Flavour Physics at the start of a new era

The University of Manchester

Experiment Outlook

- Kaon
- Charm
- Beauty

"The Future"

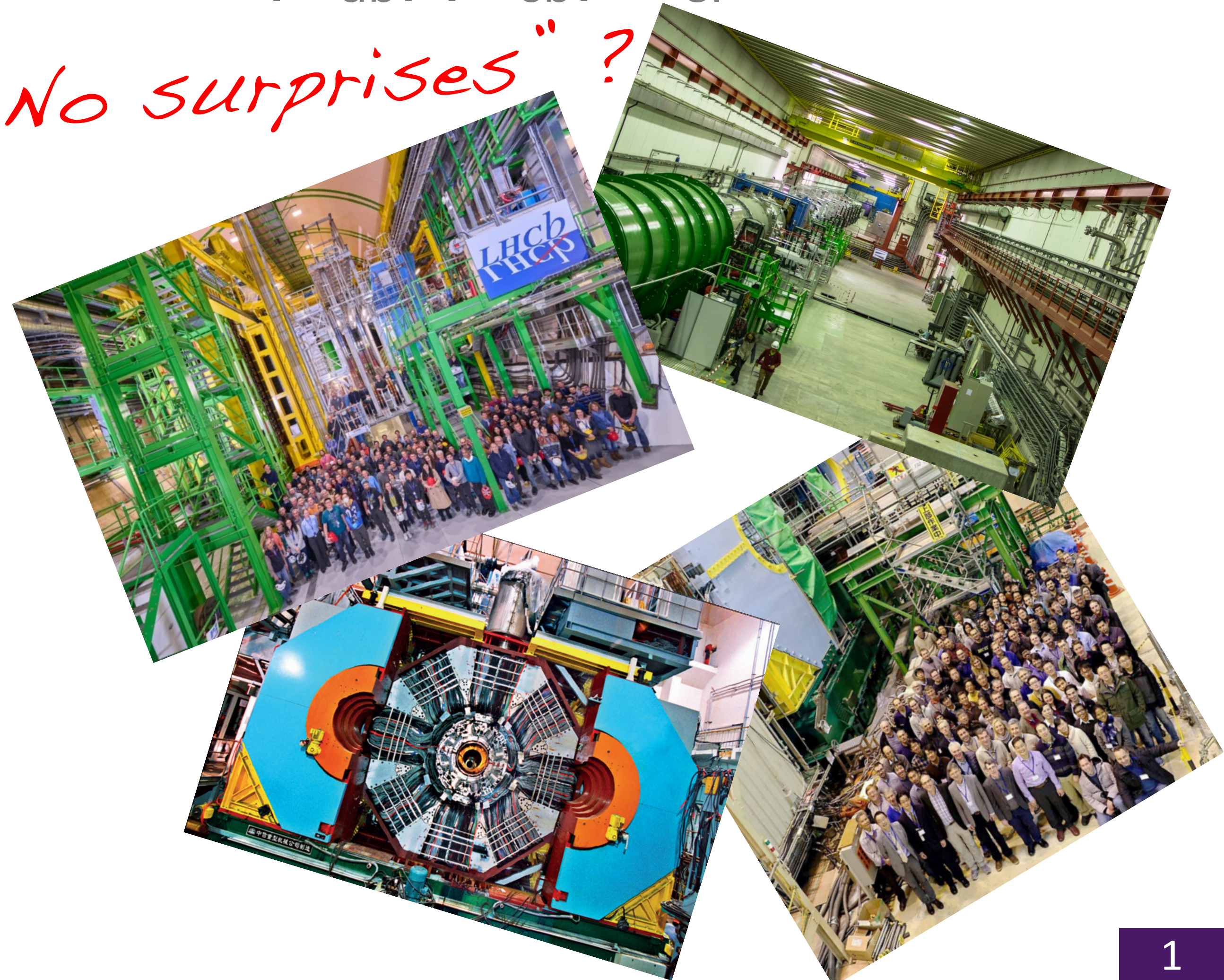
LHCb "Born to Run" 3

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

Semileptonic B-decays

- LFV, $|V_{ub}|/|V_{cb}|$, a_{sl}

"No surprises" ?



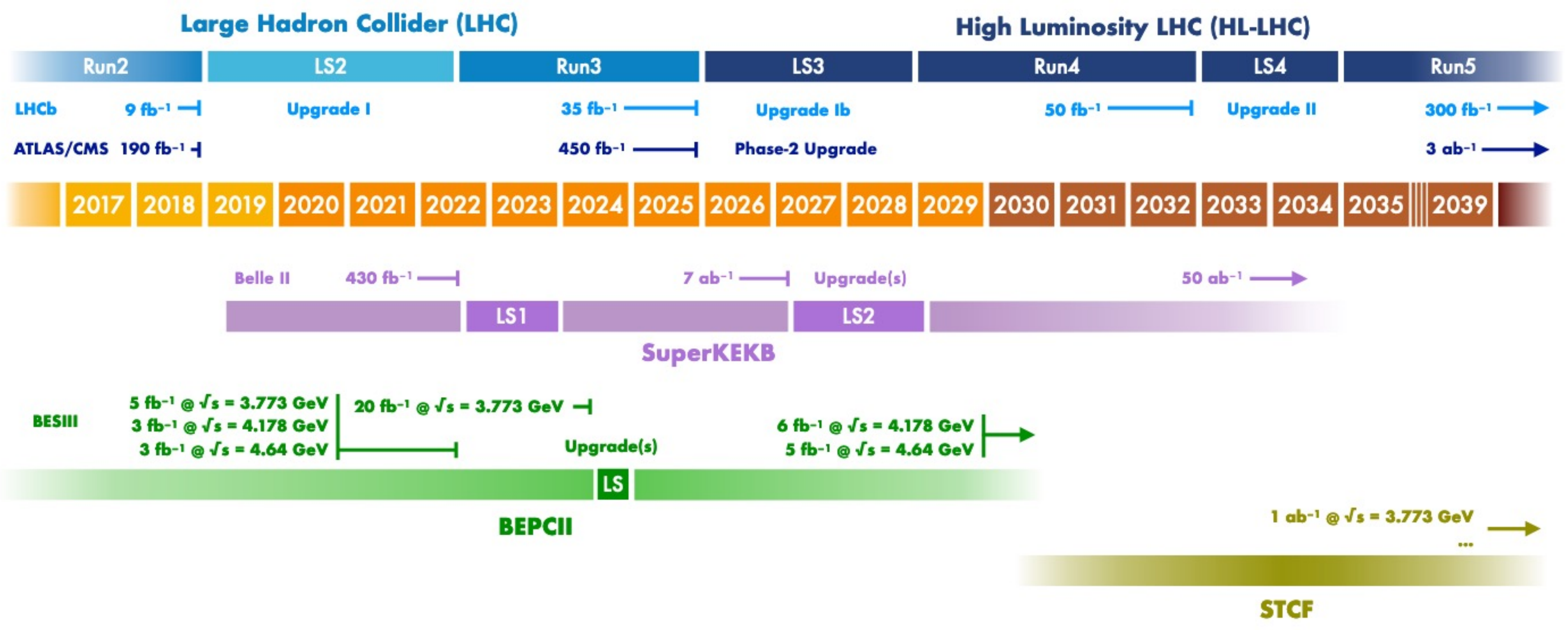
3rd August 2023, YETI, Durham

Chris Parkes

Flavour Physics at the start of a new era

Part 1: Experiment Outlook (other than LHCb)

- Kaons
- Charm
- Beauty

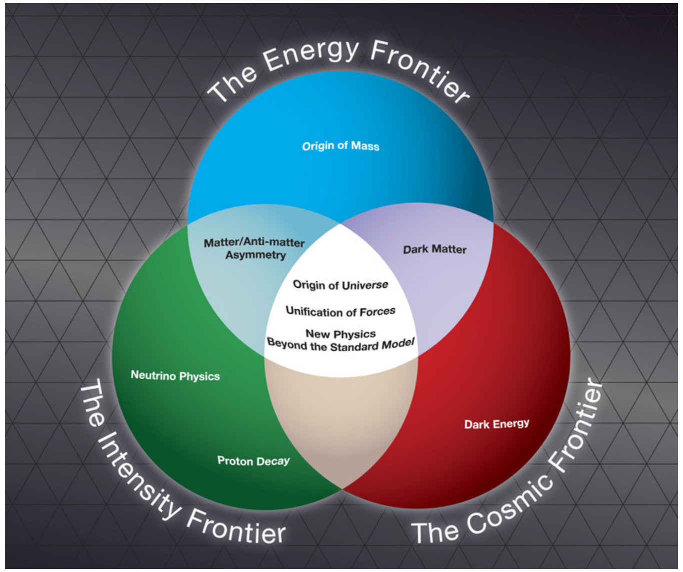


FCC-ee
>2045

"I've seen the future, brother, It is murder"

Chris Parkes

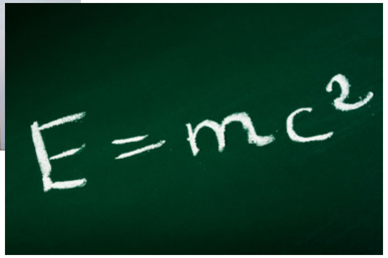
Flavour Physics



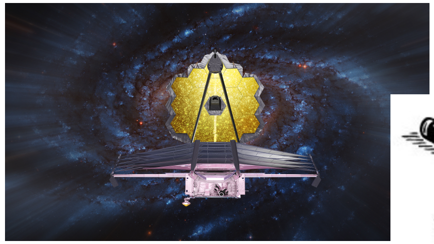
https://science.osti.gov/hep/About/Vision-for-HEP

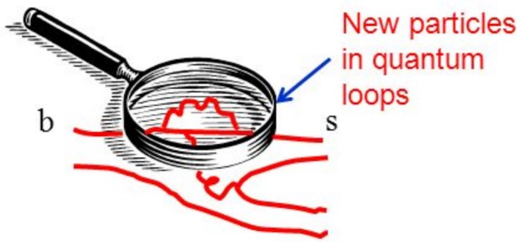
"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887



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

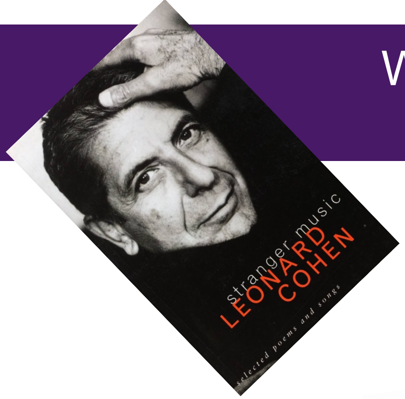


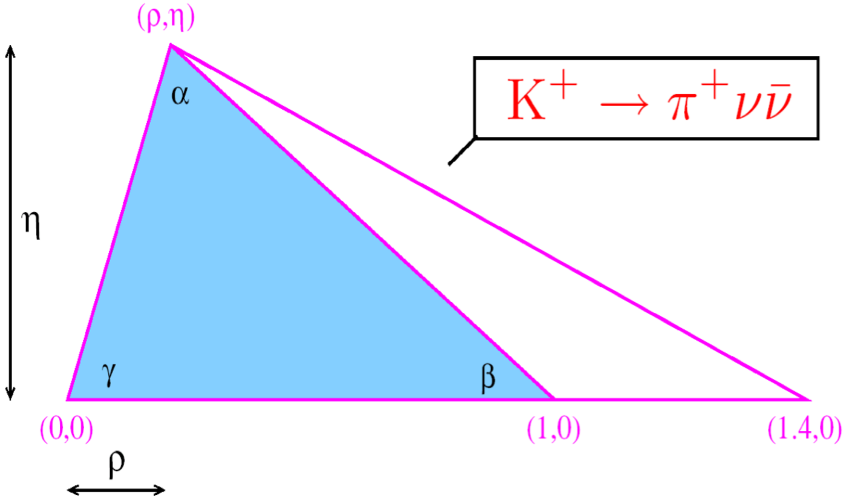


- **Intensity**
- Precision measurements and compare with theory

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

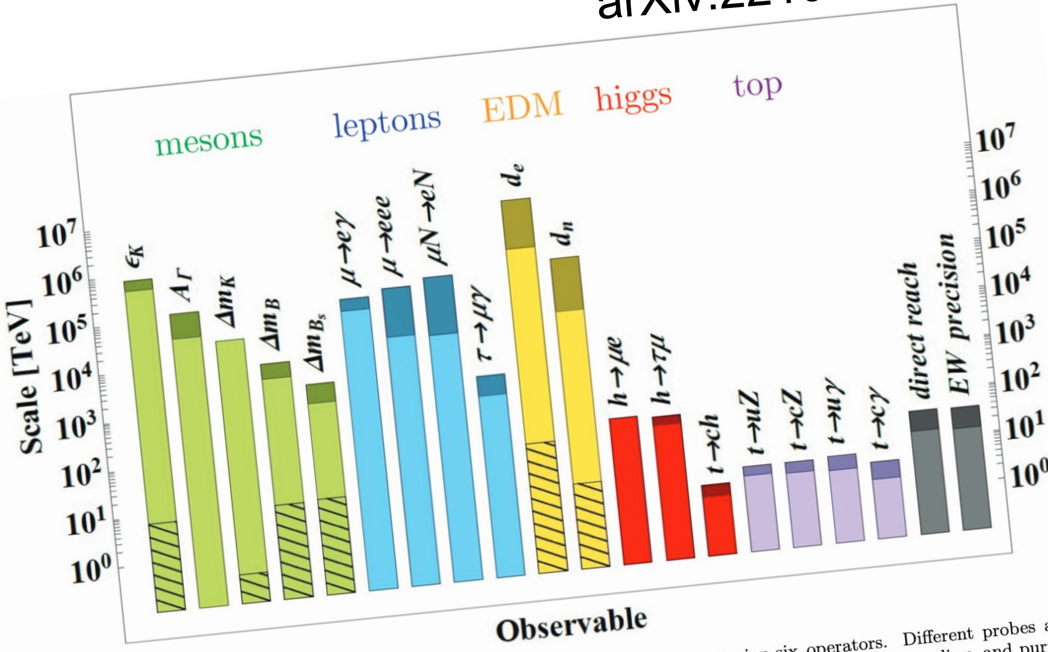
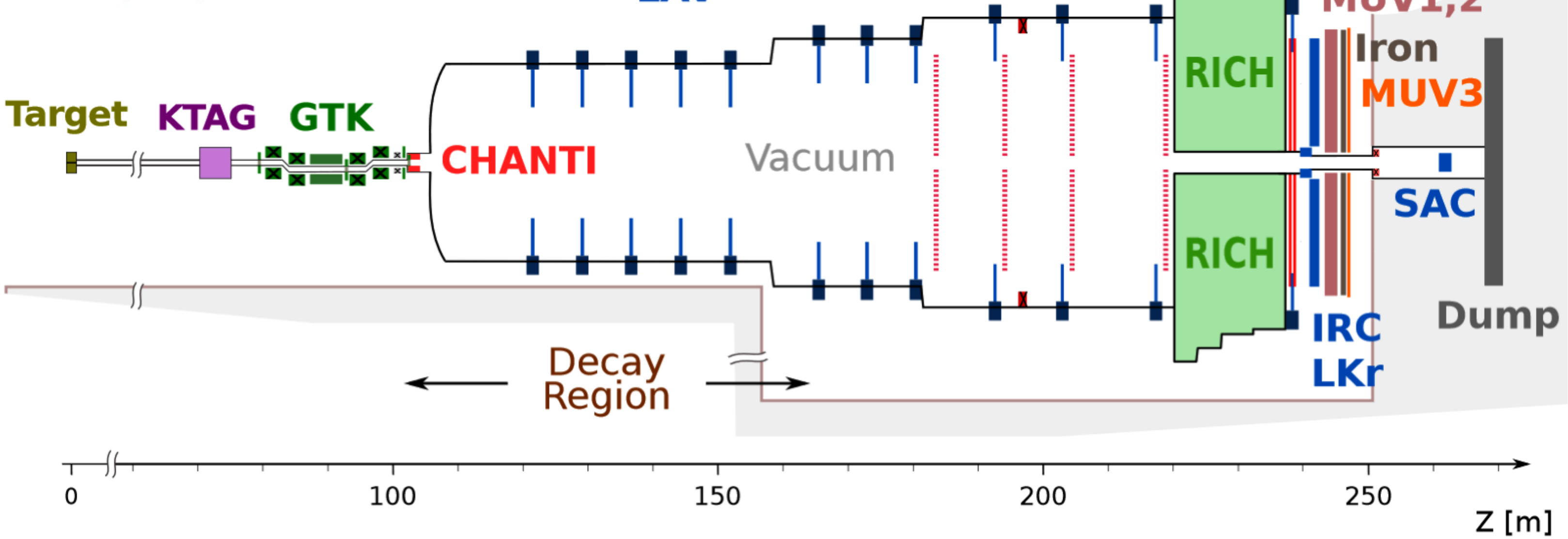


FIG. 1. Reach in new physics of present and future facilities, from generic dimension-six operators. Different probes are identified by color coding: green is for mesons, blue for leptons, yellow for EDMs, red for Higgs flavored coupling, and purple for the top quark. The grey columns illustrate the 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

NA62 collaboration,
JINST 12 (2017) P05025

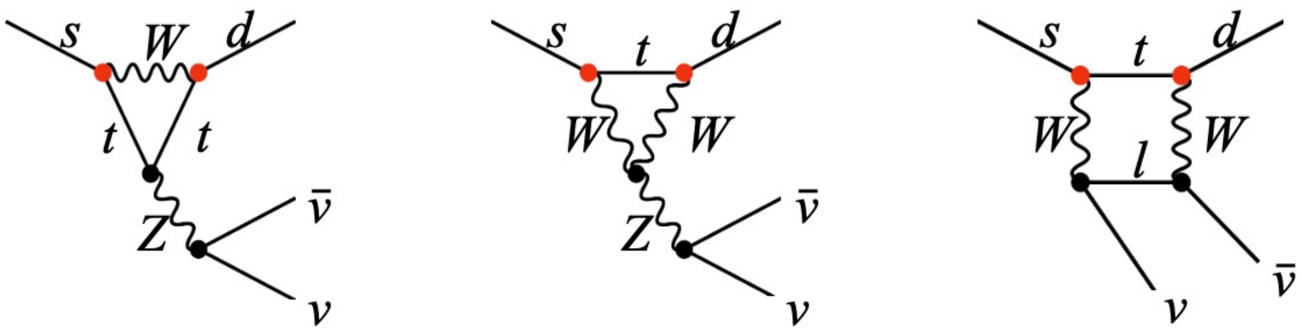


- K decay volume – hence 300m long !
- Kaons: KTAG – Cherenkov kaon tagger, GTK – silicon tracker
- Decay products – Straw tracker, RICH, Calorimeters

Kaons - NA62 at CERN. Physics Results & Aims

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

JHEP 06 (2021) 093

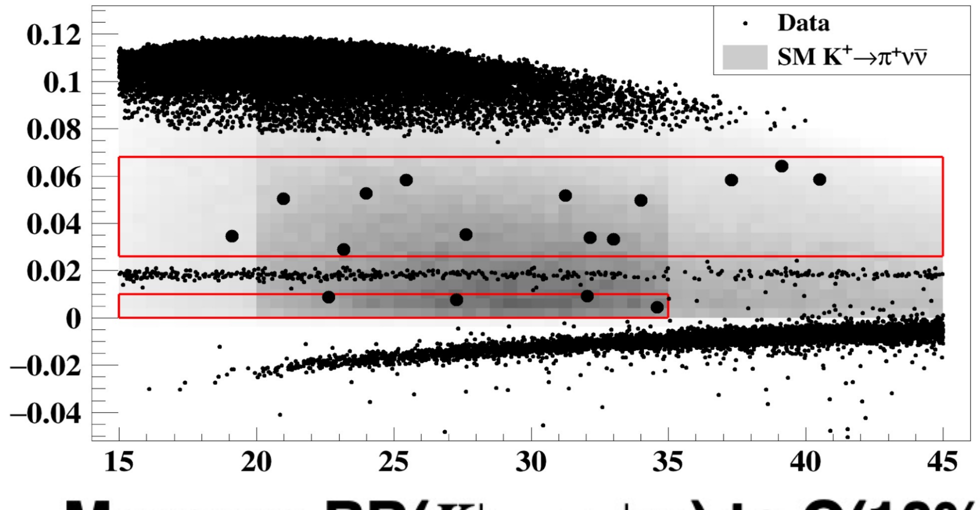


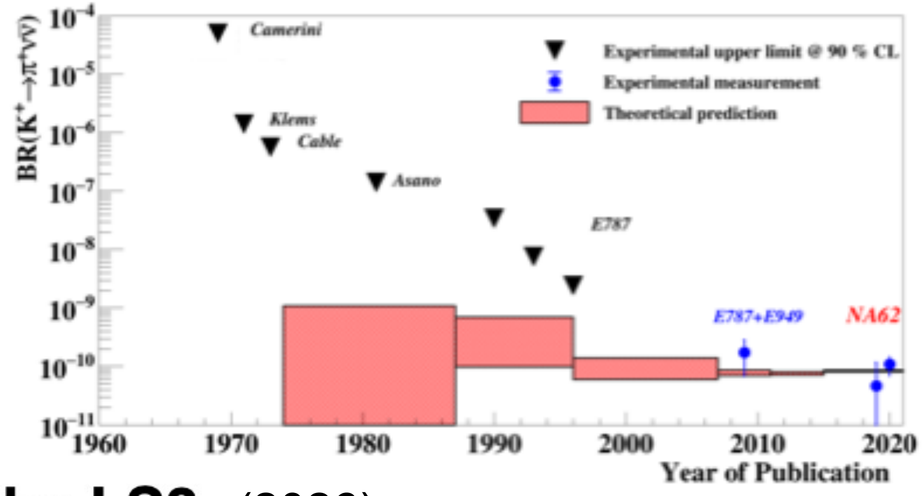
A high-order process with highest CKM suppression:

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

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

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





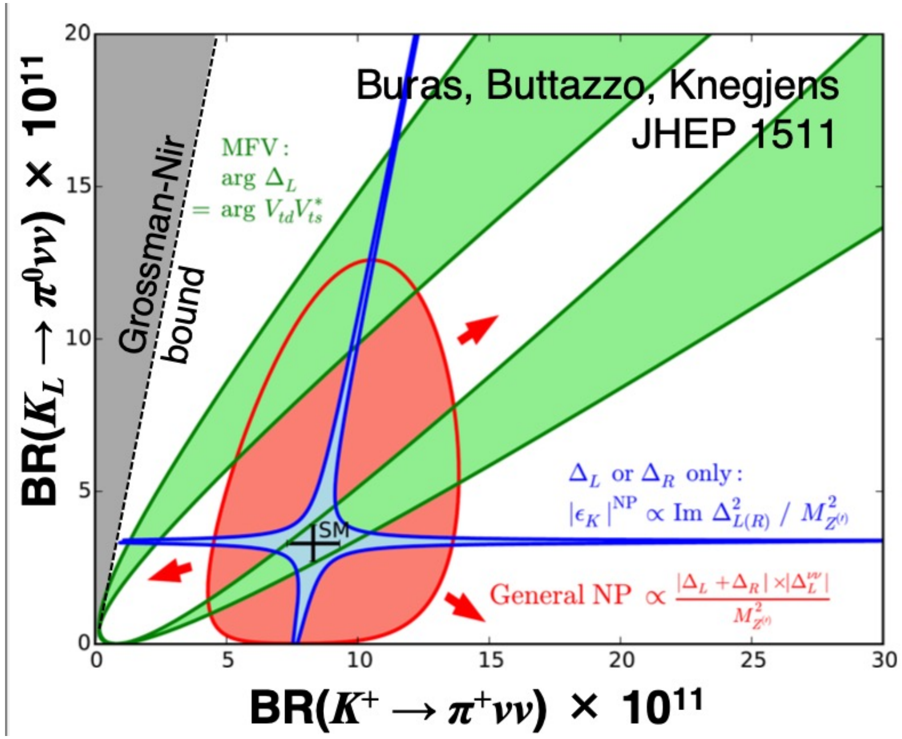
Measure $BR(K^+ \rightarrow \pi^+ \nu\nu)$ to O(10%) by LS3 (2026)

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

High Intensity Kaon Experiments



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum

Phase 1:

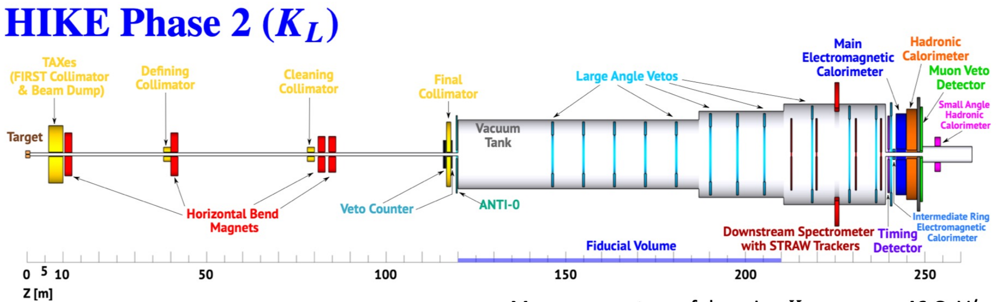
$B(K^+ \to \pi^+ \nu\bar{\nu})$ to O(5%) precision

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



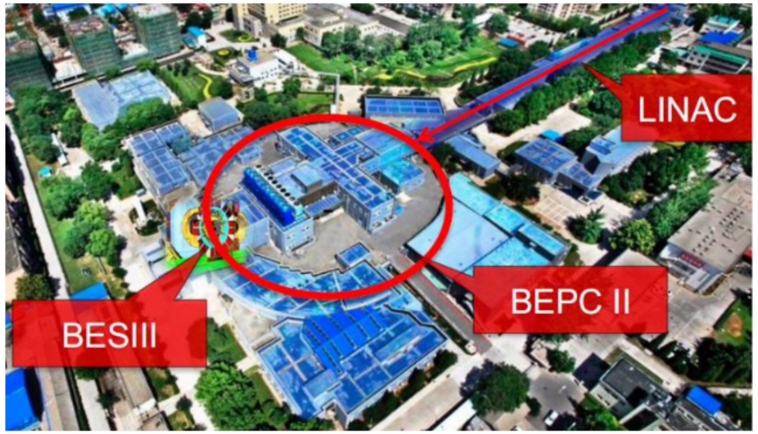
Mean momentum of decaying K_L mesons = 46 GeV/c

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

Charm dedicated facilities – BESIII at IHEP, Beijing

arXiv:1912.05983

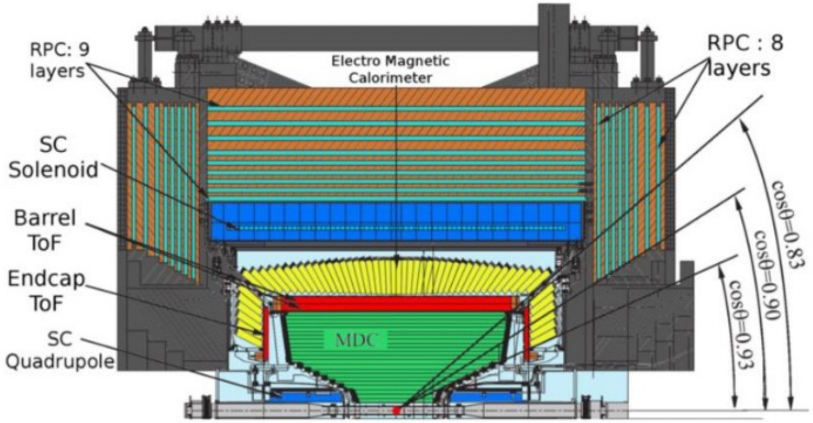
- LHCb dominates charm statistics and with boost -but **BESIII** has unique properties



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.



