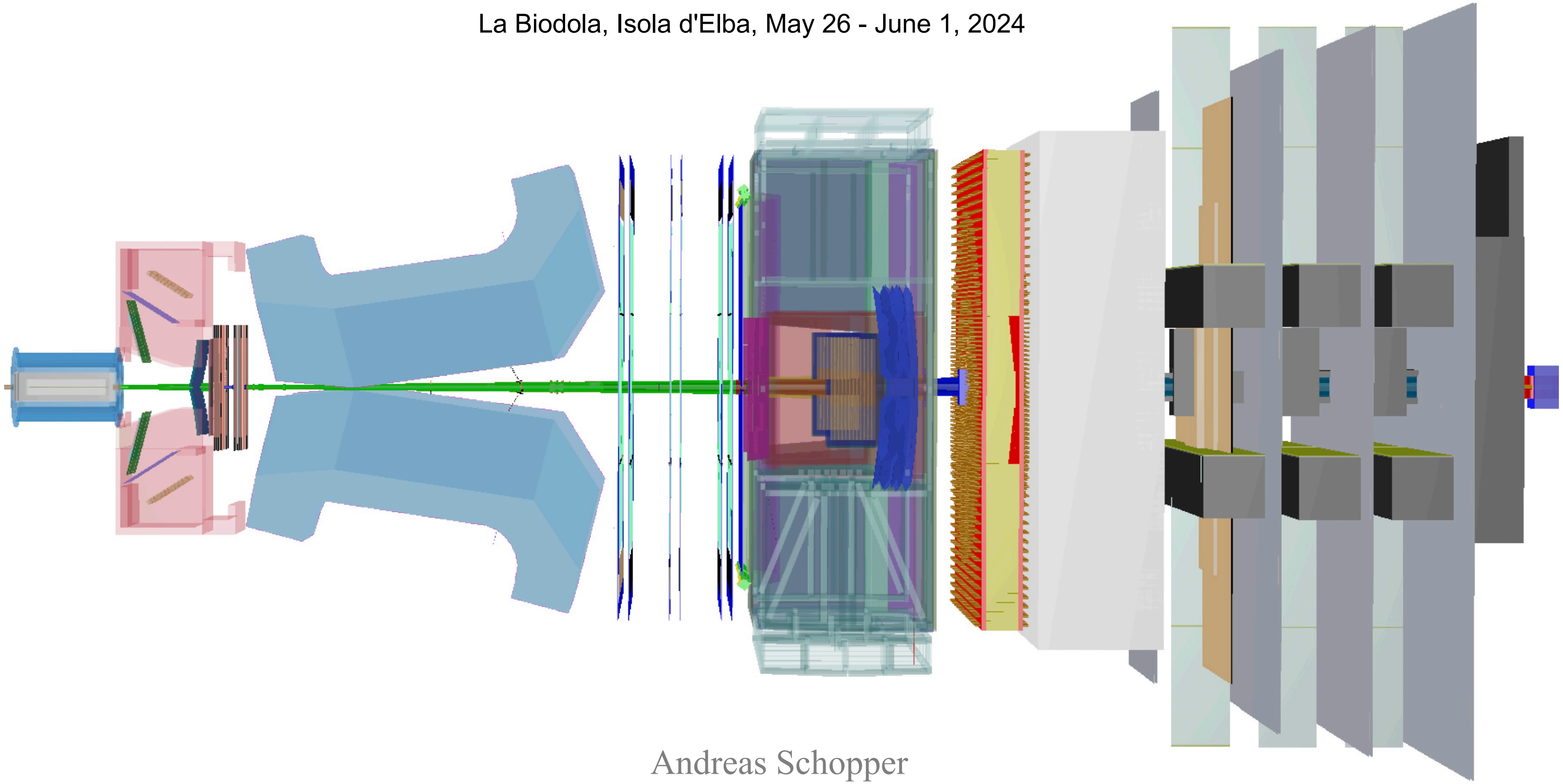
The LHCb Upgrade II

16th Pisa Meeting on Advanced Detectors

La Biodola, Isola d'Elba, May 26 - June 1, 2024



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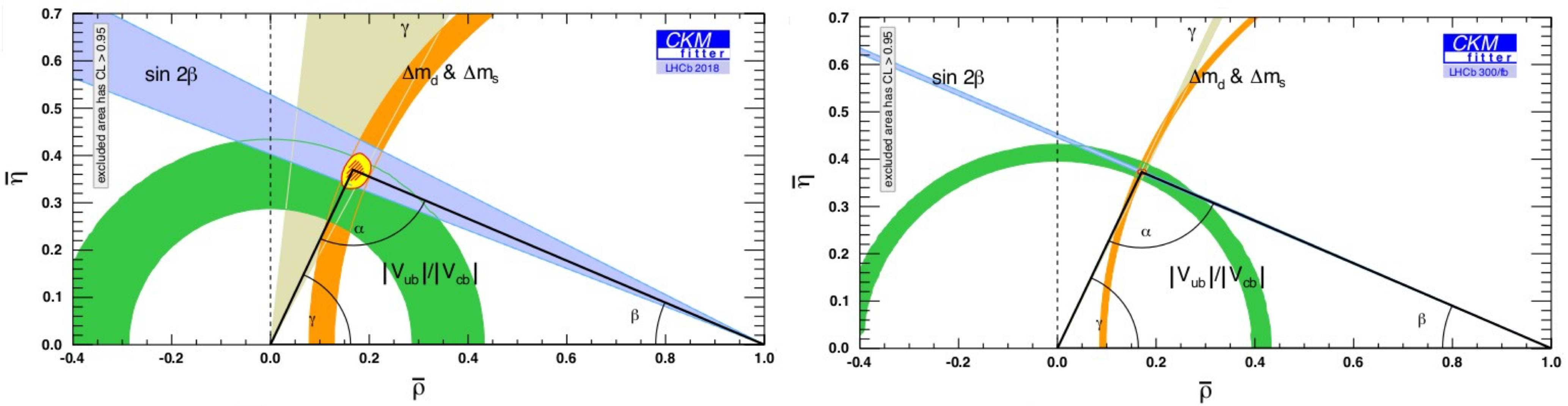
on behalf of the LHCb Collaboration

Physics case of LHCb for Upgrade II

- So far no evidence for physics Beyond the Standard Model (BSM) → either very heavy or highly complex new particles
- Flavor physics can probe BSM physics without having to produce and observe new particles directly, by looking at indirect effects in already accessible energy scale processes (e.g. D and B decays)



LHCb has unique science programme with BSM discovery potential:

- Unprecedented sensitivity for B & D physics (e.g. CKM unitarity triangle)
- Broad, general purpose programme
  - ✓ unique forward acceptance
  - ✓ spectroscopy, EW precision measurements, top quark and Higgs physics, dark sector, heavy ions, fixed target physics ...

- Maximizing Upgrade II physics performance requires huge statistics (high L), beyond √N scaling with new subdetectors (high granularity, fast timing, extreme radiation hardness) and new reconstruction techniques

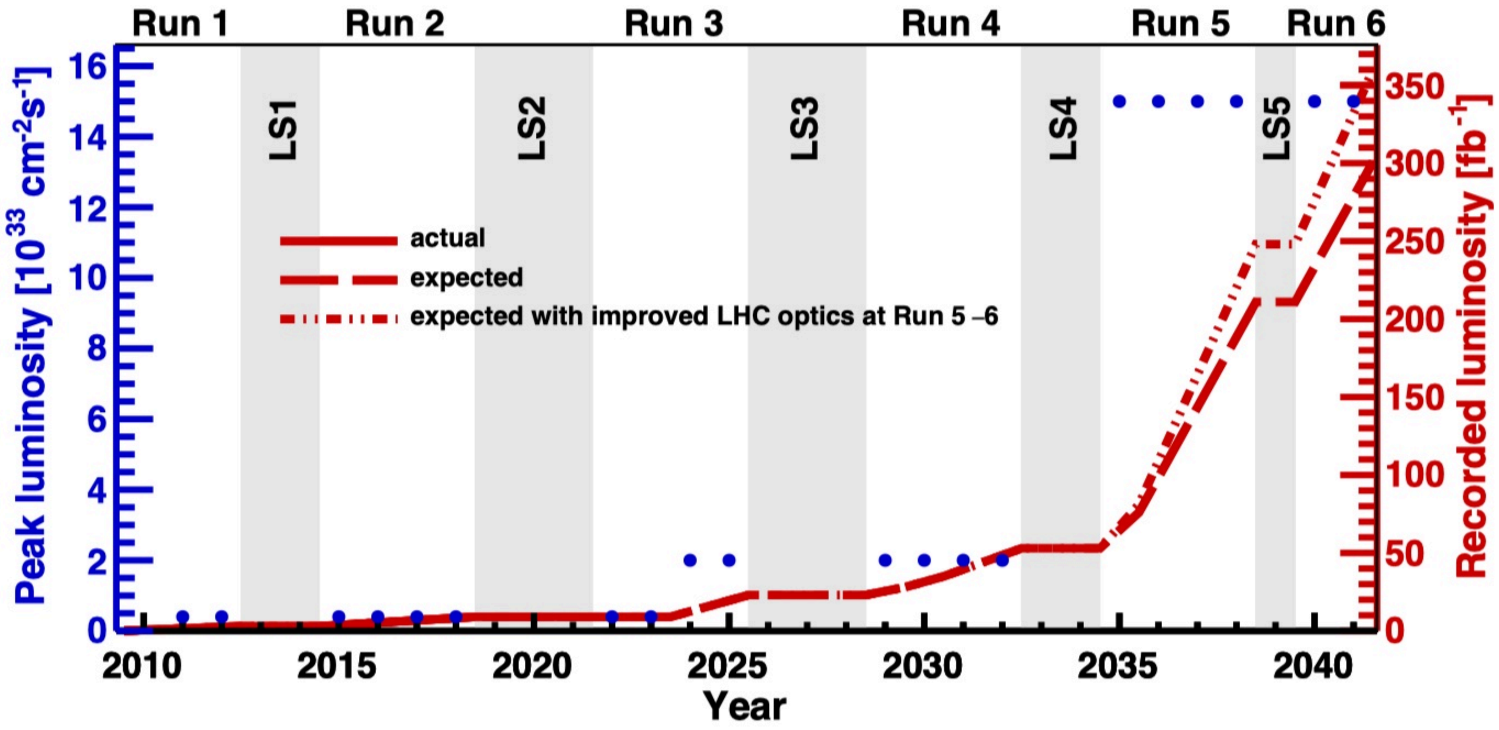
Evolution of LHCb

Pre-Upgrade
- ✓ L peak = 4 x 10^{32} cm^{-2} s^{-1}
- ✓ L_{int} = 9 fb^{-1} (Run 1 & 2)

Upgrade I (LS2)
- ✓ L peak = 2 x 10^{33} cm^{-2} s^{-1}
- ✓ L_{int} = 50 fb^{-1} (Run 3 & 4)

PID & DAQ Enhancement (LS3)
- ✓ improved ECAL granularity
- ✓ improved RICH timing
- ✓ improved DAQ and trigger

Upgrade II (LS4)
- ✓ L peak = 1.5 x 10^{34} cm^{-2} s^{-1}
- ✓ L_{int} = 300 fb^{-1} (Run 5 & 6)



→ Design Upgrade II detector to be able to accumulate maximum possible integrated luminosity (baseline assumes 50 fb^{-1}/y)

- ➢ Same spectrometer footprint as current detector
- ➢ Innovative technology for detector and data processing

Key ingredients:
- ✓ high/increased granularity
- ✓ fast timing (few tens of ps)
- ✓ radiation hardness (up to few 10^{16} n_{eq} /cm^2)
- ✓ data throughput ~200 Tb/s

