The University of Manchester

LHCb Upgrade II

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

6th February 2022,

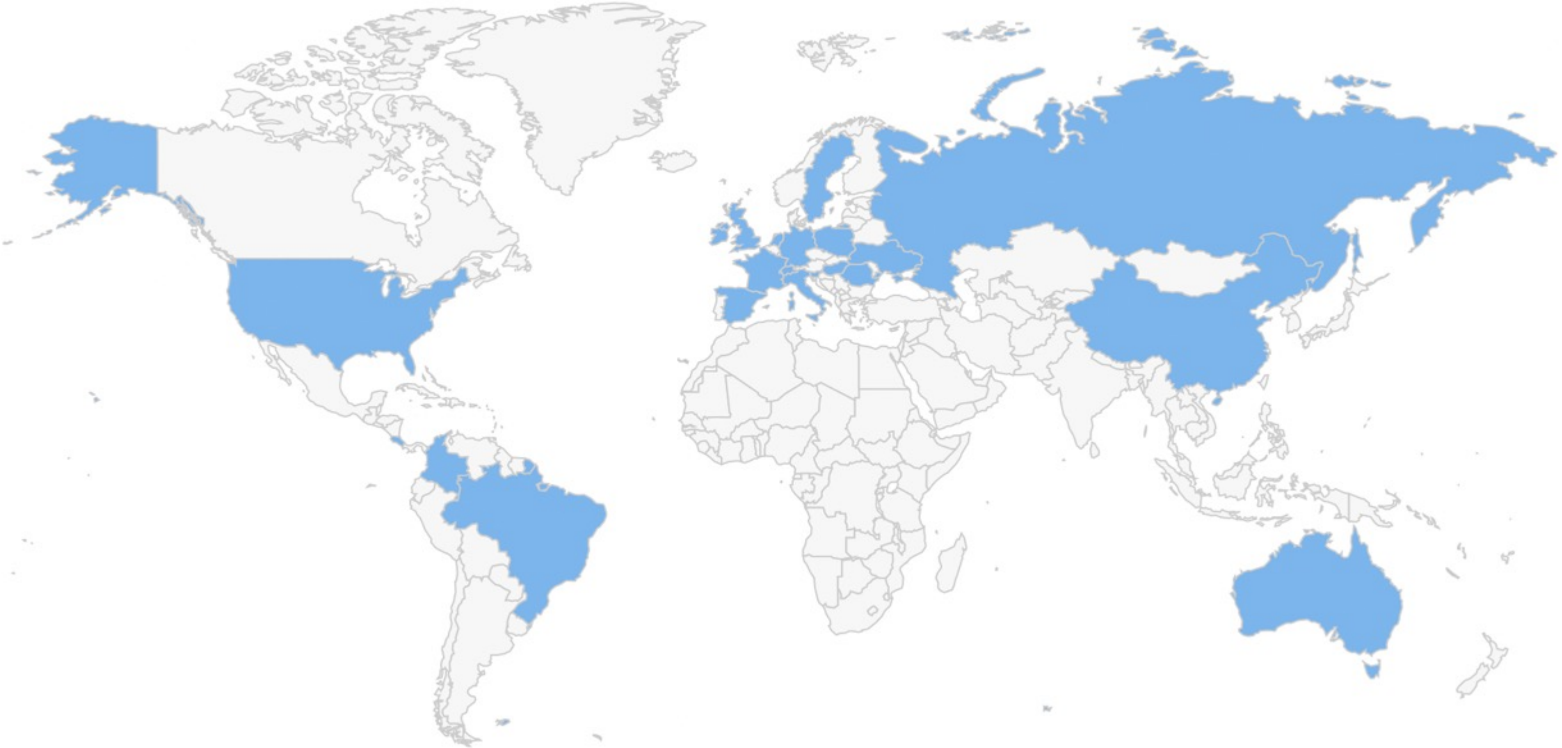
Conseil Scientifique de l'IN2P3

Chris Parkes

On behalf of the LHCb Collaboration

LHCb Collaboration

- **1069** authors from **96** institutes in **21** territories
  - **1547 members**
  - **Expanding Collaboration**
  - **341** authors signing the exp. proposal in 1998, **690** the upgrade proposal in 2012



Growth in recent years
Includes in areas outside Flavour Physics, notably in Heavy ions and fixed target

B DECAYS TO CHARMONIUM

B DECAYS TO OPEN CHARM

CHARMLESS b-HADRON DECAYS

b-HADRONS AND QUARKONIA

CHARM PHYSICS

FLAVOUR TAGGING

LUMINOSITY

QCD, ELECTROWEAK AND EXOTICA

RARE DECAYS

SEMILEPTONIC B DECAYS

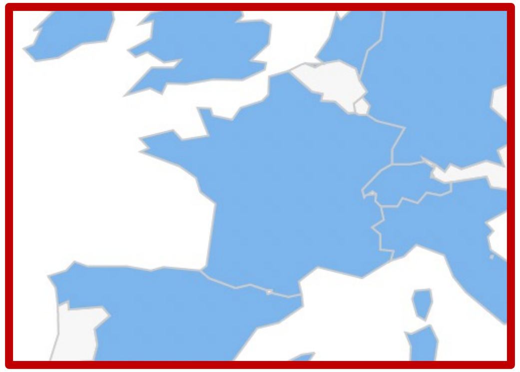
DETECTOR PERFORMANCE

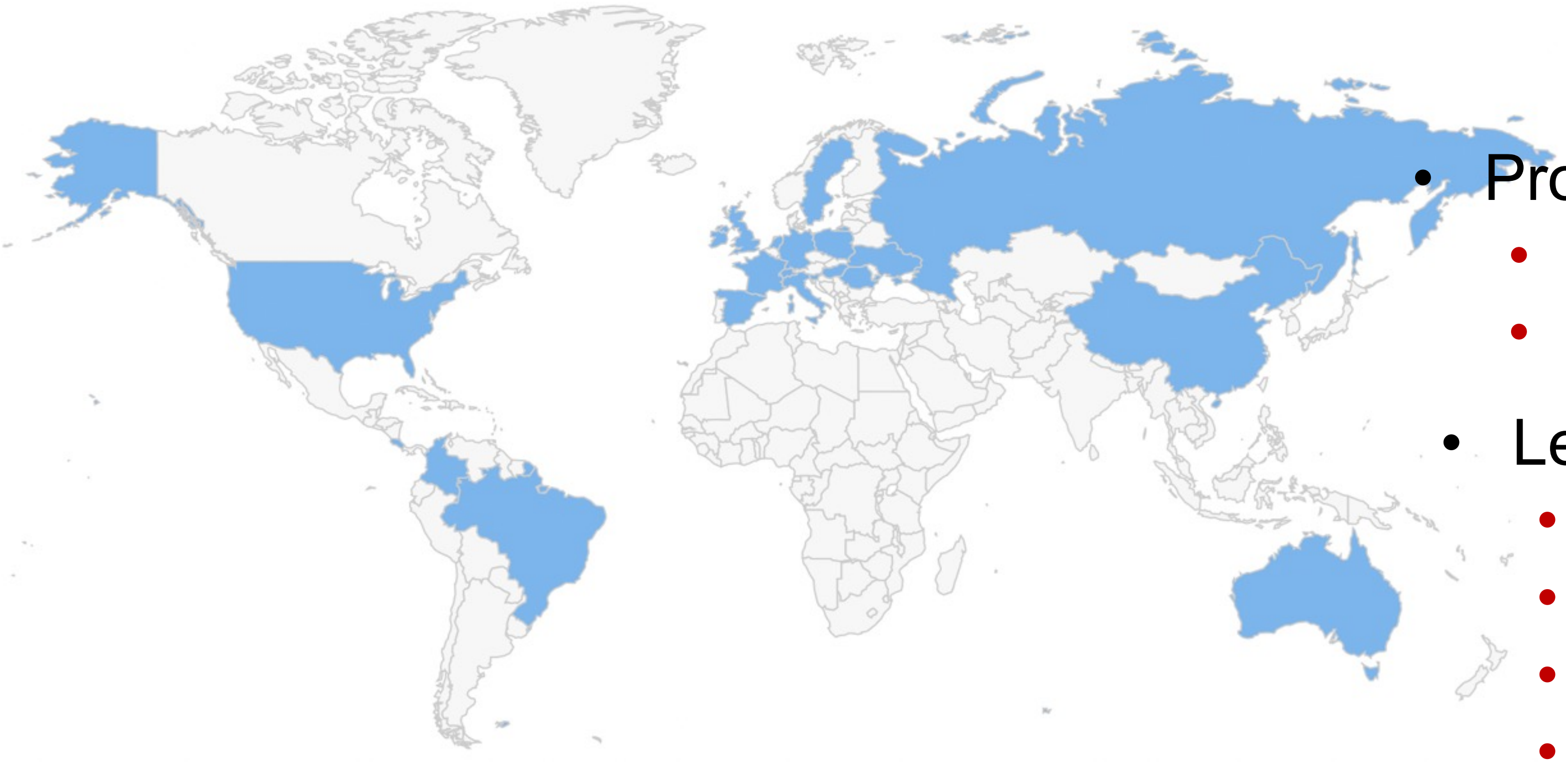
IONS AND FIXED TARGET

LHCb Collaboration - France

- CPPM, IJCLab, LAPP, LLR,
- LPC,LPNHE, CC IN2P3
- IRFU technical associate group
- Interest from other groups

7%





- Projects Upgrade I
  - ECAL, SciFi
  - DAQ & Real Time Analysis
- Leading involvements & positions
  - Physics Coordinator,
  - Operations Coordinator
  - Project Leaders
  - Physics Group Coordinators…

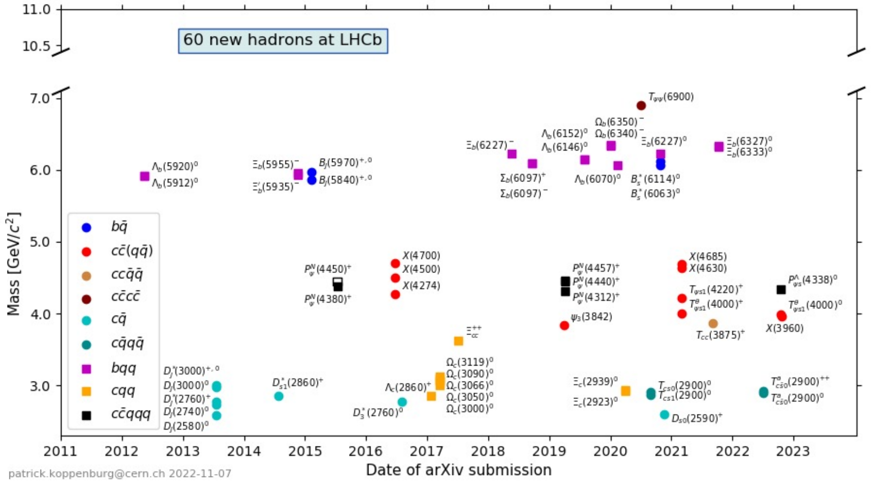
LHCb – Flavour & beyond

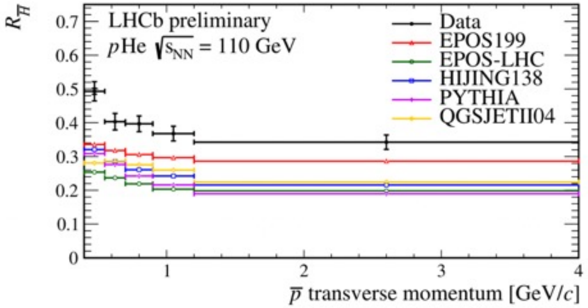
Original

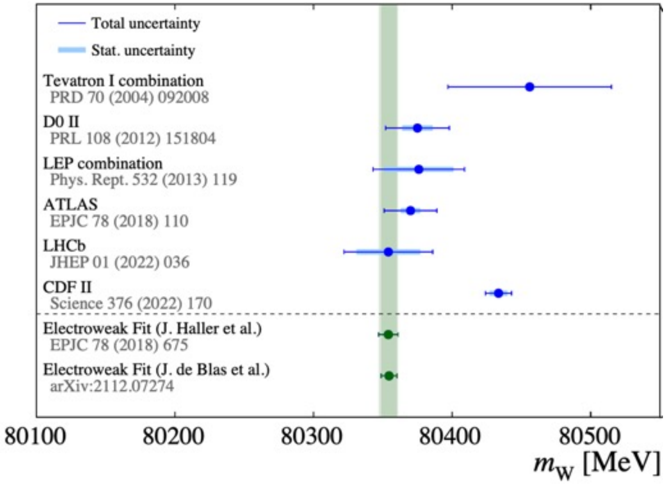
2009-2018

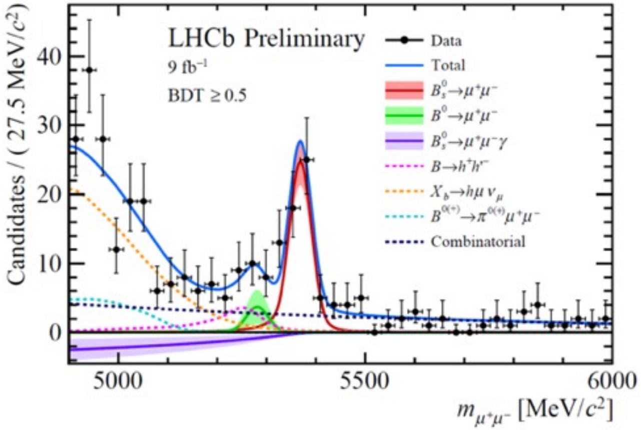
- **Future plans build on the success of the experiment during Run 1 & 2**

- > 650 physics papers (most per author of any LHC experiment)
- Series of significant discoveries
  - Rare decays
  - Matter anti-matter differences in three new systems
  - 60 of the 68 hadronic particles discovered at the LHC
- Breadth of physics programme
  - World leading experiment in core field
  - But also leading or unique far beyond
    - Heavy ions
    - Fixed Target
    - Electroweak
    - Dark Sector

