LHCb Upgrade II

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

18th May 2022, Snowmass meeting

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On behalf of the LHCb Collaboration
The University of Manchester
CERN

LHCb Highlights

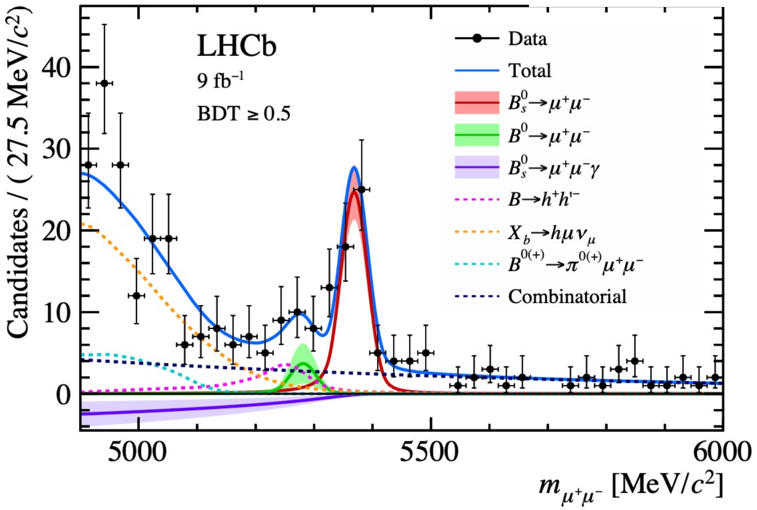
Original | 2009-2018

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

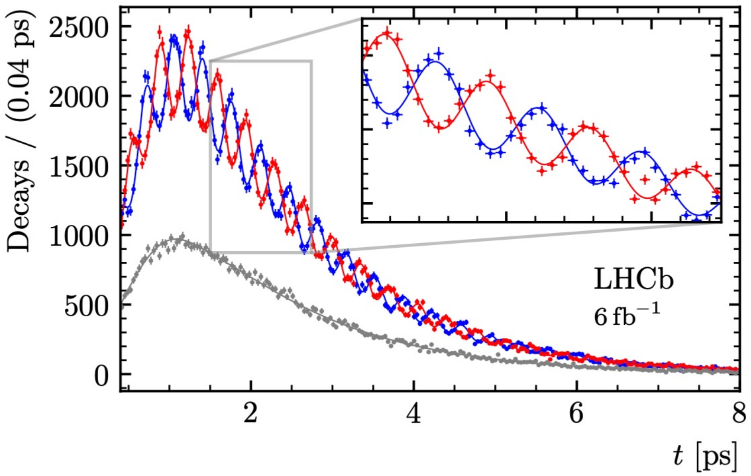
the expected…

$B_s^0 \to \mu\mu$

arXiv:2108.09284



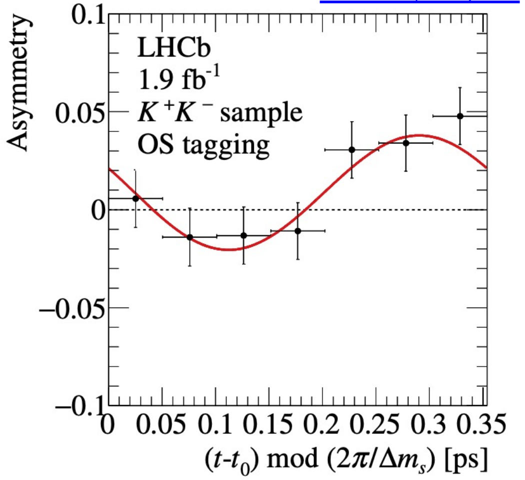
arXiv:2104.04421



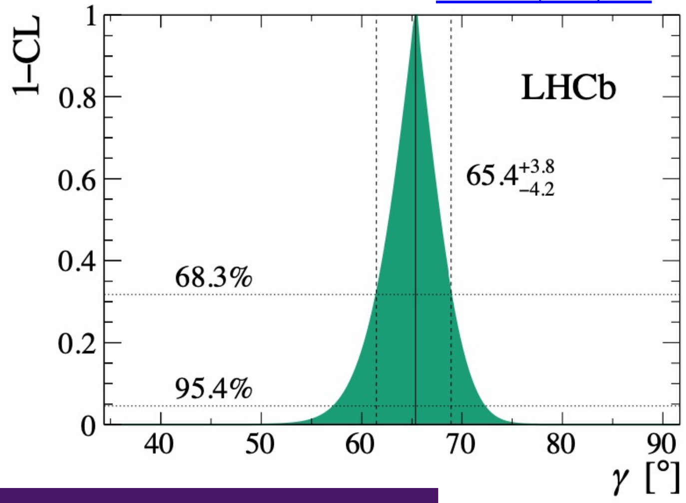
Δm_s

Time-dependent CPV in B_s

JHEP 03 (2021) 075



JHEP 12 (2021) 141



CKM angle γ

LHCb Highlights

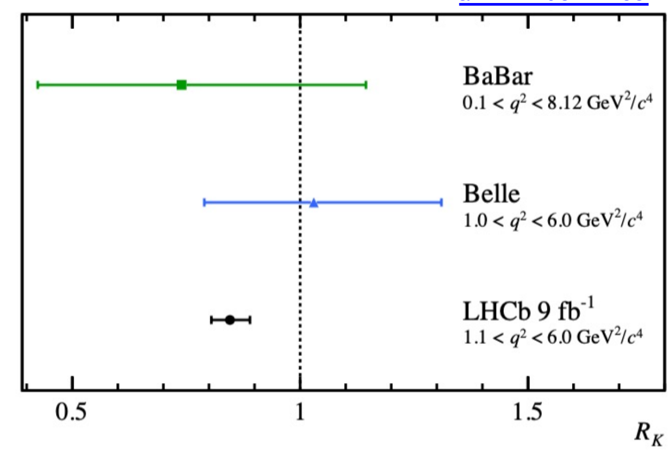
Original | 2009-2018

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

the unexpected…

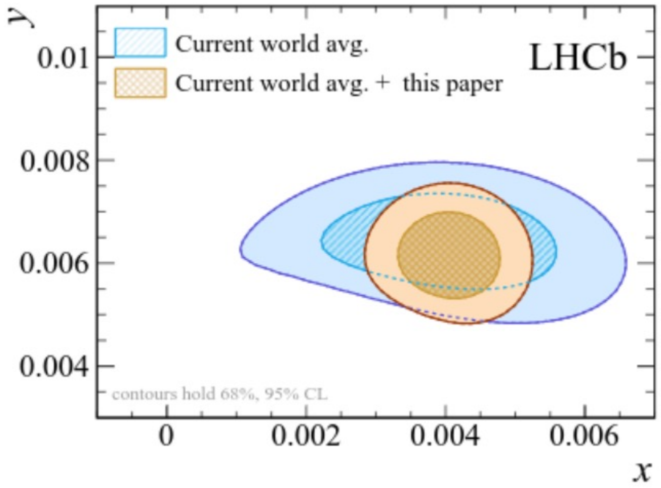
Lepton Flavour Universality

arXiv:2103.11769



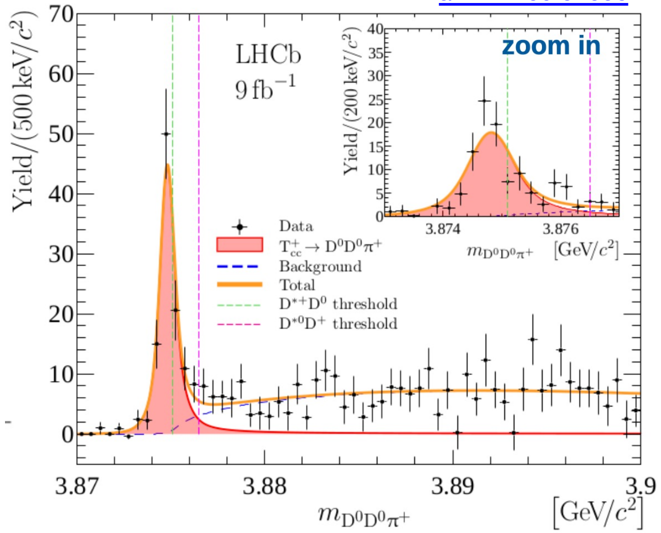
Charm physics

PRL 127 (2021) 111801



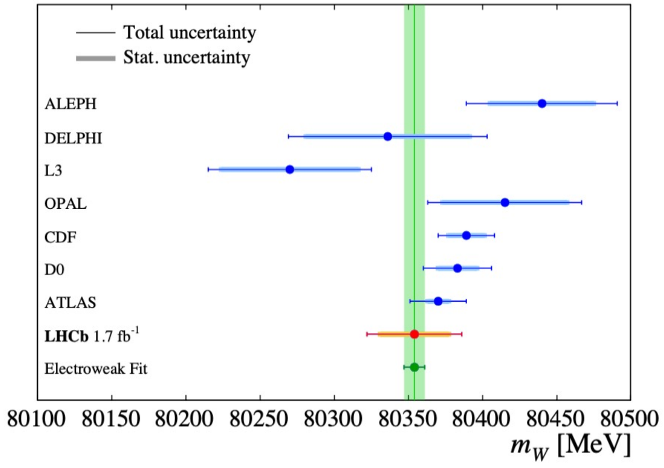
Exotic Hadrons

arXiv:2109.01038



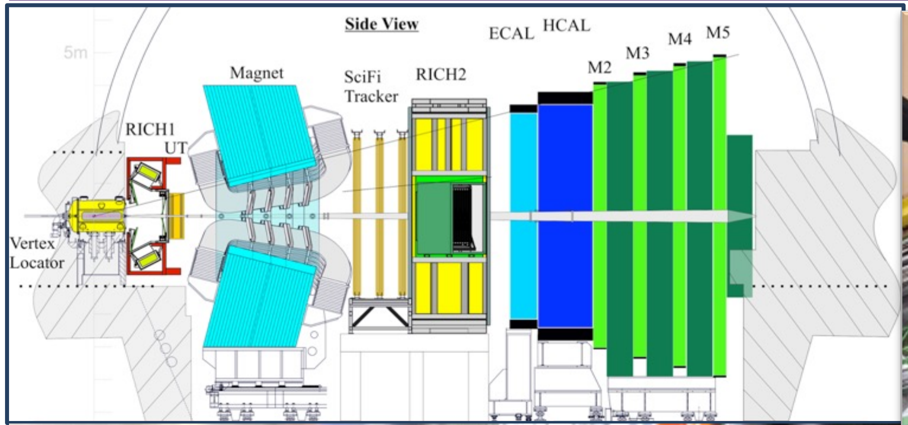
EW physics

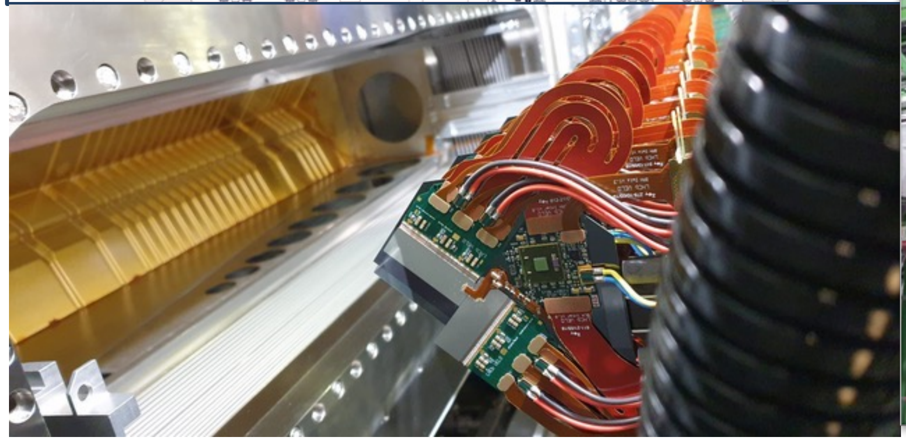