- ➢ The only general flavor physics facility at this timescale

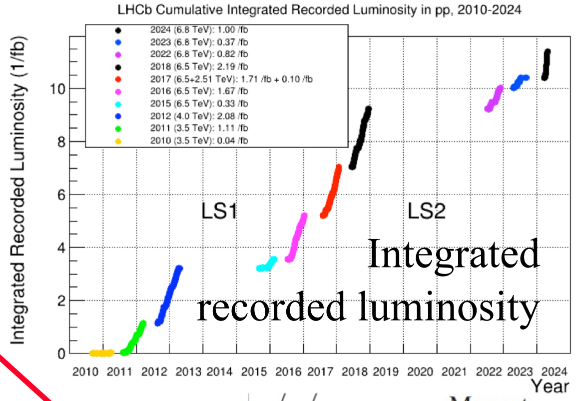
	LHC era			HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5/6
LHCb $\int\mathcal{L}dt$	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

The LHCb detector after Upgrade I

Five times luminosity of **Run 1 & 2**
→ higher rate, occupancy, fluence, **pile up of ~6**

Vertex Locator (VELO): **Hybrid pixel detector**

- Closer to the beam (from 8.2 mm to 5.1 mm)
- New RF box
- Max fluence: 8×10^{15} MeV n_{eq} cm^{-2}

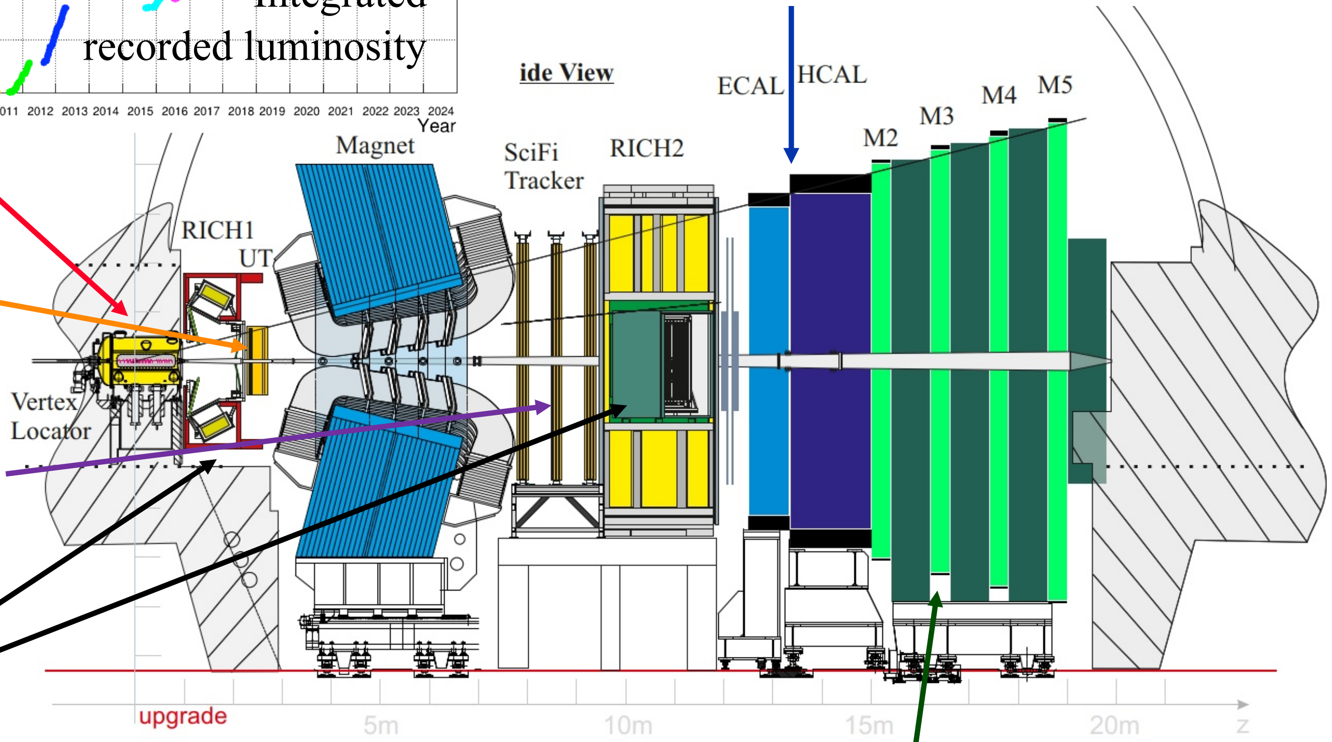


Calorimeters: **Shashlik-ECAL and tile-HCAL**

- Detection elements unchanged
- Electronics upgraded to 40 MHz R/O

Upstream Tracker (UT): **Si strip detector**

- Higher coverage, segmentation, resolution
- Speed up Track Reconstruction & reduce Ghost Track probability



Scintillating Fiber (SciFi): **Scintillating fibers detector**

- 3 station with 4 detection layers
- 2x2.5 m long modules with SiPM R/O

RICH1 & RICH2: **Ring Imaging Cherenkov radiators**

- MaPMTs with external R/O
- Electronics upgraded to 40 MHz

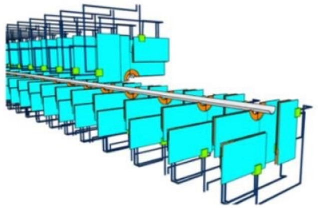
Muon System: **MWPCs**

- Detection elements unchanged
- Electronics upgraded to 40 MHz R/O

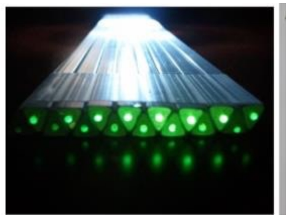
The LHCb detector in Upgrade II

Up to **seven times** luminosity of **Run 3 & 4**
→ even higher rate, occupancy, fluence, **pile up of ~40**

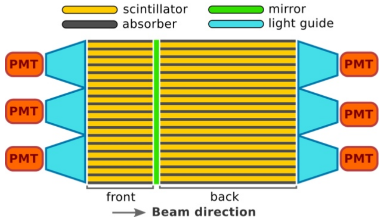
Vertex Locator (VELO):
- 3D silicon pixel, 28 nm
- 50 ps timing
- new RF-foil



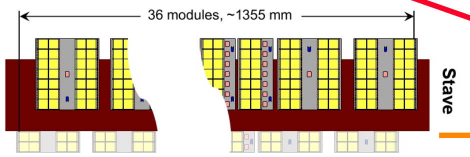
Magnet Stations (MS): **NEW**
- Scintillating slabs
- Low momentum particles

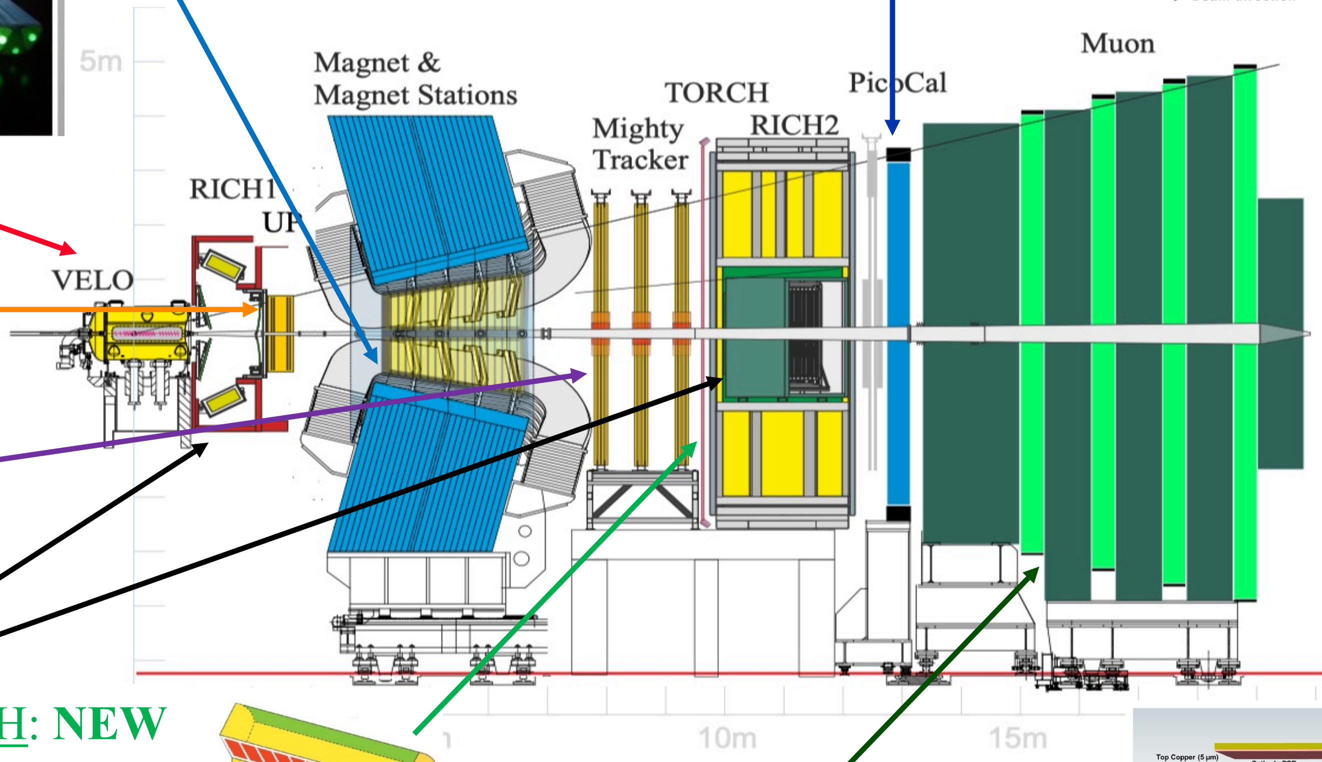


Picosecond ECAL (PicoCal):
- timing & longitudinal segmentation
- SpaCal, rad. hard crystals (inner)
- refurbished Shashlik (outer)

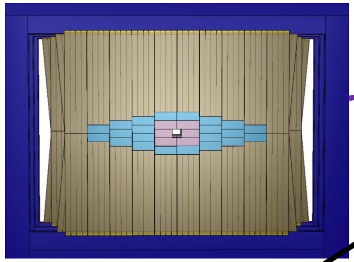


Upstream Tracker (UP):
- MAPS CMOS pixel
- Radiation tolerant

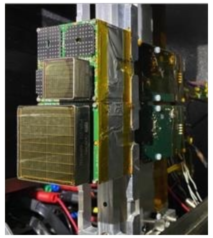




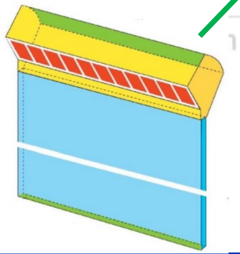
Mighty Tracker (MT):
- MAPS CMOS pixel (inner)
- Keep SciFi (outer)



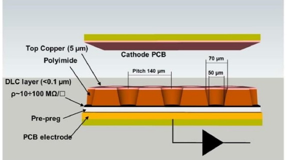
RICH1 & RICH2:
- Reduced pixel size
- Add timing information
- SiPM, MCPs



TORCH: **NEW**
- Time-of-flight
- Quartz plates
- SiPM/MCPs



Muon System:
- µ-Rwell for inner regions
- Old MWPC for outer regions



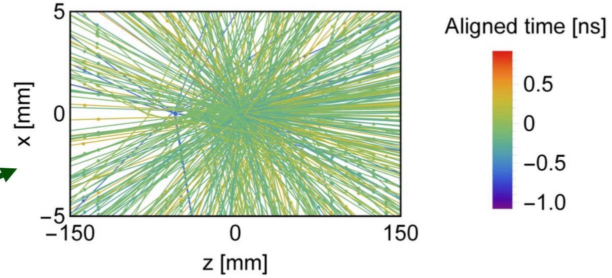
Vertex Locator (VELO)

