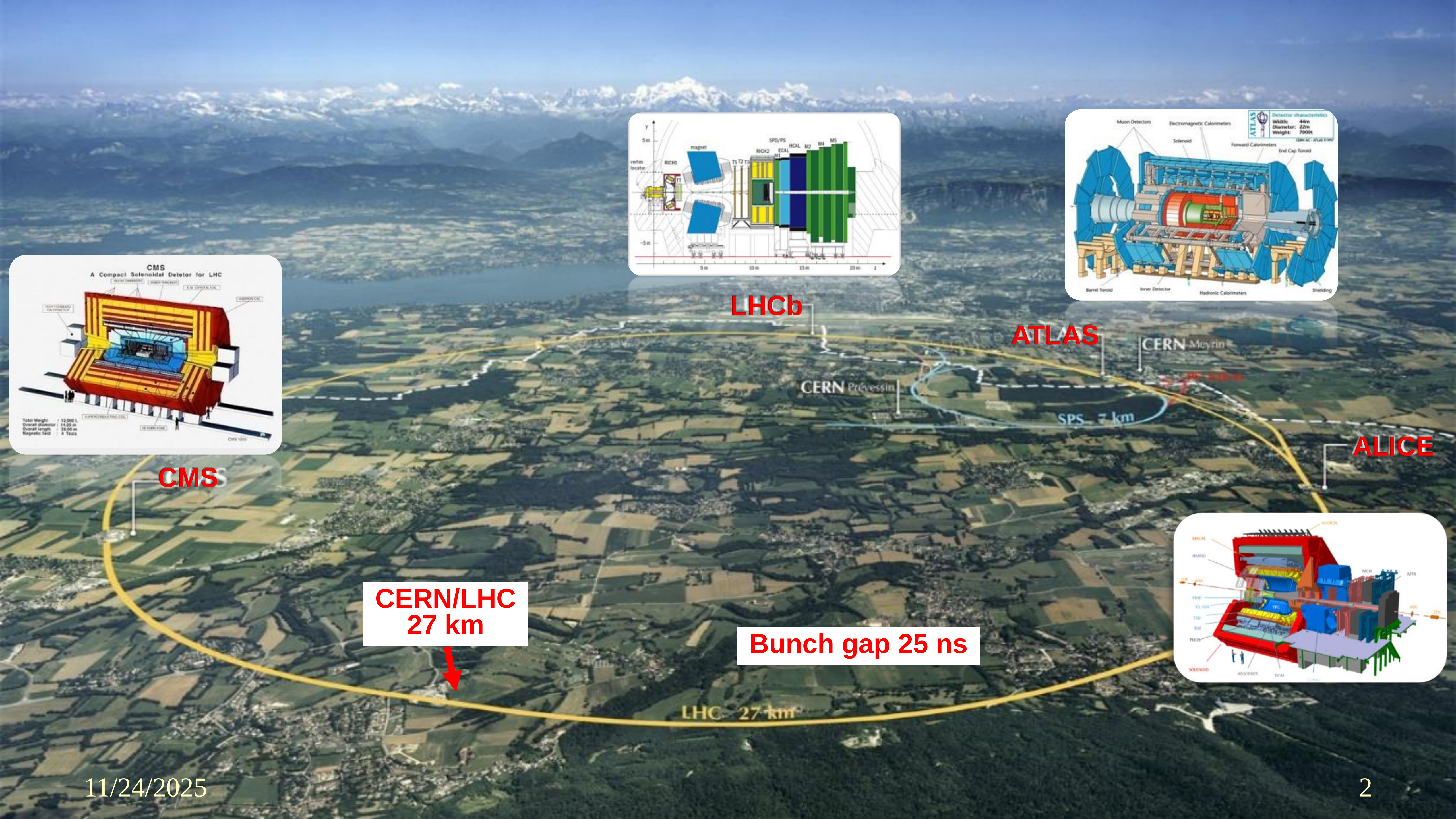
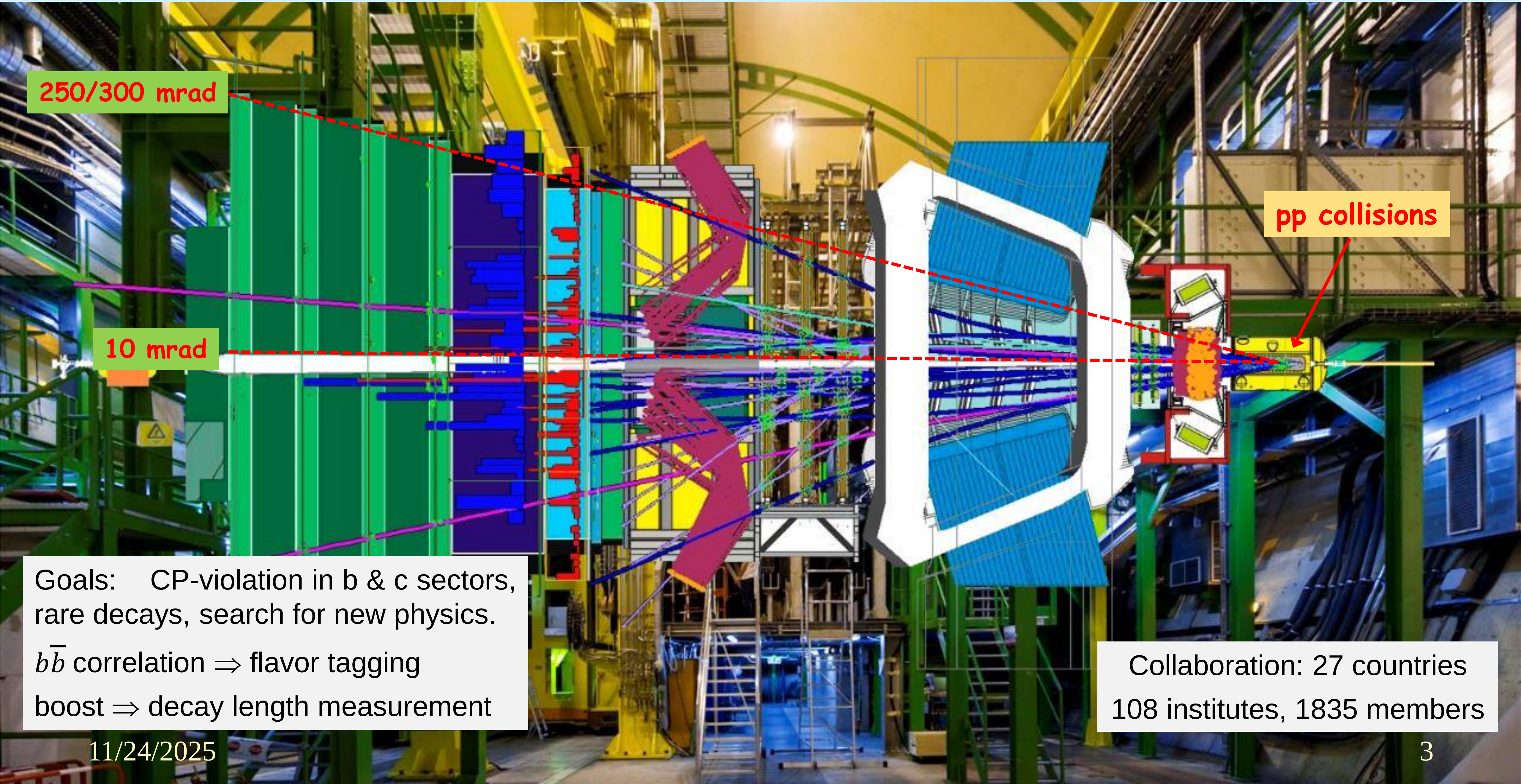
Upgrade of The LHCb Detector

Jianchun Wang, IHEP/CAS
For The LHCb Collaboration

FTCF2025, Huangshan, Nov 24-27, 2025


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
CERN/LHC
27 km
Bunch gap 25 ns
LHC 27 km
CMS
A Compact Solenoidal Detector for LHC

LHCb – A Forward Spectrometer @ LHC



Goals: CP-violation in b & c sectors, rare decays, search for new physics.

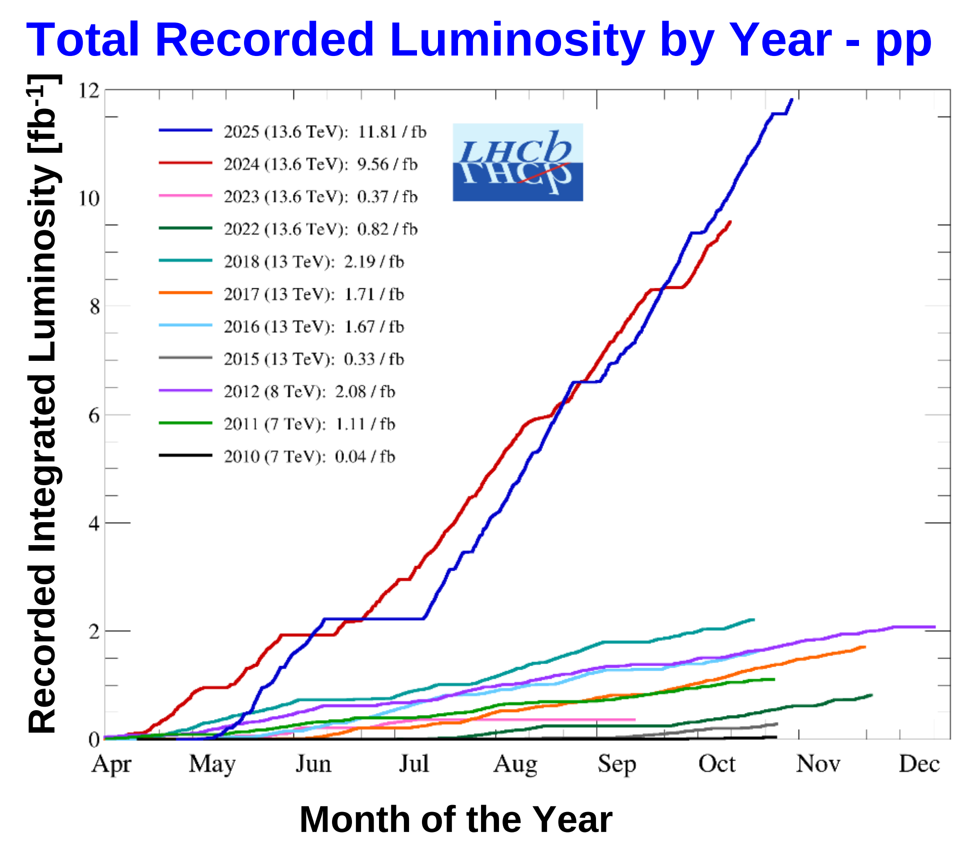
$b\bar{b}$ correlation $\Rightarrow$ flavor tagging

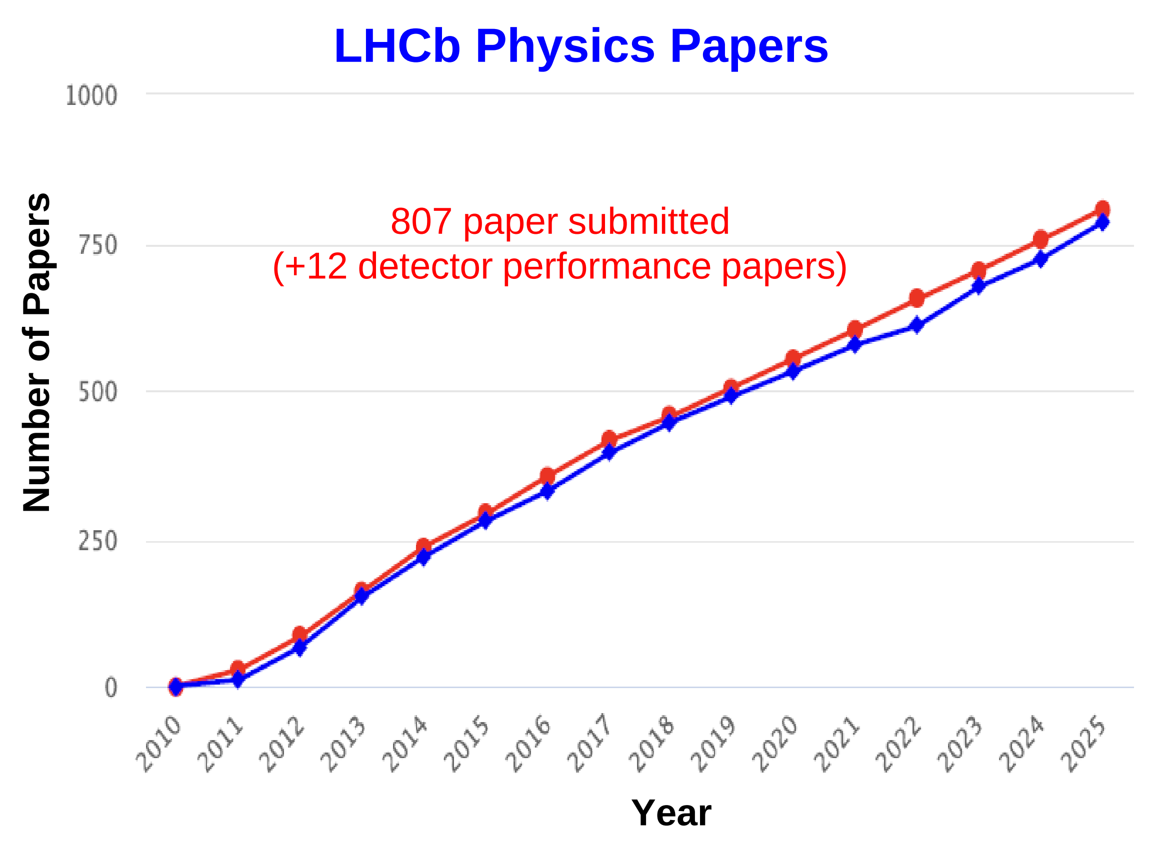
boost $\Rightarrow$ decay length measurement

