Upgrade of
The LHCb Tracking System

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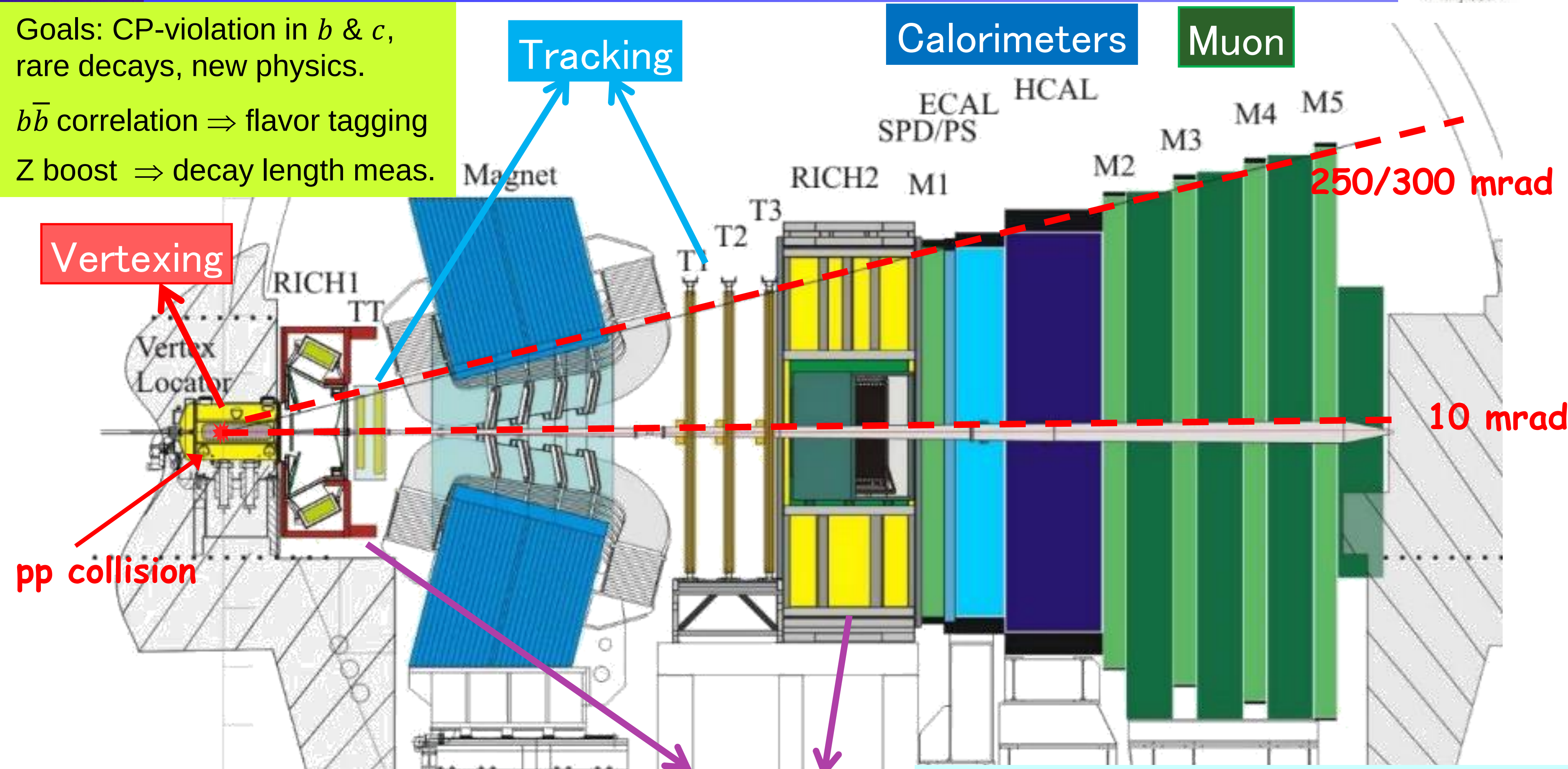
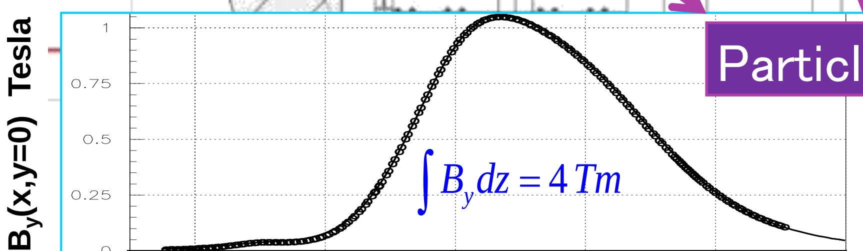
The LHCb Detector Before LS2

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

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

Z boost $\Rightarrow$ decay length meas.