At peak Luminosity of 1.5 x 10^{34} cm^2 s^{-1}

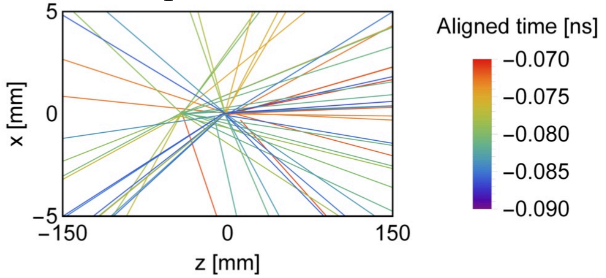
- ✓ ~ 42 interactions/crossing
- ✓ ≈ 2k charged particles in VELO acceptance

- ➢ 50 ps per hit timestamp required (i.e. 20 ps/track)
- ➢ adding timestamp → similar performances as for UI
- ➢ ASIC bandwidth > 250 Gb/s
- ➢ 6 times radiation hardness wrt UI

without 20 ps time window

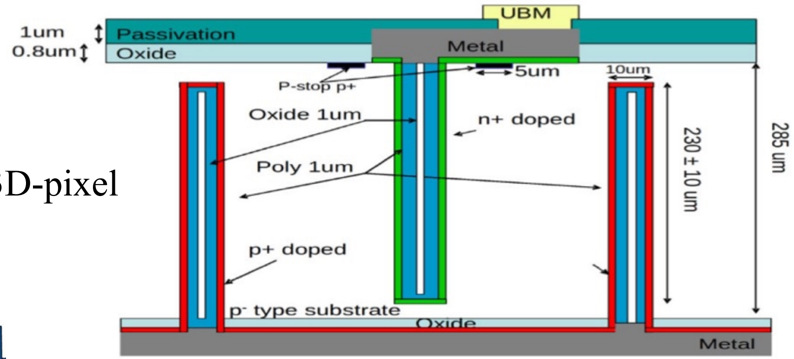


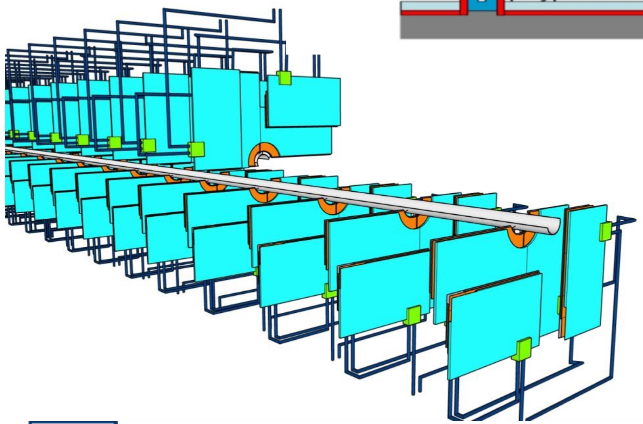
with 20 ps time window

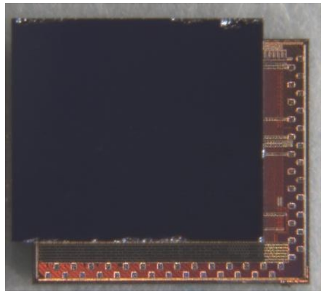


- ➢ Explored different technologies to achieve full 4D reconstruction
- ➢ Baseline: 3D-sensors (e.g. Timespot, ParaColl)
- ➢ Timespot demonstrator chips implemented in 28 nm CMOS to evaluate performances → excellent time resolution of sensor (σ_{eff} = 10.3 ps @ 150 V after irradiating w/ 2.5 x 10^{16} n_{eq}/cm^2)
- ➢ FE electronics (ASIC) has to match per-hit time measurement and pixel pitch of VELO (e.g. IGNITE/Fractal, PicoPix)
- ➢ PicoPix design on track, similar pixel & chip size, 20-50 ps resolution

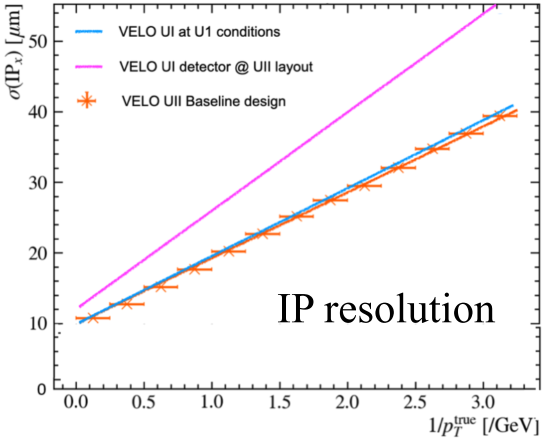
3D-pixel

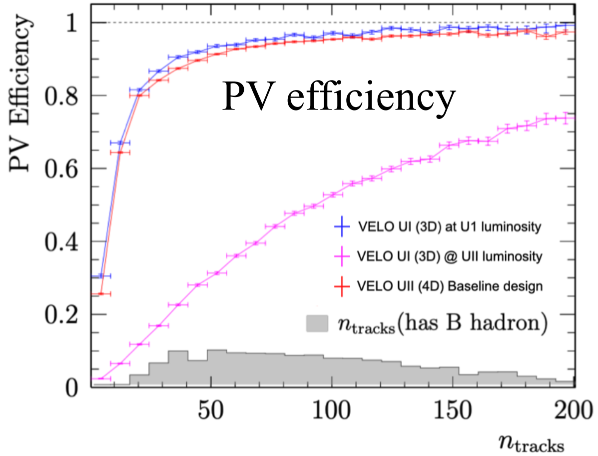






Hybridized Timespot1 ASIC
32x32 pixels, 55 μm pitch

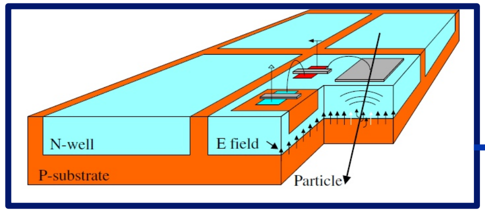




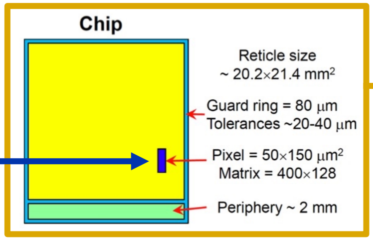
- ➢ Can recover UI performance at UII conditions

Upstream Tracker (UP)

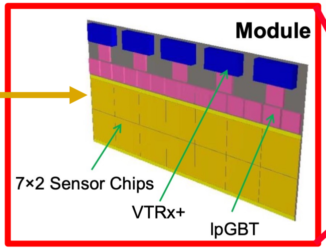
Monolithic Active Pixel Sensor (MAPS)

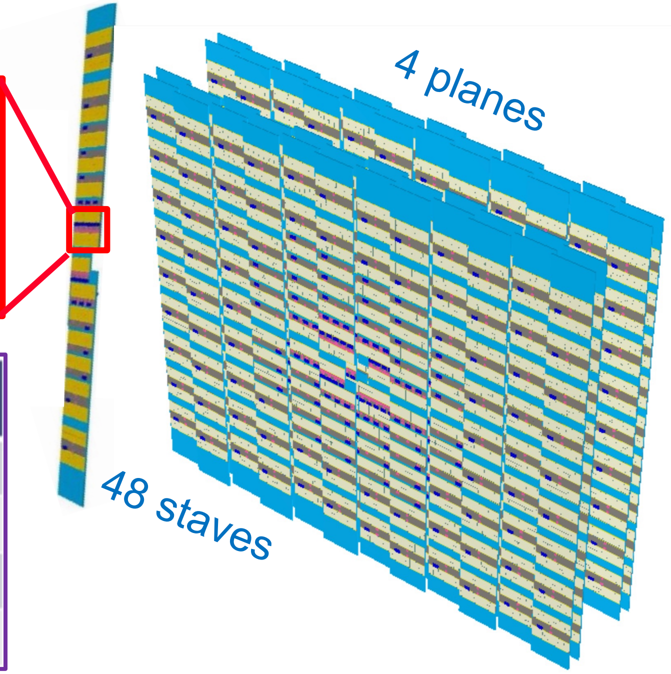


24128 sensor chips



1728 modules

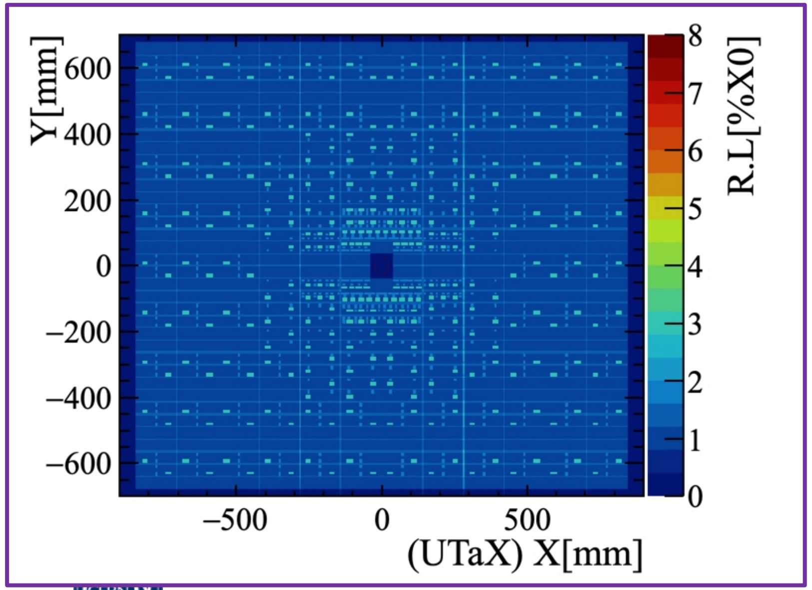


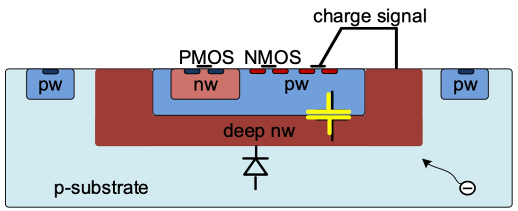


- ➢ Silicon pixels to cope with data rate & occupancy (160 MHz/cm^2)
- ➢ Radiation dose 3x10^{15} n$_{eq}$/cm^2, 240 Mrad
- ➢ Candidate technologies: HV- or LV-CMOS
  → choice led by radiation hardness
- ➢ Extensive R&D with several chips
- ➢ Material budget aimed to be at ~1% level

Technology	Small pixel (LV-CMOS)	Large pixel (HV-CMOS)	Sensor
TowerJazz 180 nm	X		MALTA
AMS/TSI 180 nm		X	MightyPix
TPSCo 65 nm	X		SPARC
SMIC 55 nm		X	COFFEE