Collaboration: 27 countries

108 institutes, 1835 members

LHCb Performance

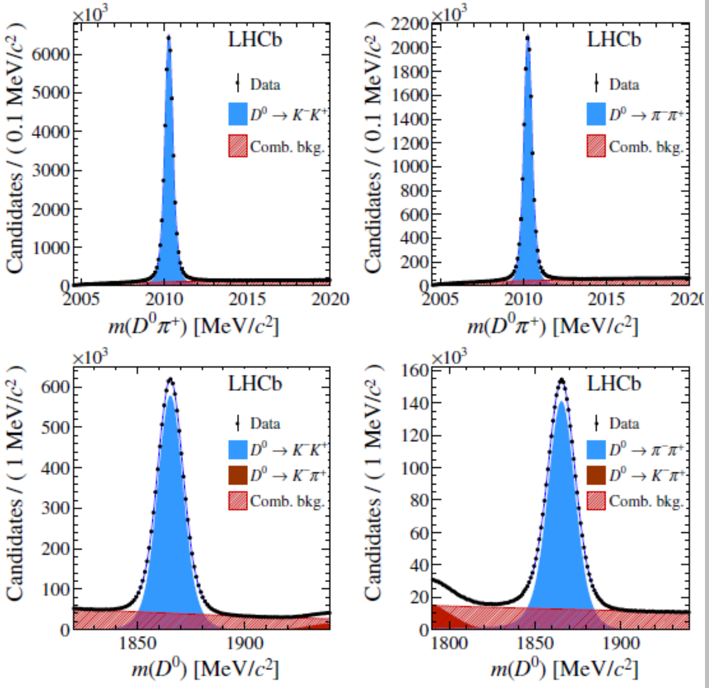




Selected LHCb Physics Results

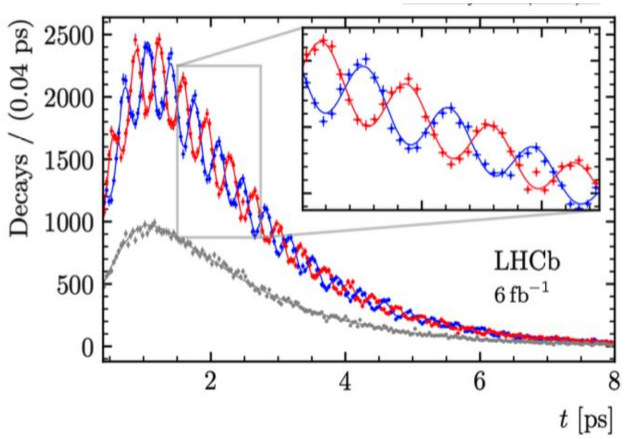
CPV in Charm decays

Phys. Rev. Lett. 122 (2019) 211803



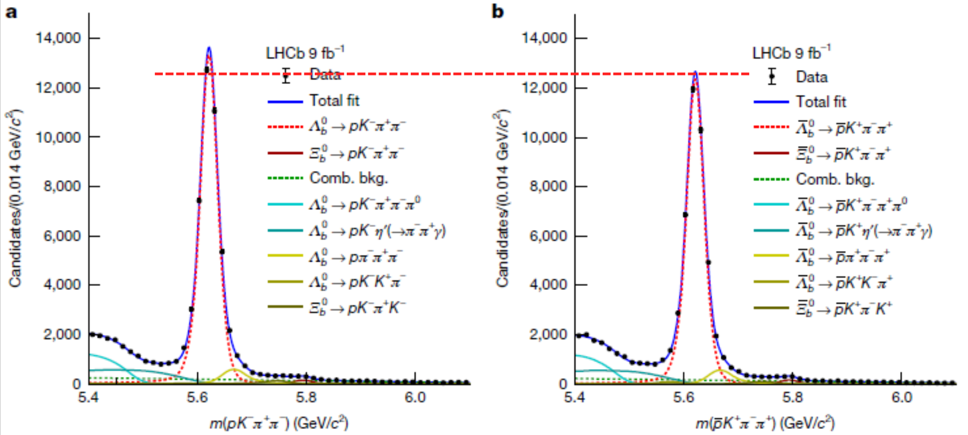
Δm_s

Nature Physics 18, (2022) 1-5



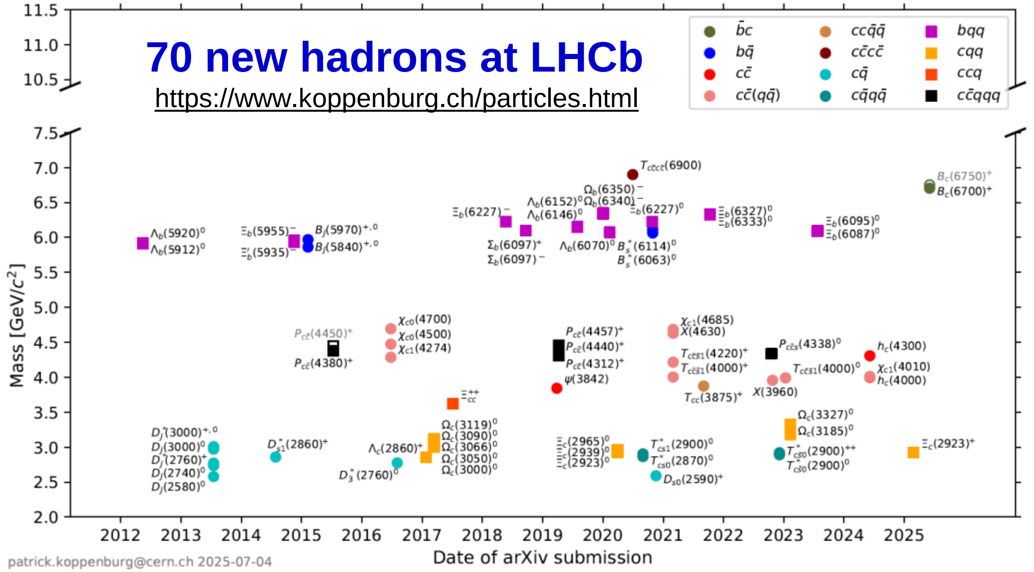
CPV in Baryon Decays

Nature 643 (2025) 1223



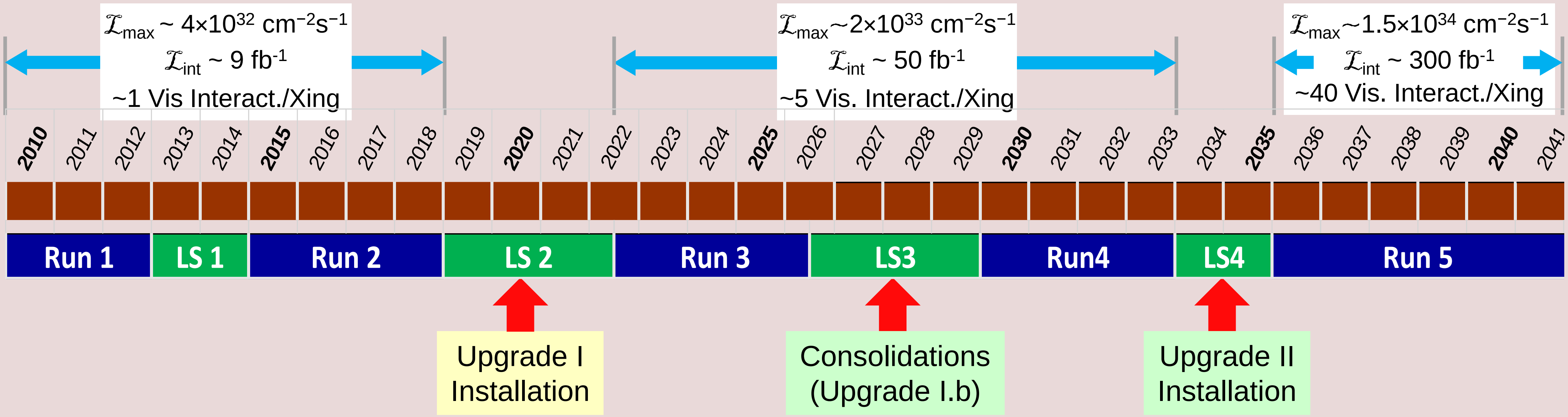
70 new hadrons at LHCb

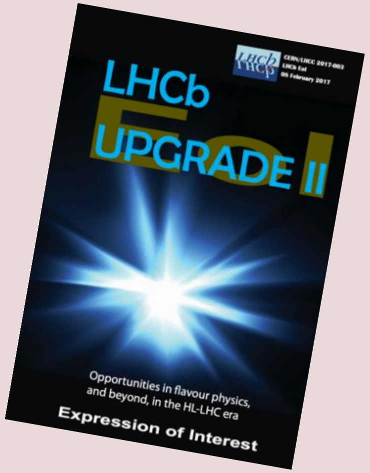
https://www.koppenburg.ch/particles.html



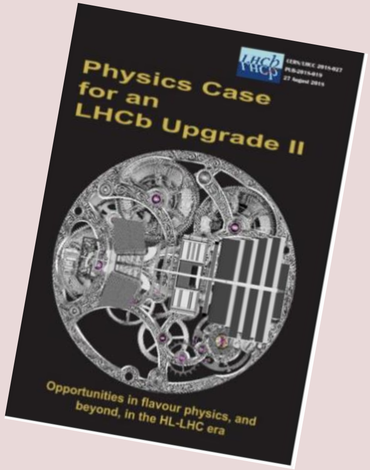
LHCb contributed a series of discoveries and precision measurements

Towards Upgrade II



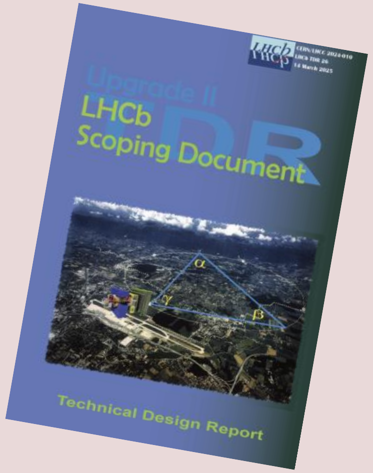


Expression of Interest
LHCC-2017-003



Physics Case
LHCC-2018-027

Framework TDR
LHCC-2021-012



Scoping Document
LHCC-2024-010

Physics Reach of The Upgrade II

Key observables in flavor physics

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.*)	2.8°	[20, 21]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[24]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[56, 57]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[27]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[31]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[58]	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%	[32, 33]	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	[59]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[60]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[61]	0.148	0.097	0.038

(***Ref:*** ***LHCC-2024-010*** ***and references therein***)

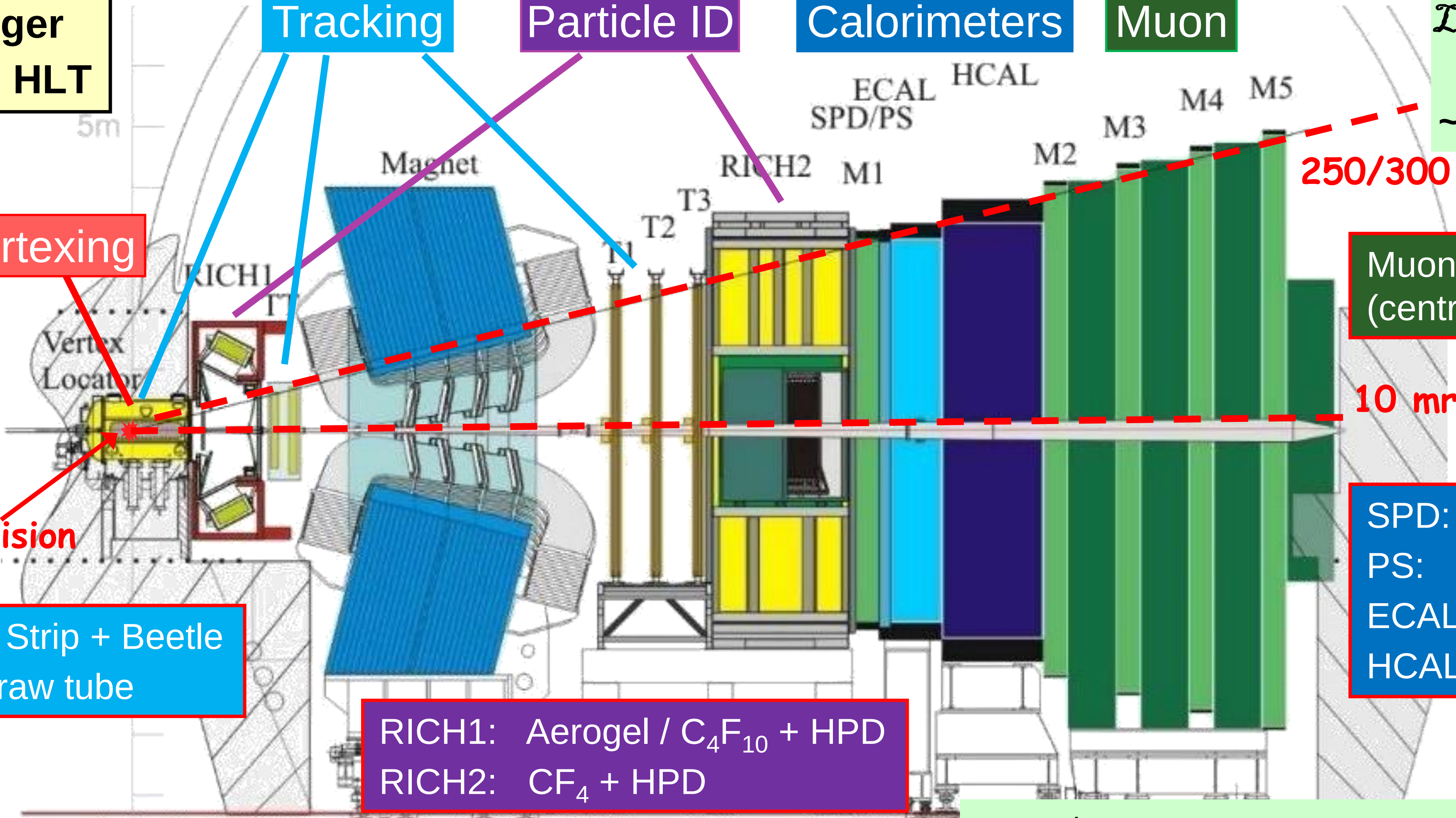
- Upgrade II will fully realize the flavor physics potential of the HL-LHC
- Further pursue a broad physics program (spectroscopy, high precision EW, dark sector and other exotic search, heavy ions and fixed target)
- Success of the program relies on a detector with similar or better performance as the present one

