LHCb Upgrade

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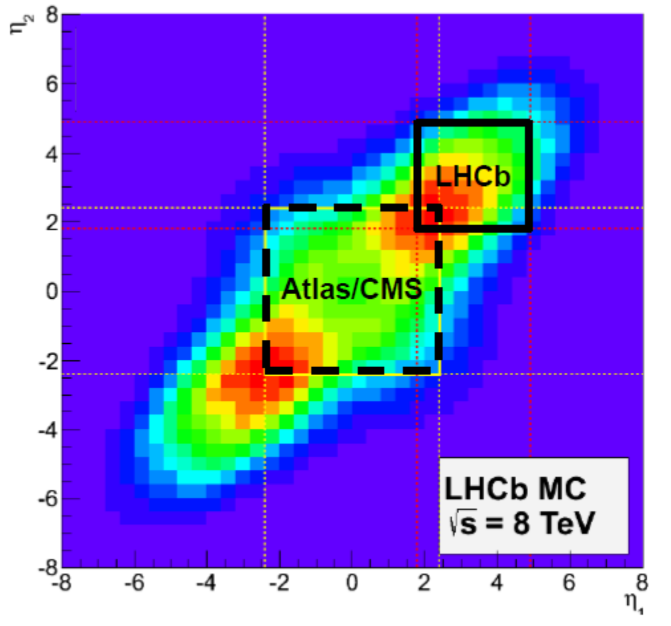
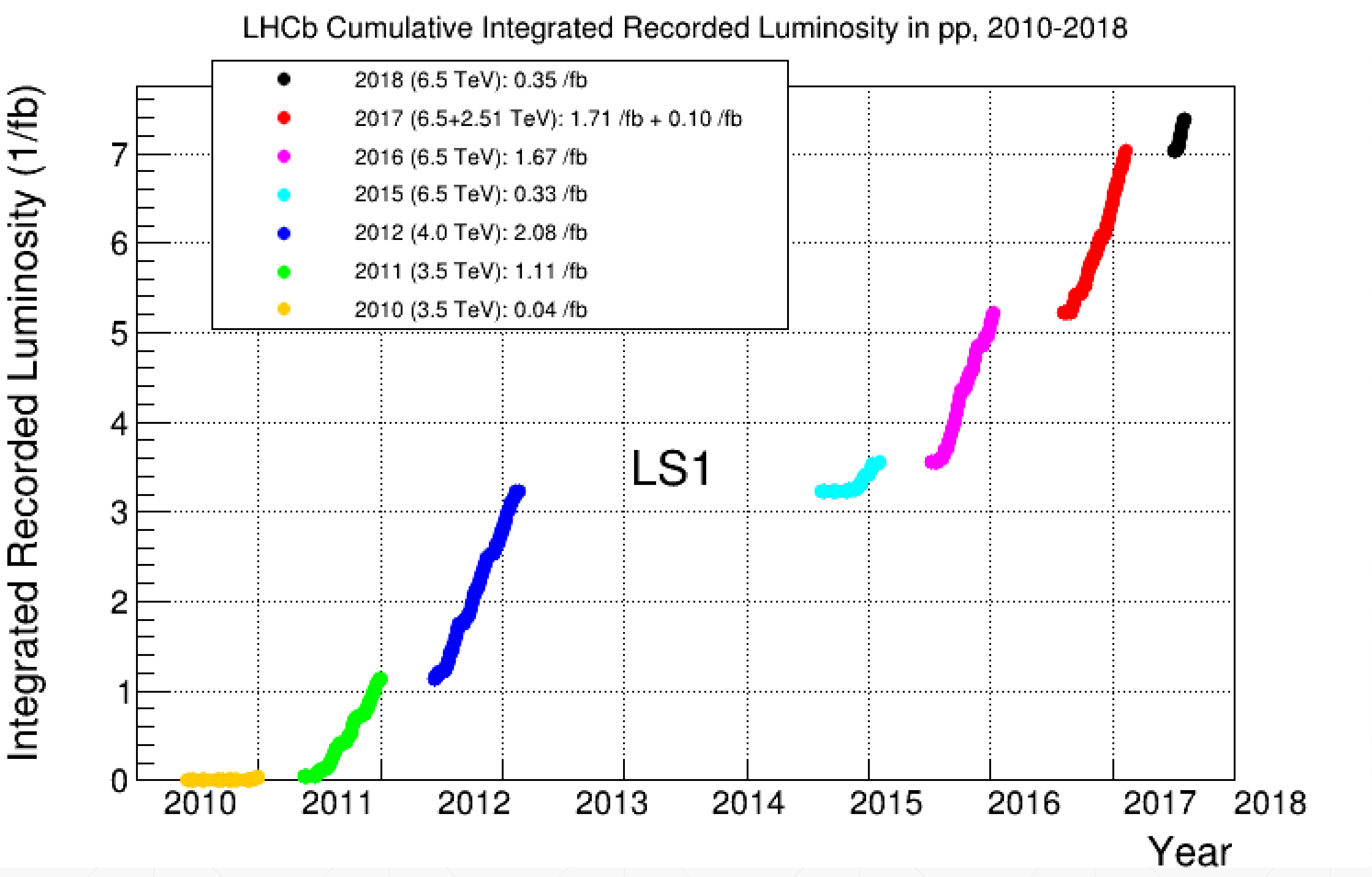
XIII Workshop on Particle Correlations and Femtoscopy, 21 – 26/05 2018

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 $\mathbf{2 < \eta < 5}$ (solid angle coverage ~ $\mathbf{4\%}$, $\mathbf{40\%}$ B mesons)
  - High performance tracking system (critical!)
    - Spatial resolution ~$\mathbf{4\ \mu m}$ at vertex detector
    - $\frac{\Delta p}{p} = (0.4 - 0.6)\%$ for tracks with momentum between p $\rightarrow$ (5 - 100) GeV
    - Impact parameter resolution ~$\mathbf{20\ \mu m}$ for high p_T tracks
    - Decay time resolution ~$\mathbf{45\ fs}$ ($B_s \rightarrow J/\psi\varphi$)
    - Excellent particle identification capability



Collected Data



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

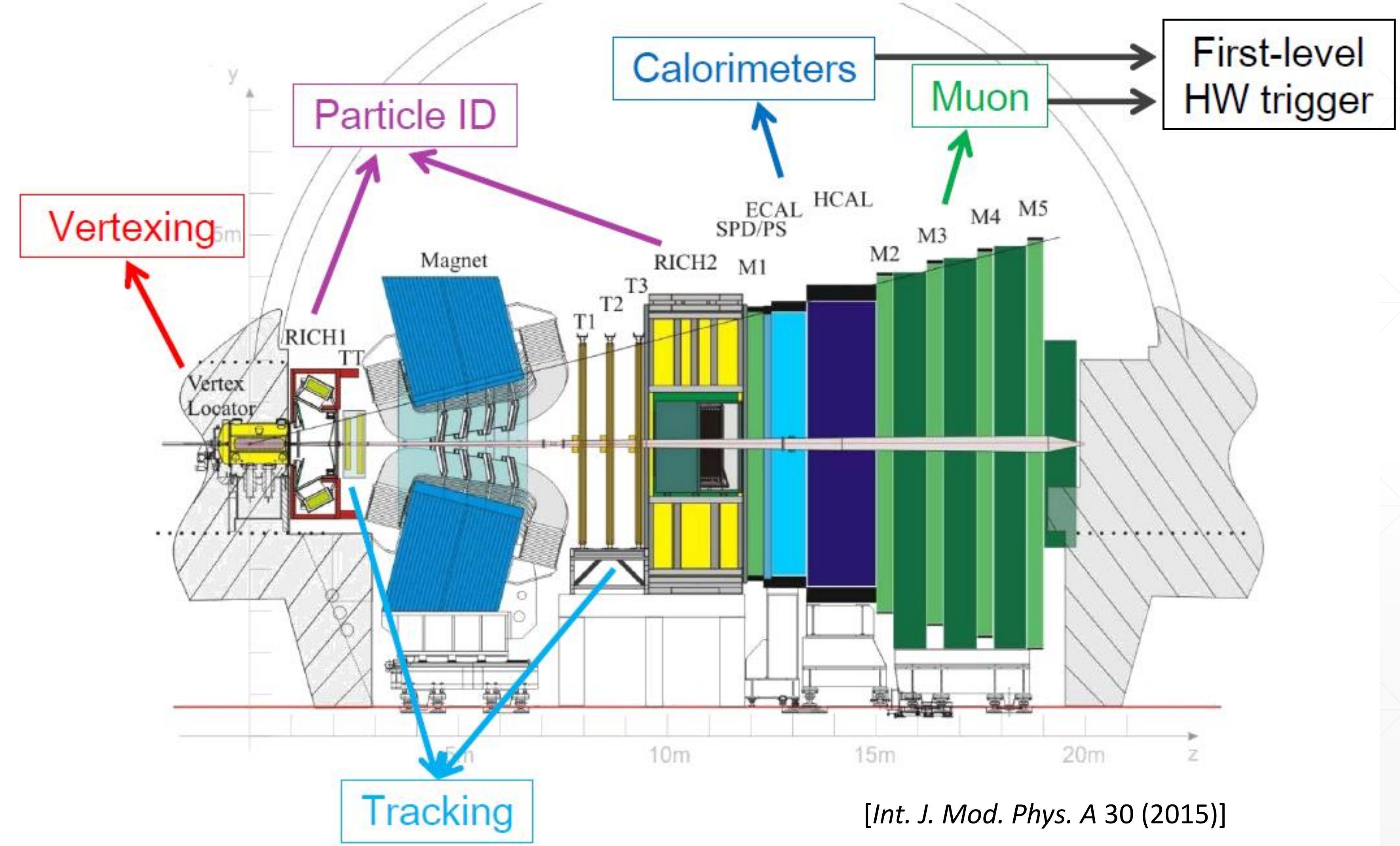
Collected data (on tape):

