Flavour programme at colliders

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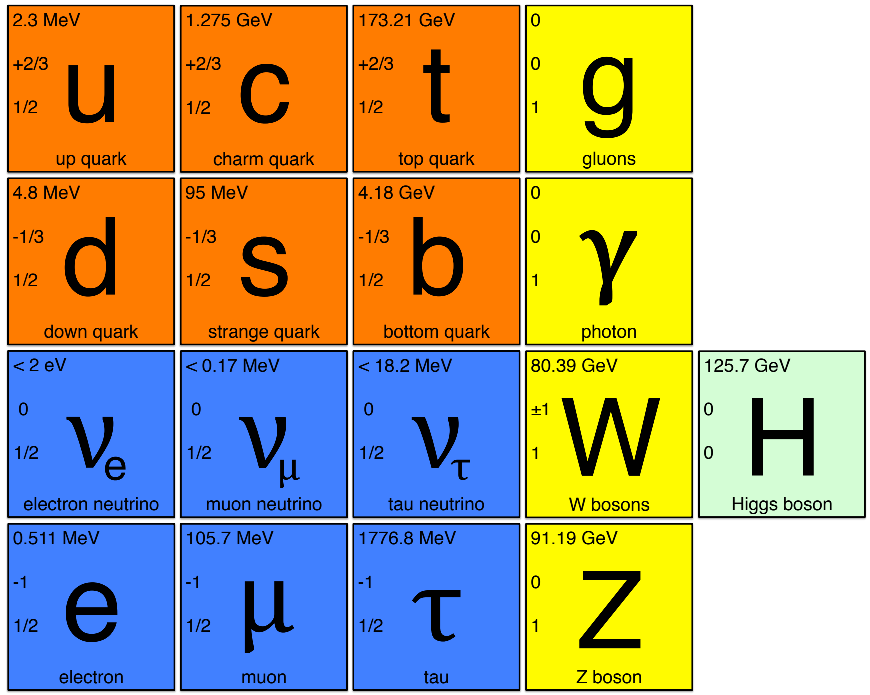
UNIVERSITY OF CAMBRIDGE

Flavour physics

Why six quarks and six leptons?

CP violation?

What drives the hierarchy of fermion masses?



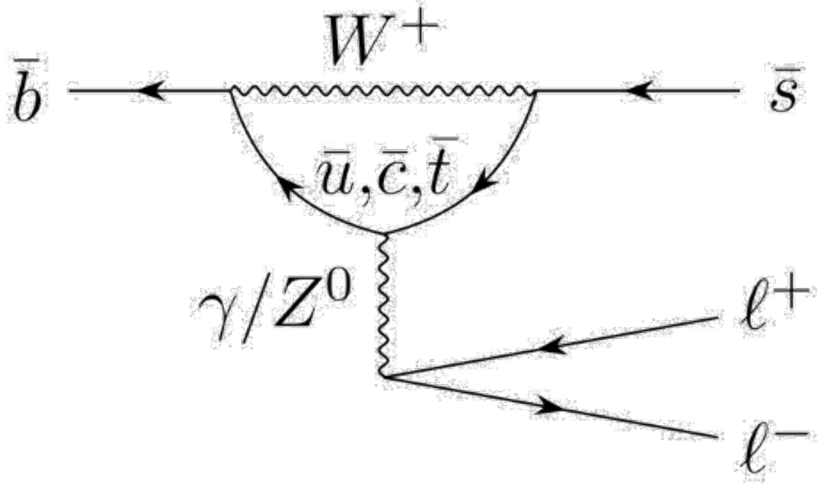
What explains the pattern of mixing between generations?

Are quarks and leptons connected?

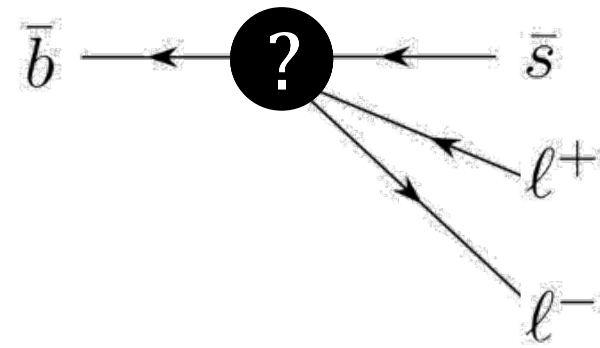
All these questions can be probed by studying beauty and charm quarks

Flavour as a probe of new physics

Standard Model

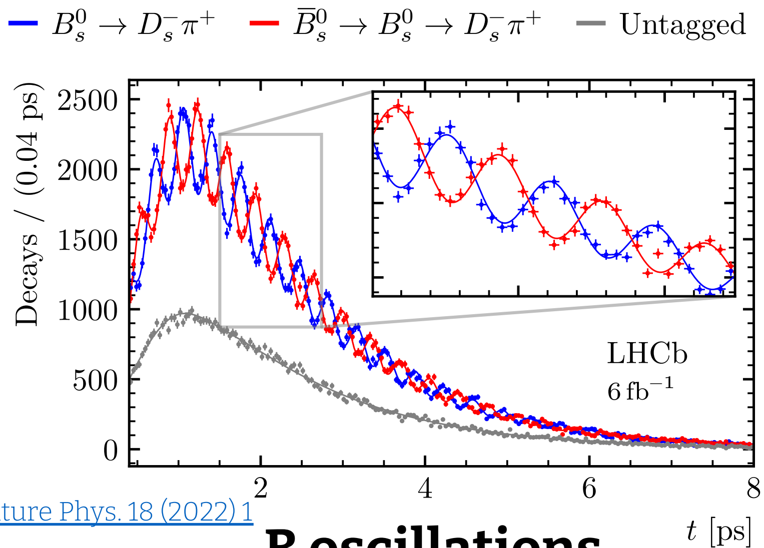


New Physics



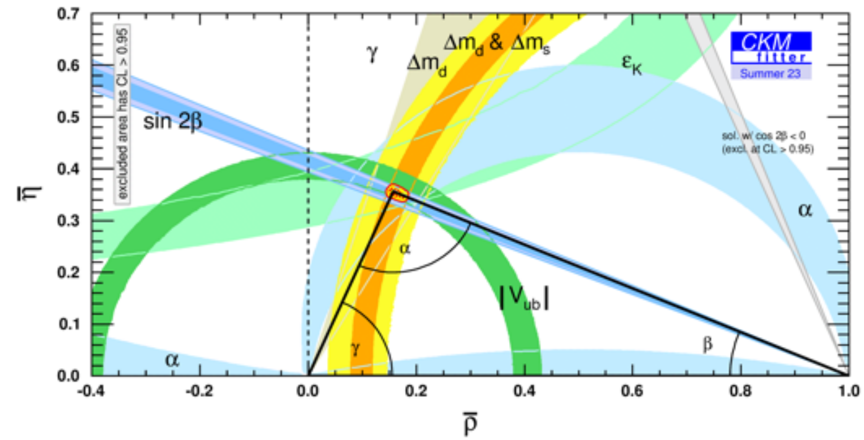
- studying heavy flavour decays gives sensitivity to BSM quantum fields in the loops
- sensitive to energy scales above direct reach of LHC (up to 100 TeV in FCNC b decays)

Flavour physics at the LHC



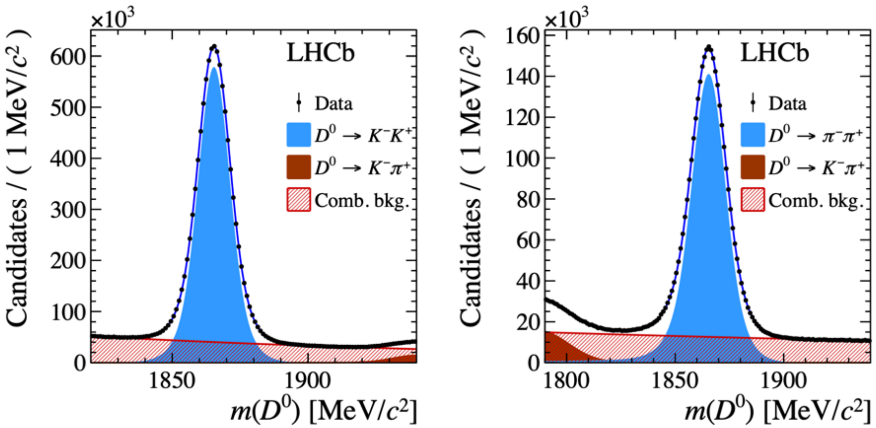
[Nature Phys. 18 (2022) 1]

