CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework TDR

LHCb UPGRADE II

Technical Design Report

LHCb upgrades

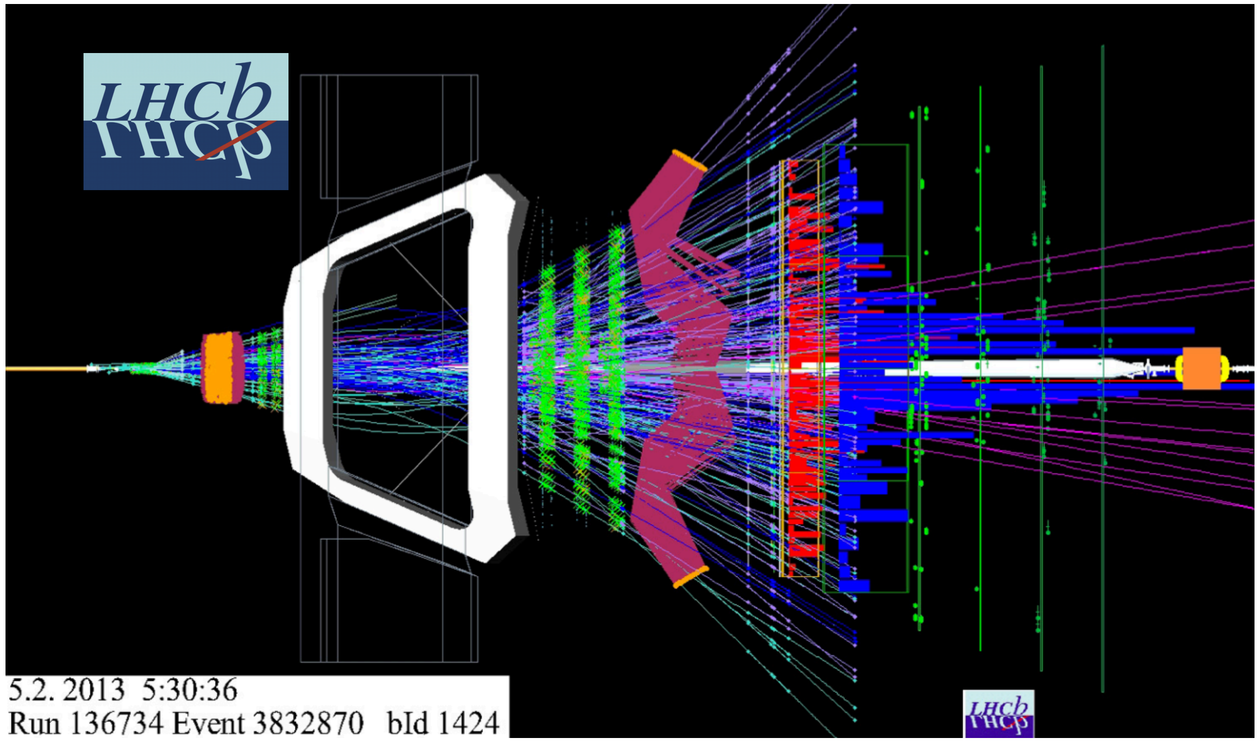
Matteo Palutan

Perspectives of physics at high intensity

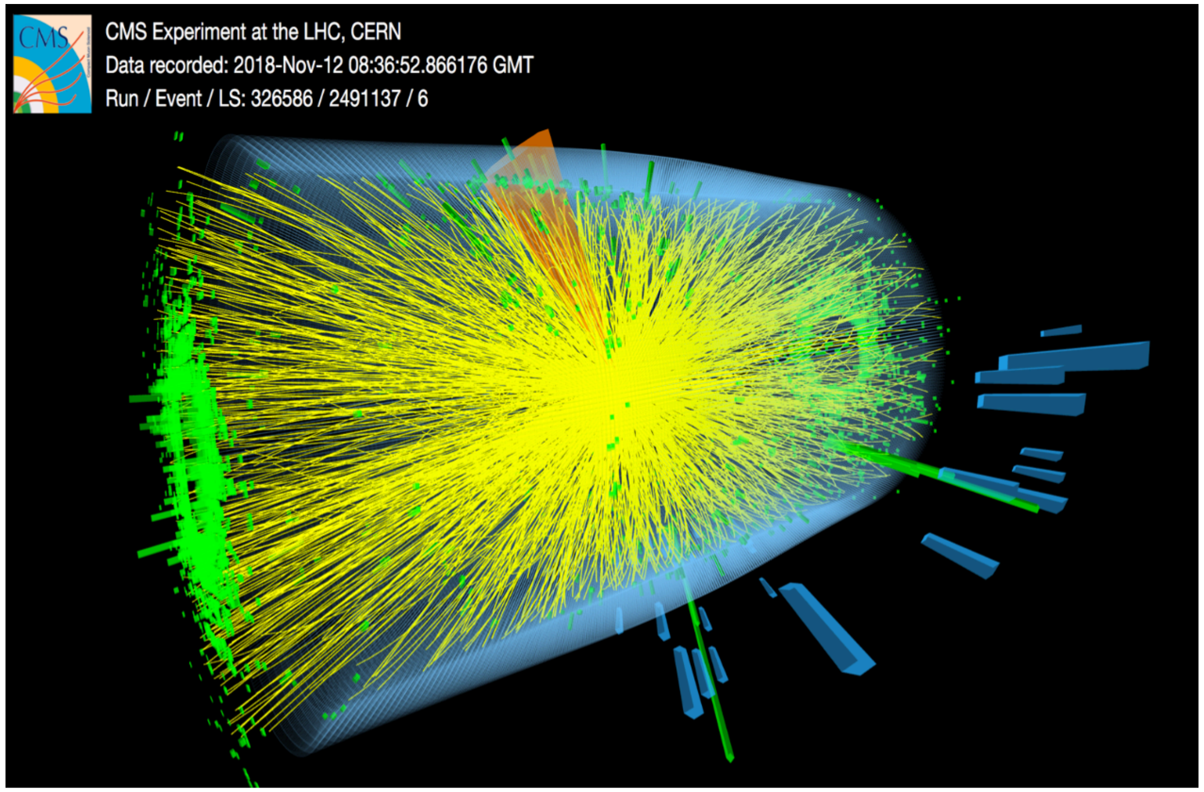
LNF, November 11th, 2022

Flavour physics at the LHC

High gain: unprecedented statistics
+ access to all c- and b-hadrons



High risk: extremely difficult event topology

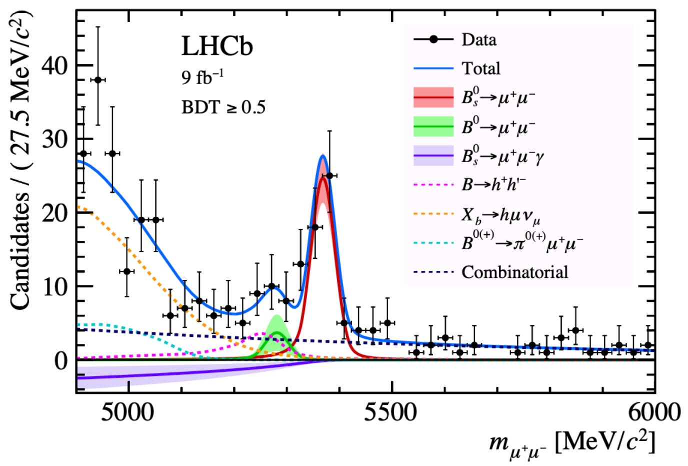


Need excellent tracking and PID, and capability to trigger with low p_T → LHCb!!

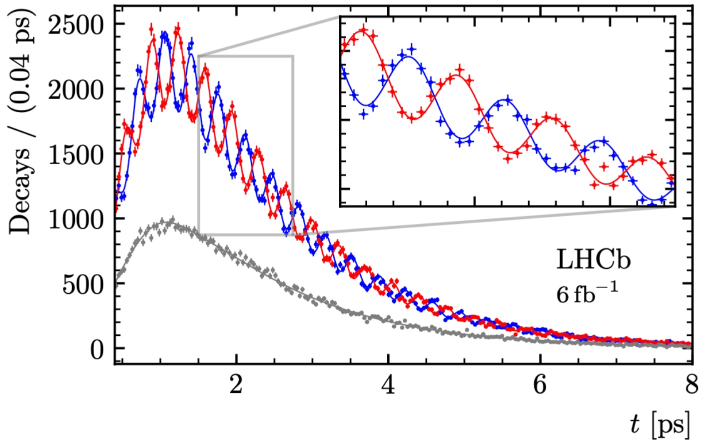
LHCb: the flavour experiment at the LHC

*9 fb^{-1} accumulated during Run1 and 2, yielding **precision measurements** including*

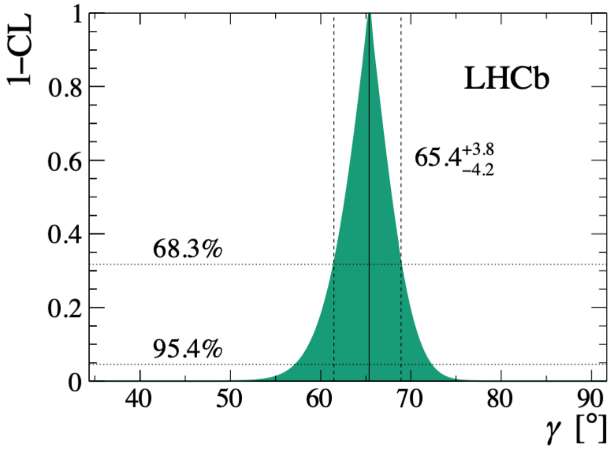
$B_s^0 \to \mu\mu$



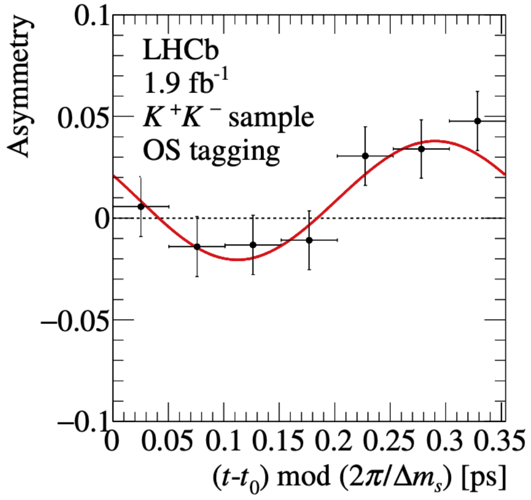
Δm_s



CKM angle γ



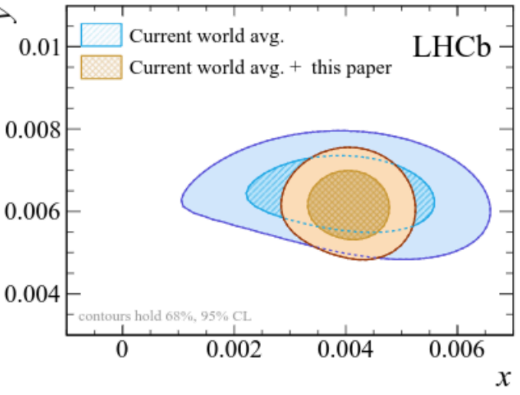
CPV in B_s



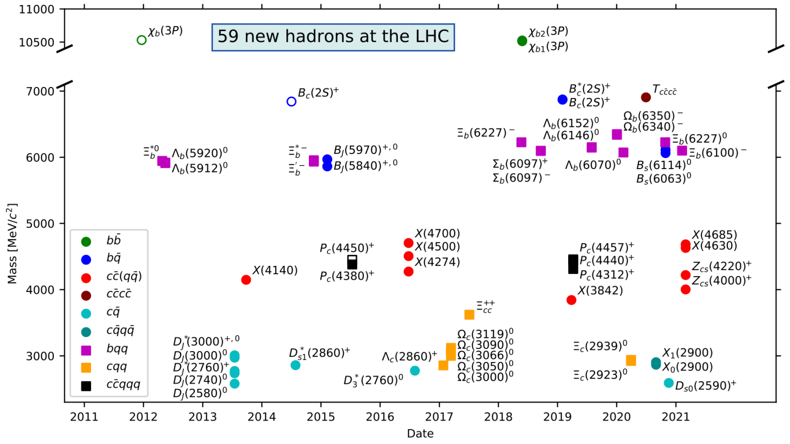
*and **the intriguing anomalies:** R(D*), R(K), R(K*), angular analysis of $K^*\mu^+\mu^-$*

***But also** a wealth of **further measurements and discoveries** including:*

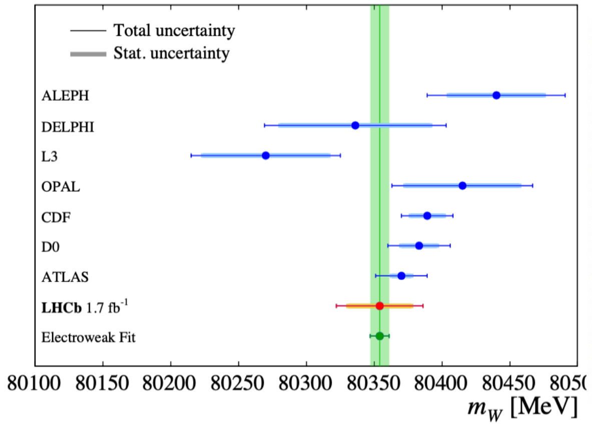
Charm physics



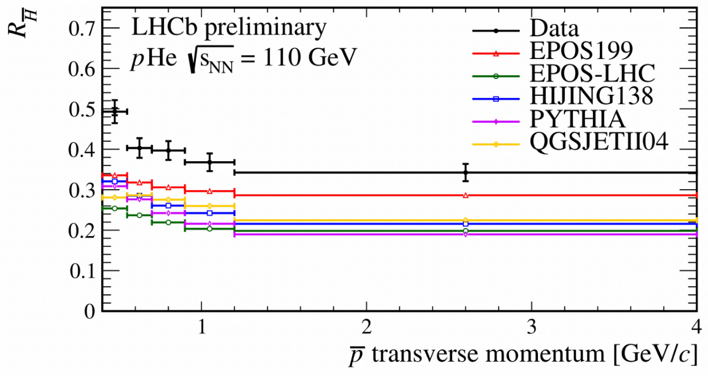
Hadron spectroscopy



EW physics



pHe physics

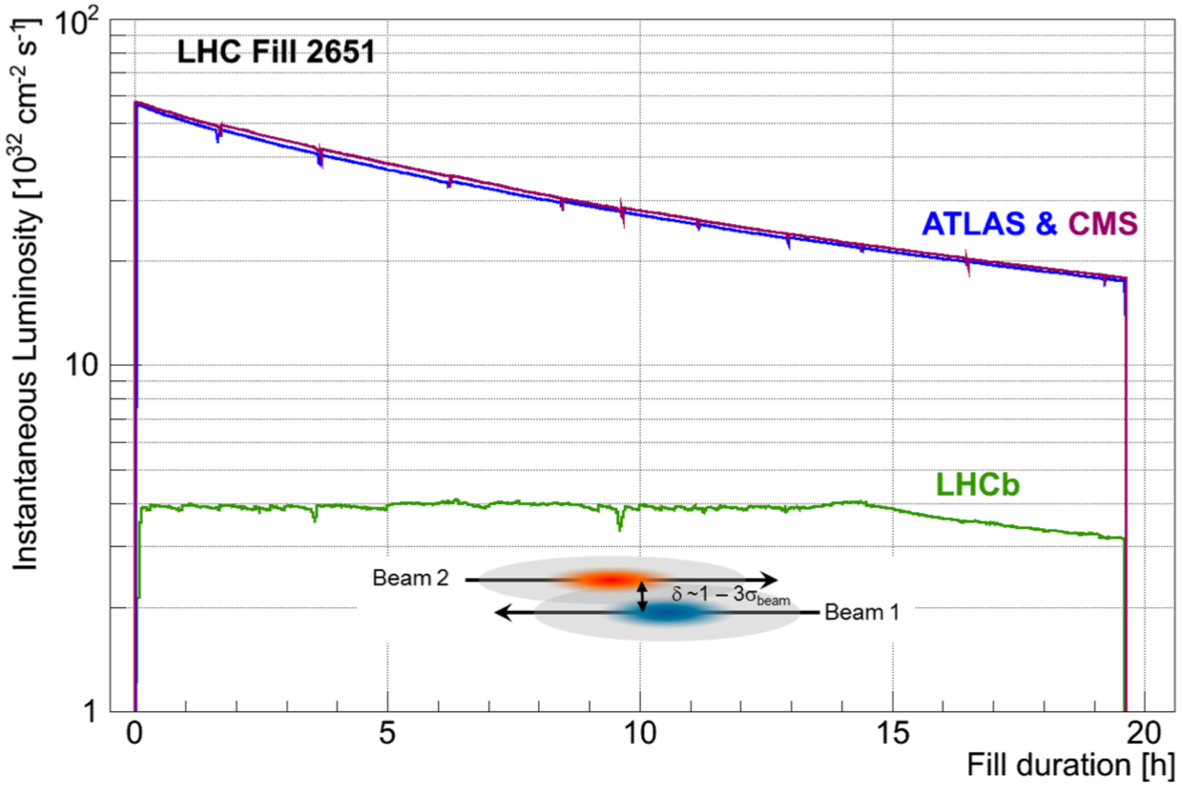


*This was all achieved thanks to the **wonderful perfomance of the LHC and of our detector…***

LHCb: the flavour experiment at the LHC

…but we didn't exploit the full potential of the LHC during Run 1&2

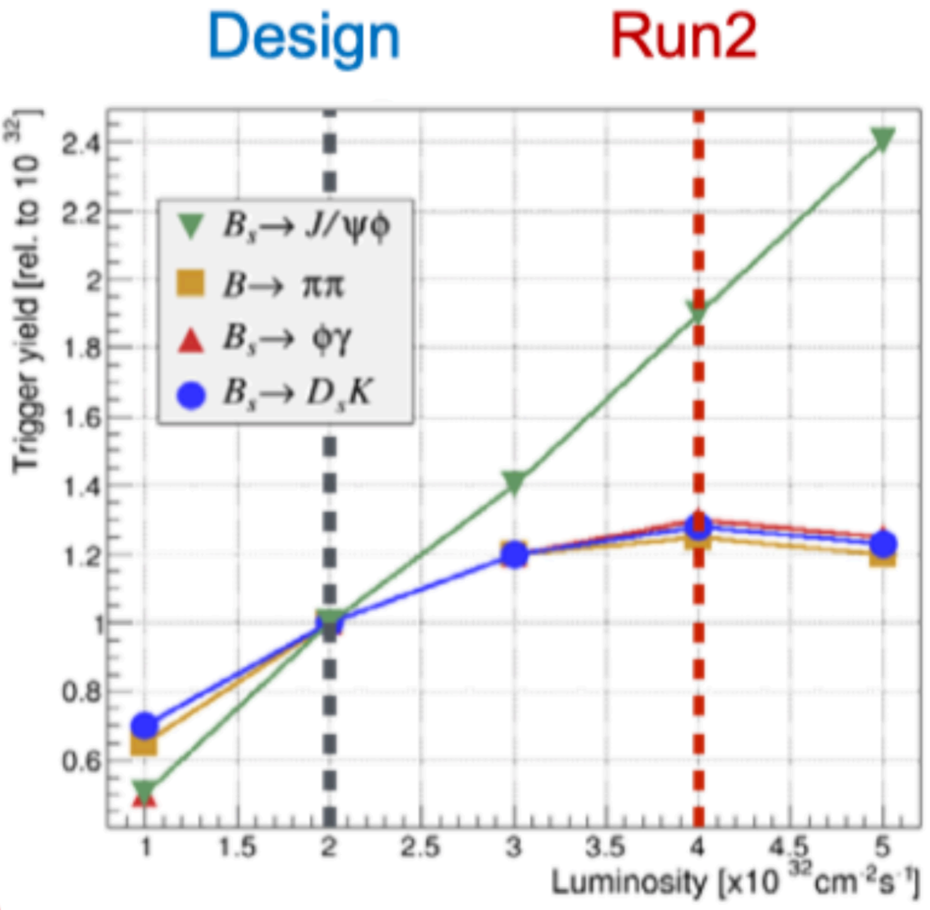
LHCb running at lower luminosity than the machine could provide



LHCb: $L_{peak} \sim 4{\times}10^{32}$ cm^{-2} s^{-1} levelled,
pile-up ~1

ATLAS/CMS: $L_{peak} \sim 2{\times}10^{34}$ cm^{-2}s^{-1},
pile-up ~40

Programme limited by detector and readout



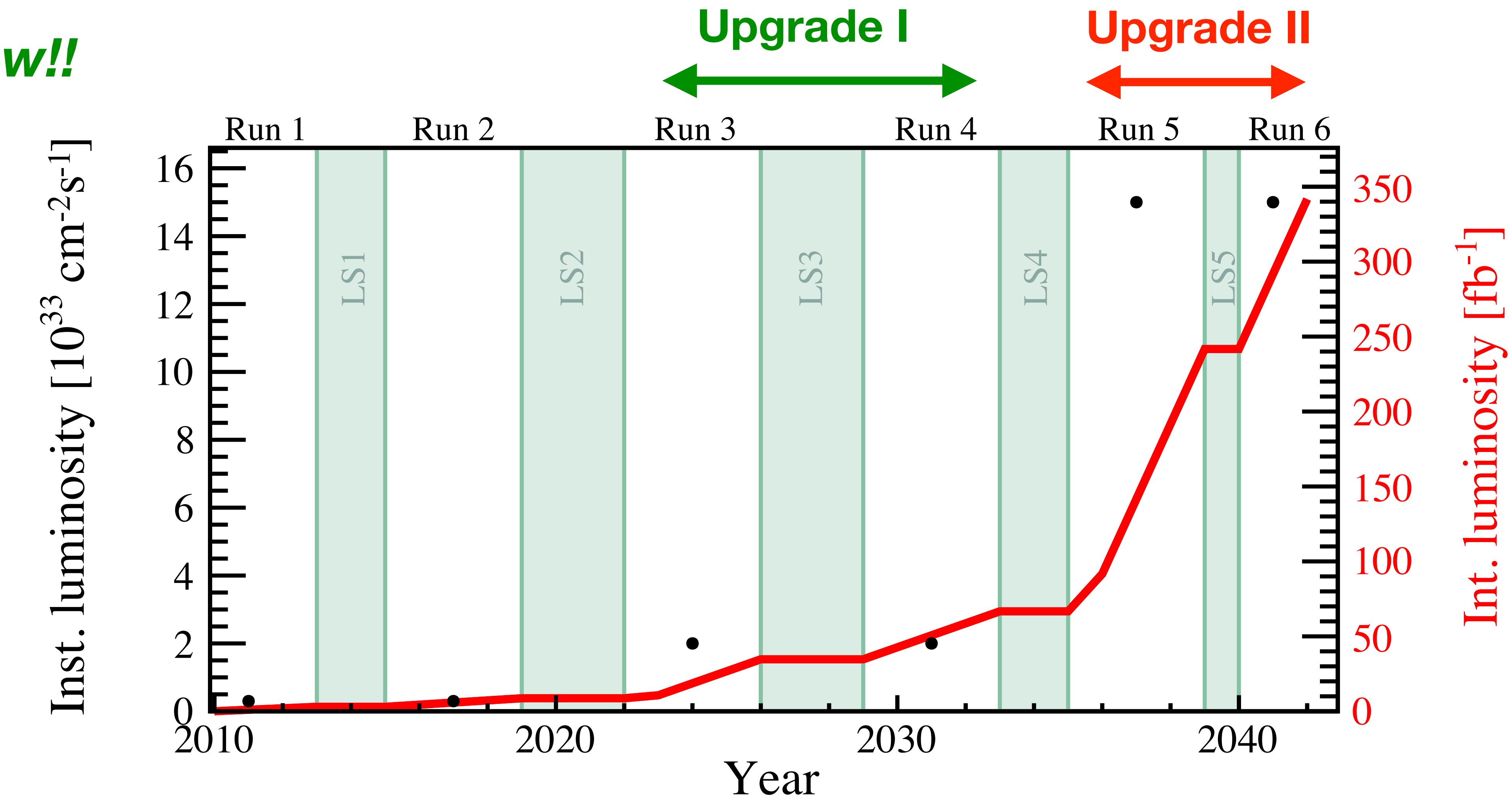
L0 hardware trigger max bandwidth of 1 MHz forced to increase the CALO E_T thresholds, thus saturating the hadronic yields

LHCb upgrades

Physics programme limited by detector, so there's a clear case for an ambitious plan of upgrades covering the full HL-LHC phase

Upgrade I starting now!!