- Run 1: 3 fb^{-1} $@(7-8)\,TeV$
- Run 2: $\sim 4\ fb^{-1}$ $@13\,TeV$

High hopes we get another 2 to 3 fb^{-1} this year

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

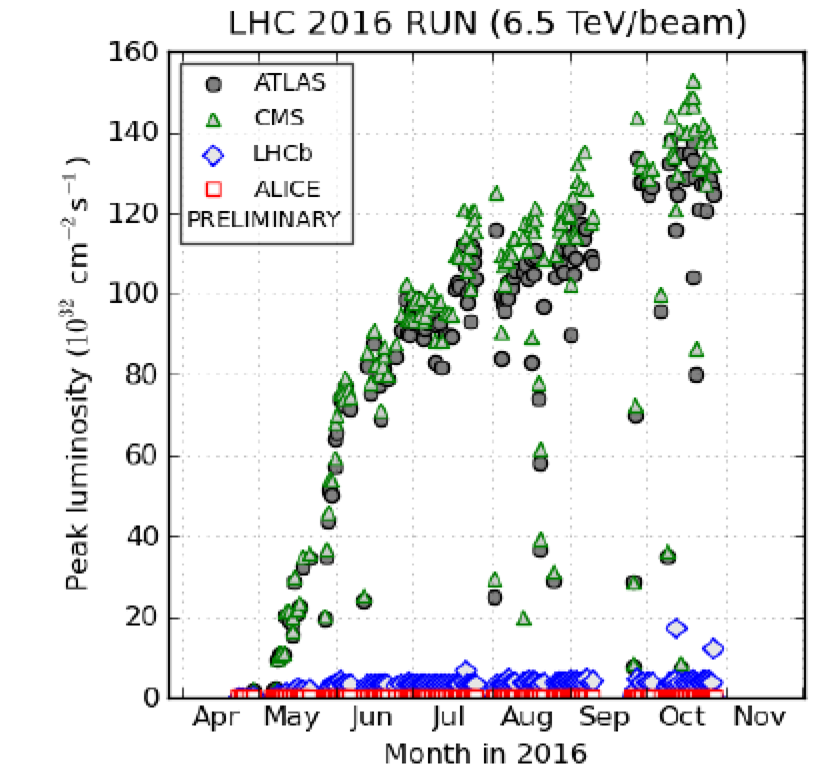


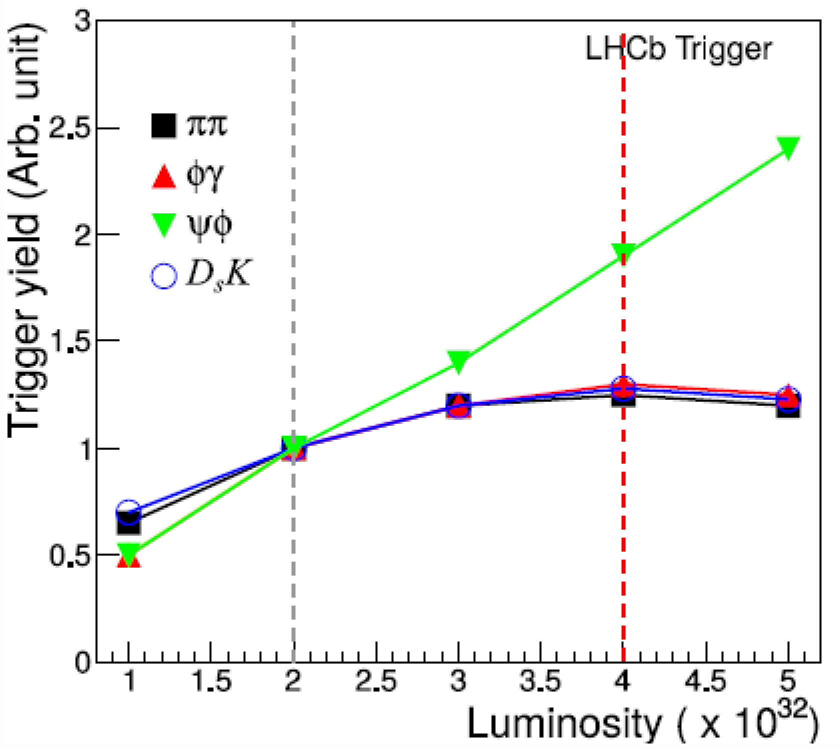
[*Int. J. Mod. Phys. A* 30 (2015)]

Current Detector Limitations (or WHY?)

- 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 2018 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





- 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

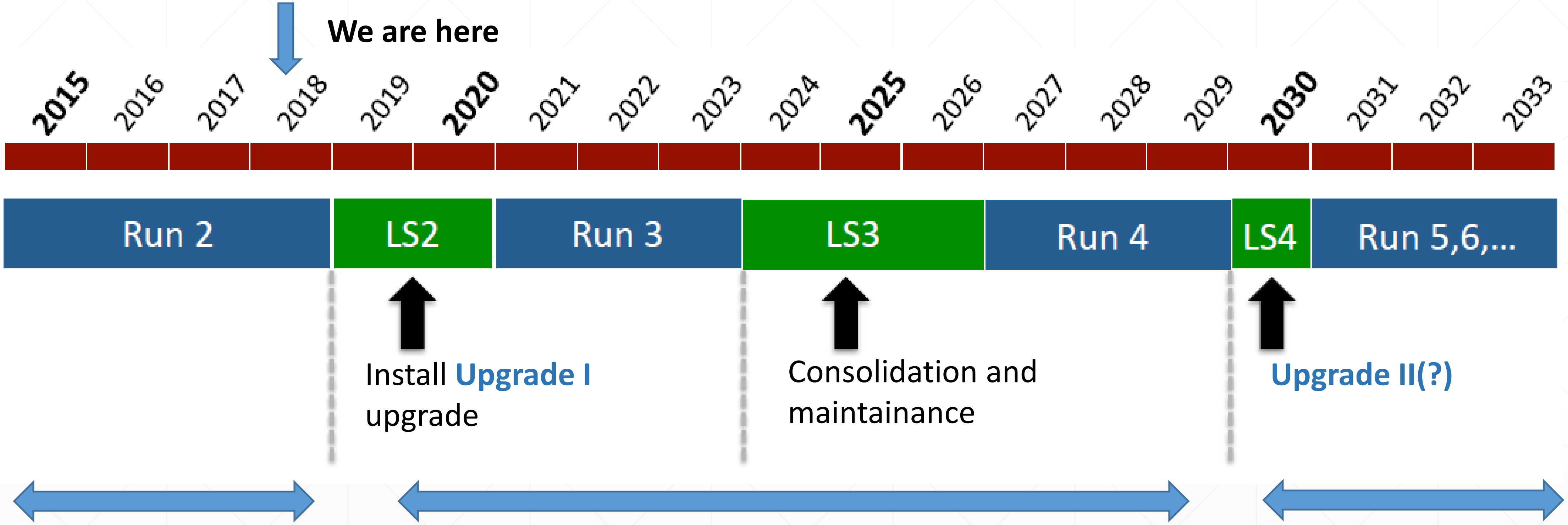
Upgrade I Strategy

- Remove the hardware trigger completely – read-out the full detector at each LHC bunch crossing
  - New **triggerless** readout front-end electronics
  - Redesign current readout network to cope with **multi-TB/s data stream**
  - Readout at $40\ MHz$ (actually 30 MHz of visible interactions)