B oscillations

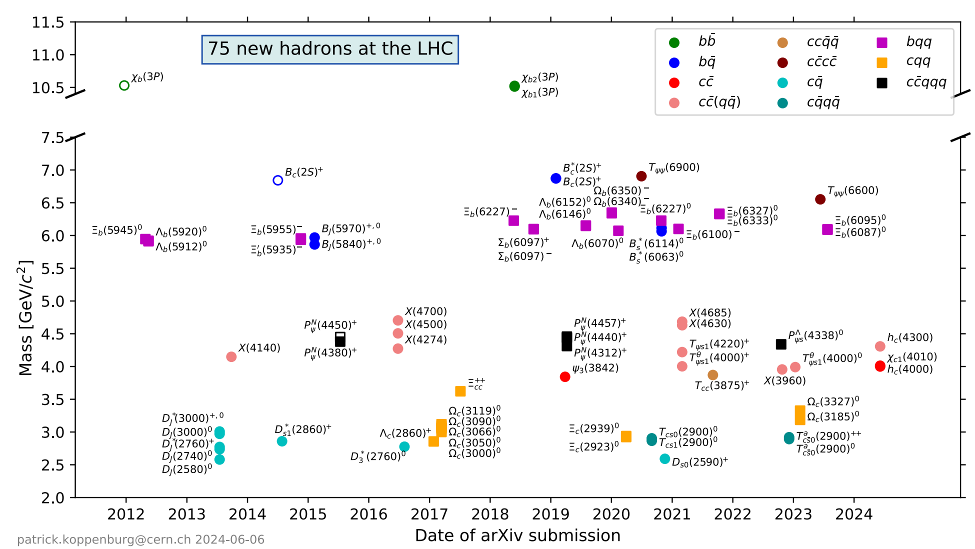


CKM triangle

[Phys. Rev. Lett. 122 (2019) 211803]



CP violation in charm

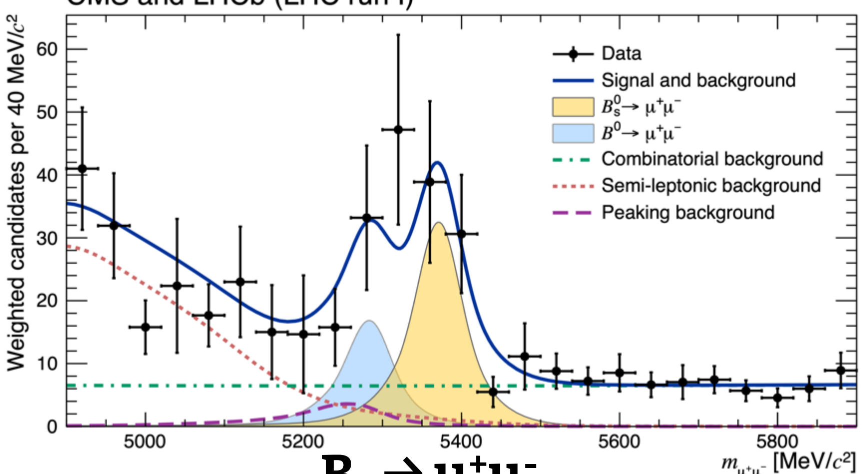


Exotic hadrons

Flavour physics at the LHC

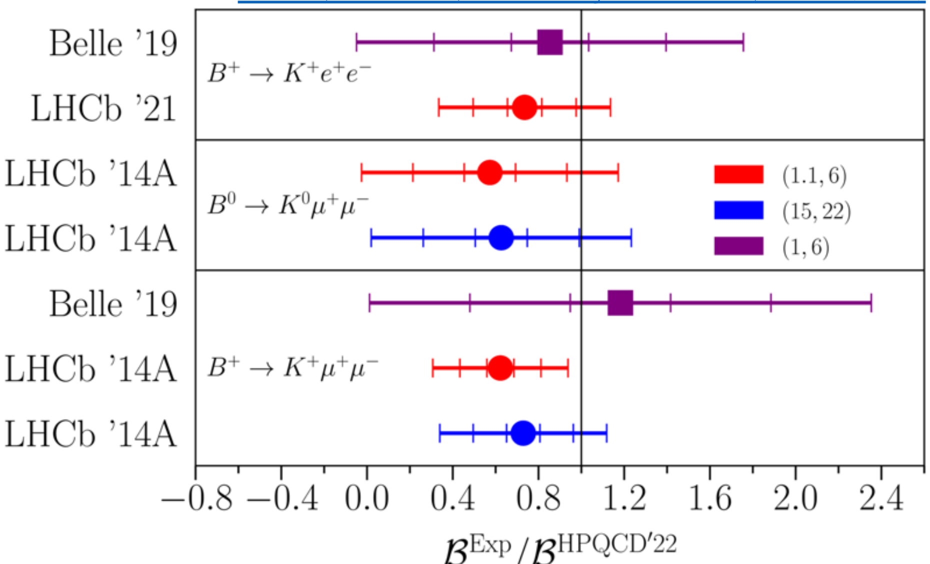
[Nature 522 (2015), 68-72]

CMS and LHCb (LHC run I)



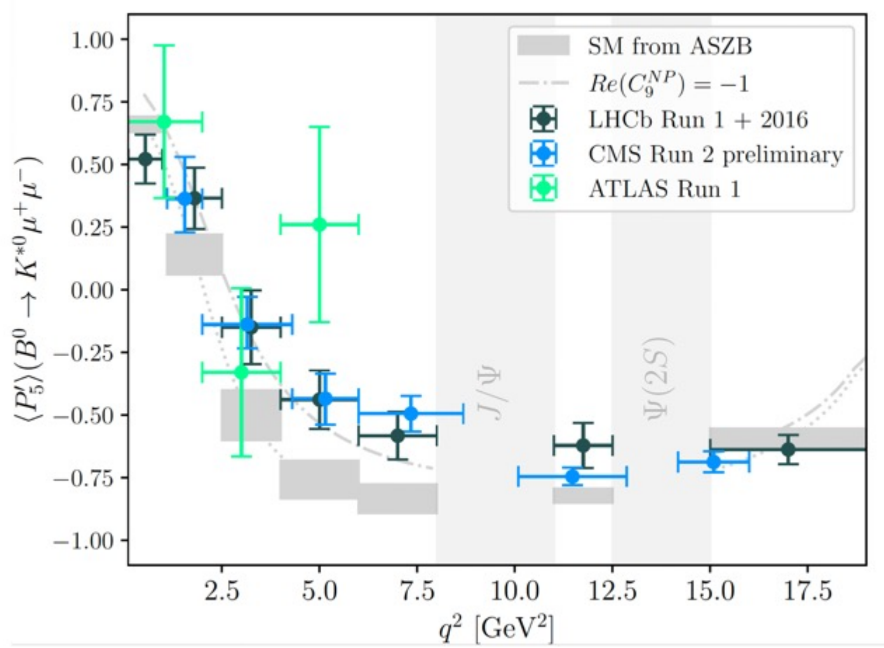
$B_s \to \mu^+\mu^-$

[Parrott, Bouchard, Davies: Phys. Rev. D 107, 014511 (2023)]



FCNC branching fractions

[Eluned Smith @LHCP]



