Status of The LHCb Upgrade

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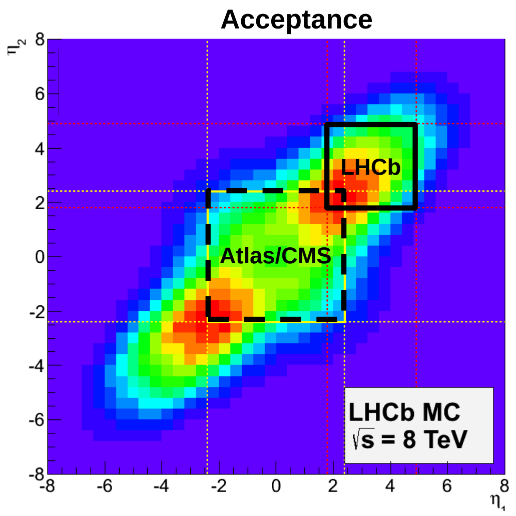
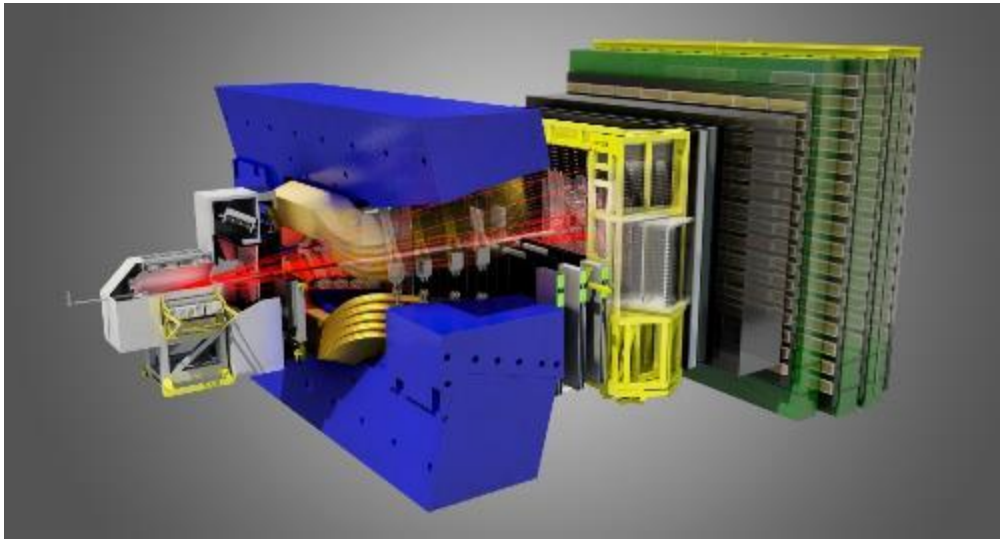
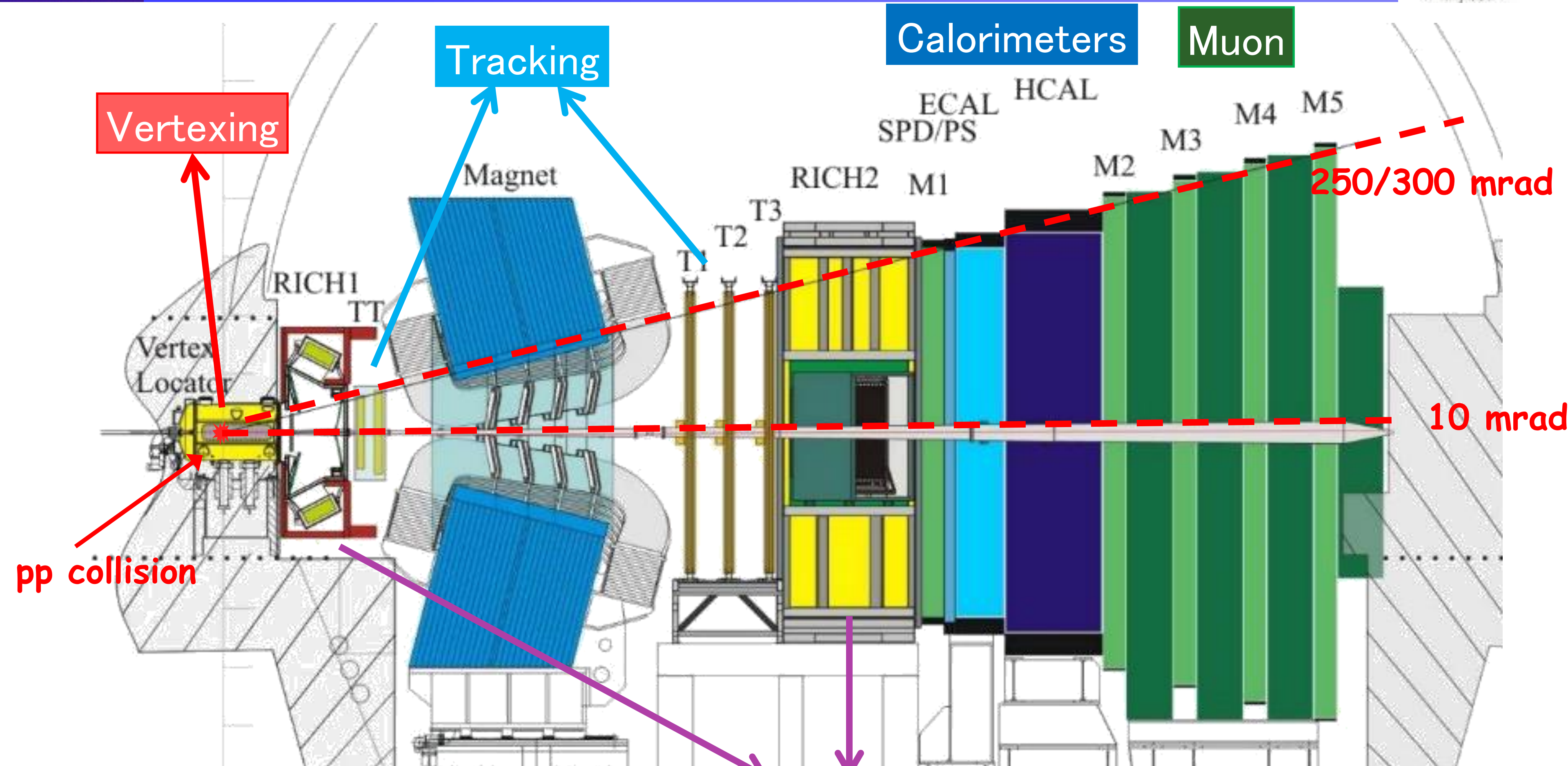
LHCb – A Forward Spectrometer

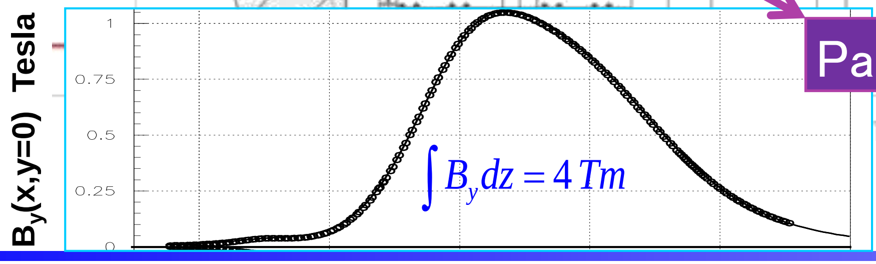
- The LHCb detector covers the forward region. This is driven by the physics goals: to study b & c sectors on CP-violation, rare decays, & search for new physics.
- Correlated production of $b\bar{b} \Rightarrow$ flavor tagging. Boost in Z $\Rightarrow$ decay length measurement.
- It provides precision measurements:
  - Spatial resolution ~ 4 μm @ vertex detector.
  - $\Delta p/p = 0.4\%$ at 5 GeV/c, 0.6% at 100 GeV/c.
  - Impact parameter resolution ~20 μm for high-pT tracks.
  - Decay time resolution $45\ fs$ (e.g. $B_s \rightarrow J/\psi\ \varphi$).
  - Excellent particle identification.