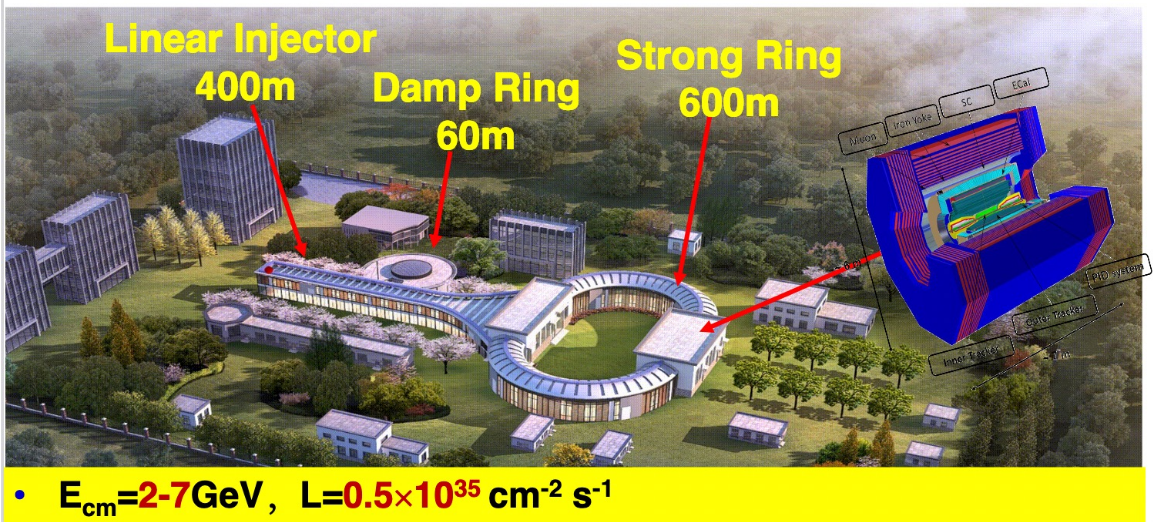
Hadron Spectroscopy and Exotic Hadrons

Nature of exotic hadrons much debated:

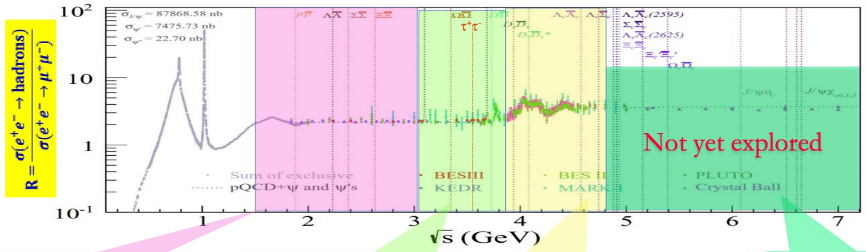
- Different production mechanism
- Low backgrounds

Charm dedicated facilities – Super Charm-Tau in China?

From Yangheng Zheng, Charm 2023 arXiv:2303.15790



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

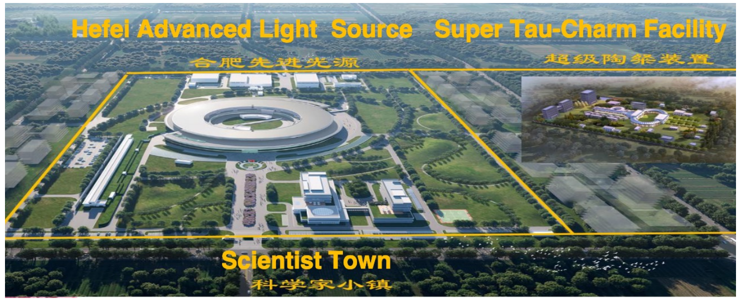


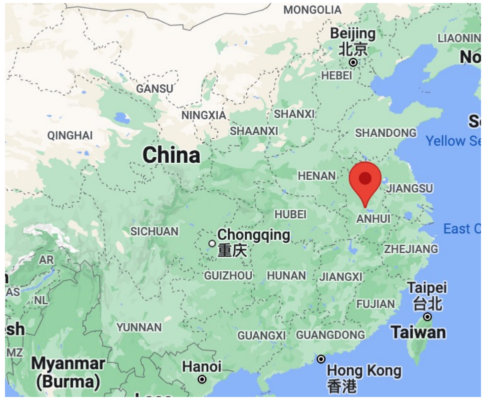
- Nucleon/Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

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

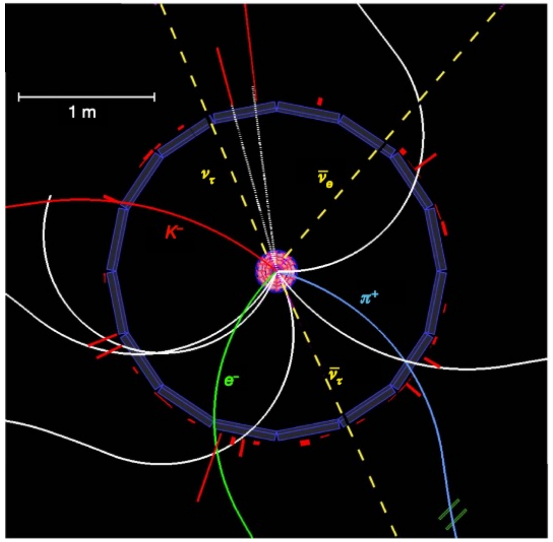
- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-$\bar{D}_0$ mixing
- Charm baryons

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



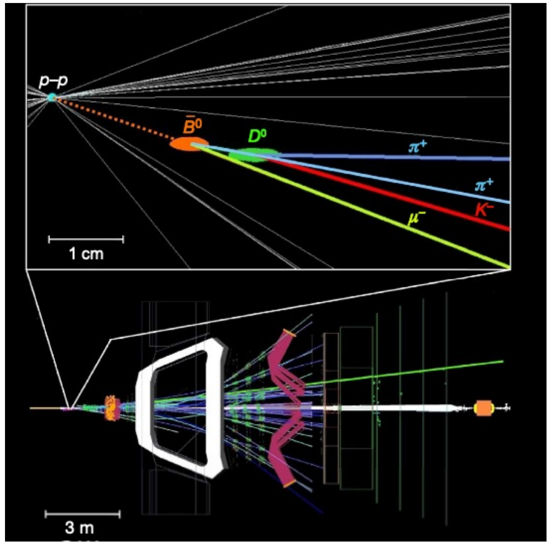


Beauty dedicated facilities – threshold e^+e^- or p-p



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

Belle II



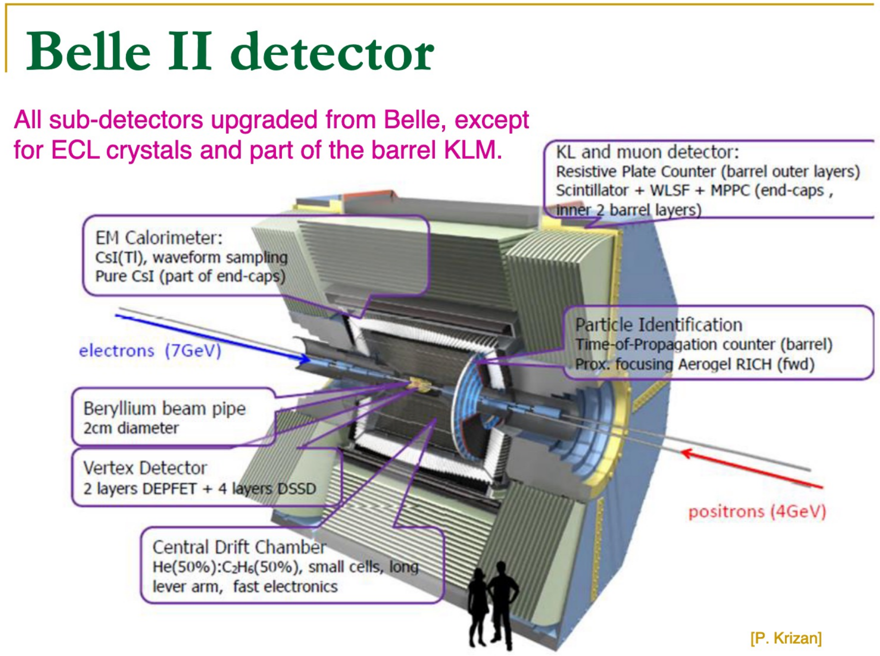
$$B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$$
$$D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$$
$$\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$$

LHCb

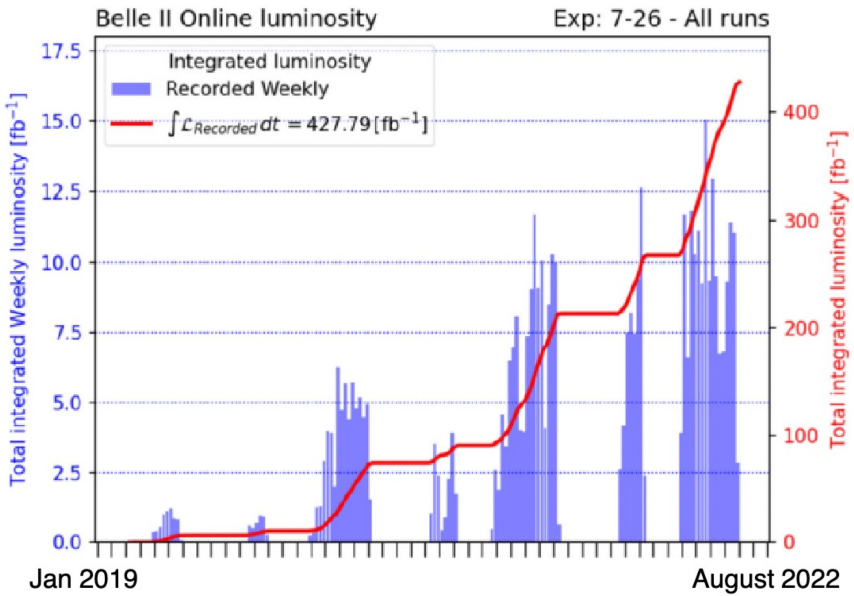
- Clean environment
  - no additional tracks
- Initial state
  - B^0B^0 or B^+B^-
- B mesons ~ 20% σ_{tot}
  - simpler triggering

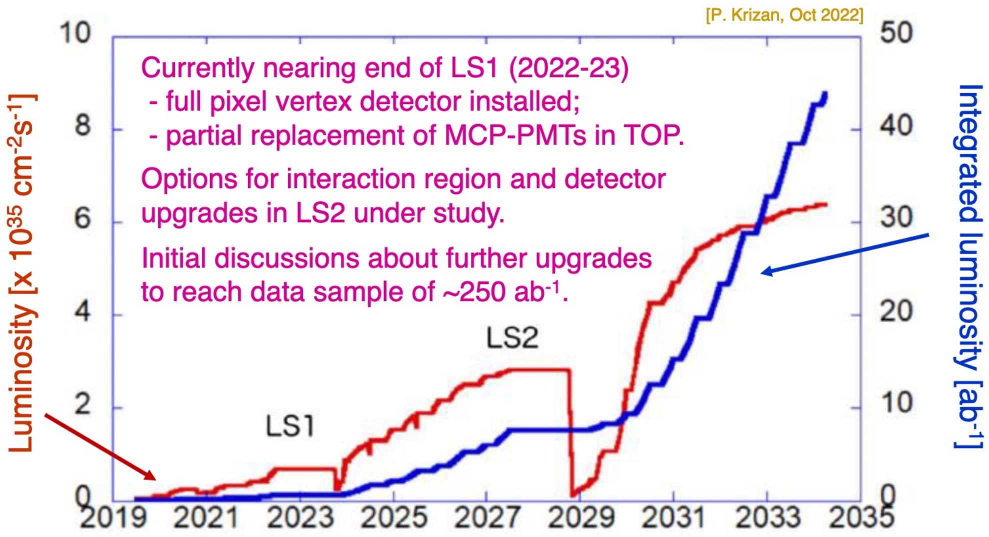
- Huge production rates
  - pp fb^{-1} ~ e^+e^- ab^{-1}
- All Beauty hadrons species
  - $B^0, B^+, B_s, B_c, \Lambda_b$
- Large boost factor
  - Time resolution

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 428 fb^{-1} (cf. Belle 710 fb^{-1})

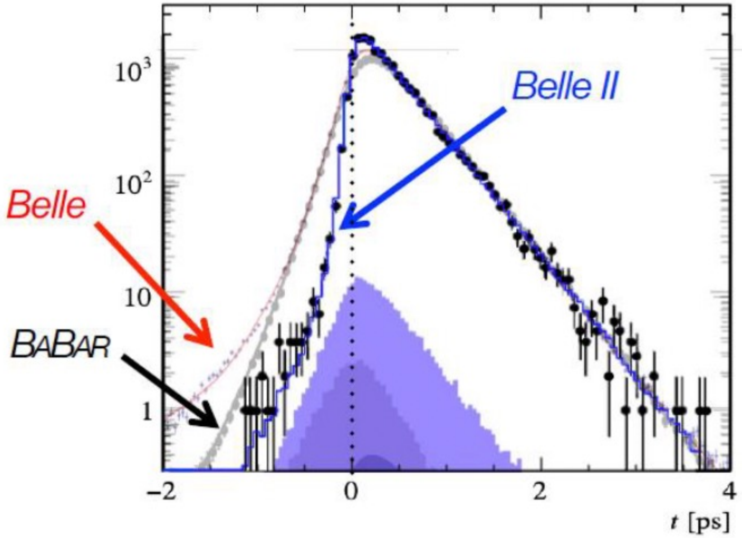




Beauty dedicated facilities – Belle II Results & Prospects

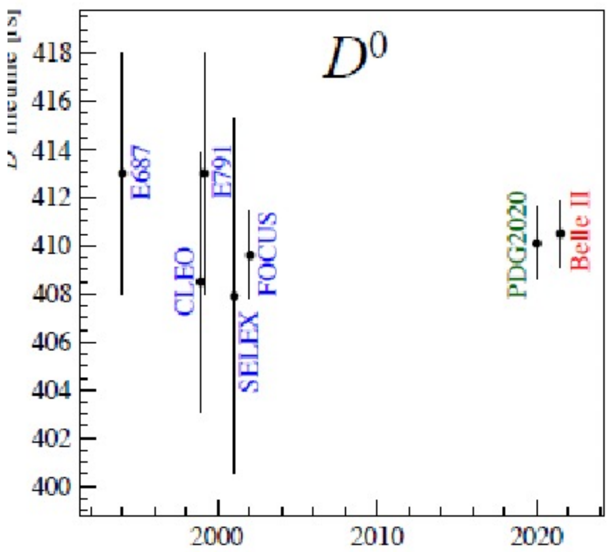
- Detector performance demonstrated
  - And full pixel detector installed in current shutdown
- Initial results with some world bests

Improved time resolution



D lifetime

[PRL 127 (2021) 211801]



Important calibration in CPV measurements

arXiv:1808.10567

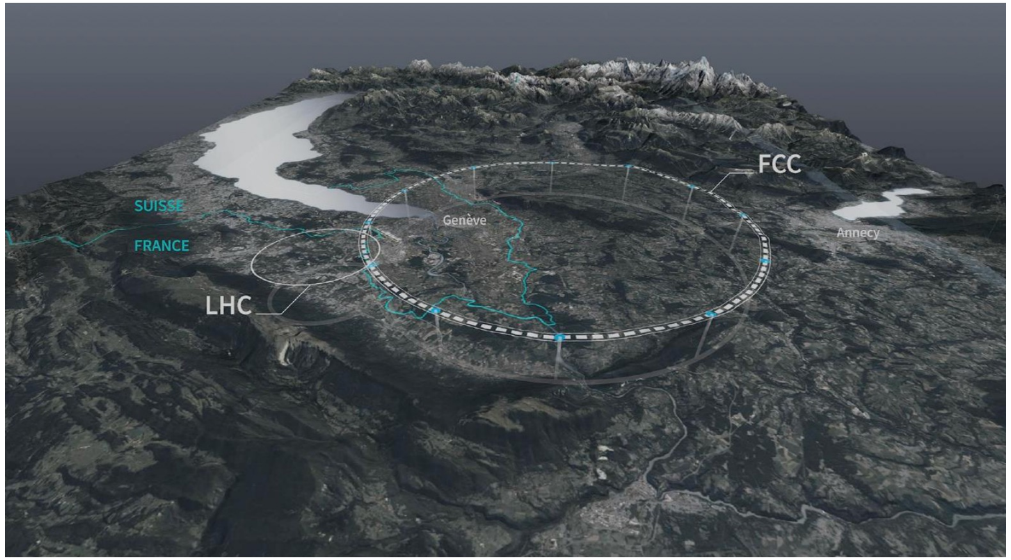
Observables	Expected the. accuracy	Expected exp. uncertainty
UT angles & sides		
ϕ_1 [°]	***	0.4
ϕ_2 [°]	**	1.0
ϕ_3 [°]	***	1.0
$\lvert V_{cb}\rvert$ incl.	***	1%
$\lvert V_{cb}\rvert$ excl.	***	1.5%
$\lvert V_{ub}\rvert$ incl.	**	3%
$\lvert V_{ub}\rvert$ excl.	**	2%
CP Violation		
$S(B \to \phi K^0)$	***	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
$S(B \to K_S^0\pi^0\gamma)$	***	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%
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	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:

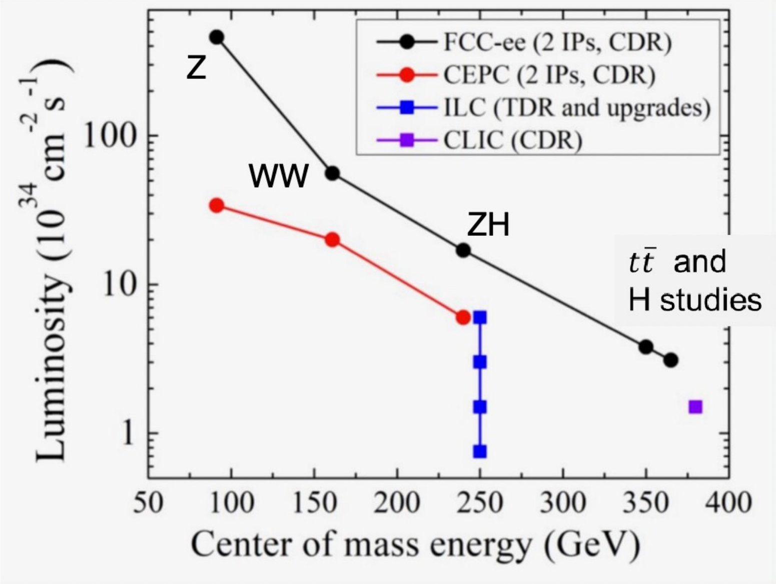
- States difficult at LHCb (e.g. neutrals)
- Similar projections on γ and semi-leptonics

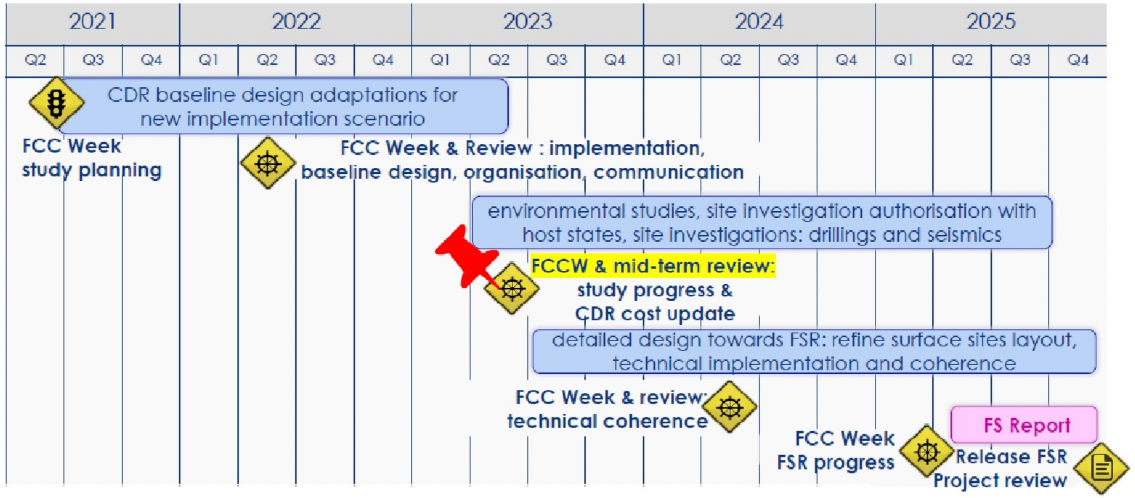
Flavour @ FCC-ee (or CEPC – very similar machine)



~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

Part 2: Semileptonic B-decay

Potential for surprises ?

- Lepton Flavour Violation
- CKM elements: $|V_{ub}|/|V_{cb}|$
- CP Violation in B mixing: a_{sl}

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

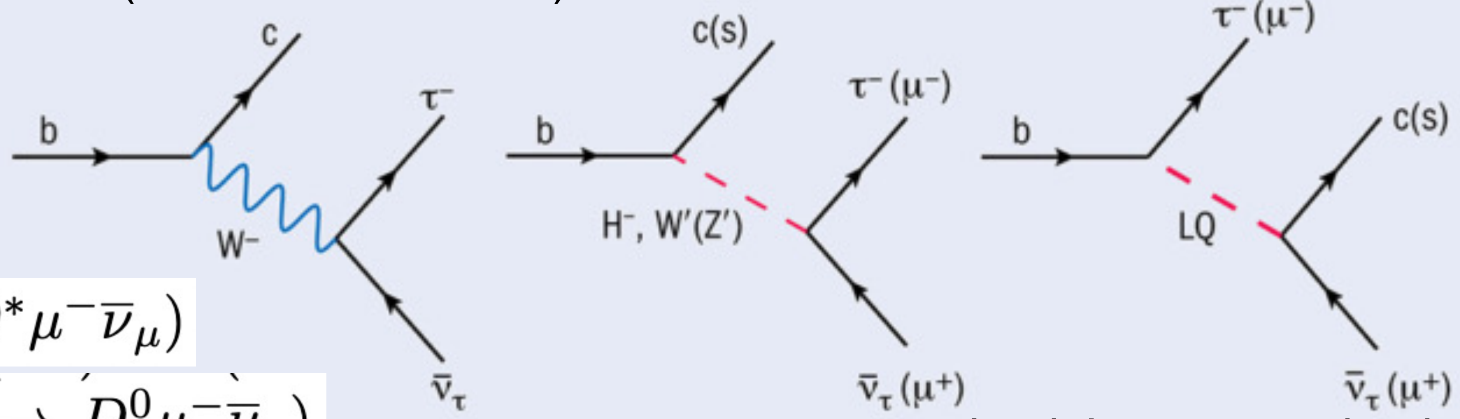
- "B anomalies" – several results in tension with standard model (SM)
- Including lepton flavour universality ratios in **semi-leptonic b→clv processes**
  - Couplings of electron, muon, tau expected to be same.
  - Difference in rates arising from masses of leptons

Evidence for an Excess of $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ Decays

J. P. Lees *et al.* (BABAR Collaboration)
Phys. Rev. Lett. **109**, 101802 – Published 6 September 2012

Taken together, our results disagree with these expectations at the 3.4σ level.

SM: (or electron or muon) New Physics, differ by lepton type

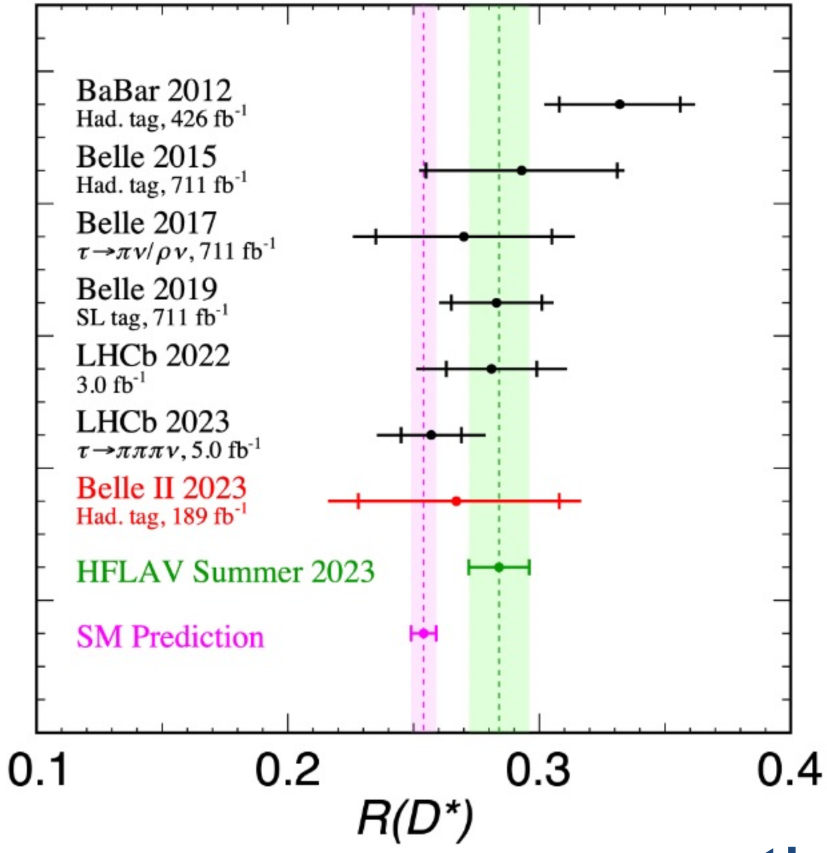


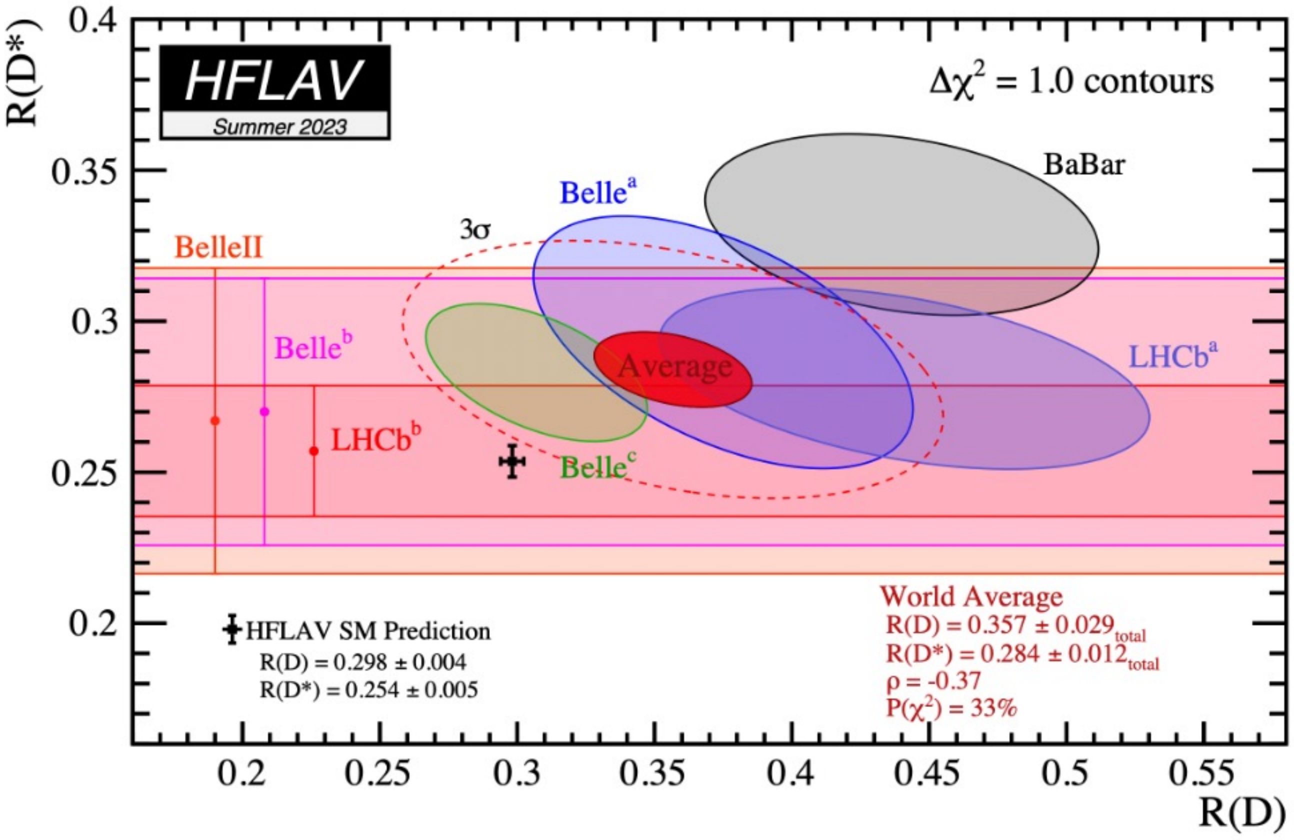
more constrained, less constrained

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

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

Key Topics: Lepton Flavour Universality b→clν





- Hot topic - Lots of activity ! 3.3 σ from SM
  - Belle II first result RD*, hadronic tag, leptonic tau decays, summer 2023
  - LHCb R(D*), hadronic tau decay, spring 2023
  - LHCb first combined R(D),R(D*), muonic tau decays, autumn 2023
- Previously largely dominated Belle/Babar, LHCb now major player