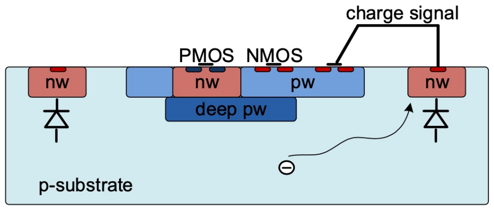
Radiation Length (X,Y)





large collection electrode

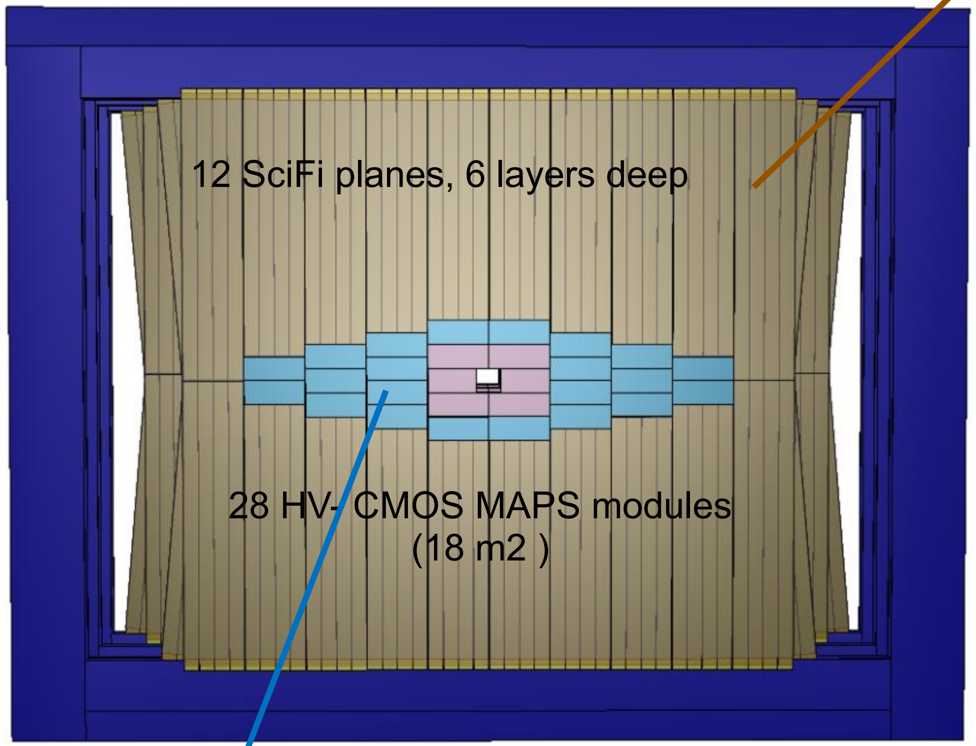
- ✓ Typical pixel size: 50 x 150 μm2
- ✓ Circuitry inside the collection well (requires high field: "**HV-CMOS**")
- ✓ High radiation hardness
- ✓ Higher noise (high capacitance)
- ✓ Higher power consumption
- ✓ Possible cross-talk (digital to sensor)



small collection electrode

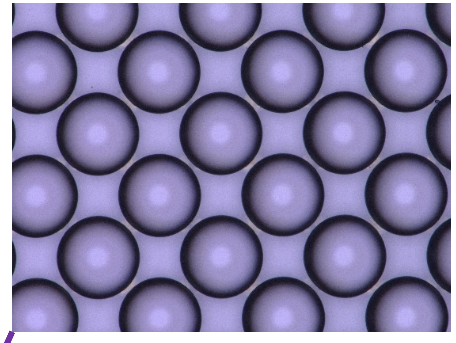
- ✓ Typical pixel size: 30 x 30 μm2
- ✓ Circuitry outside the collection well (requires low/moderate field: "**LV-CMOS**")
- ✓ High radiation hardness thanks to process modification (increase of depletion zone)
- ✓ Lower noise (low capacitance)
- ✓ Lower power consumption
- ✓ Less sensitive to cross-talk

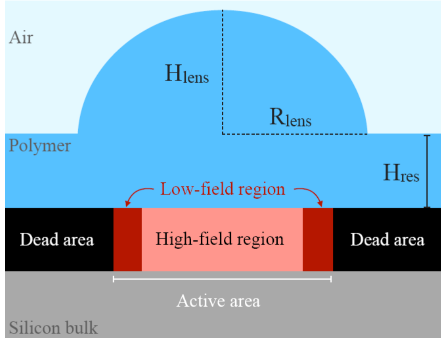
Mighty Tracker (MT)



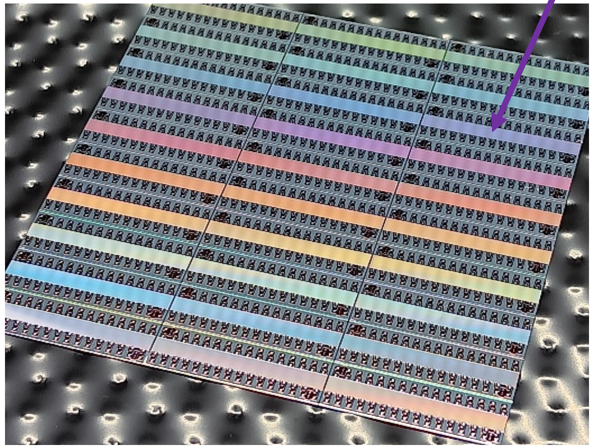
<u>Outer region</u>:
Keep SciFi design at outer region but reduce SiPM noise and improve radiation hardness

- Further away from beam → less radiation
- Micro-lens on SiPM to enhance light collection
- Cryogenic cooling for SiPM: -40°C ⇒ -120°C
- Reduction of cluster size:
  - ✓ less dark count rate
  - ✓ same efficiency





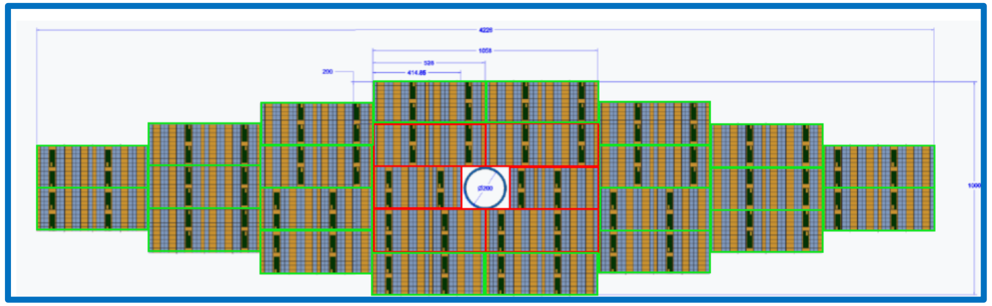
SiPMs with microlenses

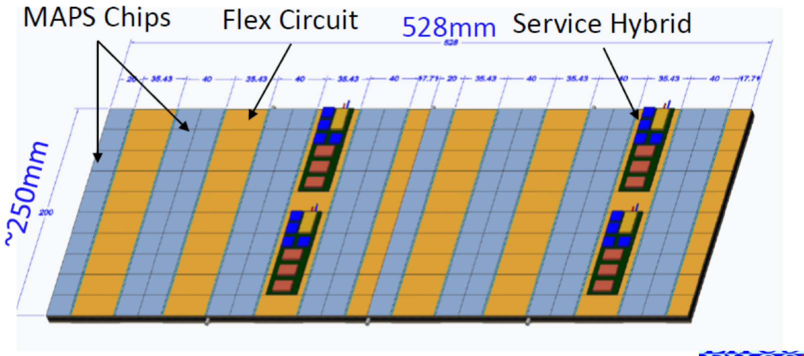


- expect +20% light detection with micro- lensing

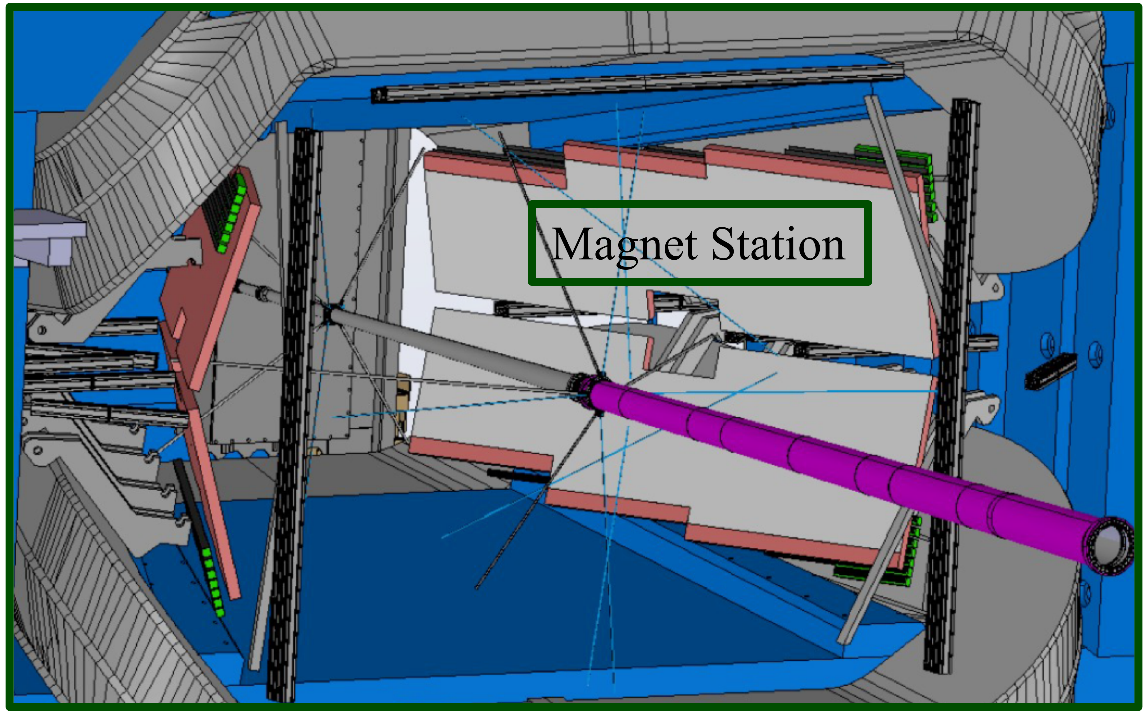
<u>Inner region</u>:
HV-CMOS MAPS detector (synergy with Upstream Tracker)

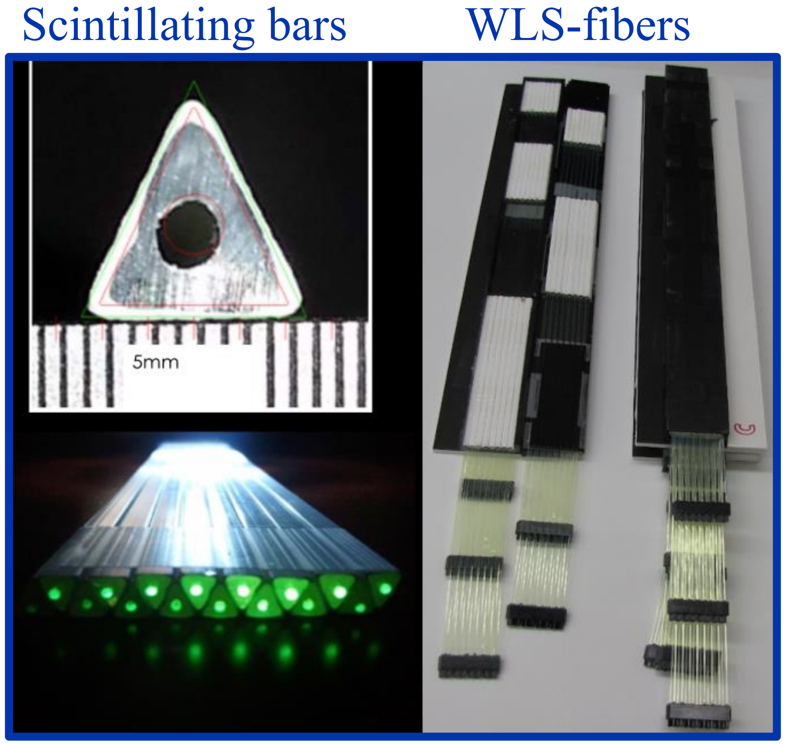
- 6 layers, 18 m^2 in total
- pixel size ~50 x 150 μm^2
- improve σ_{res} up to 3 ns
  w/ radiation hardness
  w/o increasing consumption



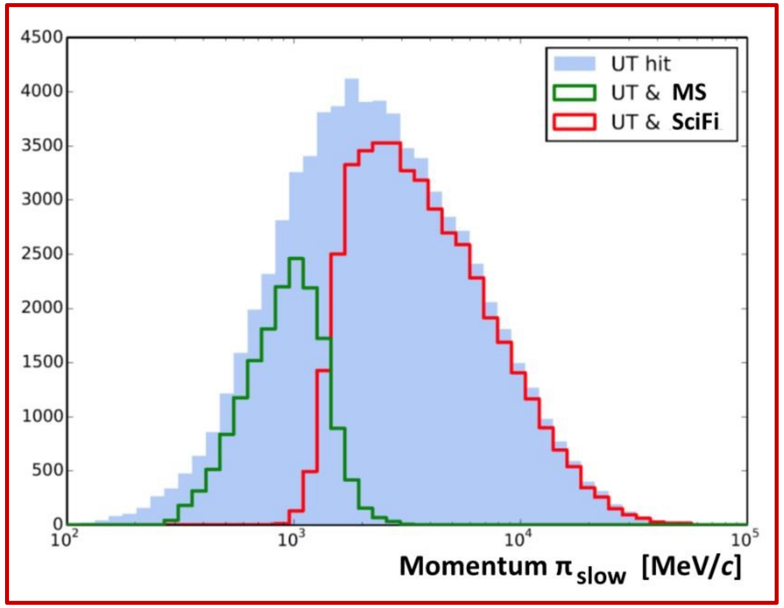


Magnet Station (MS)

