Flavor Physics at The HL-LHC
LHCb Upgrade II

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For The LHCb Collaboration

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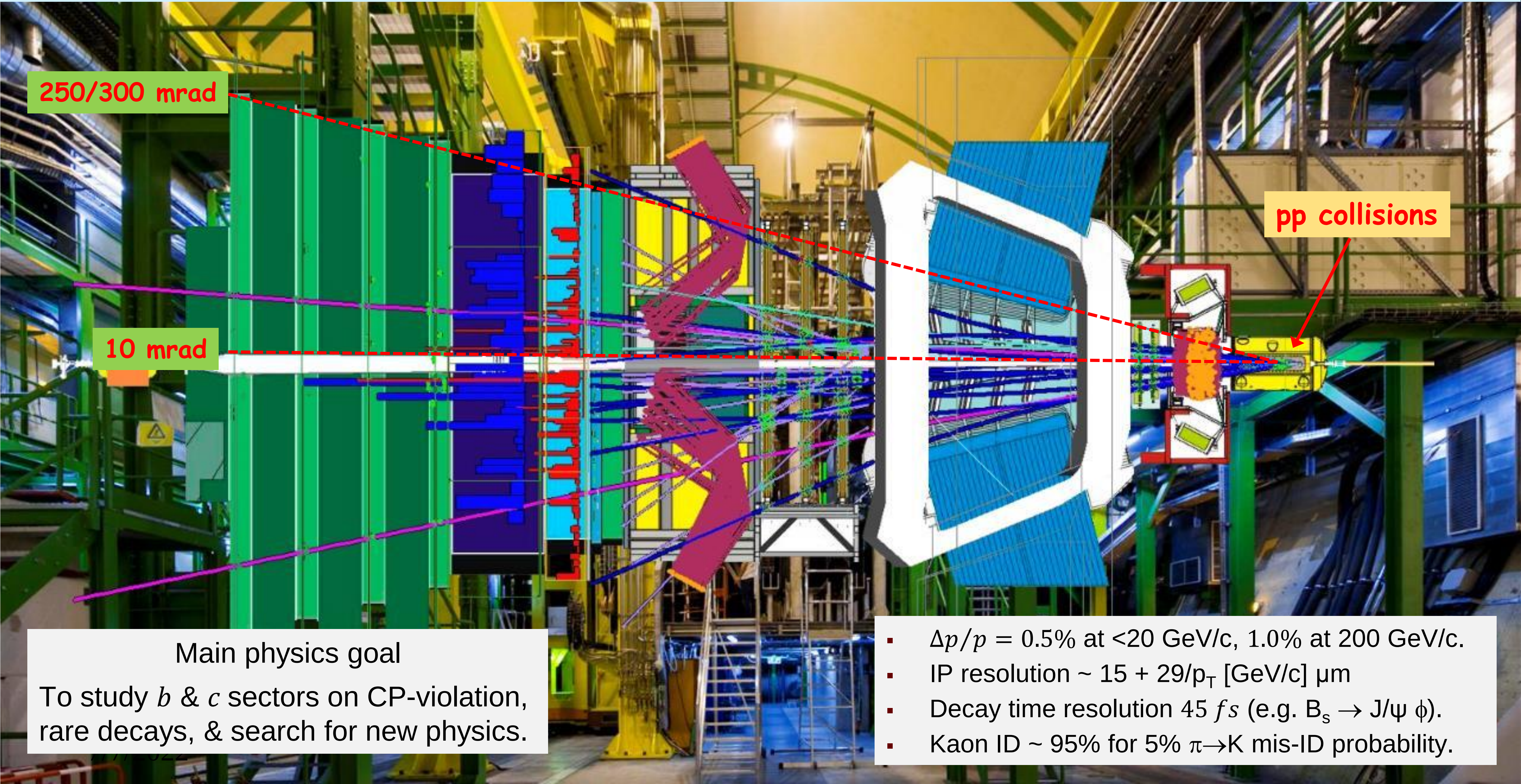
LHCb – A Forward Spectrometer @ LHC



Main physics goal

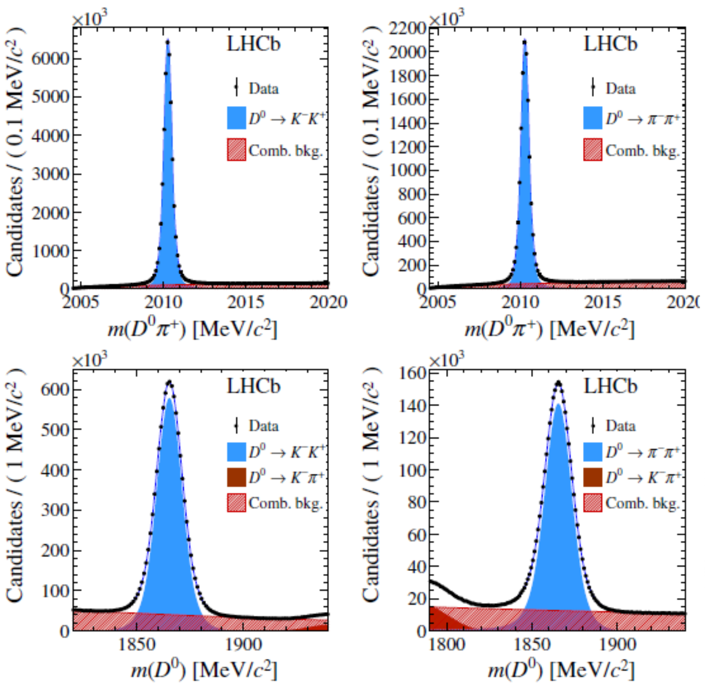
To study b & c sectors on CP-violation, rare decays, & search for new physics.

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

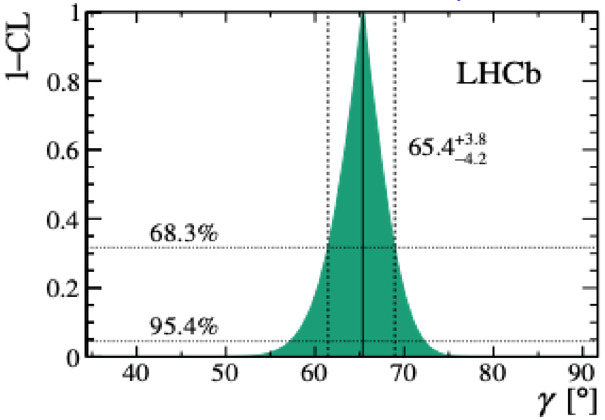
LHCb Performance During Runs 1 & 2

Selected precision measurements

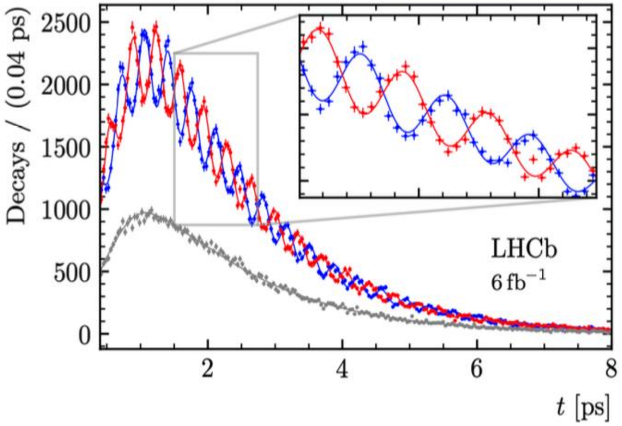
CPV in Charm decays



CKM angle γ

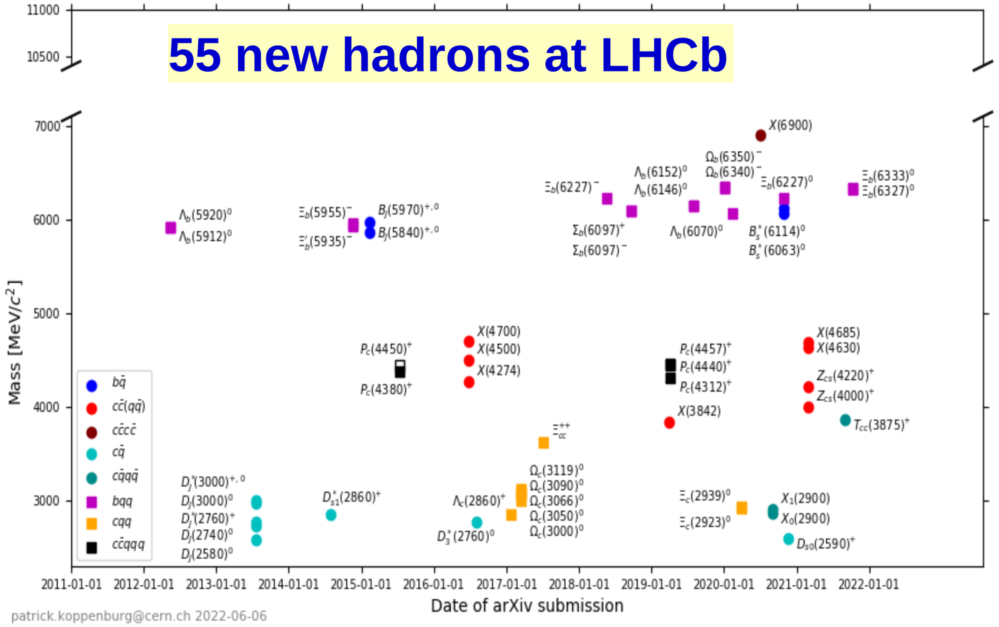


Δm_s



- Phys. Rev. Lett. 122 (2019) 211803
- JHEP 12 (2021) 141
- Nature Physics 18, (2022) 1-5

LHCb accumulated 9 fb^{-1} data during LHC Runs 1 & 2, and contributed a series of discoveries and precision measurements