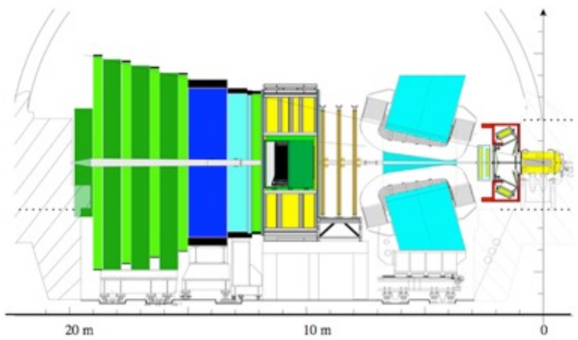








LHCb unique attributes



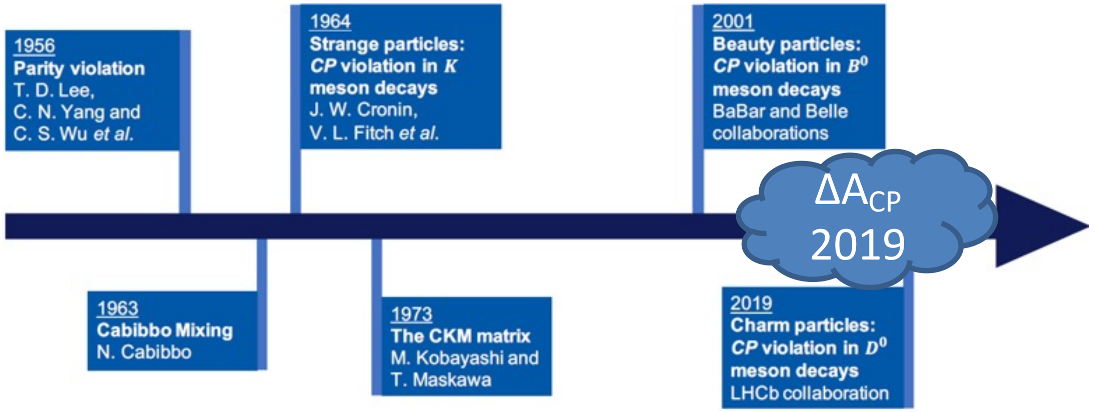
- Requirements:
  - efficient **trigger** on leptons and hadron channels
    - **Upgrade I&II : 40MHz software trigger**
  - efficient **particle ID** for flavour tagging and background rejection
    - **RICH 1&2 for hadron identification**
  - good **proper time resolution** for time dependent measurements of Bs decays
    - **VELO: Geometry and beam proximity**
  - good **mass reconstruction** for background rejection
    - **UT,SciFi: High resolution tracking and geometry**

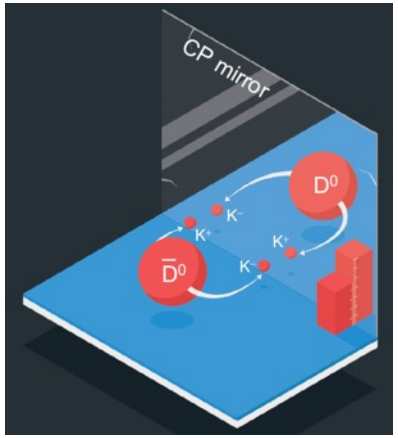
Some examples of recent results

First evidence Charm CP Violation in specific decay

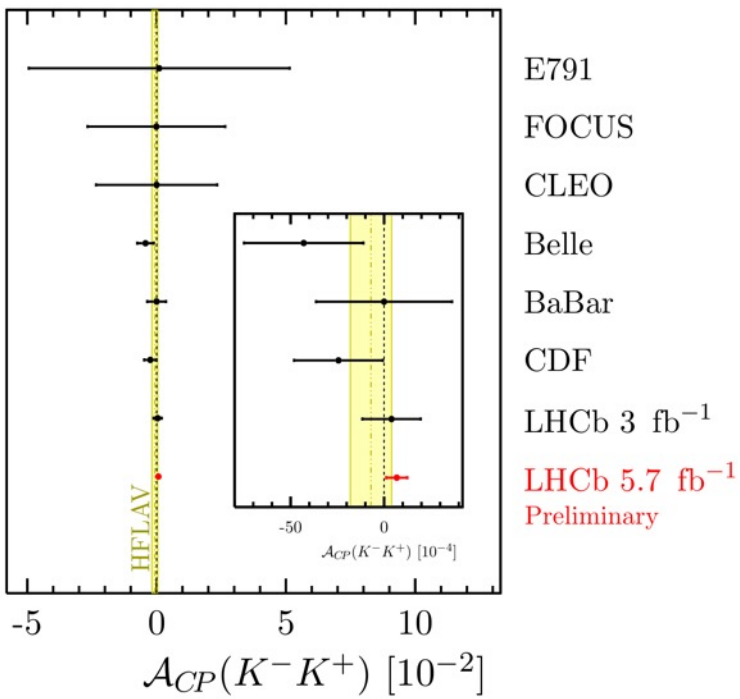
ICHEP 2022

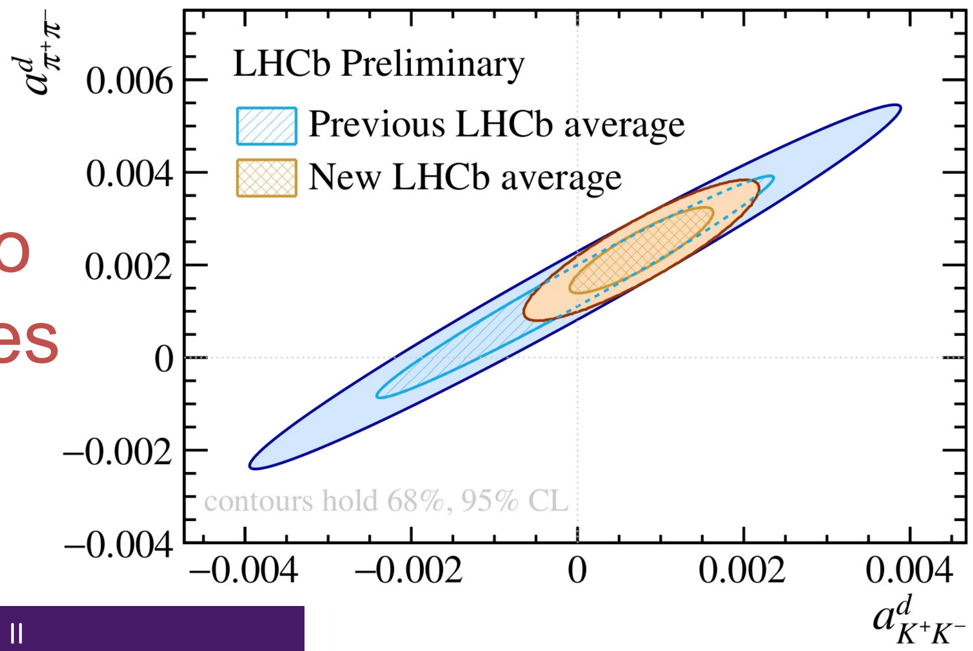
LHCb-PAPER-2022-024





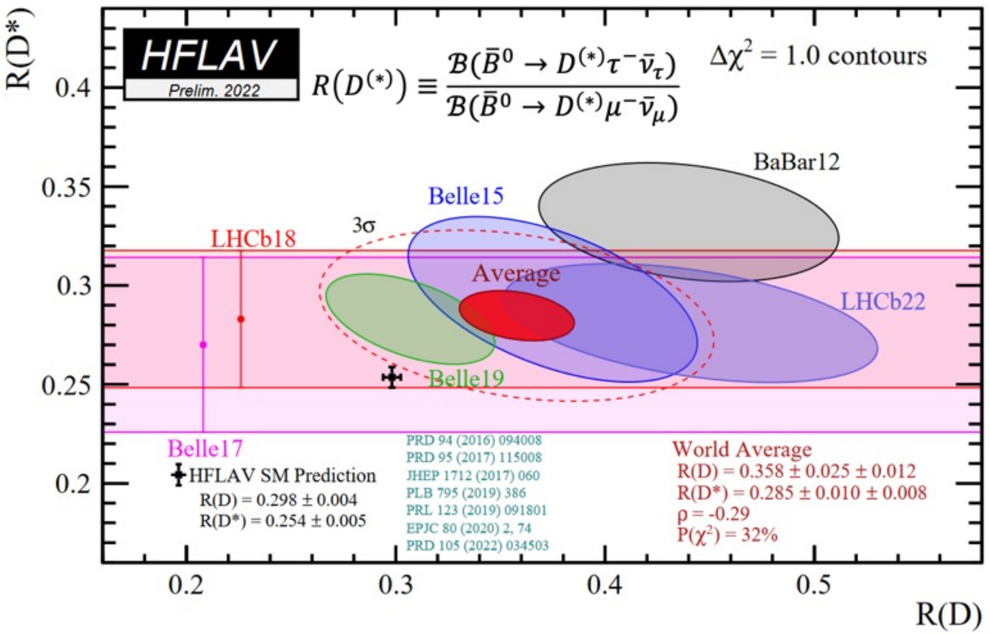
- Direct CP Discovery 2019
- ΔA_{CP} difference KK,ππ
- Cancel systematics
  - Production, detection asymmetries
- Upper end of SM prediction – separate into individual symmetries
  - Control channels to correct asymmetries
  - 3.8σ asymmetry evidence in KK

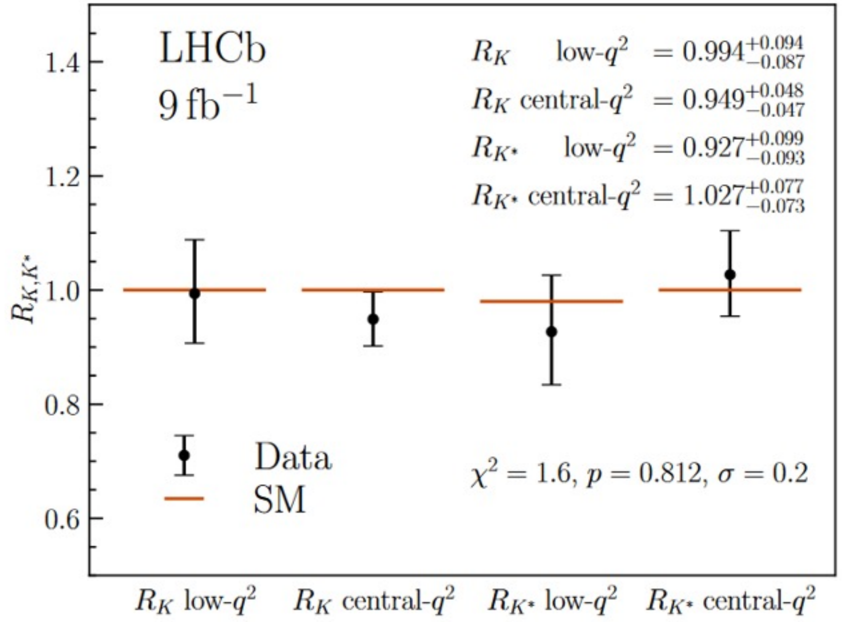




Lepton Flavour Universality

LHCb-PAPER-2022-039
LHCb-PAPER-2022-045/46





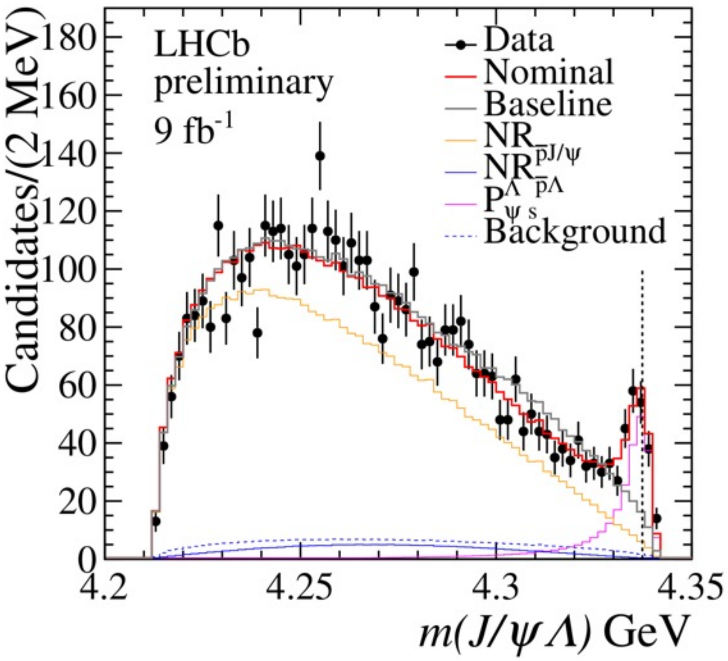
- B→clν: First combined R(D),R(D*) at hadron collider
  - Much anticipated result, pathfinder result with Run 1 data
- Excellent agreement with world average, 1.9σ from standard model

- B→sll: Combined R(K),R(K*) with full Run 2 & improved electron – hadron background
  - Much anticipated result
- Previous R(K)-central 3σ from SM
- All 4 results compatible with SM

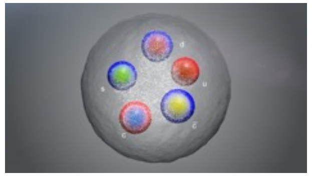
Pentaquark & Tetraquarks

LHCb-PAPER-2022-031
LHCb-PAPER-2022-026

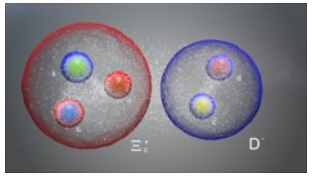
ICHEP 2022



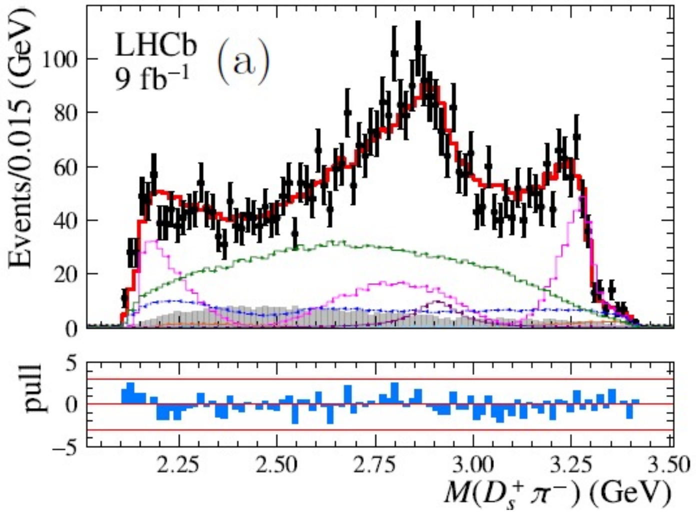
- Discovery of new states continues
- First strange pentaquark $P^{\Lambda}_{\psi s}(4338)^0$ $c\bar{c}sud$
  - Confirms pentaquarks in different decay to LHCb 2015 discovery
- Tetraquark isospin partners $T^{a}_{c\bar{s}0}(2900)^{++}$ $c\bar{s}u\bar{d}$ $T^{a}_{c\bar{s}0}(2900)^{0}$ $c\bar{s}\bar{u}d$
  - First doubly charged tetraquark
  - Start to build up **multiplets**

