ISOLDE Workshop and Users meeting 2022

Wednesday, 30 November 2022 - Friday, 2 December 2022

CERN

The first decade and the next decade of the Large Hadron Collider beauty experiment

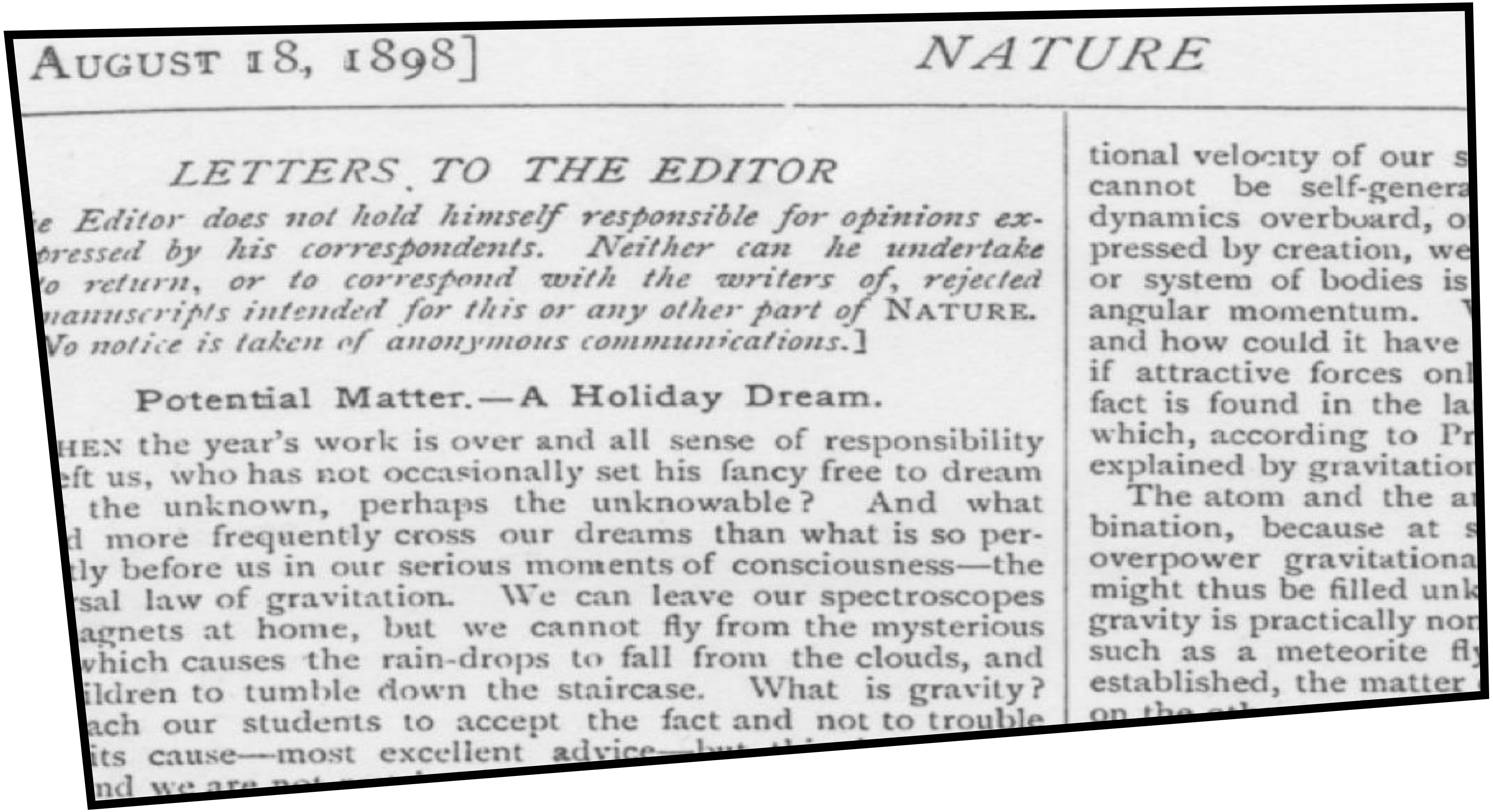
- Physics Highlights
- LHCb Upgrade I

2nd December 2022

Chris Parkes

Spokesperson of LHCb Collaboration

Introduction



August 18, 1898] NATURE

LETTERS TO THE EDITOR

[e Editor does not hold himself responsible for opinions ex- pressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.*]

Potential Matter.—A Holiday Dream.

HEN the year's work is over and all sense of responsibility eft us, who has not occasionally set his fancy free to dream the unknown, perhaps the unknowable? And what d more frequently cross our dreams than what is so per- tly before us in our serious moments of consciousness—the rsal law of gravitation. We can leave our spectroscopes agnets at home, but we cannot fly from the mysterious which causes the rain-drops to fall from the clouds, and ildren to tumble down the staircase. What is gravity? ach our students to accept the fact and not to trouble its cause—most excellent advice—but thi nd we are not

tional velocity of our s cannot be self-genera dynamics overboard, o pressed by creation, we or system of bodies is angular momentum. and how could it have if attractive forces onl fact is found in the la which, according to Pr explained by gravitation The atom and the a bination, because at s overpower gravitationa might thus be filled unk gravity is practically non such as a meteorite fl established, the matter on the oth

AUGUST 18, 1898] NATURE

LETTERS TO THE EDITOR

tional velocity of our
cannot be self-gen…

1. Live Frog taken out of a Snake.

ROSE HAIG THOMAS.

"may be interested to hear of another incidence of a (frog) returning alive from the stomach of a snake"

"out slid the frog; rather off-colour, and not very happy looking"

August 18, 1898] NATURE

LETTERS TO THE EDITOR

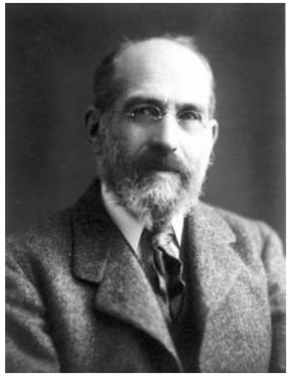
tional velocity of our
cannot be self-gen

2. Potential Matter.—A Holiday Dream.

"Surely something is wanting in our conception of the universe... positive and negative electricity, north and south magnetism..."

- Matter Antimatter Symmetry

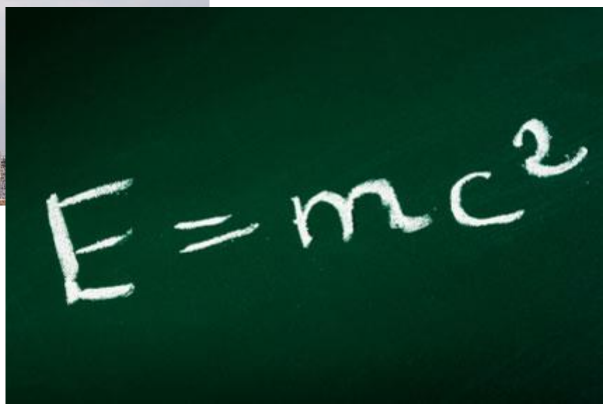
"matter and antimatter may further co-exist in bodies of small mass"

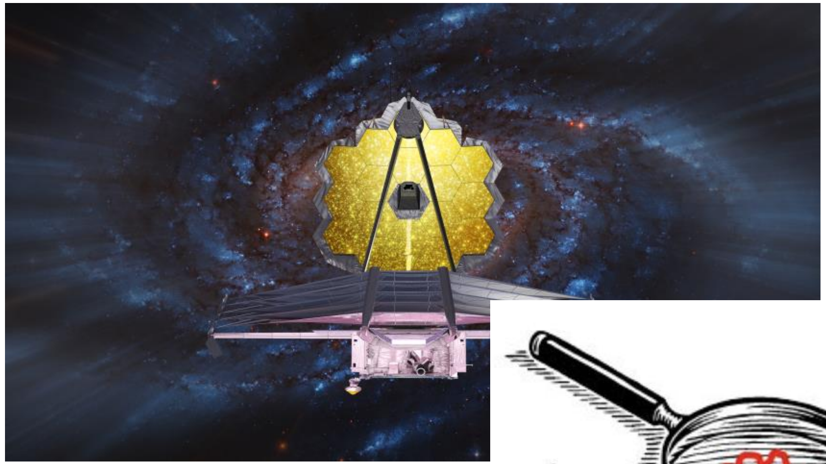


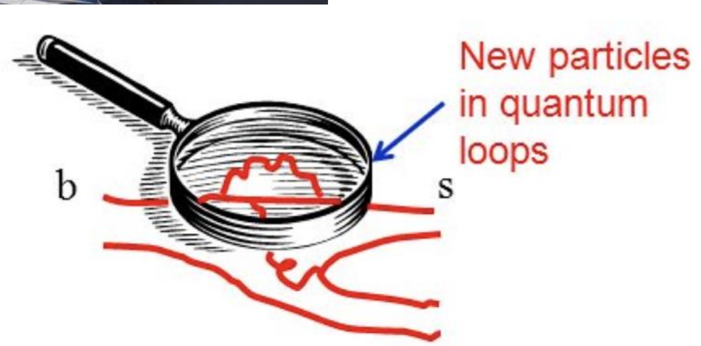
ARTHUR SCHUSTER.

Do dreams ever come true?

Physics exploration at the LHC



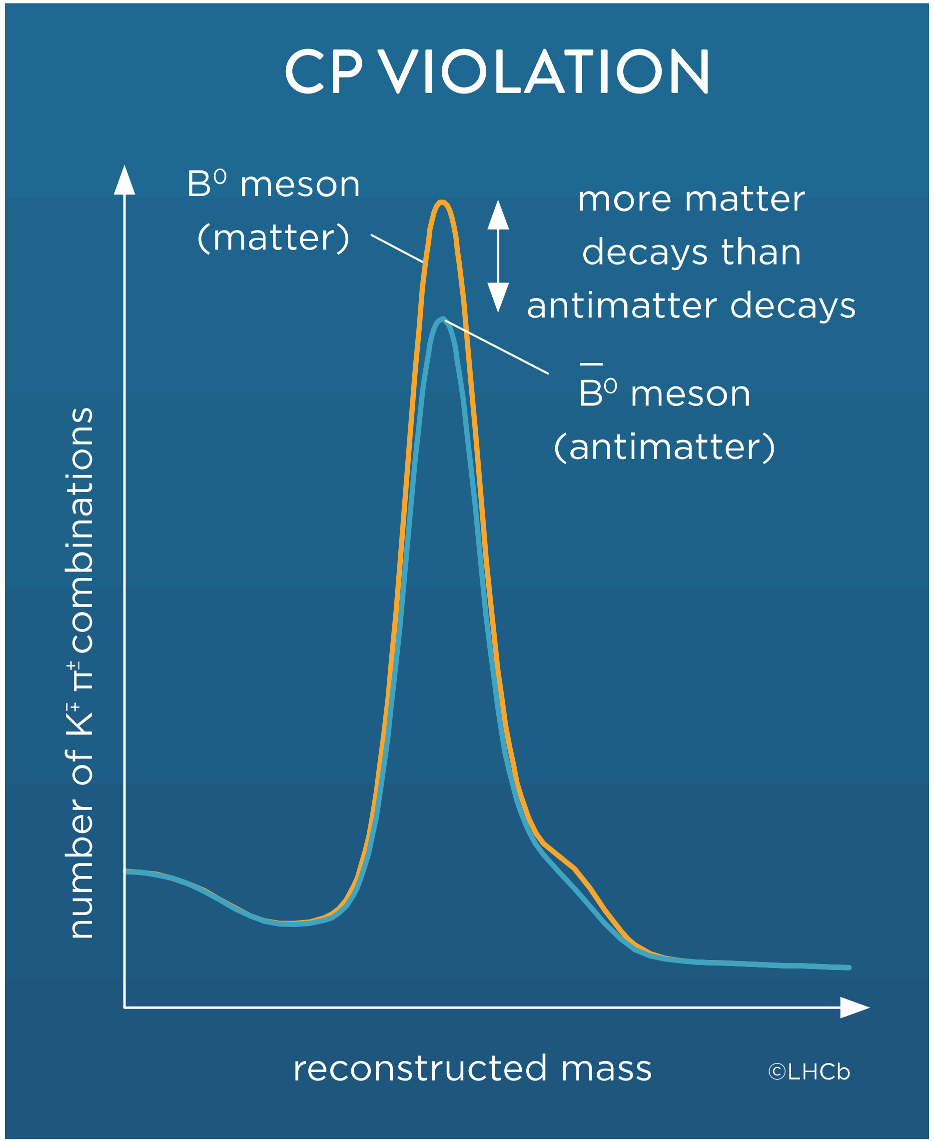




- **Energy**
- Directly produce new particles and observe from their decays.

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

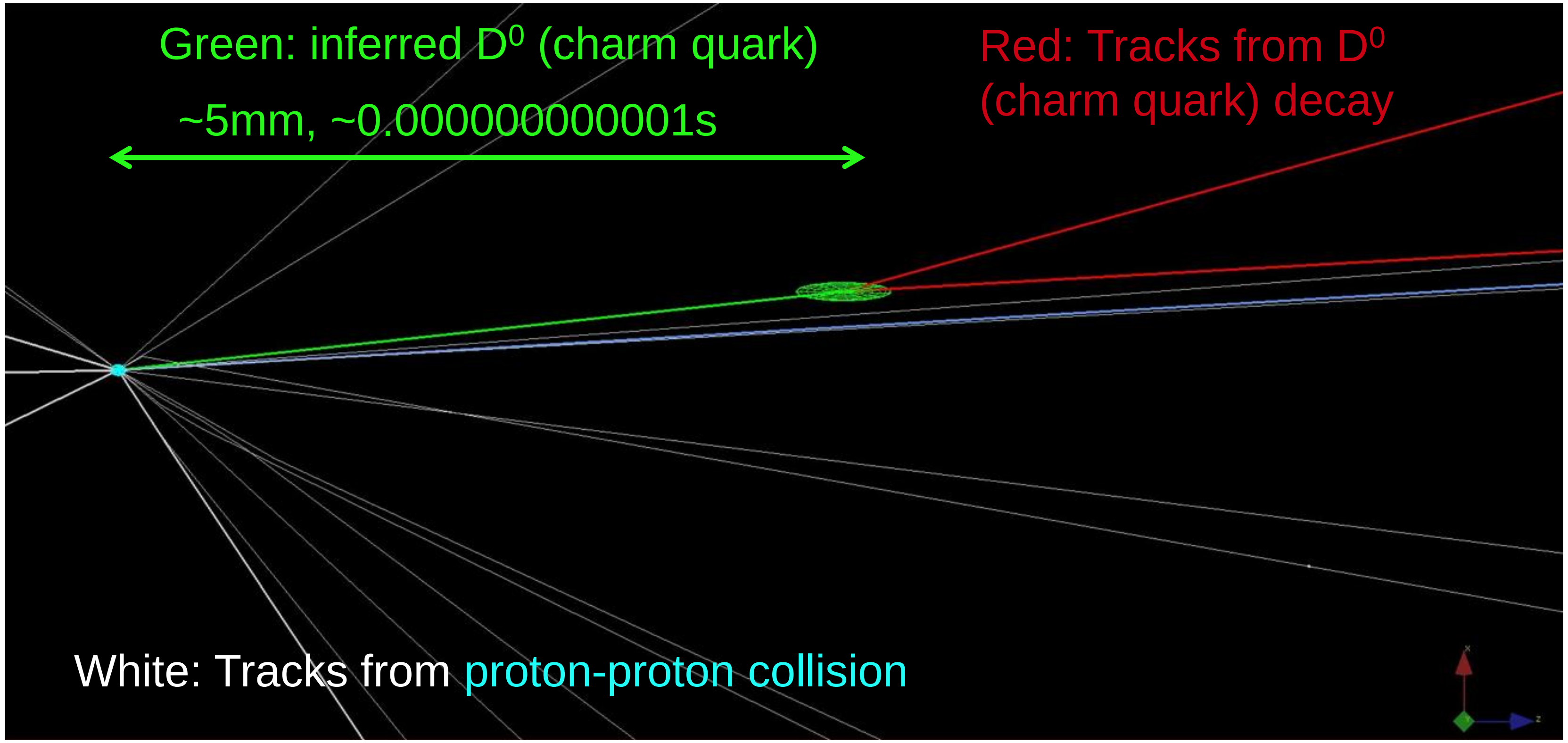
Matter & Antimatter at LHCb

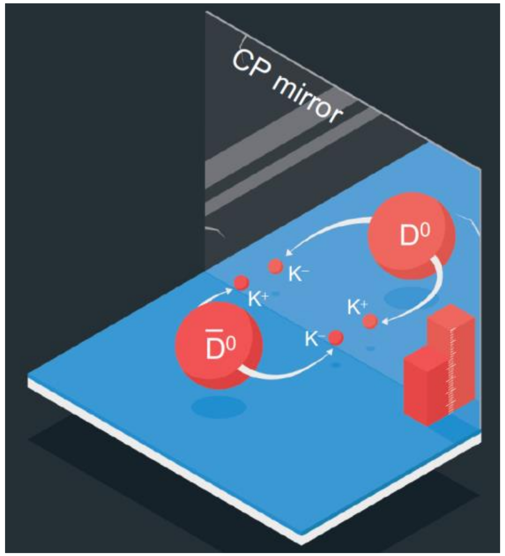


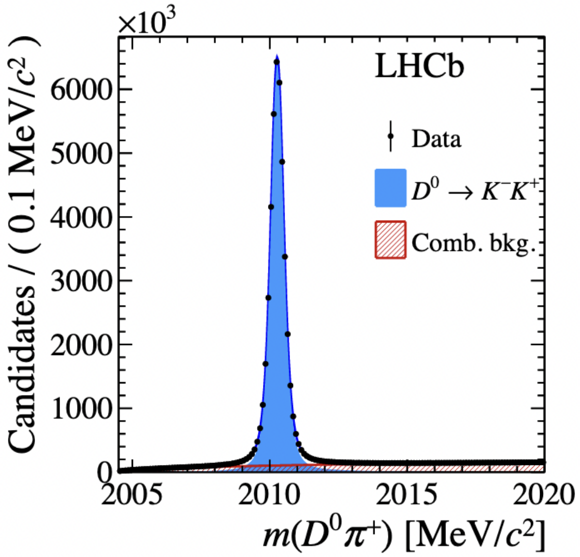
Fundamental difference between matter and antimatter