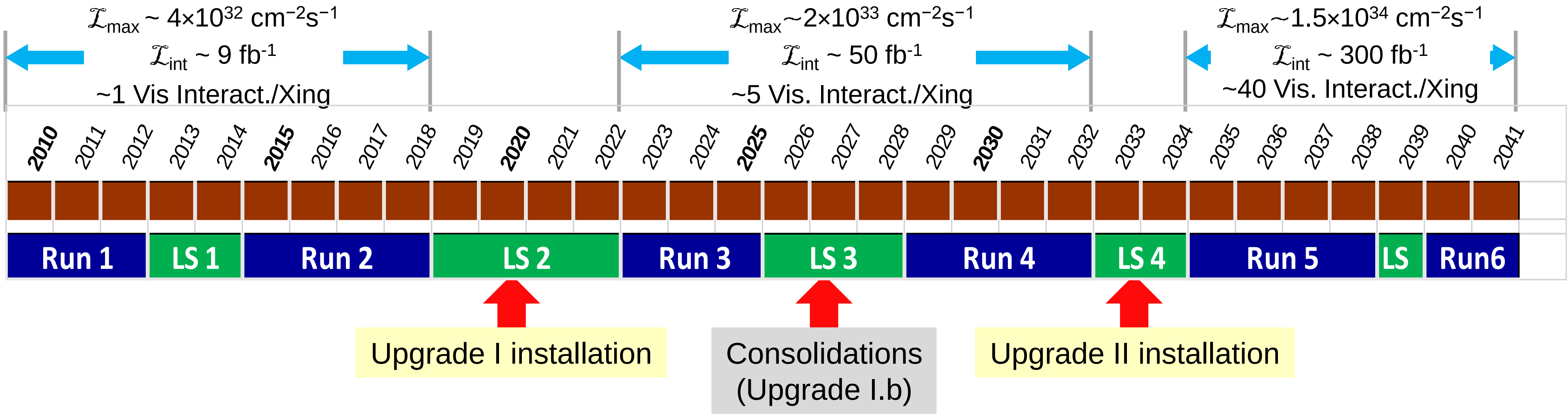


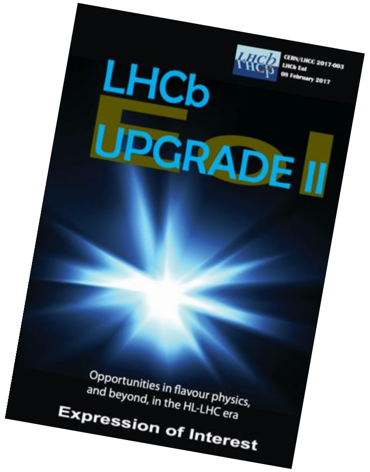
+ 4 new exotic states announced on Jul 5, 2022:

$P^{\Lambda}_{\psi s}(4338), T^{a}_{c\bar{s}0}\ (2900)^{++/0}, X(3960)$

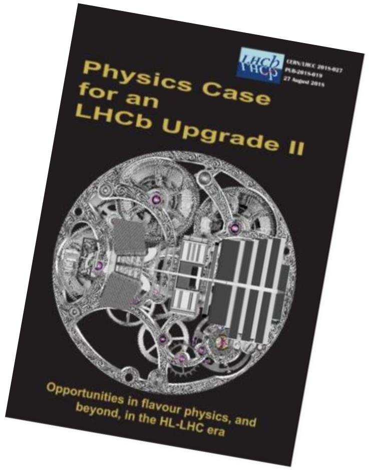
https://indico.cern.ch/event/1176505/

Towards Upgrade II

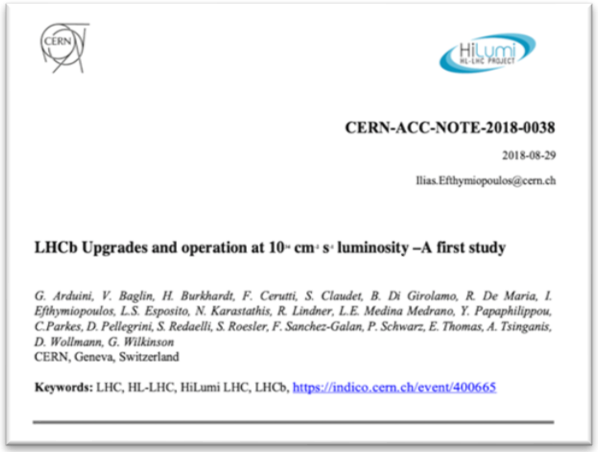




Expression of Interest
LHCC-2017-003



Physics Case
LHCC-2018-027



CERN-ACC-NOTE-2018-0038

2018-08-29

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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

Accelerator Study
CERN-ACC-2018-038

Framework TDR
LHCC-2021-012

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.*)	$4°$	[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
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_S^0\pi^+\pi^-$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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

(Ref: LHCC-2021-012 and references therein

Upgrade II will fully realize the flavor physics potential of the HL-LHC.

Further pursue a broad physics programme (spectroscopy, high precision EW and Higgs, dark sector and other exotic search, heavy ions and fixed target).

Success of the physics programme relies on

- HL-LHC providing LHCb ~50 fb^{-1}/year during Runs 5 and 6.
- A detector with similar or better performance as the present one for Run 3.

Detector Challenge in Upgrade II

$\mathcal{L}_{max}$~1.5×10^{34} cm^{-2}s^{-1}

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

~40 visible interactions/Xing

Improve granularity

Better radiation hardness

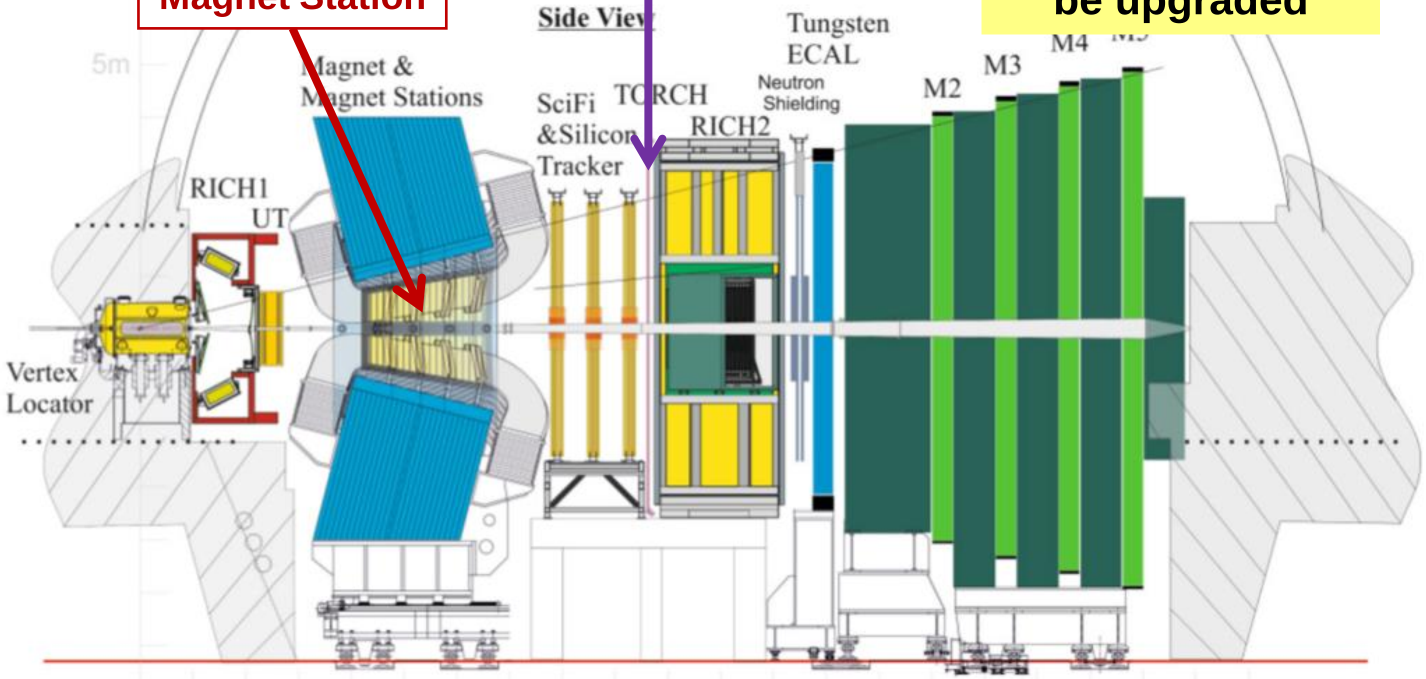
Use timing to distinguish vertices (high-pileup)