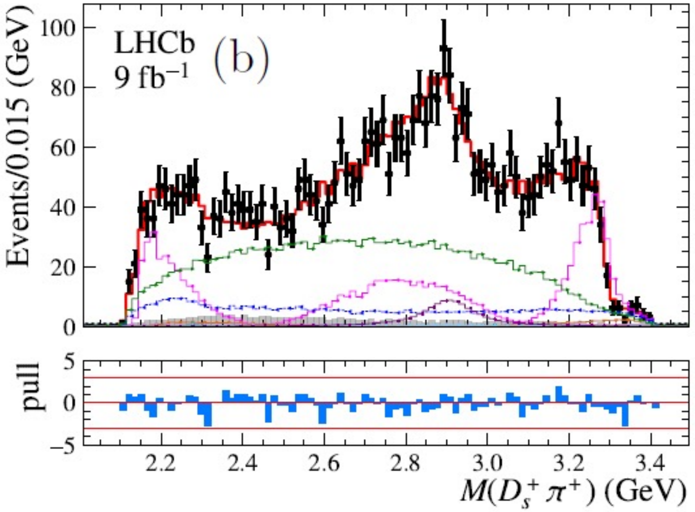


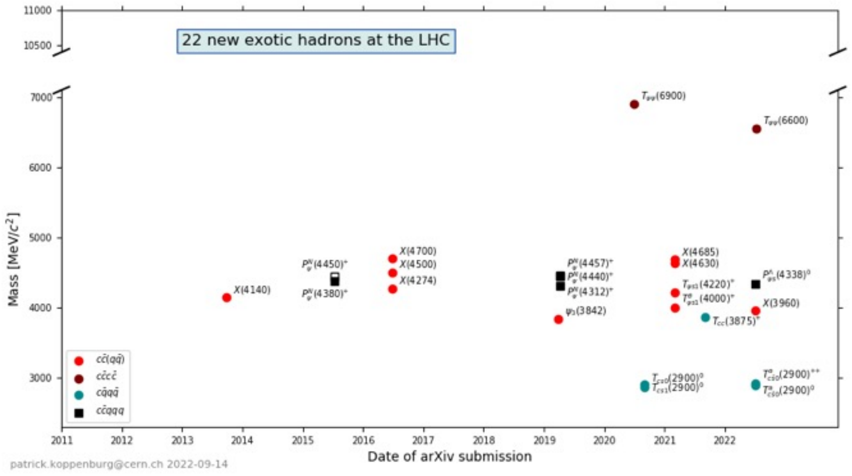
or



or…. understand nature of states





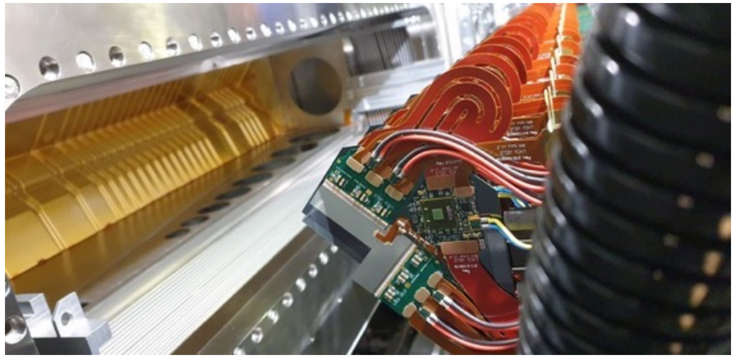


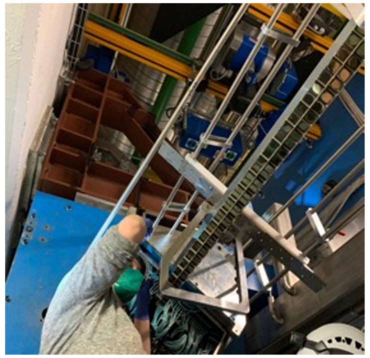
Upgrade I: major project

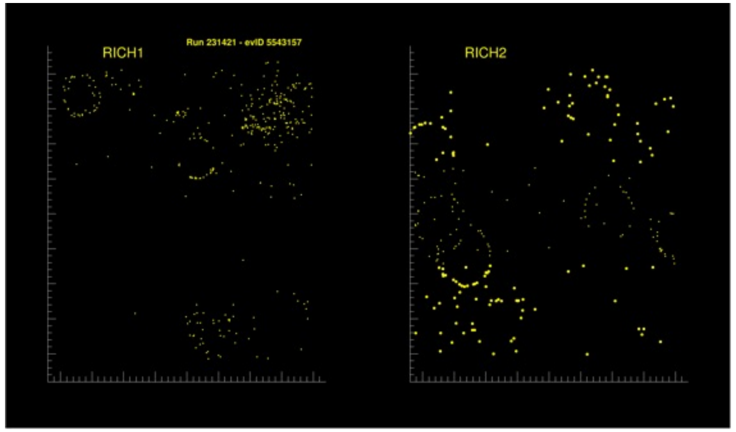
Upgrade I

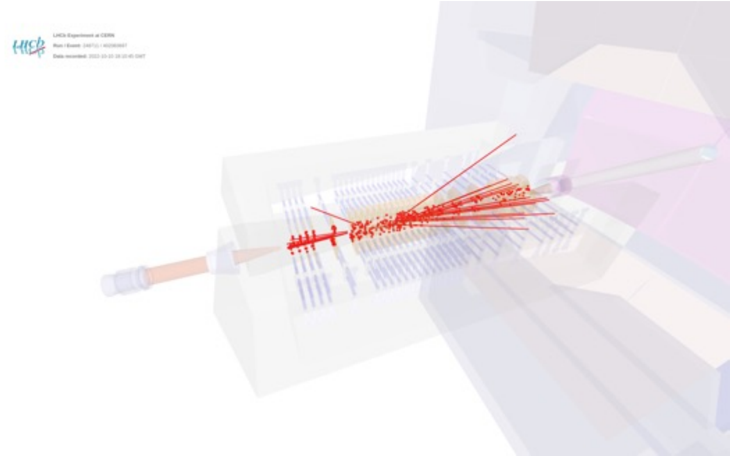
2022-2032

- Major project achieved **on budget**



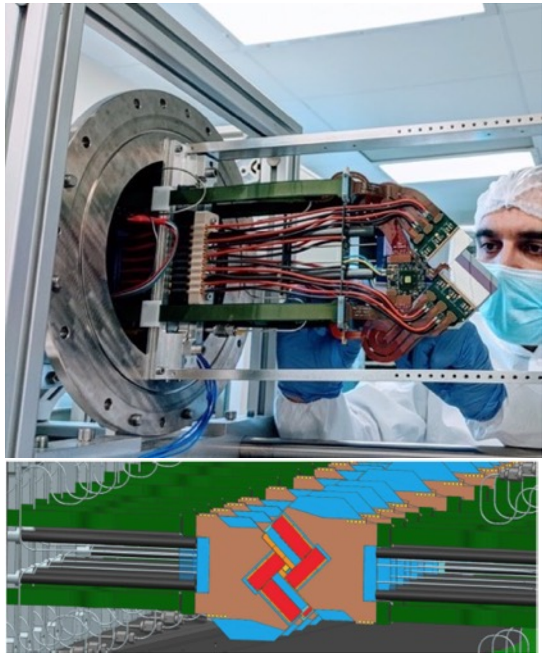






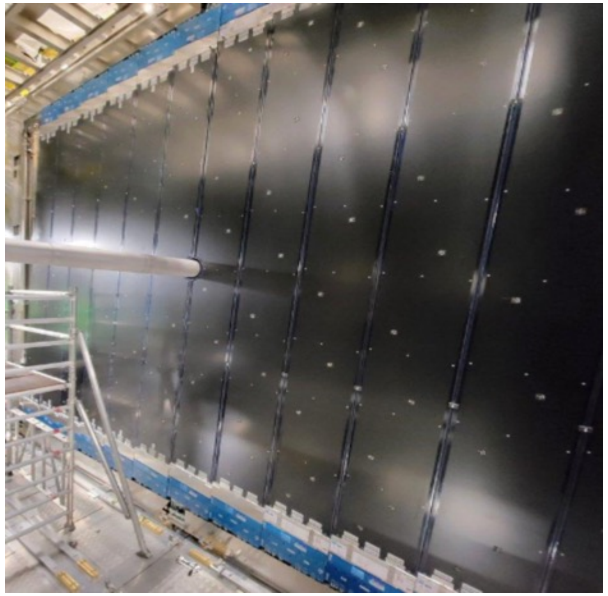
Upgrade I – example key innovative technologies

VELO



- 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

SciFi

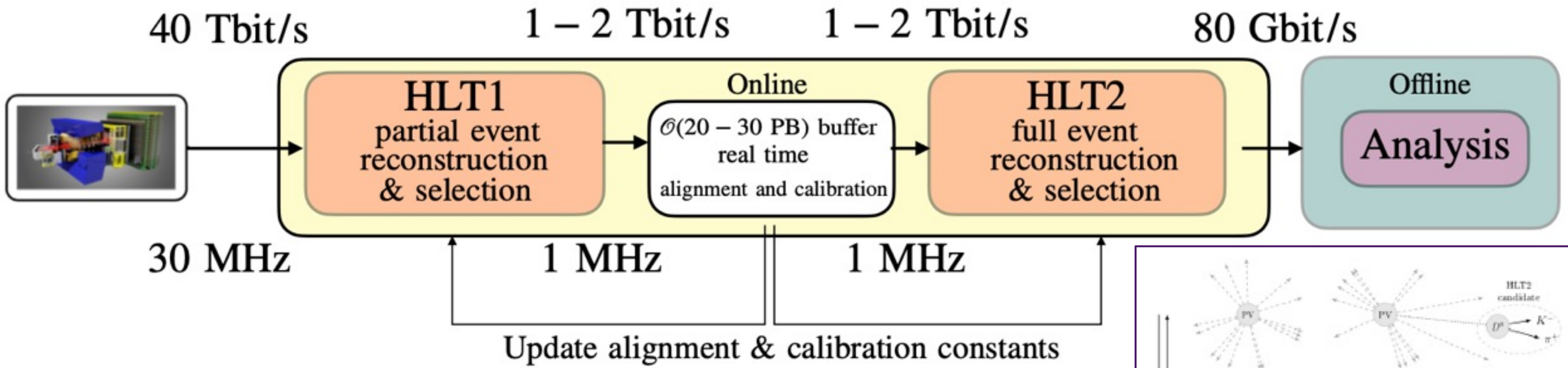


- Large scale tracking stations
- Scintillating Fibres
  - 250μm diameter, 2.5m long
- Signal readout by SiPMs
  - Operate at -40 C
- 12,000 km of fibre !

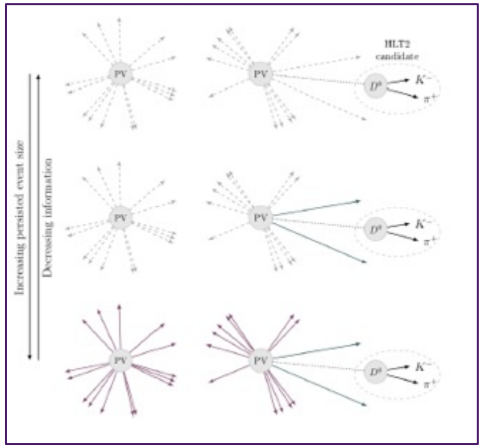
LHCb Upgrade I: Trigger Revolution

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



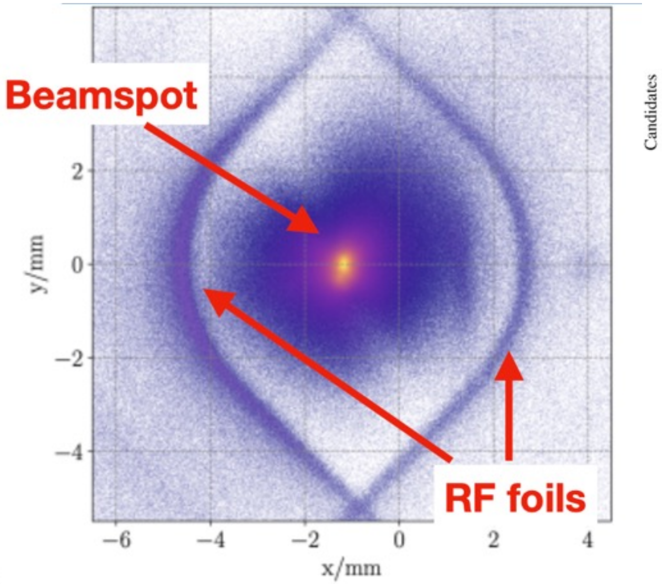
- 30 MHz of inelastic collisions will be reduced to ~1MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**
  - 2nd set of cards in installation, total 400
- Highest throughput of any HEP experiment



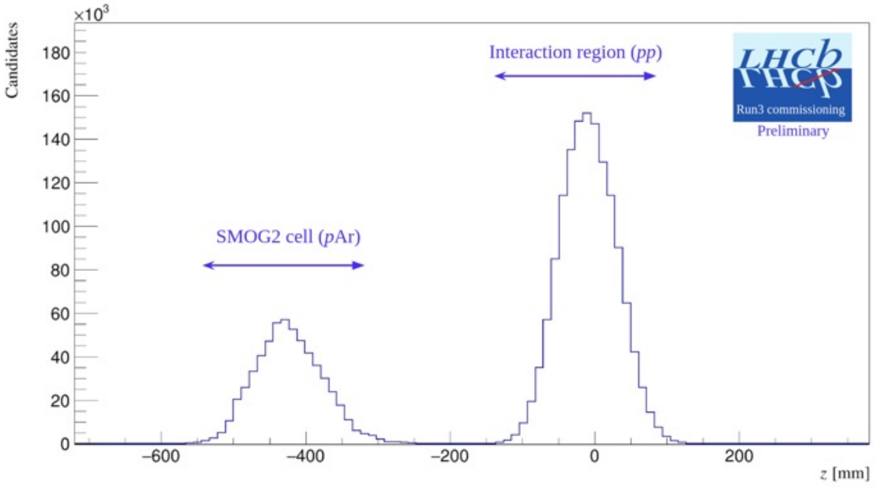
Selective persistence to maximise physics for computing resources