- Far too small to explain matter dominance over antimatter in the universe
- Embedded in SM as an 'add-on' mechanism
- Delicately broken symmetry allows to search for new physics phenomena

Observation of *CP* Violation in Charm Decays







70 million decays observed

PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

Featured in Physics

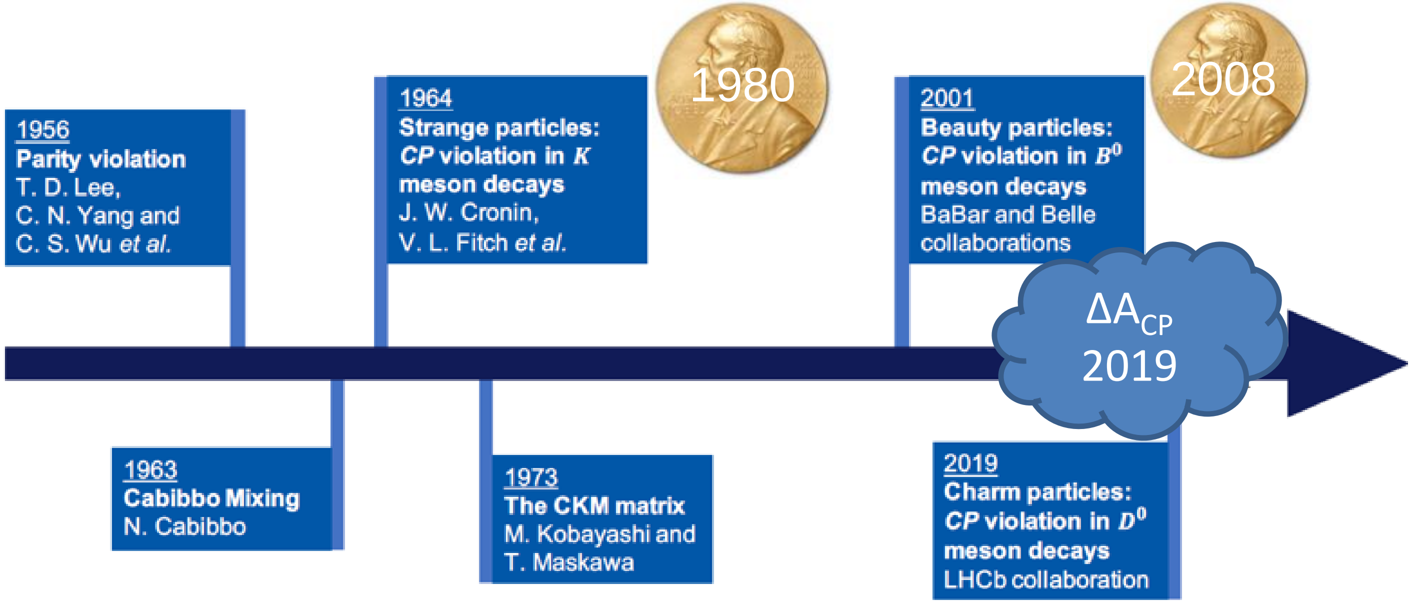
Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

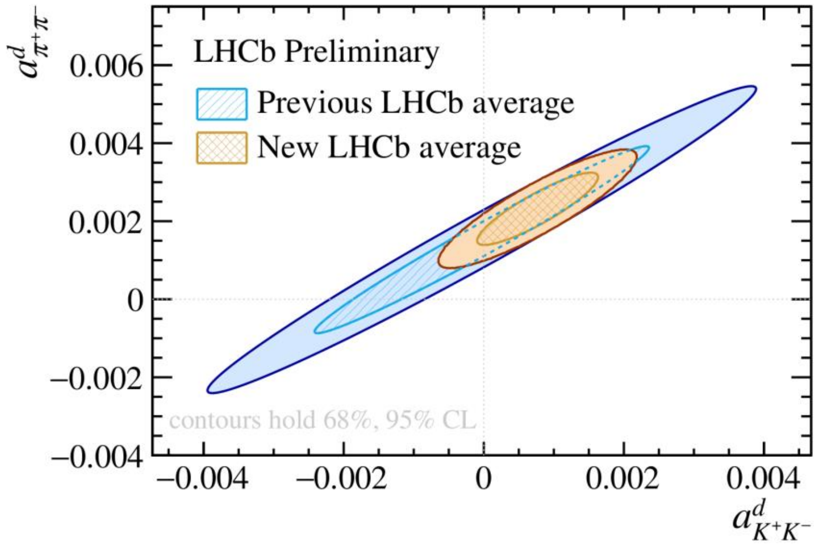
$$\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4},$$

1 in 1000 difference
Upper end of SM predictions
separate into
two decay channels

New !



LHCb-PAPER-2022-024

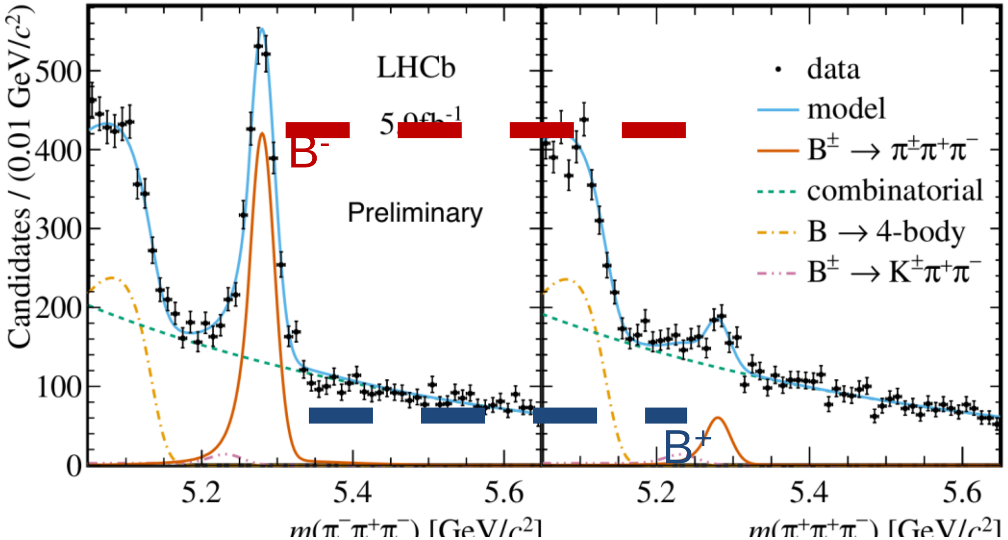


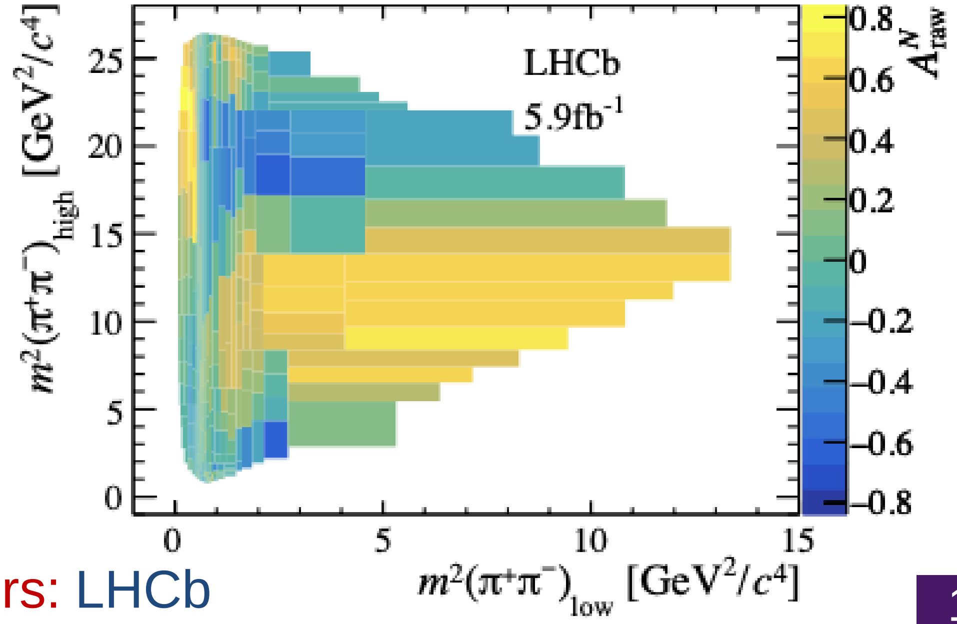
CP Violation in 3-body B decays

New !

LHCb-PAPER-2021-049
LHCb-PAPER-2021-050

- CP Violation discovered in three different $B^\pm$ 3-body decays
  - $B^\pm \to K^\pm K^+ K^-$, $B^\pm \to \pi^\pm \pi^+ \pi^-$, $B^\pm \to \pi^\pm K^+ K^-$
- Largest CP asymmetry ever observed
  - **75%** in selected phase space region
    - 7 times more B^- contribution than B^+
- In different phase space regions flips between more B^+ or more B^-
- Understanding relationships between different decays
  - Cancellations needed as particle anti-particle lifetimes are same

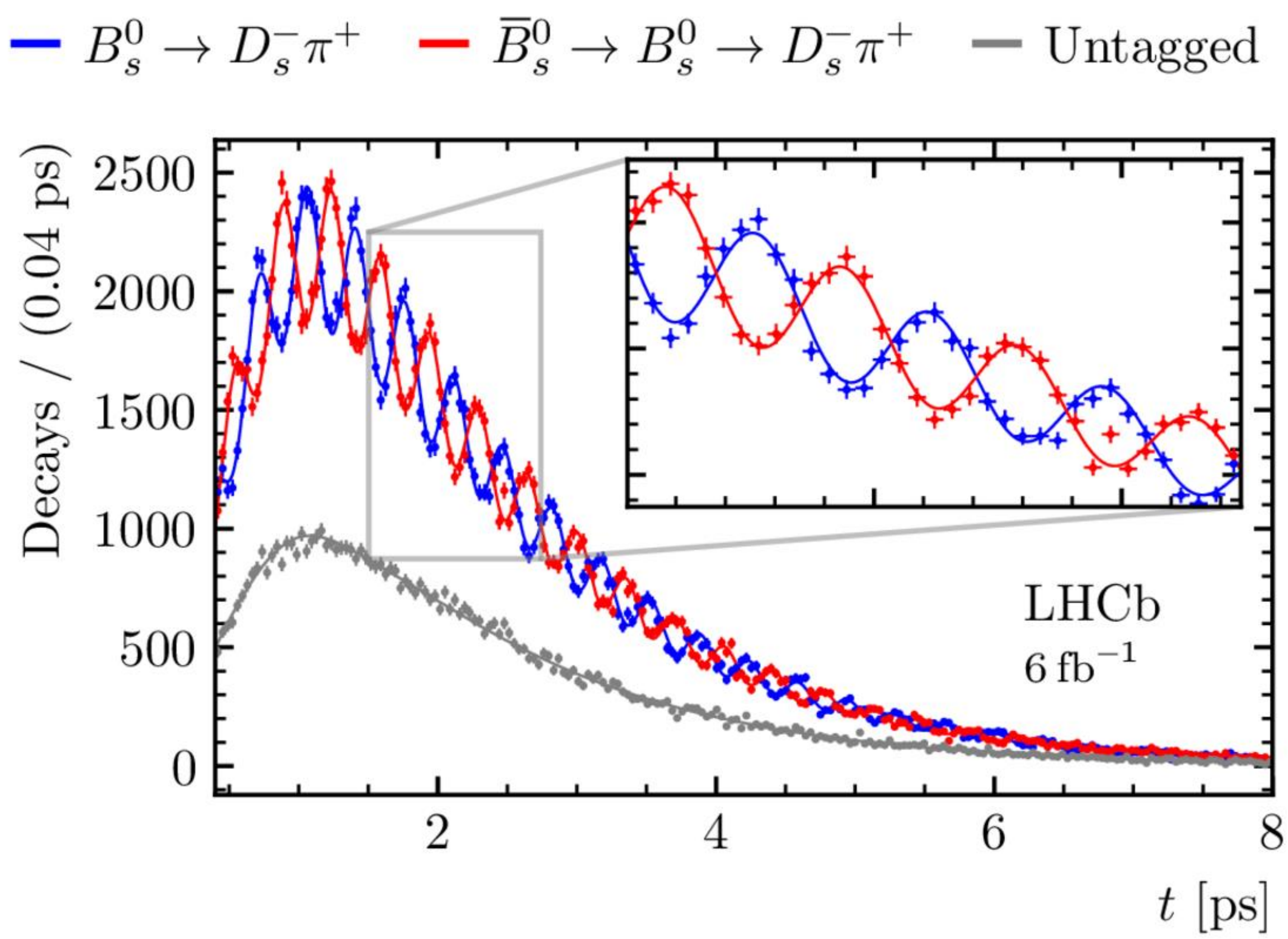




LHCb Recent Results: 3 Trillion Hz of Quantum Mechanics

LHCb-PAPER-2021-005

- Fascinating Quantum Mechanics
  - B_s particle anti-particle oscillations



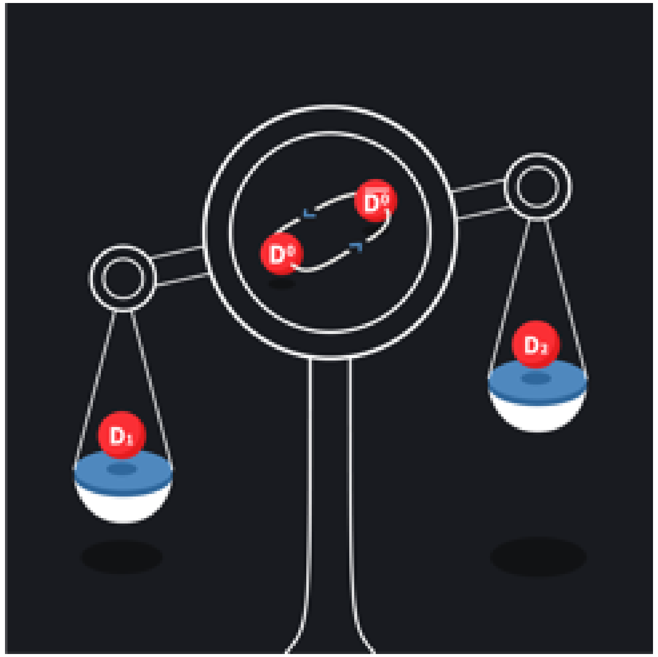
- Clear oscillations - text book plot !

