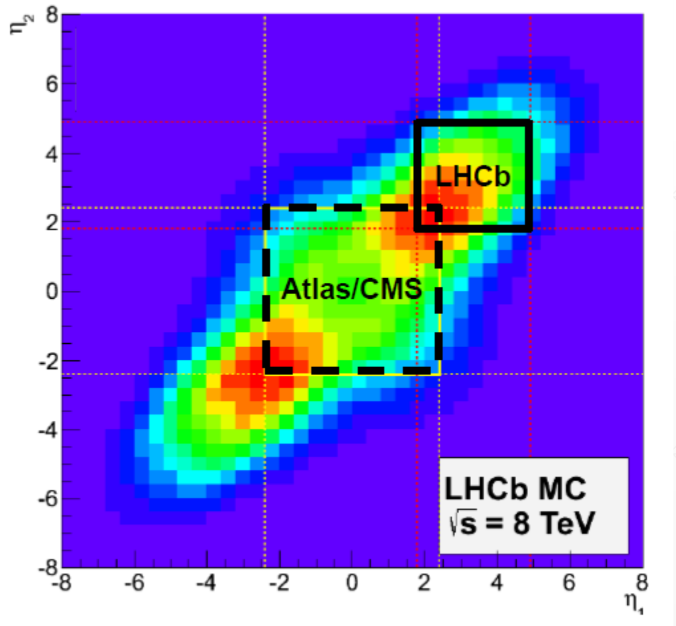
Plans and Status of the LHCb Upgrade

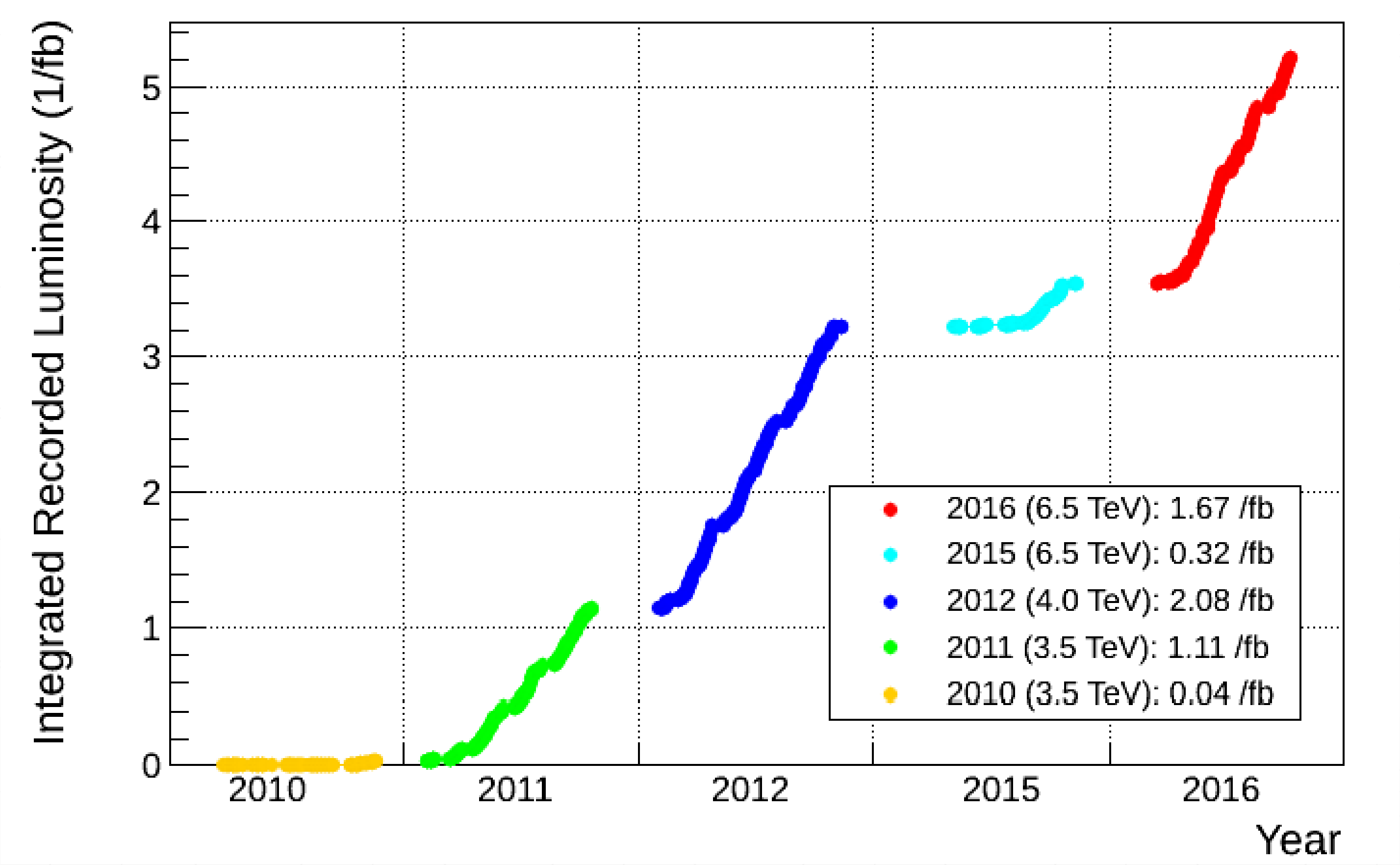
Tomasz Szumlak on behalf of the LHCb Collaboration
15th Conference on Flavour Physics and CP Violation, 5-9 June 2017, Prague

LHCb Detector and its Performance

- LHCb experiment was designed to studying CP-violation and search for New Physics phenomena in heavy flavour (beauty and charm) quark sector
- It proved itself to be a **General-purpose Forward Detector** (nicely complementary to ATLAS/CMS)
- Main features
  - Single-arm spectrometer, fully instrumented in pseudo rapidity range $2 < \eta < 5$ (solid angle coverage ~ 4%, 40% B mesons)
  - High performance tracking system (critical!)
    - Spatial resolution ~$4\ \mu m$ at vertex detector
    - $\frac{\Delta p}{p} = (0.4 - 0.6)\%$ for tracks with momentum between $p \rightarrow (5 - 100)\ GeV$
    - Impact parameter resolution ~$20\ \mu m$ for high p_T tracks
    - Decay time resolution ~$45\ fs$ $(B_s \rightarrow J/\psi\varphi)$
    - Excellent particle identification capability



Collected Data



Cumulative Integrated Luminosity for LHCb, Prepared by the LHCb Online Team

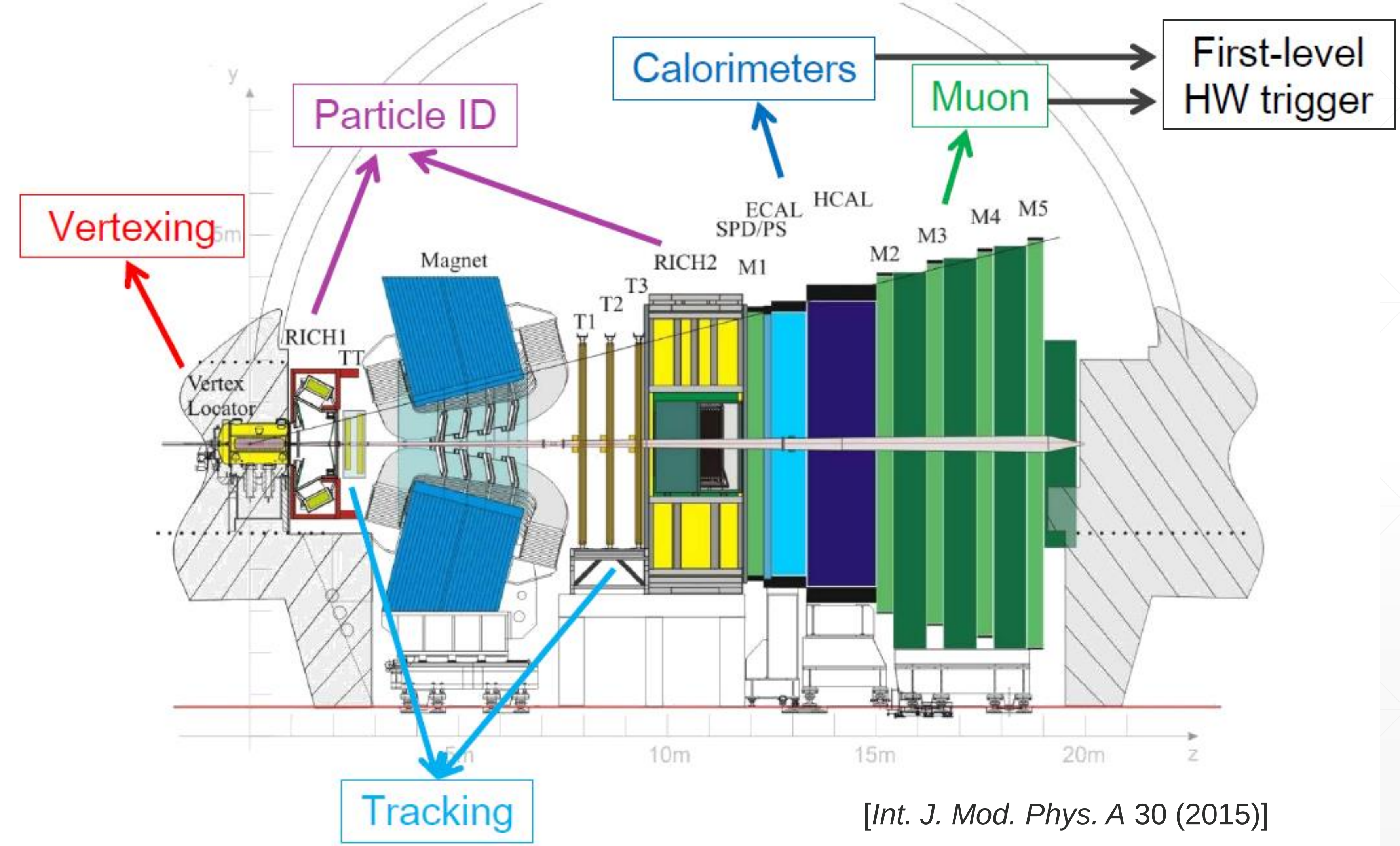
Collected data (on tape):

- ❑ Run 1: $3\ fb^{-1}$ $@(7-8)\ TeV$
- ❑ Run 2: $2\ fb^{-1}$ $@13\ TeV$

High hopes we get another 3 to $4\ fb^{-1}$ within next two years

Note! With higher x-sections (due to higher energy) we expect to get 5 Times larger data samples (w.r.t. Run I) in key physics channels!

Current Detector

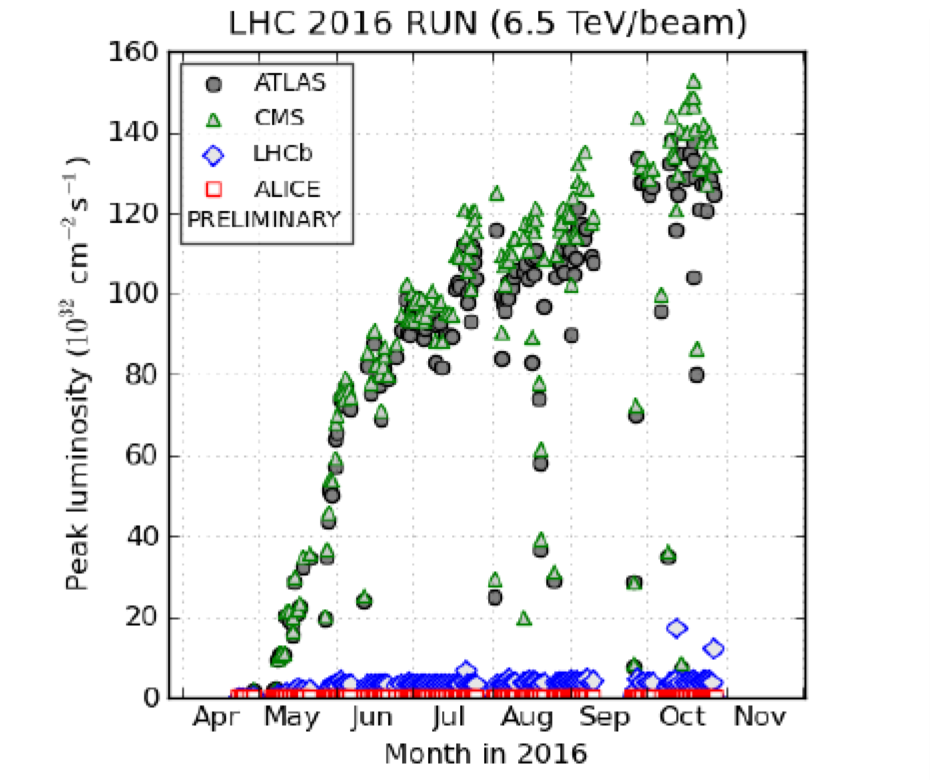


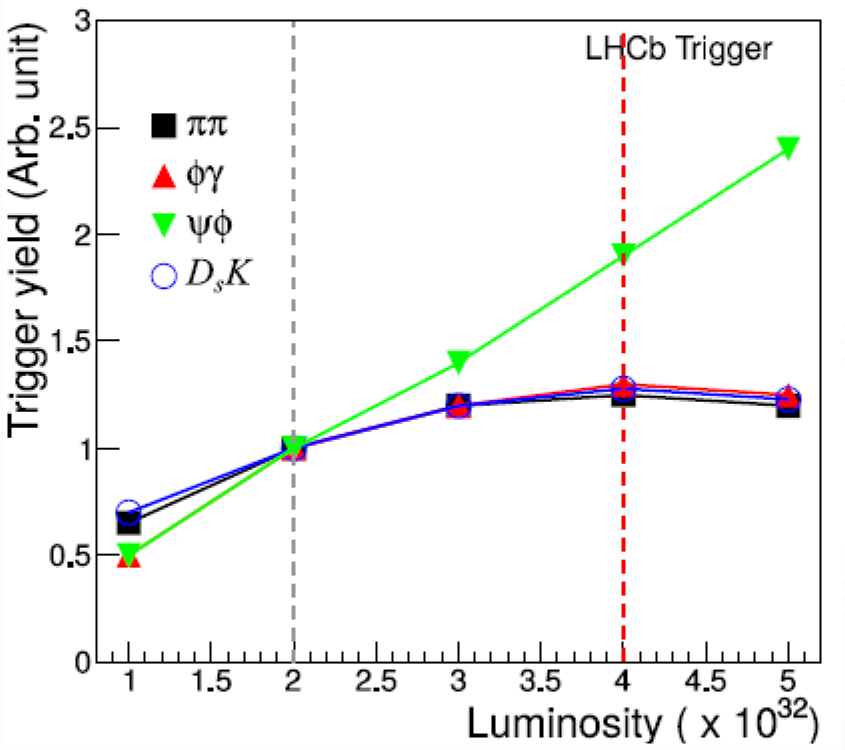
[*Int. J. Mod. Phys. A* 30 (2015)]

Current Detector Limitations I

- The amount of data that can be taken (recorded) is limited by the present detector
  - The luminosity of the LHC will be increasing
    - At present LHCb is running at instantaneous luminosity that is roughly 40 times smaller than ATLAS/CMS
  - At the same time the data bandwidth for LHCb detector would be limited to **1.1 MHz**
  - Sub-detectors could not cope with radiation damage (performance degradation)
    - Designed to survive **5 years** of data taking at $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}s^{-1}$
    - We successfully operated at $\mathcal{L} = 4 \times 10^{32}\ cm^{-2}s^{-1}$ and still have two years to go in Run II!
  - Physics yields for **hadronic channels would be saturated**
  - At higher luminosities the current detector could not perform successfully track reconstruction
    - Much higher track/primary vertex multiplicity
    - Processing time in the online farm to high

Current Detector Limitations II





- The most **sever bottleneck** is due to hardware trigger
  - Yield is almost factor 2 smaller for hadronic channels
  - This is mainly due to trigger criteria (cuts on p_T and E_T) to fit the trigger rate into the 1.1 MHz readout bandwidth