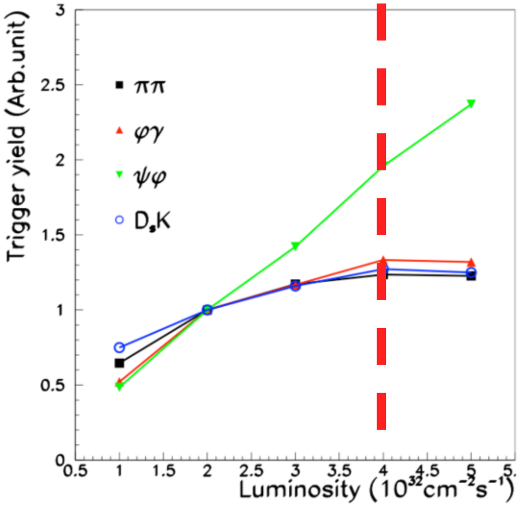


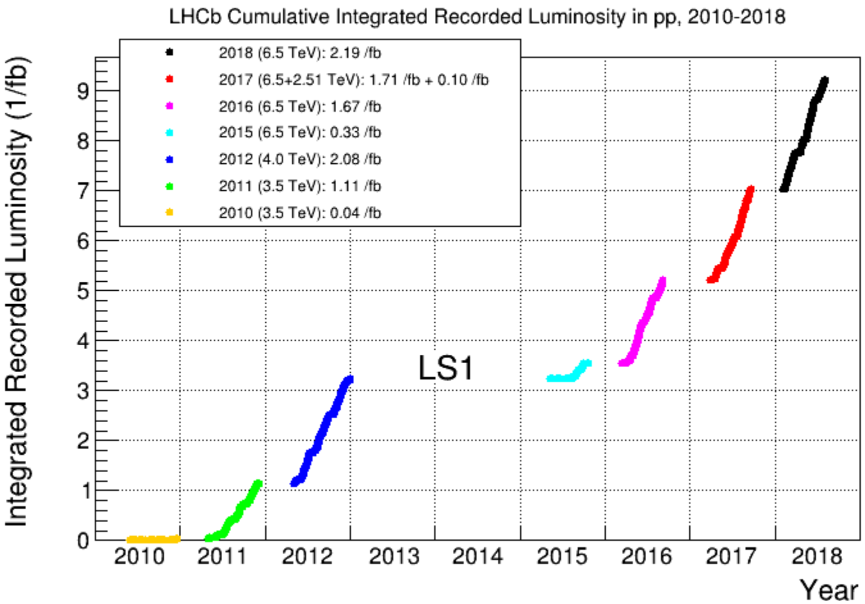


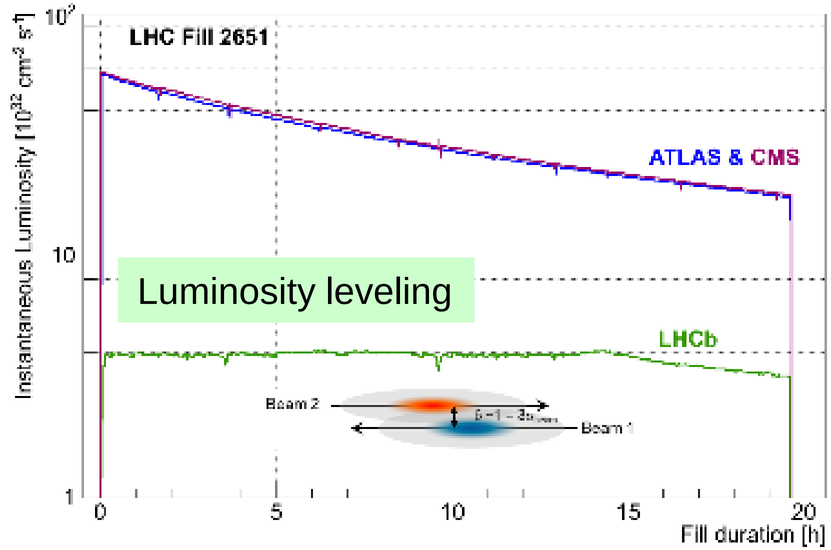
- Spatial resolution ~ 4 μm @ VELO
- $\Delta p/p = 0.4\%$ @ 5 GeV, 0.6% at 100 GeV.
- IP resolution ~20 μm for high-pT tracks.
- Decay time resolution 45 fs ($B_s \to J/\psi\ \varphi$).

LHCb Operation Before LS2

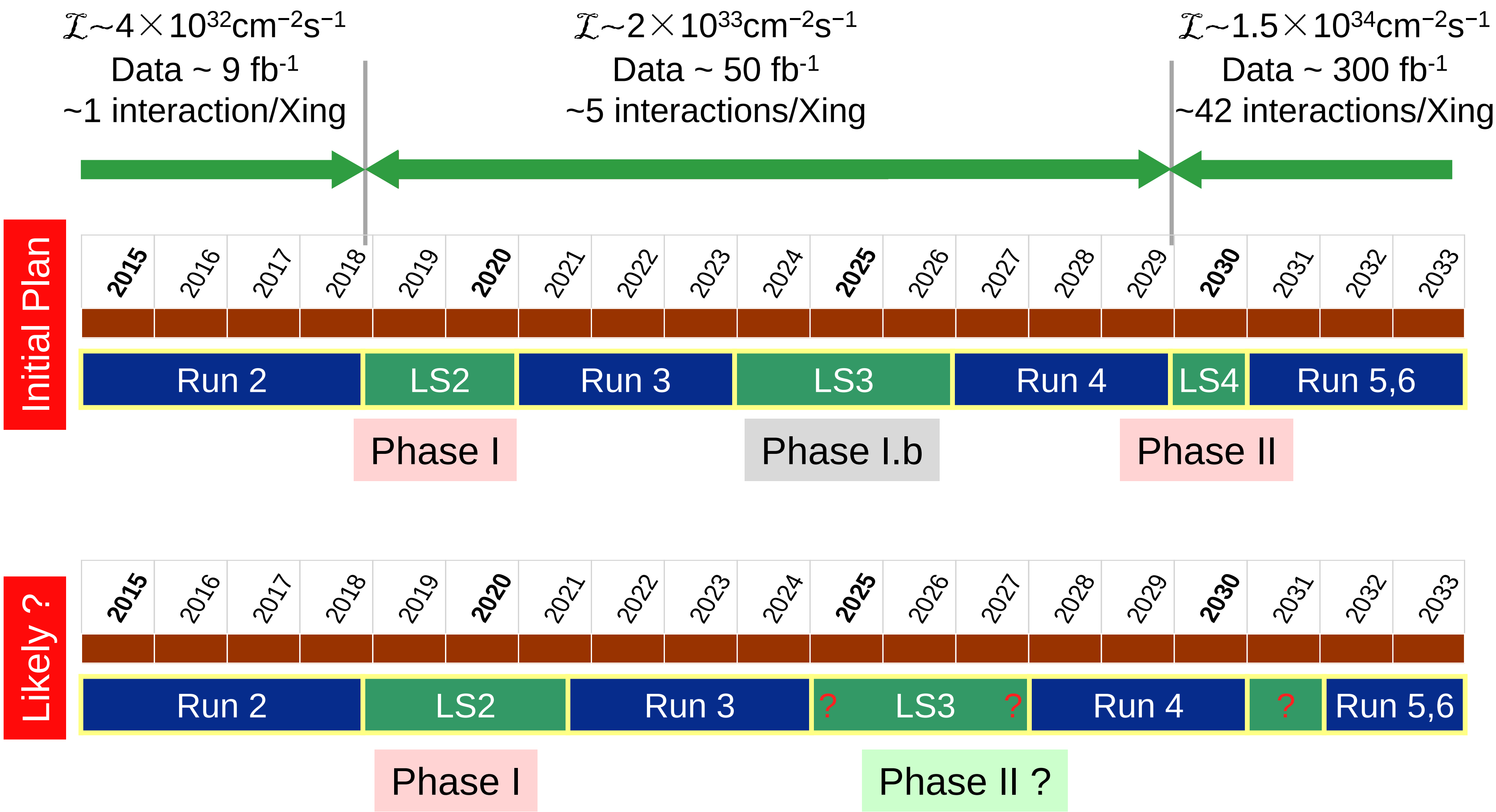
- In runs 1&2 LHCb records 9.2 fb^{-1} data,~1-2 fb^{-1}/yr.
- LHCb operated at a reduced luminosity.
  - Lower efficiency for hadronic decays at higher luminosity due to the hardware trigger.
  - Overall performance degrades with higher occupancy.
  - Limited radiation hardness of the trackers.







The LHCb Upgrade Plan



Remove The Hardware Trigger

LHCb Run 2 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high E_T / P_T signatures — *Eliminated*