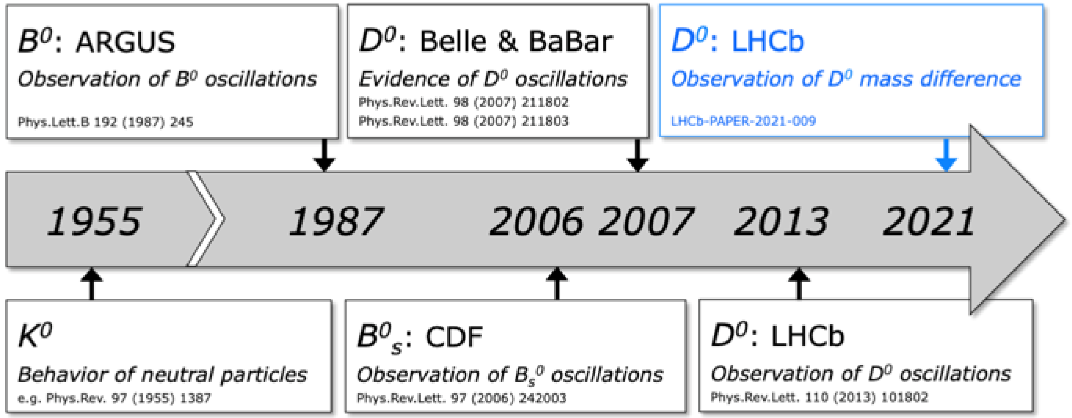
- Precision: 3 x 10^{-4}, LHCb Legacy Δm_s

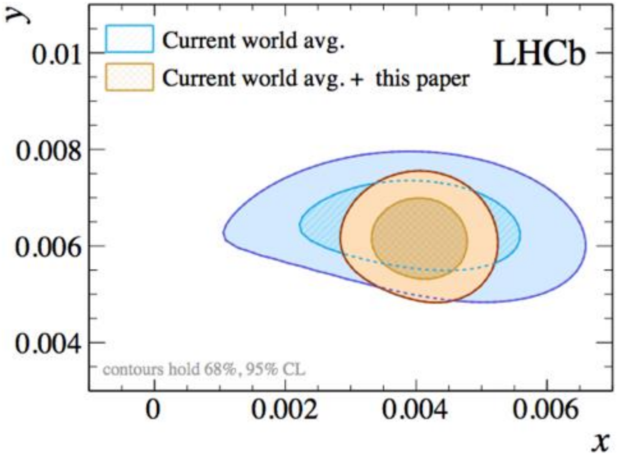
Charming Mass Difference

LHCb-PAPER-2021-009

- D^0 particle anti-particle oscillations
  - Frequency controlled by mass difference
  - **m_1-m_2 = 6.4x10^{-6} eV = 0.00000000000000000000000000000000000001 grams**
    - Fascinating quantum mechanics – milestone in field



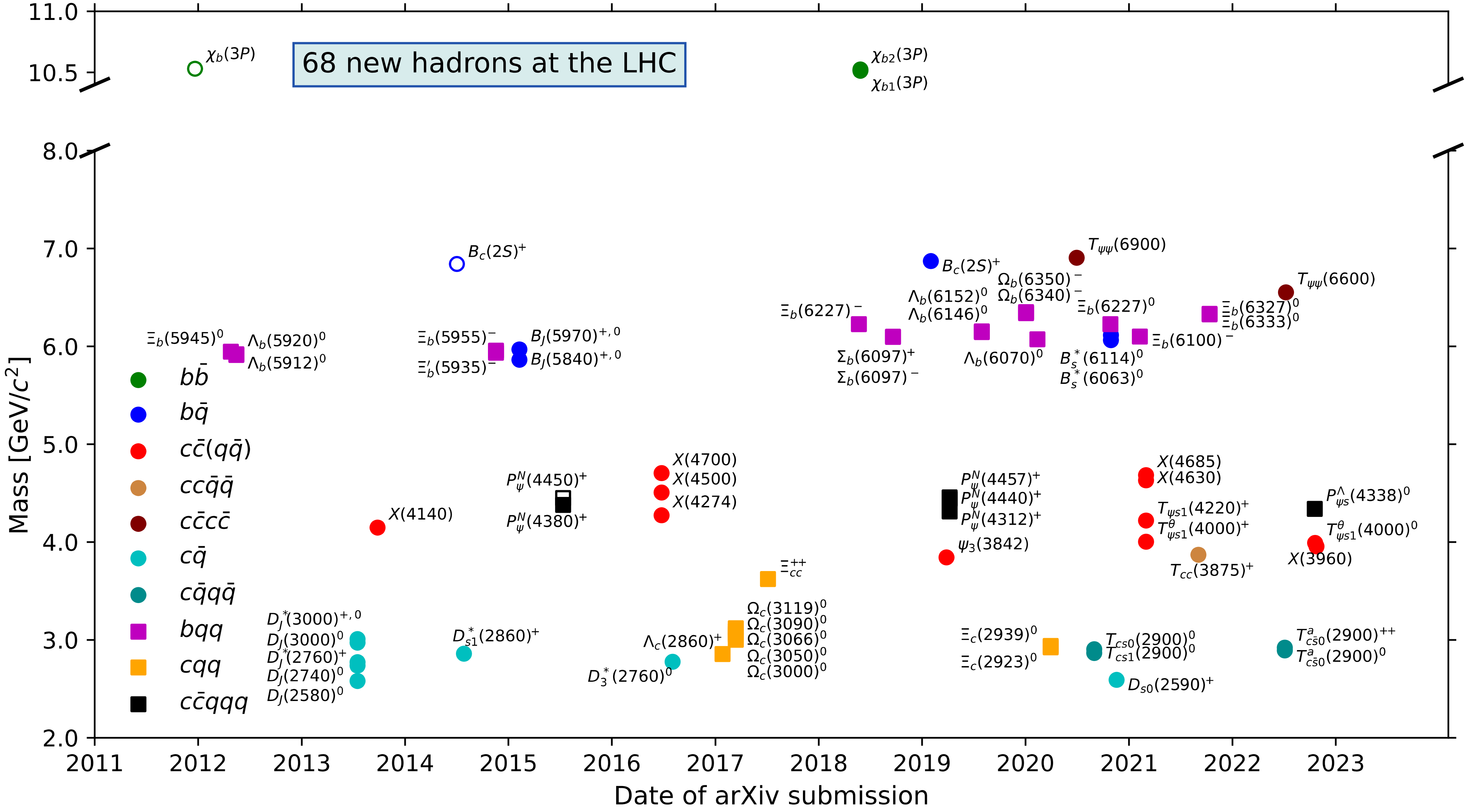




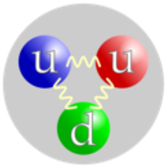
New particle discoveries

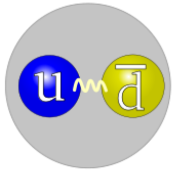
Hadrons

- **68 particles discovered at LHC**
- **60 at LHCb**



Hadrons

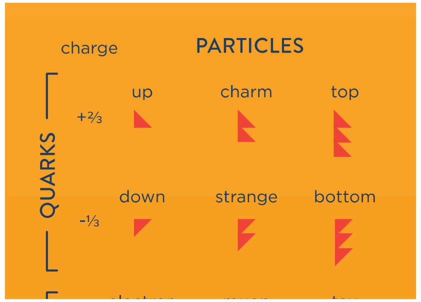


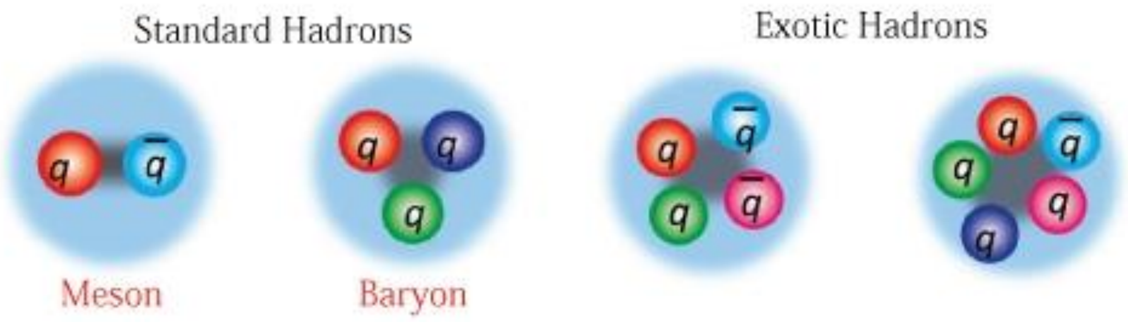


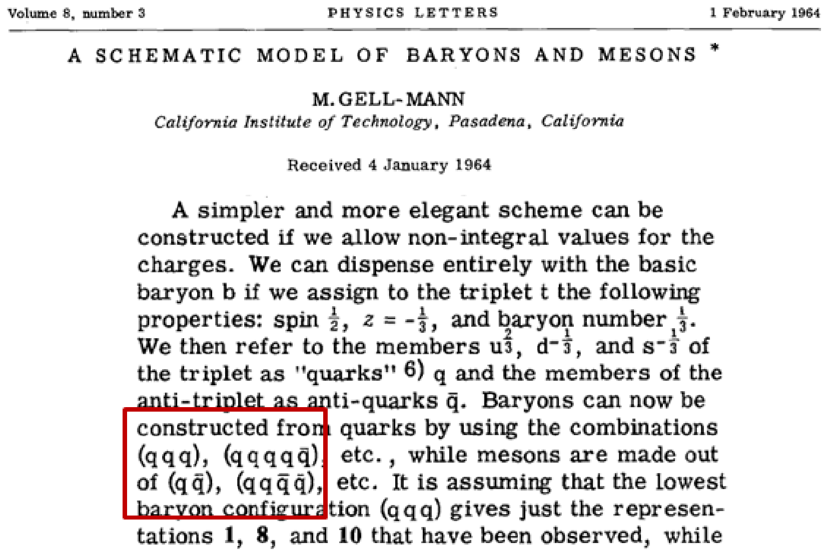
- Many many particles containing quarks, hadrons, known:
  - Proton, neutron, pion, kaon…..
  - Ground states and excited states,
  - most are unstable
  - Classify: **Mesons: 2** quarks (quark antiquark).

    Baryons: **3** quarks

    More ?







Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

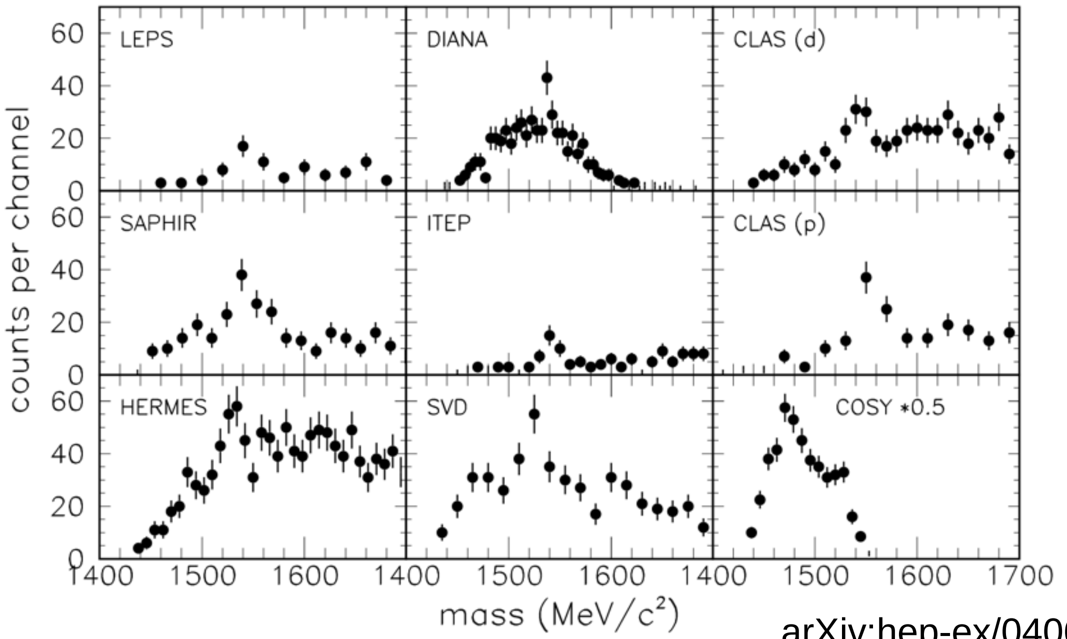
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while

A note on history of exotic hadrons

- Claimed but not confirmed pentaquarks…..

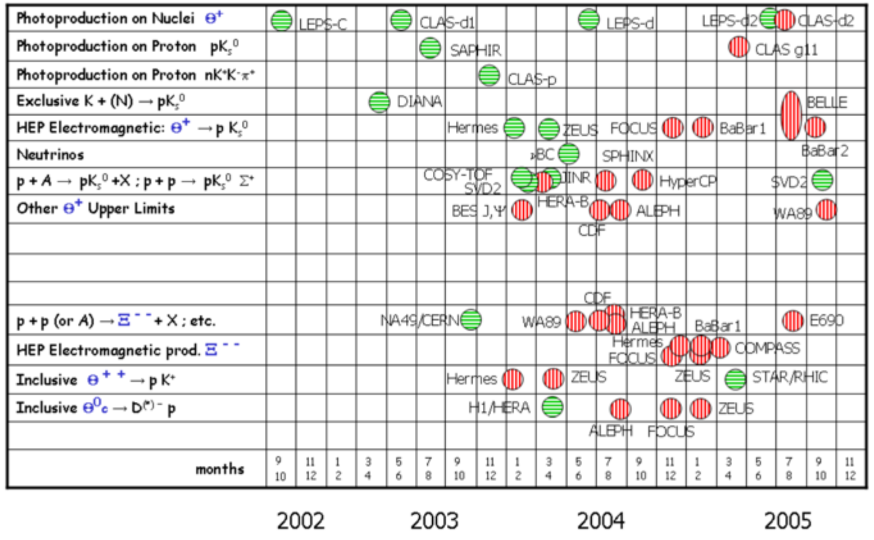
"Observation" of a pentaquark

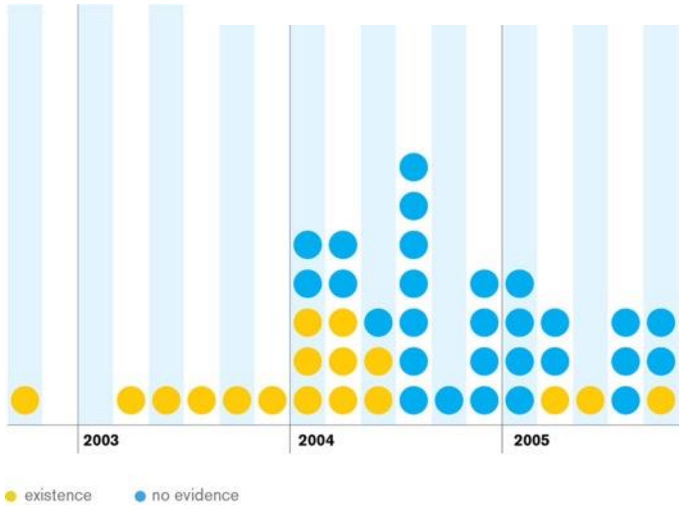
$\Theta^+ \rightarrow nK^+/pK^0_S$



arXiv:hep-ex/0406077

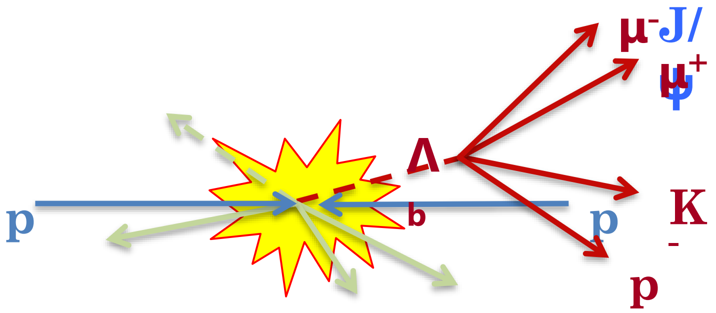
AIP Conf.Proc. 842 (2006) 1, 409-417





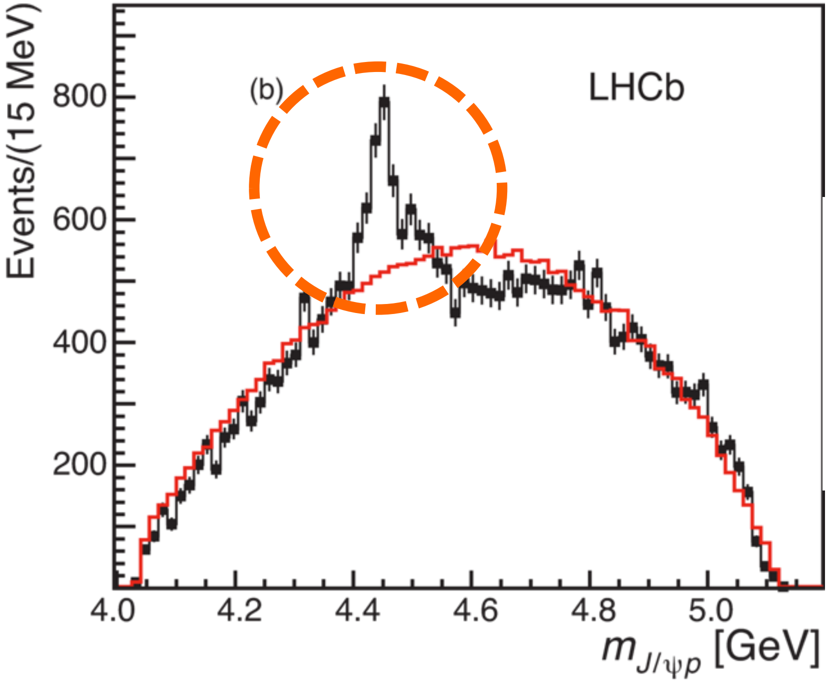
Pentaquarks at LHCb

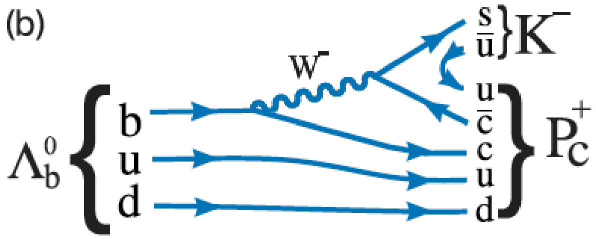
[LHCb: PRL 115 (2015) 072001]