FCNC angular

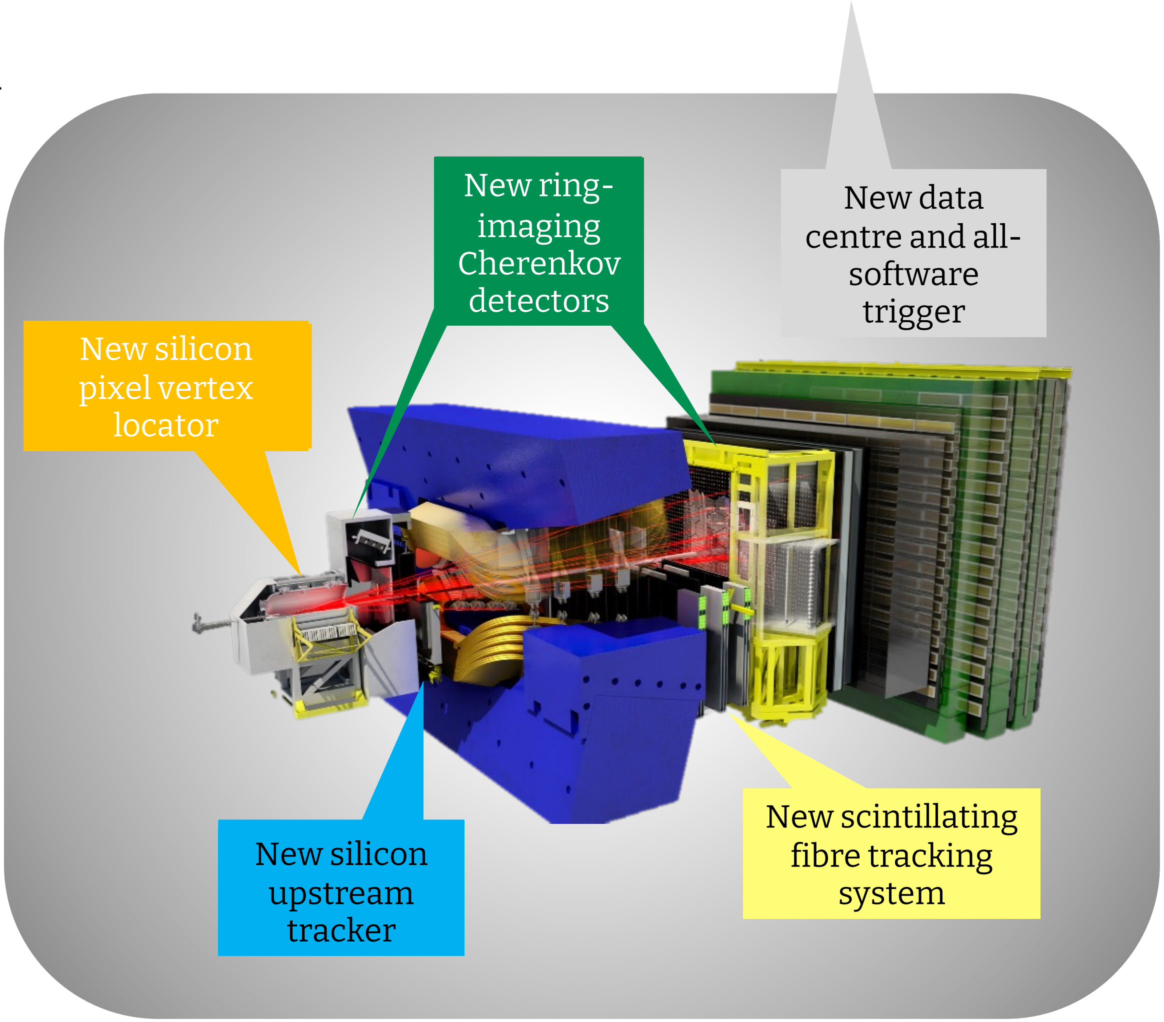
The LHCb Upgrade I

Major upgrade to LHCb now in operation:

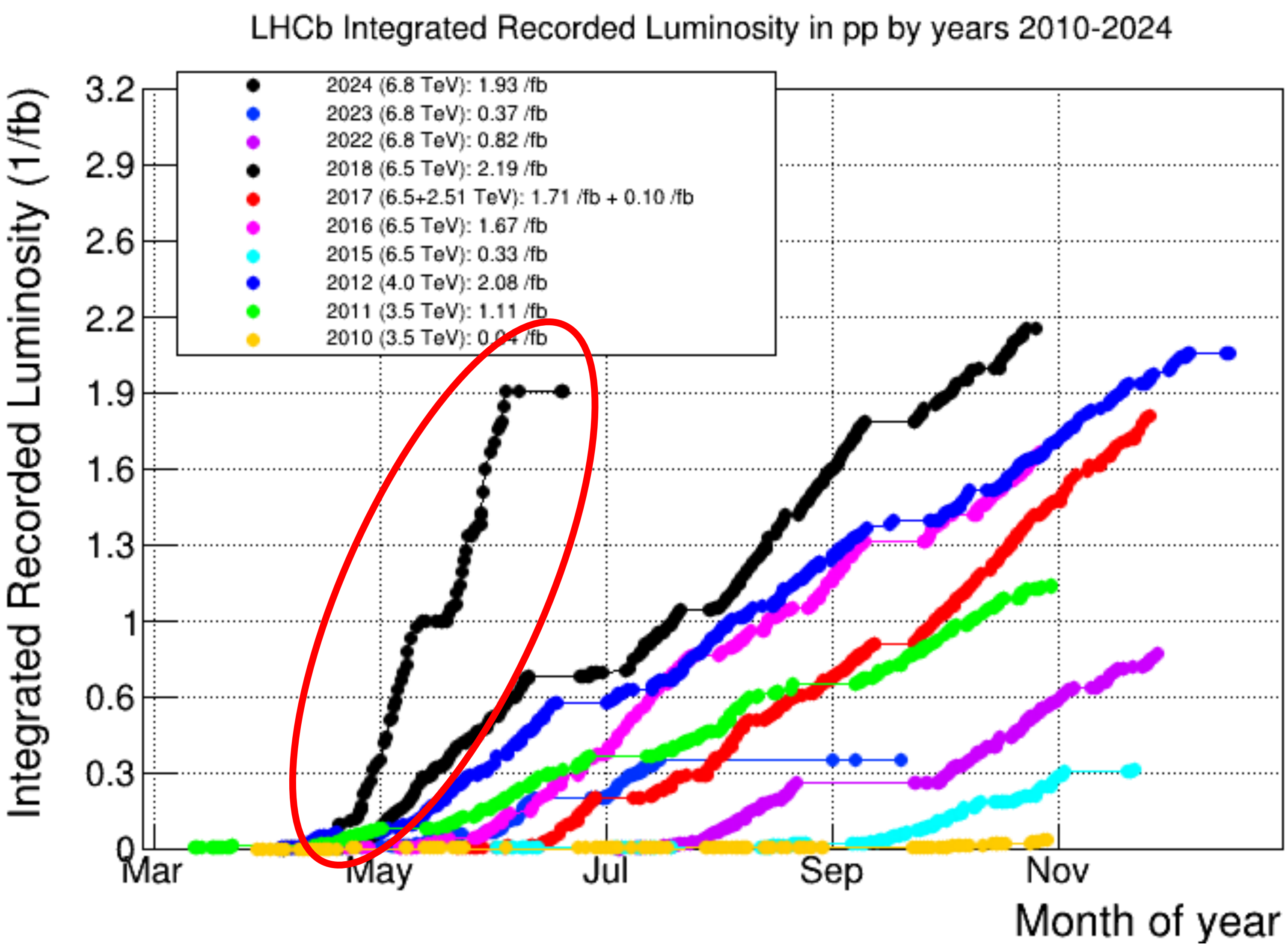
- Almost all-new detector to allow readout at 30 MHz
- Removal of hardware trigger
- Full software trigger

Unprecedented beauty samples:

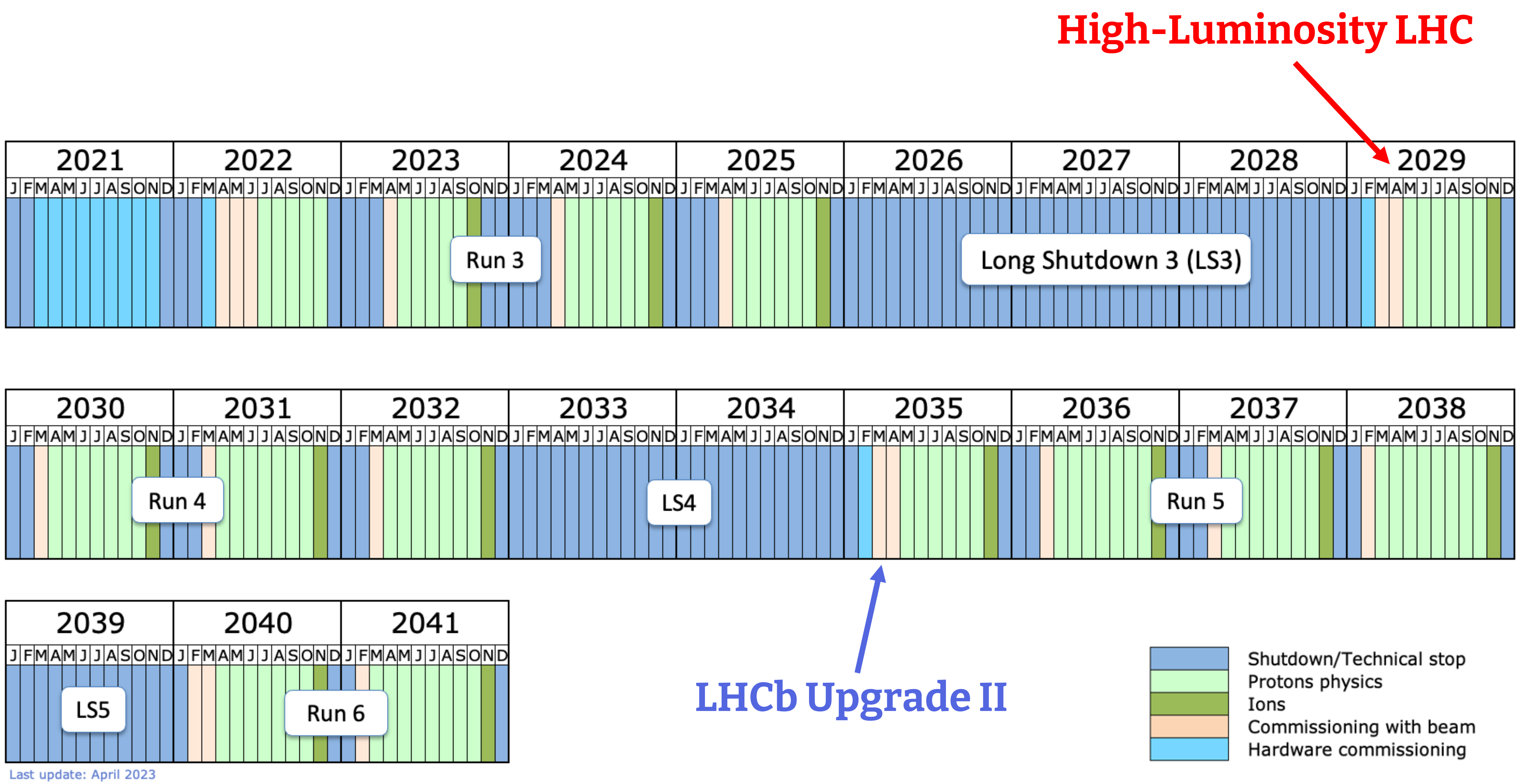
- Targeting 50fb^{-1} by end of Run 4
- Significant increase in trigger efficiencies for many modes



LHCb Upgrade I



LHC Schedule



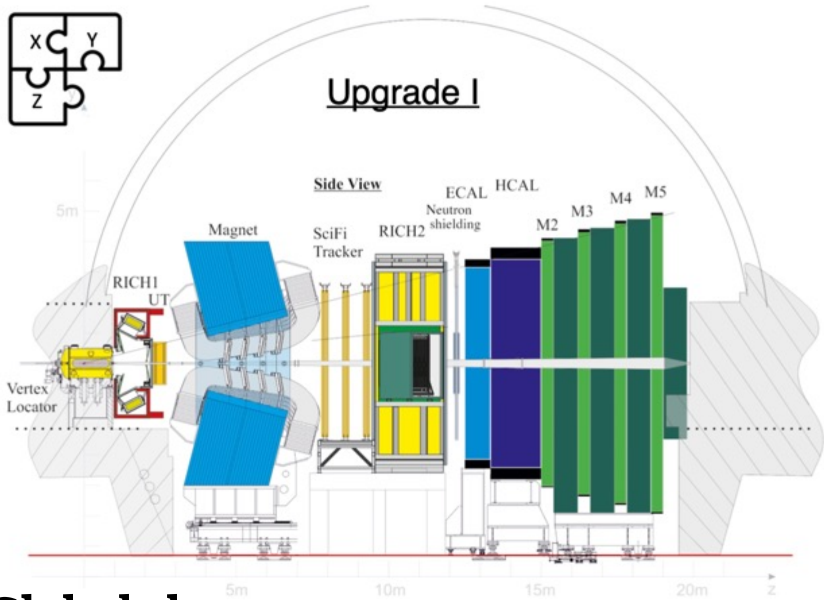
European Strategy Update 2020: *"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"*

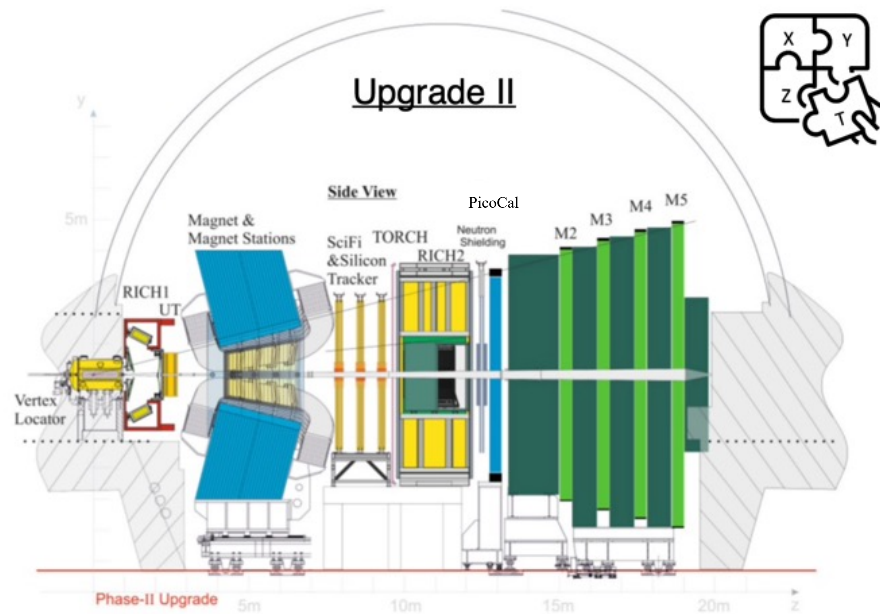
LHCb Upgrade II

Detector for the HL-LHC era

Most physics statistically rather than systematically or theoretically limited→ motivates high luminosity experiment.

Aim to record 300fb^{-1} by end of HL-LHC.