LHCb Base Detector

Hardware trigger
Computer farm HLT

Tracking | Particle ID | Calorimeters | Muon

$\mathcal{L}_{max}$ ~ 4×10^{32} $cm^{-2}s^{-1}$
$\mathcal{L}_{int}$ ~ 9 fb^{-1}
~1 Vis Interact./Xing

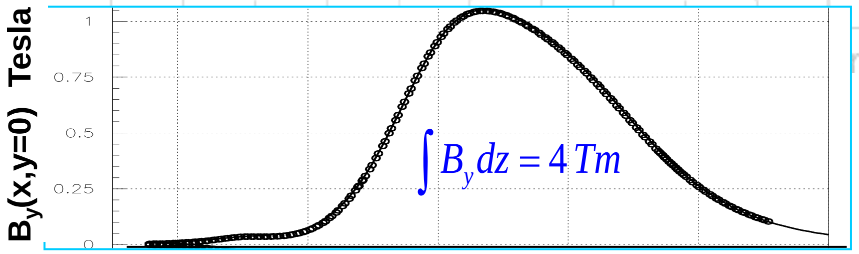


Muon: MWPC
(central M1): Triple-GEM

SPD: PS+Pb+PMT
PS: PS+Pb+PMT
ECAL: PS+Pb+PMT
HCAL: PS+Fe+PMT

VeLo/TT/IT: Si Strip + Beetle
OT: Straw tube

RICH1: Aerogel / C_4F_{10} + HPD
RICH2: CF_4 + HPD

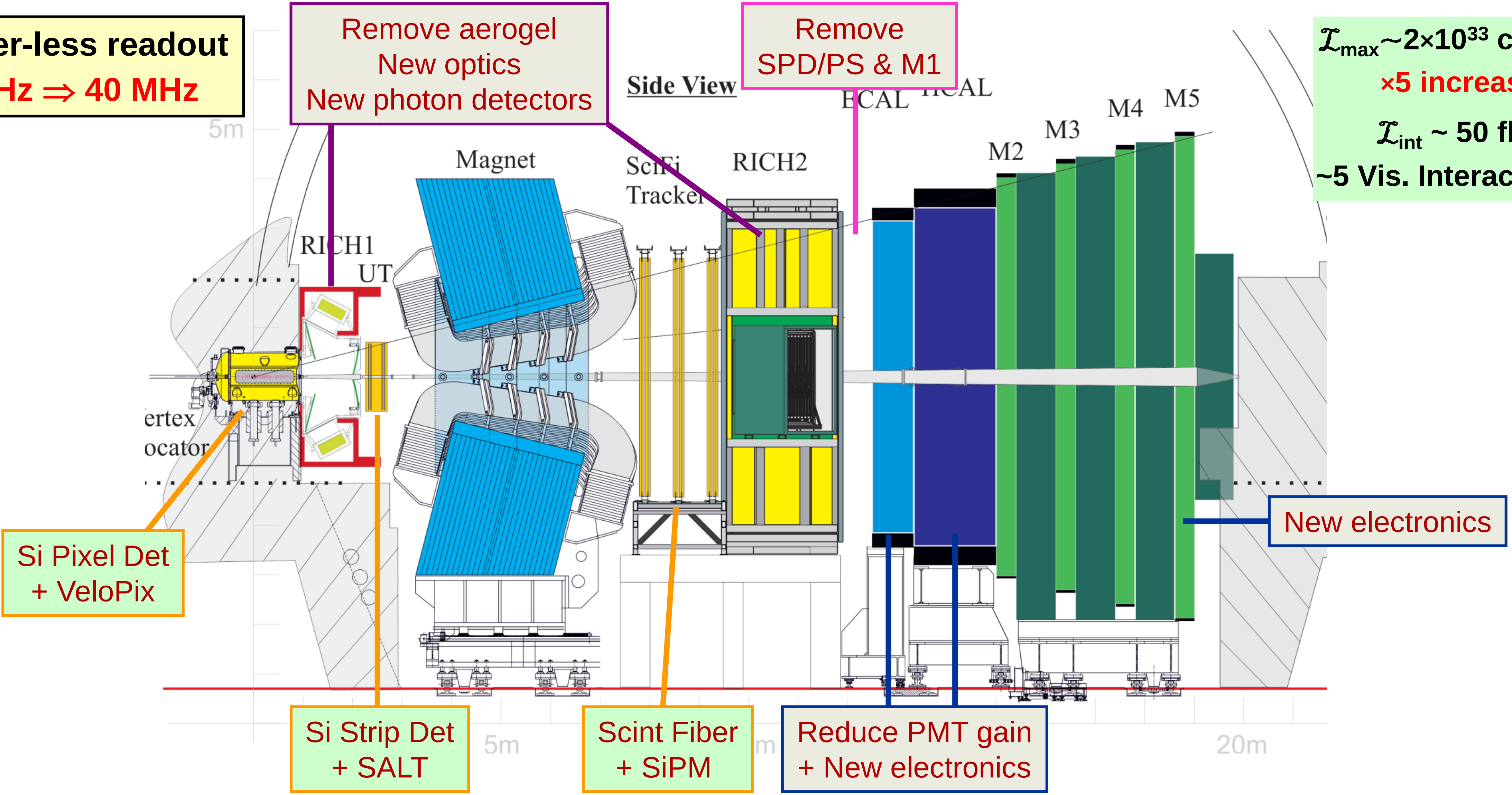


- $\Delta p/p = 0.5\%$ at <20 GeV, 1.0% at 200 GeV
- IP resolution ~ 15 + 29/p_T [GeV/c] μm
- Decay time resolution 45 fs (e.g. $B_s \to J/\psi\ \phi$)
- Kaon ID ~ 95% for 5% $\pi\to K$ mis-ID probability

LHCb Phase I Upgrade

Trigger-less readout
1 MHz ⇒ 40 MHz

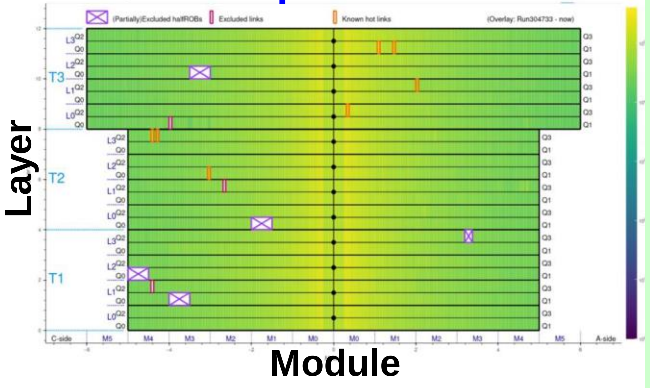
$\mathcal{L}_{max}$~2×10^{33} $cm^{-2}s^{-1}$
×5 increase
$\mathcal{L}_{int}$ ~ 50 fb^{-1}
~5 Vis. Interact./Xing



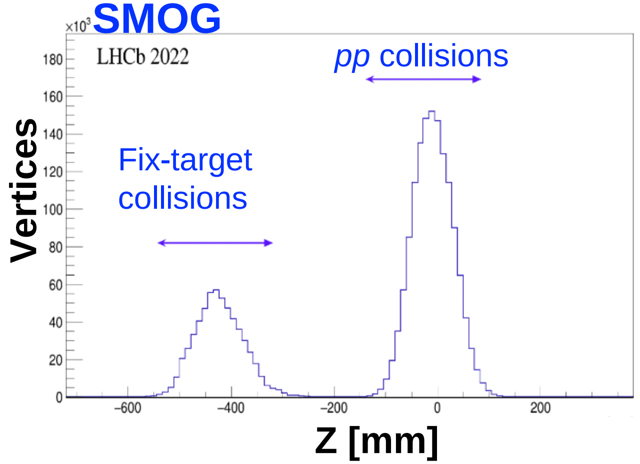
Upgrade I Performance

- Completion of installation in Mar 2023, commissioning since 2022, physics production in 2024
- All subdetectors working as designed!

