\bar{\nu})$ to O(5%) precision

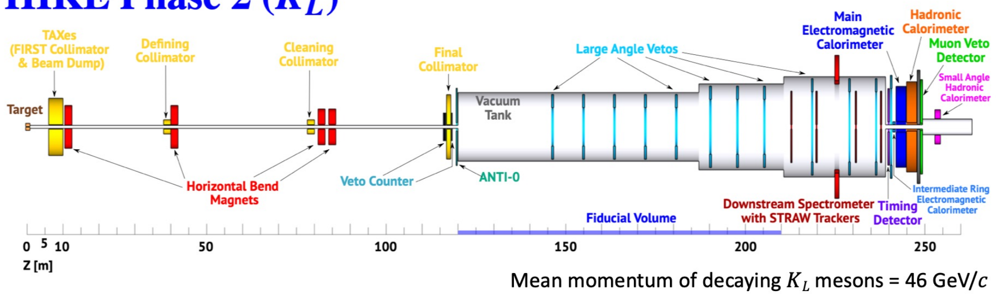
Phase 2:

First observation of the $K_L \to \pi^0 l^+ l^-$

Phase 3: KLEVER (nothing-to-nothing!)

$B(K_L \to \pi^0\nu\nu)$ to O(20%) precision

HIKE Phase 2 (K_L)



Also JPARC KOTO Experiment (Phys. Rev. Lett. 126, 121801) for $K_L \to \pi^0\nu\nu$

No decision yet

HIKE
High Intensity Kaon Experiments

SHADOWS
Search for Hidden And Dark Objects With the SPS

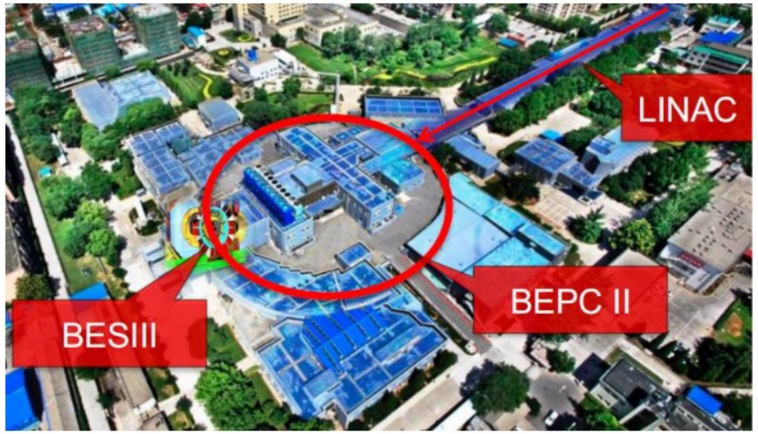
Vs

SHiP
Search for Hidden Particles

Charm dedicated facilities – BESIII at IHEP, Beijing

arXiv:1912.05983

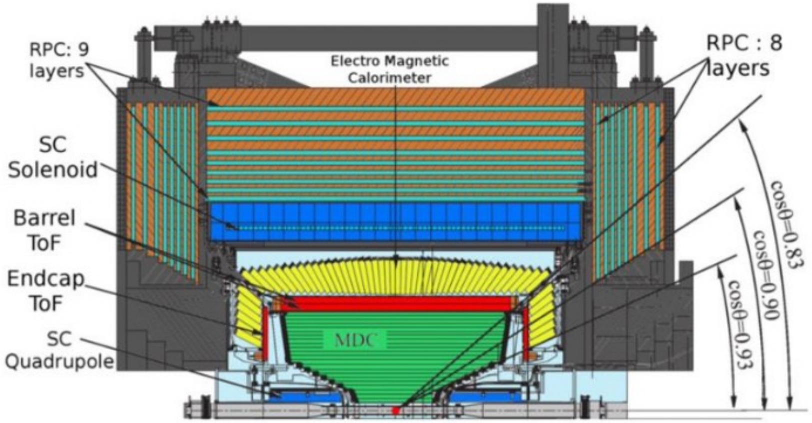
- LHCb dominates charm statistics and with boost -but **BESIII** has unique properties



D^0 Strong Phase Difference in γ/ϕ_3

Quantum entangled threshold charm mesons at threshold:

- Tag one meson in a CP eigenstate
- Sensitivity to strong phases, CP fraction in other meson decay.
- Vital input to γ measurement and charm mixing studies at LHCb & Belle II.



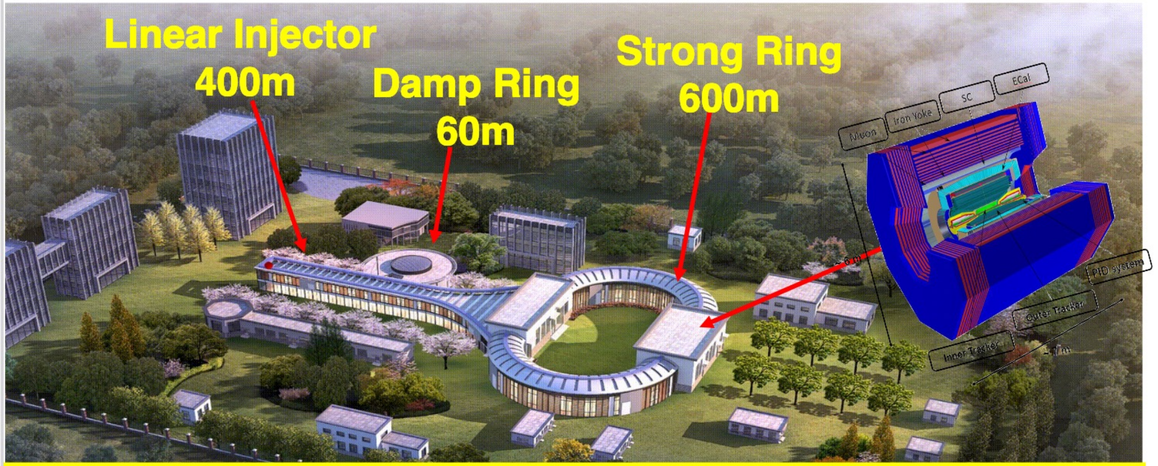
Hadron Spectroscopy and Exotic Hadrons

Nature of exotic hadrons much debated:

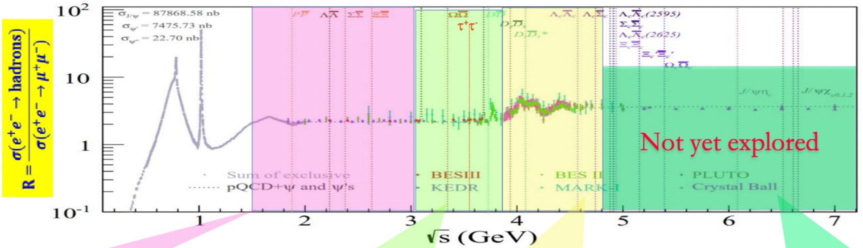
- Different production mechanism
- Low backgrounds

Charm dedicated facilities – Super Charm-Tau in China?

With thanks to Yangheng Zheng, Charm 2023



- E_{cm}=2-7GeV， L=0.5×10^{35} cm^{-2} s^{-1}



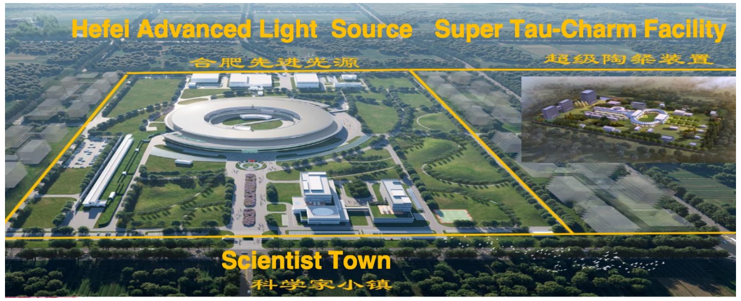
- Nucleon/Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

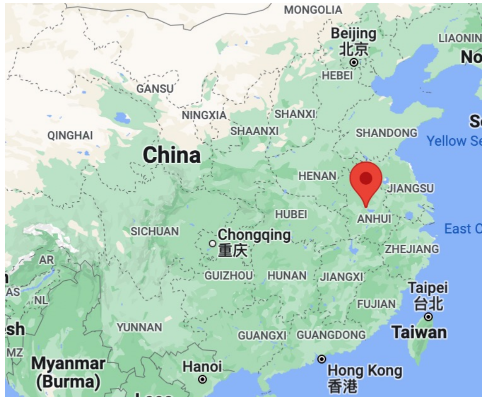
- LH spectroscopy
- Gluonic and exotic
- LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{D_s}
- D_0-$\bar{D}_0$ mixing
- Charm baryons

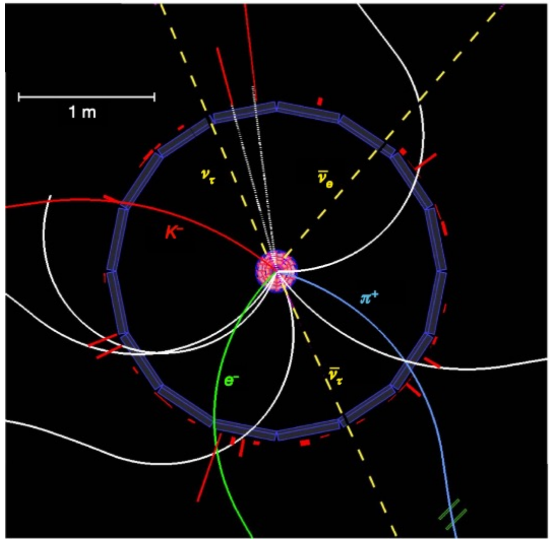
- New XYZ particle
- Hidden-charm pentaquark
- Multiquark state
- Di-charmonium state
- Charm baryons
- Hadron fragmentation

- Proposed new facility arXiv:2303.15790
- Build on BESII success, two orders of magnitude higher luminosity
- Apply to Chinese government for construction funding in 2026-2030

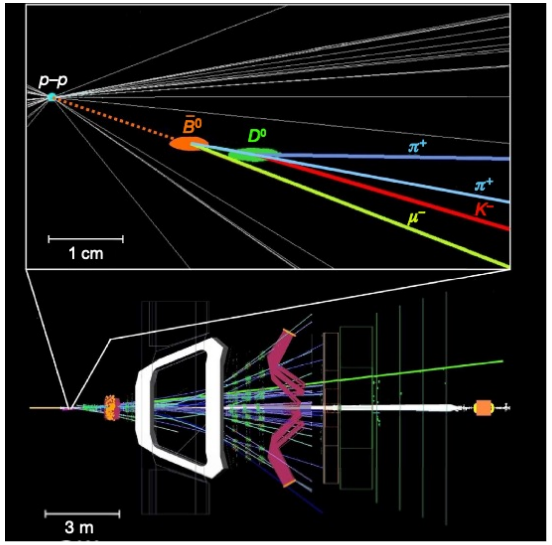




Beauty dedicated facilities – threshold e^+e^- or p-p



$\Upsilon(4S) \to B^+B^-$
$B^- \to D^0\tau^-\bar{\nu}_\tau$
$D^0 \to K^-\pi^+$
$\tau^- \to e^-\nu_\tau\bar{\nu}_e,$

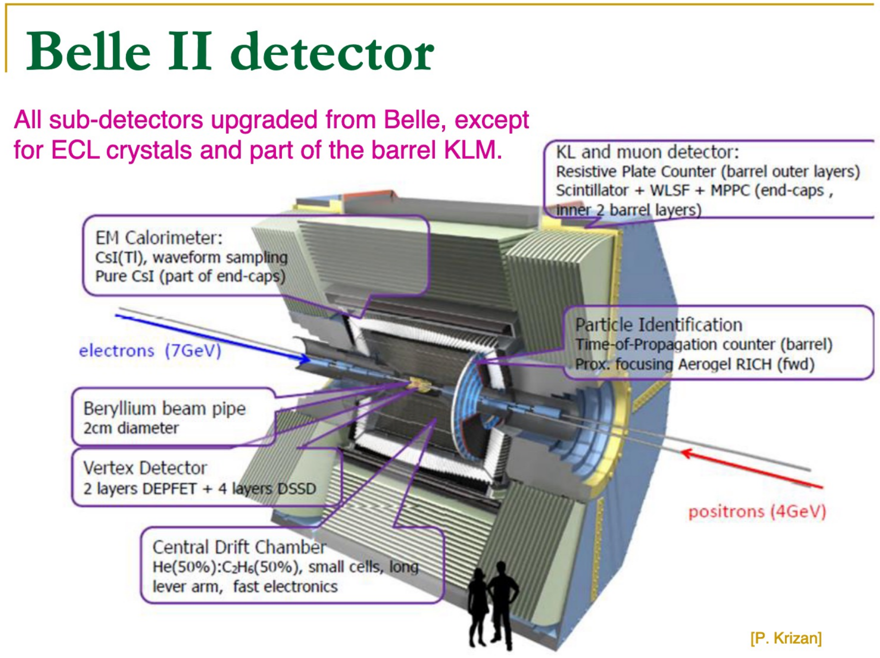


$B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$
$D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$

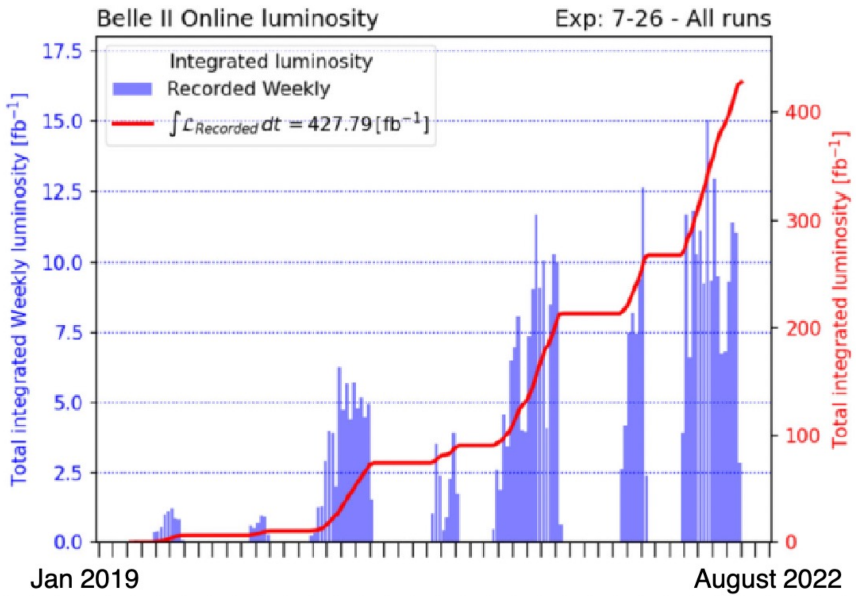
- Clean environment
  - – no additional tracks
- Initial state
  - – B^0B^0 or B^+B^-
- B mesons ~ 20% σ_{tot}
  - – simpler triggering

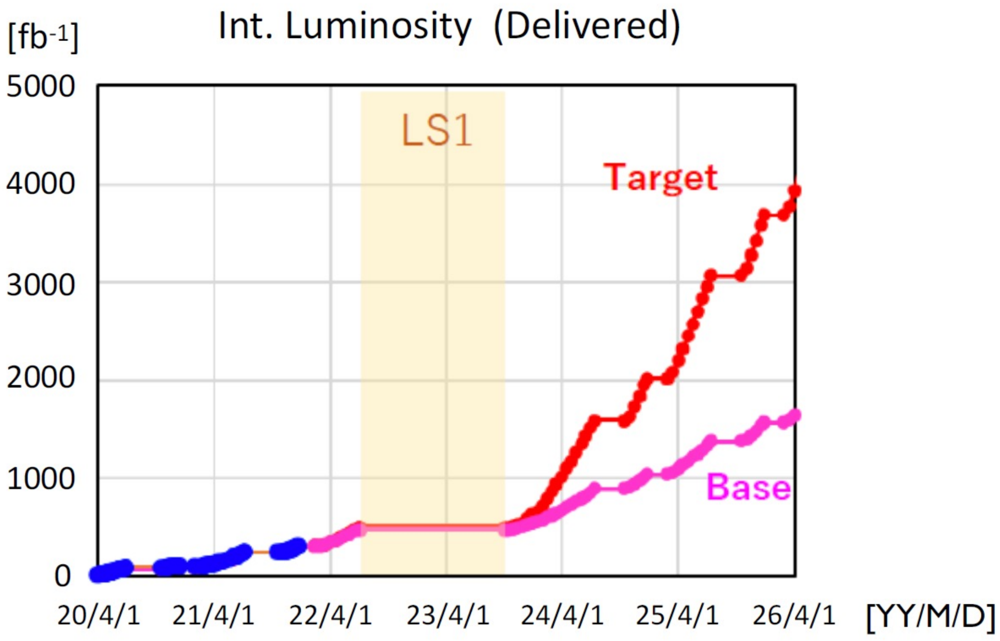
- Huge production rates
  - – pp fb^{-1} ~ e^+e^- ab^{-1}
- All Beauty hadrons species
  - – $B^0,B^+,B_s,B_c,\Lambda_b$
- Large boost factor
  - – Time resolution

Beauty dedicated facilities – Belle II Detector



- Asymmetric beam energy e^+e^- at $\Upsilon(4S)$
  - B Bbar with boost
- Aim to collect $50ab^{-1}$ by mid-2030s
- Luminosity has been below expectations
  - Current sample 0.4 ab^{-1} (cf. Belle 0.7 ab^{-1})

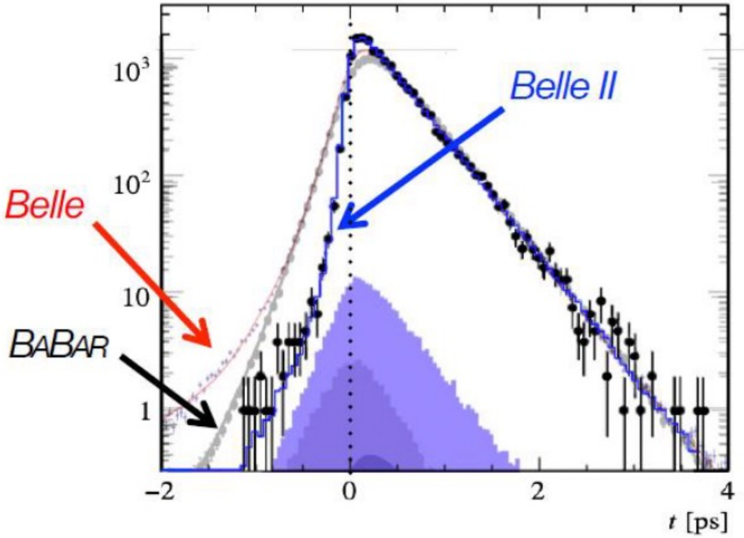




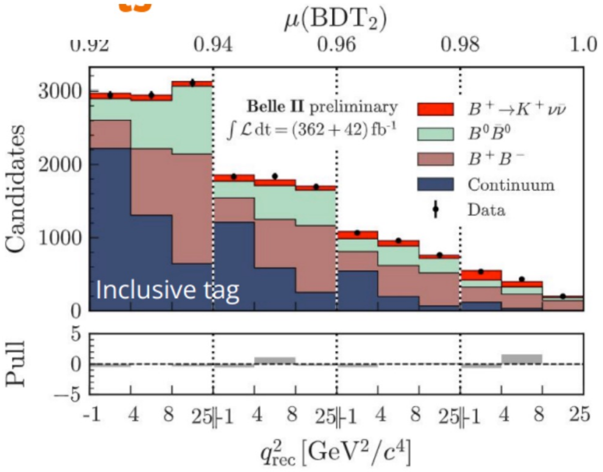
Beauty dedicated facilities – Belle II Results & Prospects

- Detector performance demonstrated
  - And full pixel detector installed in current shutdown
- Initial results with some world bests

Improved time resolution



$B^+ \to K^+ \nu\bar{\nu}$



Combined result

- **Evidence @ 3.6σ**
- **Tension with SM (0.6×10^{-5}) @ 2.8σ**

arXiv:1808.10567

Observables	Expected the. accuracy	Expected exp. uncertainty
UT angles & sides		
ϕ_1 [°]	***	0.4
ϕ_2 [°]	**	1.0
ϕ_3 [°]	***	1.0
$\lvert V_{cb}\rvert$ incl.	***	1%
$\lvert V_{cb}\rvert$ excl.	***	1.5%
$\lvert V_{ub}\rvert$ incl.	**	3%
$\lvert V_{ub}\rvert$ excl.	**	2%
CP Violation		
$S(B\to\phi K^0)$	***	0.02
$S(B\to\eta' K^0)$	***	0.01
$\mathcal{A}(B\to K^0\pi^0)[10^{-2}]$	***	4
$\mathcal{A}(B\to K^+\pi^-)$ $[10^{-2}]$	***	0.20
(Semi-)leptonic		
$\mathcal{B}(B\to\tau\nu)$ $[10^{-6}]$	**	3%
$\mathcal{B}(B\to\mu\nu)$ $[10^{-6}]$	**	7%
$R(B\to D\tau\nu)$	***	3%
$R(B\to D^*\tau\nu)$	***	2%
Radiative & EW Penguins		
$\mathcal{B}(B\to X_s\gamma)$	**	4%
$A_{CP}(B\to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005
$S(B\to K^0_S\pi^0\gamma)$	***	0.03
$S(B\to\rho\gamma)$	**	0.07
$\mathcal{B}(B_s\to\gamma\gamma)$ $[10^{-6}]$	**	0.3
$\mathcal{B}(B\to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%
$R(B\to K^*\ell\ell)$	***	0.03
Charm		
$\mathcal{B}(D_s\to\mu\nu)$	***	0.9%
$\mathcal{B}(D_s\to\tau\nu)$	***	2%
$A_{CP}(D^0\to K^0_S\pi^0)$ $[10^{-2}]$	**	0.03
$\lvert q/p\rvert(D^0\to K^0_S\pi^+\pi^-)$	***	0.03
$A_{CP}(D^+\to\pi^+\pi^0)$ $[10^{-2}]$	**	0.17
Tau		
$\tau\to\mu\gamma$ $[10^{-10}]$	***	< 50
$\tau\to e\gamma$ $[10^{-10}]$	***	< 100
$\tau\to\mu\mu\mu$ $[10^{-10}]$	***	< 3

Broad programme Belle II at 50 ab^{-1} highly competitive with LHCb Upgrade I at 50fb^{-1}

Notably:

- States difficult at LHCb (e.g. neutrals)
- Similar projections on γ and semi-leptonics

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

Part II: LHCb Trilogy

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

Chris Parkes

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2020-2023: Three special years…

With its challenges….

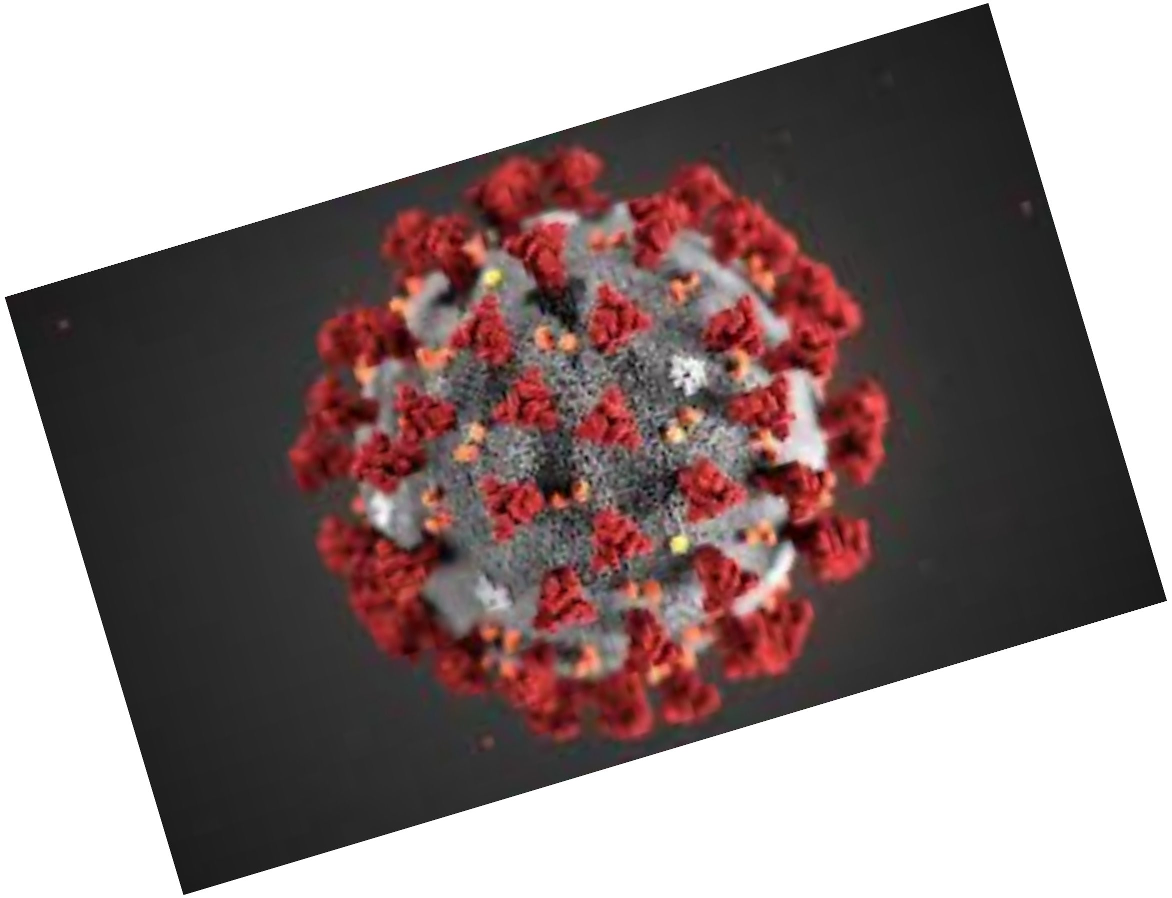
LHCb Upgrade

- 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….