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

LHCb Upgrade I/II – Timeline



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

1.1 visible interactions / crossing

8 fb^{-1} collected

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

5.5 visible interactions / crossing

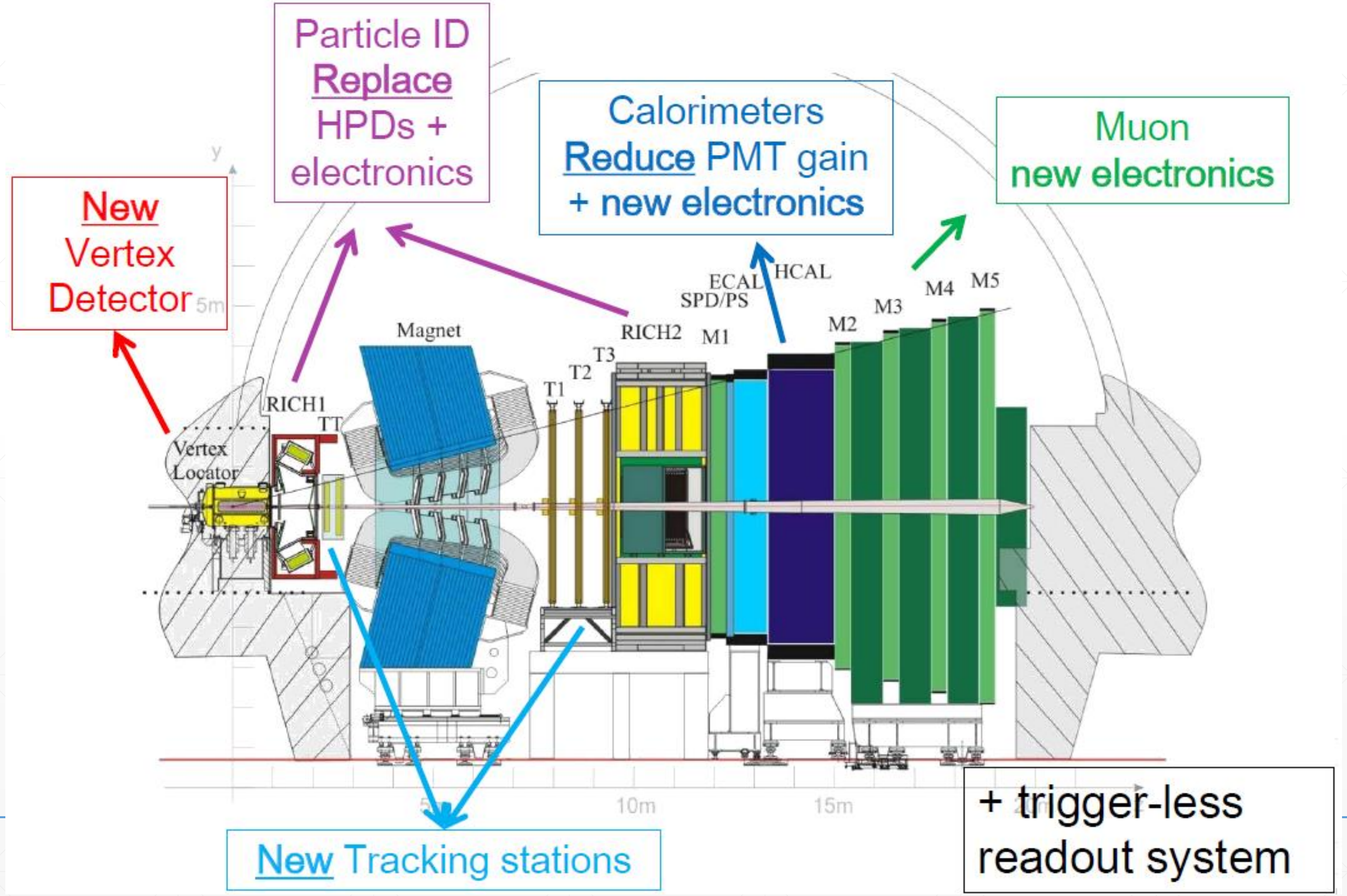
50 fb^{-1} collected

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

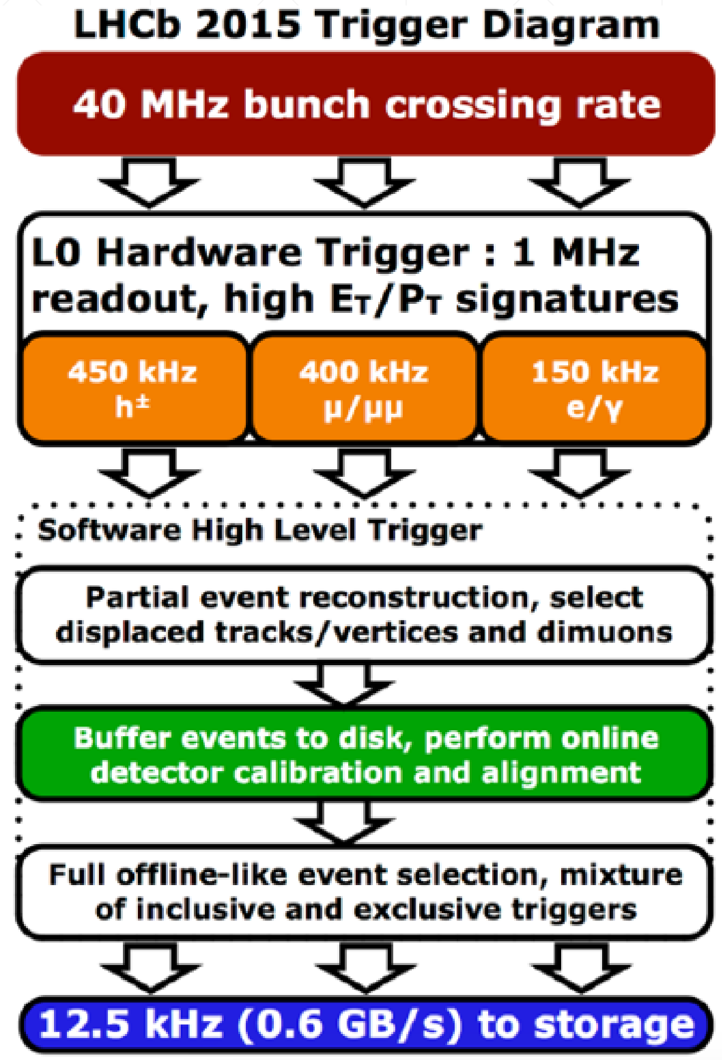
55 visible interactions / crossing

300 fb^{-1} collected

LHCb Upgrad I Detector

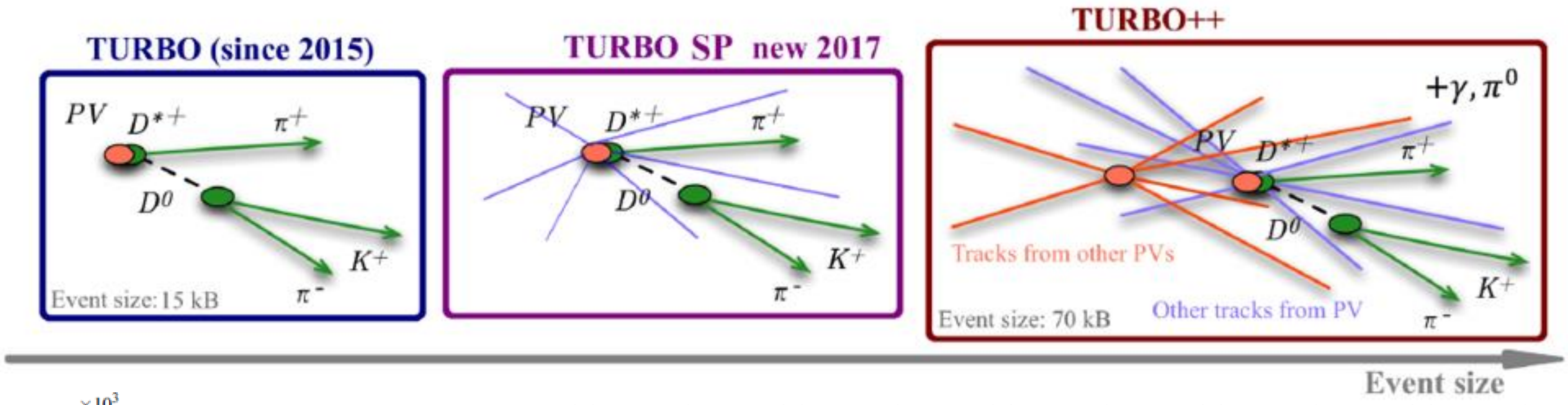


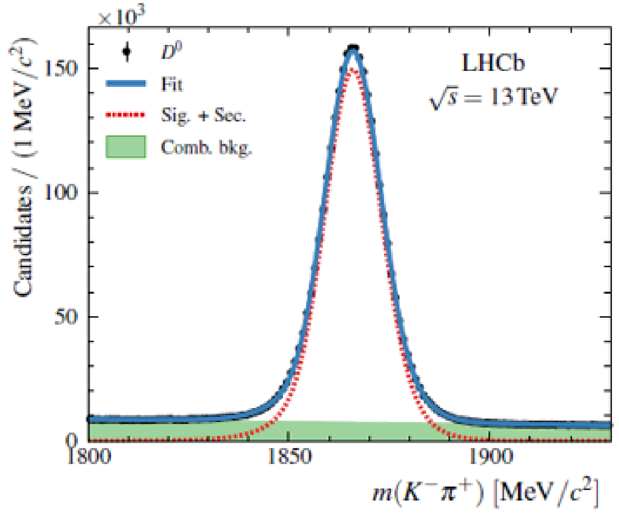
Current Trigger System



- Hardware layer **L0**
  - Based on information from calorimeter and muon systems
  - The readout is limited to 1.1 MHz (electronics)
  - Need to apply tight cuts ($p_T(\mu) > 1.4\frac{GeV}{c}, E(e) > \frac{2.5GeV}{c}$)
- Software layer (HLT):
- **HLT1**
  - Partial reconstruction (tracking and PV search)
  - Track reconstruction for $p_T > 0.5\frac{GeV}{c}$
  - Multivariate inclusive selections (based on impact parameter, kinematic and muon ID)
- **HLT2**
  - Full event reconstruction
  - Inclusive lines (selection algorithms) using displaced vertices and high p_T
  - Exclusive lines (more than 300 of them…)