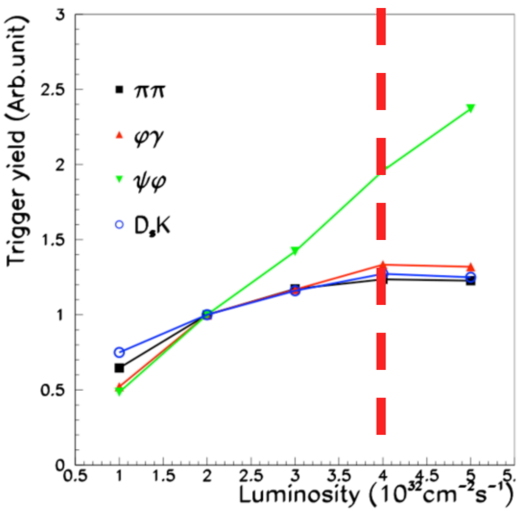
The LHCb Detector Before LS2

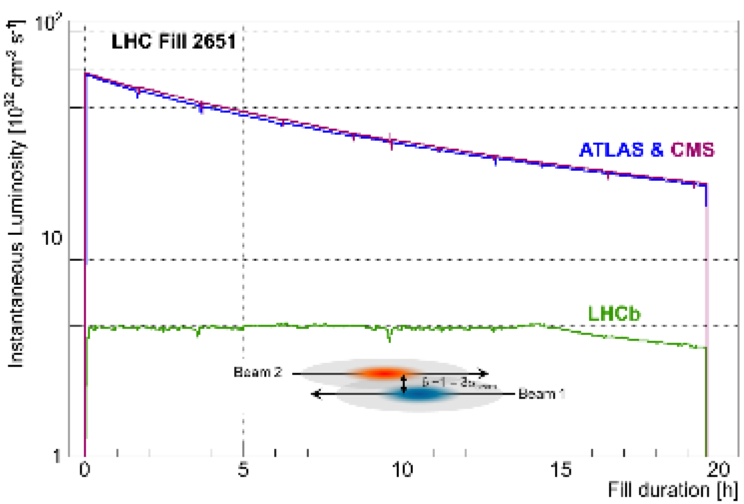


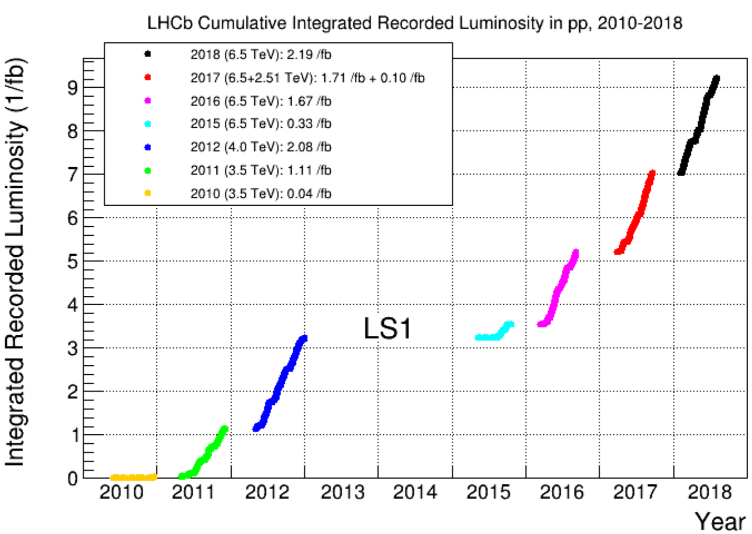


LHCb Operation Before LS2

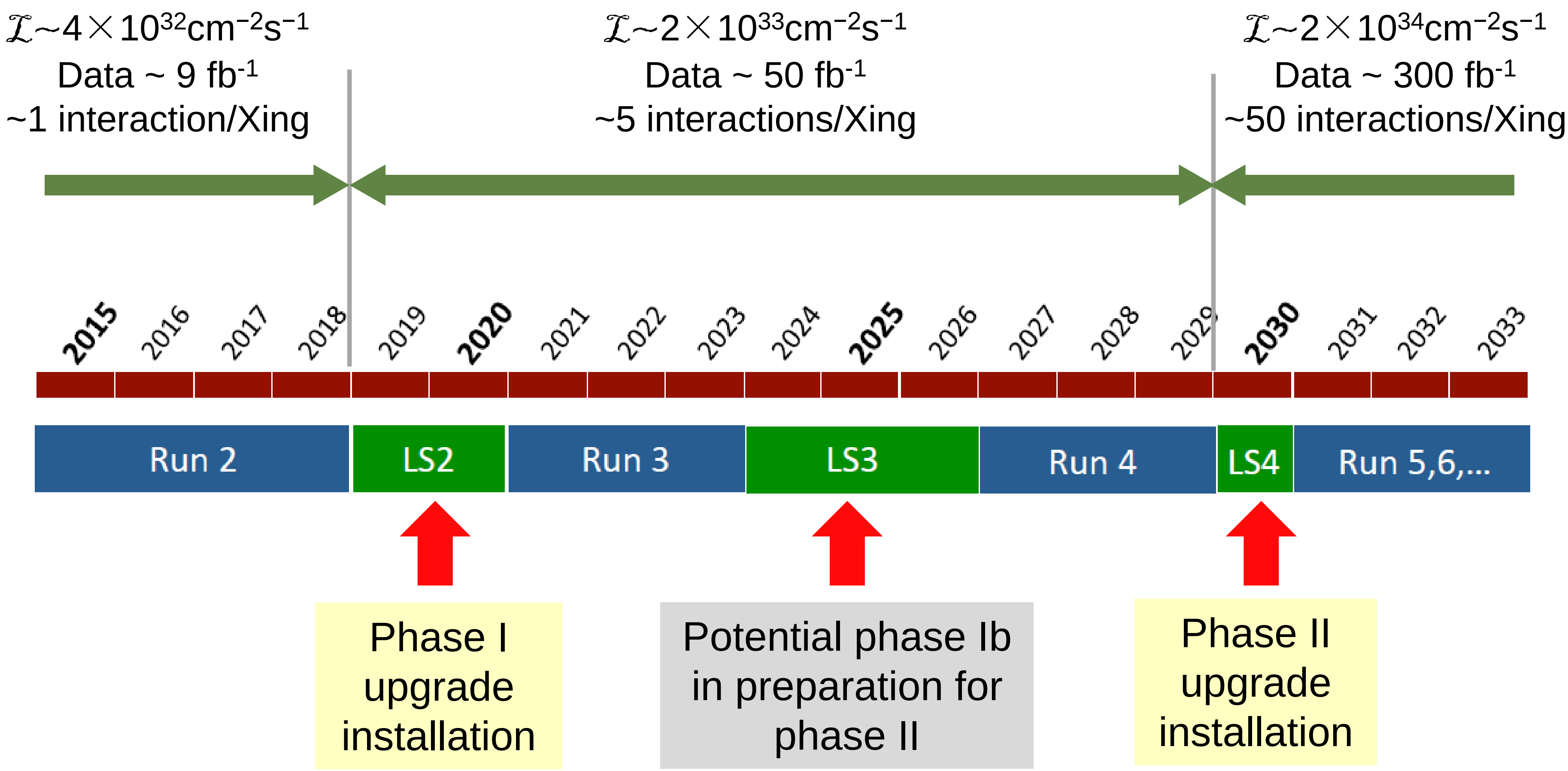
- LHCb records 1–2 fb^{-1}/year, 9.2 fb^{-1} in Runs 1 & 2.
- It did not explore the full capability that the LHC can deliver, but operated at a reduced luminosity.
  - Overall performance degrades with higher occupancy.
  - Lower efficiency for hadronic decays at higher lumin due to the hardware trigger.
  - Limited radiation hardness of the trackers.
- Luminosity leveling within each run.