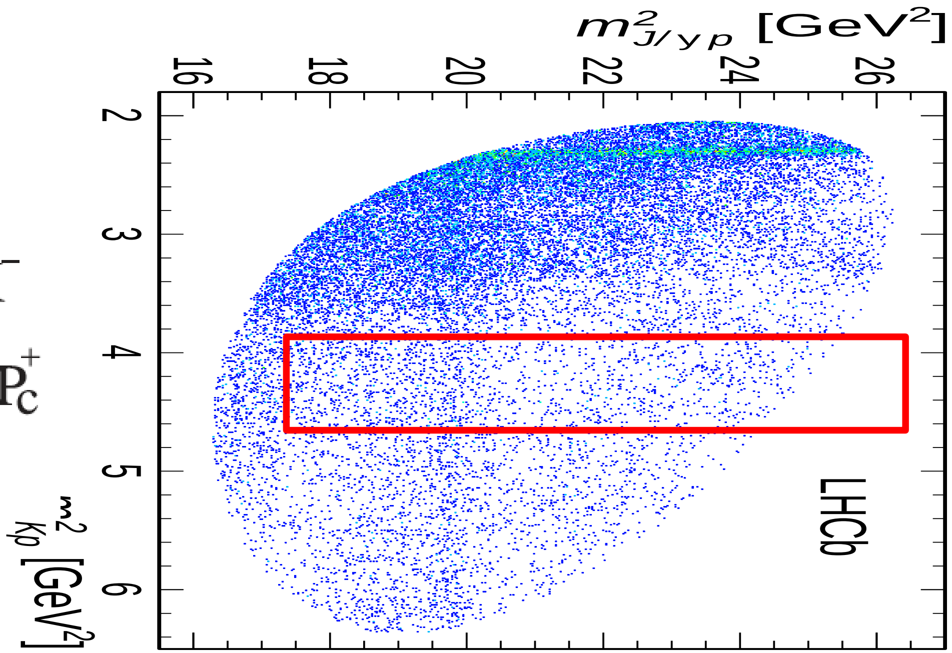


Observation of J/ψ p resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi\, p\, K^-$ decays

Λ*(1520)

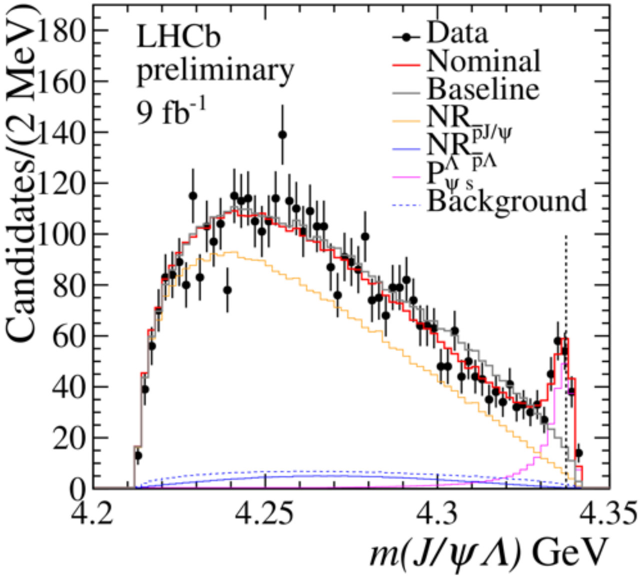




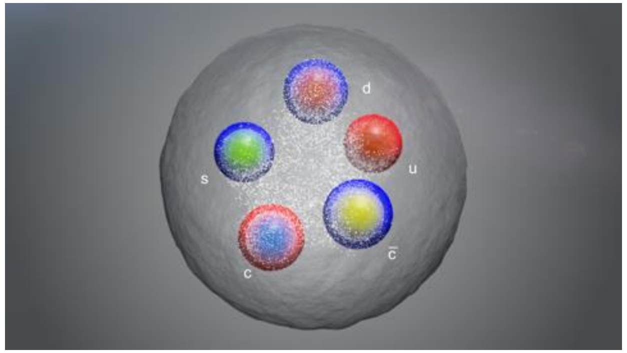


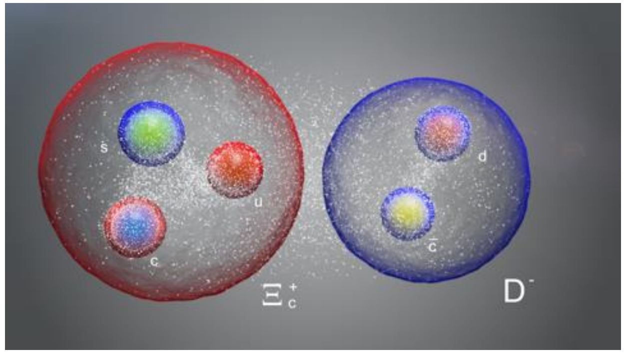
Exotic Hadrons at LHCb

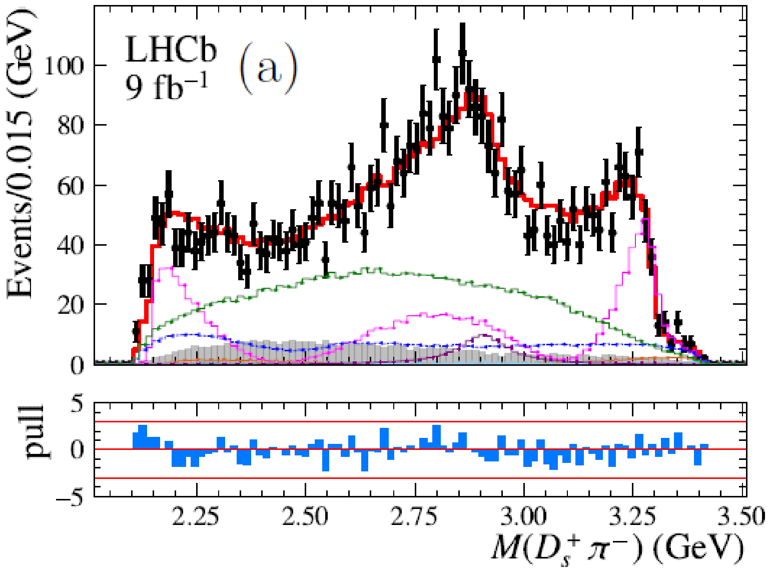
New !

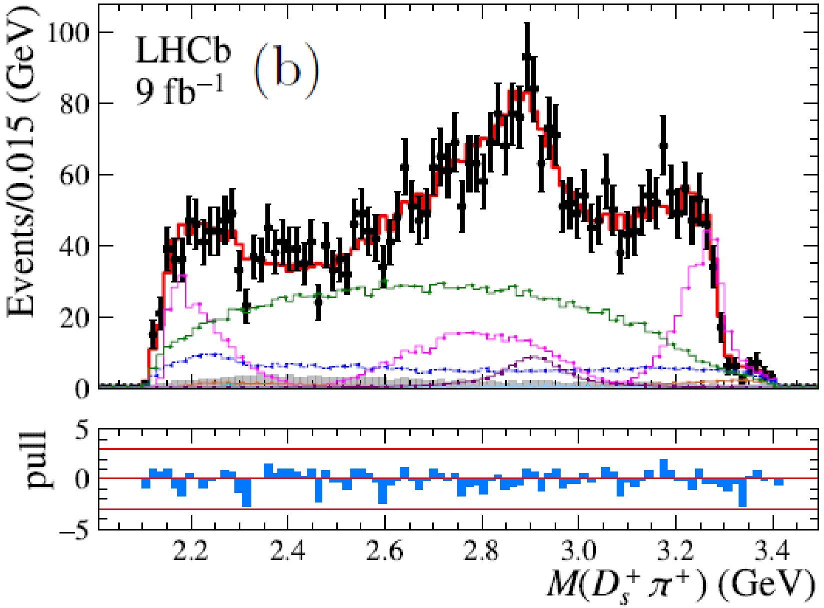


- Pentaquark in different decay channel, containing the strange quark







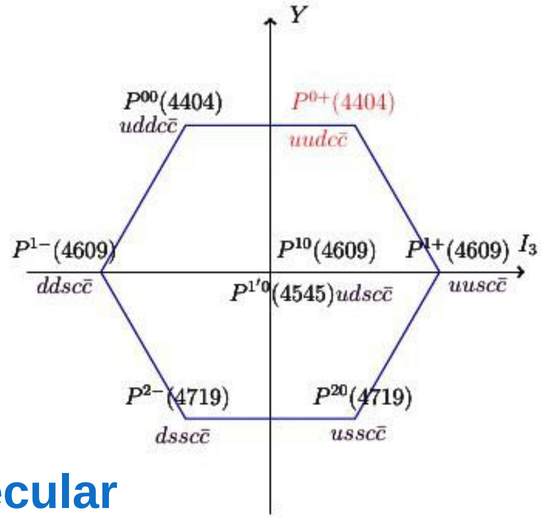


Isospin partners

- Pair of tetraquarks at the same mass
  - $T^a_{cs0}(2900)^{++}$
  - $T^a_{cs0}(2900)^0$

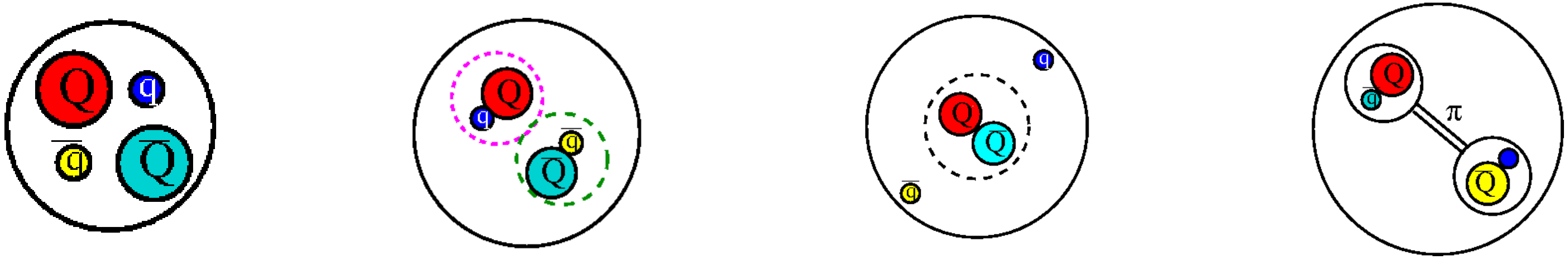
Exotic Hadrons: Tetraquarks & Pentaquarks

- We have observed quite a collection of exotic hadrons in recent years
- Starting to understand that they can be placed in multiplets
  - – Families of related exotic hadrons



- Many models of the quark configurations
  - – Molecule-like ? Tightly bound ?

"plain" **diquark model** **hydro-charmonium model** **molecular model**

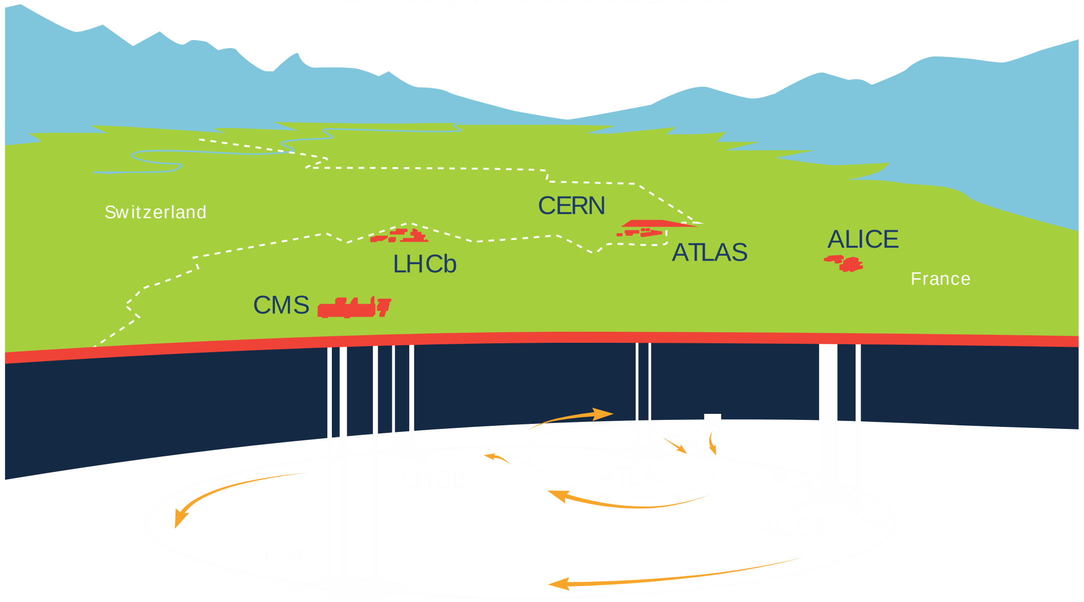


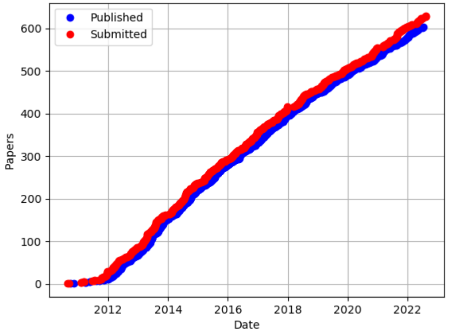
  - – New observations will allow us to disentangle their nature

LHCb Collaboration & Detector

LHCb Community

- 1065 members
- 96 Institutes
- 21 Countries





- 646 papers

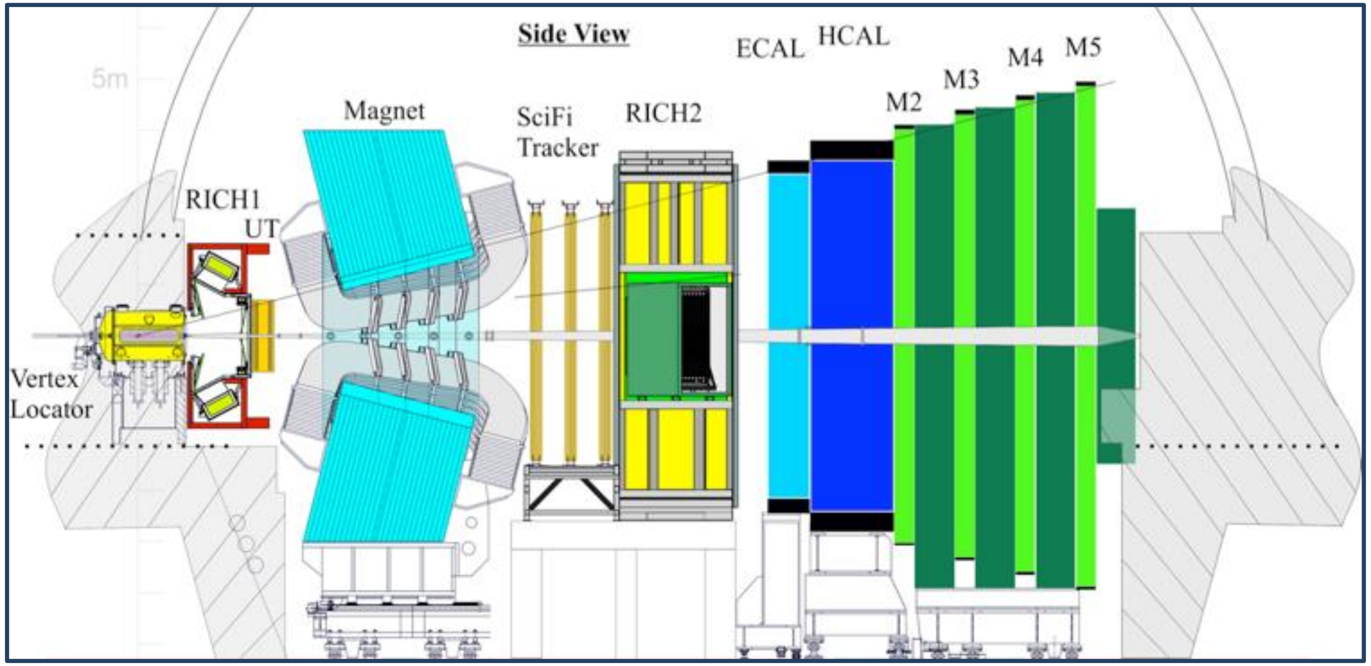
~ 1/week

- One of four large experiments at the CERN Large Hadron Collider
- Detector is designed, built, operated and data analysed by the full international collaboration
- Collaboration is organized in projects and working groups

