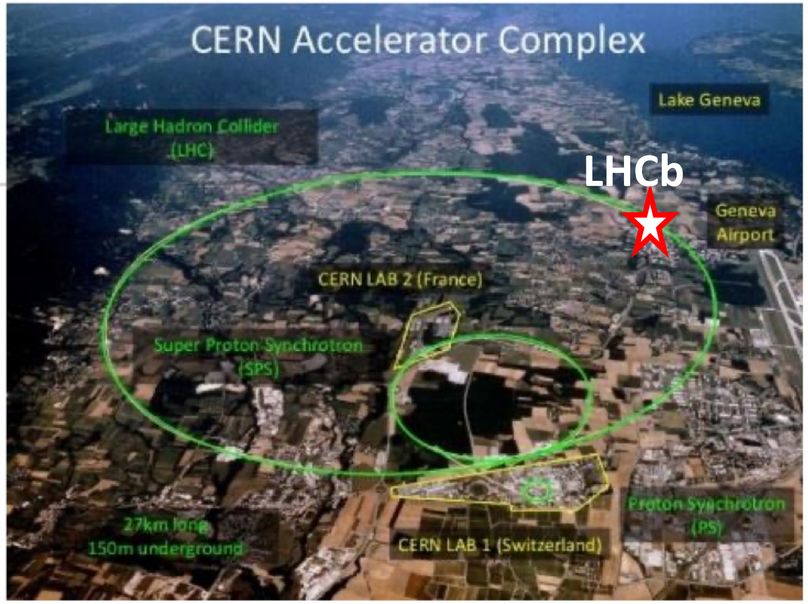
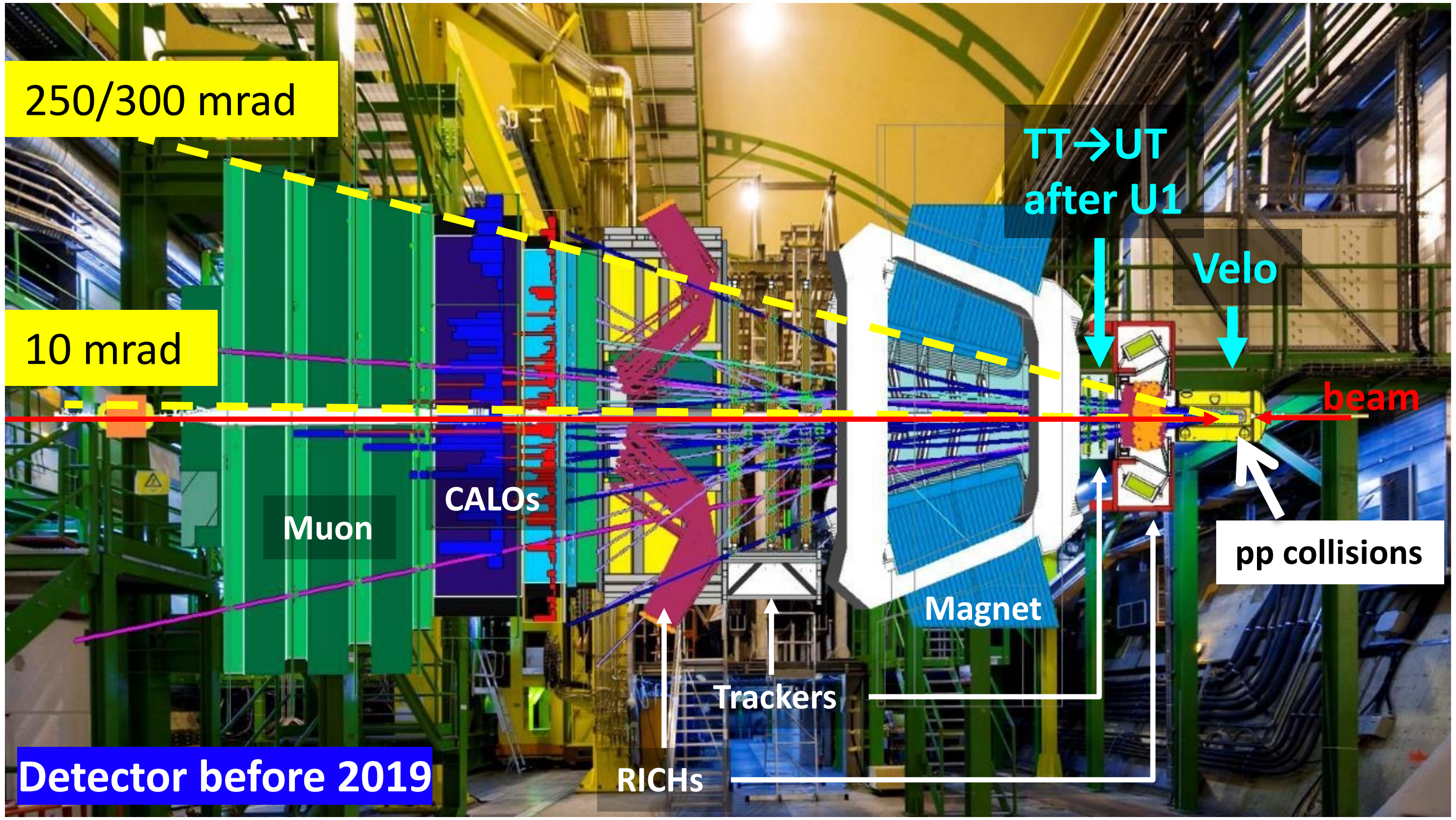
LHCb upgrade II

Xuhao Yuan (IHEP, CAS)
On behalf of LHCb collaboration

2024-04-09

LHCb: a forward spectrometer @ LHC





Main physics goal

- To study b & c sectors on CPV, rare decays, new physics...

$\Delta p/p = 0.5\%$ @ < 20 GeV$/c$, 1% @ < 200 GeV$/c$

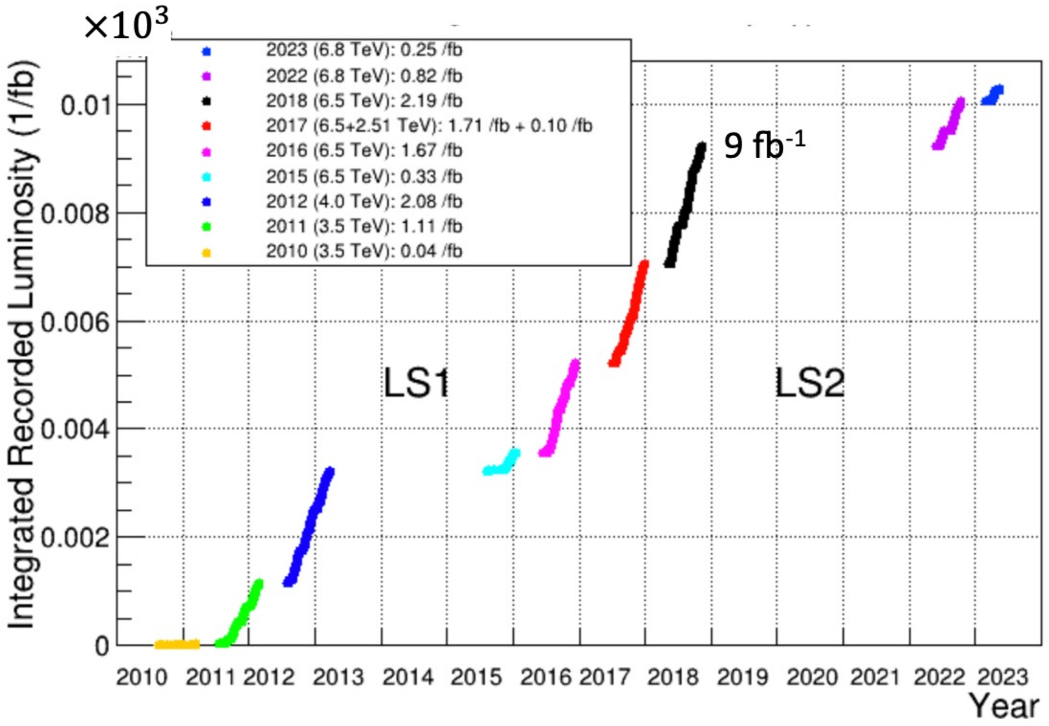
IP resolution ~ $15 + 29/p_T$ [GeV$/c$] μm