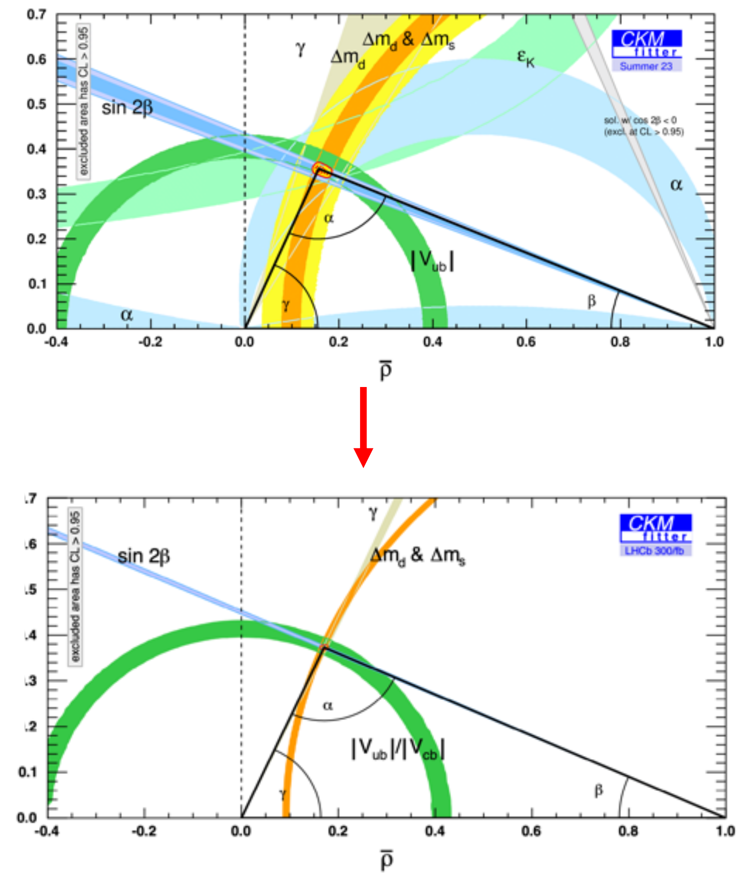
Global changes:

- Fast timing to reduce backgrounds
- Radiation hardness
- Removal of HCAL, introduction of TORCH and magnet tracking stations

LHCb Upgrade II - Physics

Targeting huge improvements in precision on key flavour observables

Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)		Upgrade I ($23\,\text{fb}^{-1}$)	($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
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
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a^d_{sl} ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a^s_{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 ($D^0 \to K^0_S\pi^+\pi^-$)	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
$A^{(2)}_{\text{T}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A^{Im}_{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
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038



LHCb Upgrade II – Luminosity

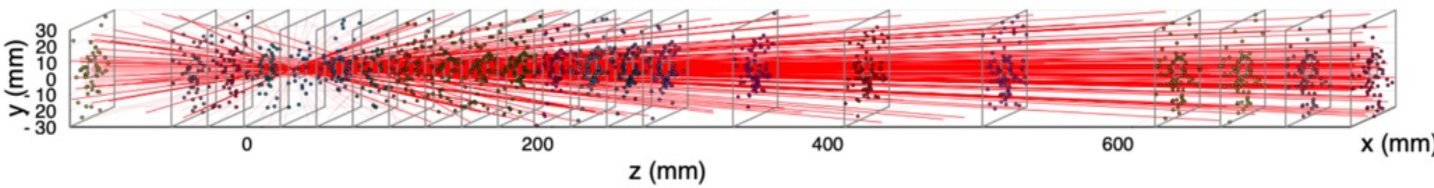
The challenge of luminosity

- Instantaneous luminosity increase from 2×10^{33} cm^{-2} s^{-1} to 1.5×10^{34} cm^{-2}s^{-1}
- 42 interactions per bunch crossing
- 2000 charged particles within LHCb acceptance

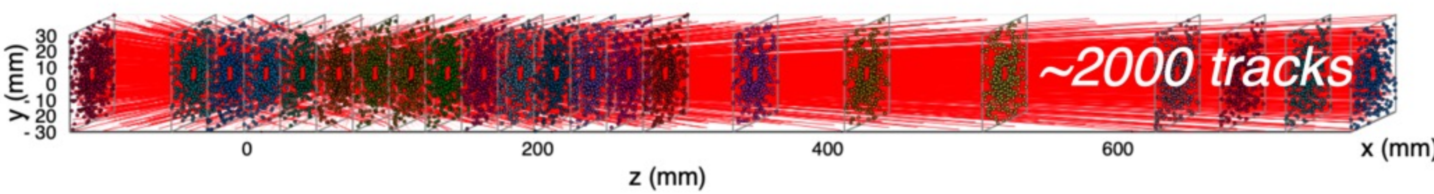
Design challenges:

1. Higher granularity, non-uniform detectors to cope with busier events
2. Radiation-hard detectors to survive intense conditions
3. Introduce fast timing to separate overlapping pp interactions

Run 3: pile-up ~6



Upgrade II: pile-up ~42



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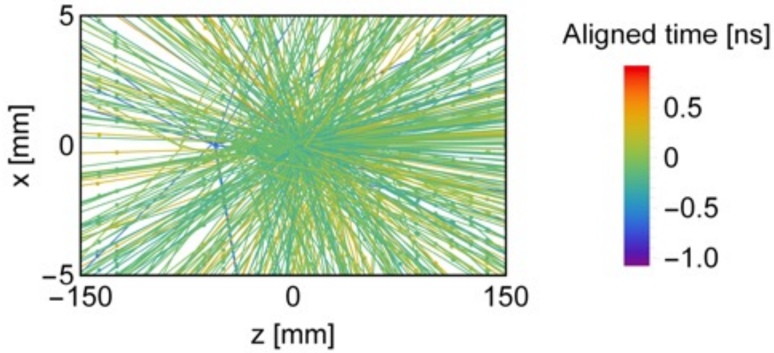
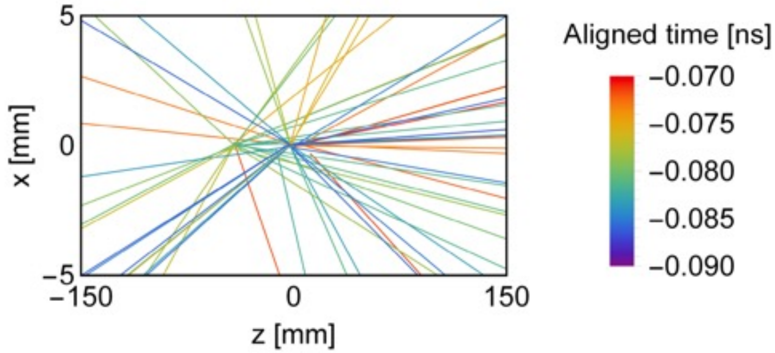
LHCb Upgrade II – Timing

Fast timing crucial to reduce backgrounds in high luminosity environment



No timing



20 ps window

LHC bunches are long (50mm) and pp interactions occur over 0.2 ns.

Timing with a few tens of ps resolution per particle allows charged tracks and photons to be associated to the correct primary vertex.

VELO, RICH, TORCH and ECAL will be fast timing detectors:

- Adds **new dimension** to information exchanged between sub-detectors
- New potential for **data suppression** in front-end hardware and software trigger
- Sets **challenging R&D requirements**, particularly for sensors and front-end ASICs.

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LHCb Upgrade II –Tracking

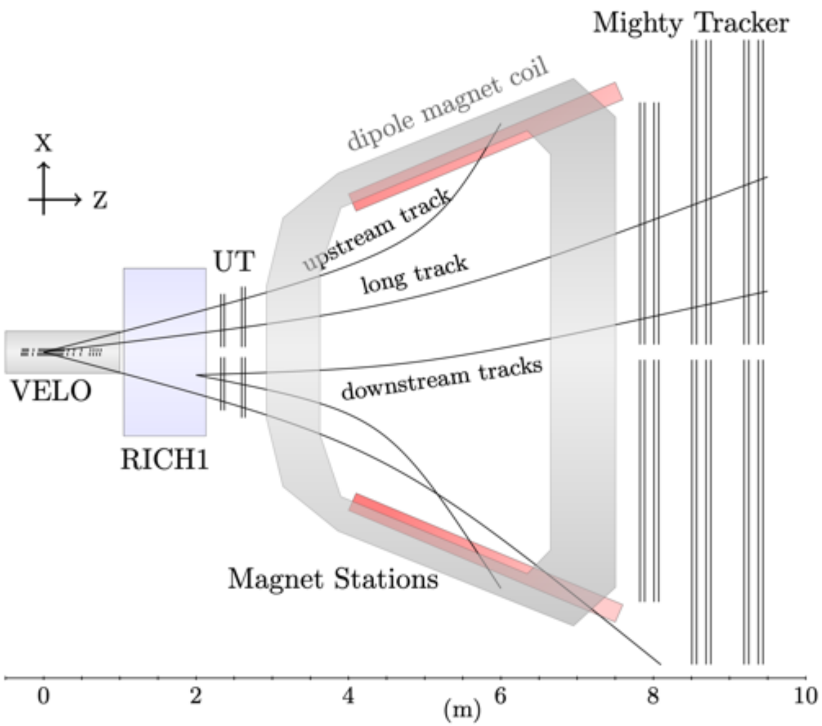
Tracking system comprised:

- **Vertex Locator** (VELO)
- **Upstream Tracker** (UT)
- **Magnet Stations** (new addition)
- **Mighty Tracker** (SciFi + inner silicon)

Higher occupancies require higher granularity.