Upgrade I
2022-2032

Upgrade I

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



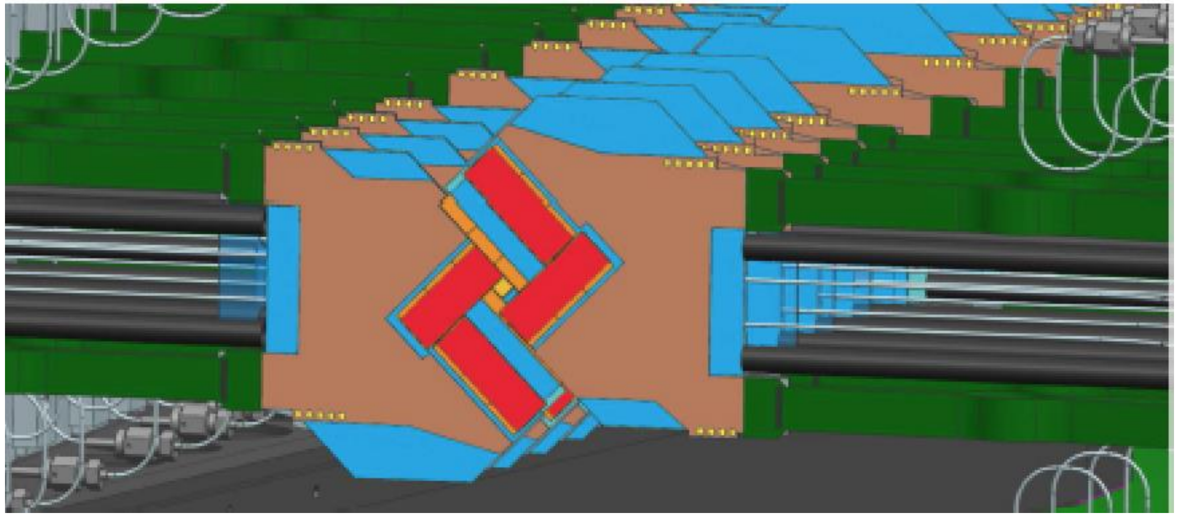
- Target $L_{peak} = 2x10^{33}\ cm^{-2}\ s^{-1}$, pile-up ~5

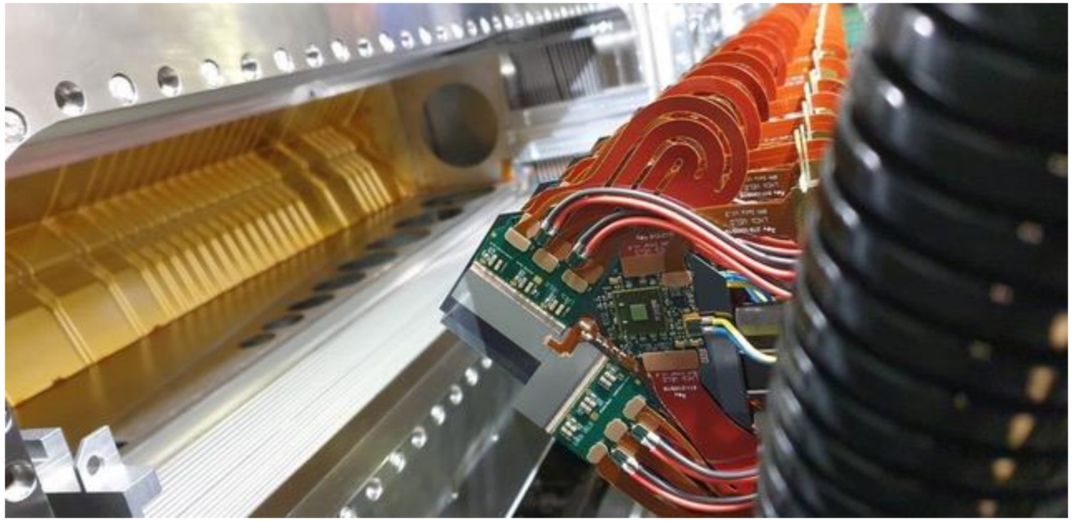
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

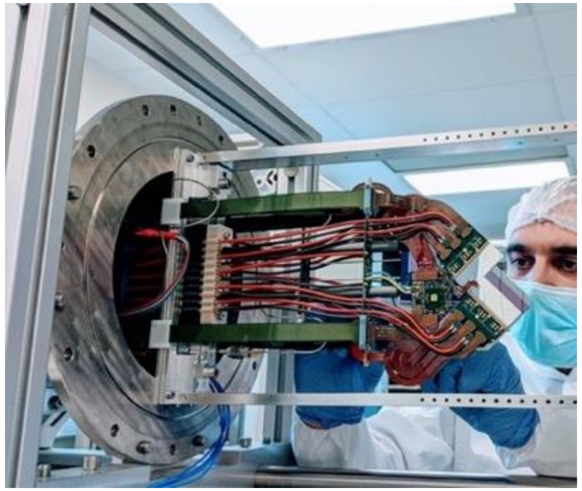
Major project installed for operation in Run 3

LHCb Upgrade I: VELO

CERN-LHCC-2013-021





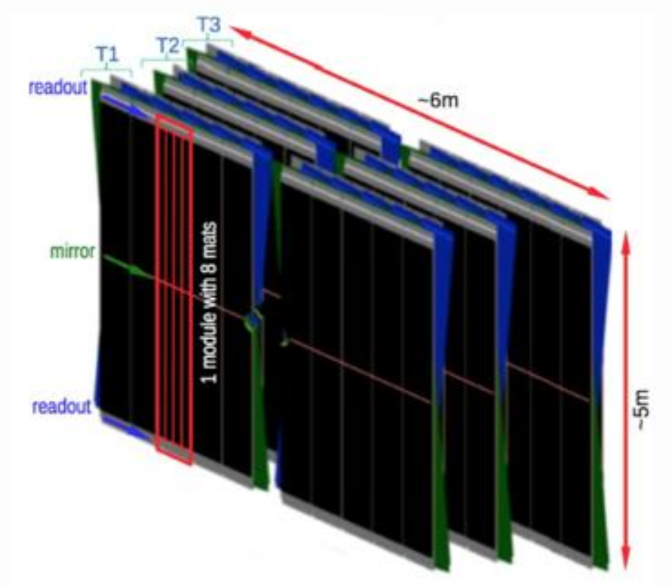


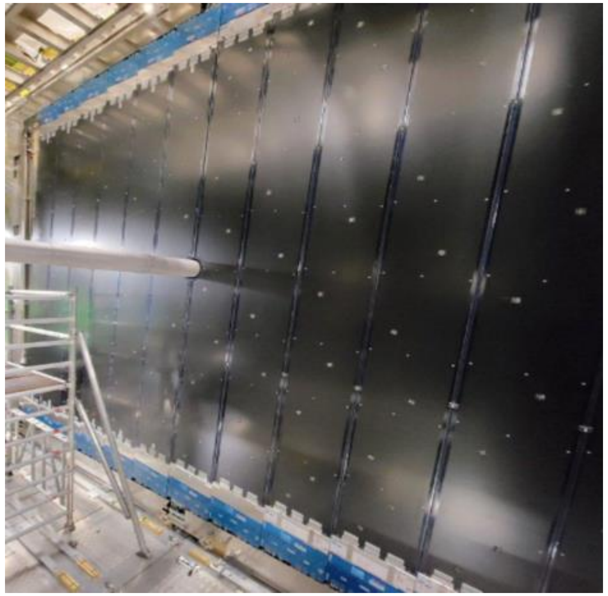
- Hybrid Pixel Detectors (55μm pitch)
- Close to the LHC beam (5.1 mm)
  - retracted/reinserted each fill
- Innovative silicon microchannel substrate
  - Bi-phase CO_2 cooling
- **Installation completed May 2022, now commissioning**

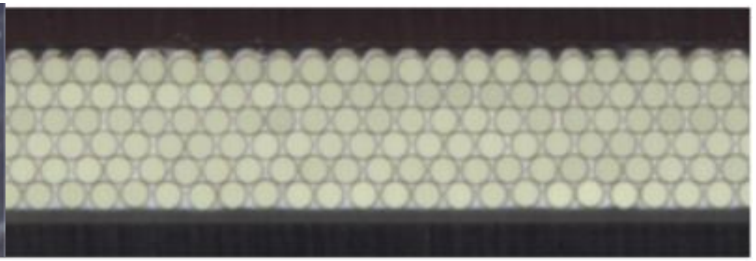
LHCb Upgrade I: SciFi

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, now commissioning**



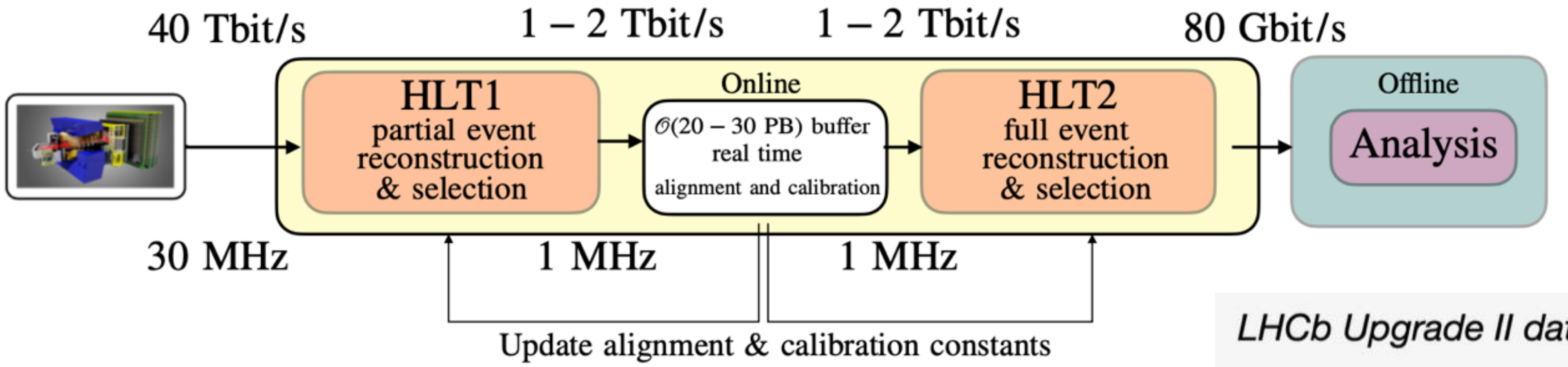




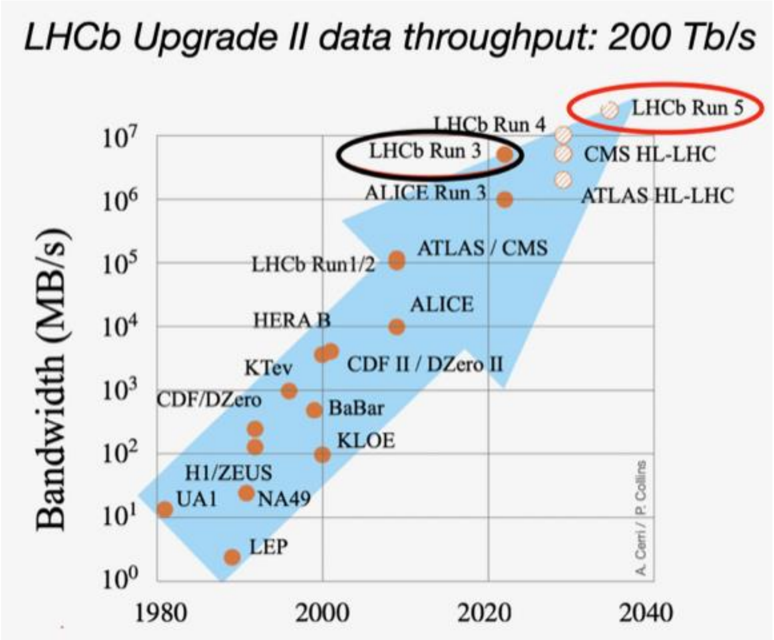
LHCb Upgrade I: Trigger Revolution

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 reduced to ~1MHz by the first trigger (tracking/vertexing and muon ID) running on **GPUs**
  – ~ 200 cards
- Highest throughput of any HEP experiment

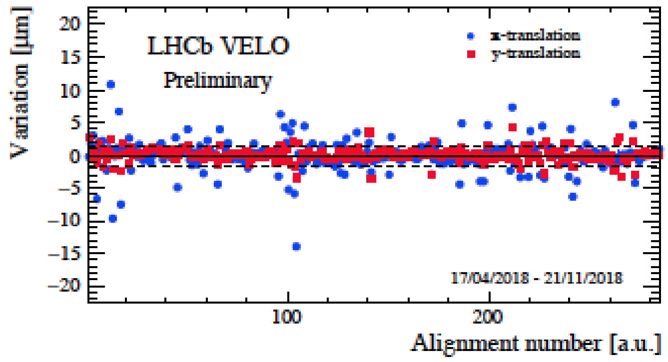


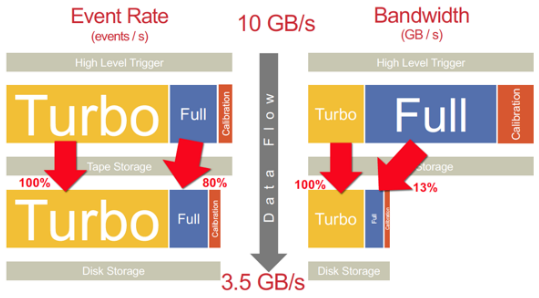
Real Time Analysis - Turbo

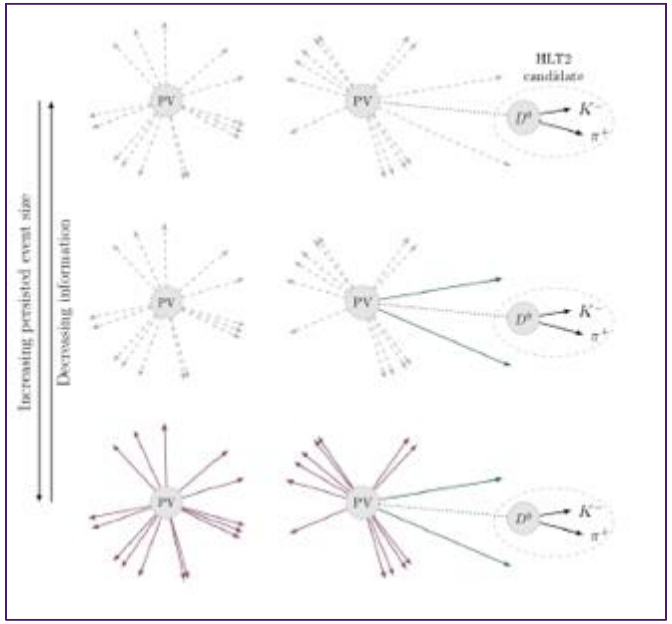
CERN-LHCC-2018-014
CERN-LHCC-2018-007

- 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….

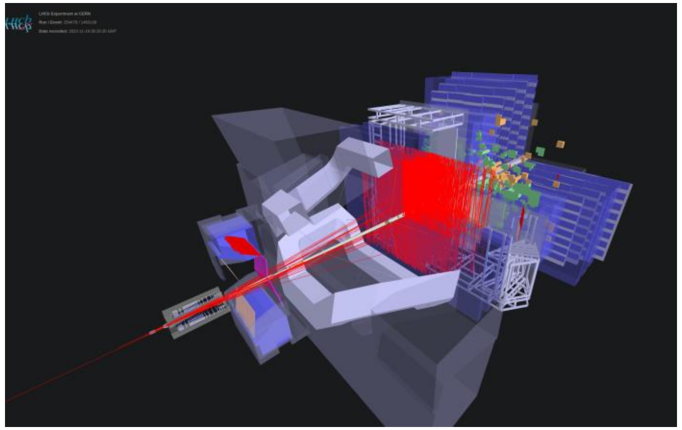
  those in cone around...

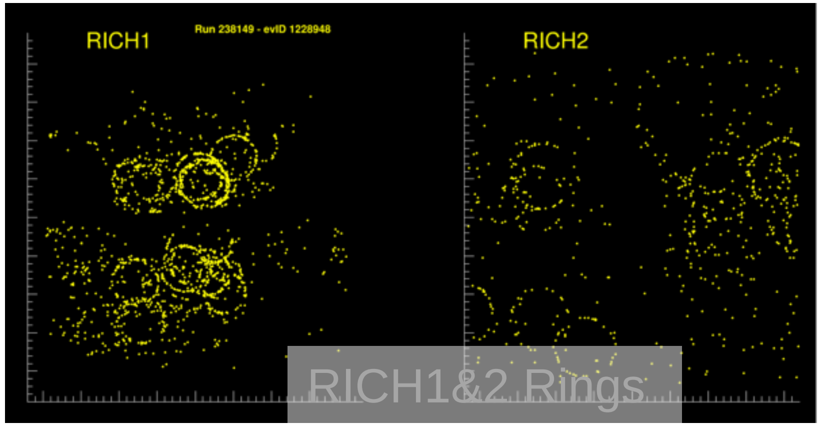
  those from same PV....

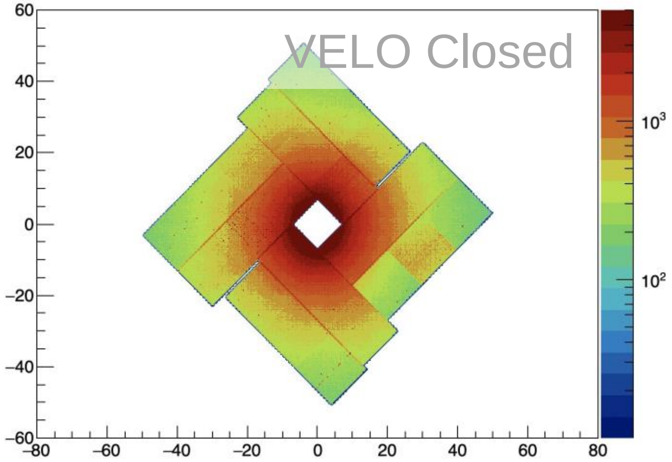
  All tracks in event….