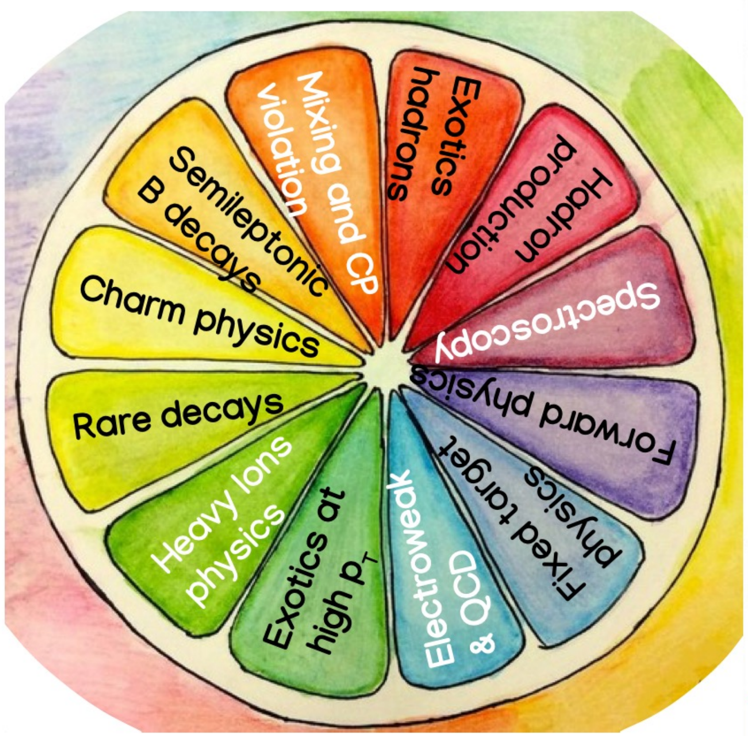
Decay time resolution 45 fs ($B_s \to J/\psi\phi$)

Kaon ID ~ 95% for 5% $\pi \to K$ mis-ID probability

LHCb physics performance in Run 1 & 2

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





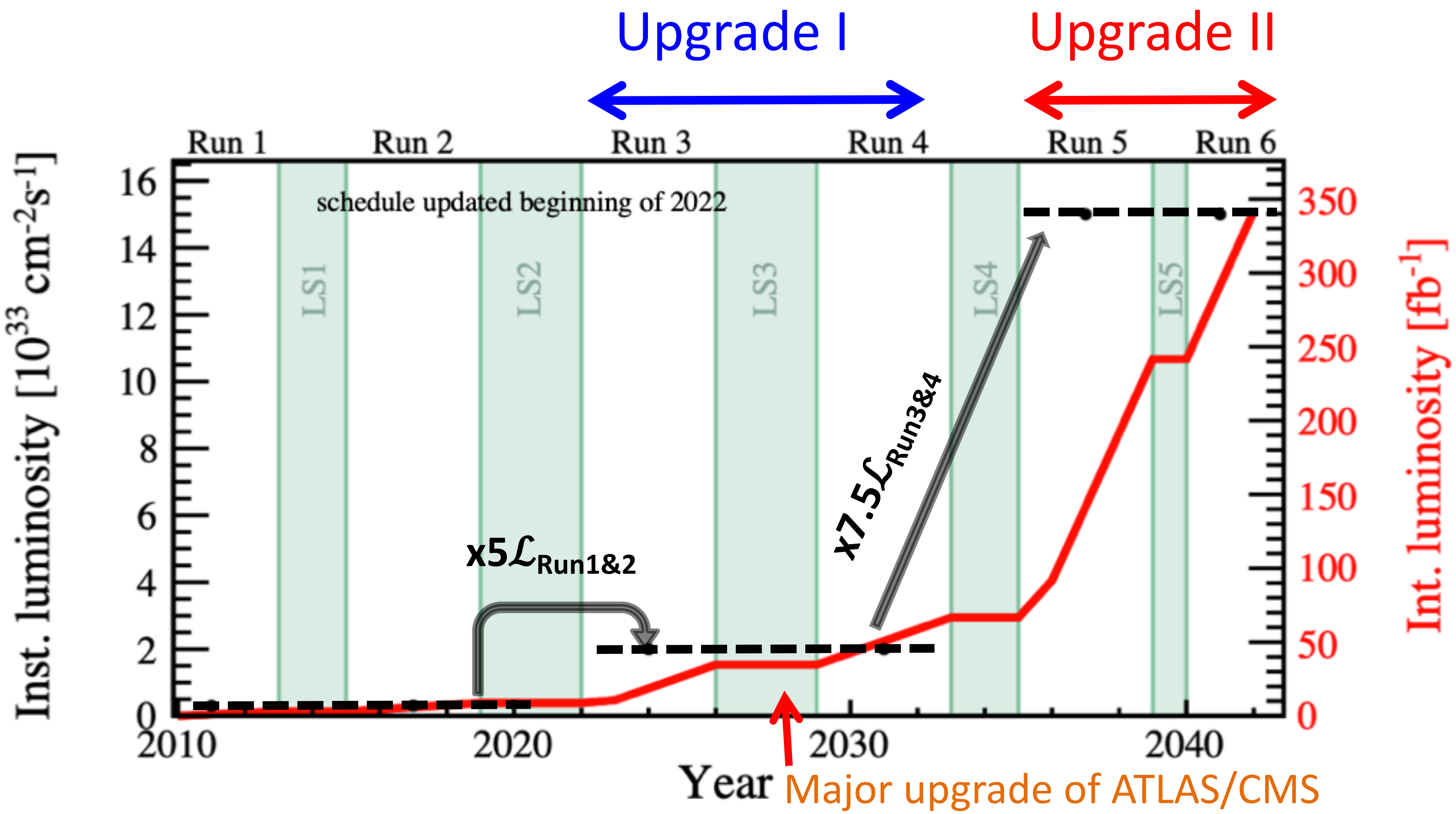
More physics results reported by my LHCb colleagues
Chenxi Gu,
Cesar Da Silva,
Camilla De Angelis,
Alessandro Bertolin,
Chen Chen,
Cynthia Nunez

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
$\mathcal{L}_{max}$~1.5x10^{34} cm^{-2}s^{-1}
$\mathcal{L}_{int}$~300 fb^{-1}

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

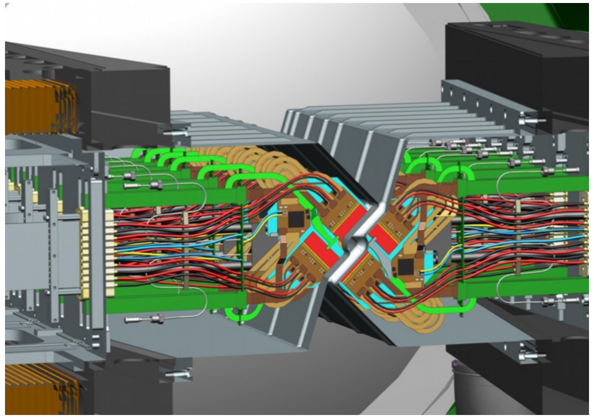


Major upgrade of ATLAS/CMS
LHCb also plan enhancements (U1b)