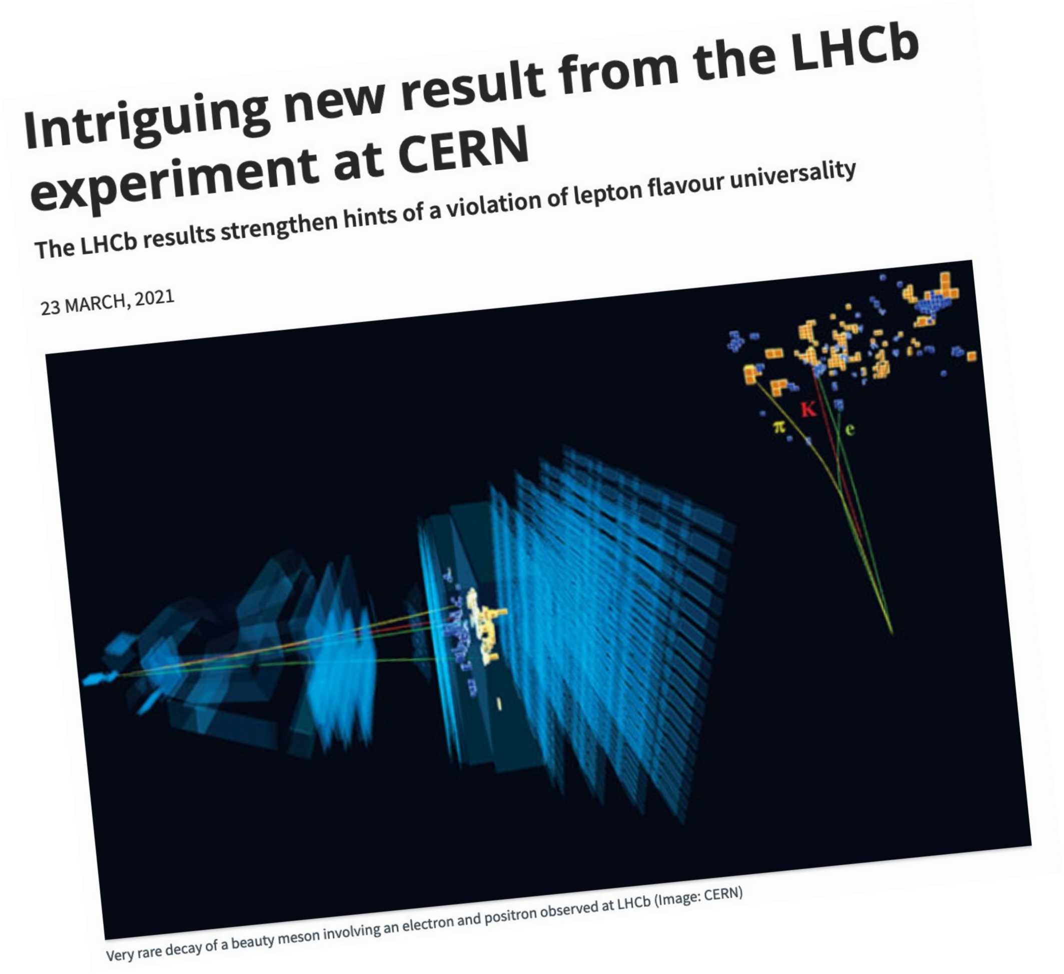
Started in covid lockdown of 2020:
- Daily crisis meetings

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 new result from the LHCb experiment at CERN

The LHCb results strengthen hints of a violation of lepton flavour universality

23 MARCH, 2021

Very rare decay of a beauty meson involving an electron and positron observed at LHCb (Image: CERN)

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….

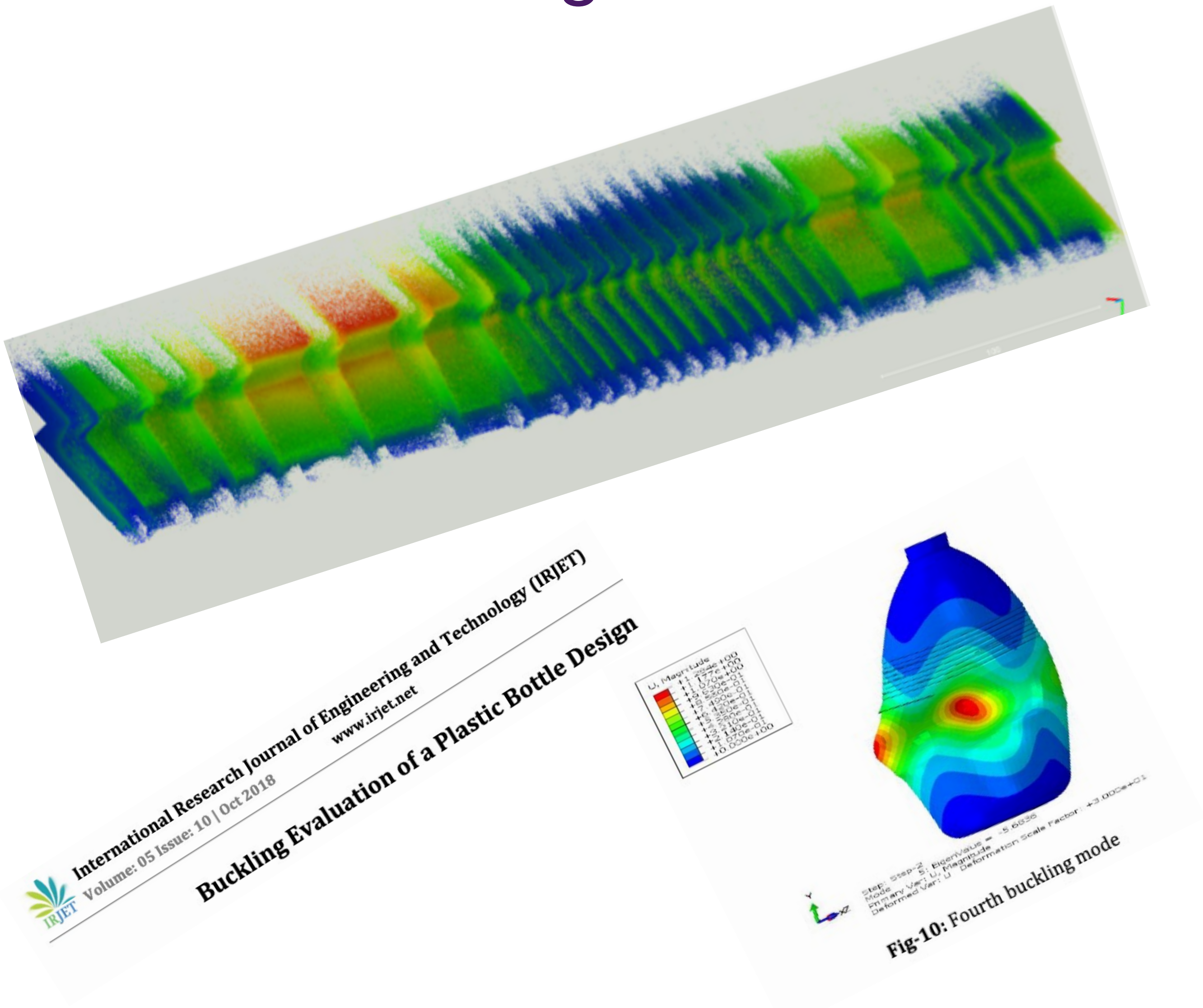
LHCb Collaboration

- 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….

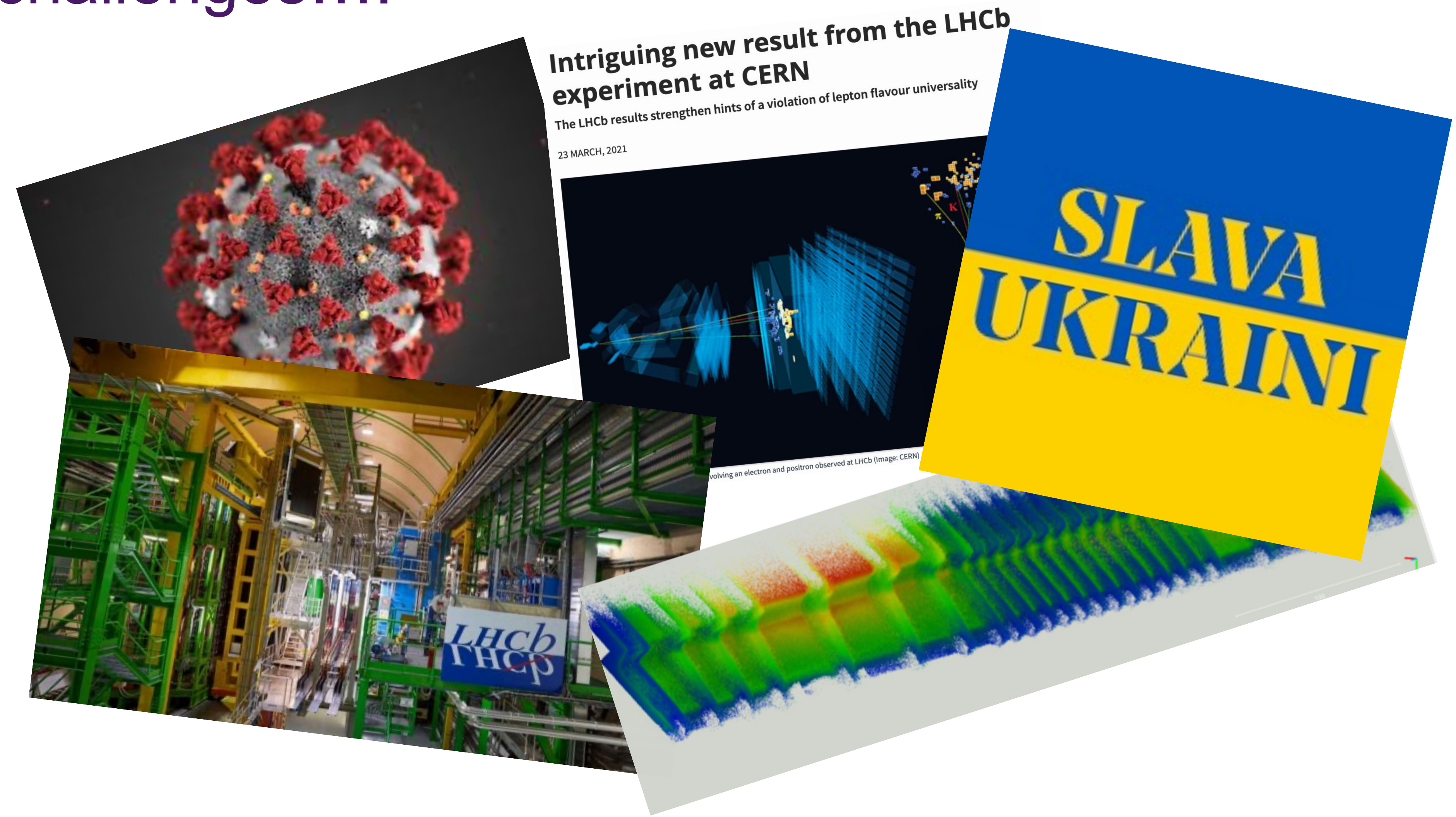


January 2023

- 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

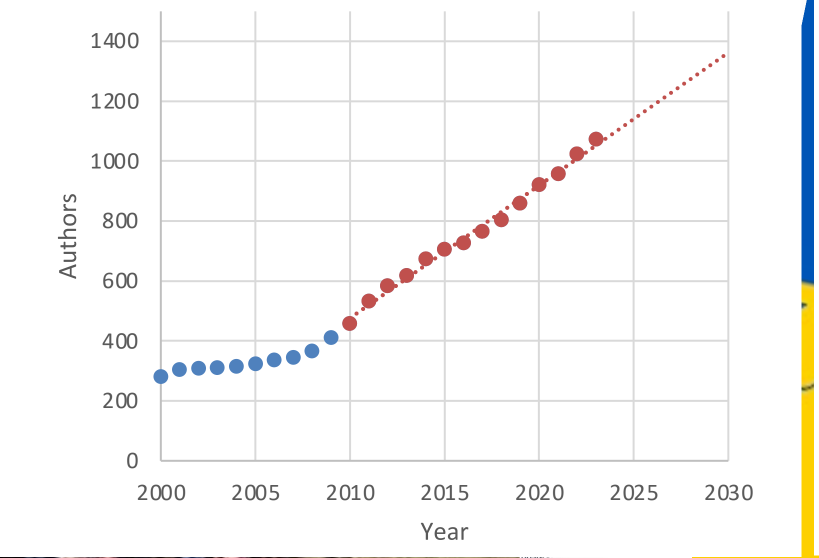
2020-2023: Three special years…

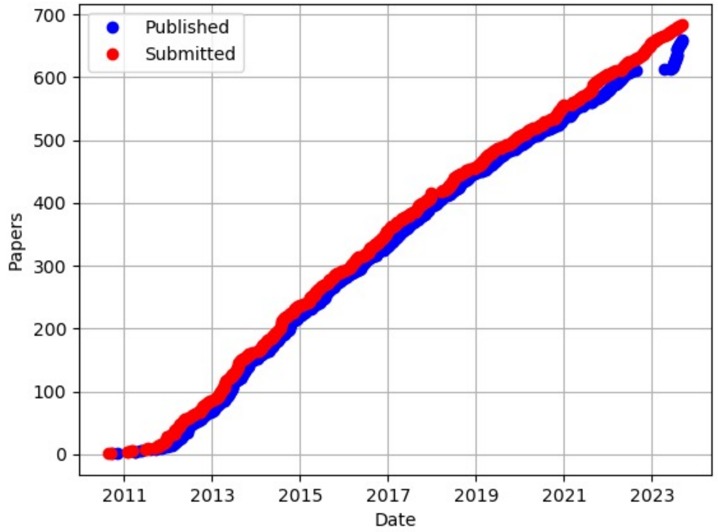
With its challenges….



2020-2023: Three special years…

And its successes….





1100 authors, 98 institutes, 22 countries

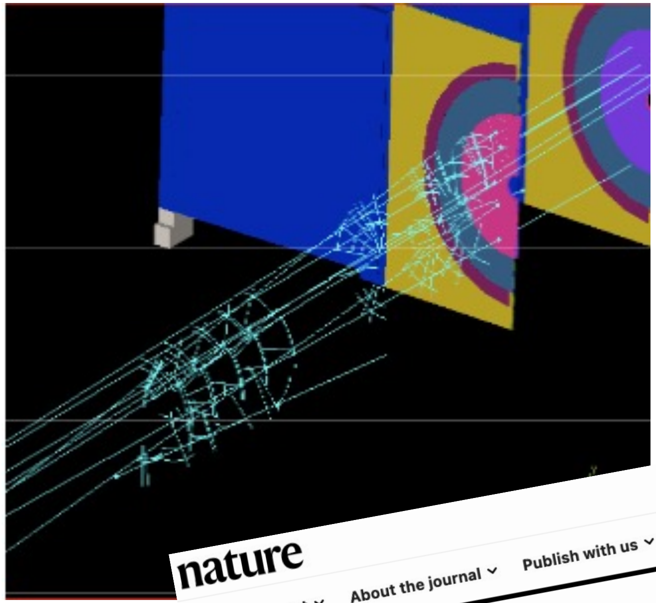
700 submitted papers

LHCb Original – LHC Run 1&2

2009 : we didn't know what we were doing but I still had hair

Original

2009-2018

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nature › news › article

Published: 25 August 2008

Double first for Large Hadron Collider

Matthew Chalmers

Nature (2008) | Cite this article

Celebrating "LHCb-original"!

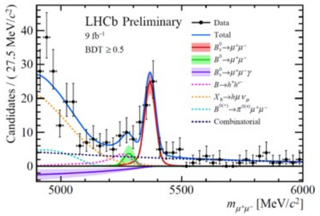
LHCb was originally designed for CP violation and b & c-hadron rare decays…

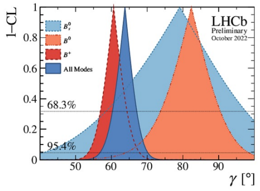
$B_s^0 \to \mu\mu$

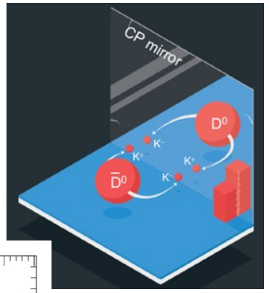
Δm_s

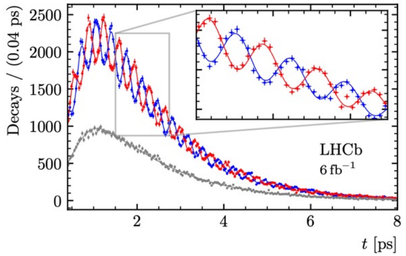
Time-dependent CPV in B_s

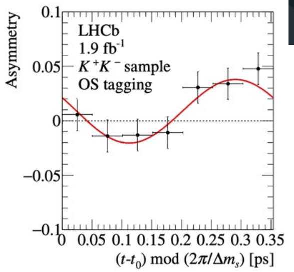
CKM angle γ

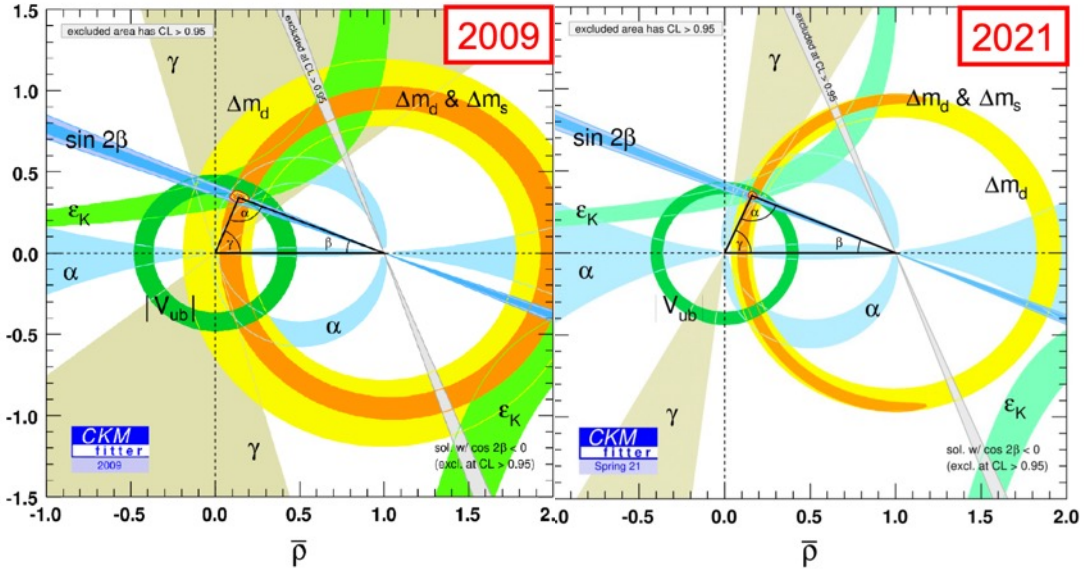




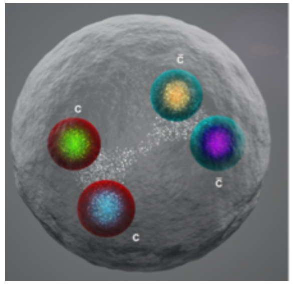


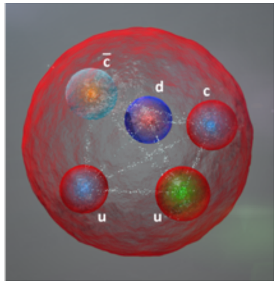






… but it achieved much more: exotic spectroscopy, heavy ions, fixed target programme, EW precision physics, dark sector searches…





Today recent results on

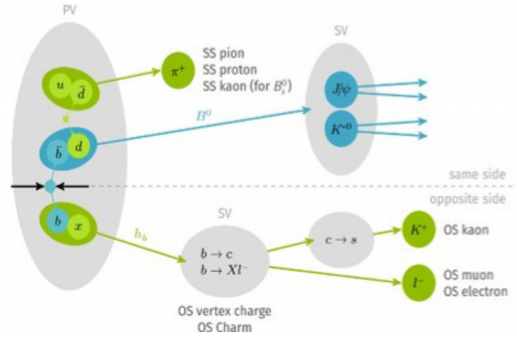
CP violation in B decays and D^0 mixing, Lepton Flavour Universality, Spectroscopy, breadth of programme

Sin(2β) – full LHCb data

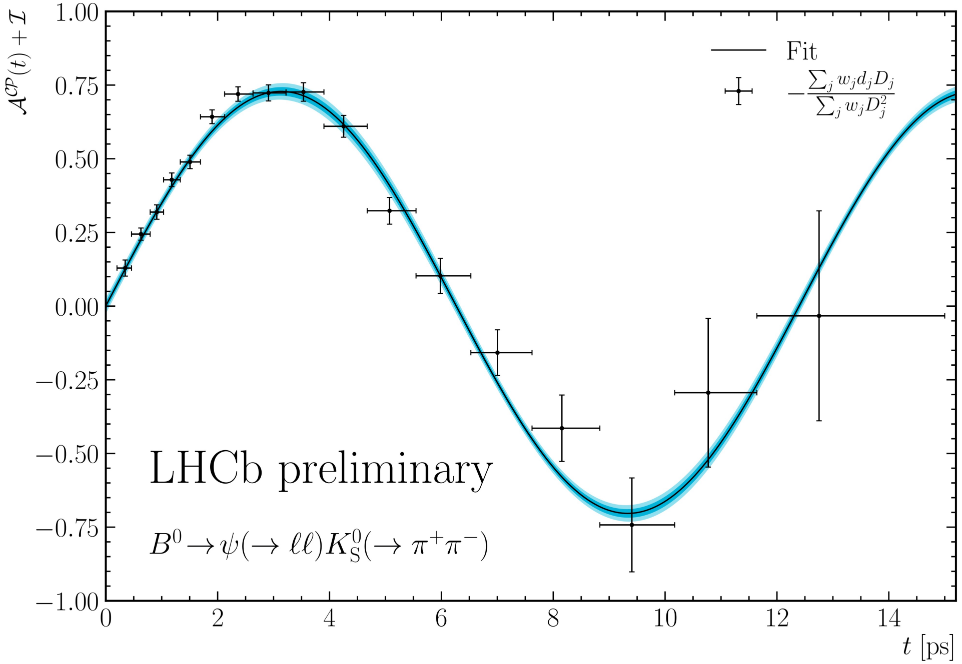
- obtained by the "golden mode" $B^0 \rightarrow J/\psi K^0$

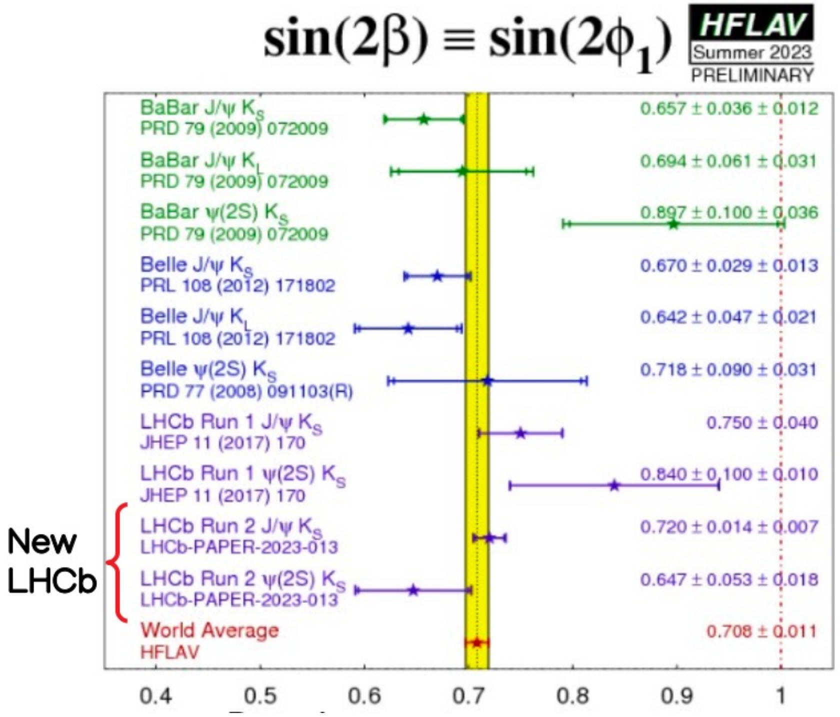
CP violation in interference between decay and mixing $P(B \rightarrow f_{CP}) = P(B \rightarrow \bar{B} \rightarrow f_{CP})$