„TURBO" events – LHCb speciality

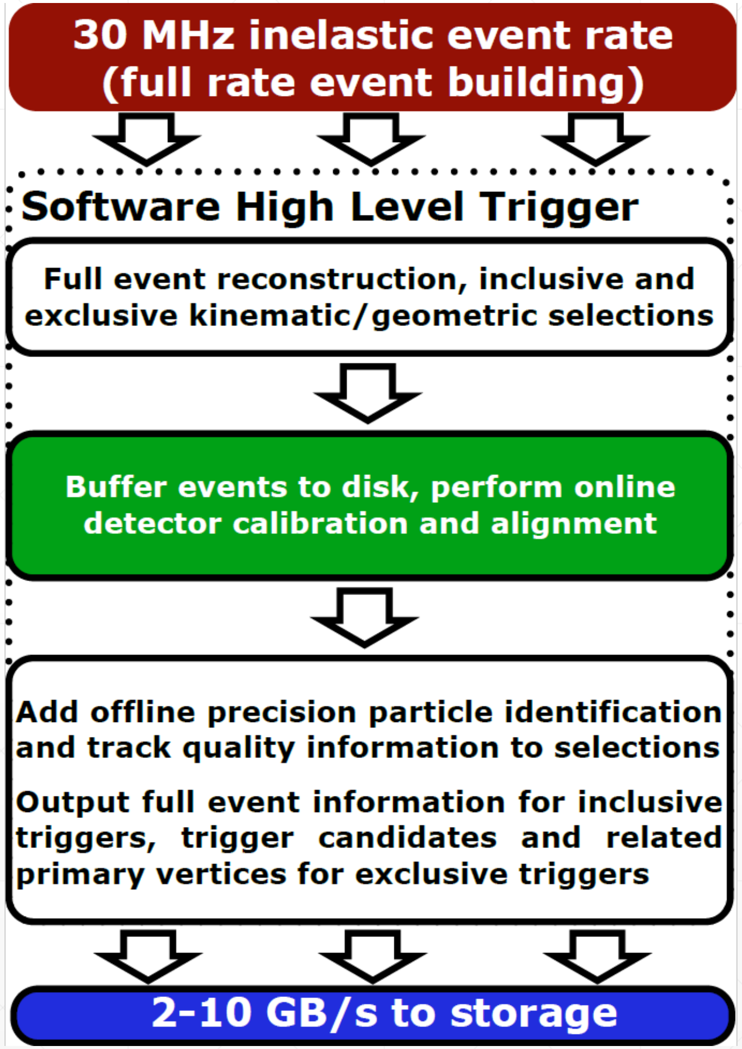




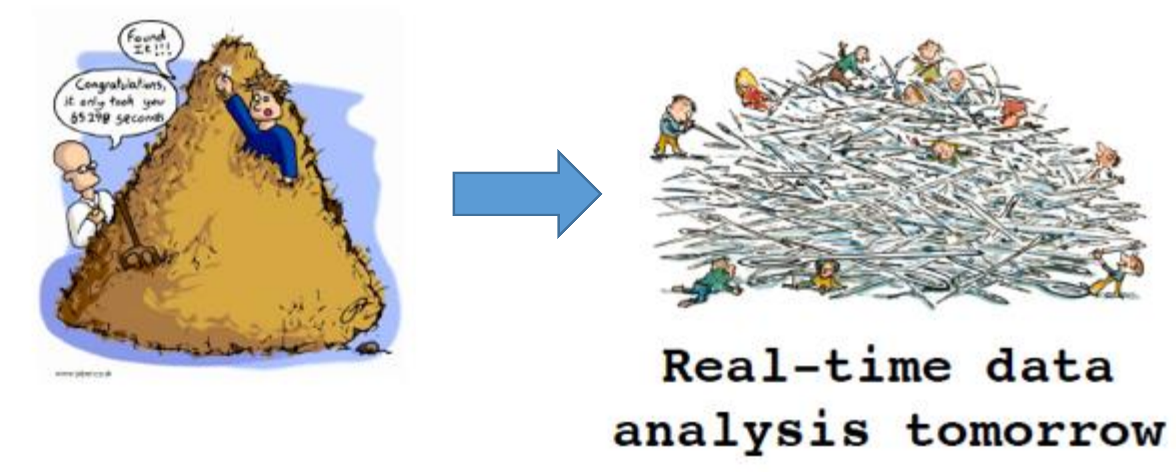
[JHEP03(2016)159]

- **Turbo data stream**
  - Save only reconstructed object pertaining to a given observed decay and **nothing else** (part of the whole data stream produced by LHCb)
- **Turbo++**
  - Full event reconstruction can be persisted
  - Write out more complicated variables such isolation, jets, etc
- **Turbo SP**
  - „Intermediate" solution – apart a trigger candidate save a sub set of reconstructed objects

LHCb Upgrade I Trigger System



- **Triggerless readout and full software trigger**
  - Process data at machine clock (40 MHz crossings and 30 MHz of visible interactions)
  - No L0 (hardware) bottleneck
- **No further offline processing**
  - All data taken in Turbo mode
  - Run II is a critical testbed for this technology
  - Offline resources can be used for simulation and central data analysis

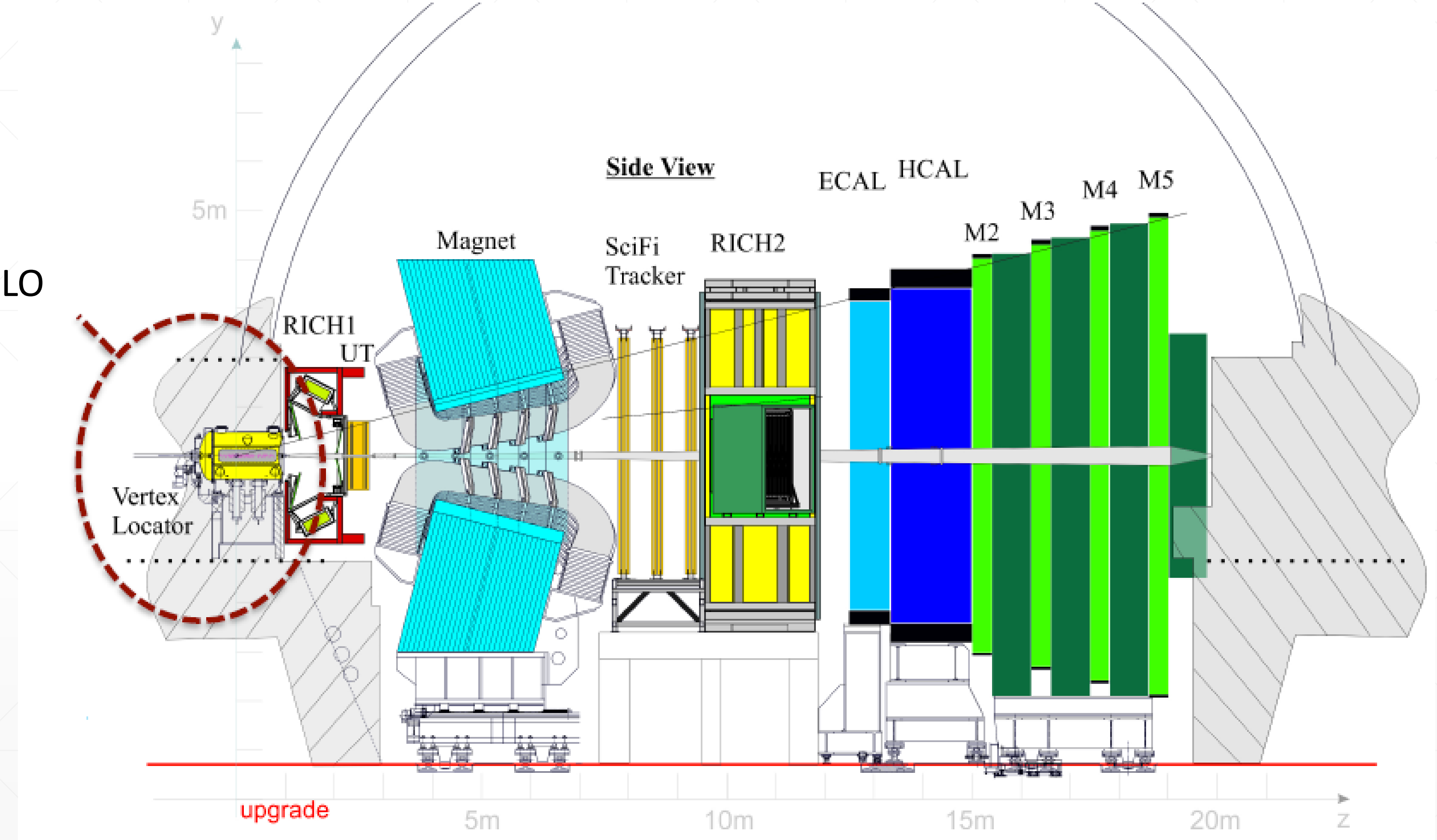


CERN-LHCC-2014-016

Vertex Locator

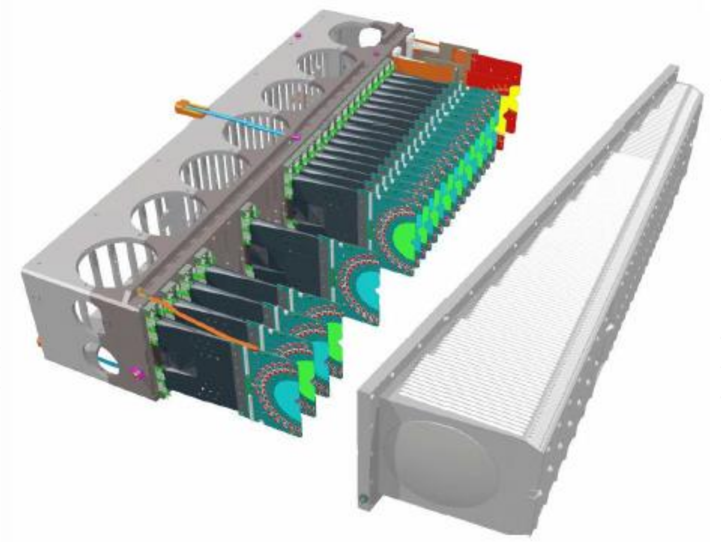
[*LHCB-TDR-013*]