Upgrade I: a brand new detector

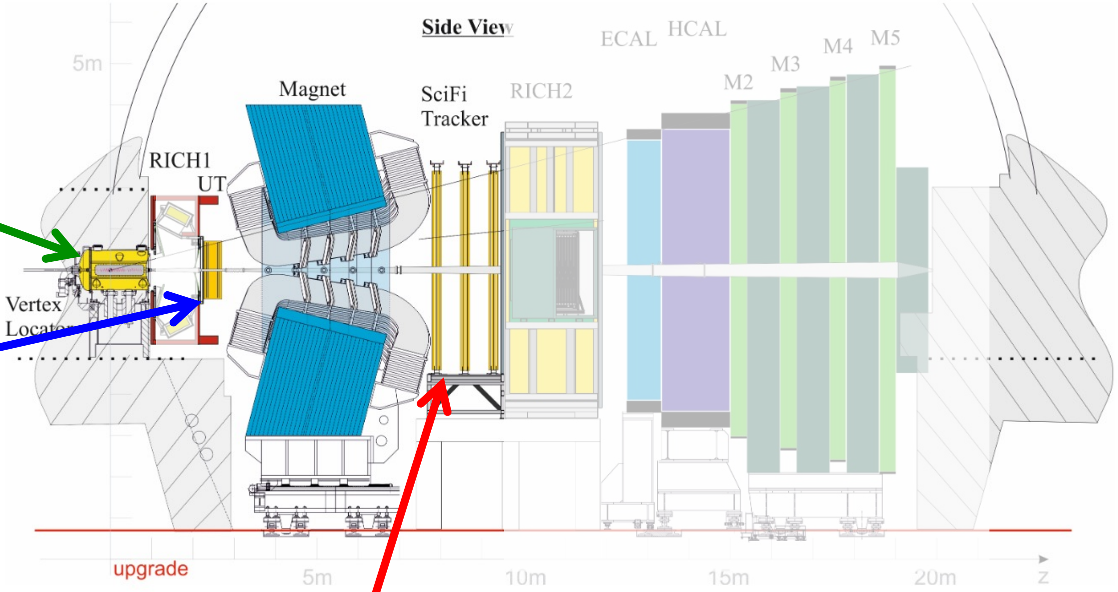
Higher luminosity ($5x\mathcal{L}_{Run1\&2}$) results in

- Higher rate, pile up, occupancy, fluence



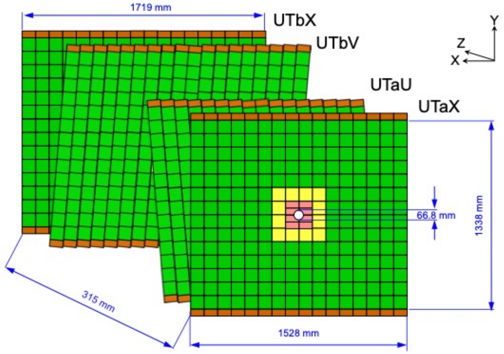
VELO: hybrid pixel detector

- Closer to the beam (from 8.2 mm to 5.1 mm)
- New RF box
- MAX fluence: $8x10^{15}$ $MeVn_{eq}cm^{-2}$



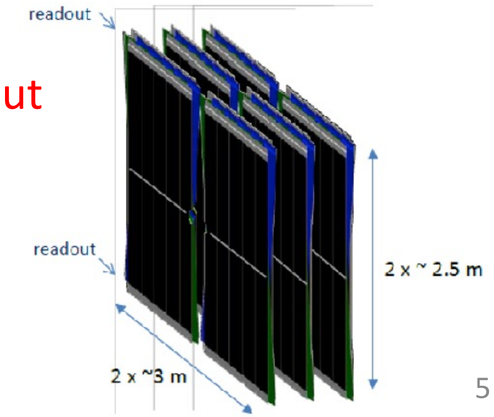
UT: Si Strip detector

- Higher coverage, segmentation, resolution
- Speed up tracks reconstruction & reduce $P_{GhostTrk}$

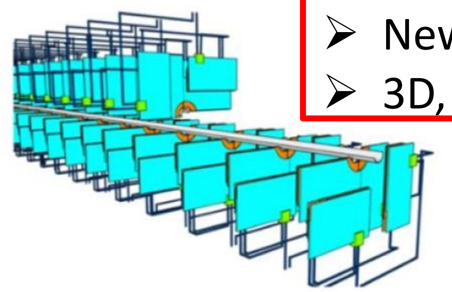


SciFi: Scintillating fibers detector

- 3 station with 4 detection layers
- 2x2.5 m long modules with Readout SiPMs at the outer edge