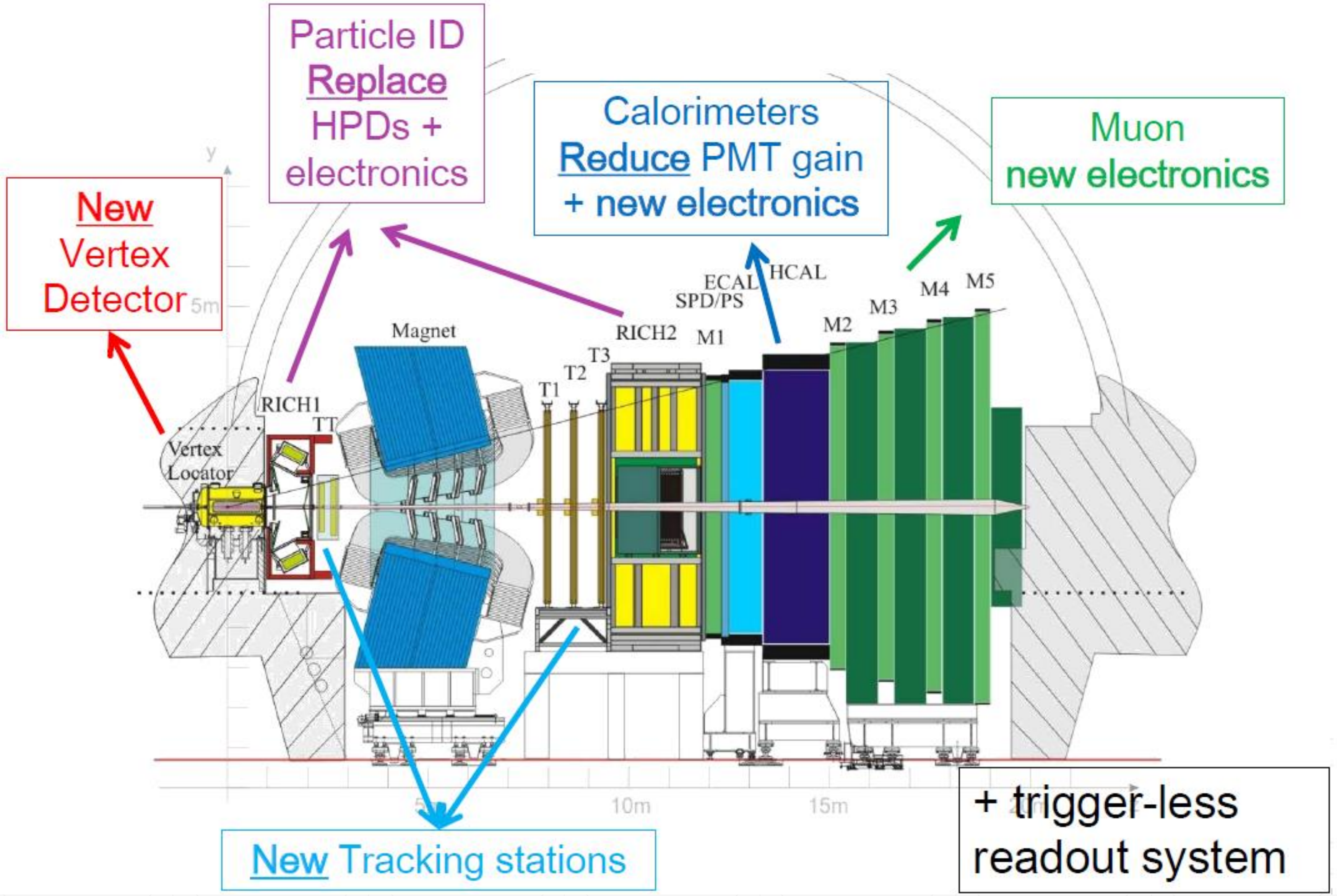
Phase-I Upgrade Strategy

- Remove the hardware trigger completely – read-out the full detector at each LHC bunch crossing
  - New **trigger-less** readout front-end electronics
  - Redesign current readout network to cope with **multi-TB/s data stream**
  - Readout at $40\ MHz$

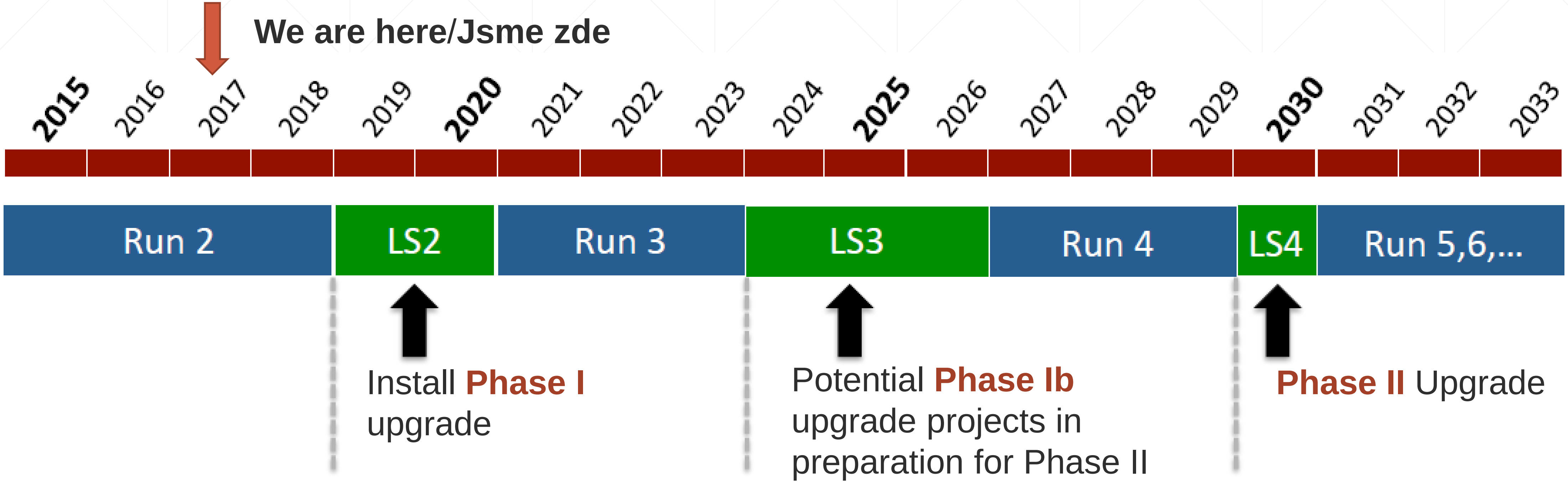
- Flexible fully software trigger system
  - Information from each sub-detector available to enhance trigger decision
  - Maximise signal efficiencies at high event rate

- Detectors incompatible with higher luminosities must be re-designed
  - The target peak luminosity of $\boldsymbol{\mathcal{L} = 2 \times 10^{33}\ cm^{-2}s^{-1}}$, that is 10 times higher than the nominal and 5 times higher than the one we running at today
  - Finer granularities and more radiation hardness

Phase-I Upgraded LHCb Detector

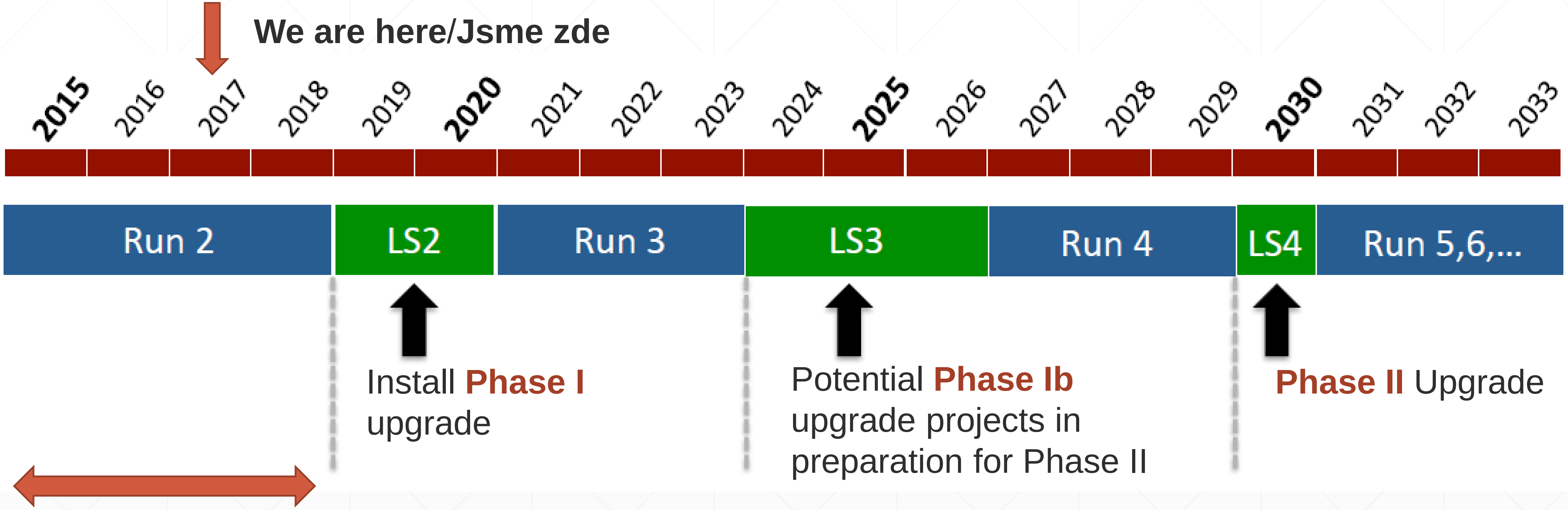


LHCb Upgrade – Timeline I



Fully aproved and fundings are secured

LHCb Upgrade – Timeline II

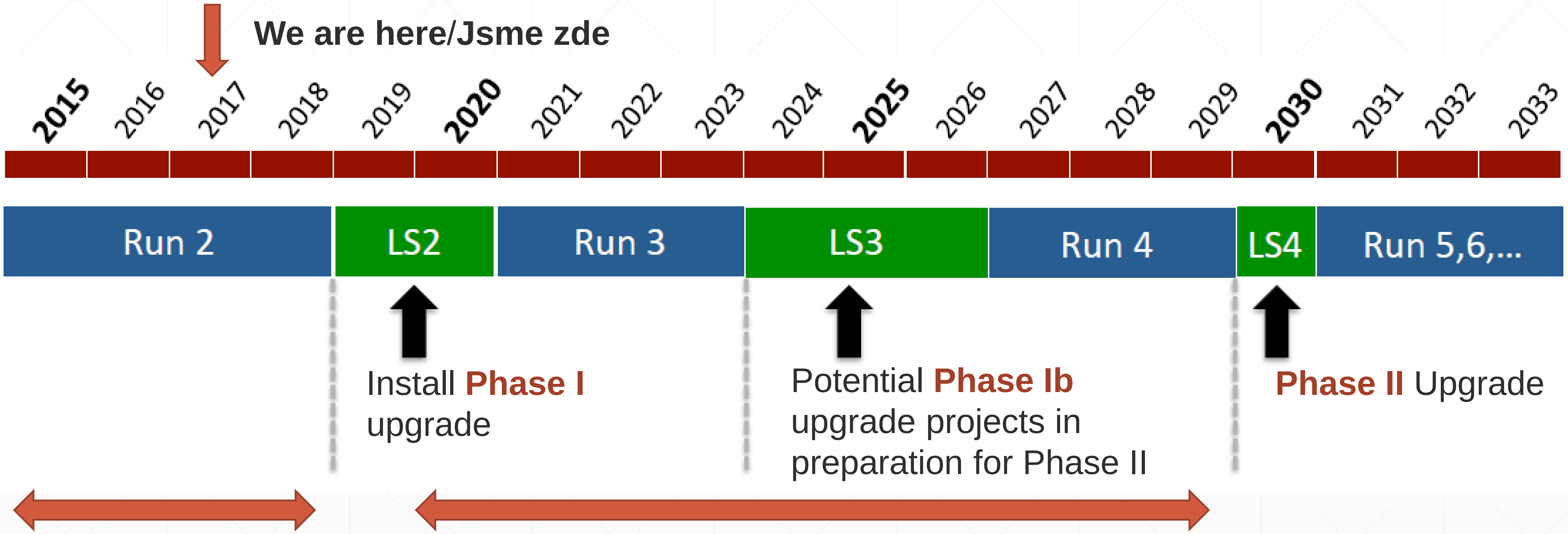


$\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

1.1 visible interactions / crossing

8 fb^{-1} collected

LHCb Upgrade – Timeline II



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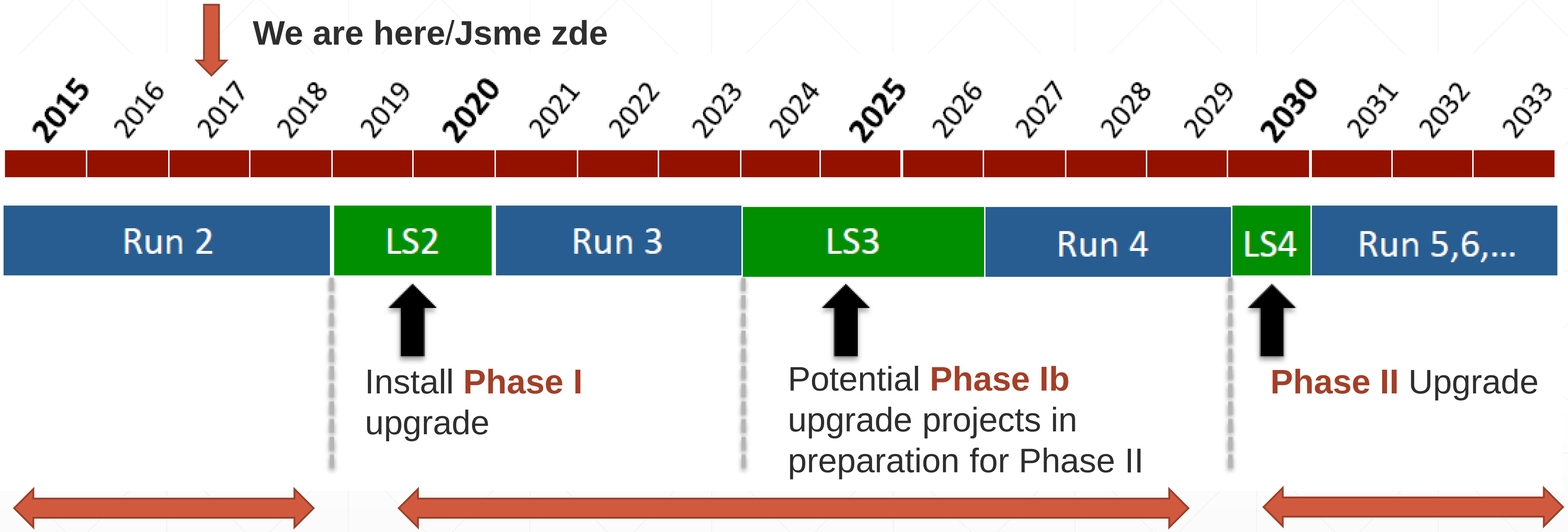
$\mathcal{L} = 2 \times 10^{33}\ cm^{-2}s^{-1}$

5.5 visible interactions / crossing

50 fb^{-1} collected

LHCb Upgrade – Timeline II



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1.1 visible interactions / crossing

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$\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