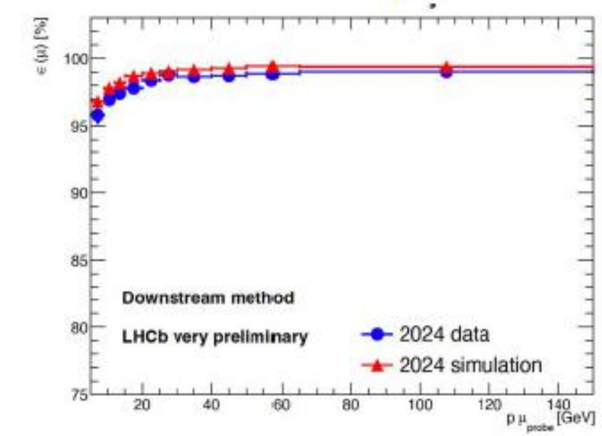
SciFi Hitmap



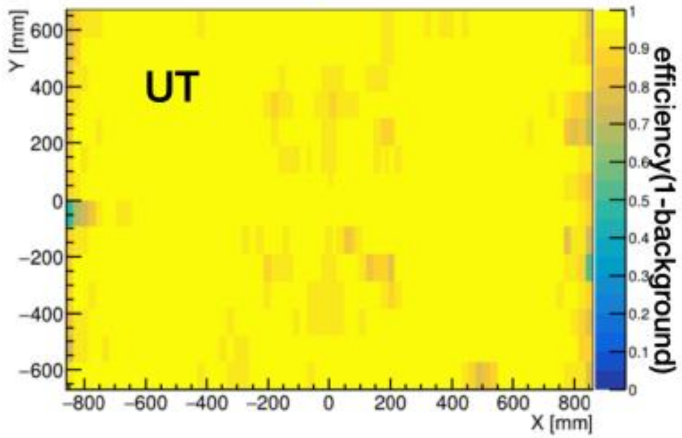
SMOG



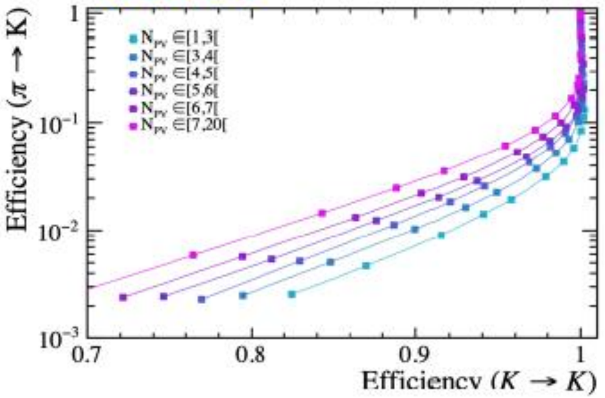
VELO efficiency



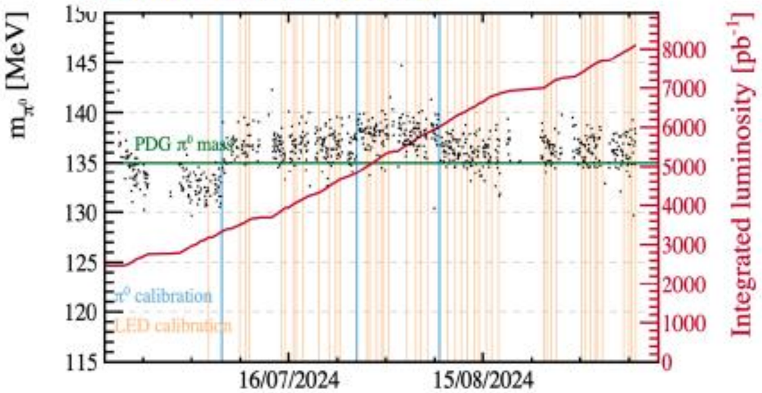
UT efficiency



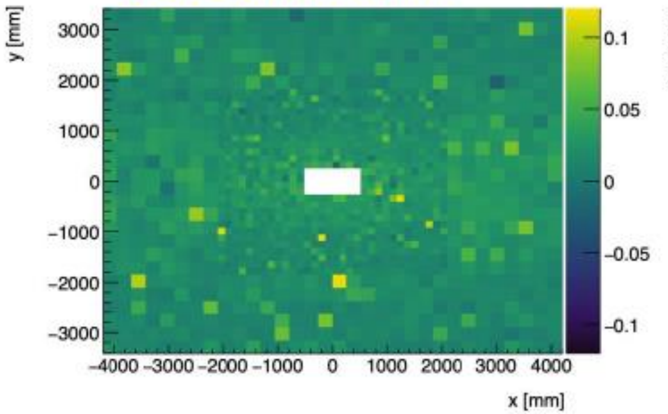
RICH PID



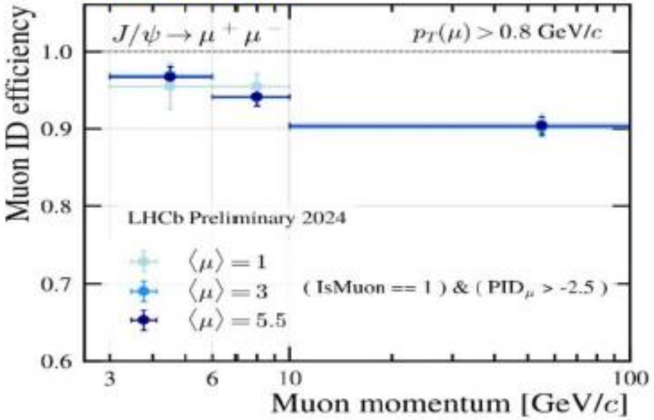
ECAL calibration



HCAL calibration



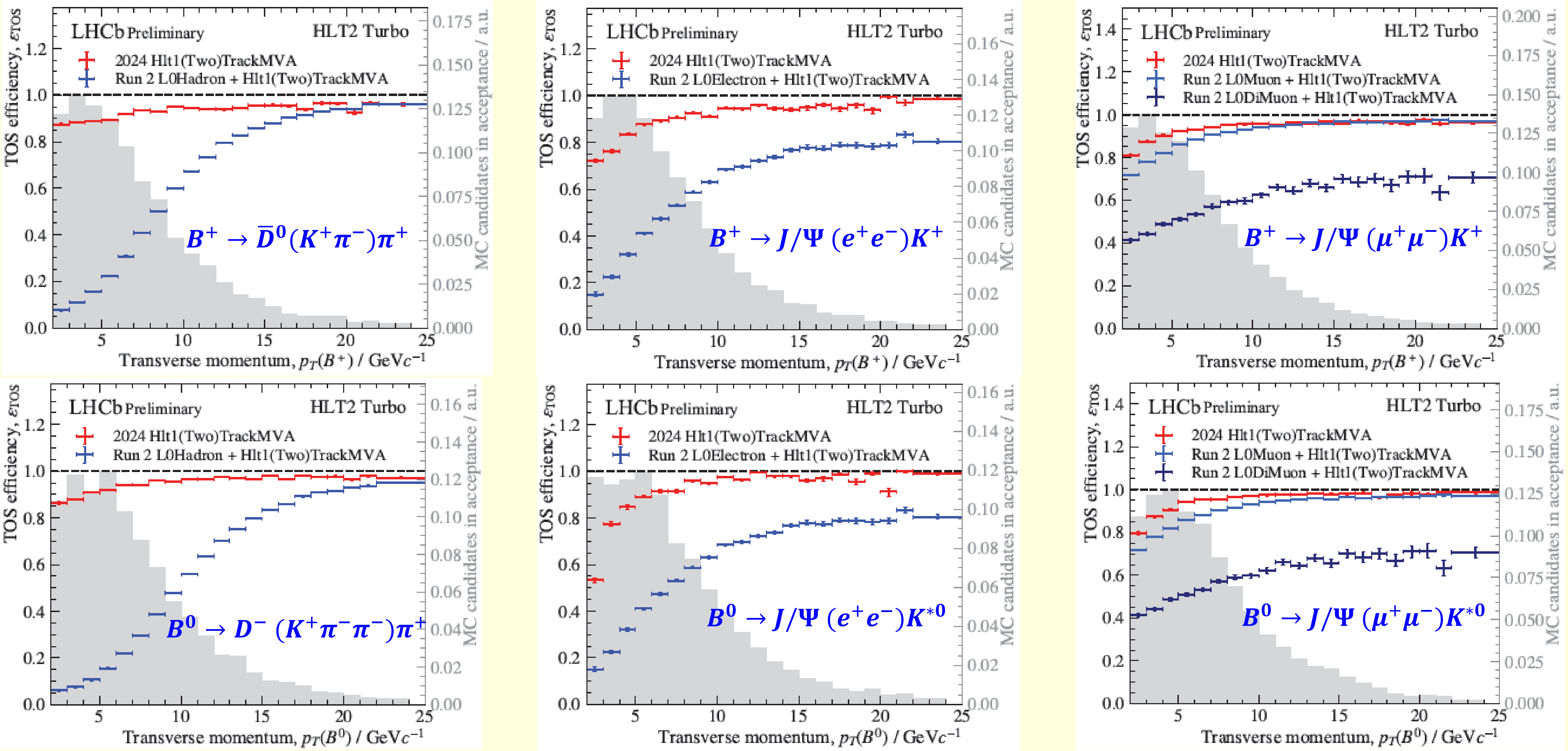
MUON ID



Upgrade I Performance

Trigger efficiency significantly improved – removal of L0 working for hadron and electron as intended, and also for muons

LHCb-Figure-2024-030



LHCb Phase II Upgrade

$\mathcal{L}_{max} \sim 1.5\times10^{34}\ cm^{-2}s^{-1}$

×7.5 increase

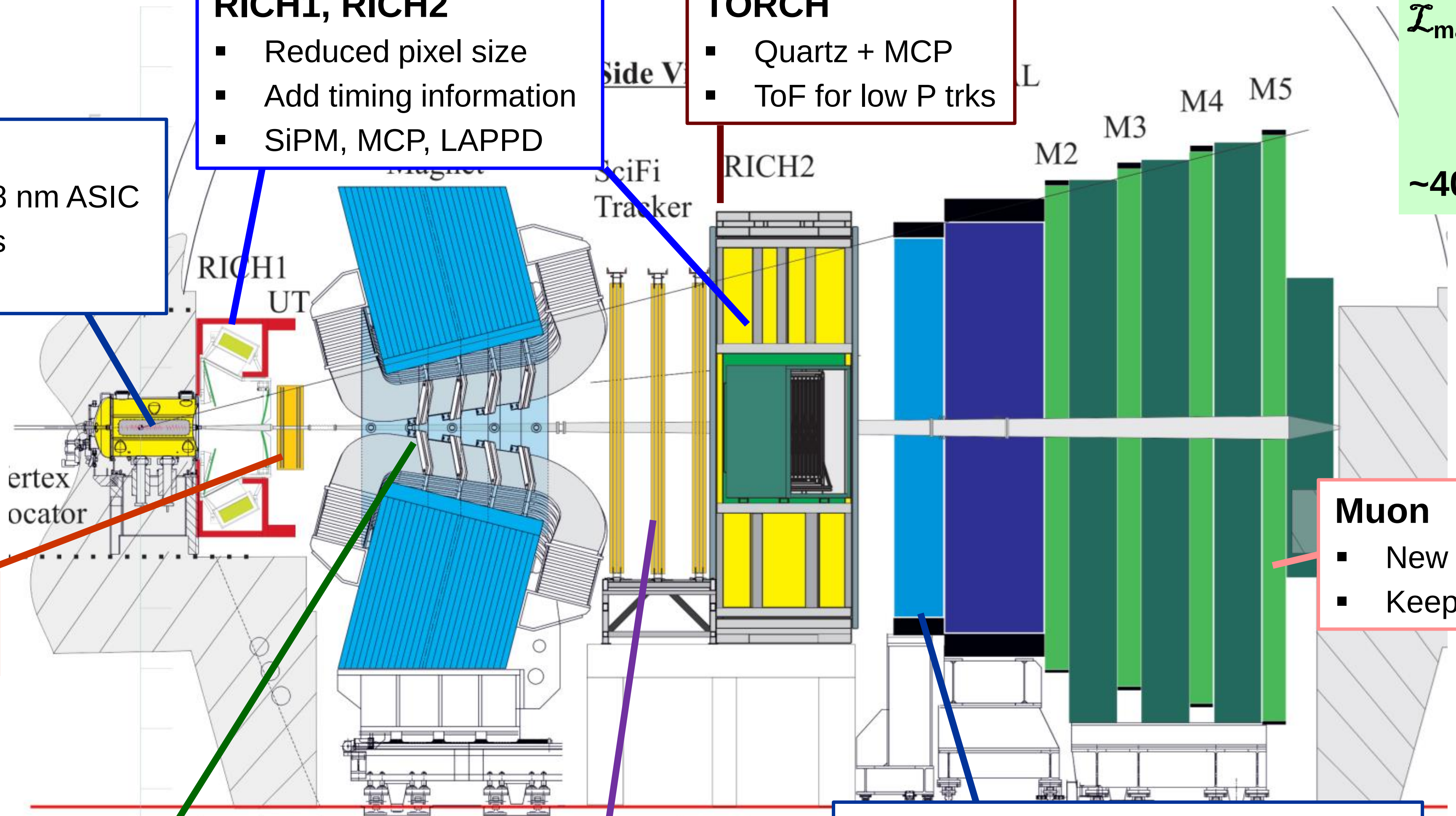
$\mathcal{L}_{int} \sim 300\ fb^{-1}$

~40 Vis. Interact./Xing

VELO → TV
- 3D Si Pixel, 28 nm ASIC
- Timing ~ 50 ps
- New RF-foil

RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP, LAPPD

TORCH
- Quartz + MCP
- ToF for low P trks



UT → UP
- MAPS pixel

Muon
- New MPGD (inner)
- Keep MWPC (outer)

Magnet Stations (MS)
- Scintillating bar
- Low P particles

MightyTracker (MT)
- MAPS pixel (inner)
- Keep SciFi (outer)

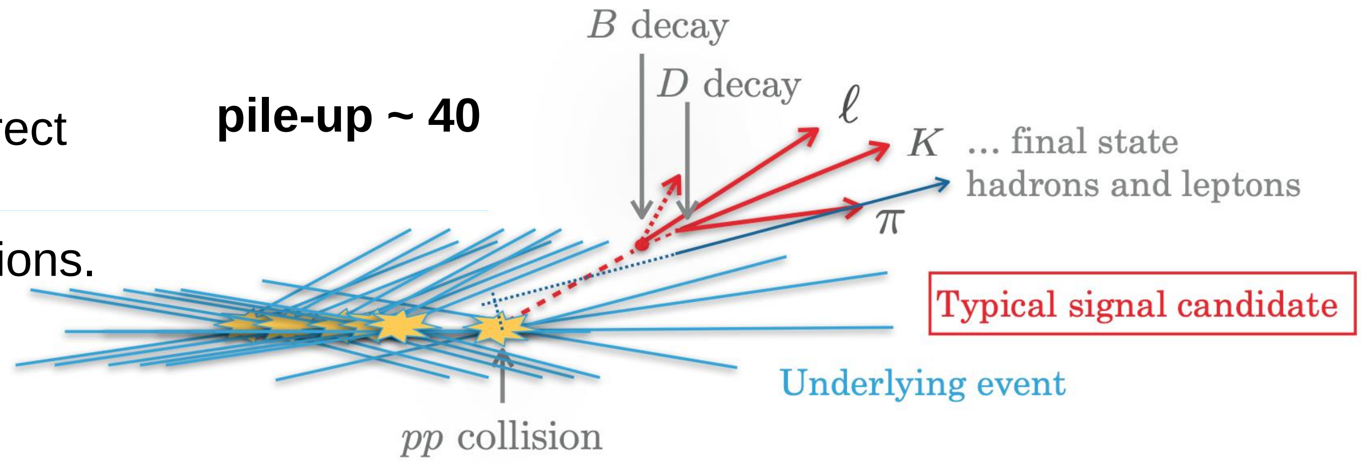
PicoCal (ECAL)
- Timing, longitudinal segmentation
- SPACAL with radiation hard crystals
- Keep Shashlik for outer region

4D Vertexing with Precision Timing

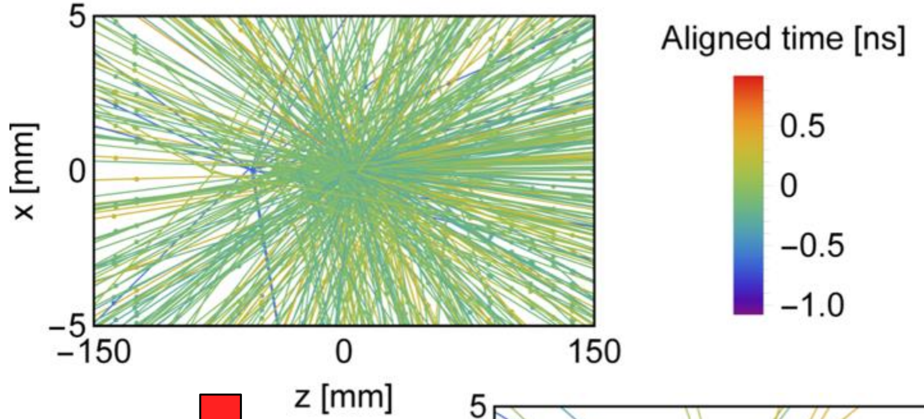
Essential for flavor physics

- Primary vertex (PV) reconstruction, correct association with B decay vertex.
- Decay time and impact parameter solutions.