Prospects: Lepton Flavour Universality b→clν

One of most watched areas in particle physics

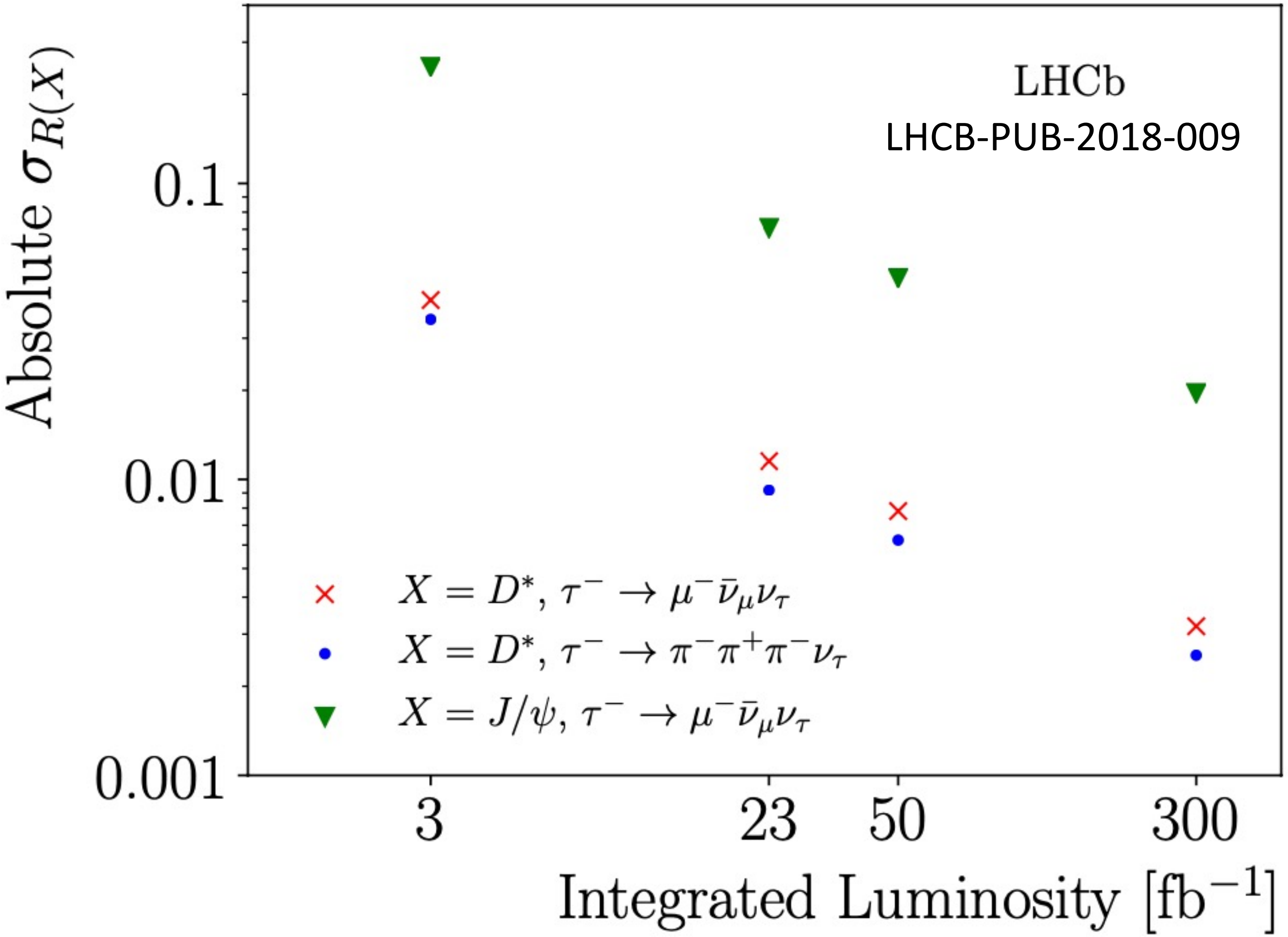
LHCb-PAPER-2022-039

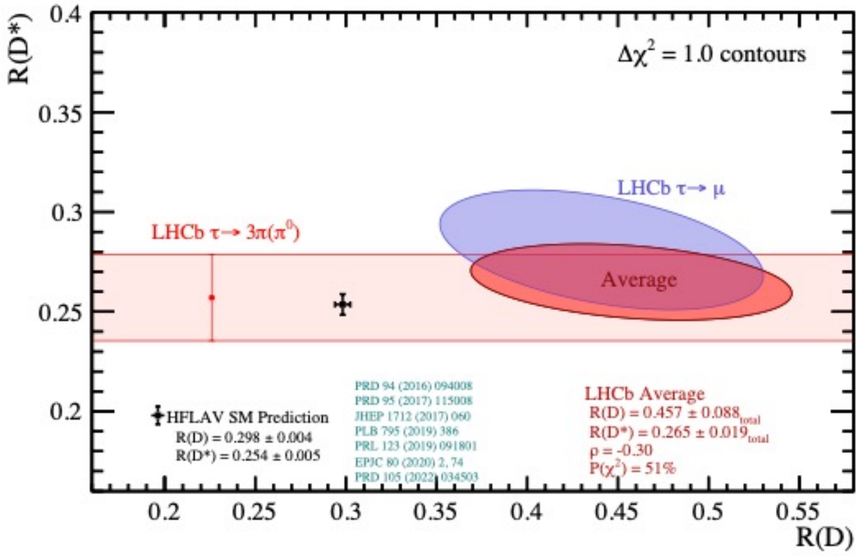
LHCb-PAPER-2023-052

La Thuile '23

Red band – LHCb hadronic tau result

Blue elipse – LHCb muonic result, October '22



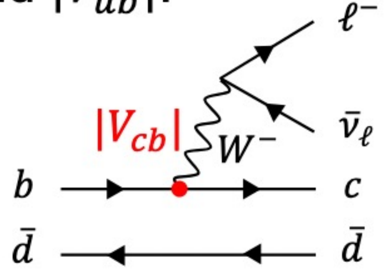


- LHCb Future results with full Run1&2 will give significant improvement in precision

Key Topics: $|V_{ub}|/|V_{cb}|$

Semileptonic B decays are studied to determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$.

- $|V_{xb}|$ are limiting the global constraining power of unitarity triangle fits.
- Important inputs in predictions of the SM rates of ultrarare decays, such as $B_s \to \mu\nu$ and $K \to \pi\nu\nu$.



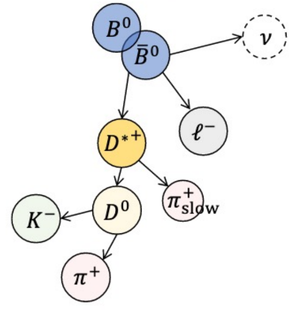
BUT situation confused due to two puzzles

- Form factor discrepancy with q^2
  - (LCSR and LQCD)

A longstanding discrepancy between inclusive and exclusive determinations is observed.

LHCb & Belle

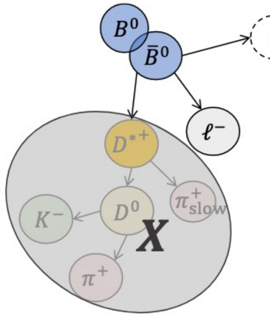
Exclusive



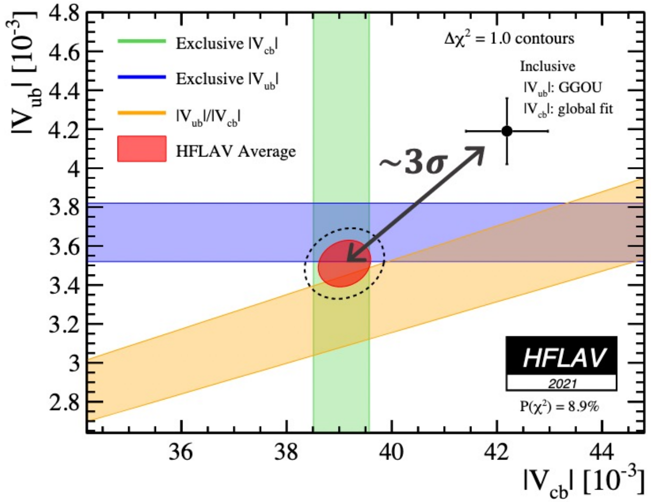
Reconstruct all daughters through specific channels exclusively.

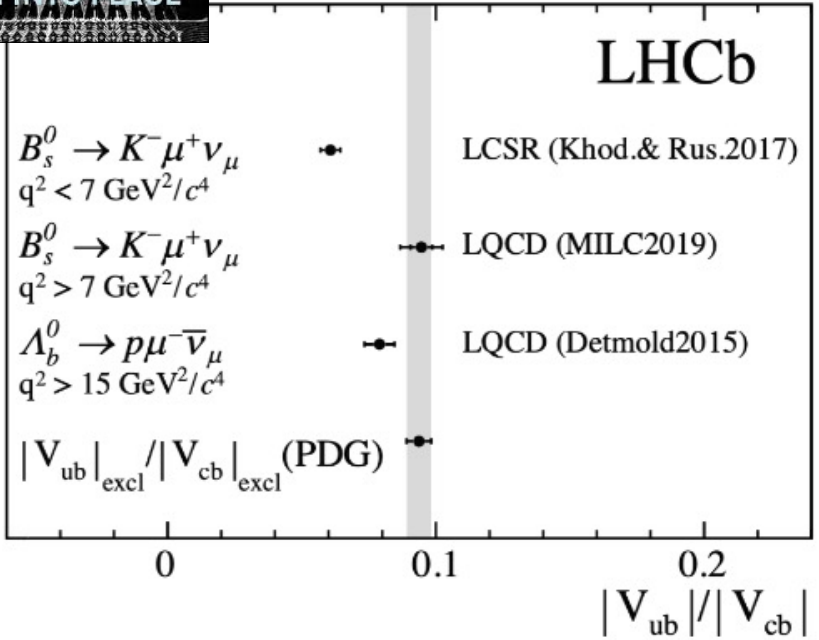
Belle

Inclusive



Reconstruct a lepton and assign other tracks and clusters as an inclusive daughter X.





The current experimental focus is on understanding the origin of this discrepancy.

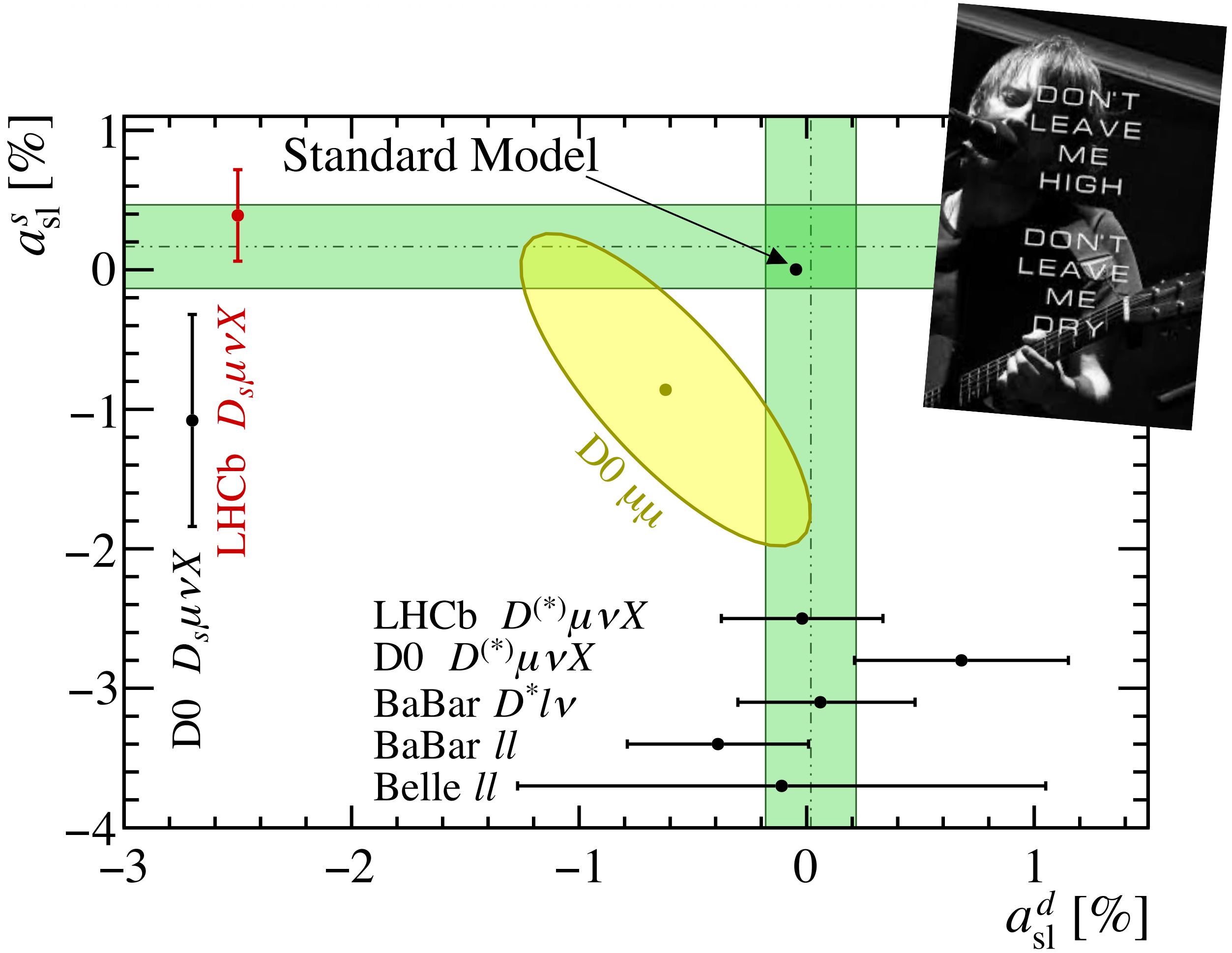
New analyses should cast light on these
e.g. $|V_{ub}|$ exclusive vs q^2, Belle Inclusive $|V_{ub}|/|V_{cb}|$

Longterm: 1% $|V_{ub}| / |V_{cb}|$ with LHCb Upgrade II

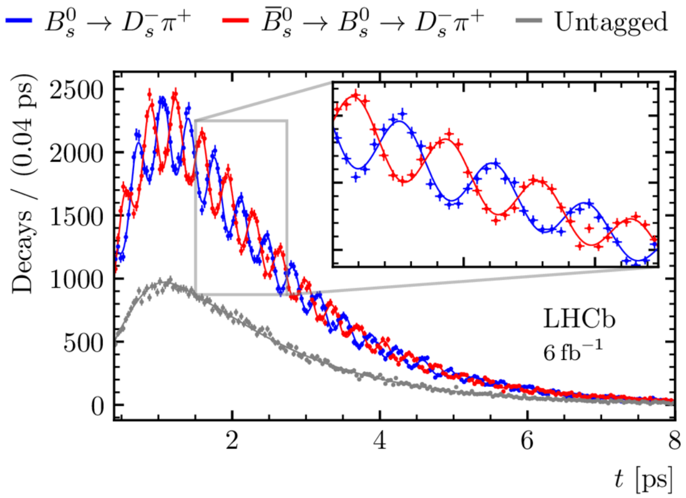
Key Topics: a_{sl} – CP asymmetry in B mixing

$$a_{sl} \equiv \frac{\Gamma\left(\overline{B}(t) \to f\right) - \Gamma\left(B(t) \to \bar{f}\right)}{\Gamma\left(\overline{B}(t) \to f\right) + \Gamma\left(B(t) \to \bar{f}\right)}$$

D0 Collaboration



- CP asymmetry in $B_{(s)}$ mixing
- No longer an anomaly but very sensitive to BSM effects – good place to look
- Current LHCb results based on Run 1 data



Prospects: a_{sl} – CP asymmetry in B mixing

$$a_{\rm sl} \equiv \frac{\Gamma\left(\overline{B}(t)\to f\right)-\Gamma\left(B(t)\to \bar{f}\right)}{\Gamma\left(\overline{B}(t)\to f\right)+\Gamma\left(B(t)\to \bar{f}\right)}$$

- B_s system not accessible at Belle II, B_d is but LHCb likely to dominate precision

- LHCb – Run 2 results will be a highlight of coming period.

- Control systematic uncertainties – e.g. detection asymmetries

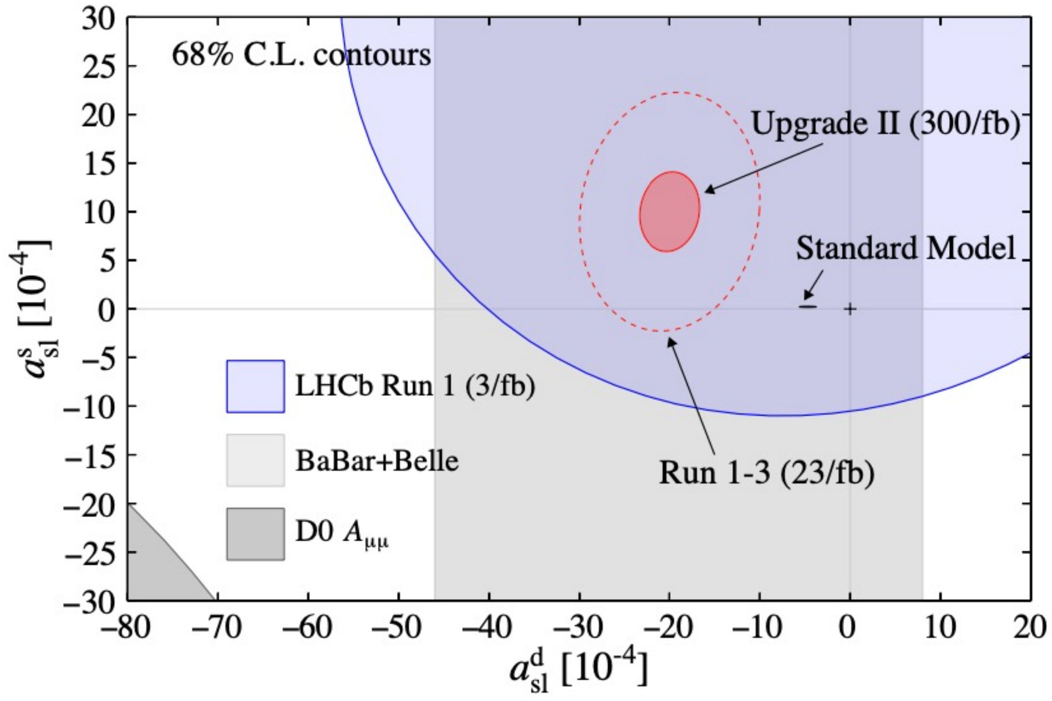
Sample ($\mathcal{L}$)	$\delta a^s_{sl} [10^{-4}]$	$\delta a^d_{sl} [10^{-4}]$
Run 1 (3 fb^{-1}) [210, 211]	33	36
Run 1-3 (23 fb^{-1})	10	8
Run 1-3 (50 fb^{-1})	7	5
Run 1-5 (300 fb^{-1})	3	2
Current theory [34, 200]	0.03	0.6

PRL 105, 081801 (2010) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS week ending 20 AUGUST 2010

Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

D0 Collaboration

LHCb current and long term expectation - LHCb-PUB-2018-009



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

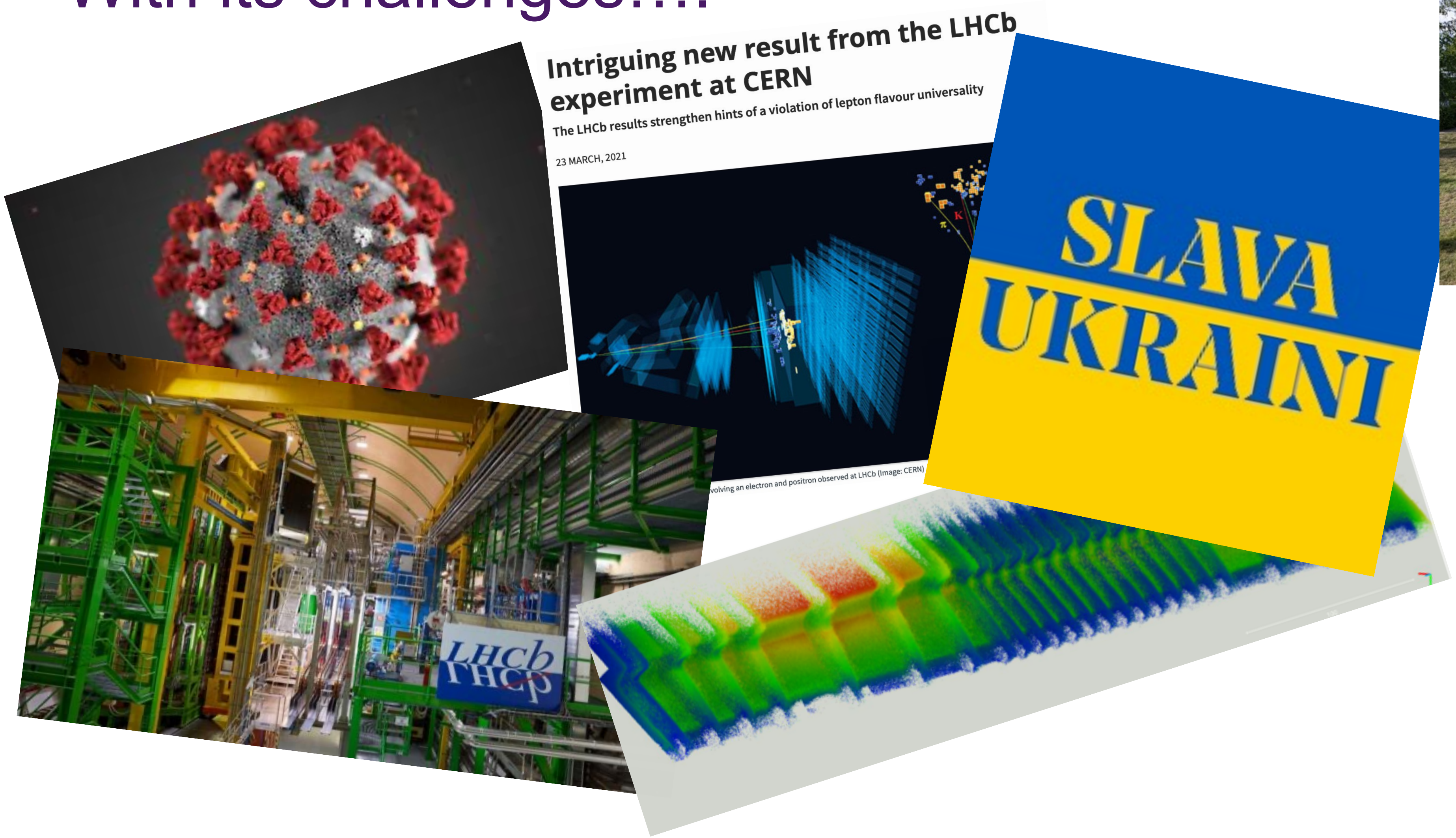
Part 3: "*Born to Run*" 3: LHCb at the start of a new era

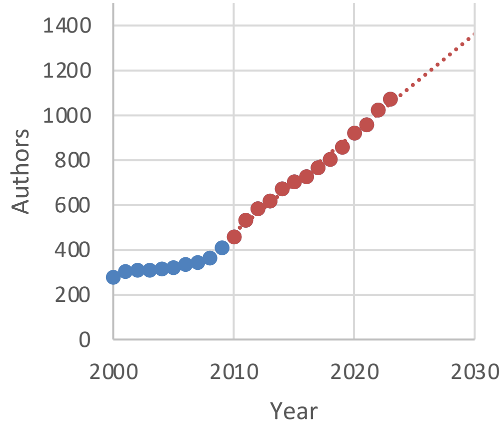
- Recent Physics Highlights
- LHCb Upgrade I Status
- LHCb Upgrade II Opportunities

Chris Parkes

2020-2023: Three special years…

With its challenges….





1100 authors,
96 institutes,
21 countries

And its successes….

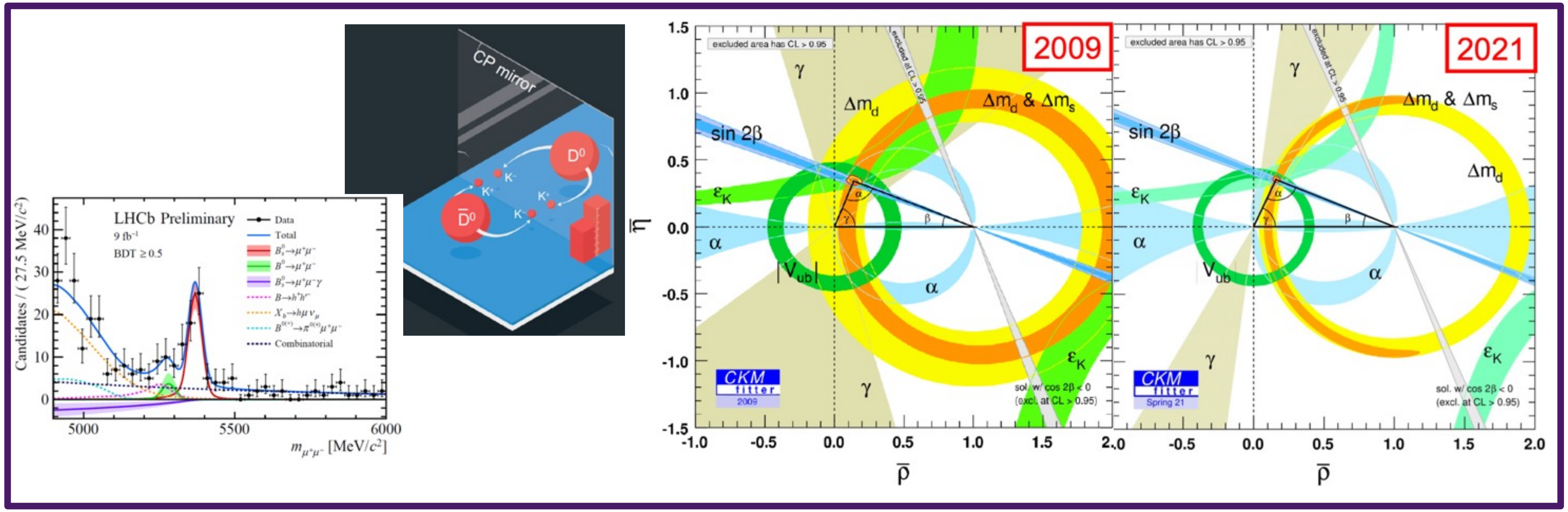
LHCb Original – LHC Run 1&2

Original

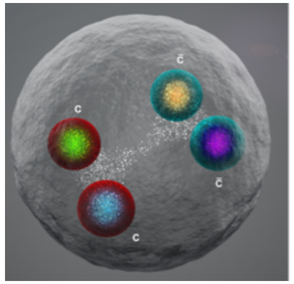
2009-2018

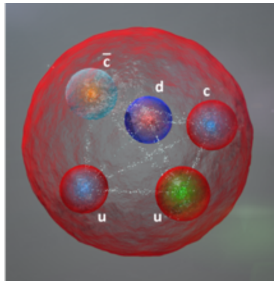
Celebrating “LHCb-original"!