5.5 visible interactions / crossing

50 fb^{-1} collected

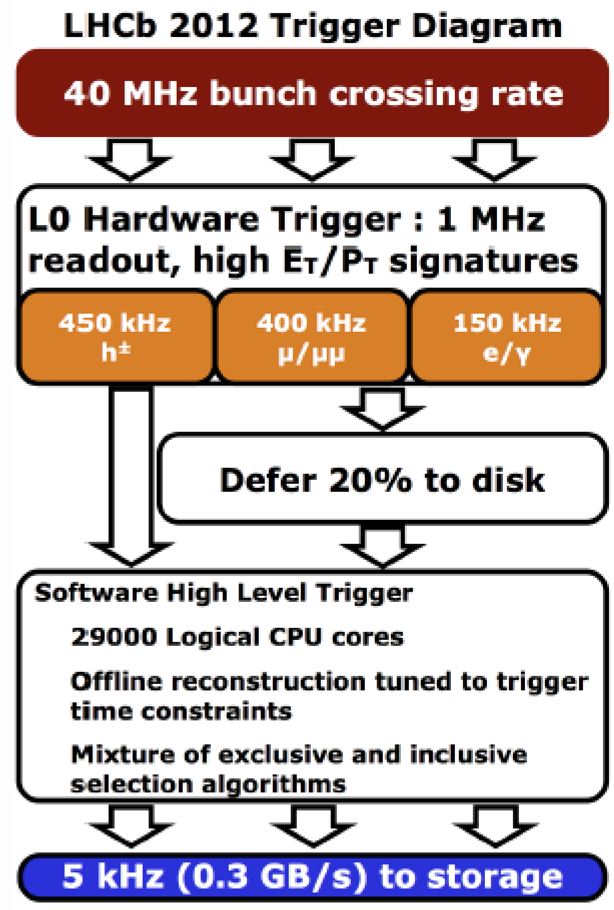
$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

55 visible interactions / crossing

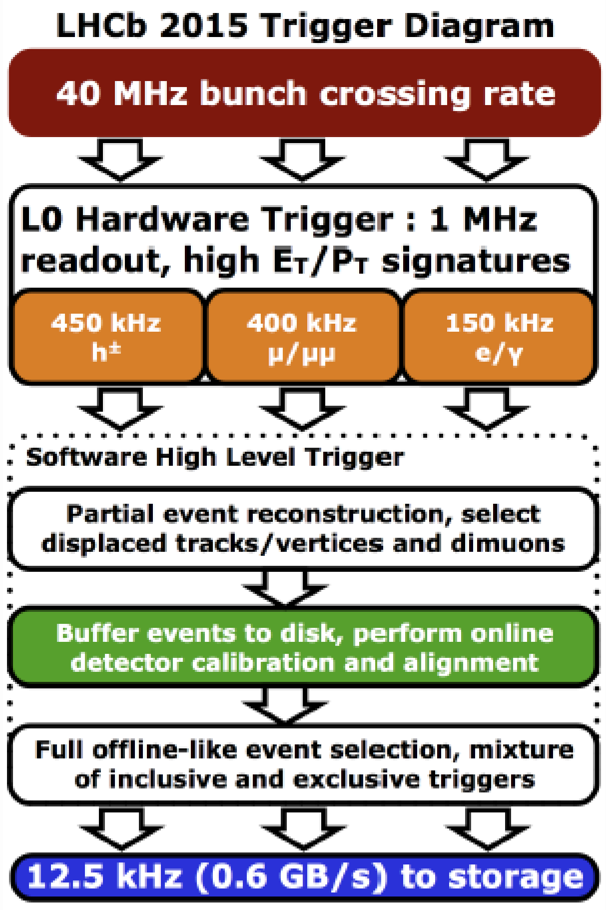
300 fb^{-1} collected

Upgraded Trigger System

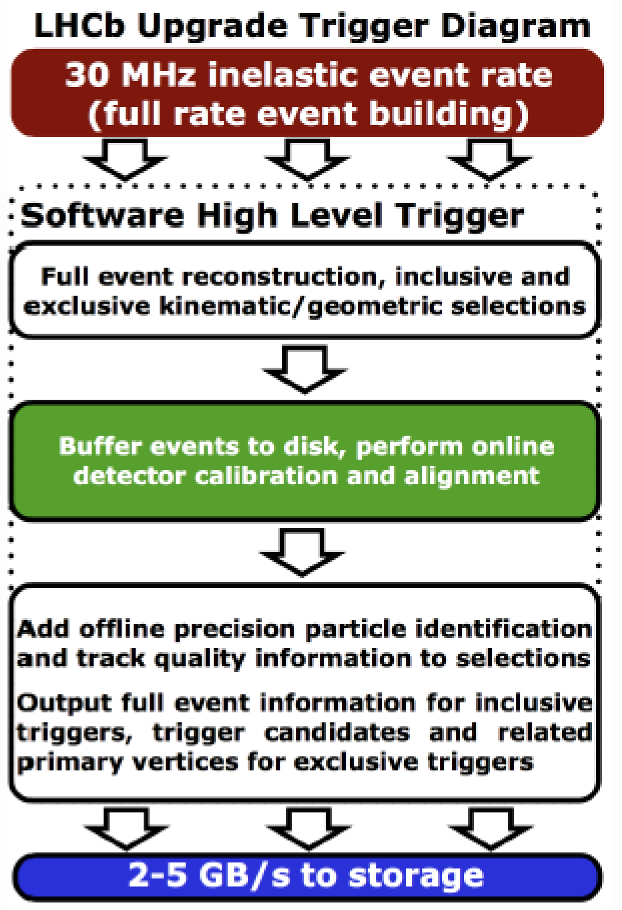
[*LHCB-TDR-016*]



Run 1



Run 2

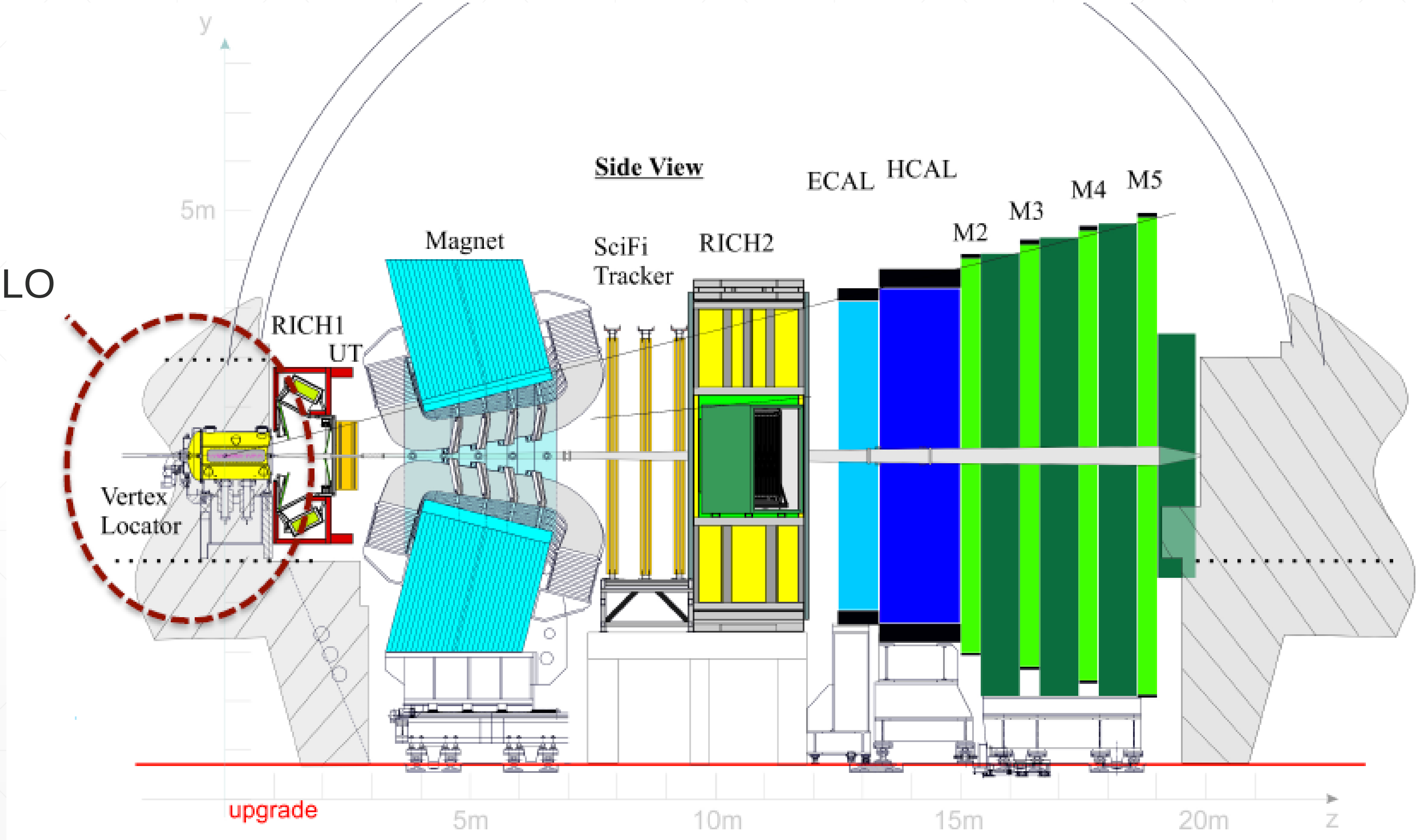


Run 3, 4

Vertex Locator

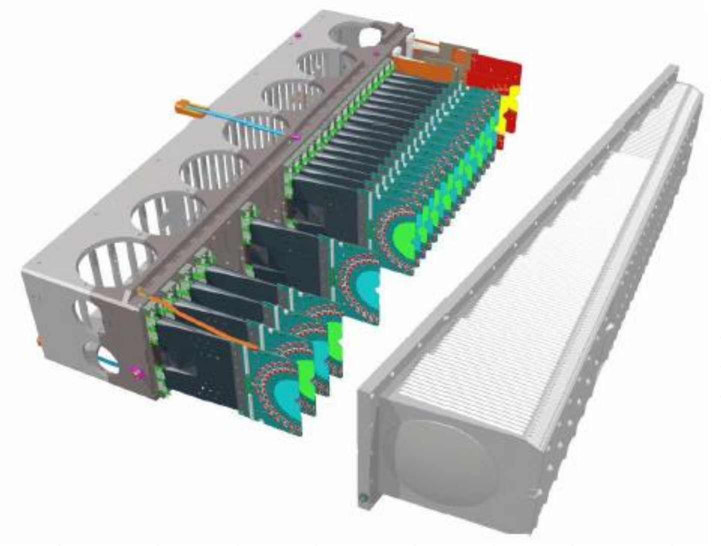
[*LHCB-TDR-013*]

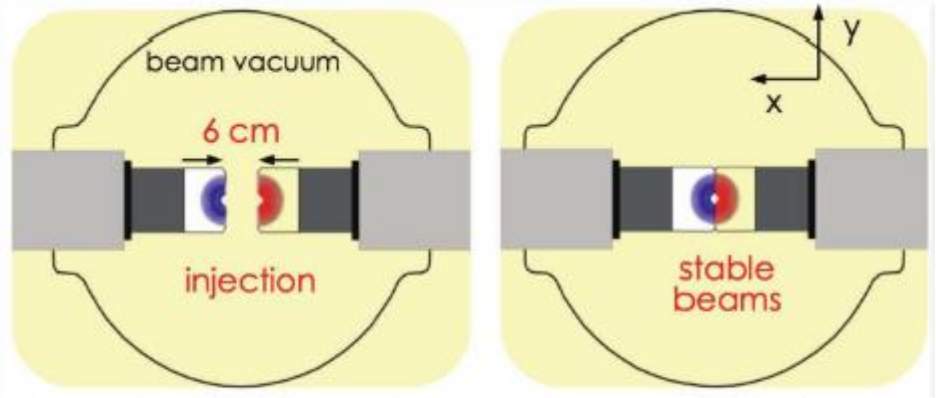
VELO



Vertex Locator (VELO) I

[*LHCB-TDR-013*]

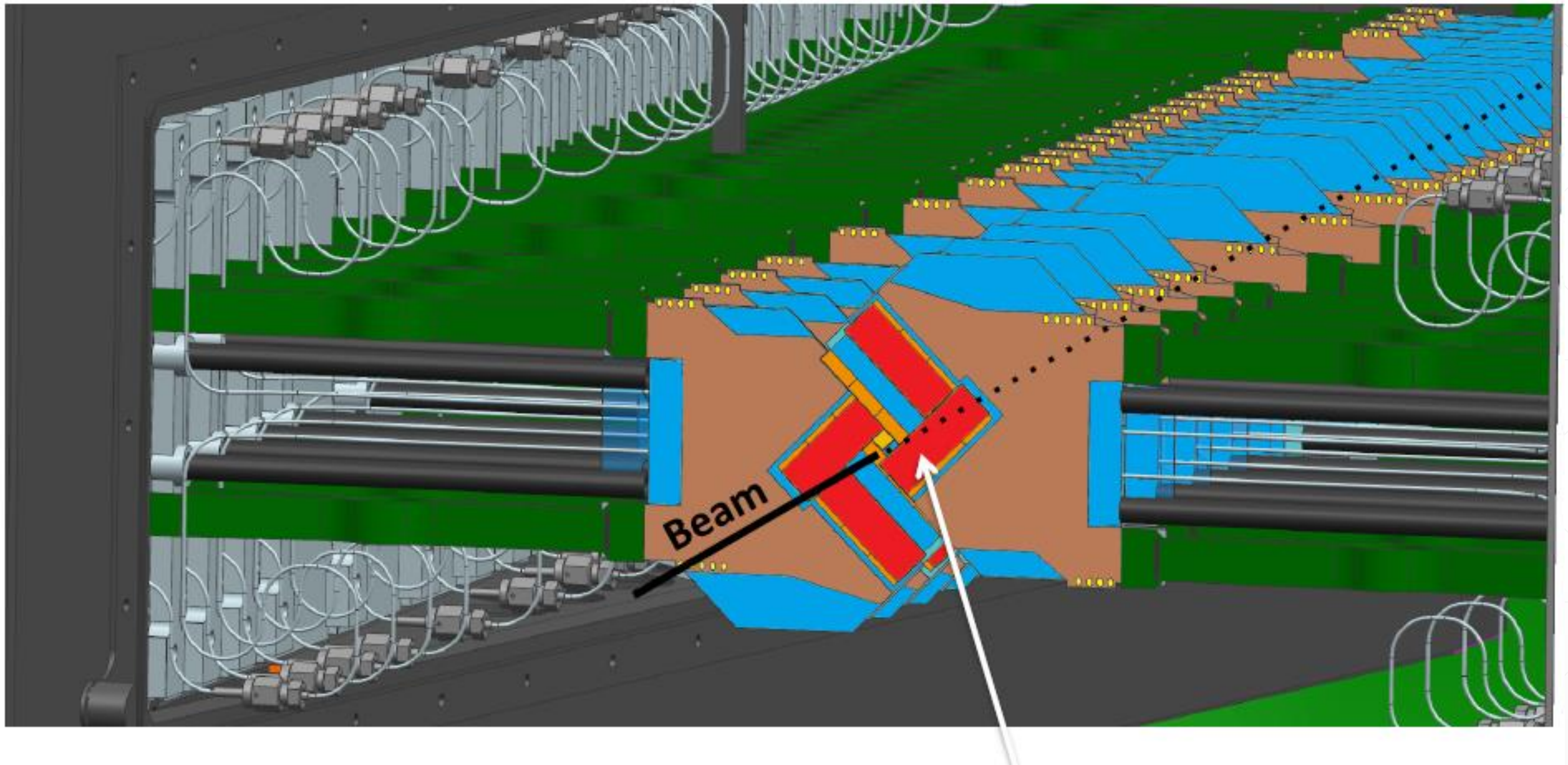




- Current detector
  - Two retractable halves separated by a thin RF foil from LHC vacuum
  - Semi-circular silicon microstrip sensors
  - First active strips at $8\ mm$ from the proton beams
  - Coping well with ~ 1 proton interaction per beam crossing
  - $\sigma_{IP} \sim 20\ \mu m$ for high p_T tracks
- Vertex detector for the upgrade
  - Much higher radiation dose comparing with the current detector ($\sim 8 \times 10^{15} n_{eq} cm^{-2}$)
  - Must cope with ~ 5 interactions per crossing
  - High tracking efficiency
  - Measure impact parameter with high precision
  - Higher granularity