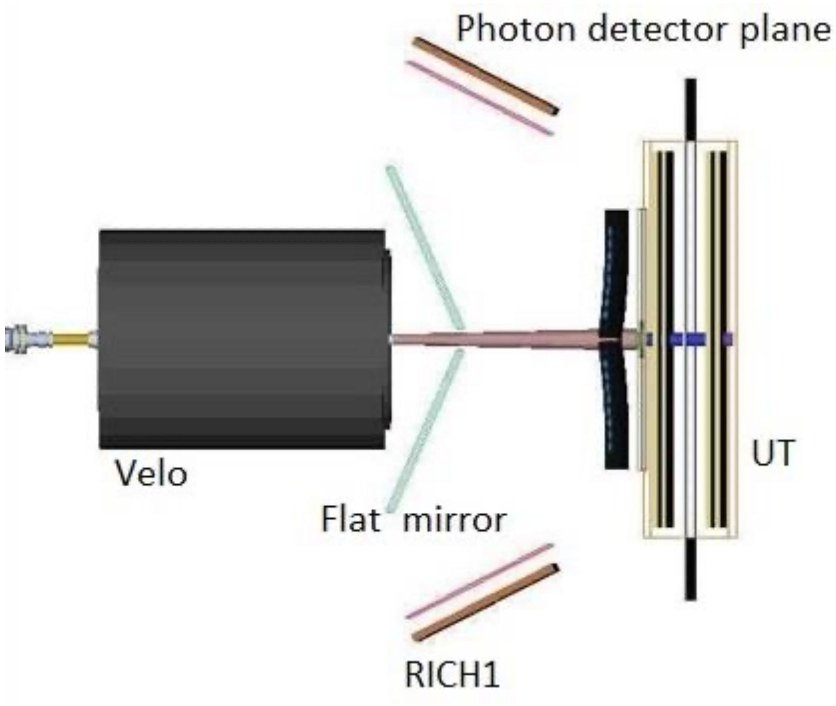




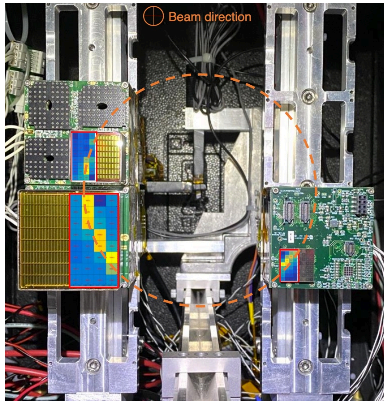
- **New subsystem for Upgrade II**
- Scintillator-based tracking system to measure position/direction of particles hitting the magnet inner walls
- Triangular scintillating bars with 1mm WLS-fibers and SiPM readout (outside the magnet)
- Improves momentum resolution of upstream tracks (<1%)
- Significant increase in acceptance for low-momentum tracks (e.g. large gain for prompt D^{*+} with slow π) →



RICH 1 & 2

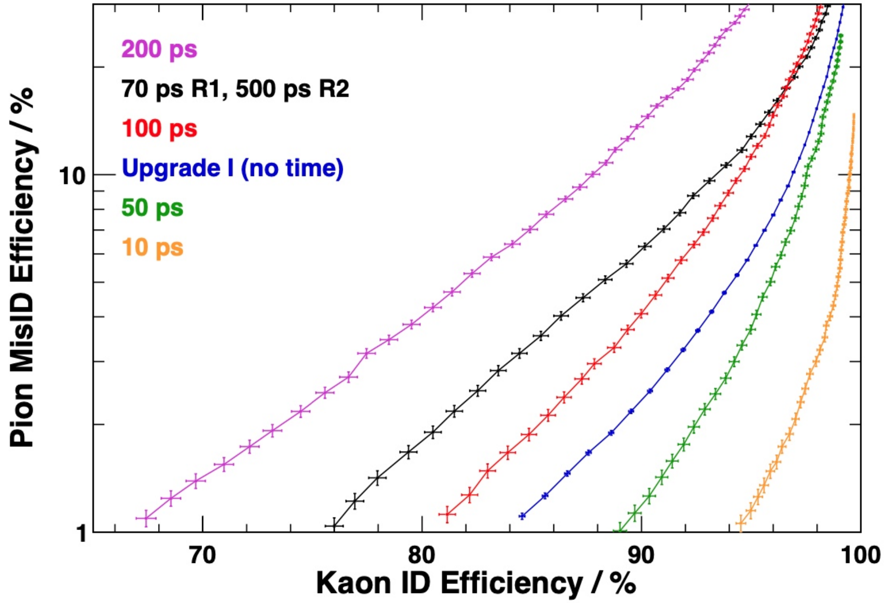


- ✓ UII baseline → re-design RICH system with similar footprint to RICH 1 & 2
- ✓ Increased luminosity → high-resolution timing, better θ_{Ch} resolution
- ✓ Key specs → occupancy below 30%, single-γ $\sigma_\theta < 0.5$ mrad
- ➢ Reduced tilt in mirrors to decrease chromatic aberration → flat mirror in acceptance
- ➢ Testing new gas mixtures → improve angular precision
- ➢ Foreseen resolutions: $\sigma_\theta \sim 0.22$ (0.13) mrad for RICH1(2)



Massive R&D, simulation and reconstruction effort, as well as prototyping

Kaon ID efficiency vs pion MisID as function of time gate

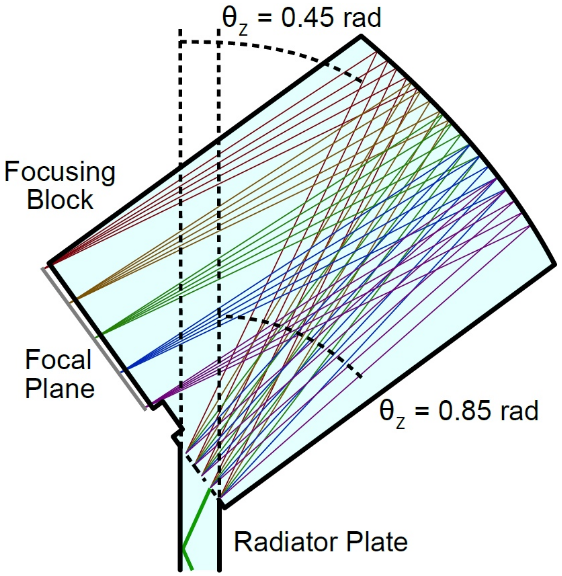


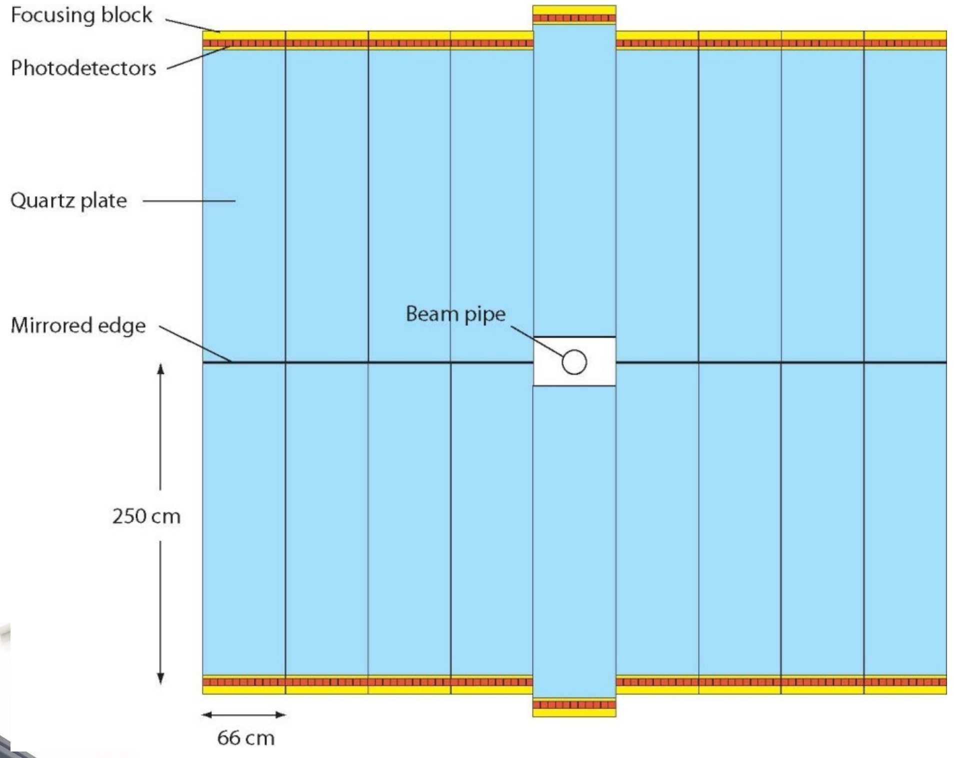
Photon detectors with high radiation tolerance and good space & time resolution:

- ➢ SiPMs: highly attractive option for high-occupancy regions
  - ✓ good PDE, 1 mm² pixel, low V, no B shielding needed but..
  - ✓ Requirements: σ_t ~100 ps and dark count rate < 100 kHz/mm²
    - → needs cryogenic cooling and neutron shielding
    - → micro-lensing & FE time gate can reduce dark count rate (DCR)
- ➢ Microchannel-plate (MCP): attractive for lower-occupancy regions
  - ✓ exceptional σ_t (~30 ps) and low DCR, but less radiation hard
    - → new design with pixelated anode made of CMOS ASIC under study

TORCH

- **New subsystem for Upgrade II**
- ToF detector with quartz planes read by MCP-PMTs in front of RICH2
- 10-15 ps time resolution per track
- Provides p/K (improves π/K) separation below 10 (5) GeV





- Exploit prompt production of Cherenkov light in an array of fused-silica bars to provide timing
- Cherenkov photons are propagated to detector plane via total internal reflection from the quartz surfaces
- Cylindrical focussing block, focusses the image onto a detector plane (to correct for chromatic dispersion)
- Large area detector required to cover the LHCb acceptance (5x6 m^2)

R&D with prototype
- ✓ Measured photon yields compared with MC
- ✓ Time resolution approaching 70 ps/photon

Full-scale half-length module with 1250x660x10 mm^3 fused-silica radiator bar

Fused-silica radiator

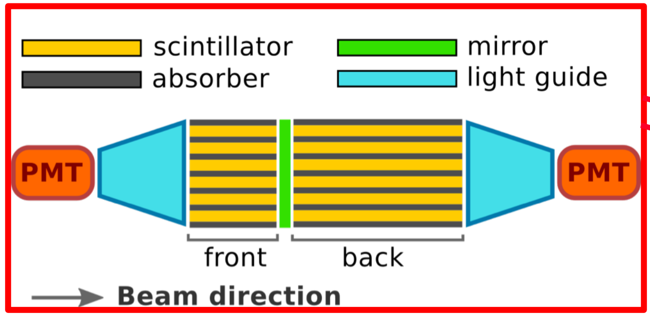
Requirements for Upgrade II luminosity:

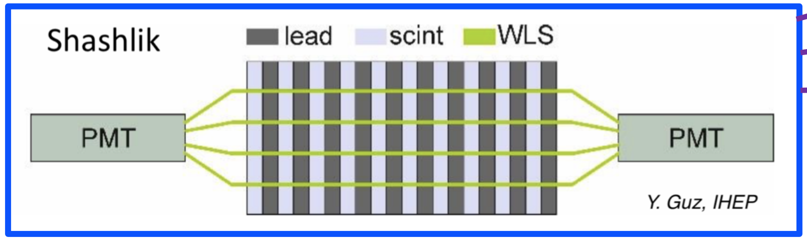
- ✓ Sustain radiation doses up to 1 MGy and $\leq 6 \times 10^{15}$ 1 MeV n_{eq}/cm in the centre:
  - ➢ SpaCal w/ rad. hard garnet crystals
- ✓ Keep energy resolution of current ECAL:
  - ➢ $\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$
- ✓ Mitigate pile-up:
  - ➢ timing capabilities of $\mathcal{O}(10)$ ps
  - ➢ increase granularity
- ✓ Introduce longitudinal segmentation:
  - ➢ better time resolution
  - ➢ less impact of radiation damage
  - ➢ improved event reconstruction and particle identification
- ✓ New fast electronics → SPIDER chip

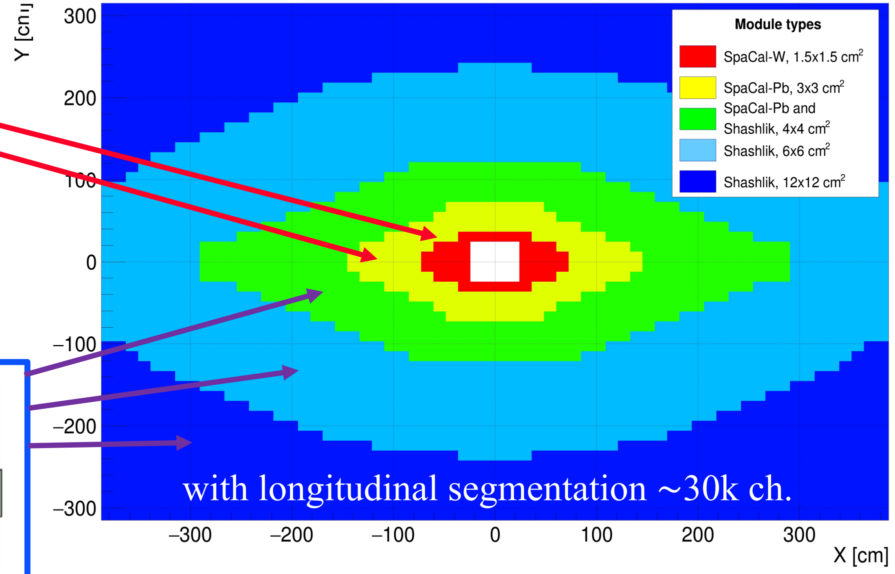
PicoCal

SpaCal technology for inner region

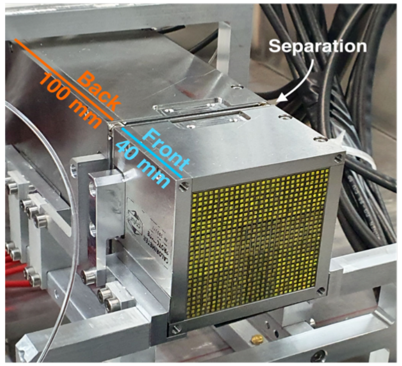
Shashlik technology for outer region



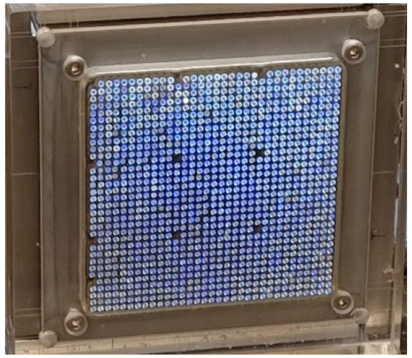




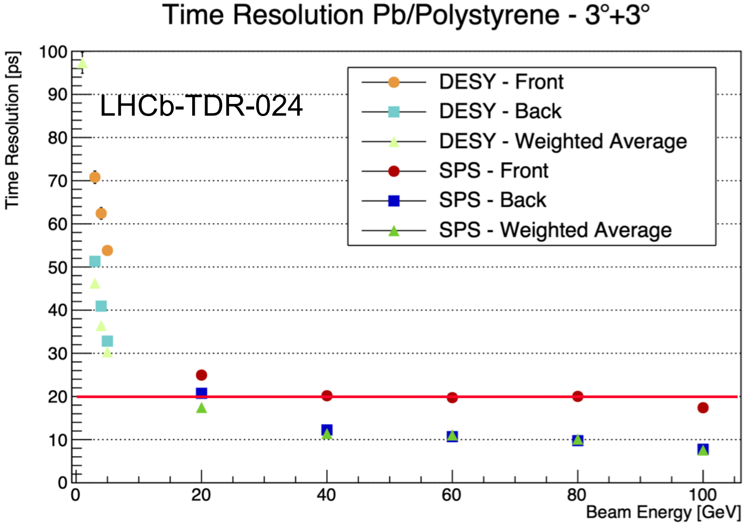
SpaCal-W/Garnet Crystal



SpaCal-Pb/Polystyrene

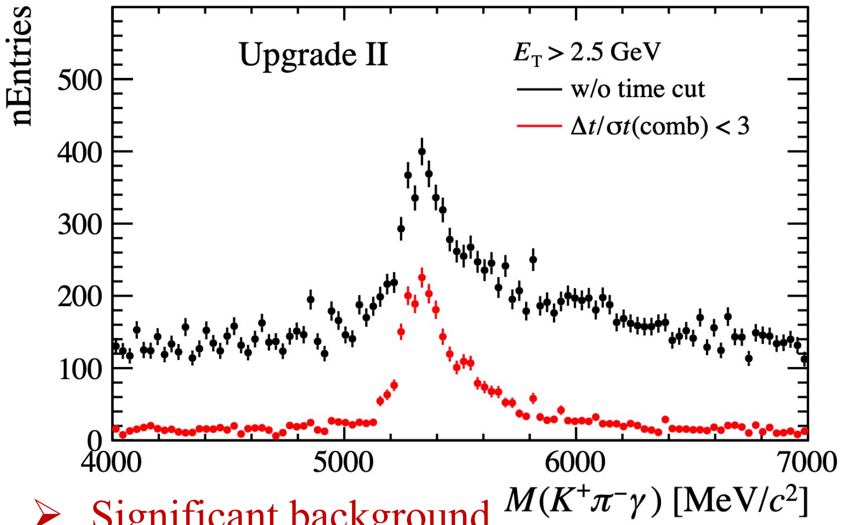


Garnet crystals rad. hard up to 1 MGy



➢ better than 20 ps time resolution with high-energy electron beams

Invariant mass of $B \to K^{*}\gamma$



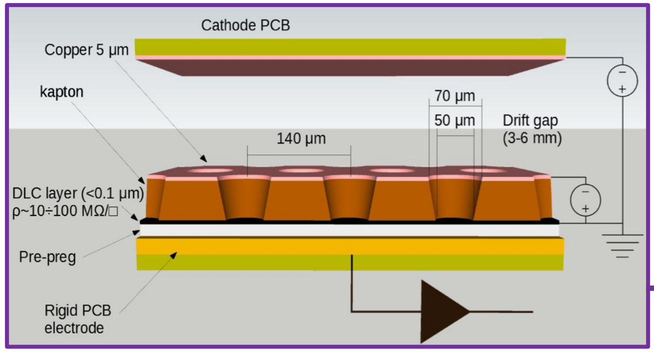
➢ Significant background reduction with time cut

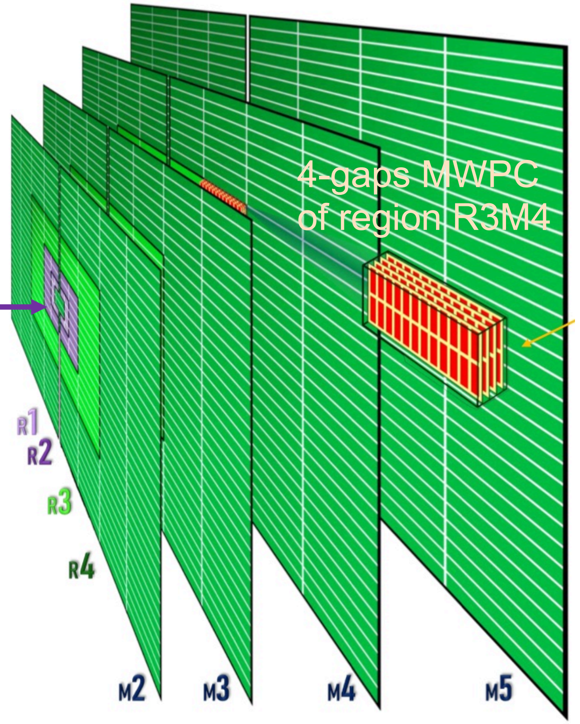
Muon system

Current system:

- Made up of four stations (M2-M5)
- Divided into four regions (R1-R4) from the beam pipe
- Three 80-cm thick iron absorbers between stations
- Each station is equipped with 4-gap MWPCs

μ-Rwell detectors in R1&R2

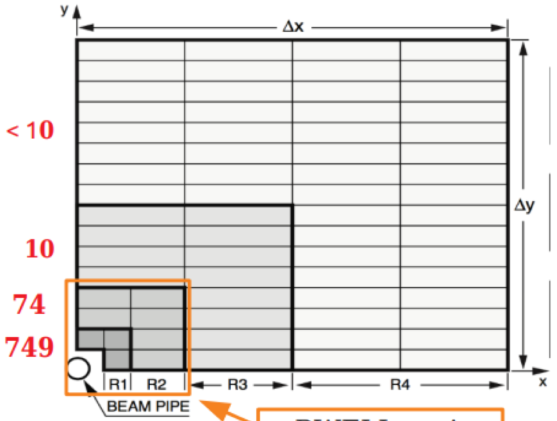




Challenge for UII: maintain current MUON performance at U2 luminosity

- Limiting factors:
  - ✓ FEE deadtime for muon detection efficiency
  - ✓ High misID due to increased combinatorial rate & particle flux
- Three "handles" to solve it:
  - ✓ improved granularity → μ-Rwell detectors with small pads in R1 & R2
  - ✓ new R/O architecture → 4 gaps read separately applying ≥ 2 gaps cut (no 4-OR)
  - ✓ additional shielding → replace HCAL or increase its shielding capacity

M2 station - max rate (kHz/cm²)



Deadtime induced inefficiency: **MWPC**

Maximum deadtime inefficiency % HCAL - MWPC

	M2	M3	M4	M5
R1	17.14	6.65	7.50	8.66
R2	17.81	4.62	5.69	7.34
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

Deadtime induced inefficiency: **μ-Rwell**

Maximum deadtime inefficiency % HCAL - μRWELL

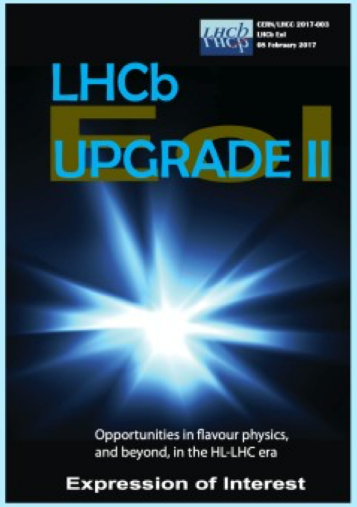
	M2	M3	M4	M5
R1	1.18	0.48	0.79	0.95
R2	1.22	0.32	0.31	0.41
R3	7.21	1.72	3.49	5.68
R4	8.24	3.37	2.30	8.55