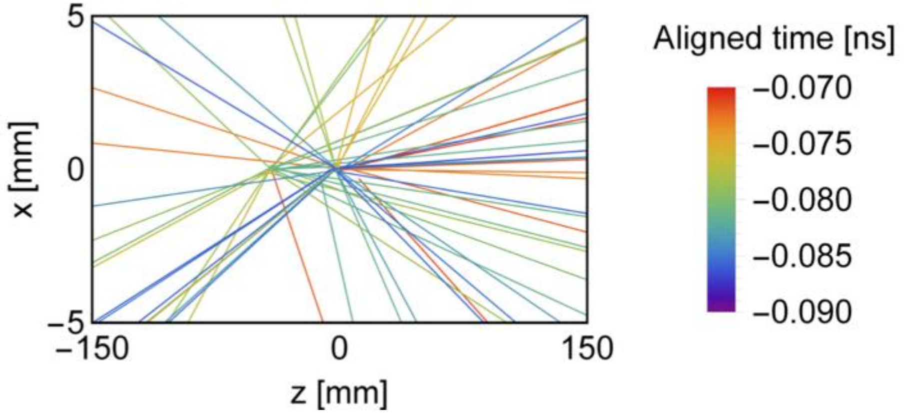
pile-up ~ 40



Track density with ~40 visible interactions

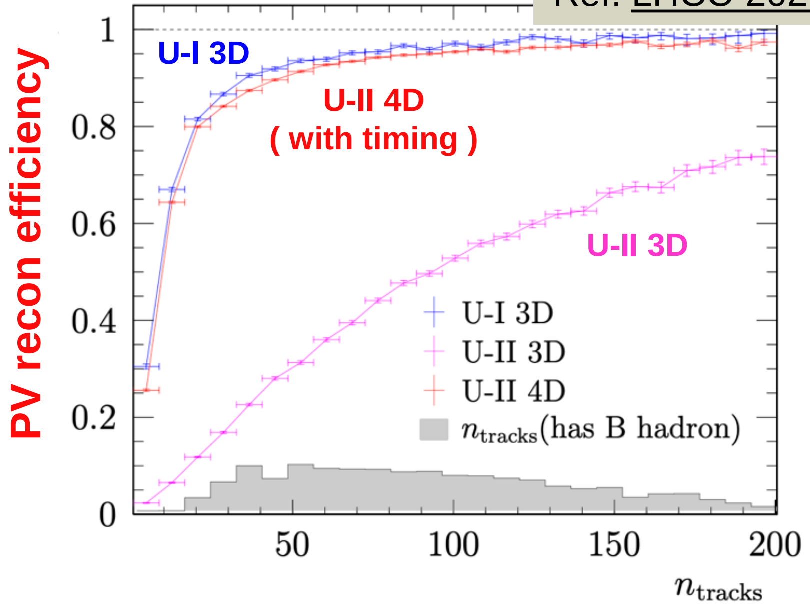


20 ps time window

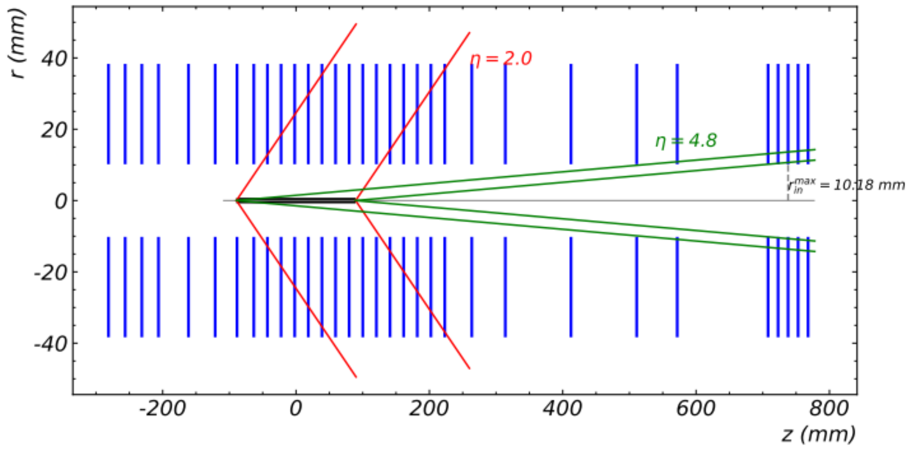


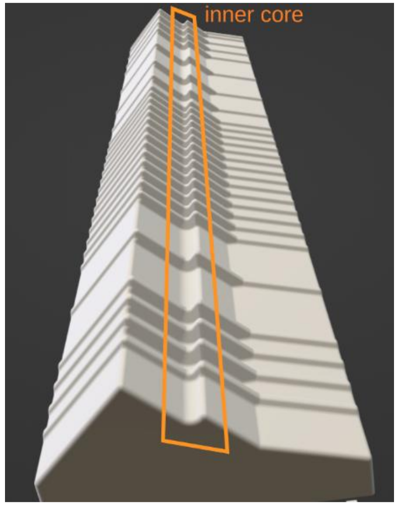
Timing to the rescue: each hit in VELO will be time-stamped with ~50 ps resolution → ~20 ps per track.

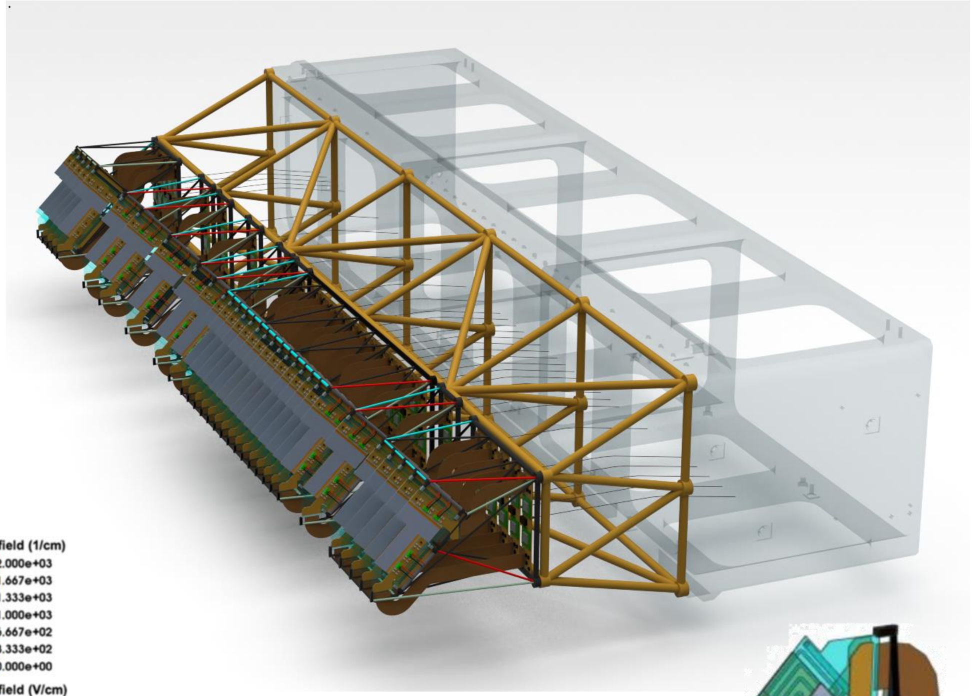
Ref: LHCC-2021-012



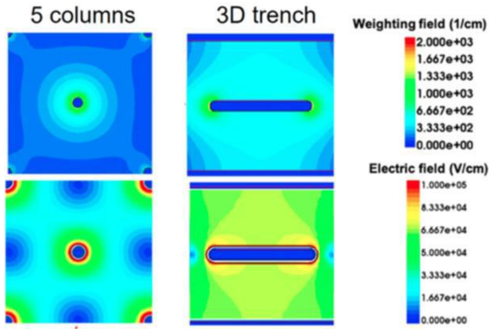
Timing Vertex Detector - TV

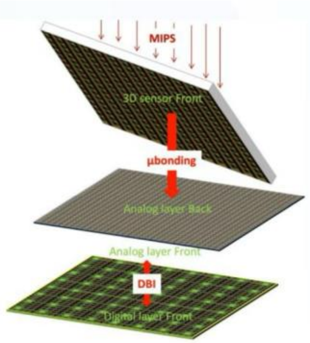


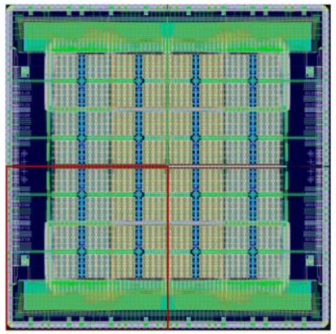


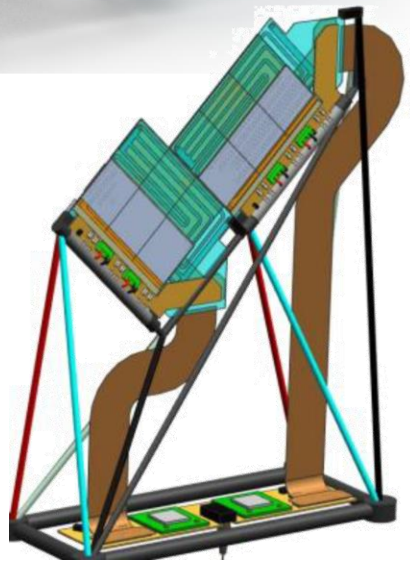


- Baseline: 32 stations
- Sensor 3D sensor
  - Radiation tolerant, max ~ 6×10^{16} n_{eq}/cm^2
  - Trench vs column
- ASIC (28 nm technology)
  - Requirement < 30 ps
  - Picopix (50 μm pixel pitch)
  - Ignite (45 μm pixel pitch), 3D integration
- Module cooling
  - Coolant: CO_2 or Krypton
  - Substrates: silicon, ceramics, Metal 3D printing
- RF shield: 50 μm Al + 20 μm Carbon Fiber



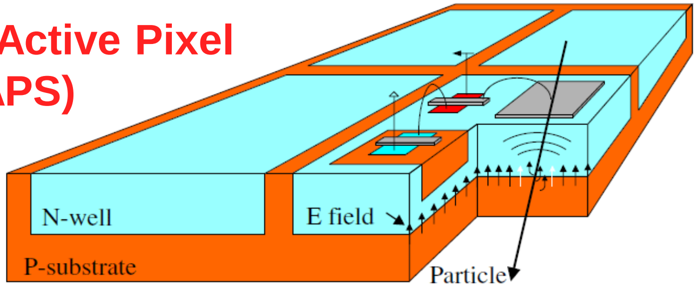




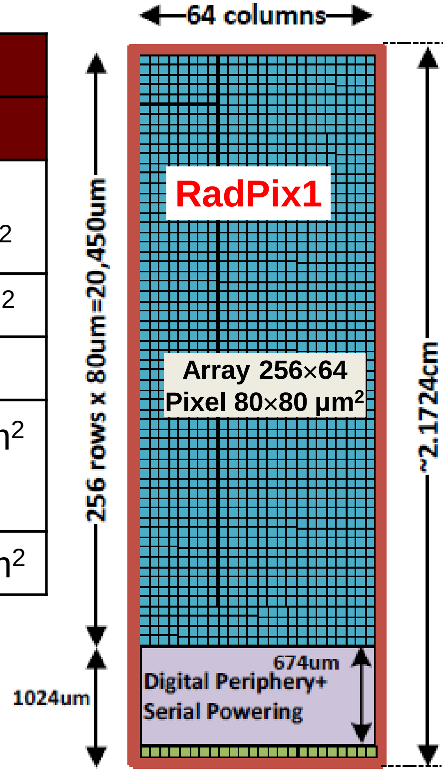


MAPS Technology For Tracker

Monolithic Active Pixel Sensor (MAPS)



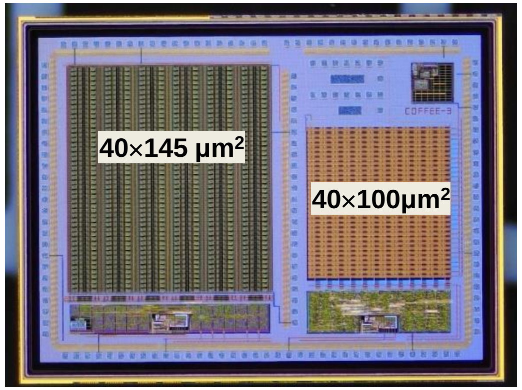
Parameter	Key Specification	
	MT-Pixel	UP
Pixel size, square rectangular	≤ 100×200 μm²	≤ 85×85 μm² ≤ 50×200 μm²
Max hit rate	34 MHz /cm²	150 MHz /cm²
In-time efficiency	> 99% within 25 ns	
Rad-hard (NIEL) (TID)	3×10^{14} n_{eq}/cm^2 40 Mrad	3×10^{15} n_{eq}/cm^2 240 Mrad
Power consumption	≤ 150 mW/cm²	≤ 200 mW/cm²



- MightyPix (AMS 180 nm)
  - MightyPix1 / TSI-180, time resolution 2.93 ns
  - LF-MightyPix uses LF-150 , power ~ 200 mW/cm²
  - MightyPix2 expected to be available by April 2026
- RadPix (LF 180 nm)
  - LFMonoPix, 99% efficiency after $10^{15} n_{eq}/cm^2$
  - RadPix1 to be submitted in Q1 of 2026
- COFFEE (55 nm)
  - COFFEE3 responds to laser and radiation source correctly, digital functions validated
- MANTA (TPSCo 65 nm)
  - Based SPARC for ALICE
  - Available by Q1 of 2027

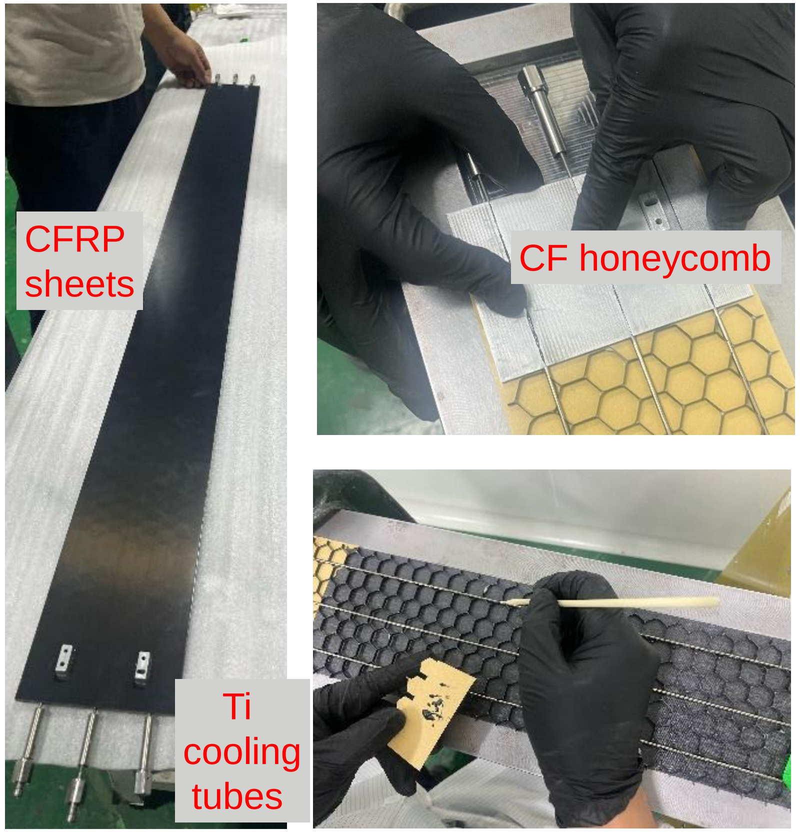
MightyPix2

COFFEE 3



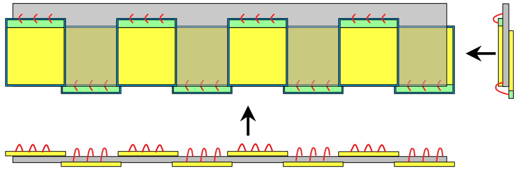
MAPS-based UP Detector

- Four layers based on MAPS, total active area ~7 m^2
- Module and stave designs to be compared and finalized
- Readout electronics at the end of staves
- Prototyping started