+ Better coverage for low momentum tracking

Add Magnet Station

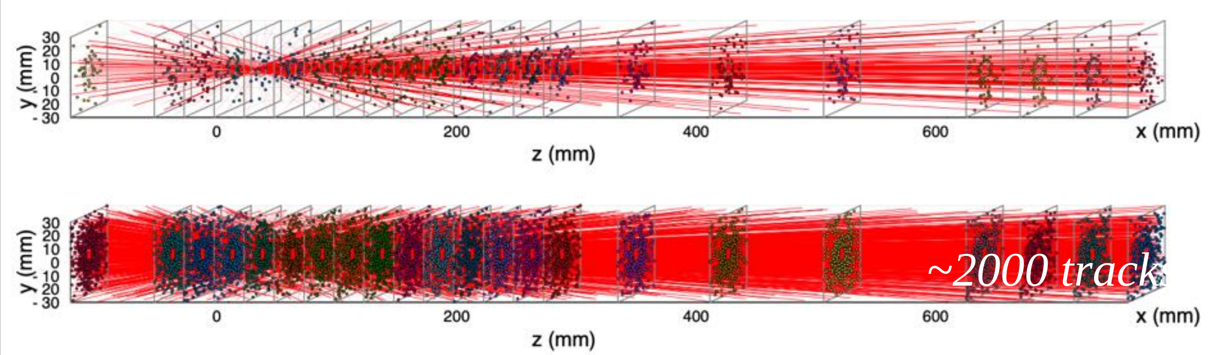
Add TORCH

All detectors will be upgraded



Run 3: pile-up ~5

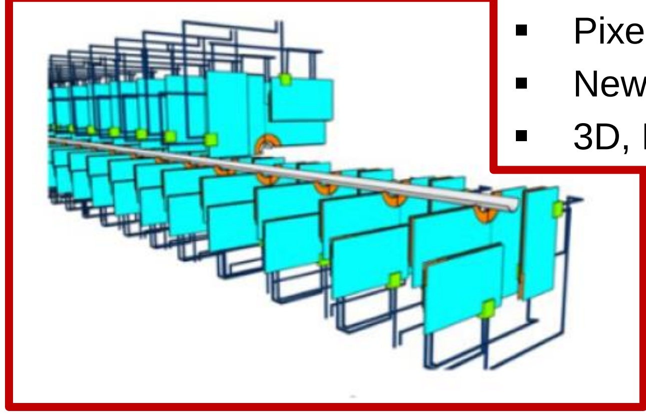
Upgrade II: pile-up ~40



In VELO

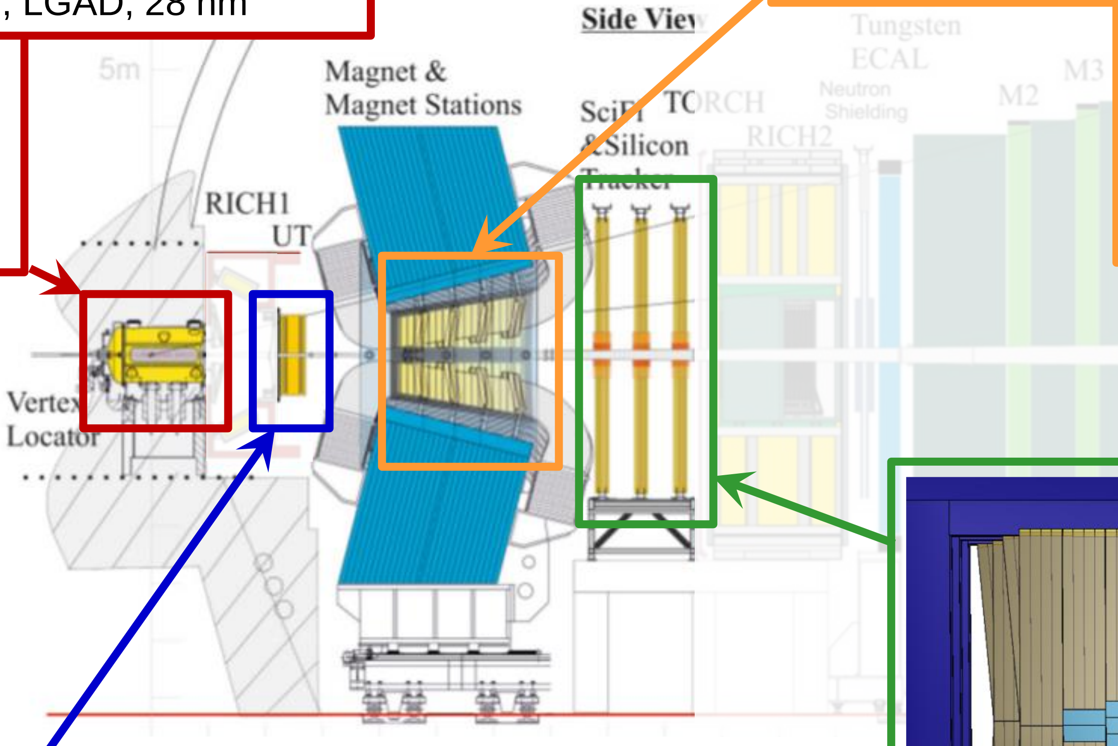
~6 cm

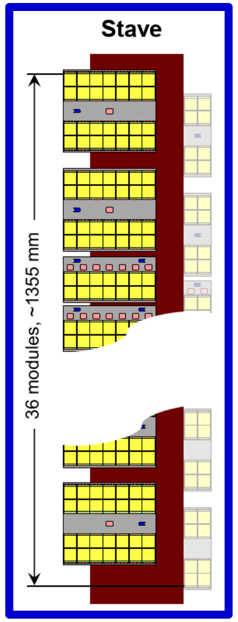
The Tracking System



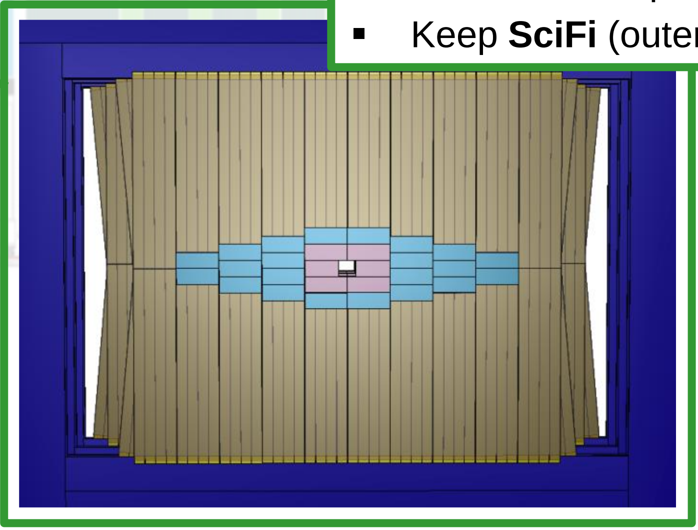
Vertex Locator (VELO)
- Pixel with timing
- New RF-foil
- 3D, LGAD, 28 nm

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





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



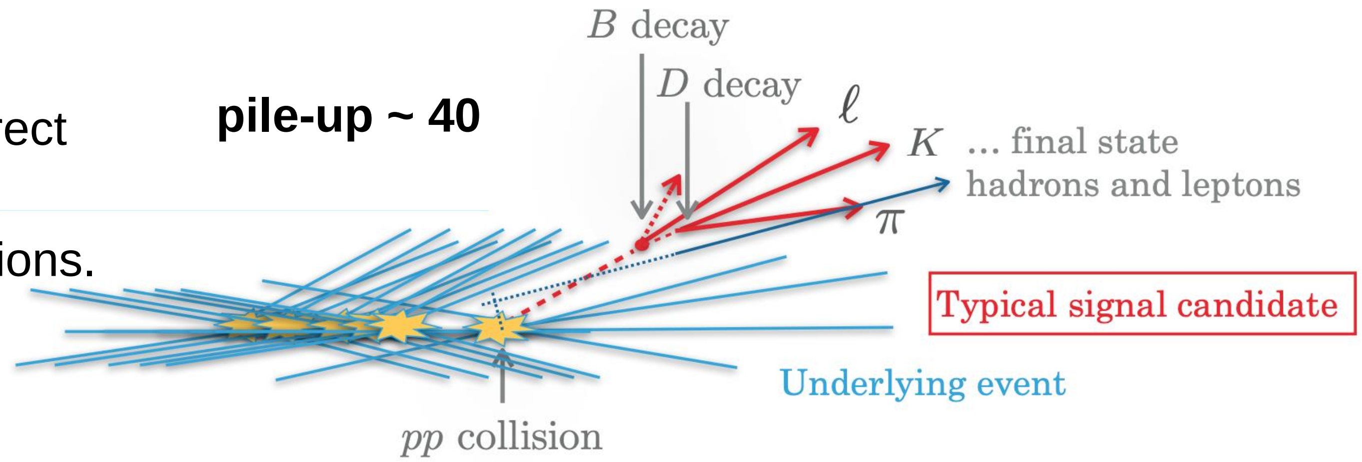
Upstream Tracker (UT)
- MAPS CMOS pixel
- Radiation tolerant