Vertex Locator (VELO) II

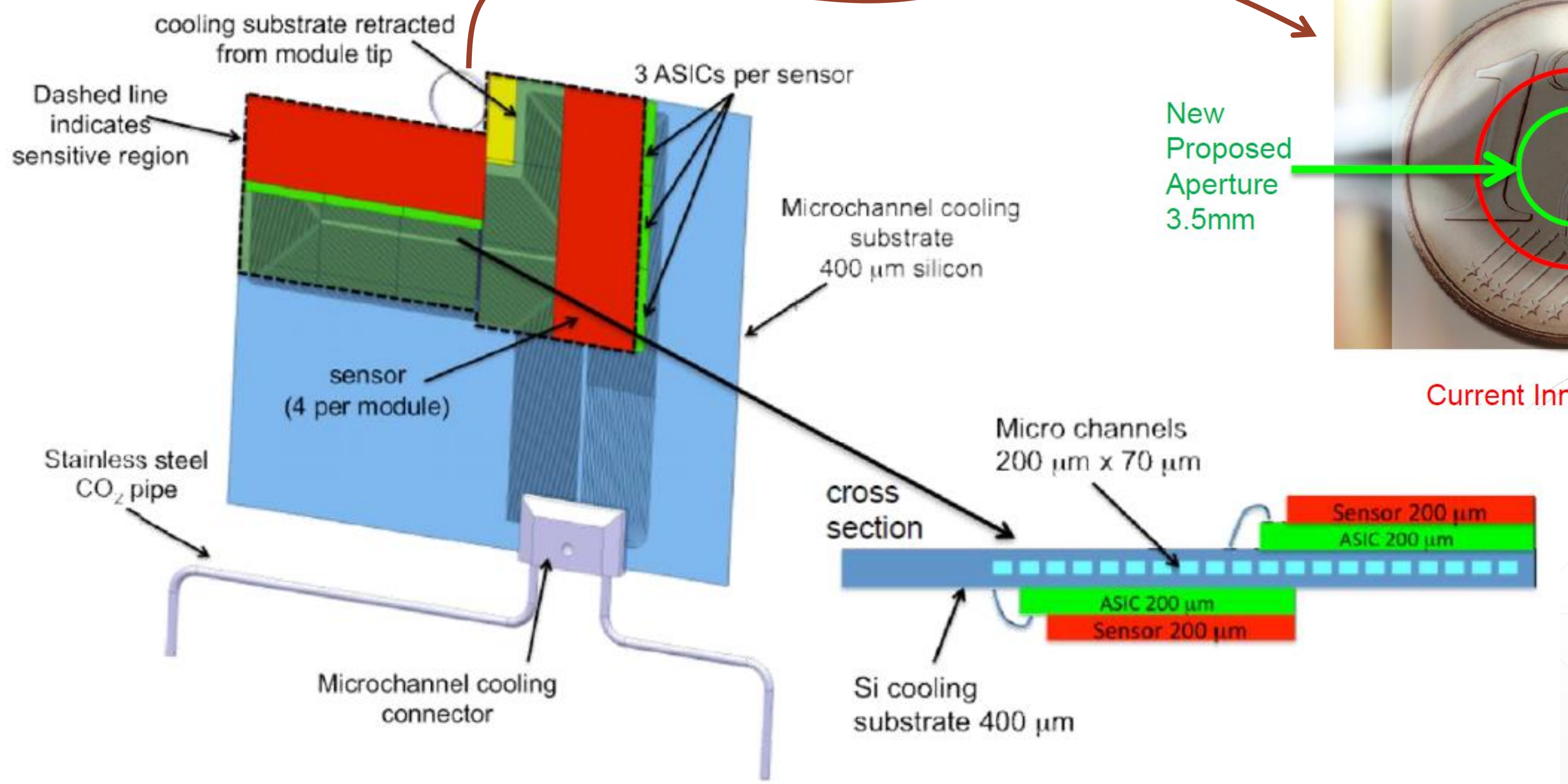
[*LHCB-TDR-013*]

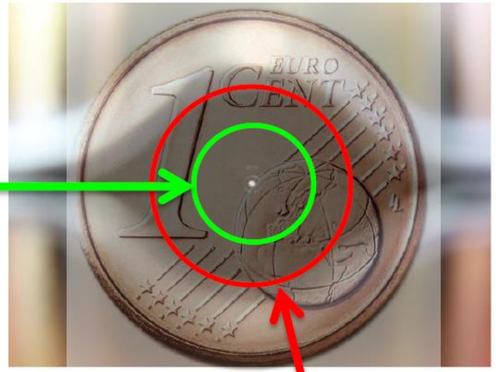


- Similar construction concept
  - Two retractable halves, separated by RF foil ($0.25\ mm$ thick) from LHC vacuum
  - 52 modules perpendicular to the proton beams
  - First active part $5.1\ mm$ from the beams (aperture $3.5\ mm$)

Vertex Locator (VELO) III

[*LHCB-TDR-013*]



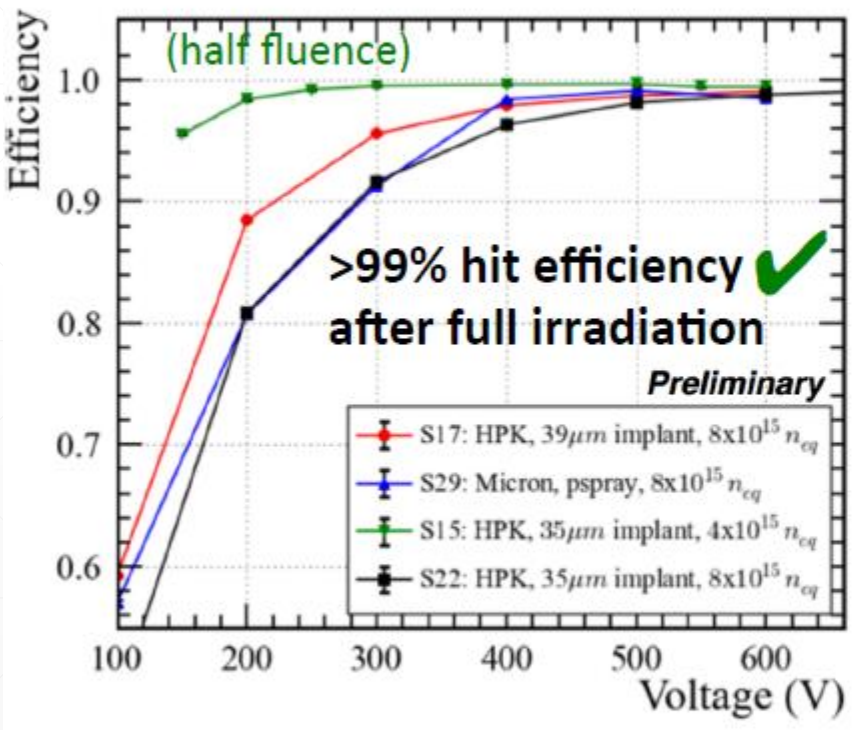


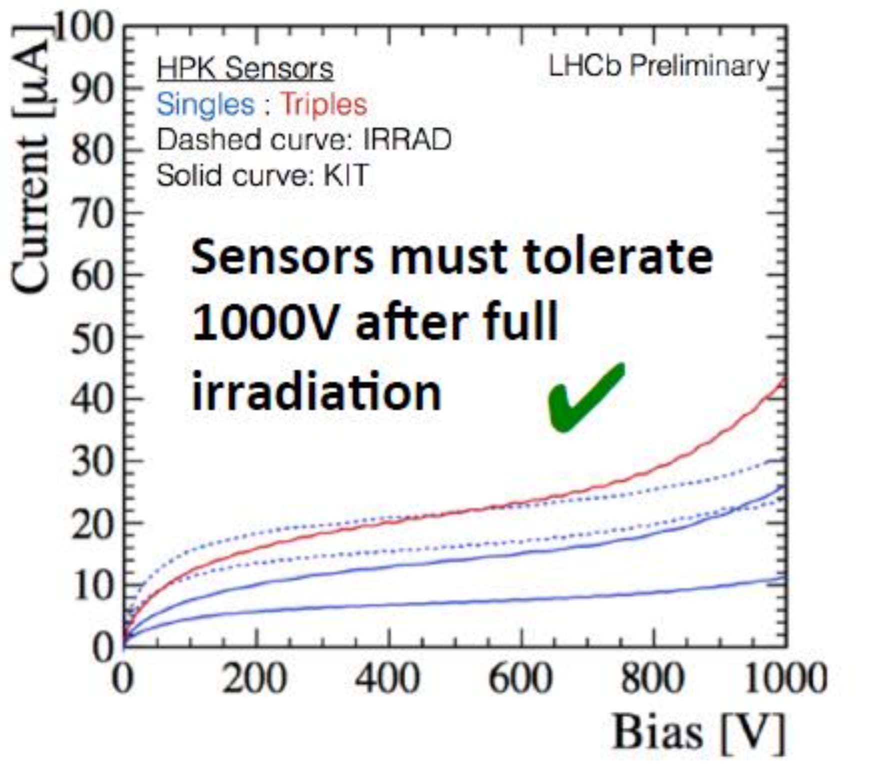
- Silicon pixel sensors
  - Four per module, powered and readout via kapton cables and hybrid boards
  - $55 \times 55\ \mu m$ square pixels (resolution the same in x and y direction)
  - Versatile sensor evaluation program is on the way (test beam campaign)

Vertex Locator (VELO) IV

[*LHCB-TDR-013*]

- Hard requirements for VELO pixels
  - High enough charge collection efficiency after irradiation (~ 6000 electrons)
  - Must tolerate high bias voltage (~ 1000 V)
  - High cluster finding efficiency after irradiation





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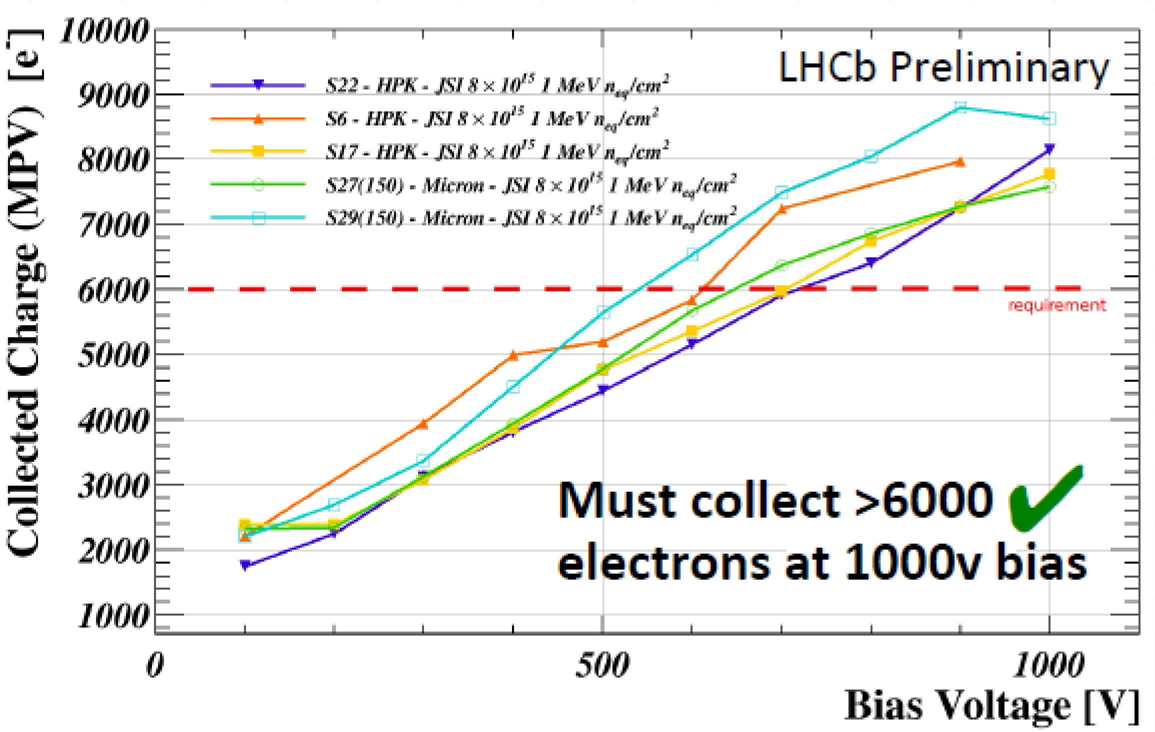
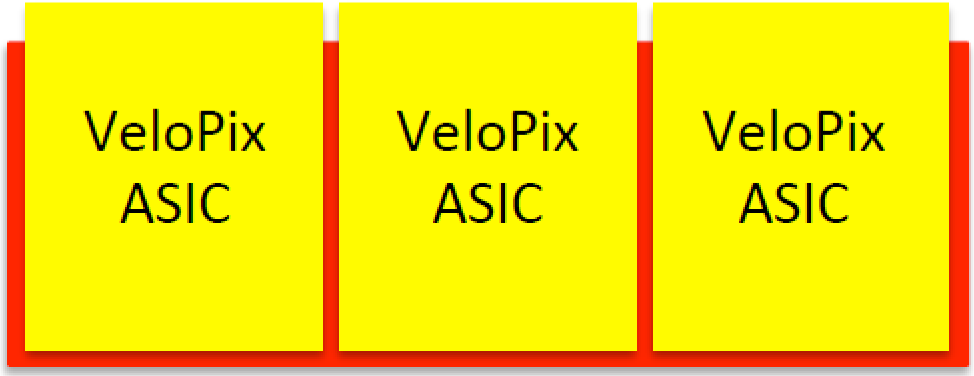


Vertex Locator (VELO) IV

[*LHCB-TDR-013*]

- Readout front-end chip – VeloPix ASIC
  - Each sensor ($43 \times 15\ mm$) bump-bonded to three VeloPix chips
  - Must cope with high data rate: $\sim 800 \times 10^6\ hits\ /\ s$
  - Power dissipation: ~ 1.5 W / ASIC
  - All testbeam results very good – final chip to arrive this year



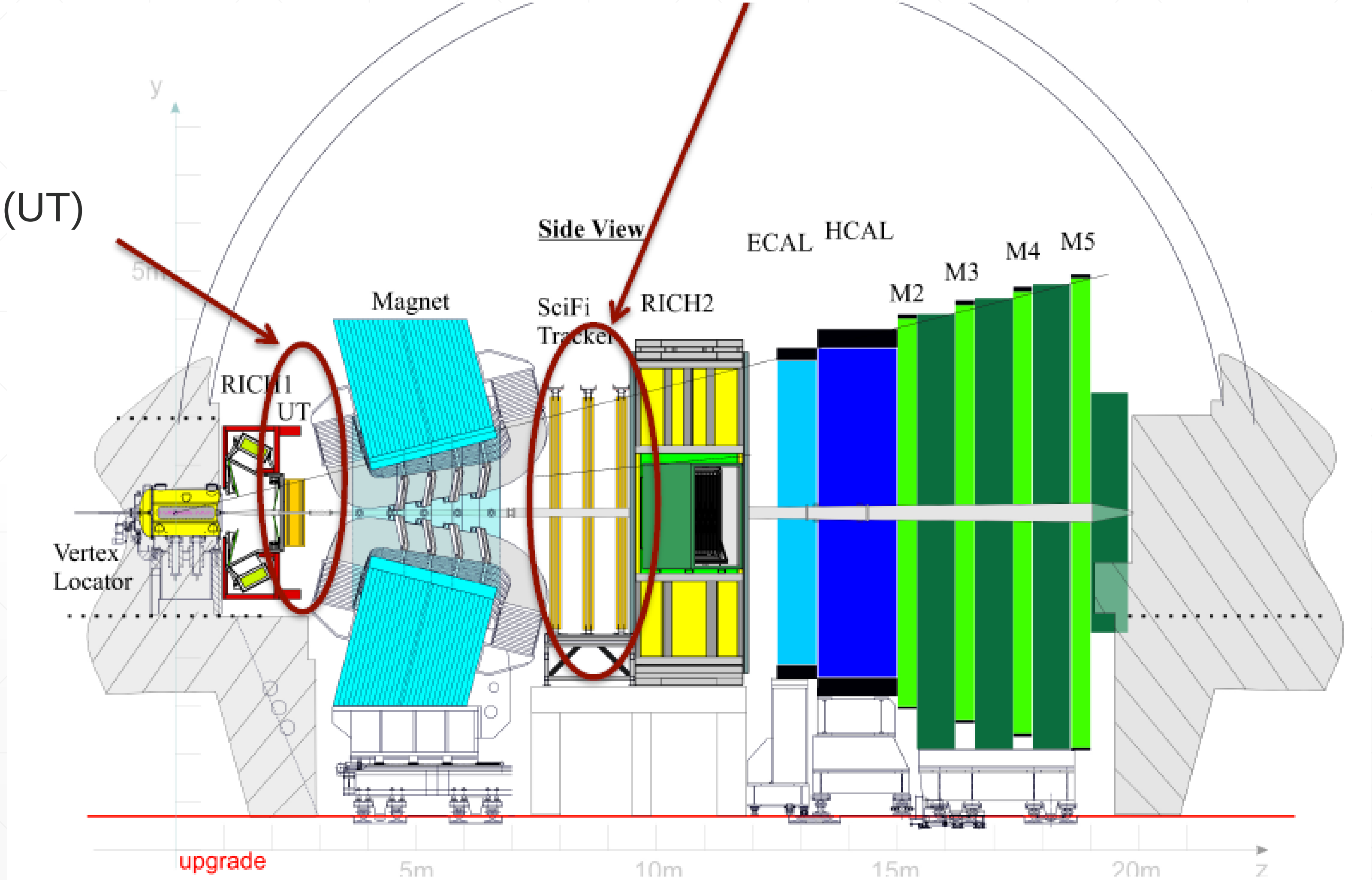
- Sensors and read-out electronics are mounted on cooling substrate with CO_2 micro-channels
  - Excellent cooling performance
  - Minimal material within detector acceptance
  - Now in full production