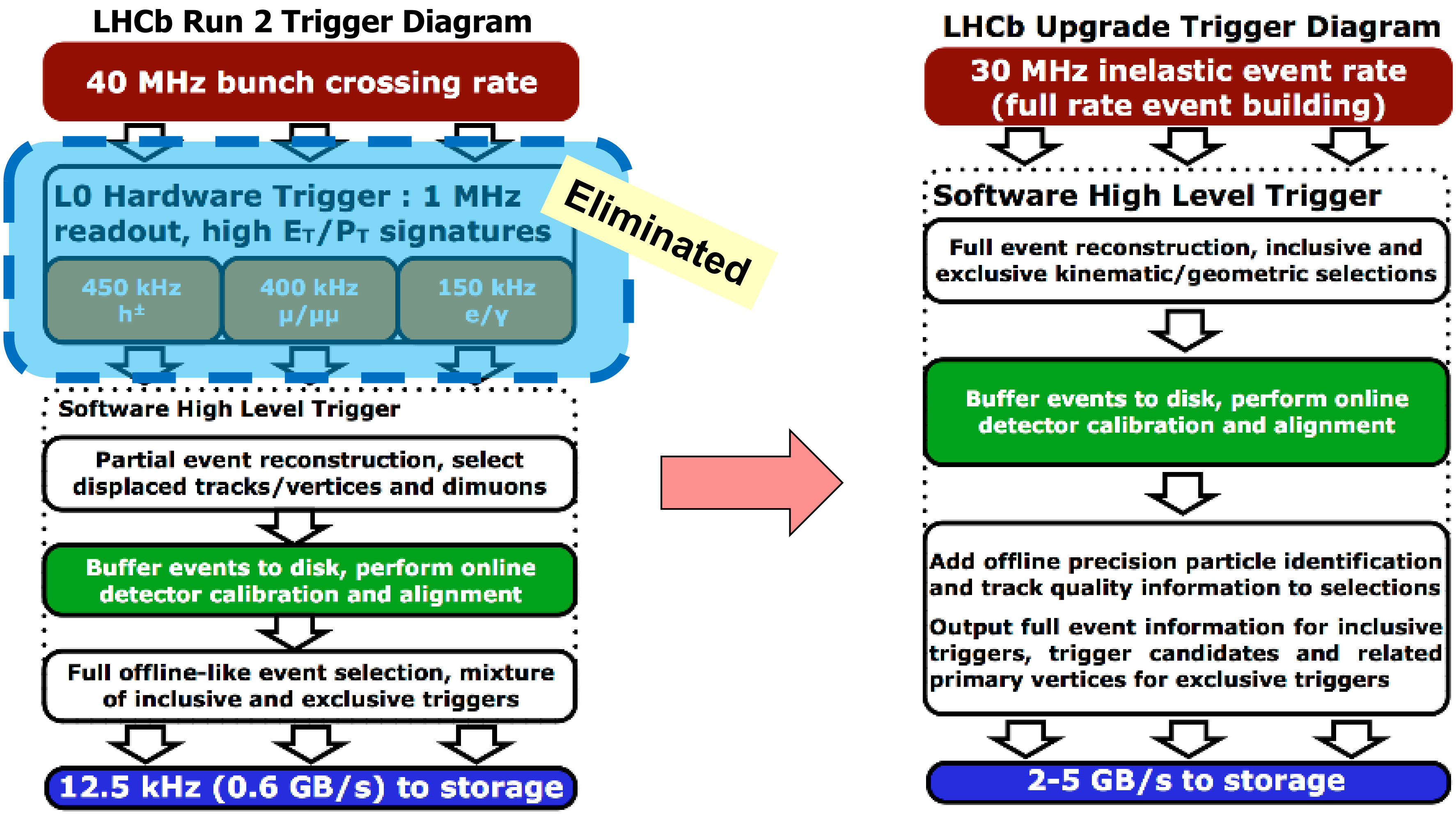




LHCb Upgrade Plans



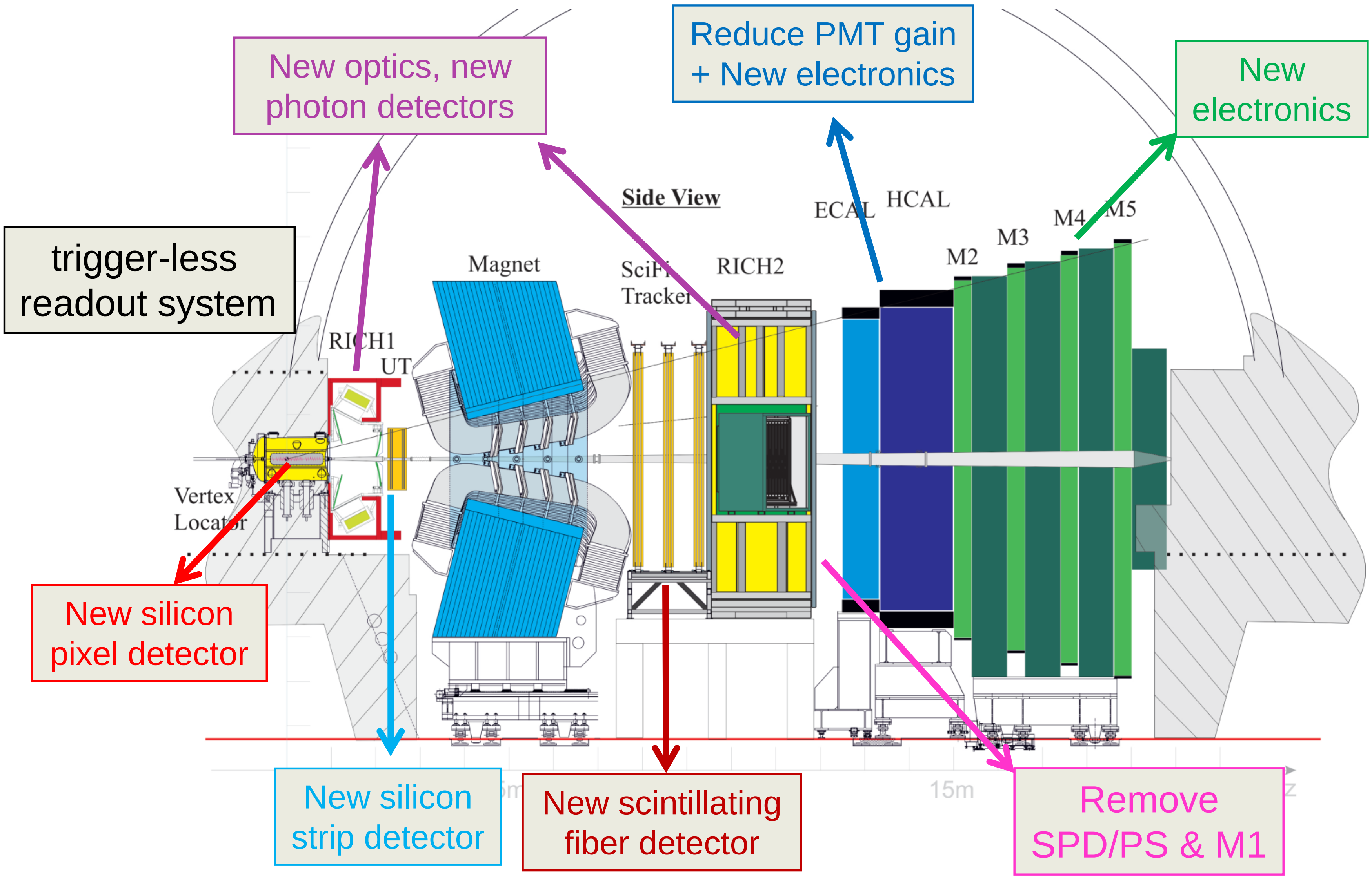
Remove The Hardware Trigger



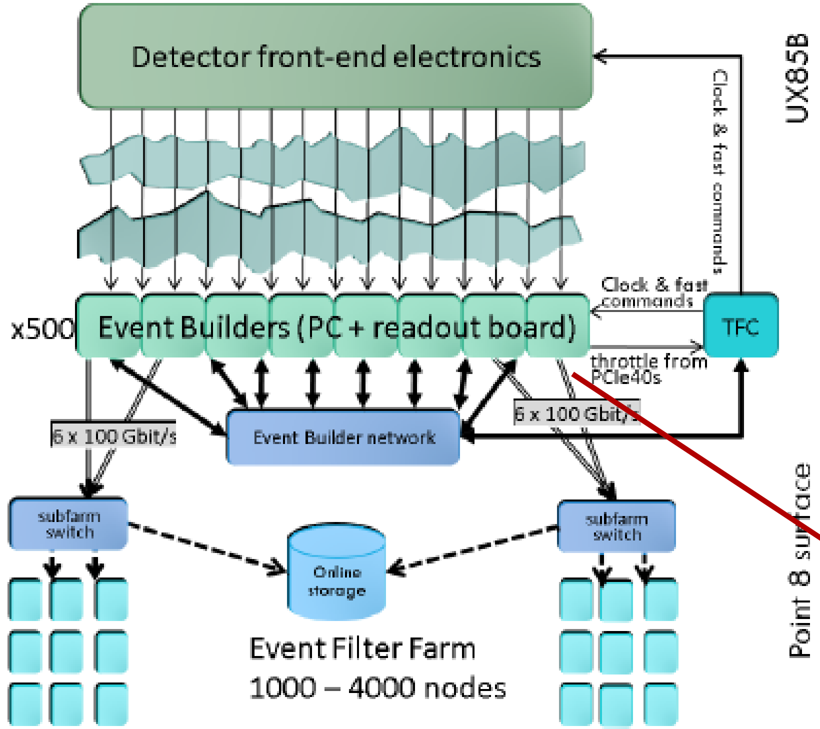
The LHCb Phase-I Upgrade Strategy

- Remove the L0 hardware trigger.
- A flexible software trigger is performed entirely on a CPU farm.
- Information from all sub-detectors are available to enhance the trigger decision and maximize the signal efficiency at higher luminosity.
- All detectors be read out @ 40 MHz
  - Replace FE electronics of all detectors.
  - A new read out network to cope with multi-TB/s data stream.
- Detectors work at a higher luminosity
  - High granularity for increased multiplicities.
  - Radiation resilience.

The Phase-I Upgraded Detectors



LHCb Upgrade Readout Architecture



- A computer farm on the surface.
- Connect to FE via ~300m optical fibers.
- GBTx, GBT-SCA, VTRx, VTTx etc are commonly used at the FE.

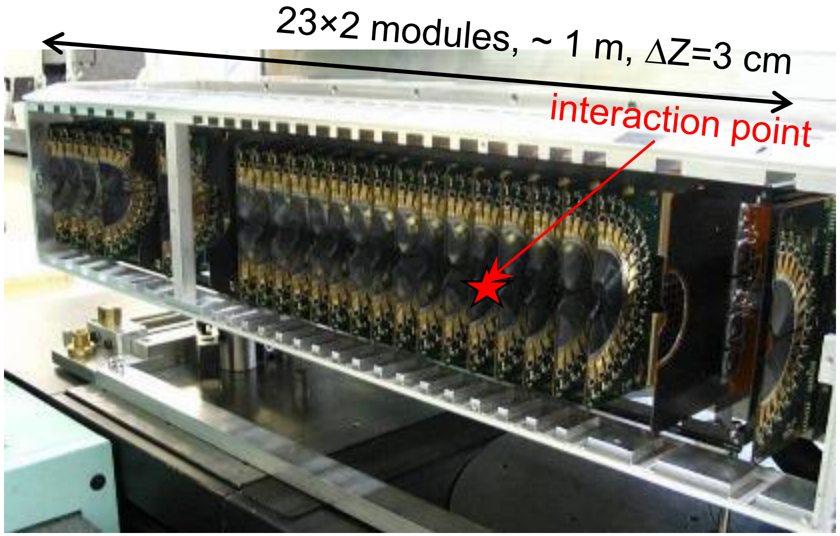
- A PCIe40 module for detector readout, ECS & TFC, common to all sub-detectors.
- The production (~700 cards) is nearly done.

The Data Center On The Surface

Total 6 modules: 2 already running, 2 under commissioning, 2 delivered.

All long optical fiber trunks between FE & the data center are pulled, connected and tested (# ~19,000)

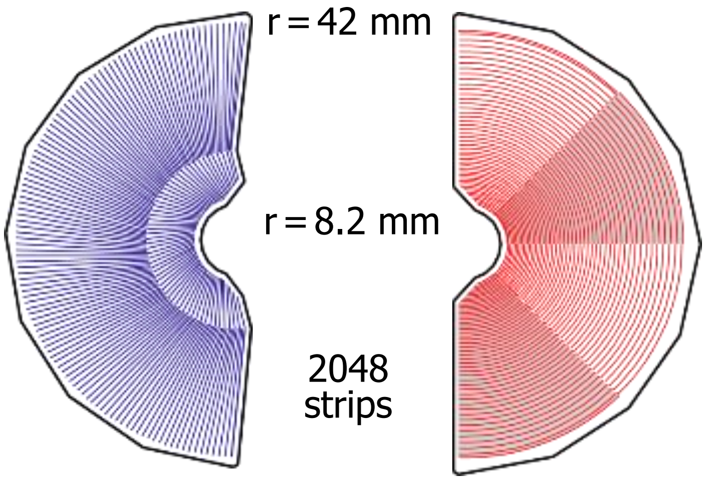
VELO Upgrade

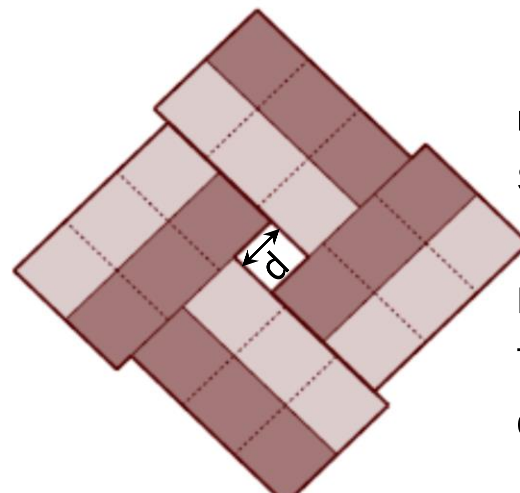


- Similar overall geometry as the old one, total 26×2 modules, 2.5 cm gaps in Z. Two halves are retractable.
- Strip detector ⇒ pixel detector.
- VeloPix readout ASIC, 256 x 256 pixel matrix, binary readout at 40 MHz.
- Significantly increased number of channels: ~0.2 M ⇒ ~40 M
- More radiation hard sensor:
  Φ_{max} ~$7\times10^{14} \Rightarrow 8\times10^{15}\, n_{eq}\mathrm{cm}^{-2}$