4D Vertexing with Precision Timing

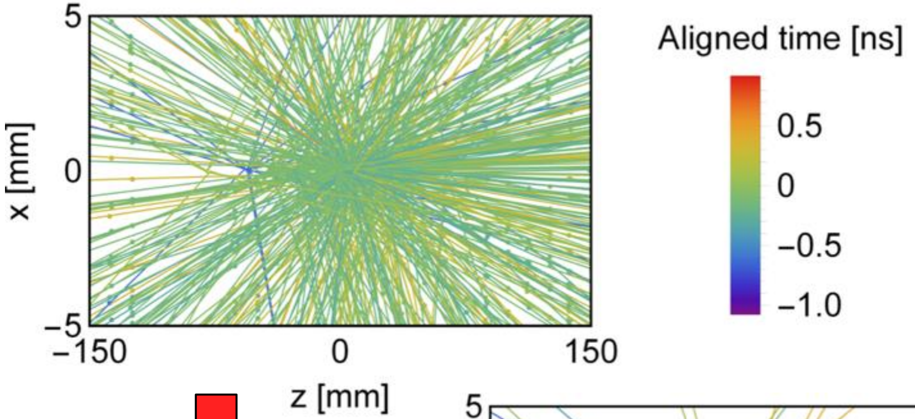
Essential for flavor physics

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

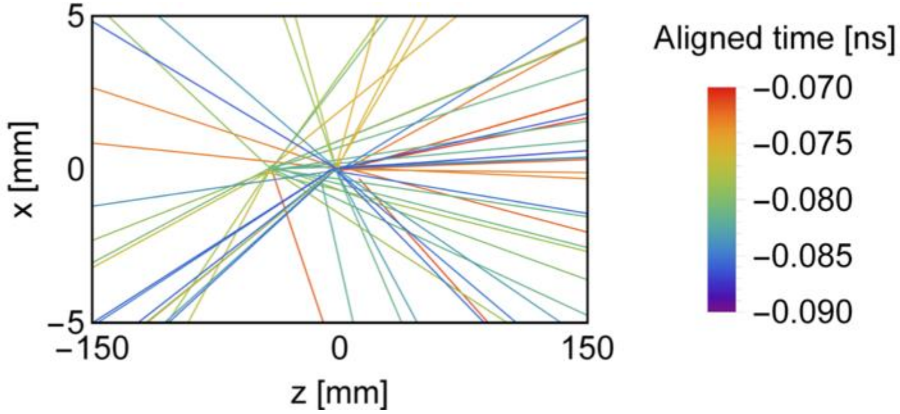
pile-up ~ 40



Track density with ~40 visible interactions

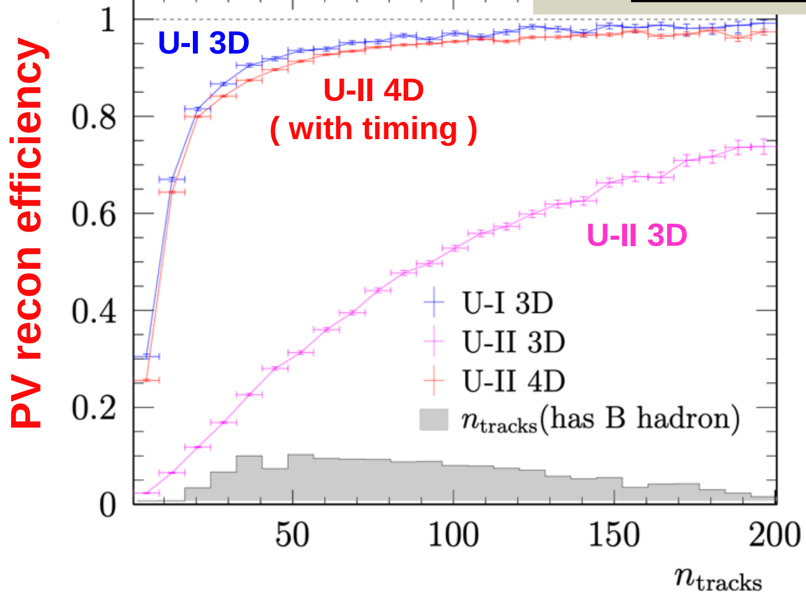


20 ps time window



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

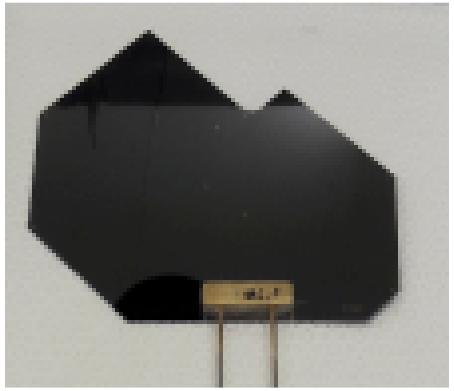
Ref: LHCC-2021-012



VELO Upgrade II

- VELO Sensor R&D targets on timing (~50 ps), radiation hardness (max $\sim 6 \times 10^{16} n_{eq}/cm^2$), and could incorporate thin planar, LGAD, 3D or new concepts.
- Candidates of 28 nm technology ASICs: VeloPix2 from TimePix4 (Picopix as a small demonstrator chip being developed), Timespot, …
- R&D on lightweight partially replaceable modules, thinner or no RF foil, robust 3D printed Titanium cooling substrate, …

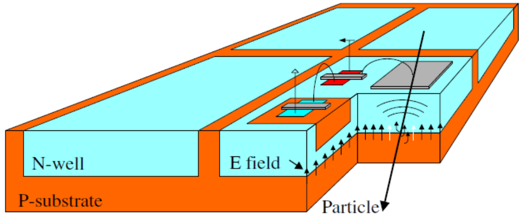
	VeloPix (2016)	Timepix4 (2019)	Picopix++/4DPix ??
Technology	130 nm	65 nm	28 nm
Pixel Size	55 x 55 μm	55 x 55 μm	42/55 x 42/55 μm
Pixel arrangement	3-side buttable 256 x 256	4-side buttable 512 x 448	4-side buttable 256 x 256
Sensitive area	1.98 cm²	6.94 cm²	1.98 cm²
Event Packet	24 bit	64-bit	32-bit
Max rate	~400 Mhits/cm²/s	178.8 Mhits/cm²/s	~ ~4000 Mhits/cm²/s
TDC bin width	25 ns	$\boxed{\text{~200ps}}$ →	~ ~30 ps
Readout bandwidth	19.2 Gb/s	≤81.92 Gb/s	~ ~250 Gb/s



Microchannel Si substrate for bi-phase CO_2 cooling in Upgrade I

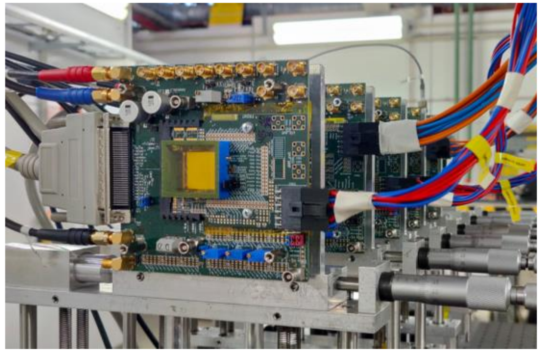
3D printed Ti substrate already prototyped

MAPS Technology For UT & MT-CMOS



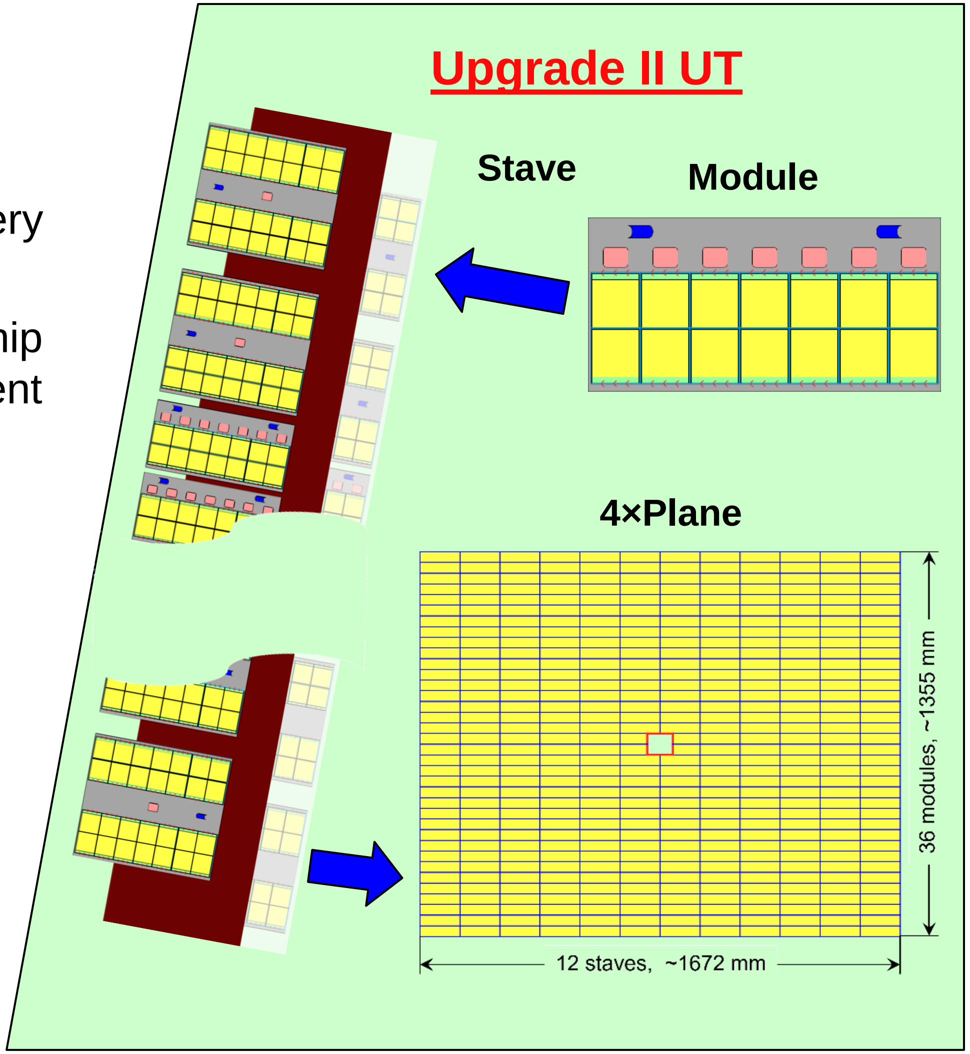
Monolithic Active Pixel Sensor (MAPS)

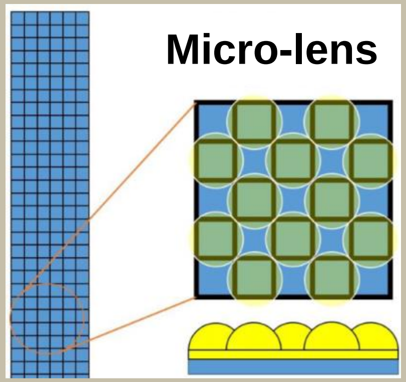
- UT & MT-CMOS both use the MAPS technology, which is very promising and cost effective for large area pixel detectors.
- It is advantageous for the two to use exactly the same chip design. However, small variations are possible due to different data rates, rad-hardness requirement, ...
- Very active design and test work towards the final chips.