Tracking System I

Scintillating Fibre Tracker (SciFi)

[*LHCB-TDR-015*]

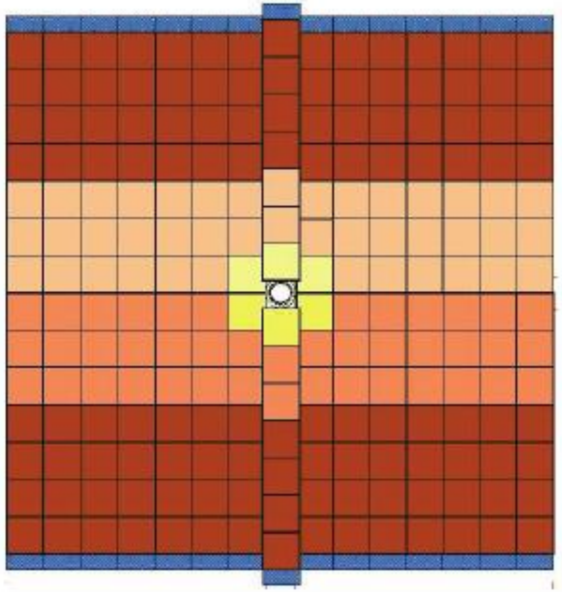
Upstream Tracker (UT)



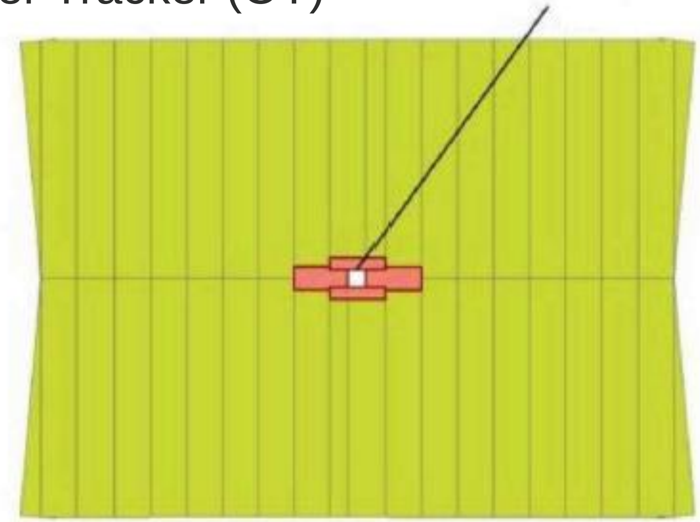
Tracking System II

[LHCB-TDR-015]

TT



T1 – T3

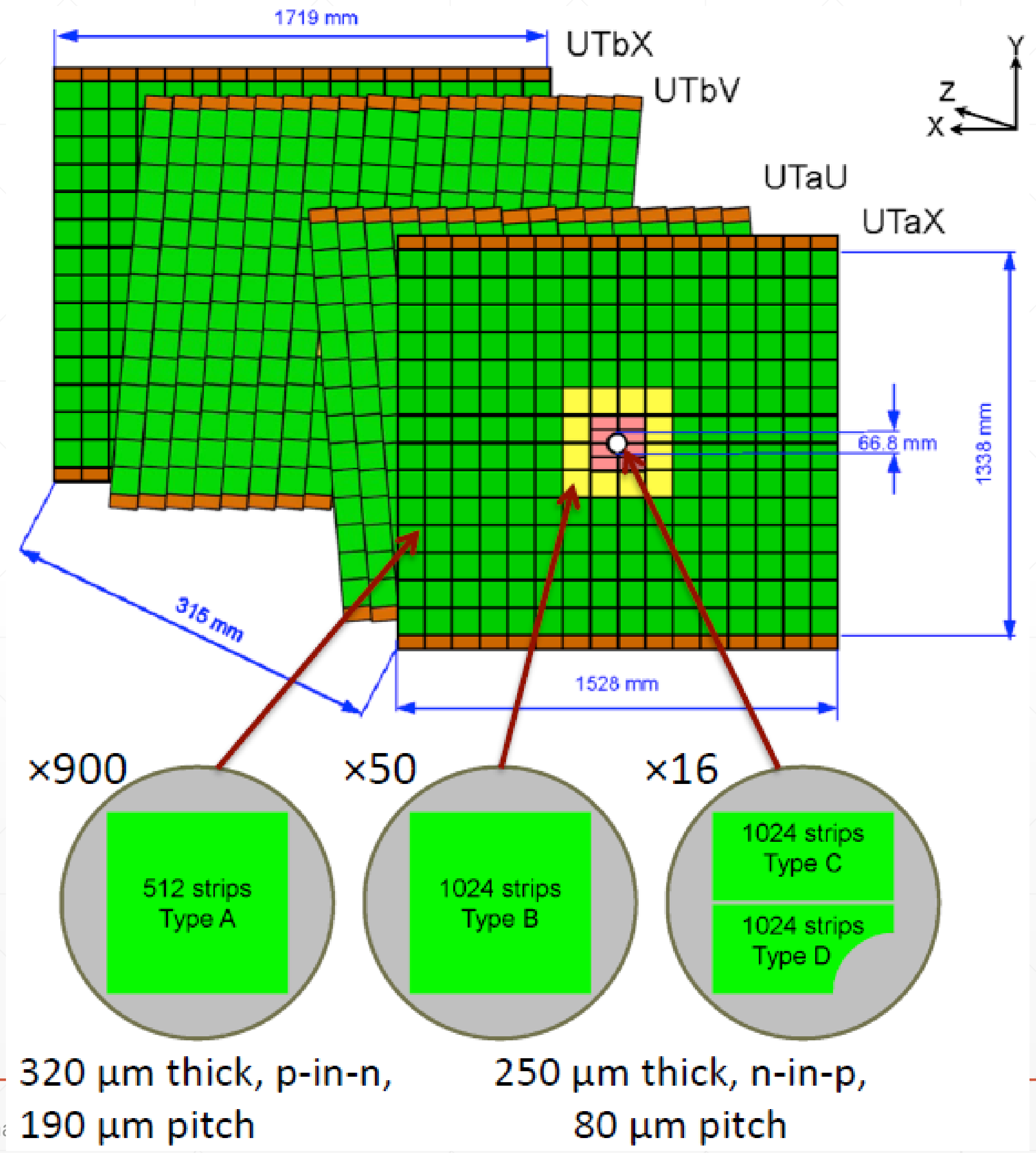


- Current detector – TT
- Four planes of silicon strip detectors vital for reconstructing tracks outside VELO
- Not radiation hard enough for the upgrade
- New front-end read-out electronics needed for $40\ MHz$ trigger
- Need finer granularity to cope with higher occupancies

- Current detector – IT and OT
- Four planes of silicon sensors close to the beam (high η tracks)
- Four planes of straw tube gas detectors outside
- New read-out electronics needed in both cases
- Cannot cope with high occupancies

Tracking System – UT I

[*LHCB-TDR-015*]

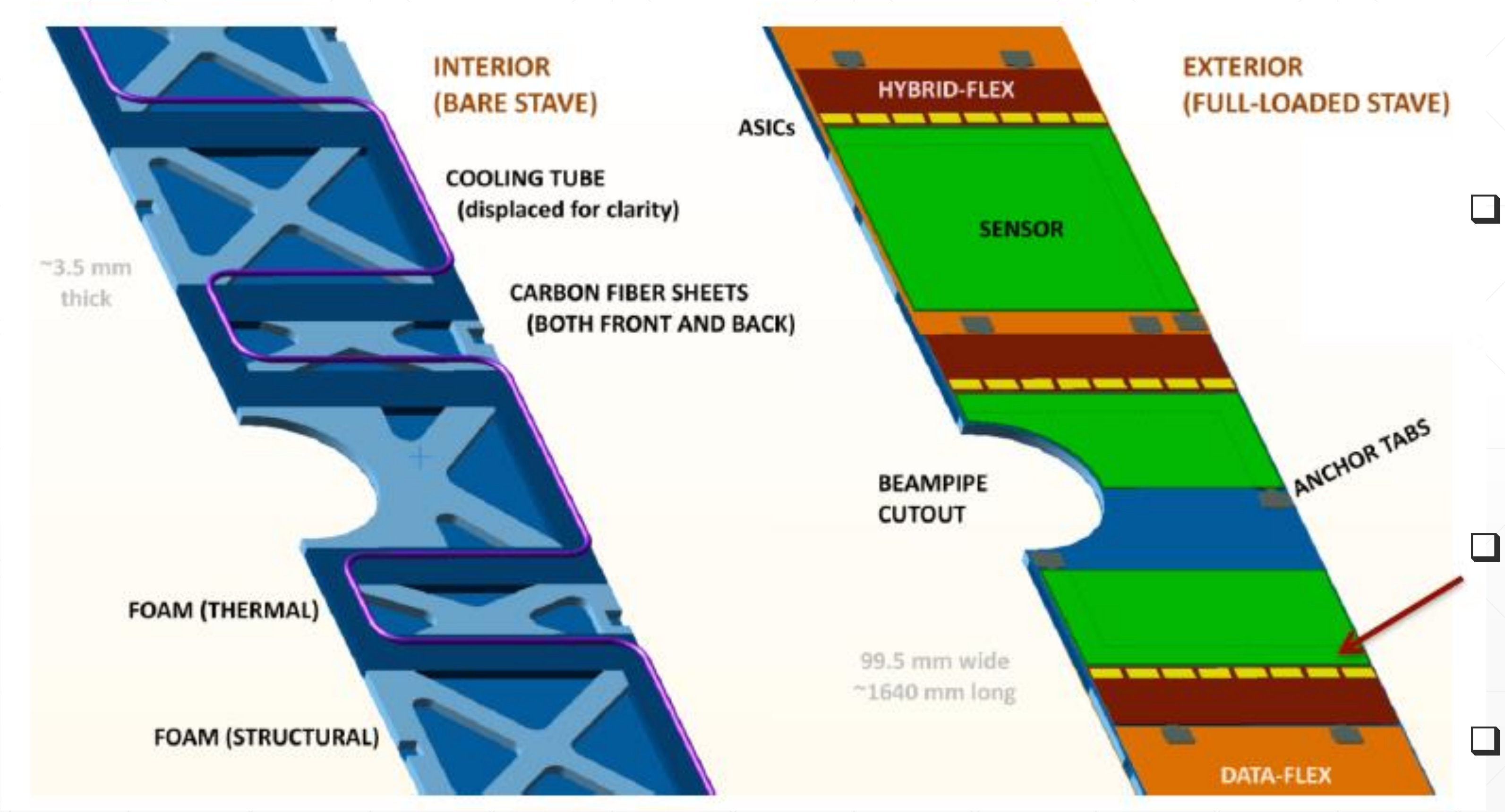


- Four planes of silicon strip detectors mounted to very lightweight staves – **less material**
- Sensors are on both sides of the staves and are closer to the beam – larger coverage
- Finer granularity – strip pitch $\mathbf{95 - 190\ \mu m}$
- Four different types of sensors – to flatten out occupancy and fit to the beam pipe (cut-outs)
- Embedded pitch adapters to ASIC (with $73\ \mu m$ pitch)

Tracking System – UT II

[*LHCB-TDR-015*]

- ❑ Stave design well advanced – now switching to construction phase



- ❑ Staves provide support for 14 or 16 hybrid modules, data flex connectors and CO_2 cooling tubes

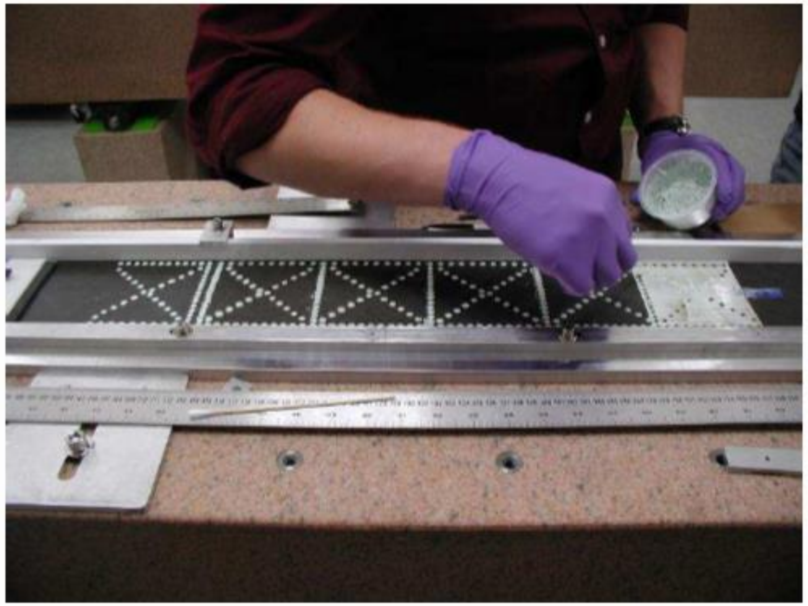
- ❑ Staves are $\sim \mathbf{10\ cm}$ wide and $\sim \mathbf{1.6\ m}$ long

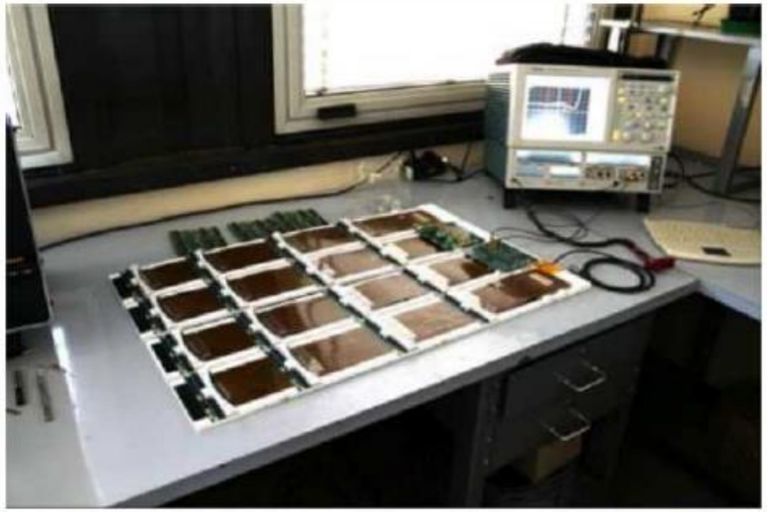
- ❑ Dedicated read-out ASIC chip SALT (**S**ilicon **A**SIC for **L**HCb **T**racking) is being extensively tested
- ❑ Second engineering run before summer