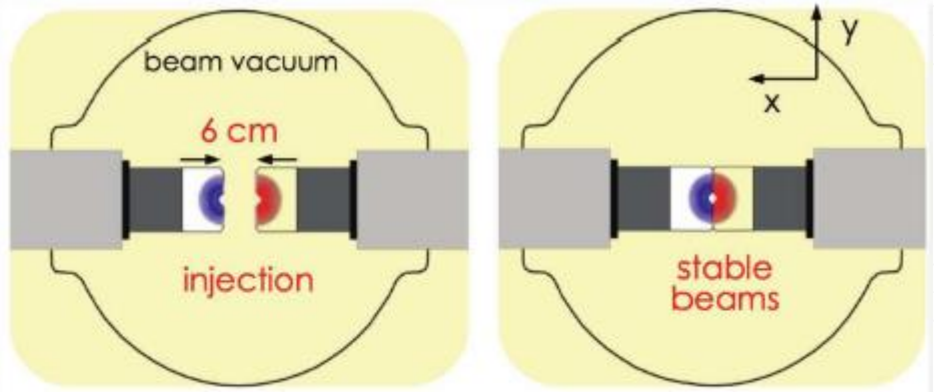
VELO



Vertex Locator (VELO) I

[*LHCB-TDR-013*]



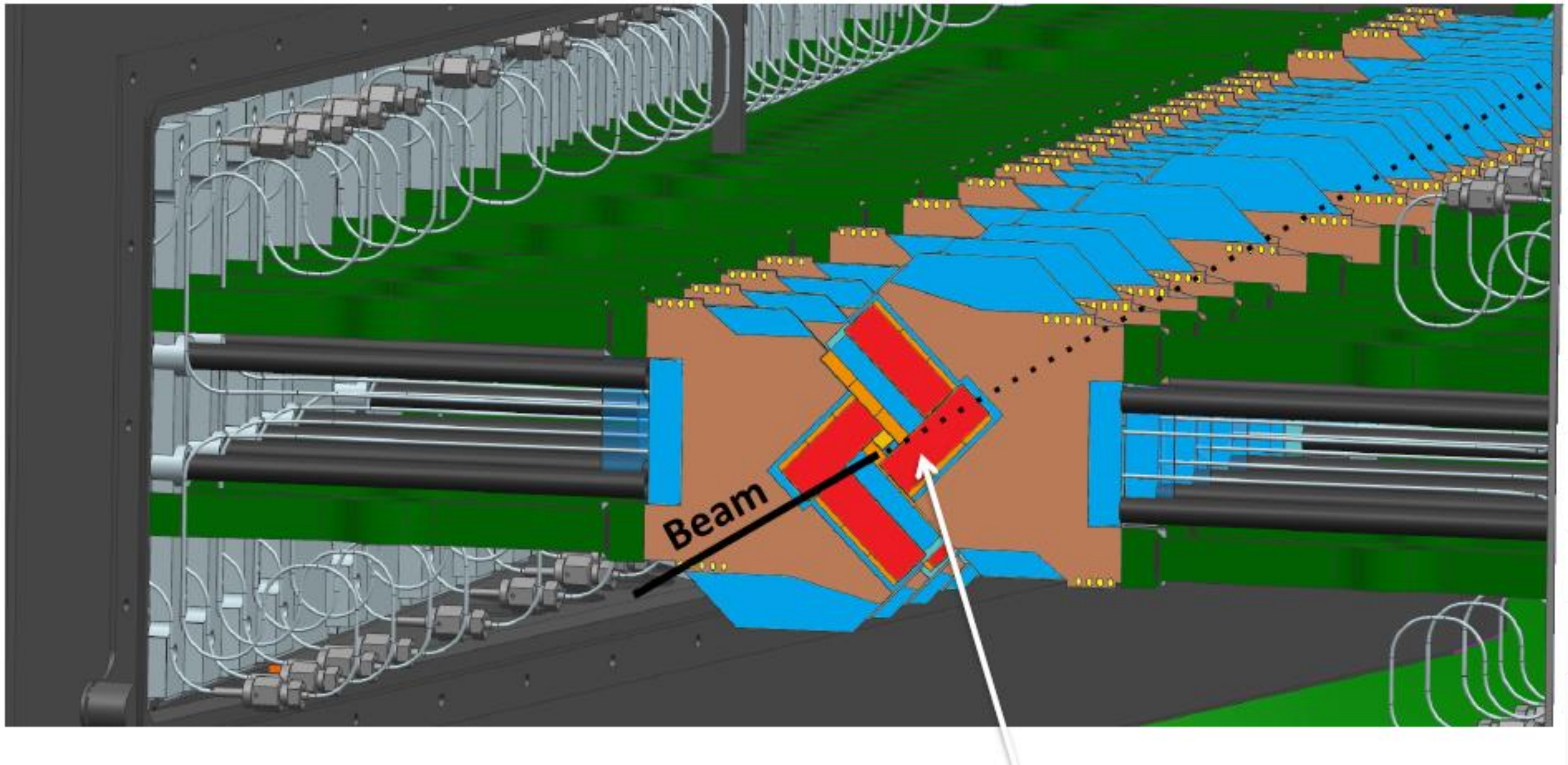


- **Current detector**
  - Two retractable halves separated by a thin RF foil from LHC vacuum
  - Semi-circular silicon microstrip sensors
  - First active strips at $8\ mm$ from the proton beams
  - Coping well with ~ 1 proton interaction per beam crossing
  - $\sigma_{IP} \sim 20\ \mu m$ for high p_T 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

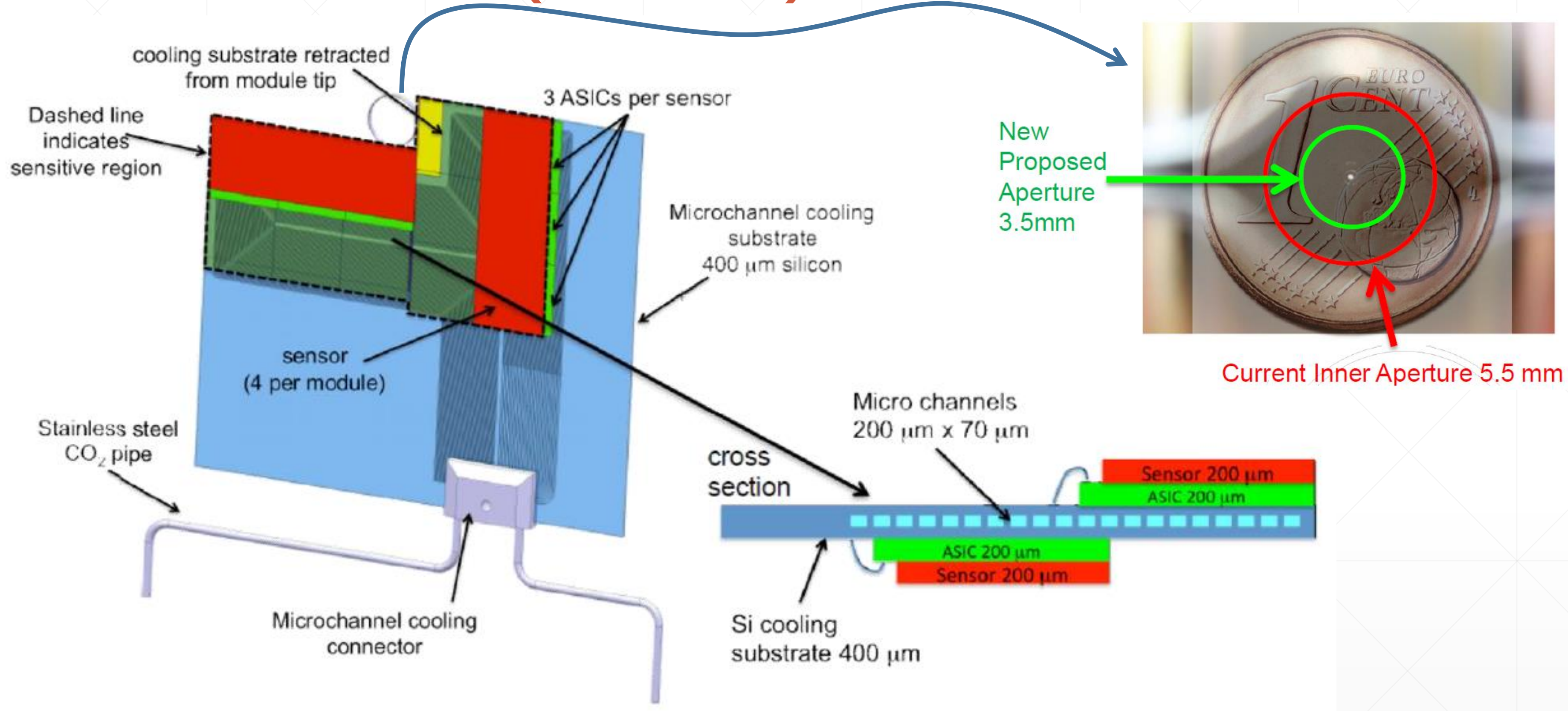
[LHCB-TDR-013]



- **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]