Mismatch rate between upstream and downstream track segments needs to be minimised.

Shift from strip to pixel technology and add fast timing.



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LHCb Upgrade II –VELO

Candidate sensors:

- thin planar, 3D sensors

Candidate ASICs (28 nm technology)

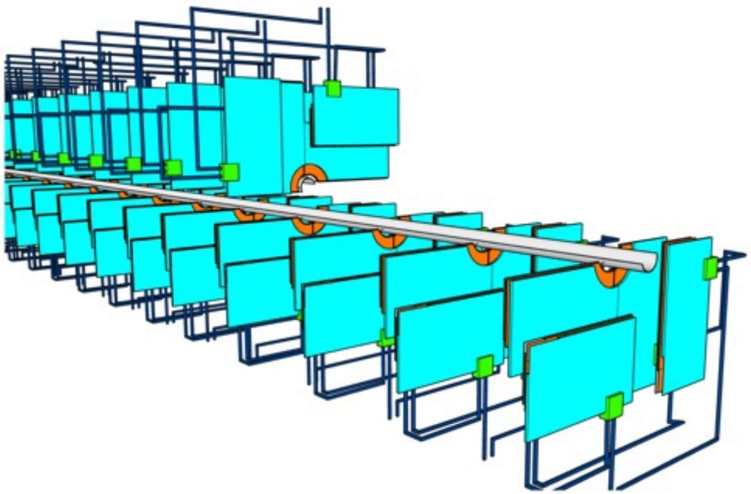
- VeloPix2, IGNITE

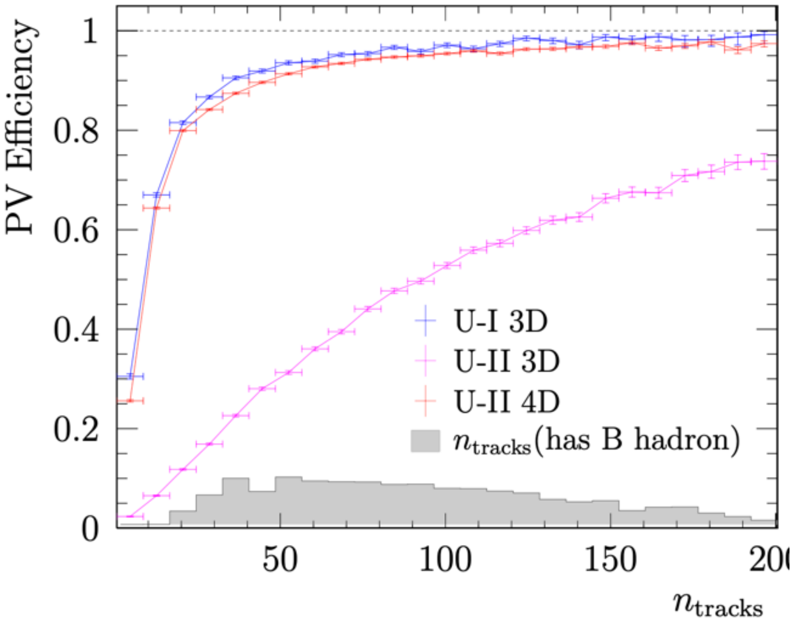
Mechanical design challenges:

- cooling, module replacement, minimisation of material (RF foil), vacuum compatibility

Timing

- Improvements in spatial resolution not sufficient
- Require track time resolution of ~20ps and hence hit time resolution of 50 ps for the 4D pixels.





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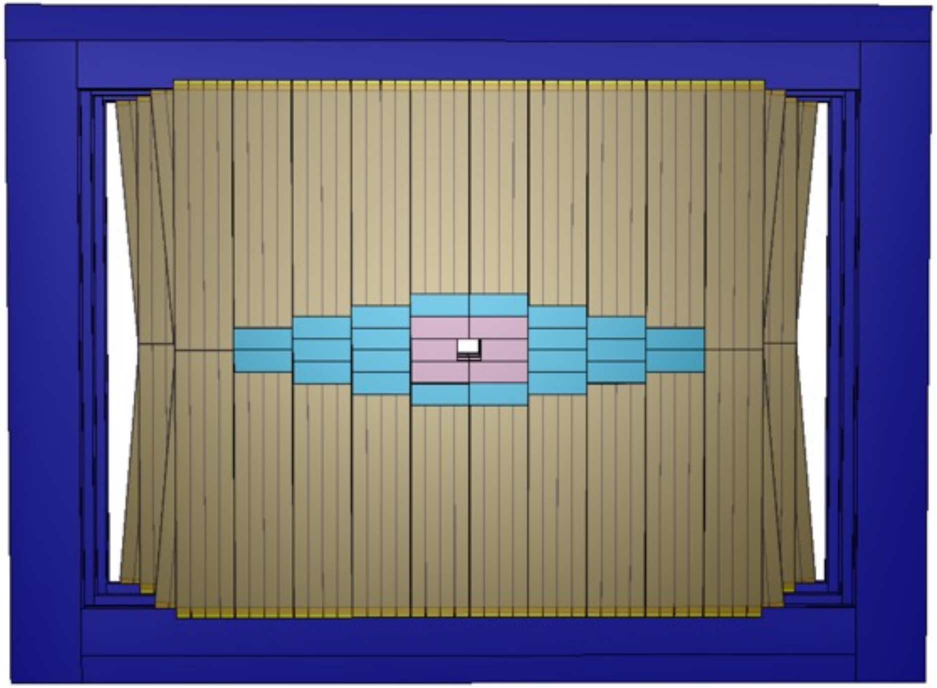
LHCb Upgrade II –MAPS Trackers

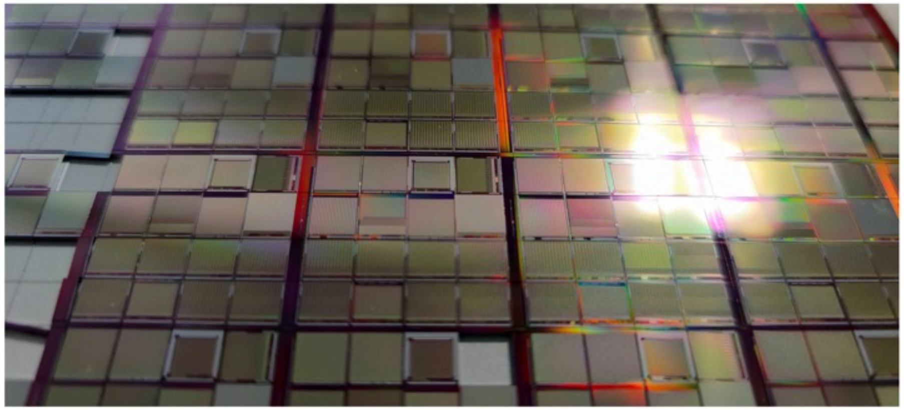
Mighty Tracker

- Replace central region of of SciFi tracking stations with silicon detecors

Use **Monolithic Active Pixel Sensors** (MAPS) for both **Mighty Tracker** and **UT**

- First large-scale tracking detector with this technology
- Meets radiation requirement ($3 \times 10^{15}\ n_{eq}/cm^2$ at UT)
- Building on experience from STAR, ALICE, ATLAS and mu3e