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



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





Today recent results on

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

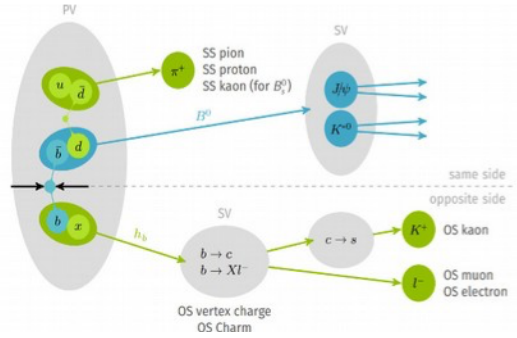
Sin(2β) – full LHCb data

LHCP ‘23 LHCb-PAPER-2023-013

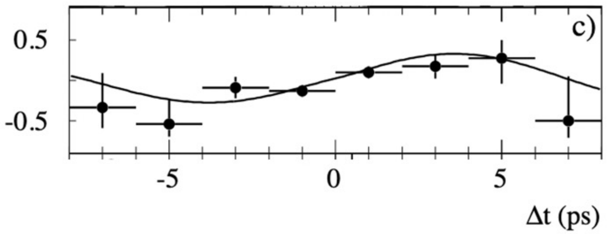
- obtained by the “golden mode” $B^0 \rightarrow J/\psi K^0$

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

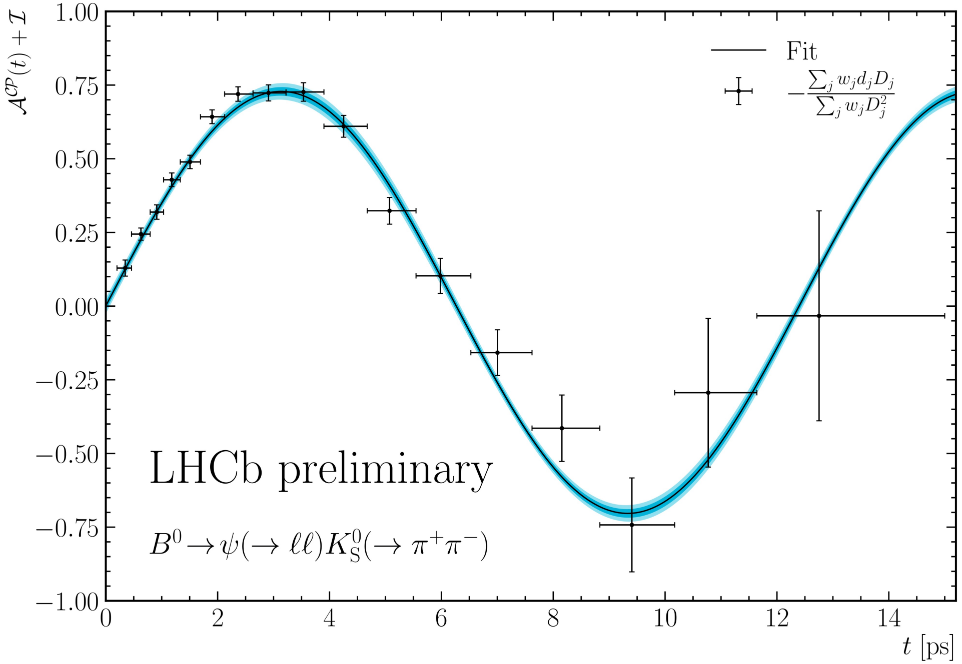
Flavour Tagging

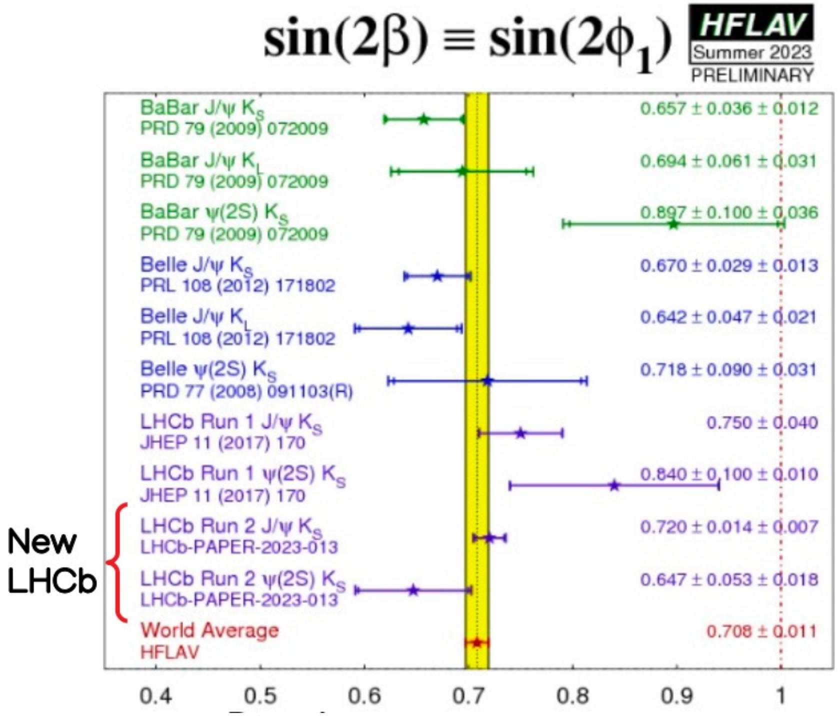


Belle 2001



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





- 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

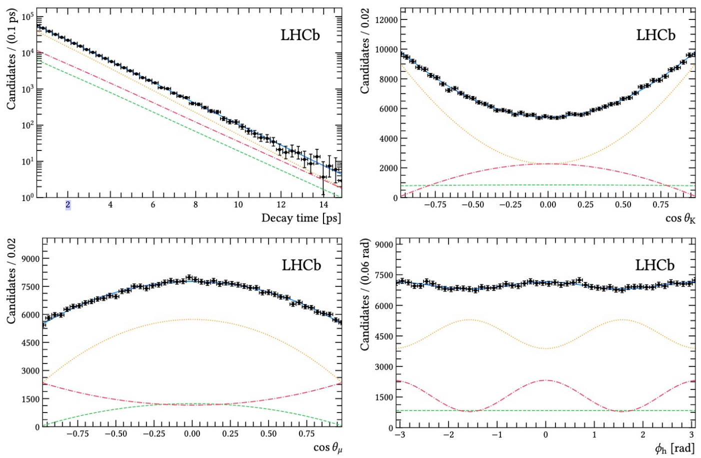
- Obtained by the "golden mode" $B^0 \rightarrow J/\psi K^+K^-$
  - Similar role to β but for B_s system – not accessible Belle

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

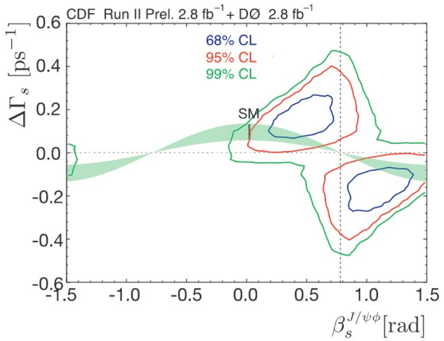
Run2: LHCb ϕ_s = -0.039±0.022±0.006 rad

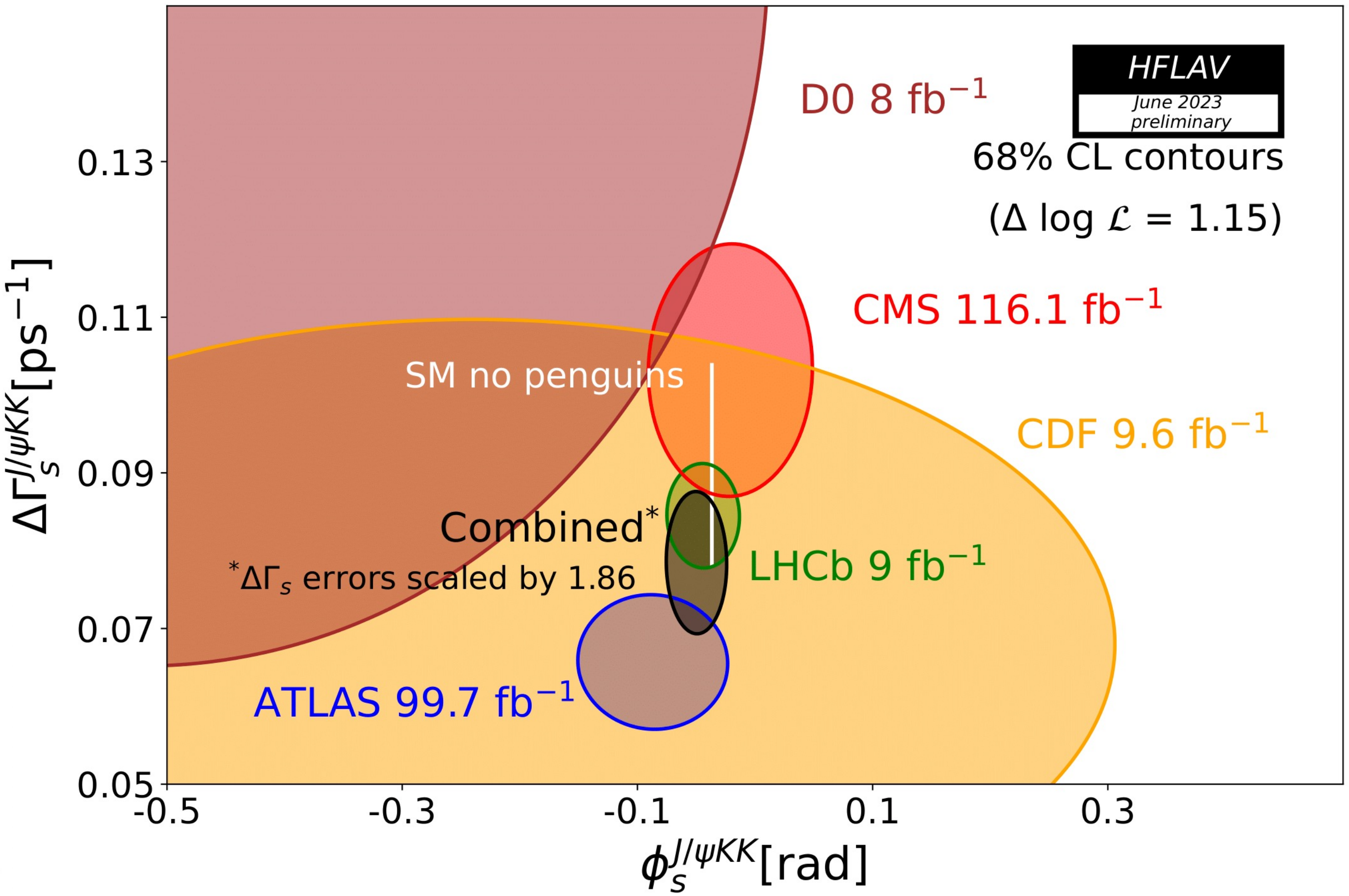
Time-dependent and angular analysis – separate CP even and odd components

CP-even
CP-odd
S-wave



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

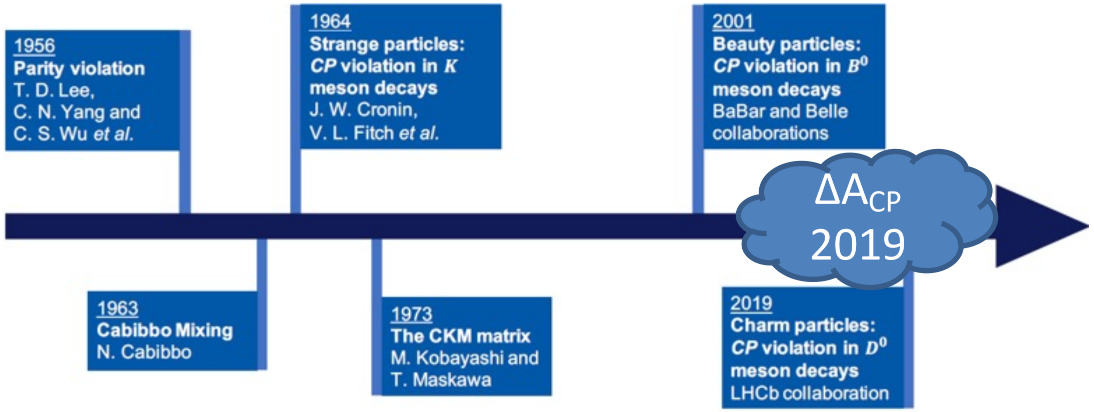


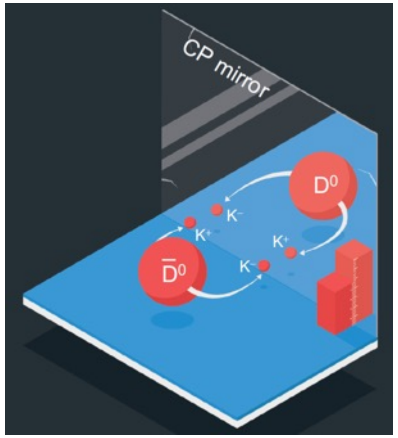


First evidence Charm CP Violation in specific decay

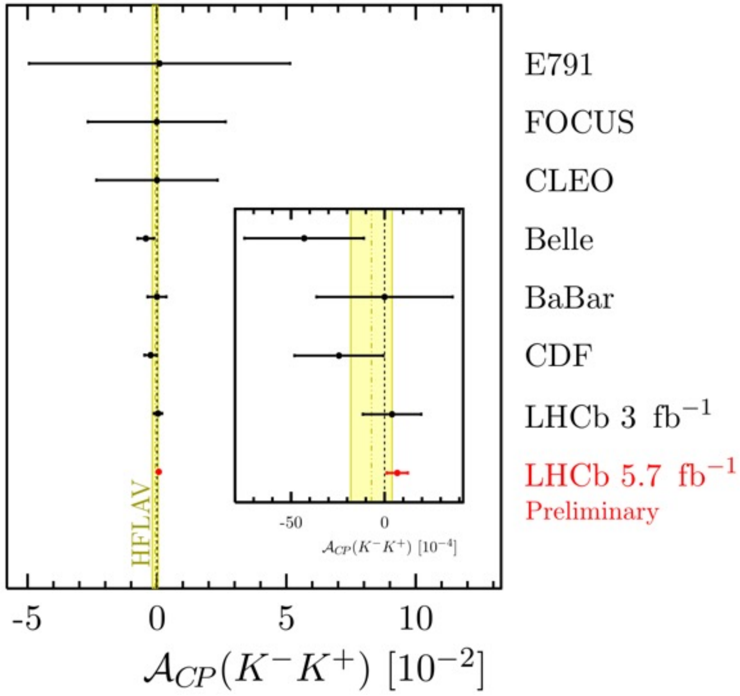
ICHEP '22

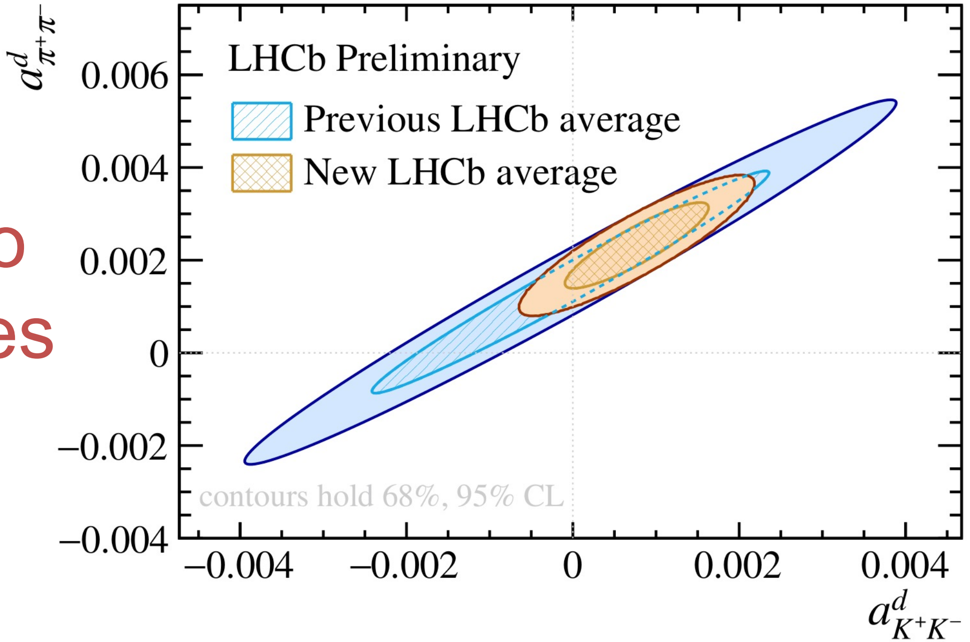
LHCb-PAPER-2022-024





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





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

LHCb-PAPER-2022-045/046

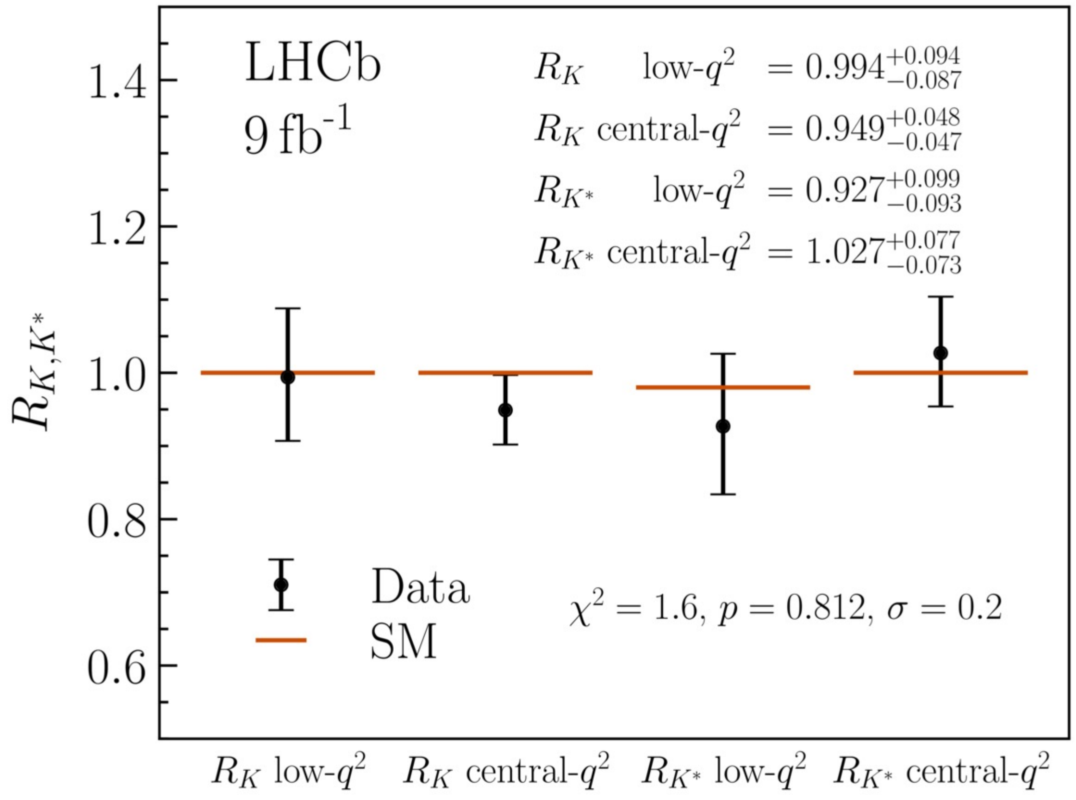
December '22

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

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

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

- 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



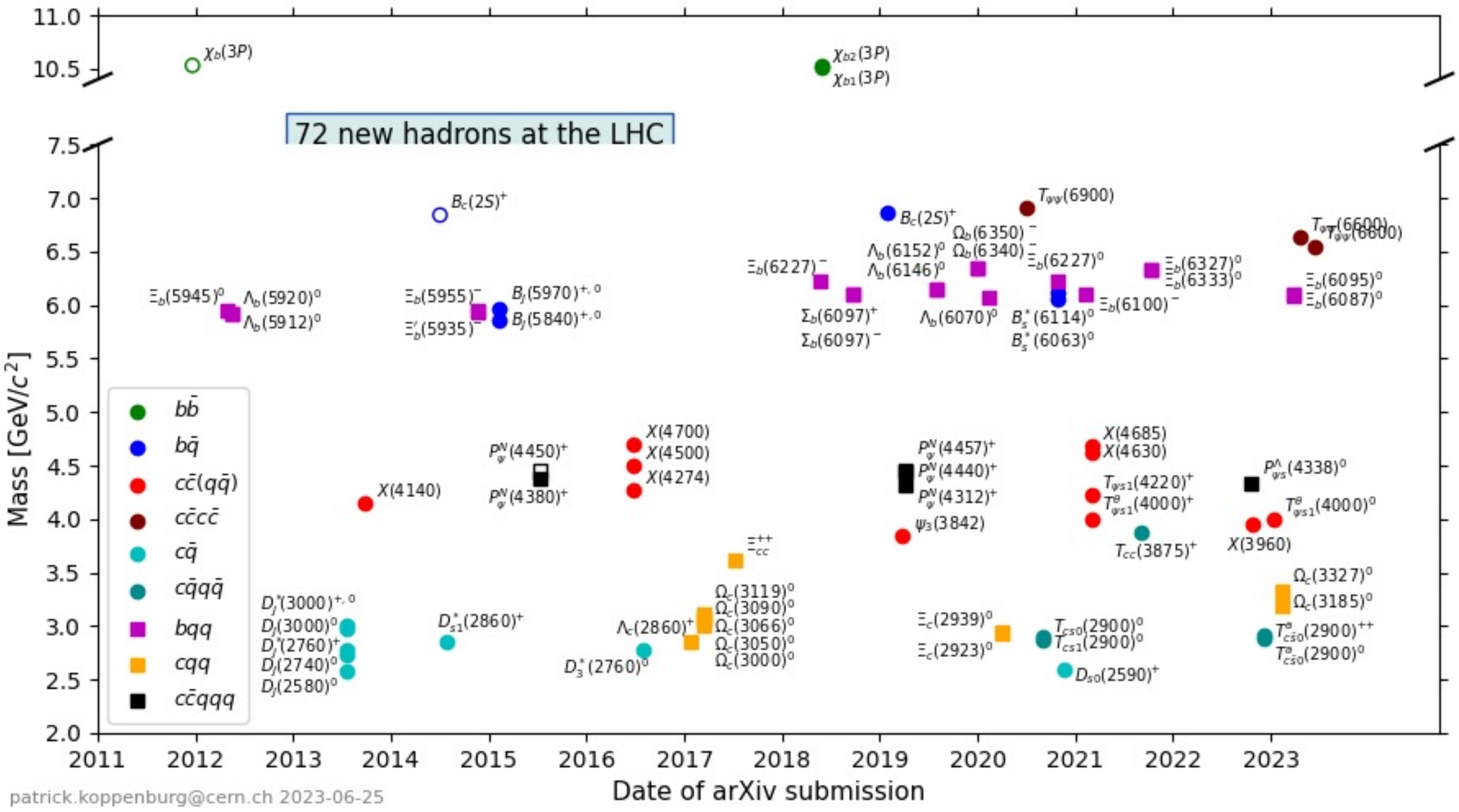
Measurement of lepton universality parameters in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. D **108**, 032002 – Published 2 August 2023

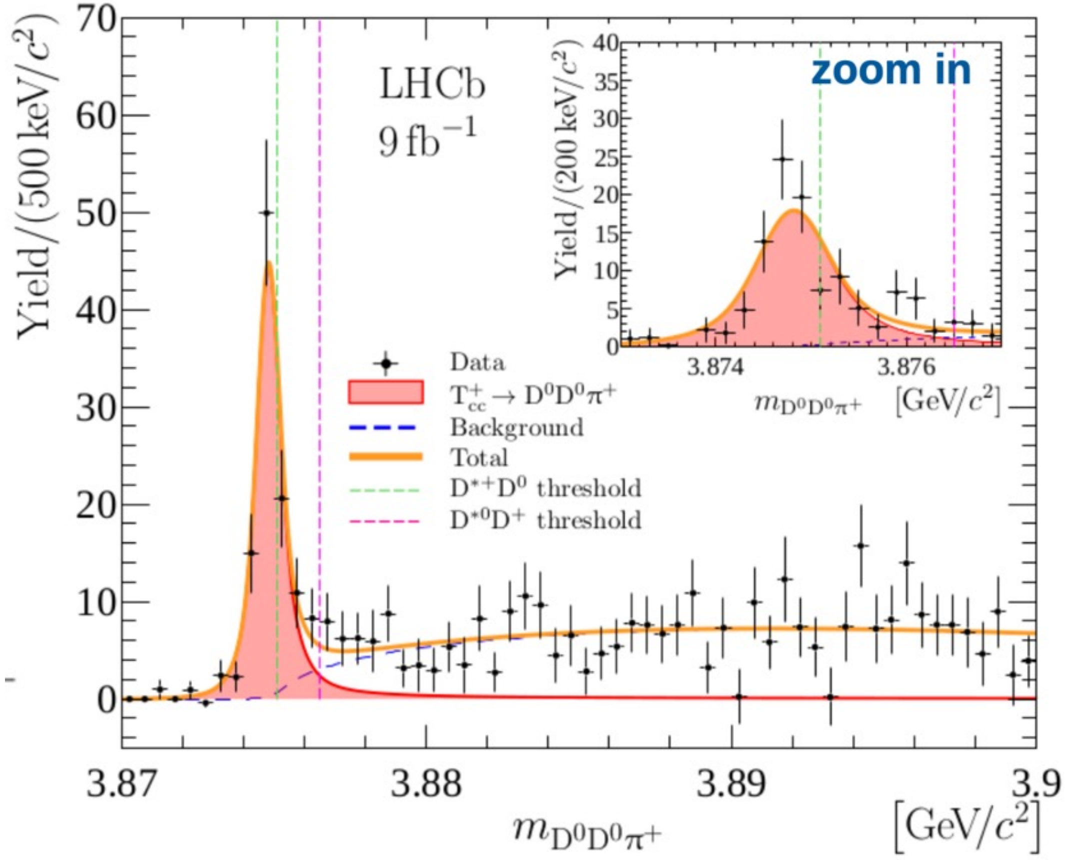
Hadrons

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

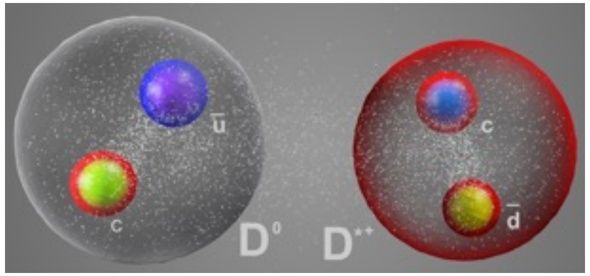
Including 23 exotic hadrons
Tetraquarks & Pentaquarks



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



Dedicated to Simon Eidelman



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

$$\delta m_{BW} = -273 \pm 61 \pm 5 \,^{+11}_{-14}\, \text{keV}/c^2,$$

$$\Gamma_{BW} = 410 \pm 165 \pm 43 \,^{+18}_{-38}\, \text{keV},$$

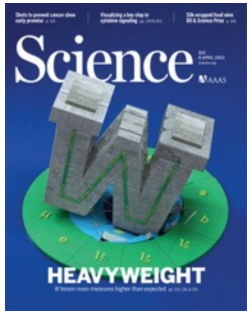
Increased interest for T_{bc} , T_{bb} as possible first long-lived, weakly decaying, states!