Flavour Tagging

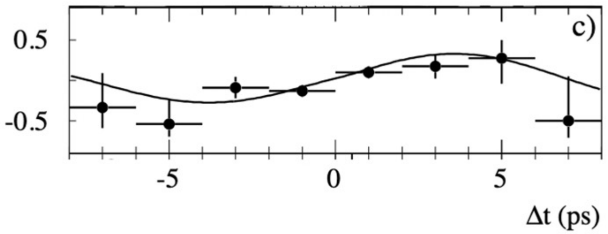


$A_{CP}(t) = \sin(2\beta)\sin(\Delta m_d t)$





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

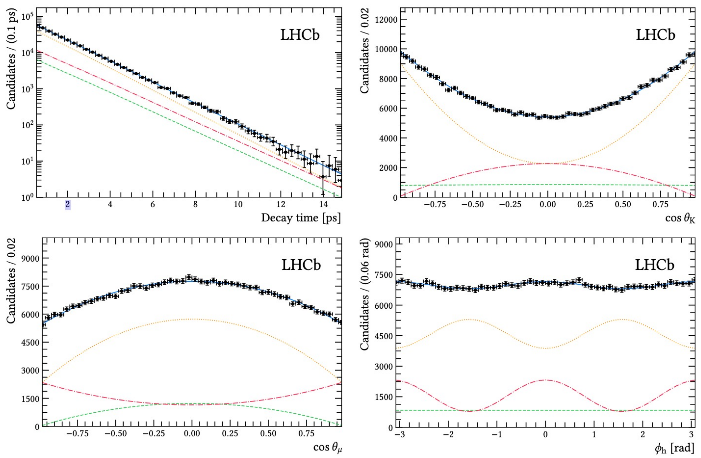
LHCb-PAPER-2023-013

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

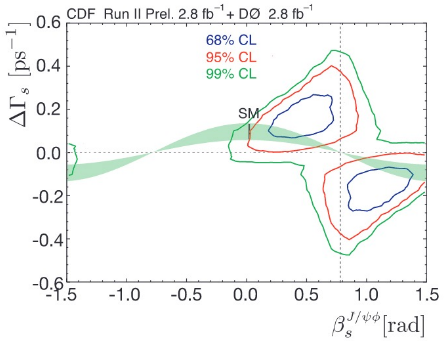
CP violation in interference between decay and mixing $P(B \rightarrow f) = P(B \rightarrow \bar{B} \rightarrow f)$

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

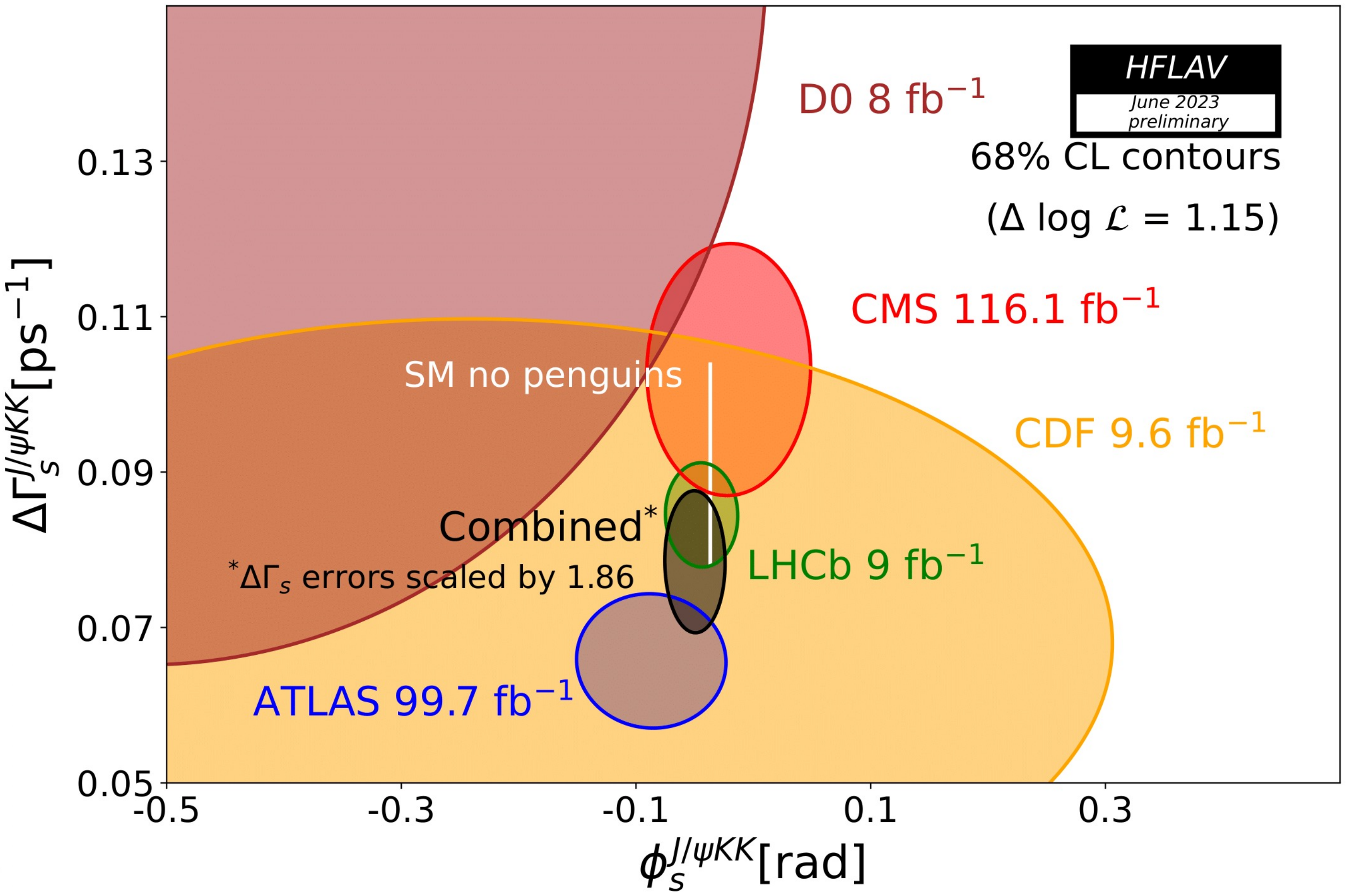
CP-even
CP-odd
S-wave



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



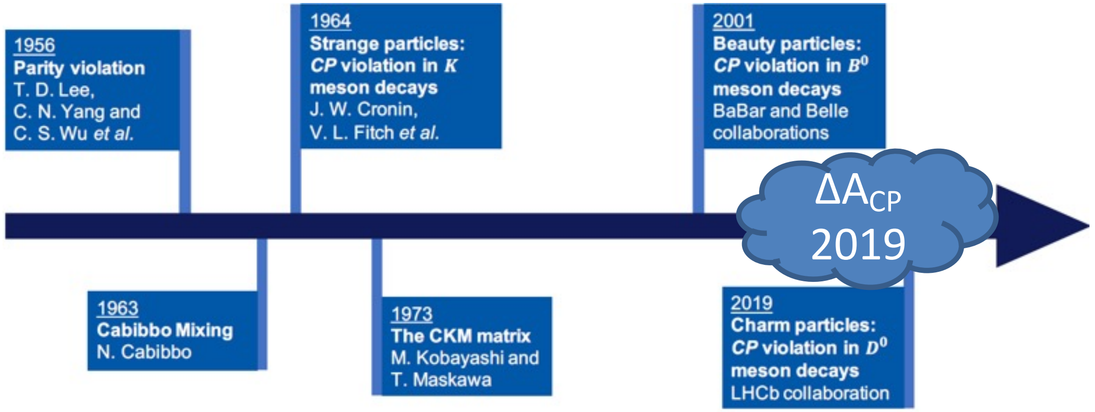
Run2: LHCb ϕ_s = -0.039±0.022±0.006 rad

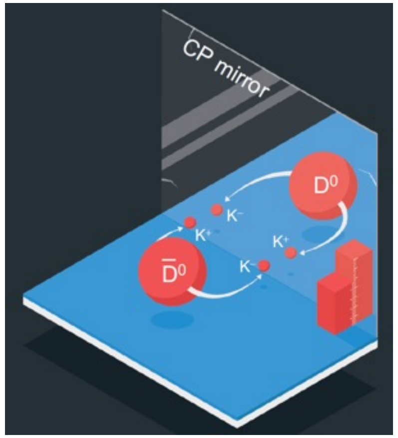


First evidence Charm CP Violation in specific decay

ICHEP '22

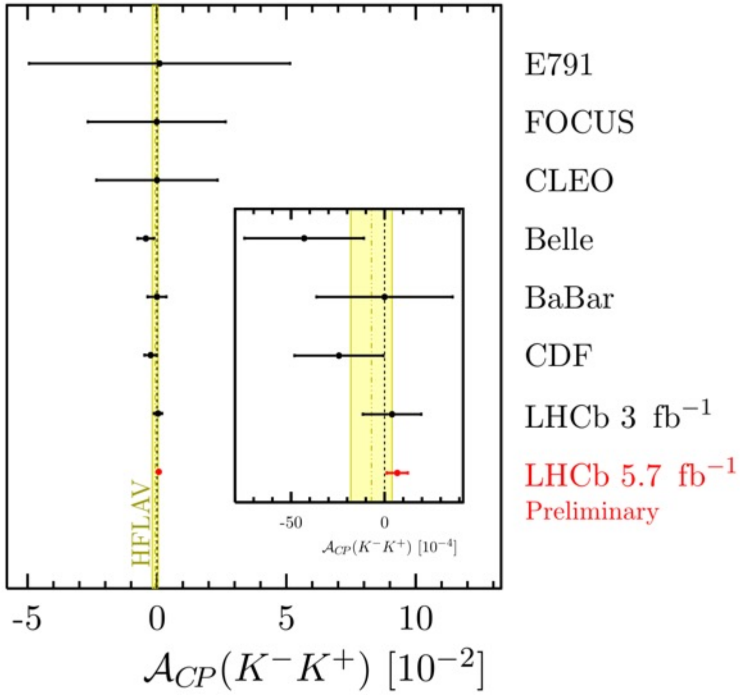
LHCb-PAPER-2022-024

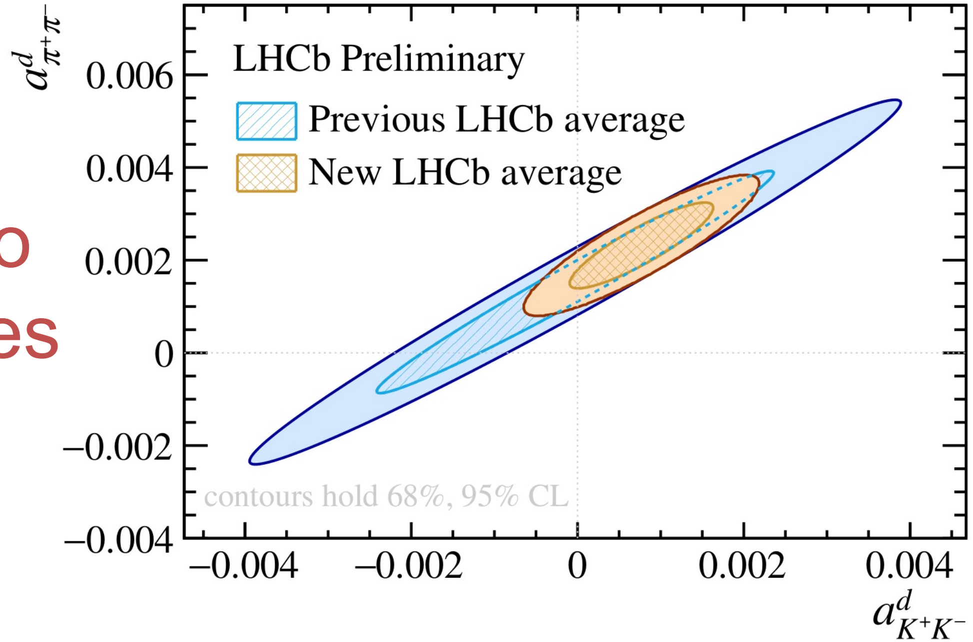




- Direct CP Discovery 2019
- ΔA_{CP} difference KK,ππ
- Cancel systematics
  - Production, detection asymmetries

- 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

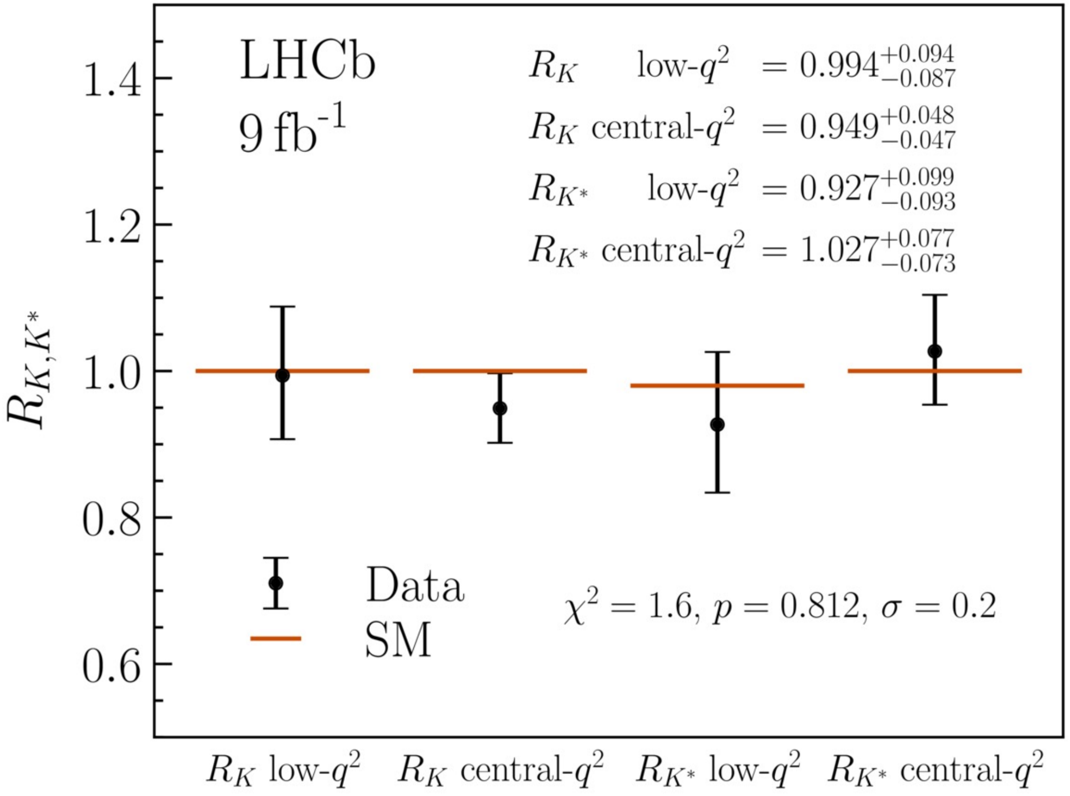
December '22

- "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

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

- 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

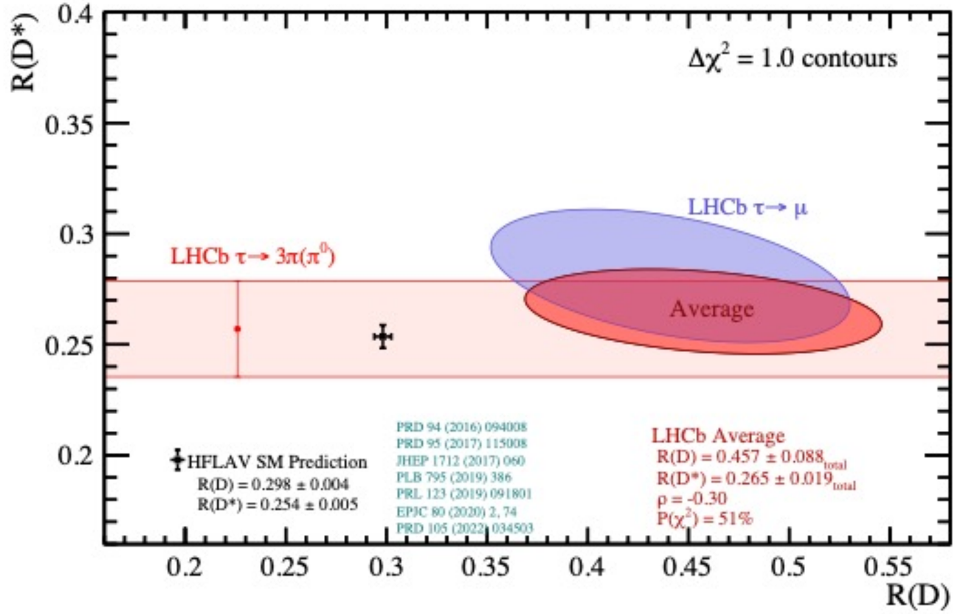
La Thuile '23

- "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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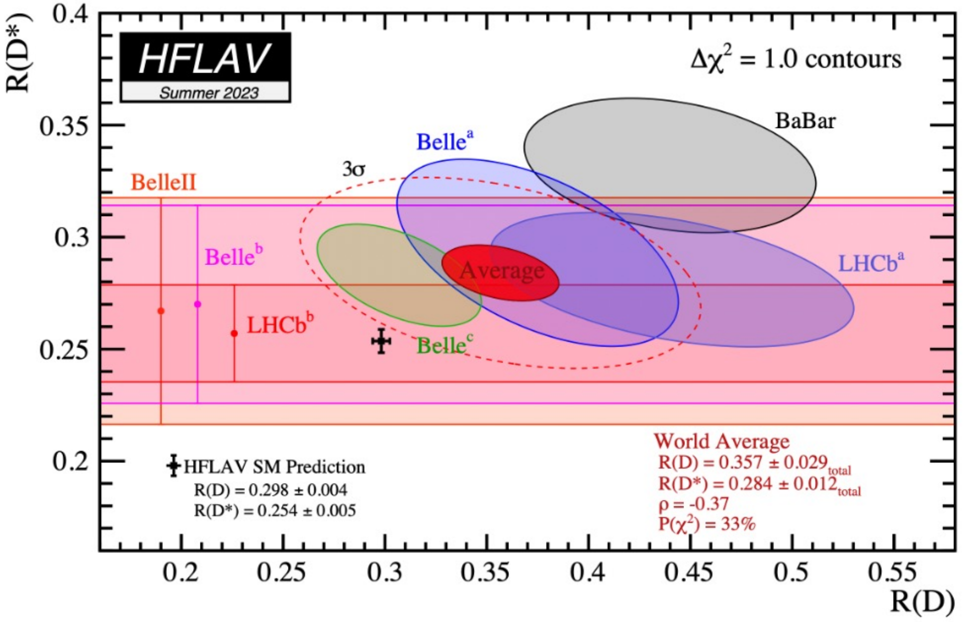


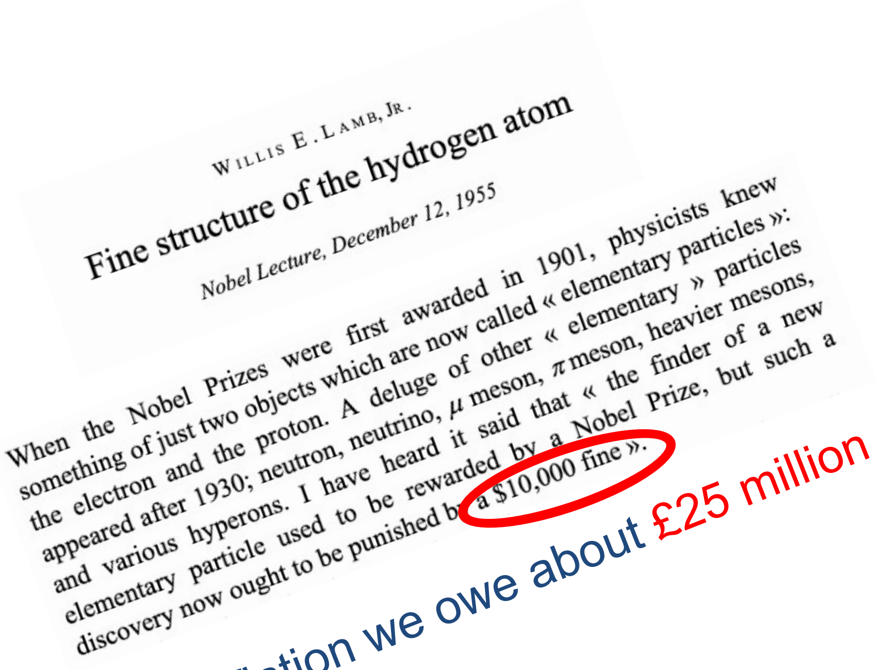
Hot topic – lots of activity !

- 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



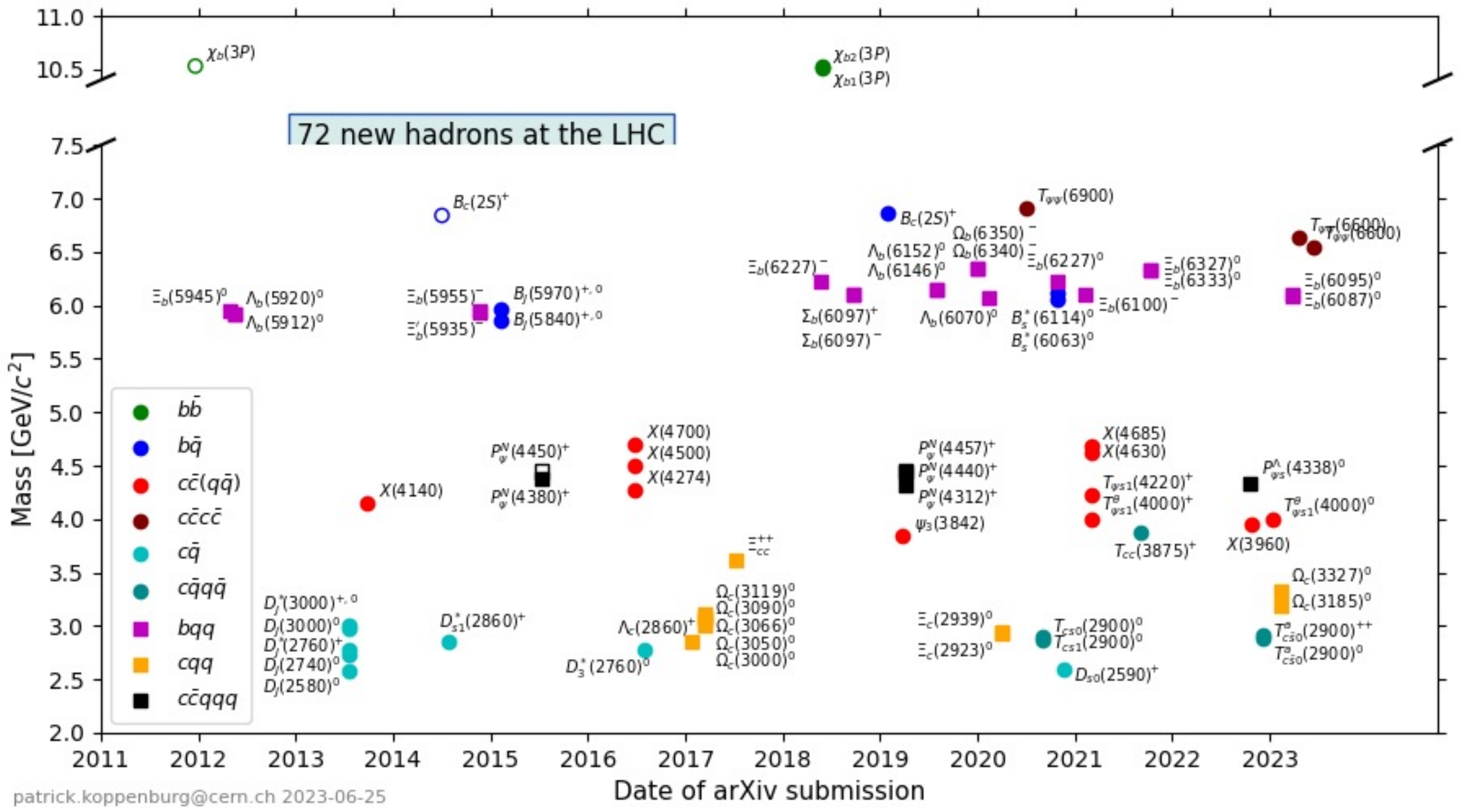
WILLIS E. LAMB, JR.