arXiv:2109.01113

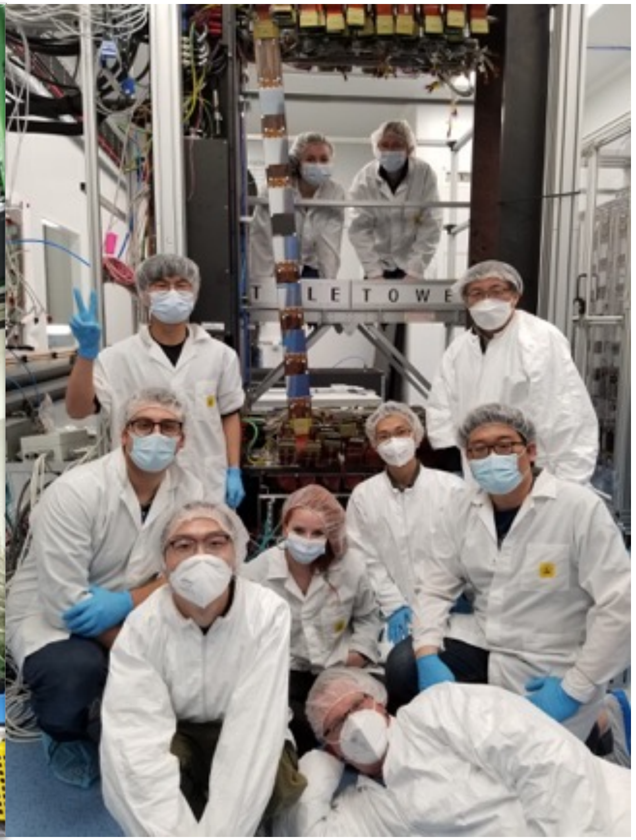


Upgrade I: major project installed

Upgrade I | 2022-2032



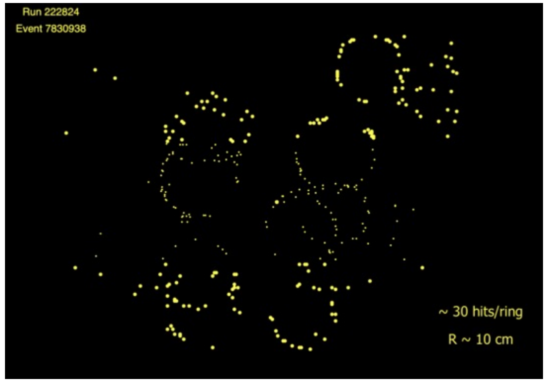




- Flexible fully software trigger
- GPUs at 1st level
- Real time analysis

(US leadership)

- Pixel detector VELO with silicon microchannel cooling 5mm from LHC beam
- New RICH mechanics, optics and photodetectors
- New silicon strip upstream tracker UT detector (**US leadership**)
- New SciFi tracker with 11,000 km of scintillating fibres

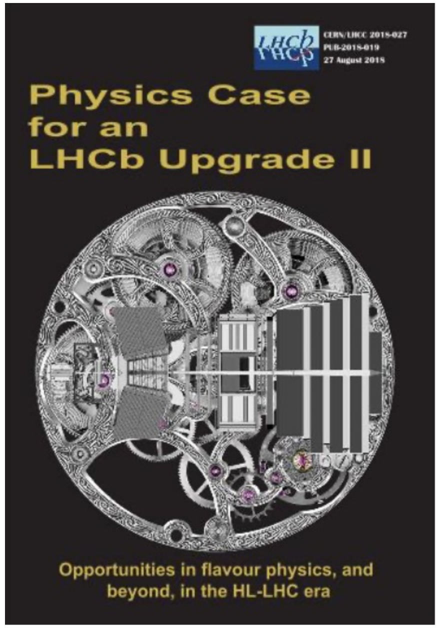


Upgrade II: steps so far

Expression of Interest

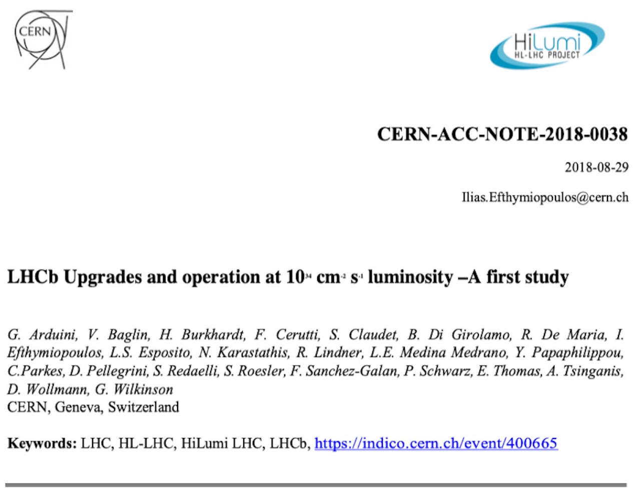
[LHCC-2017-003]

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

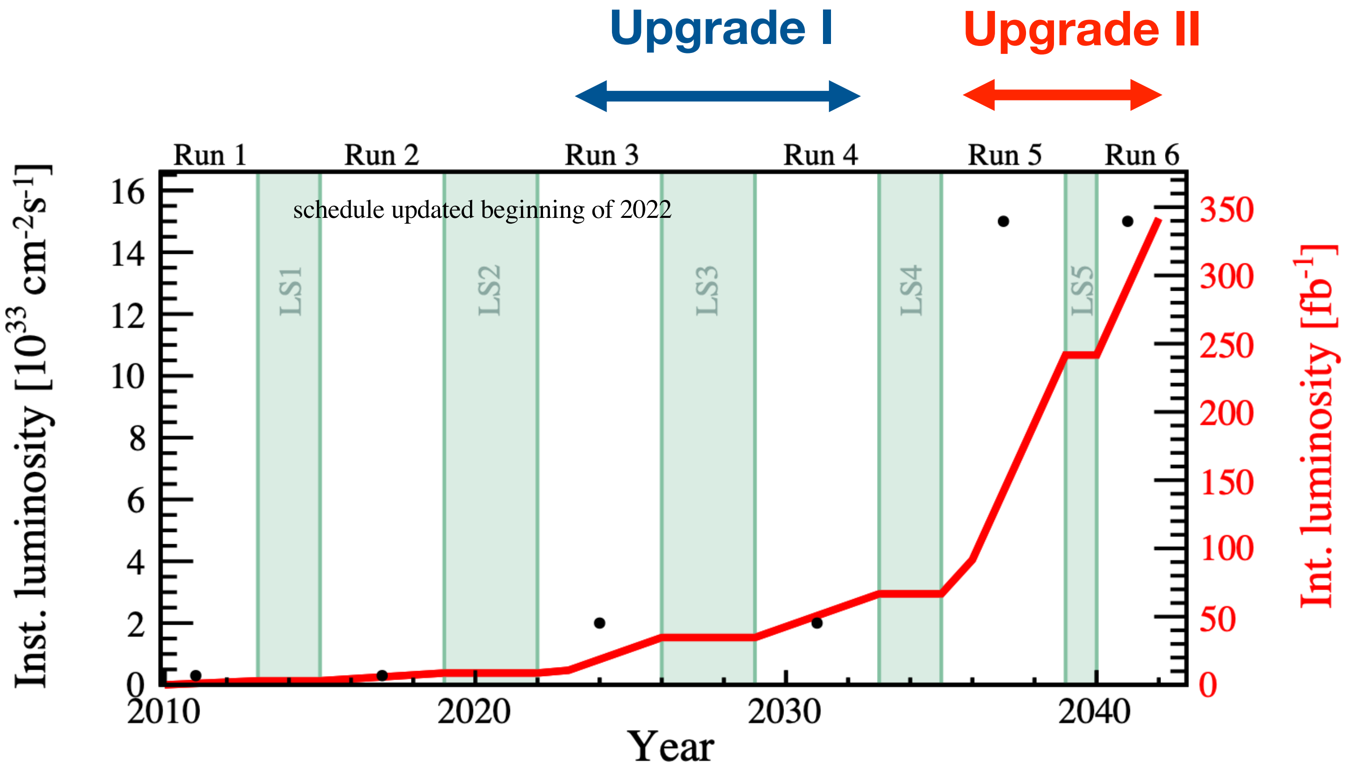
European Strategy Update 2020 ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

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*

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 ($D^0 \to K^0_S\pi^+\pi^-$)	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
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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