Need Upgrade statistics

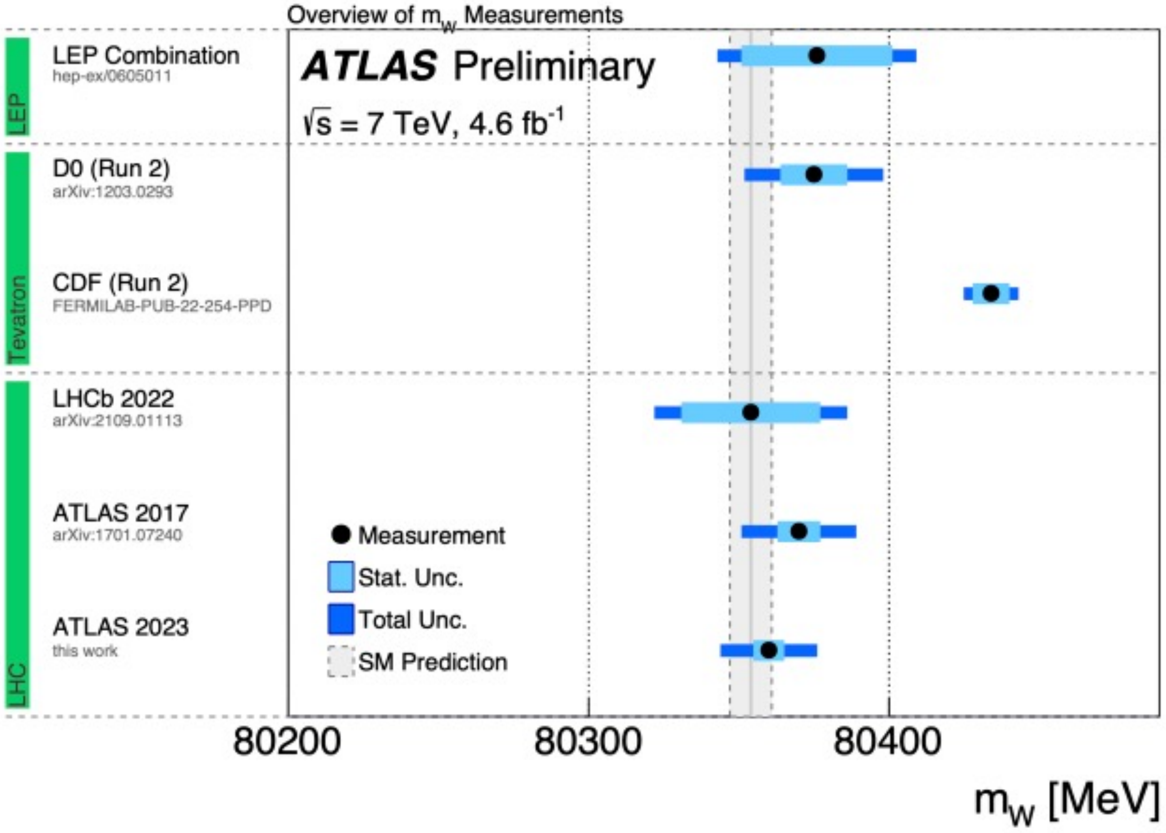
Breadth of LHCb Physics: Electroweak

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



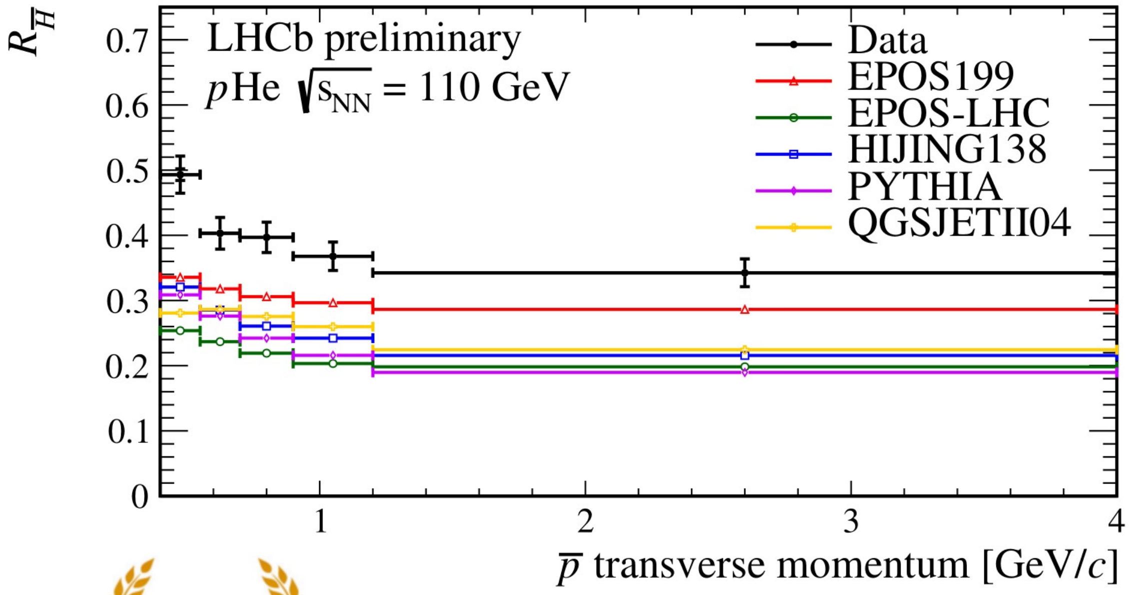
- LHCb results combined with ATLAS reduce sensitivity to the parton distribution functions. PDFs.
- In LHCb W bosons are produced in collisions of high- with low-x partons
- ATLAS mainly collisions of mid-x partons produce the W bosons observed

Breadth of LHCb: Understanding Dark Matter in Space

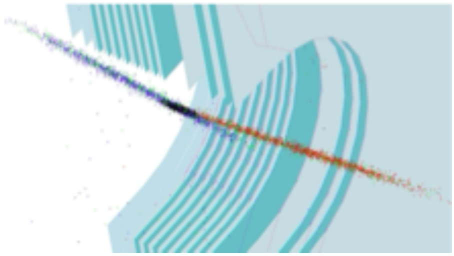
LHCb-PAPER-2021-031/032

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



THESIS

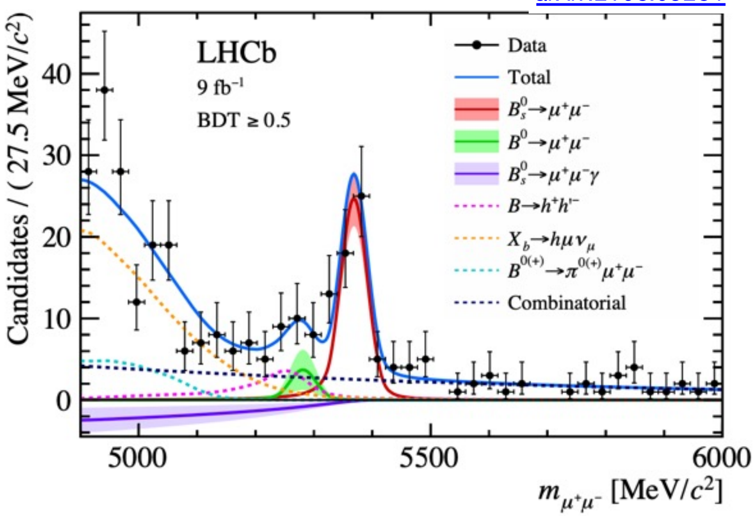
- Saverio Mariani (Universita di Firenze (Italy)) : "Fixed-target physics with the LHCb experiment at CERN"

Original 2009-2018

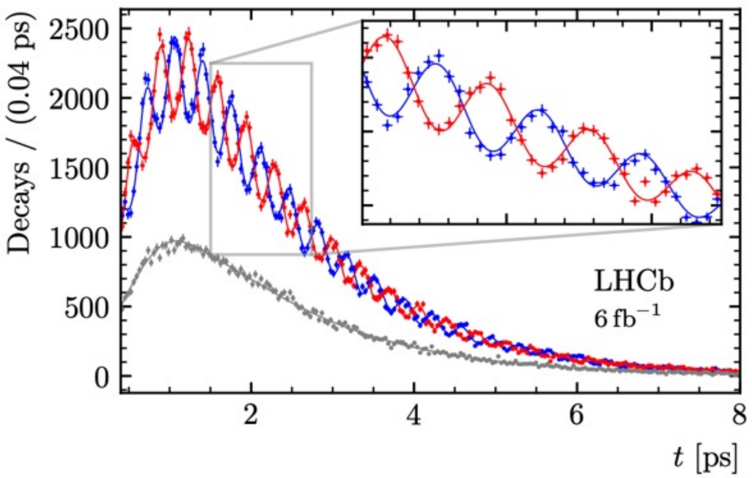
- Future plans build on the success of the experiment during Run 1 & 2

$B_s^0 \to \mu\mu$

arXiv:2108.09284



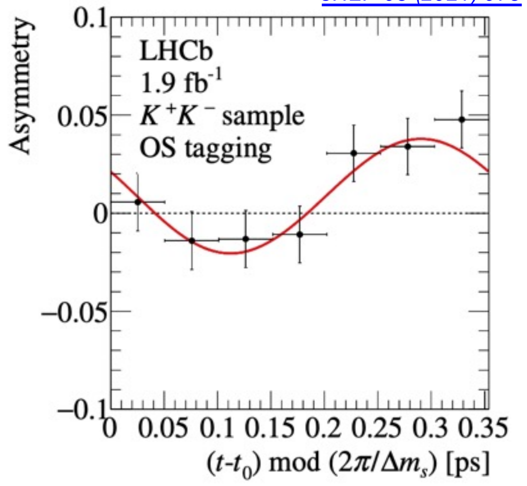
arXiv:2104.04421



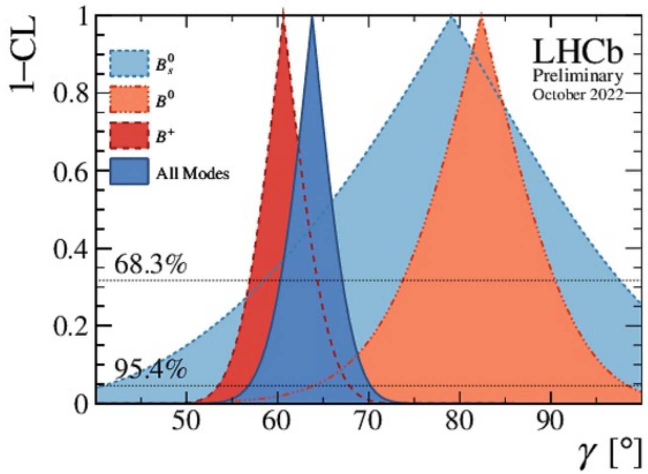
Δm_s

Time-dependent CPV in B_s

JHEP 03 (2021) 075



LHCb-CONF- 2022-003



CKM angle γ

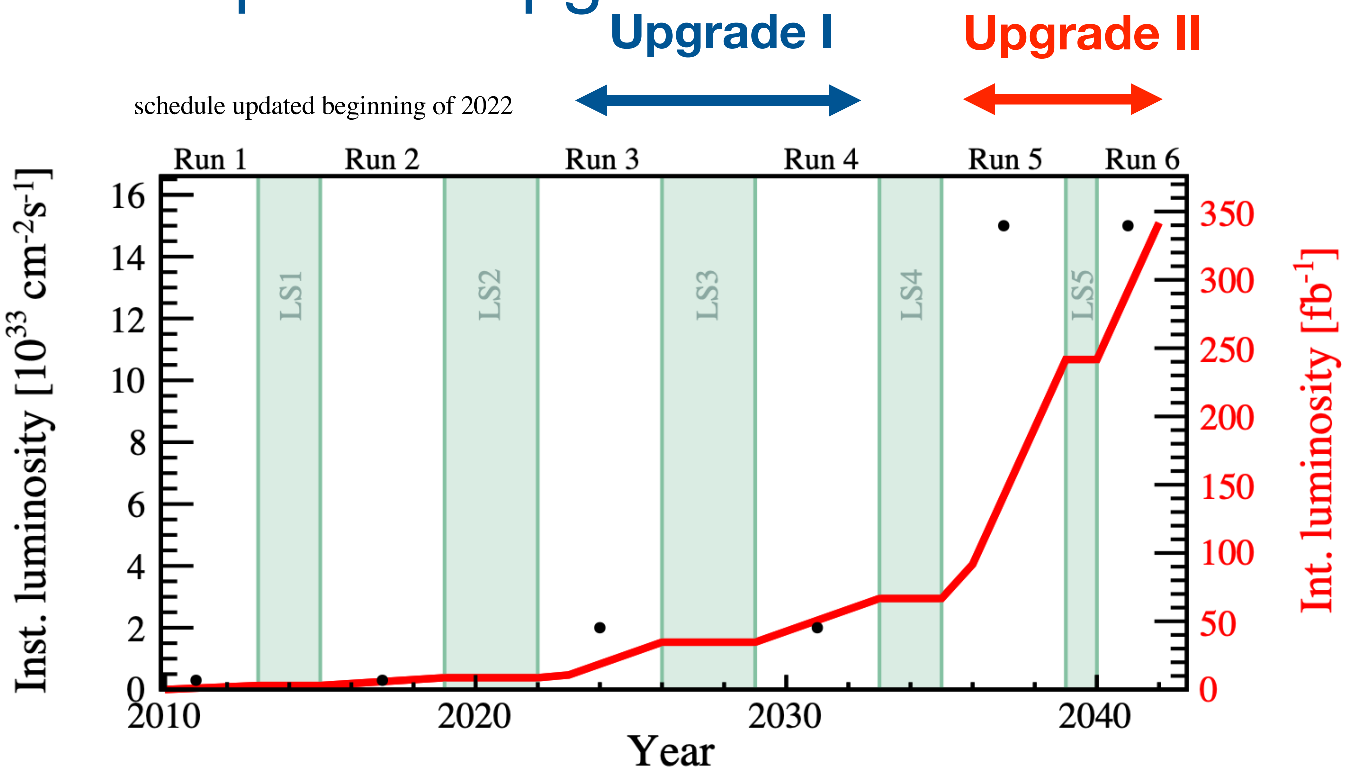
$(63.8^{+3.5}_{-3.7})^\circ$

LHCb Upgrades

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

Upgrade I started now!

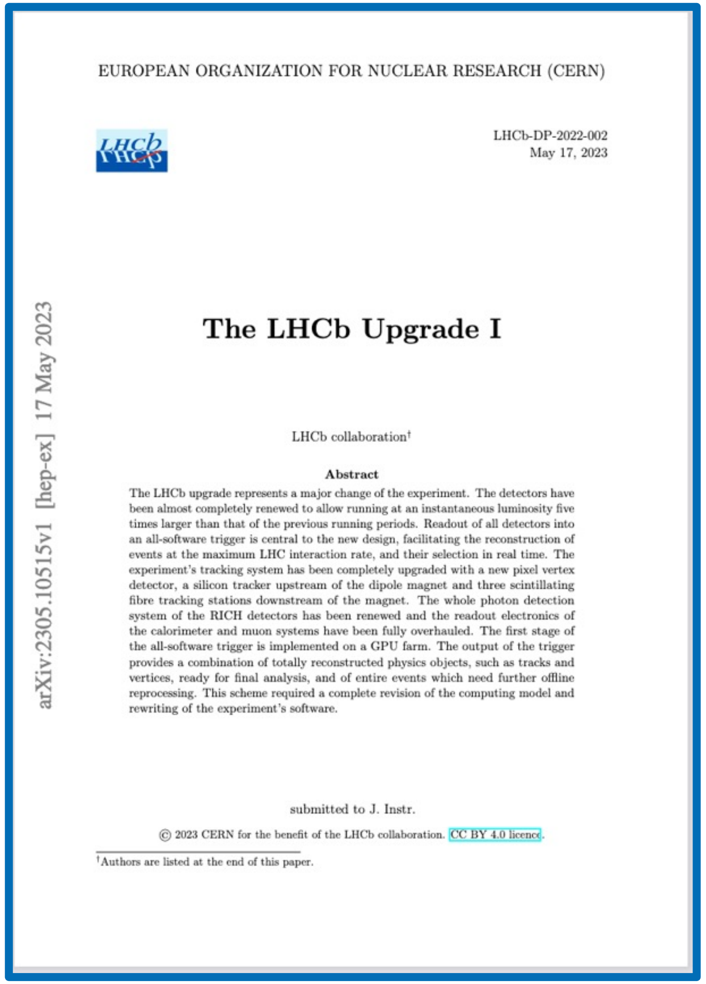
- L_{peak} = 2x10^{33} cm^{-2} s^{-1}
- L_{int} = 50 fb^{-1} during Run 3 & 4
- *Healthy competition with Belle II if reach 50 ab^{-1}*



Upgrade II

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

LHCb Upgrade I



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.

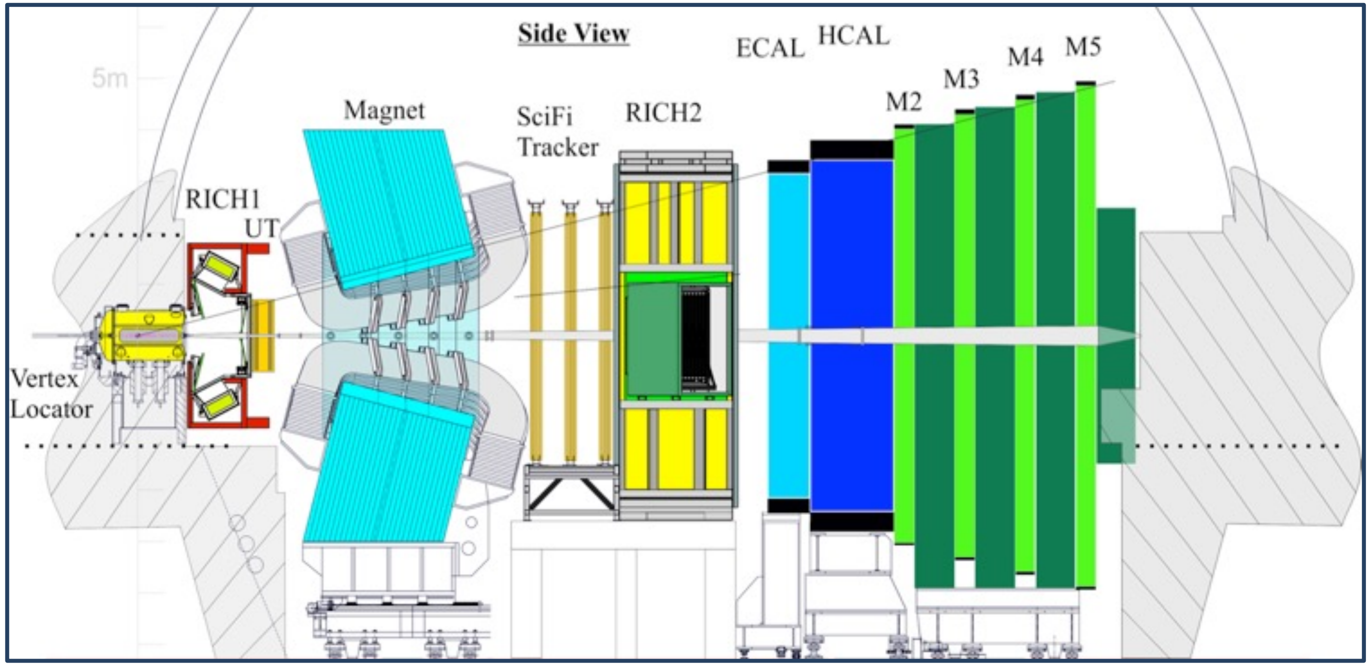
†Authors are listed at the end of this paper.

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

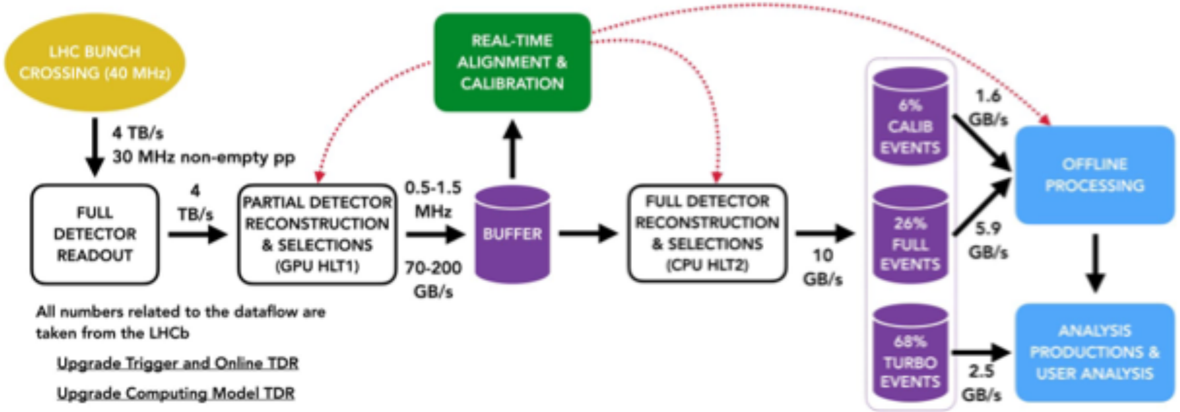
- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector
- New SciFi tracker with 11,000 km of scintillating fibres
- New electronics for muon and calorimeter systems

Major project installed for operation in Run 3

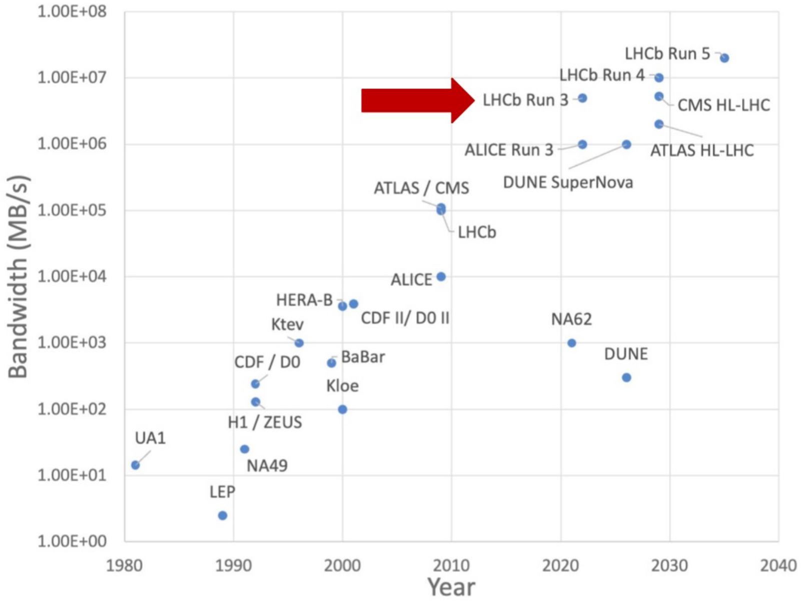
LHCb Upgrade I: Trigger Revolution

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

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



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



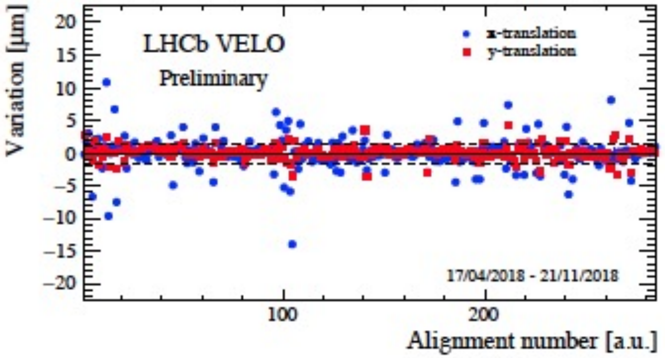
A. Cerri, LHCP 2022

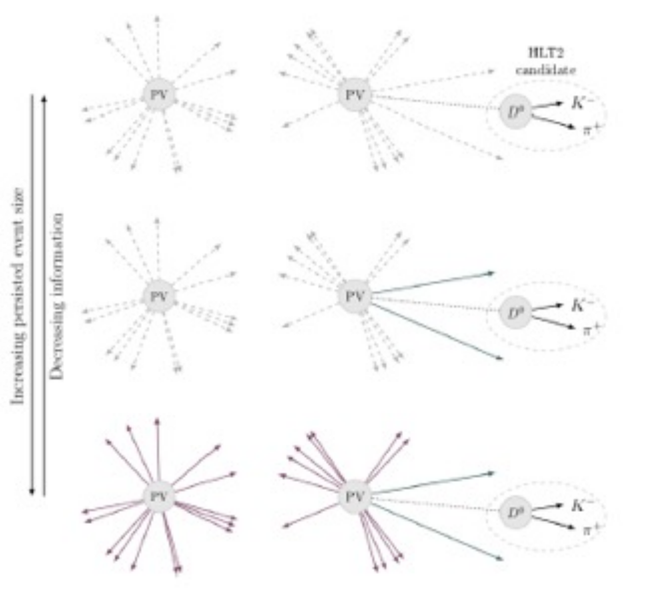
Real Time Analysis - Turbo

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

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

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





- Selective persistence

  Only signal decay tracks….

  those in cone around...

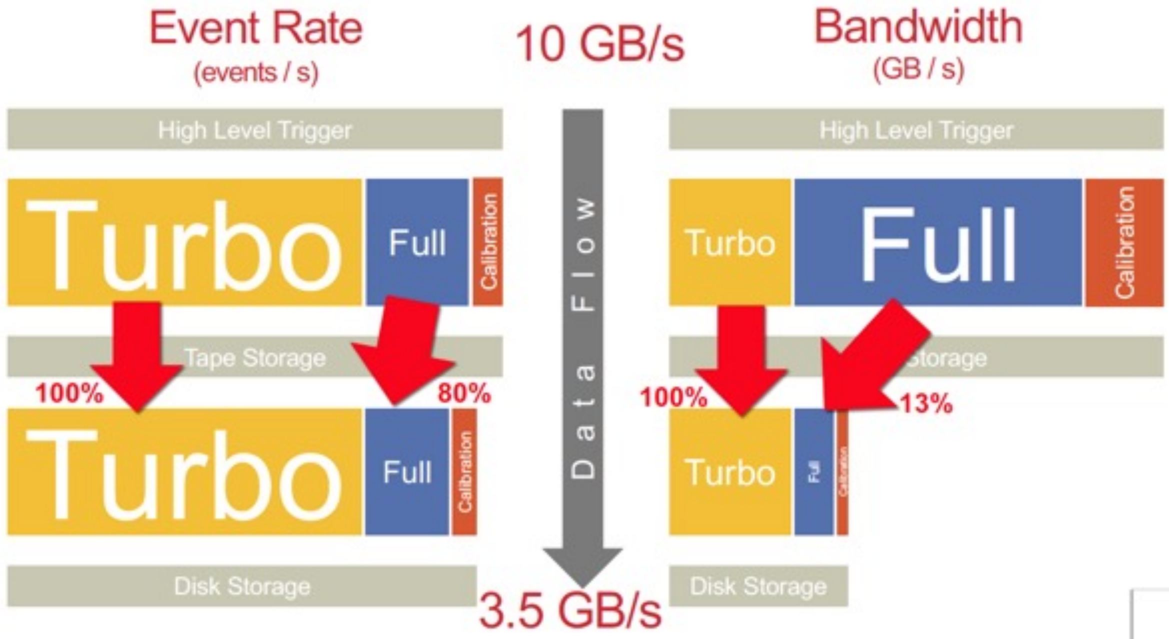
  those from same PV....

  All tracks in event….

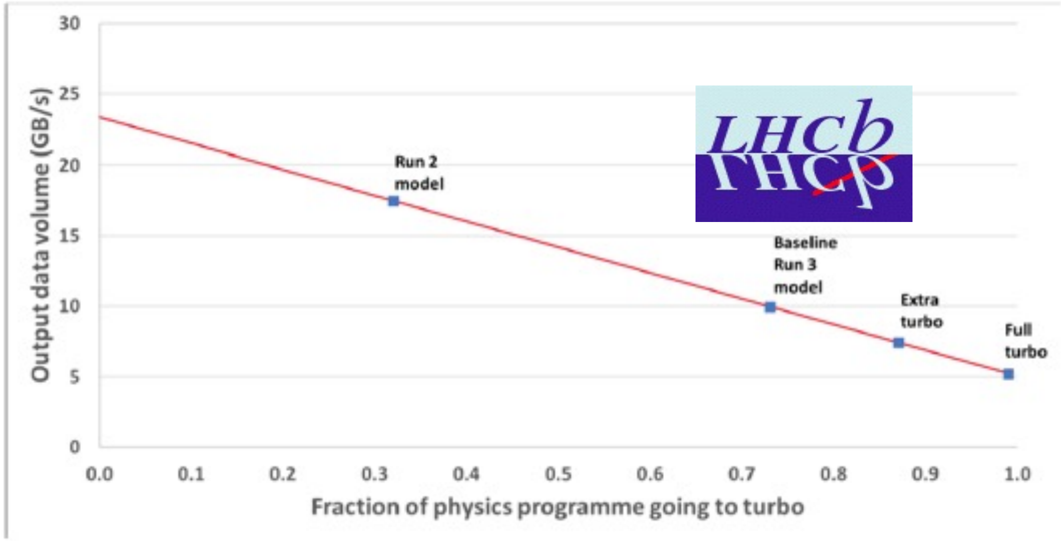
  All ECAL clusters....