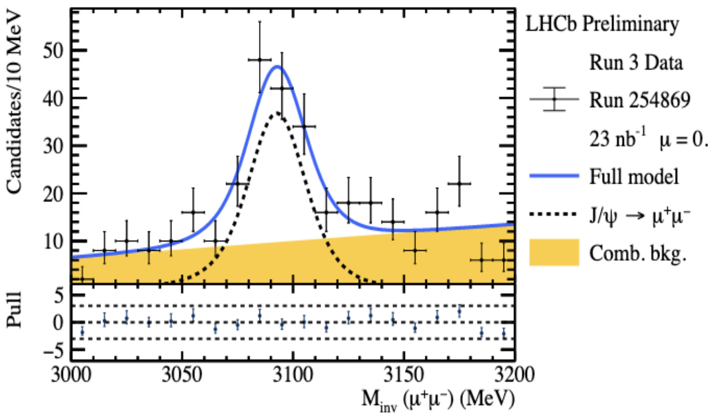
  All ECAL clusters....

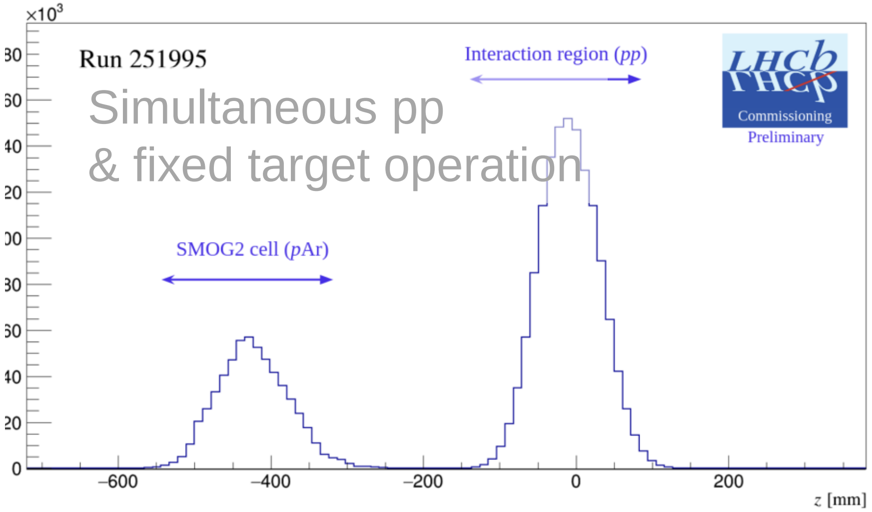
Commissioning











- Commissioning proceeding well – recent milestones include:
  - Full VELO closing, first alignment, first fixed target operation
  - GPU based trigger operation with track reconstruction

LHCb Upgrades

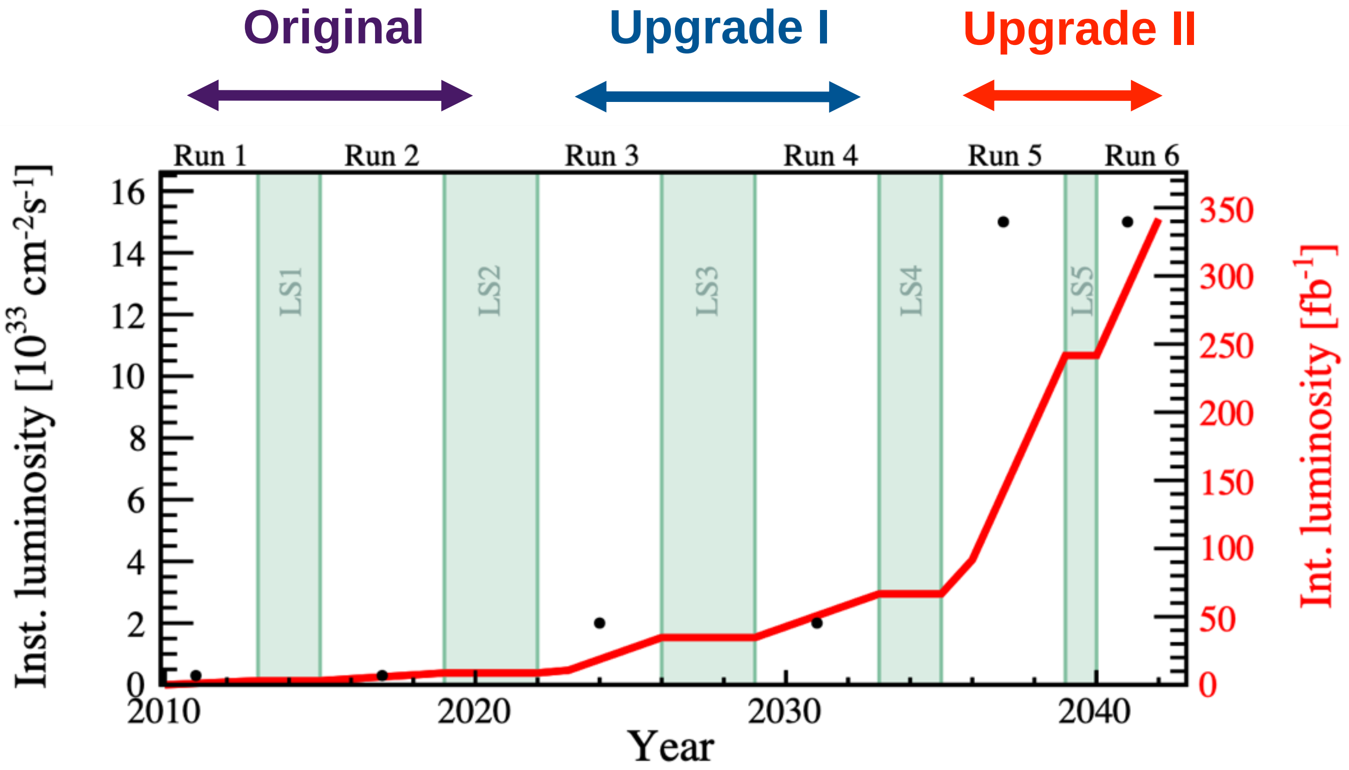
- Physics programme limited by detector, NOT by LHC
- Hence, clear case for an ambitious plan of upgrades

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

Approved March 2022

Precision timing < 50ps

CMOS tracking



- Still only at the start of our journey

Summary

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

- LHCb physics
  - ~650 papers so far, many more to come from Run 2 analysis
  - CP Violation discoveries
  - Exotic hadron discoveries

- LHCb Upgrade I
  - Largest CERN particle physics project since LHC completion
  - Despite pandemic completed on-budget near-schedule

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

Backup

LHCb Upgrade I: RICH 1 & 2

CERN-LHCC-2013-022

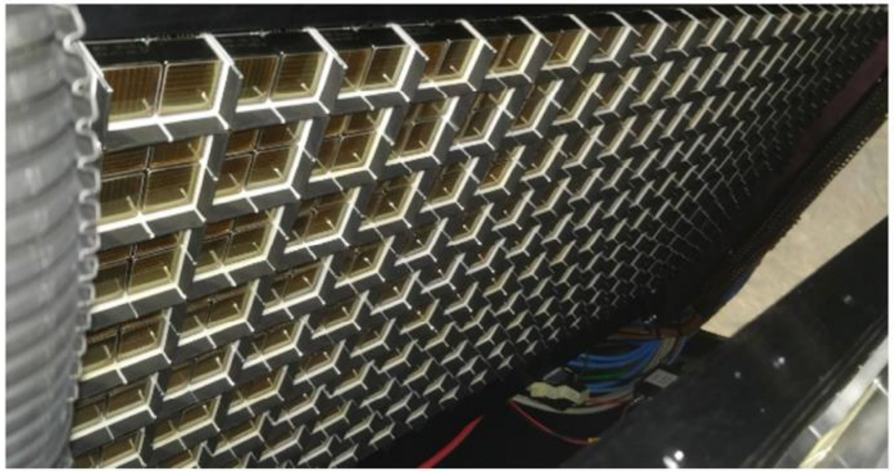
- Unique particle identification system, key for success of physics programme

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

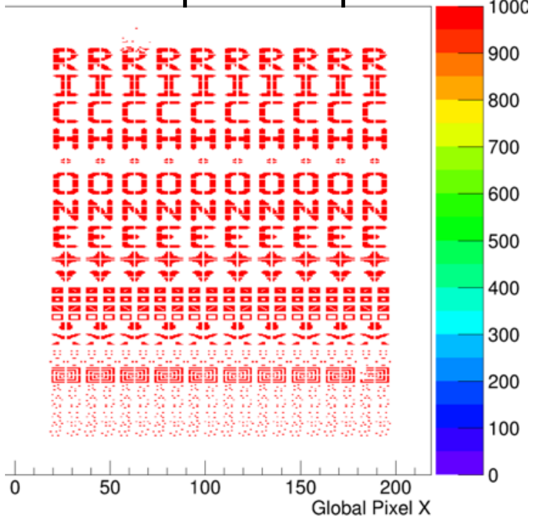
- RICH1: new design with new optical system with increased focal length, to halve occupancy

- **Installation successfully completed in February '22**
- **Detector commissioned & now in data taking**

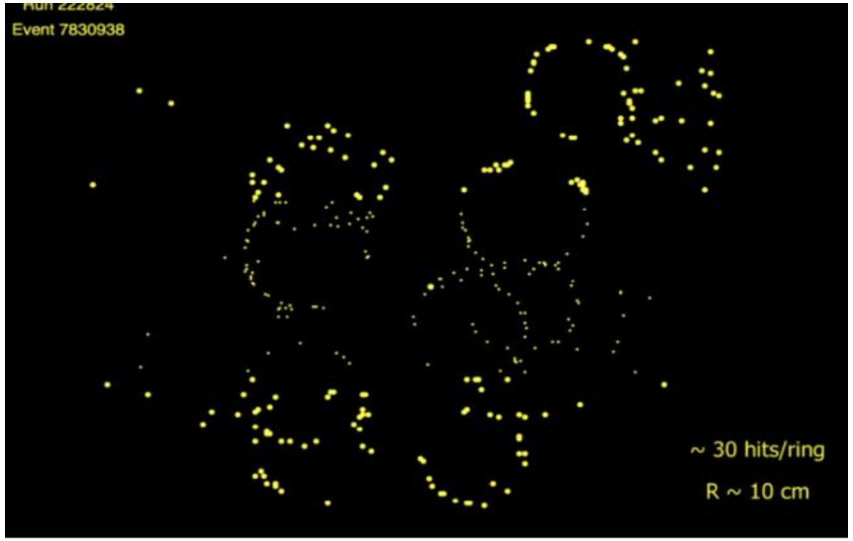
RICH1: MaPMTs installed upper side



RICH1: pixel map



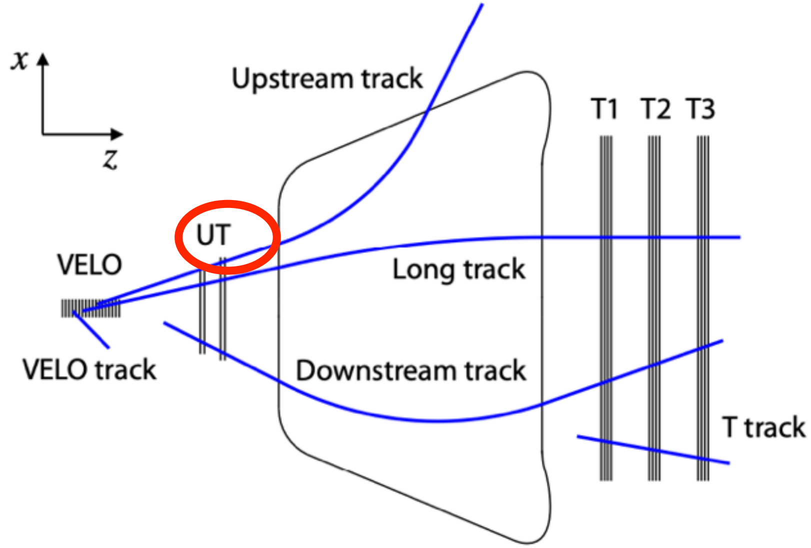
RICH2: first rings, LHC October '21 test

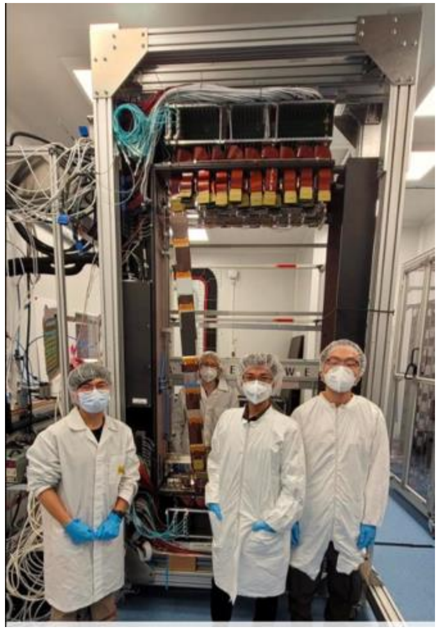


LHCb Upgrade I: Upstream Tracker

CERN-LHCC-2014-001

- 68 staves with silicon strips and integrated cooling, arranged in 4 planes
  - fast p_T determination for track extrapolation
    $\rightarrow$ reduce ghost track, and improve trigger bandwidth
  - long-lived particles decaying after VELO (K_S, Λ)
- Detector assembly ongoing at surface
  - services in the cavern completed, first stave mounted