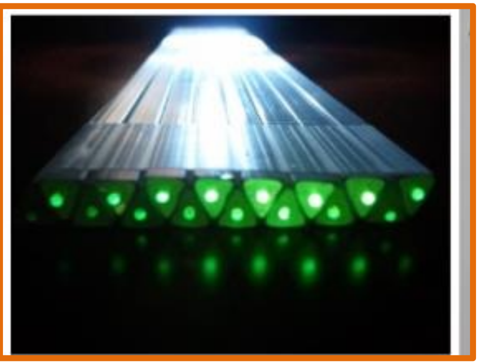


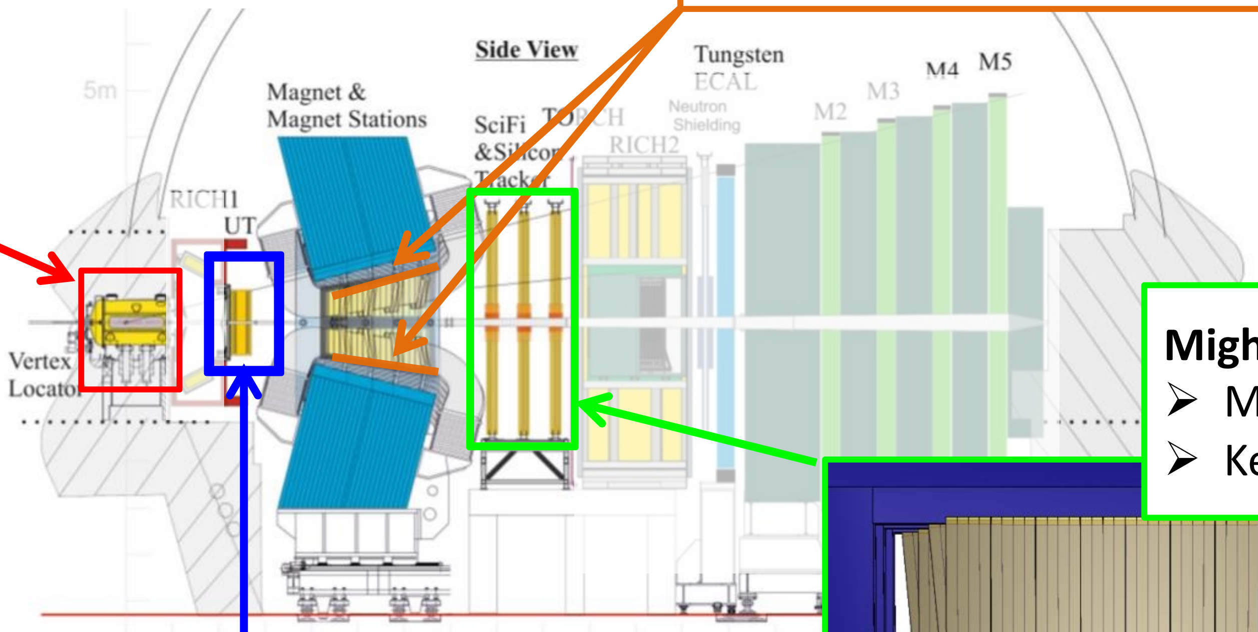
The Tracking System in Upgrade II

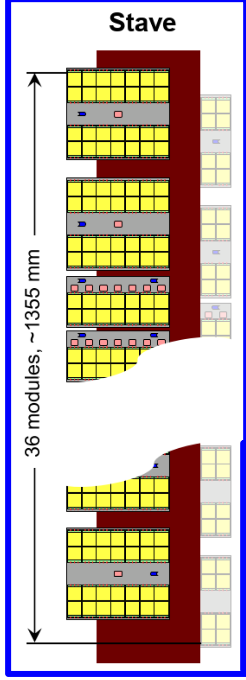


Vertex Locator (VELO)
- Pixel with timing
- New RD-foil
- 3D, LGAD, 28 nm

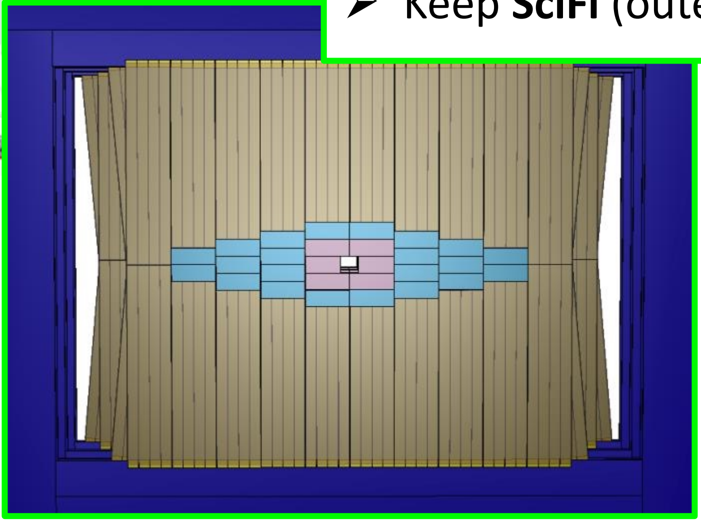
Magnet Stations (MS)
- Scintillating bar
- Low P particles







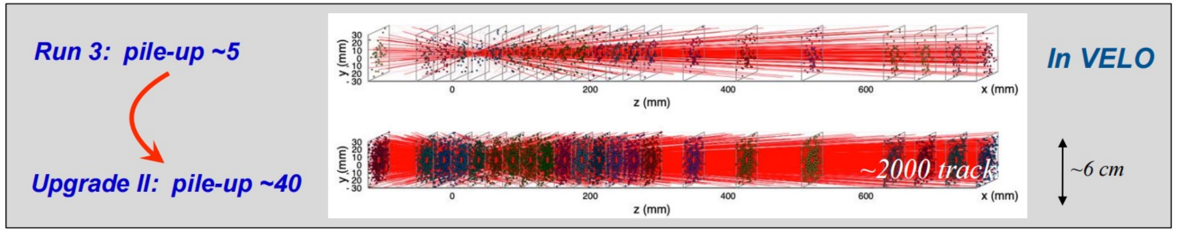
Might Tracker (MT)
- MAPS CMOS pixel (inner)
- Keep **SciFi** (outer)

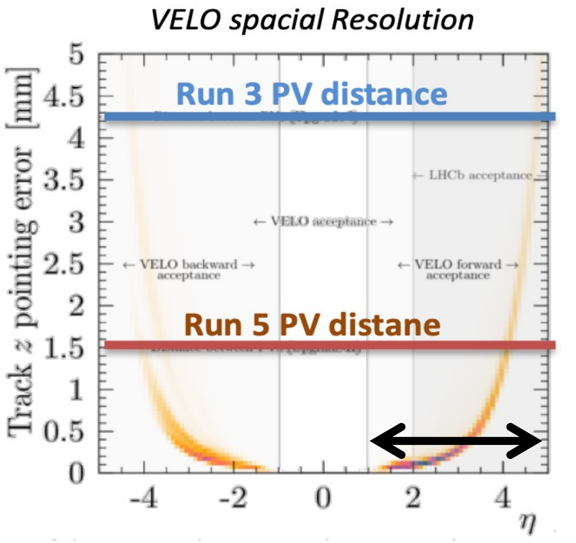


Upstream Tracker (UT)
- MAPS CMOS pixel
- Radiation tolerant

High pile-up in Upgrade II

In Upgrade II
$\mathcal{L}_{max}$~1.5x10^{34} $cm^{-2}s^{-1}$
$\mathcal{L}_{int}$~300 fb^{-1}
~ 40 visible interactions/Xing

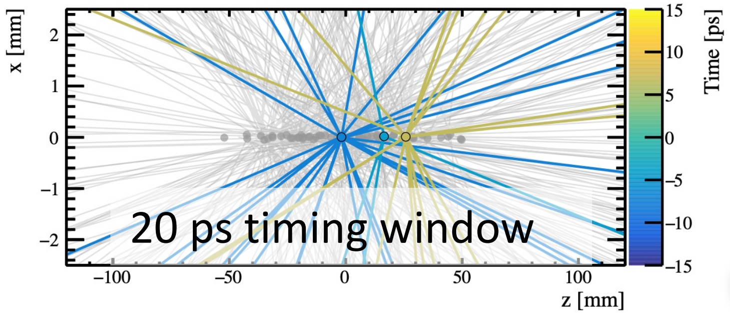


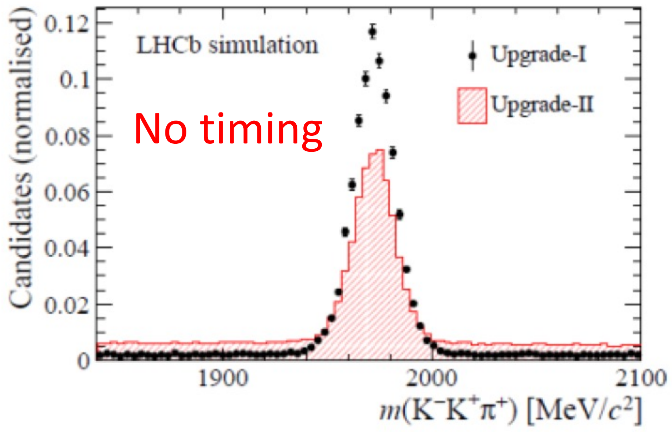


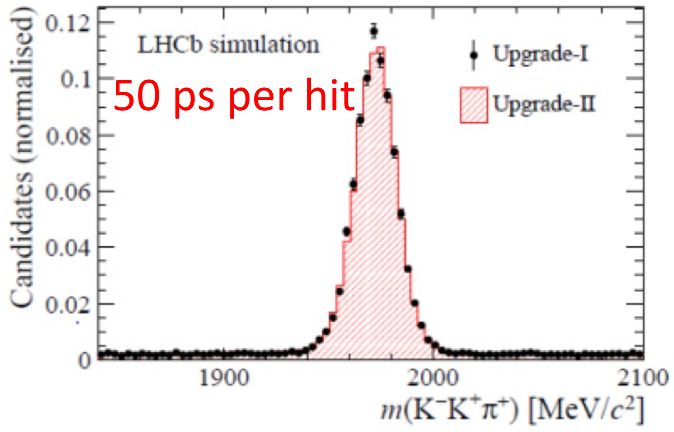
VELO Acceptance

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

VELO: 4D detector with timing







σ_t(Track)=20 ps restores the performance to U1 level

Velo R&D

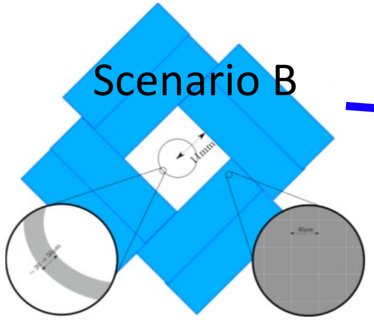
Balance btw Φ_{eq} and σ_{Hit}

- $\sigma_{IP} = \sigma_{extrap} + \sigma_{scatter}$
- Two different layouts optimized

