Flavour Physics Lecture

味物理讲座

味物理前沿研讨会暨味物理讲座100期特别活动

LHCb 探测器与升级

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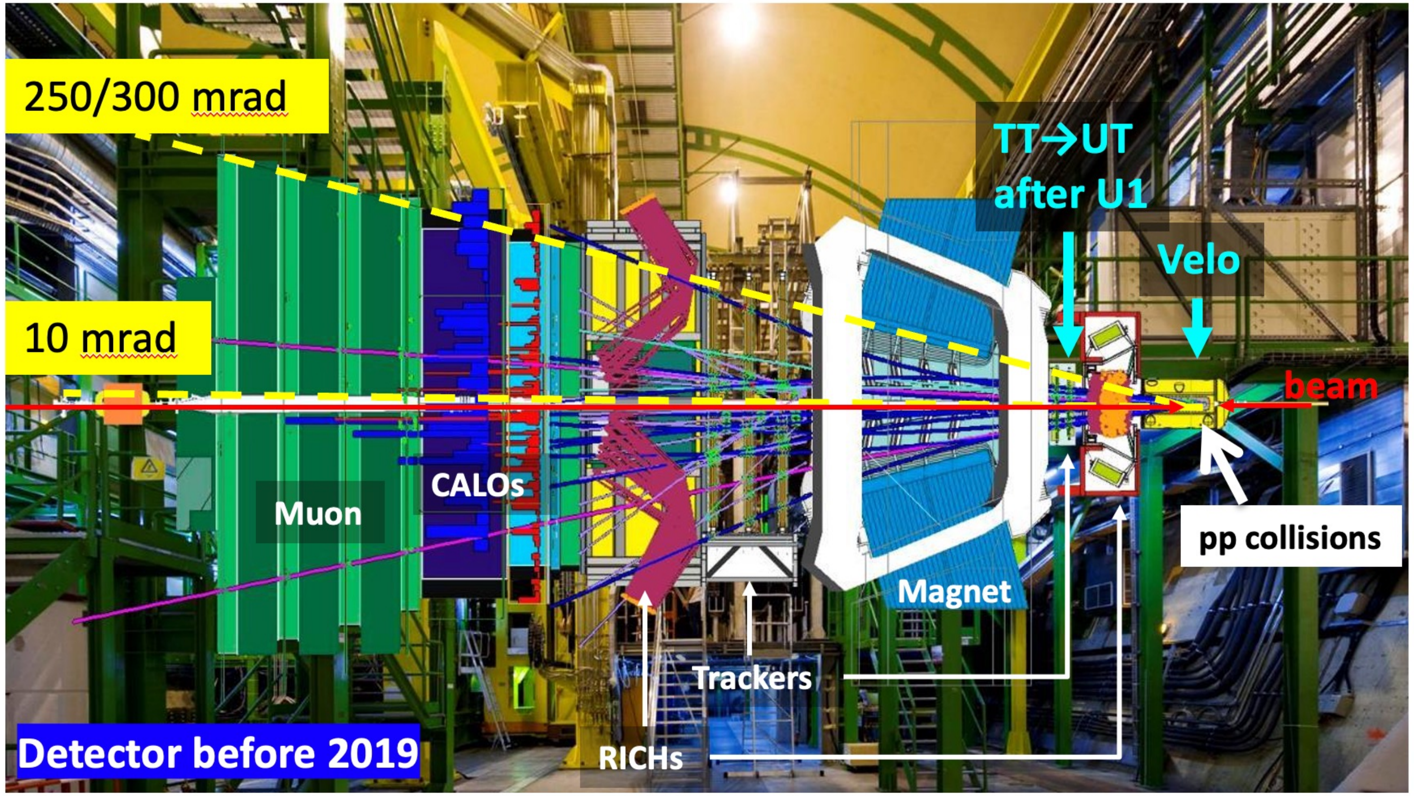
2026-02-02，三亚

LHCb: a forward spectrometer @ LHC



$\mathcal{L}_{\rm inst} = (2\sim4)\times10^{32}\ cm^{-1}s^{-1}$ before 2019

Vertex	$\sigma_{\rm IP} = 20\ \mu m$
Time	$\sigma_\tau = 45$ fs for $(B_s \to J/\psi\phi)$ or $D_s^+\pi^-$
Momentum	$\Delta p/p = 0.4\sim0.6\ \%$ @ $(5-100\ \mathrm{GeV}/c)$
Mass	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
Hadron ID	$\epsilon(K \to K)\sim95\%$; mis-ID $\epsilon(\pi \to K)\sim5\%$
Muon ID	$\epsilon(\mu \to \mu)\sim97\%$; mis-ID $\epsilon(\pi \to \mu)\sim1-3\%$
ECAL	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

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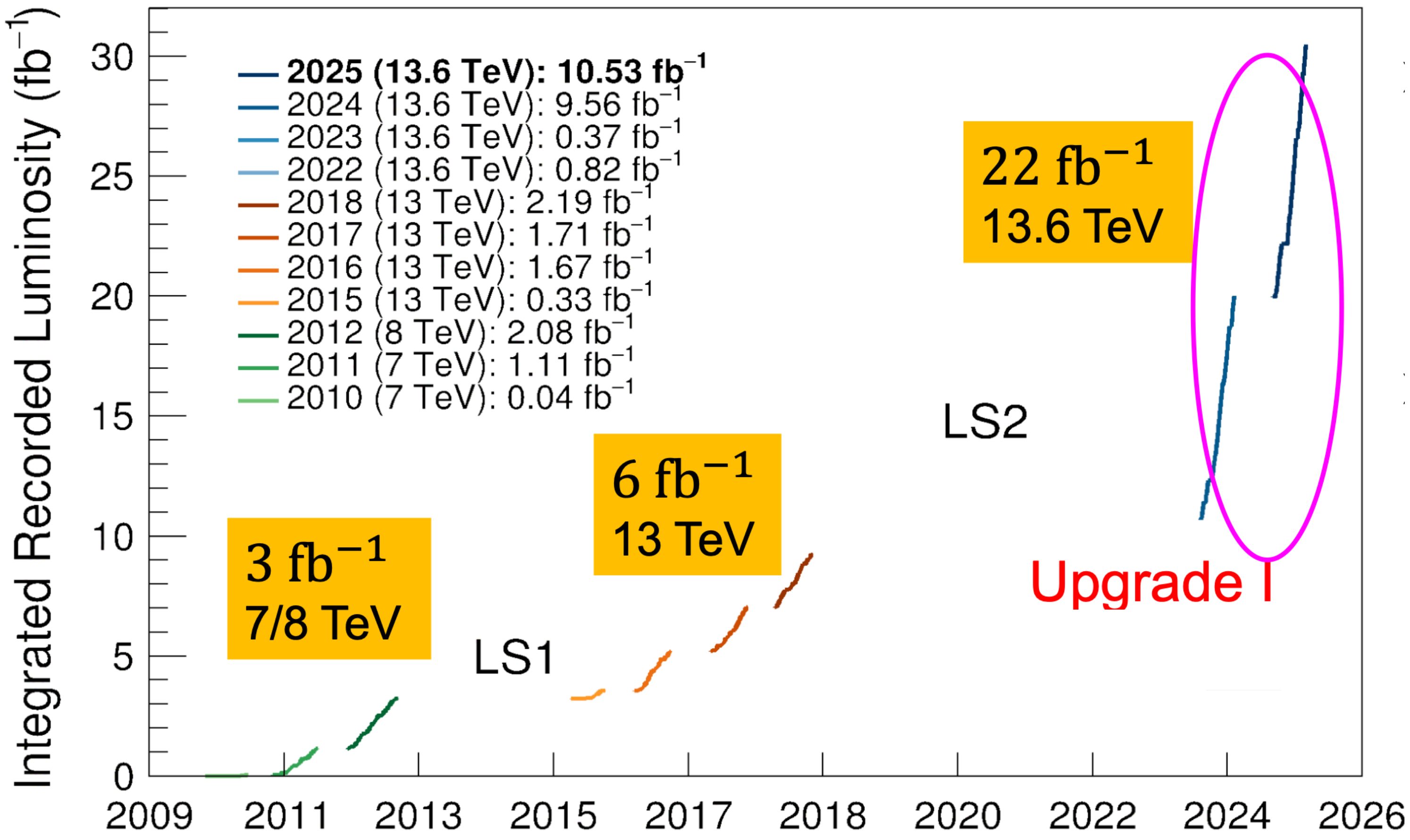
LHCb physics performance

A decade of important discoveries and precision measurements (9 fb^{-1} pp data by end of 2018)