- 450 kHz $h^{\pm}$
- 400 kHz μ / $\mu\mu$
- 150 kHz e / γ

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB / s) to storage

All detectors read out @ 40 MHz

LHCb Upgrade Trigger Diagram

40 MHz bunch crossing rate (30 MHz inelastic event building)

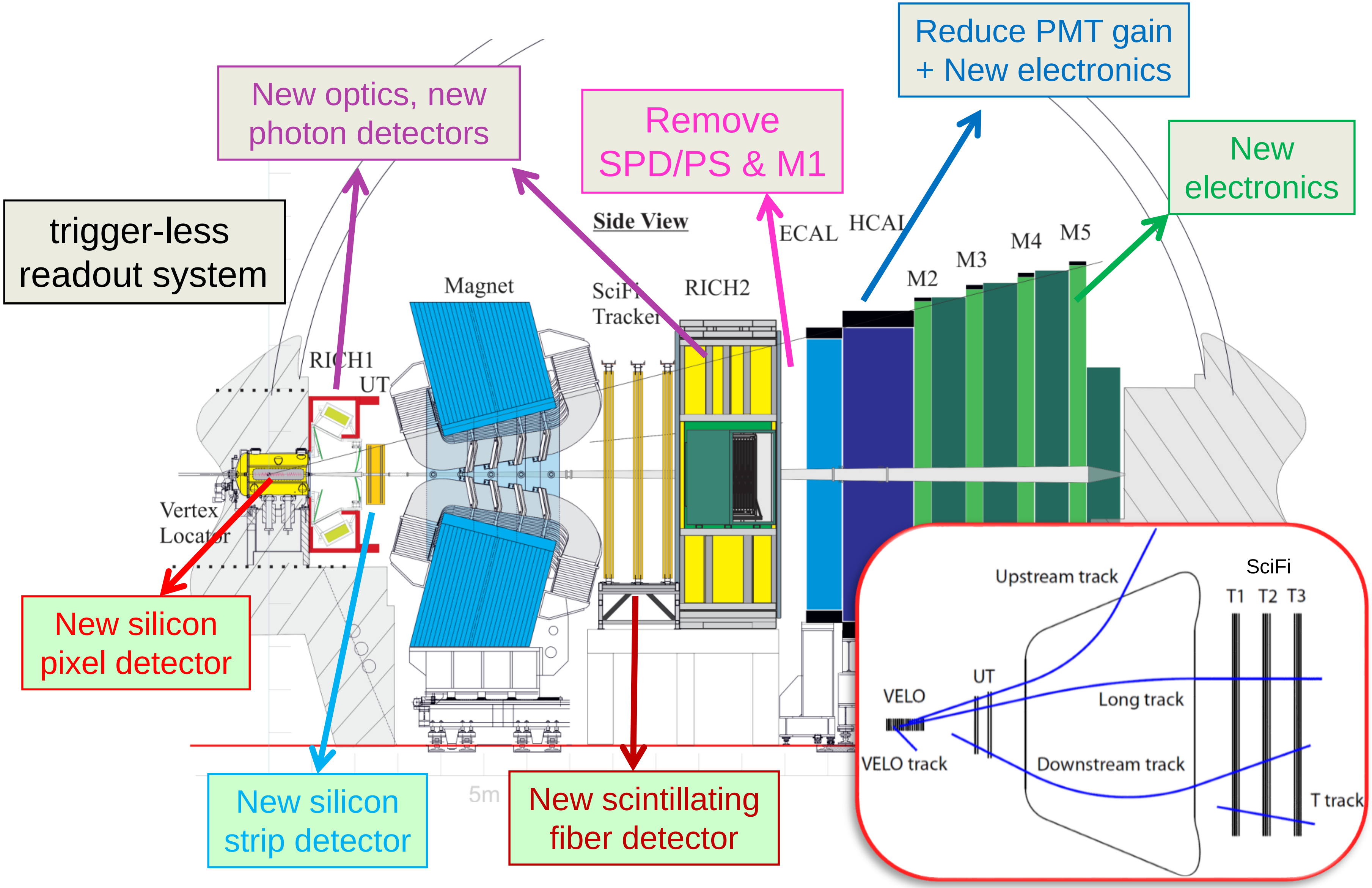
Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections

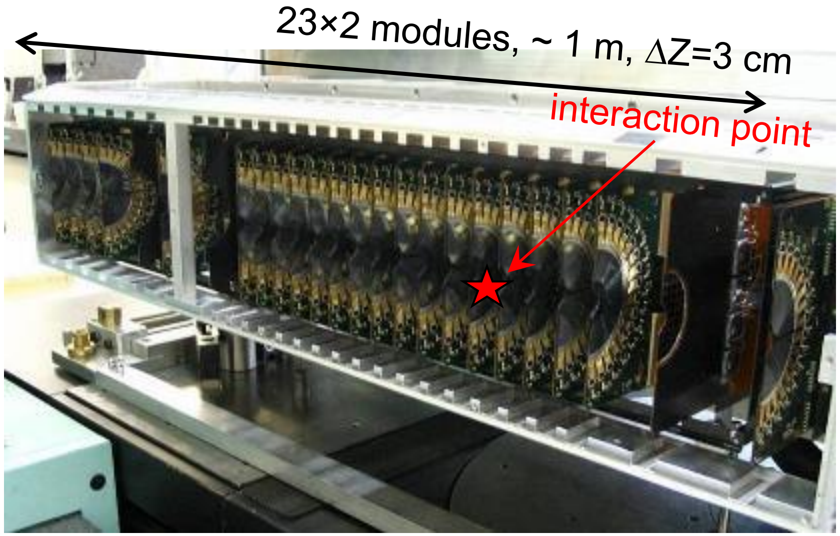
  Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB / s to storage

The Phase-I Upgraded Detectors



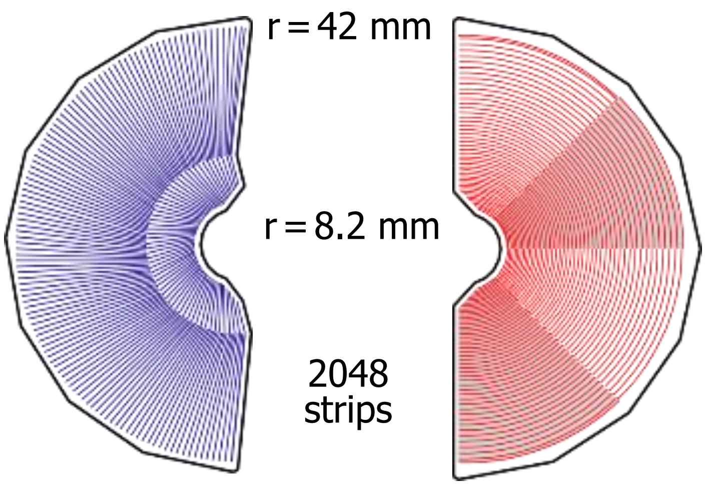
VELO Upgrade

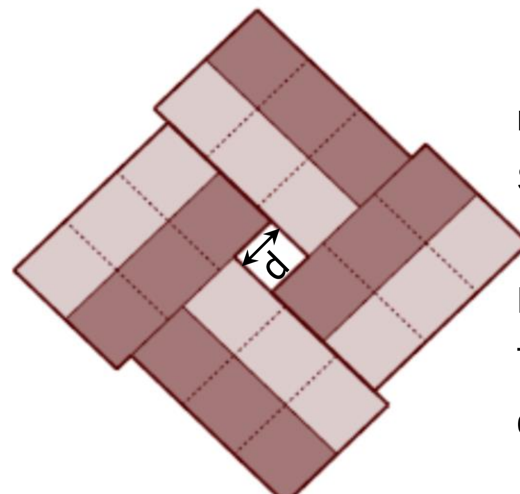


- Similar overall geometry as the old one, total 26×2 modules, 2.5 cm gaps in Z. Two halves are retractable.
- Strip detector ⇒ pixel detector.
- VeloPix readout ASIC, 256 x 256 pixel matrix, binary readout at 40 MHz.
- Significantly increased number of channels: ~0.2 M ⇒ ~40 M
- More radiation hard sensor:
  Φ_{max} ~7×10^{14} ⇒ $8\times10^{15}\, n_{eq}\mathrm{cm}^{-2}$