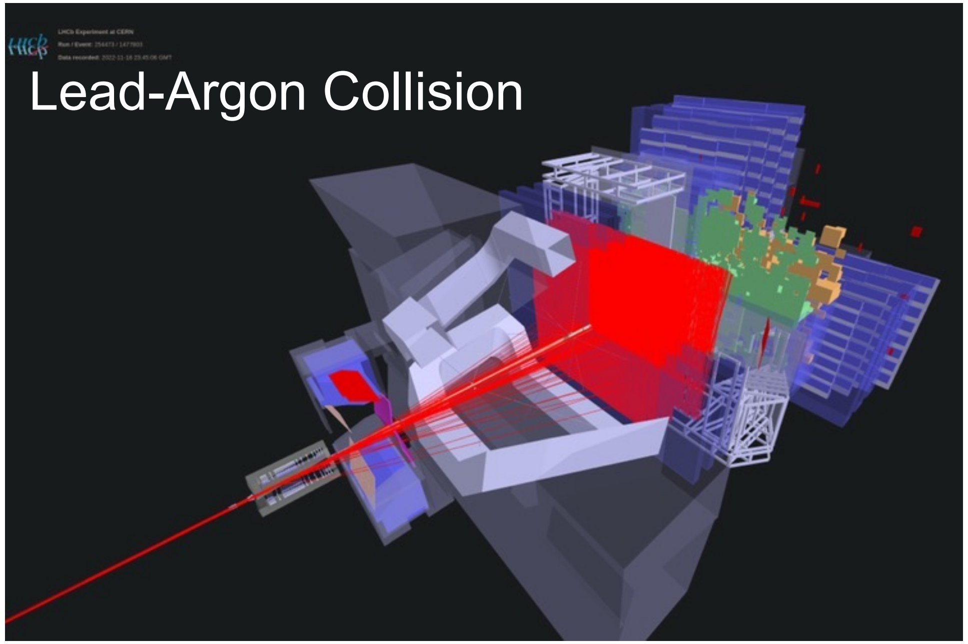
LHCb Upgrade I Commissioning

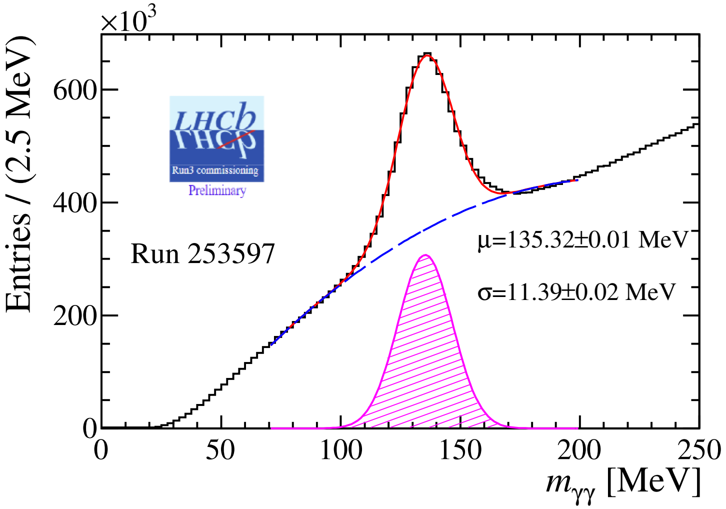
- Reconstructed vertices with fully closed VELO



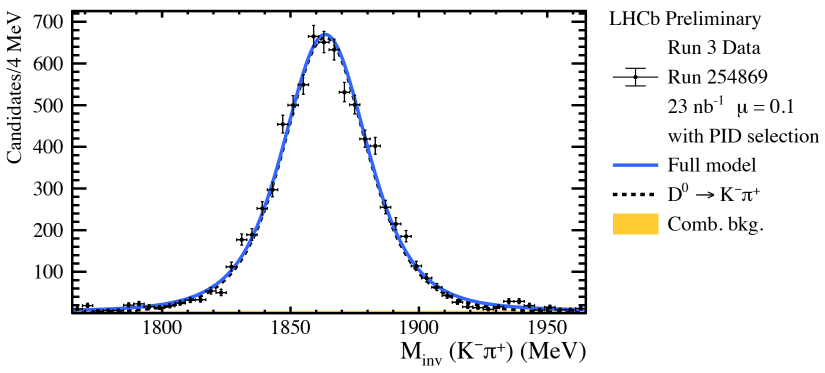
- Simultaneous beam-beam and fixed target collisions

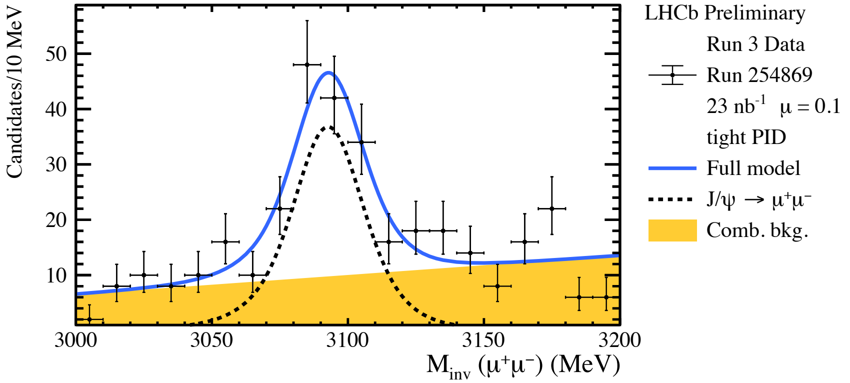






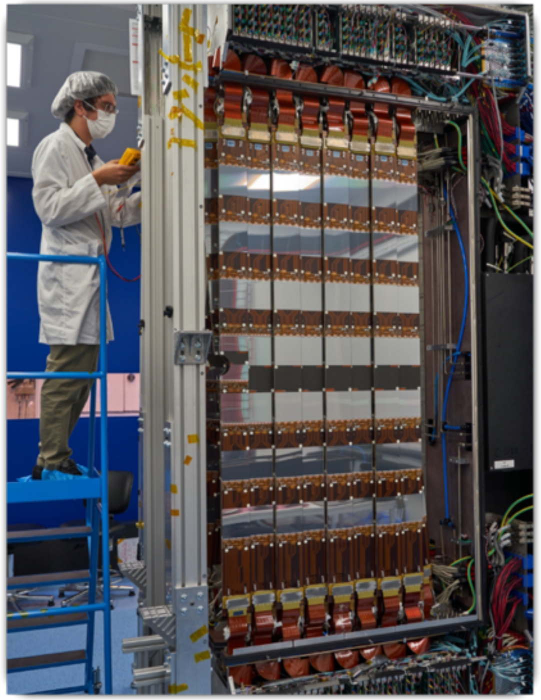
- Mass peaks using novel fully software trigger (1st level in GPUs)

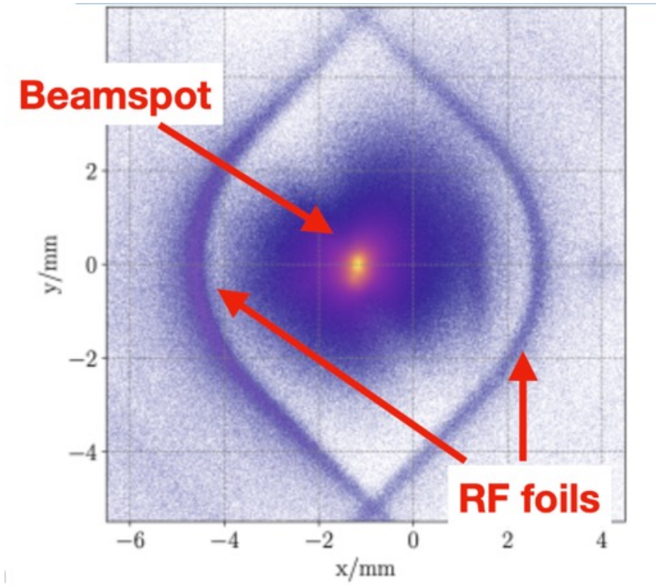




Upgrade I - Status & VELO incident

- Successful commissioning of Upgrade I in 2022
  - Performance of all systems demonstrated
  - Data-taking for commissioning
- Upstream Tracker
  - Currently in installation, completion March 2023
- LHC VELO vacuum safety system failed 10/1/23





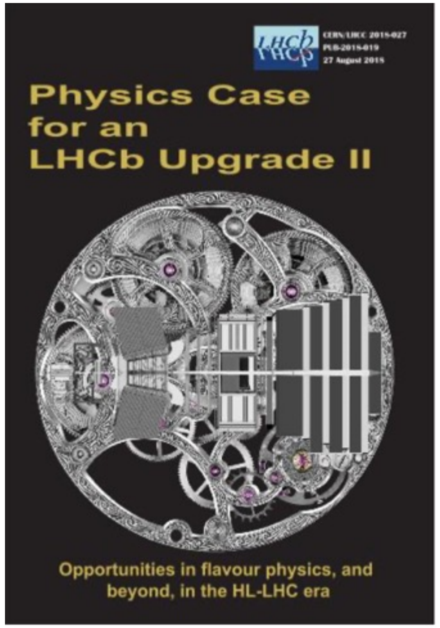
- Sizeable pressure difference of neon between primary/secondary vacuum volumes
- RF foil plastic deformation
- Modules believed not damaged
- Significant effect on 2023 data-taking

Upgrade II: approval steps so far

Expression of Interest

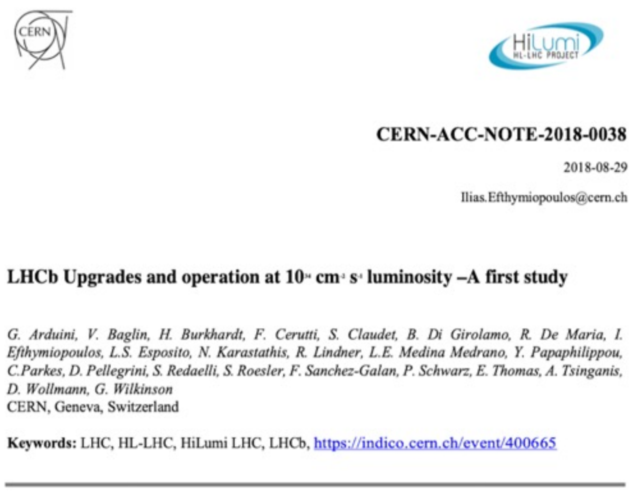
LHCC-2017-003

Physics case



LHCC-2018-027

Accelerator study



CERN

HiLumi HL-LHC PROJECT

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."

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

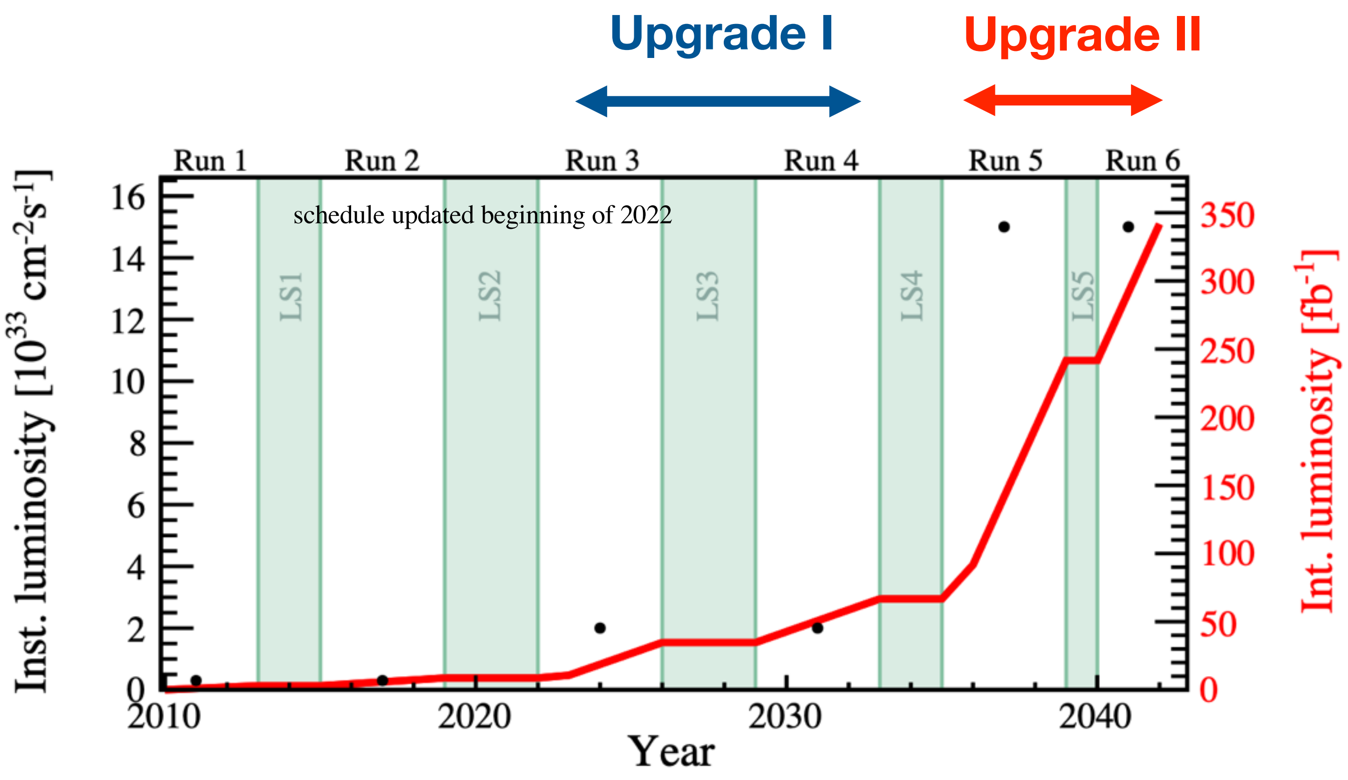
Approved March 2022 R&D programme, scoping document to be prepared followed by sub-system TDRs