Tracking System – UT III

[*LHCB-TDR-015*]

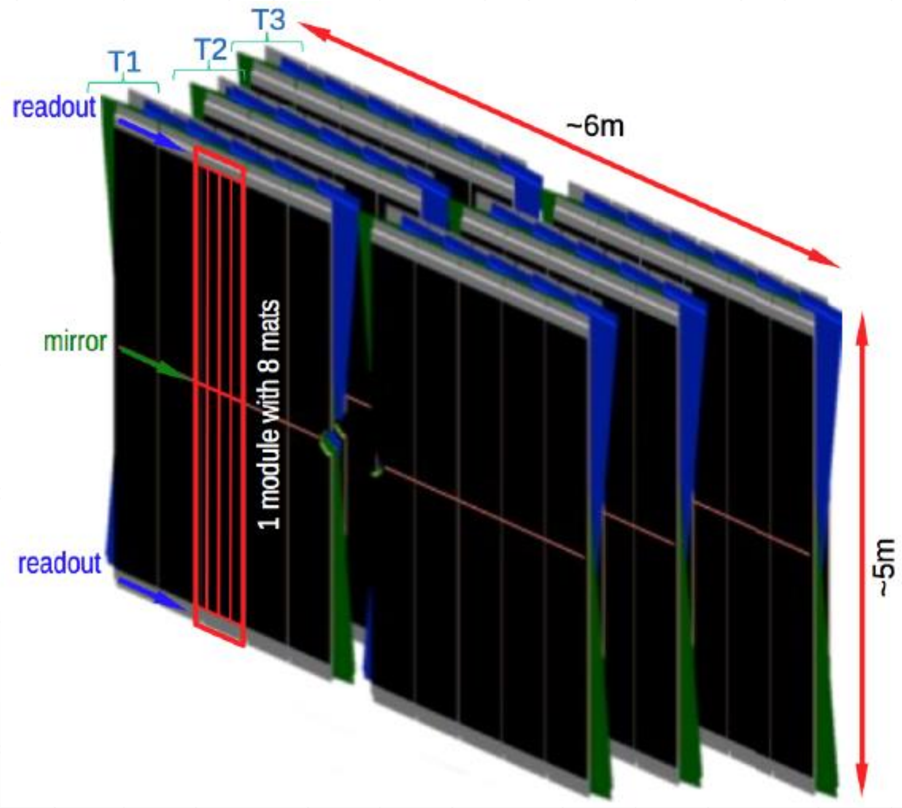
- Stave design well advanced – now switching to construction phase

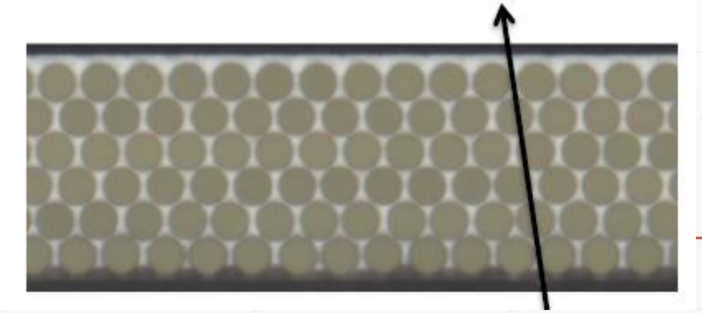




Tracking System – SciFi I

[*LHCB-TDR-015*]

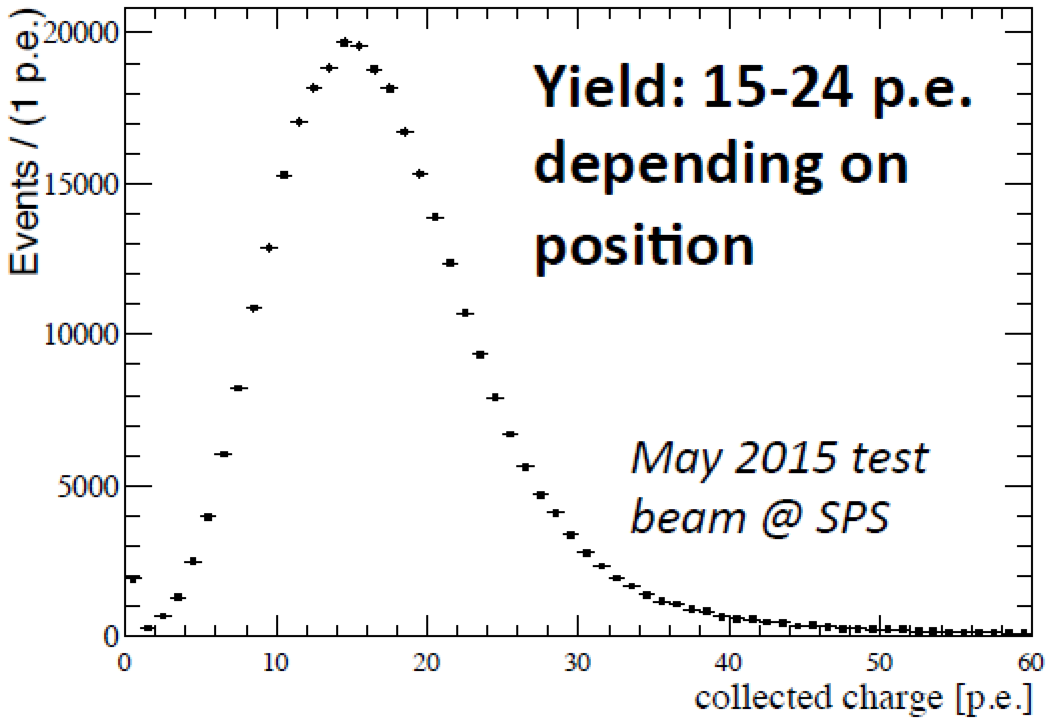


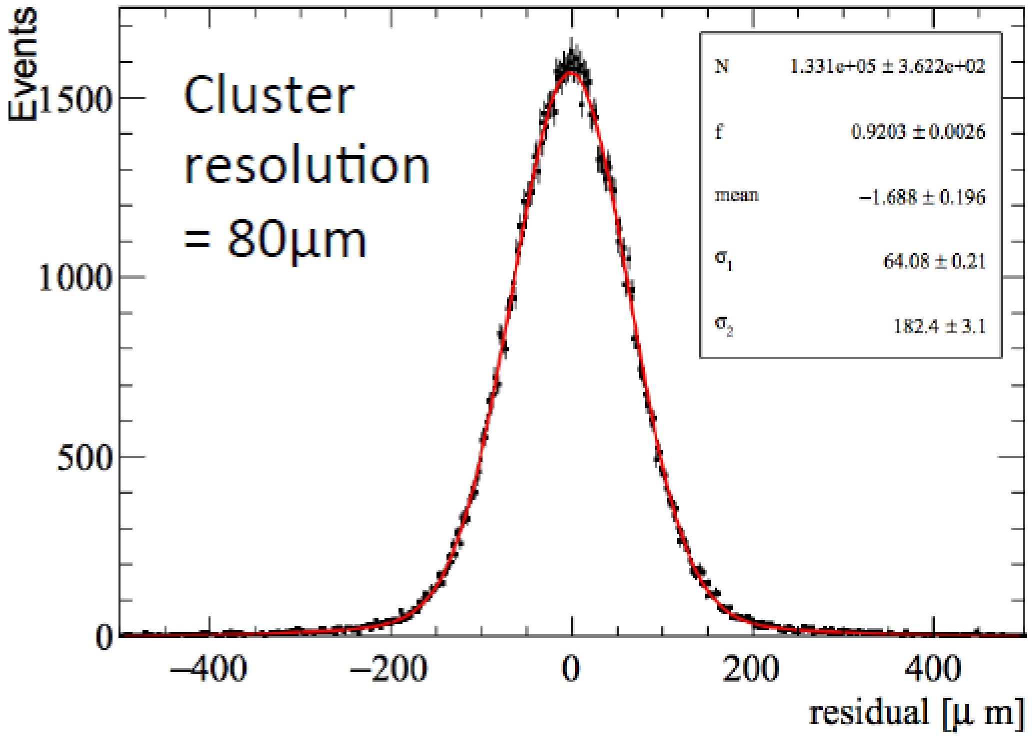


- 3 x 4 layers of scintillating fibre mats of total area close to $\mathbf{340\ m^2}$ (each mat features material thickness of $1.1\ X_0$)
- Excellent coverage up to $\mathbf{3\ m}$ from the beam pipe
- Each mat comprises 6 layers of $\mathbf{250\ \mu m}$ thick fibres (total length for SciFi $\sim \mathbf{11000\ km}$)
- Signal read-out by SiPMs that are cooled to -40^o (significant radiation levels and neutron fluence)
- Spatial efficiency close to $\mathbf{80\ \mu m}$
- Single hit efficiency close to $\mathbf{99\%}$

Tracking System – SciFi II

- Extensive test beam experiments

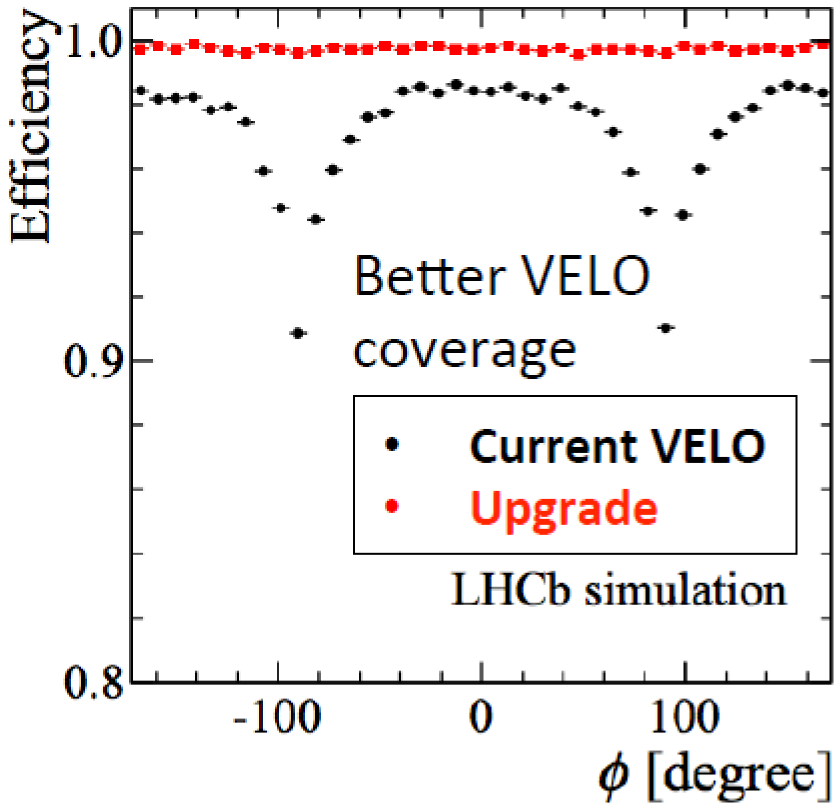


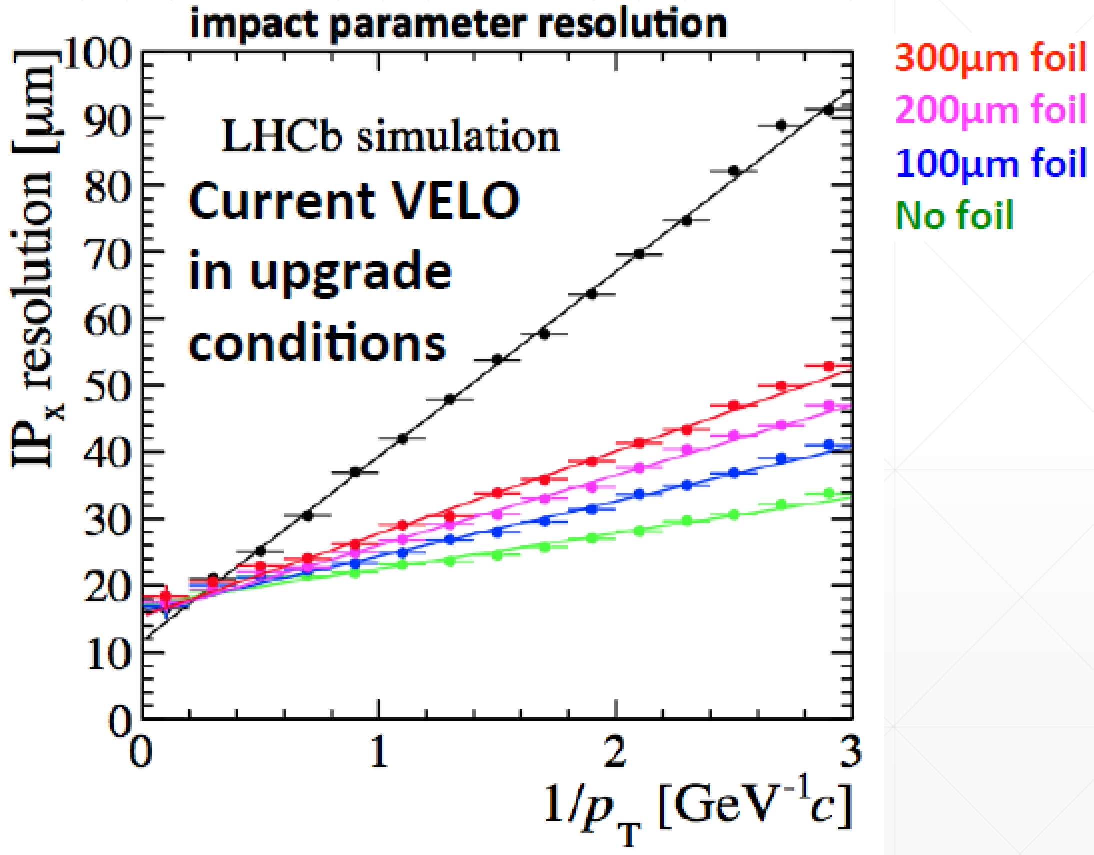


Tracking System – Simulated Performance

- Very promising results, all systems seems to surpass the current detectors in the most crucial metrics at higher luminosity