n^+-in-n sensor

Pitch = 40-100 μm
Thickness = 300 μm





n-in-p sensor

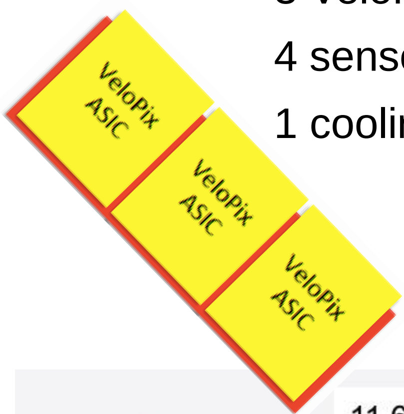
Size ~43×15 mm^2

Pixel size 55×55 μm^2

Thickness = 200 μm

d/2 = 5.1 mm

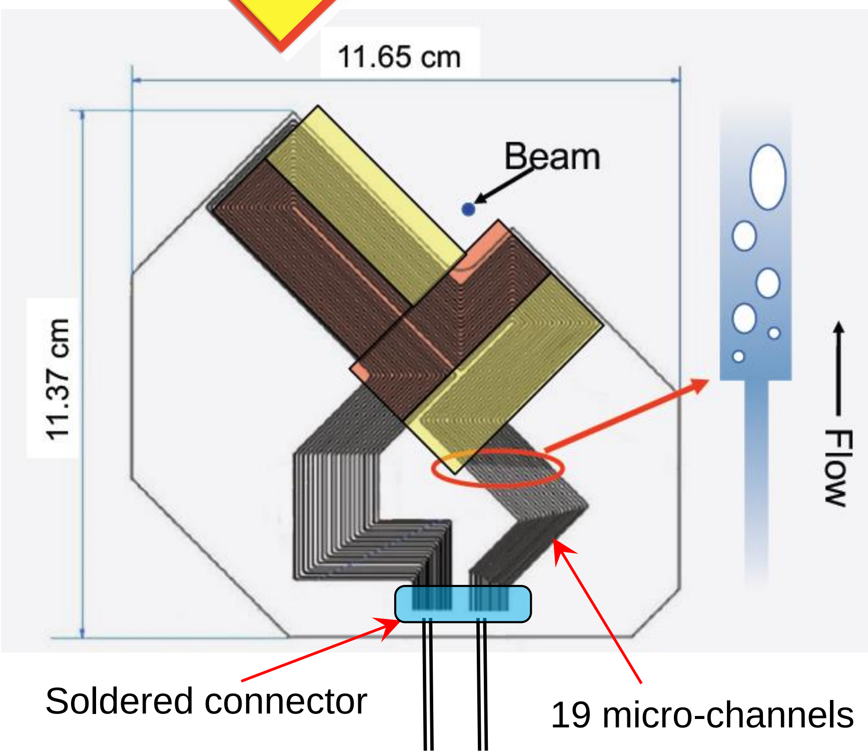
VELO Cooling Substrate



3 VeloPix ASICs / sensor

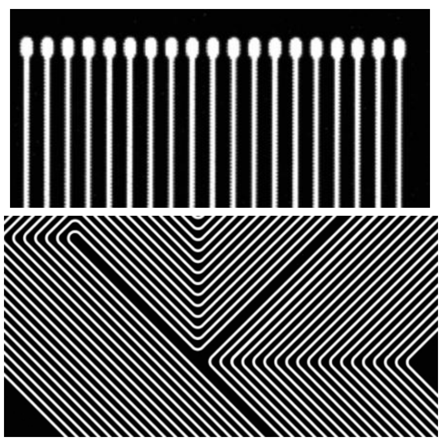
4 sensors / module

1 cooling substrate / module

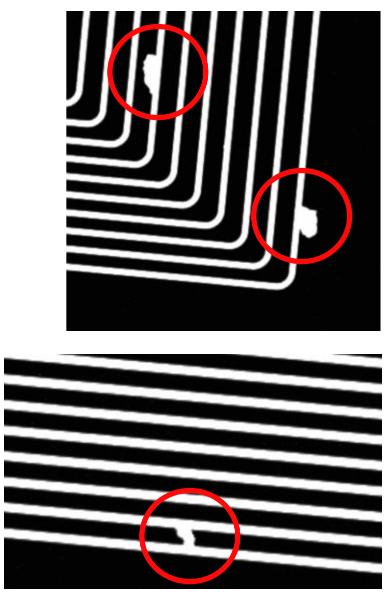


- VELO uses evaporative CO_2 cooling. So that the silicon sensor operates <-20°C.
- 120×200 μm² micro channels are etched in 500 μm silicon substrate, 60×60 μm² at the entrance for stability.
- It is a real challenge. But enough good quality substrates have been produced.

Good



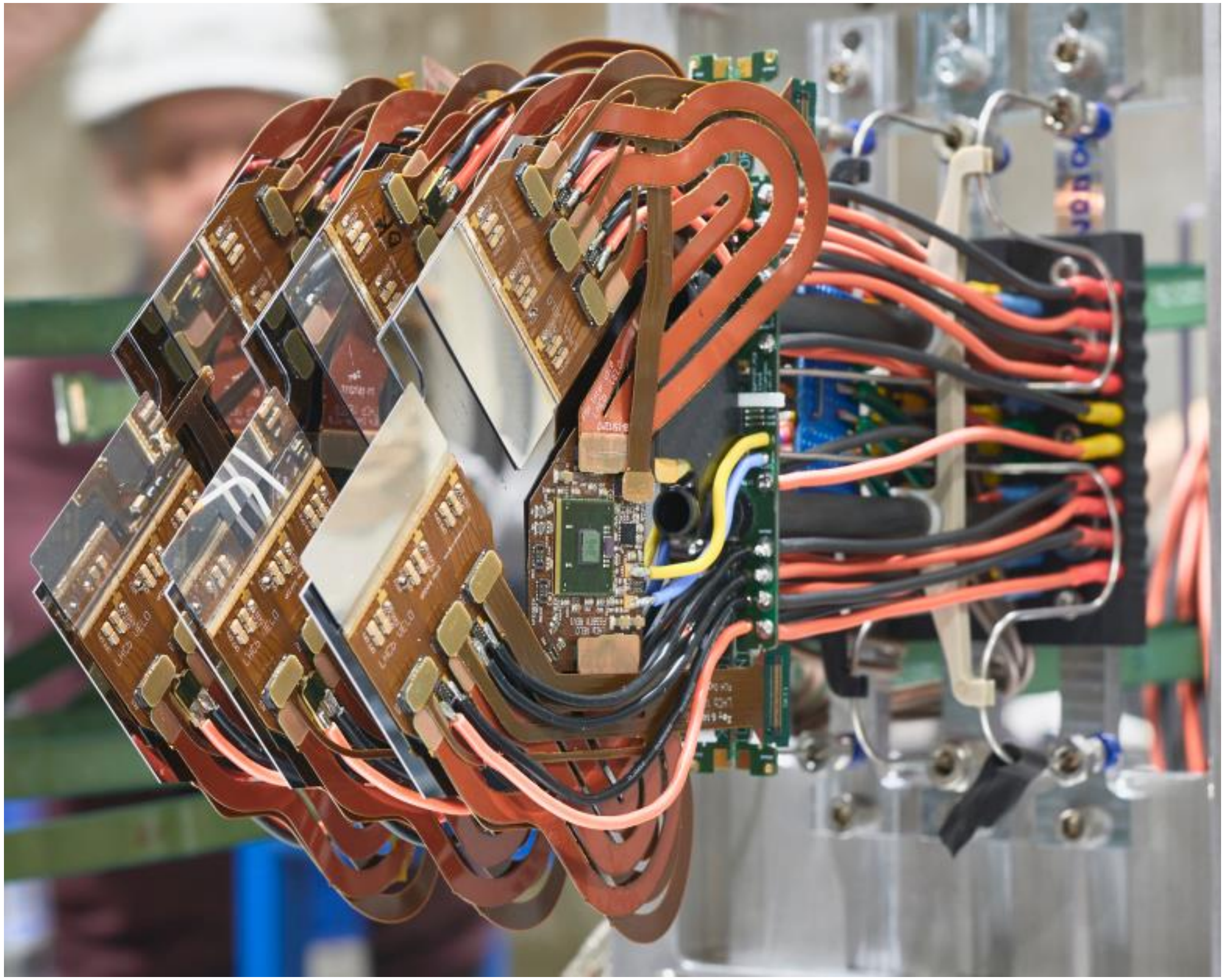
Defected



SEM images

VELO Module Production

3 prototype modules at a testbeam



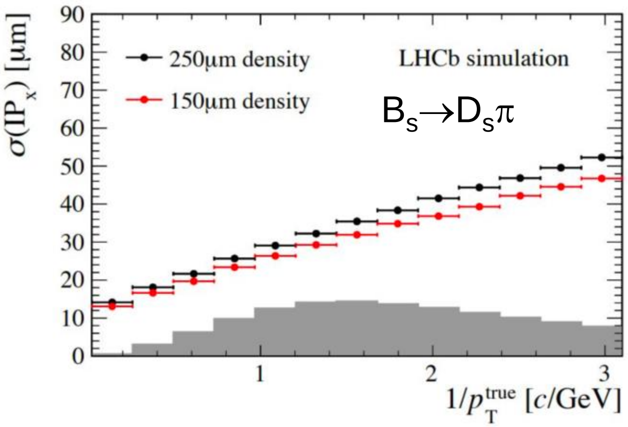
Need 52 modules in the system.

7 modules were produced as of mid of September.

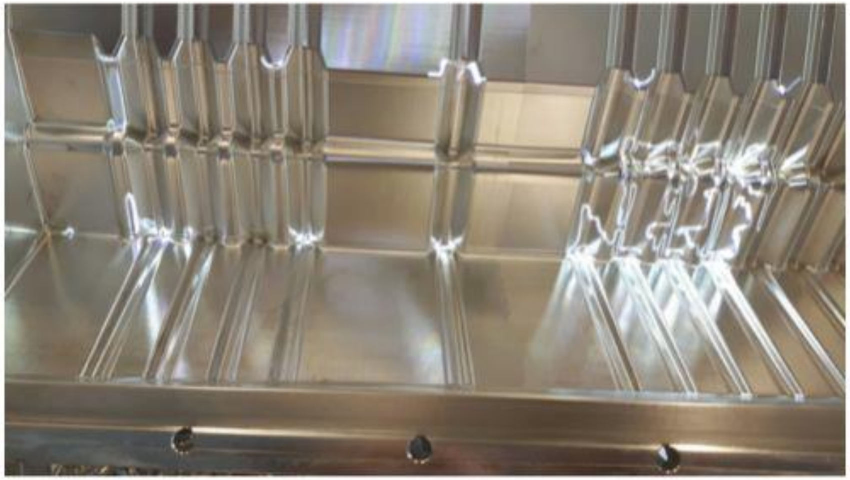
More are being produced.

VELO RF Shield

- RF shields separate the beam vacuum and the detector volume (~10 mbar difference).
- The thickness significantly affects the performance.
- The RF shields were milled from AlMg3 alloy blocks, to reach ~250 μm at tips of the VELO module.
- Chemical etching was proved to work properly (NaOH solution, in steps of 20-50 μm).
- The proposal to thin the RF shield to 150 μm was approved by the TB this September.

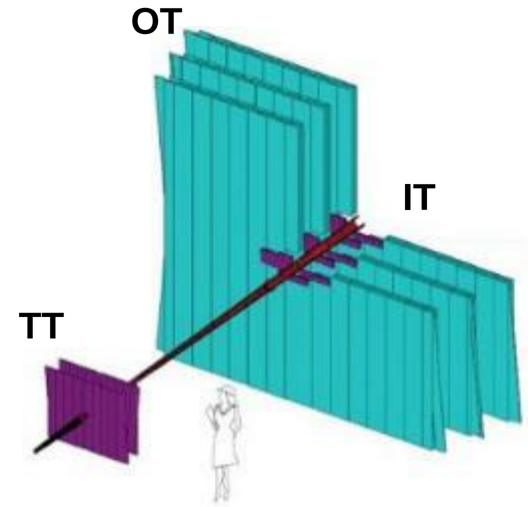


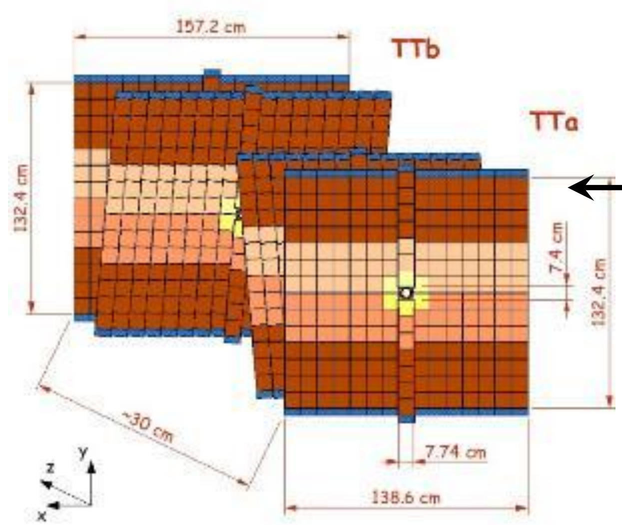
Impact parameter improves by 10%, if thickness is reduced from 250 μm to 150 μm.