- ***$L_{peak} = 2\times10^{33}$ cm^{-2} s^{-1}***
- ***$L_{int} = 50$ fb^{-1} during Run 3 & 4***
- *Move to full software trigger, improved effi on hadronic modes*
- *Healthy competition with Belle II @50ab^{-1} in this phase*



Upgrade II, installation at LS4

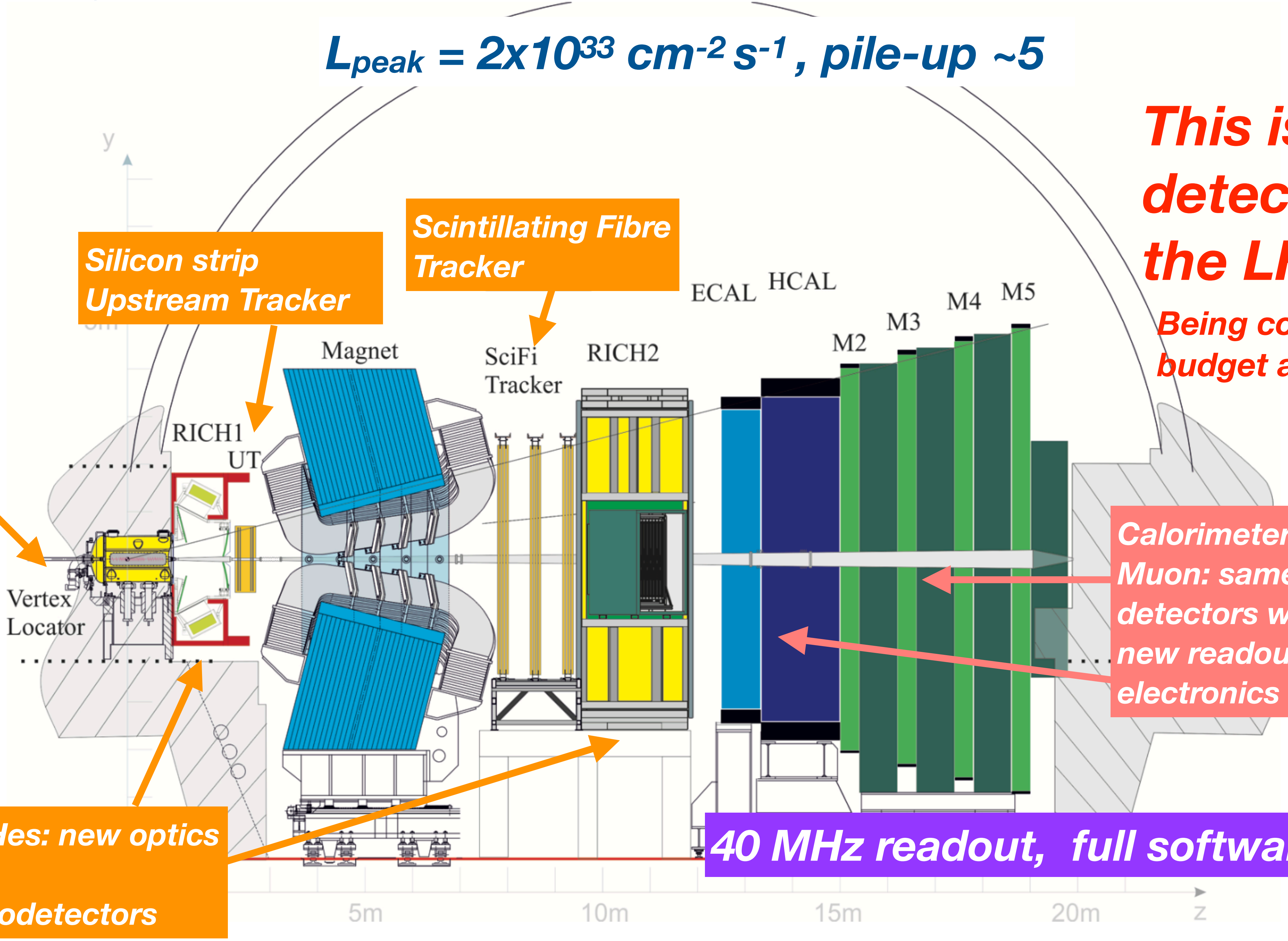
- ***$L_{peak} = 1.5\times10^{34}$ cm^{-2} s^{-1} , $L_{int} = \sim300$ fb^{-1} during Run 5 & 6***

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 I at the starting line!

Major upgrade of all subdetectors, less than 10% of channels kept

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



Silicon pixel vertex

Silicon strip Upstream Tracker

Scintillating Fibre Tracker

RICHes: new optics and photodetectors

Calorimeters and Muon: same detectors with new readout electronics

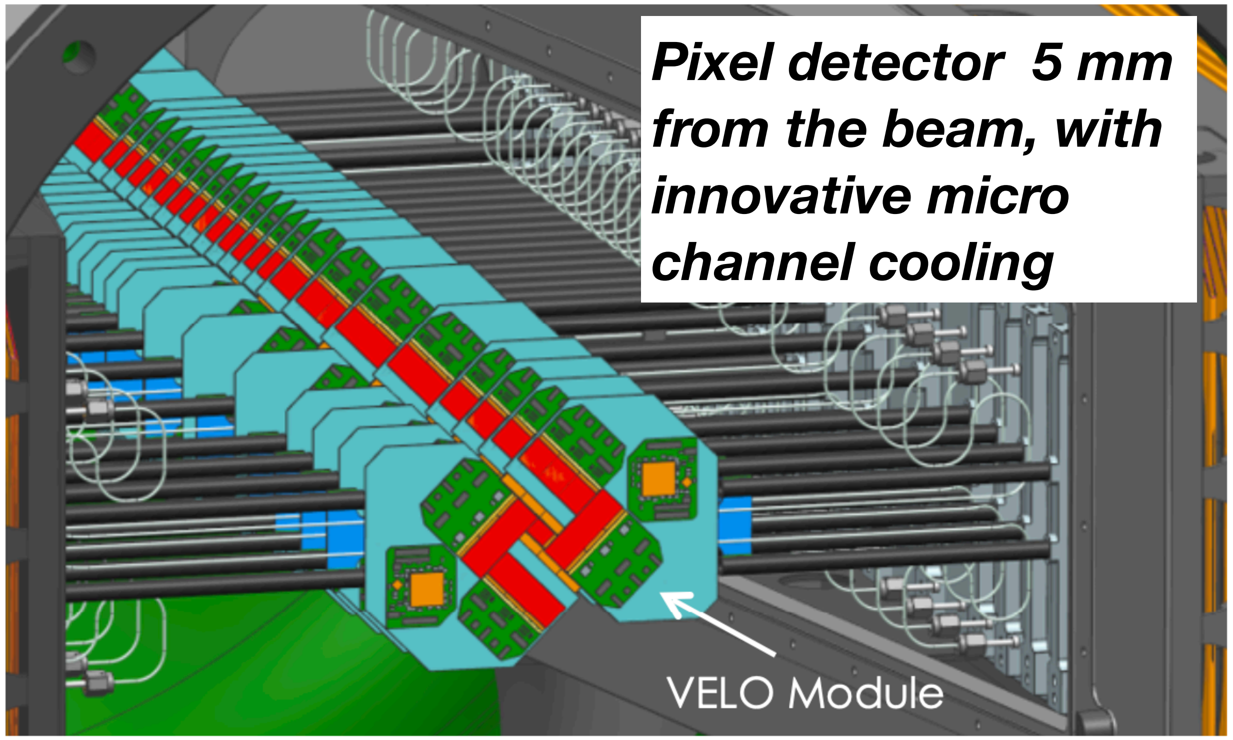
This is a NEW detector at the LHC!

Being completed on-budget and near schedule

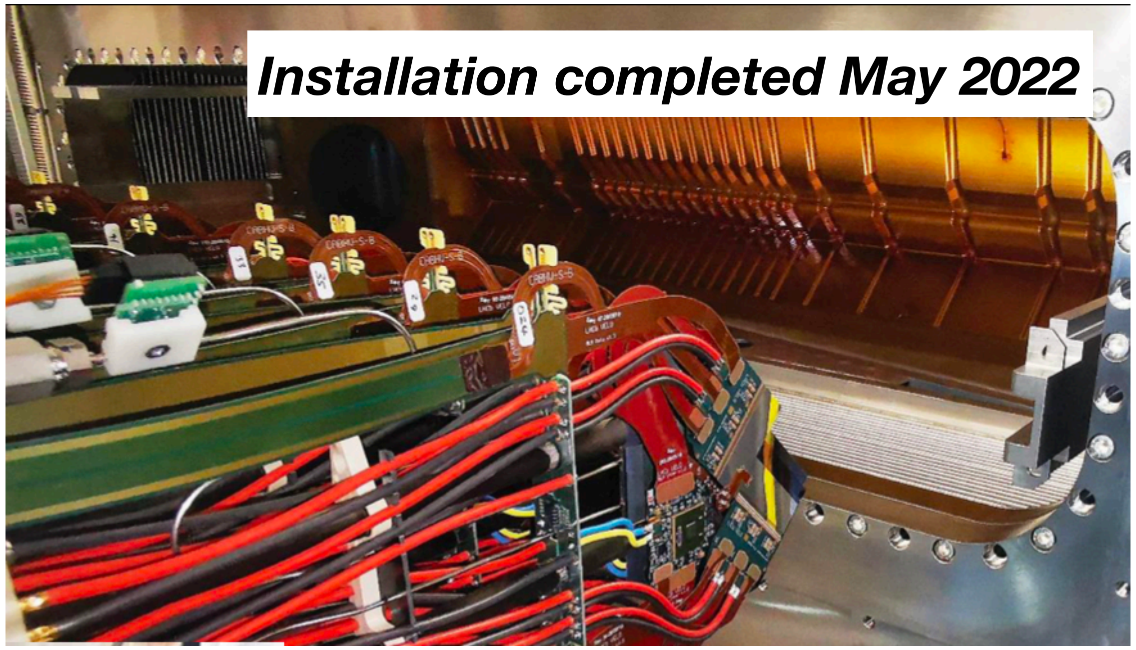
40 MHz readout, full software trigger

Goal is to maintain the excellent Run 1/2 performance with the increased occupancy foreseen at Run 3

Vertex Locator (VELO)

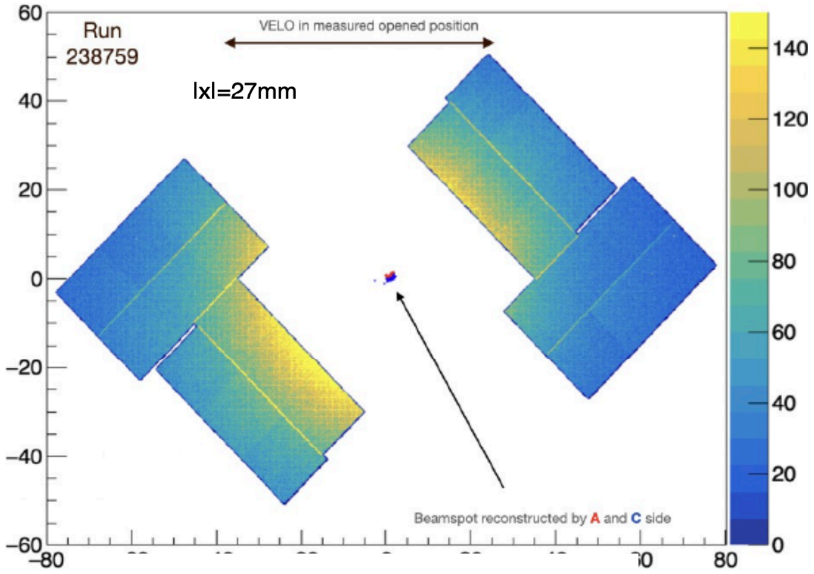


Pixel detector 5 mm from the beam, with innovative micro channel cooling

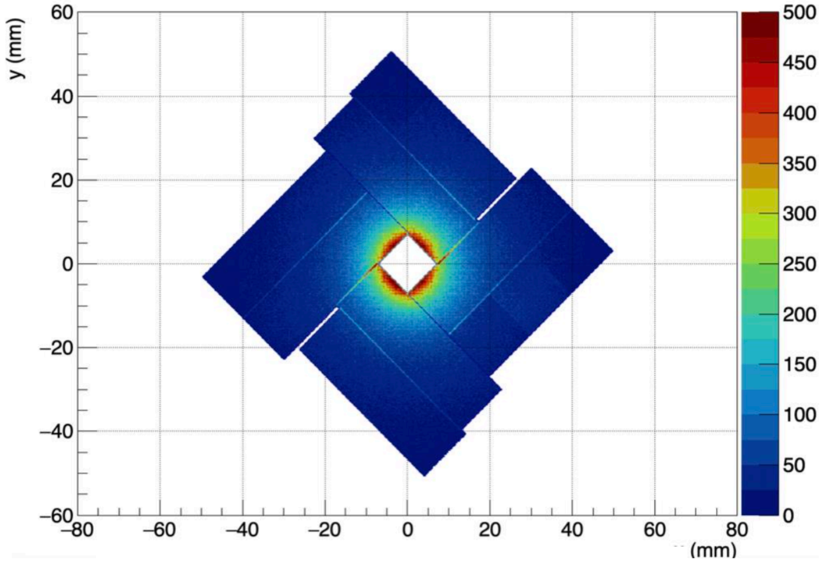


Installation completed May 2022

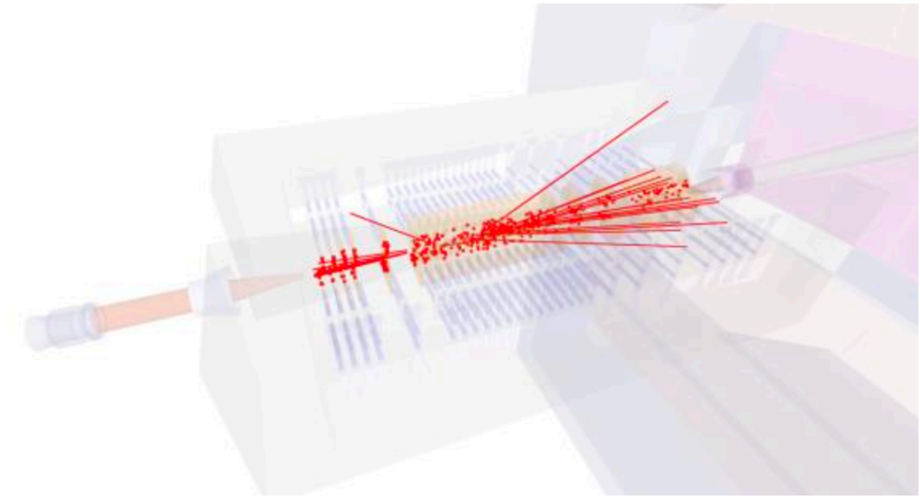
Detector commissioning with collision data ongoing, ***first closing october 21st***



VELO in open position (during injection)



VELO in closed position (with stable beams)

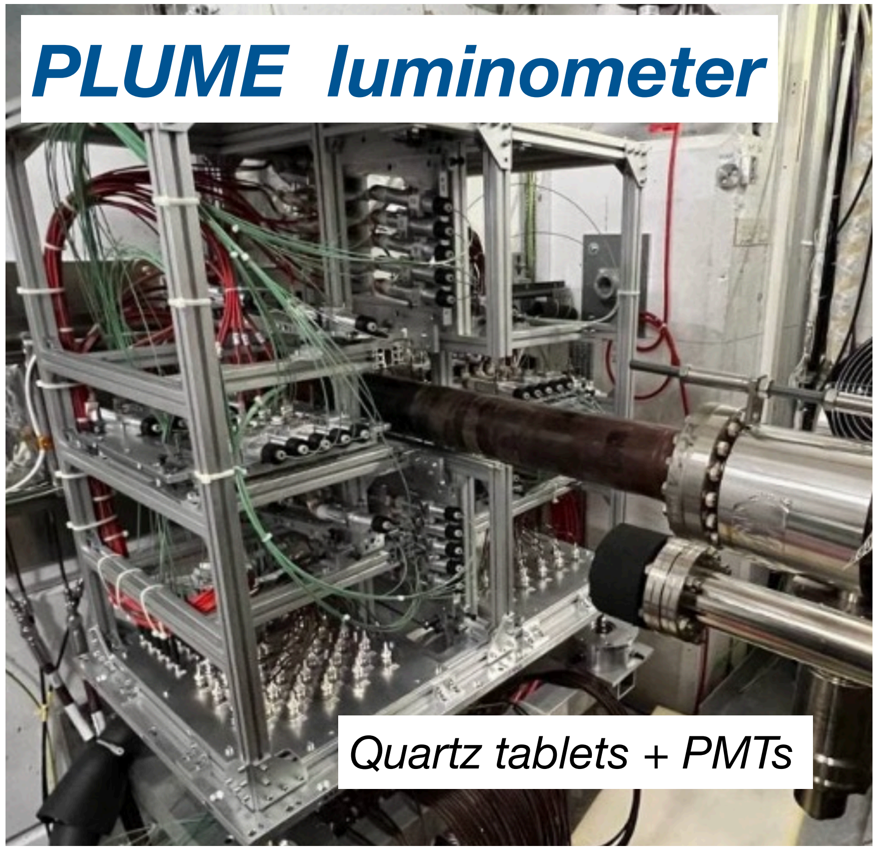


Track reconstruction commissioning

VELO clusters from RETINA algo running in readout FPGA (+15% HLT1 throughput!)

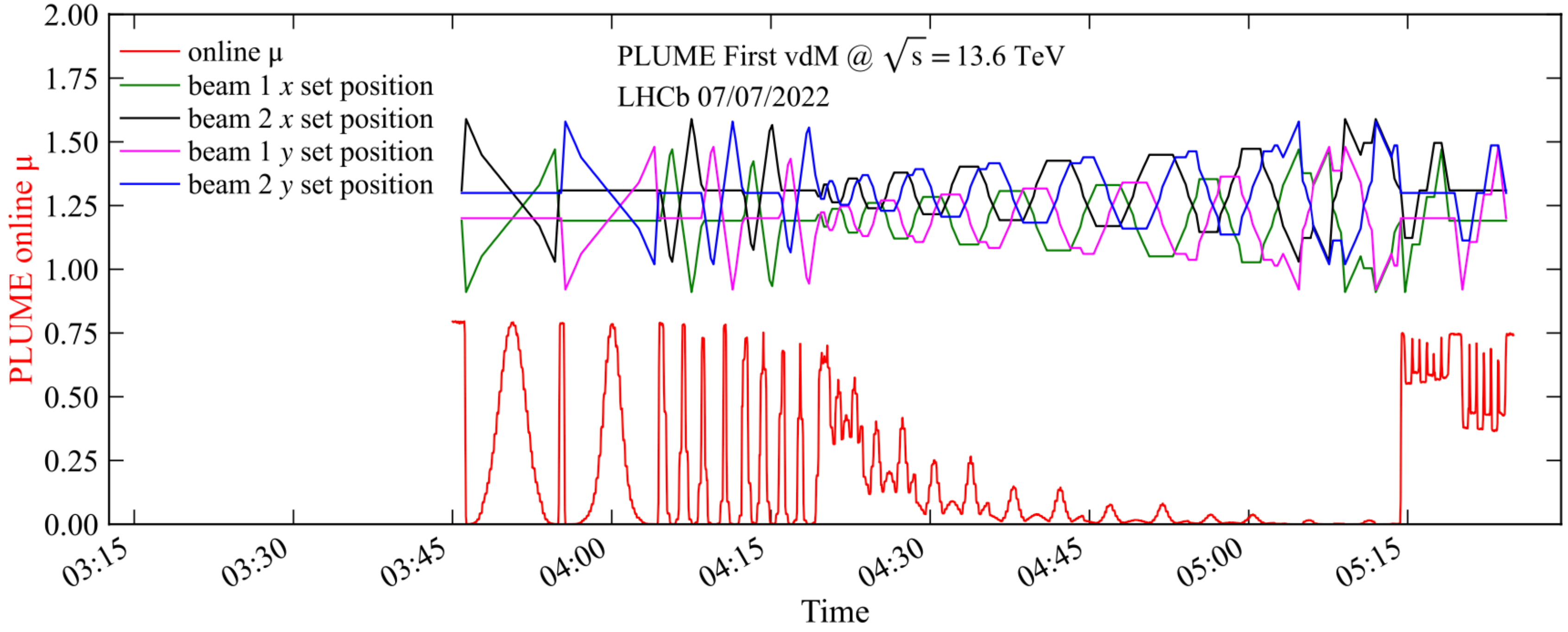
PLUME luminometer and SMOG2

PLUME luminometer

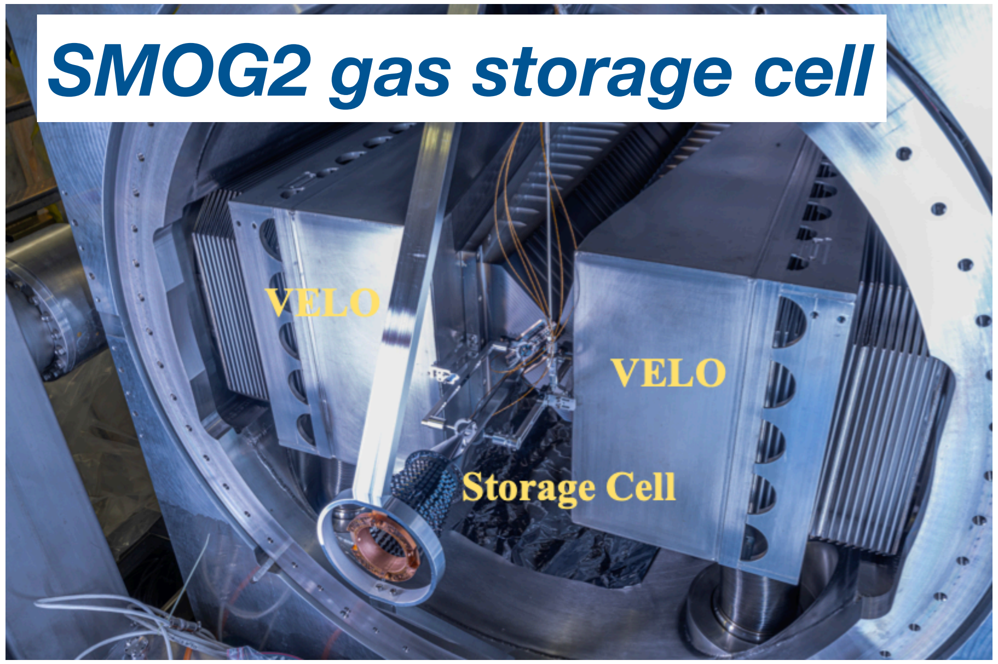


Quartz tablets + PMTs

Provides online measurement used by LHC for luminosity levelling in LHCb

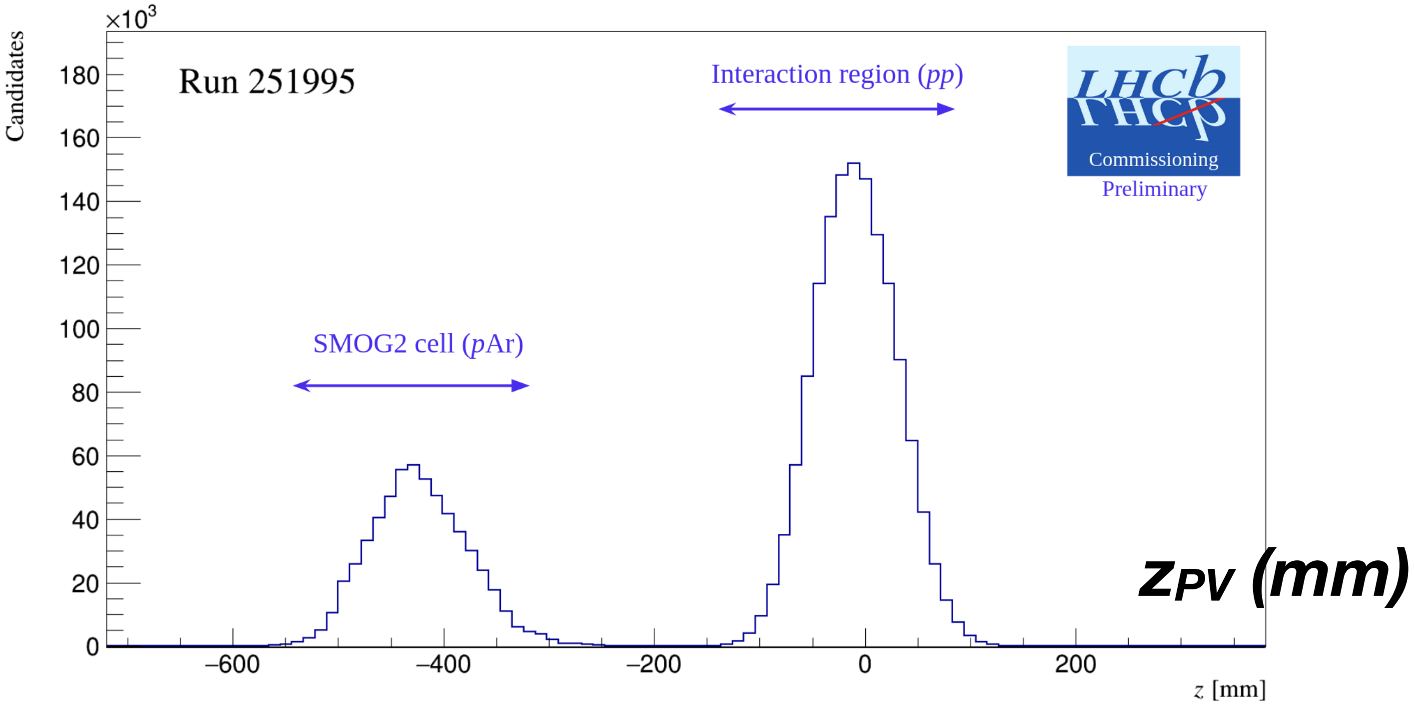


SMOG2 gas storage cell



Installed at the entrance of VELO, p-gas collisions produced upstream of the nominal p-p