n^+-in-n sensor

Pitch = 40-100 μm
Thickness = 300 μm





n-in-p sensor

Size ~43×15 mm^2

Pixel size 55×55 $\mu\mathrm{m}^2$

Thickness = 200 μm

d / 2 = 5.1 mm

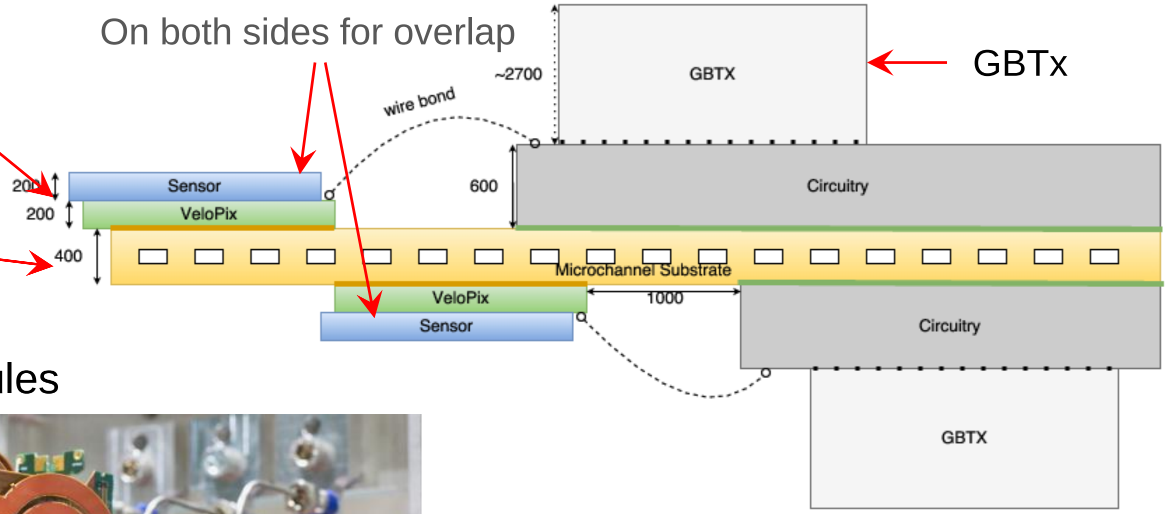
VELO Module

A sensor is bump-bonded to 3 VeloPix ASICs

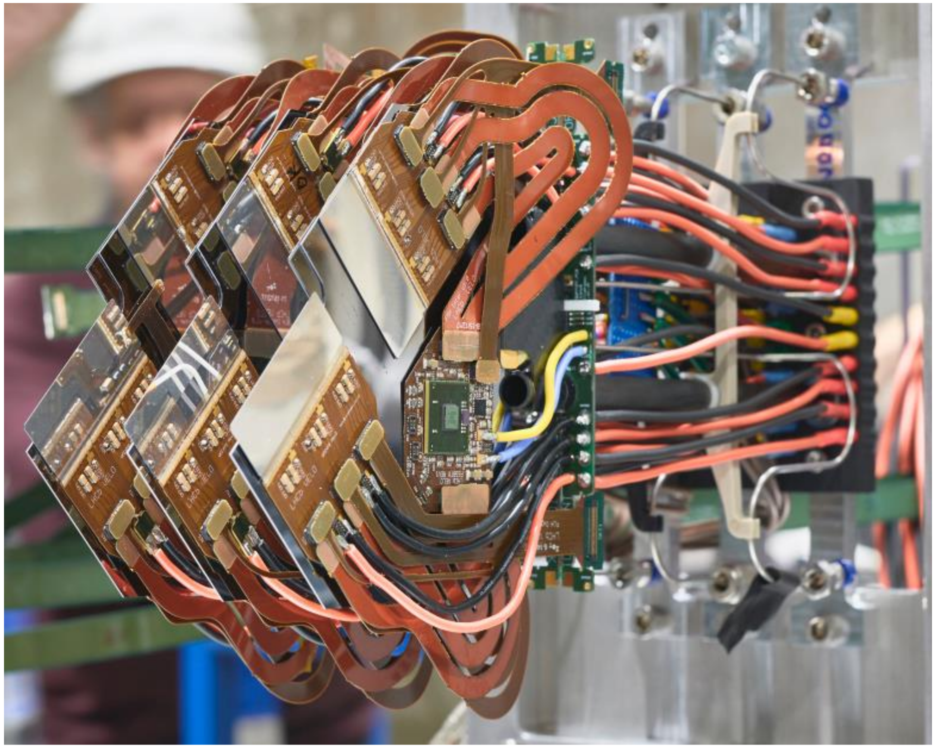
On both sides for overlap

Micro-channel substrate

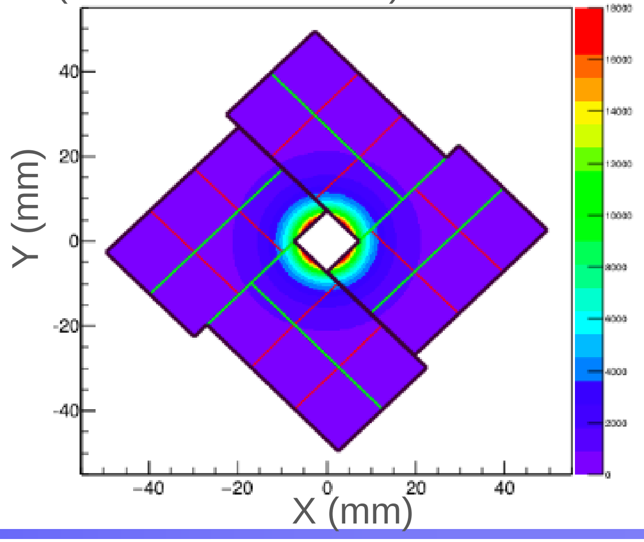
GBTx



Prototype modules



Up to 900 Mhits/s/ASIC
(data driven readout)

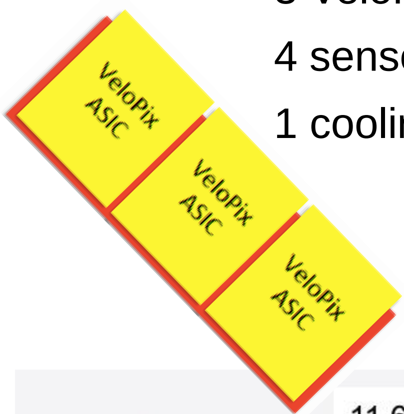


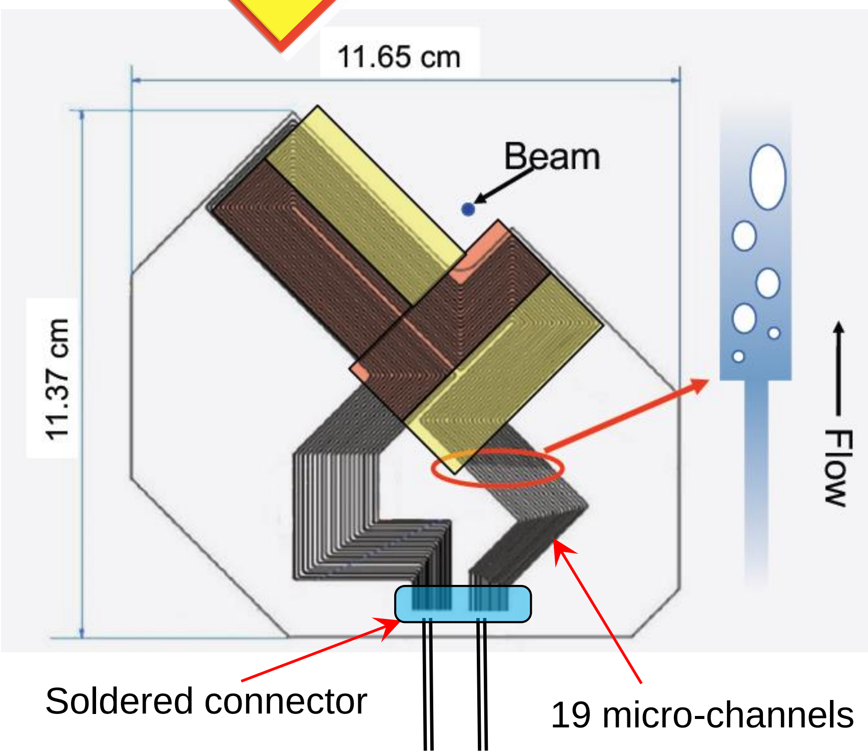
VELO Cooling Substrate

3 VeloPix ASICs / sensor

4 sensors / module

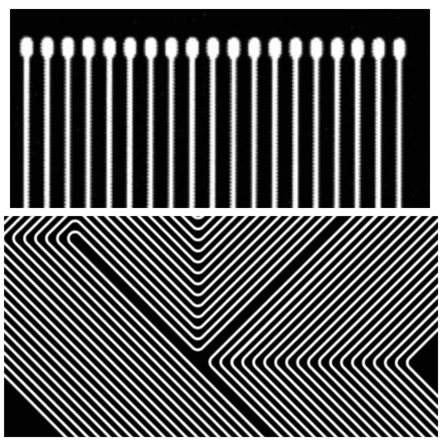
1 cooling substrate / module





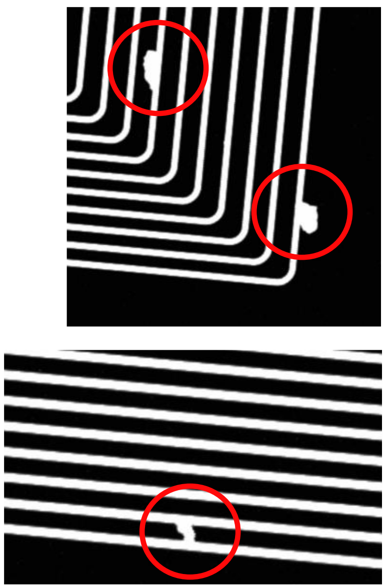
- VELO uses evaporative CO_2 cooling. So that the silicon sensor operates <-20°C.
- 120×200 μm² micro channels are etched in 500 μm silicon substrate, 60×60 μm² at the entrance for stability.
- It is a real challenge. But enough good quality substrates have been produced.