VELO





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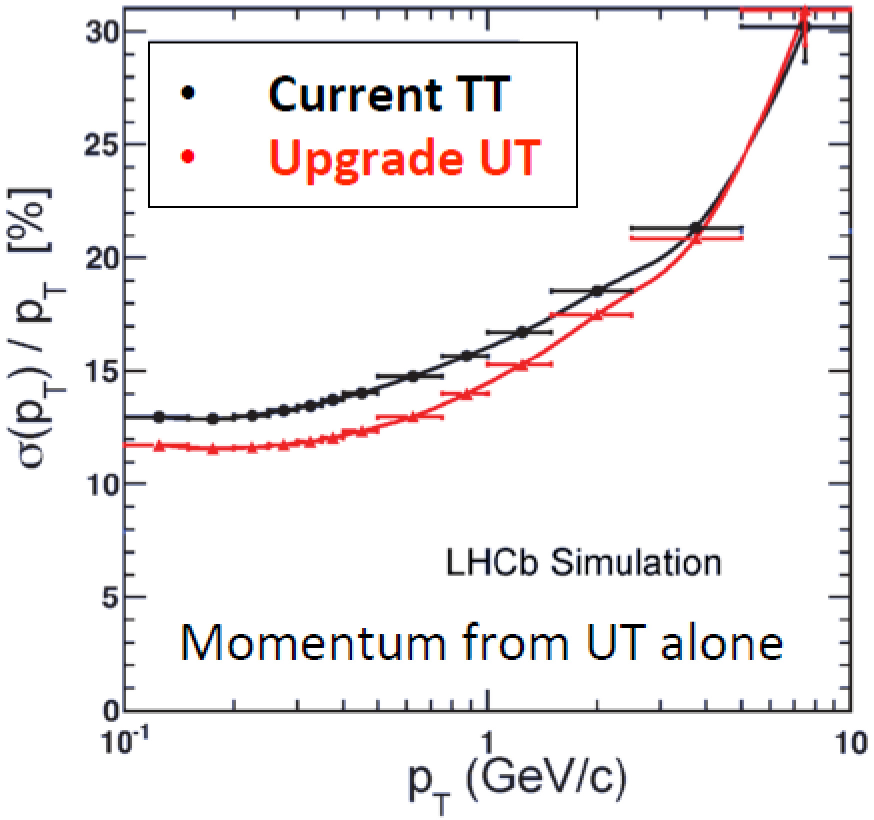
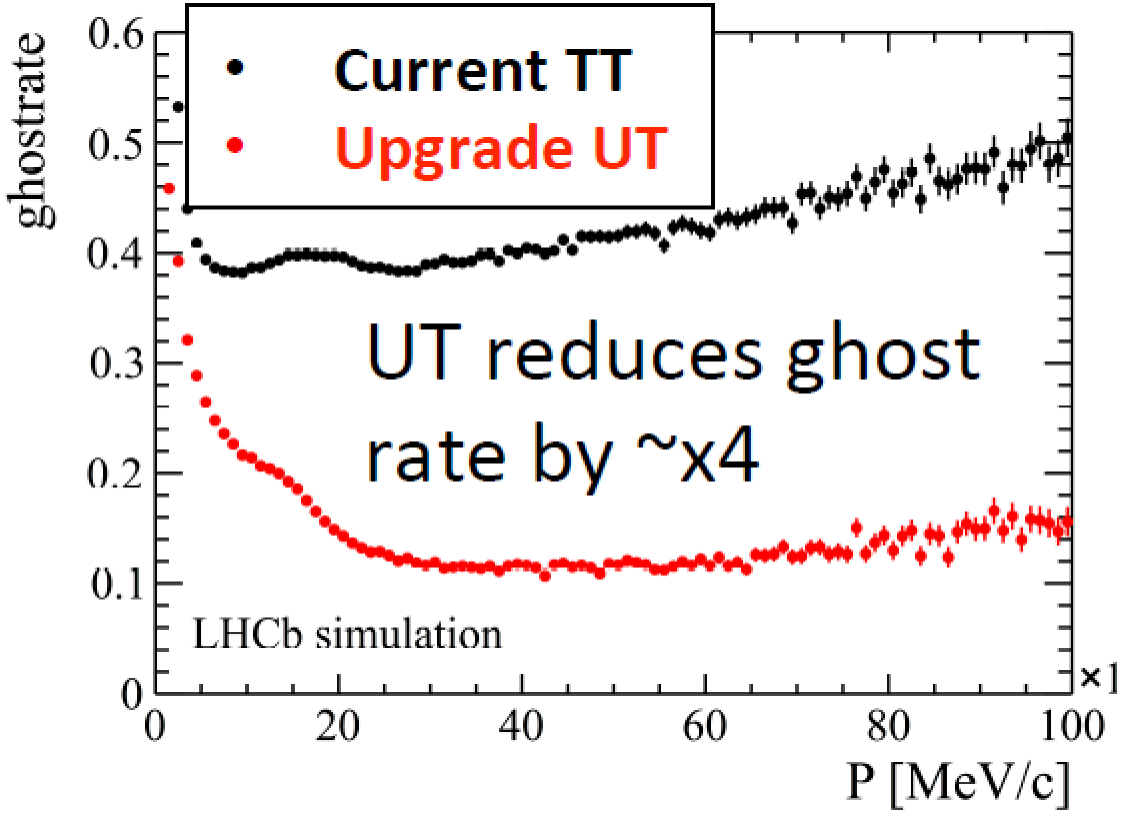
UT





Tracking System – Simulated Performance

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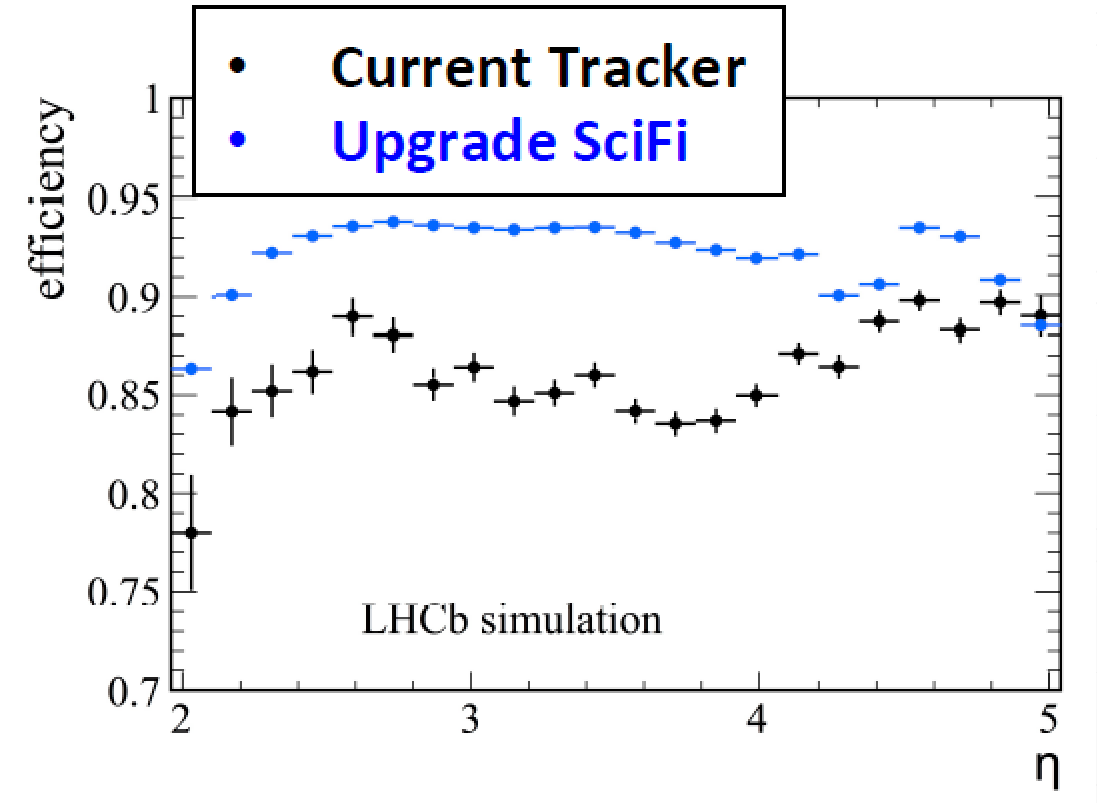
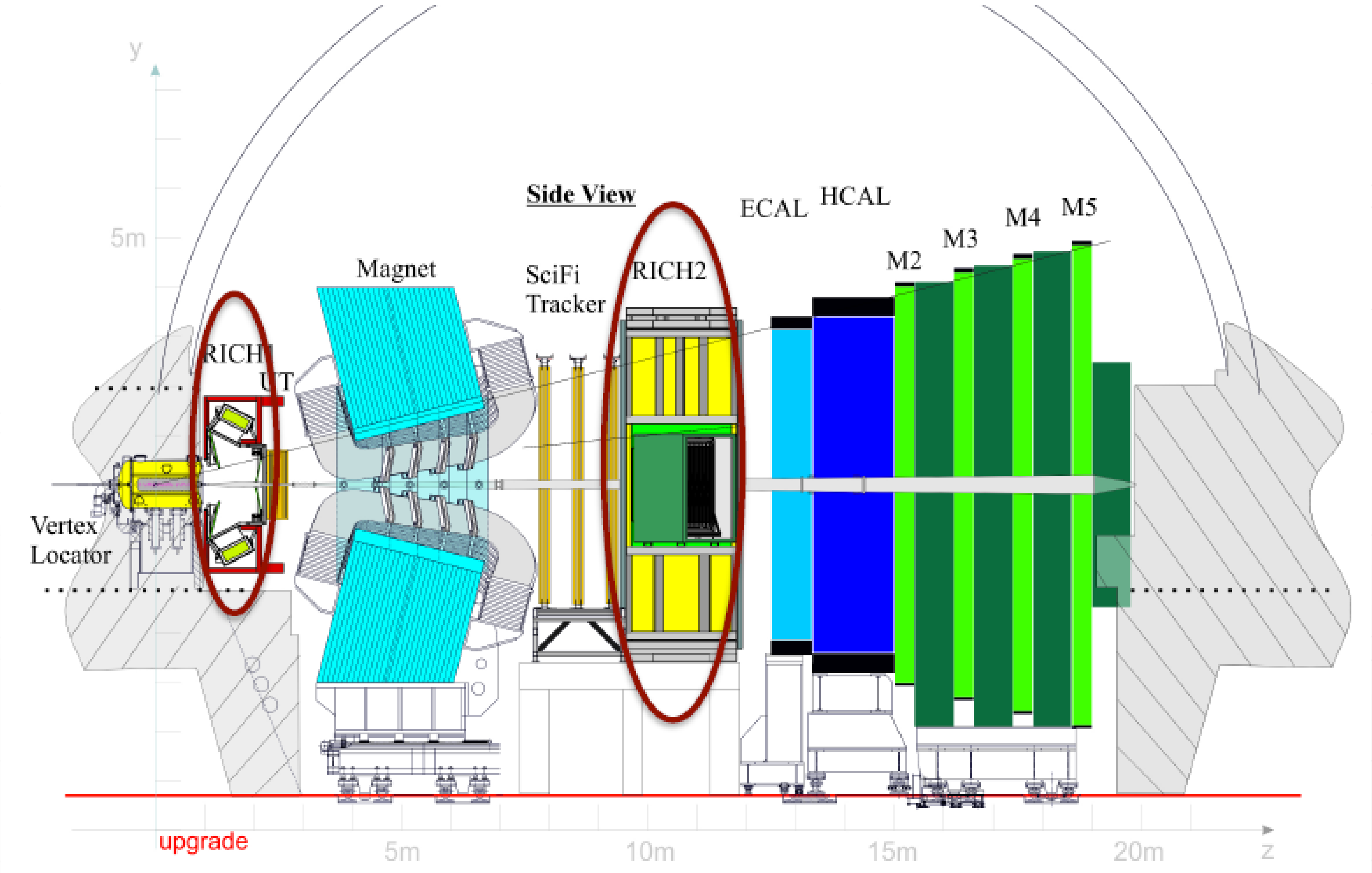
SciFi



RICH Detectors I

[*LHCB-TDR-014*]



RICH Detectors II

[*LHCB-TDR-014*]

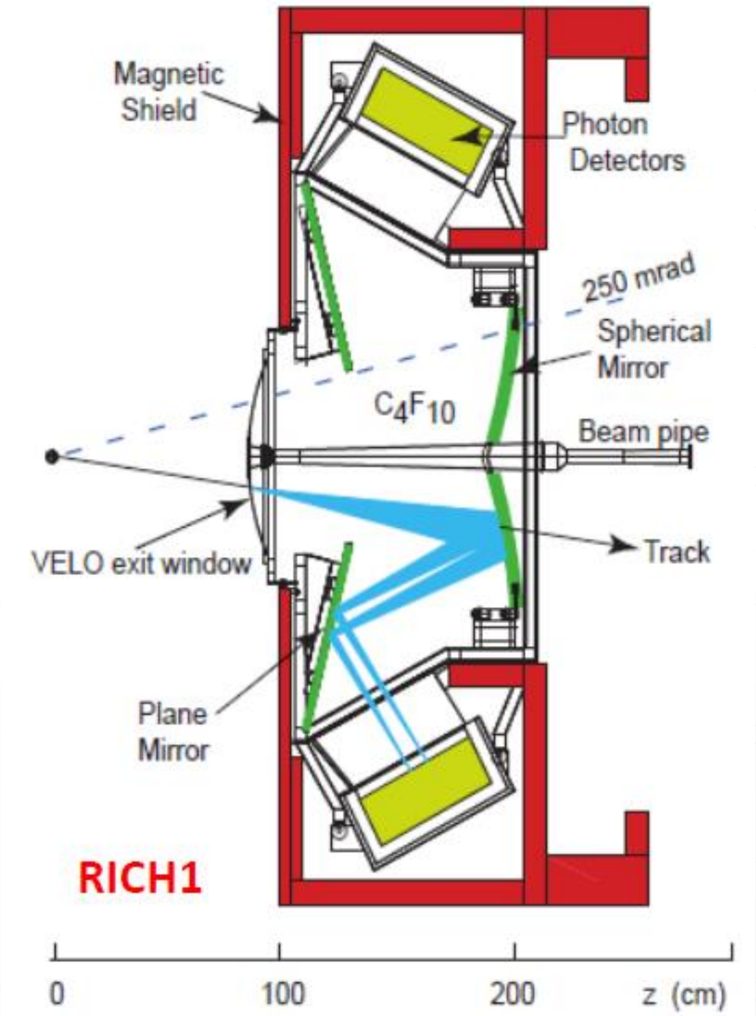
- Currently LHCb features two of these:
  - Upstream RICH1: $2\ GeV/c - 40\ GeV/c$ over $25\ mrad - 300\ mrad$
  - Downstream RICH2: $30\ GeV/c - 100\ GeV/c$ over $15\ mrad - 120\ mrad$
- Excellent performance in Run 1 and Run 2

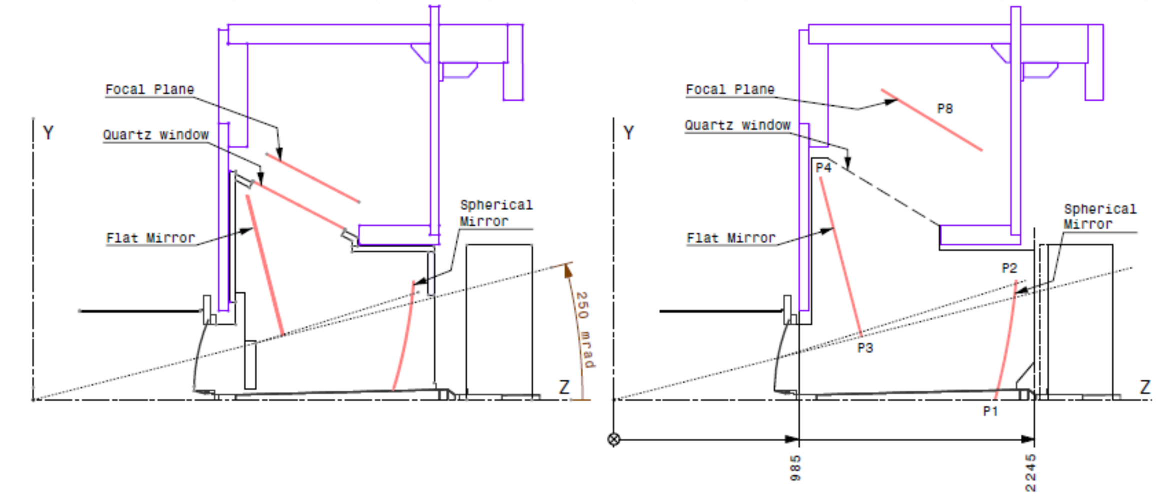
- Charged hadrons interact with gaseous radiator and produce Cherenkov photons, that in turn are focused on Hybrid Photon Detectors (HPD)

- Current HPDs are equipped with embedded read-out electronics that is not compatible with new 40 MHz DAQ system
  - Need to replace all HPDs
  - Move to higher granularity

RICH Detectors III

[*LHCB-TDR-014*]