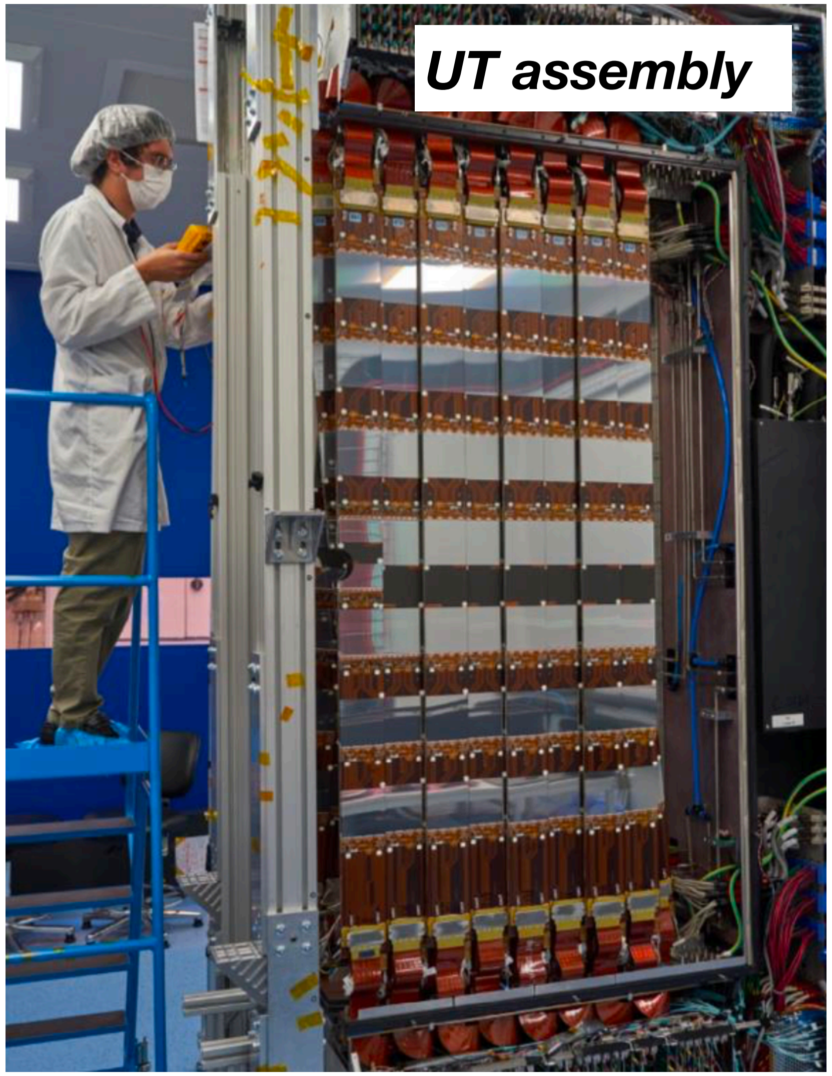
November 1st: first SMOG2 gas injection with simultaneous p-p and p-gas collisions!

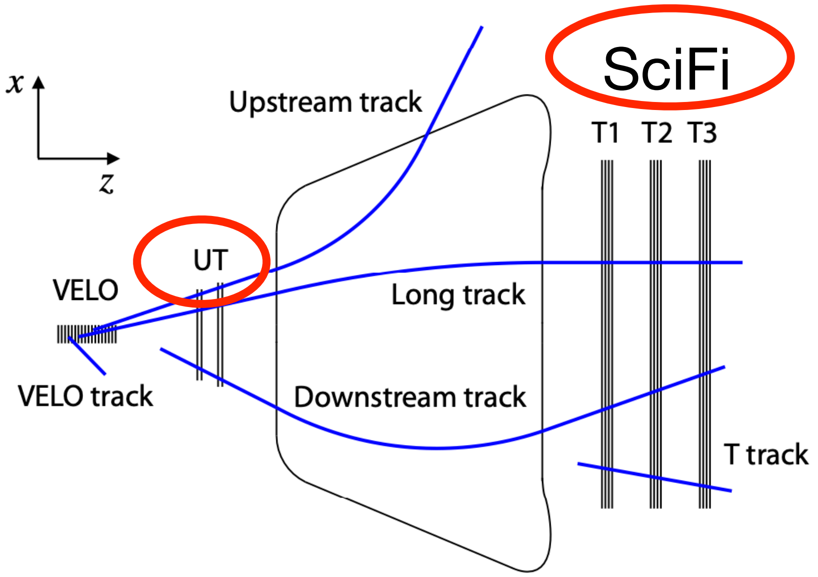


Tracking detectors

Upstream Tracker (UT): 4 planes of silicon strips

- fast p_T determination for track extrapolation → reduce ghost track, and improve trigger bandwidth
- long-lived particles decaying after VELO (K_S, Λ)
- **finalising assembly,** on schedule for installation during year-end technical stop

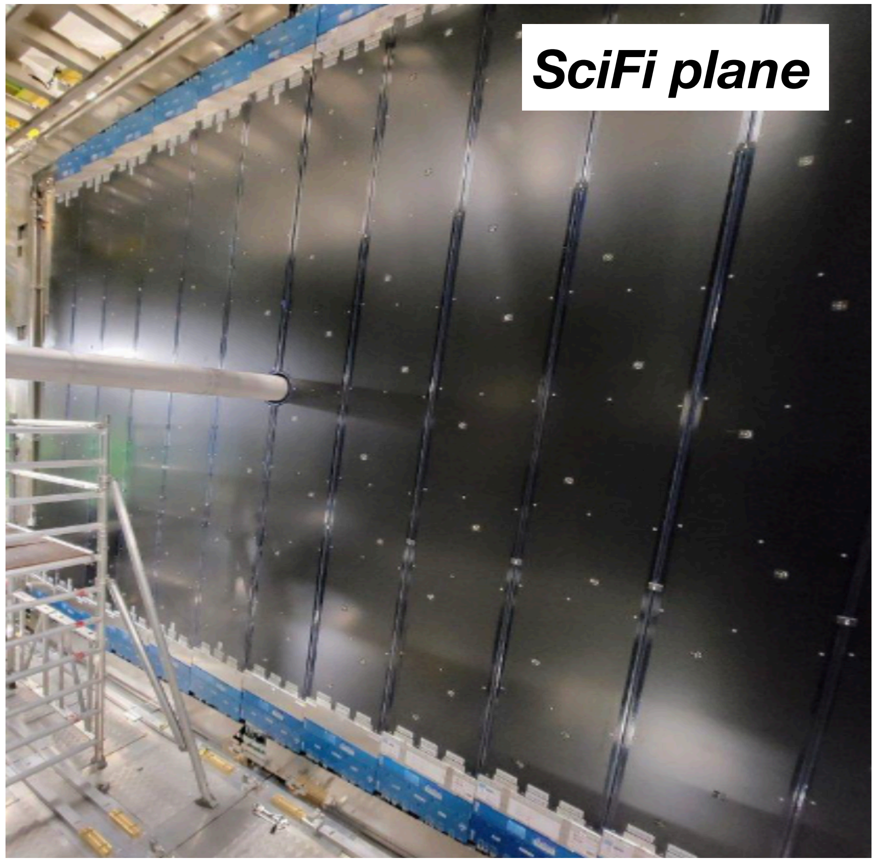

UT assembly



SciFi downstream tracker: 12 planes of scintillating fibres readout by SiPMs

- each plane, with dimensions 6x5 m^2, is made of 6 layers of scintillating fibres (250 μm diameter)

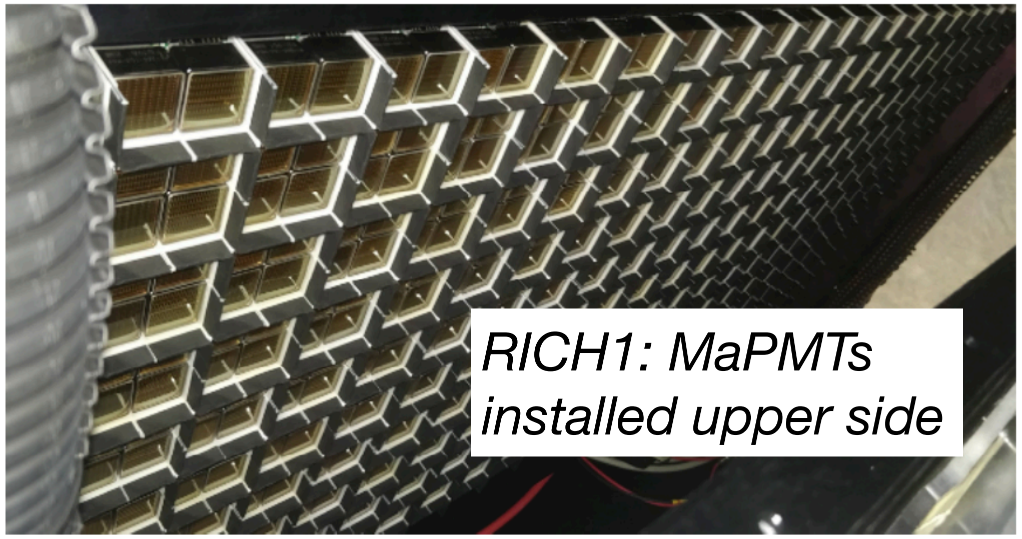
SciFi fully operational, is providing track momentum reconstruction with VELO


SciFi plane

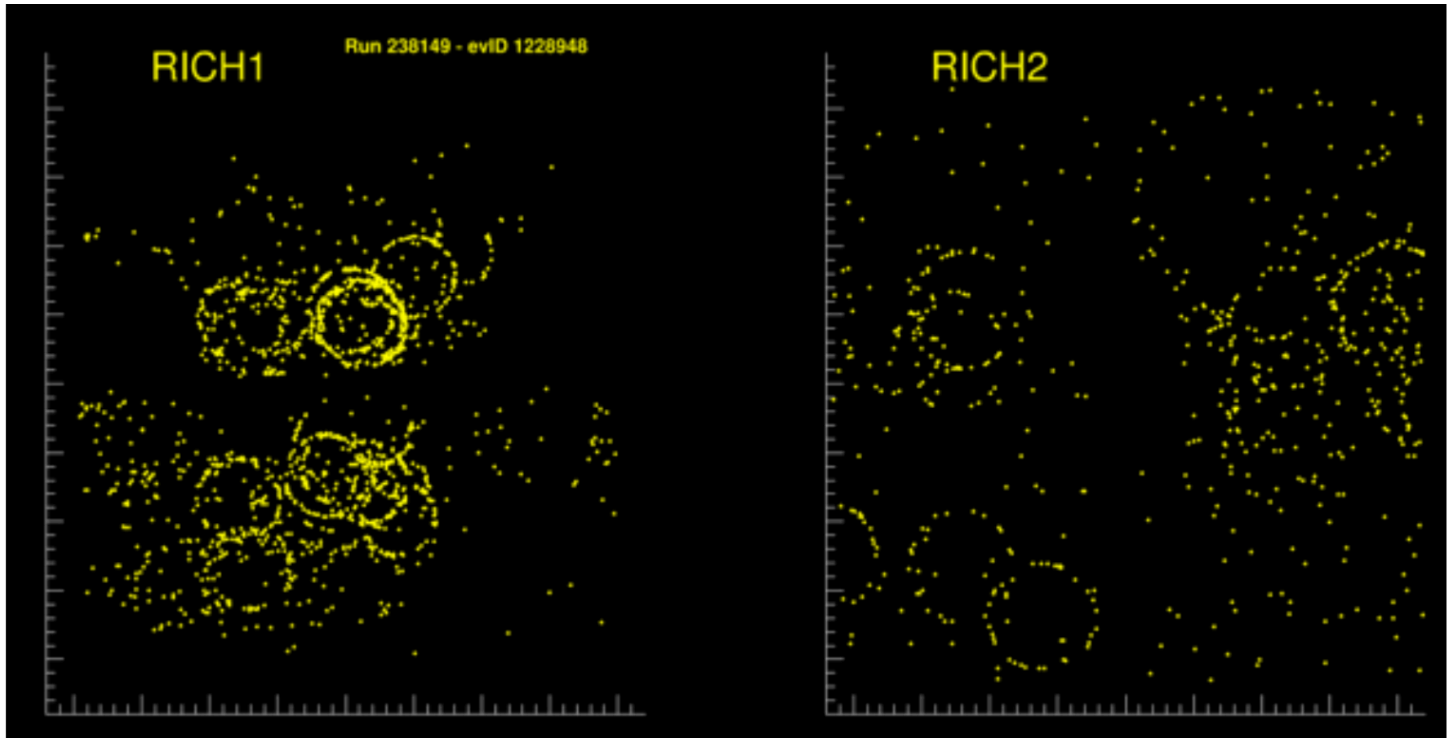
PID detectors: RICH and MUON

RICHes

- *new mirrors for RICH1*
- *new photodetectors MaPMTs with increased granularity and 40 MHz readout*

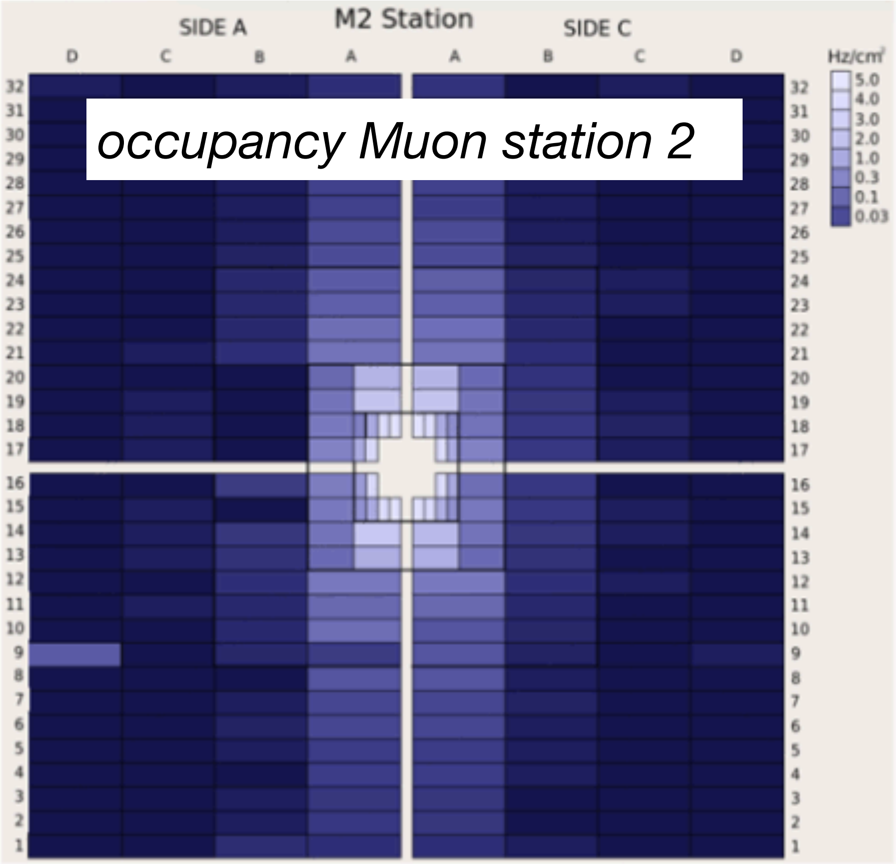


RICH1: MaPMTs installed upper side



MUON stations

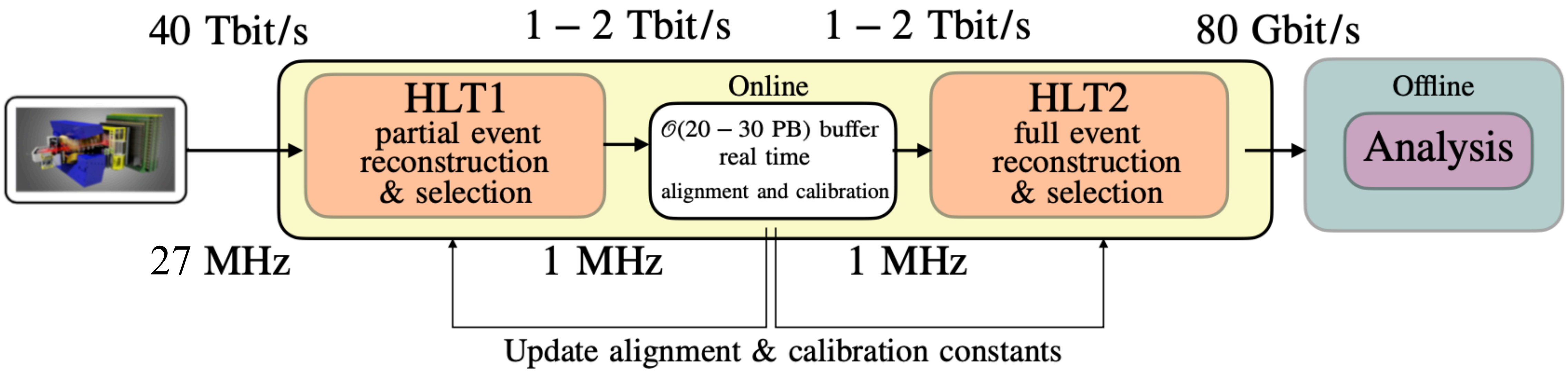
- *4 walls equipped with MWPCs, and interleaved with iron filters*
- *front-end electronics upgraded for 40 MHz readout, granularity increased on first station to reduce occupancy*



occupancy Muon station 2

Run 3 trigger revolution

L0 hardware has been removed, a full software trigger processes 27 MHz of inelastic collisions → factor of ~10 expected in hadronic yields at Run 3 (and x5 on muons)


40 Tbit/s

1 – 2 Tbit/s

1 – 2 Tbit/s

80 Gbit/s

Online

HLT1
partial event
reconstruction
& selection

$\mathcal{O}(20-30\ \text{PB})$ buffer
real time
alignment and calibration

HLT2
full event
reconstruction
& selection

Offline

Analysis

27 MHz

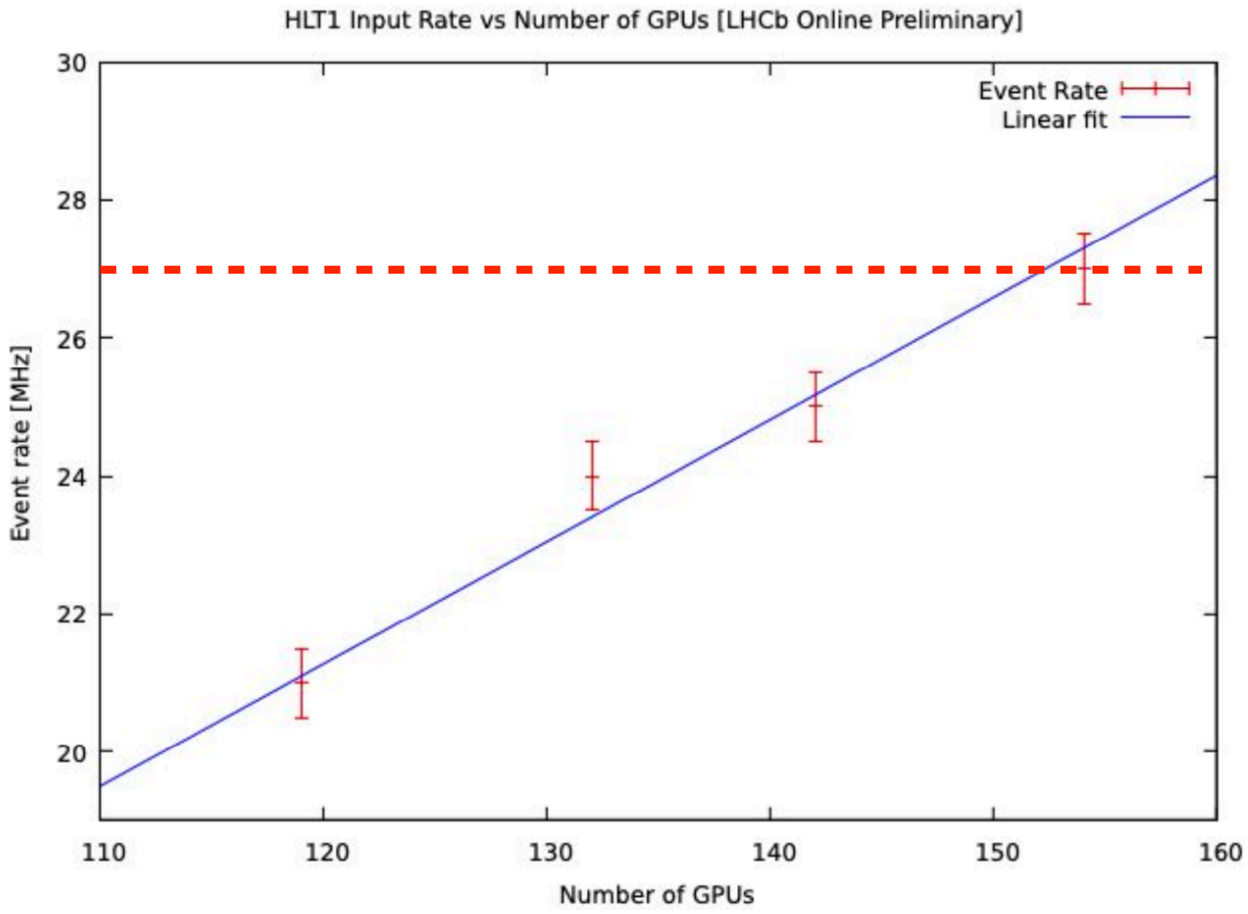
1 MHz

1 MHz

Update alignment & calibration constants

27 MHz of inelastic collisions reduced to ~1MHz by the HLT1: tracking/vertexing and muon ID running on ***GPUs***

- ***100% HLT1 throughput achieved with ~160 GPU cards***
- *room to expand to ~500 cards when porting more reco/selection functionalities into HLT1*


HLT1 Input Rate vs Number of GPUs [LHCb Online Preliminary]