Good



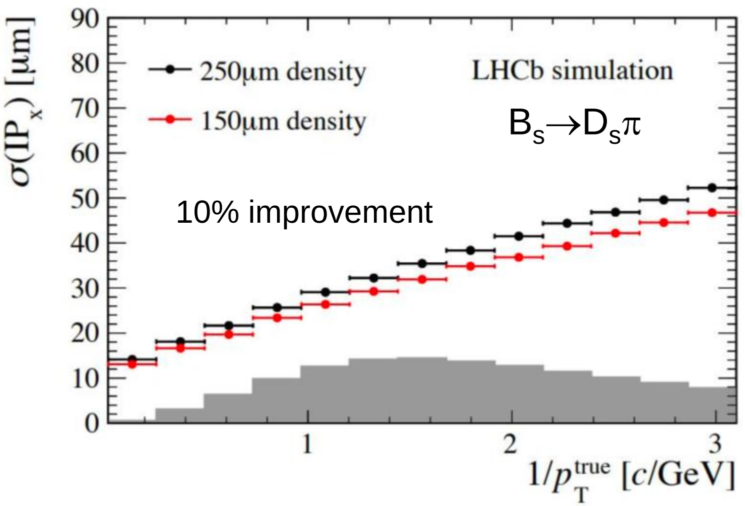
SEM images

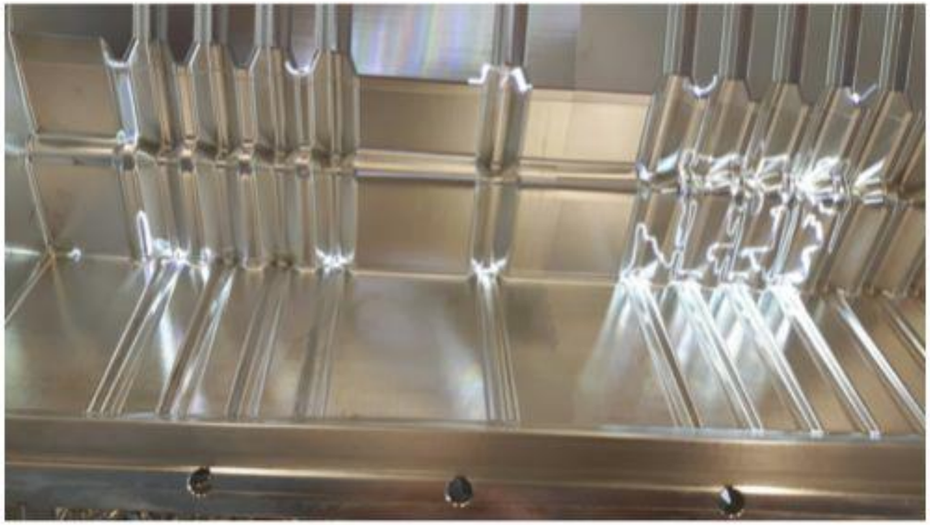
Defected



VELO RF Shield

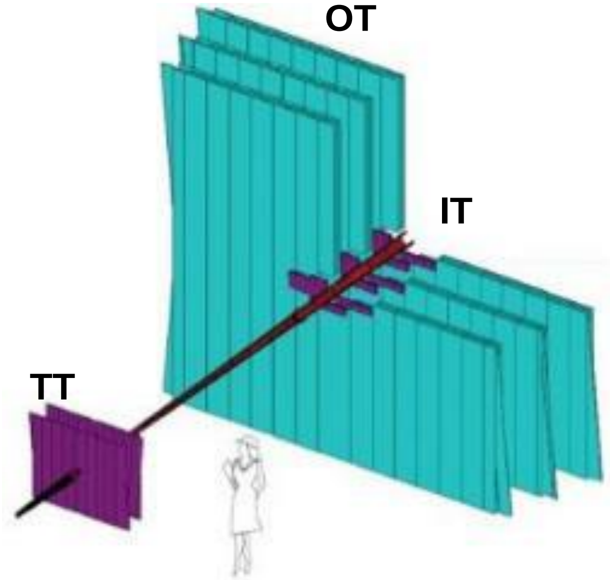
- RF shields separate the beam vacuum and the detector volume (~10 mbar difference).
- The thickness significantly affects the performance.
- The RF shields were milled from AlMg3 alloy blocks, to reach ~250 μm at tips of the VELO module.
- Chemical etching down to 150 μm.

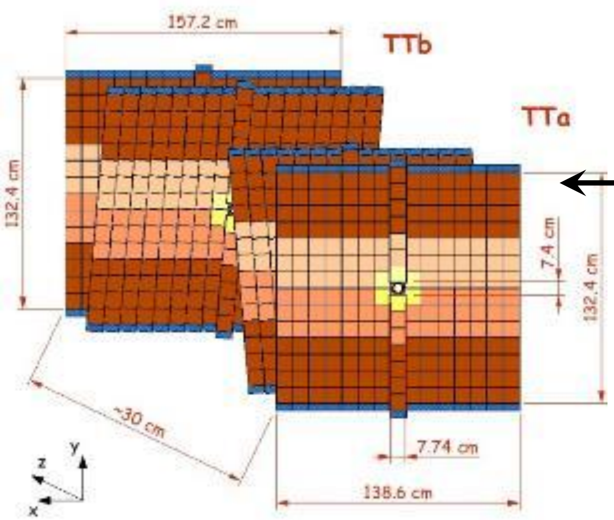




The Tracking Stations Before LS2

- 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.

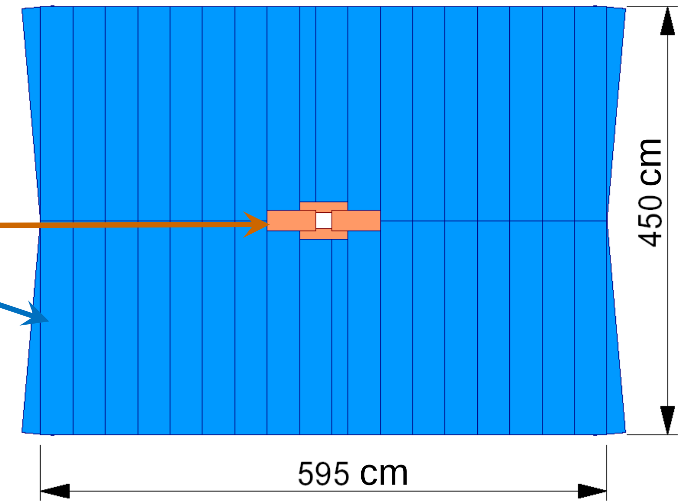




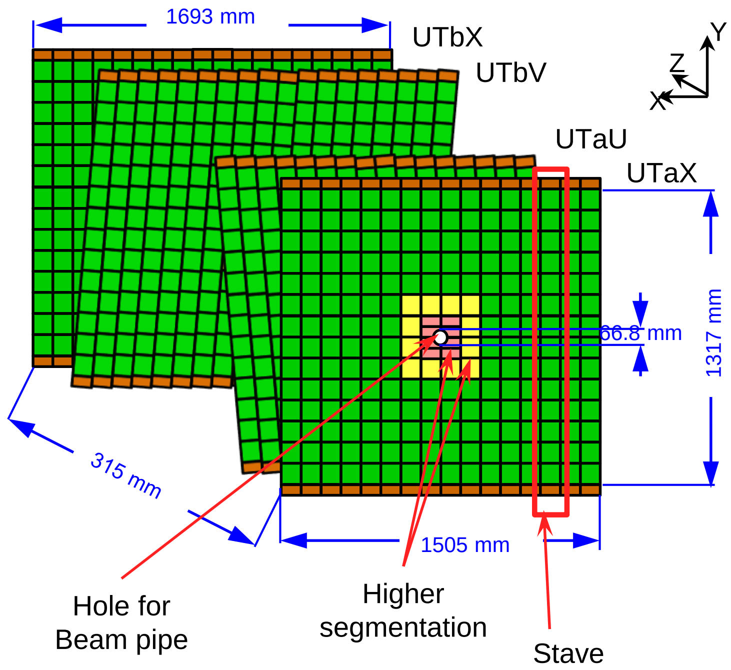
Trigger Tracker (TT)