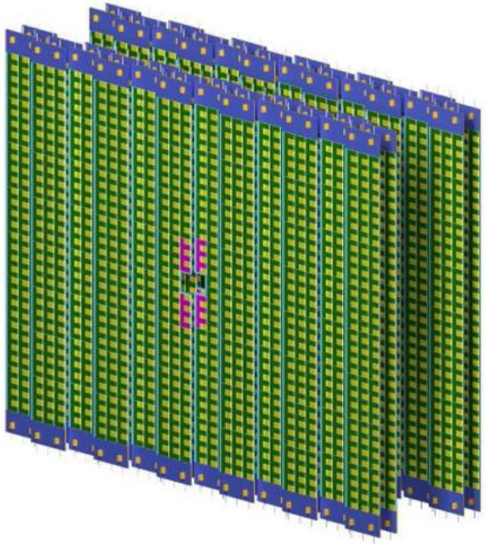


Prototype bare stave

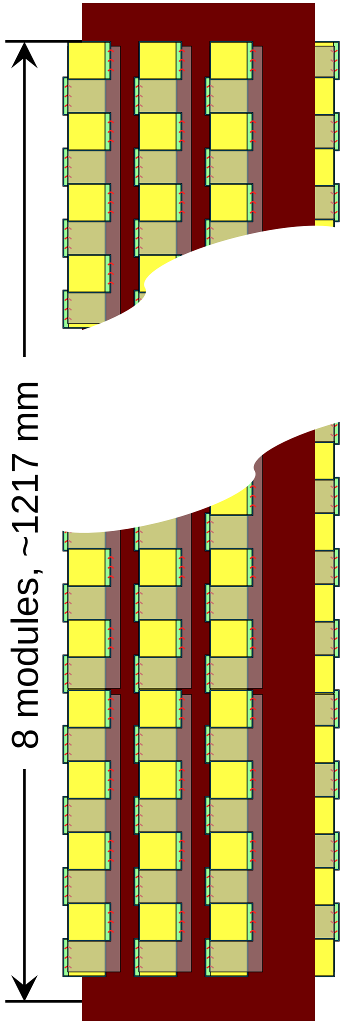
Module

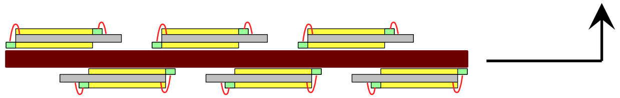


Prototype module



Stave





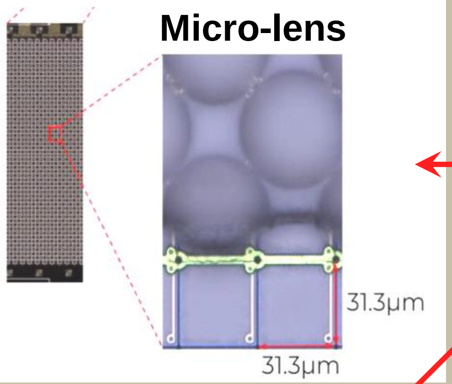
Mighty Tracker of Two Technologies

Keep SciFi design at outer region

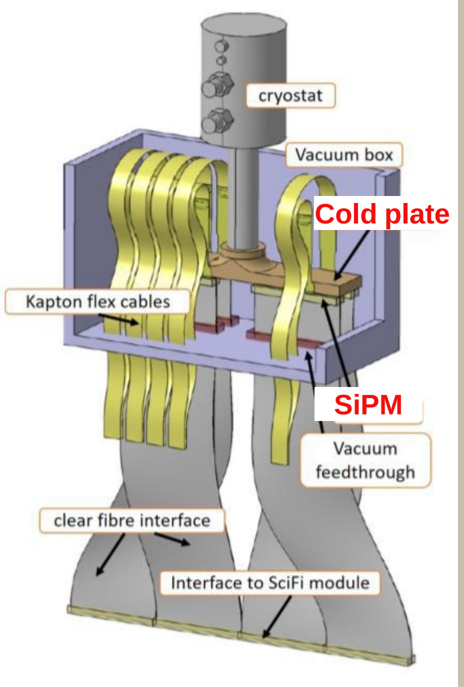
- Further away from beam
- Micro-lens on SiPM to enhance light collection.
- Cryogenic cooling for SiPM: –40°C ⇒ ~100 K

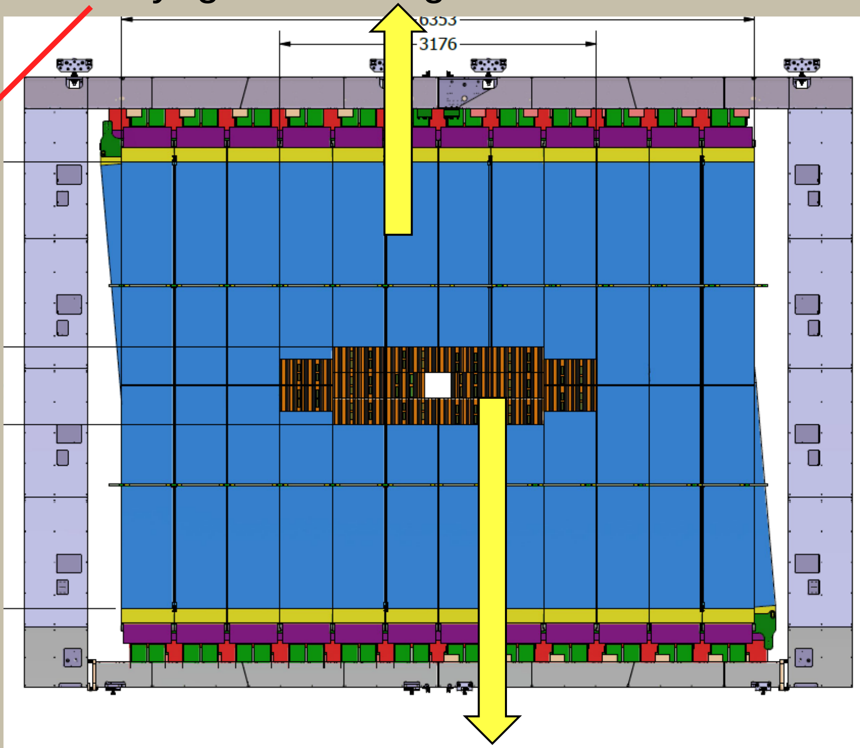
SciFi will be upgraded to Mighty Tracker of MT-SciFi + MT-Pixel

Micro-lens



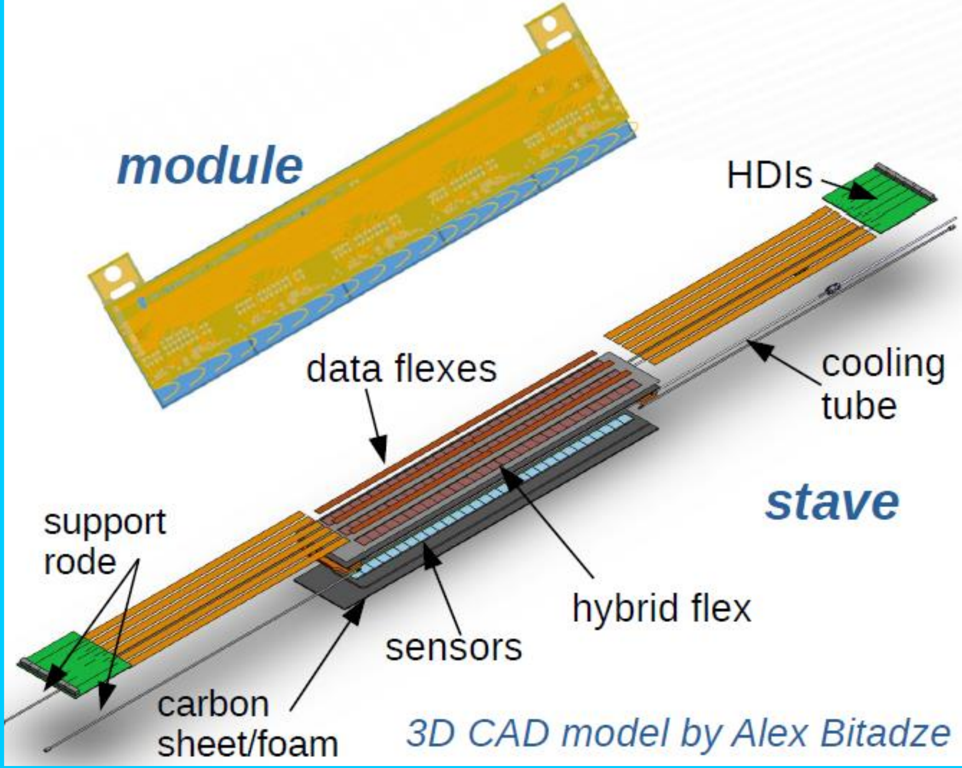
Cryogenic cooling





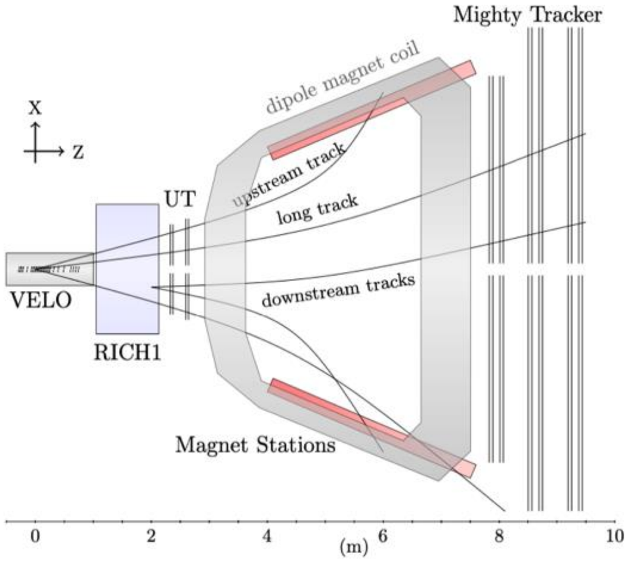
HV-CMOS MAPS detector

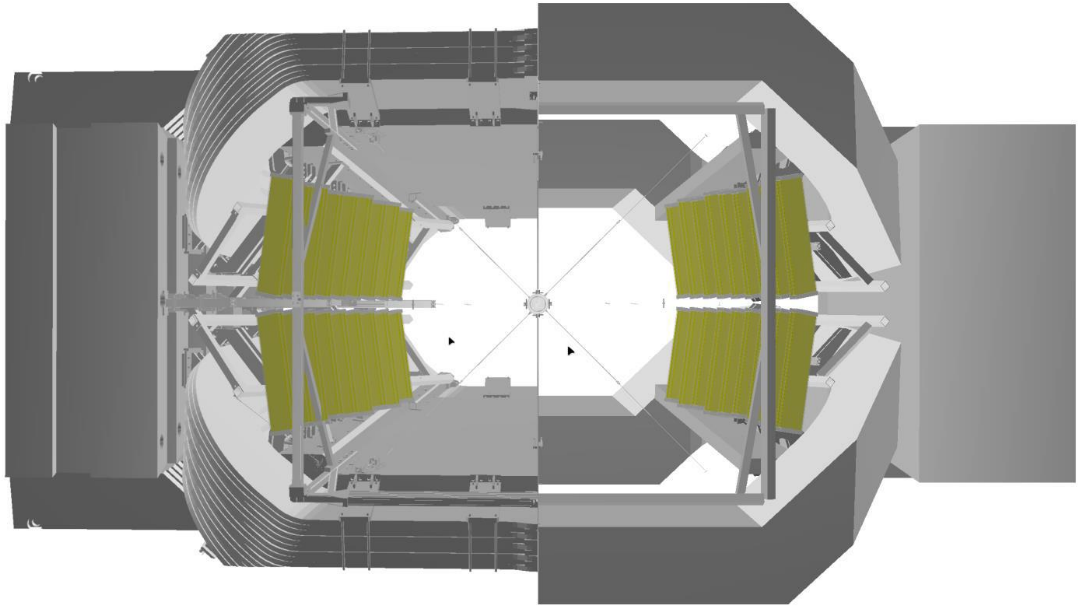
- 6 layers, baseline area ~13 m^2
- Pixel size ~ 84×84 μm^2