Physics case: the full table

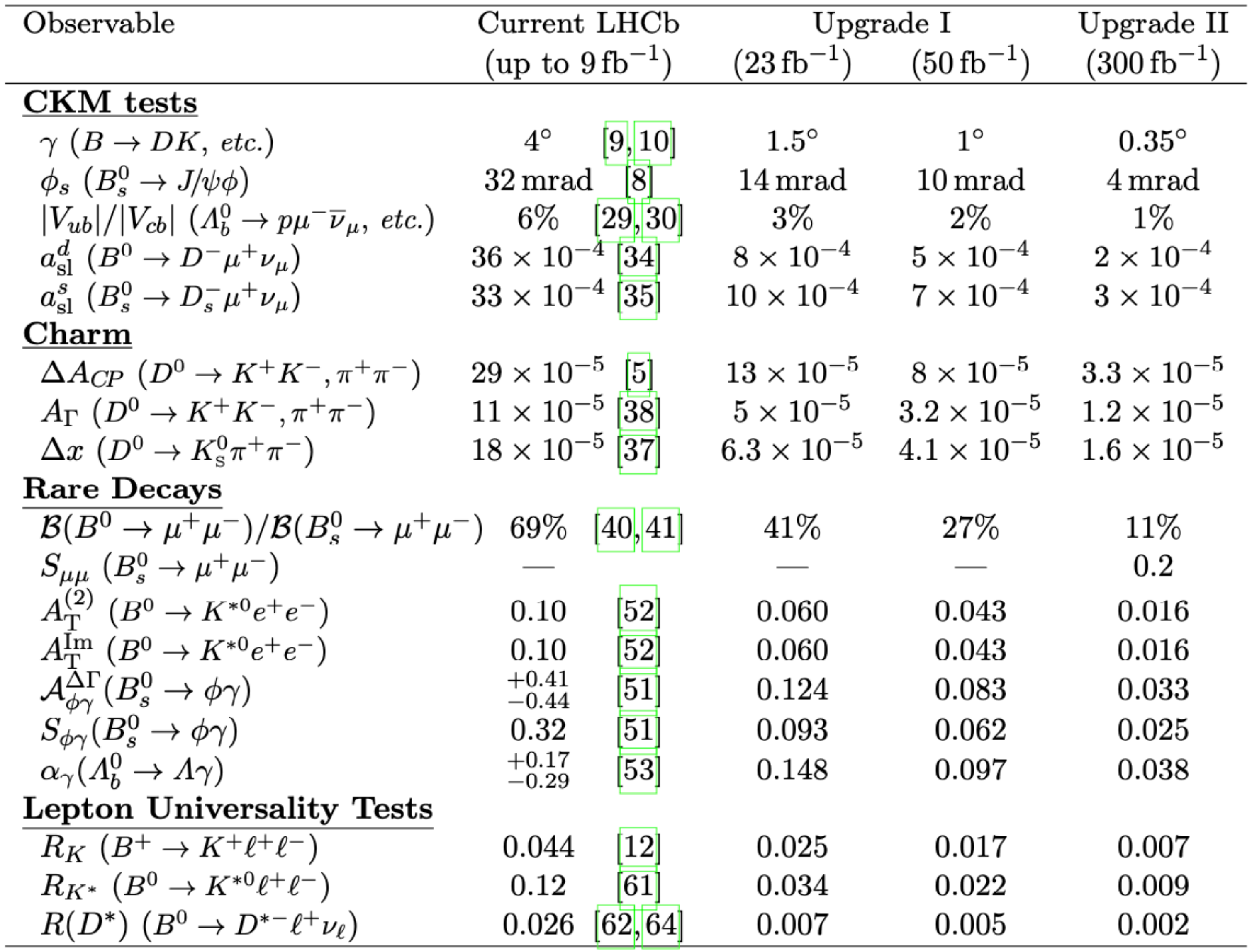
LHCC-2018-027

LHCC-2021-012

Upgrade I will not saturate precision in many key observables ⇒ Upgrade II will fully realise the flavour-physics potential of the HL-LHC

— Run 3 — Run 4 — Run 6 →

Key observables in flavour physics



Observable	Current LHCb		Upgrade I		Upgrade II
	(up to $9\,\mathrm{fb}^{-1}$)		($23\,\mathrm{fb}^{-1}$)	($50\,\mathrm{fb}^{-1}$)	($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_{\mathrm{S}}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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

NOT ONLY: *LHCb, as a general purpose detector in forward region, will keep pursuing an ambitious programme in spectroscopy, EW precision and Higgs physics, dark sector, heavy ions and fixed target physics ...*

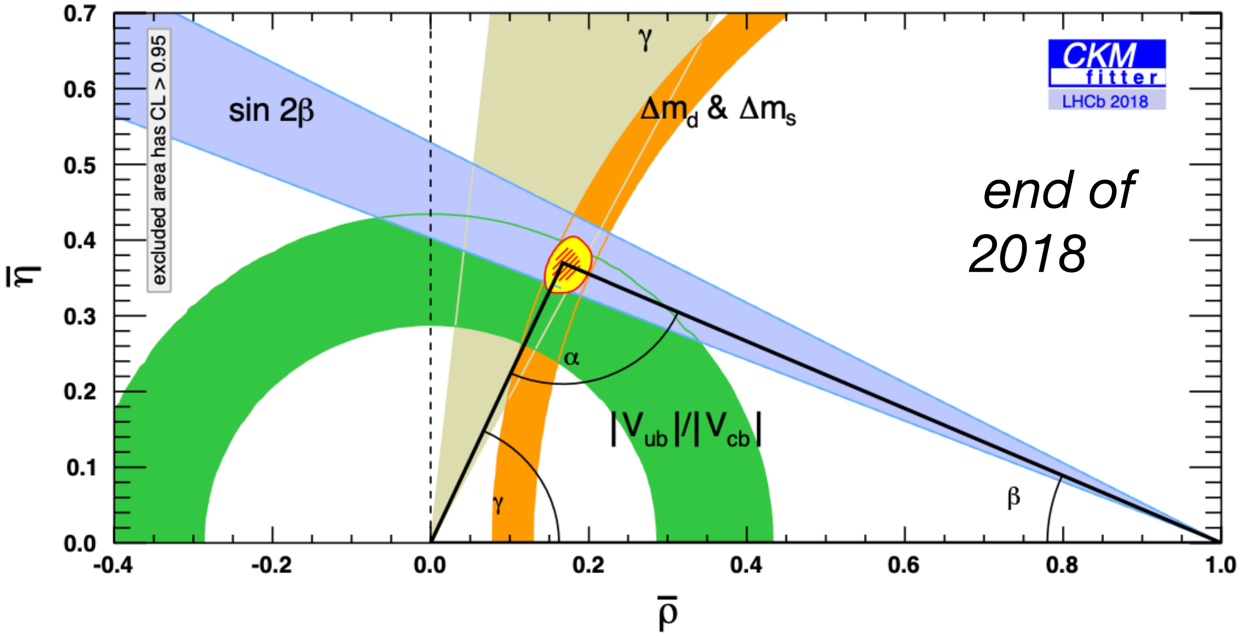
LHCC-2018-027

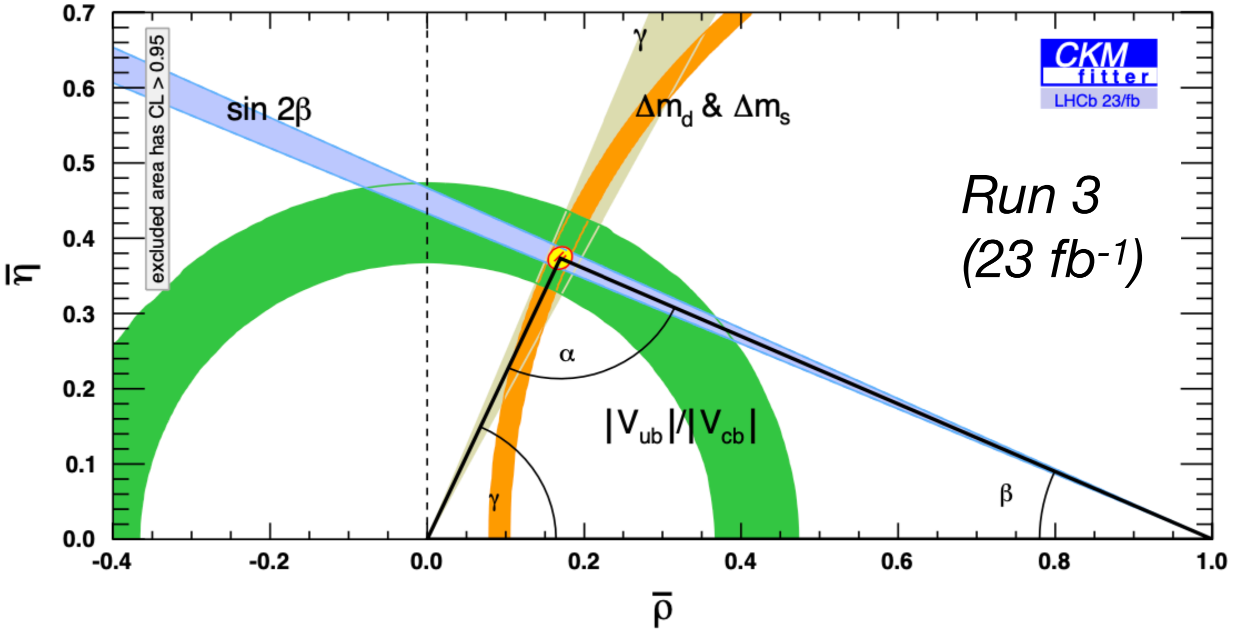
Constraining the unitarity triangle

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 will test the CKM paradigm with unprecedented accuracy

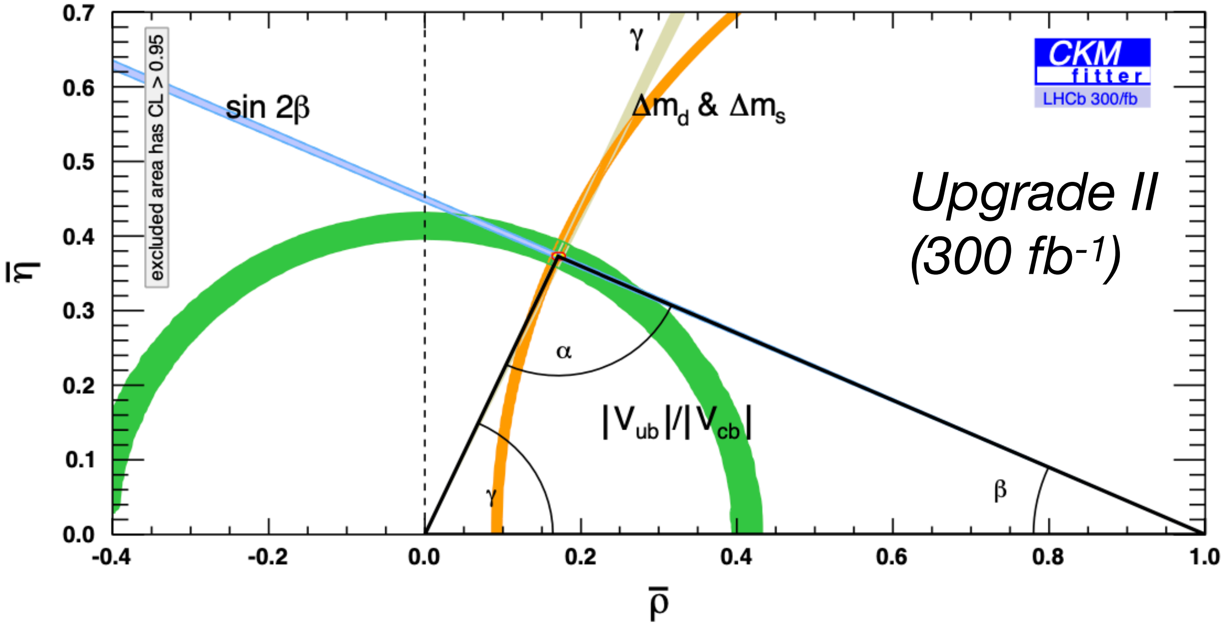
LHCb-only inputs, prepared for LHCC-2018-027





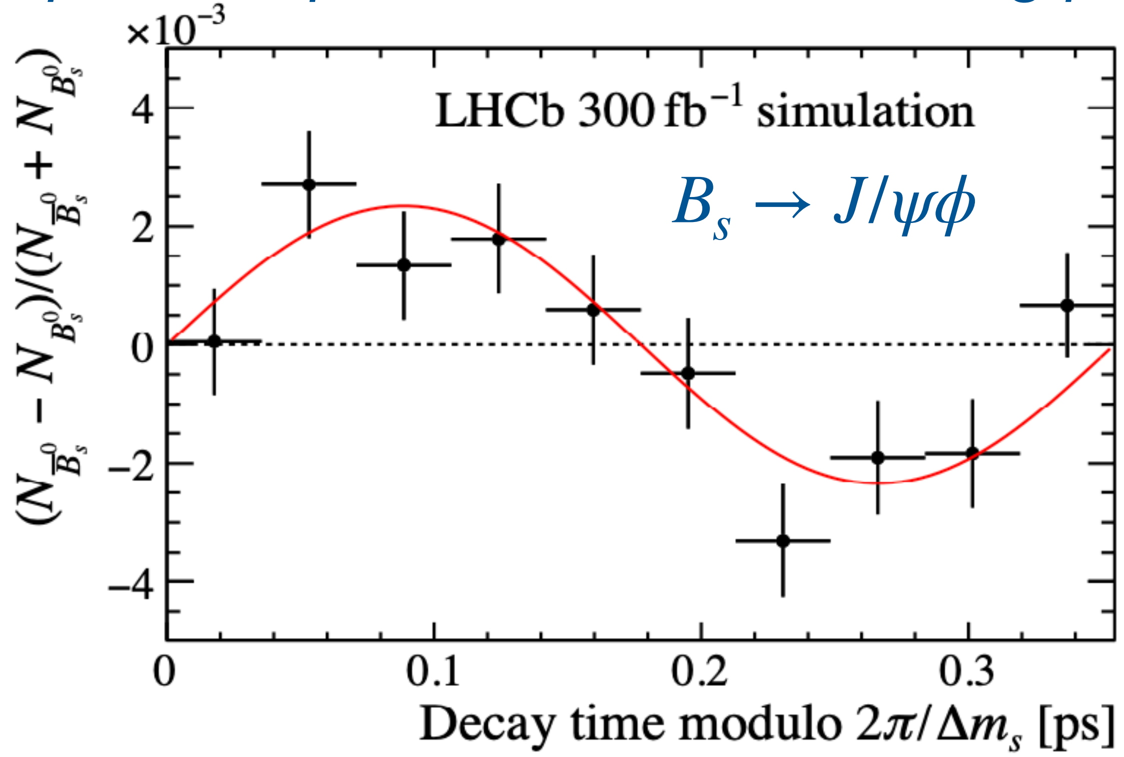
- *Two independent measurements of triangle apex: $(\Delta m_d/\Delta m_s, \sin 2\beta)_{loop}$ and $(V_{ub}, \gamma)_{tree}$*
- *Both pairs require Upgrade II for statistics ($\sin 2\beta$ and γ) and time for theory improvements ($\Delta m_d/\Delta m_s$ and V_{ub})*

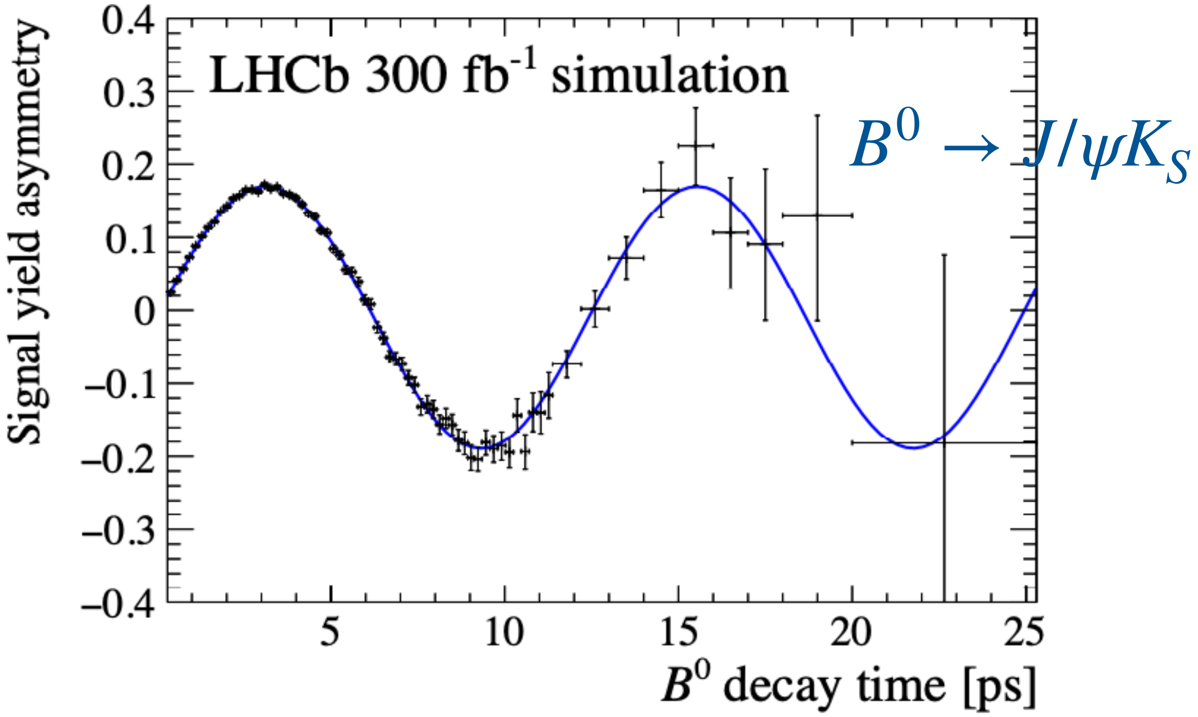
~order of magnitude improvement in LQCD is assumed for Upgrade II



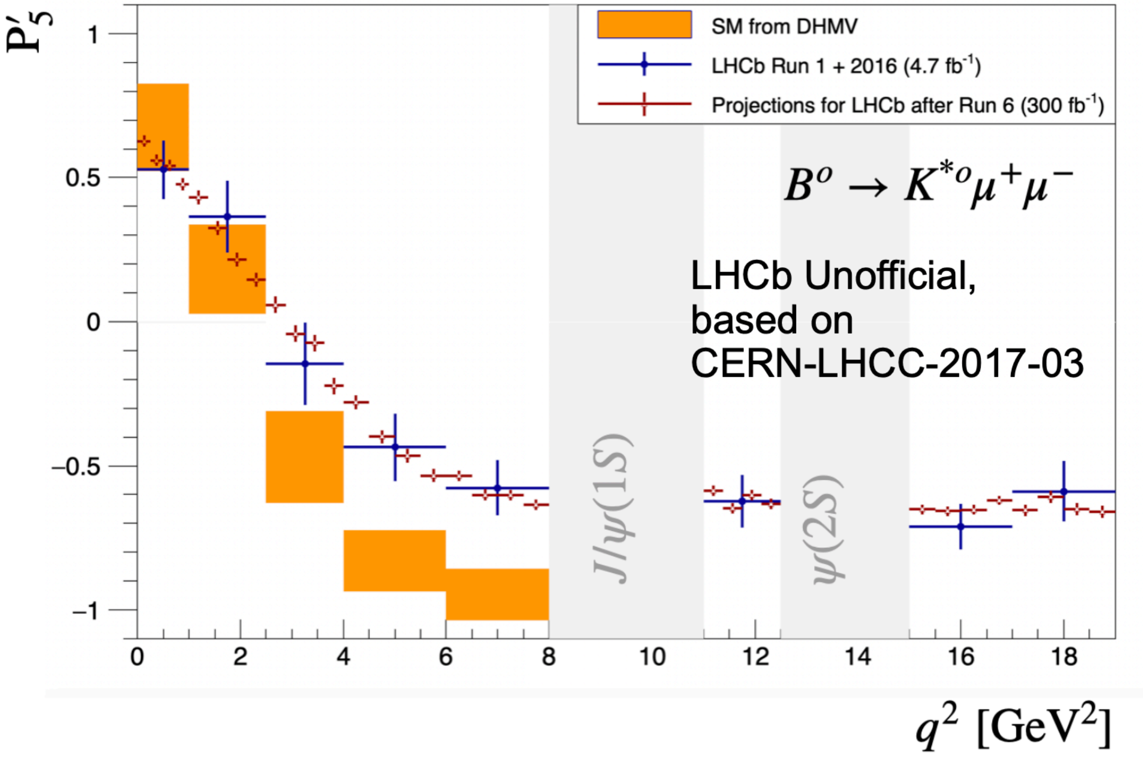
The power of statistics

Impressive precision on CP violating phases will be reached at Upgrade II

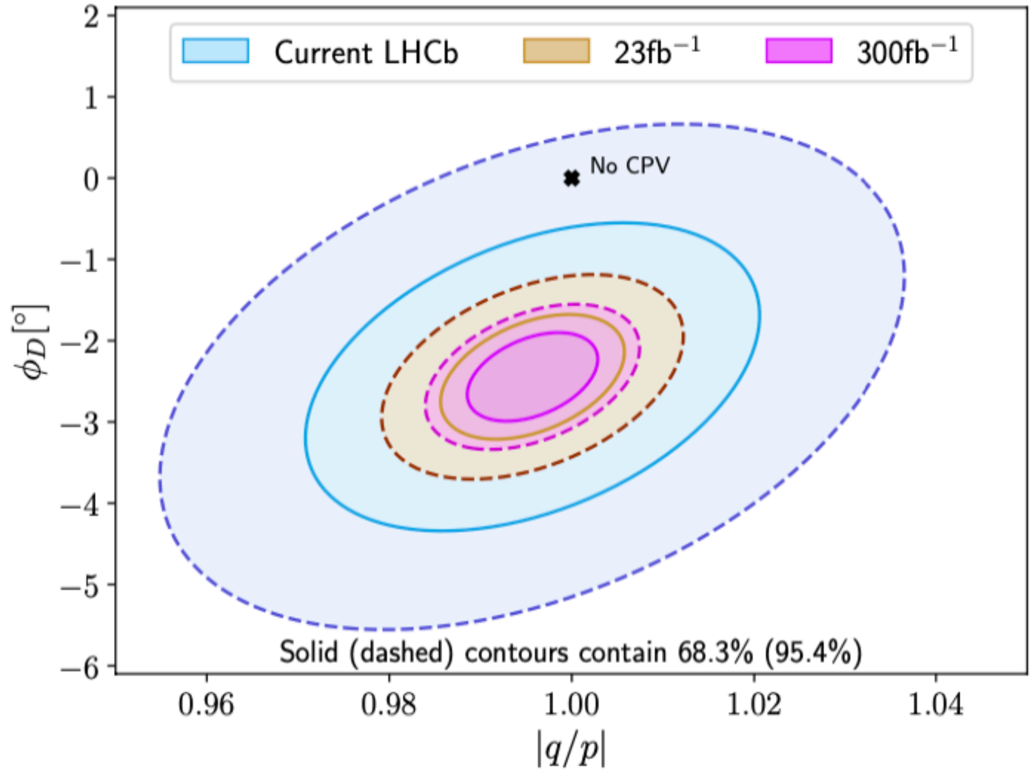




Rare $b \to s\ell^+\ell^-$ decays and lepton universality



LHCb Upgrade II is the only planned facility with a realistic possibility to observe CPV in charm mixing



Solid (dashed) contours contain 68.3% (95.4%)