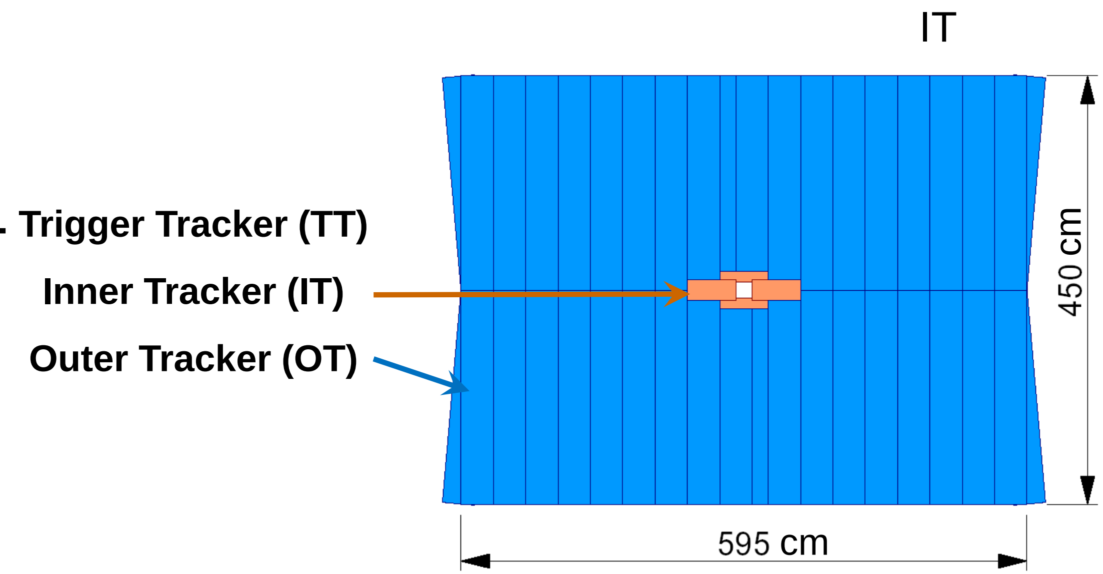


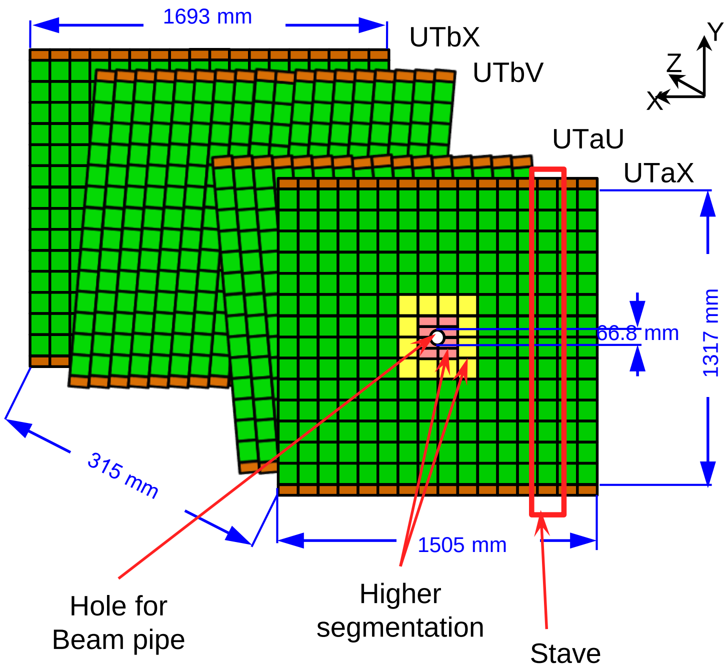
The Tracking Stations Before Upgrade

- The tracking stations consist of 4 planes TT before the magnet, and 3x4 planes of IT & OT after the magnet.
- Four planes (x,u,v,x) at (0°,+5°,-5°,0°), provide stereo measurements, with horizontal precision.
- TT & IT are silicon strip detectors, read out by Beetle ASICs outside active area.
- OT is made of Kapton/Al straw drift tubes d=5 mm, with $Ar+CO_2+O_2$ gas, providing ~200 μm resolution.

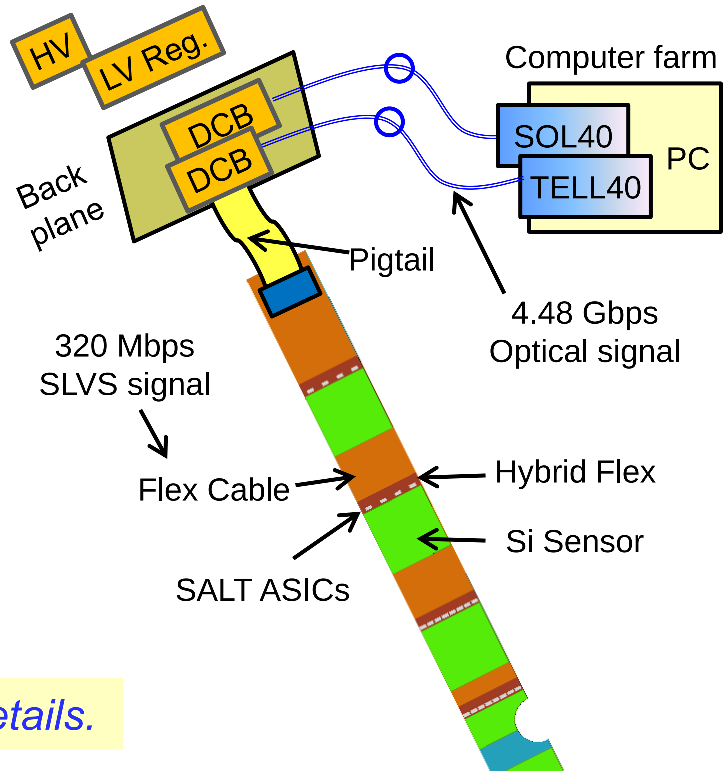








- Similar geometric configuration as TT.
- Improved coverage and segmentation.
- Sensor is more radiation resilience, Φ_{max} ~$5\times10^{14}\, n_{eq}cm^{-2}$.



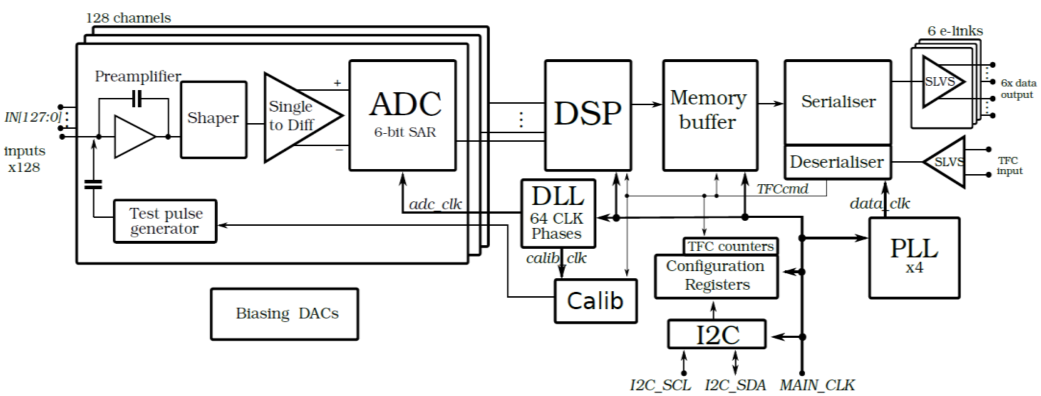
- Read out at 40 MHz by custom SALT ASICs in the sensor proximity.
- Digital events are packed in ASIC, sent out at the end of detector via optical fibers.

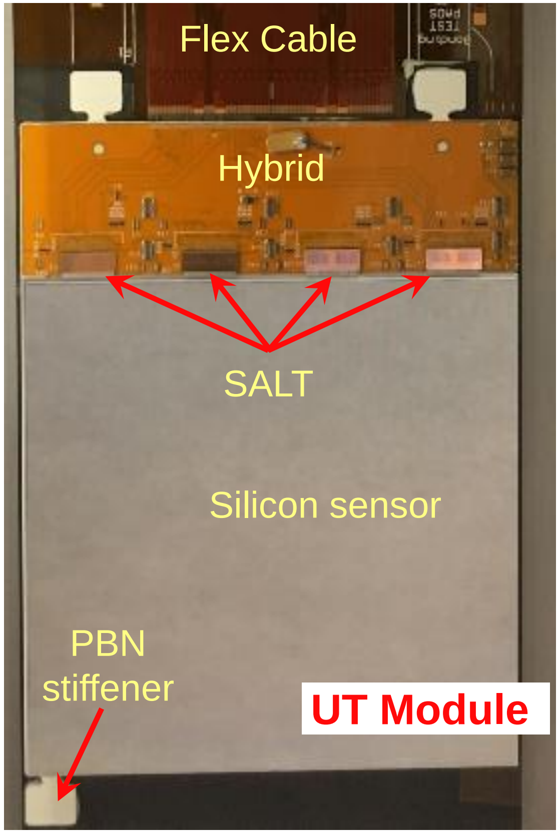
See Yiming Li's presentation for more details.

UT Module And Readout ASIC

- Silicon sensor p-in-n, n-in-p types, thickness 320, 250 μm, strip pitch 187.5, 93.5 μm, length ~10, 5 cm.
- The FE readout ASIC, SALT, is custom designed: TSMC 130 nm technology, 6-bit SAR ADC, input signal of both polarities, a peaking time ~25ns, quick return, SLVS digital output.
- SALT still needs to settle an issue, especially for modules in the high radiation central area.