LHCb Upgrades

Upgrade I (U1), started in LS2

$\mathcal{L}_{max}$~ 2x10^{33} cm^{-2}s^{-1}

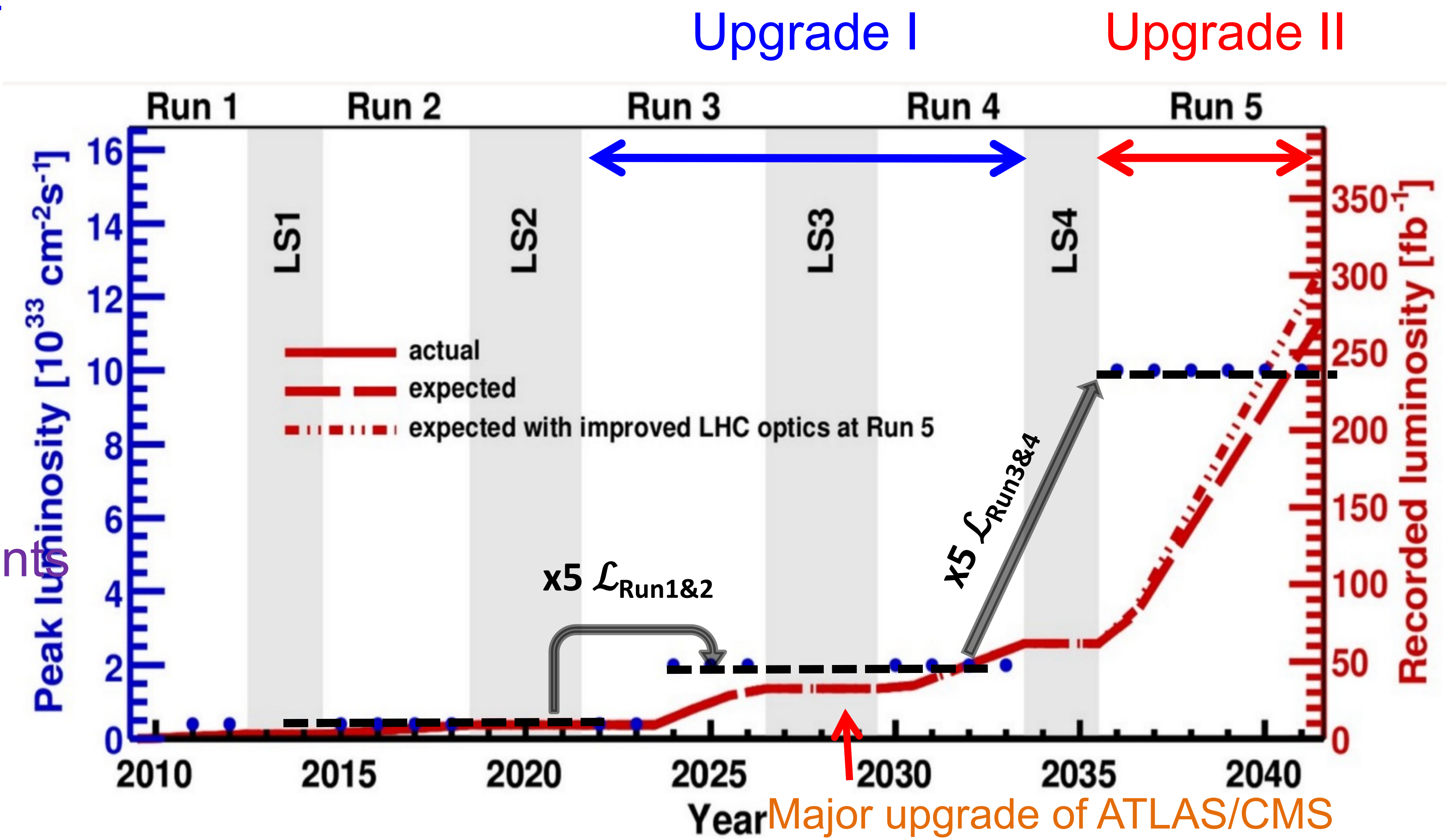
$\mathcal{L}_{int}$~ 50 fb^{-1}

Upgrade II (U2), starts in LS4

$\mathcal{L}_{max}$~ 1.0-1.5x10^{34} cm^{-2}s^{-1}

$\mathcal{L}_{int}$~ 250 - 300 fb^{-1}

Some smaller detector consolidation and enhancements in LS3 (2026) ⇦ U1b



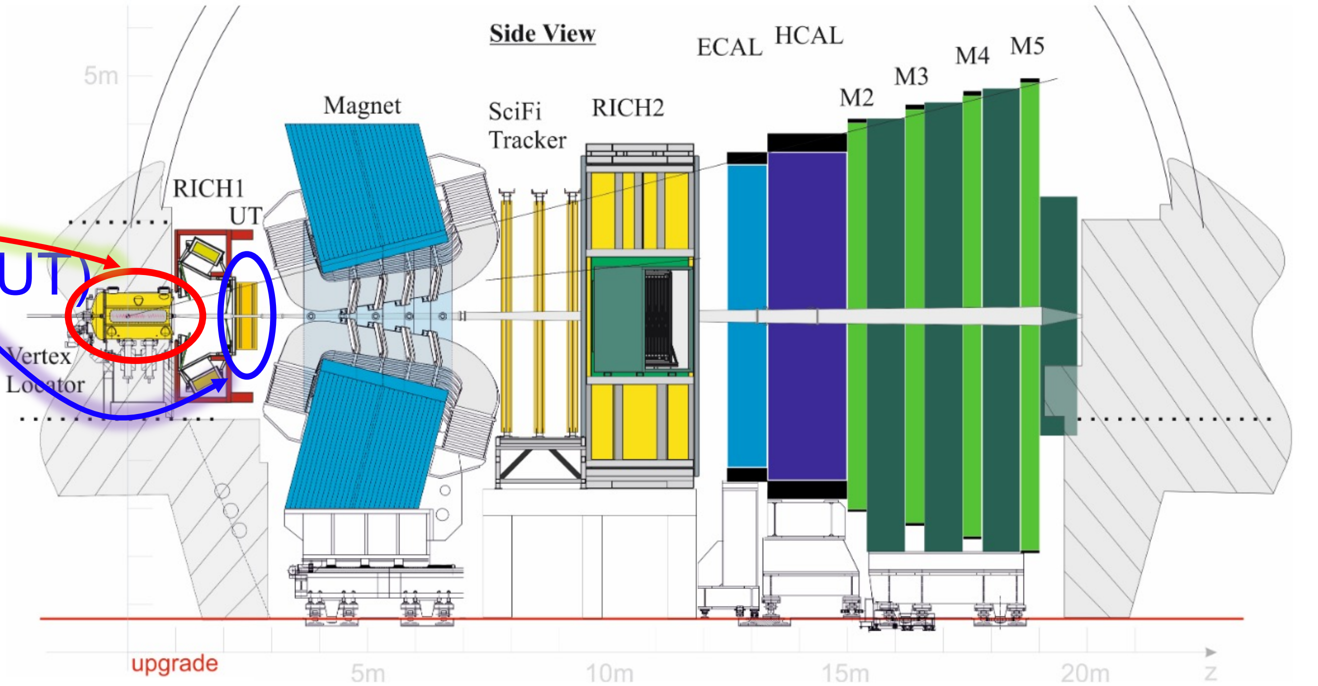
Major upgrade of ATLAS/CMS

LHCb also plan enhancements (U1b)

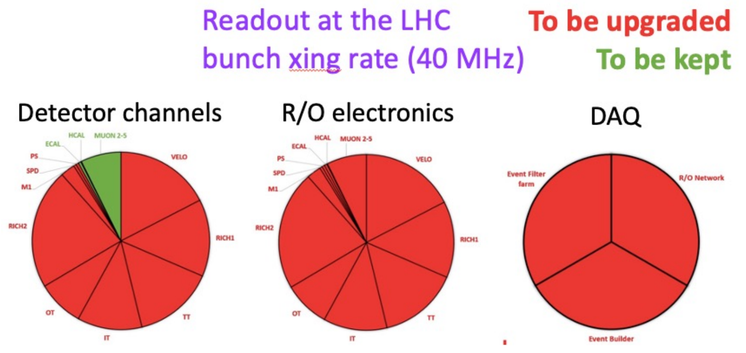
Upgrade I: a brand new detector

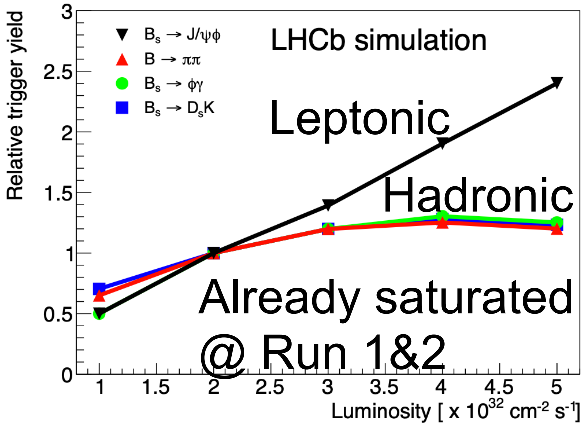
Higher luminosity ($5\mathrm{x}\mathcal{L}_{Run1\&2}$) results in
- ➢ Higher rate, pile up, occupancy, fluence

New tracking system
- ➢ **VErtexLOcator (VELO)**, **Upstream Tracker (UT)** and **Sci**ntillating **Fi**ber Tracker (SciFi)



RICHs: New optics + photon detectors
Calos: Reduce PMT gain + new electronics
MUON: new electronics





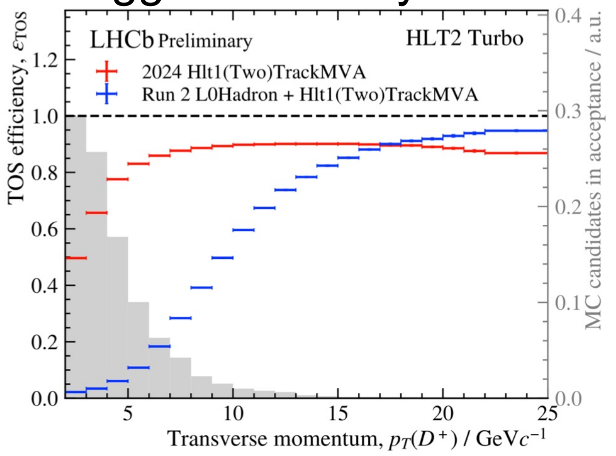
No hardware trigger
- ➢ 1st GPU trigger in a HEP experiment

Performance of current detector

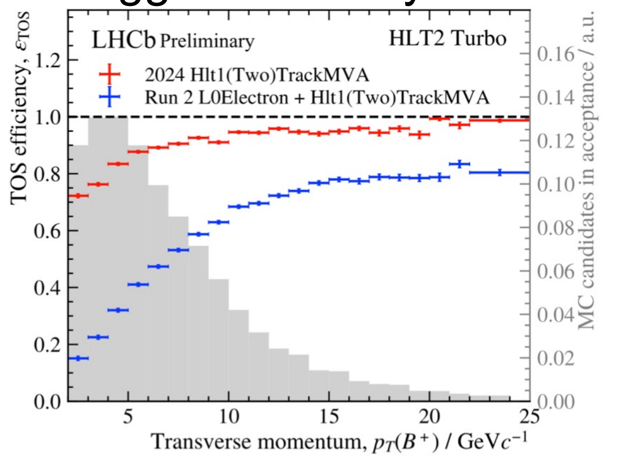
Clear benefit from L0 removal

- Improved HLT1 efficiency at low p_T
- Low p_T objects can be retained in more complex HLT2 selections

Trigger efficiency for D^+



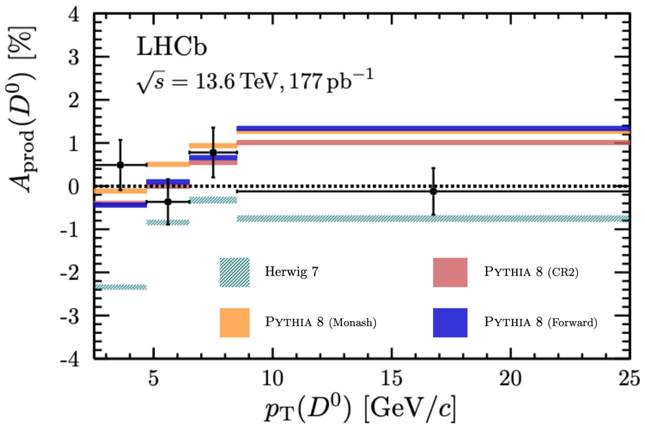
Trigger efficiency for B^+

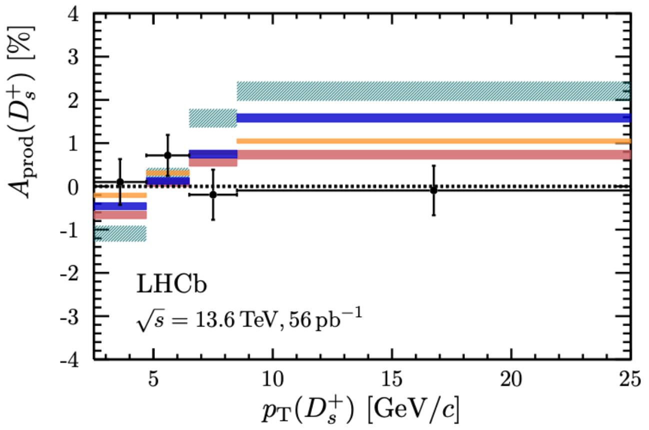


First LHCb run3 analysis

Charm meson production asymmetries measured

- Using 2022 + 2023 data, $\sqrt{s} = 13.6$ TeV
- Comparable statistical uncertainty as Run 1, but only with ~1/15 int-luminosity → Gain in selection/trigger efficiency





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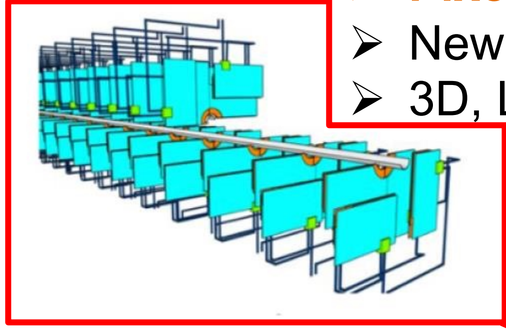
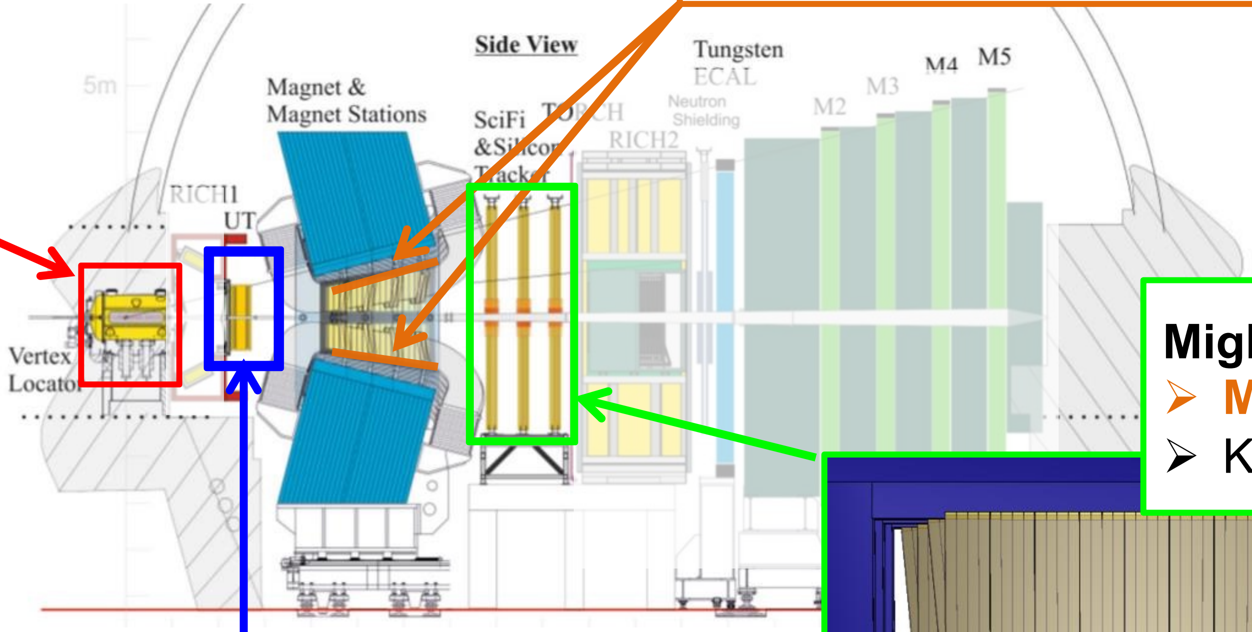
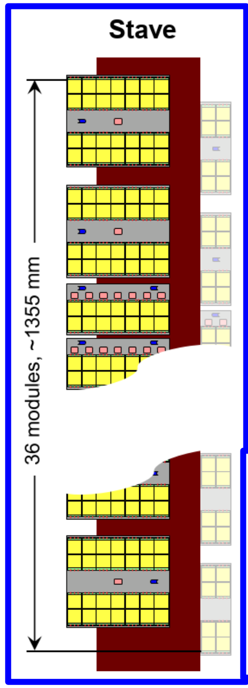
The Tracking System in Upgrade II