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

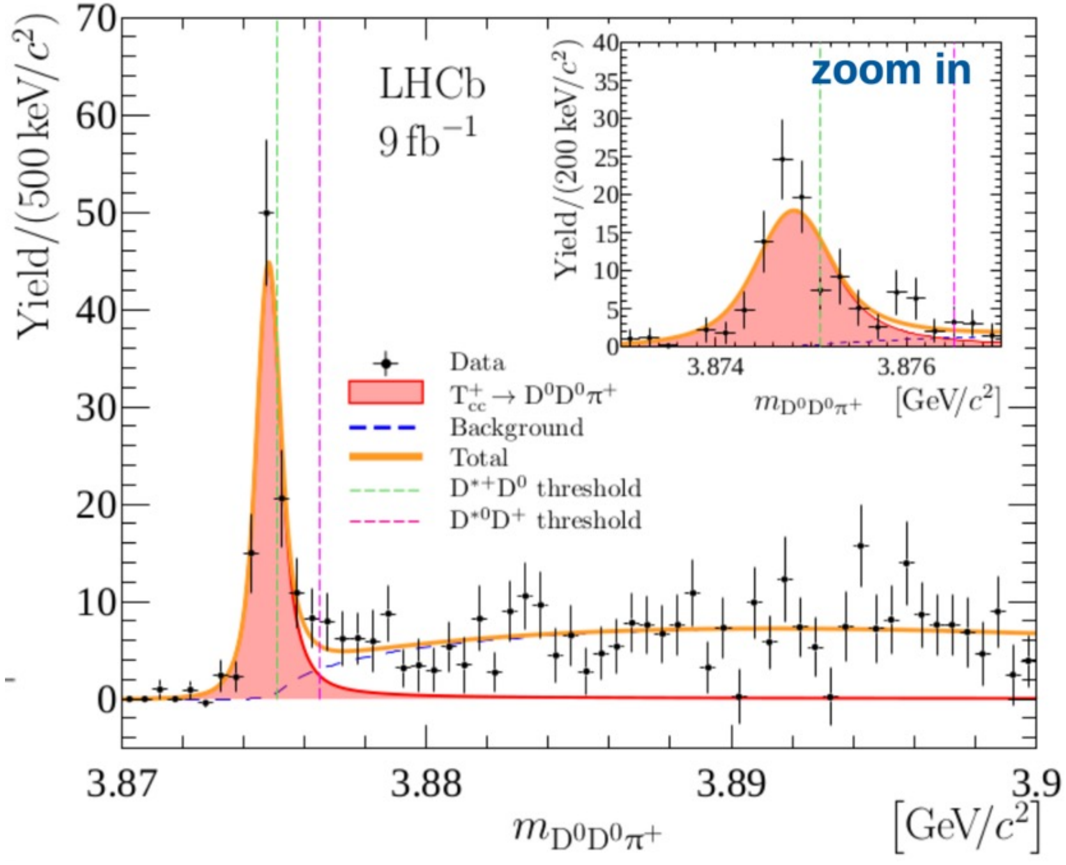


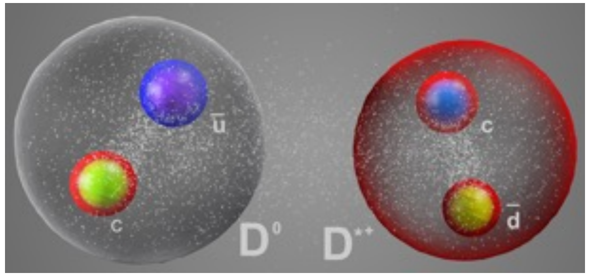
Exotic Hadrons

EPS '21

arXiv:2109.01038
arXiv:2109.01056

- *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

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

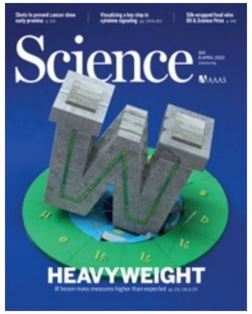
Increased interest for T_{bc} , T_{bb} as possible first long-lived, weakly decaying, states!

Need Upgrade statistics

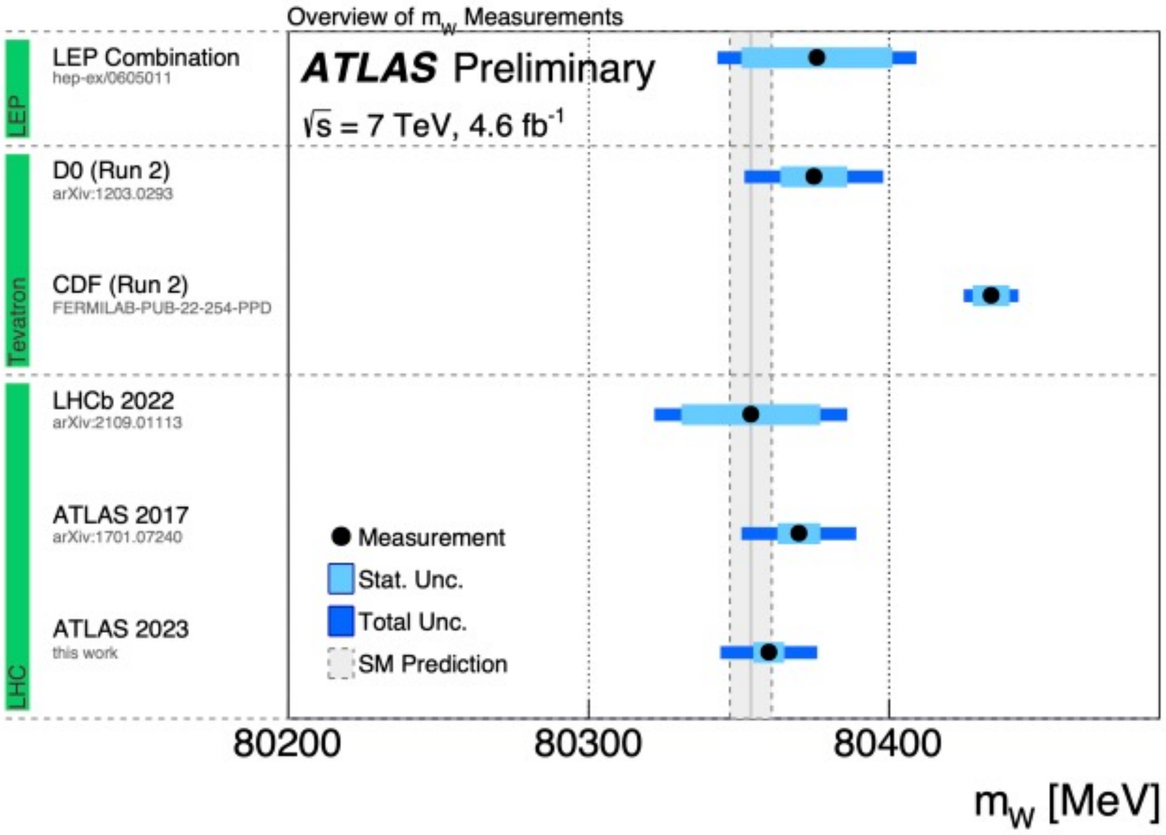
Breadth of LHCb Physics: Electroweak

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



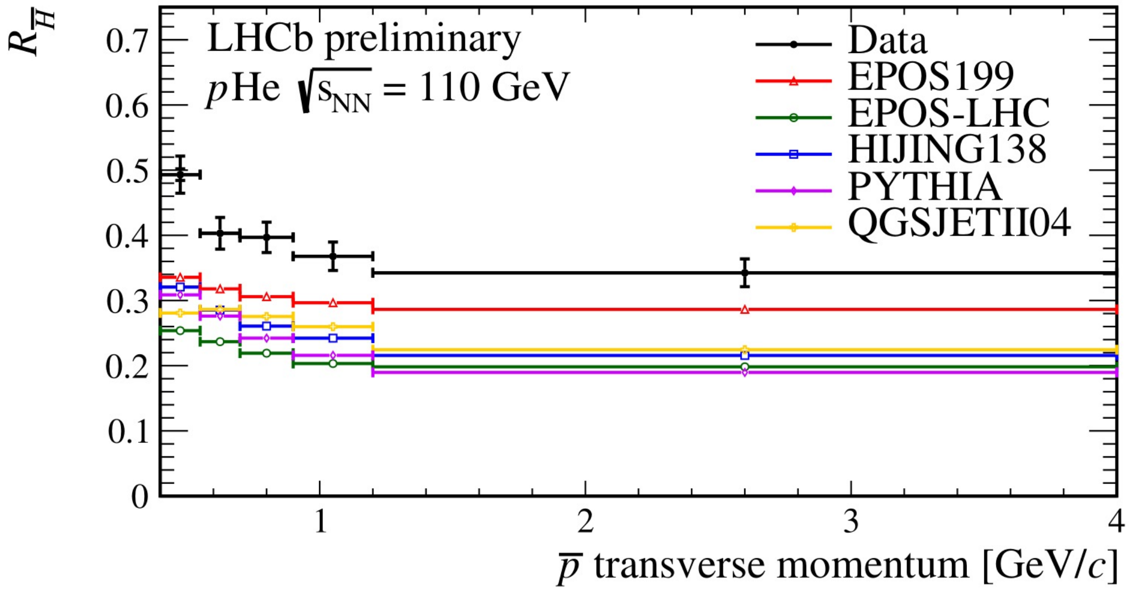
- LHCb results combined with ATLAS reduce sensitivity to the parton distribution functions. PDFs.
- In LHCb W bosons are produced in collisions of high- with low-x partons
- ATLAS mainly collisions of mid-x partons produce the W bosons observed

Breadth of LHCb: Understanding Dark Matter in Space

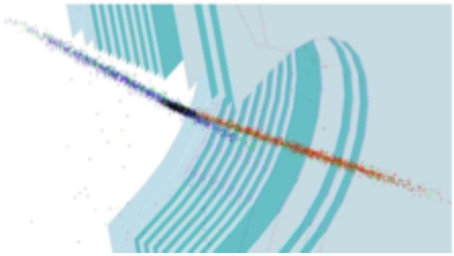
LHCb-PAPER-2021-031/032

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 Upgrades

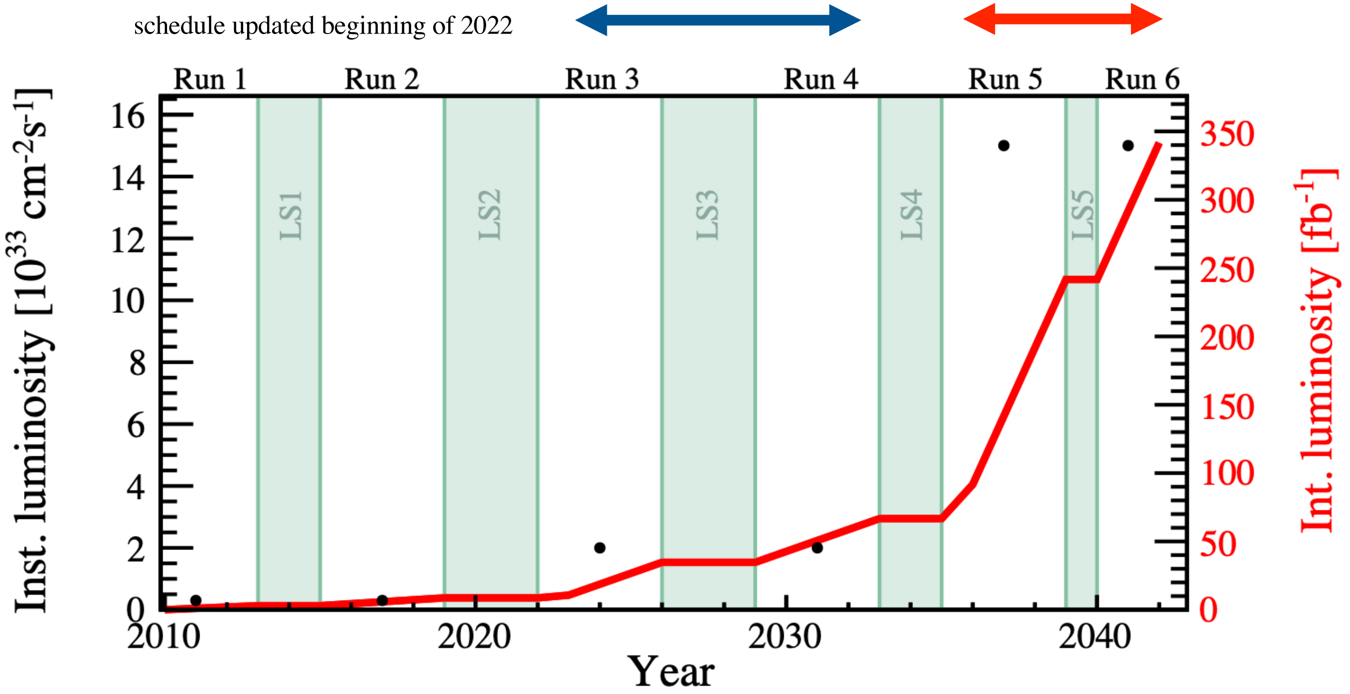
- Physics programme limited by detector, NOT by LHC
- Hence, clear case for an ambitious plan of upgrades

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 I

Upgrade II



Upgrade II

- *$L_{peak} = 1.5x10^{34}\ cm^{-2}\ s^{-1}$*
- *$L_{int} = \sim 300\ fb^{-1}$ 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*

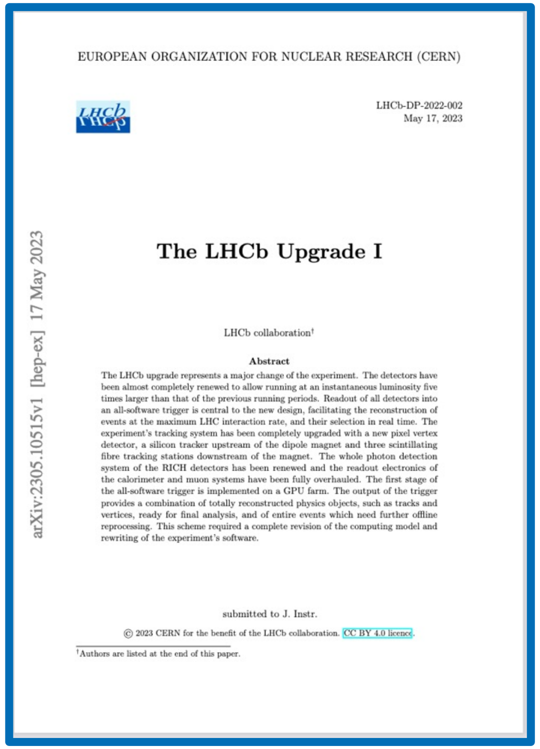
LHCb Upgrade I

Upgrade I

2022-2032

Does the sequel live up to the original ?

The next step



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.

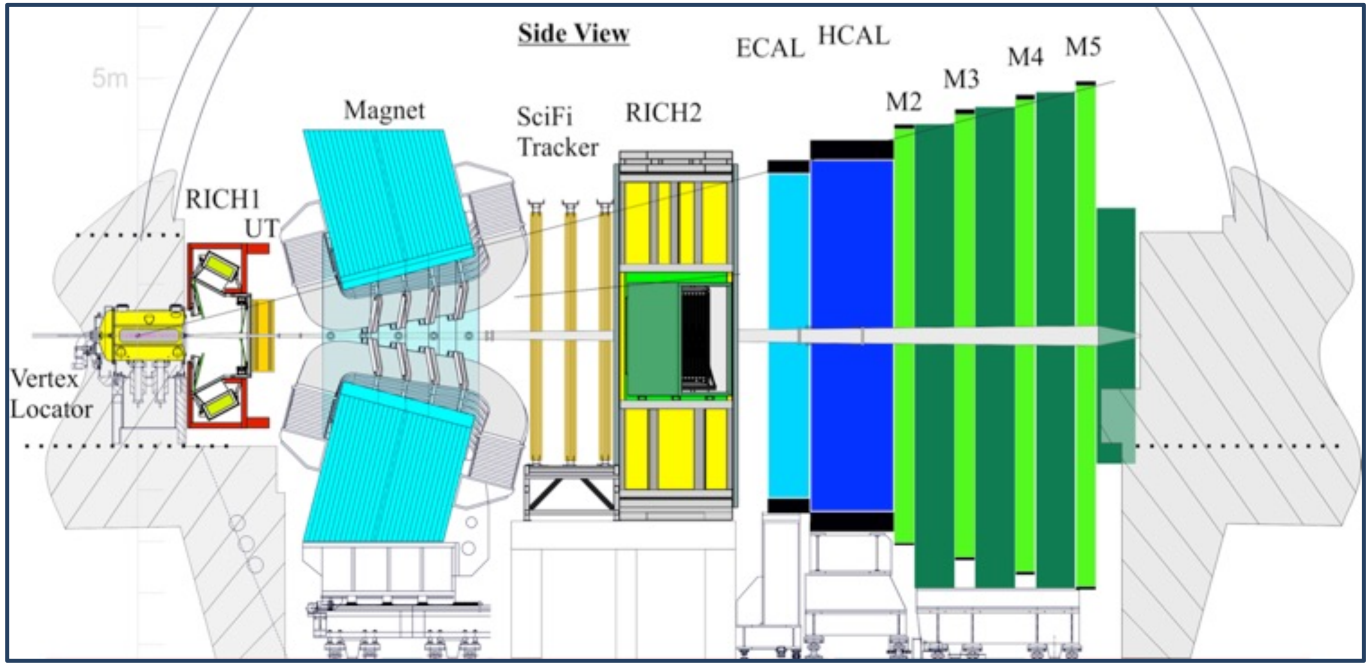
†Authors are listed at the end of this paper.

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 $L_{peak} = 2\times10^{33}\ cm^{-2}\ s^{-1}$, pile-up ~5

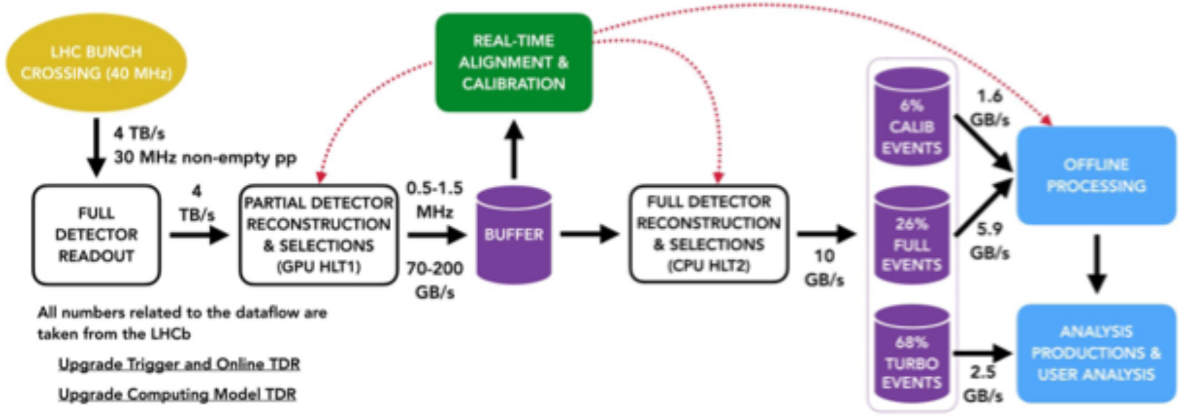
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Major project installed for operation in Run 3

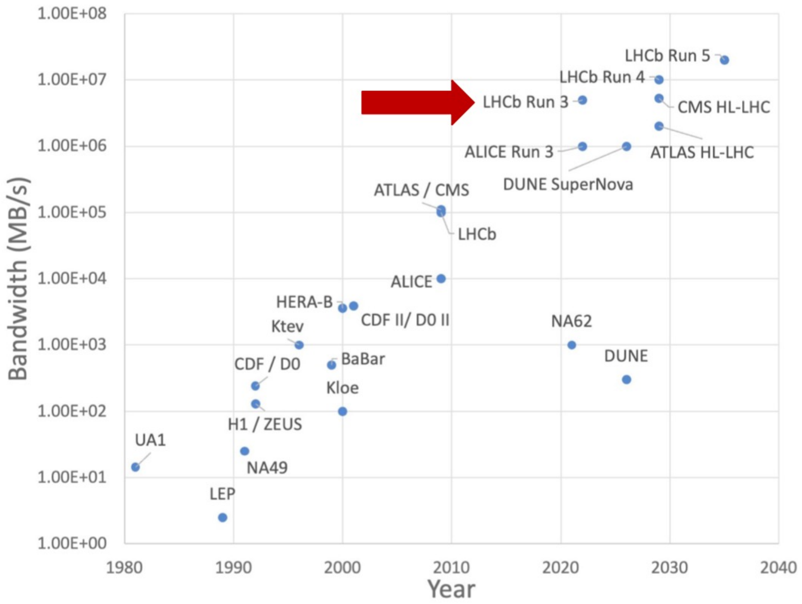
LHCb Upgrade I: Trigger Revolution

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

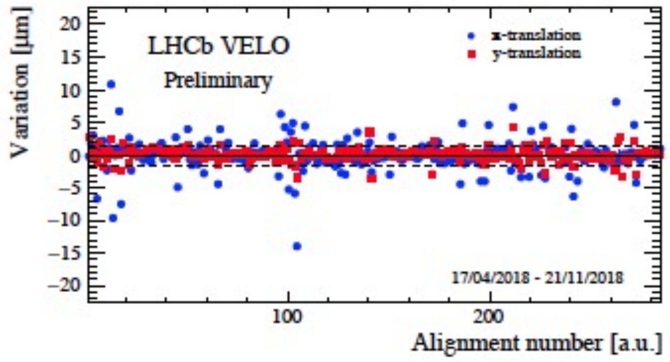


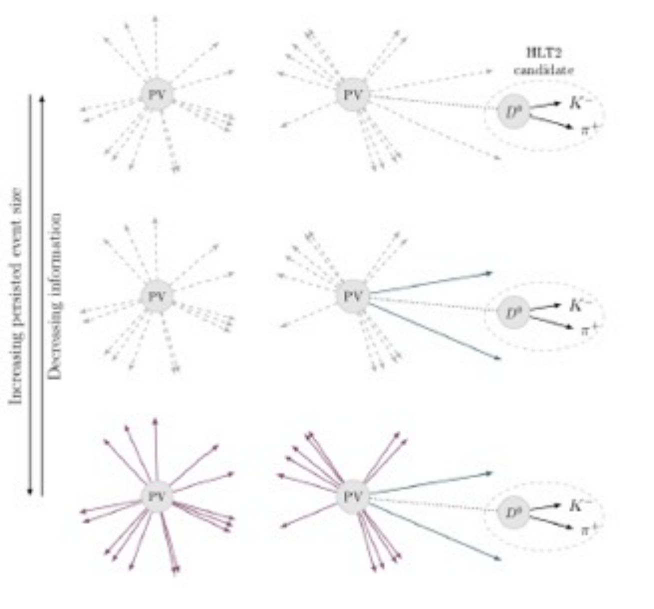
A. Cerri, LHCP 2022

Real Time Analysis - Turbo

- 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

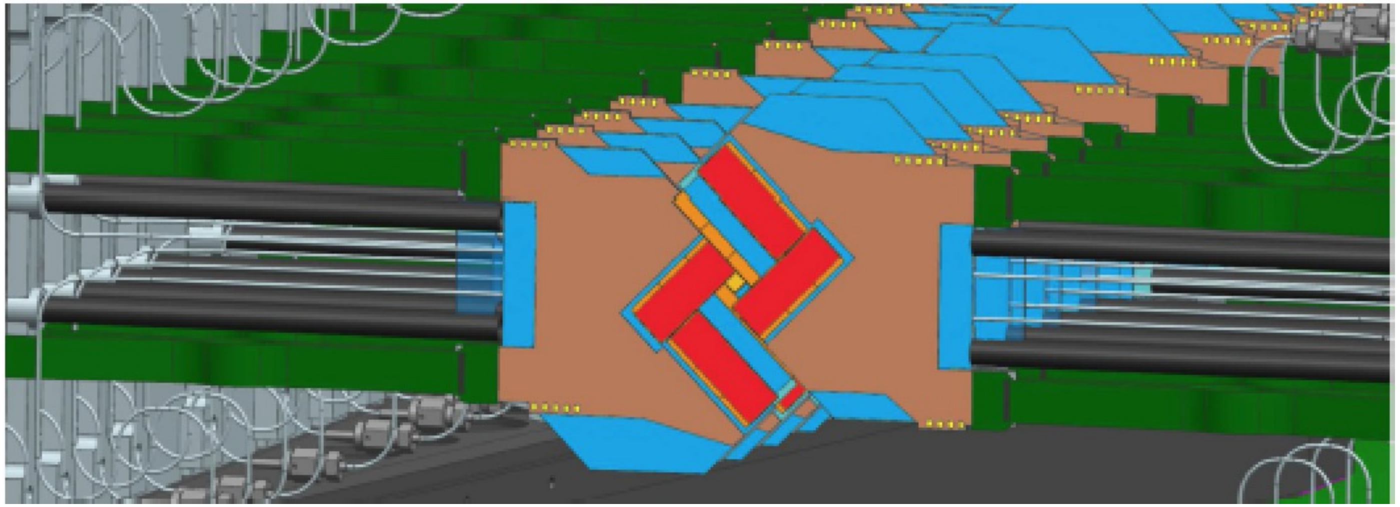


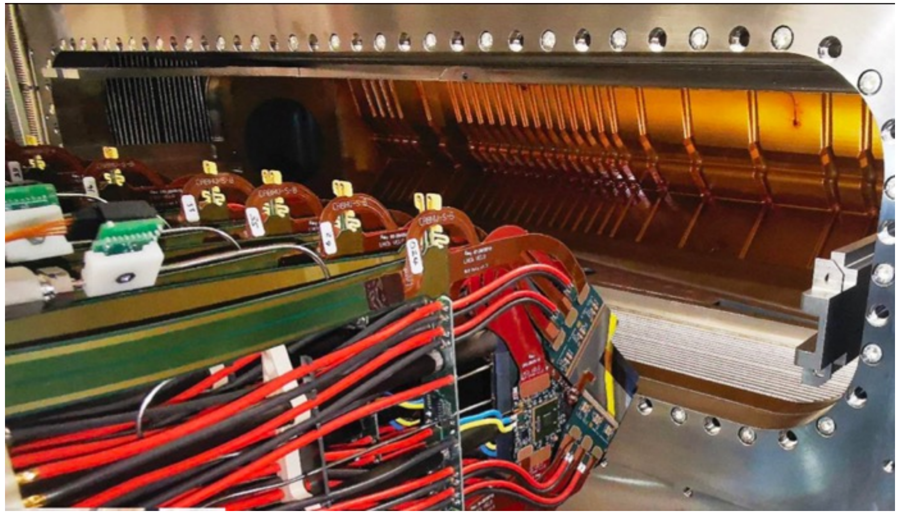


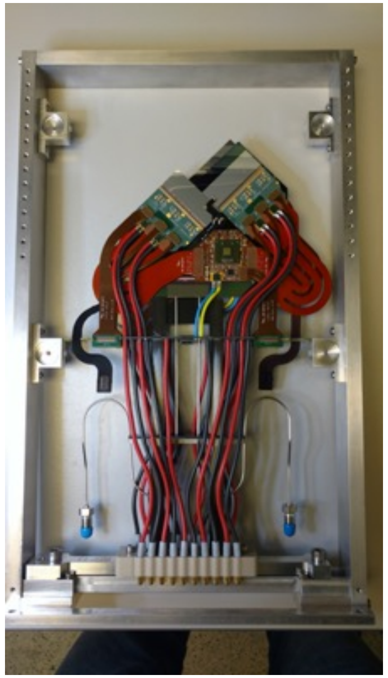
- Selective persistence
  - Only signal decay tracks….
  - those in cone around...
  - those from same PV....
  - All tracks in event….
  - All ECAL clusters....