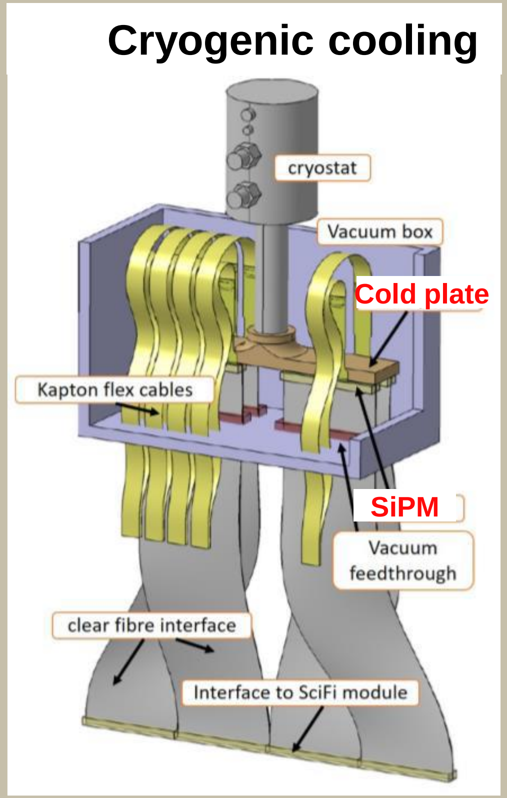


MightyPix1 tested in a beam at DESY

Malta2 bench test at Saclay



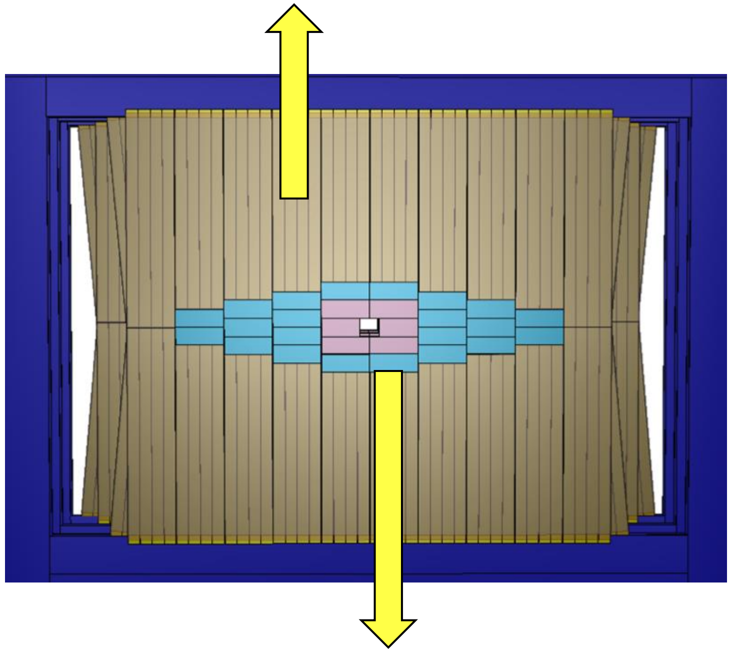


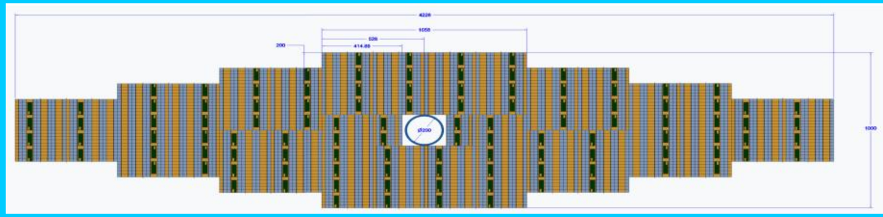


Keep SciFi design at outer region

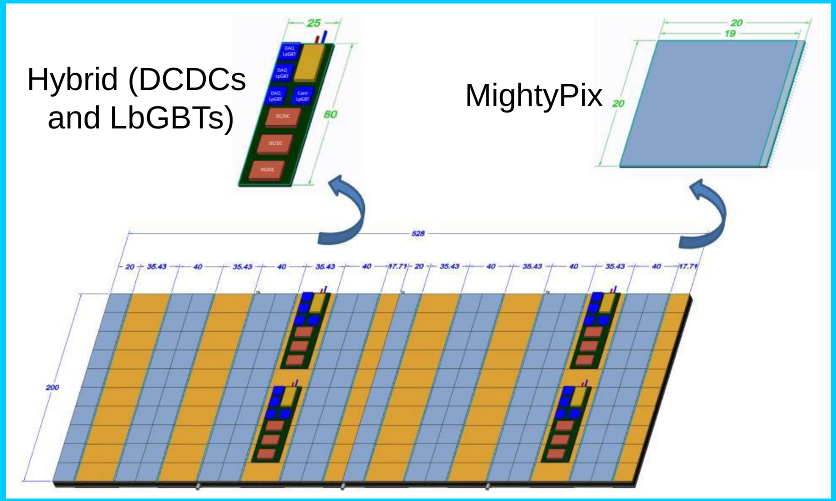
- Further away from beam
- Micro-lens on SiPM to enhance light collection.
- Cryogenic cooling for SiPM: -40°C ⇒ -120°C

SciFi operatiing at Run3
is upgraded to
MT-SciFi + MT-CMOS





MT-CMOS Plane

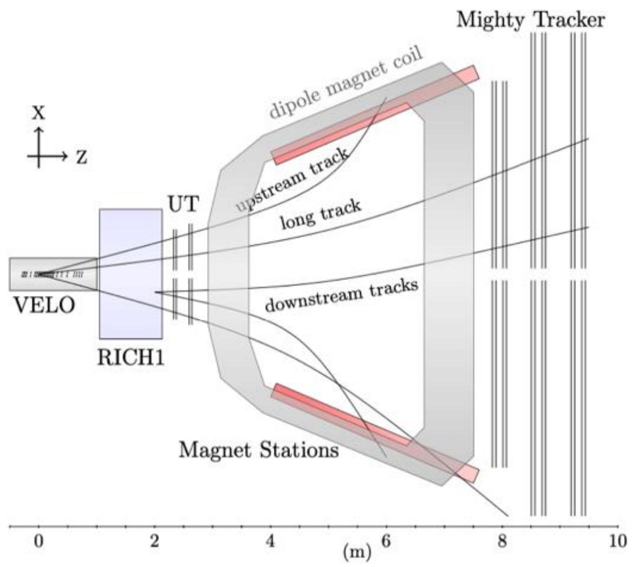


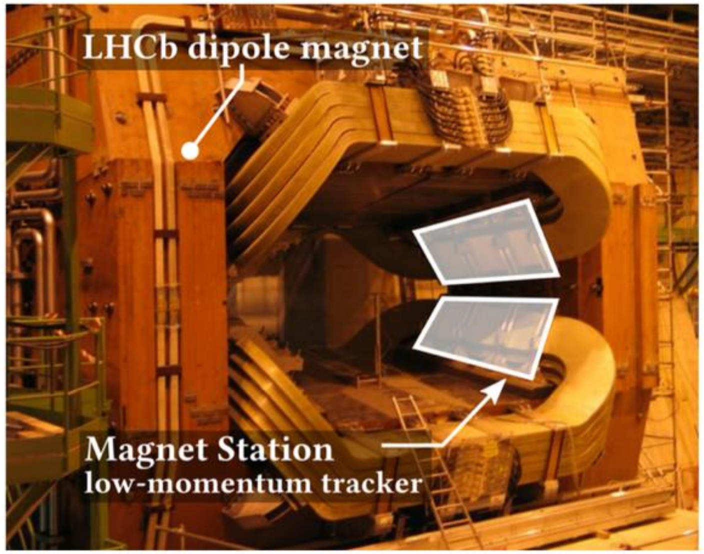
MT-CMOS Module

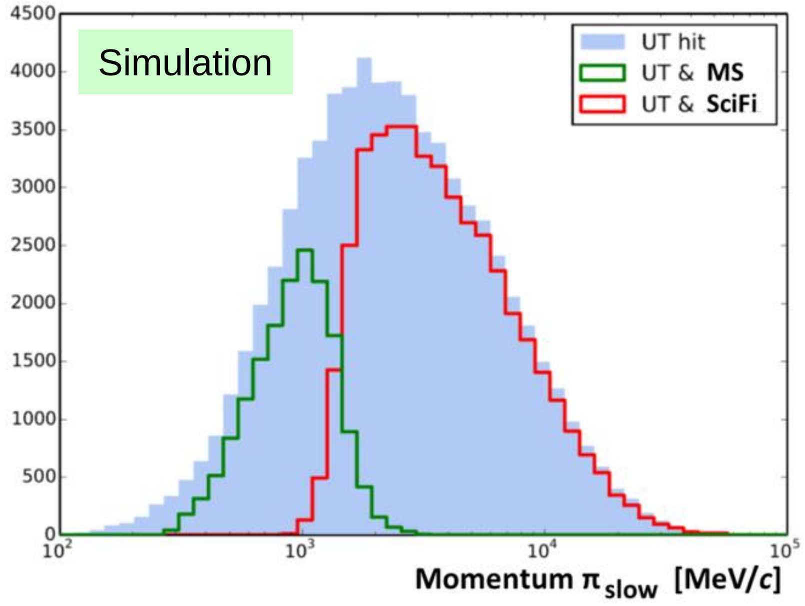
HV-CMOS MAPS detector

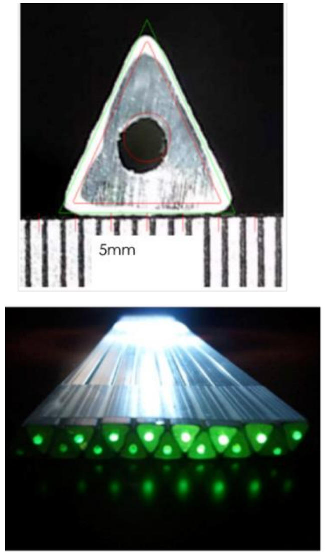
- 6 layers ,18 m^2 in total
- Pixel size ~ 50×150 μm^2
- Upgrade the inner-most at LS3.