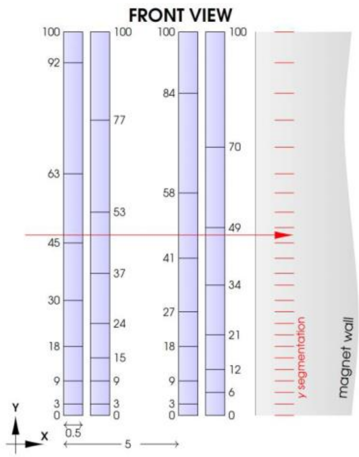


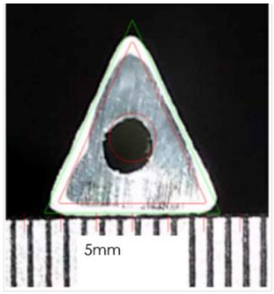
MT-Pixel Module & Stave

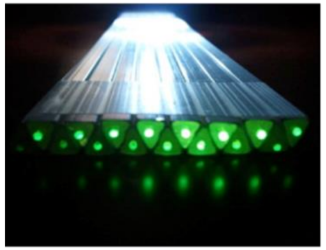
Magnet Stations of PS+SiPM









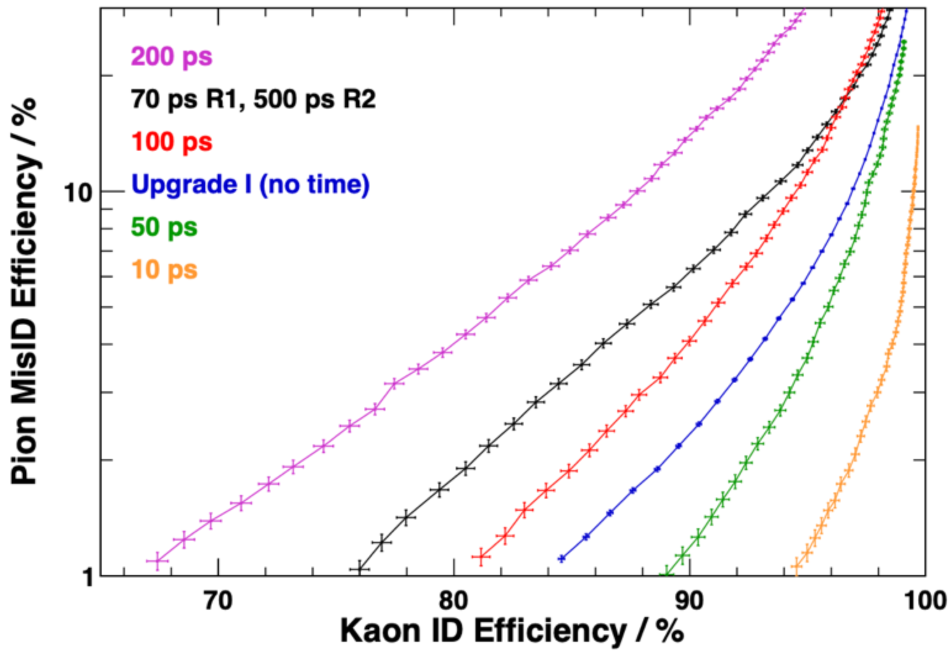


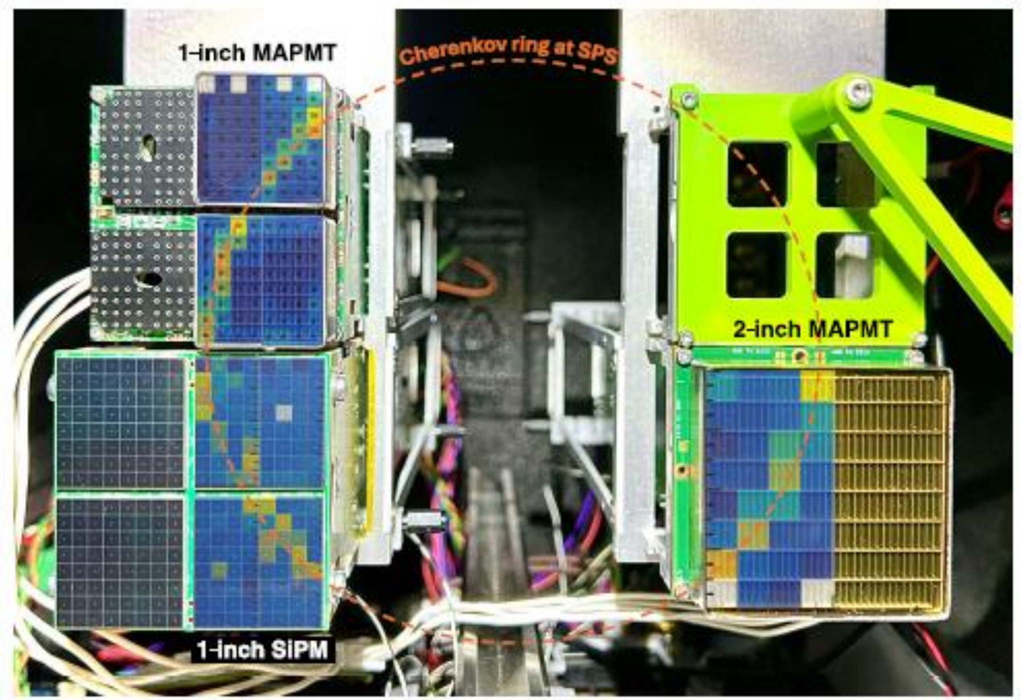
- To enhance the tracking capability, improve track reconstruction, particularly in the outer edges of SciFi acceptance and for low momentum tracks
- Instrument walls of magnet with extruded triangular scintillating bars
- Light collected by WLS, guided through clear fibers to SiPMs outside magnet
- It delivers sub-% momentum measurement precision
- Significantly increase the acceptance of low momentum tracks, e.g. gain a factor of ~2 in prompt D^{*+} with slow π
- The Magnet Stations could be installed at LS3

RICH Detectors With Better Timing

Ref: LHCC-2021-012

- RICH 1 & 2 will maintain same geometry, reduce pixel size using SiPM, MCP, or LAPPD. MAPMT may be backup for low occupancy area
- Time-stamping each photon with high precision, which is crucial to PID performance.
- FastRICH has 25 ps time-stamping and digital output compatible with lpGBT

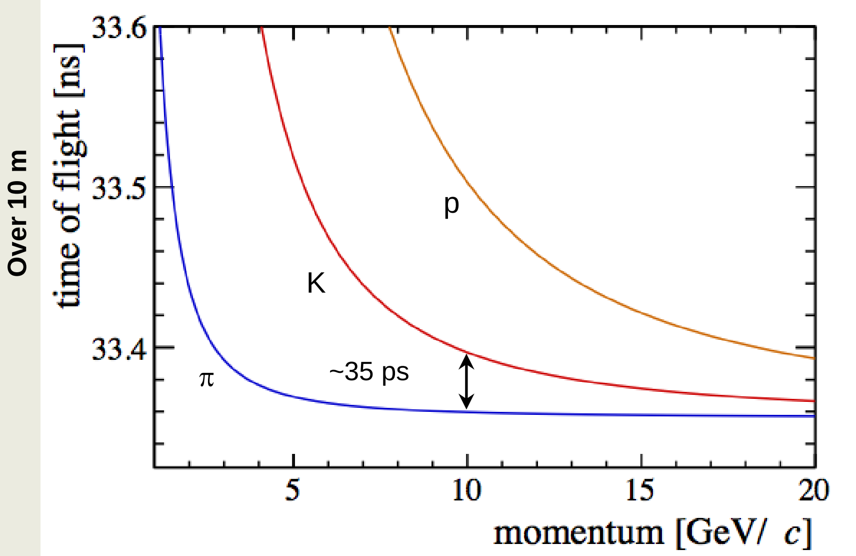




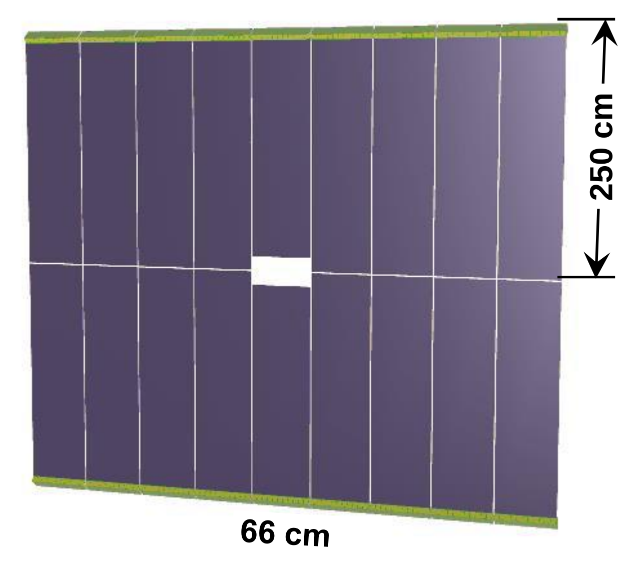
Upgrade	Photon Detector	FE ASIC	Time Resolution	TimeStamp Precision
I	MAPMT	CLARO	~ 150 ps	3.125 ns
I.b*	MAPMT	FastRICH	~ 150 ps	25 ps
II	SiPM, MCP LAPPD	FastRICH	< 100 ps	25 ps

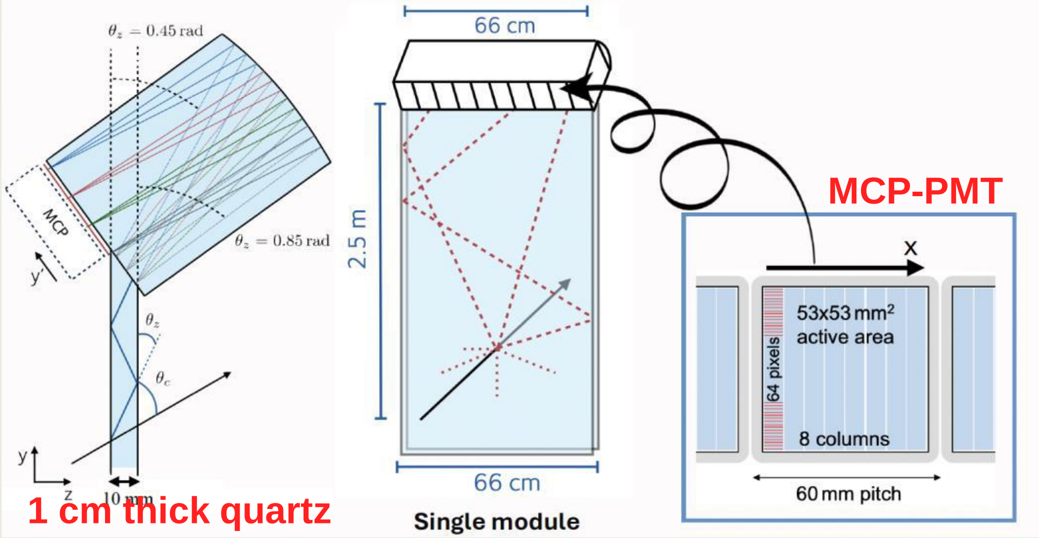
* LS3 consolidation

TORCH Time of Flight Detector

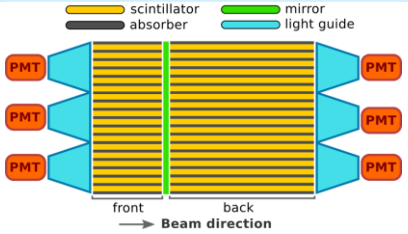


- Brand new detector to enhance low momentum PID capabilities, improve background suppression and flavour tagging.
- Cherenkov photons produced by charged particles traversing quartz plane, then transported by total internal reflection to focusing block and detected with MCP-PMTs
- Measurement of Cherenkov angle, path length, and time of arrival.
- Aim for 10-15 ps resolution/track, needs ~30 photons, 70 ps/photon



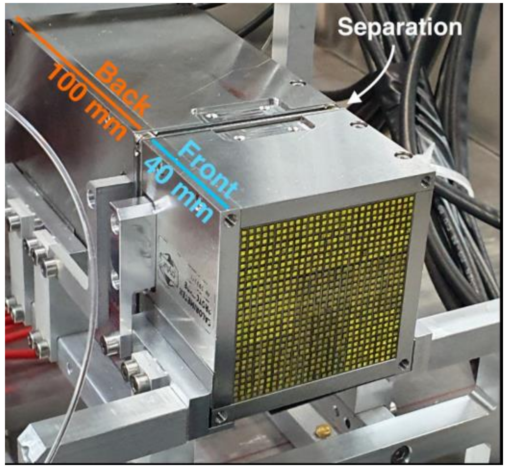


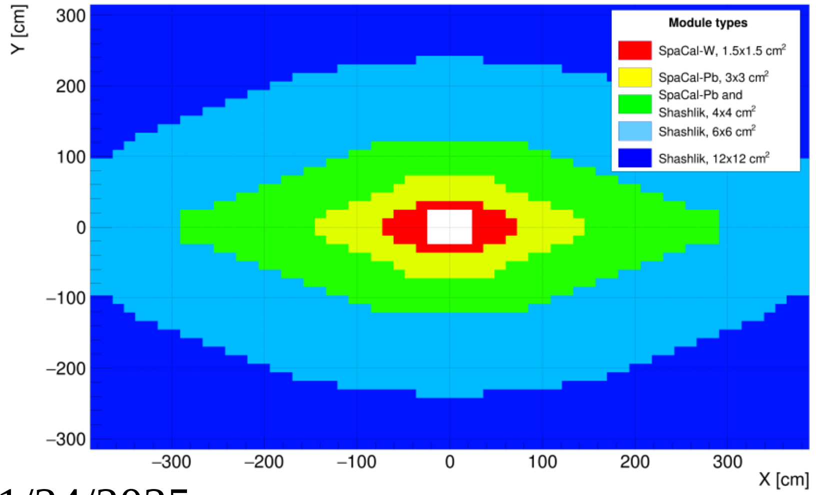
5D Calorimetry with Precision Timing

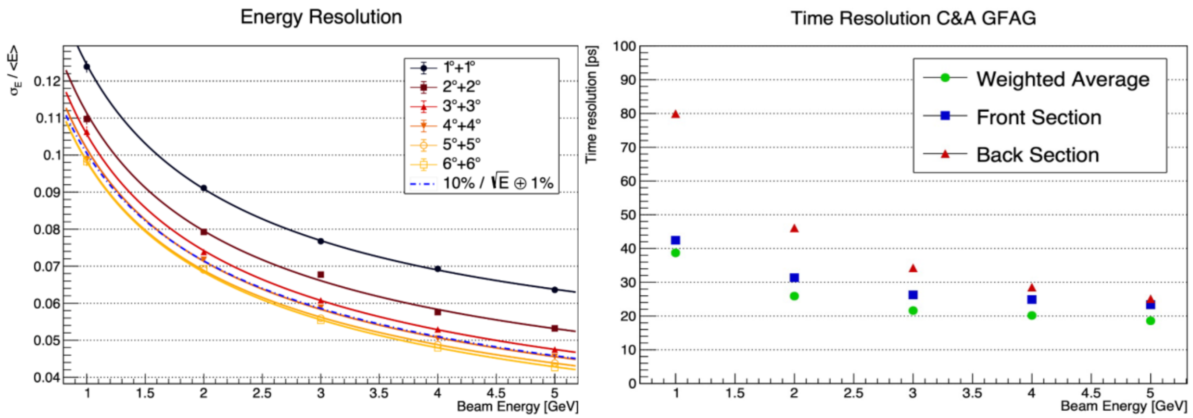


- Improve efficiently the performance at high luminosity
- Re-organize ECAL zones to follow the radiation and occupancy map
- Baseline: combination of technologies for different regions starting from the inner-most,
  - SpaCal W / GAGG fibers
  - SpaCal Pb / Plastic fibers
  - Shashlik / WLS fibers