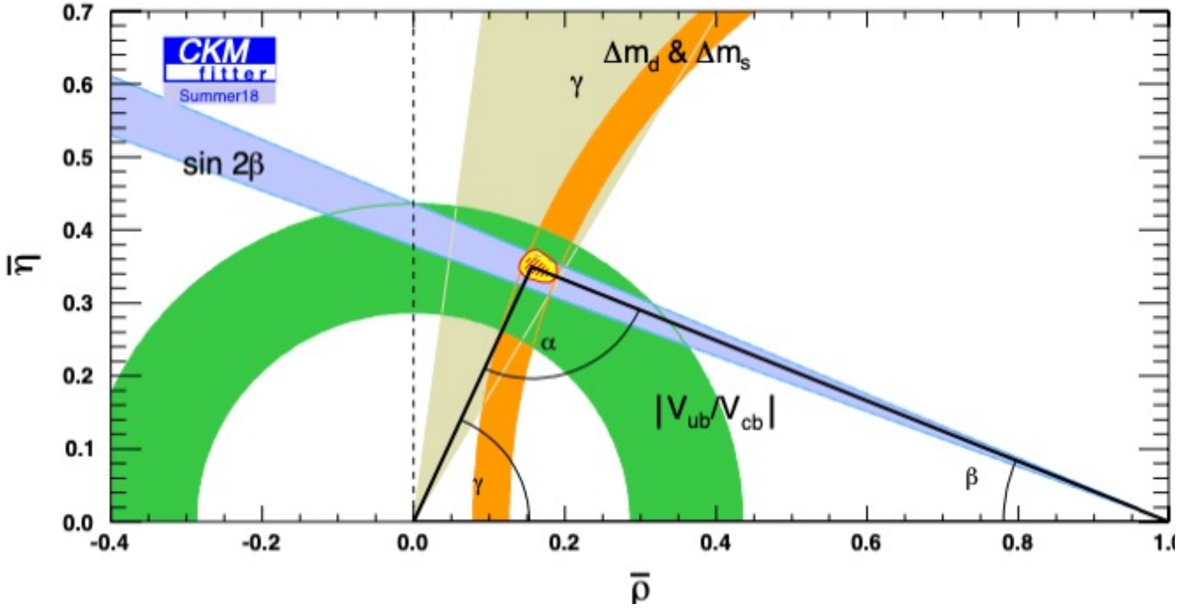
- Full range of beauty & charm mesons & baryons accessible
- Strong results with π^0, photons, missing particles reconstruction
- Beyond Flavour: LHCb as general purpose detector in forward region
- Spectrocopy, EW precision, dark sector and exotic searches, heavy ions and fixed target physics

Constraining the Unitarity Triangle

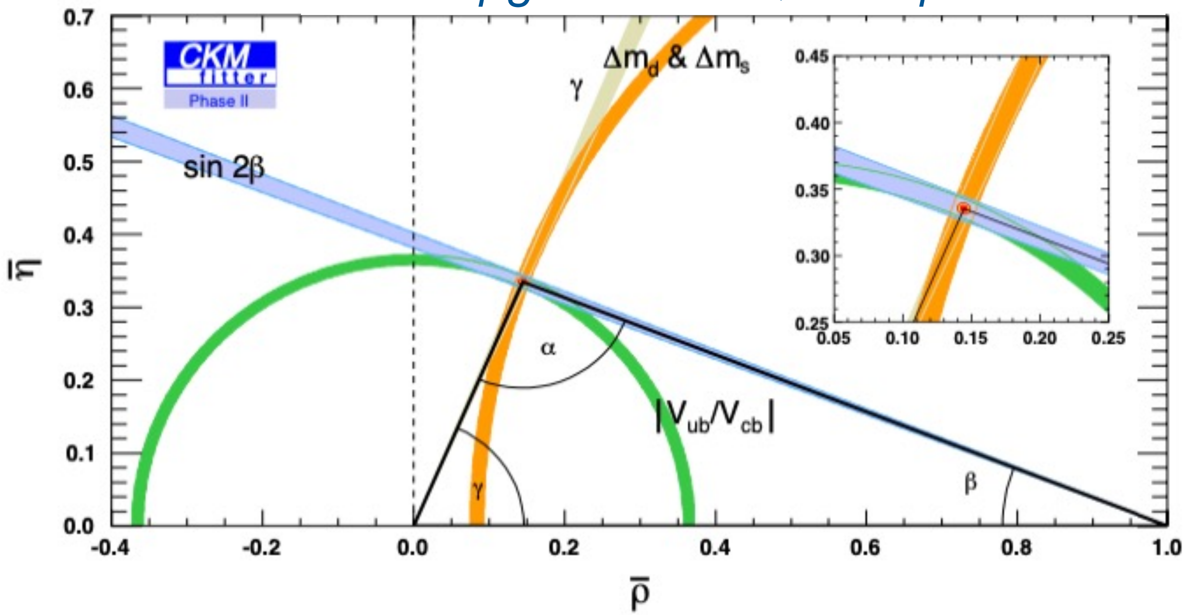
- *Current data show no significant deviations from the SM on ΔF=2 observables and many other flavour-changing processes*
- *Either NP is very heavy of it has a highly non trivial structure*

LHCb Upgrade II will test the CKM paradigm with unprecedented accuracy

LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement

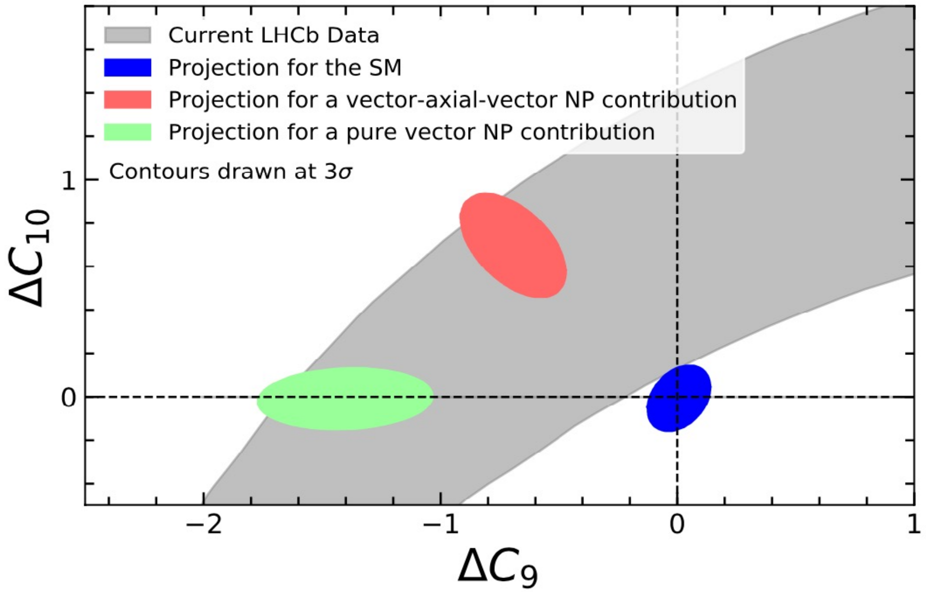


Arguably the greatest likelihood of a further paradigm shifting discovery at the HL-LHC lies with flavour physics