Real Time Analysis - Computing Resources

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



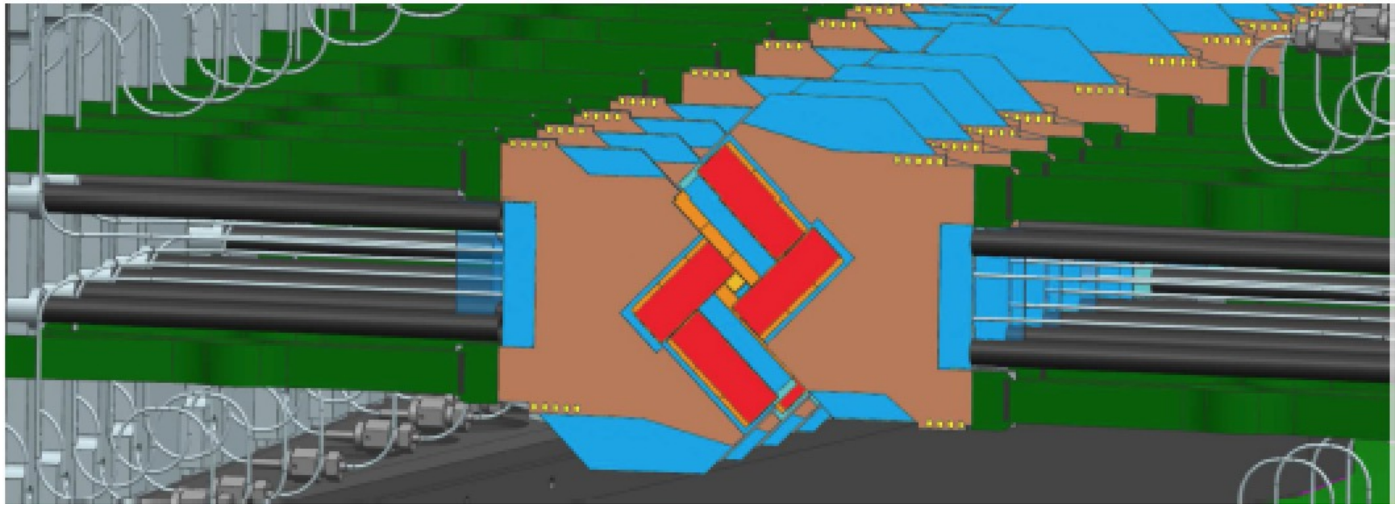
- Efficient use of computing resources
- Focus on bandwidth not event rate
- Minimise expensive disk resource

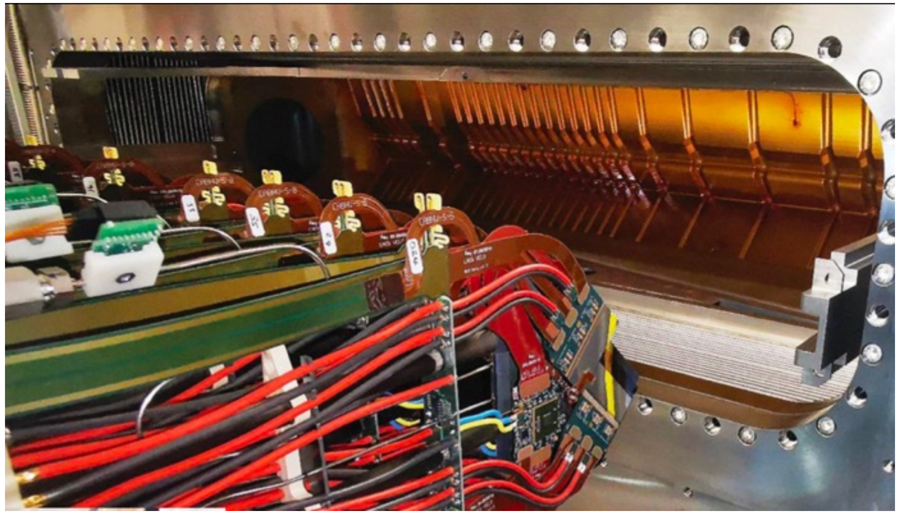


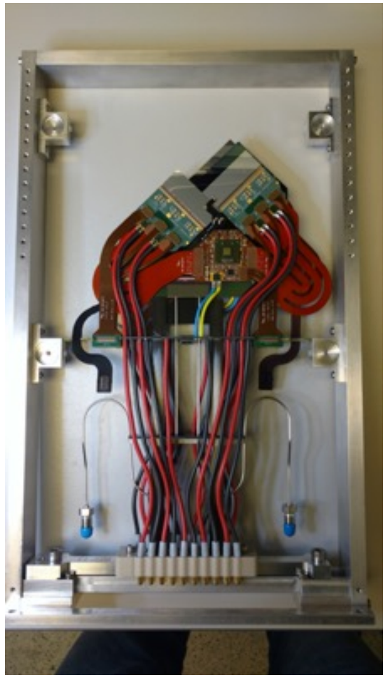
- Real time analysis already extensively used in Run 2
- >70% of events in Upgrade I will use real time analysis

LHCb Upgrade I: VELO

CERN-LHCC-2013-021



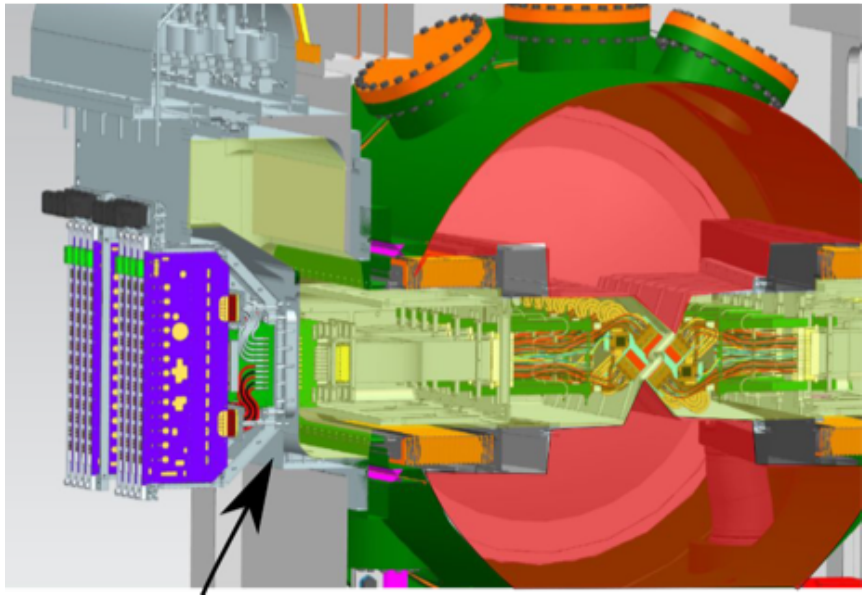




- Hybrid Pixel Detectors (55μm pitch)
- Close to the LHC beam (5.1 mm)
  - retracted/reinserted each fill
- Innovative silicon microchannel substrate
  - Bi-phase CO_2 cooling
- DAQ capable of handling 40TB/s
- **Installation completed May 2022**

LHC Vacuum Volume Incident in VELO

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



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

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

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

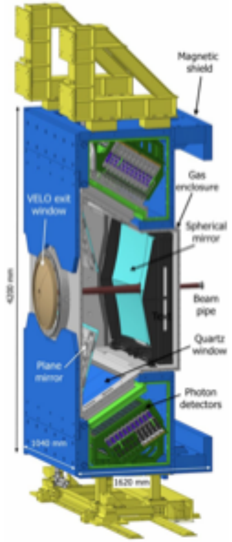
LHCb Upgrade I: RICH 1 & 2

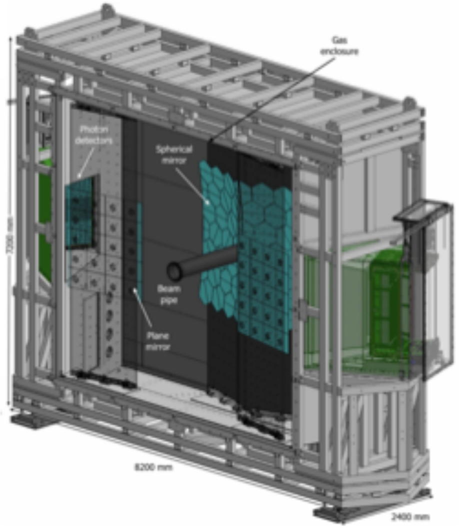
CERN-LHCC-2013-022

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

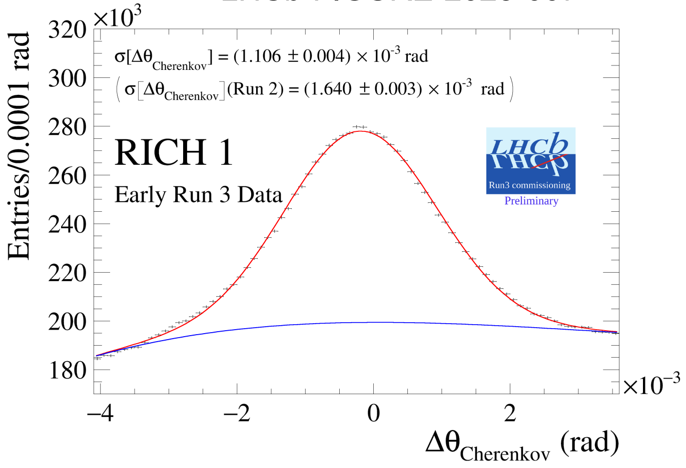
- RICH1&2: new photodetector MaPMTs with Increased granularity and 40MHz readout

- RICH1: new design with new optical system with increased focal length, to halve occupancy
- **Installation successfully completed Feb. '22**

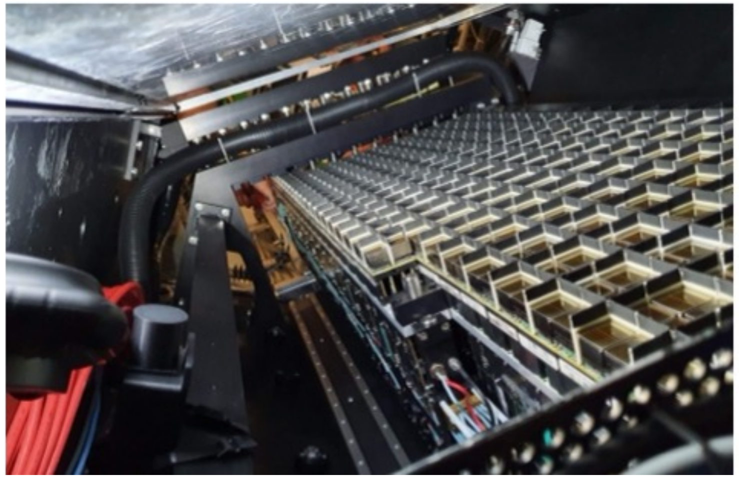




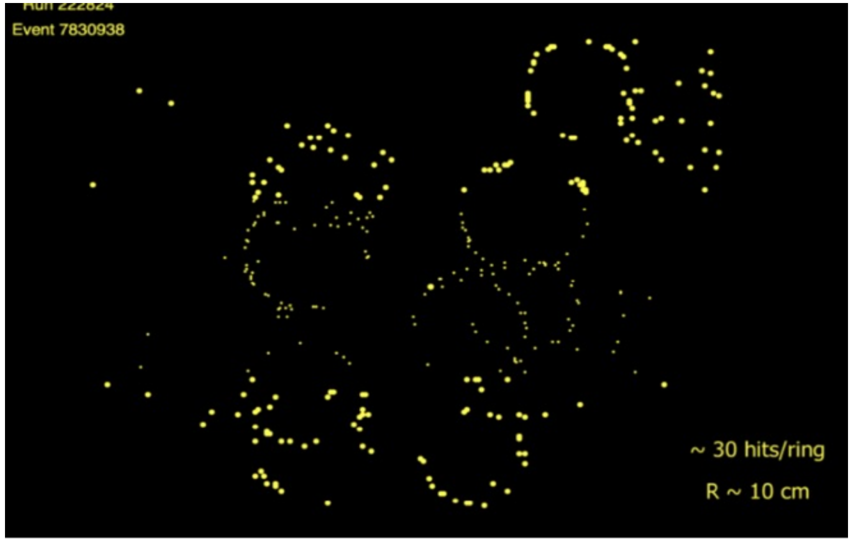
LHCb-FIGURE-2023-007



RICH1: MaPMTs installation



RICH2: first rings, LHC October '21 test

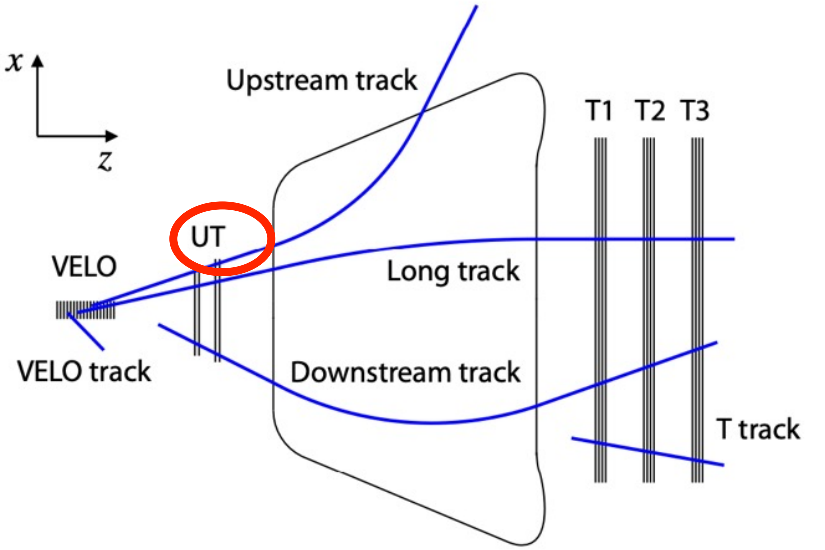


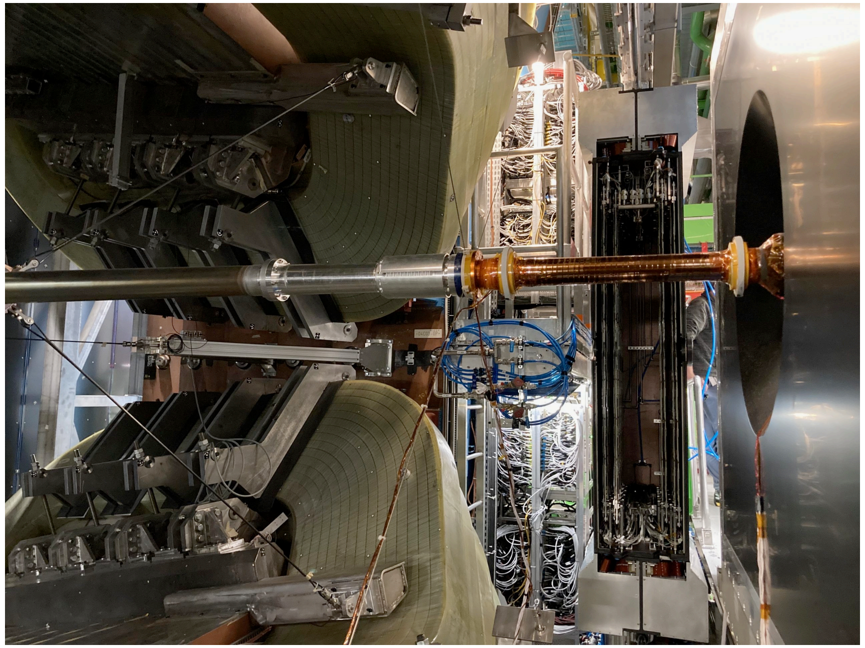
LHCb Upgrade I: Upstream Tracker

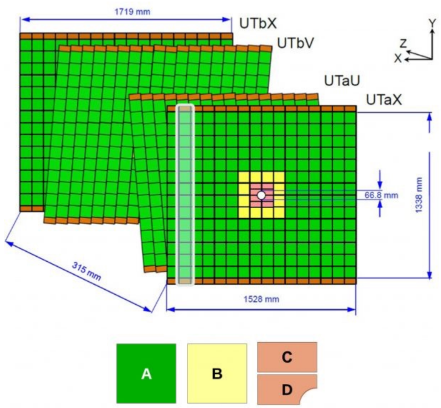
CERN-LHCC-2014-001

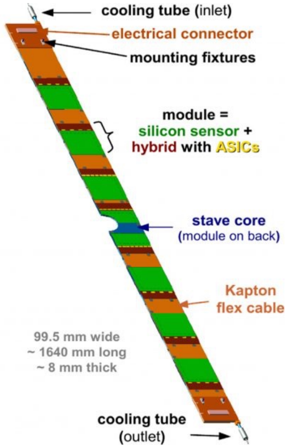
- 68 staves with silicon strips and integrated cooling, arranged in 4 planes
  - fast p_T determination for track extrapolation

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





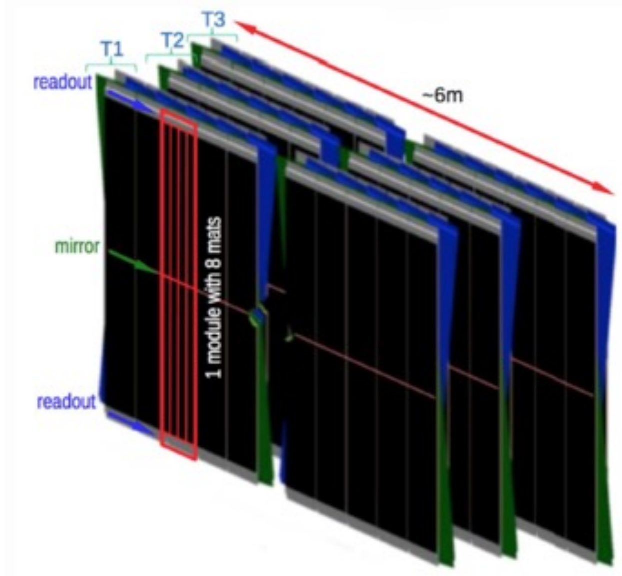


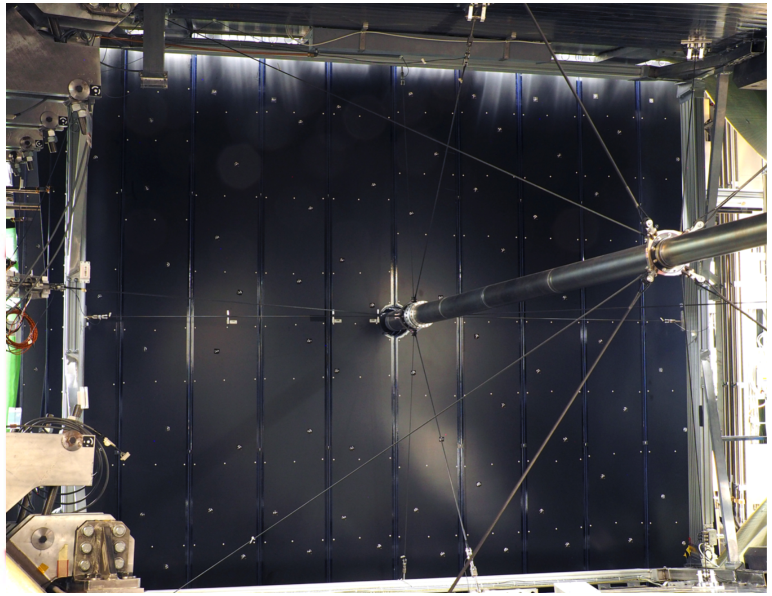


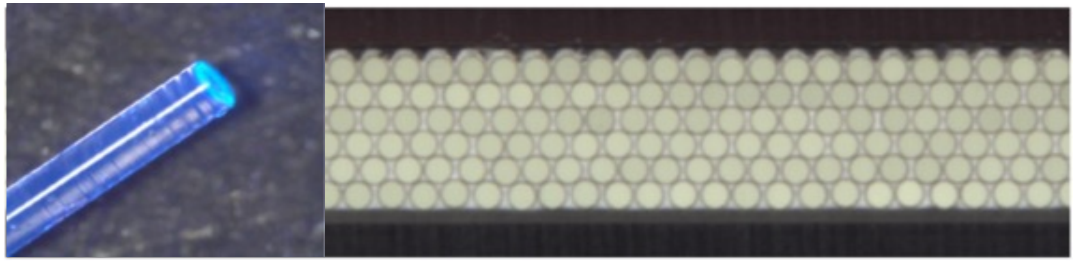
LHCb Upgrade I: SciFi

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**



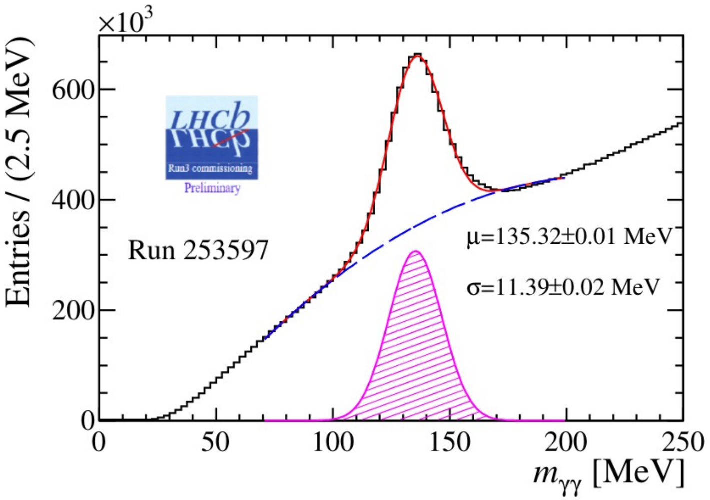


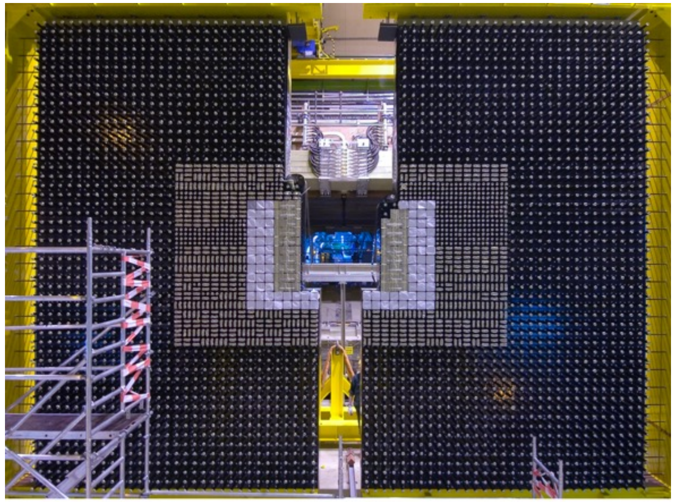


LHCb Upgrade I: CALO & Muon

CERN-LHCC-2013-022

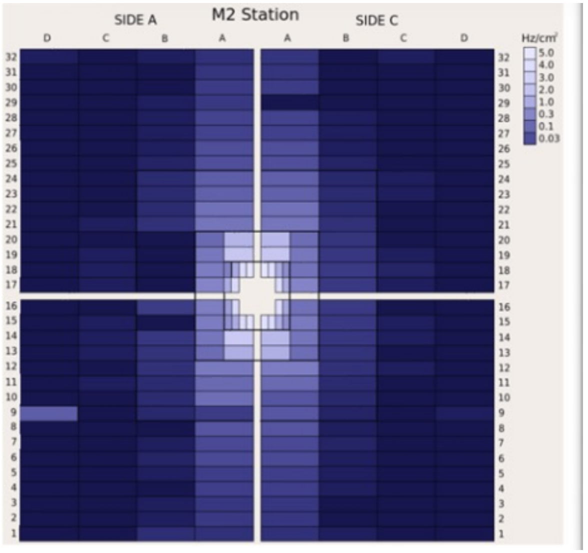
- New Electronics readout
- Existing detectors able to stand increased luminosity of Run3
  - Inner ECAL upgrade for LS3

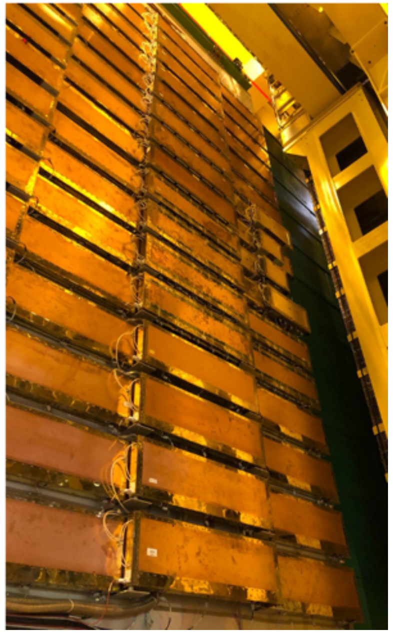




- **Shashlik Calorimeters**
  - PMT gains reduced
  - New front-end electronics with improved S/N and 40MHz readout
- **Muon stations**
  - 4 walls equipped with MWPCs, and interleaved with iron filters
  - 40Mz readout electronics

Occupancy Muon station 2

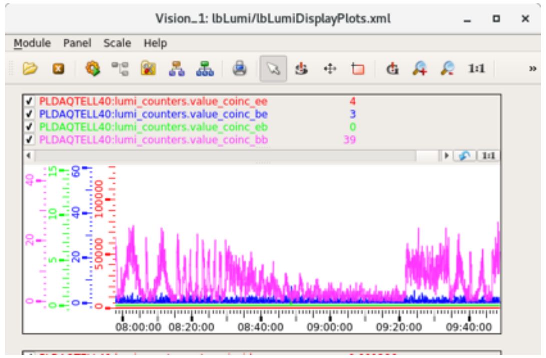


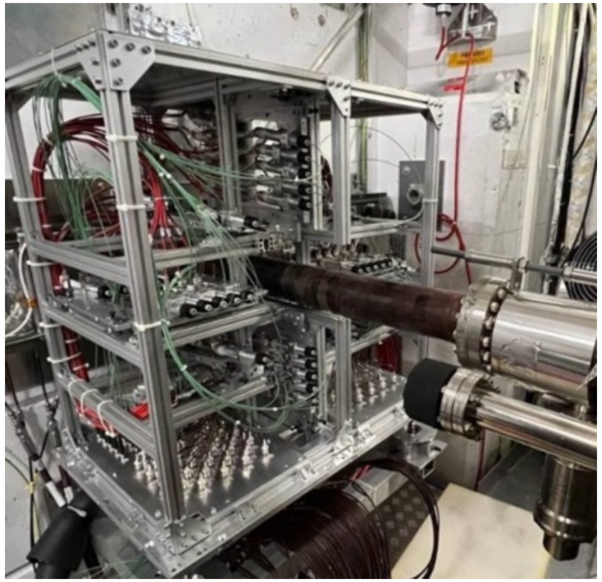


LHCb Upgrade I: PLUME & SMOG

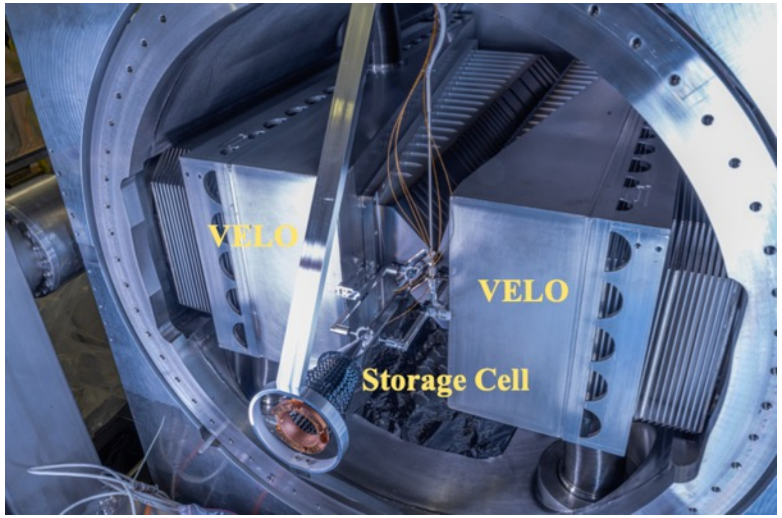
CERN-LHCC-2021-002
CERN-LHCC-2019-005

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





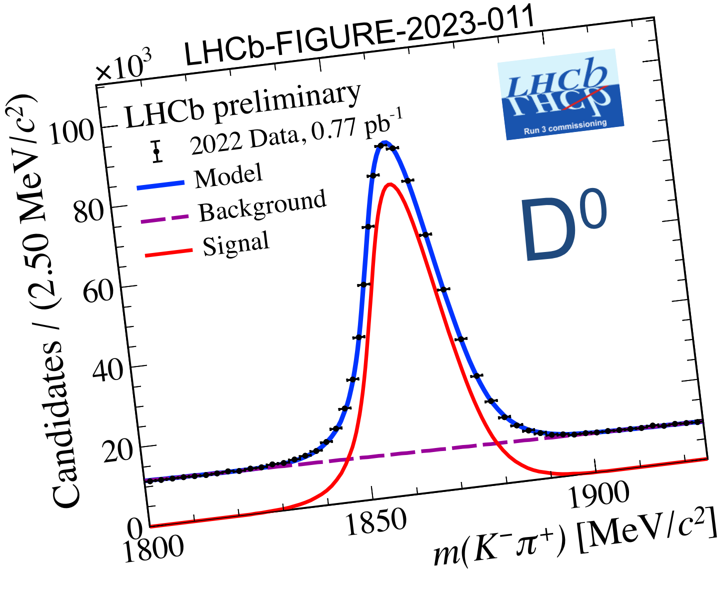
- **PLUME luminometer**
  - quartz tablets + PMTs
  - online+offline per-bunch luminosity measurement
  - **in Global data taking**
- **SMOG2 gas target**
  - New storage cell for the gas upstream of the nominal IP
  - Gas density increased by up to two orders of magnitude → much higher luminosity
  - 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!**