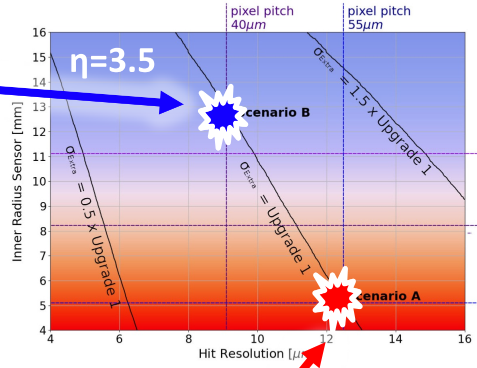
Sensor R&D, candidates: 3D pixel, Planar, LGAD, CMOS …

- timing ~50 ps
- Radiation hardness (max ~$6\times10^{16} n_{eq}/cm^2$)

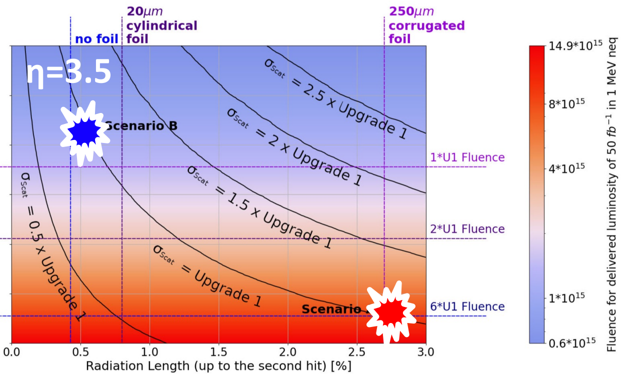
- ❑ R&D on 28 nm technology: PicoPix, IGNITE
- ❑ Replaceable modules, thinner or no RF foil, robust 3D printed Ti cooling substrate...

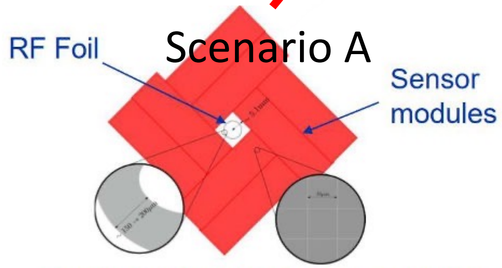


Extrapolation Term

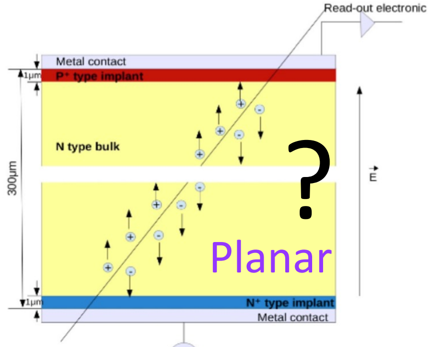


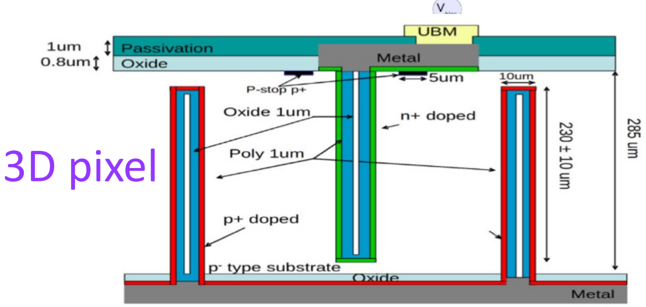
Scattering Term



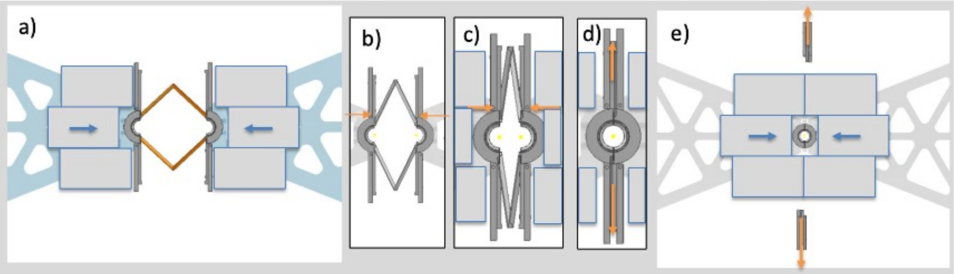


Sketch of a Scenario A using the current sensor modules





Additional shielding when RF foil in open position



Upgrade II UT

Channel occupancy [%]

0.42	0.45	0.47	0.49	0.52	0.54	0.57	0.60	0.60
0.46	0.49	0.52	0.56	0.59	0.63	0.68	0.74	0.77
0.53	0.58	0.62	0.68	0.73	0.83	0.89	1.00	1.06
0.64	0.70	0.77	0.86	0.96	1.10	1.26	1.48	1.63
0.78	0.88	0.97	1.13	1.27	1.54	1.81	2.34	2.72
0.96	1.10	1.23	1.45	1.68	2.05	2.63	2.84	3.87
1.28	1.45	1.54	1.81	2.04	2.57	3.42	4.48	3.95 / 5.13

Beam pipe

Current UT optimized for $\mathcal{L}_{\text{Run 3\&4}}$

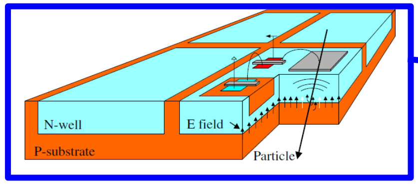
Upgrade II luminosity 1.5x10^{34} cm^{-2}s^{-1} (**x7.5 $\mathcal{L}_{\text{Run 3\&4}}$**)

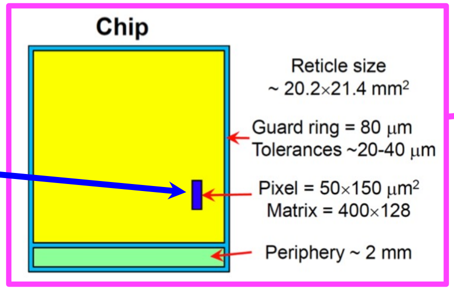
- ➢ The occupancy (max ~10%) will compromise the performance
- ➢ Radiation does (3x10^{15}n$_{eq}$/cm^2) too high for current sensor

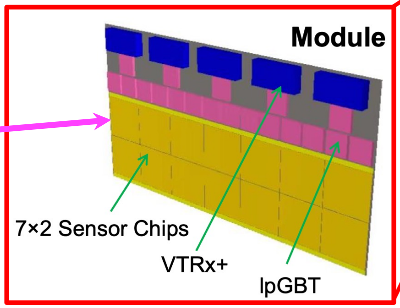
Upgrade II UT:

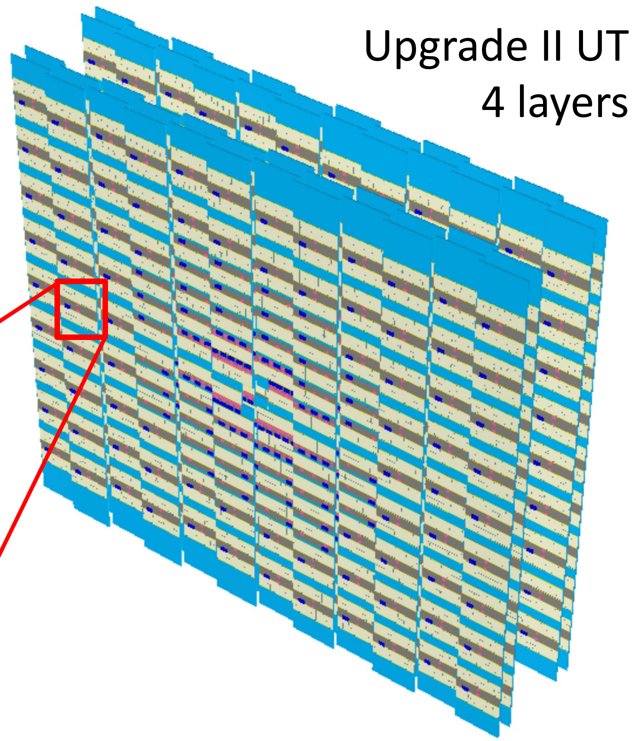
- ➢ CMOS MAPS technique applied
  Very promising and cost effective for large area pixel detectors.