LHCb Upgrades

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

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)*



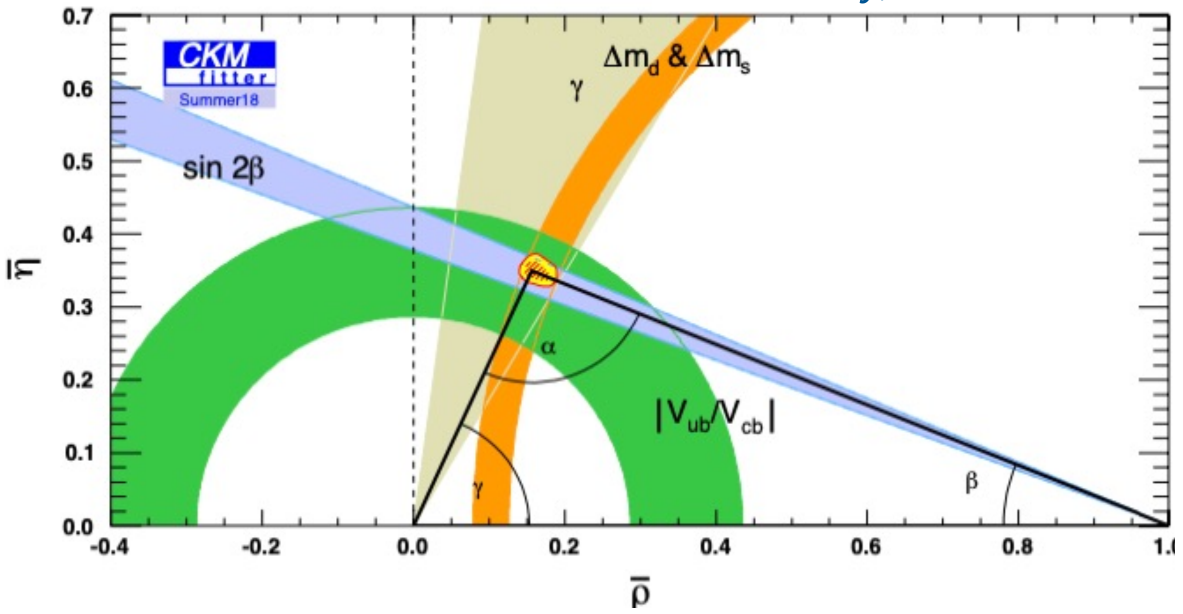
- *Potentially the only general purpose flavour physics facility in world on this timescale*

Flavour Physics at the LHC

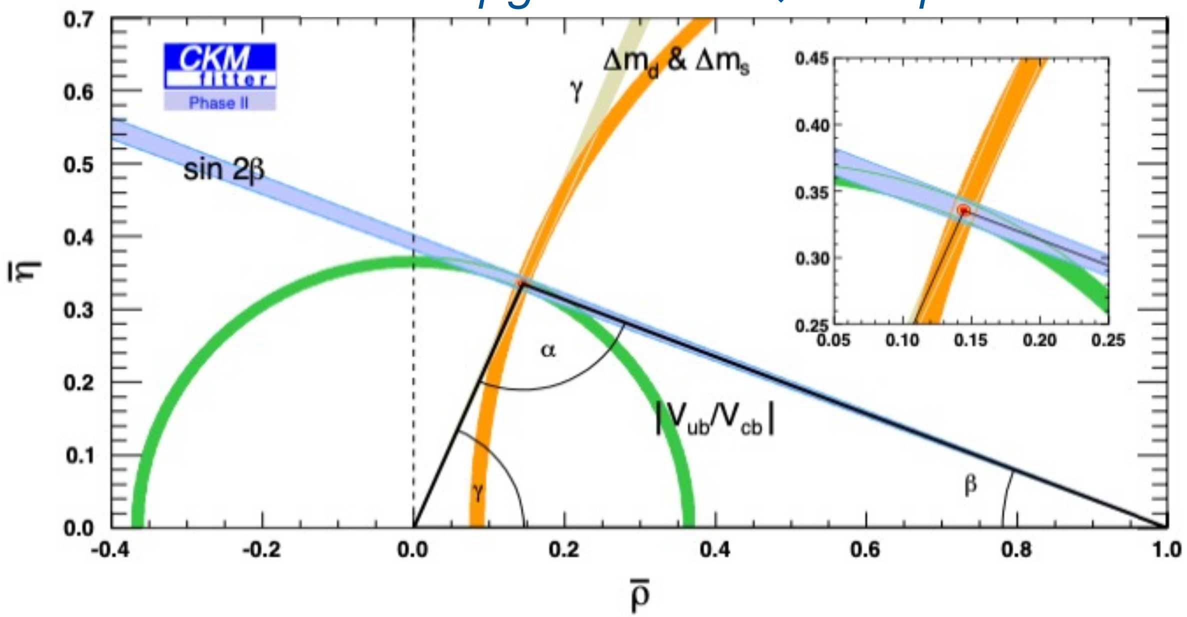
- Sensitivity to mass scales several orders of magnitude above those within reach of direct production measurements at the energy frontier
- Numerous key observables have negligible theoretical uncertainty

LHCb will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



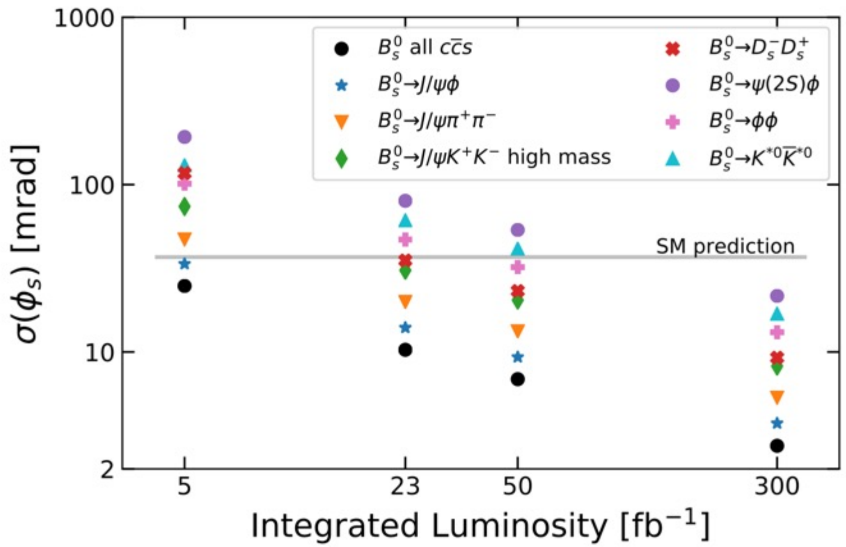
LHCb Upgrade II + LQCD improvement



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

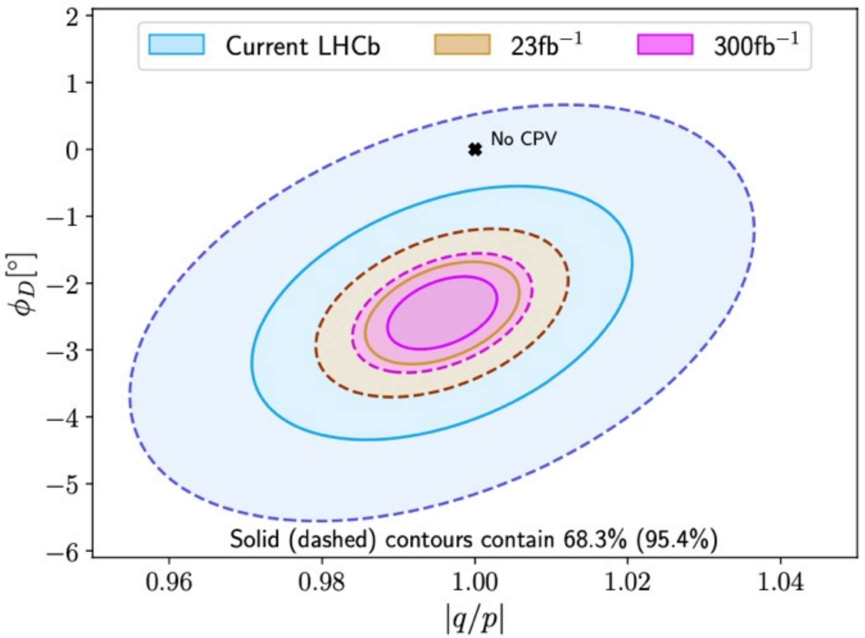
CP violating phase ϕ_s

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



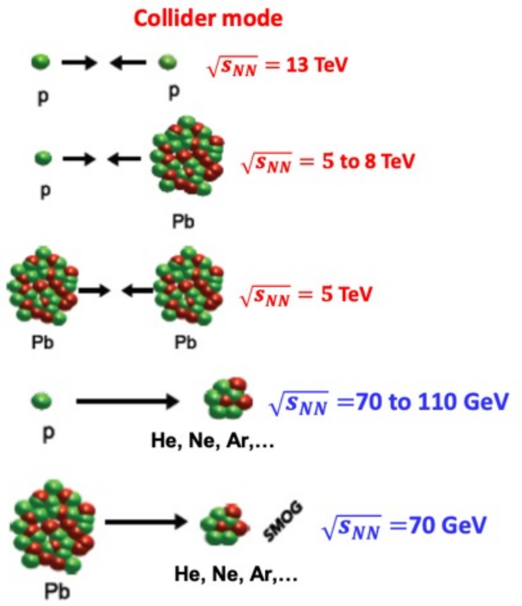
CP violation in charm

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



LHCb Heavy Ion & Fixed Target programme

- General purpose heavy-ion experiment suitable for pA and AA in forward rapidity
  - e.g. pPb low-x regime beyond reach of electron ion collider

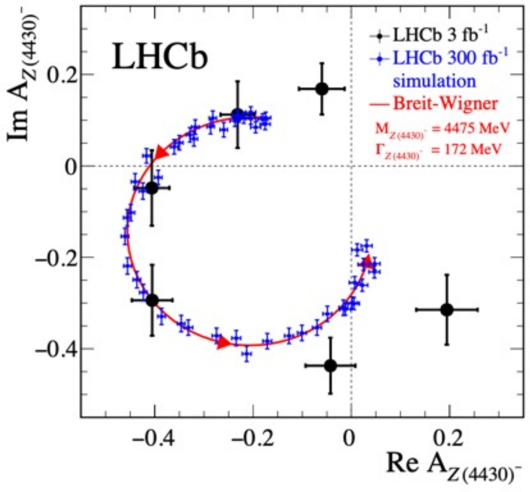


- Particle identification key to LHCb heavy-ion programme
- Low momentum tracking capabilities
- Increased granularity gives access to higher centrality
  - Detector designed with capabilities in mind

- Key topics
  - study deconfinement at finite temperature
  - chiral symmetry restoration in the QGP phase at finite temperature and thermal radiation of the QGP
  - low-x regime of the nucleus searches for gluon saturation
  - intrinsic heavy quark distributions in the nucleon & modification of nuclear PDFs
  - Polarised gas target (beyond baseline of Upgrade II) for fixed-target would probe the study of quark and gluon Transverse Momentum Dependent PDFs s in the nucleon

Further Opportunities

- Spectroscopy
  - Discovery of exotic hadrons opens new field
  - e.g. T_{cc}^{++} suggests there could be long-lived exotic hadrons
  - Understanding binding mechanisms
  - Building-up multiplets
  - Six-quark final states ?



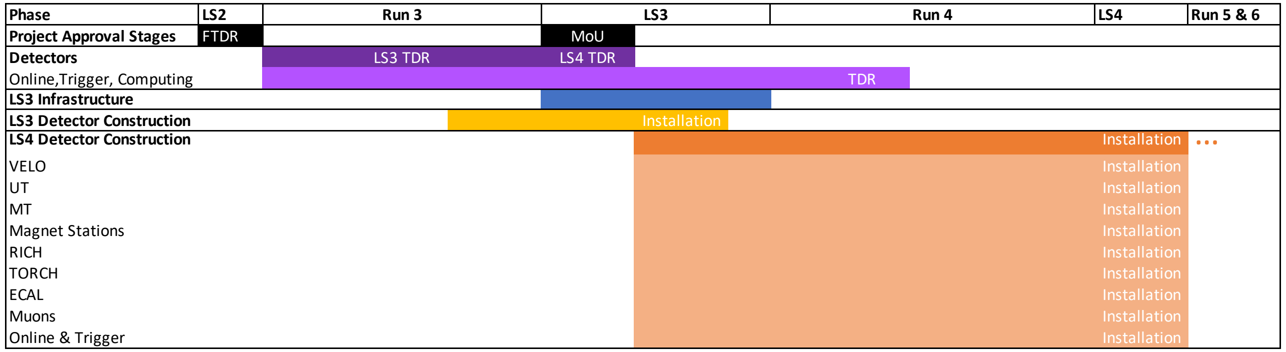
Topic	Comment
Spectroscopy	Enormous yields in gold-plated final states
	e.g. 4M $\Lambda_b^0 \to J\psi p K^-$ decays ('pentaquark' mode)
Higgs	Measure Higgs-charm Yukawa within factor 2 to 3 of SM value
$\sin^2\theta_W$	Uncertainty $< 10^{-4}$, better than LEP/SLD
Proton structure	Precision probes at extremely low and high Bjorken-x values,
	with $Q^2 > 10^5\,\text{GeV}^2$
Hidden sector	Sensitivity to most of relevant parameter space for dark-photon models

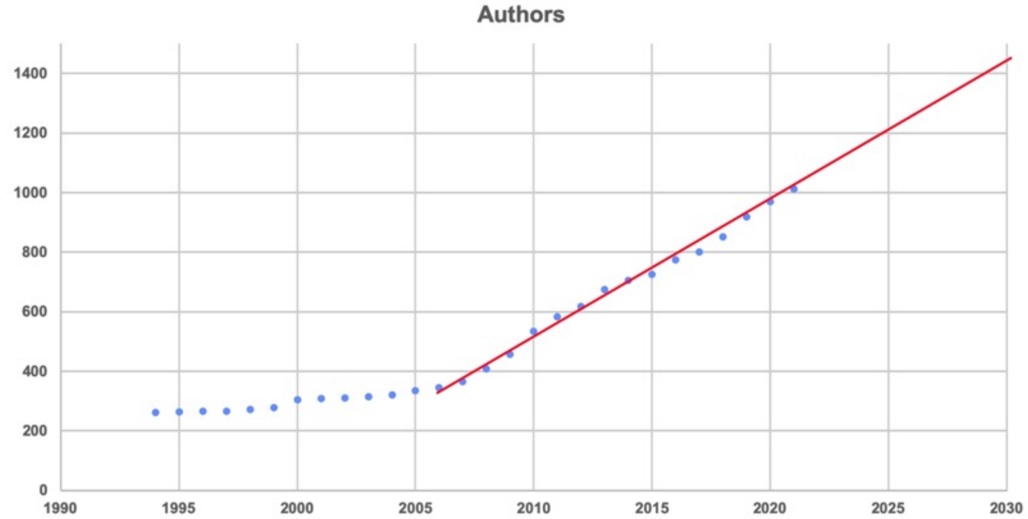
Status and Stages in Process

- Support from full collaboration
- Process from FTDR to installation defined with LHCC
- Scoping document within 2 years
- R&D underway leading to subdetector TDRs
- Funding agency discussions underway
- Expanding collaboration