Magnet Stations



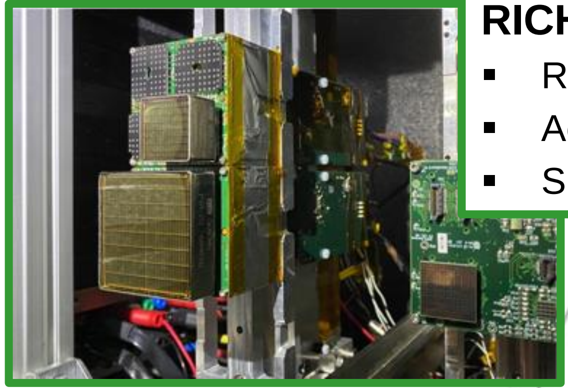






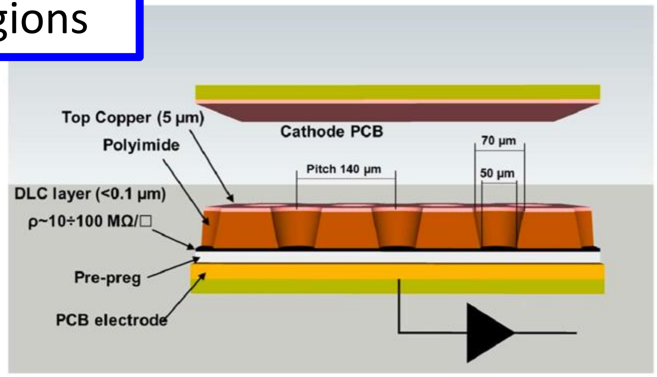
- To enhance the tracking capability, improve track reconstruction, particularly in the outer edges of SciFi acceptance and for low momentum tracks.
- Instrument walls of magnet with extruded triangular scintillating bars.
- Light collected by WS, guided through clear fibers to SiPMs outside magnet.
- 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.

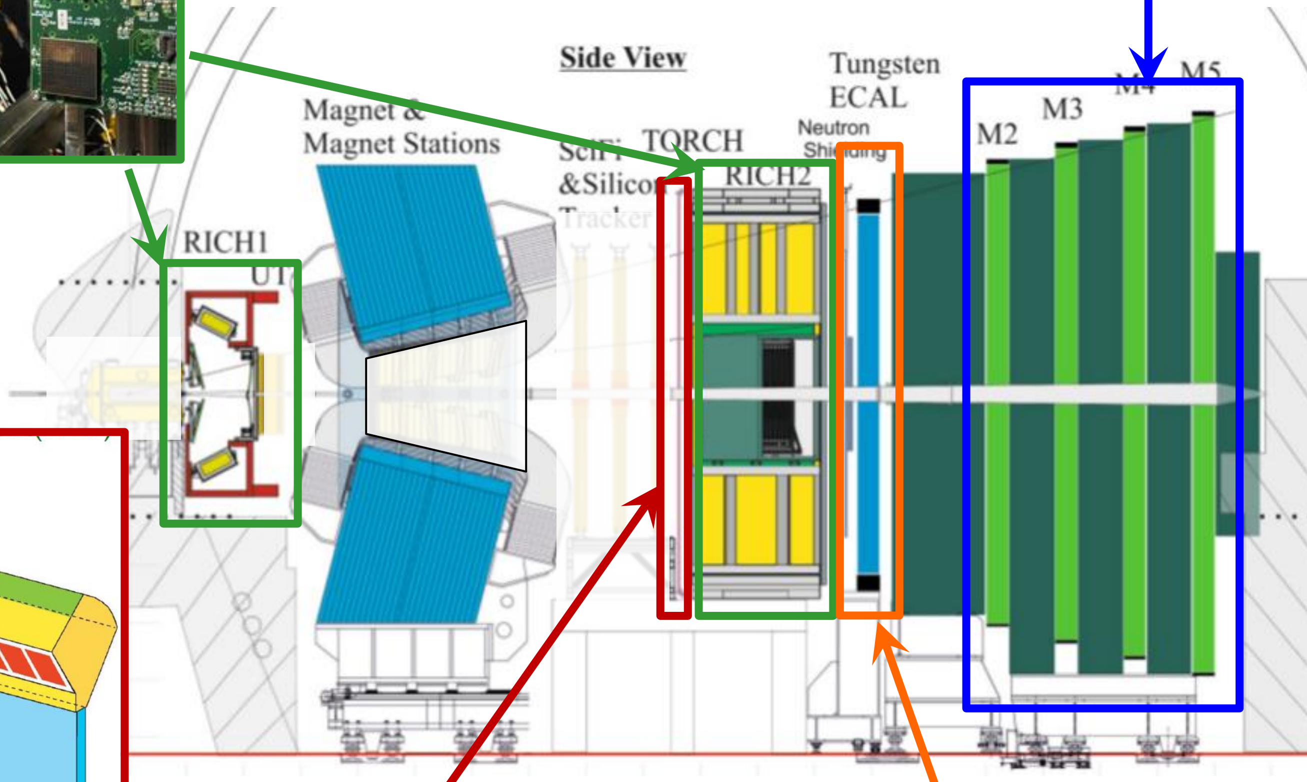
Particle Identification Detectors

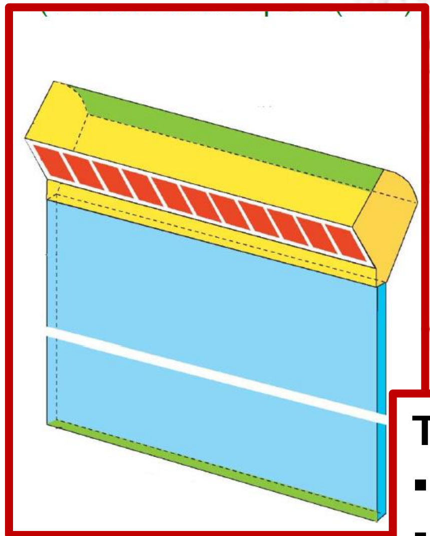


RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP

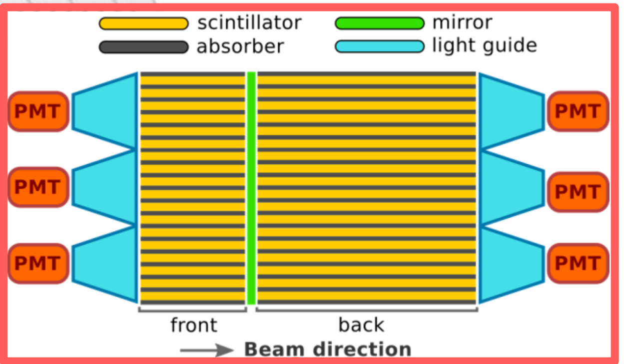
Muon
- µRWELL for inner regions
- MWPC for outer regions







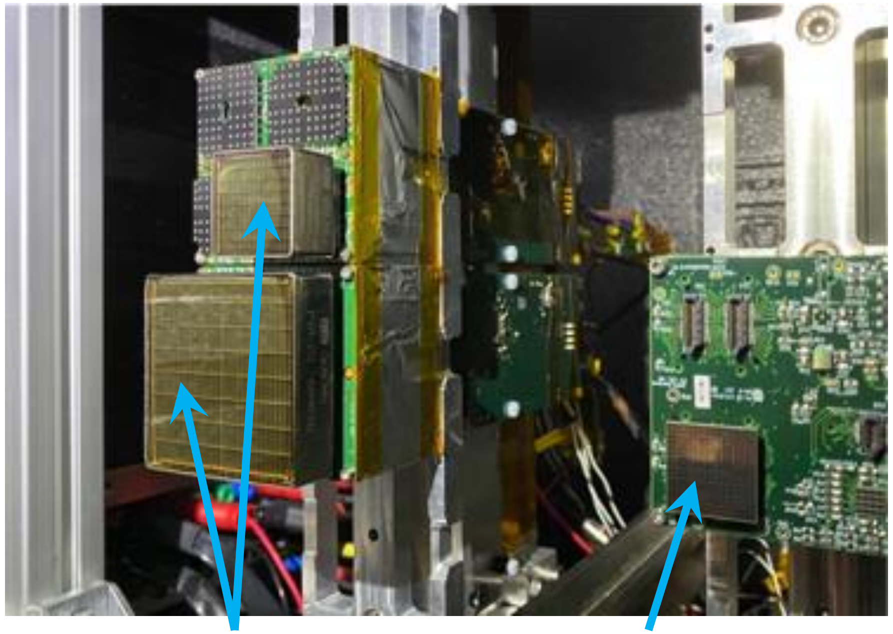
TORCH
- TOF - quartz
- MCP



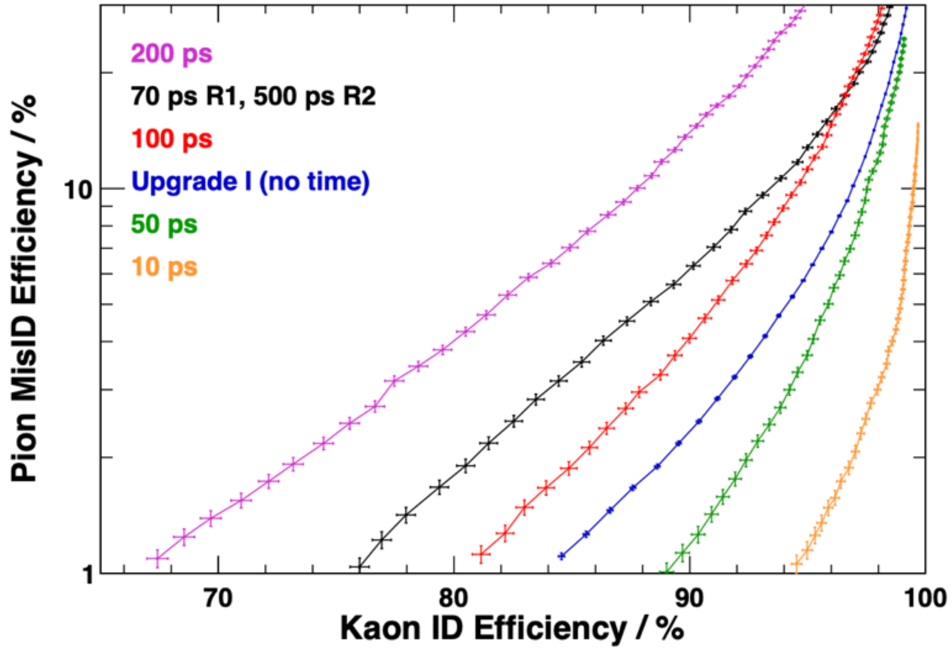
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals

RICH Detectors in Upgrade II

- RICH 1 & 2 will maintain same geometry, reduce pixel size using SiPM or MCP.
- Time-stamping each photon with high precision, which is crucial to PID performance.
- Test beam study of FastIC ASIC + external TDC.
- Design FastRICH based on FastIC with added features such as CFD, data compression and internal TDC.