LHCb Upgrade I: VELO

CERN-LHCC-2013-021



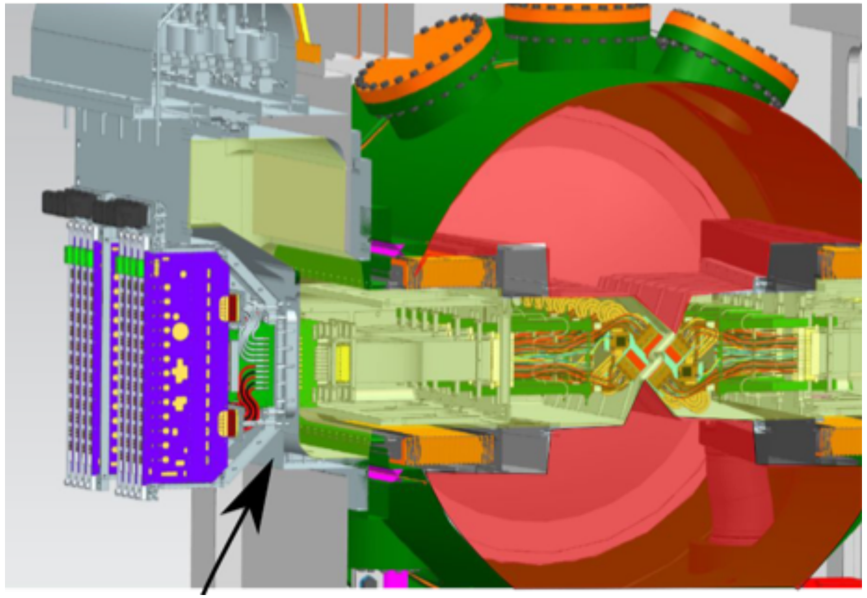




- Hybrid Pixel Detectors (55μm pitch)
- Close to the LHC beam (5.1 mm)
  - retracted/reinserted each fill
- Innovative silicon microchannel substrate
  - Bi-phase CO_2 cooling
- DAQ capable of handling 40TB/s
- **Installation completed May 2022**

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.

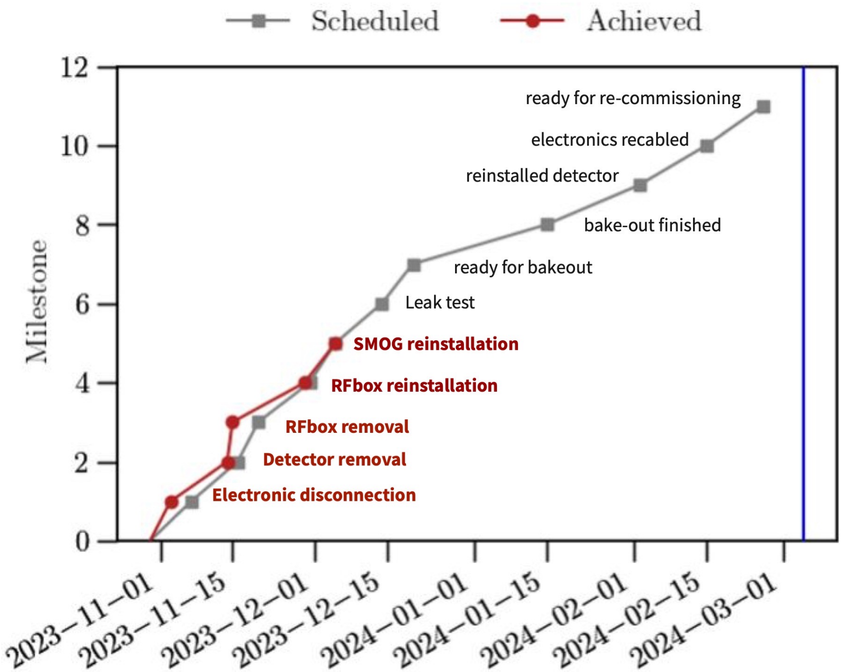
- **Detector modules & cooling are not damaged**
- The system was returned to a safe situation

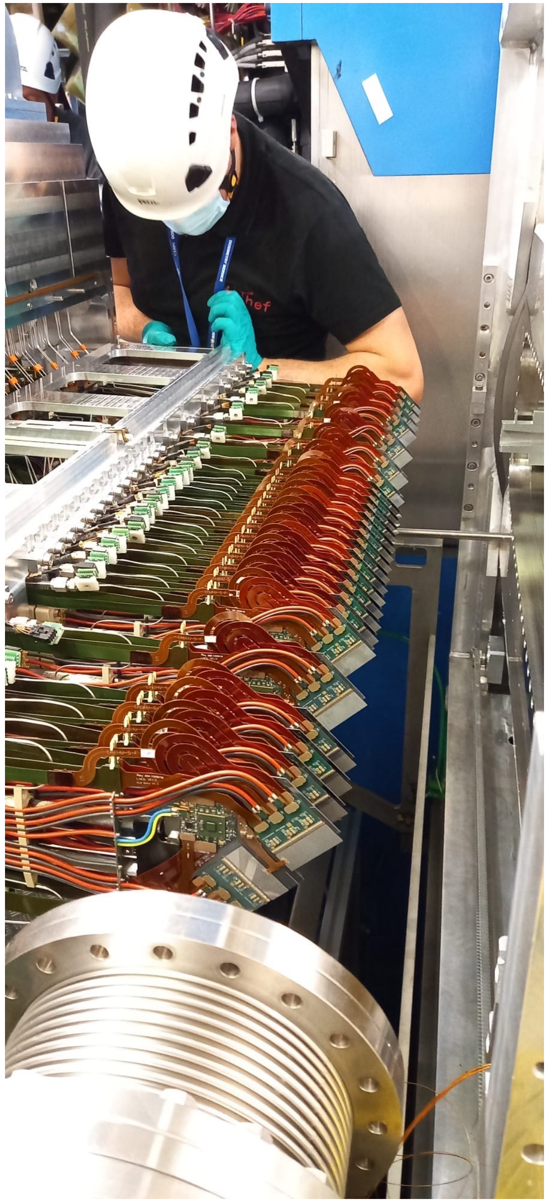
- **RF foil has undergone plastic deformation**
- Replacement in current shutdown would have significantly affected overall LHC programme
- Replace in the shutdown now at the end of 2023
  - – schedule: 13 weeks + contingency 3 weeks
- LHCb physics programme in ‘23 affected as VELO could not be fully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

VELO RF Foil Replacement

Replacement work is proceeding on schedule

Most critical tasks of foil and half removal are successfully completed





LHCb Upgrade I: RICH 1 & 2

CERN-LHCC-2013-022

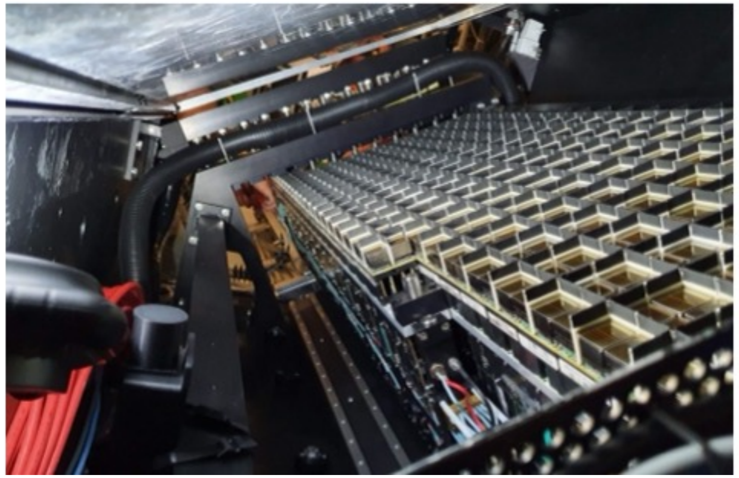
- Unique particle identification system, key for success of physics programme

- RICH1&2: new photodetector MaPMTs with Increased granularity and 40MHz readout

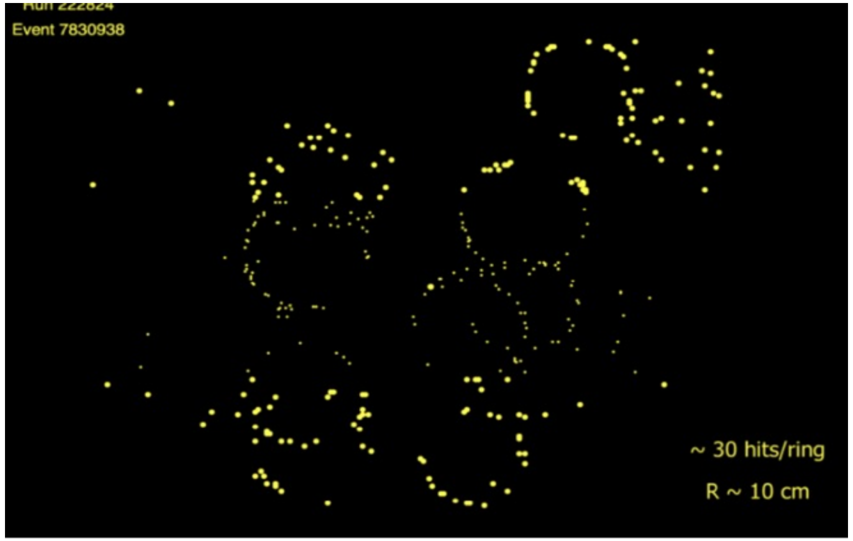
- RICH1: new design with new optical system with increased focal length, to halve occupancy

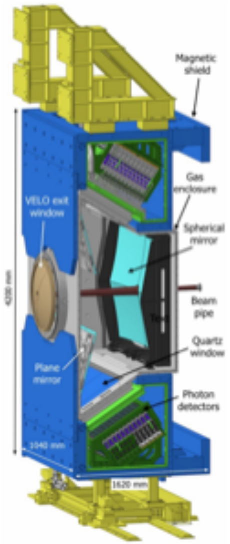
- **Installation successfully completed Feb. ‘22**

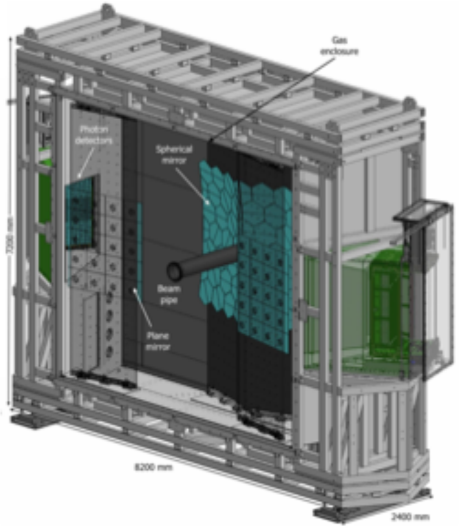
RICH1: MaPMTs installation



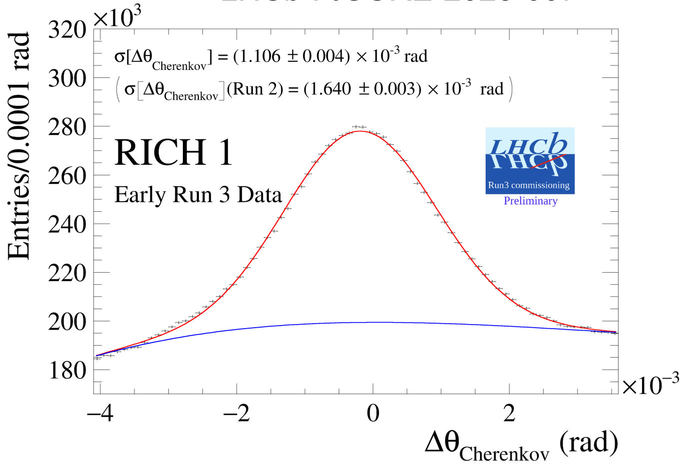
RICH2: first rings, LHC October ‘21 test







LHCb-FIGURE-2023-007

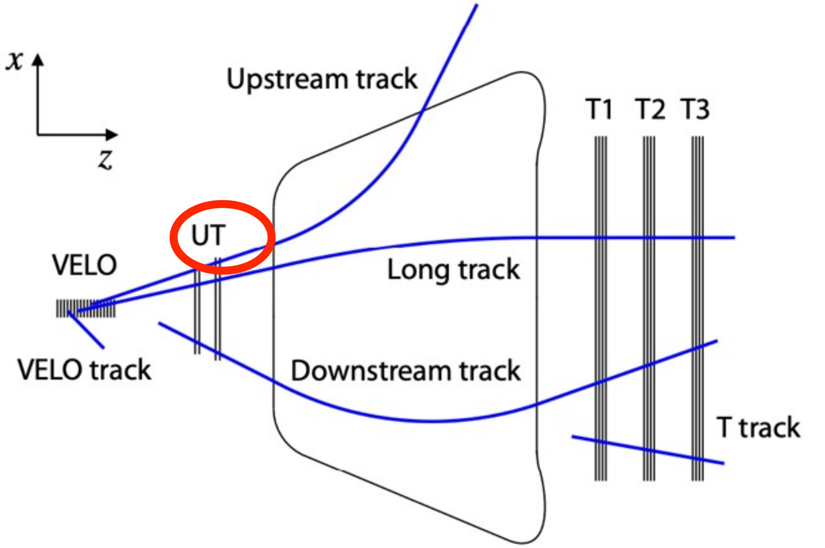


LHCb Upgrade I: Upstream Tracker

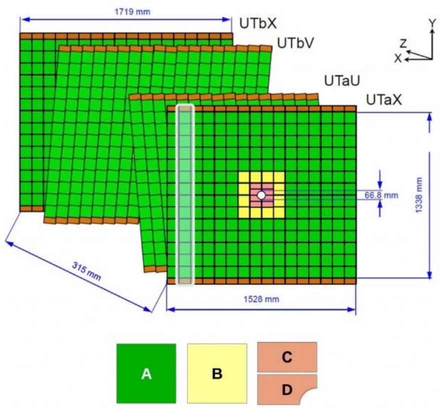
CERN-LHCC-2014-001

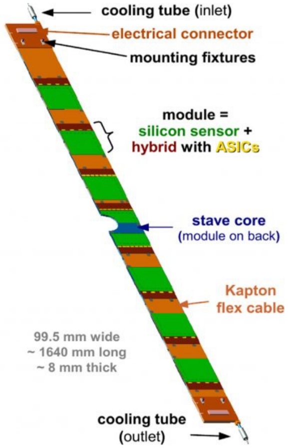
- 68 staves with silicon strips and integrated cooling, arranged in 4 planes
  - fast p_T determination for track extrapolation

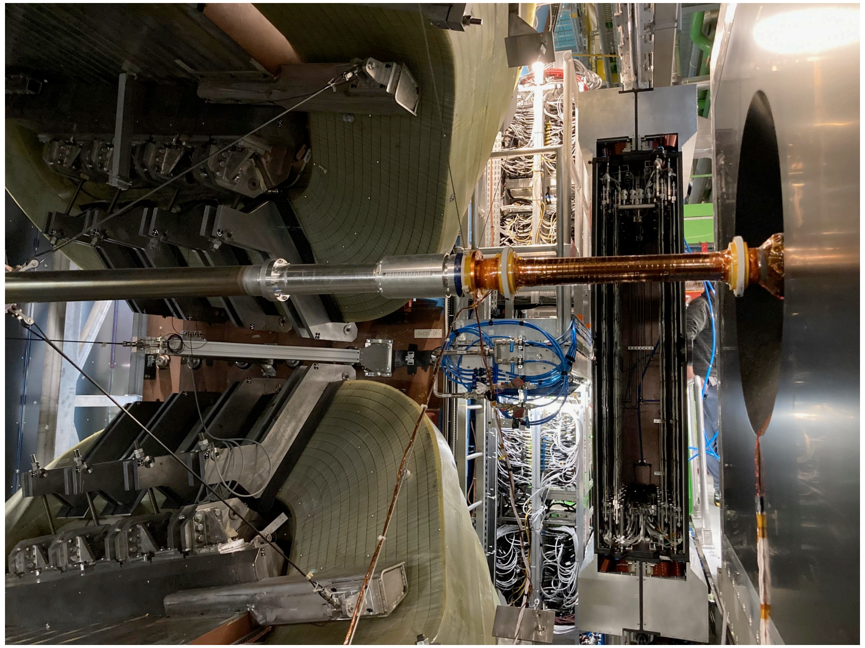
    → reduce ghost track, and improve trigger bandwidth
  - long-lived particles decaying after VELO (K_S, Λ)