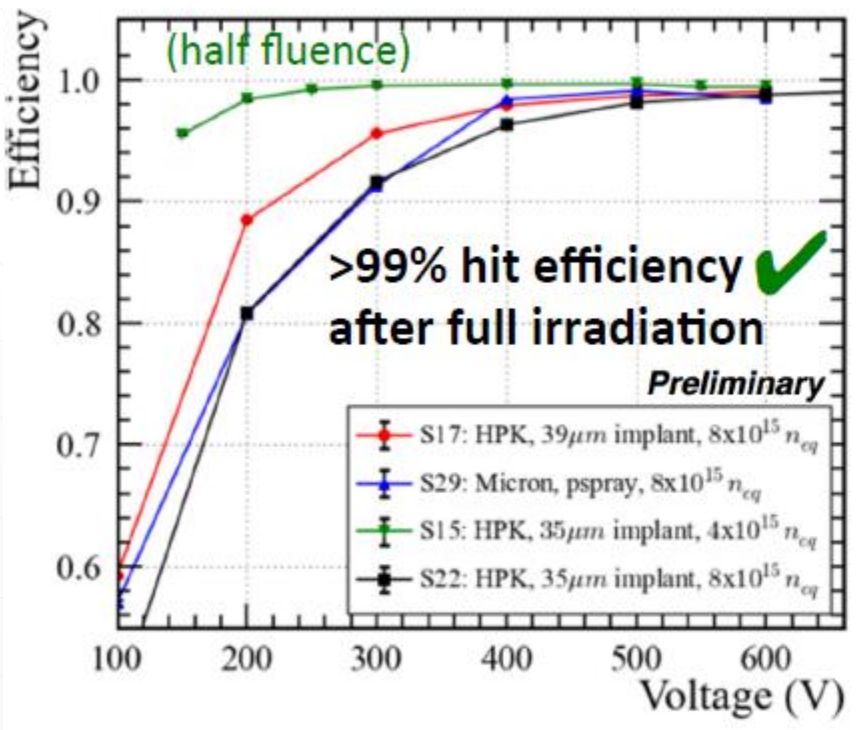


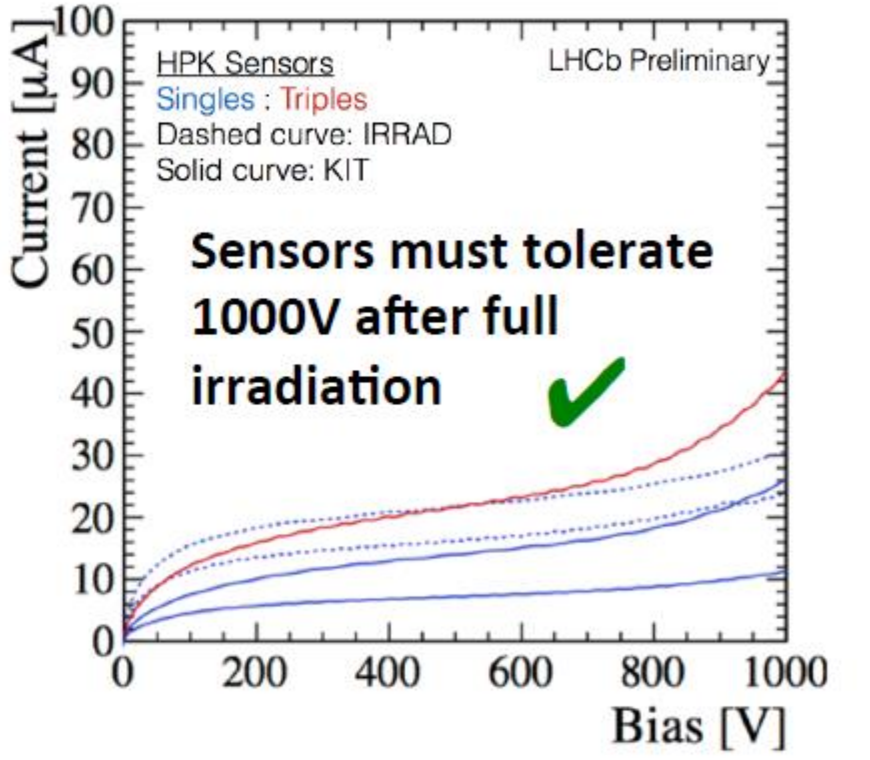
- **Silicon pixel sensors**
  - Four per module, powered and readout via kapton cables and hybrid boards
  - $55 \times 55\ \mu m$ square pixels (resolution the same in x and y direction)
  - Versatile sensor evaluation program is on the way (test beam campaign)

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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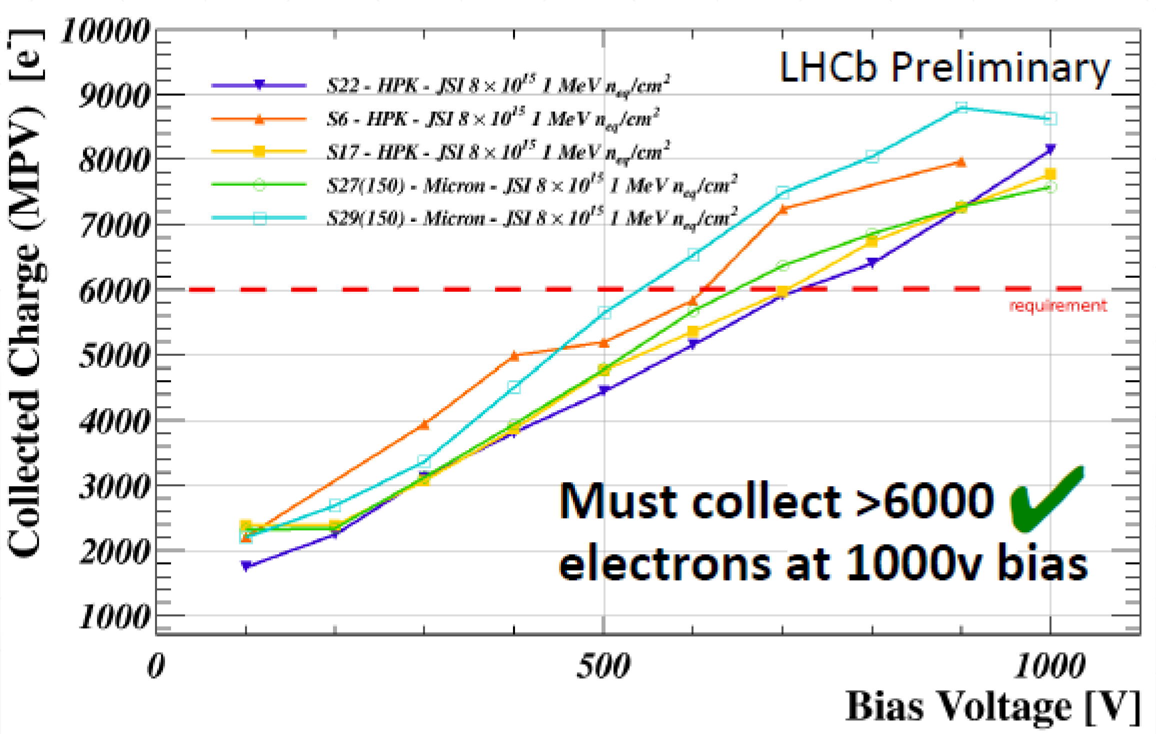
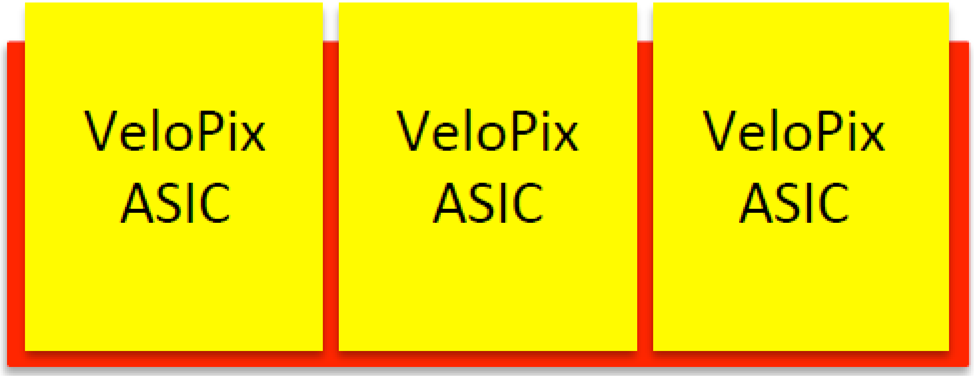