Ref: LHCC-2021-012

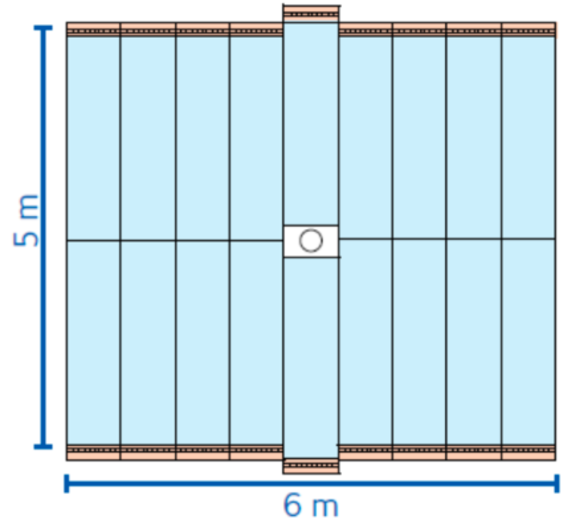


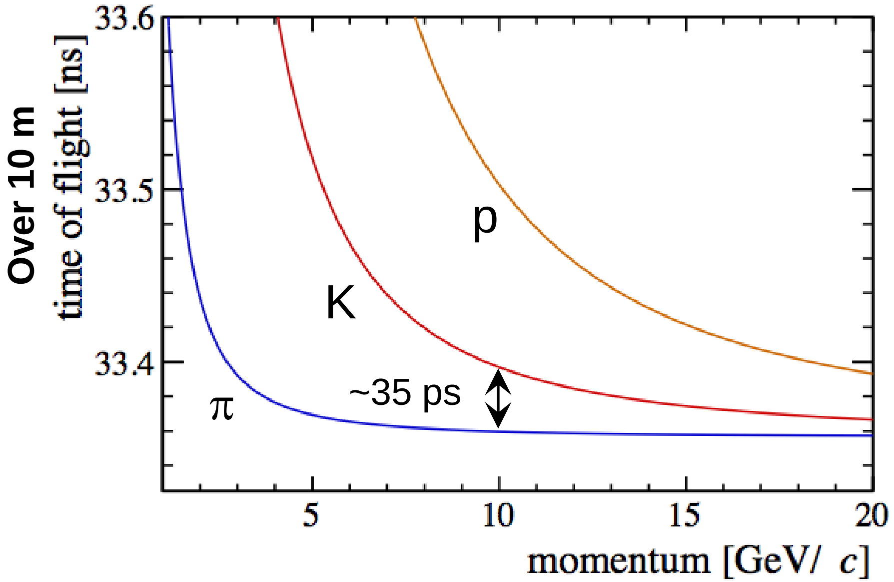
Upgrade	Photon Detector	FE ASIC	Time Resolution	TimeStamp Precision
I	MAPMT	CLARO	~ 150 ps	3.125 ns
I.b*	MAPMT	FastRICH	~ 150 ps	25 ps
II	SiPM, MCP, MAPMT	FastRICH	< 100 ps	25 ps

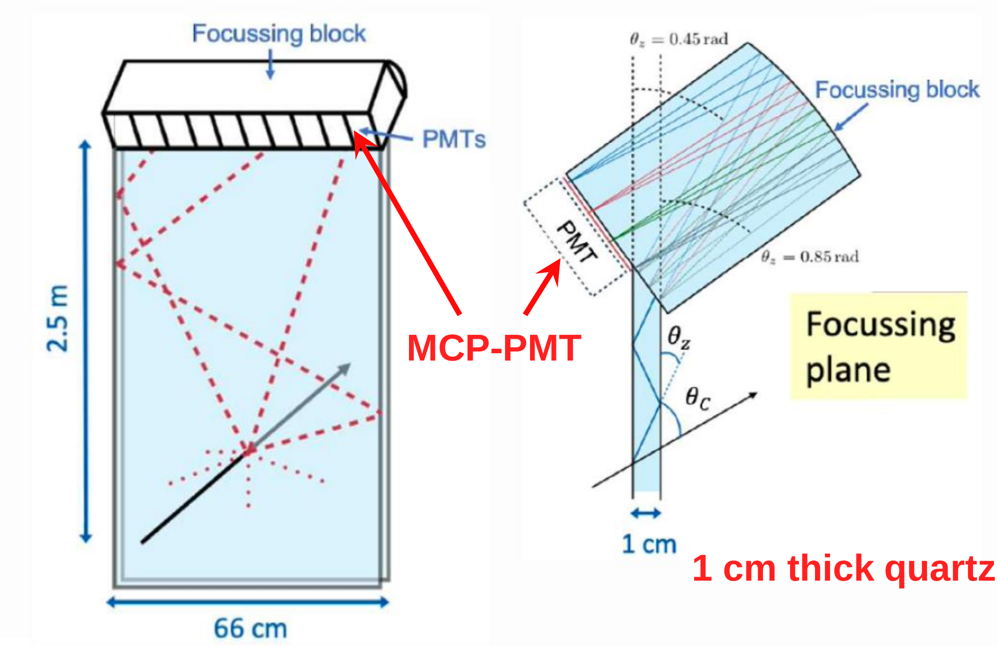
* LS3 consolidation

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



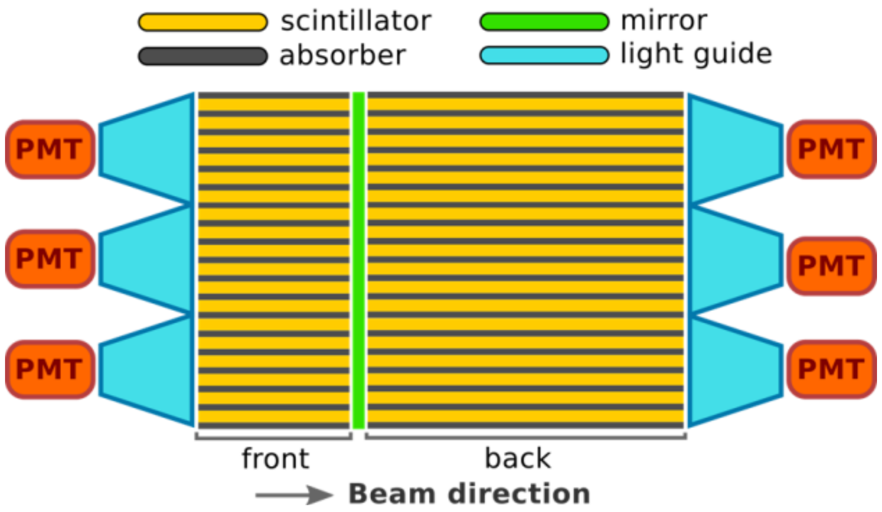


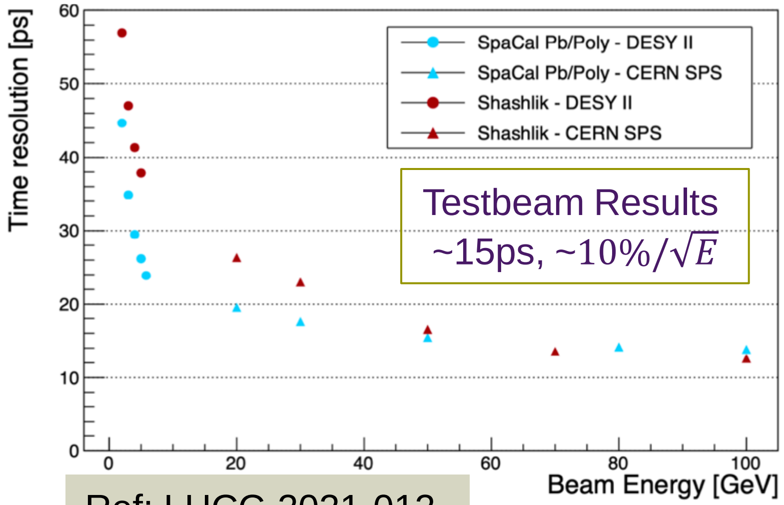


5D Calorimetry with Precision Timing

- Key features: energy resolution ($10\%/\sqrt{E} \oplus 1\%$) , radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity.
- Baseline: combination of technologies for different regions starting from the inner-most,
  - SpaCal W/GAGG
  - SpaCal Pb/Plastic Scintillator
  - Shashlik of different segmentations
- Possibility of adding timing layer: LAPPD or Si layers.
- Possibility of replacing the inner-most modules at LS3.