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

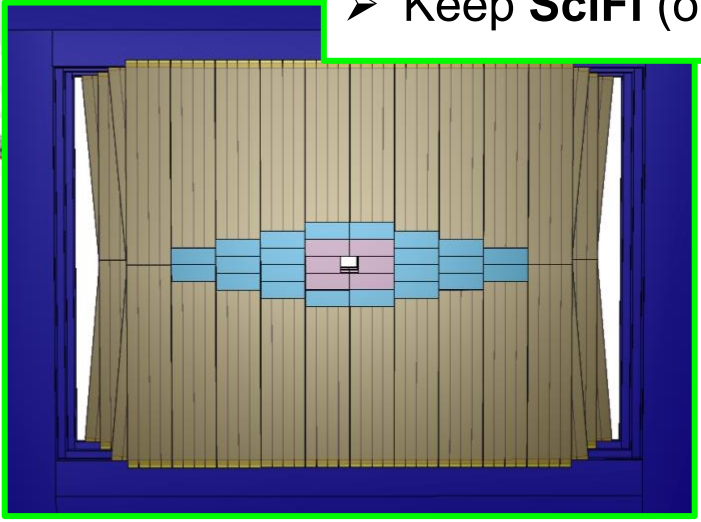
Magnet Stations (MS)
- Scintillating bar
- Low P particles





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

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



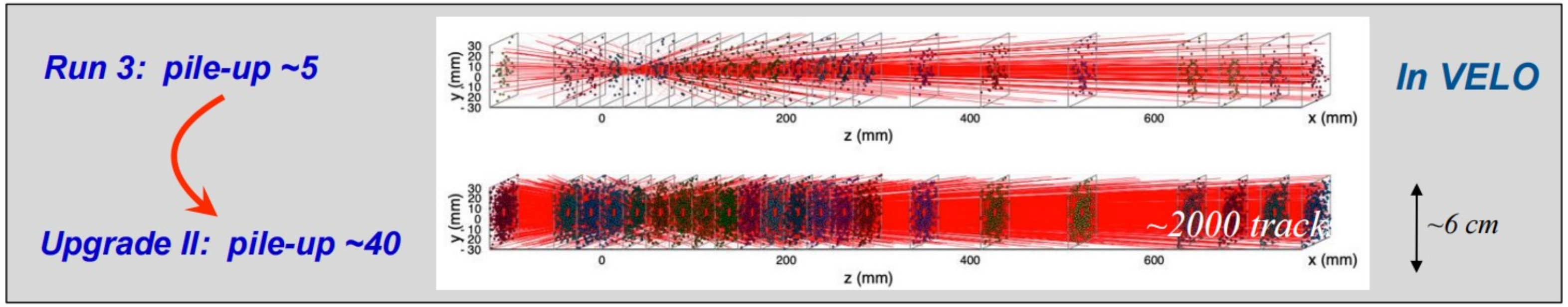
High pile-up in Upgrade II

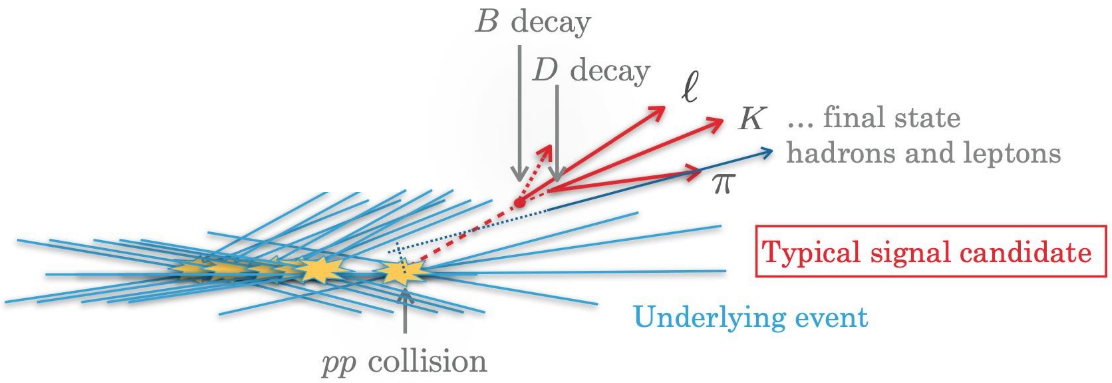
In Upgrade II

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

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

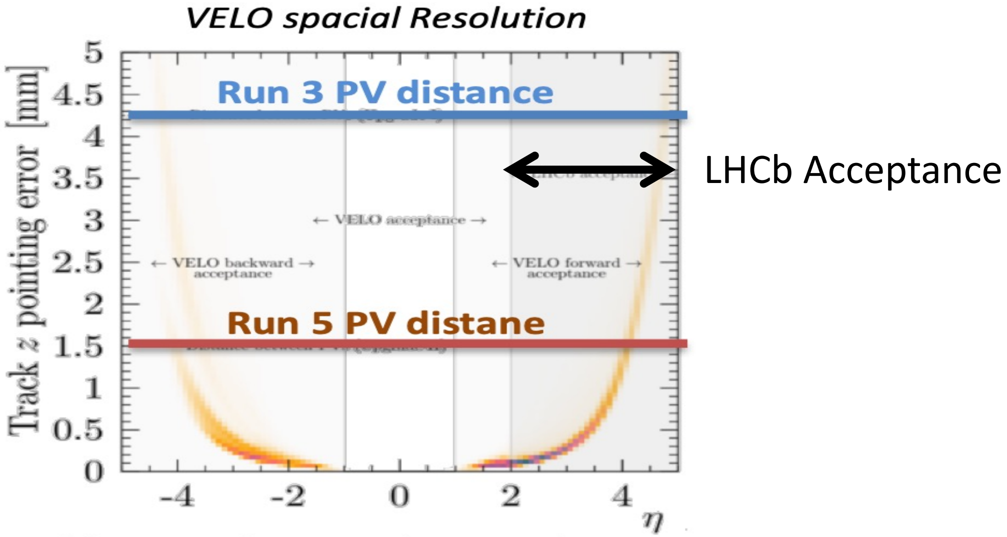
~ 40 visible interactions/Xing





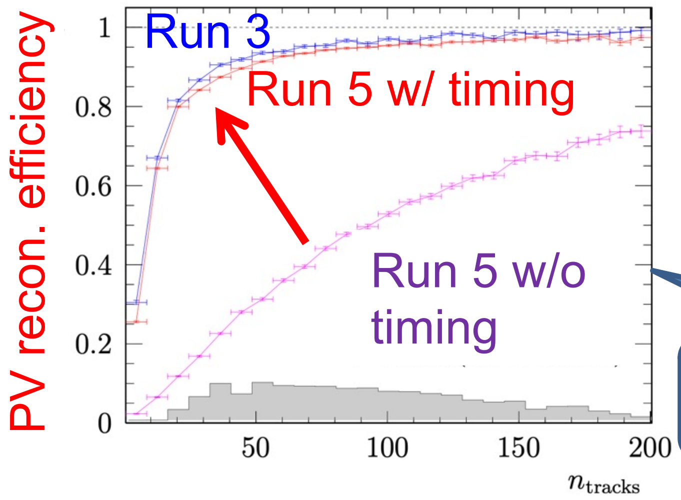
A typical *b* decay: separated from PV

- Important for b-related analysis for the identification of the displace vertex



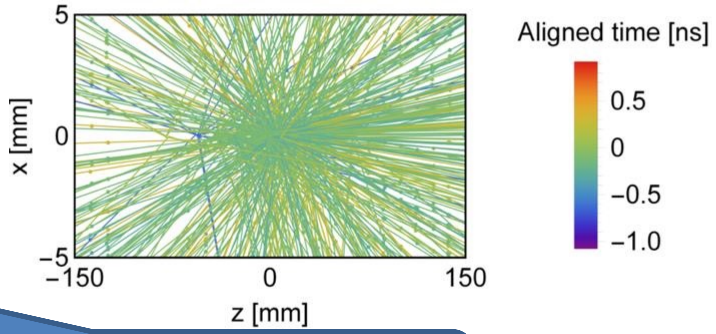
- High pile-up induces PV spacial separation of the same order as VELO resolution -> PV unresolvable
- Ensure $\varepsilon_{trigger}$ at high pileup condition

4D VELO with precision timing

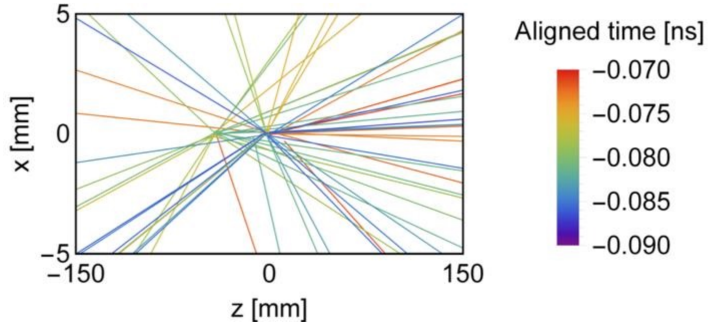


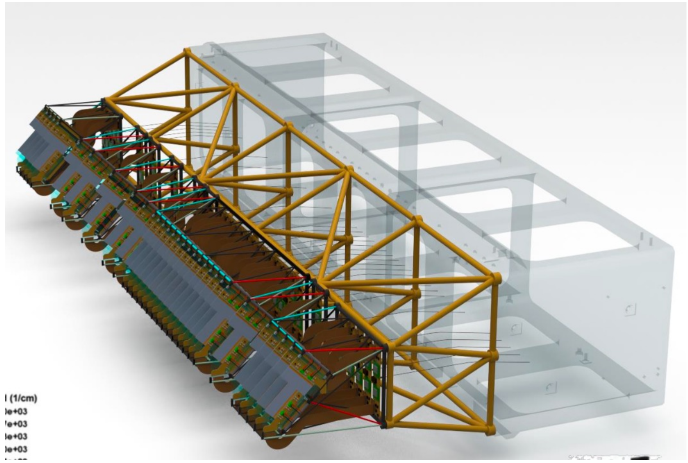
Similar performance as the present VELO for Run 3

Track density with ~40 visible interactions



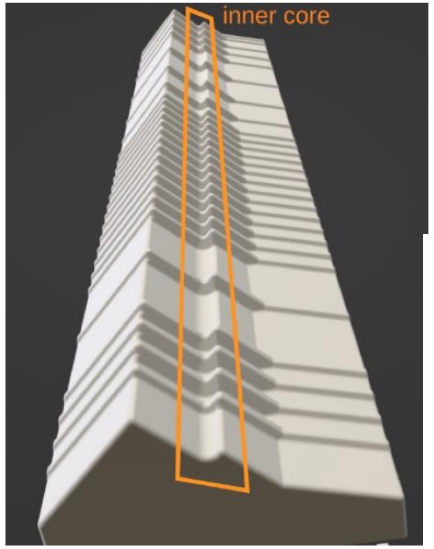
20 ps timing window

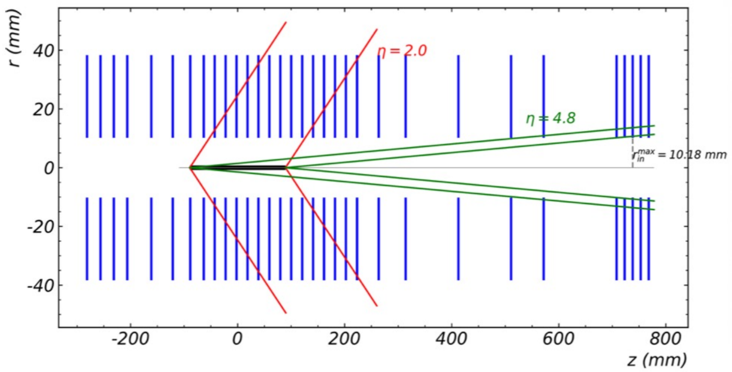




New techiques in R&D:

- Baseline: 32 stations with 3D pixel sensor
  - Timing (~50 ps),
  - Radiation hardness (max ~$6\times10^{16} n_{eq}/cm^2$)
- ASICs (28 nm tech)
  - Require <30 ps
  - PicoPix (50 μm pixel pitch)
  - Ignite (45 μm pixel pitch)
- RF shield: 50 μm Al + 20 μm CF





Upstream Pixel Tracker (UP)

Upgrade II luminosity 1.0~1.5 x10^{34} $cm^{-2}s^{-1}$ (~**5x** $\mathcal{L}_{\textbf{Run 3\&4}}$)