LFU and Charm CPV

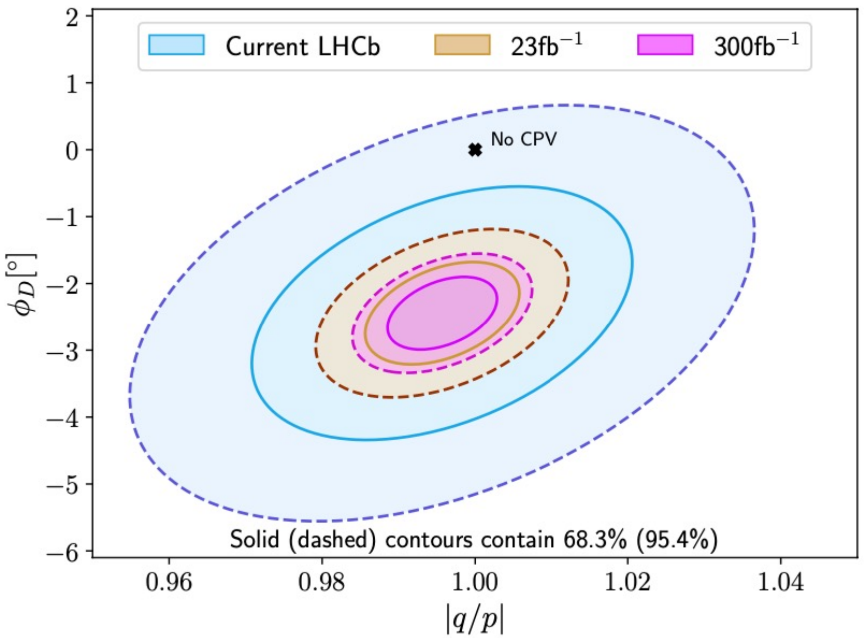
Lepton flavour universality

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



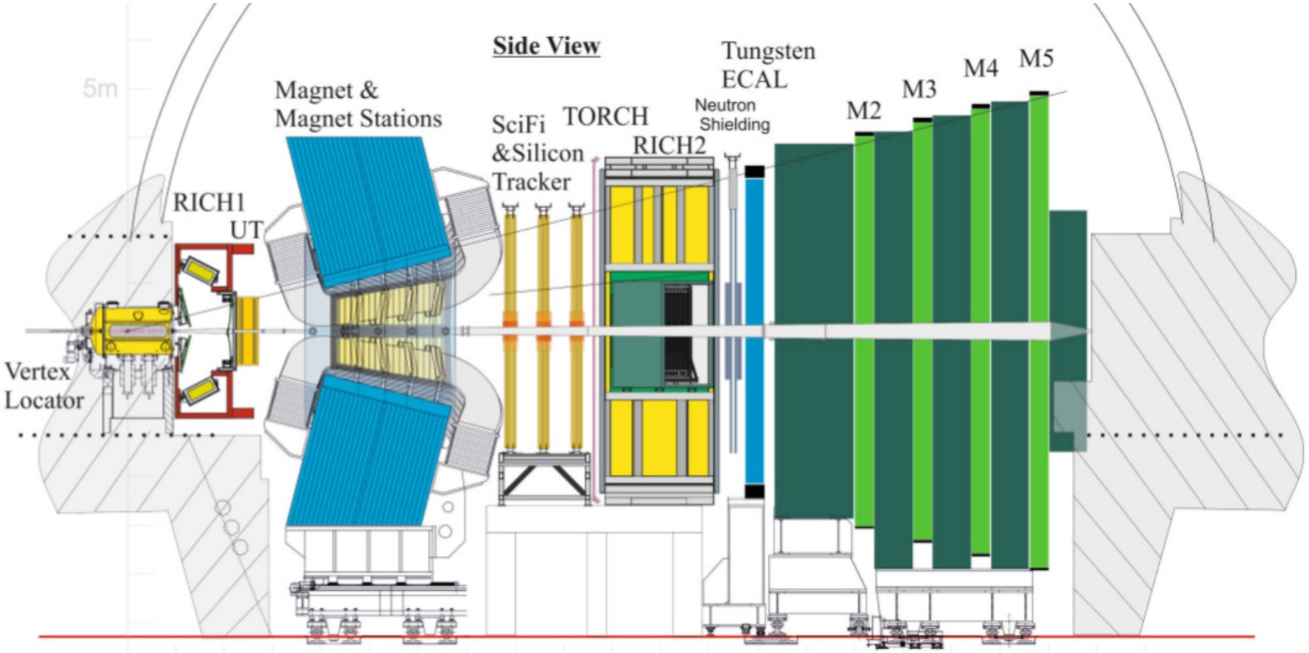
CP violation in charm

- 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!



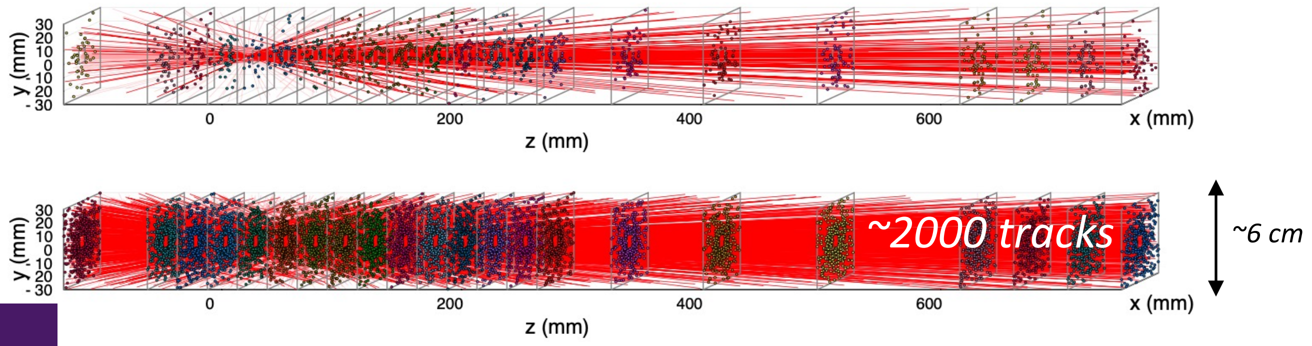
Same spectrometer footprint, innovative technology for detector and data processing

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

VErtex LOcator (VELO)

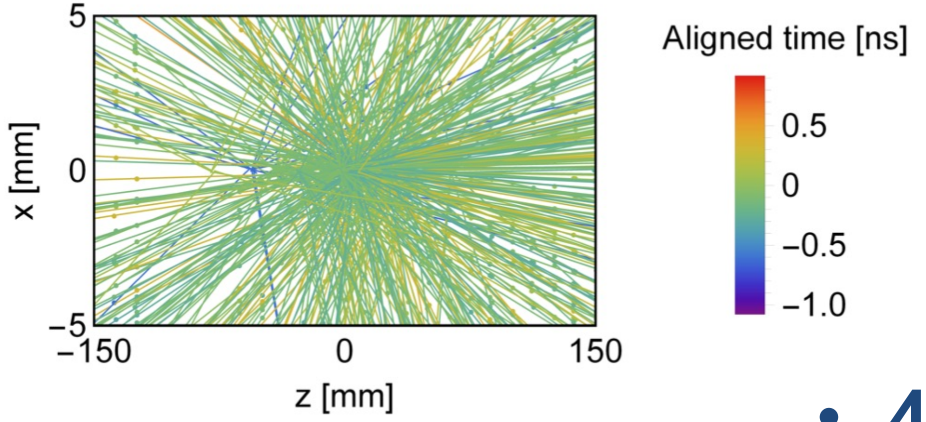
Run 3: pile-up ~6

Upgrade II: pile-up ~42

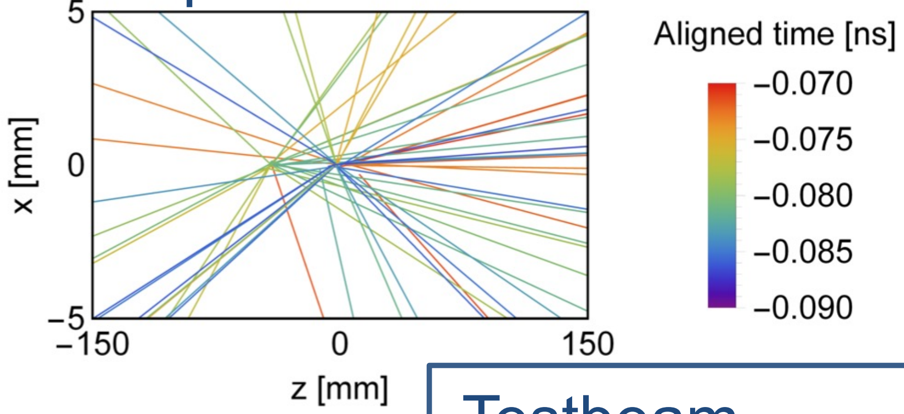


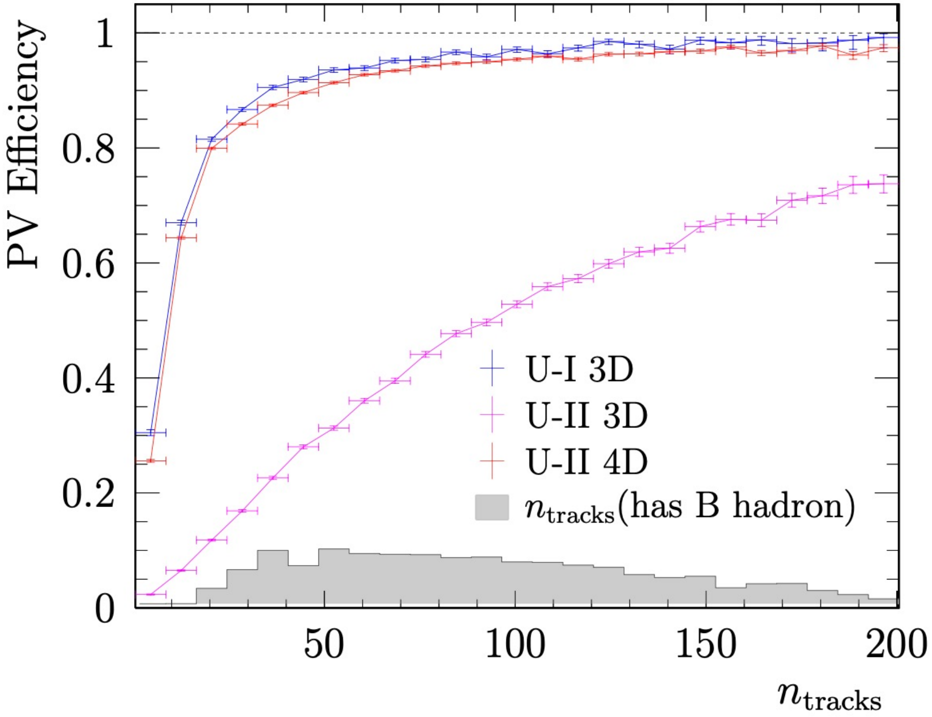
4D Vertexing: Precision Timing

42 interactions



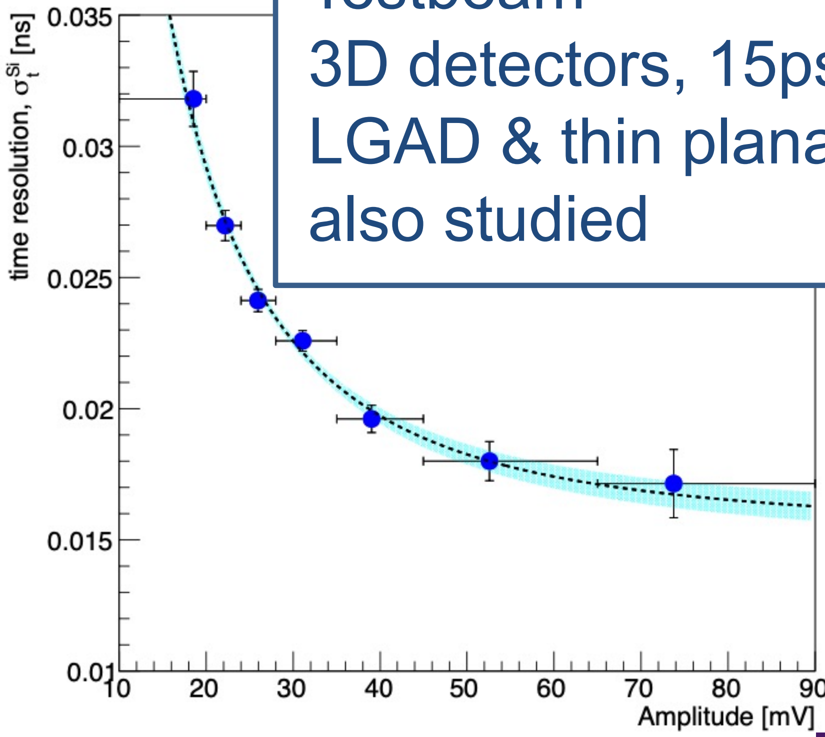
20ps time window





- **4D tracking**
- Ensures similar performance to U1 at U2
  - ~ 50ps, 50μm²
- Extreme lifetime fluence
  - $6\times10^{16} n_{eq}/cm^2$