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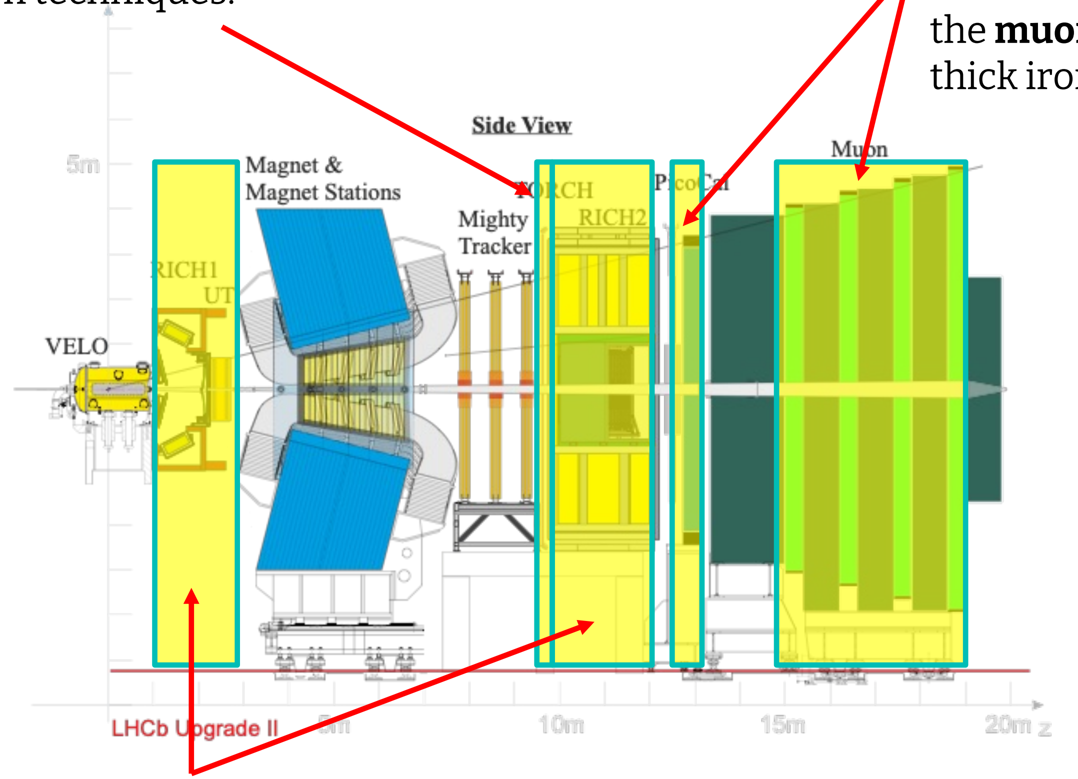
LHCb Upgrade II –Particle Identification

New **TORCH** (Time of internally reflected Cherenkov light) will cover the lower momentum range from 2-10 GeV/c by combining the time-of-flight and time-of-propagation techniques.

The electromagnetic calorimeter (**ECAL**) performs photon, electron and π^0 identification - separated from the **muon** detectors by a 1.7 m-thick iron shield.



Ring-Imaging Cherenkov detectors (**RICHs**) perform charged hadron ID from 3 GeV/c (veto mode) to 65 GeV/c using C_4F_{10} in RICH 1 and 15-100 GeV/c using CF_4 in RICH 2.

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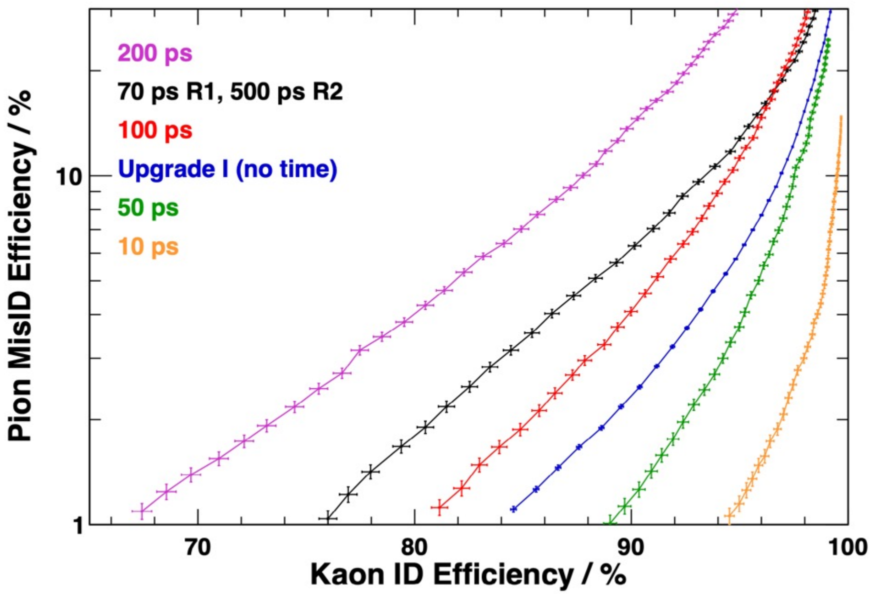
LHCb Upgrade II –RICH

RICH:

- Reduced footprint vs current detector
- Improved granularity to 1.0 x 1.0 mm^2 pixels avoids peak photon occupancy exceeding 100%
- Sensors under study: SiPMs, MCP-based detectors, next gen MaPMTs



- Using reconstructed parameters in the RICH algorithms and the PV t-zero, can predict the detector hit times to within 10 ps.
- Time gate around the predicted time significantly reduces combinatorial background and helps to recover the Run 3 particle ID performance.
- Faster detectors are better, as in practice the photon detector resolution will dominate the width of the time gate. **Aiming for a resolution better than 100 ps.**

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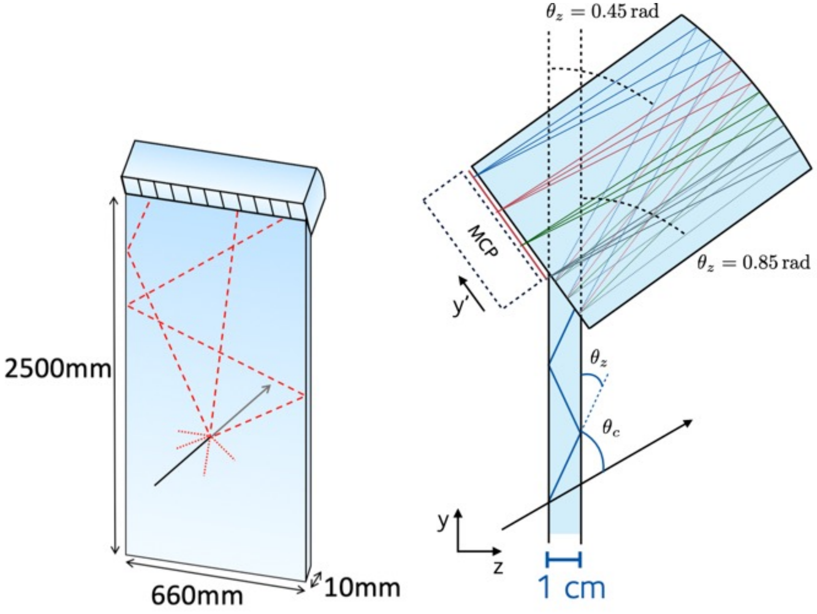
LHCb Upgrade II –TORCH

TORCH (Time Of internally Reflected CHerenkov light):

- Innovative ToF detector providing pion/kaon (kaon/proton) separation up to momenta of 10 (20) GeV.
- Highly-polished 1 cm thick quartz plate used as radiator
- Photons internally reflected and focussed onto photon detectors.
- Arrival time of photons measured precisely.