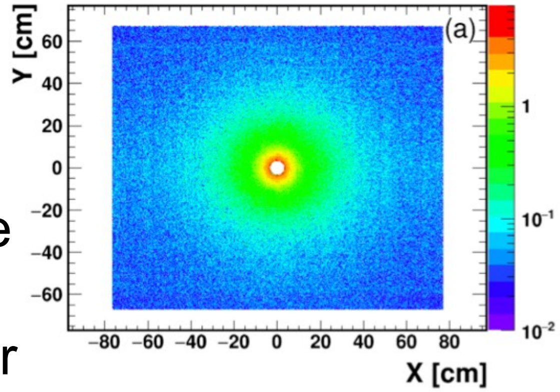
- Max hit density ~6 hits/cm^2/BX for pp collisions
- For Pb-Pb: ~3 hits/cm^2/BX, but multiplicity higher

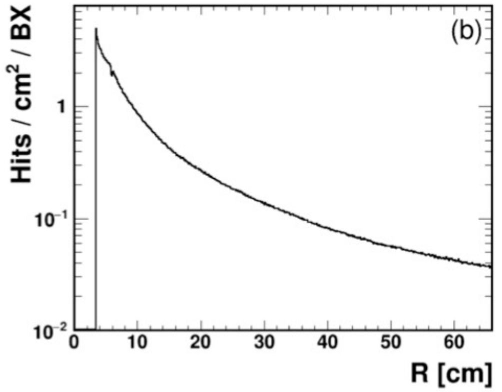
Current UT not optimized in HL-LHC

- Occupancy (max ~10%) will compromise the performance
- Data rate too high
- Radiation does (3x$10^{15}n_{eq}/cm^2$) too high for current sensor

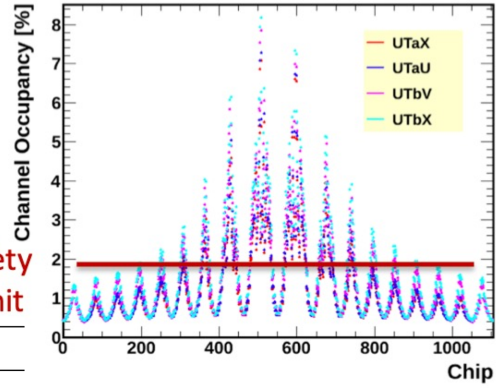
A new Upstream Pixel (UP) detector will replace UT

- CMOS MAPS technique applied

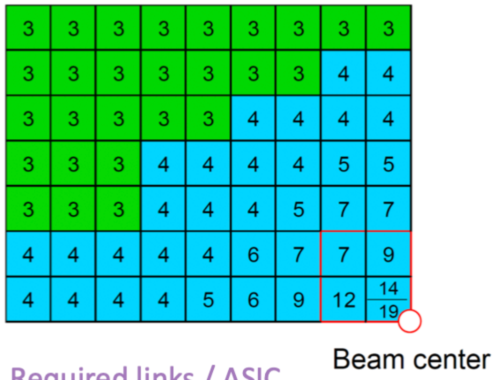




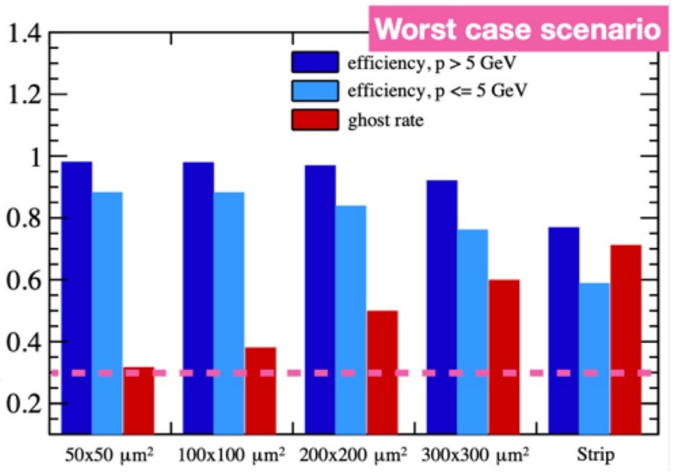
Safety Limit



Channel occupancy



Required links / ASIC
Max 5 available!



Characteristics	Specification
Hit rate in hot event and region	160 MHz / cm^2 pp (~52.5 hits / cm^2 / BX for Pb/Pb)
Time resolution	O(1 ns) for BX tagging
Pixel size	O(30×30 μm^2) or (100×300 μm^2)
Power consumption	O(100-300 mW/cm^2)
Radiation dose for 350 fb^{-1}	3×10^{15} 1-MeV n_{eq}/cm^2, 240 Mrad

Studies based on current UT in Upgrade II condition

MAPS technology for Tracker

MightyPix (AMS 180 nm)
- MightyPix1 / TSI-180, time resolution 2.93 ns
- LF-MightyPix uses LF-150, power ~ 200 mW/cm^2
- MightyPix2 expected to be available by April 2026

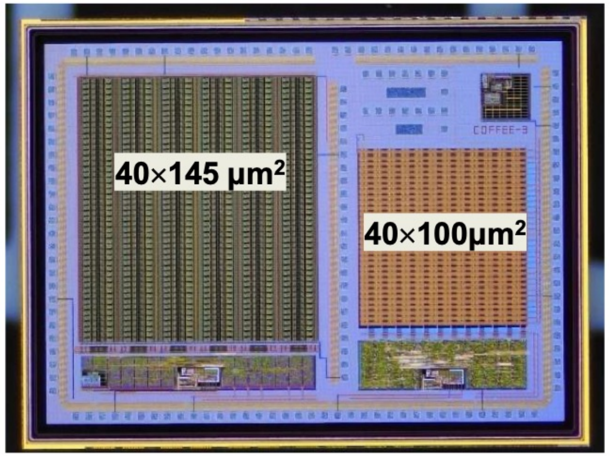
RadPix (LF 180 nm)
- LFMonoPix, 99% efficiency after $10^{15} n_{eq}/cm^2$
- RadPix1 to be submitted in Q1 of 2026

COFFEE (55 nm)
- COFFEE3 responds to laser and radiation source, digital functions validated

MANTA (TPSCo 65 nm)
- Ased on SPARC for ALICE
- Available by Q1 of 2027

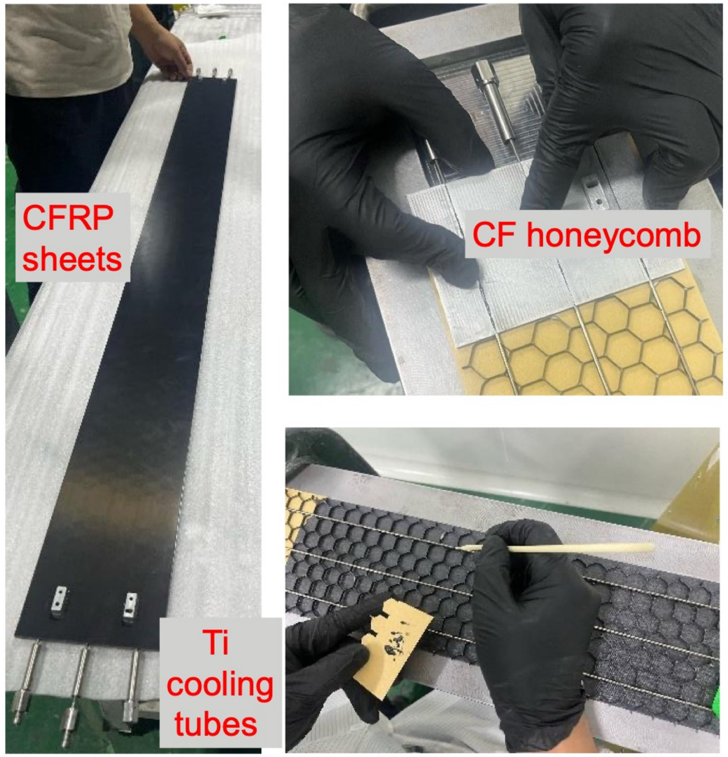
Parameter	Key Specification	
	MT-Pixel	UP
Pixel size, square rectangular	$\leq 100\times200\ \mu m^2$	$\leq 85\times85\ \mu m^2$ $\leq 50\times200\ \mu m^2$
Max hit rate	34 MHz/cm^2	150 MHz/cm^2
In-time efficiency	> 99% within 25 ns	
Rad-hard (NIEL) (TID)	$3\times10^{14}\ n_{eq}/cm^2$ 40 Mrad	$3\times10^{15}\ n_{eq}/cm^2$ 240 Mrad
Power consumption	$\leq 150\ mW/cm^2$	$\leq 200\ mW/cm^2$

COFFEE 3



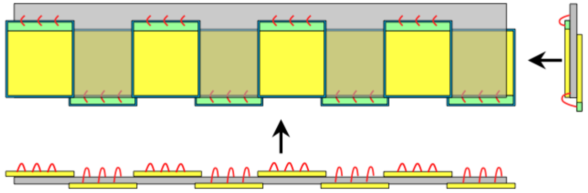
MAPS-based UP detector

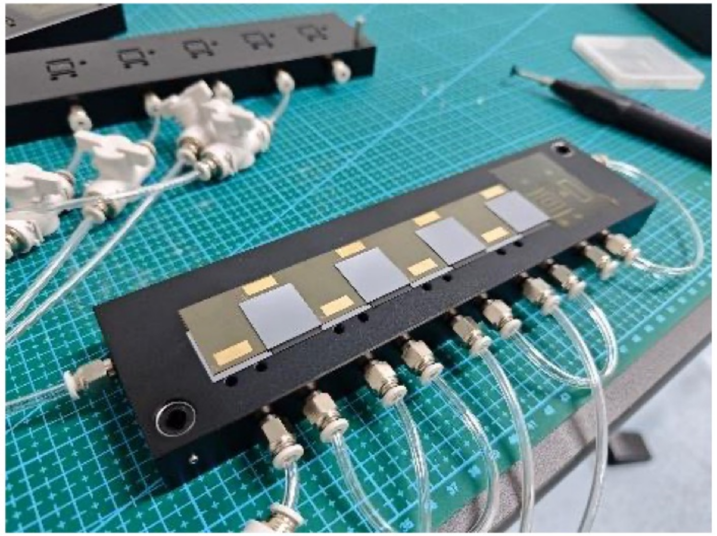
- Four layers based on MAPS, total active area ~ 7 m^2
- Module and stave designed to be compared and finalized
- Readout electronics at the end of staves
- Prototyping started