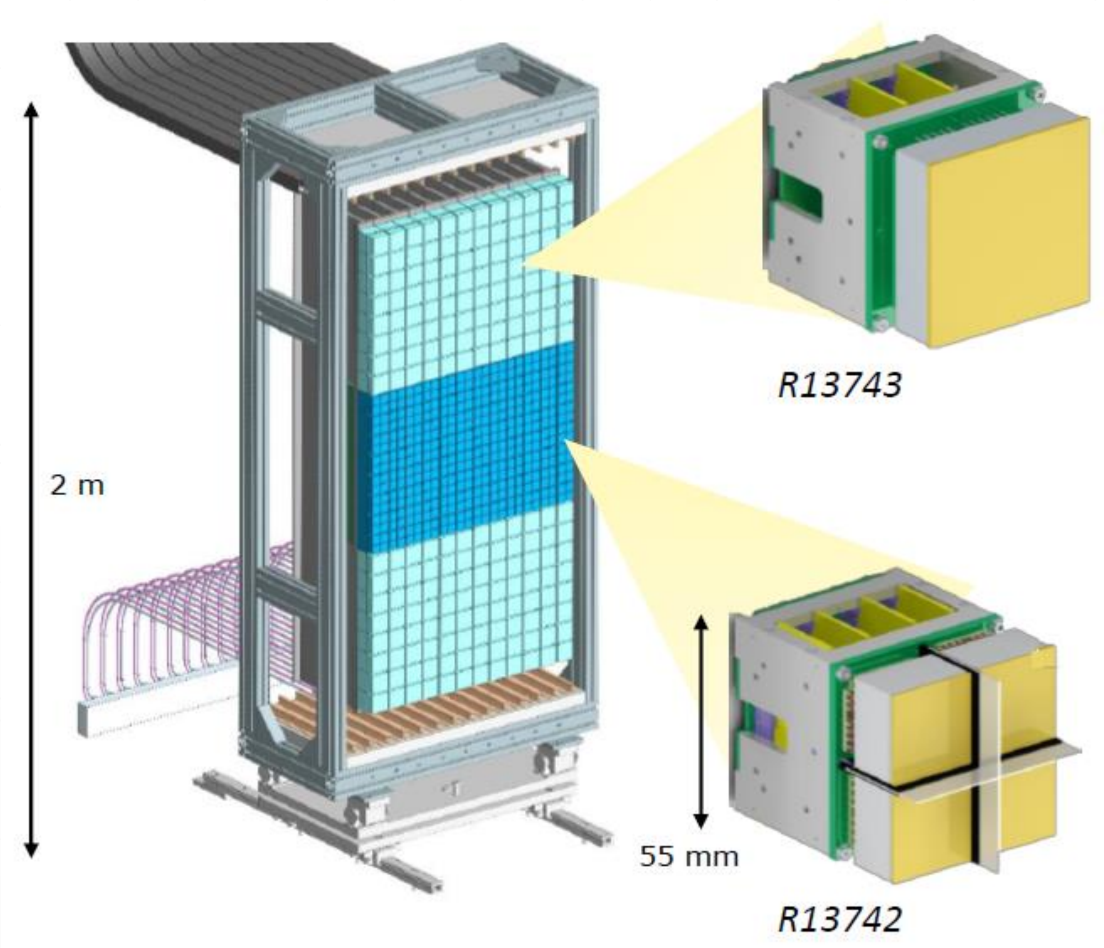




- Upgrade plans for RICH detectors comprise of two main changes:
  - New optics for RICH 1
  - Increase image area and bring down the occupancy
  - We need new mirrors, mechanics and radiator box
  - Simulation studies show drop in occupancy from 40% (current) to 27% (upgraded)

RICH Detectors IV

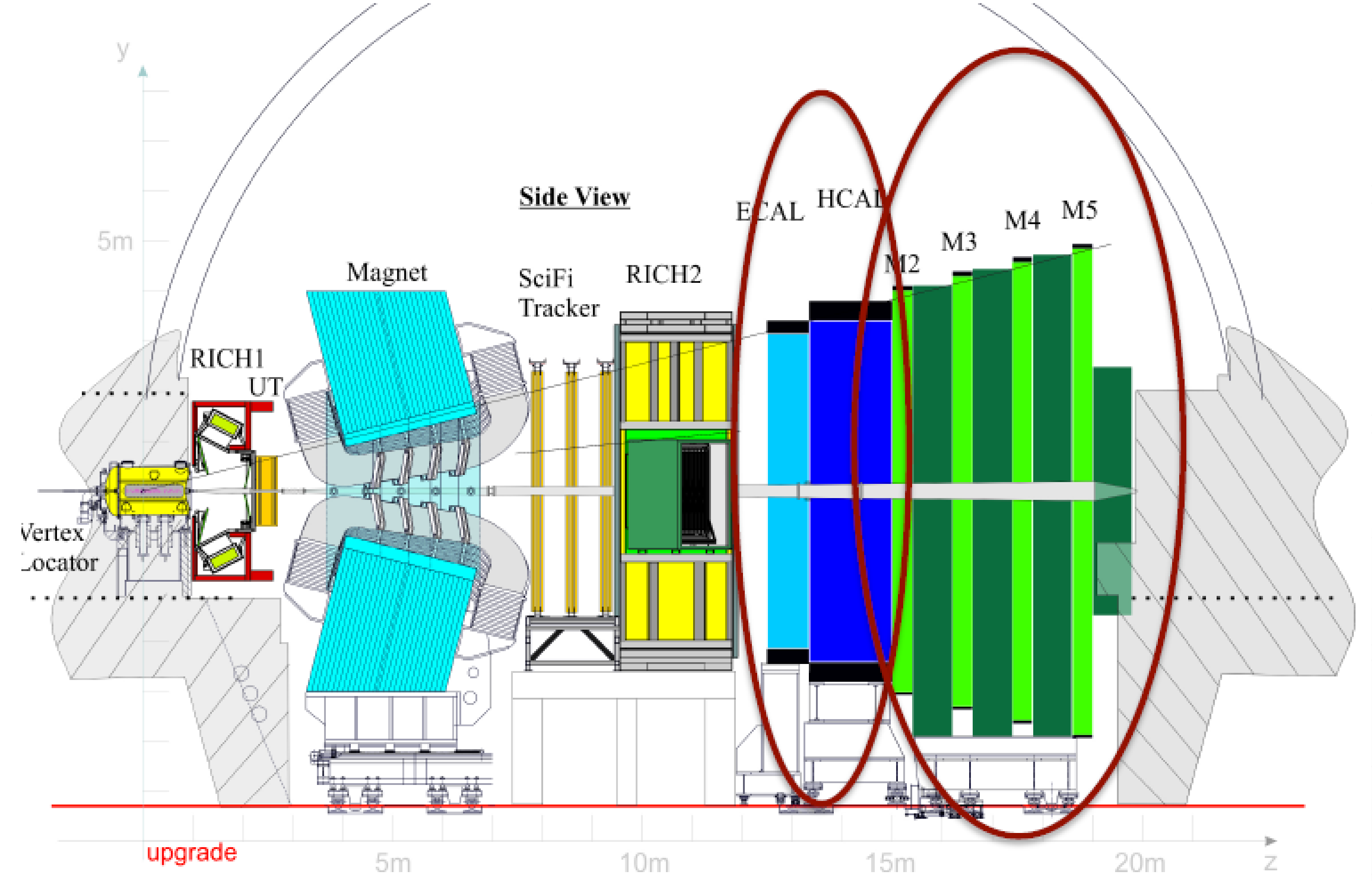
[LHCB-TDR-014]



- Upgrade plans for RICH detectors comprise of two main changes:
  - New photon detectors
  - Allow 40 MHz read-out
  - Finer granularity
  - Improvement in single photon angular resolution by 50% (RICH1) and 20% (RICH2)
- Two types of MaPMTs:
  - 48 x 48 mm with 16 pixels
  - 23 x 23 mm with 16 pixels
- Test beam campaign ongoing to validate both new detectors and read-out chip CLARO
  - Full signal processing chain to be tested soon

Calorimeter & Muon Systems

[*LHCB-TDR-014*]



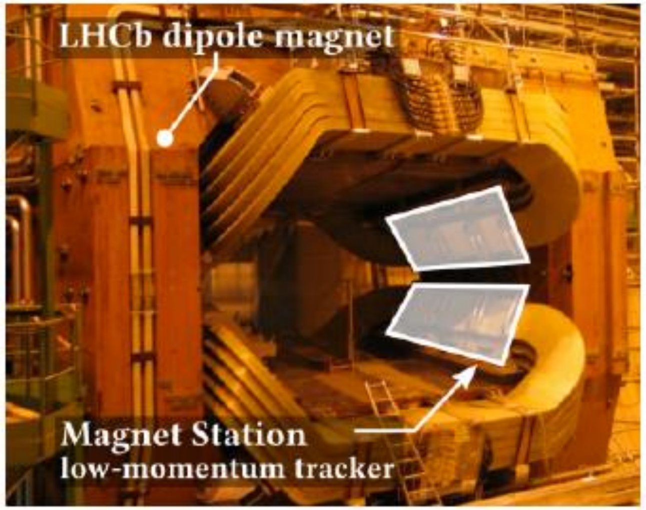
Calorimeter & Muon Systems

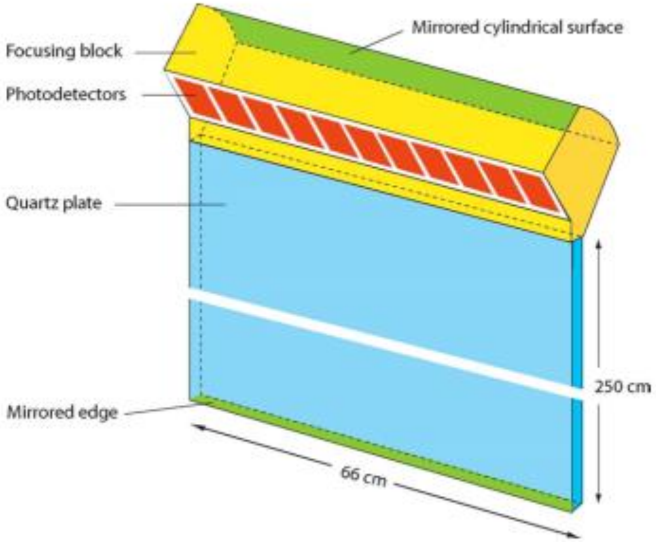
[LHCB-TDR-014]

- Since both Calo & Muon Systems were contributing to hardware trigger they are ‚almost' ready to go
- Calo Modifications
  - Remove Pre-Shower (PS) and Scintillating Pad Detector (SPD) used for hardware trigger
  - Hadron Calo (HCAL) modules can survive up to 50 fb, Electromagnetic Calo (ECAL) inner-most modules must be replaced after 20 fb
  - Reduce PMTs gain and exchange read-out electronics
- Muon Modifications
  - New read-out electronics
  - Remove the first station M1 (needed by the hardware trigger)
  - Increase shielding around the beam pipe in front of the M2 station – reduce fake hit rate

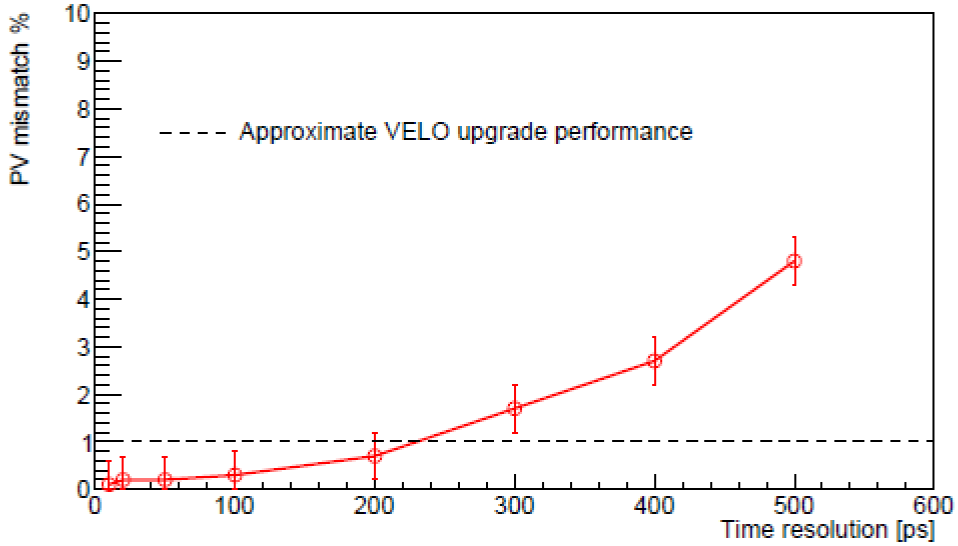
Beyond Upgrade Phase I – Phase Ib

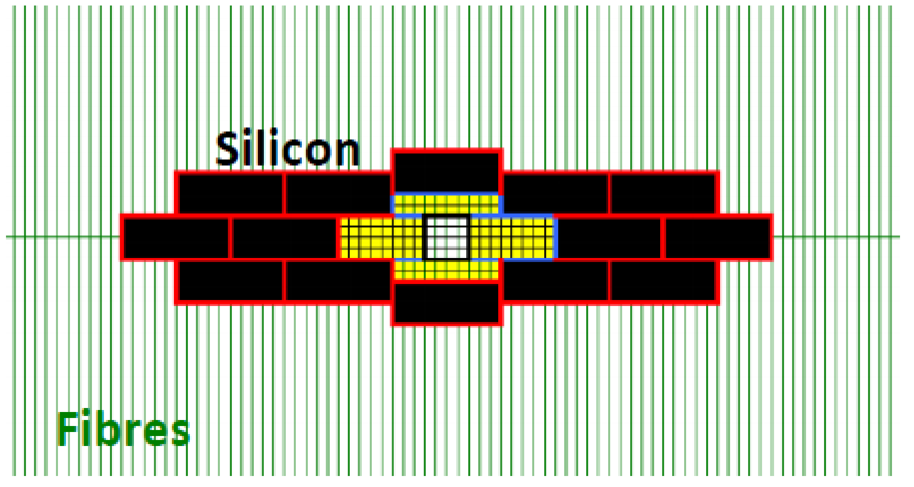
- Expression of Intent document has been released in February 2017 (**CERN-LHCC-2017-003**)
- Two step approach – potential initial modifications installed already in LS3
  - Addition tracking stations inside magnet
  - TORCH (Time-of-Flight PID Detector), high-precision timing ($\sigma_t \approx 15\, ps$ per particle) and low momentum tracks PID
  - Improve technology w.r.t. radiation damage and granularity in the highest occupancy regions (Tracker, Calo, RICH and Muon)



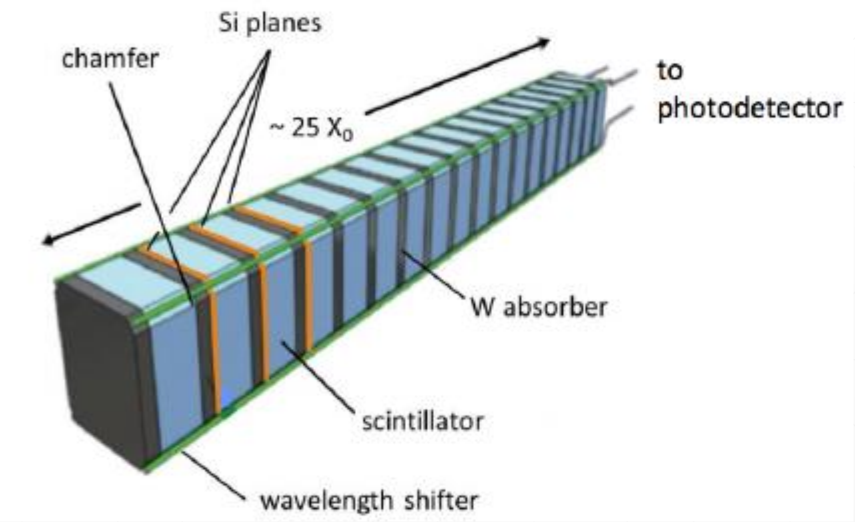


Beyond Upgrade Phase I – Phase II





- ❑ 4D Pixels
  - Timing information needed for correct long lived tracks association to PVs
  - $\sigma_t \approx 200\ ps$ time resolution enough to match the performance of the current VELO
  - Smaller pixels $25 \times 25\ \mu m$
- ❑ Enhance fibre tracker with inner silicon detector
- ❑ Smaller cells and timing information for ECAL



Summary

- **Ambitious plans for Phase I**
- R&D well underway – transition to construction phase
- Development of advanced and sophisticated r/o electronics (e.g. SALT chip)
- Trigger and computing model is being tested during Run 2
- Major changes to the LHCb spectrometer – new VELO, UT and SciFi, also deep technology update for RICH detectors

- **Future upgrades to exploit HL LHC era**
- Potential huge data samples
- Major challenge for detector design
- Timing information and radiation hardness critical