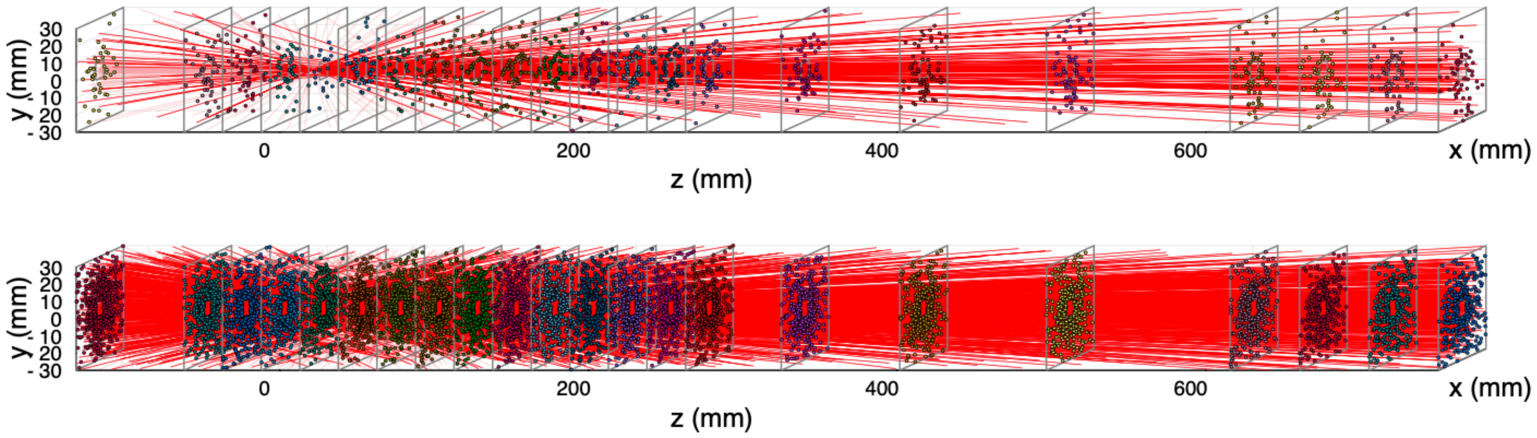
The Upgrade II challenge

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

simulated events in LHCb VELO

Run 3: pile-up ~5

Upgrade II: pile-up ~40

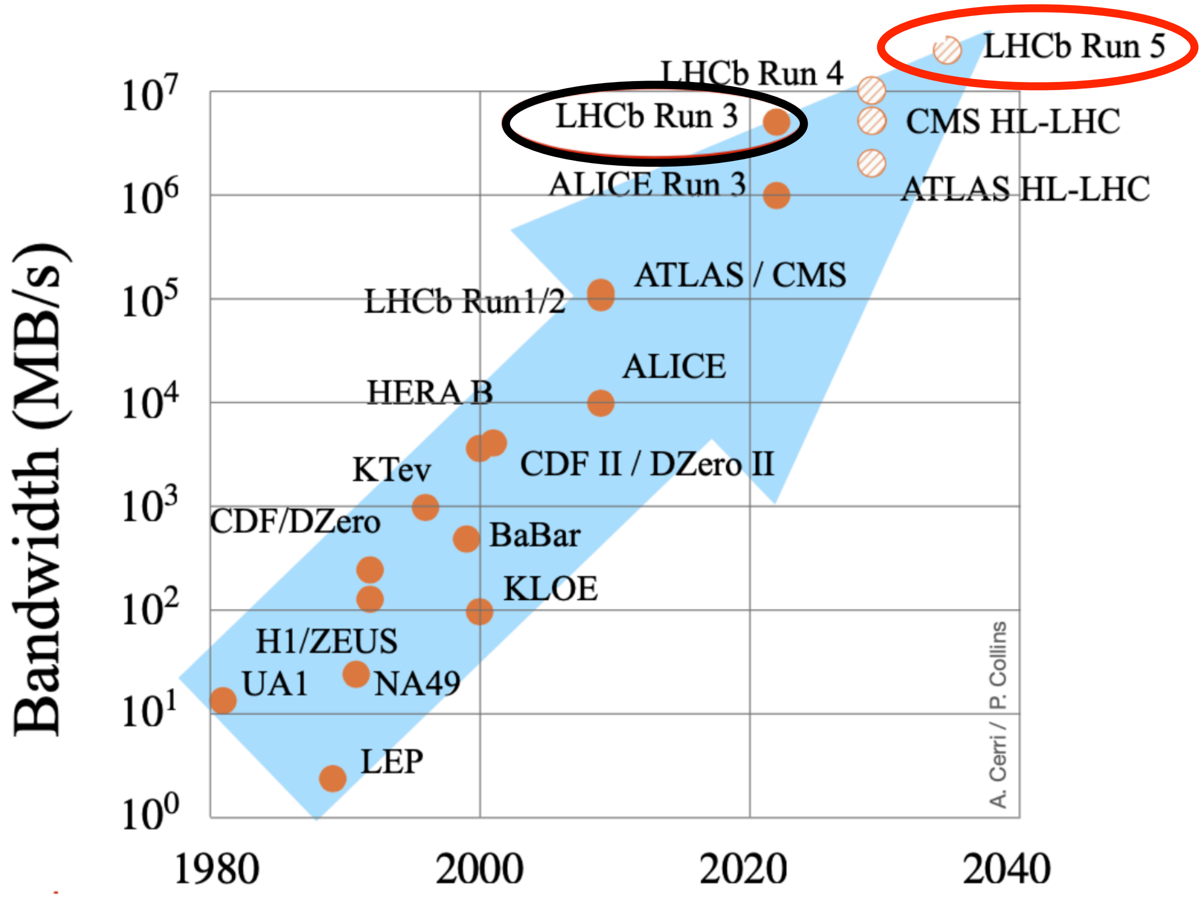


~6 cm

This is the intensity frontier!

New, lightweight technologies with high granularity, timing, extreme radiation resistance and innovative data processing all necessary to go to ~10^{34} cm^{-2}s^{-1}

LHCb Upgrade II data throughput: 200 Tb/s

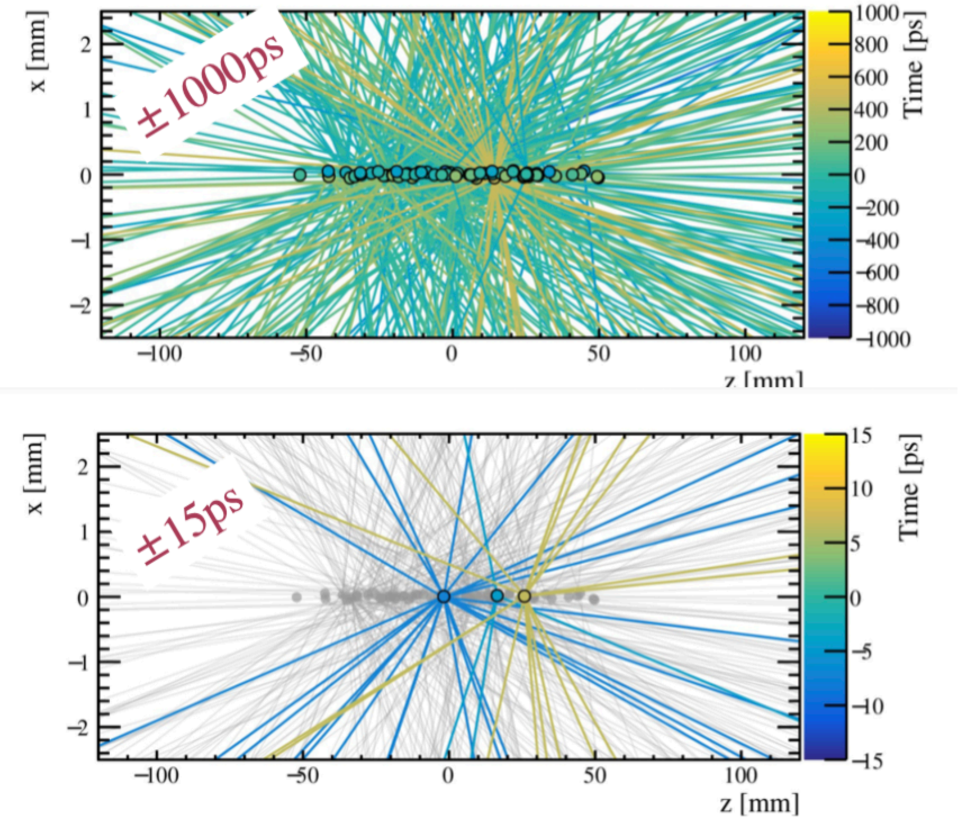


Timing to the rescue

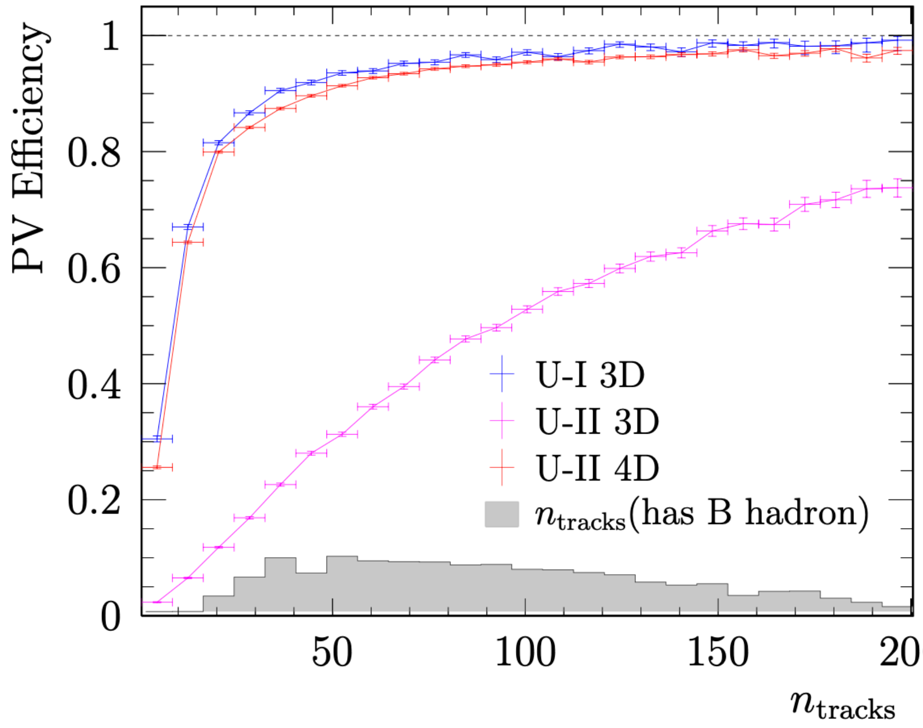
Timing capability at few tens of picosecond is crucial to reduce effective pile-up

VELO

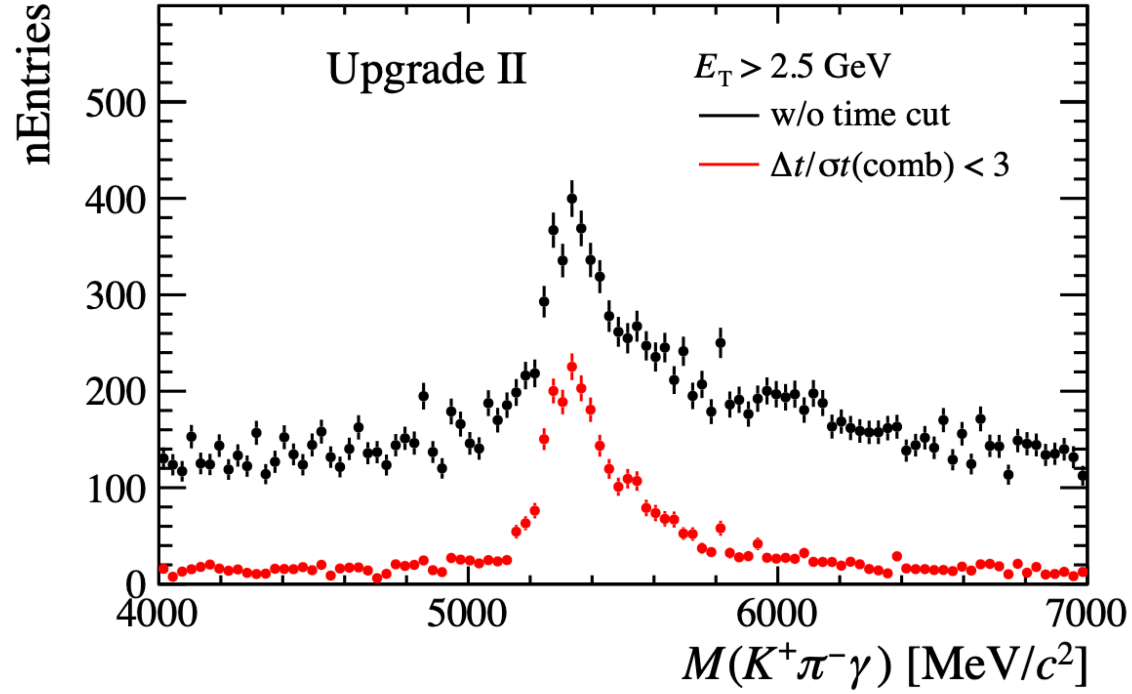
each hit in time-stamped with 50 ps resolution → 20 ps per track



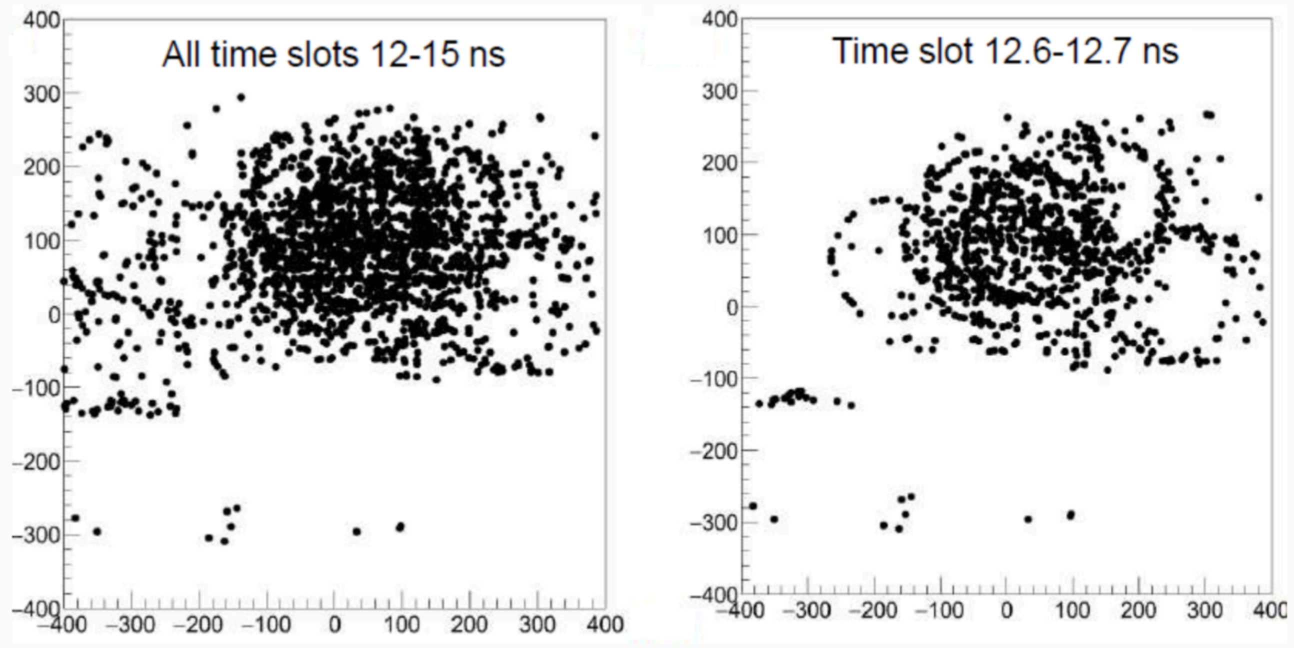
PV efficiency with and w/o timing



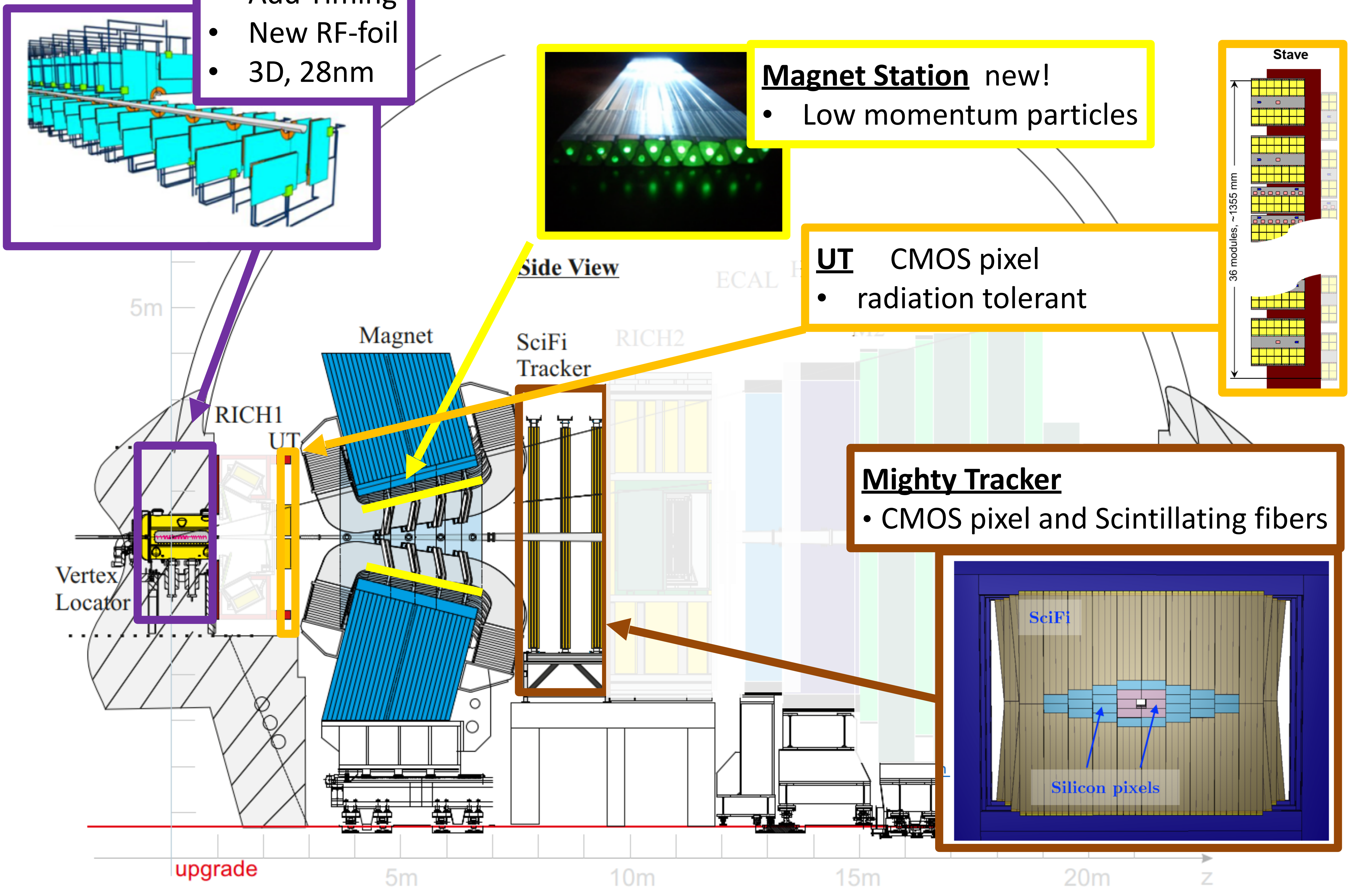
Adding timing to ECAL…



…and to RICH



The tracking system



VELO pixel

- Add Timing
- New RF-foil
- 3D, 28nm

Magnet Station new!

- Low momentum particles

UT CMOS pixel

- radiation tolerant

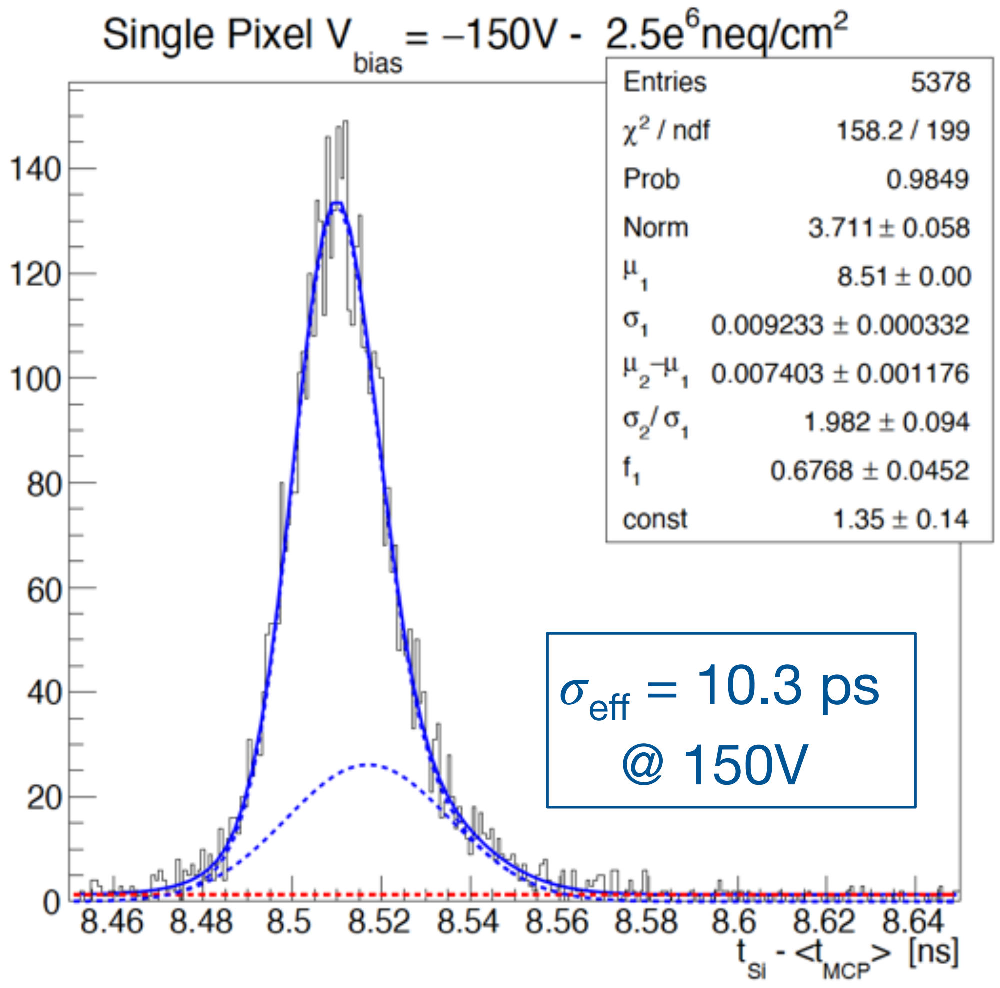
Mighty Tracker

- CMOS pixel and Scintillating fibers

VELO: 4D tracking with precision timing

Requirements: $55\mu m$ ***pitch , time reso 50 ps, fluence*** $6 \times 10^{16} n_{eq}/cm^2$, ***>250 Gb/s per ASIC***

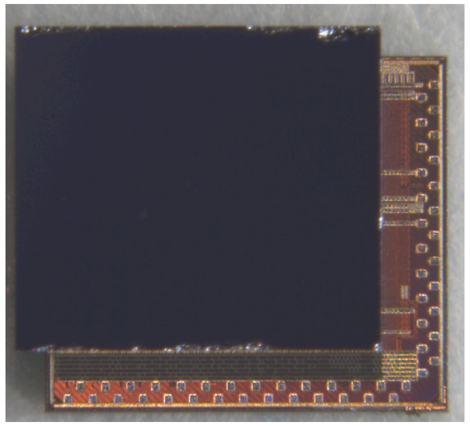
Excellent timing performances achieved with TimeSpot 3D-trench silicon sensors after irradiation $2.5 \times 10^{16} n_{eq}/cm^2$