Monolithic Active Pixel Sensor (MAPS)



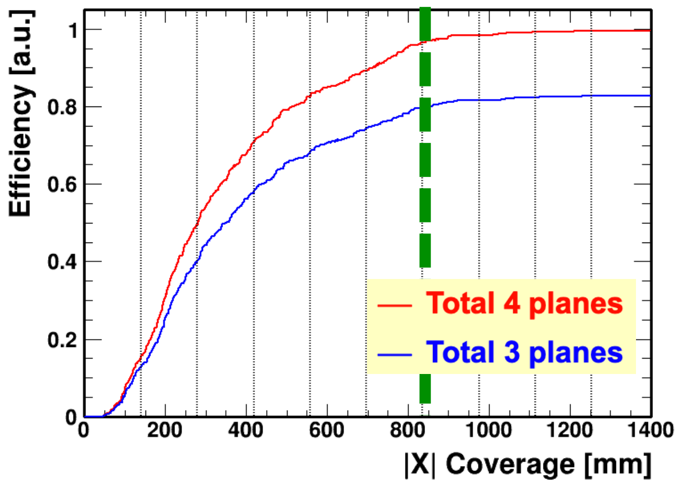




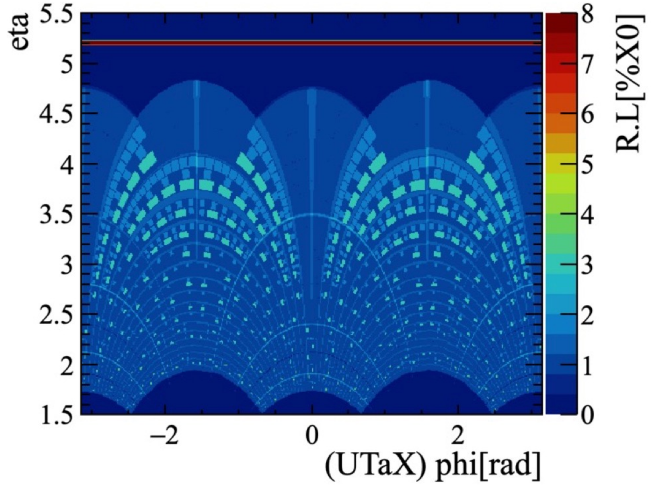


R&D status

Track efficiency vs X coverage



R.L. as functions of Φ and η

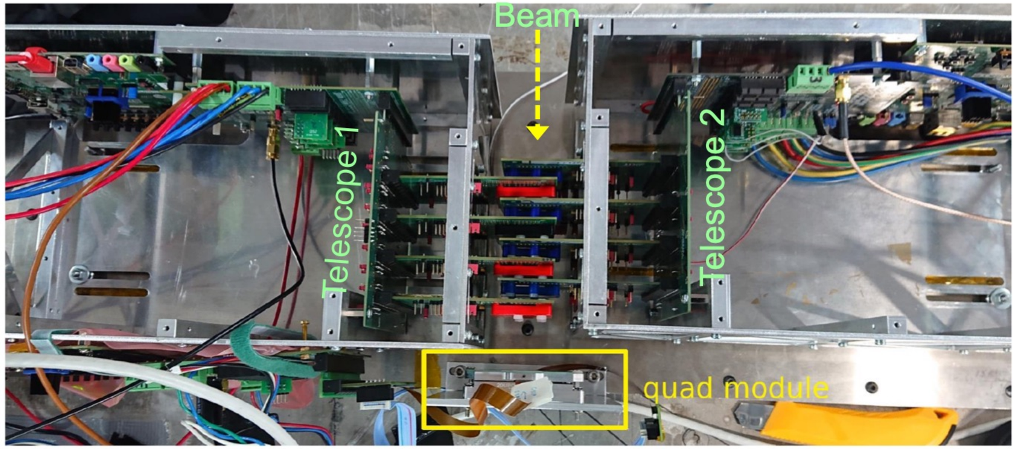


Upgrade II UT software

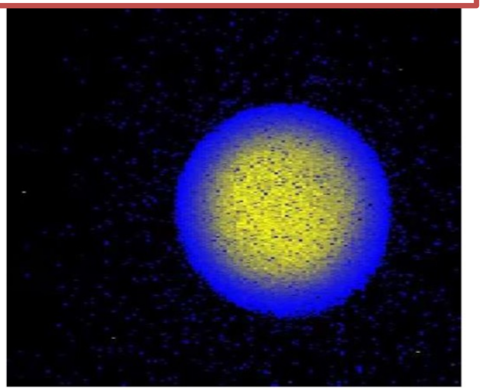
- Preliminary studies on
  - ❑ Track efficiency for $B^- \to D^0 K^-, D^0 \to K_s \pi^+ \pi^-, K_s \to \pi^+ \pi^-$ Optimizing UT coverage
  - ❑ Detector simulation and performance

Two choice of CMOS tech: HV-CMOS & Small electrode CMOS

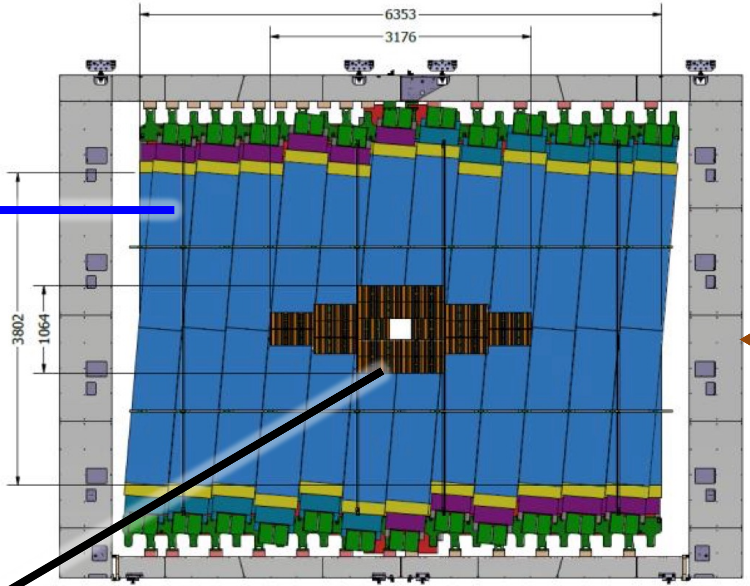
- Extensive tests using ATLASPix: lab test with cosmic ray and radioactive sources, testeam at DESY & CSNS @ 2022

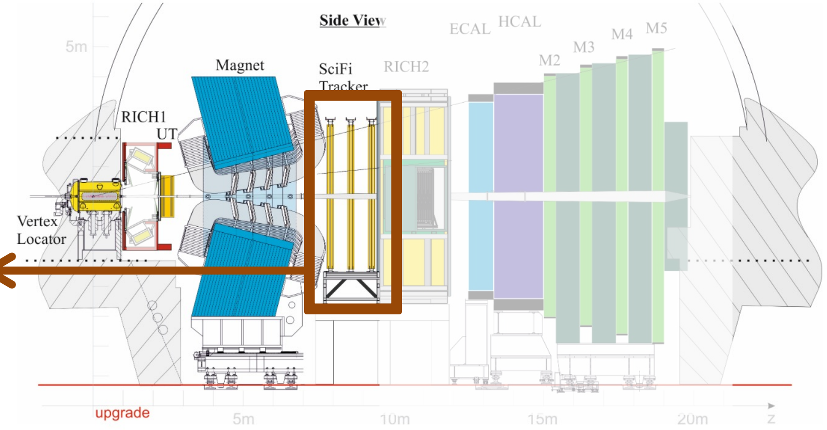


Hitmap with Fe55 source



SciFi and Mighty Tracker (MT)