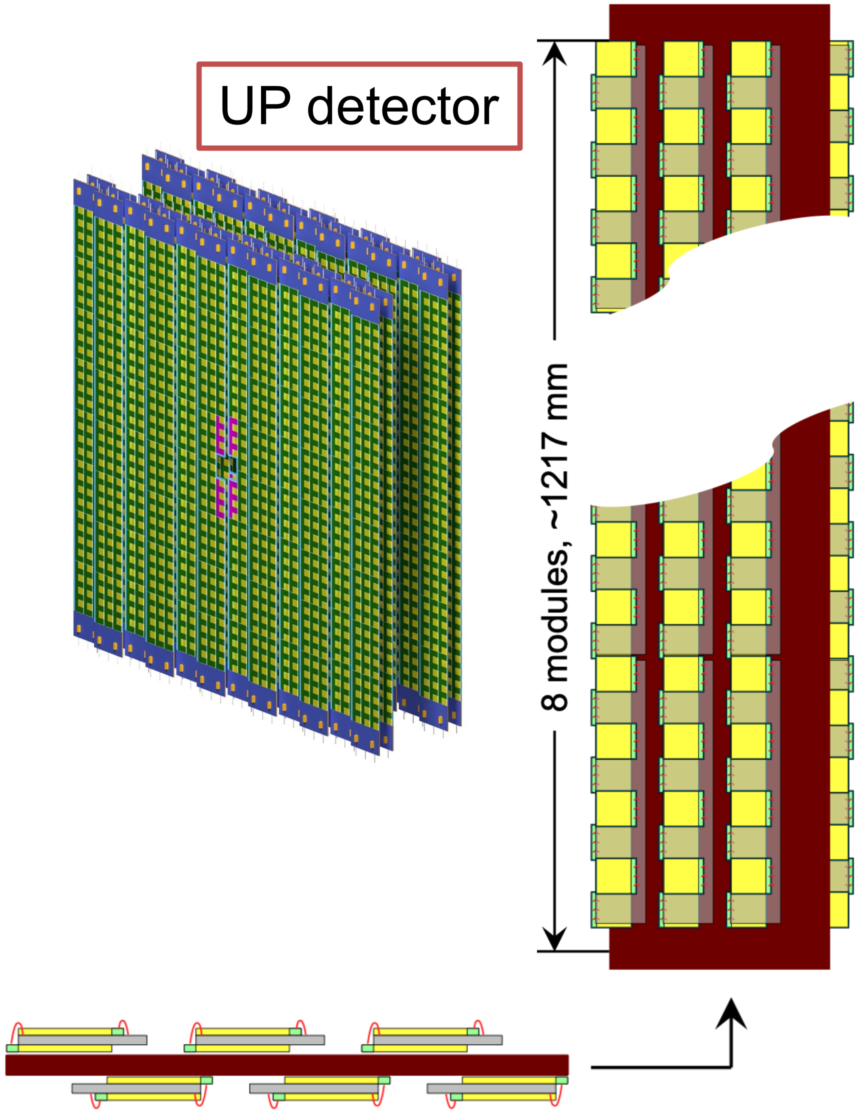


Prototype bare stave

Module

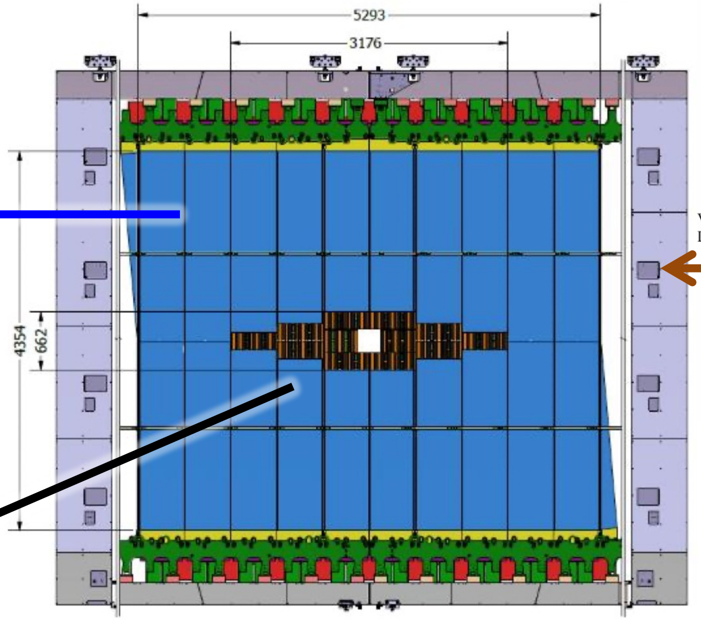



Prototype module

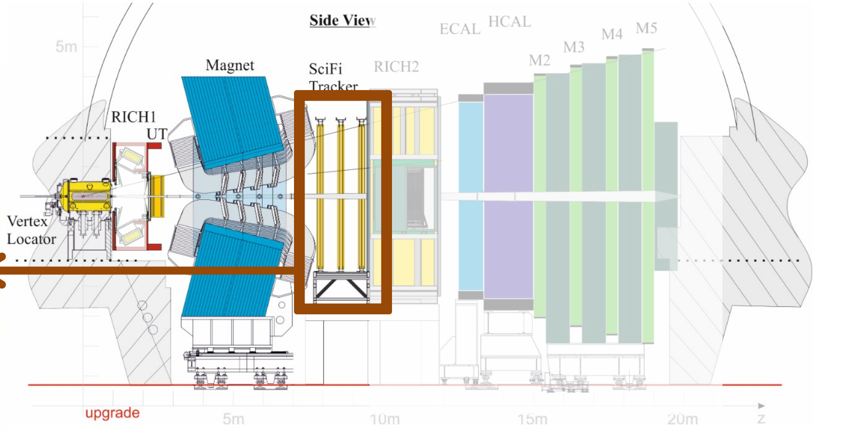


SciFi and Mighty Tracker (MT)

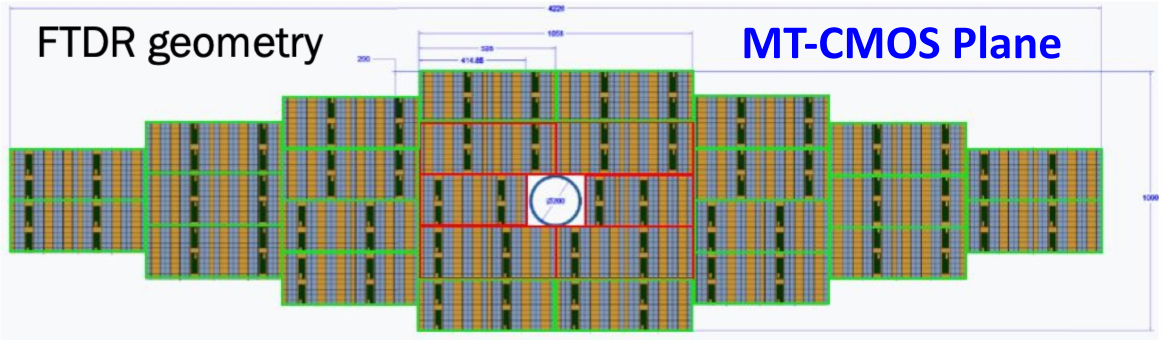
Keep SciFi design at outer region
- ➢ Further away from beam
- ➢ Micro-lens on SiPM to enhance light collection
- ➢ Crypgenic cooling for SiPM: -40℃ ⇒ -120℃

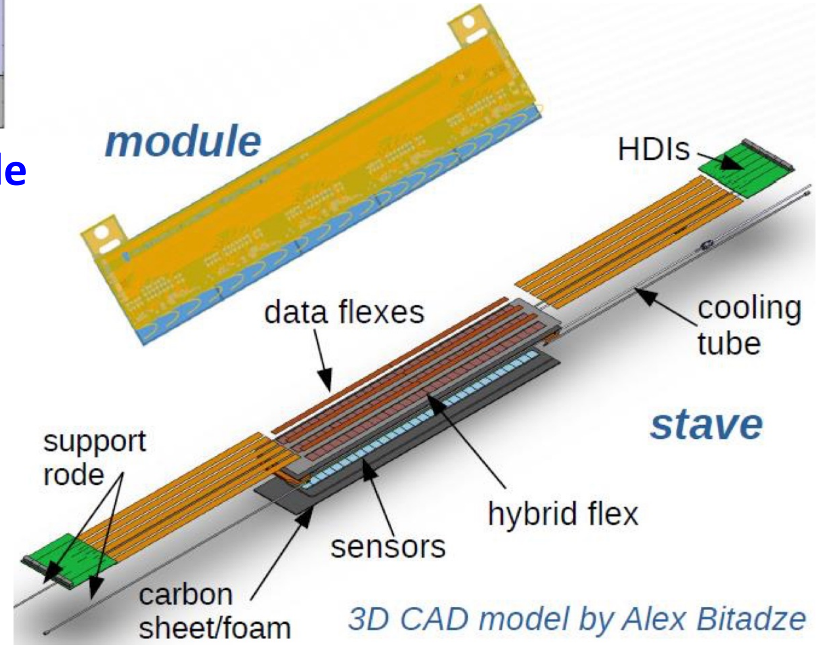


MT-CMOS Module

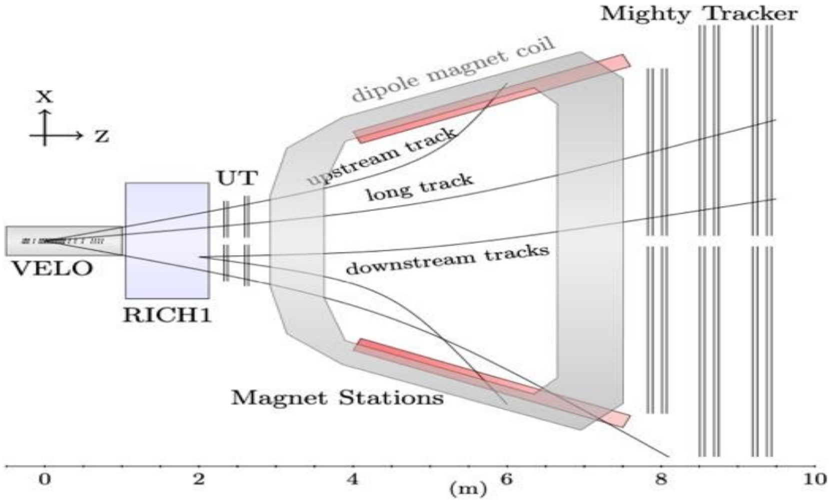


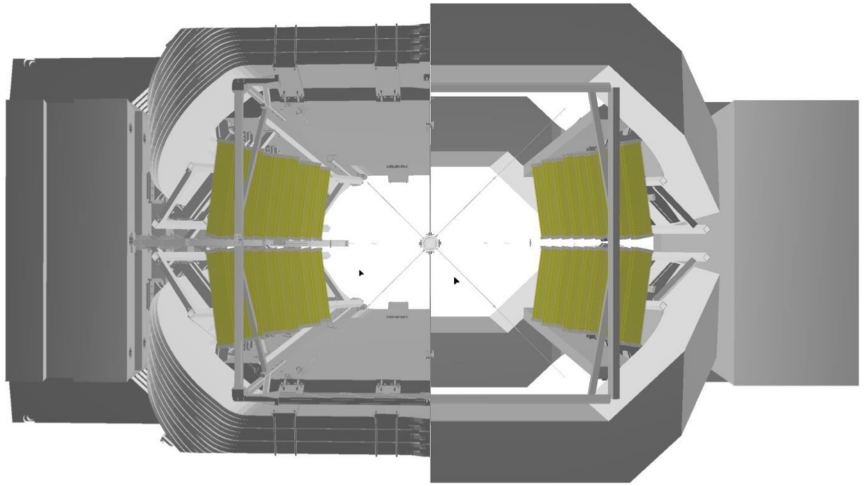
HV-COMS MAPS detector (same as UT)
- ➢ 6 layers, 13 m^2 in total
- ➢ Pixel size ~ 84x84 μm2

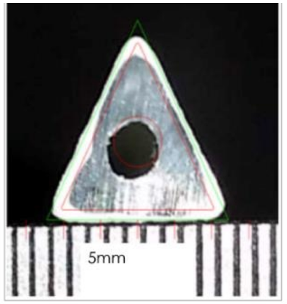


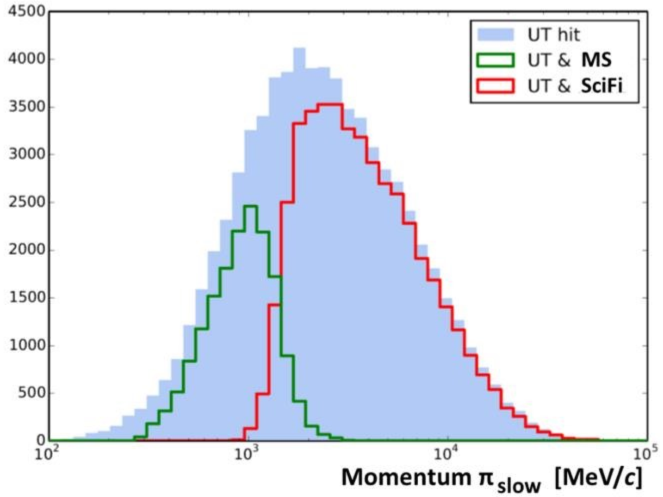


Magnet Stations (MS)









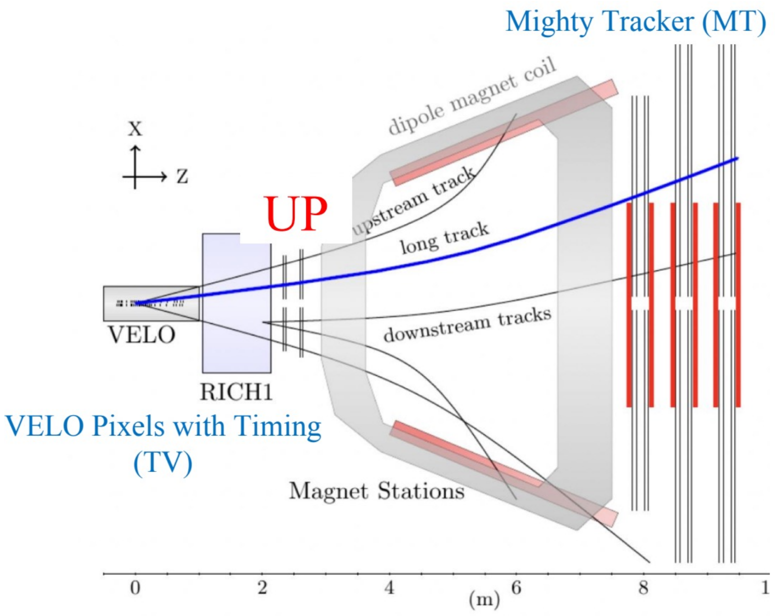
A new MS to be installed for reconstructing Upstream Tracks

- ➢ Tracking capability, reconstruction ↗ 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.
- ➢ sub-% momentum measurement precision.