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



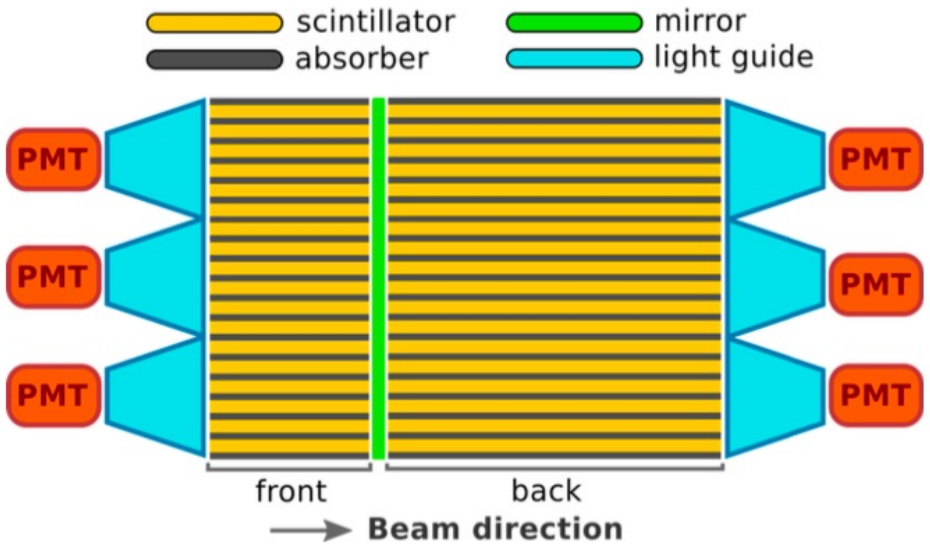
JINST 15 (2020) P09029

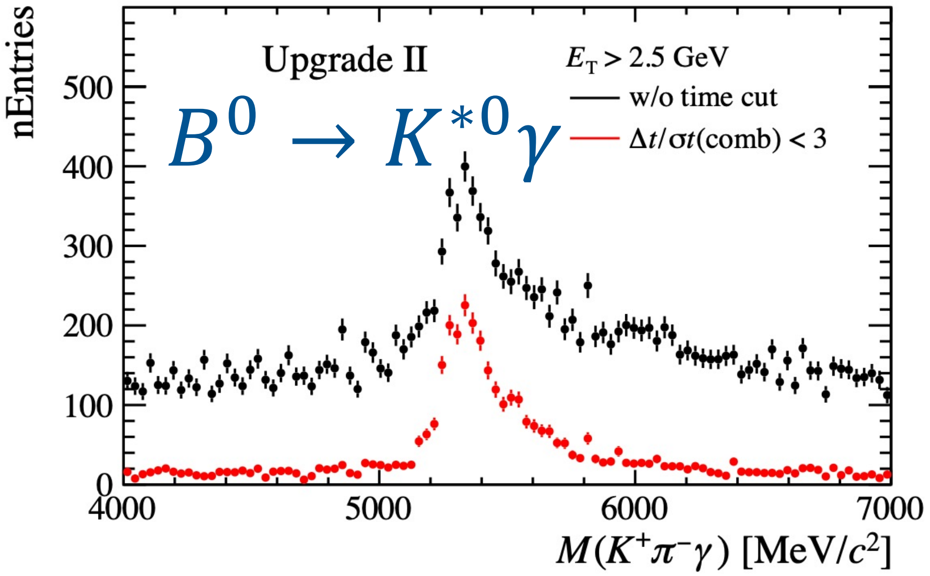
5D Calorimetry: Precision timing

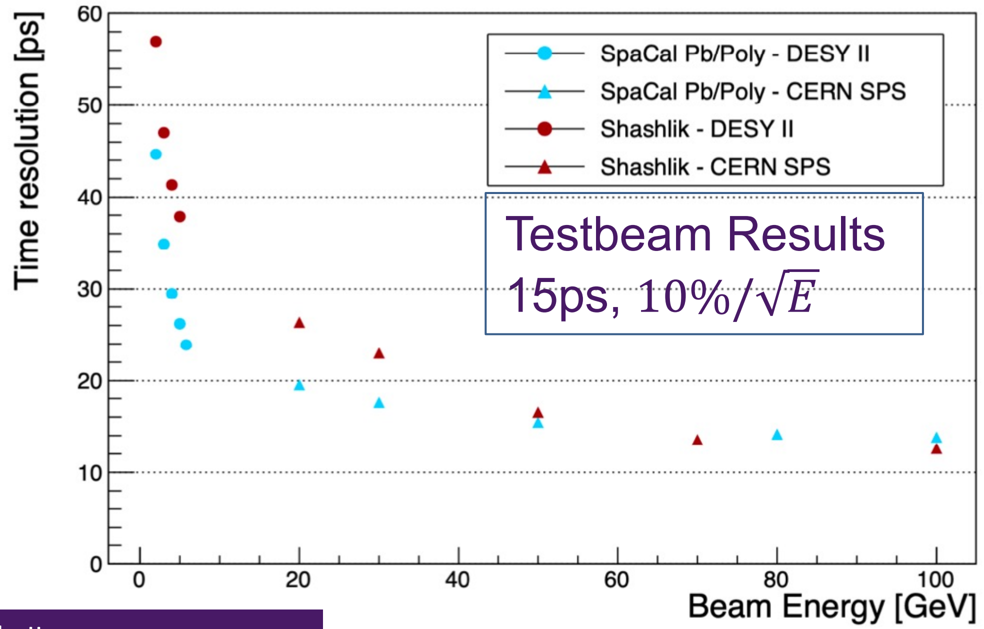
US Involvement

- Goal: achieve energy resolution and reconstruction eff. ~ to Run1&2
  - pile-up, radiation up to 1MGy
- Requires: granularity, precision timing