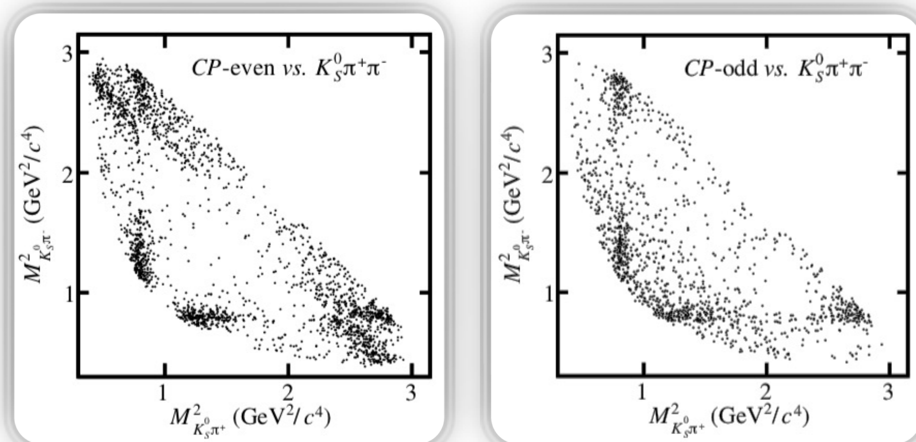


- At 10 metres from collision point require per track resolution of 15 ps for 3σ K/π separation
- Per photon resolution of 70 ps.
- "Start time" t_0 determined from timing of other tracks from primary vertex

BESIII

Beijing Spectrometer III (BESIII) runs at Beijing Electron-Positron Collider

- Variable beam energy between 2 and 4.6 GeV, luminosity 10^{33} $cm^{-2}s^{-1}$
- Charm physics with D^0/D^+: dataset 7 x larger than before now available
- Very clean e^+e^- environment. Semi-leptonic/leptonic decays for V_{cd} and V_{cs}



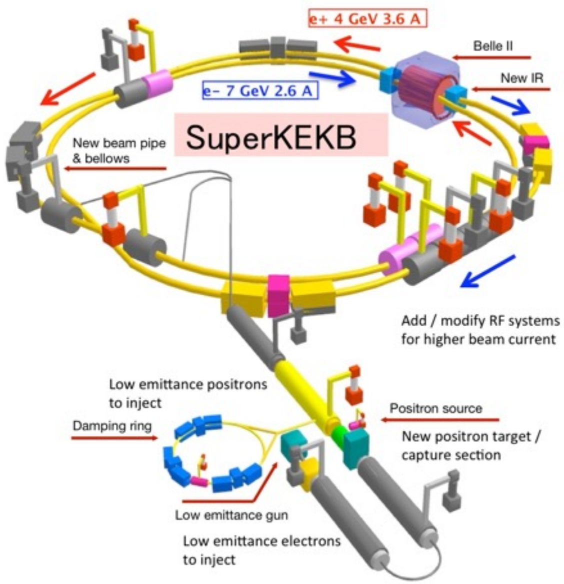
D^0 decays are quantum correlated.

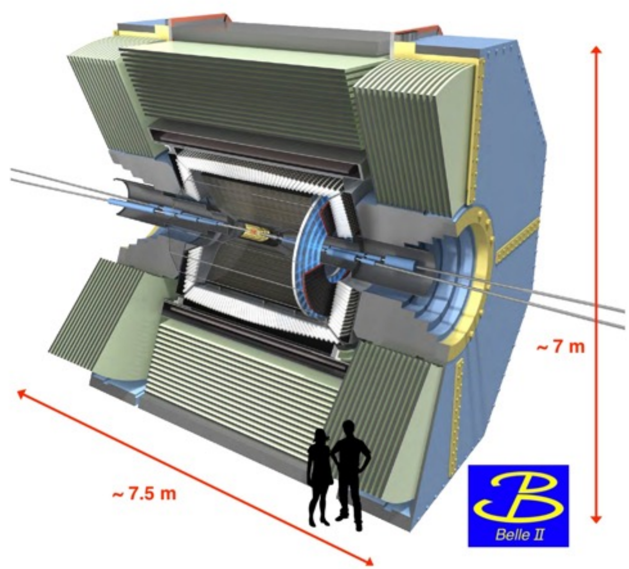
Without entanglement these plots would look identical!

- Work here forms important input to LHCb (and Belle2)
- Driven by UK groups (there are 3 on BESIII)
- Also other datasets for exotic charm spectroscopy, Λ_c physics
- **Future: Super Charm-τ Facility (STCF) -> 100 x larger dataset!**

SuperKEKB and Belle II

Major upgrade of KEKB e^+e^- collider





- Nano-beam scheme: 40 x increase in luminosity
- Asymmetric collisions at sqrt(s) = m(ϒ(4S))
- Advantages for final states with π^0, γ, K_S, K_L and neutrinos
- Higher tagging power and electron reconstruction efficiency
- Wide programme to explore e+e- → τ+τ-

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SuperKEKB and Belle II

During phase I (2019-2022) recorded 400 fb^{-1} → targeting 50 ab^{-1} by end of experiment.

Things to look forward to:

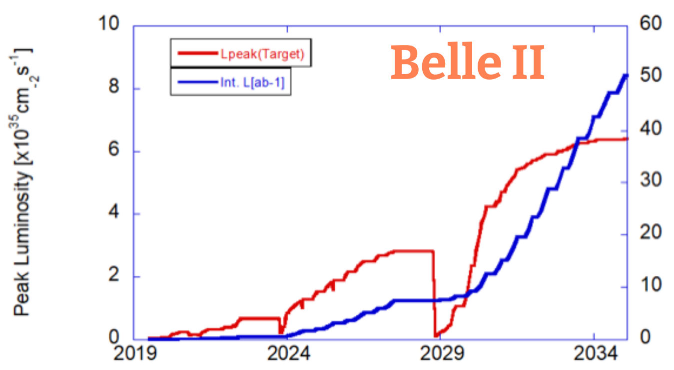
- Lepton flavour violating τ decays
- Searches for $b \to s\nu\nu$ decays
- Time dependent CPV in $b \to sg$
- Modes with neutrals, allowing flavour symmetries to be exploited
- … and many more

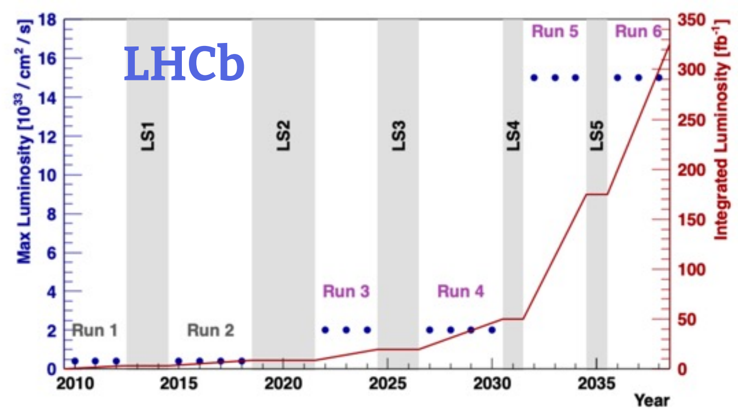
LHCb-TDR-023

Exciting times ahead

Despite all the great results that will flow from LHCb Upgrade I, most observables will still be statistically limited by the end of Run 4

- LHCb Upgrade II will make it possible to fully exploit the HL-LHC for flavour physics
- UK leadership at all levels, now in exciting R&D phase
- Also strong flavour programme at ATLAS and CMS, particularly in beauty decays to muons
- Despite challenges, Belle II will provide crucial cross-checks of LHCb results and complementary sensitivity in final states that are hard to access at LHCb
- In longer term, beauty samples from 5×10^{12} Z boson decays at FCC-ee offer opportunities in specific final states (neutrinos and taus) that complement HL-LHC programme





To FCC-ee

LHCb-TDR-023

Backup

LHCb Upgrade II –ECAL

LHCb Electromagnetic Calorimeter not replaced (except electronics) in Upgrade I

➢ During Run 3 will operate at 25x its design luminosity!

Main challenges for Upgrade II:

1. Achieving same **energy resolution** and **reconstruction efficiency** as original detector at significantly higher pile-up and occupancy
2. Radiation hard to accumulated 300 fb^{-1}

Proposal: crystal fibres (SpaCal) in central region and Shashlik (outer region)

20 ps timing information to supress background