Upgrade II tracking system

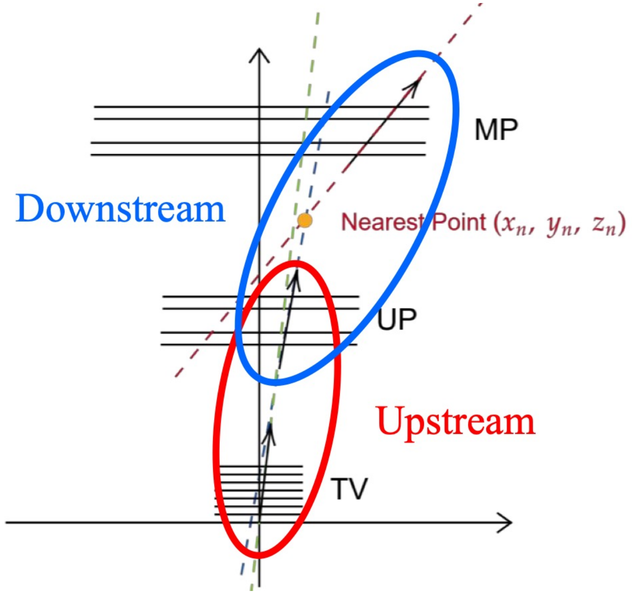


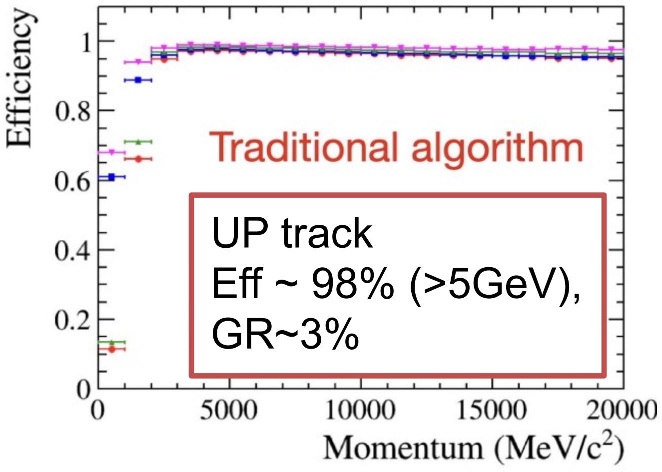
LHCb track type

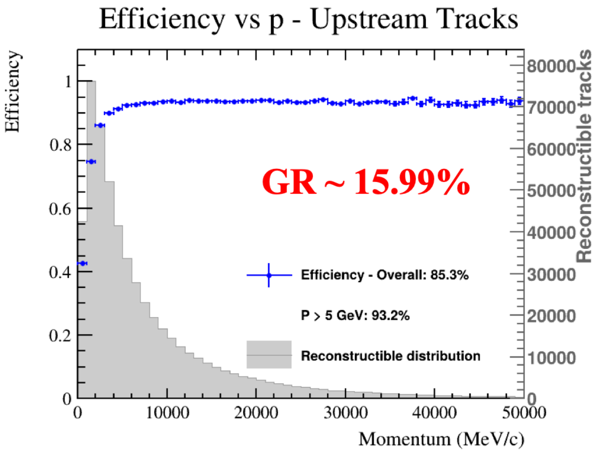
- Standalone track for TV, UP & MT
- Long track: TV-**UP**-MT
- Upstream Track: TV-**UP**(-MS)
- Downstream Track: **UP**-MT(/-MS)

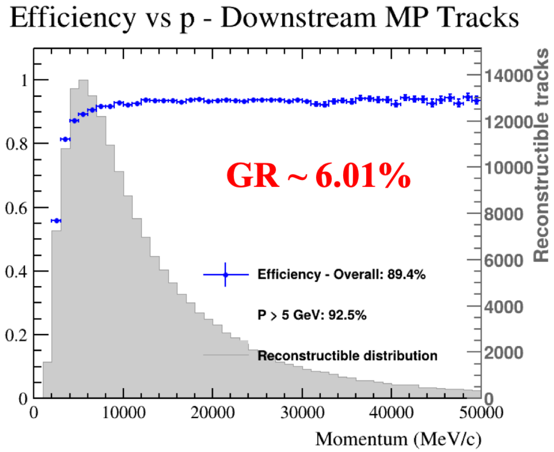
BDT-based tracks matching algorithm

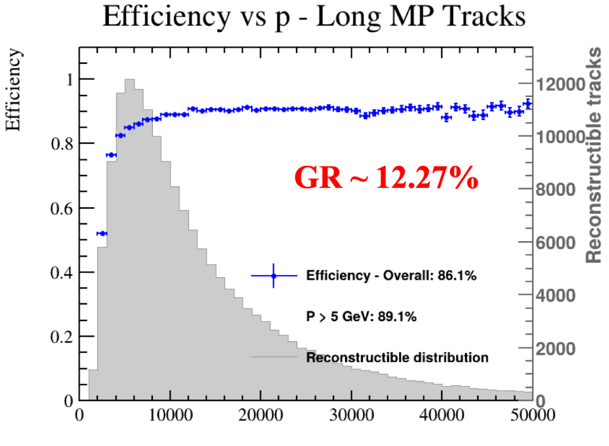
Similar tracking performance as Run3





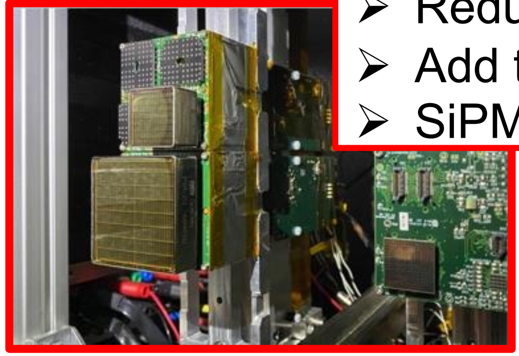






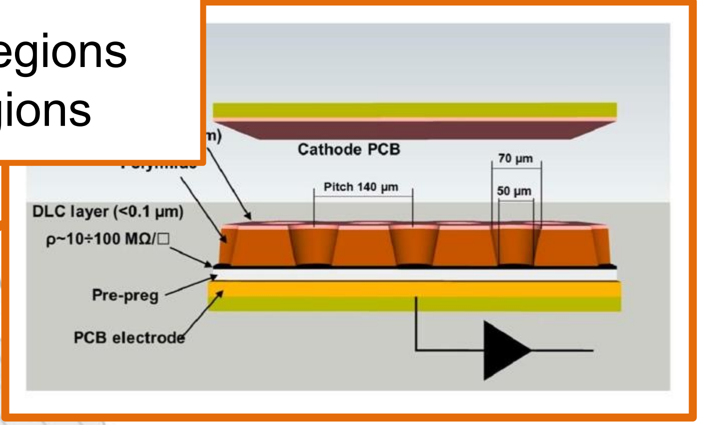
Results after PR only

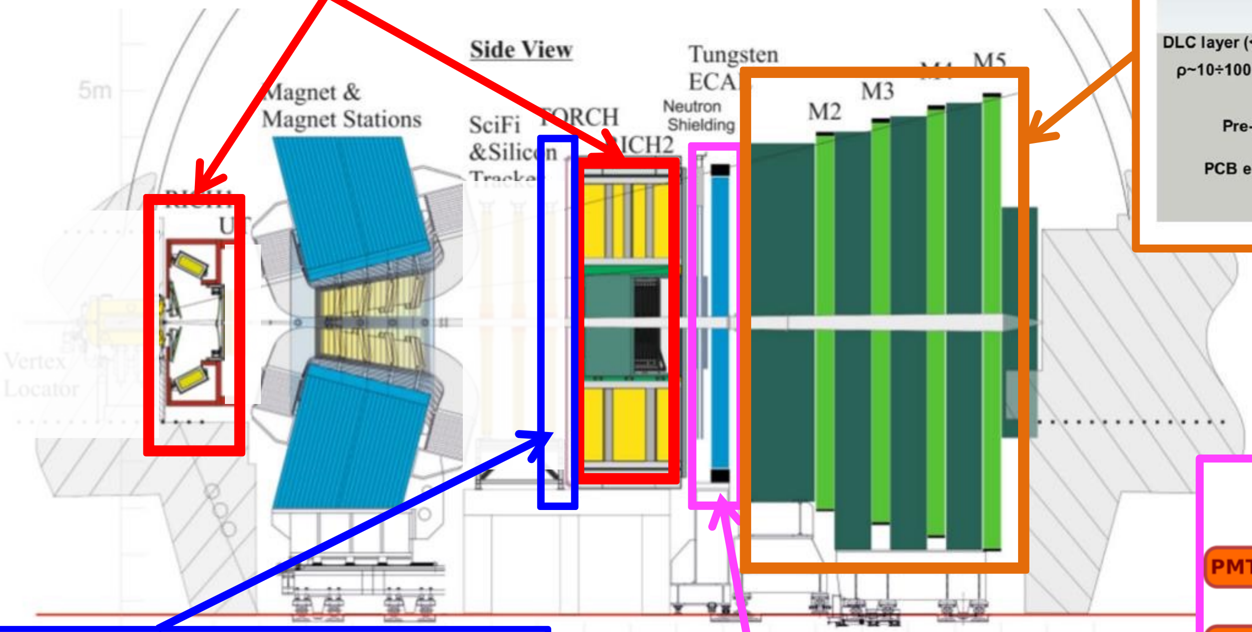
Particle Identification (PID) Detectors

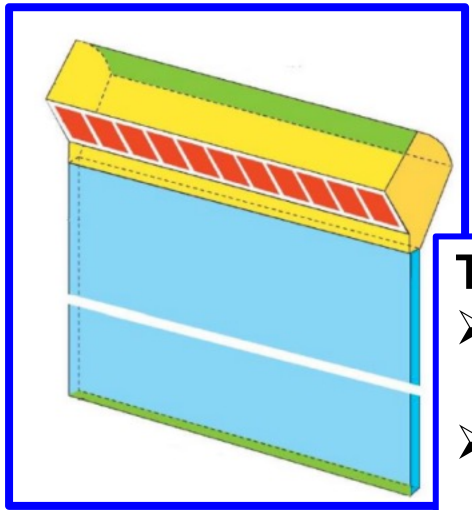


RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP

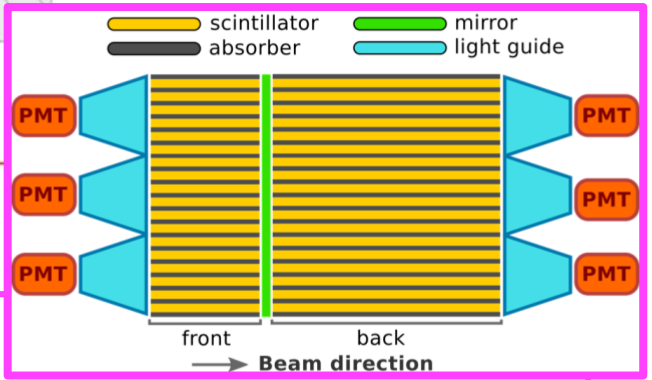
Muon
- μRWELL for inner regions
- MWPC for outer regions







TORCH
- To enhance PID capibilities for soft particles
- Measure light angle, path length and TOF

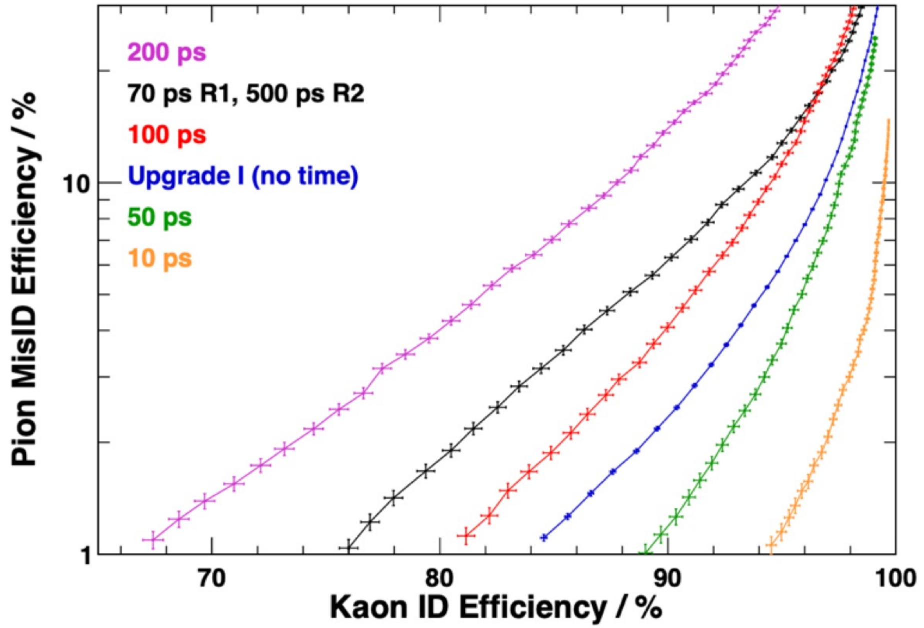


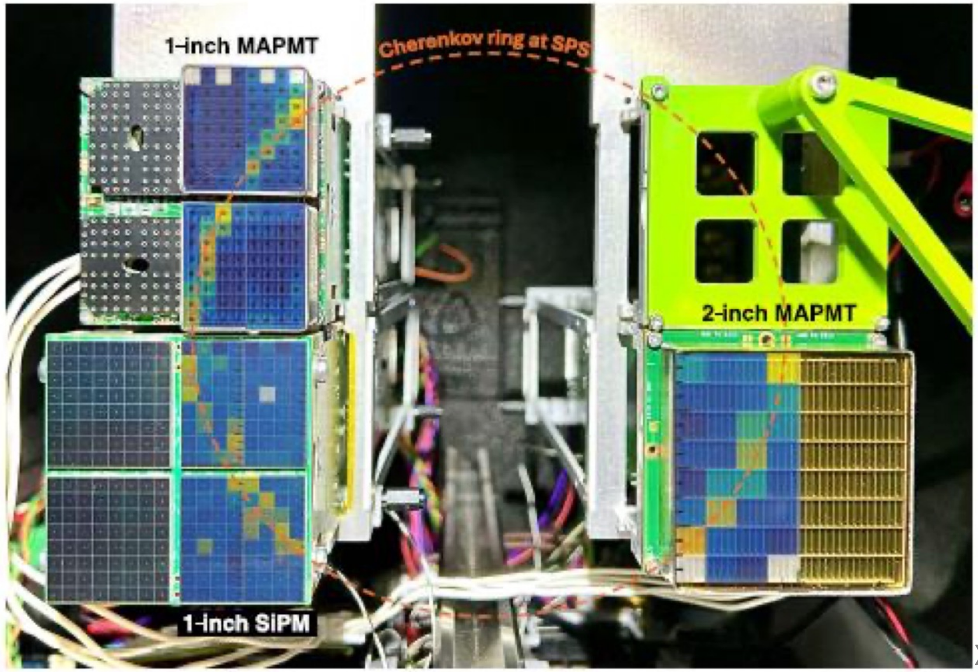
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals

RICH detectors with better timing

RICH 1 & 2 will remain same geometry, reduce pixel size using SiPM, MCP or LAPPD. MAPMT may be backup for low occupancy area

- ➢ Timie-stamping each photon with high precision, which is crucial to PID performance
- ➢ FastRICH has 25 ps time-stamping and digital output compatible with lpGBT



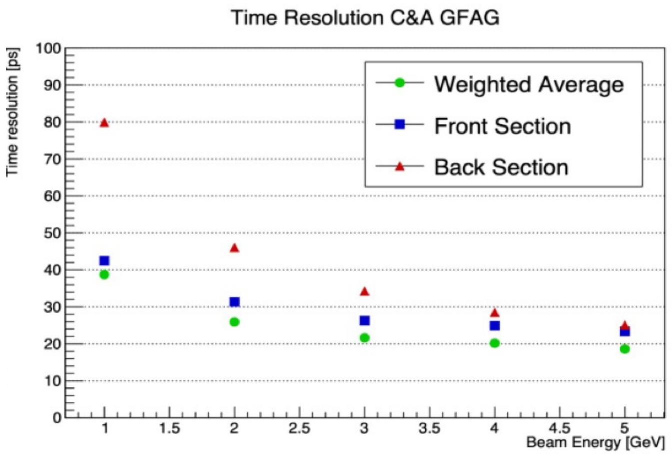


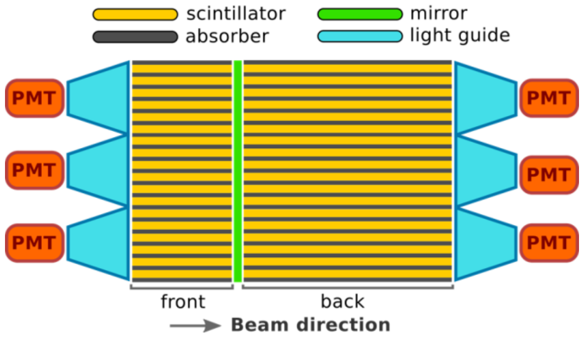
Upgrade	Photon Detector	FE ASIC	Time Resolution	TimeStamp Precision
I	MAPMT	CLARO	~ 150 ps	3.125 ns
I.b*	MAPMT	FastRICH	~ 150 ps	25 ps
II	SiPM, MCP LAPPD	FastRICH	< 100 ps	25 ps

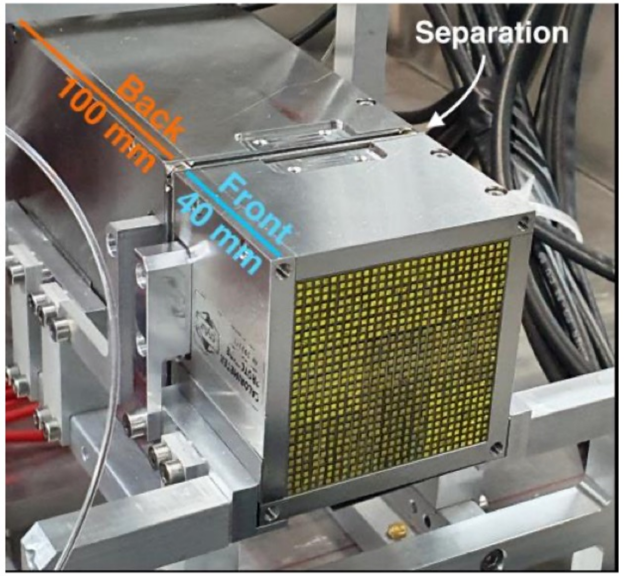
5D calorimeter with precision timing

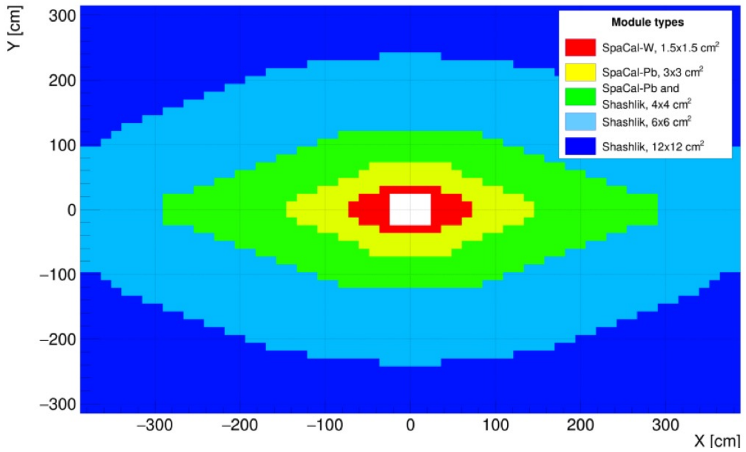
Key features: energy resolution ($10\%/\sqrt{E} \oplus 1\%$) , radiation hardness (up to 1 MGy), timing capability (tens of ps) and granularity.

- ➢ Combination of technologies for different regions from inner to outer
  - ❑ SpaCal W/GAGG
  - ❑ SpaCal Pb/Plastic Scintillator
  - ❑ Shashlik of different segmentations







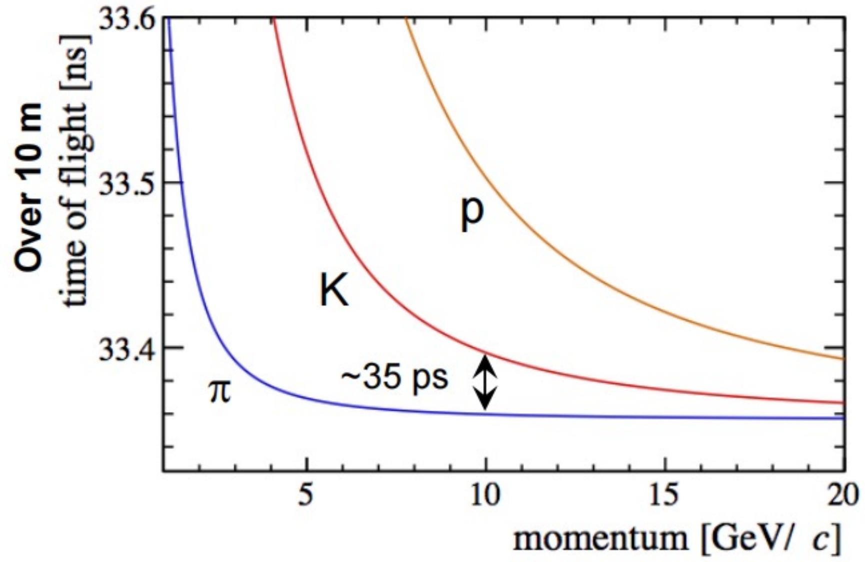


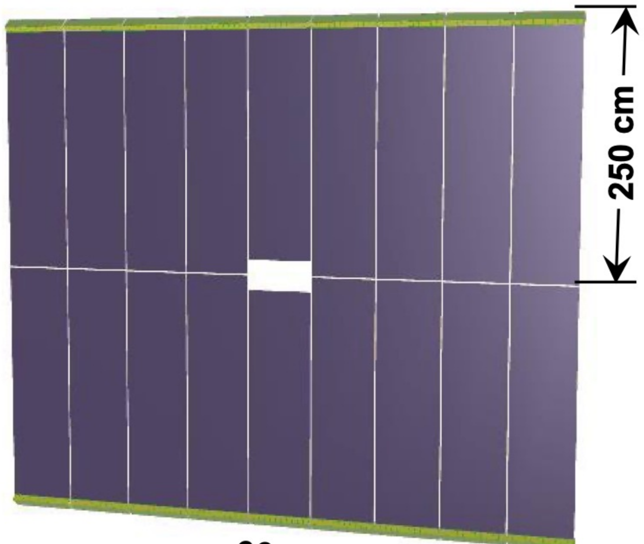
Cell size [cm²]	Module type	Modules	Cells
1.5 × 1.5	SpaCal-W with GAGG fibers	40	5120
3 × 3	SpaCal-Pb with plastic fibers	136	4352
4 × 4	SpaCal-Pb with plastic fibers	272	4896
	Shashlik with WLS fibers	176	3168
6 × 6	Shashlik with WLS fibers	448	3584
	Shashlik with new tiles and WLS fibers	896	7168
12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

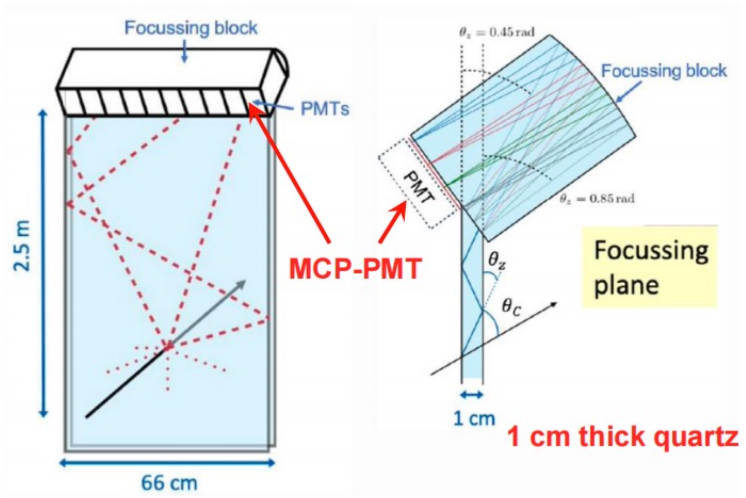
TORCH: Time of Flight Detector

Brand new detector to enhance low momentum PID capabilities, improve background suppression and flavor tagging.