- **Installation successfully completed March ’23, now commissioning,**



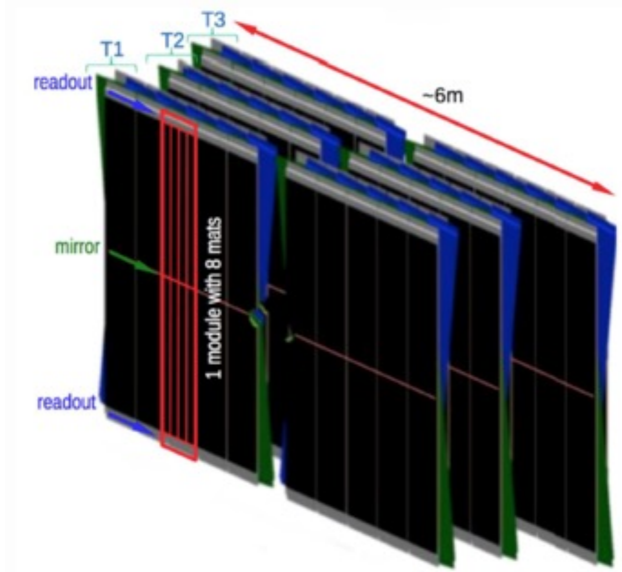


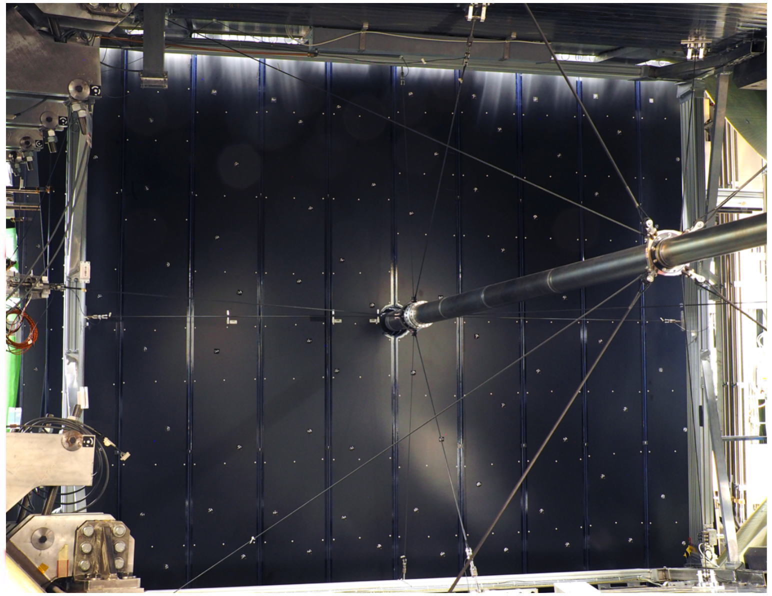


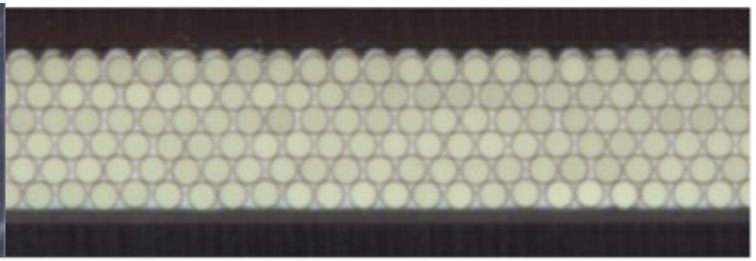
LHCb Upgrade I: SciFi

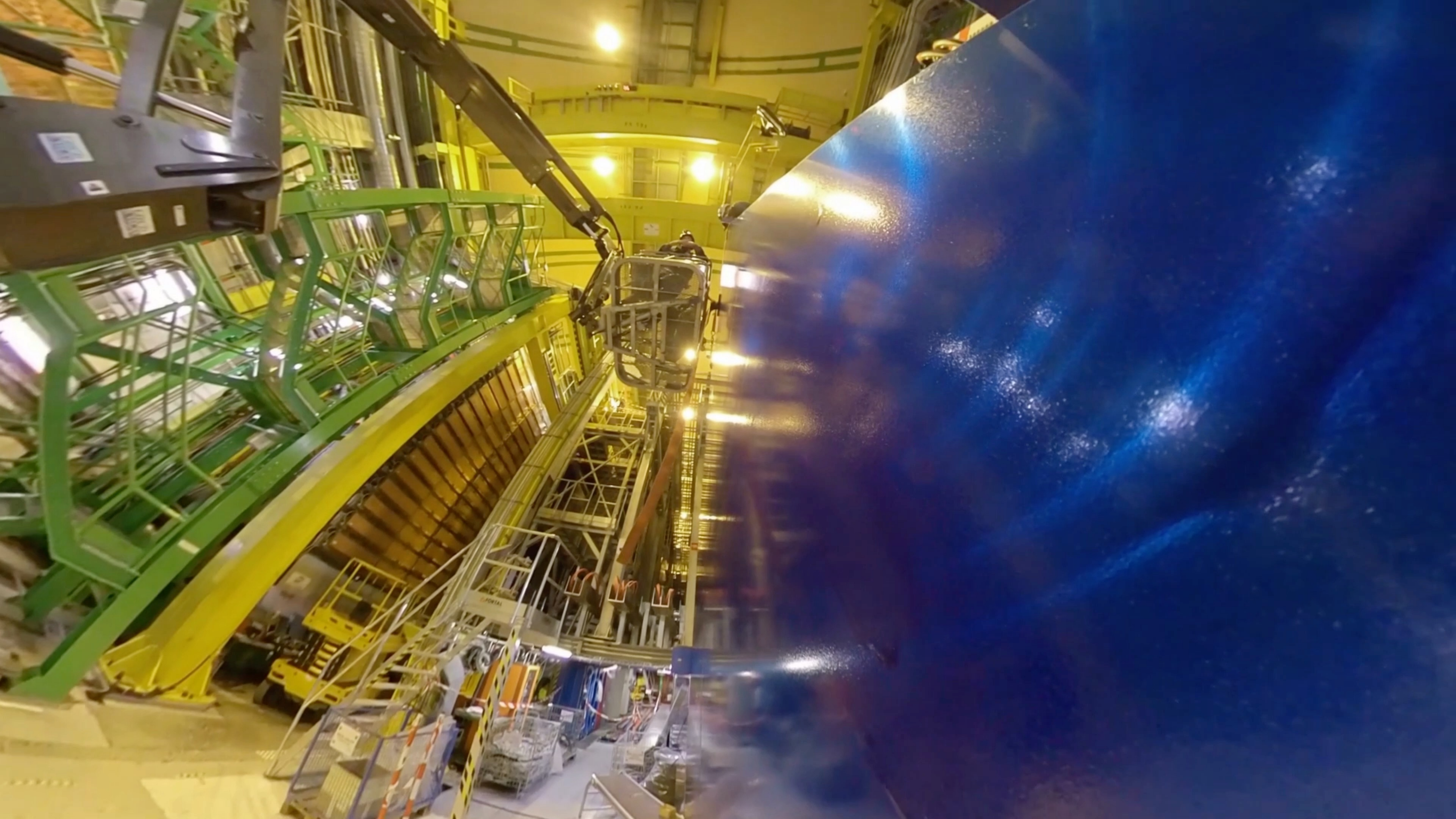
CERN-LHCC-2014-001

- 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**

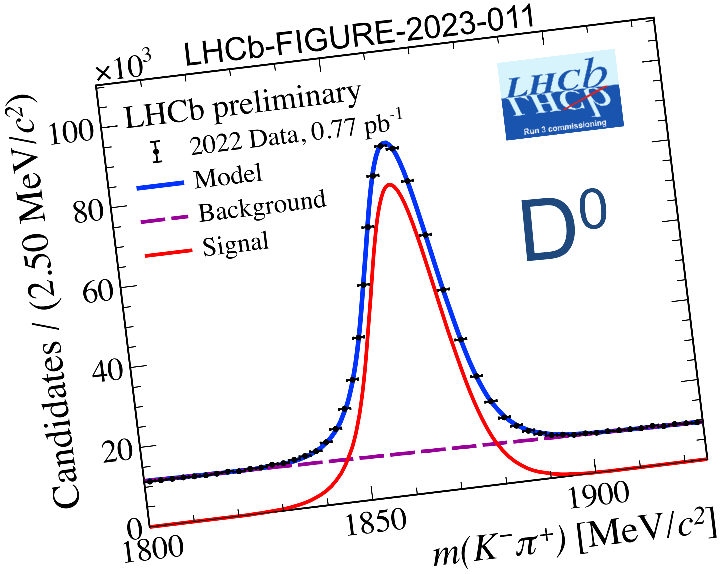


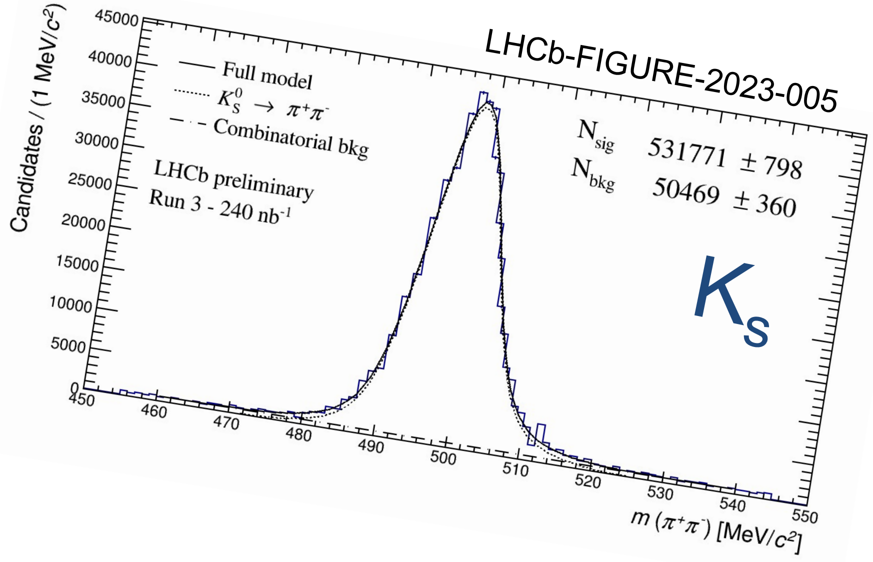


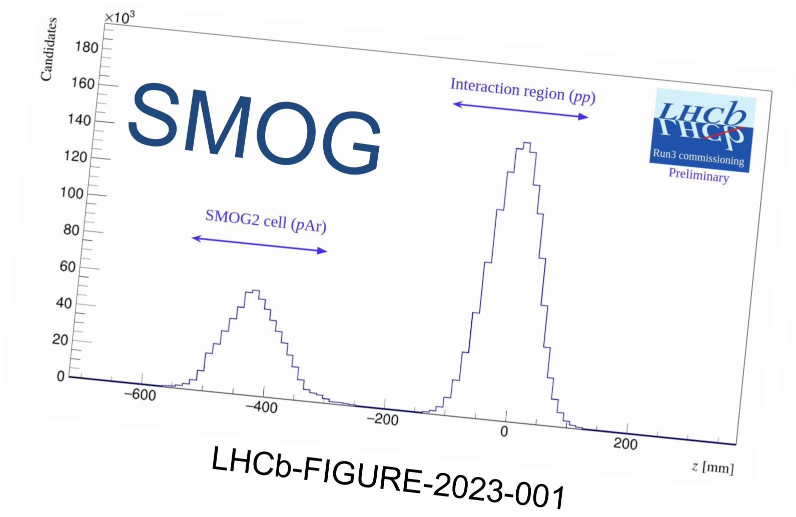


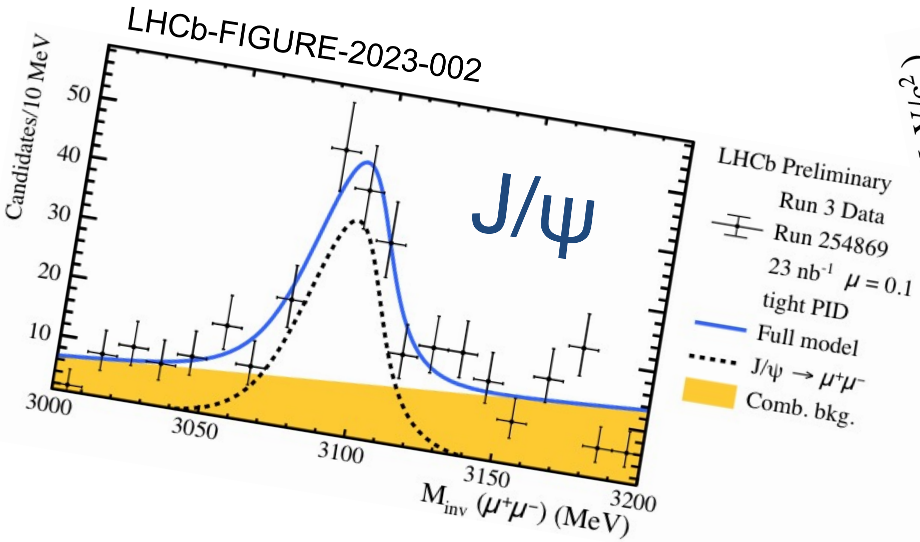


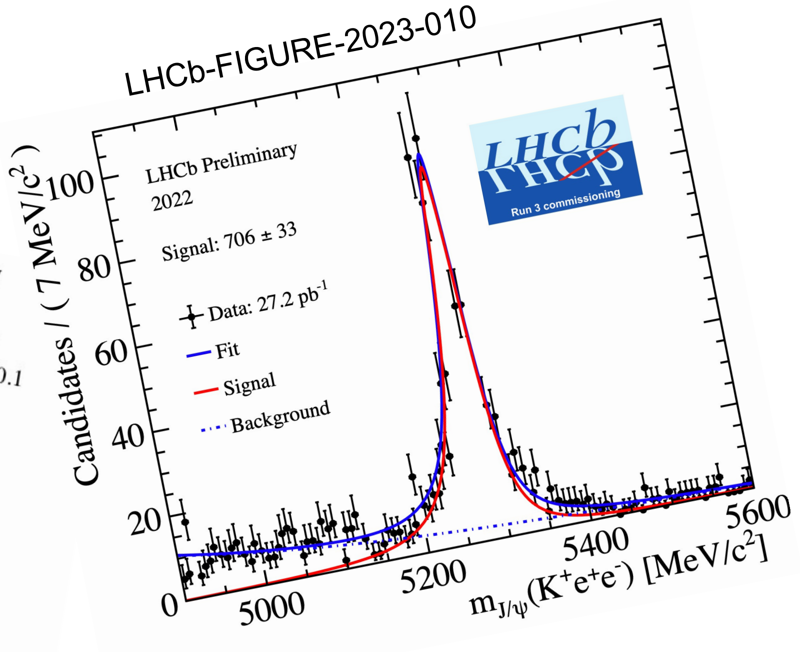
Some first plots…..









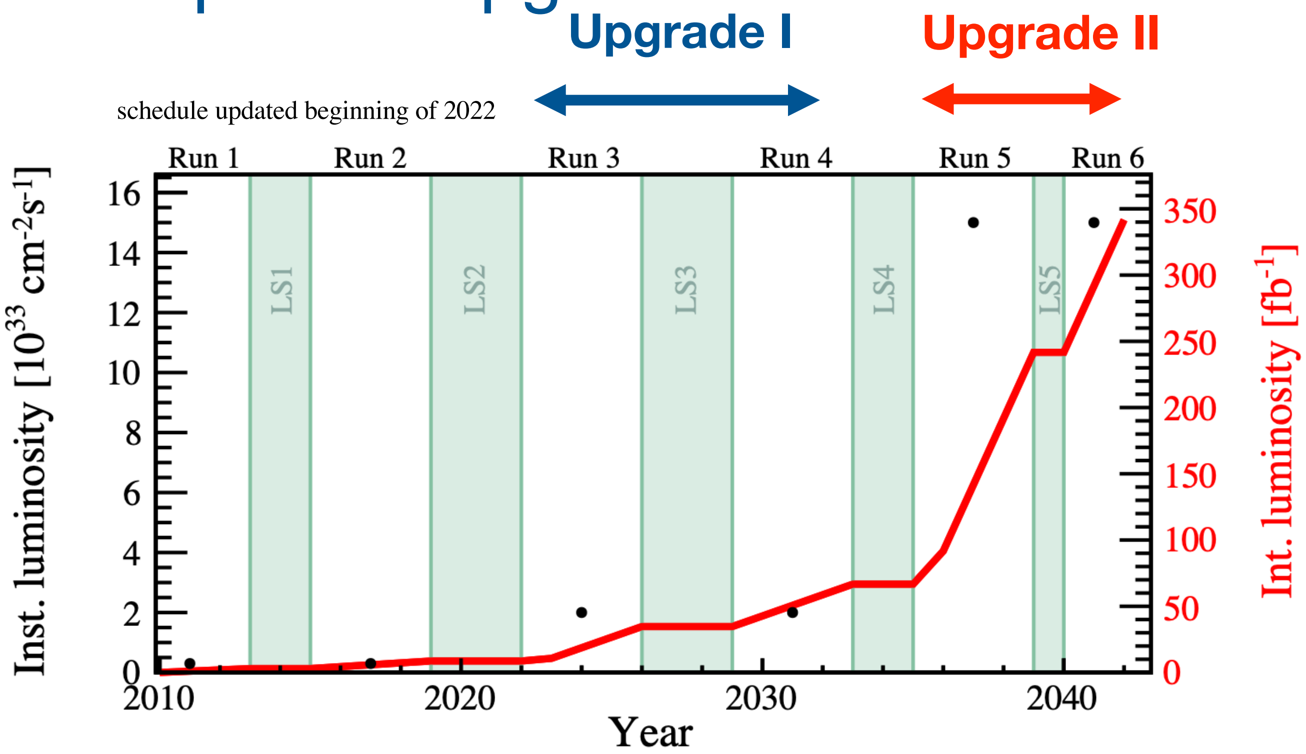


LHCb Upgrades

- 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*

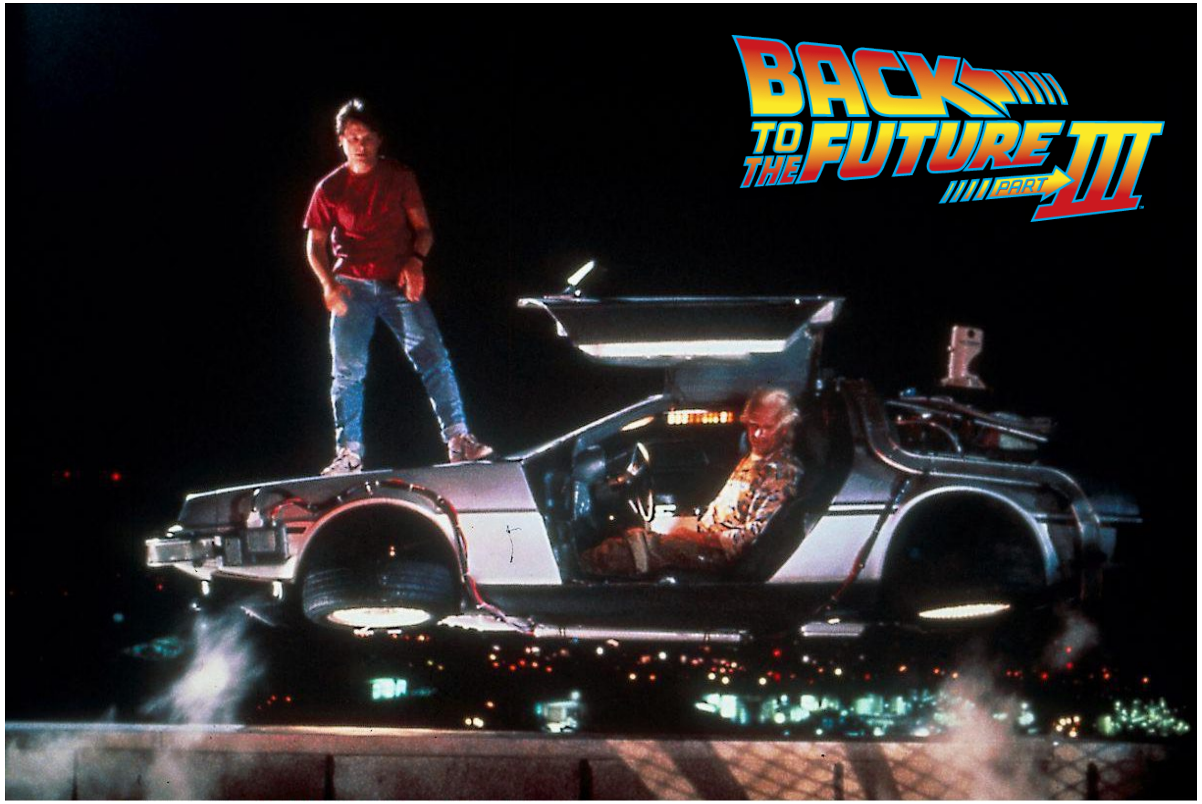
Upgrade II

Upgrade II

2033-

Critics Consensus

Back to the Future Part III draws the trilogy to a satisfying close



Powered by time travel !

Upgrade II: steps so far

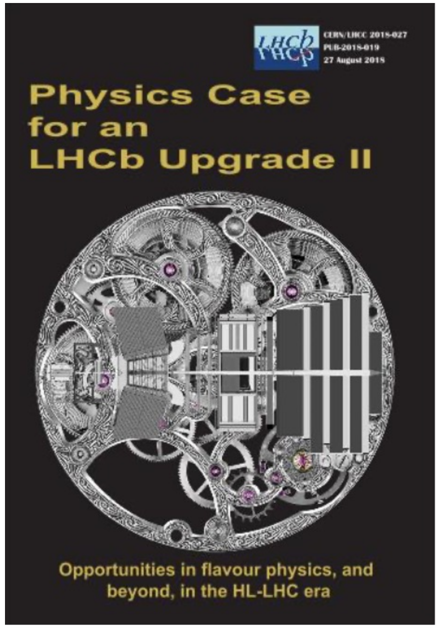
Upgrade II

2033-

Expression of Interest

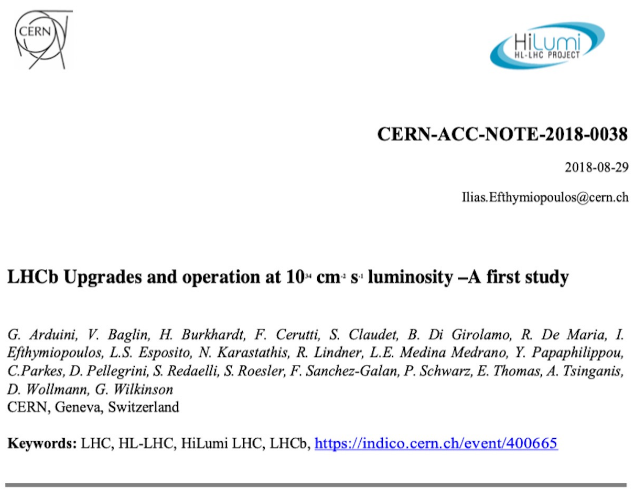
[LHCC-2017-003]

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"***

US P5 2023: "LHCb upgrade II will be a major project that opens a new era of precision"

UK Research and Innovation

Large Hadron Collider beauty (LHCb) 2030+

Funding

£1.1 million over the next three years. £49.4 million from the Infrastructure Fund in total including future funding years.

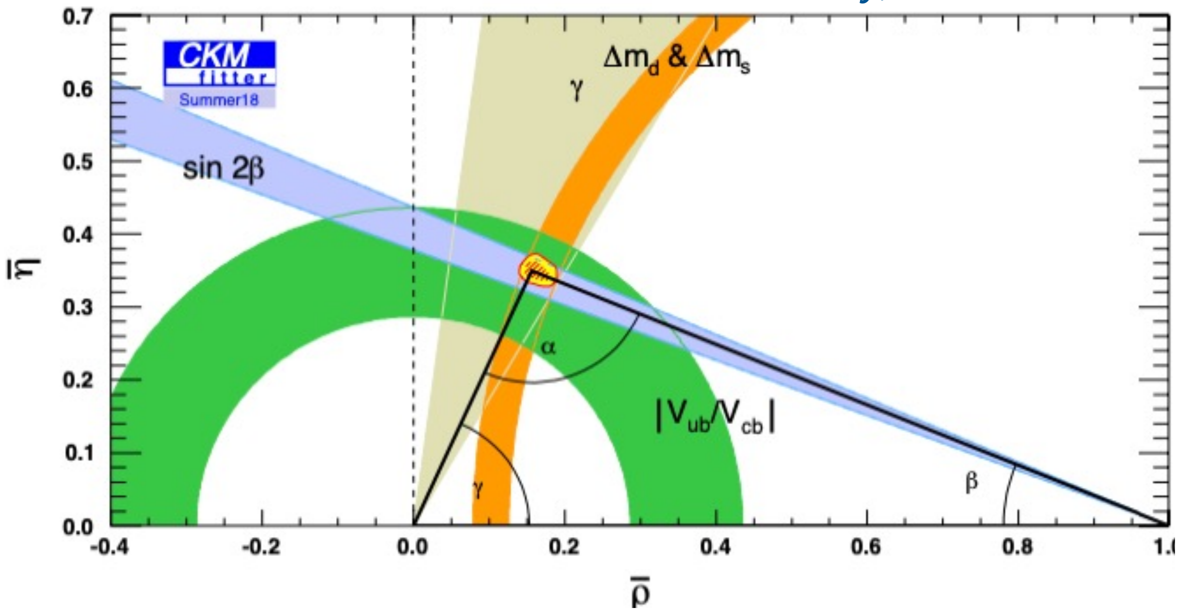
Project start date: financial year 2024 to 2025.

Constraining the Unitarity Triangle

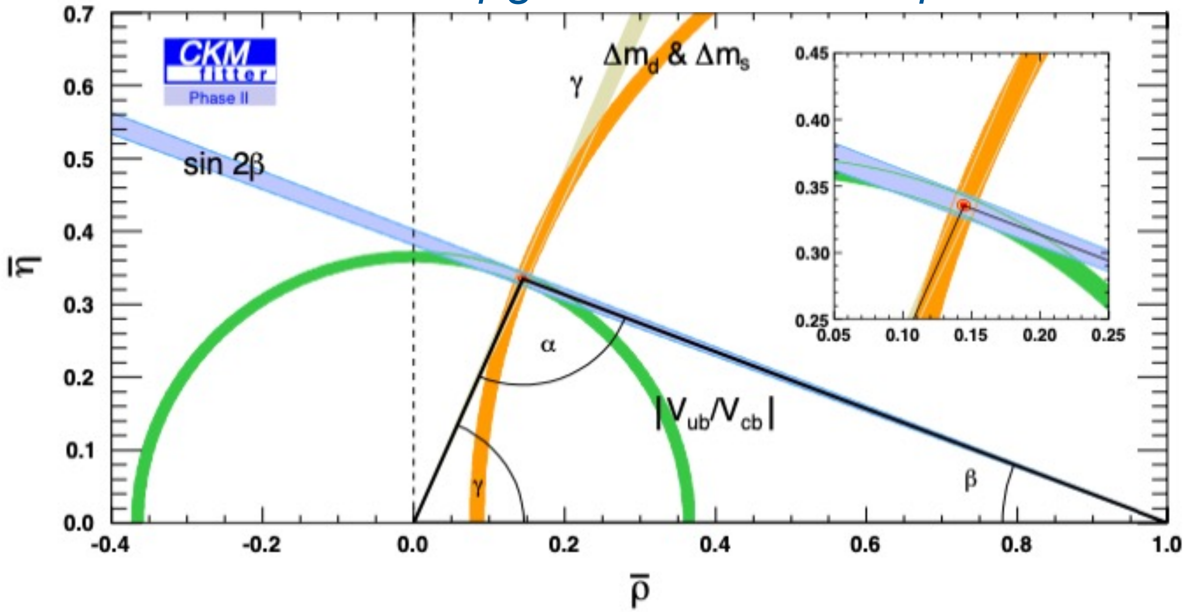
- *Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes*
- *Either NP is very heavy of it has a highly non trivial structure*

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement

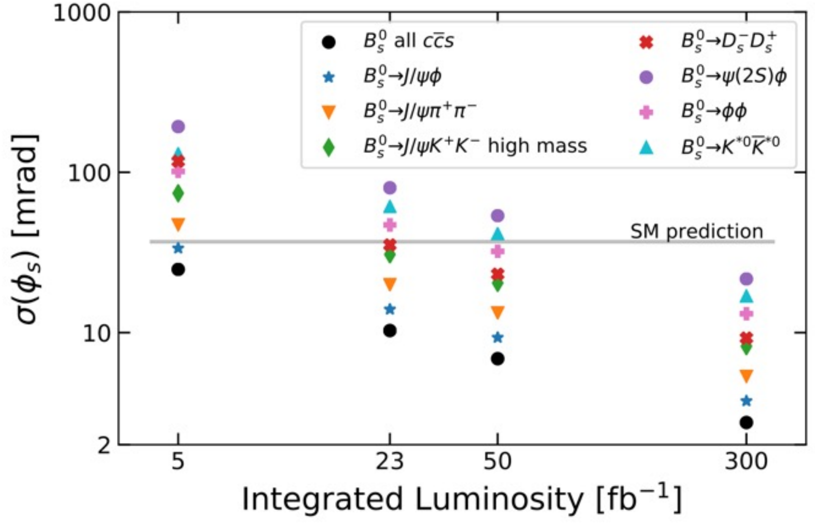


Arguably the greatest likelihood of a further paradigm shifting discovery at the HL-LHC lies with flavour physics