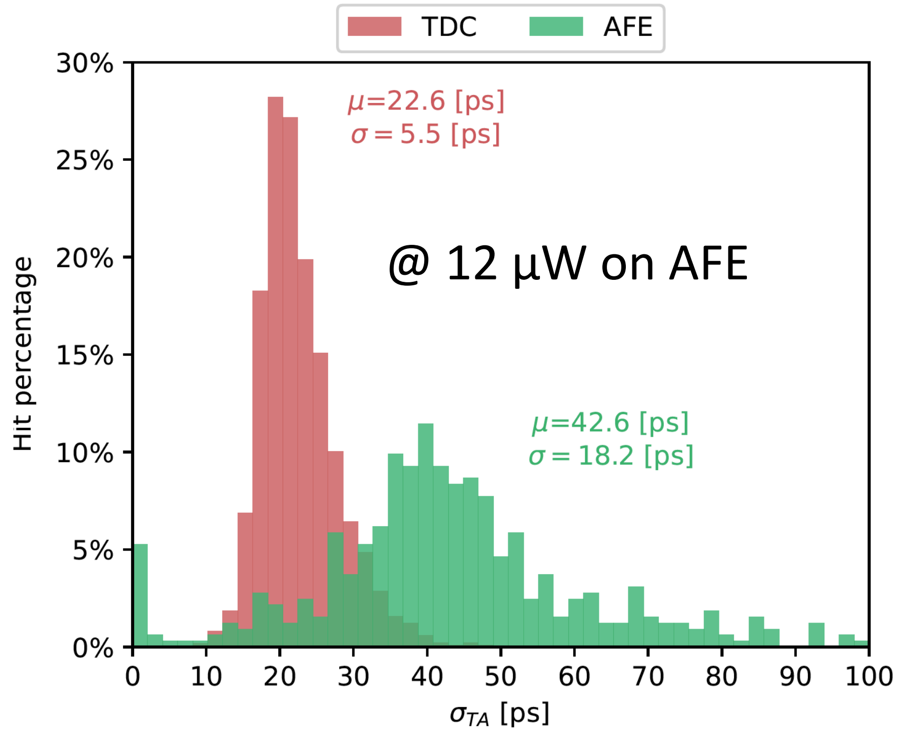


Elba '2022

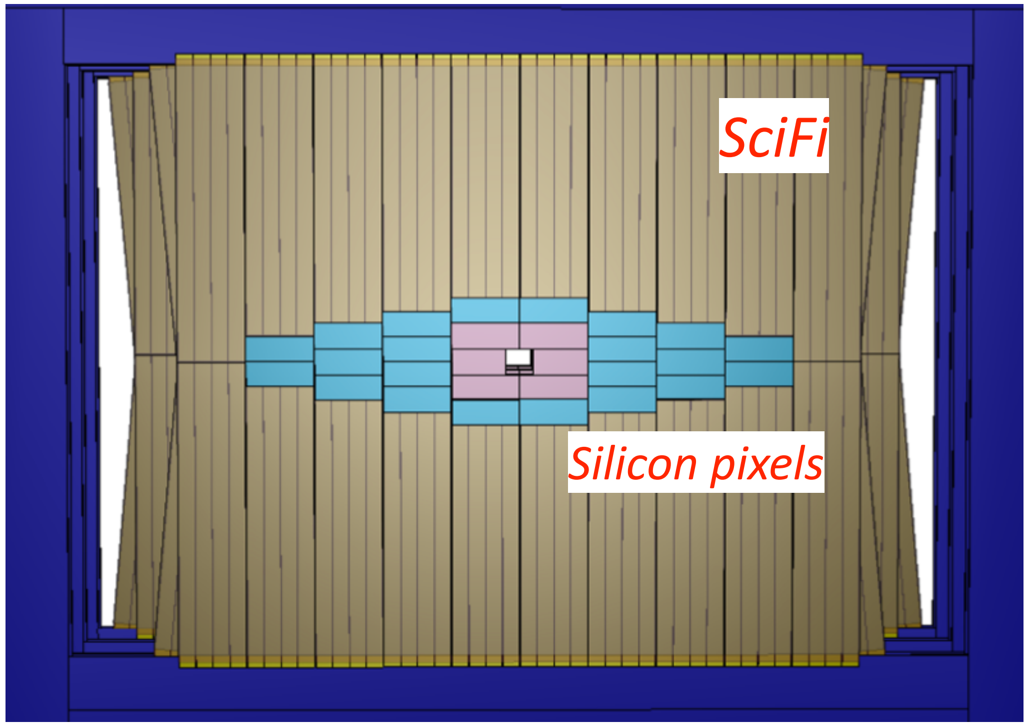
First major 28 nm CMOS ASIC design in the HEP community

Hybridized Timespot1 ASIC, 32x32 pixels, $55\mu m$ pitch





Mighty Tracker



Keep occupancy under control in the inner regions + harsh radiation environment

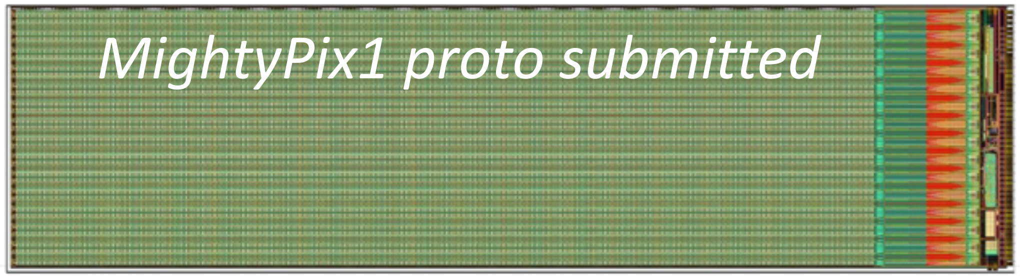
New hybrid tracker with combination of : ***HV-CMOS silicon pixels*** *(inner) and* ***scintillating fibres*** *(outer)*

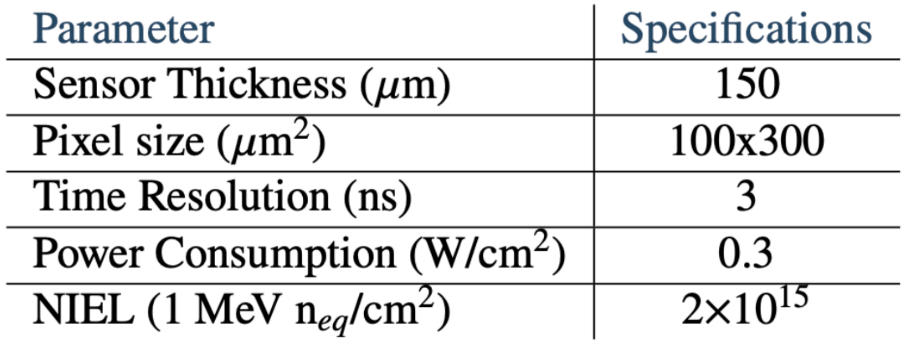
Mechanical integration btw technologies crucial, minimise material budget

CMOS pixels

Large area to be equipped ~20 m²

Testbeams and submissions stemming from MuPix and ATLASPix showing promising results



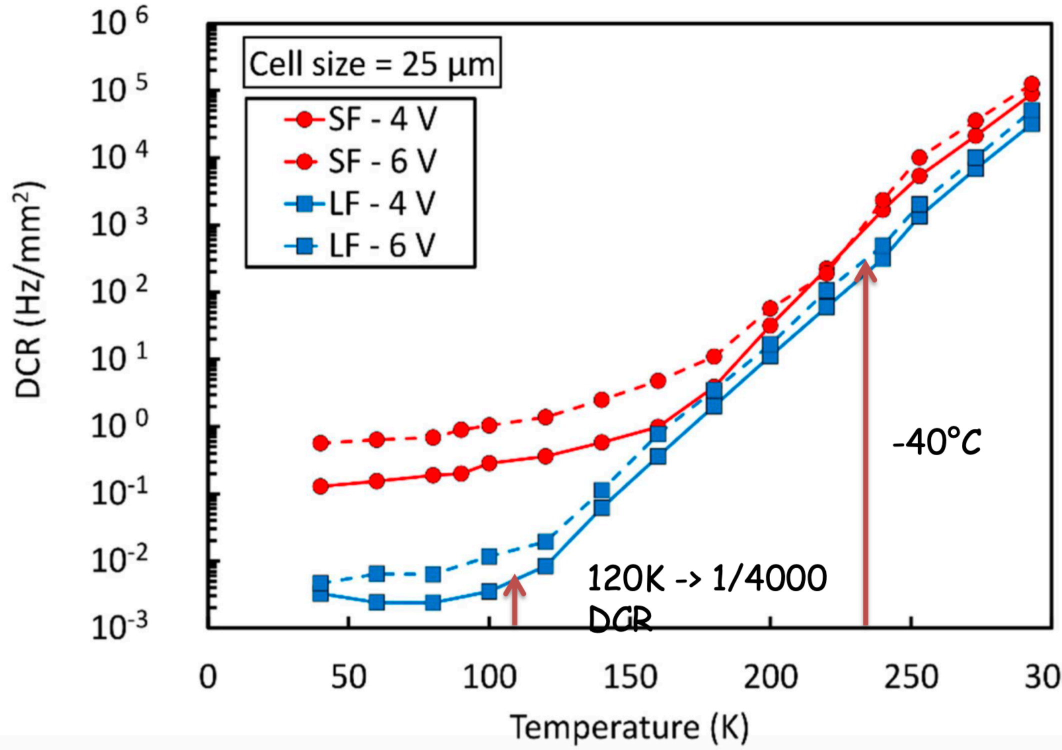


Parameter	Specifications
Sensor Thickness (μm)	150
Pixel size (μm^2)	100x300
Time Resolution (ns)	3
Power Consumption (W/cm^2)	0.3
NIEL (1 MeV n_{eq}/cm^2)	2×10^{15}

SciFi

Reduce fibre layers per mat to reduce occupancy, increase SiPM light collection with microlenses

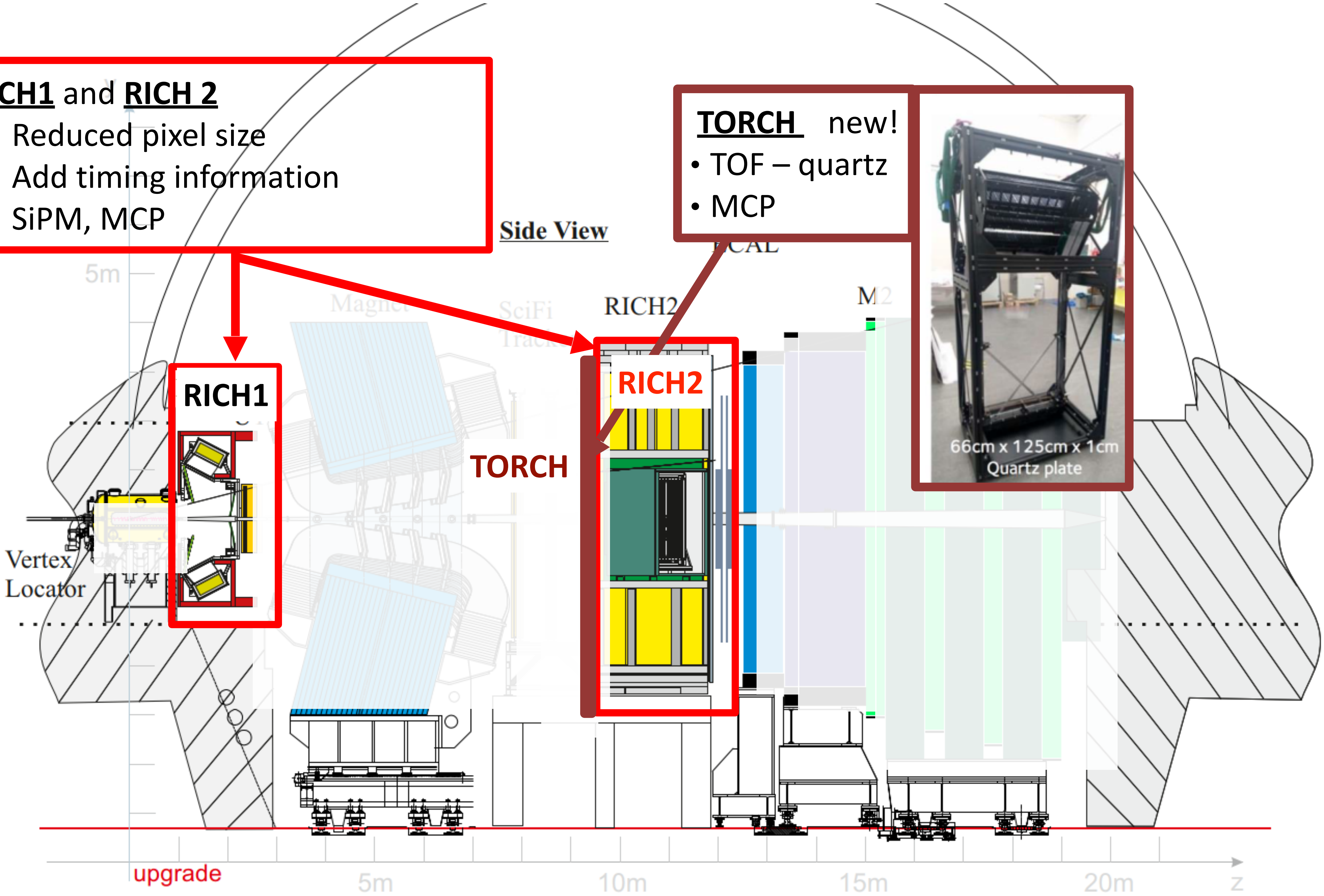
Decrease operating temperature for SiPM to limit dark current → move to cryo cooling



PID detectors 1

RICH1 and **RICH 2**
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new!
- TOF – quartz
- MCP



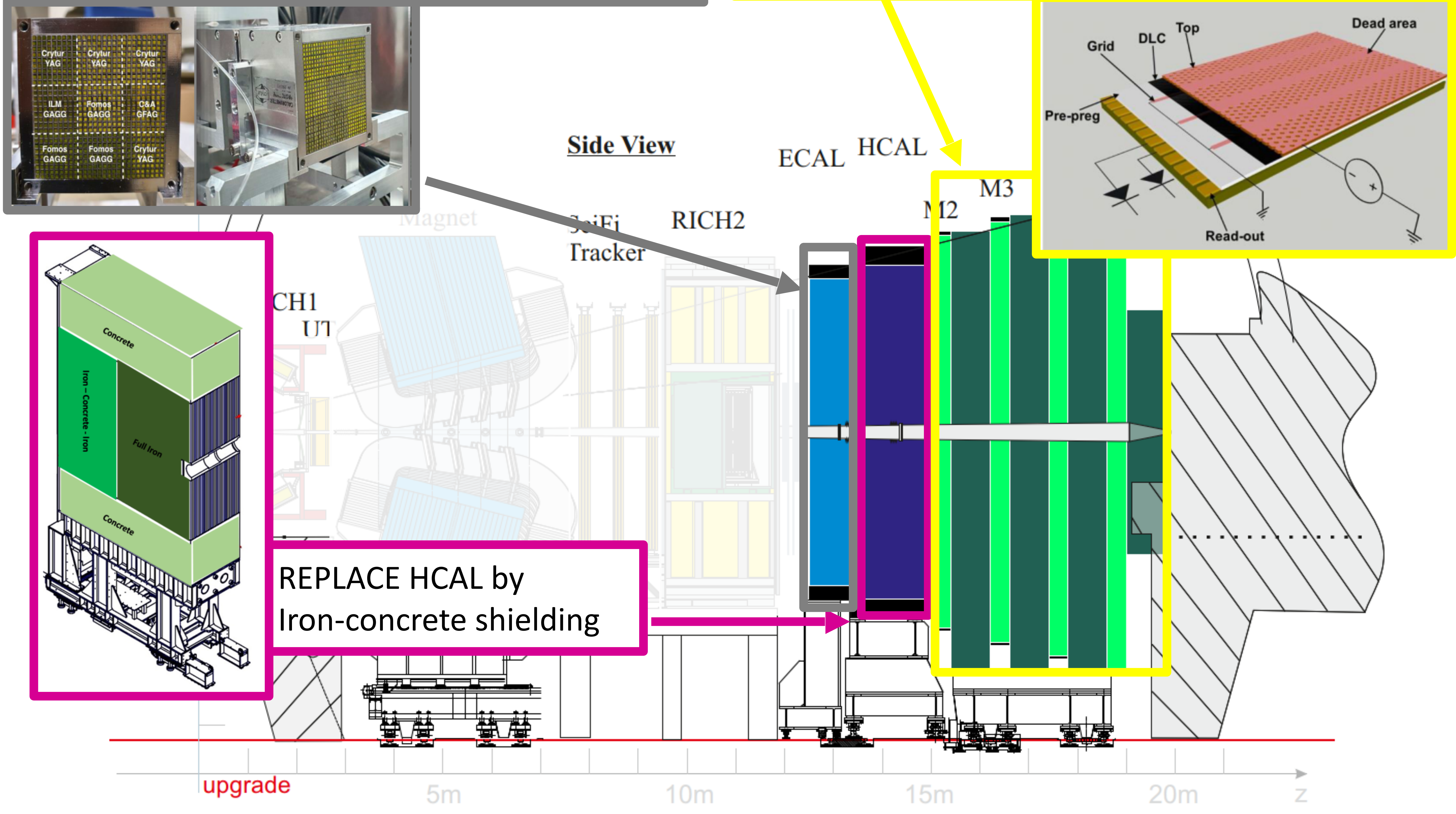
PID detectors 2

ECAL

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

MUON

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



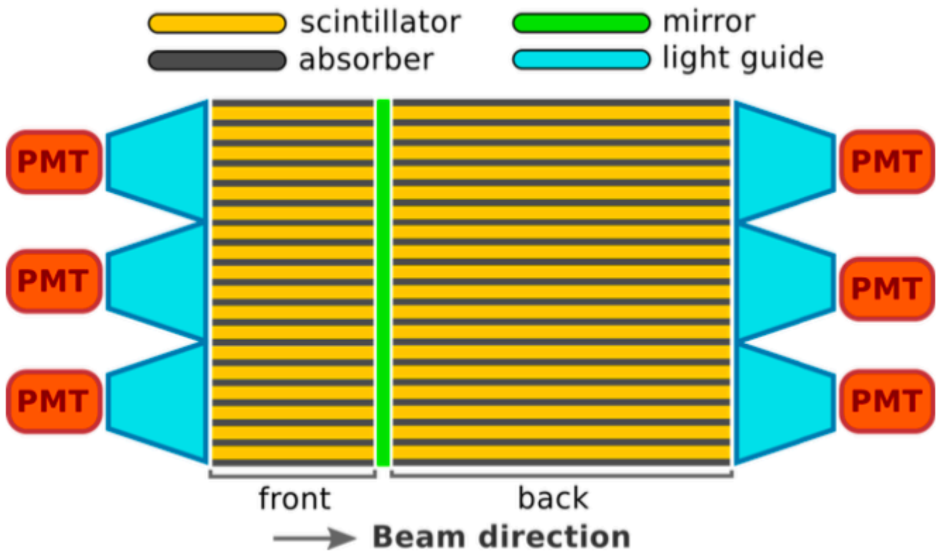
REPLACE HCAL by
Iron-concrete shielding

ECAL with timing

Challenge: *pile-up and radiation up to 1 MGy*

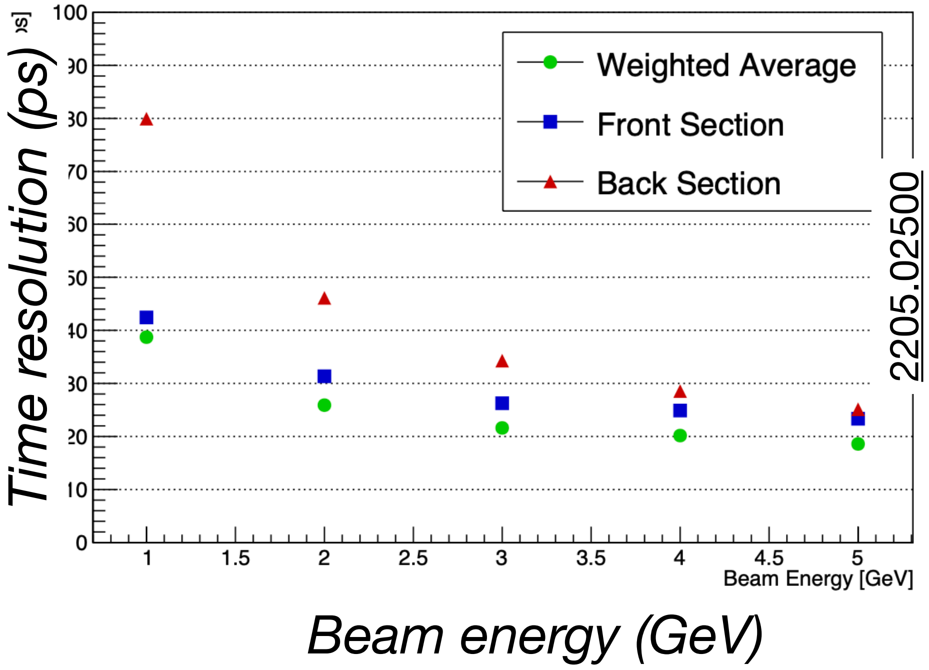
Requires: *granularity, precision timing*

Different technologies in different regions:
SpaCal/Shashlik for inner/outer regions. Option to add a timing layer is also under study

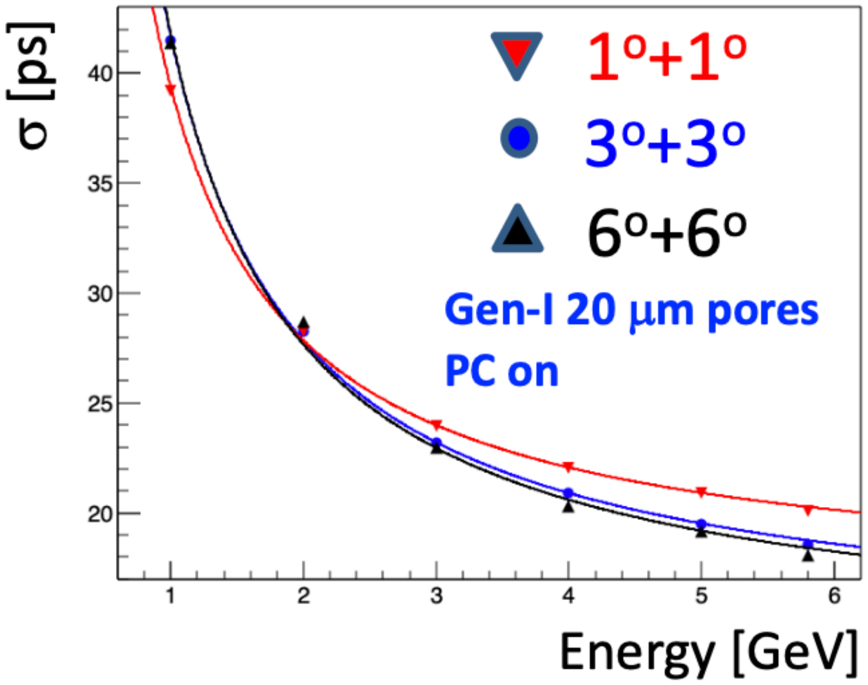


Very promising time resolution achieved in R&D

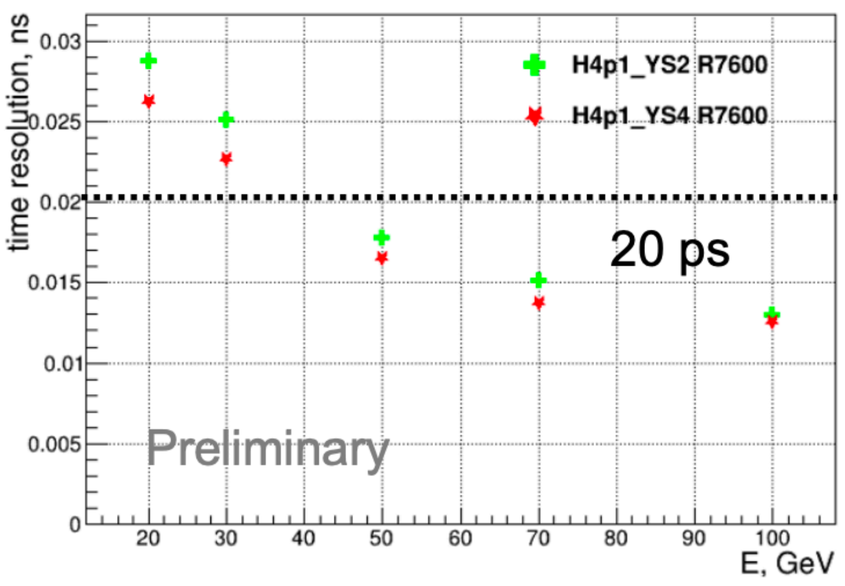
W + crystal-fibres (GAGG)



SpaCal + Timing layer (LAPDD)



Shashlik (present technology)



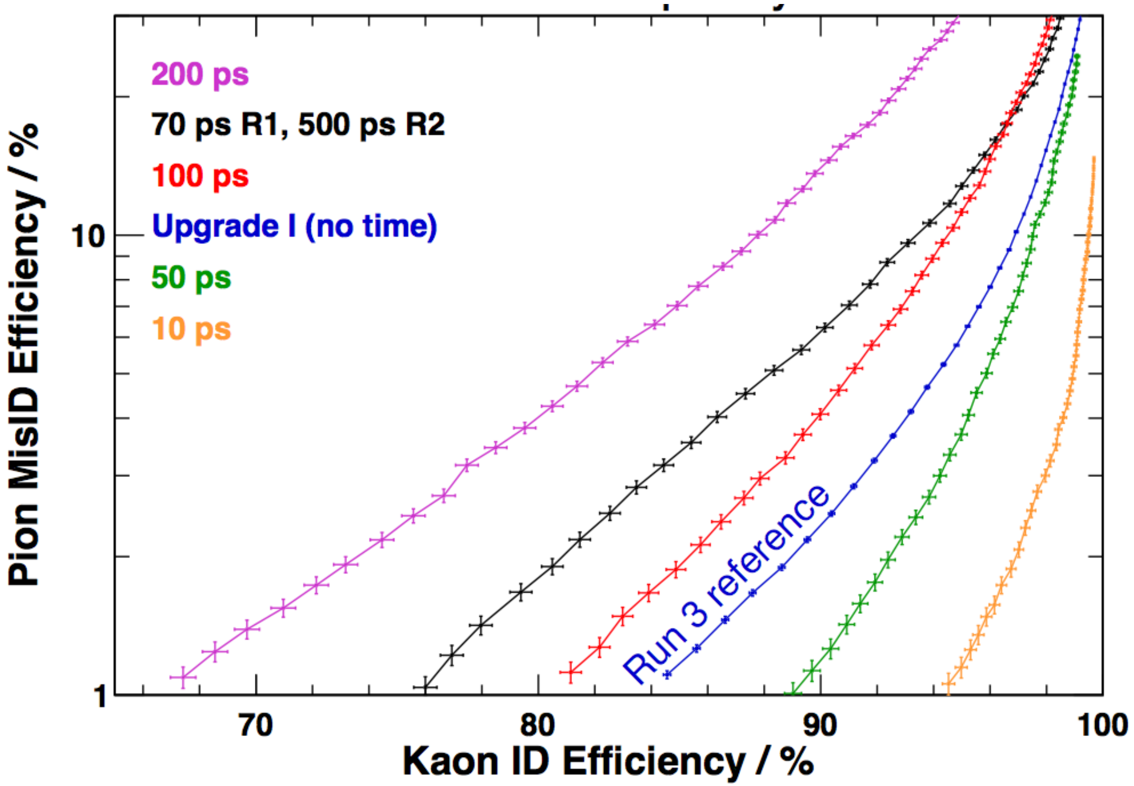
RICH with timing

*New design with **timing capability (tens of ps)** and **improved Cherenkov angle resolution (0.1-0.2 mrad)** expected to recover Run 3 performance*

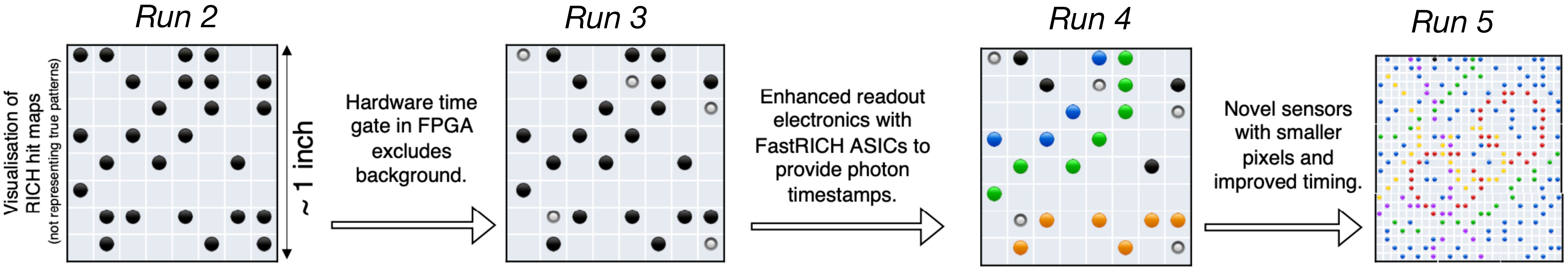
__SiPM__ baseline candidate for photon detector

- Smaller pixel size to reduce peak occupancy
- High QE shifted towards green, thus reducing chromatic error
- R&D for cryo cooling (radiation hardness)

Effect of timing on RICH performance



***Incremental implementation:** new front-end with timing capabilities from Run 4, new photodetector from Run 5*



Hardware time gate in FPGA excludes background.