Detector	Countries involved
VELO	BR, CERN, ES, FR, IT, NL, PL, RU, SE, UK
UT	CN, FR
Magnet Stations	PL, US
Mighty Tracker (SciFi + MAPS)	BR, CH, DE, ES, SE, UK
RICH	CERN, IT, PL, RO, SI, UK
TORCH	CERN, UK, SI
ECAL	AU, CERN, CN, ES, FR, HU, IT, RU, US
Muon	IT, RU
RTA	BR, CERN, CN, DE, ES, FR, IT, NL, PL, RU, UK, US
Online	CERN, FR

One significant construction award and many R&D grants – including generic applications





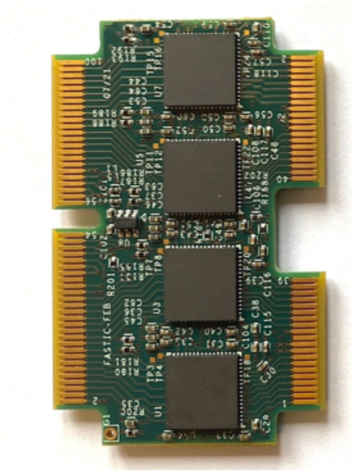
Opportunities for the detector at LS3

Modest consolidations with physics benefits already in Run 4 while preparing UII

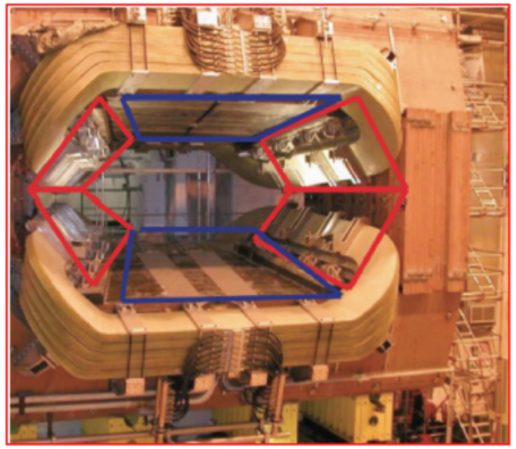
driven by ageing
driven by technology
driven by physics

Detector	Proposal
SciFi consolidation	Replace inner modules (12X + 12stereo)
MAPS modules	2 layers, 1 m^2 each
Magnet Stations	full installation
RICH	new FEE electronics
ECAL	32+144 inner modules
RTA	Downstream tracking with FPGA

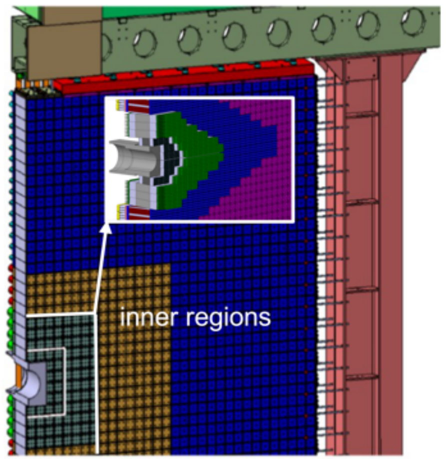
- Consolidation & Upgrade II preparatory work
- Reused for Upgrade II
  - Costs accounted as part of Upgrade II for reused elements
- Proceed with LS3 TDRs before those for Upgrade II
  - Work already proceeding on some of these



RICH electronics with timing



Magnet Stations

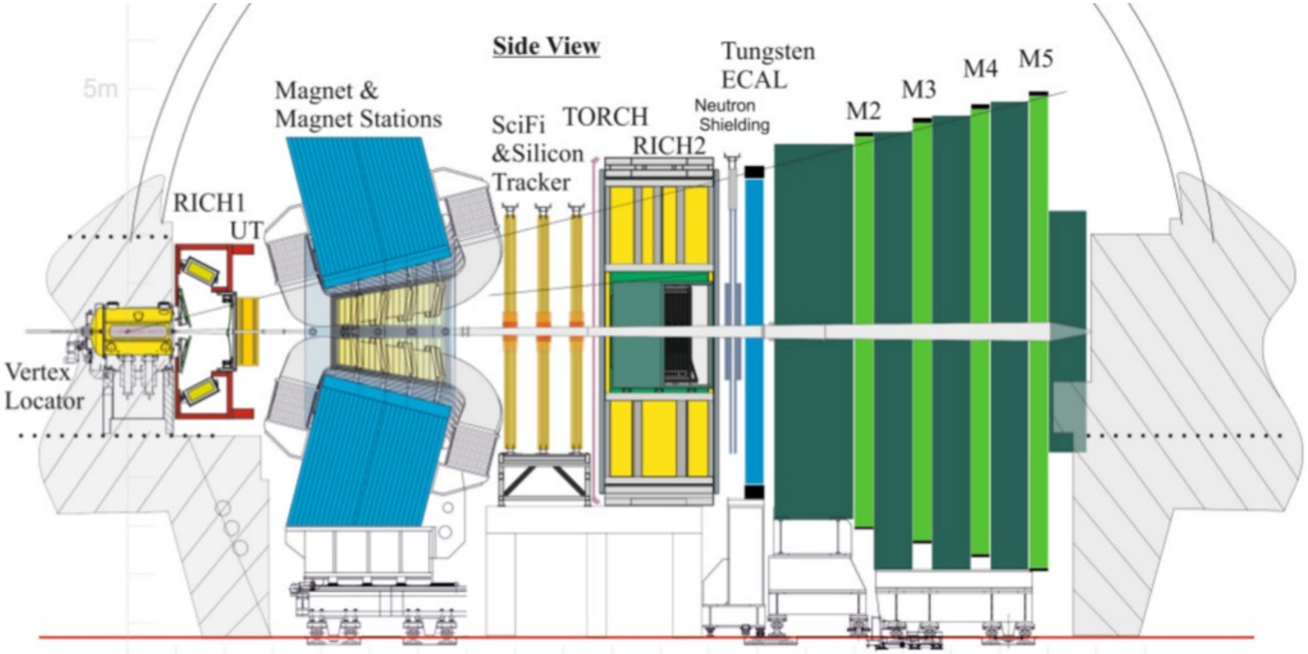


ECAL inner modules

Careful evaluation of what can be achieved on this timescale

The detector challenge & opportunity

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

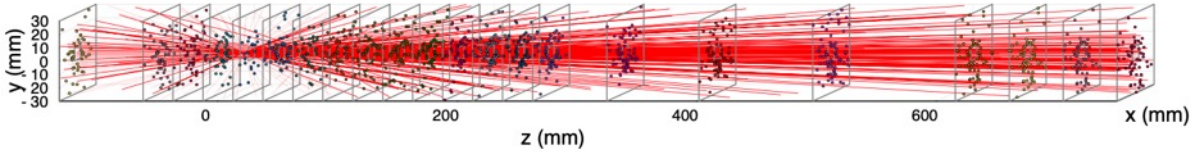


Same spectrometer footprint, innovative technology for detector and data processing

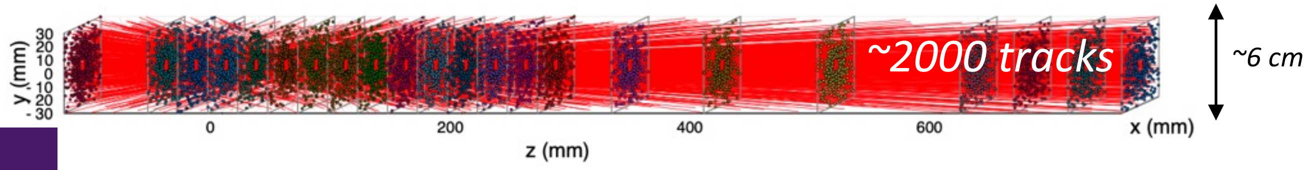
Key ingredients:
- granularity
- fast timing (few tens of ps)
- radiation hardness

VErtex LOcator (VELO)

Run 3: pile-up ~6

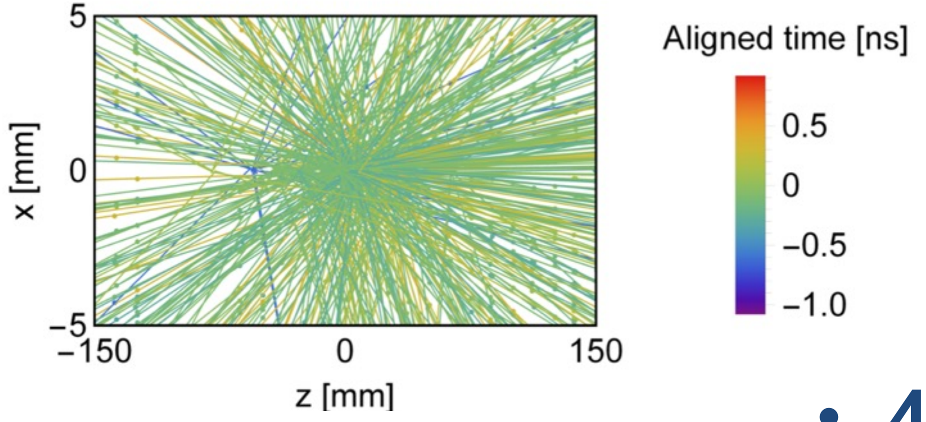


Upgrade II: pile-up ~42

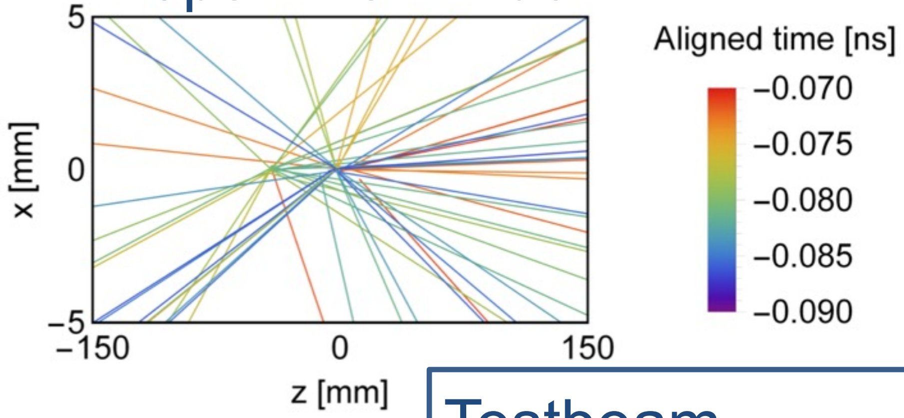


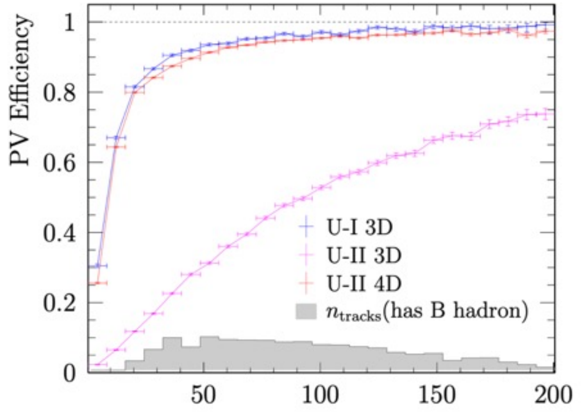
4D Vertexing: Extra Dimension of Precision Timing

42 interactions



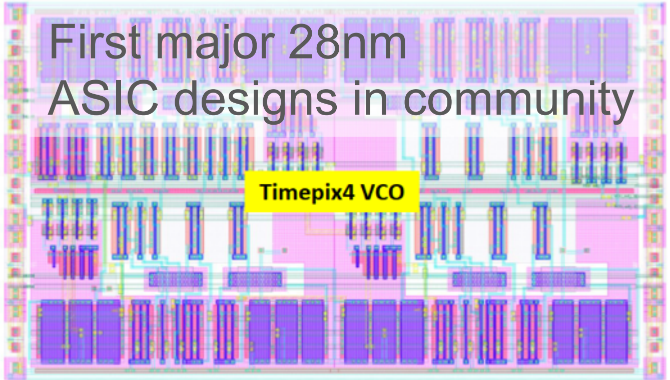
20ps time window

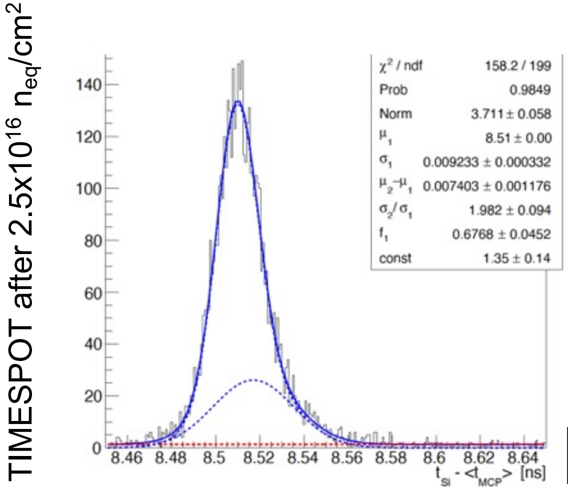




- **4D tracking**
- Ensures similar performance to Upgrade I
  - ~ 50ps, 50μm²
- Extreme lifetime fluence
  - $6\times10^{16} n_{eq}/cm^2$