Moving to high-granularity μRWell chambers

- High inefficiencies are strongly mitigated in R1&R2 with μ-Rwell chambers

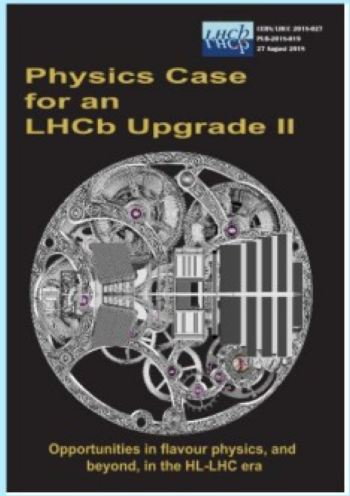
Steps towards Upgrade II

EoI



LHCC-2017-003

Physics case



LHCC-2018-027

Accelerator study

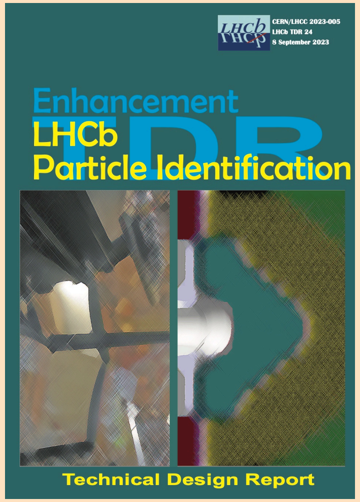
CERN-ACC-2018-038

Upgrade II FTDR

LHCC-2021-012

approved 03/2022

PID Enhancement TDR



LHCC-2023-005

approved 03/2024

DAQ Enhancement TDR

LHCC-2024-001

submitted 02/2024

➢ Enhancements during LS3 are stepping stone in view of Upgrade II in LS4

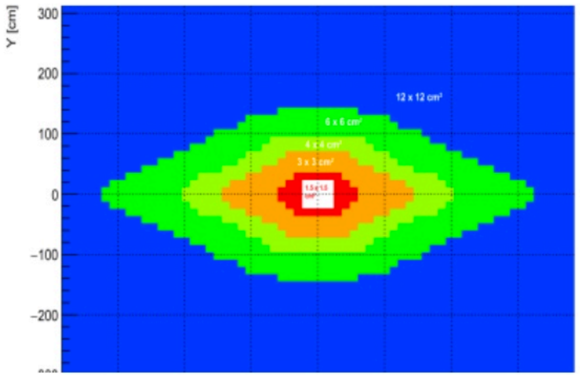
Next step: **Scoping Document** under preparation for submission to the LHCC in 09/2024

- Three detector scenarios: 1) FTDR-baseline, 2) reduced luminosity, 3) no new sub-detectors
- Impact on physics when deviating from FTDR-baseline
- Detailed cost estimate of all scenarios

Calorimeter LS3 enhancement

1) Innermost region needs replacing after Run 3 due to radiation damage
→ install new SpaCal modules that will be reused at Upgrade II
2) Rearrangement of existing modules into occupancy-motivated rhombus shape

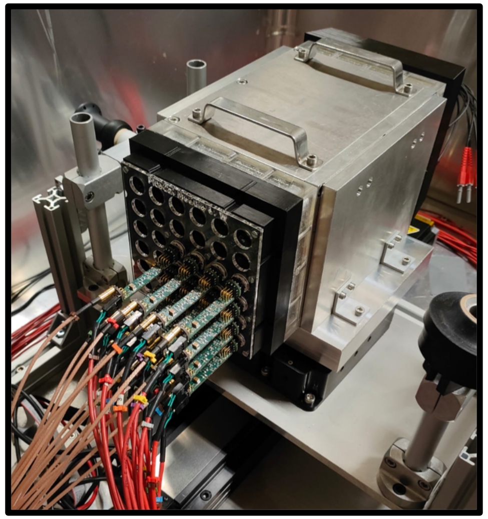
- Stepping stone in view of Upgrade II
- Early stage production and installation of new SpaCal modules for the PicoCal



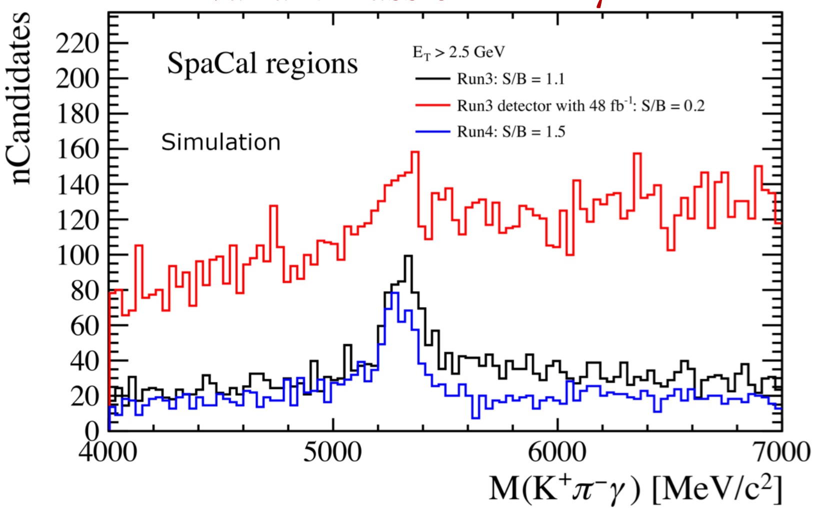
No longitudinal segmentation

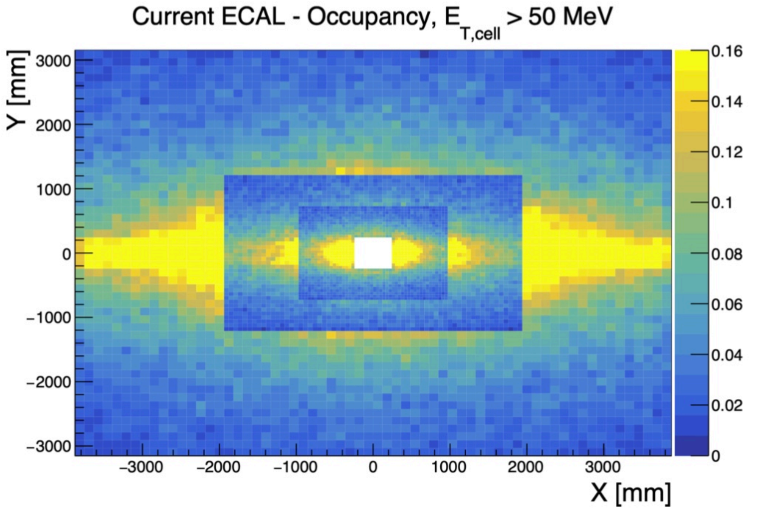
Cell size:	Modules:
2 x 2 cm²	32 *new* SpaCal-W modules
3 x 3 cm²	144 *new* SpaCal-Pb modules
4 x 4 cm²	176 existing modules in rhombic configuration
6 x 6 cm²	448 existing modules in rhombic configuration
12 x 12 cm²	2'512 existing modules in rhombic configuration

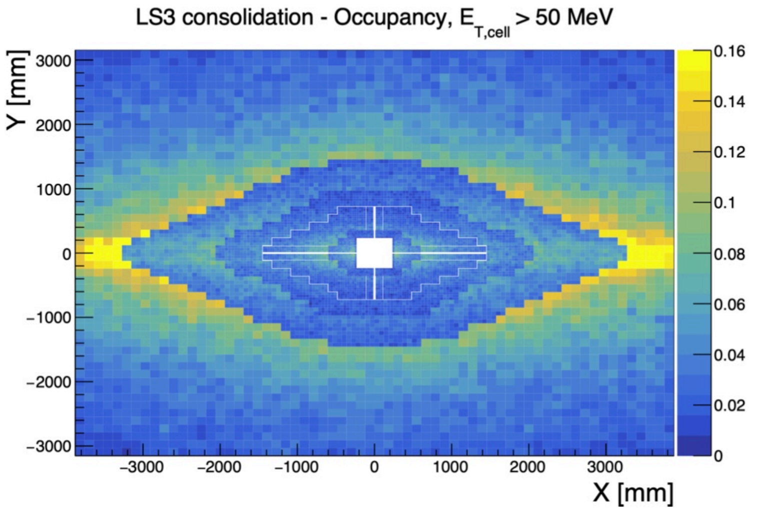
SpaCal-W "module-0"
w/ single-sided readout



Invariant mass of $B \to K^* \gamma$





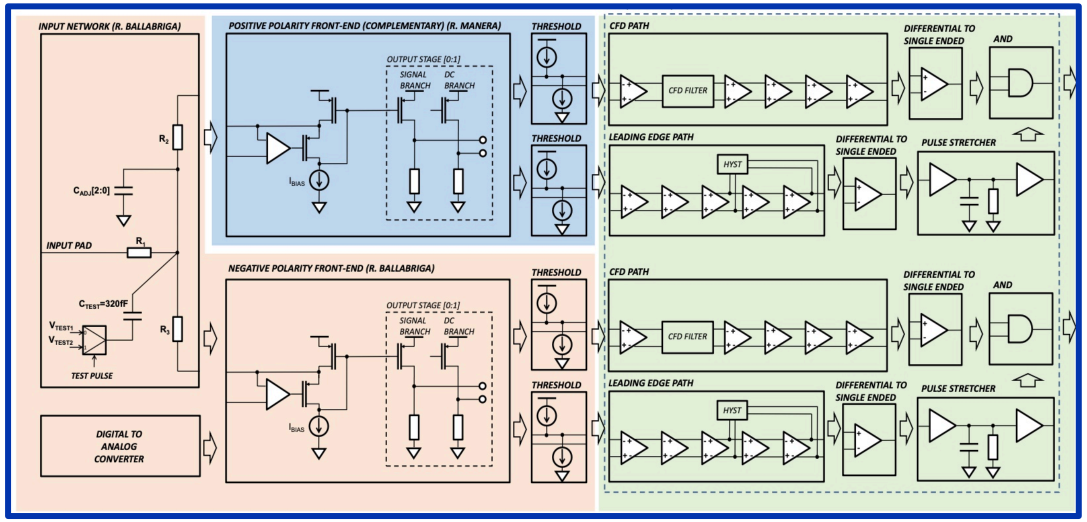


- Significant background reduction
- Great benefit expected from reducing the average occupancy

RICH LS3 enhancement

- ✓ New front-end readout electronics including FastRICH ASIC
- ✓ Capable of time-stamping photon hits with ~25 ps resolution
- ➢ Possibility to apply a narrow time window gate and reduce the combinatoric background

- ➢ Main limitation will remain at Run 4 from MaPMT photodetectors (σ ~ 150 ps)

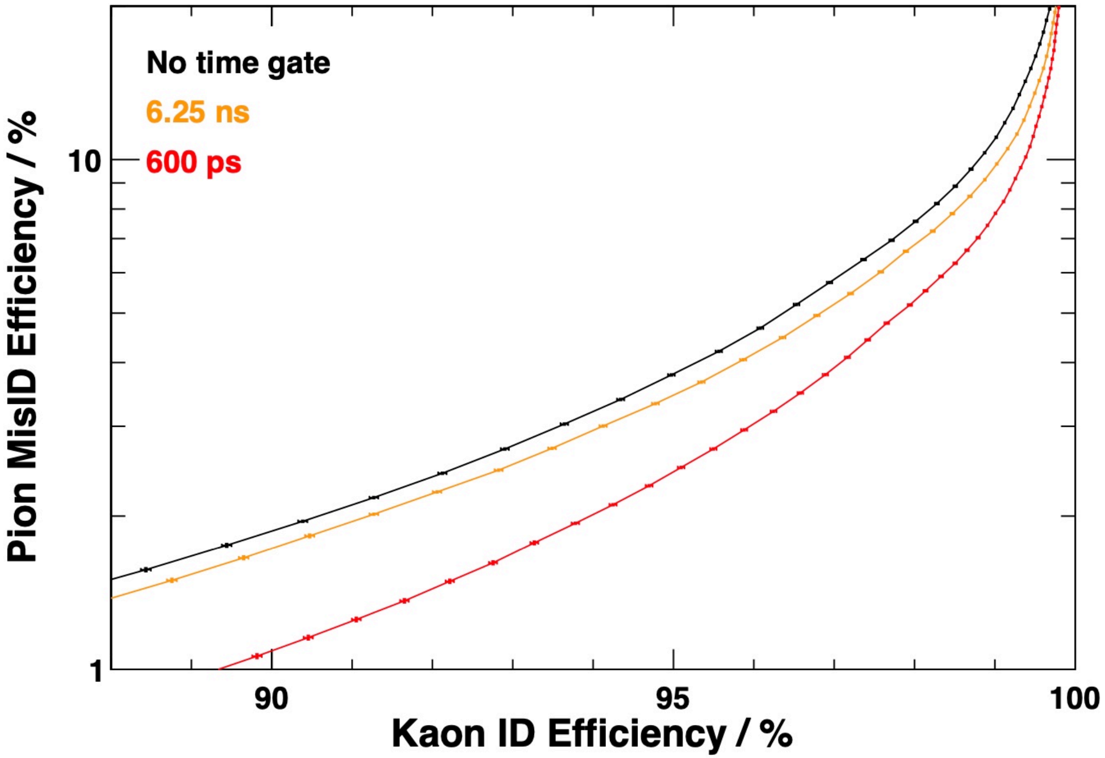


FastRICH (CMOS 65 nm)