Inner Tracker (IT)

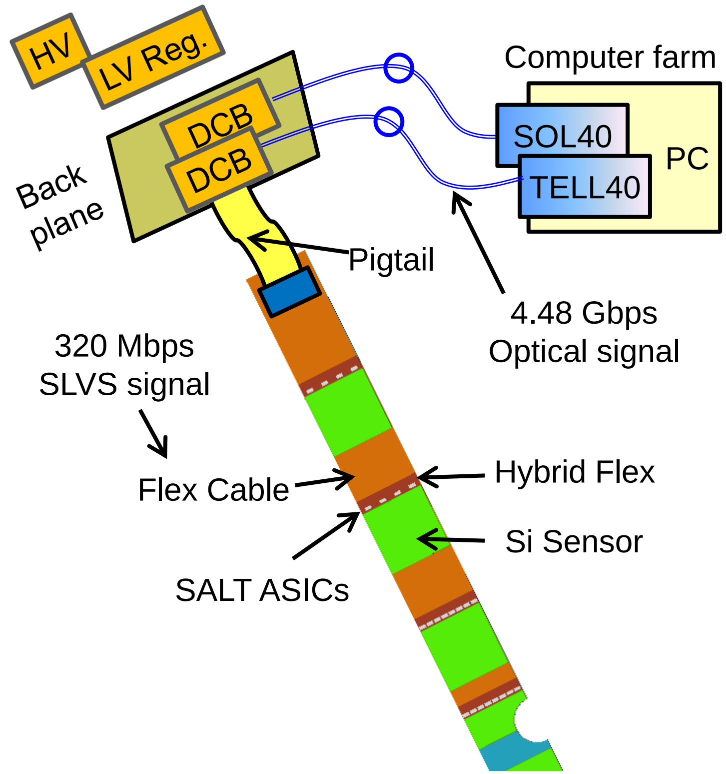
Outer Tracker (OT)



Upstream Tracker (UT)

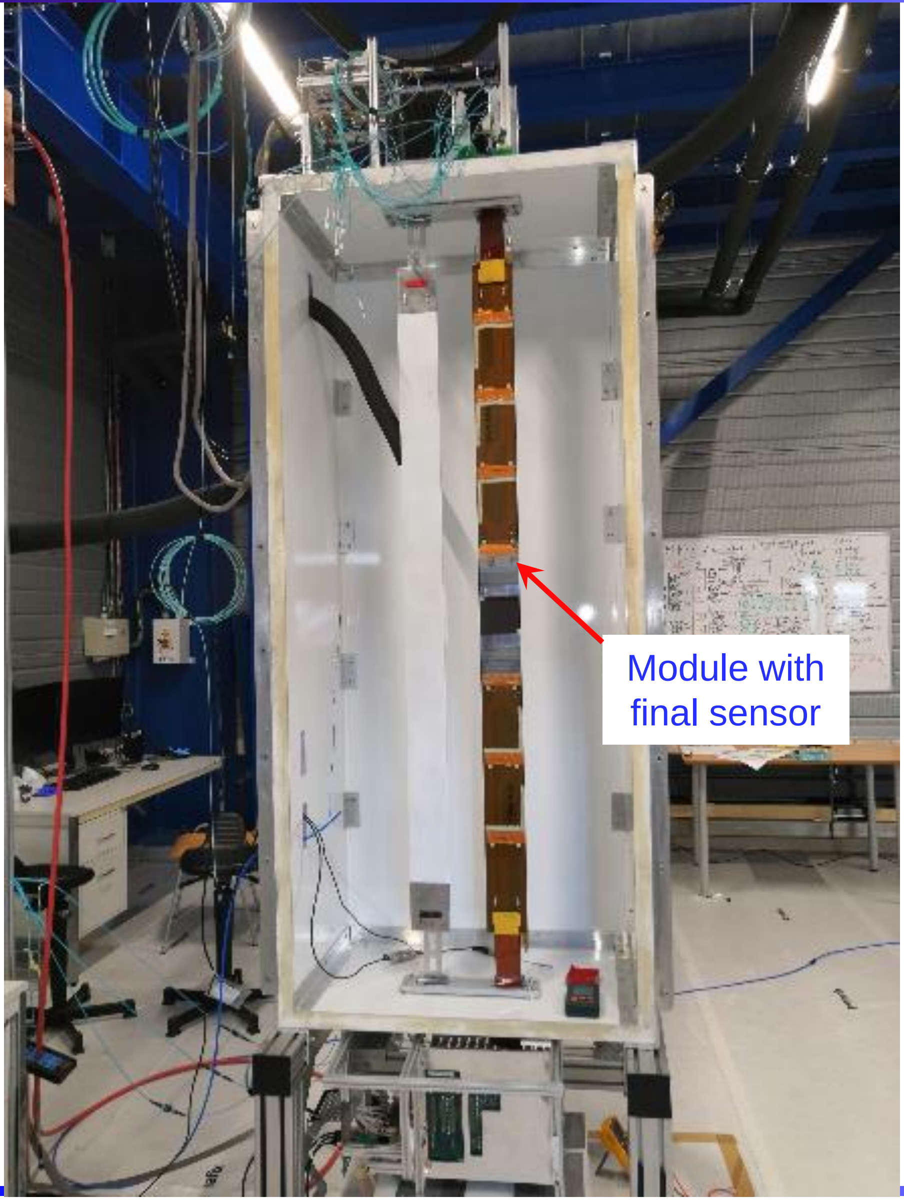


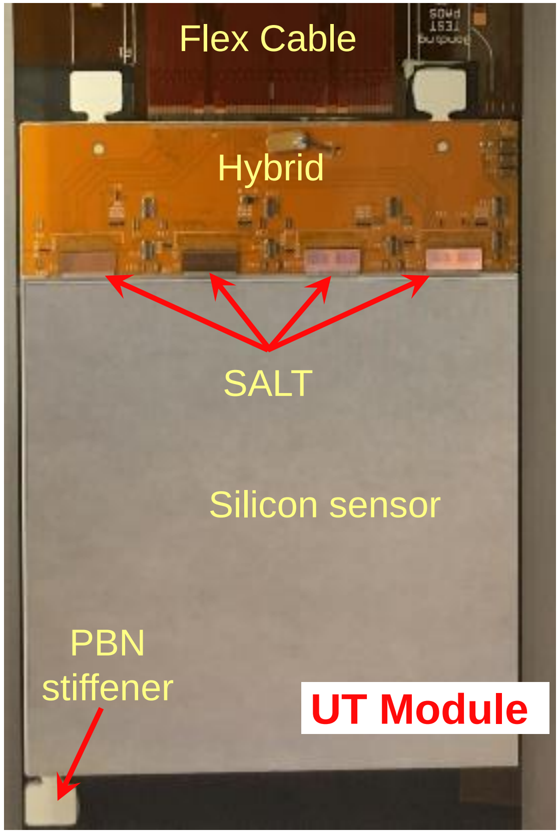
- Similar geometric configuration as TT.
- Improved coverage and segmentation.
- Sensor is more radiation resilience, Φ_{max} ~5×10^{14} n_{eq}cm^{-2}.