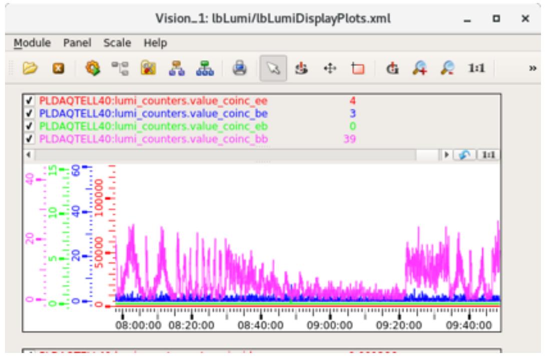


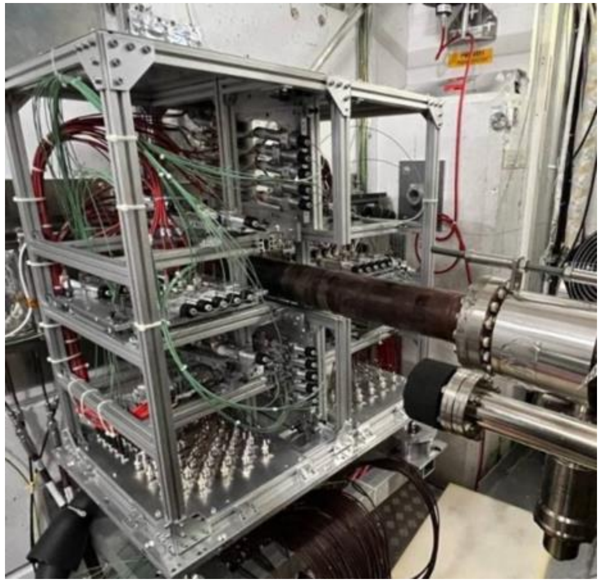


- **Detector installation underway**

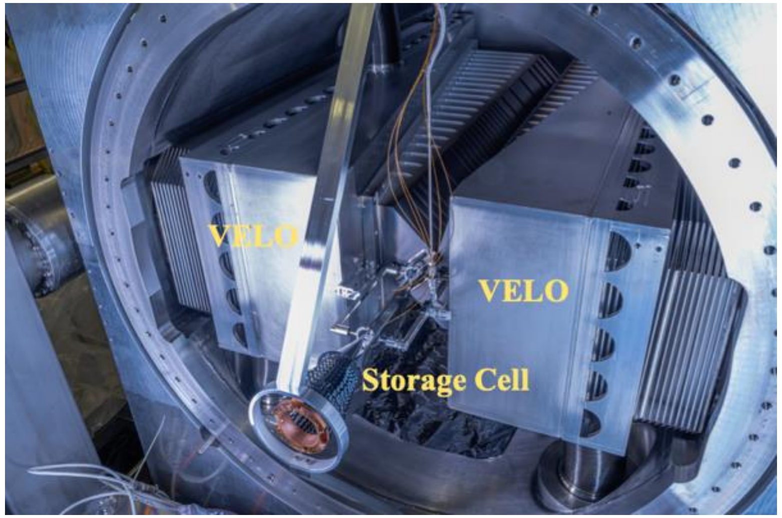
- Systems at the entrance of the VELO

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!**

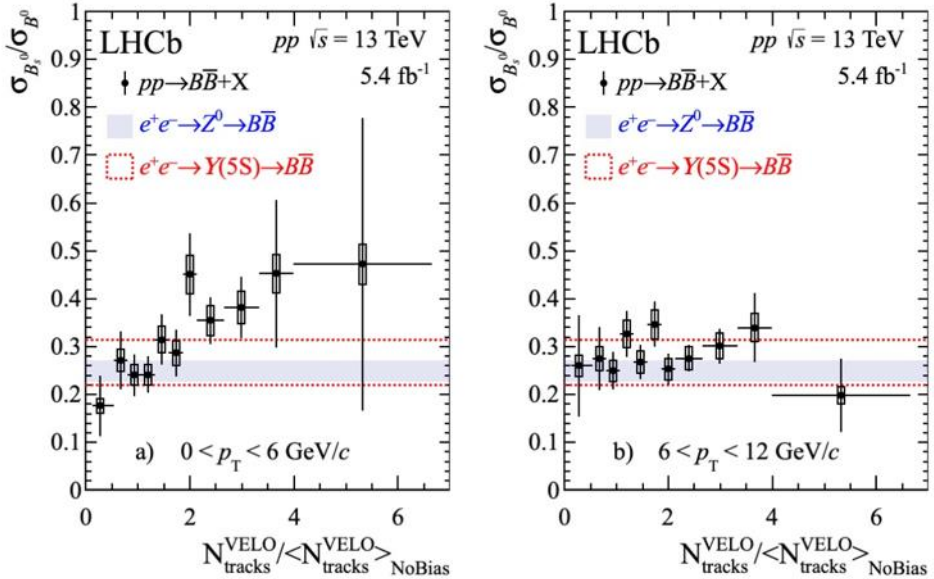


Breadth of LHCb Physics: QCD

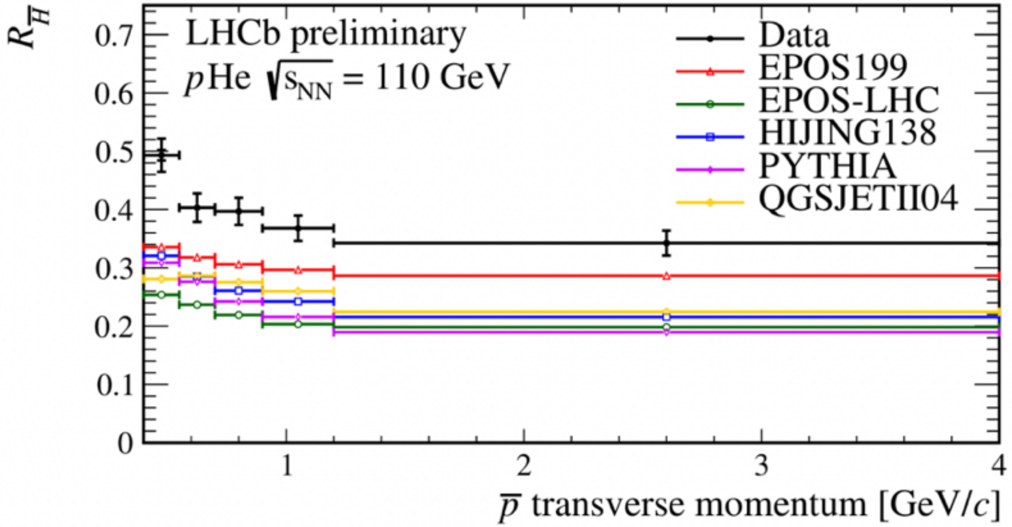
QM ‘22

- Many new LHCb results released on QCD with pp, pPb, PbPb and fixed target programme for Quark Matter in Krakow

arXiv 2204.13042



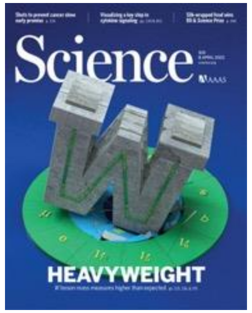
LHCb-PAPER-2022-006



- B_s^0/B^0 ratio vs multiplicity
  – evidence of a trend at low p_T
- Strangeness enhancement at high multiplicity observed by ALICE Nat. Phys. 13 (2017) 535

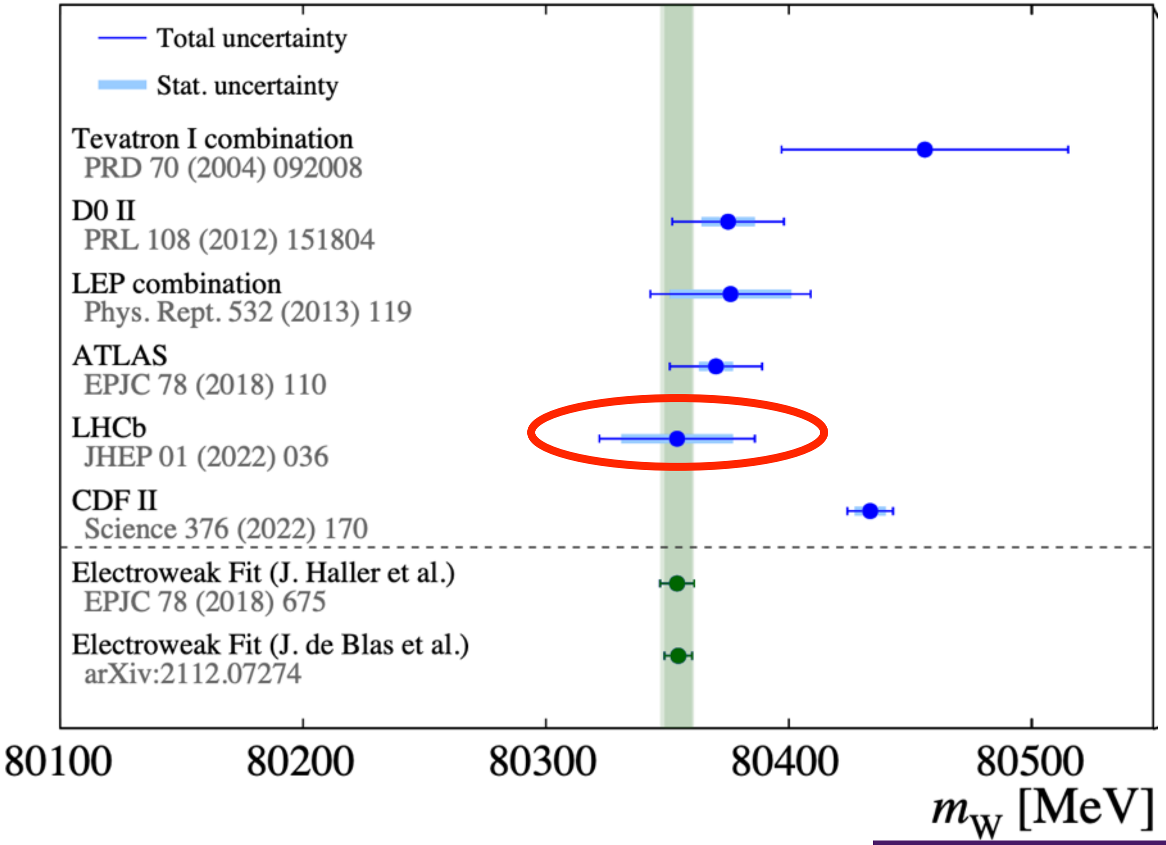
- LHCb gas injection system: p He collisions
- Detached $\overline{p}$ from anti-hyperons decays
- Interpretation AMS/PAMELA data
- Predictions underestimate

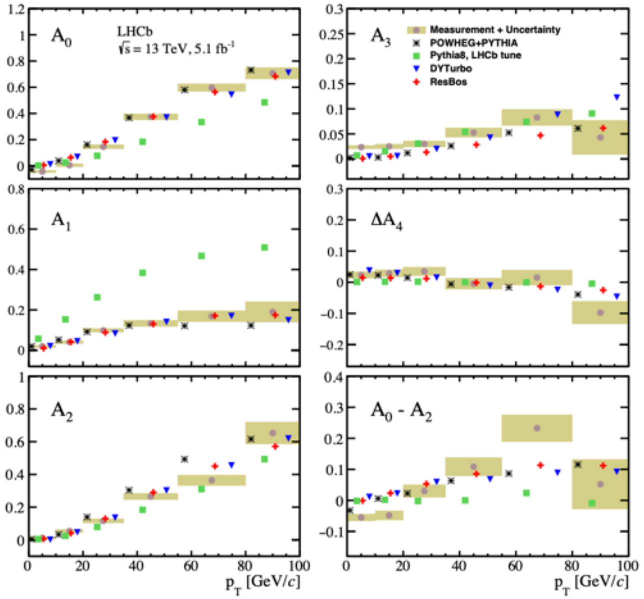
Breadth of LHCb Physics: Electroweak



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

JHEP 01 (2022) 36





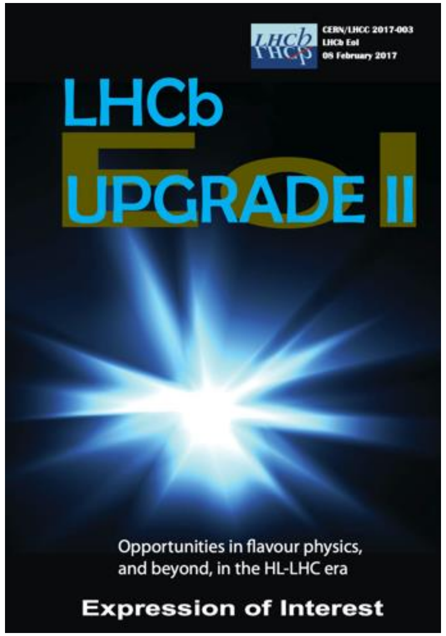
arXiv 2203.01602

arXiv 2212.07458

- First measurement of the $Z \rightarrow \mu^+\mu^-$ angular coefficients and differential cross section in the forward region

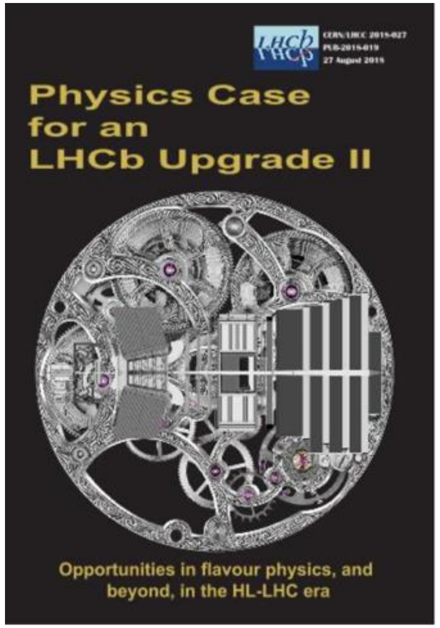
Upgrade II: steps so far

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."

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

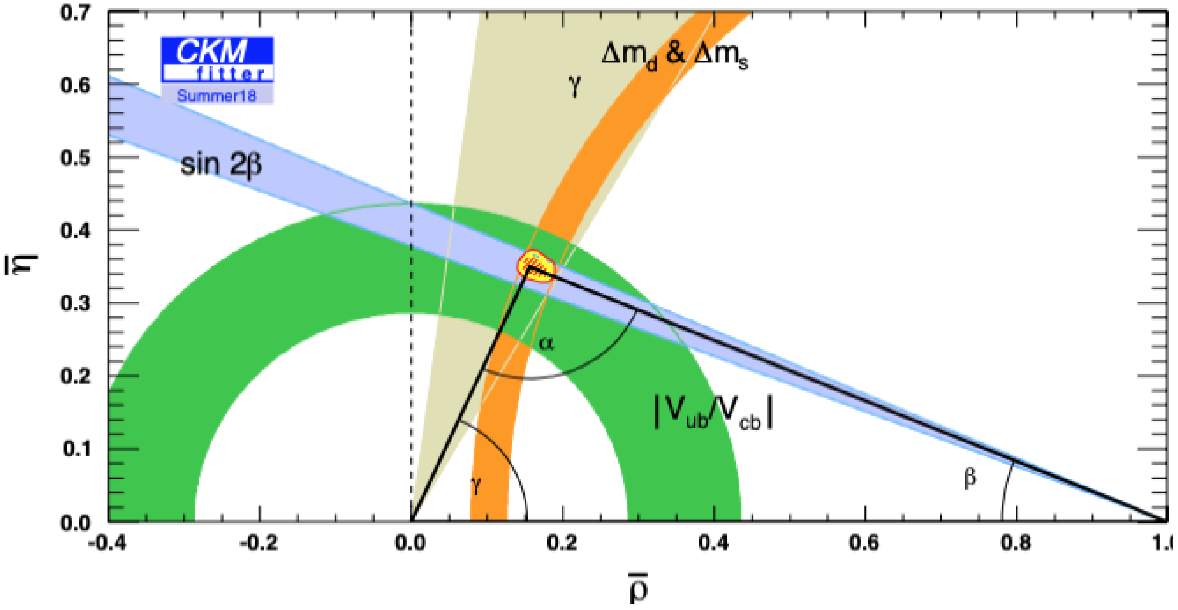
European Strategy Update 2020 ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

Constraining the Unitarity Triangle

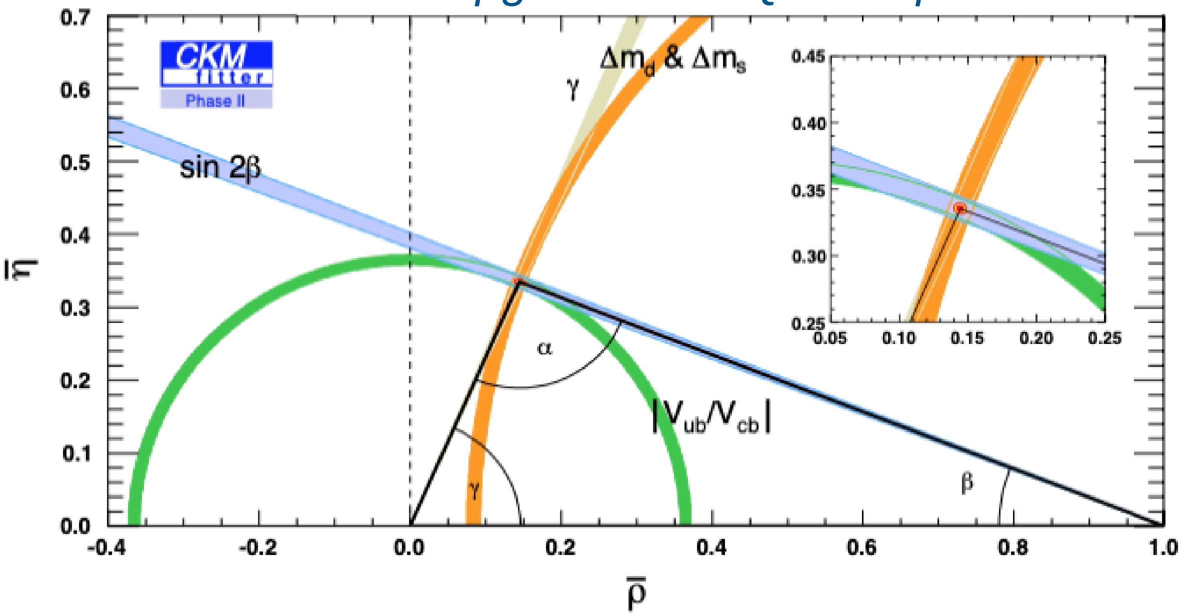
- *Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes*
- *Either NP is very heavy of it has a highly non trivial structure*

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement

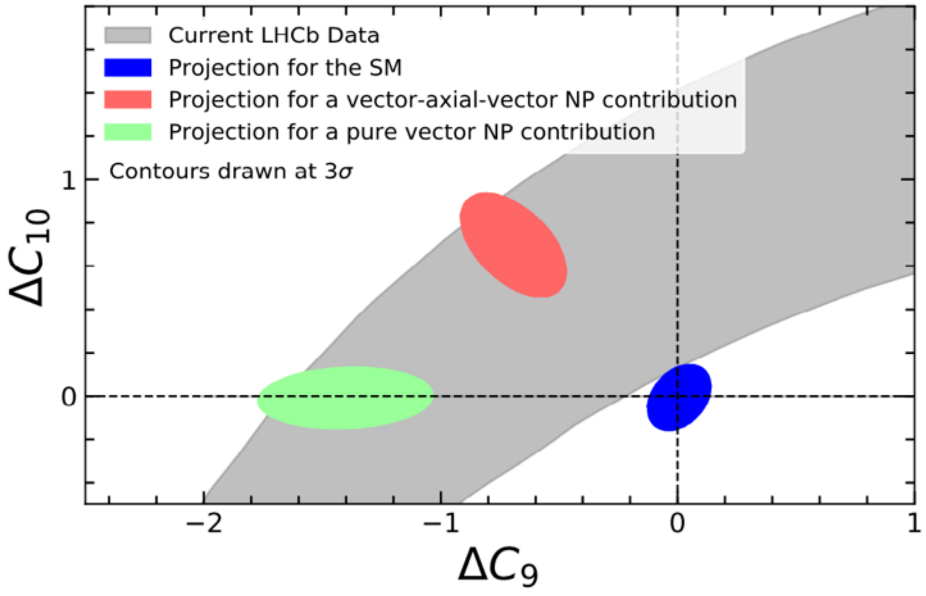


Arguably the greatest likelihood of a further paradigm shifting discovery at the HL-LHC lies with flavour physics