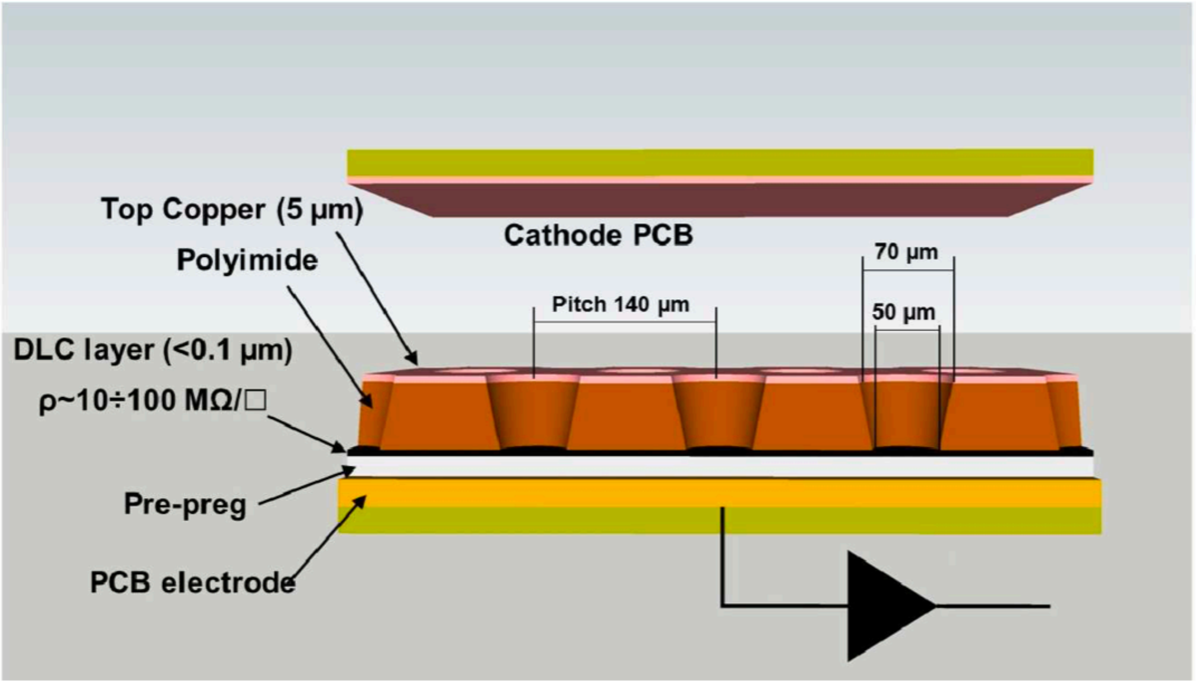
Enhanced readout electronics with FastRICH ASICs to provide photon timestamps.

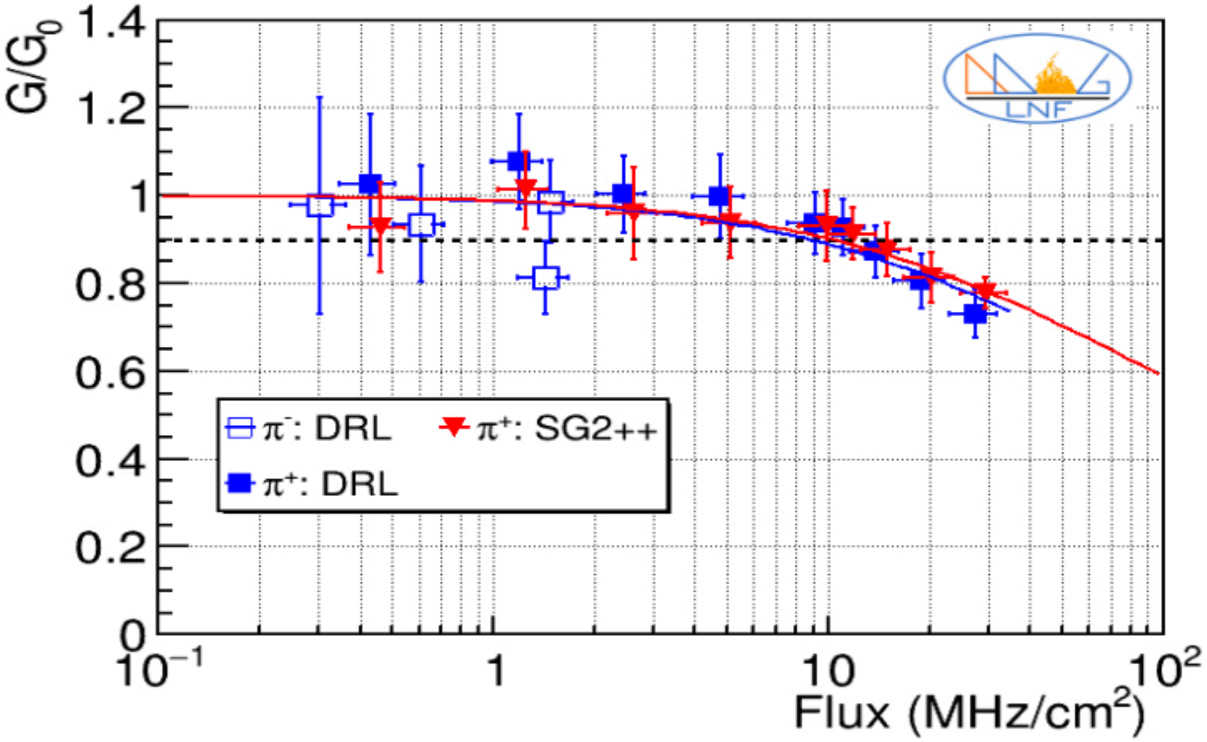
Novel sensors with smaller pixels and improved timing.

	Sensor	ASIC timewalk	FE time gate	TDC time bin
LHC Run 3	150 ps	$< 4\,$ns	6.25 ns	None
LHC Run 4	150 ps	CFD correction	2 ns	25 ps
HL-LHC Run 5	$\sim 50\,$ps	CFD correction	2 ns	25 ps

MUON

***Novel MPGD μ-RWELL** detectors proposed for innermost regions, capable to stand up to several MHz/cm^2*



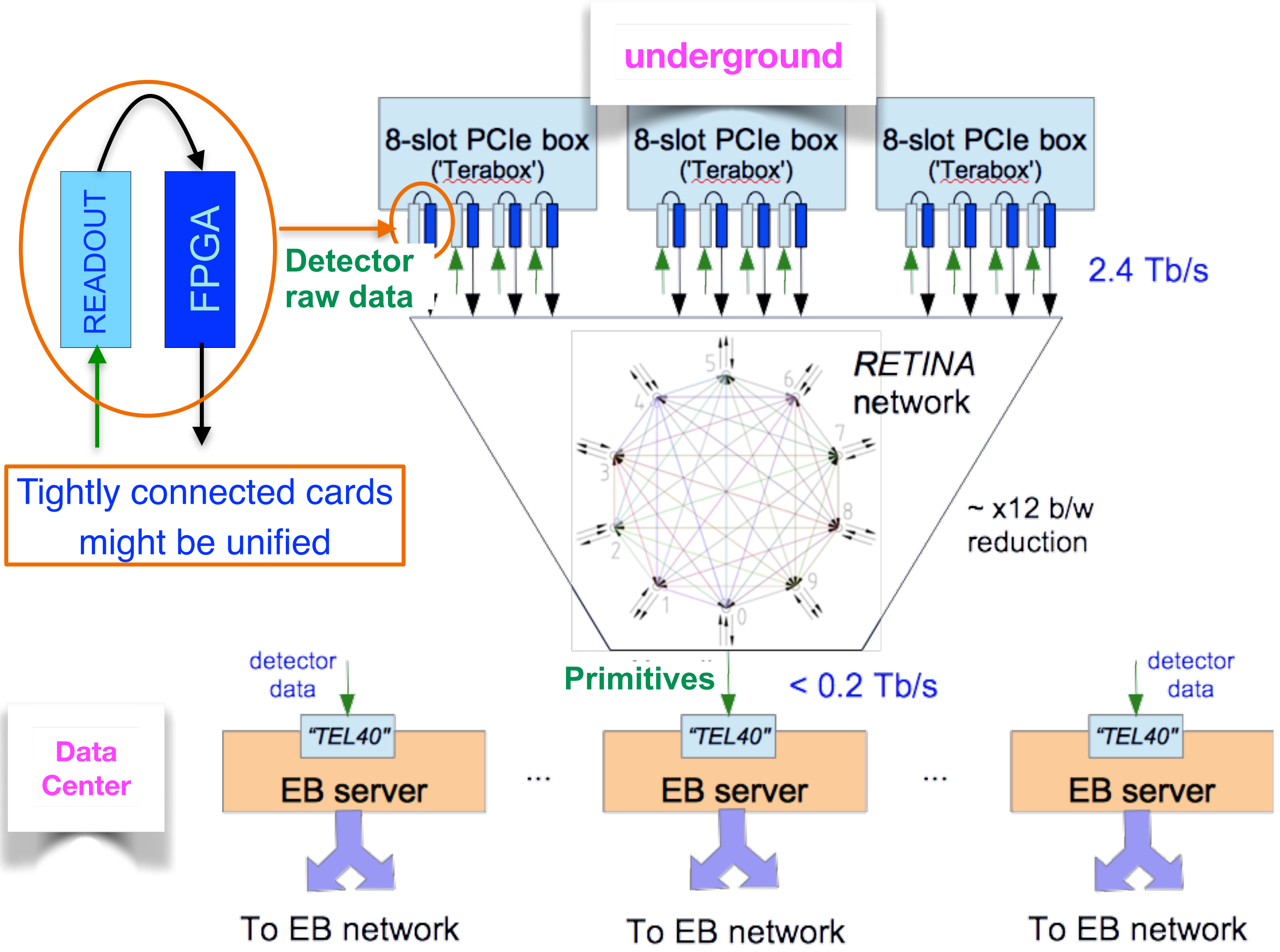


Large effort on the detector industrialisation process: DLC sputtering machine for realisation of base-material for these detectors just arrived at CERN (co-fund CERN/INFN)

Next target is to finalise the front-end electronics development

Data processing challenge

Full software trigger with 200 Tb/s from detector, store ~100 GB/s on disk



Move reconstruction as close as possible to FEE and reduce data volume

- *evaluate primitives (tracks, calo clusters, muon stubs) before the event builder*

- *drop ALL raw data not associated to the primitives*

- *real-time alignment at primitive level*

Make best use of each technology node: FPGA, GPU, CPU…

Proposal to start implementing the above concepts already at Run 4: *downstream track reconstruction at trigger level using RETINA → significant physics benefit for final states with long-lived particles (K^0_S, Λ^0, …)*

Upgrade II: approval steps so far

EoI

CERN/LHCC 2017-003
LHCb EoI
08 February 2017

LHCb
UPGRADE II

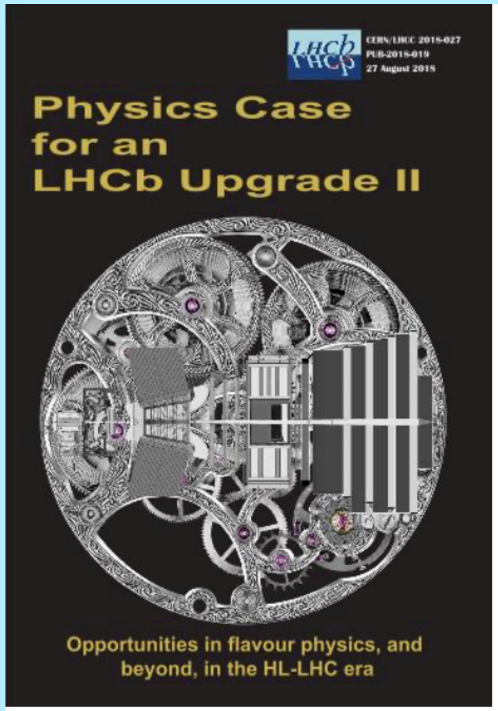
EoI

Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest

LHCC-2017-003

Physics case



CERN/LHCC 2018-027
PUB-2018-009
27 August 2018

Physics Case for an LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

LHCC-2018-027

Accelerator study CERN-ACC-2018-038

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."

CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework

TDR

LHCb
UPGRADE II

Technical Design Report

LHCC-2021-012

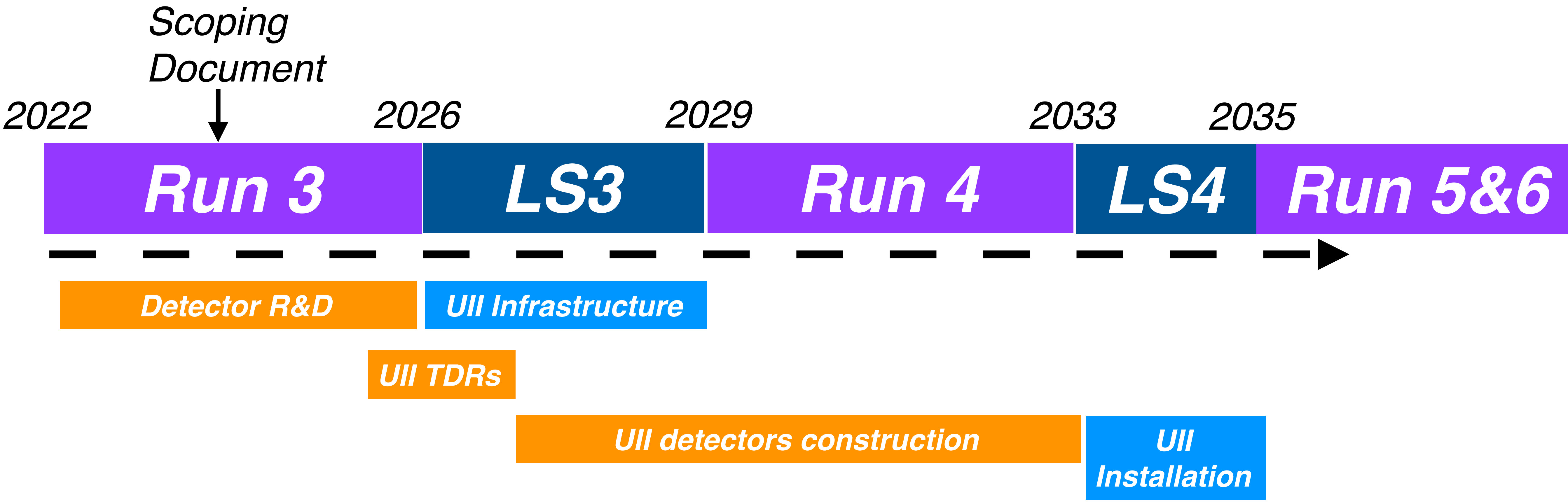
Approved March 2022

- *Detector design and technology options*
- *R&D program and schedule*
- *Cost for baseline, options for descoping*
- *National interests*

Scoping Document required, to agree on cost envelope

(within ~2 years)

Timeline for Upgrade II



Scoping Document

2022 2026 2029 2033 2035

Run 3 | LS3 | Run 4 | LS4 | Run 5&6

Detector R&D

UII Infrastructure

UII TDRs

UII detectors construction

UII Installation

- ~4 year period for detector R&D, make technology choices and optimise the detector design
- TDRs expected at beginning of LS3, then ~6 year period for detector construction → being ready for LS4 installation is of primary importance
- Significant infrastructure preparation during LS3, to optimise LS4 duration
- Limited size detector consolidations also proposed for LS3 as anticipation of Upgrade II

Upgrade II needs a significant expansion of the collaboration

Conclusions

Increase of precision in quark-flavour physics will allow to probe mass scales not accessible directly at LHC

LHCb Upgrade II is proposed for Run 5&6 (installation 2033), to fully realise the flavour physics potential of the HL-LHC

- *Discussion on the project is well advanced, a Scoping Document in due within ~2 years*

The detector challenges will require breakthrough technologies and novel design

- *Significant synergies to exploit with other projects at the high intensity frontier*
- *The present technology challenges will set the path for future projects beyond the LHC*

Exciting prospects at LHCb:

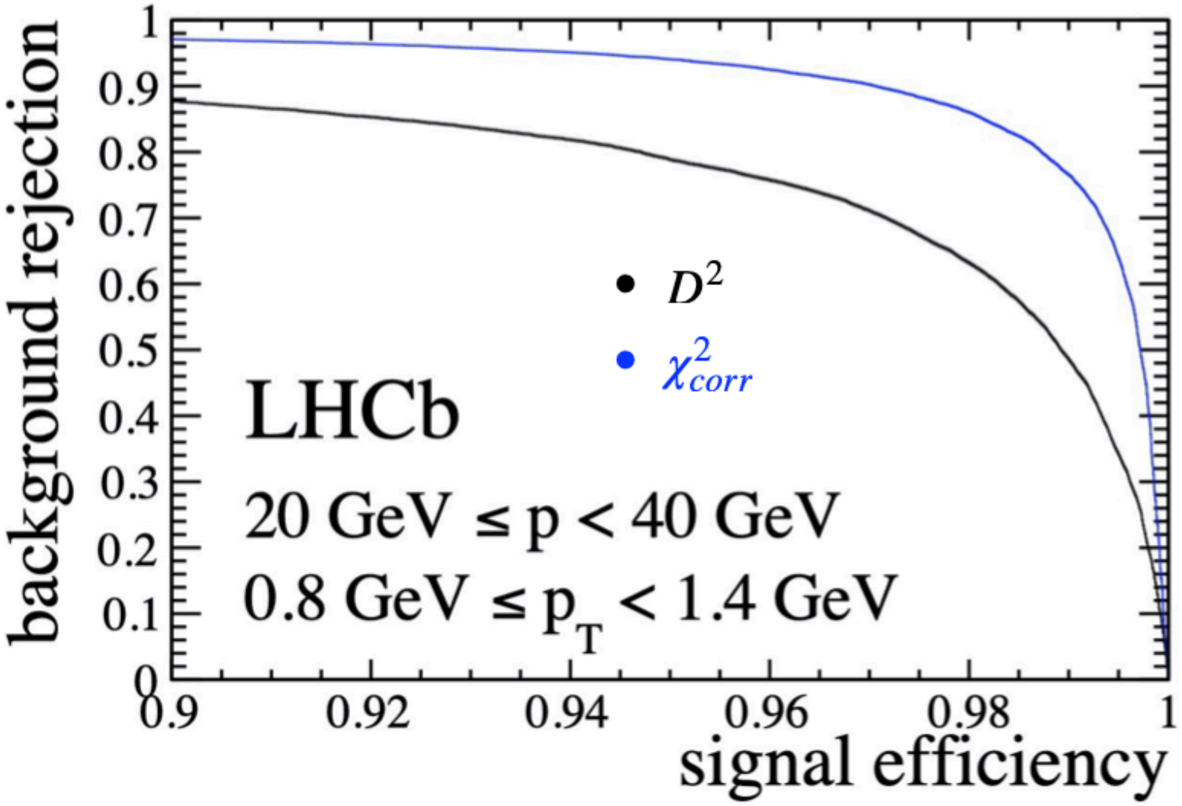
- Run 3 data taking is starting with a new detector

- Developing new technologies for the future

SPARES

A comment on muons and electrons

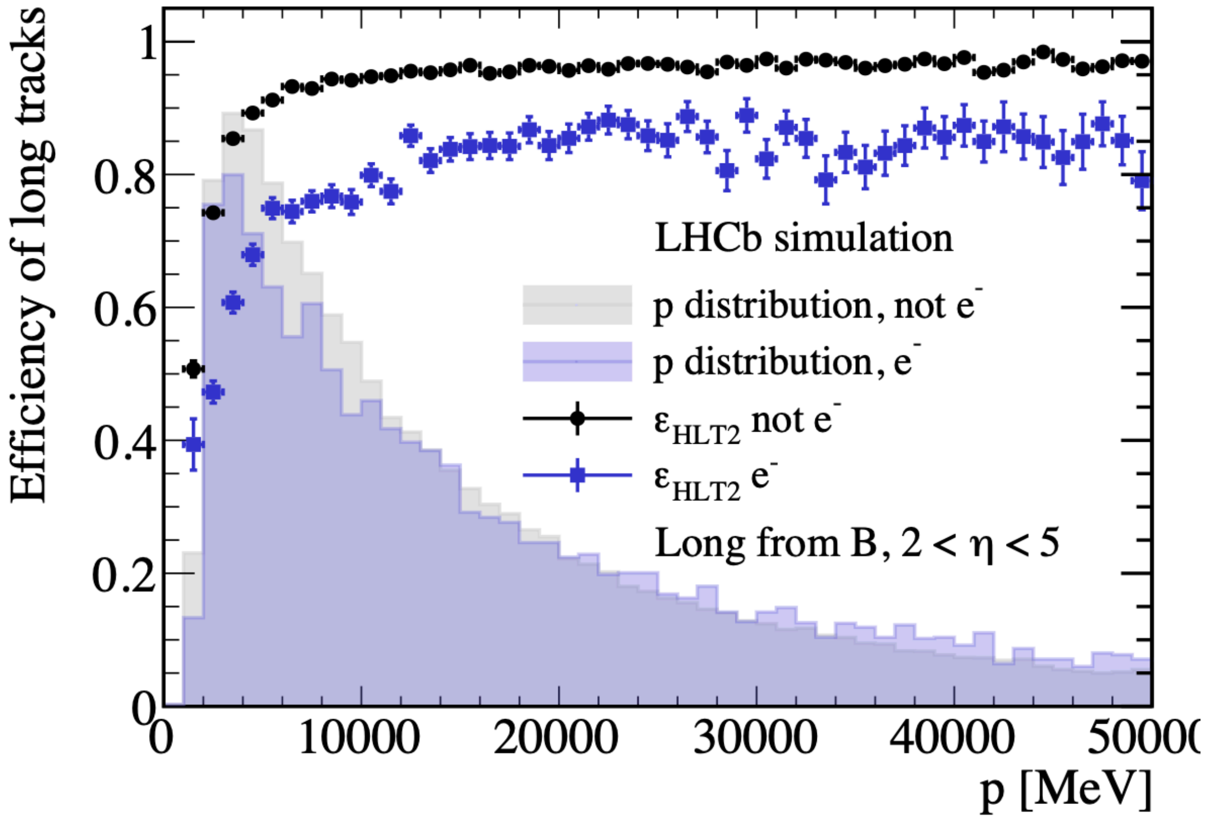
To face the increased bkg rates foreseen at Run 3, we improved the muon ID rejection power on pions