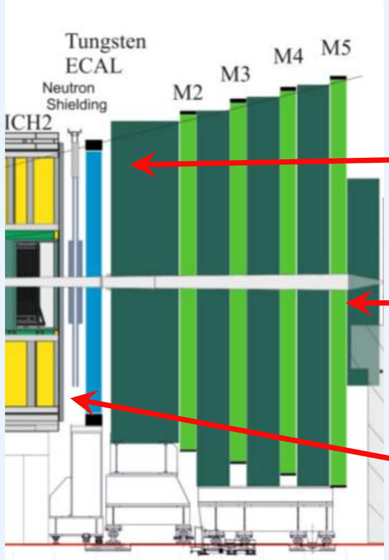
Cell size [cm²]	Module type	Modules	Cells
1.5 × 1.5	SpaCal-W with GAGG fibers	40	5120
3 × 3	SpaCal-Pb with plastic fibers	136	4352
4 × 4	SpaCal-Pb with plastic fibers	272	4896
	Shashlik with WLS fibers	176	3168
6 × 6	Shashlik with WLS fibers	448	3584
	Shashlik with new tiles and WLS fibers	896	7168
12 × 12	Shashlik with WLS fibers	1344	2688
Sum		3312	30976







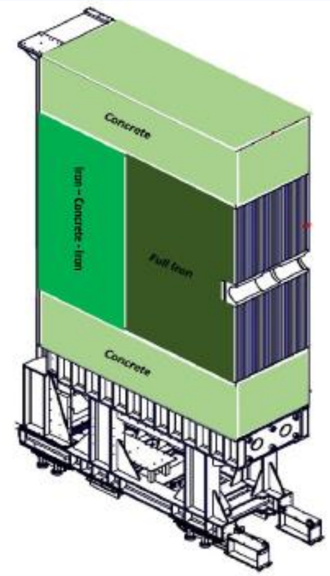
NIMA 1045, 167629 (2022)

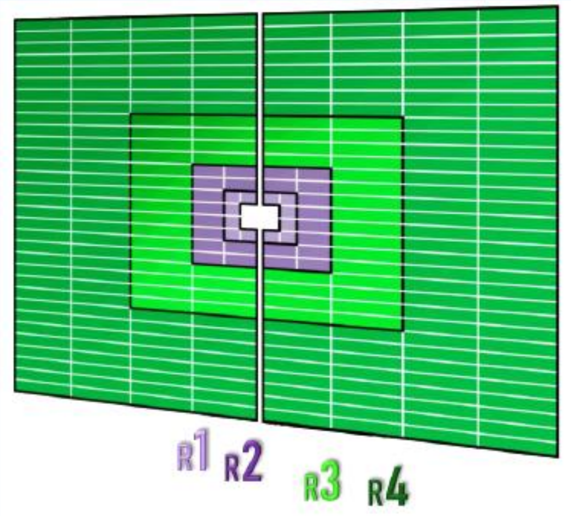


HCAL replace with Iron/concrete shield

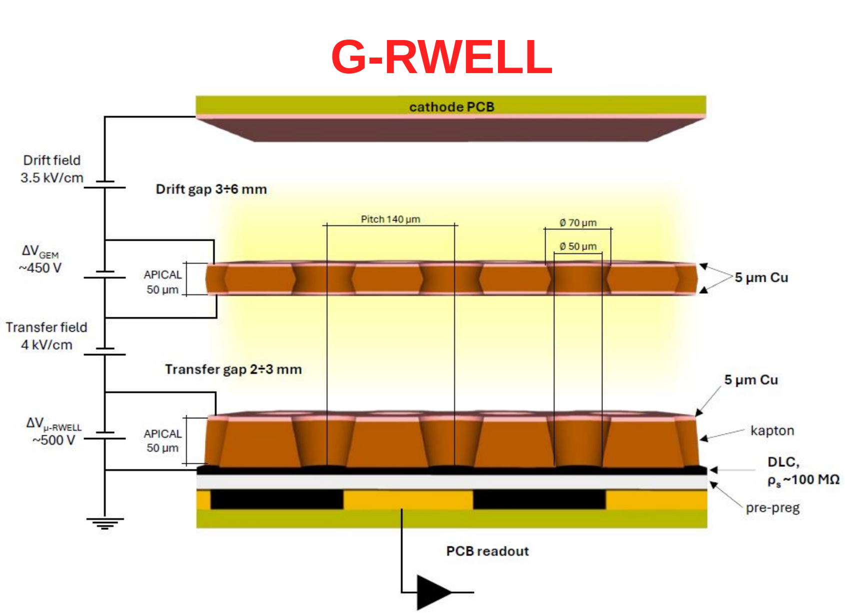
New G-RWELL detector in the Inner region

SPD/PS/M1 already removed in Upgrade I



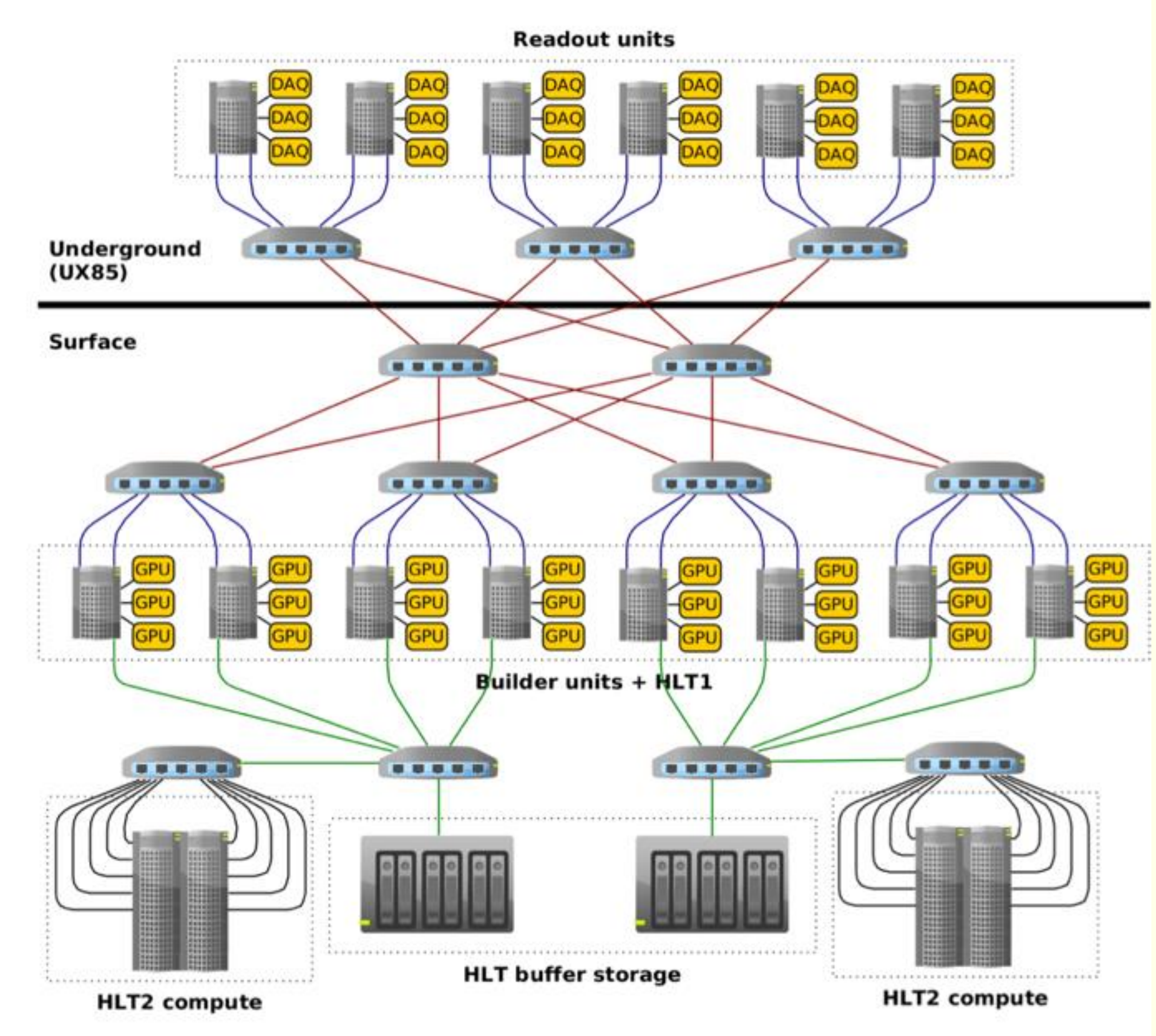


- Novel G-RWELL for the innermost region (R1, R2)
- Reuse existing MWPC in the outer region (R3, R4)
- A new readout scheme in all regions, for background reduction and a new FE electronics
- Additional shielding ($4\lambda_I \rightarrow 10\lambda_I$) will be installed in front of Muon detector



Online and Offline

Event-builder architecture for Upgrade II



- Novel trigger system for Upgrade I
  - Fully software trigger
  - HLT1 based on GPUs, HLT2 on CPUs
- Similar concept planned for Upgrade II
  - Expected data throughput for real time analysis is ~ 200 Tb/s, (~ ×5 ATLAS or CMS after L0 at Upgrade II).
  - Further exploitation of hybrid architectures: CPU, GPU, FPGA…
- Offline computing requirements are significant
  - Upgrade I model not sustainable
  - Issues in Run 5 are similar to ATLAS & CMS Upgrade II of Run 4
  - Coordination with WLCG and the HEP Software Foundation on mitigation

Information of Detector Upgrade

Detector	Original	Upgrade I	Upgrade II / I-b
VELO (VP, TV)	R-Φ SSD (40-100 μm), Beetle	SPD (55×55 μm2), VeloPix	3D-SPD, <30 ps
TT (UT, UP)	SSD (183 μm), Beetle	SSD(93.5/187.5 μm), SALT	MAPS
Magnet Station	-	-	Triangular scintillating bar (~5 mm), WLS, SiPM, PACIFIC
T-stations (SciFi, MT)	Straw tube (ϕ5mm), SSD(198 um), Beetle	SciFi (ϕ250um) / SiPM / PACIFIC	SciFi (ϕ250um) / SiPM / PACIFIC DMAPS
RICH1	Aerogel+C4F10 / HPD	New optics, no aerogel; MAPMT / CLARA σ~150ps, 25ns/8 stamp	MAPMT, FastRICH σ~150 ps, 25 ps stamp (I.b)
RICH2	CF4 / HPD		SiPM / MCP / LAPPD, FastRICH σ<100 ps, 25 ps stamp
TORCH	-	-	Quartz, MCP(8x64), 70 ps / photon
SPD/PS	Scint pad / WLS / PMT, Pb	Removed	-
ECAL	Pb + PS / WLS / PMT	Reduce gain, new electronics	GAGG+W, PS+Pb, Shashlik-MCP
HCAL	Fe + PS / WLS / PMT	Reduce gain, new electronics	Iron-concrete shielding
MUON	Triple-GEM @central M1, Rest MWPC	Remove M1, new electronics, more shielding	G-RWELL in inner regions Keep MWPC in outer regions

Scoping Scenarios

- Baseline cost ~ 182 MCHF
- Middle scenario ~14% reduction
- Low scenario further ~20% reduction

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
	VELO	
32 stations, $\eta < 4.8$	32 stations, $\eta < 4.8$	28 stations, $\eta < 4.7$
module 0.8% X_0	module 0.8% X_0	module 1.6% X_0
RF foil 75 µm	RF foil 75 µm	RF foil 150 µm
	UP	
4 planes pixel $\times 1.7\,\mathrm{m}^2$	as baseline	remove corners
	Magnet Stations	
4 panels fibres $\times 3.5\,\mathrm{m}^2$	as baseline	remove
	Mighty-Pixel	
6 planes pixel $\times 2.1\,\mathrm{m}^2$	6 planes pixel $\times 1.3\,\mathrm{m}^2$	6 planes pixel $\times 1.3\,\mathrm{m}^2$
	Mighty-SciFi	
12 planes fibres	12 planes fibres	12 planes fibres
$25.9\,\mathrm{m}^2$/plane	shorter, $23.7\,\mathrm{m}^2$/plane	narrower, $18.9\,\mathrm{m}^2$/plane

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
	RICH1/2	
inner:outer $\frac{1}{3}$:$\frac{2}{3}$	inner:outer $\frac{1}{4}$:$\frac{3}{4}$	inner:outer $\frac{1}{4}$:$\frac{3}{4}$
inner 1.4 mm SiPM	inner 2.0 mm SiPM	inner 2.0 mm SiPM
outer 2.8 mm SiPM	outer 2.8 mm SiPM	outer 2.8 mm MaPMT
new optics	new optics	new optics (RICH1 only)
750,000 channels	469,000 channels	445,000 channels
	TORCH	
18 quartz bars	12 quartz bars	removed
225,000 channels	158,000 channels	—
	PicoCal	
40 SpaCal-W	40 SpaCal-W	40 SpaCal-W
408 SpaCal-Pb	408 SpaCal-Pb	408 SpaCal-Pb
2864 Shashlik	2864 Shashlik	2864 Shashlik
double R/O	double R/O	single R/O except 176 inner
30,976 channels	30,976 channels	20,224 channels
	Muon	
µ-RWELL in R1/R2	µ-RWELL in R1/R2	µ-RWELL in R1/R2
96/192 new MWPC in R3	keep old MWPC in R3	keep old MWPC in R3
keep old MWPC in R4	keep old MWPC in R4	keep old MWPC in R4
additional shielding	keep HCAL	keep HCAL
718,848 channels	608,256 channels	608,256 channels

Summary

- LHCb plans Upgrade II to fully exploit HL-LHC for flavor physics and beyond
- The framework TDR was approved. The scoping document is being reviewed
- The TDRs are expected by the end of 2026
- The upgrade entered the R&D phase, leading towards construction, installation and eventually operation for physics
- The upgrade is ambitious with innovative technologies that may apply to future colliders
- New groups have been attracted. More collaborators are welcome

Thank you for your attention!