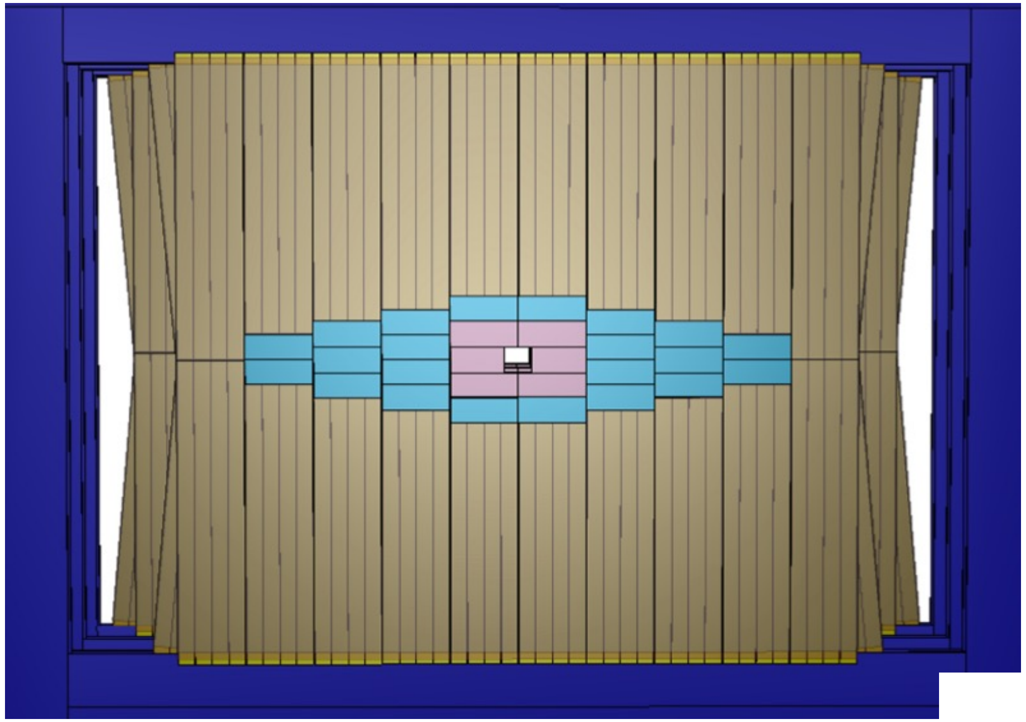
Testbeam
3D detectors, 15ps
LGAD & thin planar also studied

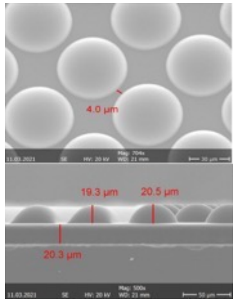


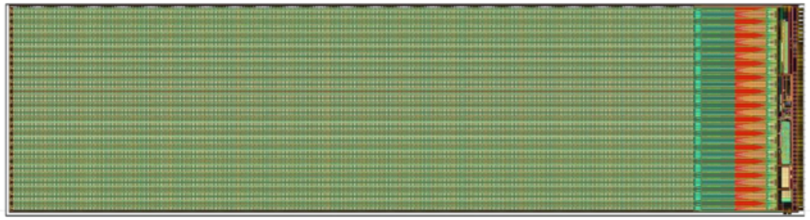


Tracker: Rad Hard MAPs, first of kind at LHC

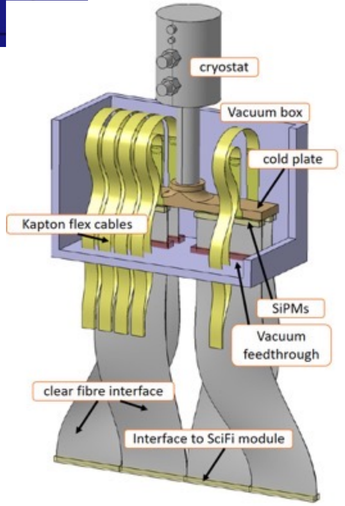
- UT – before magnet
- Mighty tracker – SciFi+CMOS –
  after magnet
- Monolithic Active Pixel Sensors
  $(50\times150\mu m^2)$
  - Radiation requirements in UT
    $3\times10^{15}n_{eq}/cm^2$
  - low-cost commercial process, low material budget
- Scintillating fibres in outer region
  - radiation-hard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



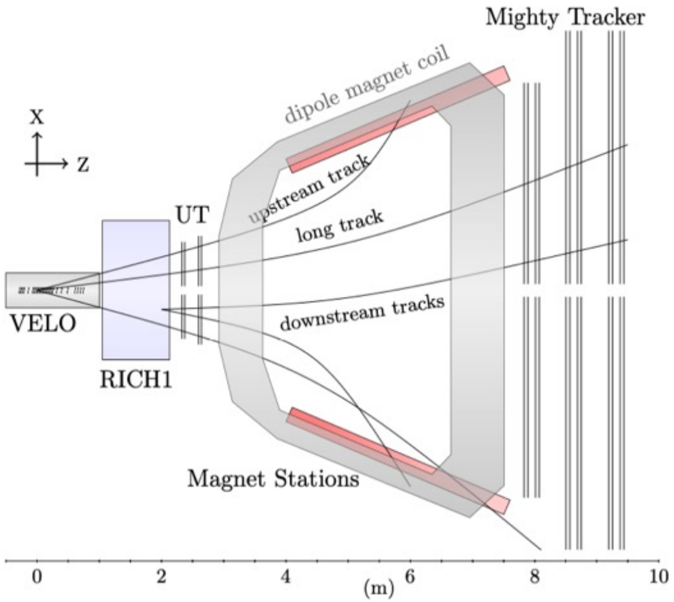


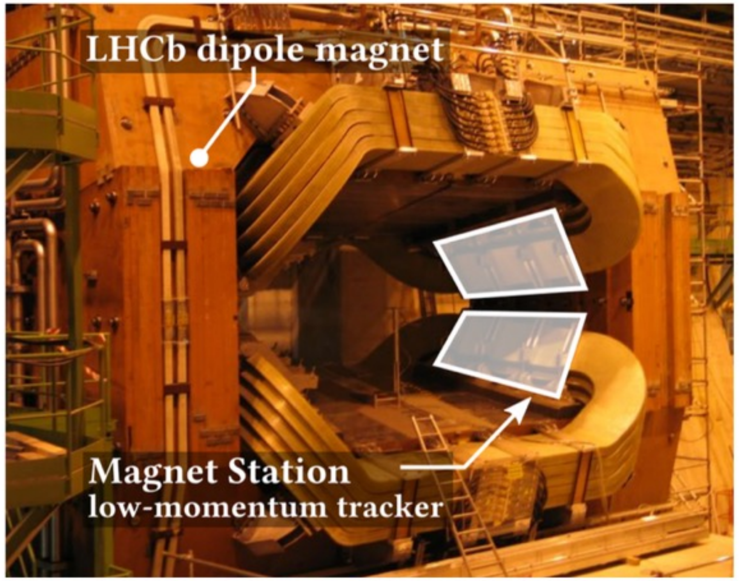


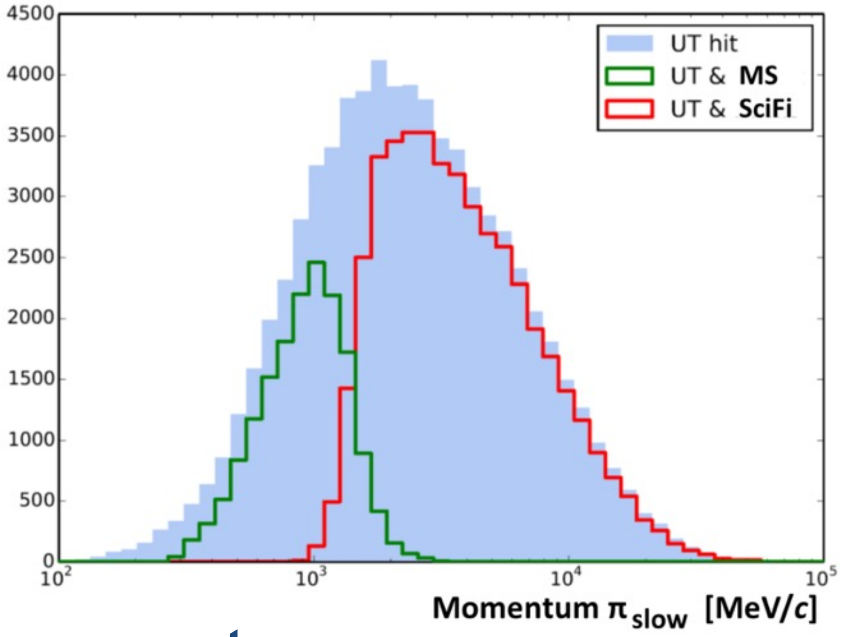
MightyPix1 1/4 scale chip fabricated



Magnet Stations: expanding physics potential





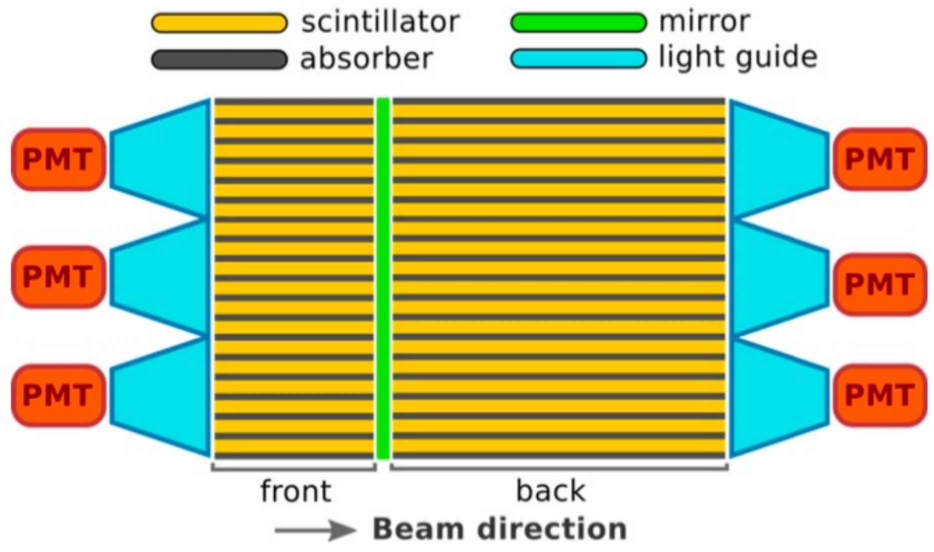


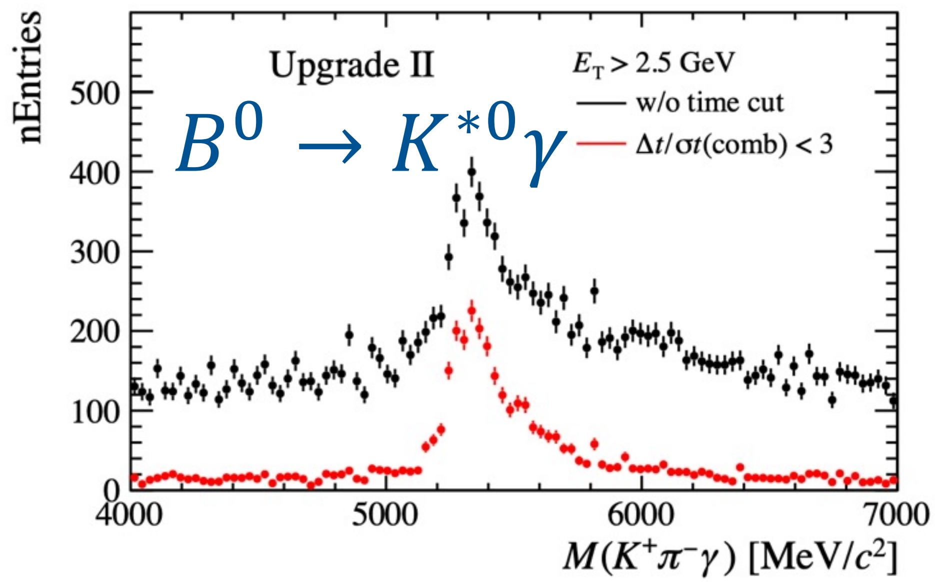
- Low momentum particles swept out by magnet
- Instrument walls of magnet with scintillating bars
- Obtain sub-% momentum measurement
- Significant increase of acceptance for low momentum

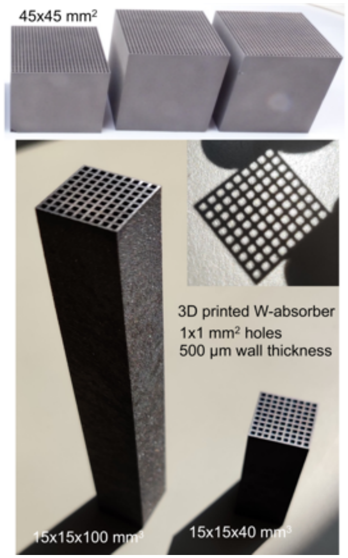
e.g. factor of ~2 gain in prompt D^{*+} with slow π