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

UT Module & Stave

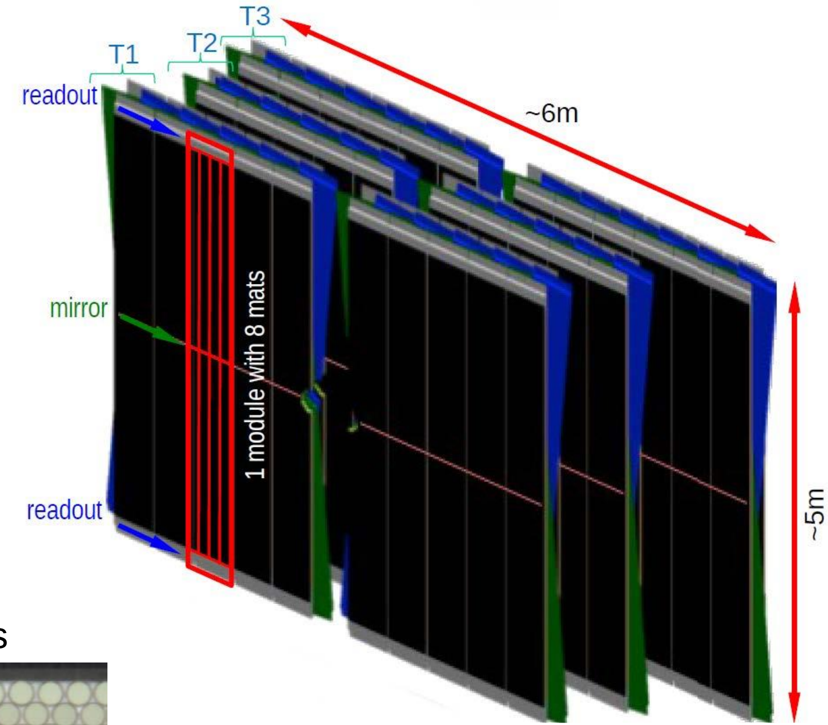




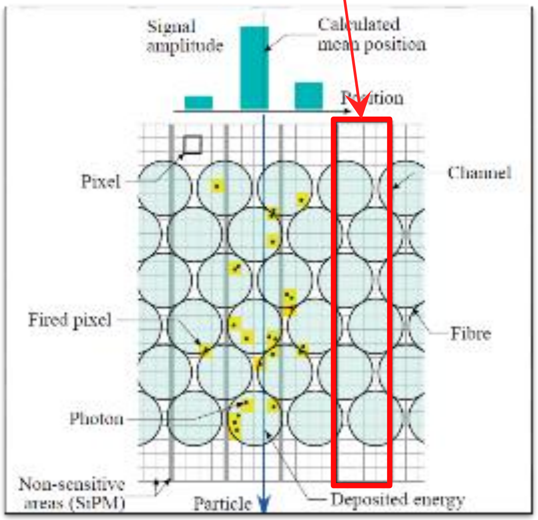
- ❑ Detector performance were verified in a slice system.
- ❑ UT stave production started.
- ❑ Installation will start in March 2020..

Scintillation Fiber (SciFi) Detector

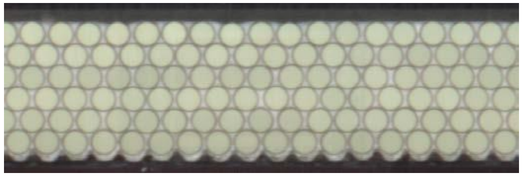
- Tracking stations are replaced by 3-station (12-plane) scintillation fiber detector.
- Read out with arrays 4096 SiPMs (-40°C) + custom made PACIFIC ASICs. In total ~ 0.59 M readout channels.
- Spatial resolution better than 100 μm in X.
- Single hit efficiency ~99%.



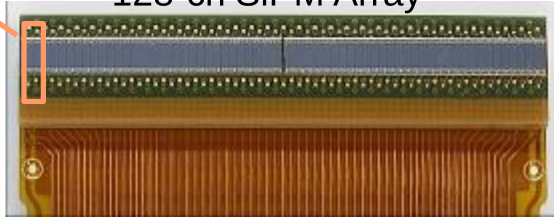
1 SiPM Channel



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.

SciFi Modules are being mounted on the support frames.

The Phase II Upgrade

$\mathcal{L}\sim 1.5\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Data ~ 300 fb^{-1}

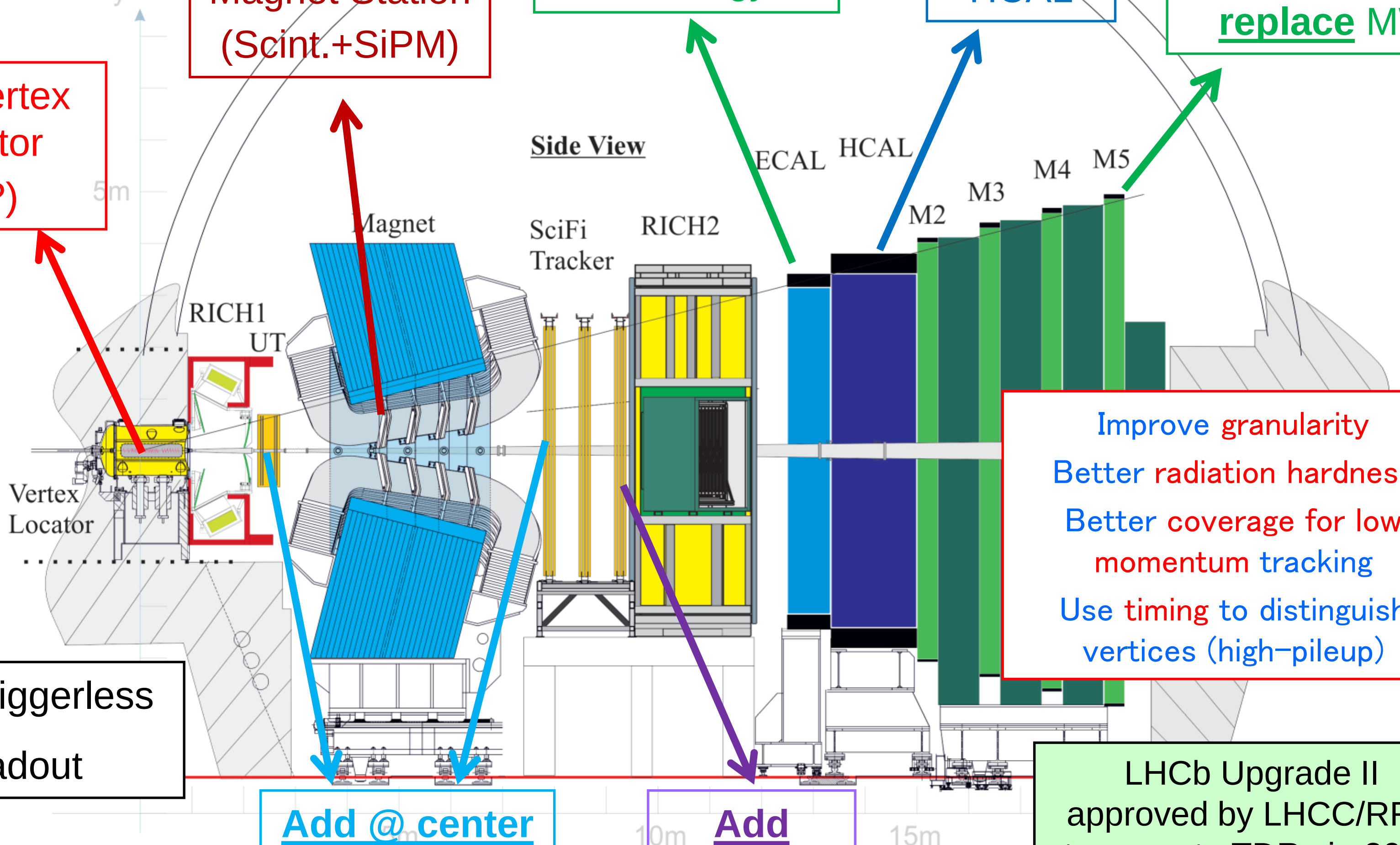
Add Magnet Station (Scint.+SiPM)

New ECAL Technology ?