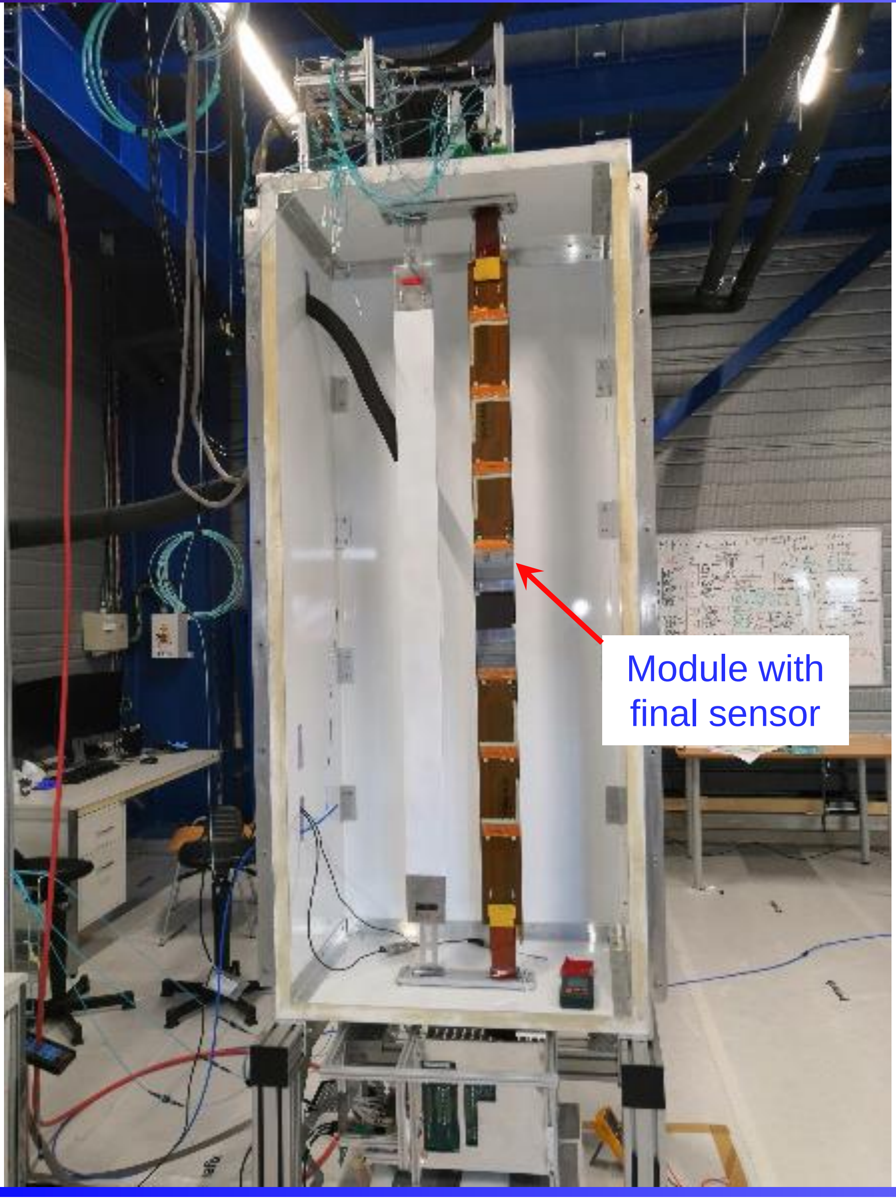
SALT



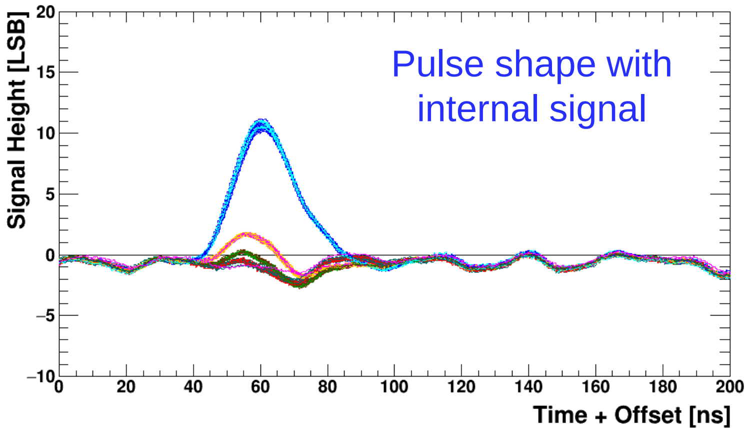


- Module production for the low radiation area started.
- Total 968 modules in the system.

UT Slice System

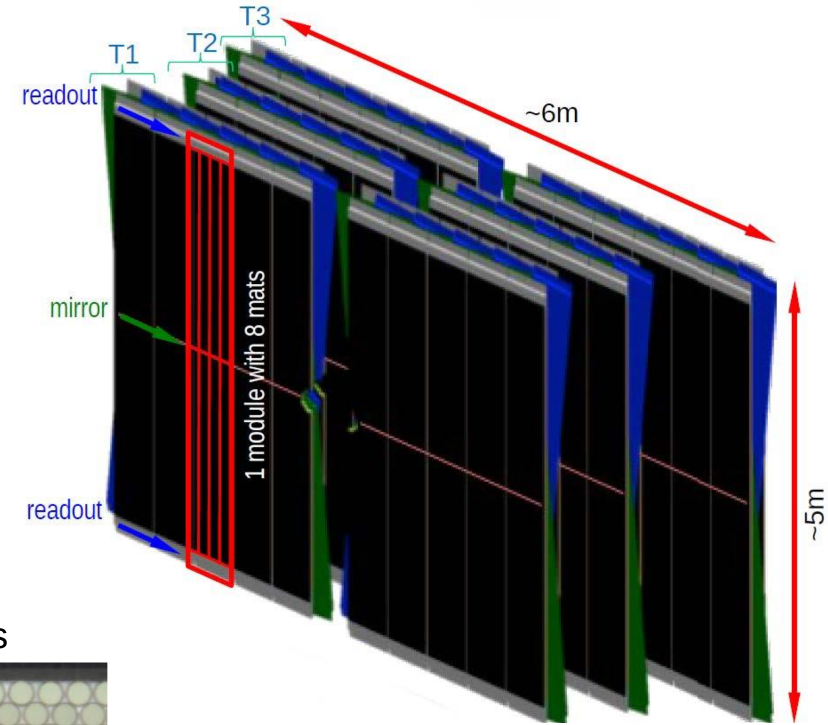


- A UT slice system was set up at CERN, including a prototype stave of all 14 modules but only 1 module has sensor.
- The readout electronics are all very close to the final version.
- Performance of the module meets the design goal.
- Stave production for the low radiation area started.
- The 1st stave will be mounted this Nov.

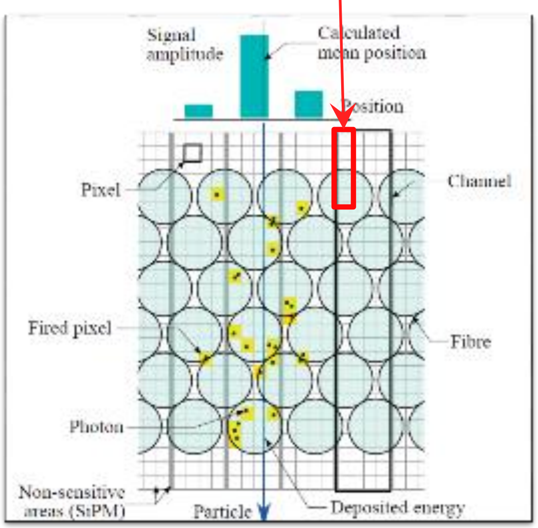


Scintillation Fiber (SciFi) Detector

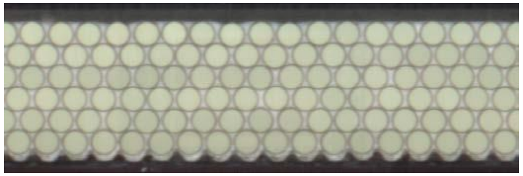
- Tracking stations are replaced by 3-station (12-plane) scintillation fiber detector.
- Read out with arrays 4096 SiPMs (-40°C) + custom made PACIFIC ASICs. In total ~ 0.5 M readout channels.
- Spatial resolution better than 100 μm in X.
- Single hit efficiency ~99%.