- ➢ Design of FastRICH ASIC almost finalised
- ➢ Submission in 2024

- ➢ Stepping stone in view of Upgrade II
- ➢ Early stage design and production of the 1st version of the Upgrade II RICH ASIC
- ➢ Deploy and commissioning of precision timing in our detector, in advance of Run 5

- ➢ The planned 600 ps time gate will bring a significant gain in PID performances



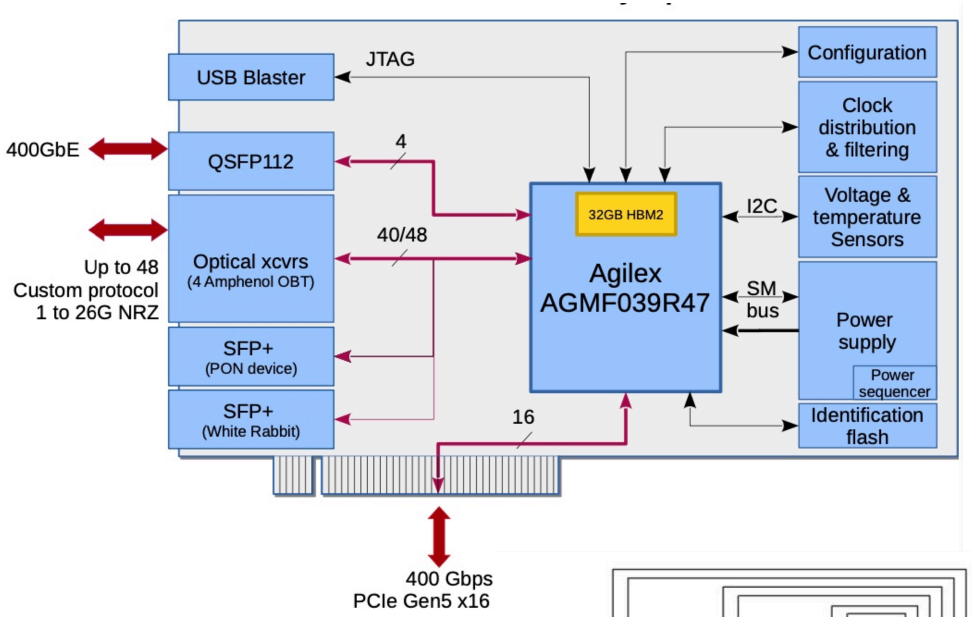
DAQ LS3 enhancement

PCIe400: new readout board with 400 Gb/s

- ✓ 48 GBT/lpGBT links compatible with PCIeGen5 or 400 GbE
  - ➢ output bandwidth x4 compared to present generation
- ✓ Make it available for LS3 LHCb detector upgrades

Run 5 prospect: fundamental development to keep pace with technology evolution (FPGA, links)

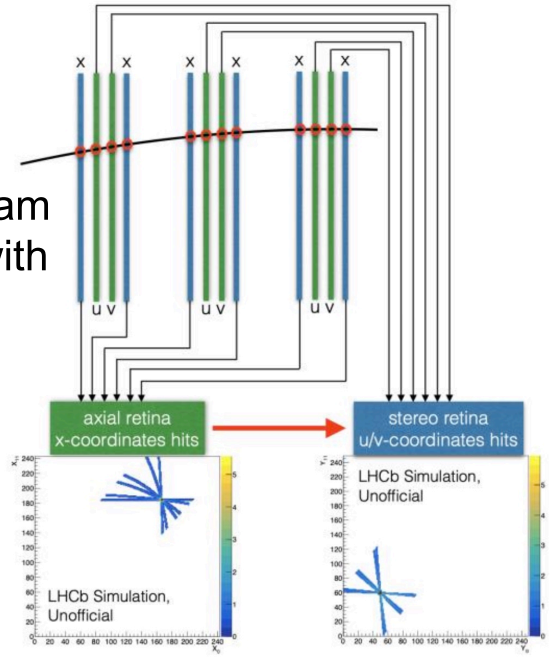
PCIe400 layout



Downstream tracking with FPGA (RETINA):

- ✓ Event reconstruction primitives (clusters, tracks) found by FPGA immediately available to event building, freeing resources for other tasks
  - ➢ already implemented in Run 3 for VELO clusters
- ✓ LS3 proposal: realise a downstream tracking unit using hits from SciFi at 30 MHz
  - ➢ clear benefit for downstream K_S and long-lived particle searches

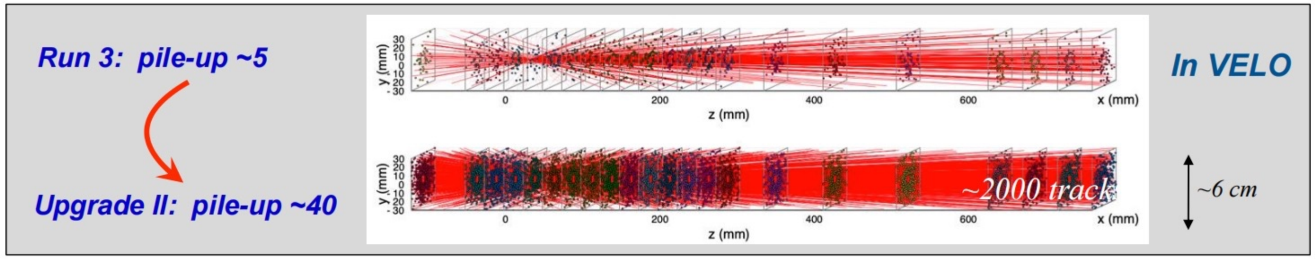
Downstream tracking with RETINA

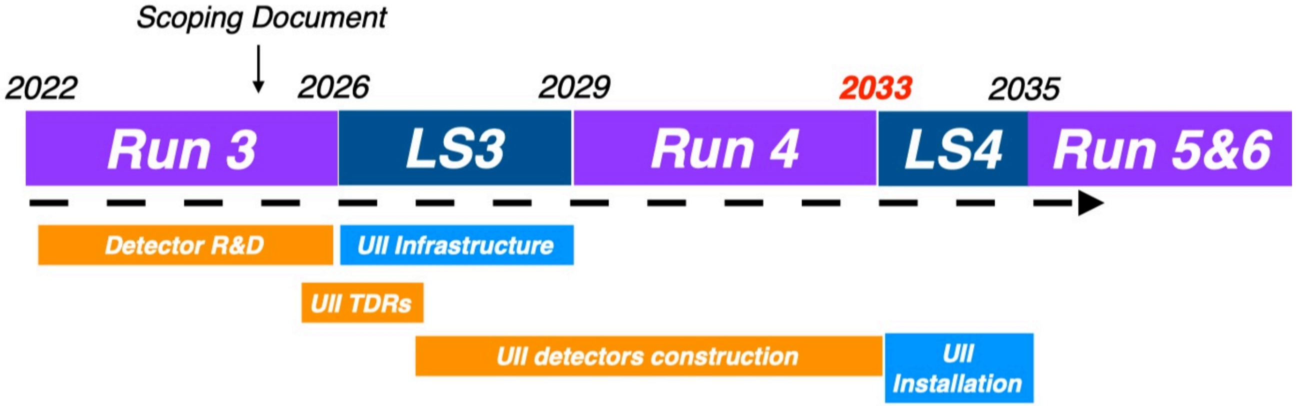


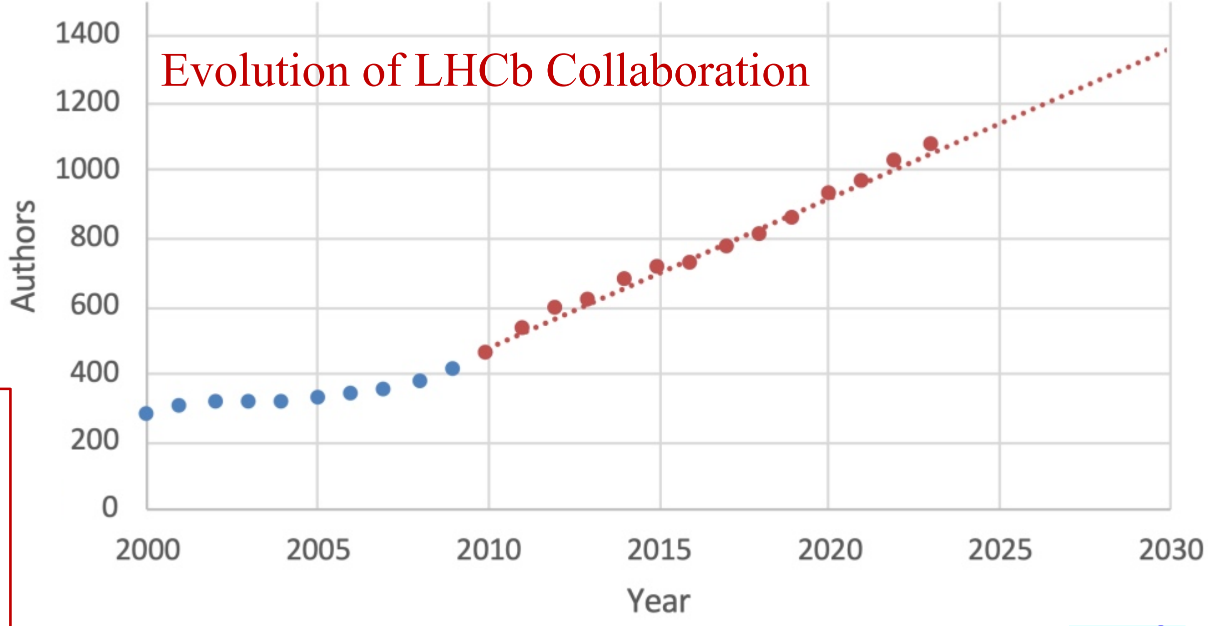
Run 5 prospect: realise a truly integrated system of FPGA+GPU+CPU+… that makes best use of specialised hardware

Summary and conclusion

- LHCb as a general-purpose detector in the forward region has produced a wide range of compelling physics results and has a unique potential to explore new physics with Upgrade II
- The increase in luminosity calls for remodelling the detector, adapting individual subsystems to the high luminosity conditions without worsening (and possibly improving) performances
- An intense and attractive R&D program is ongoing that pushes the limit of existing technologies in HEP and explores new uncharted scenarios
- First approval steps fulfilled, following a clear strategy laid by the LHCC (next step: Scoping Document in 2024)
- Upgrade II will ultimately give us the unique opportunity to fully exploit the great physics potential of HL-HLC
- The PID & DAQ enhancements in LS3 are first stepping stones in view of Upgrade II







Upgrade II is an ambitious project with excellent prospects for physics and for developing new technologies
→ **new collaborators are welcome!**