Remove HCAL

More MUON filter + **replace** MWPC

New Vertex Detector (4D?)



Improve granularity
Better radiation hardness
Better coverage for low momentum tracking
Use timing to distinguish vertices (high-pileup)

Keep triggerless readout

Add @ center Mighty Tracker

Add TORCH ?

LHCb Upgrade II approved by LHCC/RRB to move to TDRs in 2020

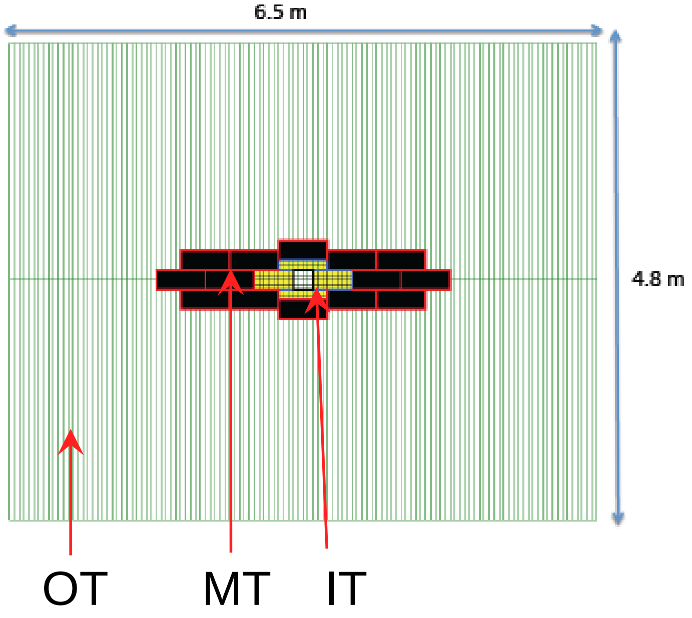
Possible Phase II Upgrade Plans

Disclaim: Non-official, possible solutions.

- The **VELO** detector may be upgraded to a 4D pixel tracker. The design could be improvement based on the phase I detector design:
  - Pixel size 55×55 μm^2 ⇒ 27.5×27.5 μm^2, sensor thickness 200 μm ⇒ 100 μm.
  - Time resolution 25 ns (BX) ⇒ 20-50 ps.
  - Silicon micro-channel cooling ⇒ 3D printed Titanium substrates.
  - 150 μm RF shield ⇒ further thinned or no RF foil.
- The main tracker (**SciFi** in phase I) could be split into 3 regions:
  - Outer part (OT) keeps the SciFi design.
  - Middle part (MT) uses UT-like strip detector.
  - Inner part (IT) uses ***HV-CMOS*** detector.
- The **UT** also upgrades the central part:
  - Outer part keeps the same design.
  - Inner part uses ***HV-CMOS*** detector.

Will benefit from joint effort, e.g. with ATLAS, CEPC, …

The Main Tracker

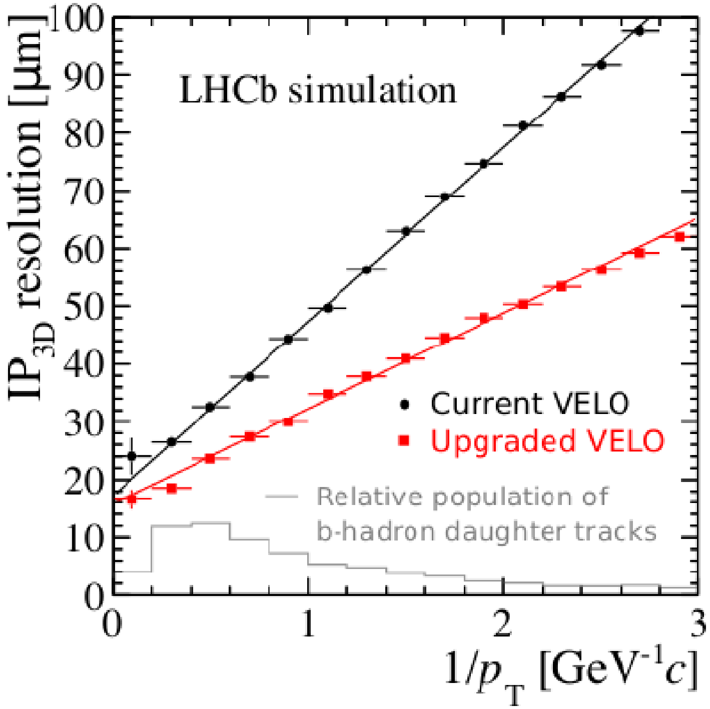


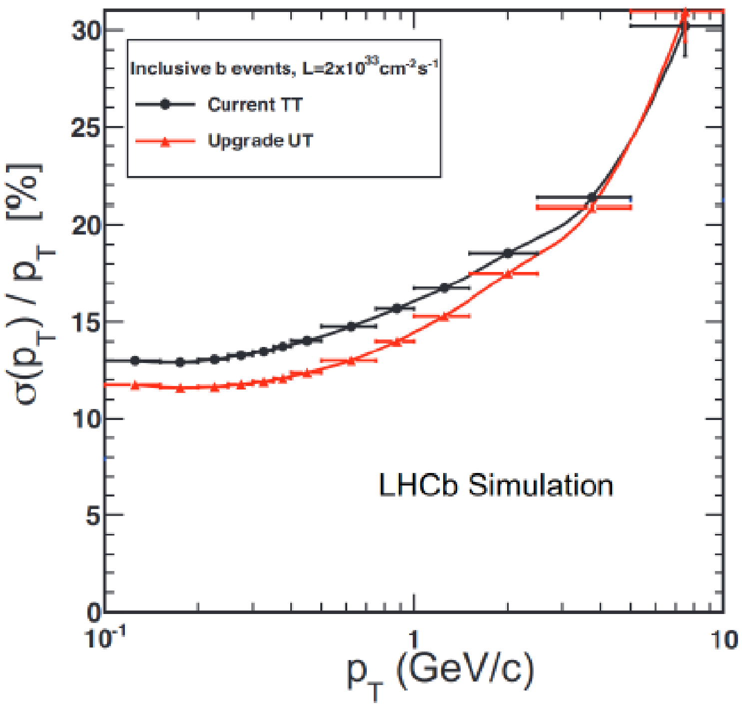
Summary

- The LHCb is upgrading its detectors during LS2, to operate at an increased luminosity (x5), and with trigger-less readout.
- The vertex detector + tracking detectors are completely new in this phase I upgrade. Other detectors all have new electronics.
- Expect to start operation in the 2^{nd} half of 2021.

- The phase II upgrade had been approved by LHCC to proceed to a Framework TDR.

Backup Slide


LHCb simulation
IP$_{3D}$ resolution [μm]
1/p_T [GeV^{-1}c]
Current VELO
Upgraded VELO
Relative population of
b-hadron daughter tracks


Inclusive b events, L=2x10^{33}cm^{-2}s^{-1}
Current TT
Upgrade UT
LHCb Simulation
σ(p_T) / p_T [%]
p_T (GeV/c)