1 SiPM Channel



6 layers staggered
Ø250 μm fiber mats

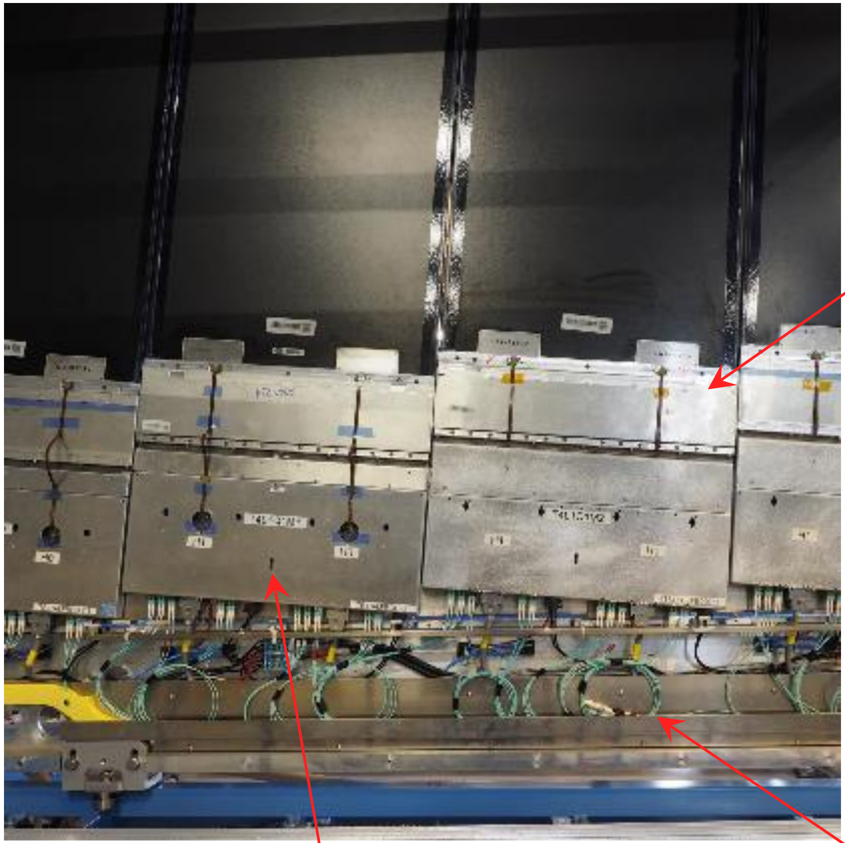


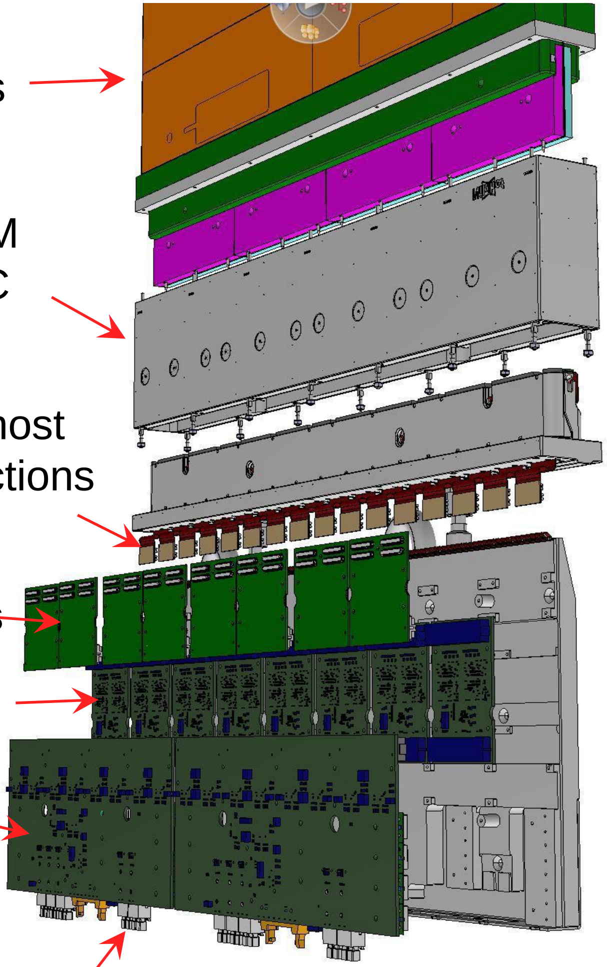
128-ch SiPM Array

3 stations × 4 planes (X,U,V,X).
10 (or 12) modules / plane
8 (4 × 2) mats / module.

See Ming Zeng's presentation for more details

SciFi Signal Readout





Fiber matts

Cold box for SiPM to work @ -40°C

Flex cable to host SiPM & connections

PACIFIC boards

Cluster boards

Master boards

Electronics boards inside FE boxes

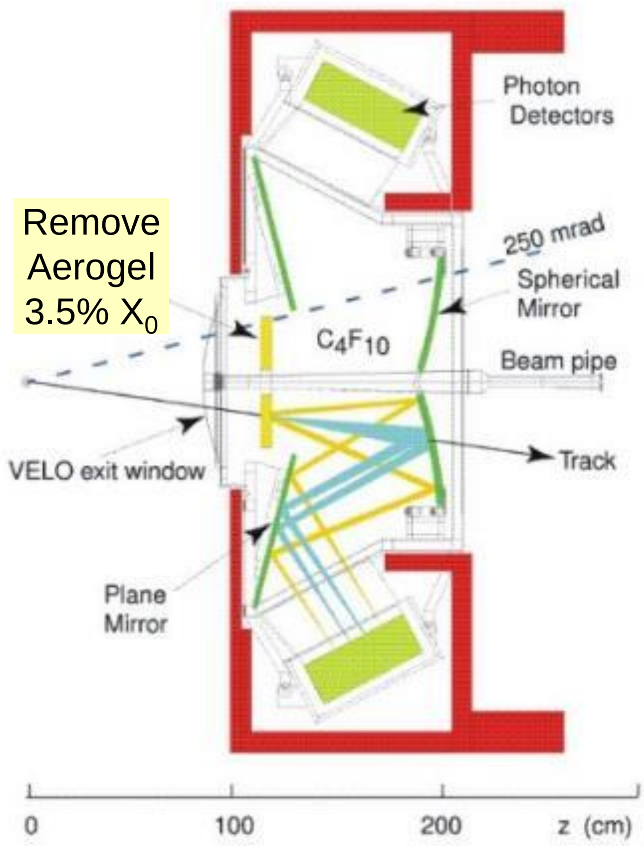
Optical connection to outside

SciFi Modules at The Installation Hall

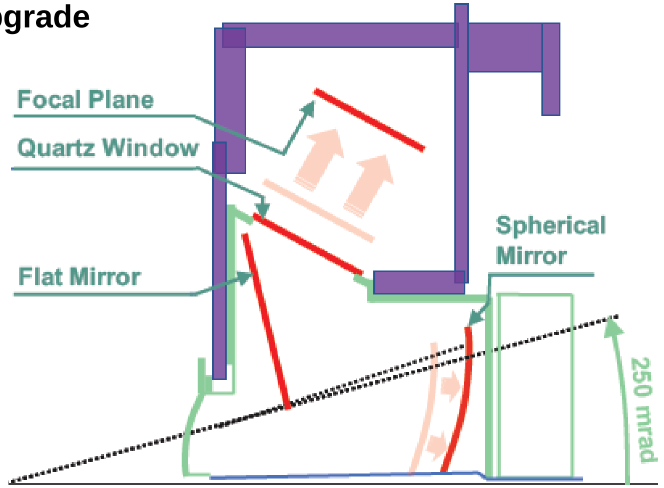
- All Modules are produced. As of September some of the modules were equipped with cold boxes. Some are already mounted on the C-frames at CERN.
- PACIFIC boards & cluster boards are ready. ~1/3 of master boards are done.

- Two RICH detectors for track PID:
  - RICH1 (aerogel + C_4F_{10}) for 2 < P < 60 GeV.
  - RICH2 (CF_4) for 15 < P < 100 GeV.
- Cherenkov photons are detected by HPDs.
- Remove aerogel radiator in RICH1.
- Focal plane and optics are modified to increase the size of Cherenkov rings.
- Replace HPDs with MaPMTs of size 1” and 2” squares, 8×8 matrix.

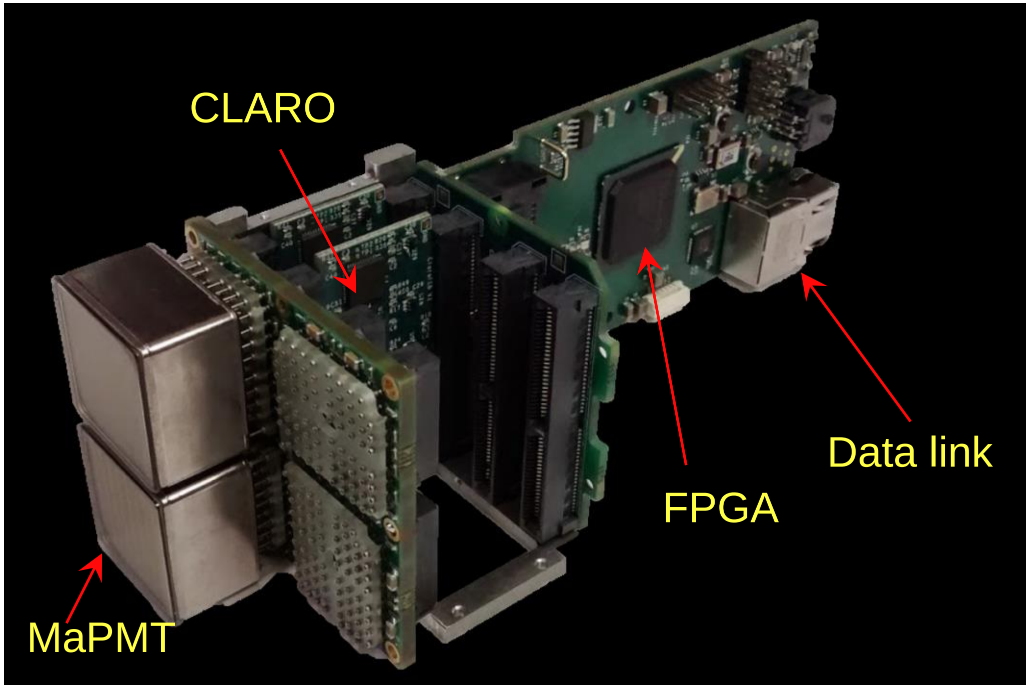
RICH1



Upgrade



RICH Photon Detector



- MaPMT production finished.
- Signal processed by CLARO ASICs: custom made 8-channel amplifier/discriminator.
- Photo detector data board production on going, all other boards are ready.
- Photon detector column construction started.

RICH1 Mechanics

Magnetic shielding

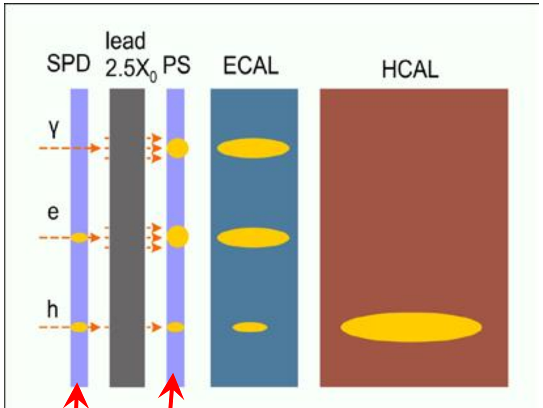
Photon detector upper chassis

Quartz window for photon exit
(not seen from this angle)

Gas enclosure

- All mechanical components are in place, including mirrors and windows.
- Assembly started at CERN.
- The upper quartz window has a crack, which will cause some delay.

Calorimeter Upgrade

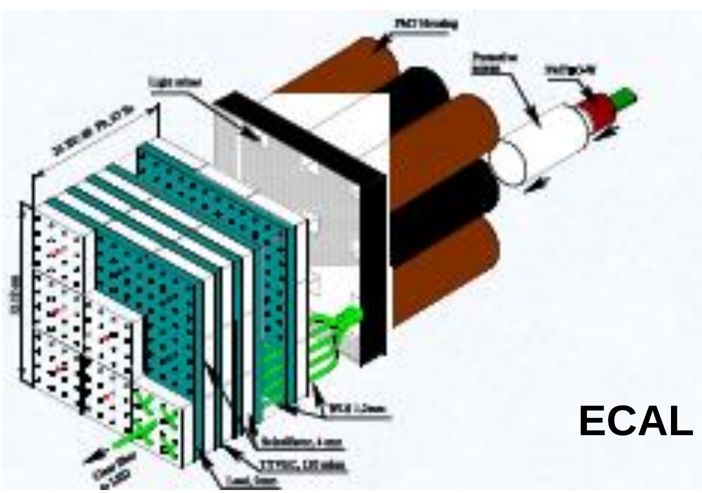


PS (Pre-shower)

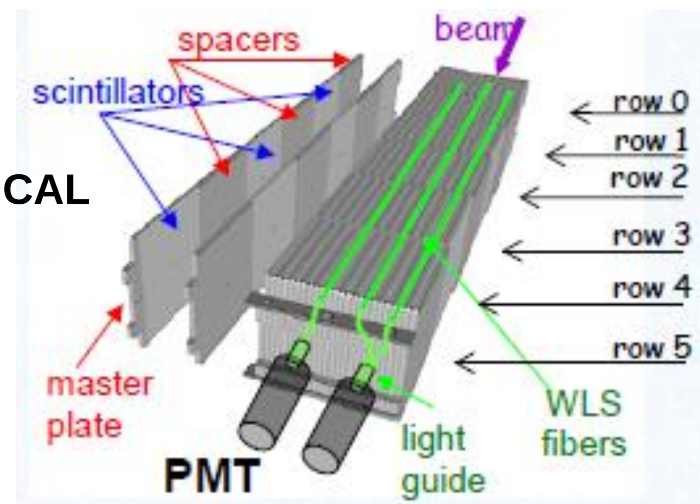
SPD (scint. pad detector)

- Scintillation/WLS technology, PMT to detect photon.
- Provide L0 trigger on high E_T e/γ/h.
- e/γ/hadron ID, energy & position.
- ECAL: Pb + scintillator, HCAL: Fe + scintillating tiles.
- Fine segmentation at the center.