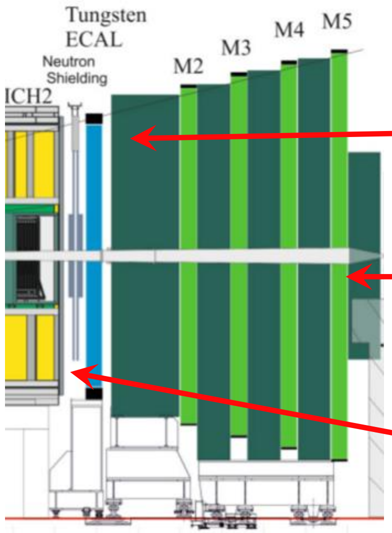
Region	Module type	Cell size [cm^2]	Segmentation [mm]/[X_0]	R_M [mm]	$\sigma_E/E = A/\sqrt{E} \oplus B$ A/B [%]
1	SpaCal W/GAGG	1.5×1.5	45+105/70+180	14.5	9.1 / 1.4
2	SpaCal Pb/PS	3.0×3.0	80+210/70+180	29.5	10.4 / 0.6
3	Shashlik	4.0×4.0	Continuous fibres	35.0	10.0 / 1.0
4	Shashlik	6.0×6.0	Continuous fibres	35.0	10.0 / 1.0
5	Shashlik	12.0×12.0	Continuous fibres	35.0	10.0 / 1.0

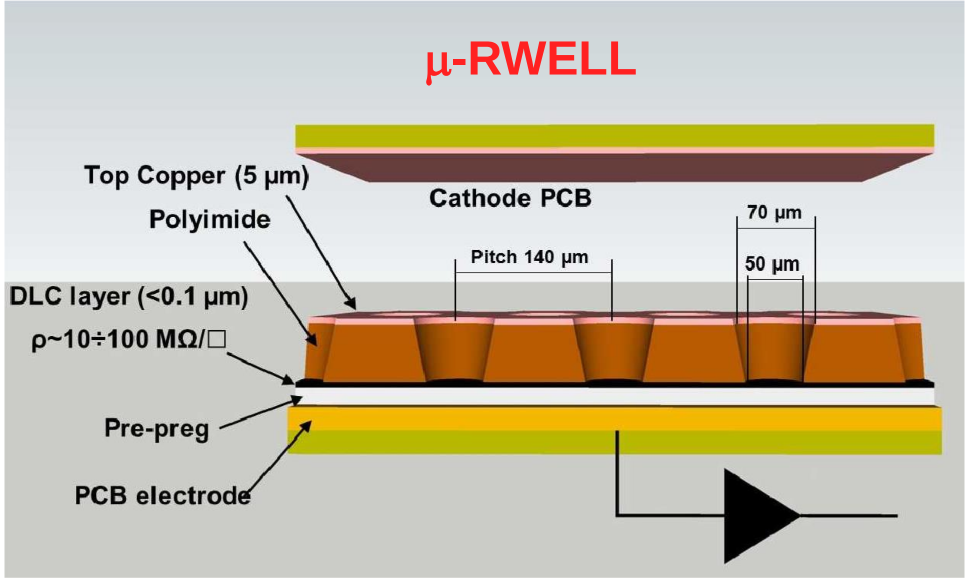


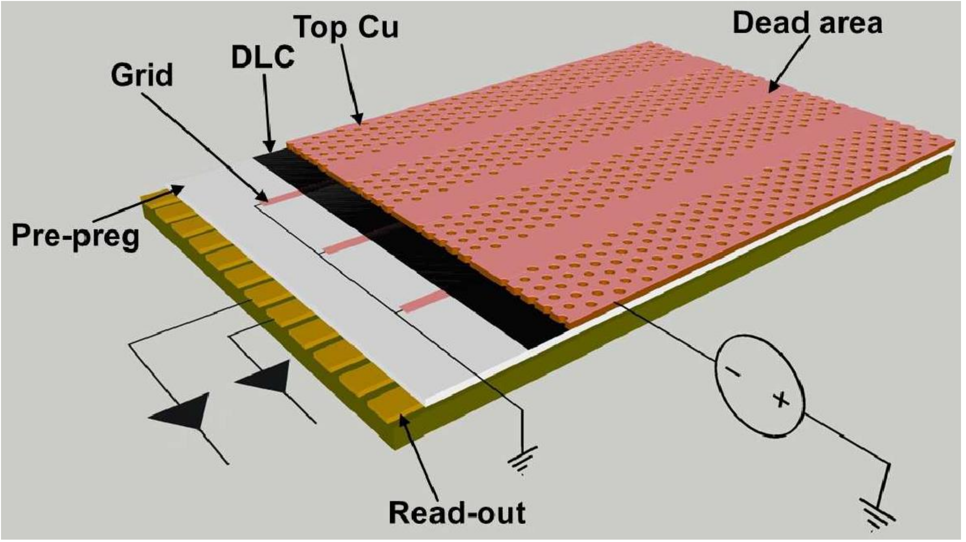


Ref: LHCC-2021-012

Muon Detector



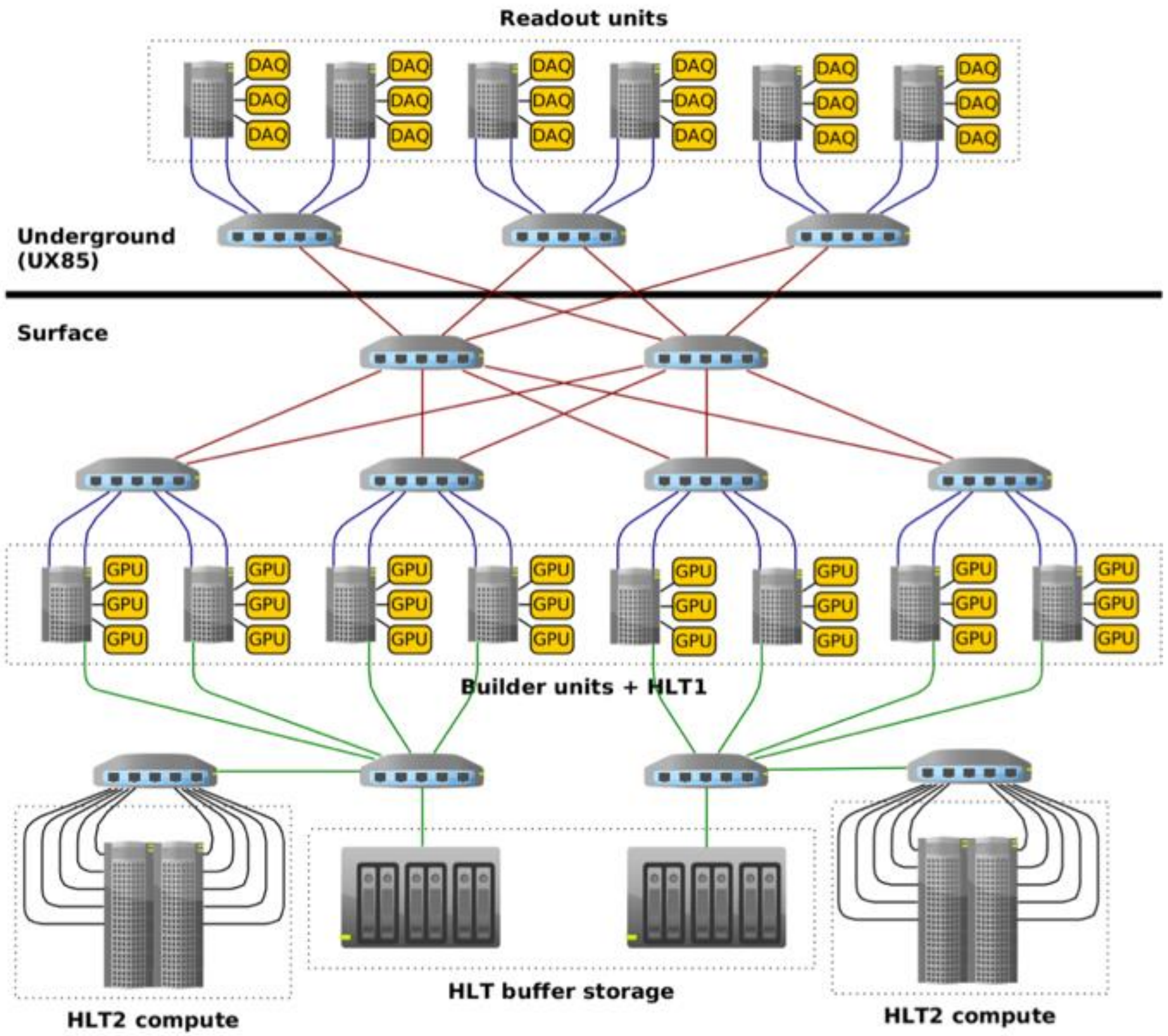




- Novel μ-RWELL for the innermost region.
- Reuse existing MWPC in the outer region.
- Additional shielding ($6\lambda_I \rightarrow 10\lambda_I$) will be installed in front of Muon detector, bring down the rate by a factor of ~2.

Online and Offline

Event-builder architecture for Upgrade II



- Novel trigger system for Upgrade I
  - Fully software trigger
  - HLT1 based on GPUs
- 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

Summary

- LHCb plans Upgrade II to fully exploit HL-LHC for flavor physics and beyond.
- The FTDR was approved. The upgrade entered the R&D phase, leading towards detector TDRs, construction, installation and eventually operation for physics.
- This is an ambitious major upgrade (~0.5 of a ATLAS/CMS Upgrade II detector). We are actively seeking new collaborators and will be happy to discuss with anyone interested.
- There are a number of innovative technologies that can act as a bridge to those for future colliders.

	2021	2022	2023	2024	**2025**	2026	2027	2028	2029	**2030**	2031	2032	2033	2034	2035	…	2041
Phase	LS2			Run 3			LS 3			Run 4			LS 4			Run 5 & 6	
Project Approval Stages	FTDR					MoU											
Detectors						TDR											
Online, Trigger, Computing										TDR							
LS3 Infrastructure																	
LS3 Detector Construction								Install									
LS4 Detector Construction														Install			

Many thanks to my colleagues for helping the preparation: Matteo Palutan, Paula Collins, Fred Blanc, Oscar Augusto, Chris Parkes, Cesar Luiz Da Silva, Bade Sayki, Neville Harnew, Jonas Rademacker, Andreas Schopper, Carmelo D'Ambrosio, Floris Keizer, Monica Pepe, Dominik Mitzel, Paras Naik……