Vertex Locator (VELO) IV

[*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



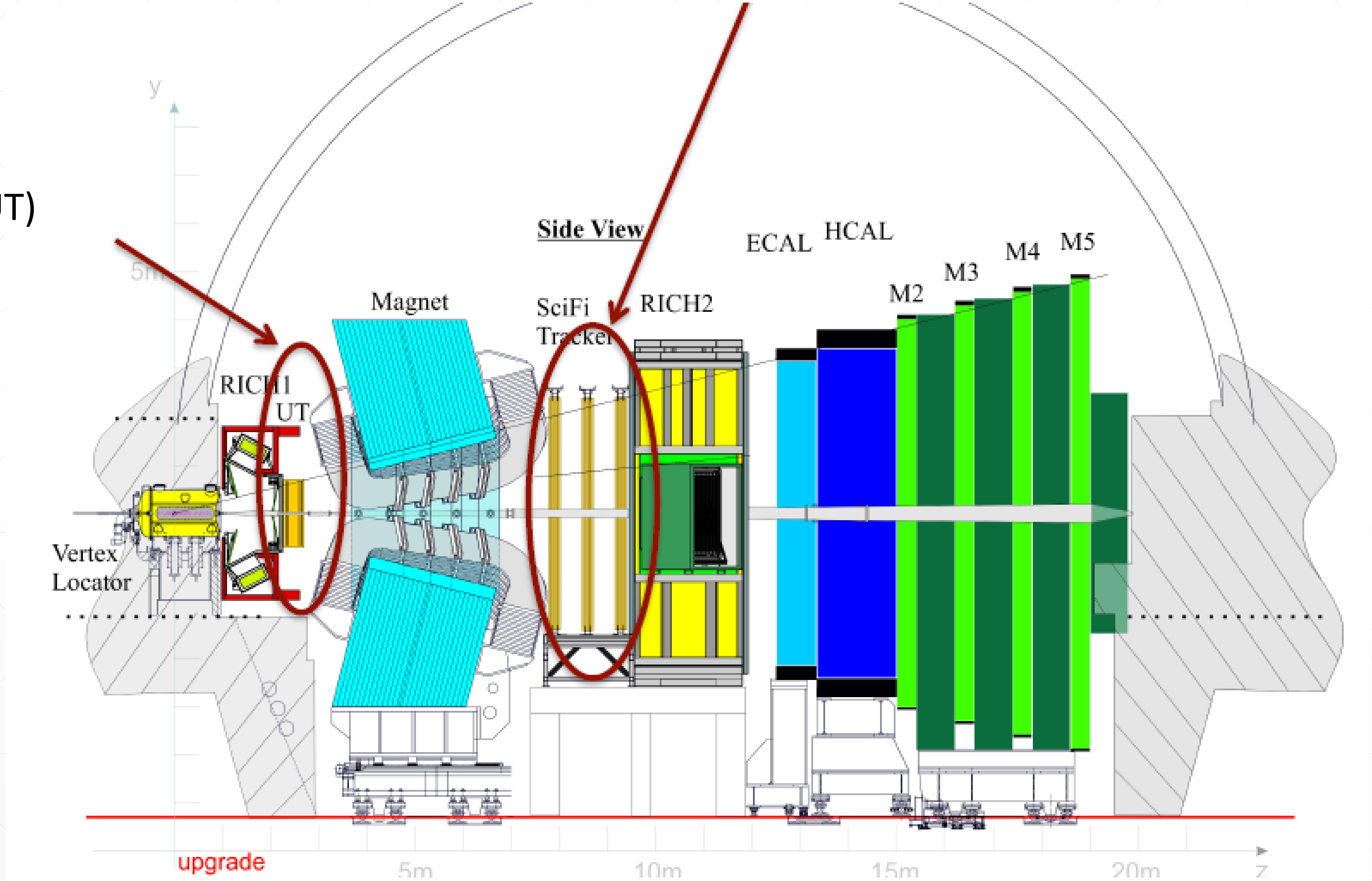
- **Sensors and read-out electronics are mounted on cooling substrate with CO_2 micro-channels**
  - Excellent cooling performance
  - Minimal material within detector acceptance
  - Now in full production

Tracking System I

Scintillating Fibre Tracker (SciFi)

[*LHCB-TDR-015*]

Upstream Tracker (UT)



Tracking System II

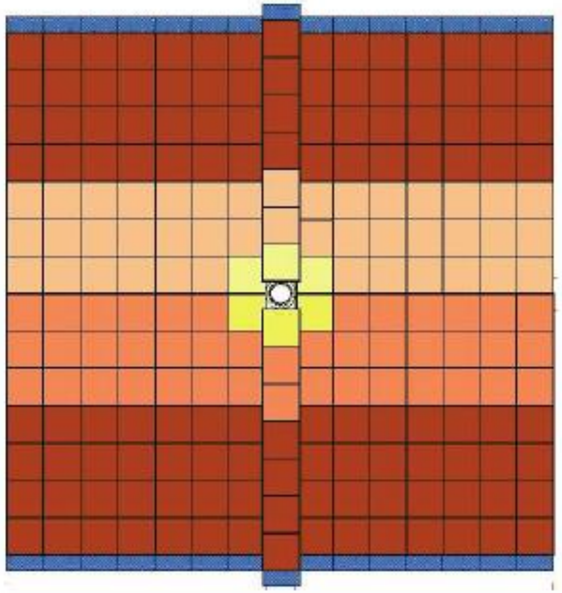
T1 – T3

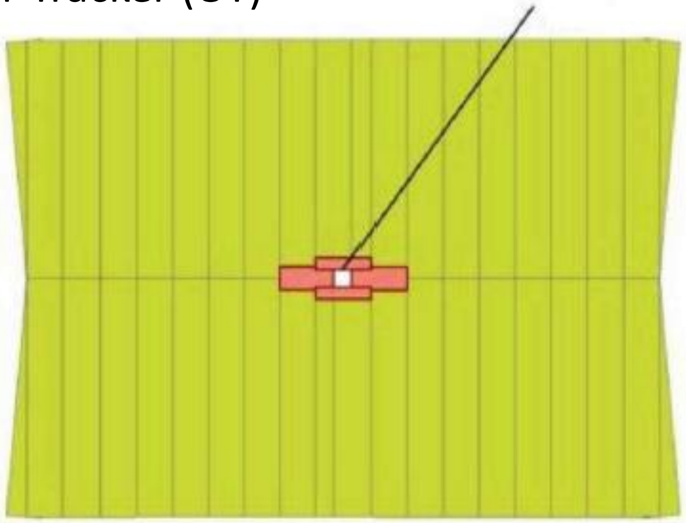
[*LHCB-TDR-015*]

Outer Tracker (OT)

Inner Tracker (IT)

TT



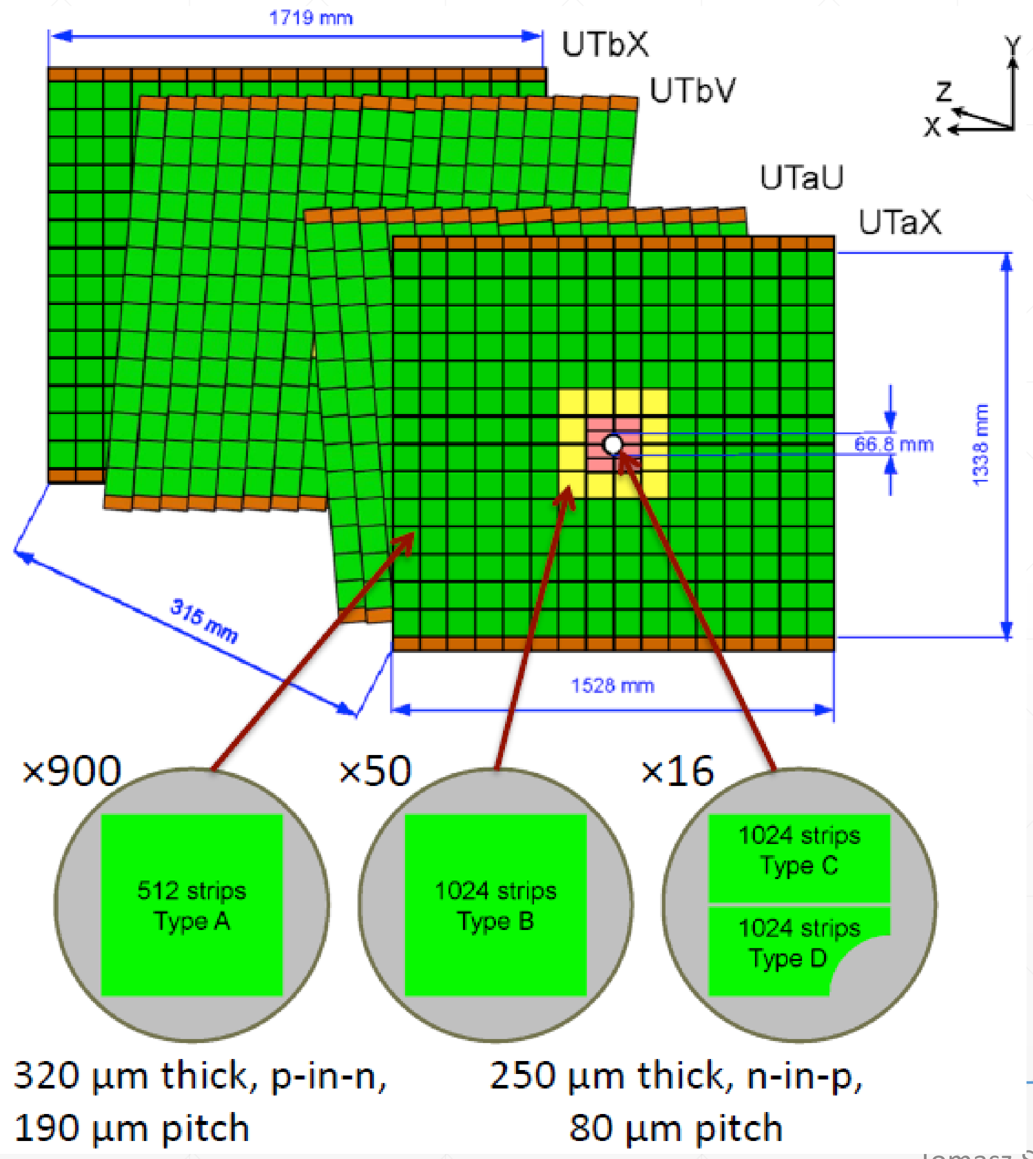


- ❑ Current detector – TT
- ❑ Four planes of silicon strip detectors vital for reconstructing tracks outside VELO
- ❑ Not radiation hard enough for the upgrade
- ❑ New front-end read-out electronics needed for $40\ MHz$ trigger
- ❑ Need finer granularity to cope with higher occupancies

- ❑ 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*]