e.g. Inner region option: SpaCal
Tungsten + GAGG crystal fibres

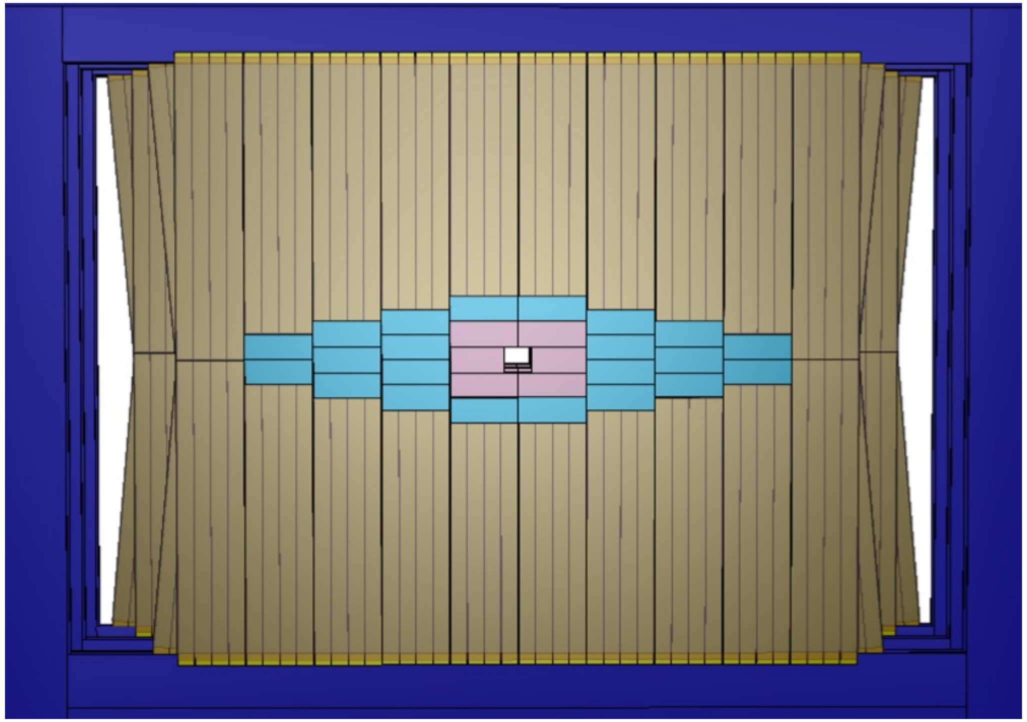


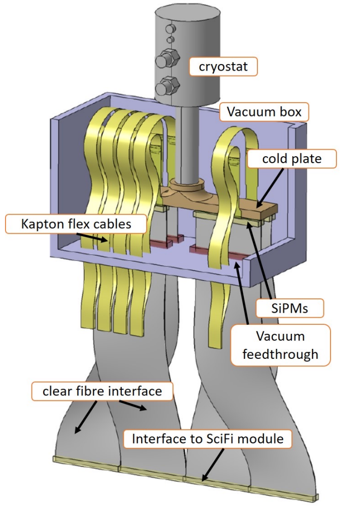


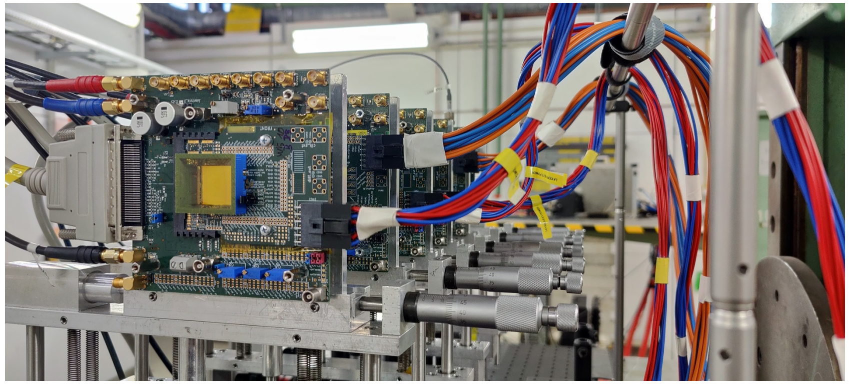


Tracker: Rad Hard DMAPs, first of kind at LHC

- 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



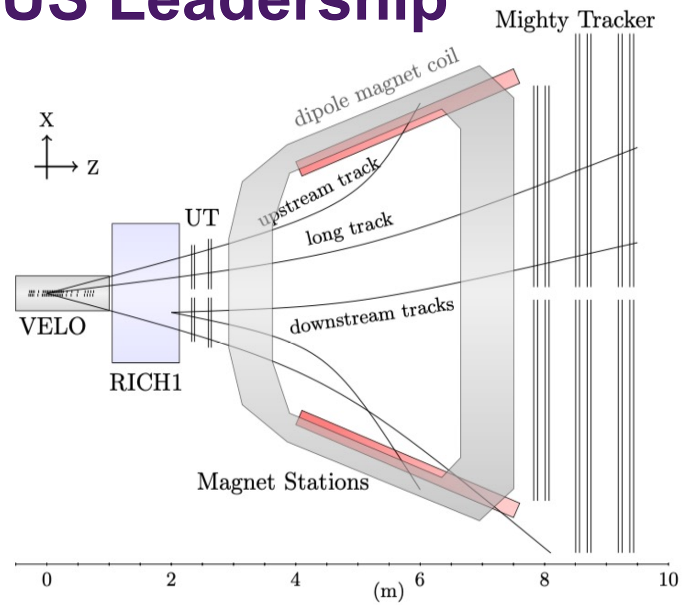


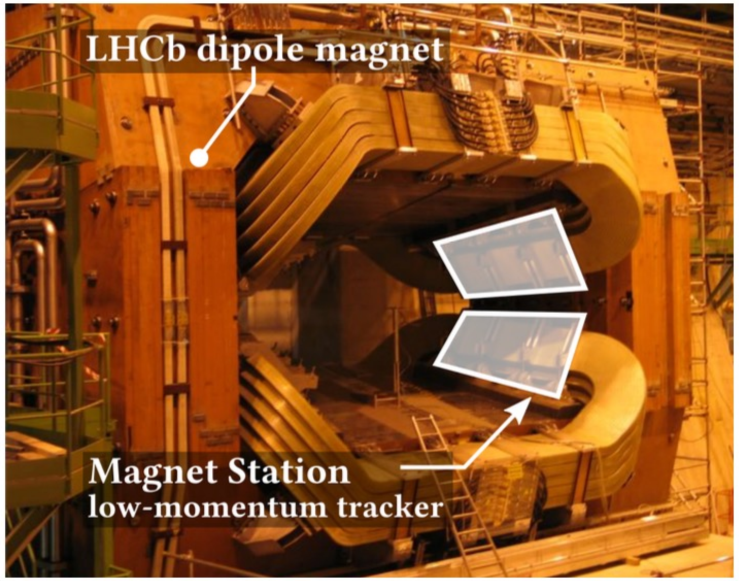


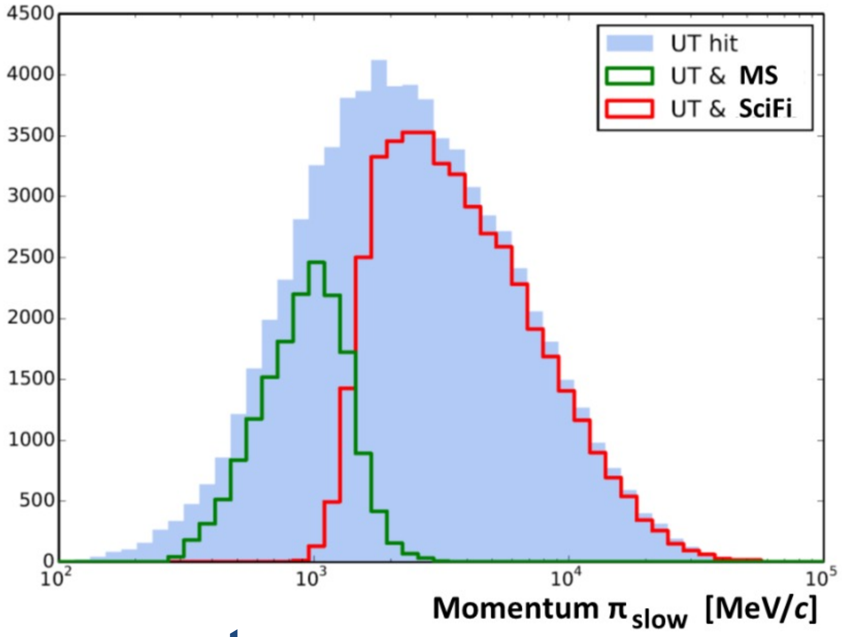
HVMAPS at testbeam

Magnet Stations: expanding physics potential

US Leadership



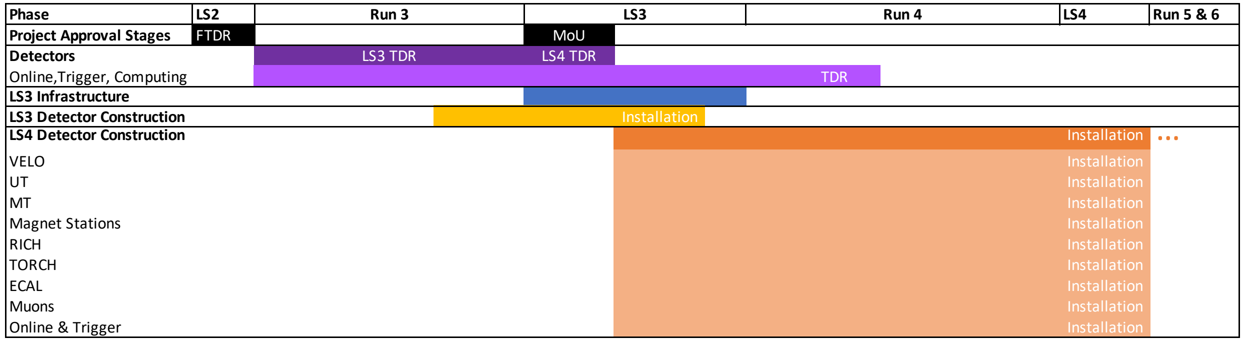




- Low momentum particles swept out by magnet
- Instrument walls of magnet with scintillating bars
- Obtain sub-% momentum measurement
- Significant increase of acceptance for low momentum

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

LHCb Upgrade II: Summary



- Fully exploit HL-LHC

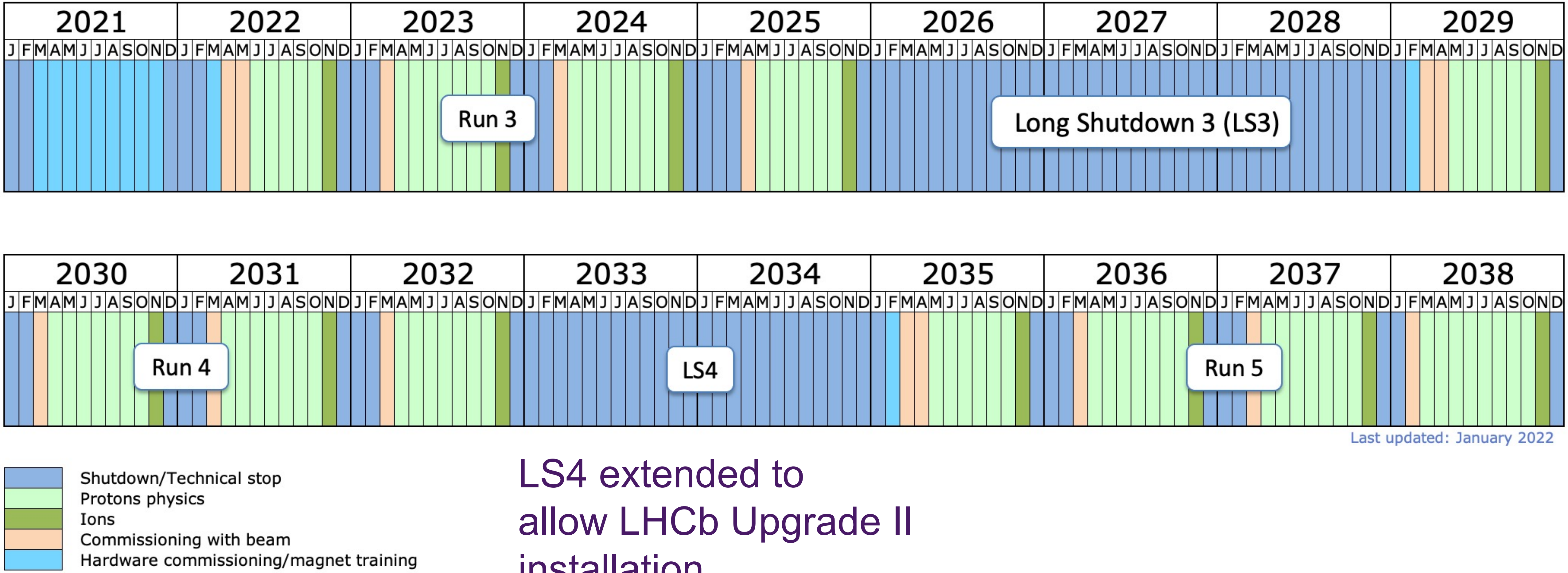
  for flavour physics & beyond

- FTDR approved
  - Main installation in LS4 (2033-2034)
  - R&D phase, leading to subdetector TDRs in LS3 (2026)
  - Innovative technologies,
  - pathfinder to future accelerator projects

- Ambitious detector, proven accelerator
  - Scale larger than previous LHCb detectors
  - FTDR describes baseline and range of descope options
- Participation new collaborators encouraged to achieve full potential
  - Technical associate membership also available

Backup

LHC Schedule



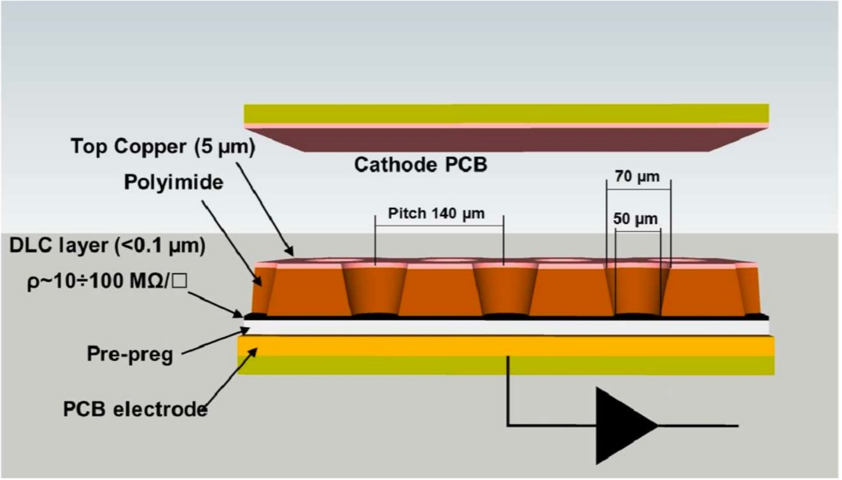
LS4 extended to allow LHCb Upgrade II installation