LFU and Charm CPV

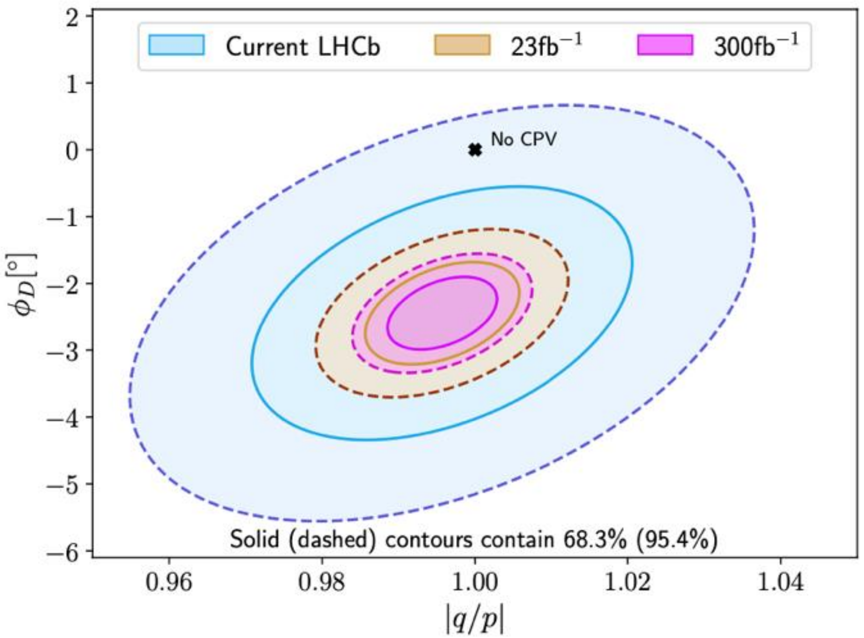
Lepton flavour universality

- Capability to discriminate between different NP scenarios, no limitations from theory



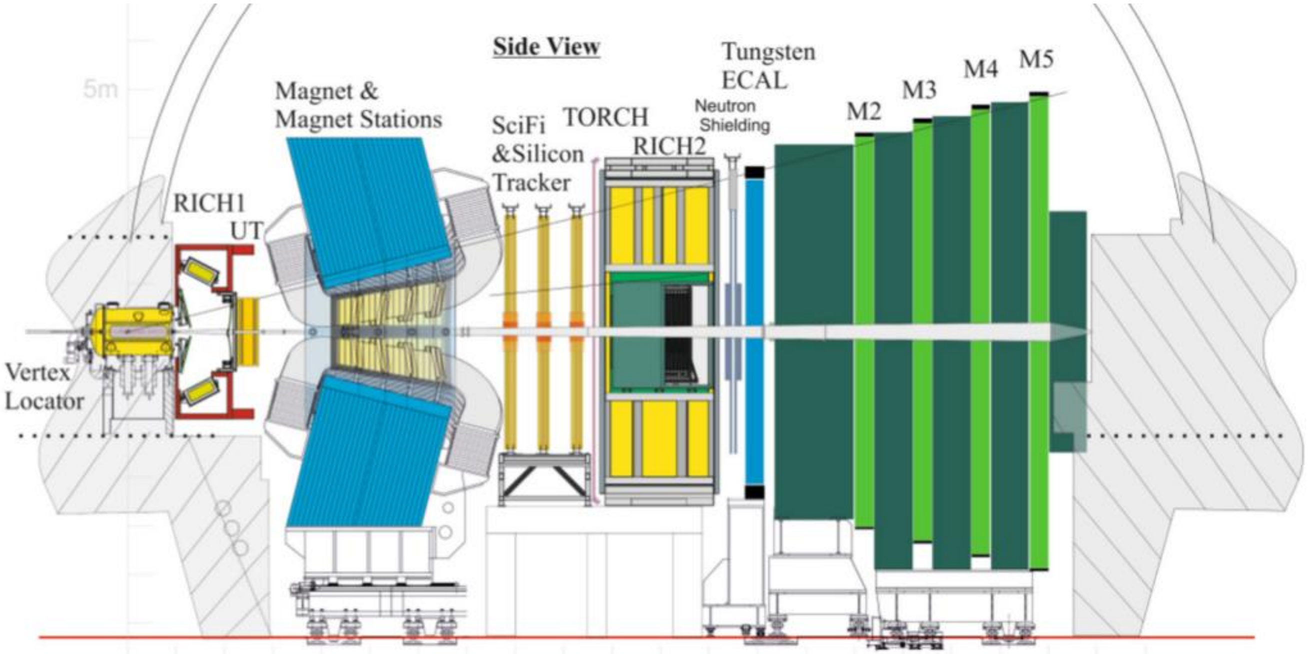
CP violation in charm

- 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)*



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

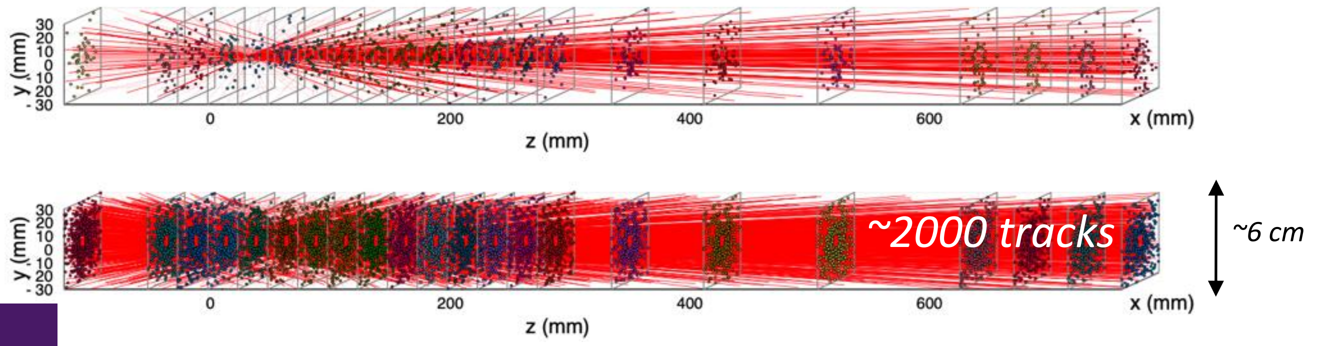
Key ingredients:

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

VErtex LOcator (VELO)

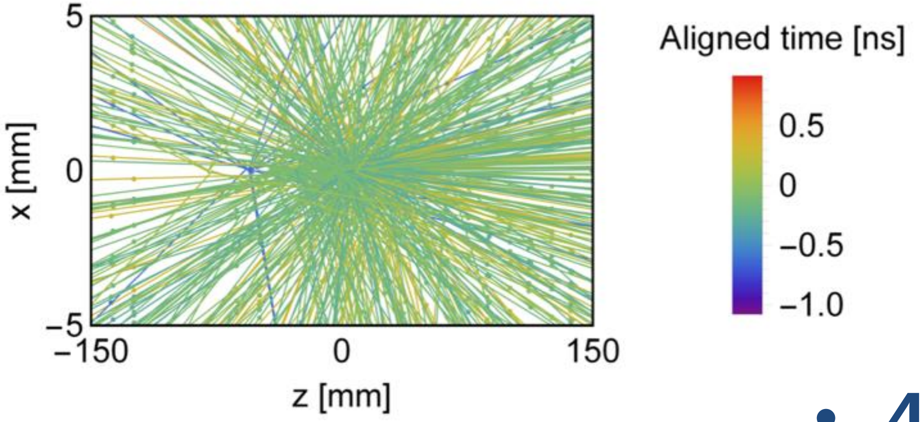
Run 3: pile-up ~6

Upgrade II: pile-up ~42

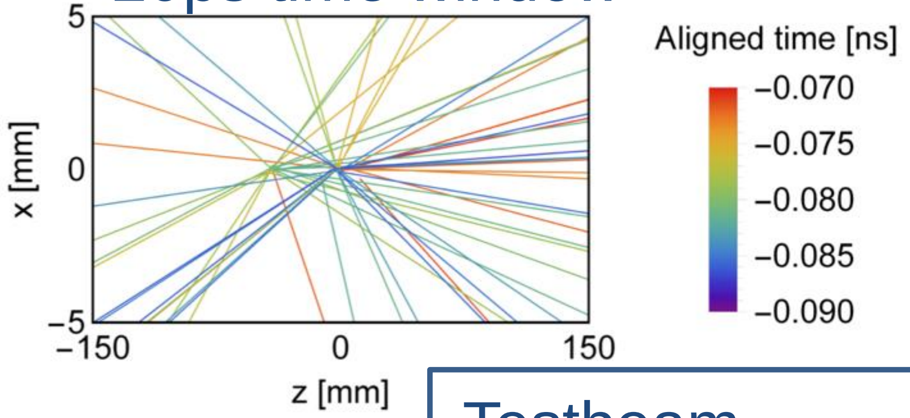


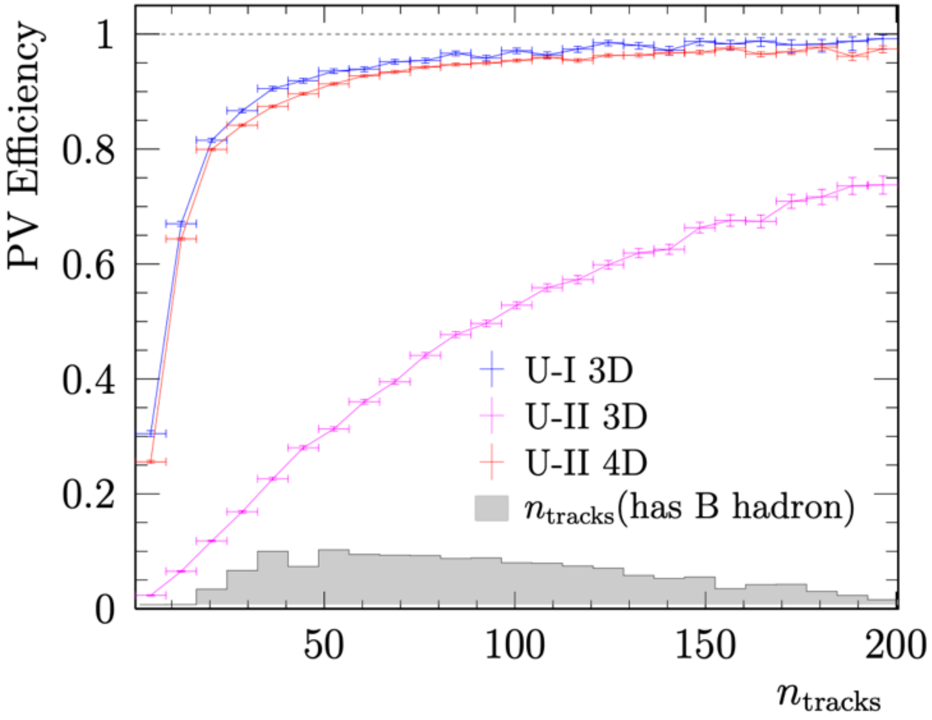
4D Vertexing: Precision Timing

42 interactions

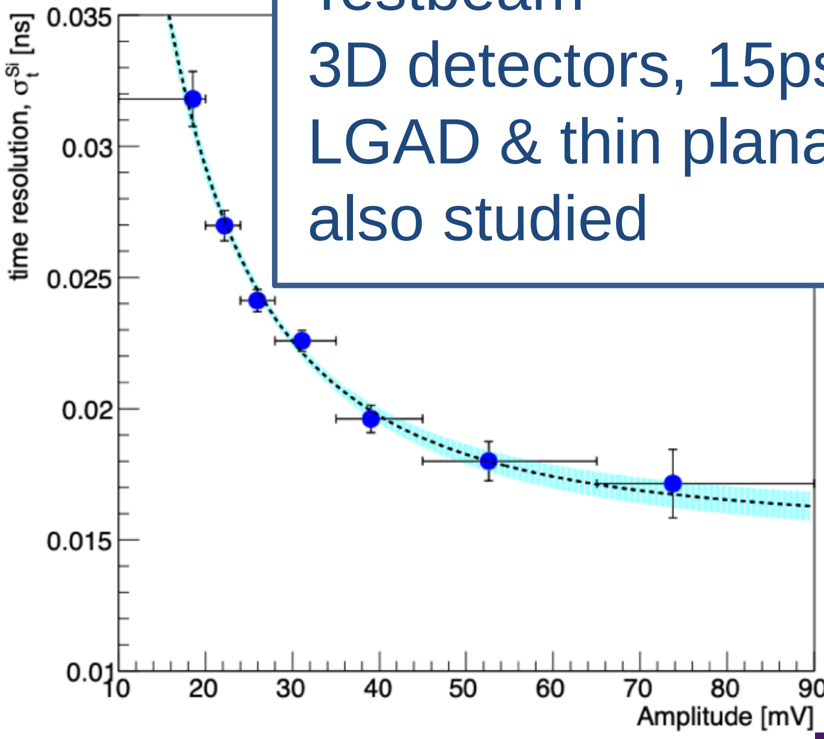


20ps time window





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

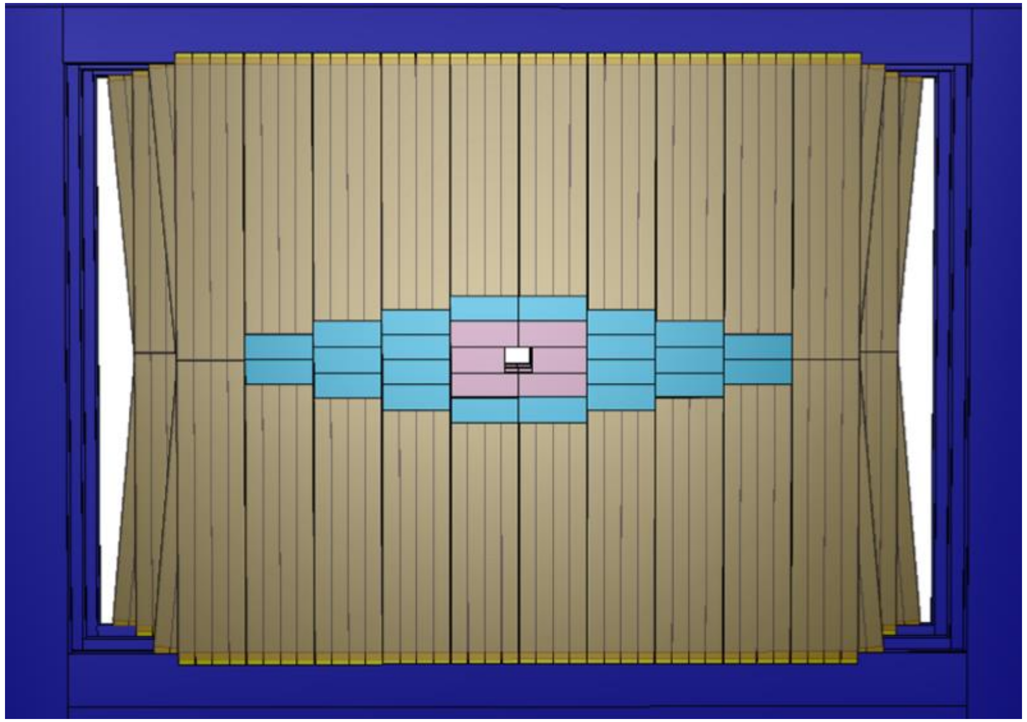


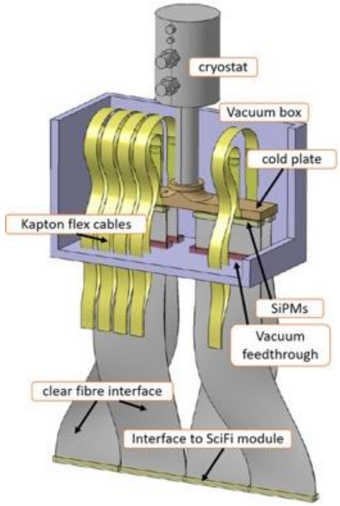
Testbeam
3D detectors, 15ps
LGAD & thin planar also studied

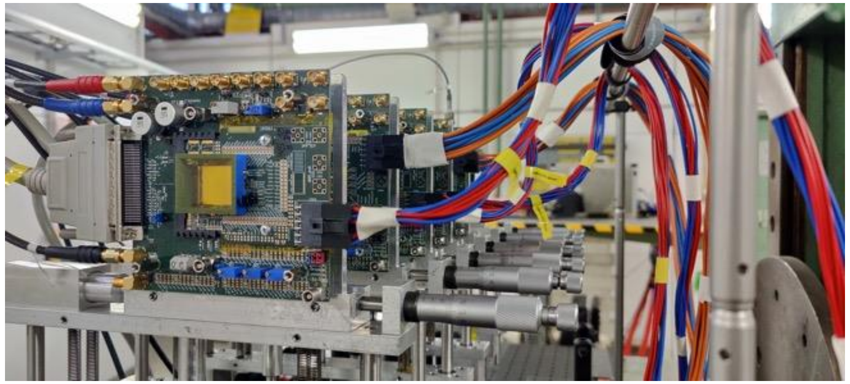
JINST 15 (2020) P09029

Tracker: Rad Hard DMAPs, first of kind at LHC

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







HVMAPS at testbeam