Beauty and Charm CPV Examples

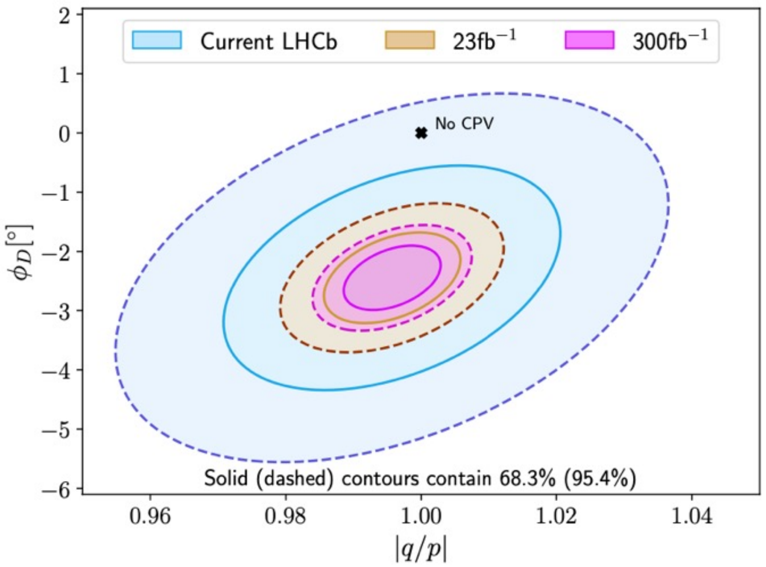
CP violating phase ϕ_s

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



CP violation in charm

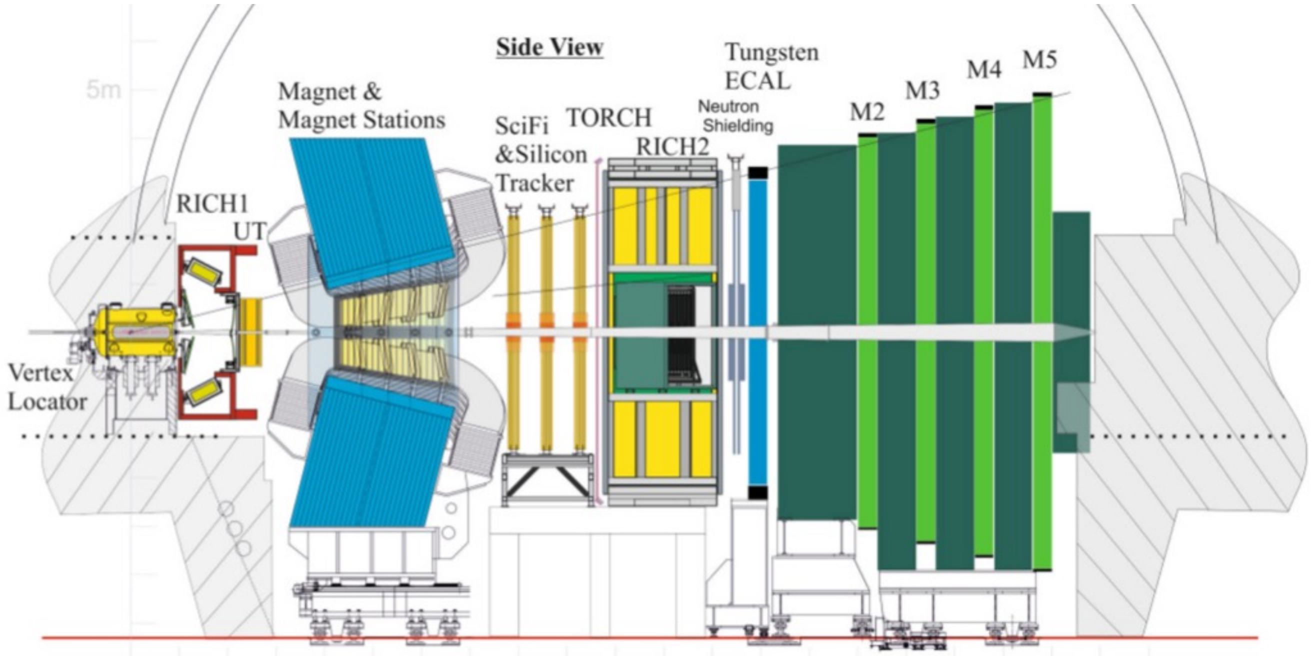
- LHCb Upgrade II is the only planned facility with a realistic possibility to observe CPV in charm mixing *(at >5σ if present central values are assumed)*



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

The detector challenge

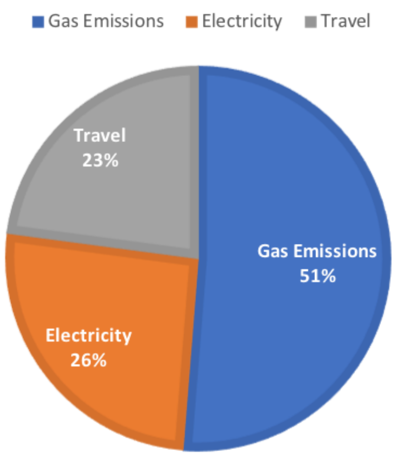
Targeting same performance as in Run 3, but with pile-up ~40!



Same spectrometer footprint, innovative technology for detector and data processing

Key ingredients:

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

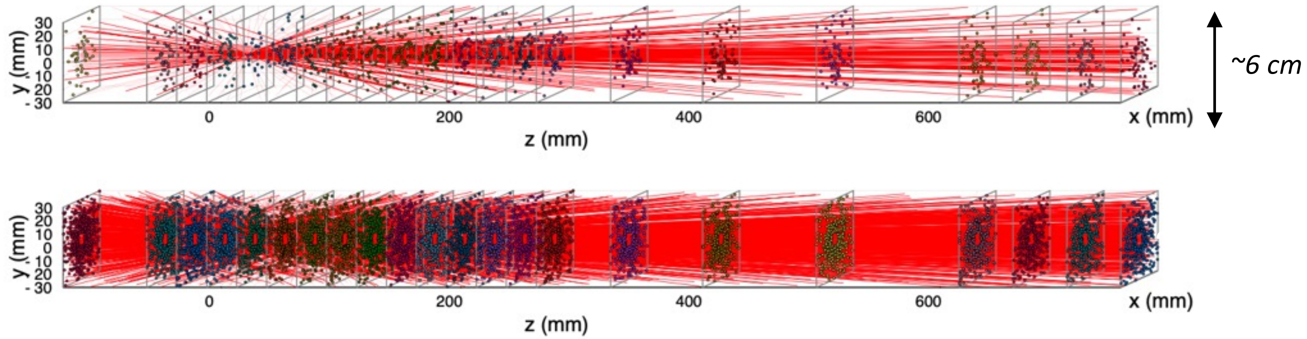


Environmental impact discussed for the first time in a TDR

VErtex LOcator (VELO)

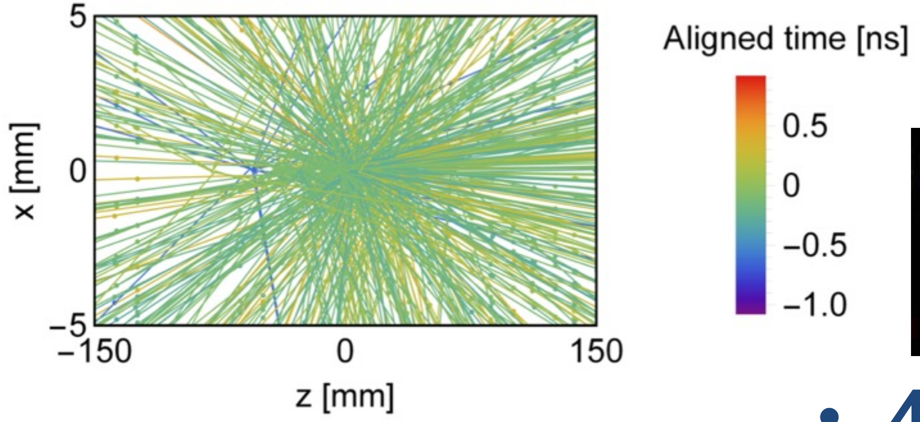
Run 3: pile-up ~6

Upgrade II: pile-up ~42

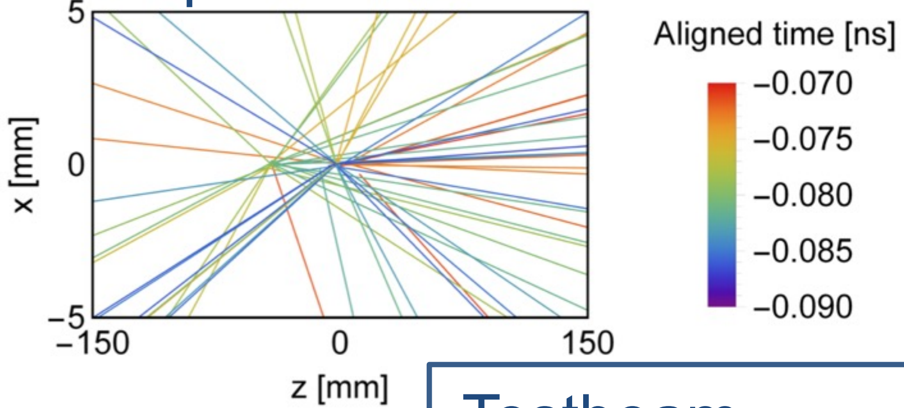


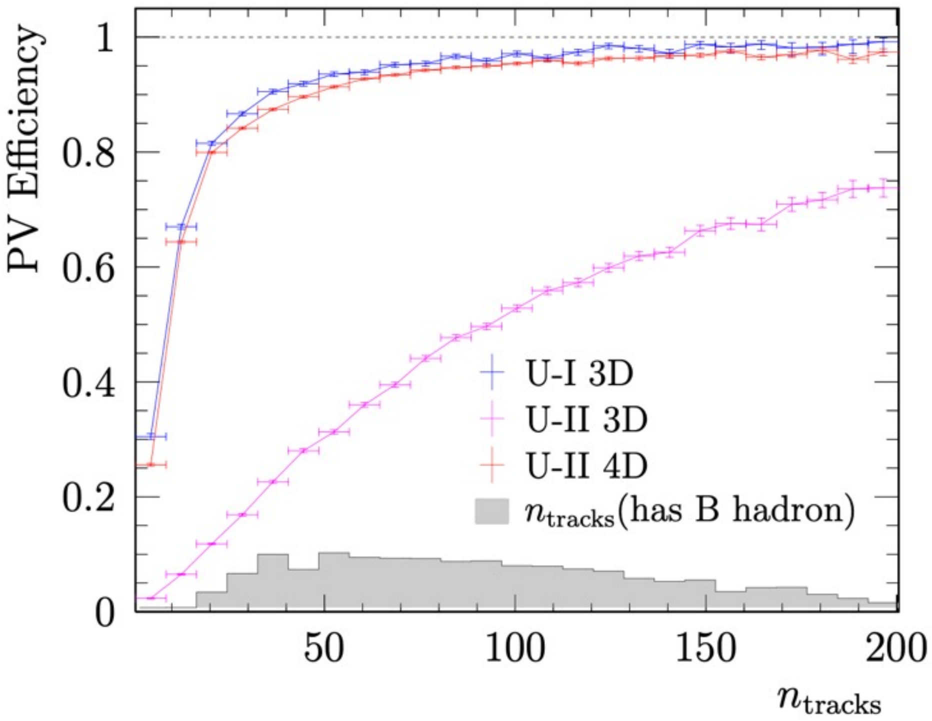
4D Vertexing: Precision Timing

42 interactions



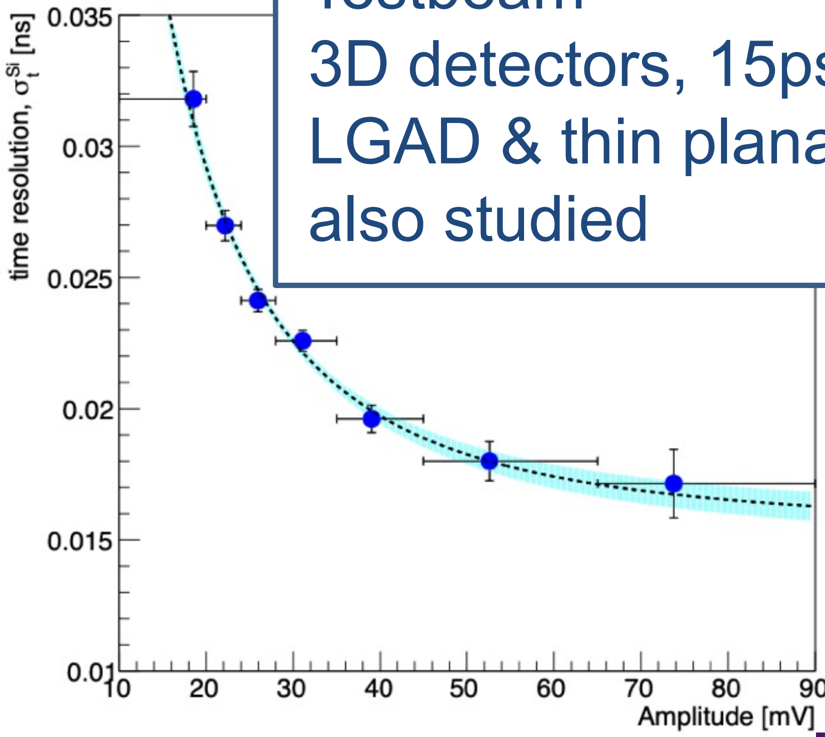
20ps time window





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

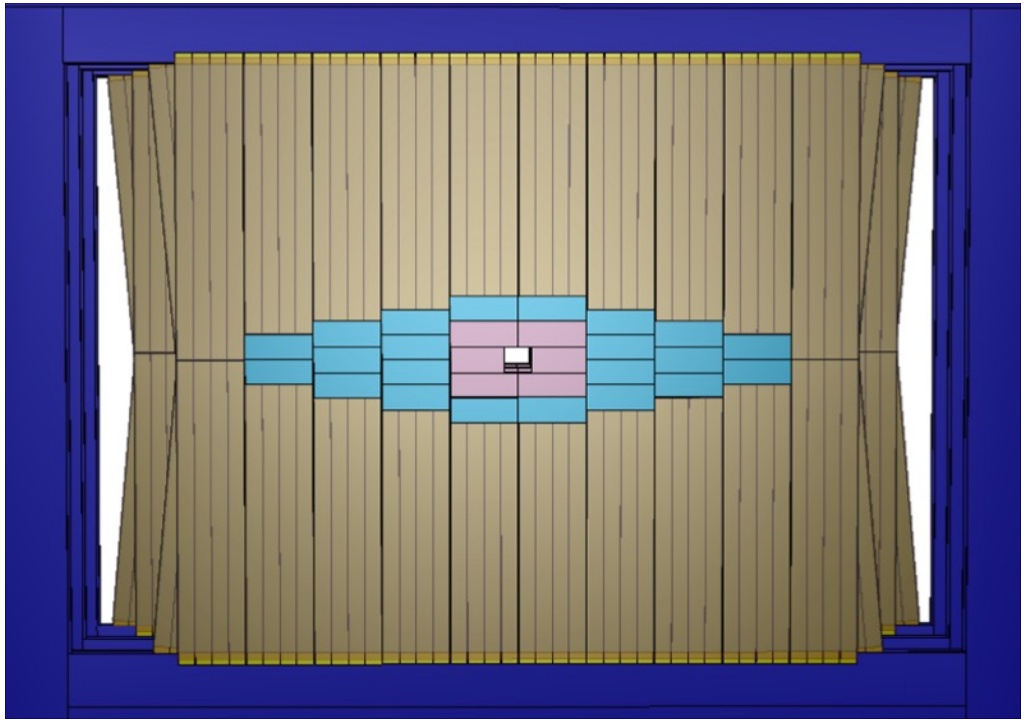
Testbeam
3D detectors, 15ps
LGAD & thin planar also studied

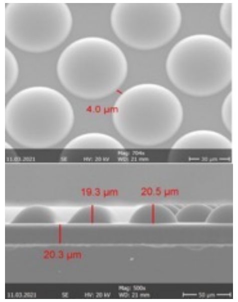


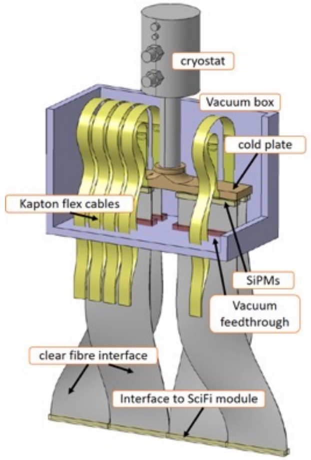
JINST 15 (2020) P09029

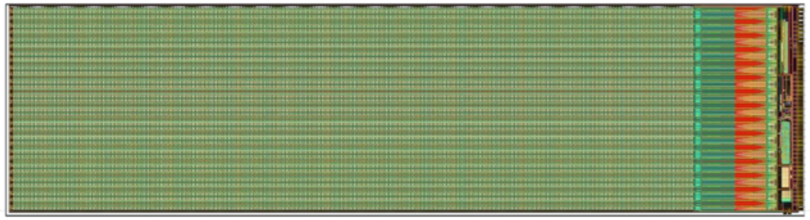
Tracker: Rad Hard MAPs, first of kind at LHC

- UT – before magnet
- Mighty tracker – SciFi+CMOS –
  after magnet
- Monolithic Active Pixel Sensors $(50 \times 150 \mu m^2)$
  - Radiation requirements in UT $3 \times 10^{15} n_{eq}/cm^2$
  - low-cost commercial process, low material budget
- Scintillating fibres in outer region
  - radiation-hard fibres, cryogenic cooling, micro-lens enhanced SiPMs

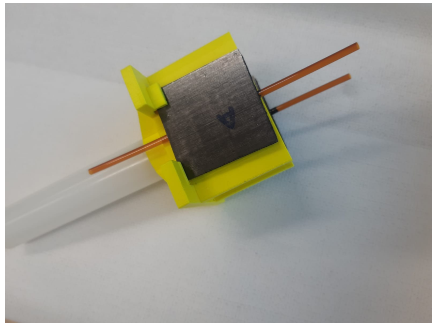








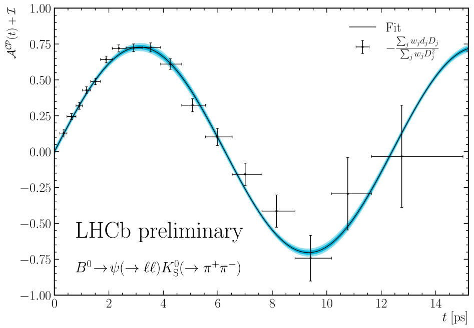
MightyPix1 1/4 scale chip fabricated

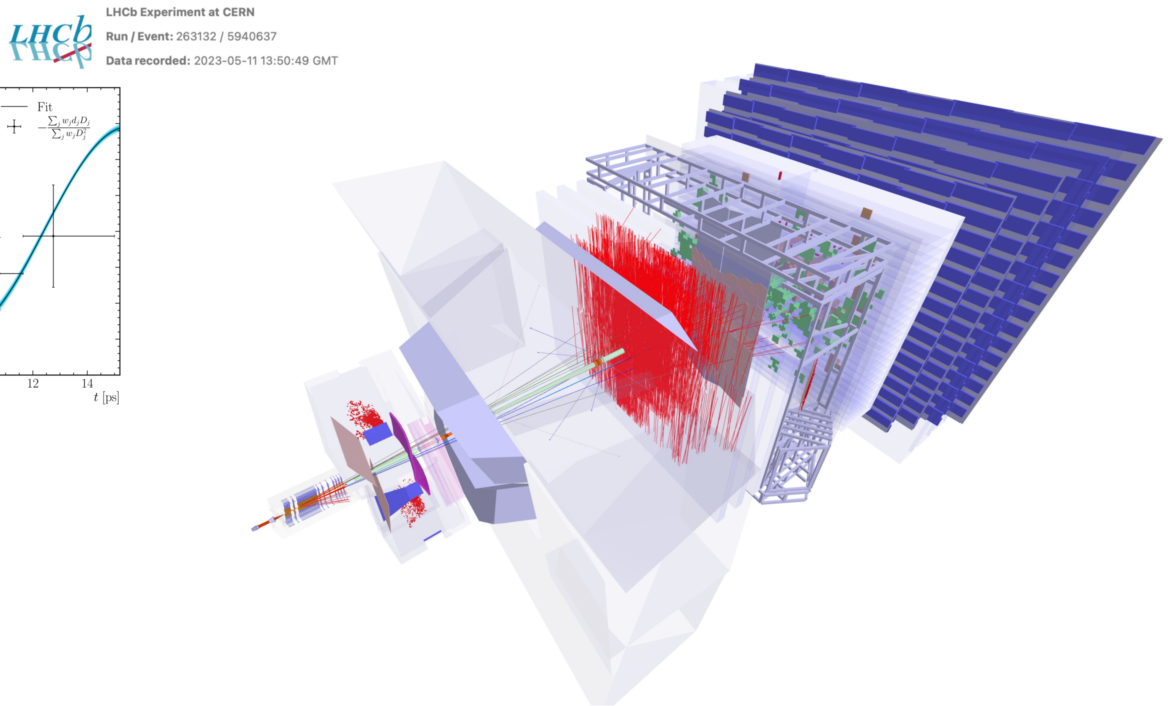


Summary

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

Summary

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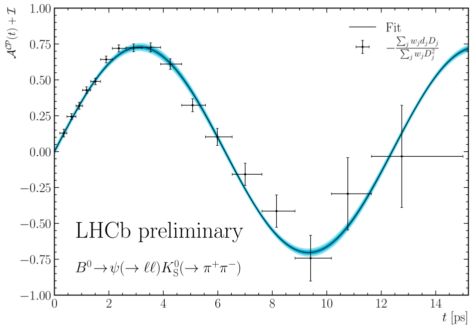

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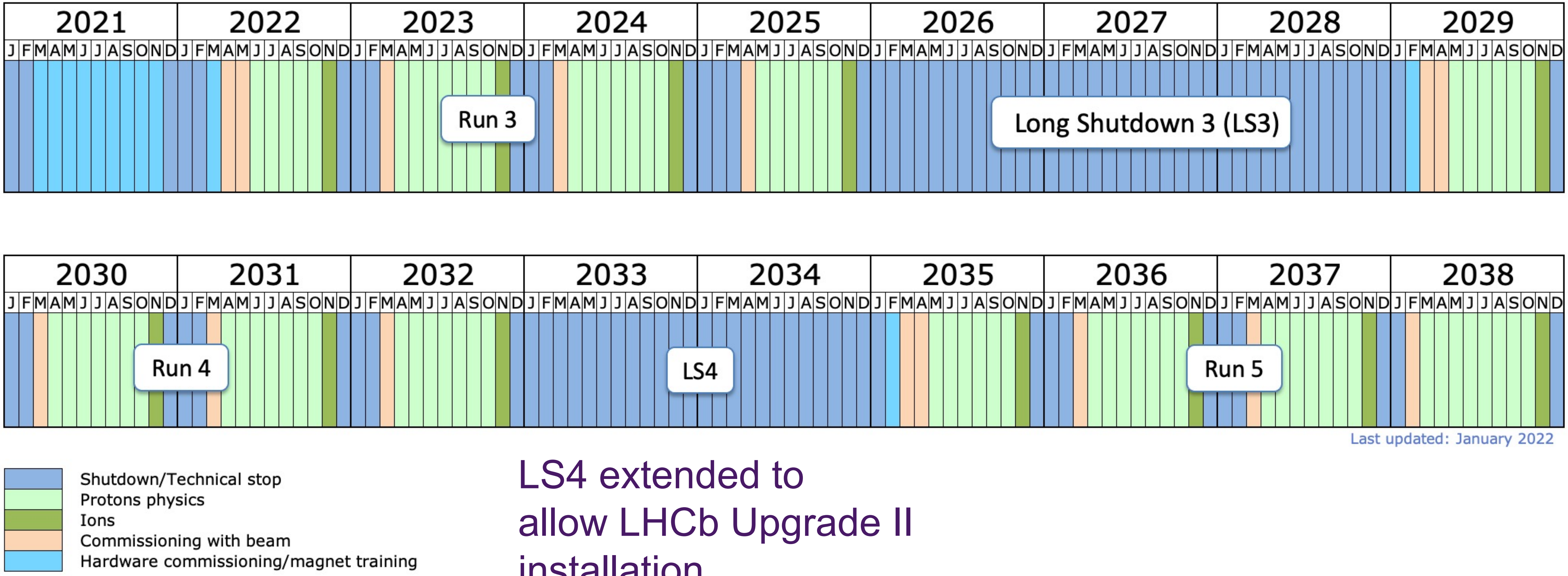
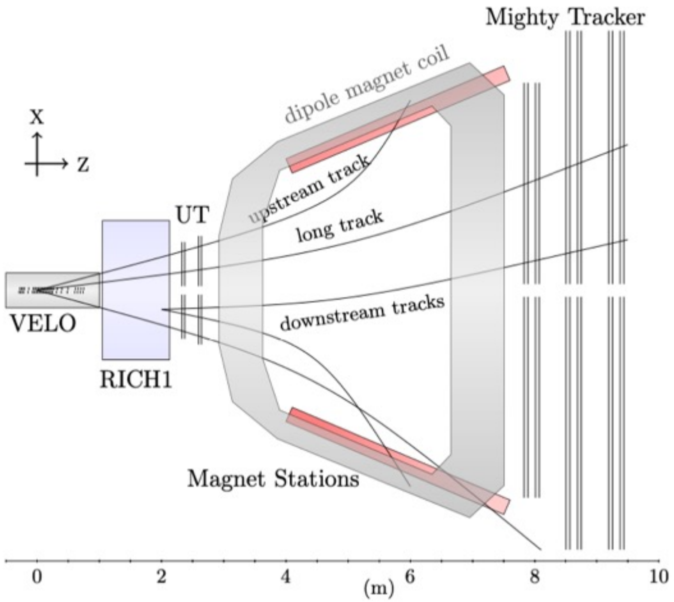
Backup