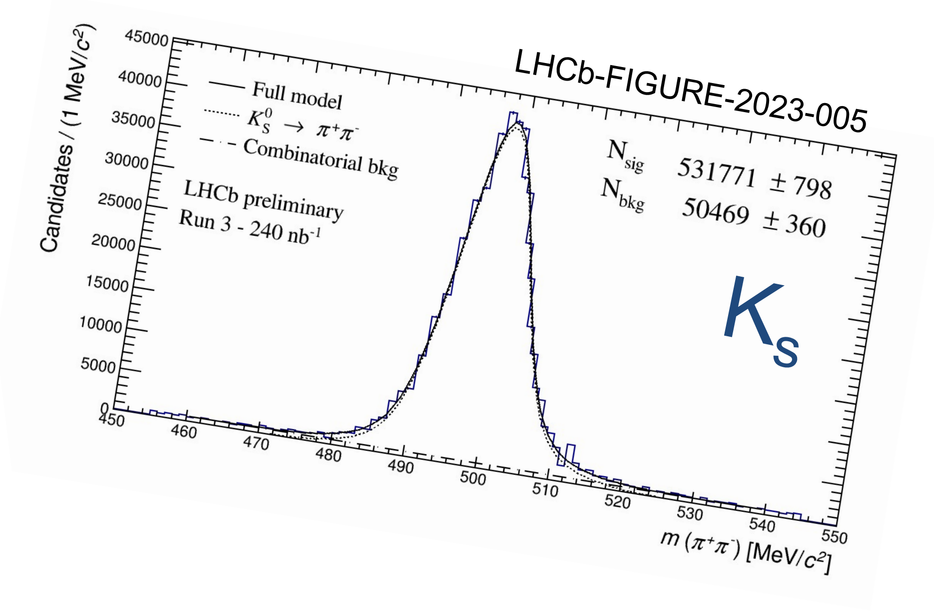


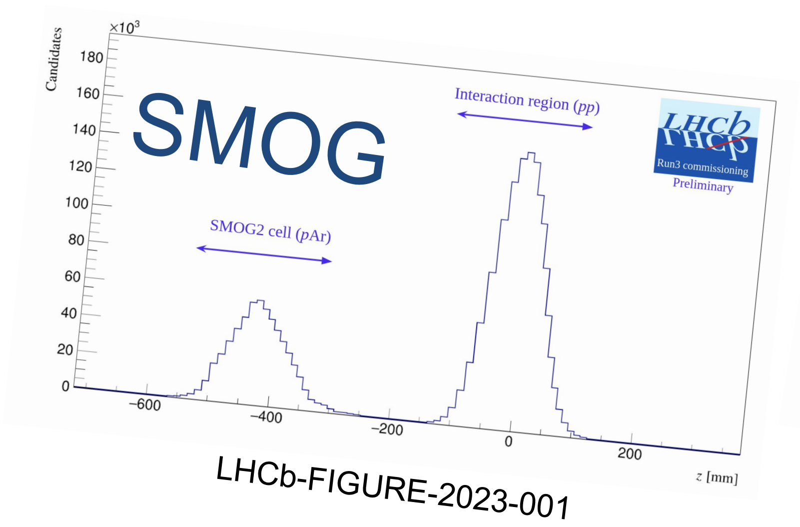
Upgrade I Video

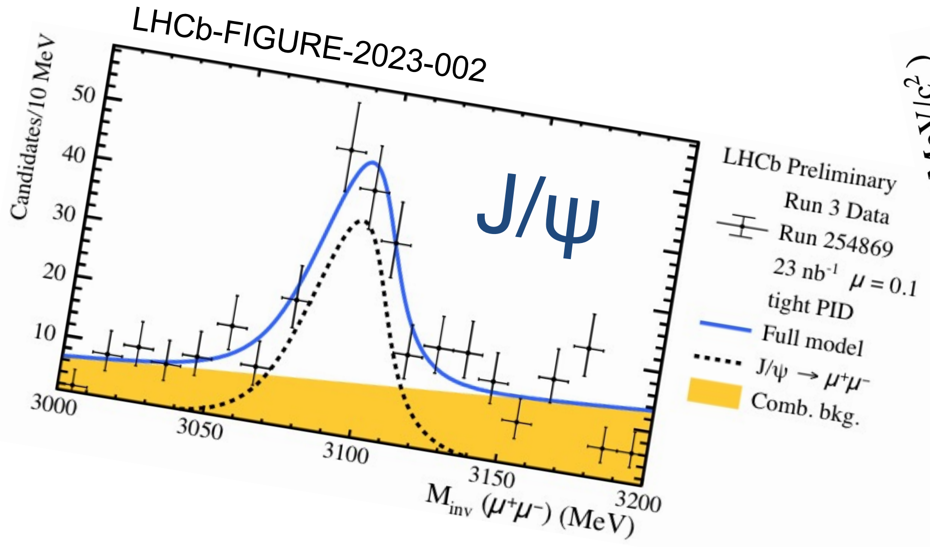
https://cernbox.cern.ch/files/spaces/eos/user/r/rlindner/Point%208%20video/LS2-1-Minuten.mp4

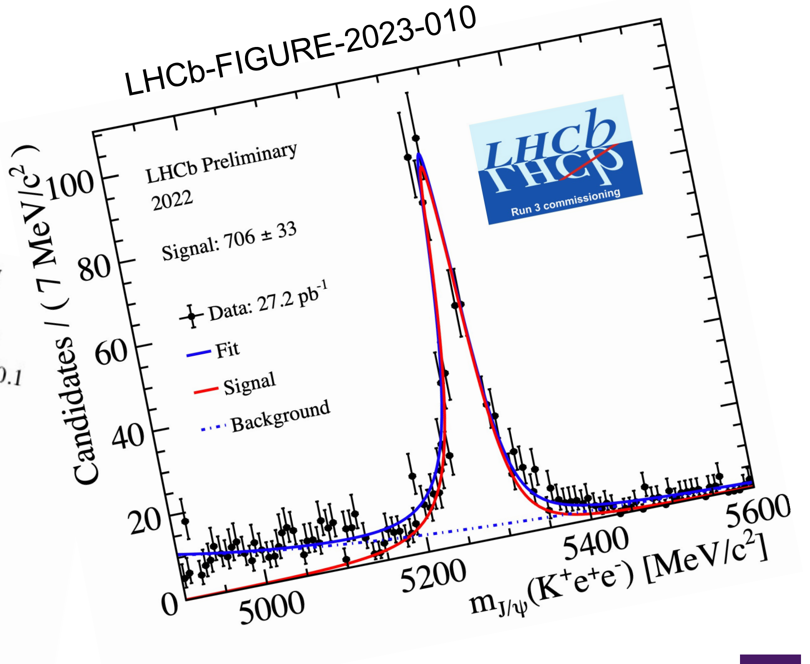
Some first plots…..





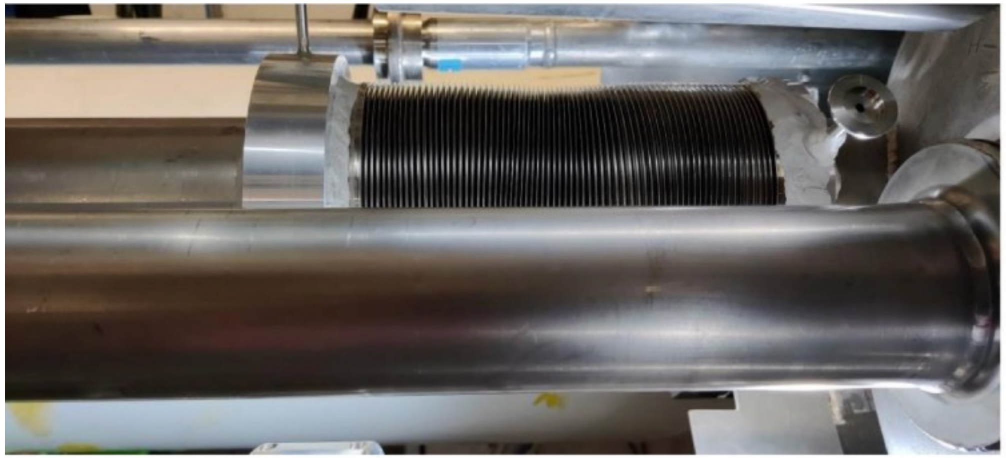






LHC Status

- Large and complex machine – things don't always go to plan……
  - Leak in a magnet 17th July



Bellow replaced, welded

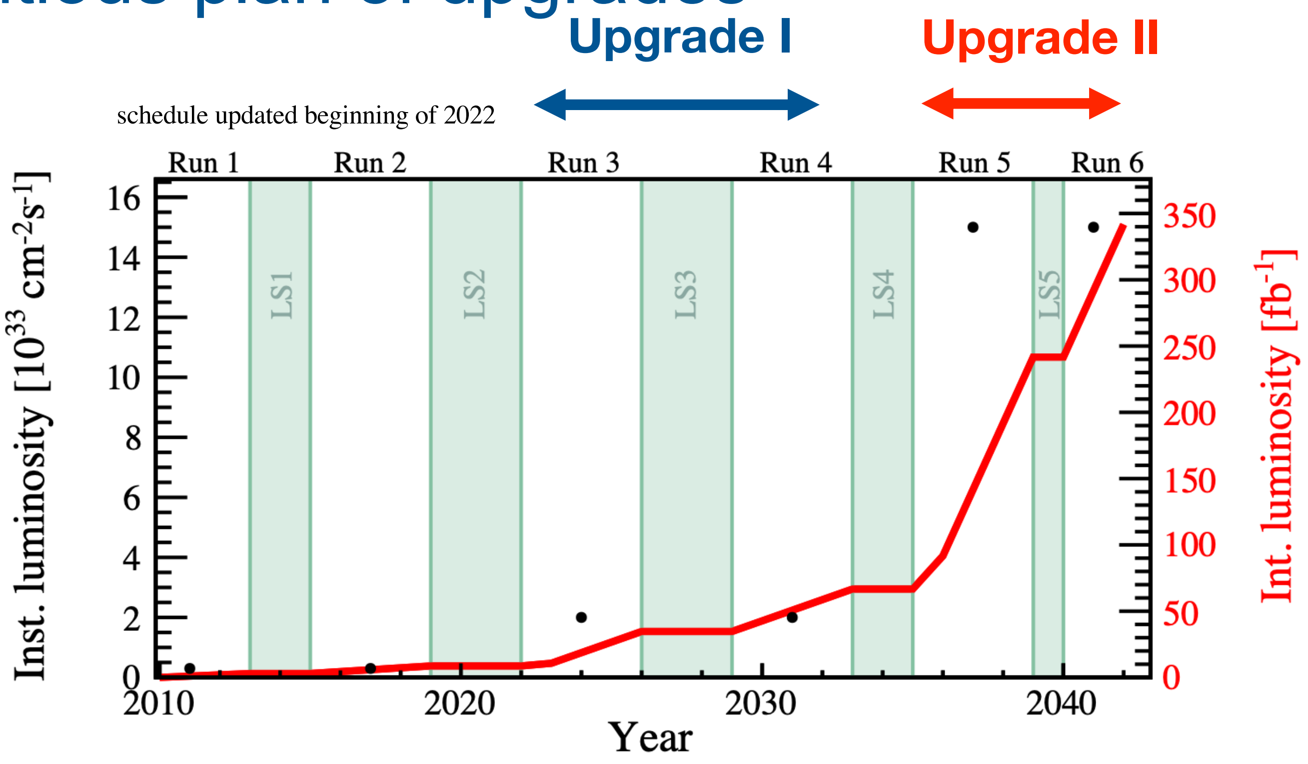
- Repairs currently going well
  - beam could be back ~ 11th September if all goes smoothly

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


Talk about a dream, try to make it real.
Bruce Springsteen


MANCHESTER 1824
THEATRE OF DREAMS
LHCb
Beyond the LHCb Phase I Upgrade
April 6th/7th 2016


6th Workshop on LHCb Upgrade II
29.03.2023-31.03 2023
Barcelona
ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
LHCb

Upgrade II

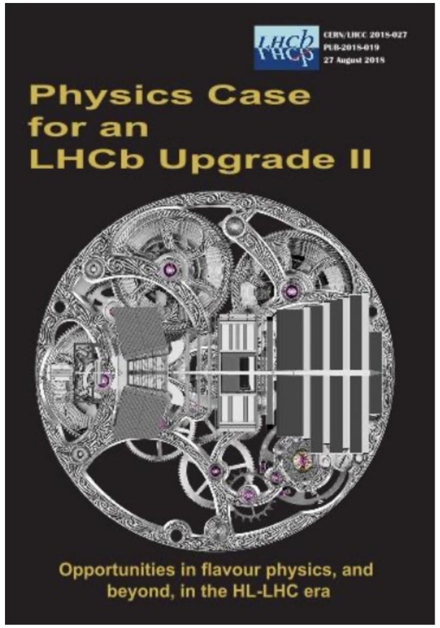
2033-

Upgrade II: steps so far

Expression of Interest

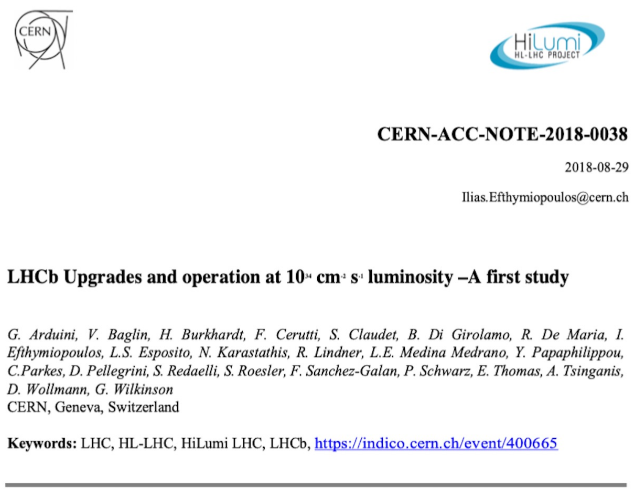
[LHCC-2017-003]

Physics case



[LHCC-2018-027]

Accelerator study



CERN-ACC-NOTE-2018-0038

2018-08-29

Ilias.Efthymiopoulos@cern.ch

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

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

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

[CERN-ACC-2018-038]

[LHCC-2021-012]

CERN Research Board September 2019

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

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

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

Physics Case: performance table

Upgrade I will not saturate precision in many key observables

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

Key observables in flavour physics

LHCC-2018-027

updated for FTDR

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	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 ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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 ($D^0 \to K^0_{\rm S}\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—		—	—	0.2
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}$($B^0_s \to \phi\gamma$)	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}$($B^0_s \to \phi\gamma$)	0.32	[51]	0.093	0.062	0.025
α_γ($\Lambda^0_b \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

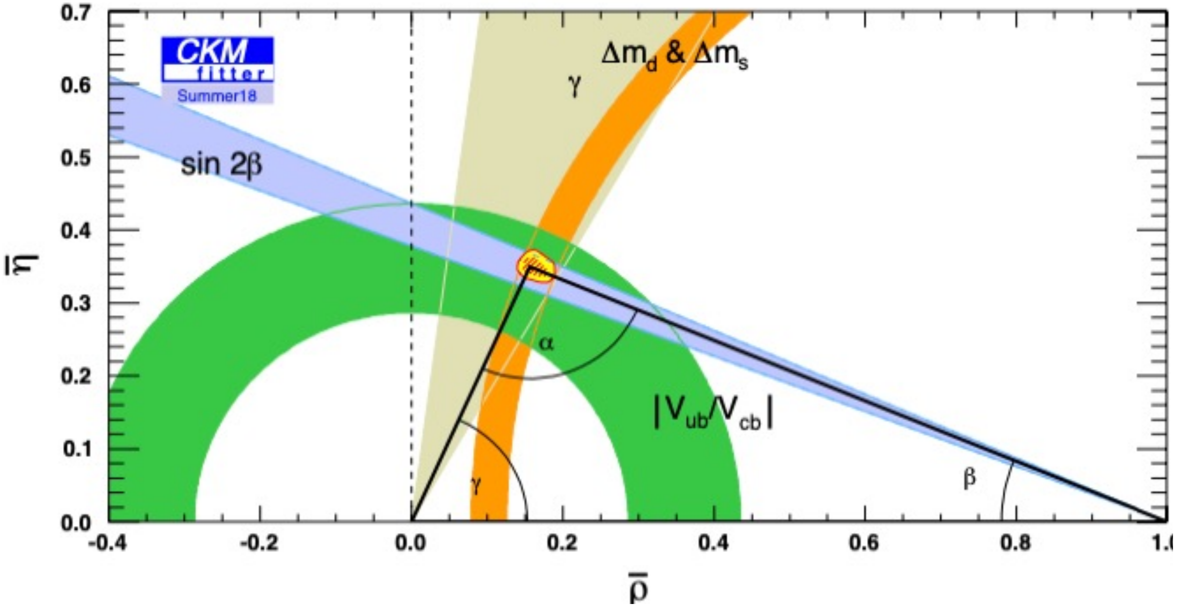
- Full range of beauty & charm mesons & baryons accessible
- Strong results with π^0, photons, missing particles reconstruction
- Beyond Flavour: LHCb as general purpose detector in forward region
- Spectrocopy, EW precision, dark sector and exotic searches, heavy ions and fixed target physics

Constraining the Unitarity Triangle

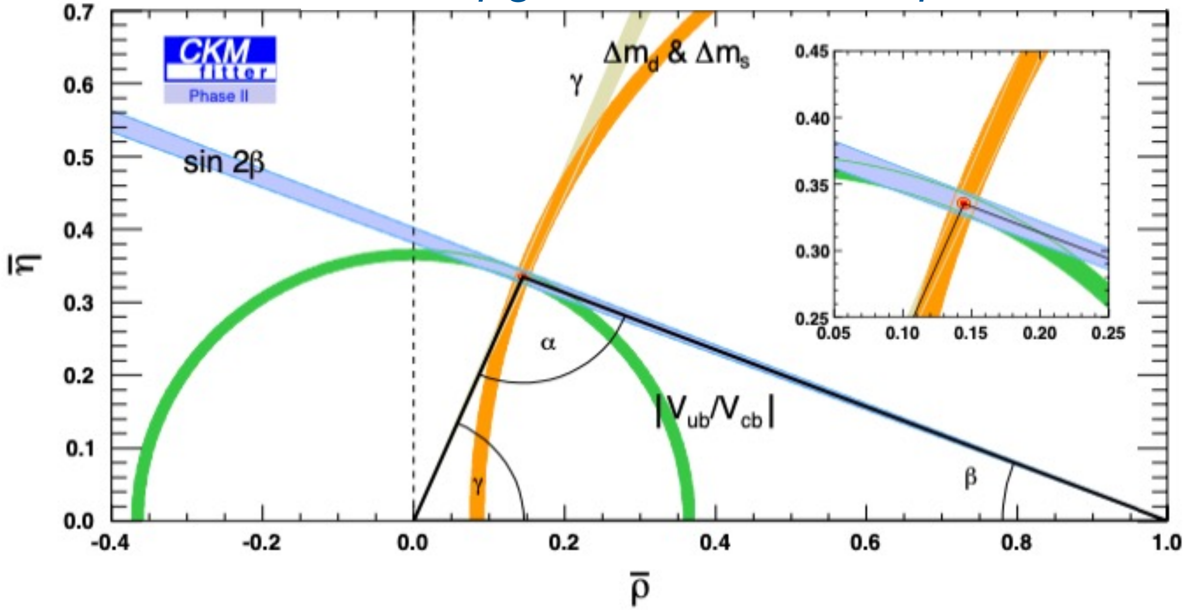
- *Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes*
- *Either NP is very heavy of it has a highly non trivial structure*

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement

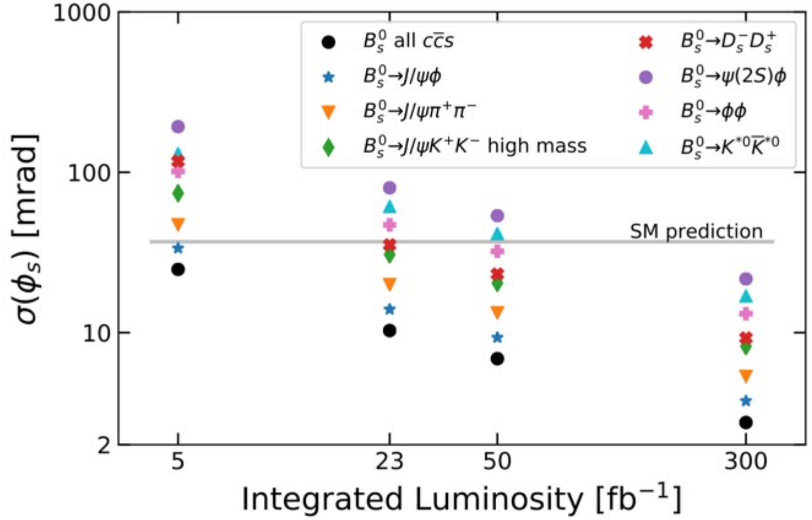


Arguably the greatest likelihood of a further paradigm shifting discovery at the HL-LHC lies with flavour physics

Beauty and Charm CPV Examples

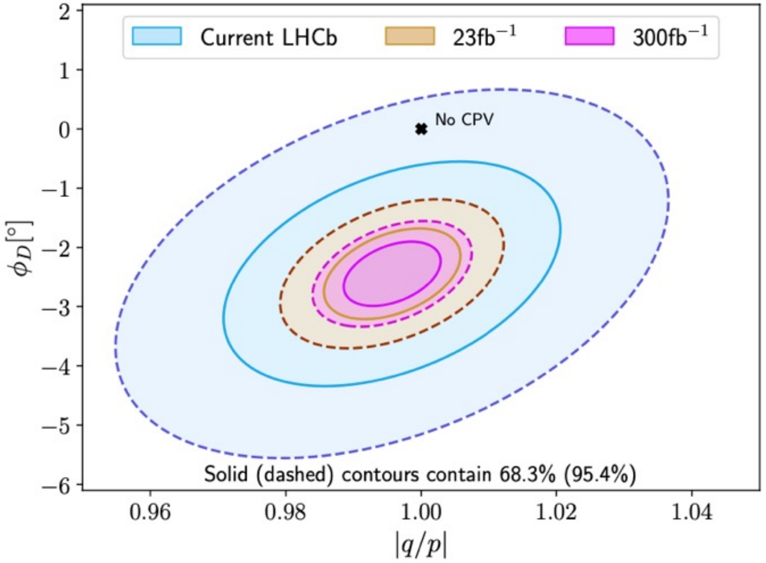
CP violating phase ϕ_s

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



CP violation in charm

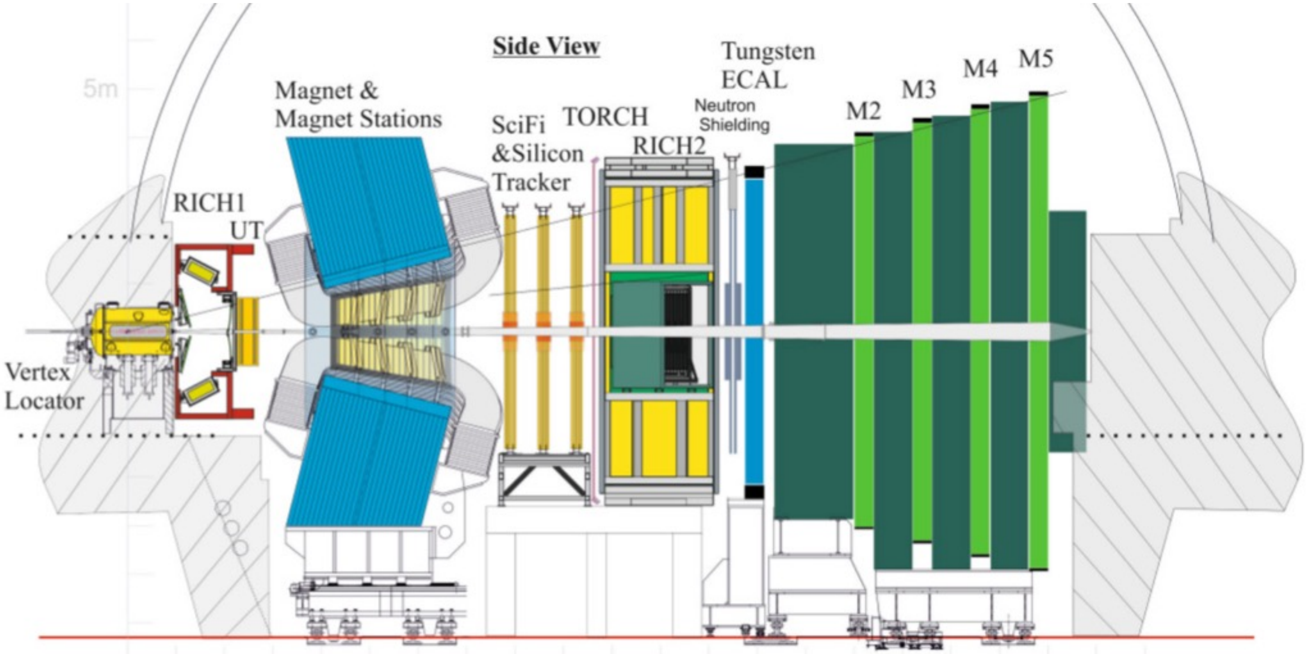
- LHCb Upgrade II is the only planned facility with a realistic possibility to observe CPV in charm mixing *(at >5σ if present central values are assumed)*



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

The detector challenge

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



Same spectrometer footprint, innovative technology for detector and data processing

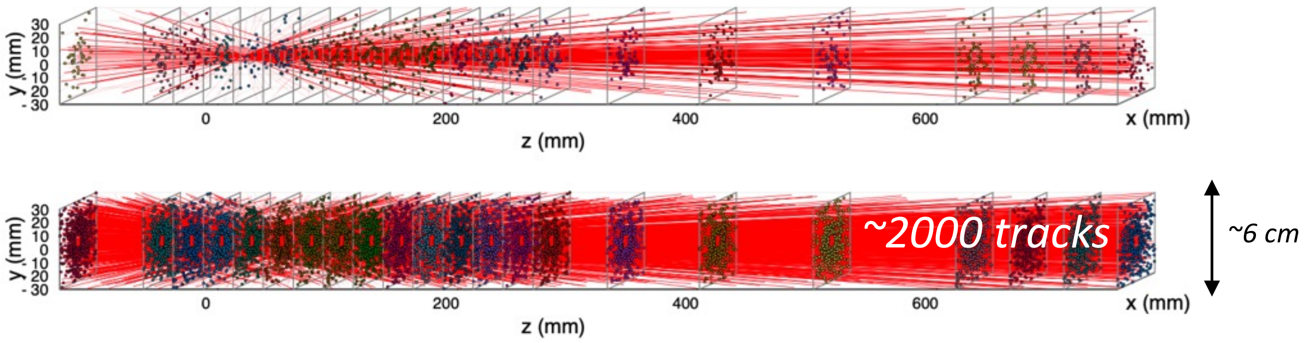
Key ingredients:

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

VErtex LOcator (VELO)

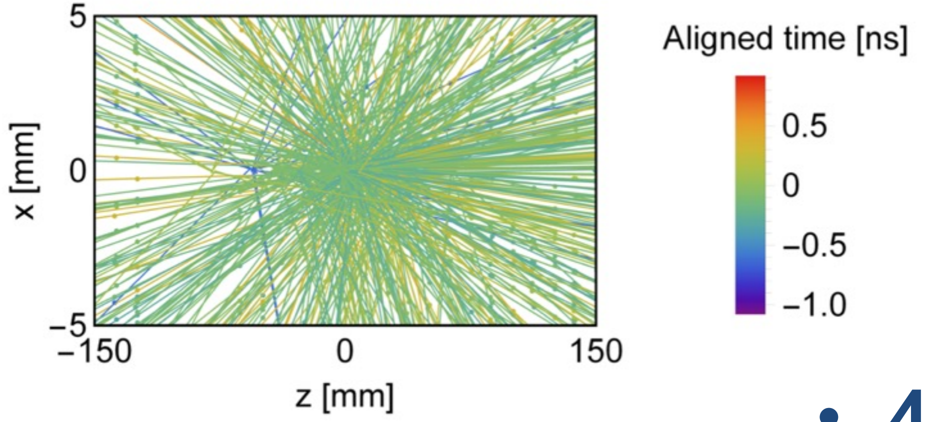
Run 3: pile-up ~6

Upgrade II: pile-up ~42

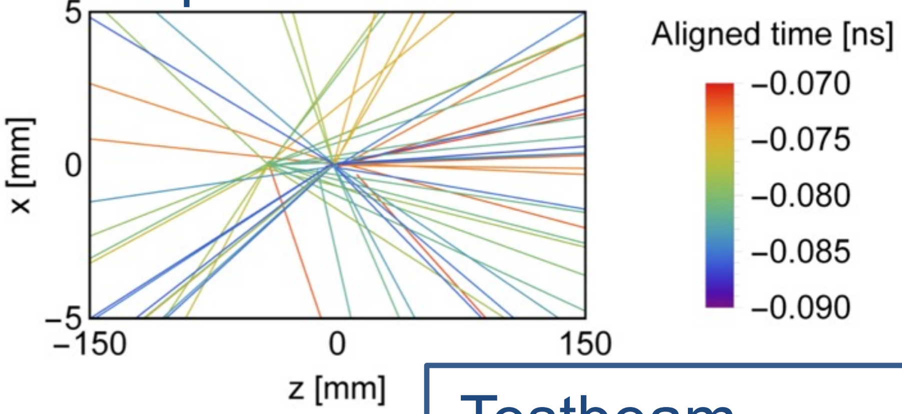


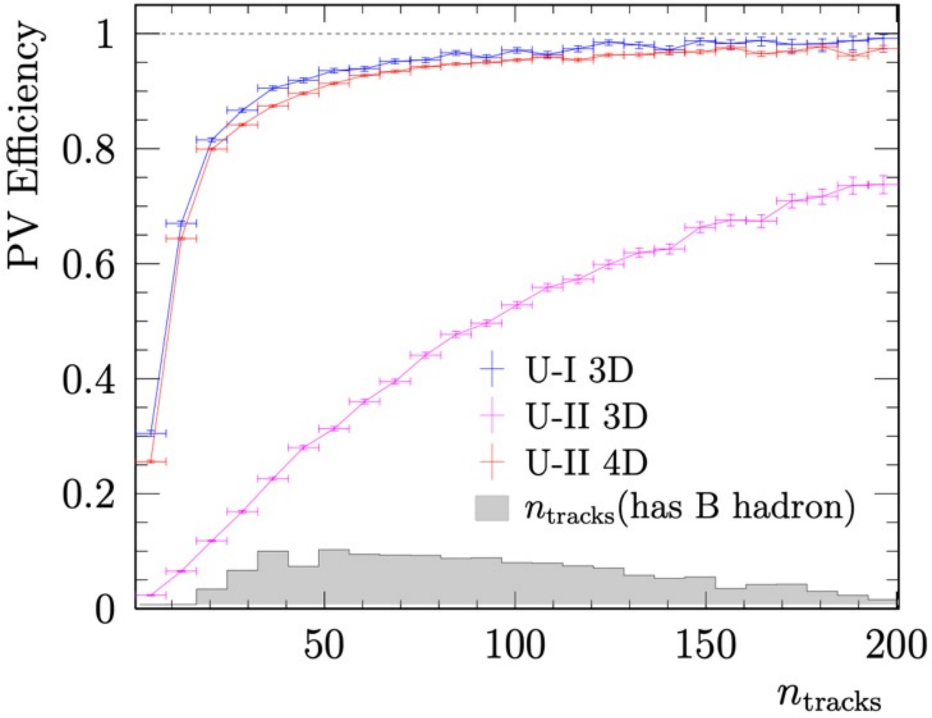
4D Vertexing: Precision Timing

42 interactions

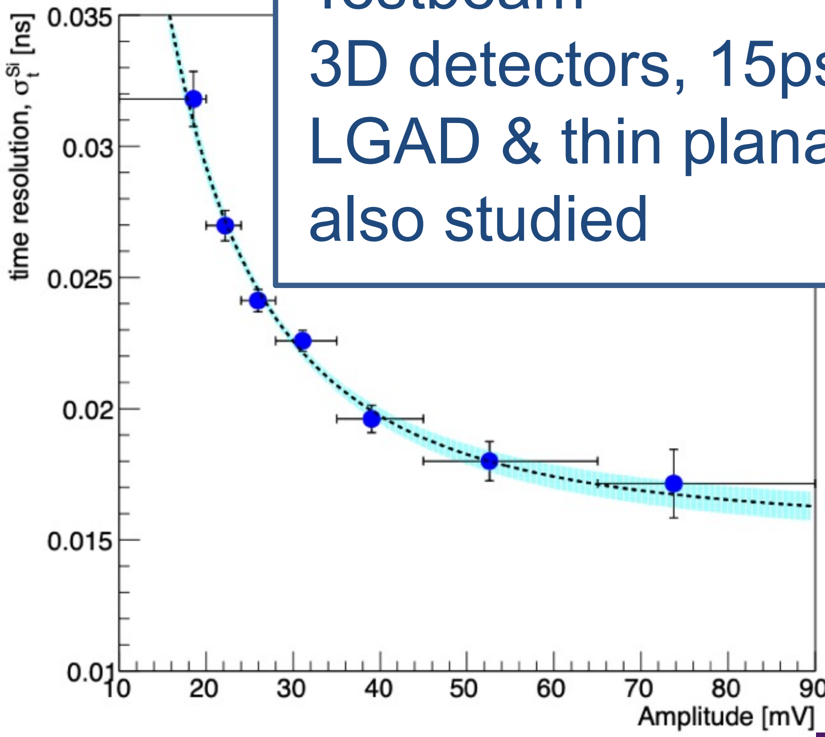


20ps time window





- **4D tracking**
- Ensures similar performance to U1 at U2
  - ~ 50ps, 50μm^2
- Extreme lifetime fluence
  - $6\times10^{16} n_{eq}/cm^2$