- Remove SPD & PS; HCAL will be removed later.
- Reduce PMT gain by factor of 5, to reduce aging.
- New FE electronics for 40 MHz readout.

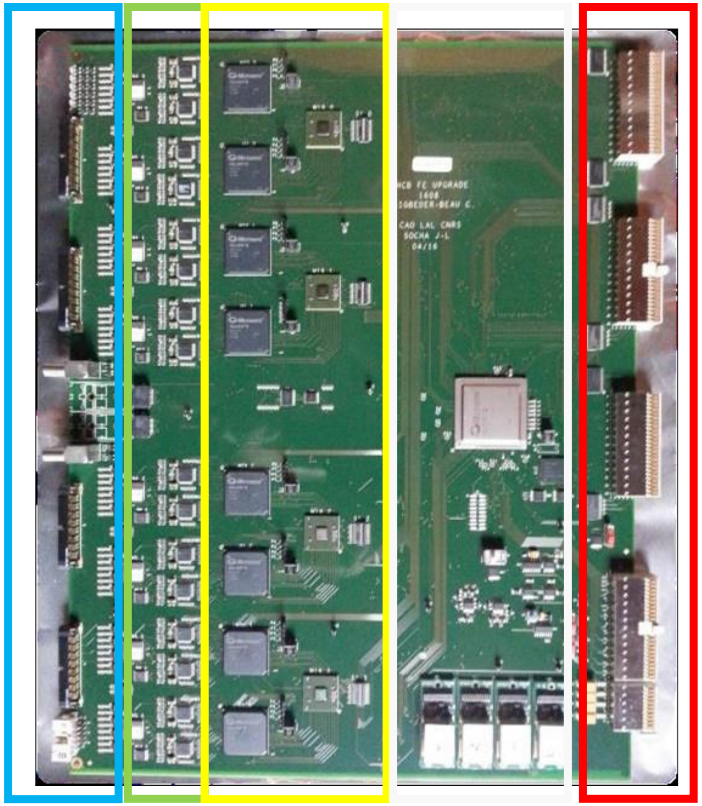


HCAL



CALO Readout Electronics

CALO FEB

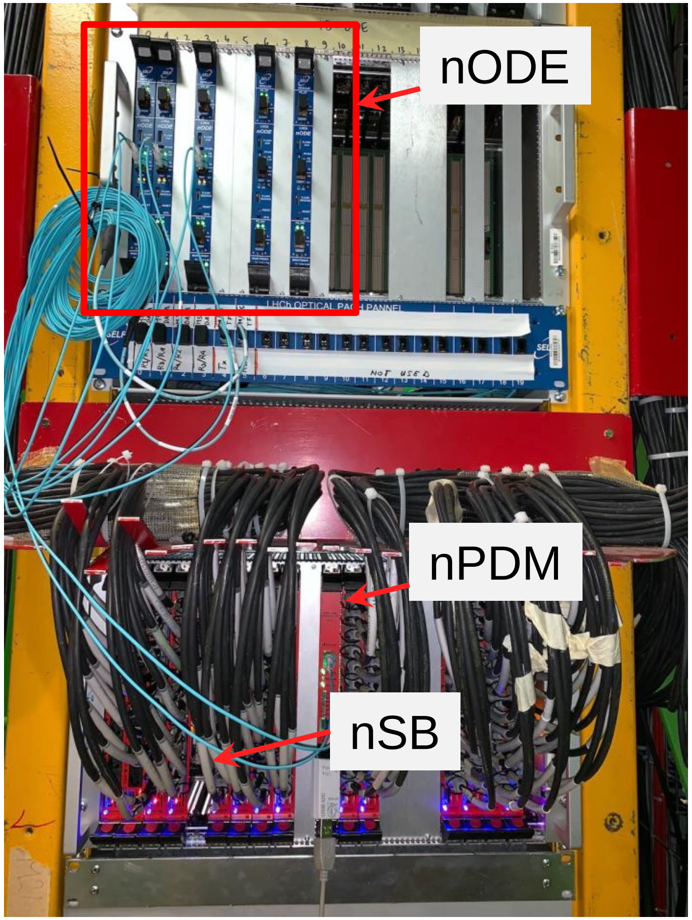


- FE boards & Control boards: preproduction are under test, production to start soon.
- HV/Monitor/Calib boards are ready.

Muon Detector Upgrade

- Total 5 stations: M1-M5.
- Triple-GEM detector @ the center of M1 for high hit rates. The rest are MWPCs, higher granularity close to beam.
- Gives δp/p ~ 20% for L0 trigger.
- Muon ID cut of ~ 6 GeV.

- Remove M1 (upstream of SPD/PS),
- Add shield in front of M2 at the center to reduce the rate, which is delivered.
- New readout electronics. Preproduction boards are deployed and OK'ed. The full production finishes next February.



Possibilities In The Phase II Upgrade

$\mathcal{L} \sim 2\times10^{34}\,cm^{-2}s^{-1}$
Data ~ 300 fb^{-1}

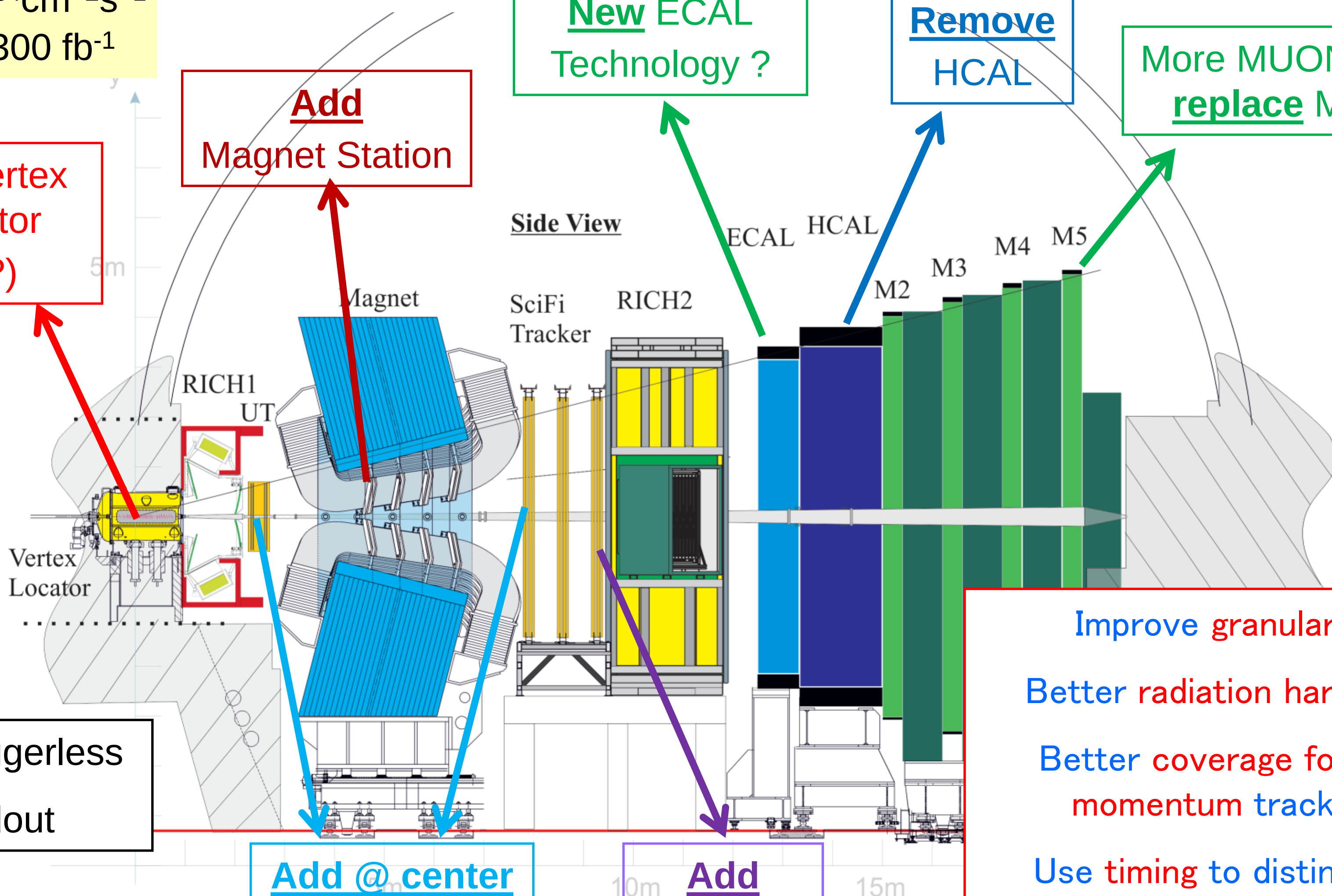
New Vertex Detector (4D?)

Add Magnet Station

New ECAL Technology ?

Remove HCAL

More MUON filter + **replace** MWPC



Keep triggerless readout

Add @ center Mighty Tracker

Add TORCH ?

Improve granularity

Better radiation hardness

Better coverage for low momentum tracking

Use timing to distinguish vertices (high−pileup)

Physics Reach of Phase II Upgrade

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- The LHCb detector is being upgraded to operate at $\mathcal{L}\sim2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and collect 50 fb^{-1} data in the next ~10 years.
  - A trigger-less readout system, with online software trigger.
  - Tracking detectors (VELO, TT & IT/OT) are replaced with new detectors.
  - New optics and removal of aerogel in RICH1. New photon detectors and electronics in both RICH1 & RICH2.
  - New electronics in ECAL, HCAL, and Muon detectors.

- The upgrade proceeds reasonably well. There are problems to be solved. At this moment, we think there is no show stopper.

- Expect a major upgrade in LS4(~2030) for x10 higher luminosity, and a small upgrade in LS3(~2025). R&D work already started.