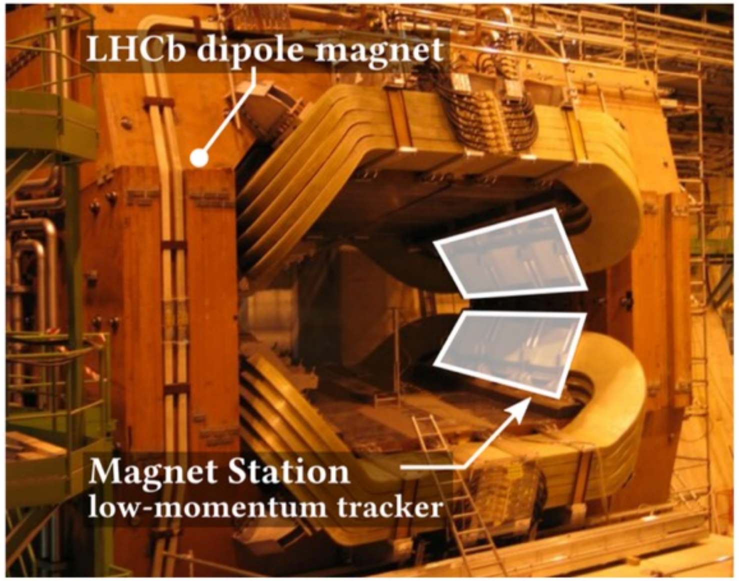
LHC Schedule

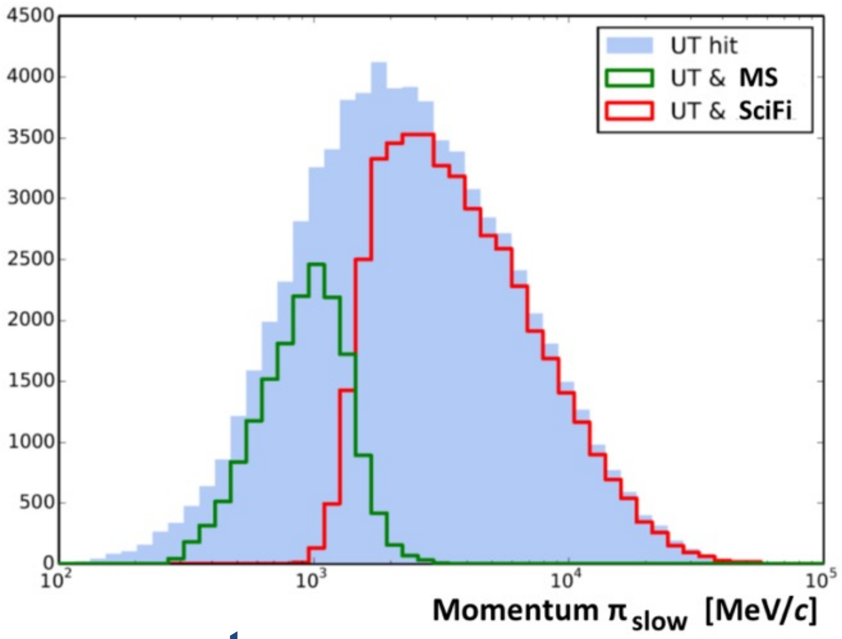


LS4 extended to allow LHCb Upgrade II installation

Magnet Stations: expanding physics potential



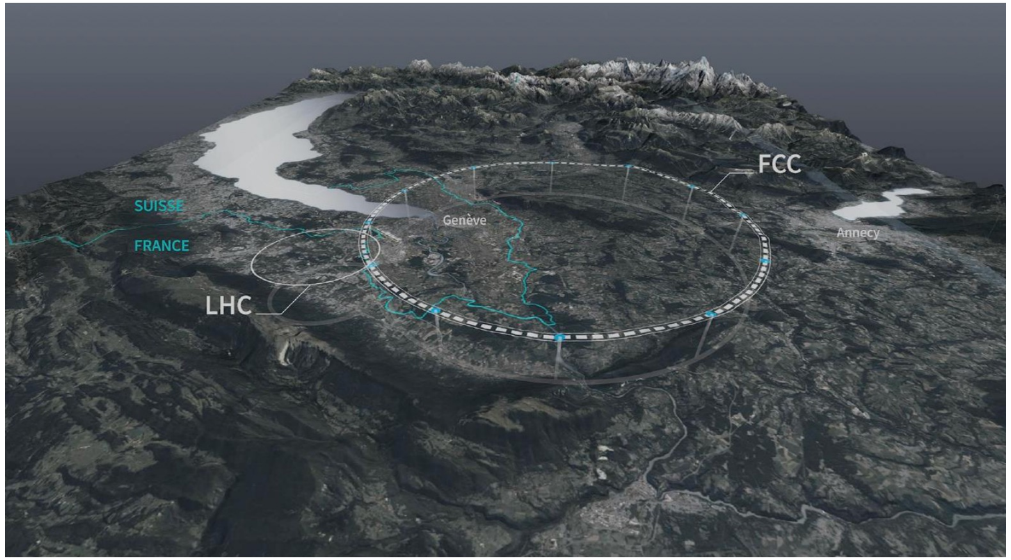




- Low momentum particles swept out by magnet
- Instrument walls of magnet with scintillating bars
- Obtain sub-% momentum measurement
- Significant increase of acceptance for low momentum

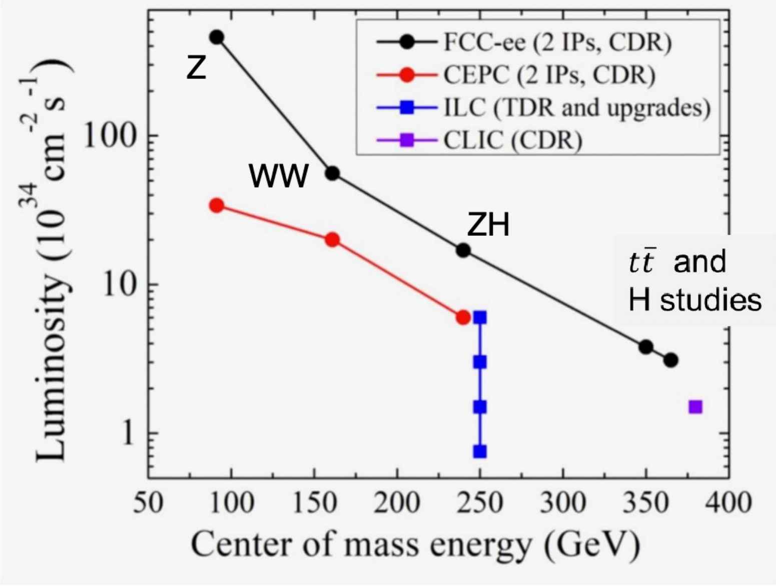
e.g. factor of ~2 gain in prompt D^{*+} with slow π

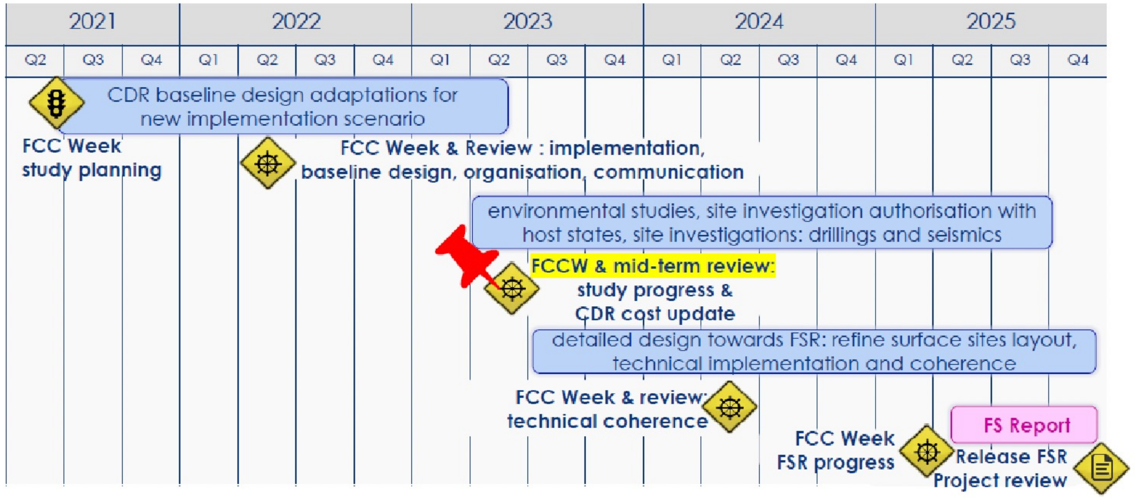
Flavour @ FCC-ee (or CEPC – very similar machine)



~100km CERN e^+e^- machine for >2045

From Guy Wilkinson, Jernej Kamenik FCC week 2023





- Running mode includes ~ 5×10^{12} Z decays, hence flavour potential

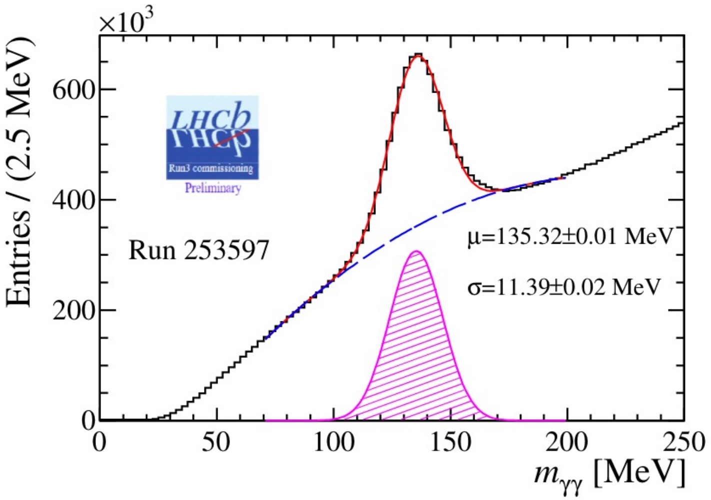
Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

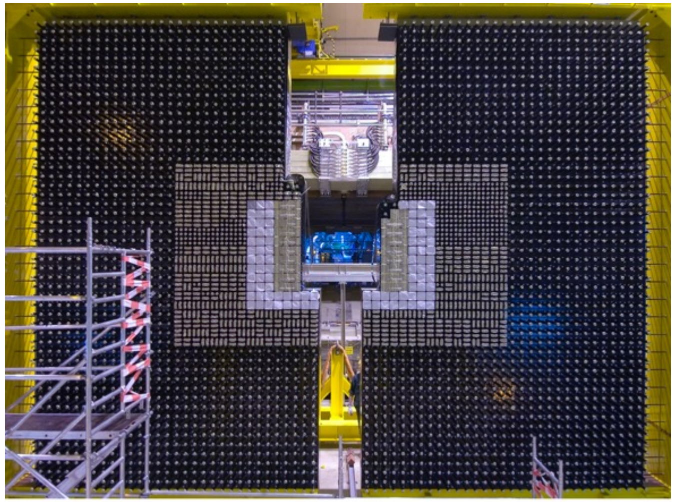
Effort underway to explore potential

LHCb Upgrade I: CALO & Muon

CERN-LHCC-2013-022

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

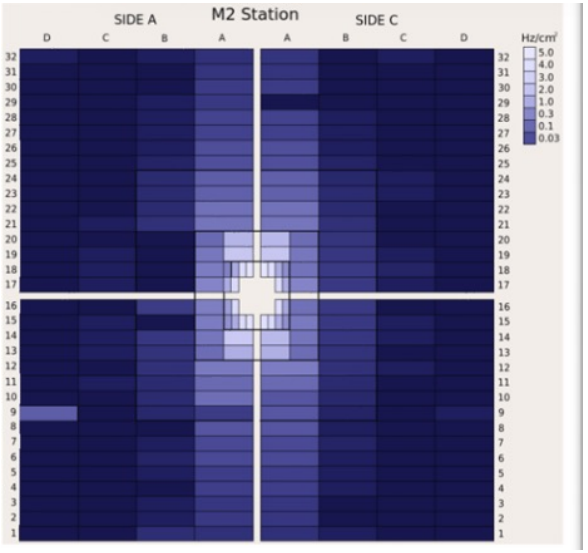


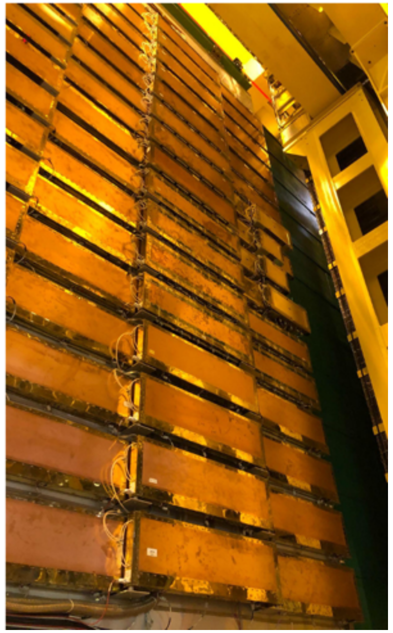


- **Shashlik Calorimeters**
  - PMT gains reduced
  - New front-end electronics

  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

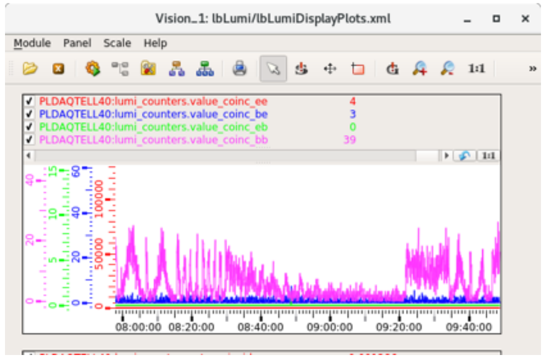


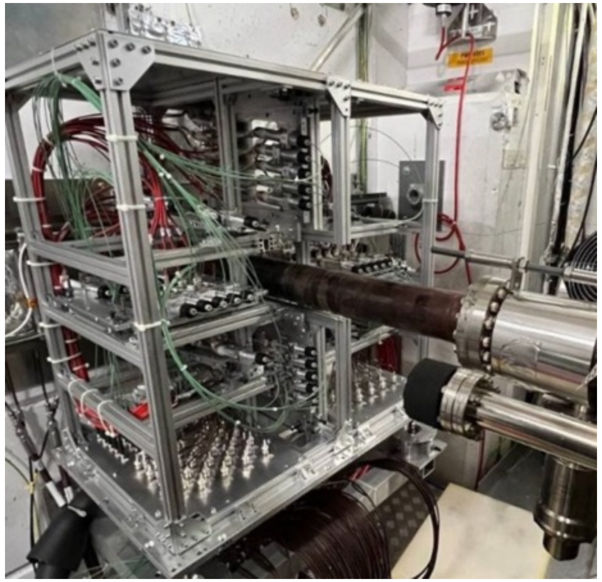


LHCb Upgrade I: PLUME & SMOG

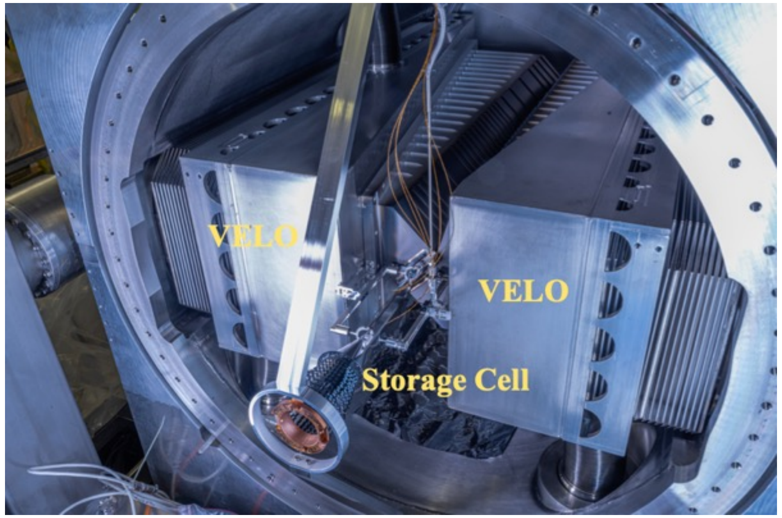
CERN-LHCC-2021-002
CERN-LHCC-2019-005

- 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!**



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

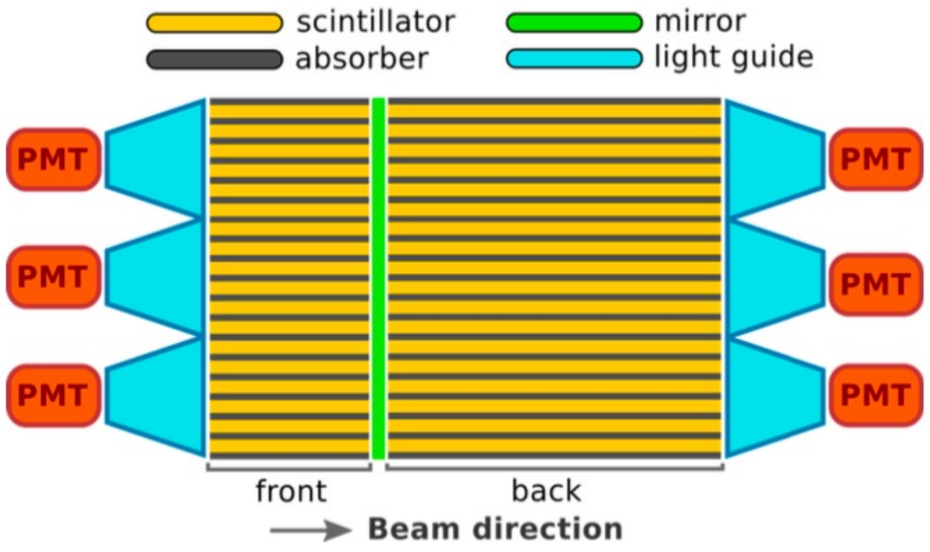
updated for FTDR

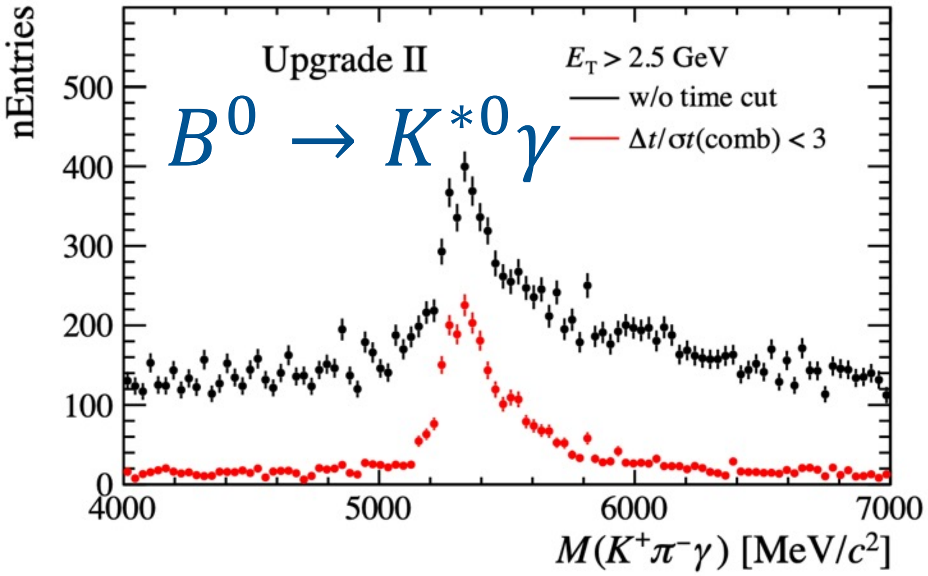
Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[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

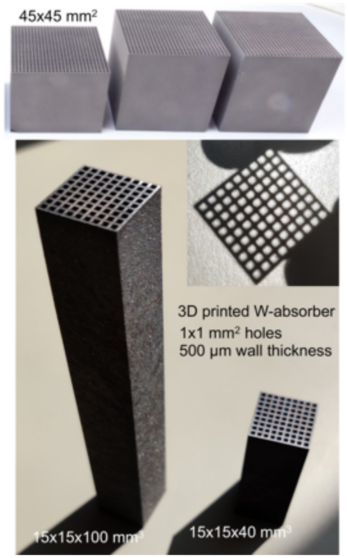
- Full range of beauty & charm mesons & baryons accessible
- Strong results with π^0, photons, missing particles reconstruction
- Beyond Flavour: LHCb as general purpose detector in forward region
- Spectrocopy, EW precision, dark sector and exotic searches, heavy ions and fixed target physics

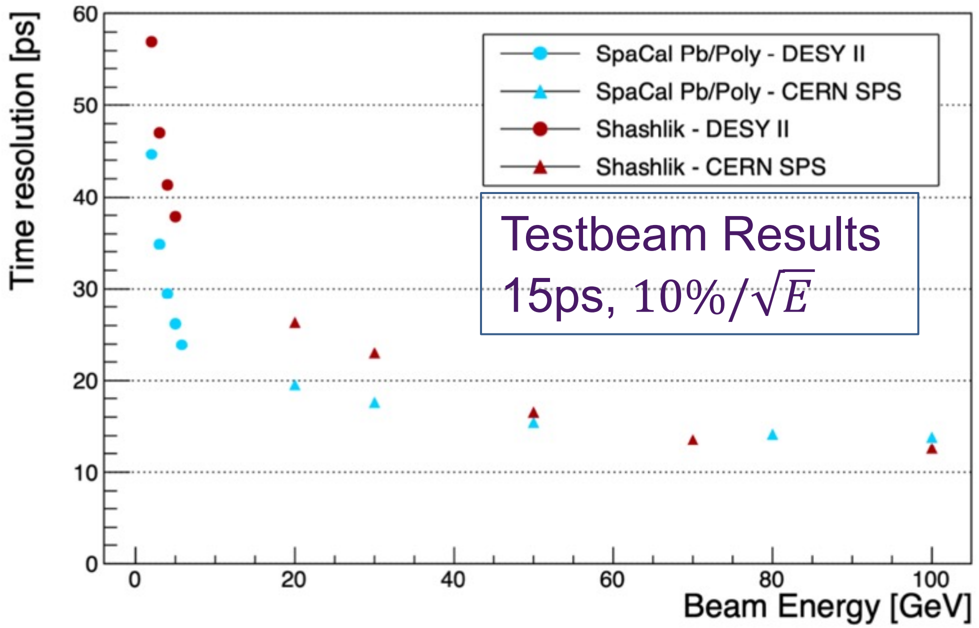
5D Calorimetry: Precision timing

- 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





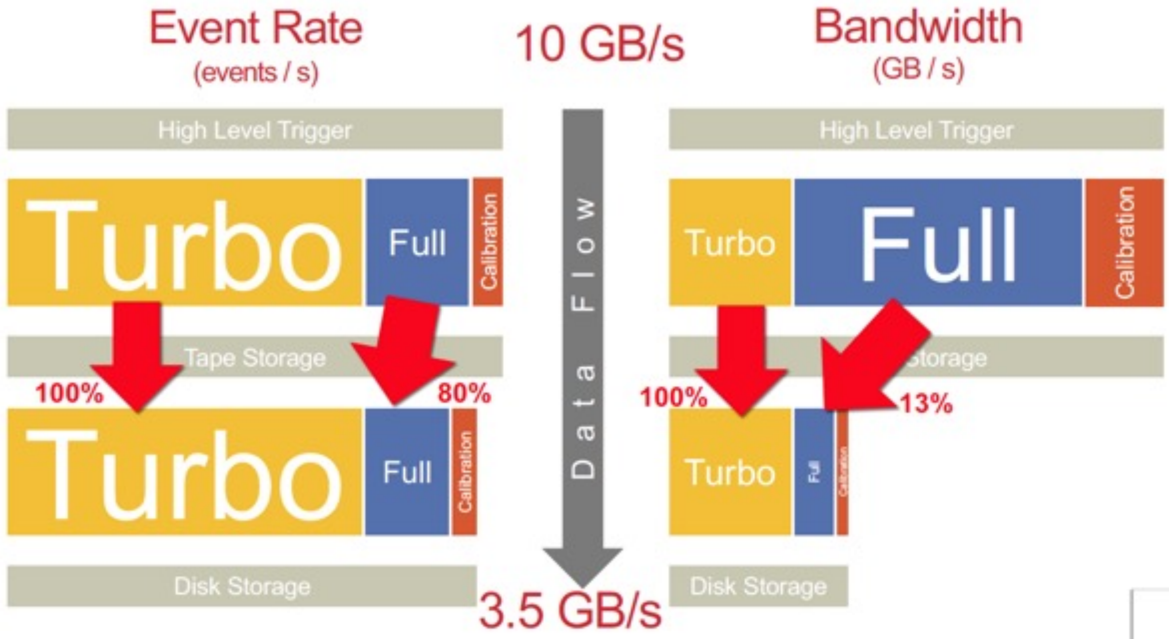




Testbeam Results
15ps, $10\%/\sqrt{E}$

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