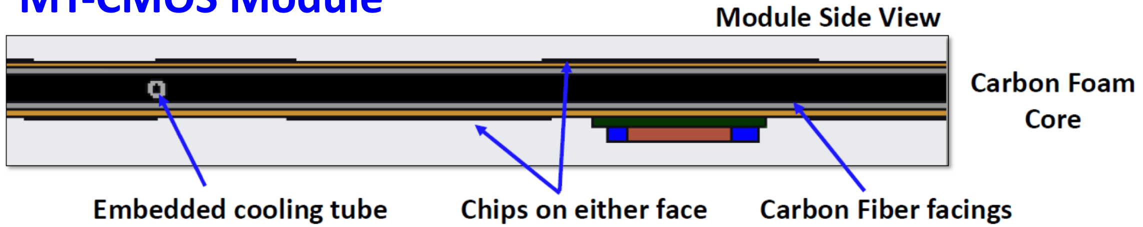
Keep SciFi design at outer region

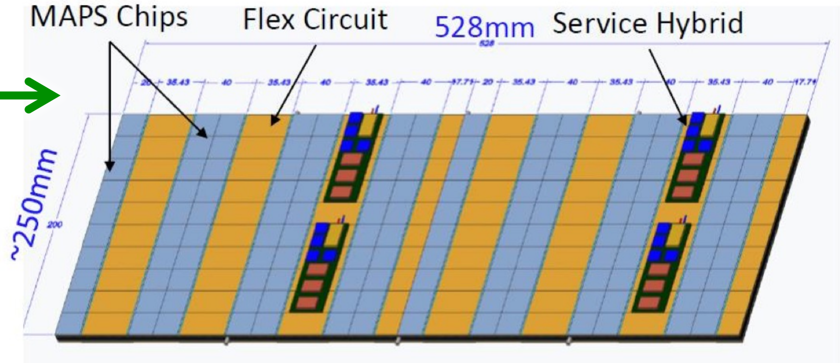
- Further away from beam
- Micro-lens on SiPM to enhance light collection
- Crypgenic cooling for SiPM: -40°C ⇒ -120°C

HV-COMS MAPS detector (same as UT)

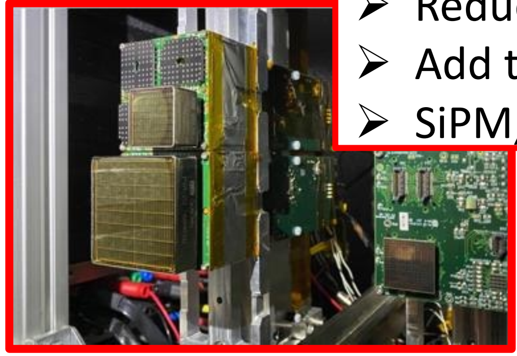
- 6 layers, 18 m^2 in total
- Pixel size ~50x150 μm2
- Upgrade the inner-most in Upgrade 1b

MT-CMOS Module



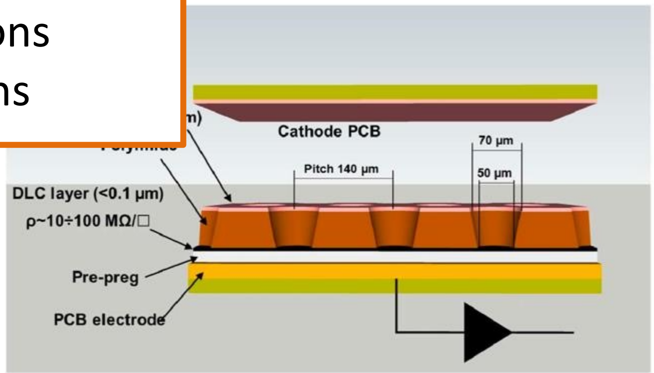


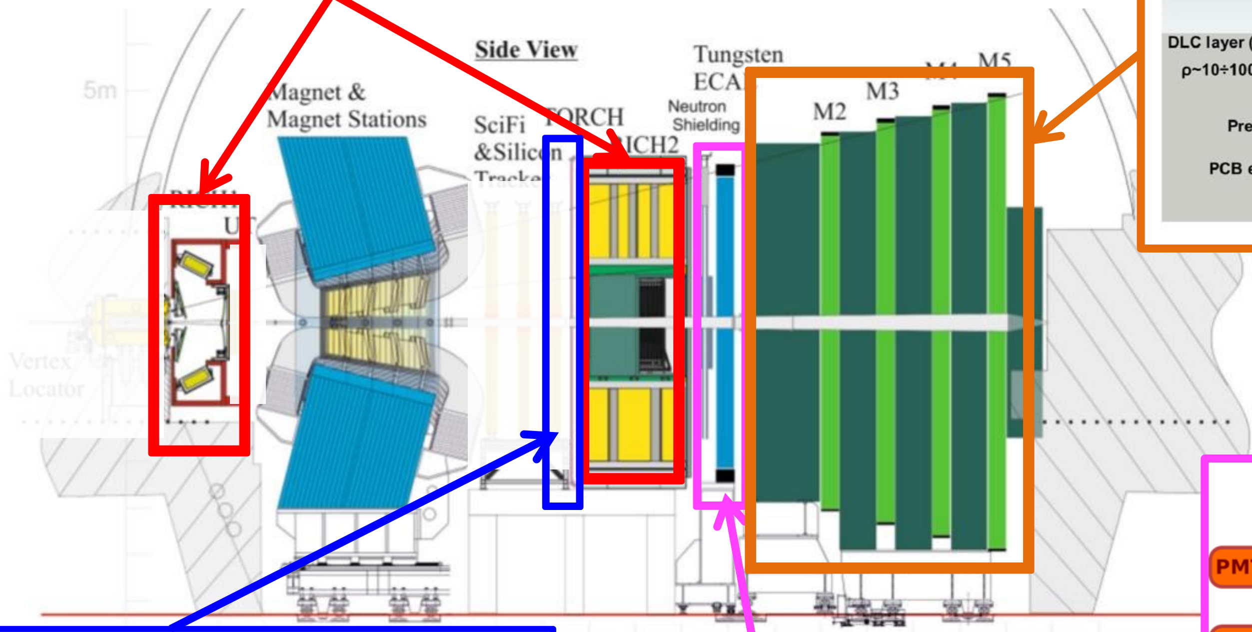
Particle Identification (PID) Detectors

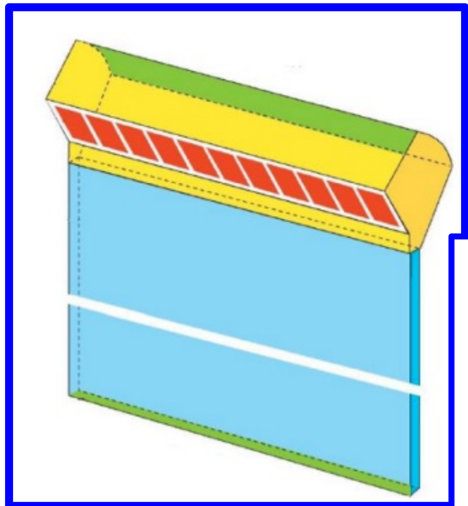


RICH1, RICH2
- Reduced pixel size
- Add timing information
- SiPM, MCP

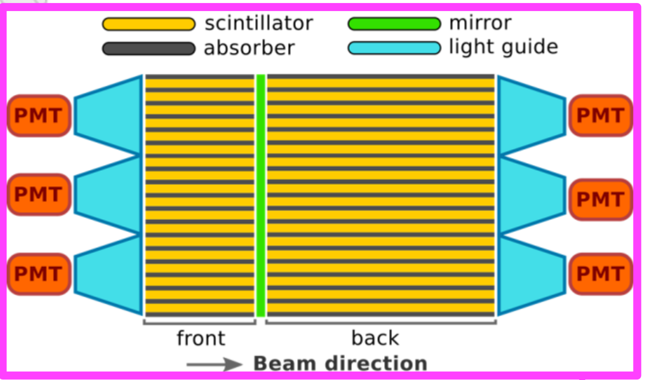
Muon
- μRWELL for inner regions
- MWPC for outer regions