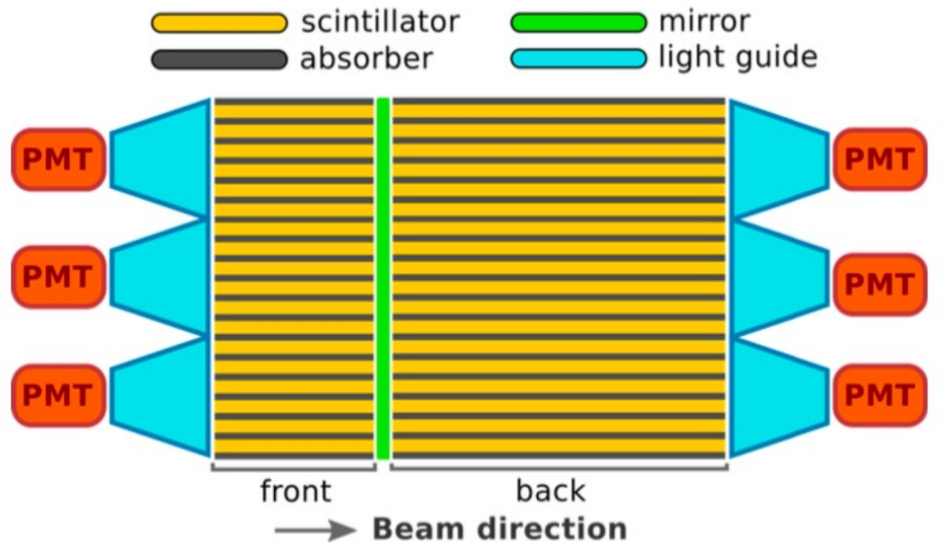


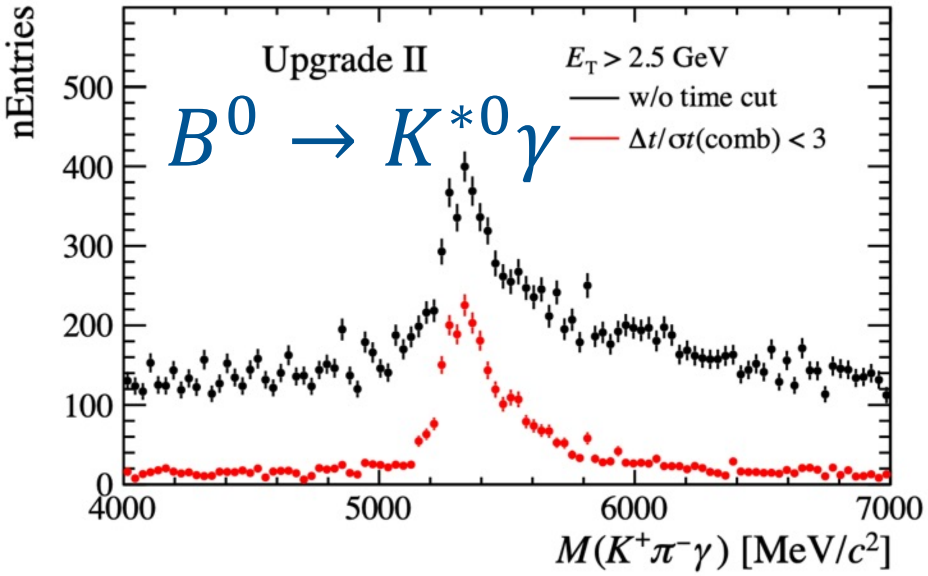
Testbeam
3D detectors, 15ps
LGAD & thin planar also studied

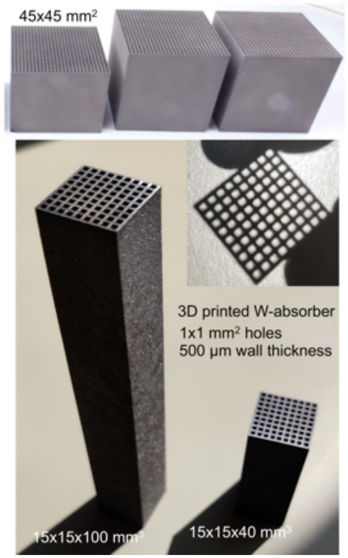
JINST 15 (2020) P09029

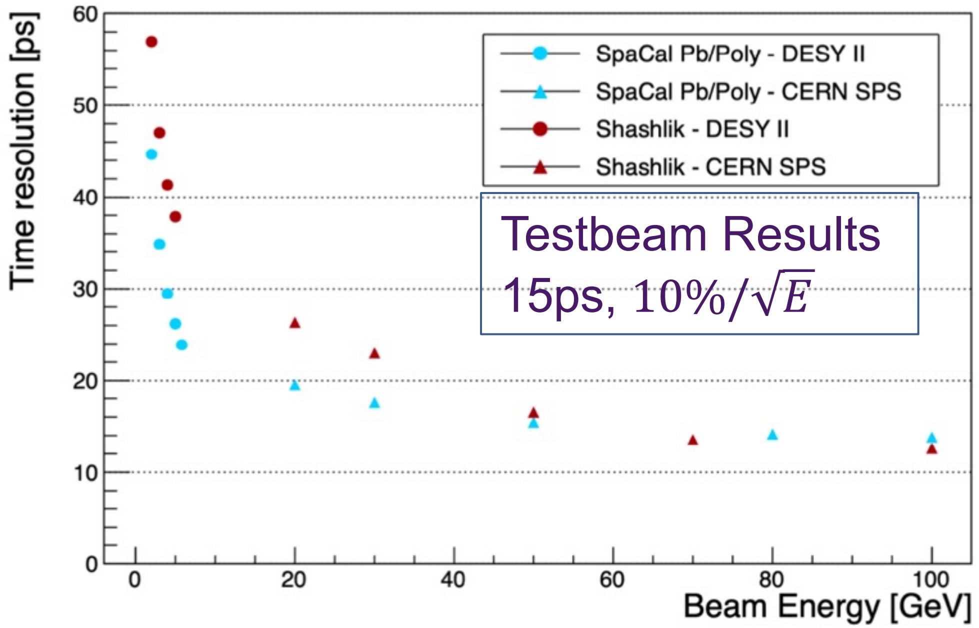
5D Calorimetry: Precision timing

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



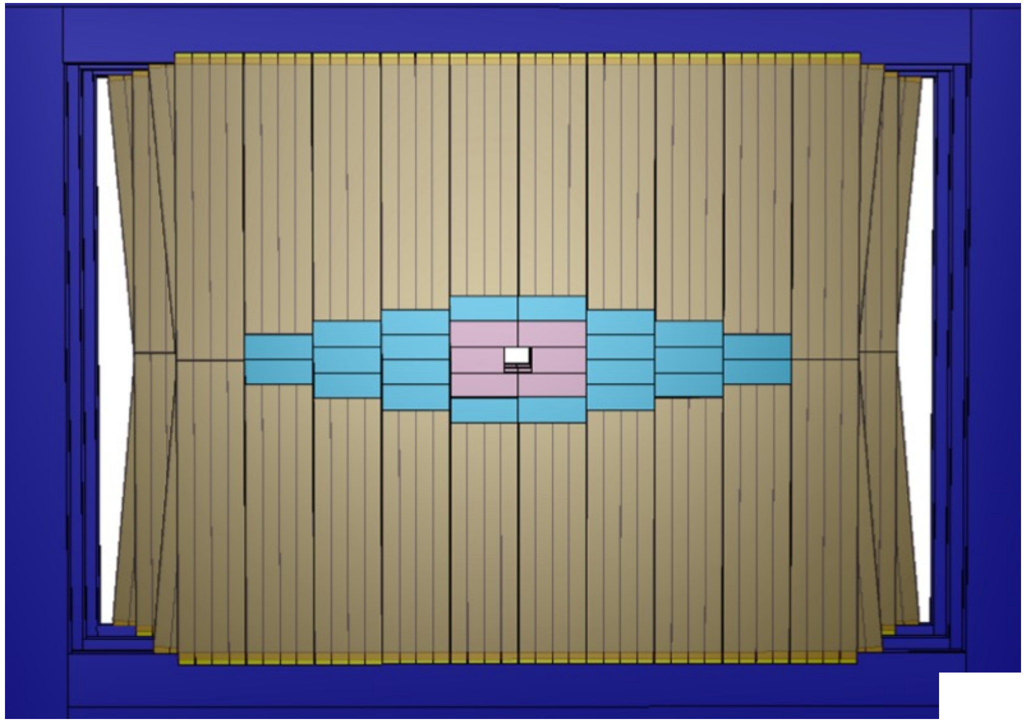


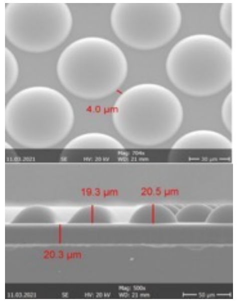


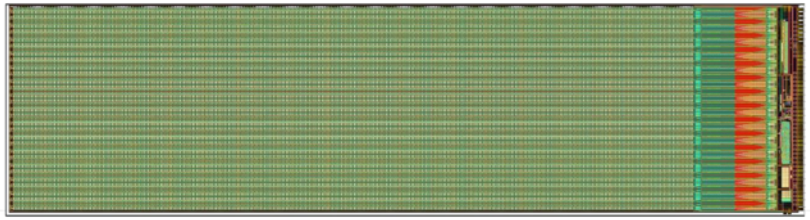


Tracker: Rad Hard MAPs, first of kind at LHC

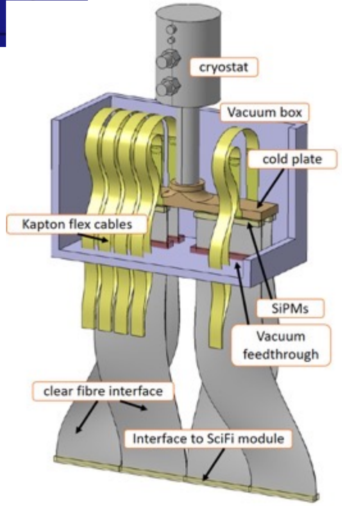
- UT – before magnet
- Mighty tracker – SciFi+CMOS – after magnet
- Monolithic Active Pixel Sensors $(50\times150\mu m^2)$
  - Radiation requirements in UT $3\times10^{15}n_{eq}/cm^2$
  - low-cost commercial process, low material budget
- Scintillating fibres in outer region
  - radiation-hard fibres,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







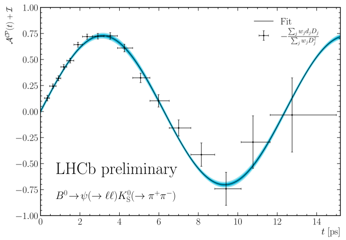
MightyPix1 1/4 scale chip fabricated



Summary

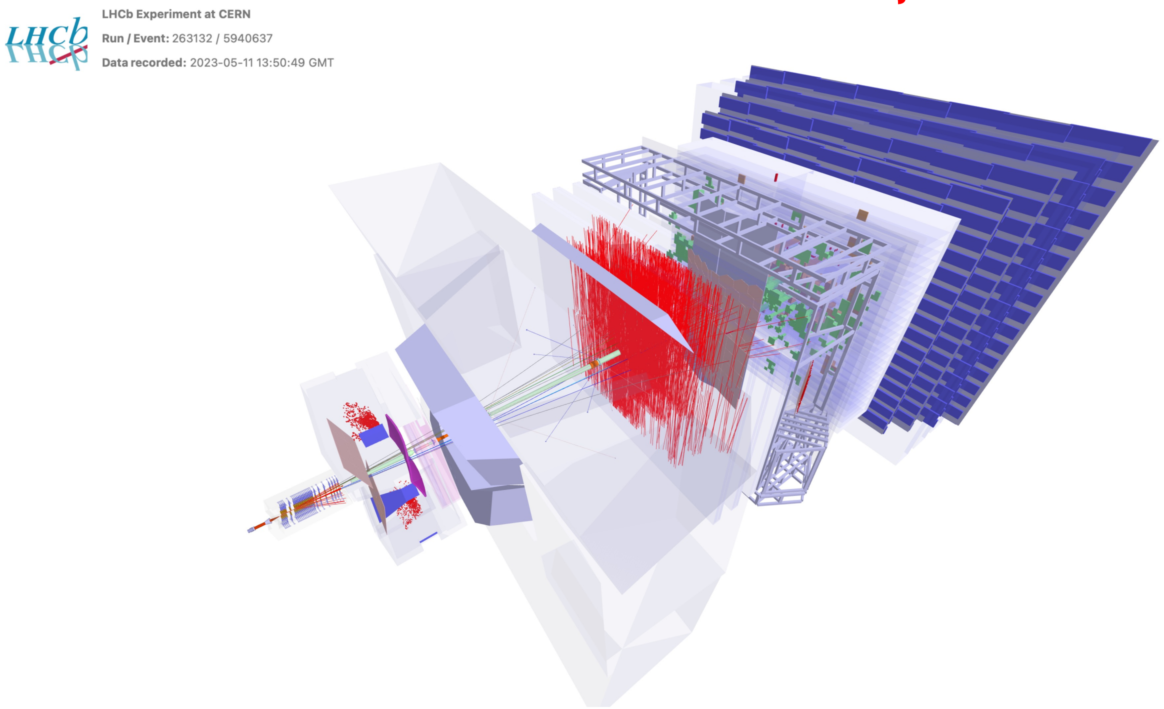
Original	Upgrade I	Upgrade II
2009-2018	2022-2032	2033-

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



- LHCb Upgrade I
  - – Largest CERN particle physics project since LHC completion
  - – Despite pandemic completed for Run 3

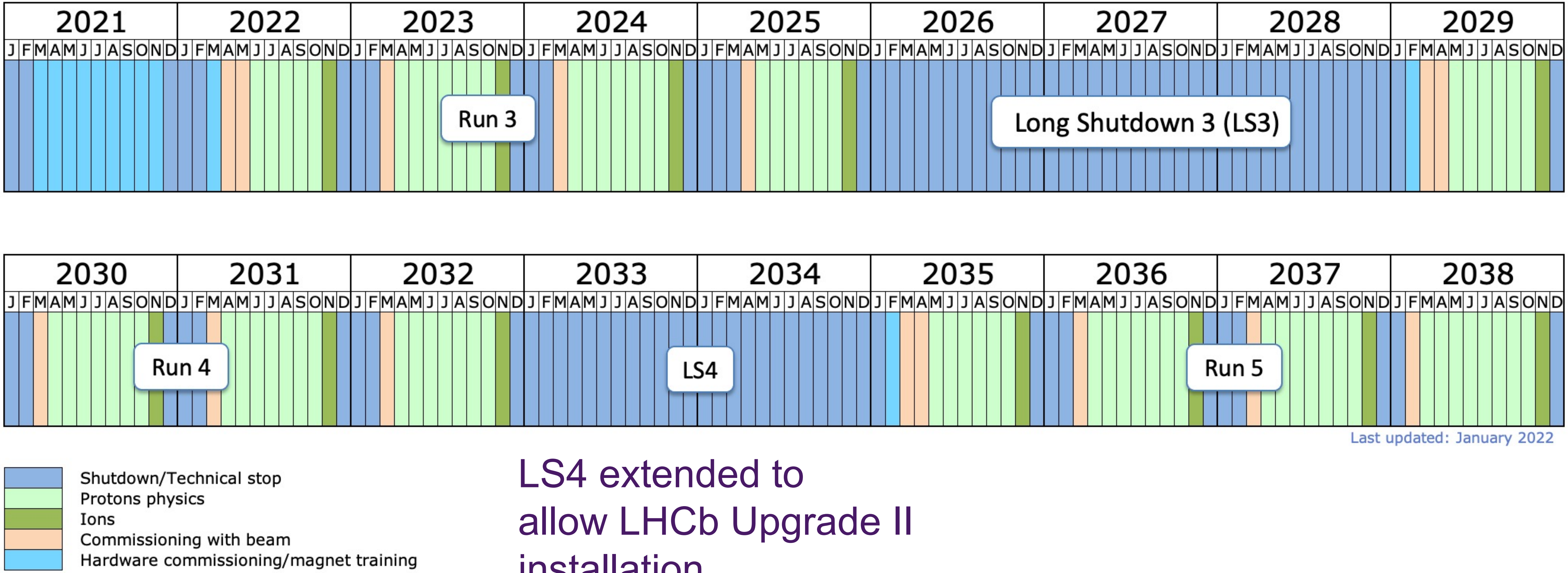
Born to Run 3



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

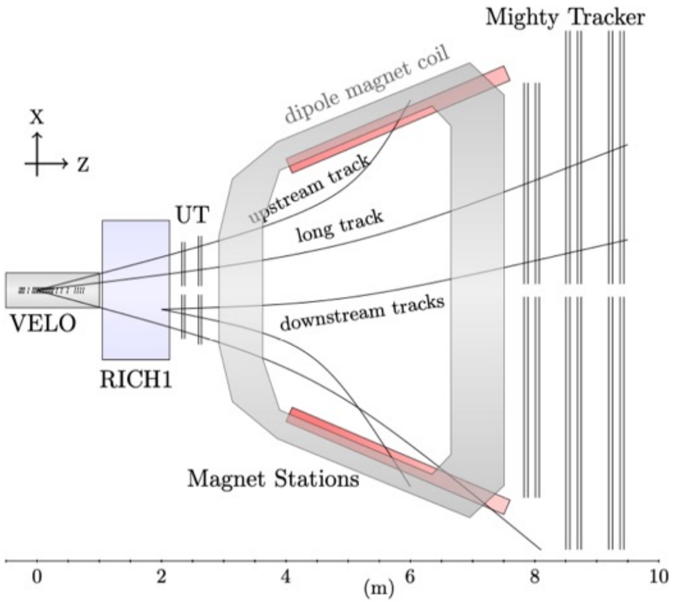
Backup

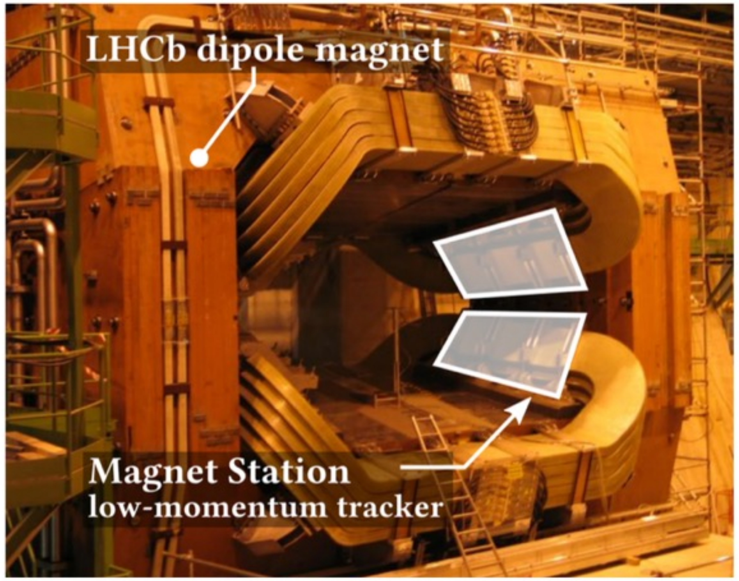
LHC Schedule

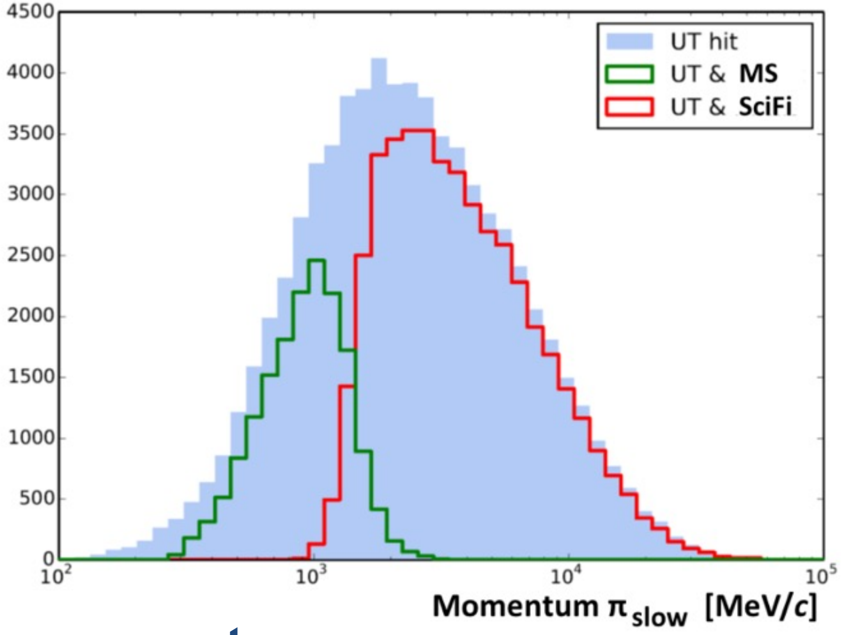


LS4 extended to allow LHCb Upgrade II installation

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

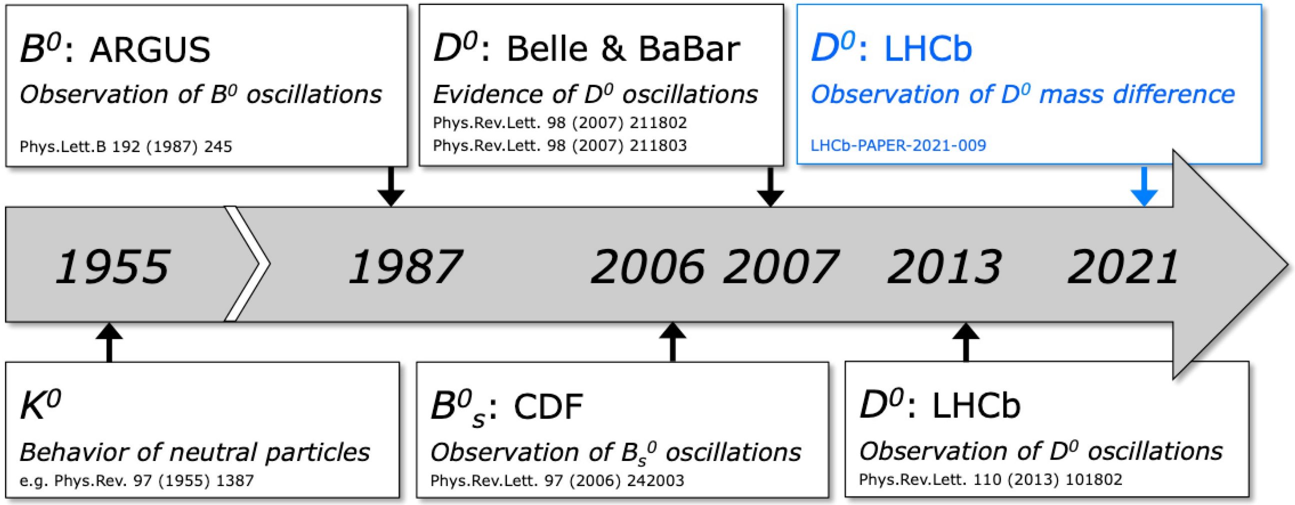
e.g. factor of ~2 gain in prompt D^{*+} with slow π

D^0 mixing

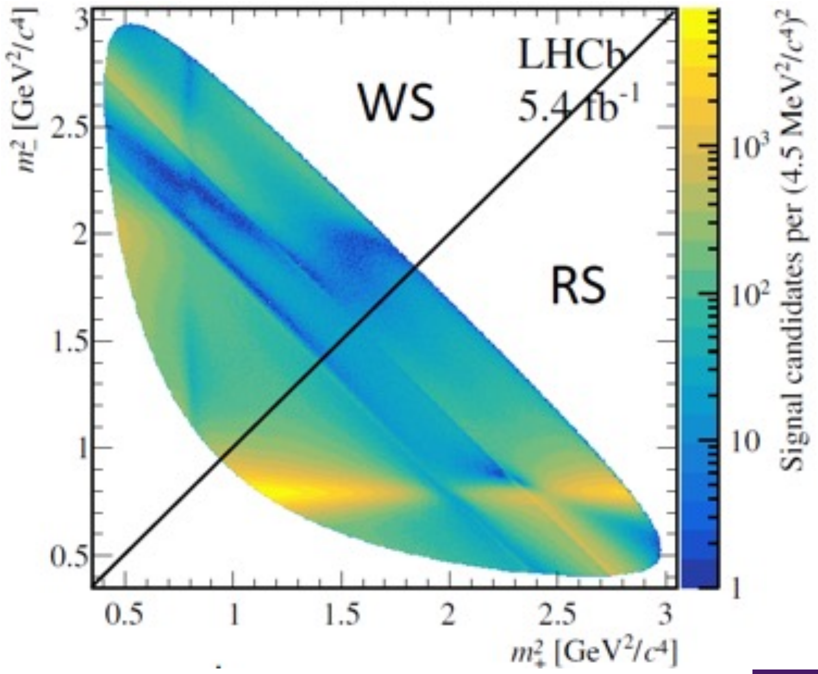
Moriond '22

arXiv 2202.09106

- Mixing parameters $x = \frac{m_1 - m_2}{\Gamma}$ & $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$ related to the mass difference and lifetime between D^0 mass eigenstates
- First observation of non-zero mass difference in 2021



$D^0 \to K_s^0 \pi^+ \pi^-$



D^0 mixing

Moriond '22

arXiv 2202.09106

- Mixing parameters $x = \frac{m_1 - m_2}{\Gamma}$ & $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$ related to the mass difference and lifetime between D^0 mass eigenstates
- First observation of non-zero mass difference in 2021
- y is accessible via the lifetime difference between $D^0 \to K^-\pi^+$ and $D^0 \to f$ $(f = \pi^+\pi^-, K^+K^-)$

$$\frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to f)} - 1 = y_{CP}^f - y_{CP}^{K\pi} \simeq y(1 + \sqrt{R_D})$$

  - 100M events available in Run 2
- Combining $\pi^+\pi^-$ and K^+K^- we get:

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26_{stat} \pm 0.13_{syst})\times 10^{-3}$$

- Four times better than previous world average (already dominated by LHCb)