JINST 15 (2020) T12005

Electron reconstruction is more difficult due to bremsstrahlung

- *moderate track efficiency loss shown at HLT2*
- *removal of hardware trigger p_T thresholds will help to equalise muons and electrons, e.g. in 2018: $E_T > 2.5$ GeV for e vs $p_T > 1.75$ GeV for μ*
- *increasing performance of PID algorithms and bremsstrahlung momentum recovery*

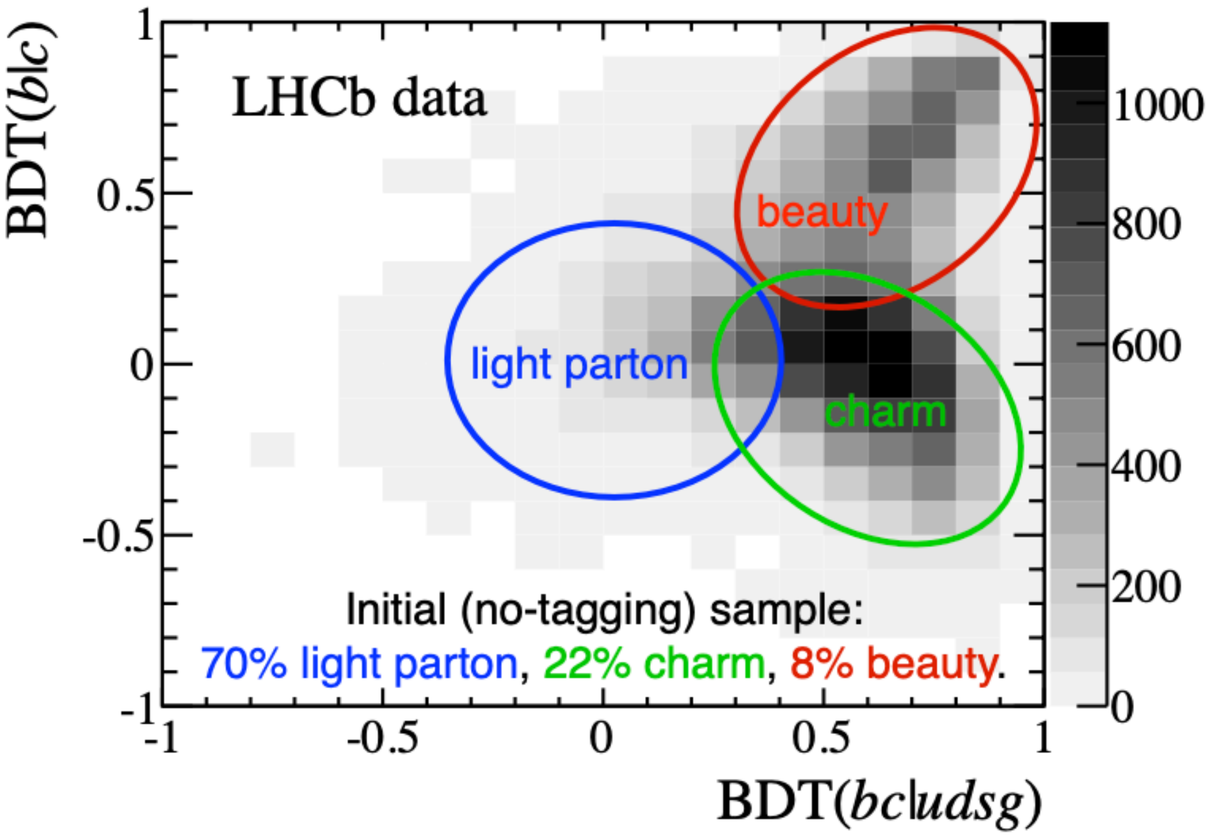


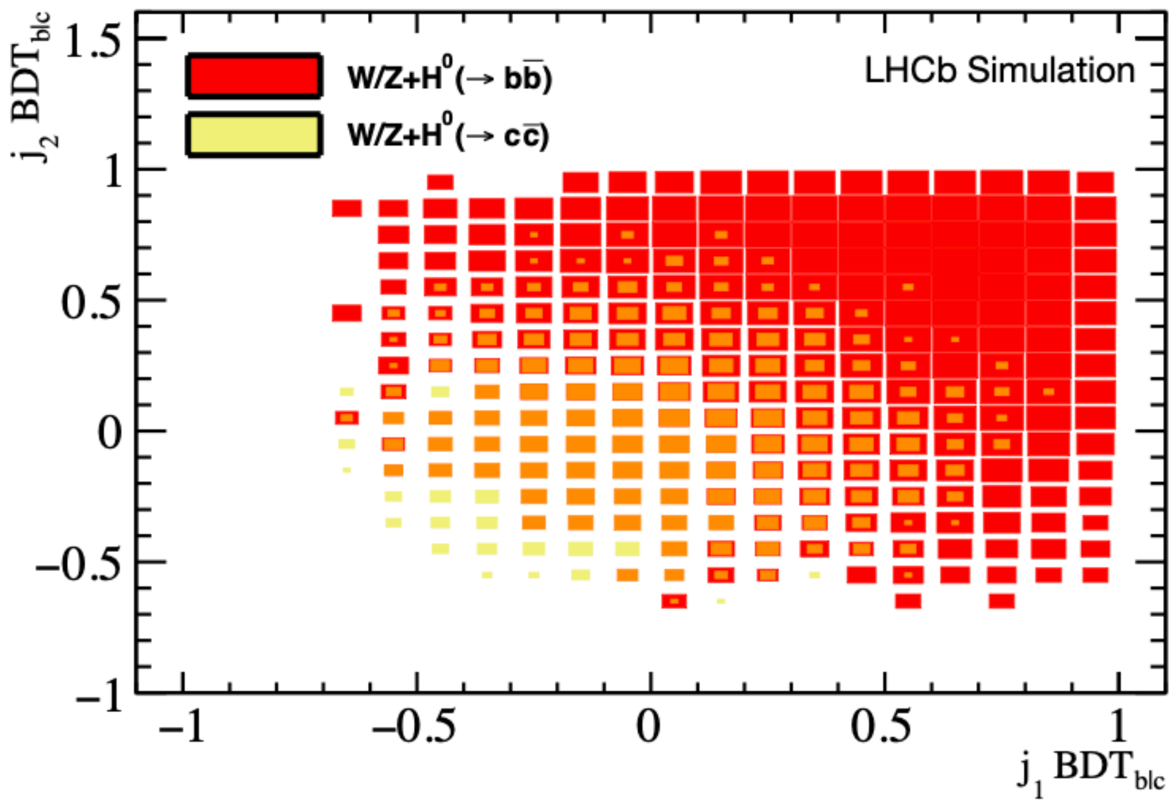
LHCB-FIGURE-2021-003

QCD and Electroweak physics

LHCb geometry and momentum coverage provides access to a kinematic region complementary to other LHC expts for: Z and W production, parton distribution functions, W mass measurement down to few MeV (μ and e final states), effective weak mixing angle ($Z \rightarrow \ell^+\ell^-$ FB asymmetry at higher rapidities).

LHCb vertexing capability provides excellent discrimination btw different flavour jets for: $t\bar{t}$ production cross-section in the FW region down to ~4%, stringent limits on charm Yukawa coupling down to $\sim 2y_{\rm SM}$



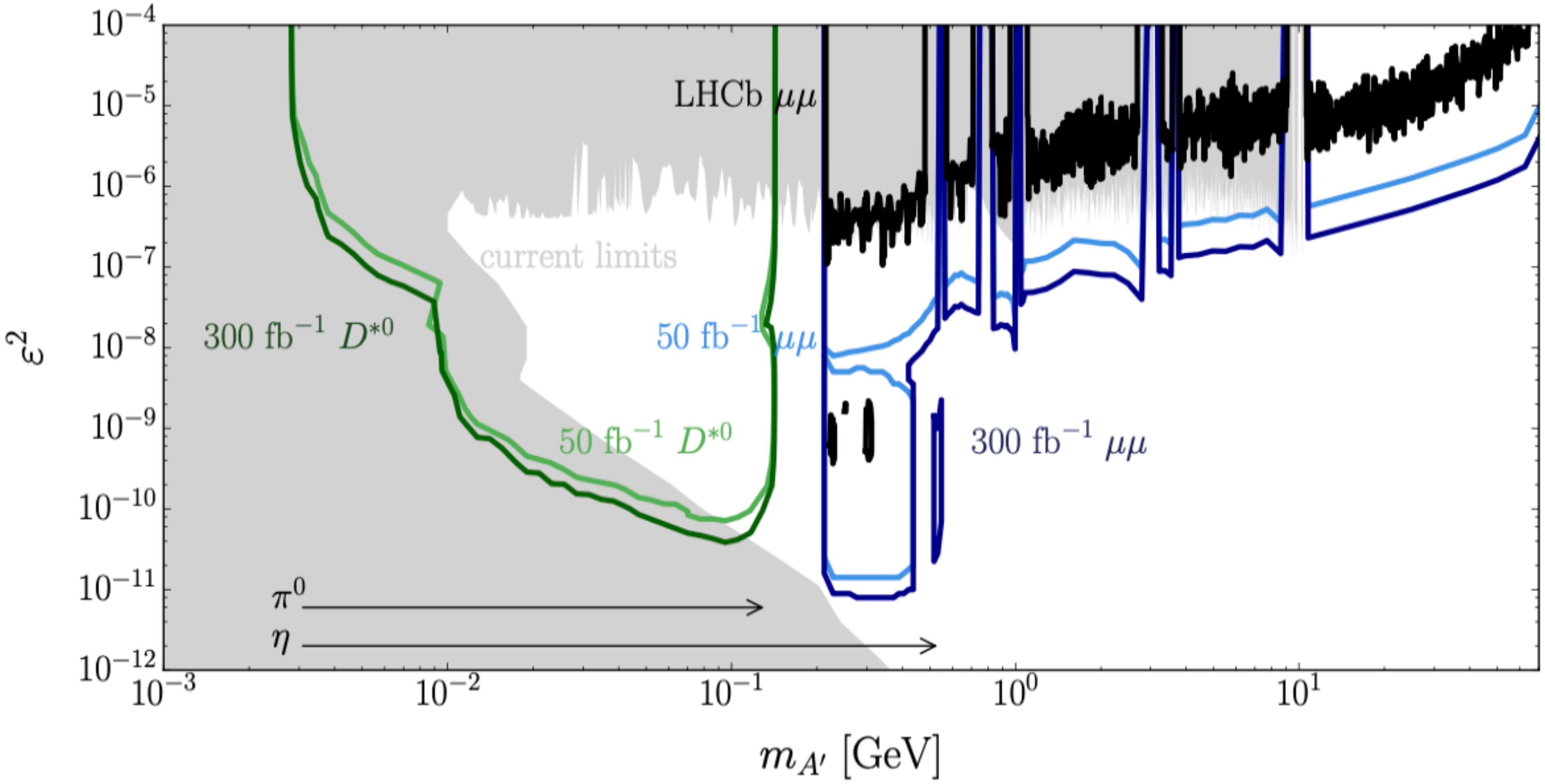


Dark Sector

LHCC-2018-027

LHCb can explore significant portions of unconstrained A' *parameter space. These searches are based on two strategies: prompt and displaced resonance searches using* $D^{*0} \to D^0 e^+ e^-$ *decays (green), and inclusive dimuon production (blue).*

Presence of VELO enhances sensitivity to long-lived particles and hence probes complementary parts of the parameter space of NP models to ATLAS and CMS.



Heavy Ions

LHCC-2018-027

Unique forward coverage, in combination with particle identification and precision vertexing, gives access to many observables of interest:

Quarkonium and open heavy flavour

- $\Psi(2S)$, Υ
- *open charm and beauty mesons down to* $p_T \sim 0$
- *P wave charmonium states, also for fixed target*

Dileptons and photons

- *dilepton spectrum in di-muon channel in the rho mass region*
- *real photons through conversions*

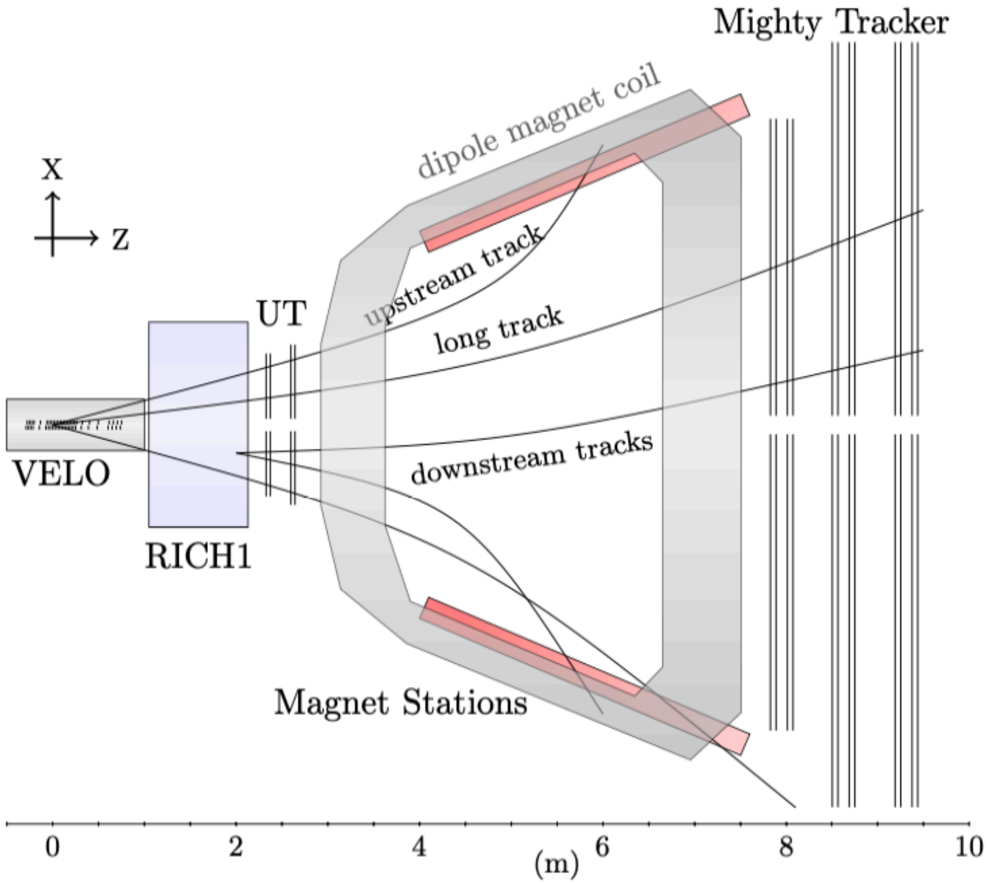
Nuclear PDFs and saturation

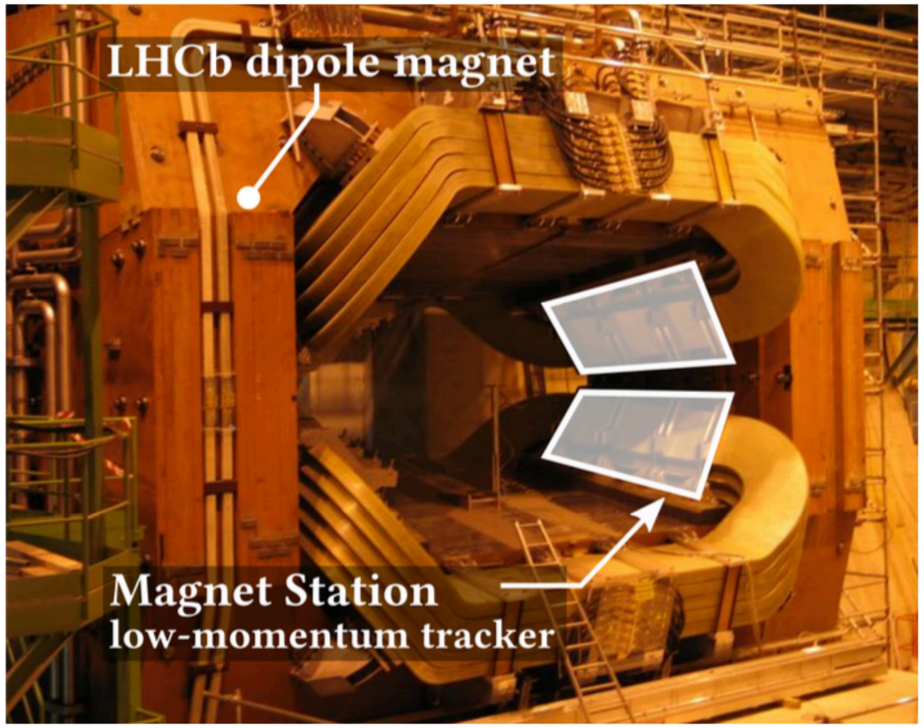
- *low-x regime of QCD*

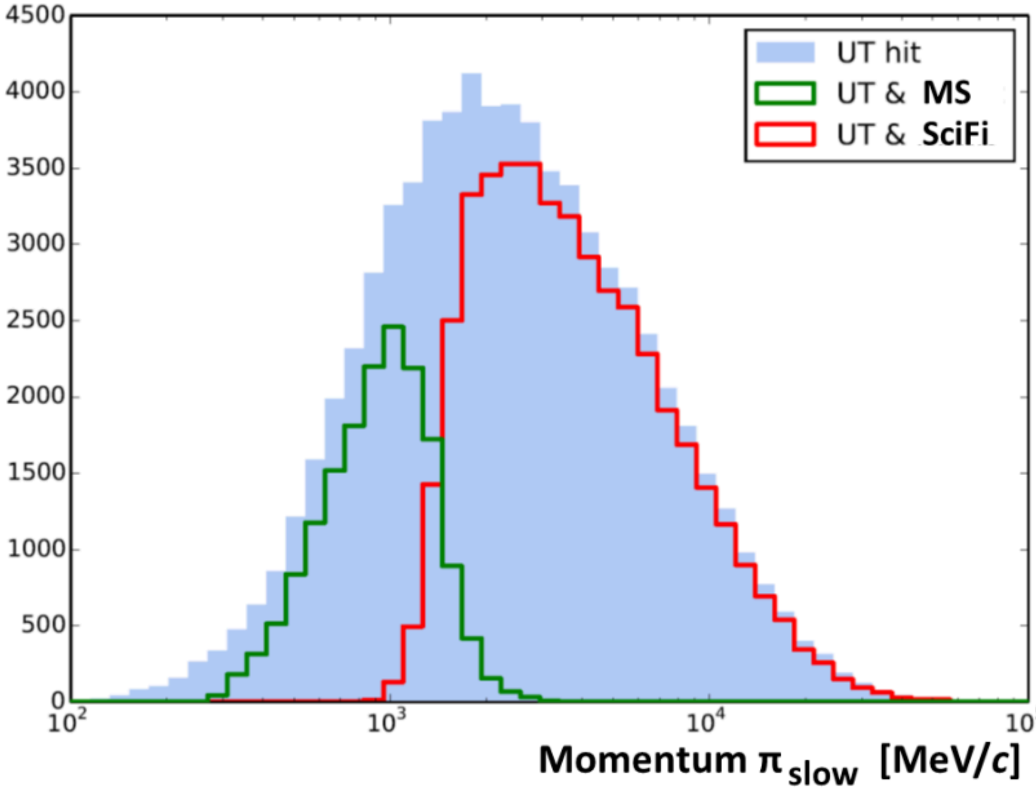
Reconstructing all the charged tracks produced in these collisions requires tracking detectors with high granularity. The use of pixel detectors in the inner region of the Mighty Tracker provides the potential to cover the full centrality range, while the addition of magnet stations will improve the efficiency for low momentum tracks.

Magnet Stations

- *Scintillating-based tracking subsystem inside the magnet to measure the position and direction of particles hitting the magnet side walls. This improves the momentum resolution of* ***upstream*** *tracks to a sub-percent level, with significant benefit for the physics program*
- *Significant increase of acceptance for low momentum tracks, e.g. factor of ~2 gain in prompt D^{*+} with slow π*

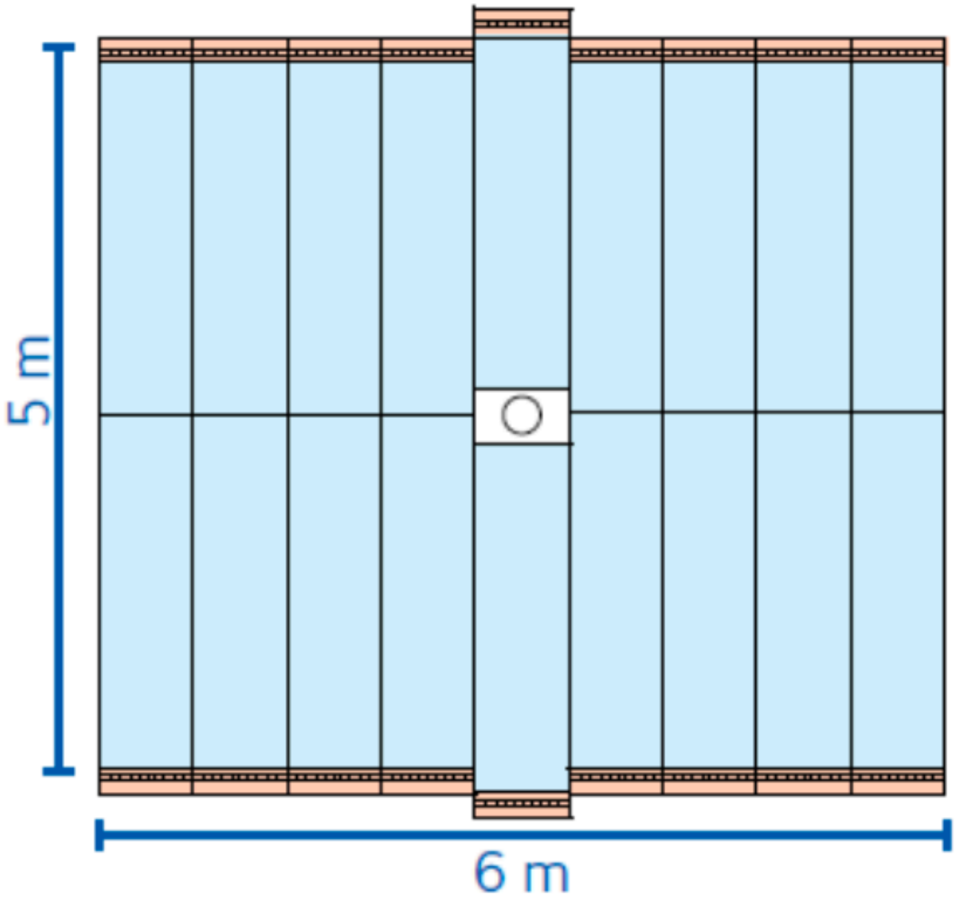






Adding TORCH time-of-flight

- *30 m² 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 $\Lambda_b \rightarrow J/\psi p K^-$ *w/o and with TORCH*