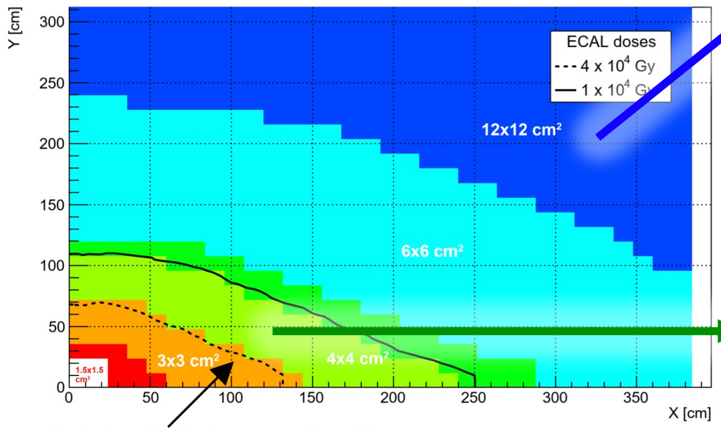


TORCH
- To enhance PID capibilities for soft particles
- Measure light angle, path lenth and TOF

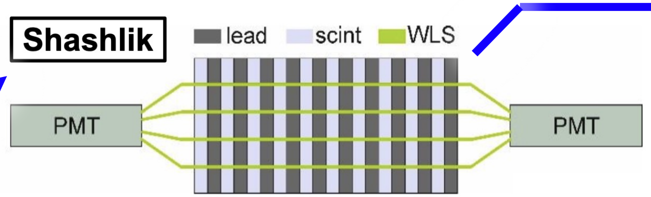


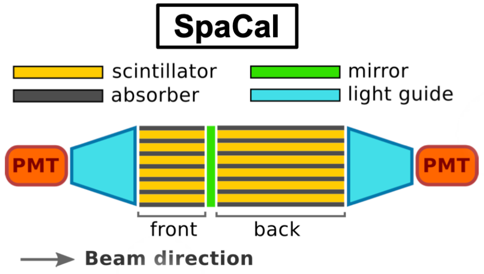
ECAL
- Space & time, longitudinal segmentation
- SPACAL with radiation hard crystals

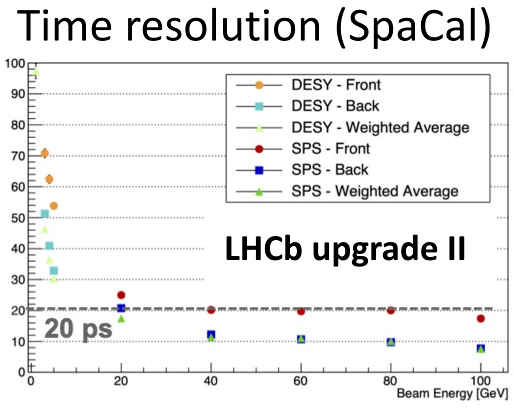
5D calorimeter with precision timing

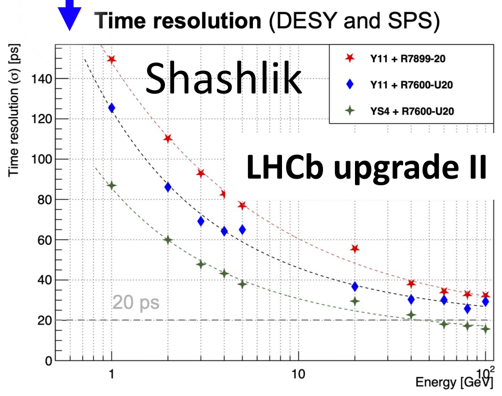


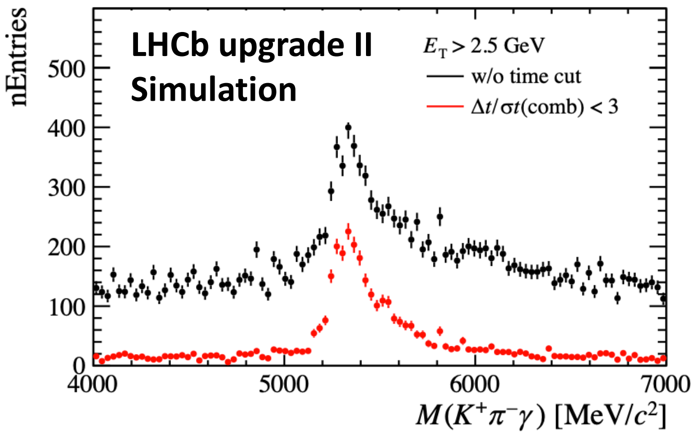
Radiation limit of current Shashlik technology

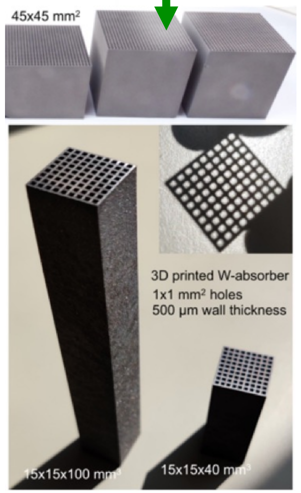












Key features: energy resolution ($10\%/\sqrt{E} \oplus 1\%$) , radiation hardness (up to 1 MGy), 20 ps timing capability and granularity.

- Multiple techs. for different regions from inner to outer
- Possibility of adding timing layer: Si layers.
- Possibility of replacing the inner-most modules at Upgrade 1b.

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_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	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
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A_{T}^{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

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

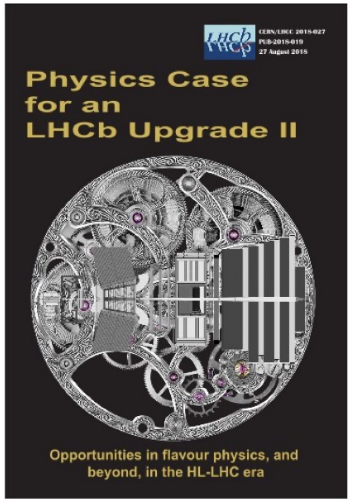
- ➢ HL-LHC providing LHCb ~ 50 fb^{-1}/year during Run 5&6
- ➢ A detector with similar or better performance as the present one for Upgrade I

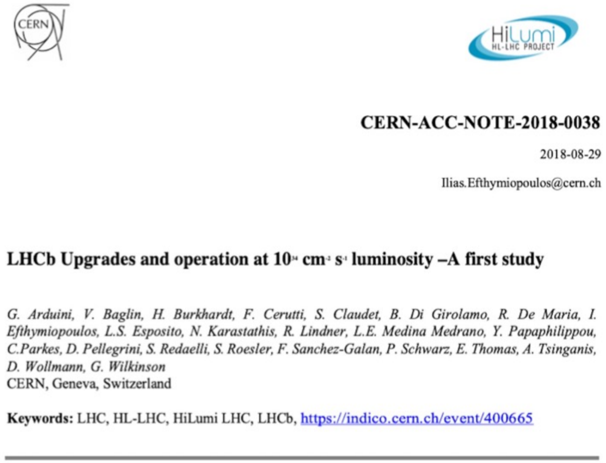
Summary

LHCb
- Upgrade I: installation 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

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- 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