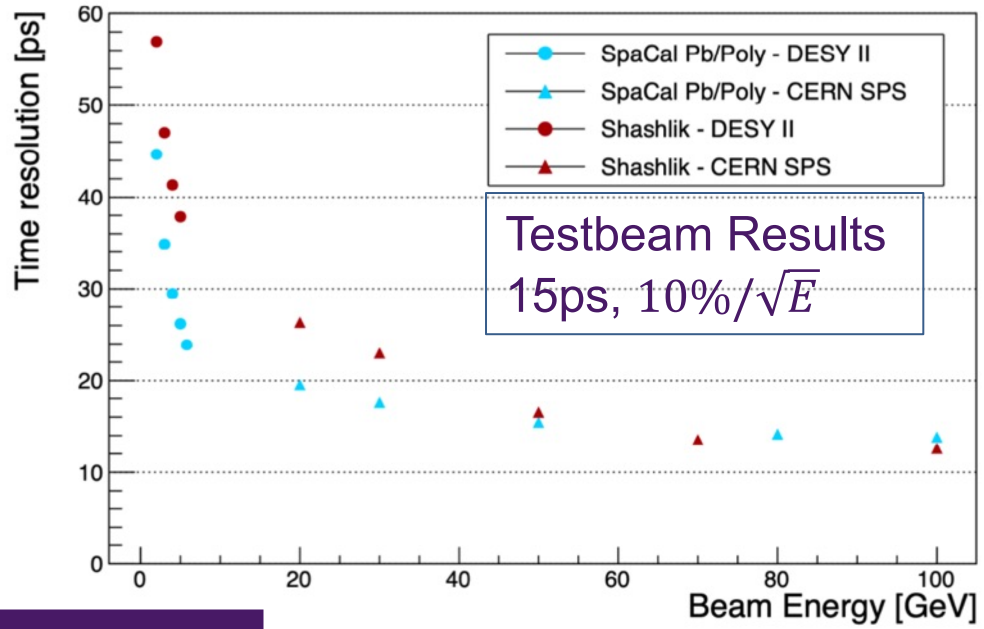
5D Calorimetry: Precision timing

- 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



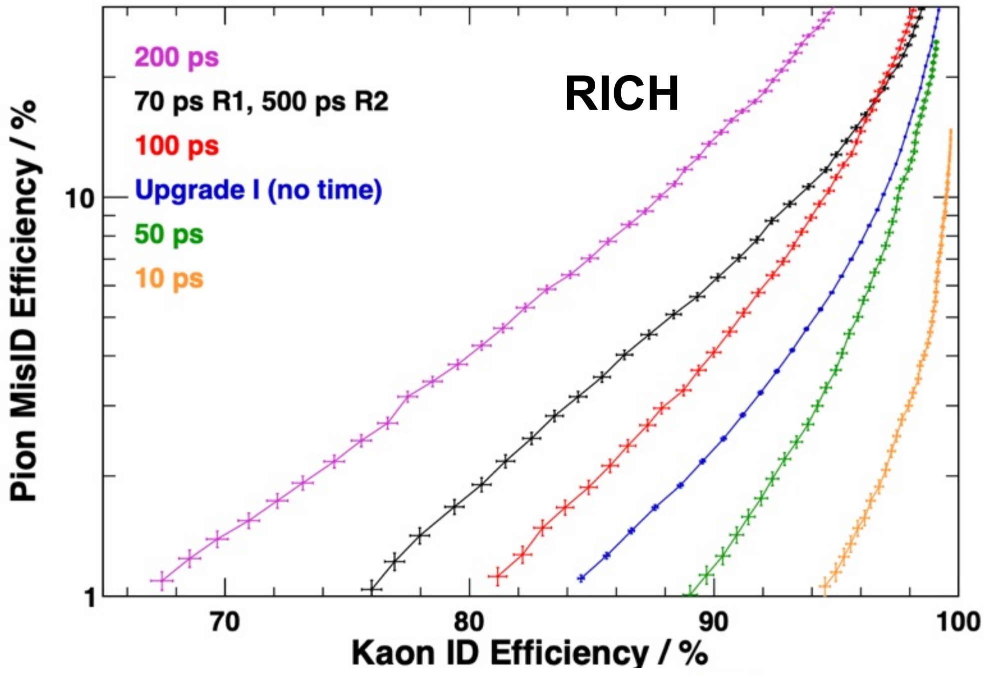


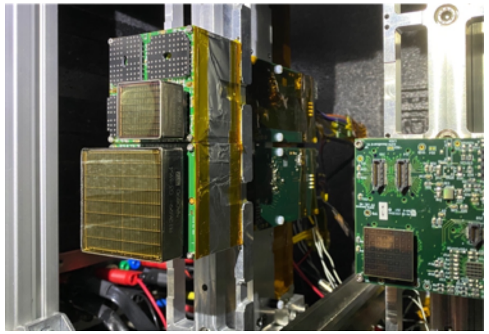


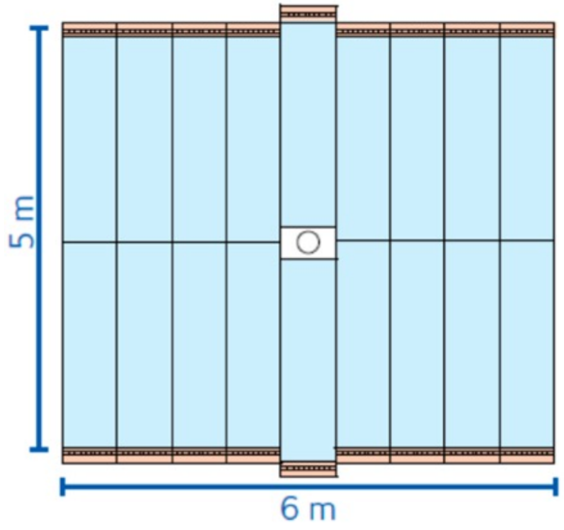


Particle ID: π/K/p – RICH & TORCH with Timing

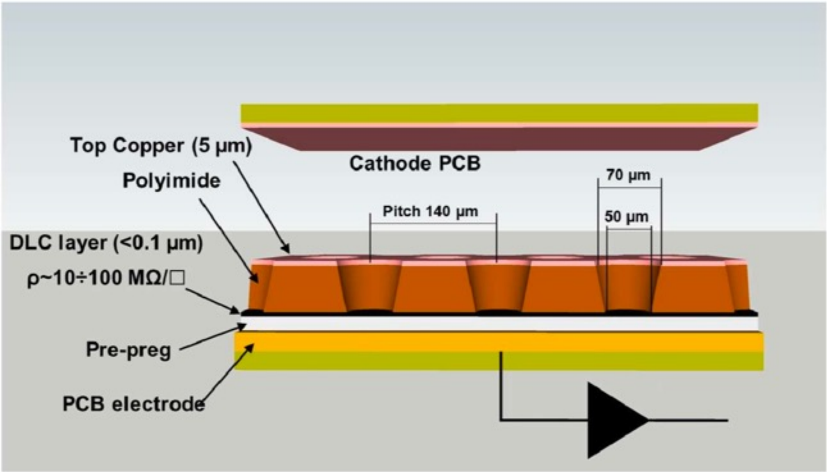
- Hadron particle identification key to LHCb unique physics capabilities
- RICH 1 & 2 geometry maintained
- Time of flight TORCH system
  - Cover wide momentum range
- In both systems precision timing is crucial for Upgrade II performance
- RICH: Time-stamping each photon with a resolution of few tens of ps
- TORCH: 10-15 ps time resolution per track
- Synergy on electronics readout

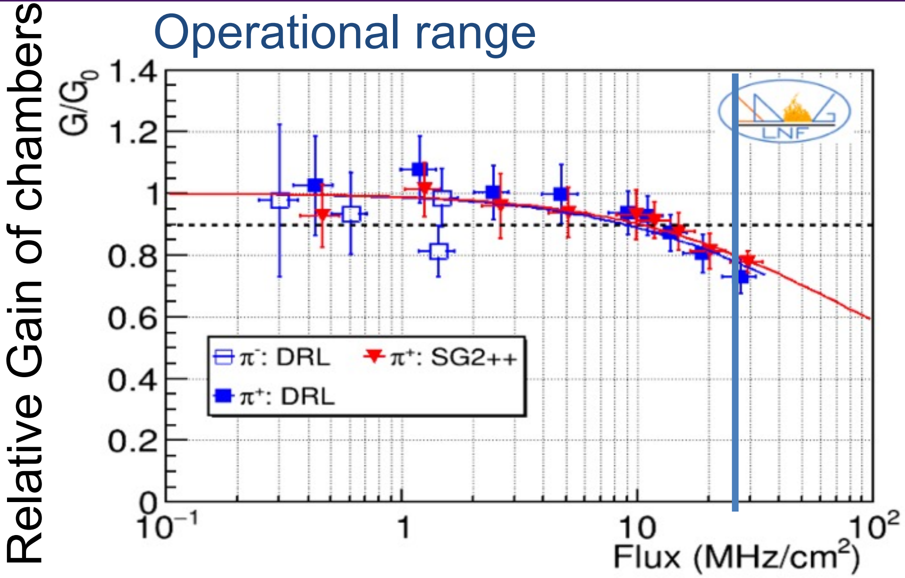






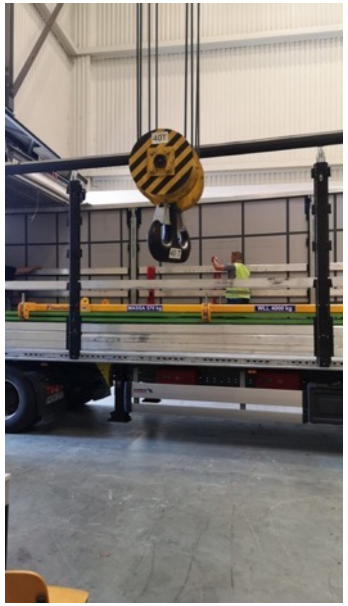
Muons





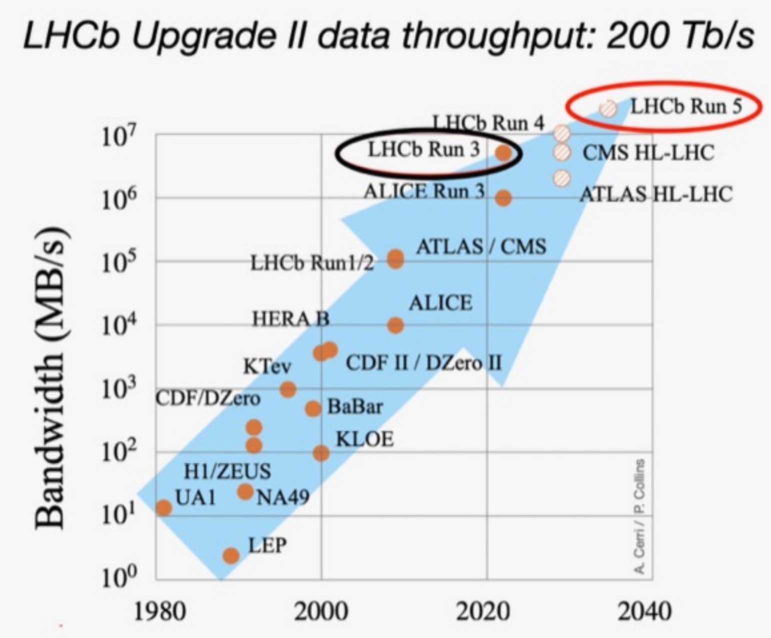
DLC sputtering machine

- Novel micro-pattern gas detectors for innermost region
- Reuse existing multi-wire proportional chambers in other region
- Additional shielding $(6\lambda_I \rightarrow 10\lambda_I)$ will be installed in front of Muon detector in place of HCAL, which will bring down the rate by a factor of ~2

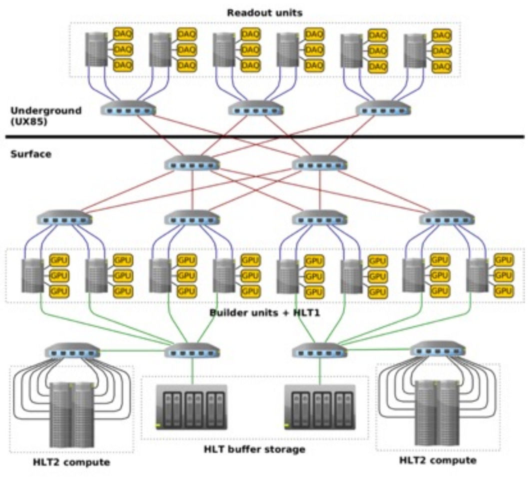


Iron slabs from Opera for LHCb Upgrade II arrived at CERN

Online & Offline



Event-builder architecture



- Novel trigger system for Upgrade I
  - Fully software trigger
  - HLT1 based on GPUs
- Similar concept planned for Upgrade II
- But at 200Tb/s!
  - Further exploitation of hybrid architectures: CPU, GPU, FPGA…
- Offline computing requirements are significant
  - Upgrade I model not sustainable
  - LHCb Upgrade II in Run 5 issues similar to ATLAS & CMS Phase II of Run 4
  - Coordination with WLCG and the HEP Software Foundation on mitigation

LHCb Upgrade II: Summary

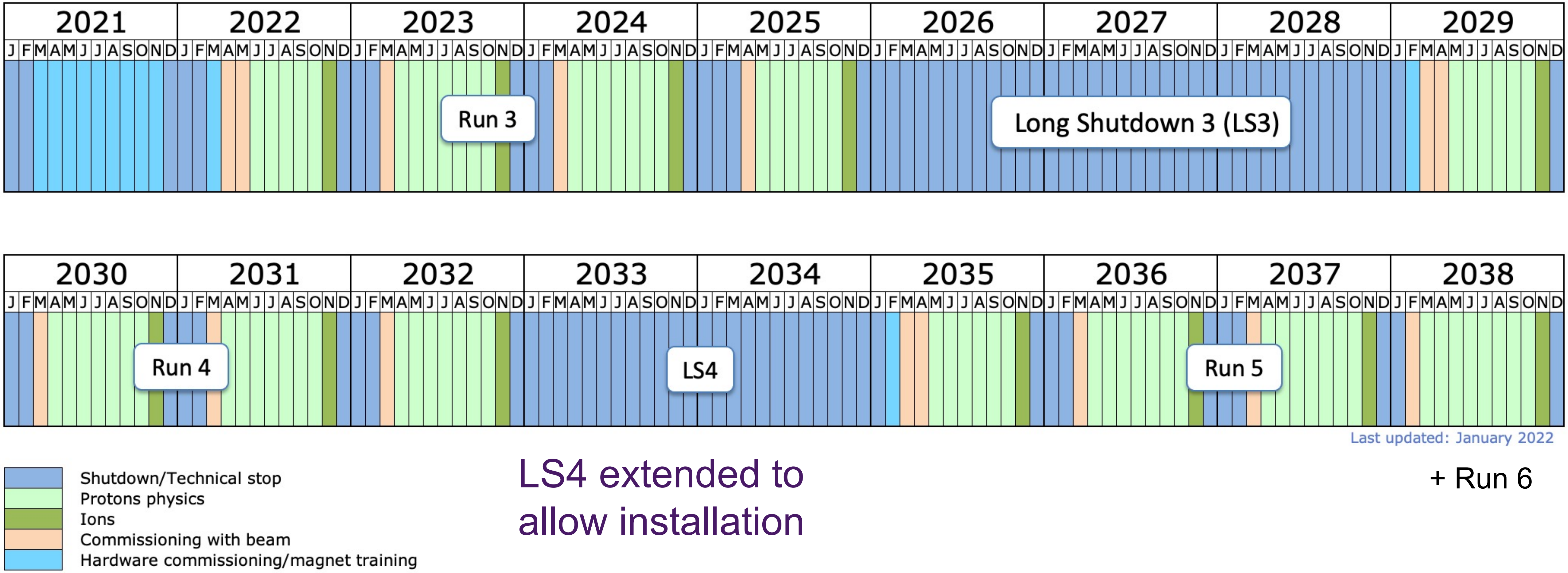
- LHCb France 7% of Collaboration
  – Leading involvements, major roles
- Fully exploit HL-LHC

  for flavour physics & *beyond*
- Major project for LS4 (2033-2034)
- R&D phase
  - Innovative technologies
  - Pathfinder to future accelerator projects

- Ambitious detector, proven accelerator
  - R&D proof of technologies advancing
- First funding of construction bids has been made
- Collaboration continues to expand

Backup

LHC Schedule



LS4 extended to allow installation

+ Run 6