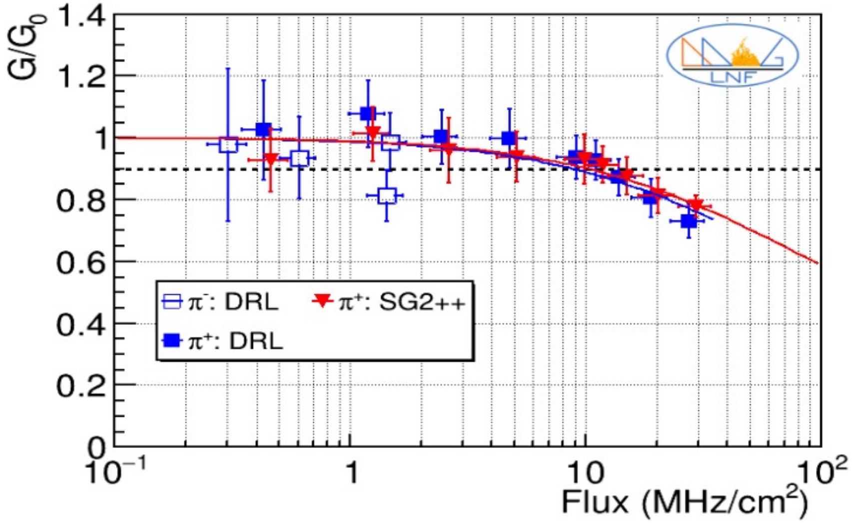
MUON

JINST 14 (2019) P05014

Novel MPGD μ-RWELL detectors proposed for innermost regions, capable to stand up to several MHz/cm^2 → 144 chambers to be built

Detector R&D *Ageing studies ongoing at PSI and GIF++, front-end electronics under development*





For external regions, baseline option is to keep most of the present MWPCs chambers → 880 MWPC reused, 80 to be rebuilt with higher granularity

Detector Studies *Ageing studies at GIF++, new options for front-end electronics under study*

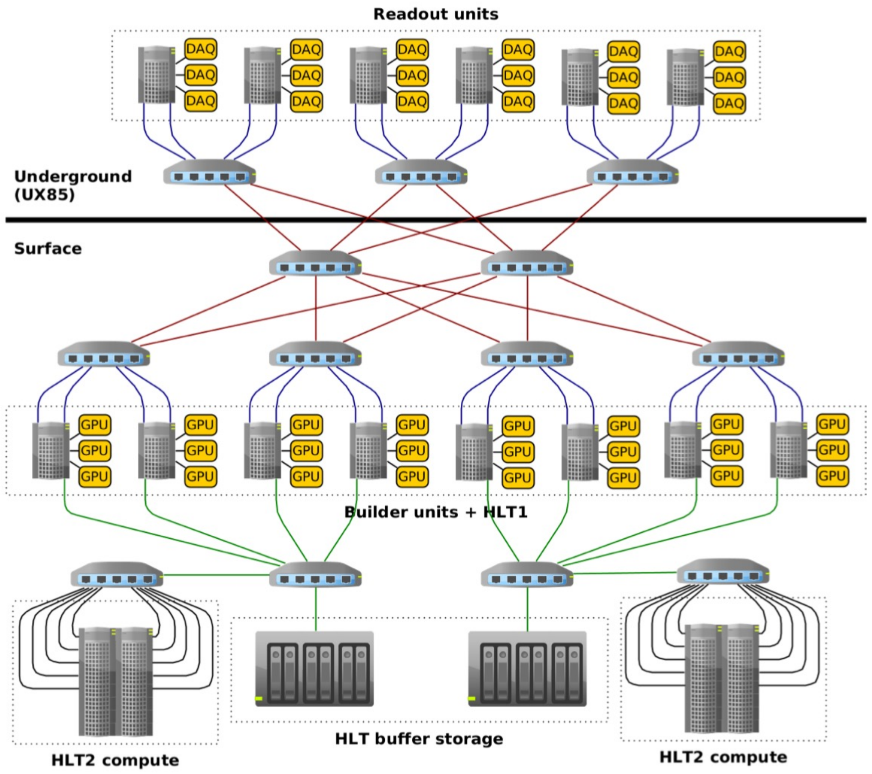
Additional shielding ($6\lambda_I \rightarrow 10\lambda_I$) will be installed in front of Muon detector in place of HCAL, which will bring down the rate by a factor of ~2

Online and Real Time Analysis

NEW at Run3

Full software trigger implemented for the fist time at an hadron collider!

HLT1 fully based on GPU will process ~40 Tb/s from detector



Event-builder architecture for Upgrade II

Upgrade II

~200 Tb/s from detector

x5 ATLAS/CMS phase 2 (after L0)

~800 Gb/s on disk

x2 ATLAS/CMS phase 2

Exploit hybrid architectures: CPU, GPU, FPGA,…

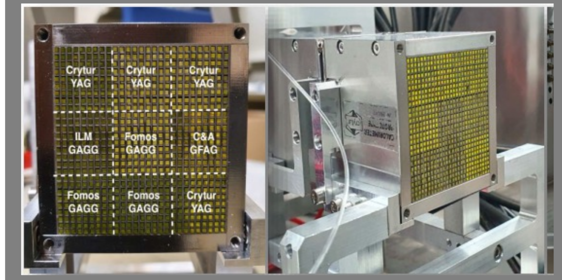
- *baseline assumes full reco (HLT1+HLT2 on GPU)*
- *testbed with new technologies in Run 3 readout environment*

PID detectors

Integrated system with multiple detectors: ECAL, MUON

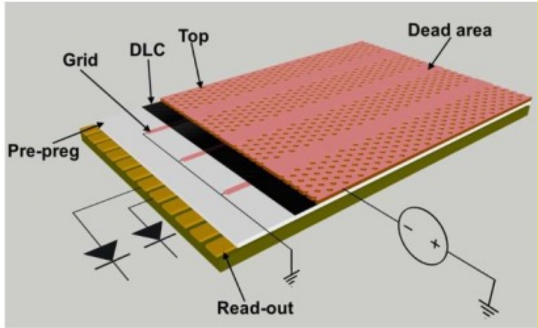
ECAL

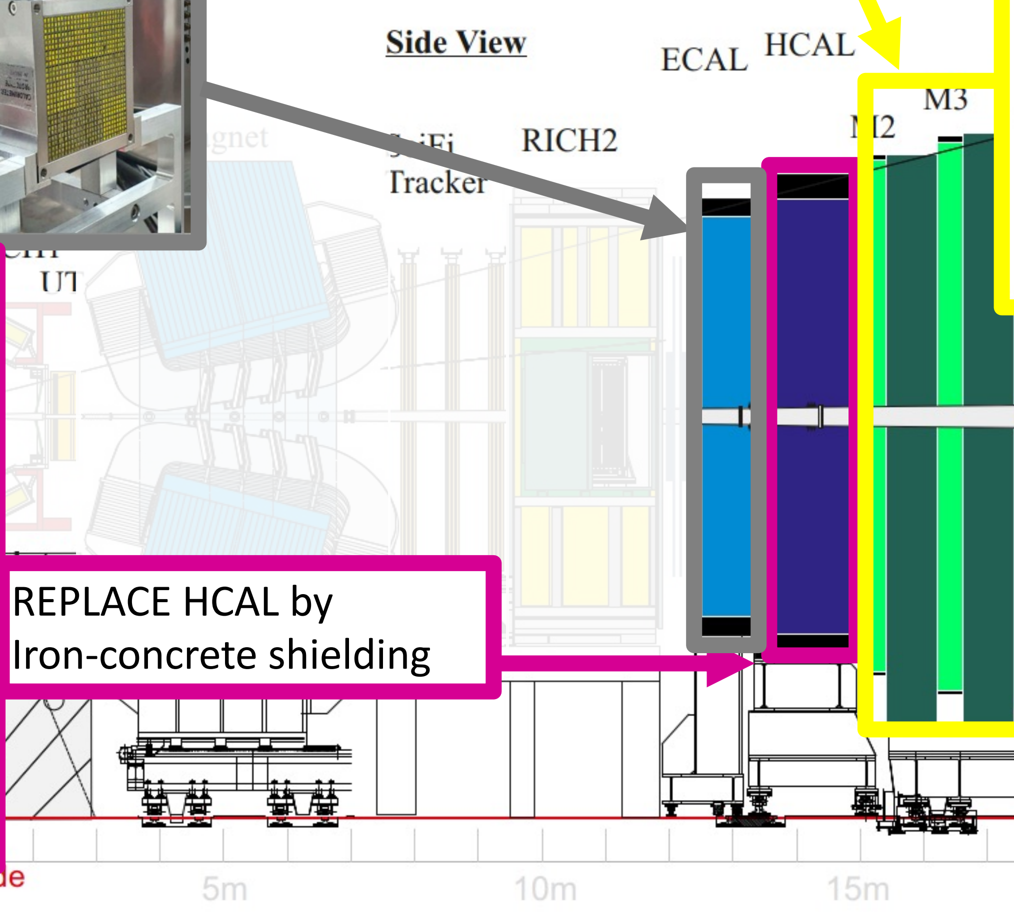
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals



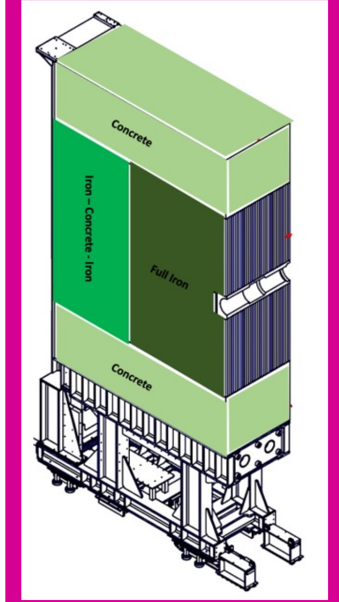
Muon

- μPΩEΛΛ for inner regions
- MWPC for outer regions (recycles)





REPLACE HCAL by
Iron-concrete shielding



RICH with timing

- *Time-stamping each photon with a resolution of few tens of ps will reduce combinatorial bkg, and will enable, together with the expected improvement of Cherenkov angle, to approach the expected UI performance*

- *SiPM is promising technology*

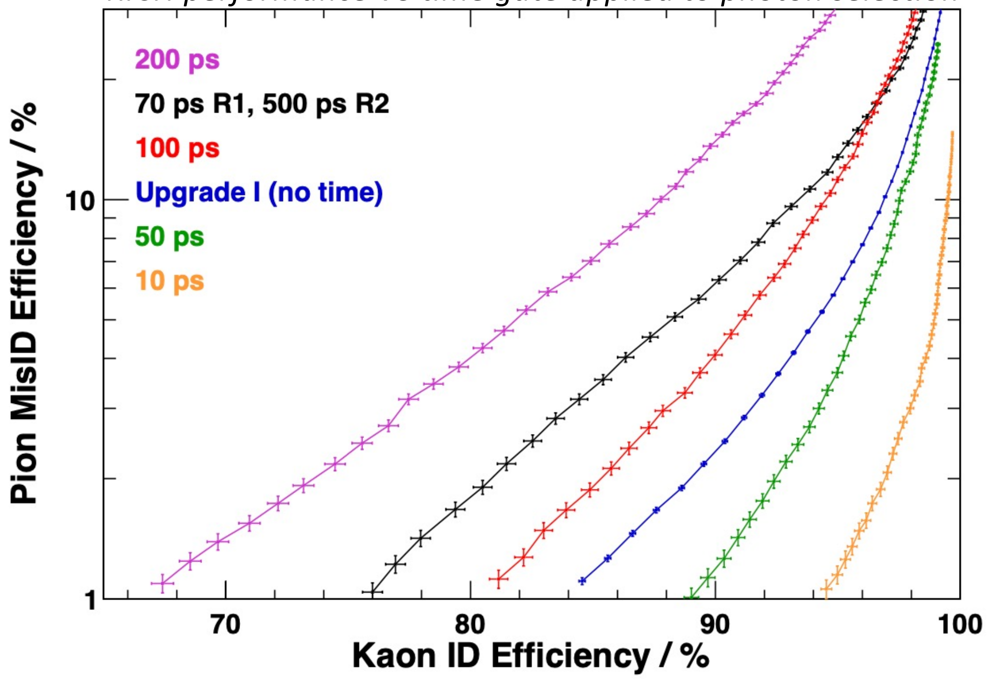
→ excellent granularity

→ robustness under magnetic field

→ time resolution <100 ps per photon

→ high efficiency, weighted towards longer wavelengths (reduce chromatic error)

RICH performance VS time gate applied to photon selection



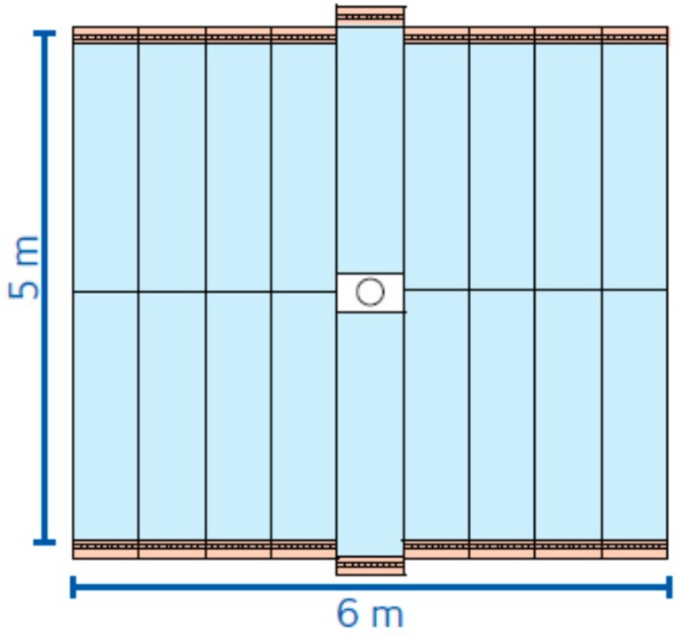
(does not include expect improvement in Cherenkov angle reso)

Detector R&D

- *ASIC for front-end readout and TDC*
- *SiPM improvements, cryogenic cooling, micro-lens*
- *Adjustment of geometry (reduce tilt of spherical mirror) to improve further on Cherenkov angle resolution; optimisation of track requirements to match the PID improvements needed*
- *Alternative options for photon detectors: MCP-PMT with pixelated anodes*

Adding TORCH time-of-flight

- *30 m^2 ToF detector with quartz plane readout by MCP-PMTs placed in front of RICH2*
- *will provide p/K separation <10 GeV/c and improve π/K separation <5 GeV/c, through 10-15 ps time resolution per track*



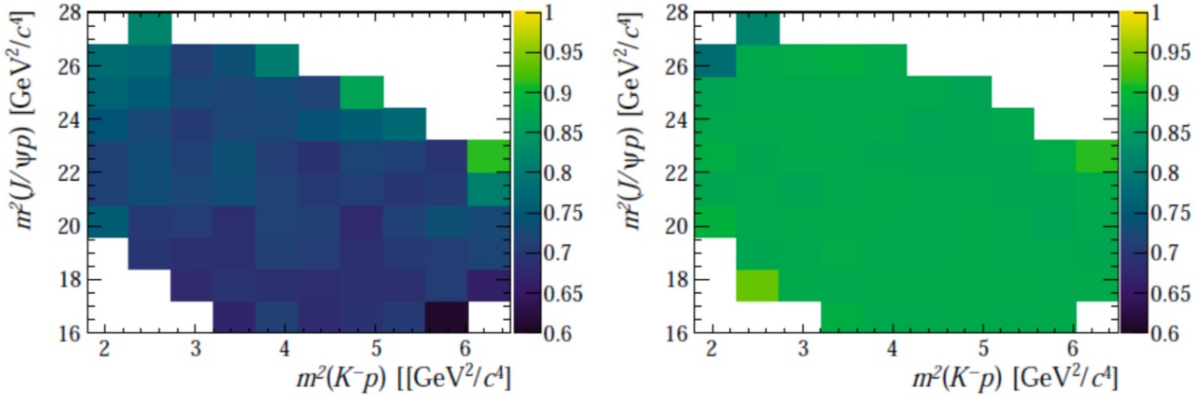
Detector R&D

- *Photon yields observed that are close to simulation, and time resolution that approach the 70 ps goal per photon*

Physics benefits from low momentum PID

- *Increased efficiency and background suppression for many channels*
- *Improvements to flavour tagging with soft kaons by 25-50%*
- *Improved uniformity in PID acceptance*

Dalitz plot efficiency for $\Lambda_b \to J/\psi p K^-$ w/o and with TORCH

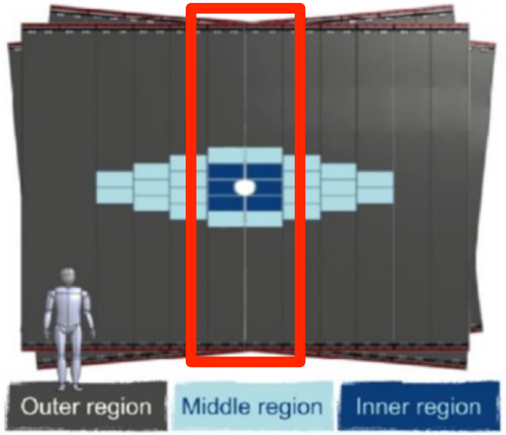


Opportunities for the detector at LS3

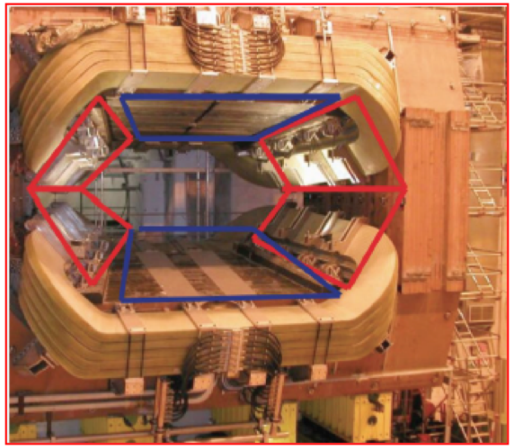
Limited-size detector consolidations also proposed for LS3, which will bring some physics benefits already in Run 4 while anticipating features of the UII

driven by ageing
driven by technology
driven by physics

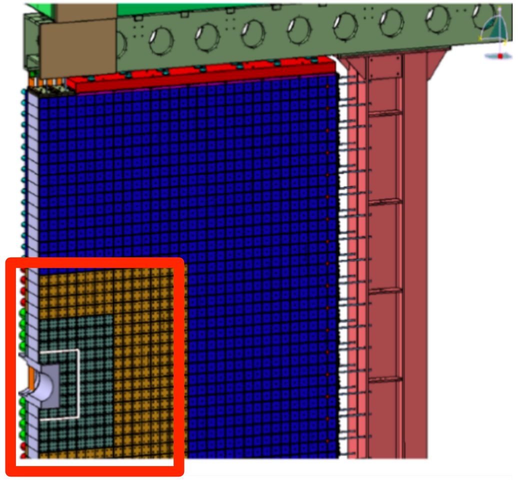
Detector	Proposal
SciFi consolidation	Replace inner modules (12X + 12stereo)
MAPS modules	2 layers, 1 m^2 each
Magnet Stations	full installation
RICH	new FE electronics
ECAL	32+144 inner modules
RTA	Downstream tracking with FPGA



SciFi consolidation plus MAPS modules



Magnet Stations



ECAL inner modules

Careful evaluation needed on what can be achieved on this timescale