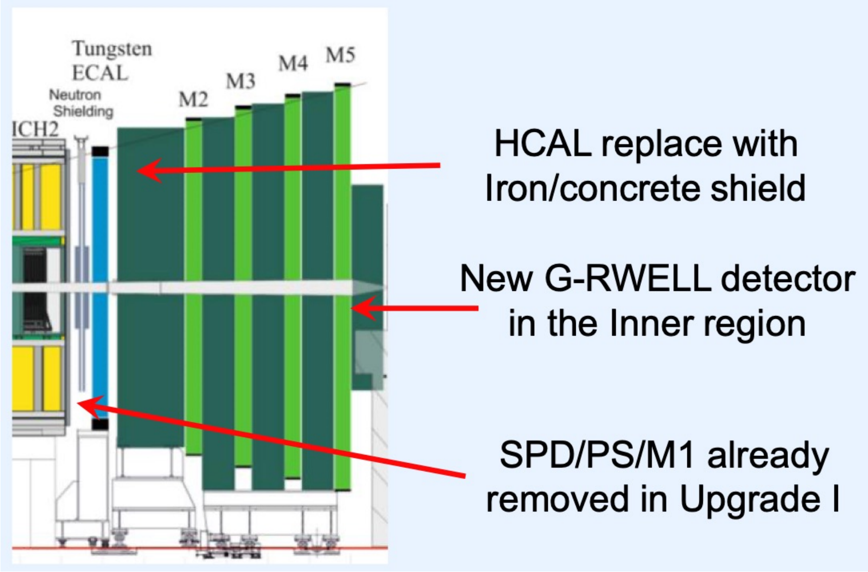
- Cherenkov photons produced by charged particles traversing quartz plane, then transported by total internal reflection to focusing block and detected with MCP-PMTs
- Measurement of Cherenkov angle, path length, and time of arrival.
- Aim for 10-15 ps resolution/track, needs ~30 photons, 70 ps/photon

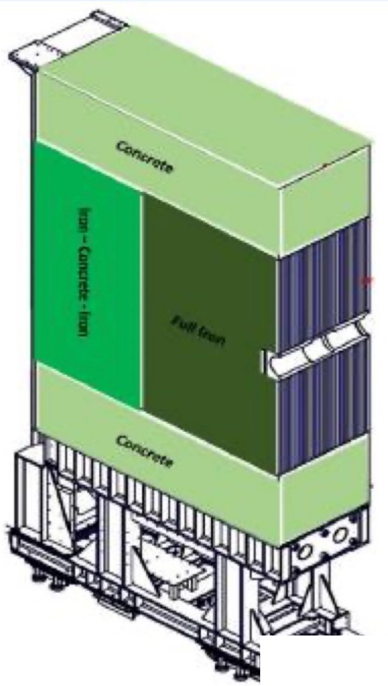


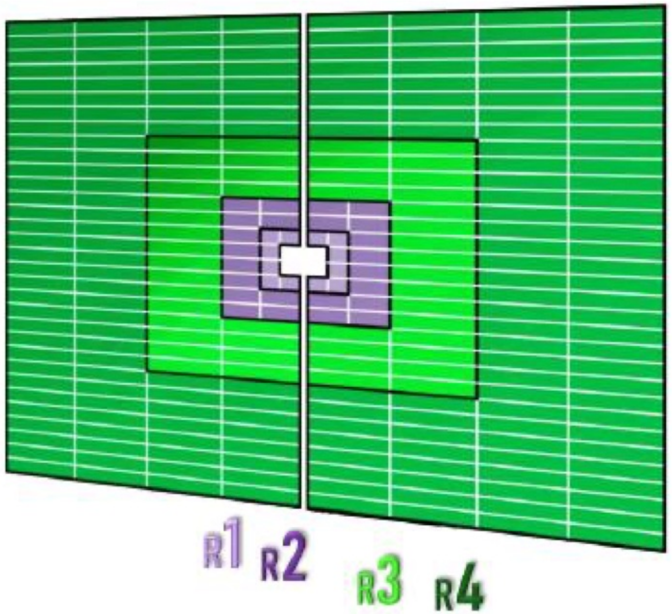




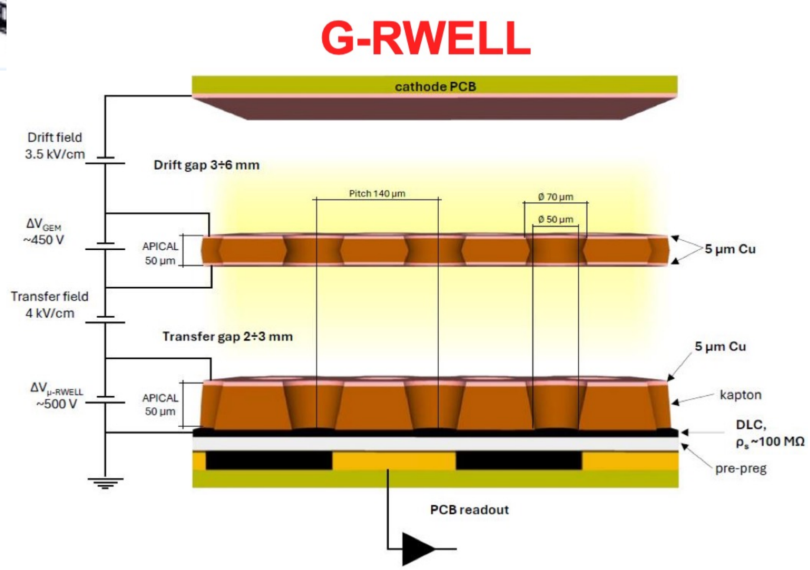
Muon detector





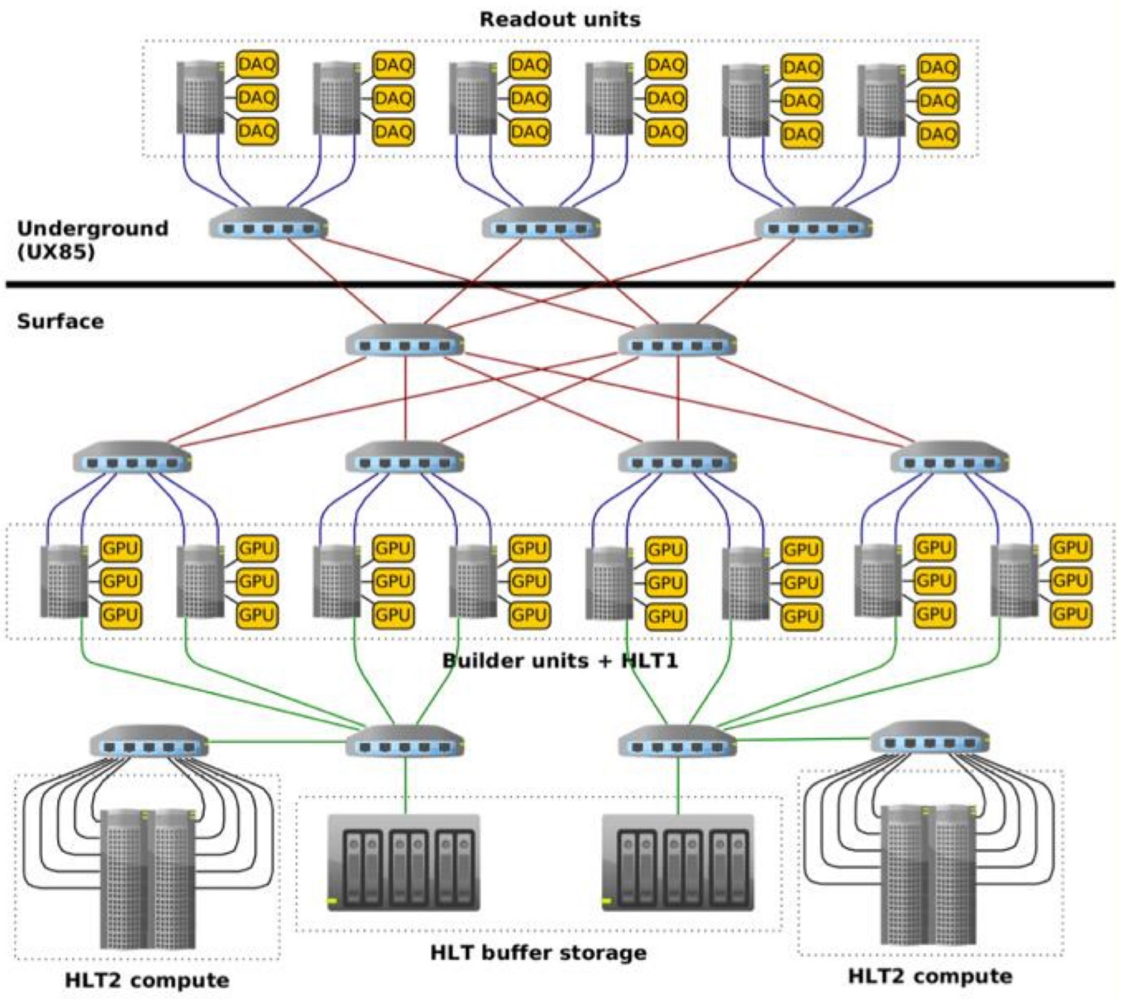


- Novel G-RWELL for the innermost region (R1, R2)
- Reuse existing MWPC in the outer region (R3, R4)
- A new readout scheme in all regions, for background reduction and a new FE electronics
- Additional shielding ($4\lambda_I$ -> $10\ \lambda_I$) will be installed in front of muon detector



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, (~ x5 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 Upgrade II are similar to ATLAS and CMS Upgrade II of Run4
  - Coordination with WLCG and the HEP software Foundation on mitigation

Scoping Scenarios

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

Baseline $1.5 \times 10^{34}\,cm^{-2}\,s^{-1}$	Middle $1.0 \times 10^{34}\,cm^{-2}\,s^{-1}$	Low $1.0 \times 10^{34}\,cm^{-2}\,s^{-1}$
	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 $\times 1.7\,m^2$	as baseline	remove corners
	Magnet Stations	
4 panels fibres $\times 3.5\,m^2$	as baseline	remove
	Mighty-Pixel	
6 planes pixel $\times 2.1\,m^2$	6 planes pixel $\times 1.3\,m^2$	6 planes pixel $\times 1.3\,m^2$
	Mighty-SciFi	
12 planes fibres	12 planes fibres	12 planes fibres
$25.9\,m^2$/plane	shorter, $23.7\,m^2$/plane	narrower, $18.9\,m^2$/plane

Baseline $1.5 \times 10^{34}\,cm^{-2}\,s^{-1}$	Middle $1.0 \times 10^{34}\,cm^{-2}\,s^{-1}$	Low $1.0 \times 10^{34}\,cm^{-2}\,s^{-1}$
	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

Very large samples of b hadrons

$9\ fb^{-1}$			Upgrade I	$50\ fb^{-1}$	Enhancement		Upgrade II	$250\ fb^{-1}$
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024 2025 2026	2027 2028 2029	2030 2031 2032 2033	2034 2035	2036 2037 2038 2039 2040 2041

Updated from Bernlochner, MFS, Robinson, Wormser, RMP, 94, 015003 (2022)

Experiment	*BABAR*	Belle	Belle II	LHCb Run 1	LHCb Run 2	LHCb Runs 3–4	LHCb Run 5
Completion date	2008	2010	2035	2012	2018	2032	2041
Center-of-mass energy	10.58 GeV	10.58/10.87 GeV	10.58/10.87 GeV	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	1.05	1.05/0.34	1.05/0.34	$(3.0/3.4)\times10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	424	711/121	$(50/4)\times10^3$	3	6	50	250
B^0 mesons [10^9]	0.47	0.77	50	100	350	3,200	16,000
B^+ mesons [10^9]	0.47	0.77	50	100	350	3,200	16,000
B_s^0 mesons [10^9]	-	0.01	0.5	24	84	760	3,800
Λ_b^0 baryons [10^9]	-	-	-	51	180	1,600	8,100
B_c^+ mesons [10^9]	-	-	-	0.8	4.4	24	120

Upgrade I Upgrade II

LHCb has access to **large samples** of **b hadrons** other than b **mesons**

Expected physics results @ LHCb 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
α_γ($\Lambda_b^0 \to \Lambda\gamma$)	$^{+0.17}_{-0.29}$	[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

LHCC-2021-012

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
- Exotic search
- Heavy ions and fixed target

Success of the physics programme relies on

- ➢ HL-LHC providing LHCb ~ 50 fb^{-1}/year during Run 5
- ➢ A detector with similar or better performance as the present one for Upgrade I

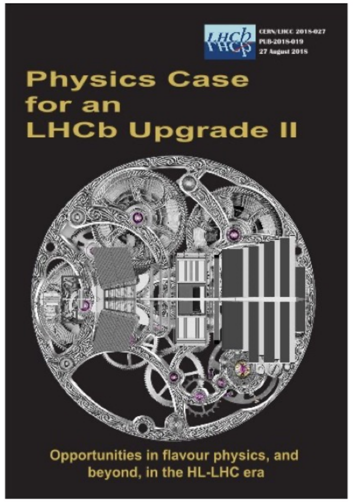
Summary

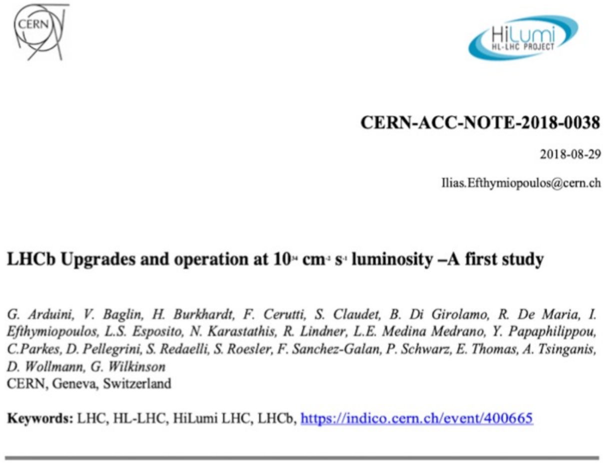
LHCb
- ➢ Upgrade I: completed
- ➢ Upgrade II: starts in LS4, R&D now

LHCb Upgrade II to fully exploit HL-LHC for flavor physics and beyond
- ➢ FTDR approved and now in R&D phase

  Next: TDR @2026, construction, installation and eventually operation for physics

More physics results can be expected from LHCb





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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

- ➢ Expression of Interest, LHCC-2017-003
- ➢ Physics case, LHCC-2018-027
- ➢ Accelerator study, CERN-ACC-2018-038
- ➢ Framework TDR, CERN-LHCC-2021-012

Thank you for your attention

感谢会务组

祝“味物理讲座”越办越好