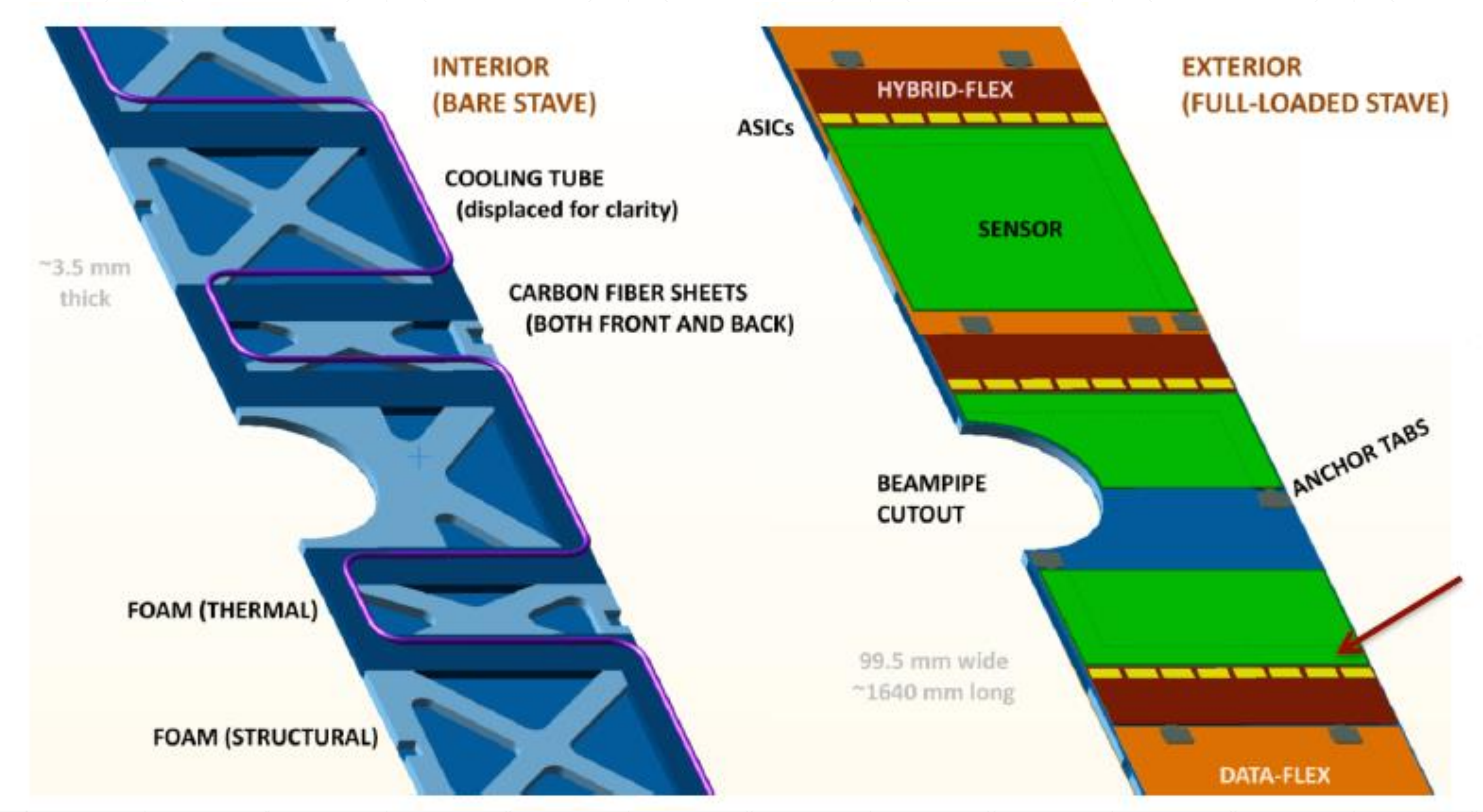


- ❑ Four planes of silicon strip detectors mounted to very lightweight staves – **keep material budget as small as possible**
- ❑ Sensors are on both sides of the staves and are closer to the beam – larger coverage
- ❑ Finer granularity – strip pitch $\mathbf{95 - 190}\ \boldsymbol{\mu m}$
- ❑ Four different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

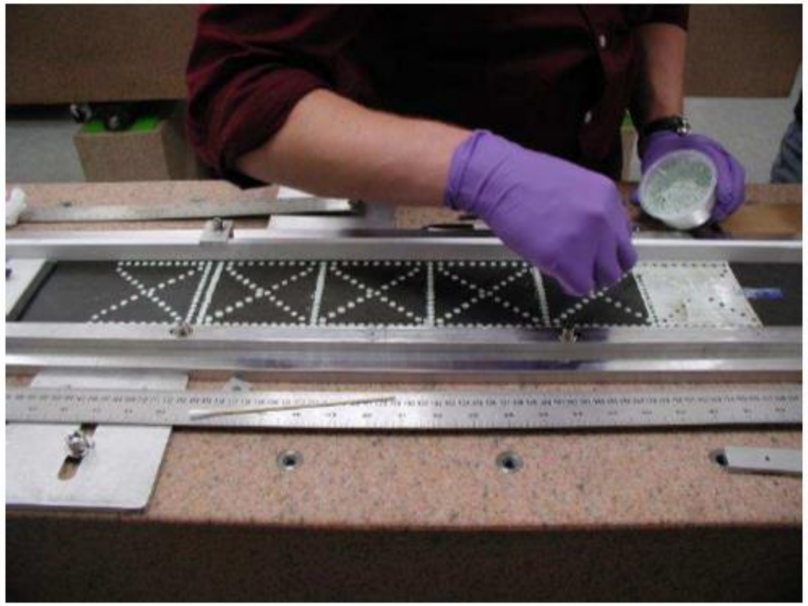
- Staves are $\sim \mathbf{10}\ \boldsymbol{cm}$ wide and $\sim \mathbf{1.6}\ \boldsymbol{m}$ long

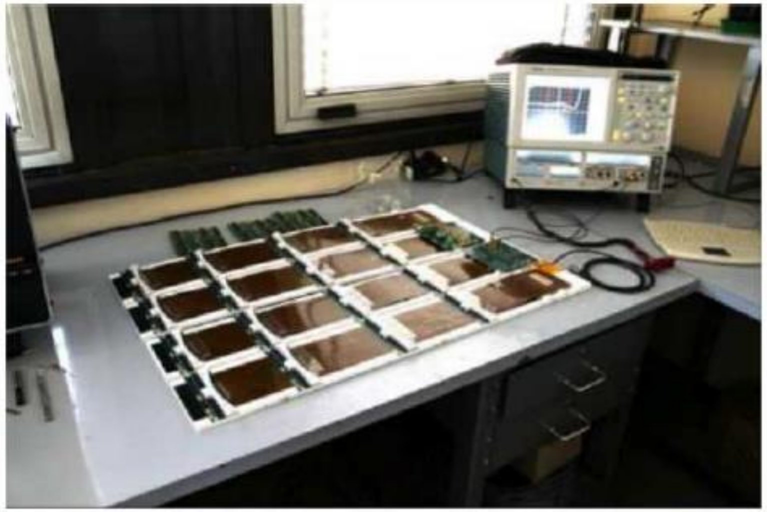
- Dedicated read-out ASIC chip SALT (**S**ilicon **A**SIC for **L**HCb **T**racking) is being extensively tested
- Second engineering run before summer

Tracking System – UT III

[*LHCB-TDR-015*]

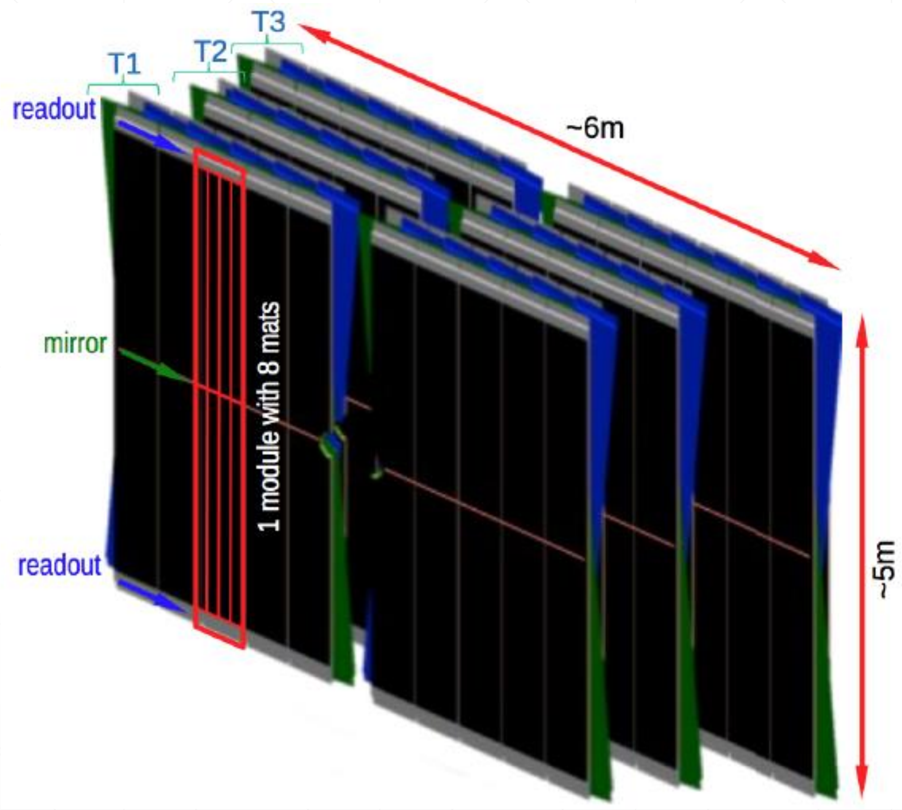
- Stave design well advanced – now switching to construction phase

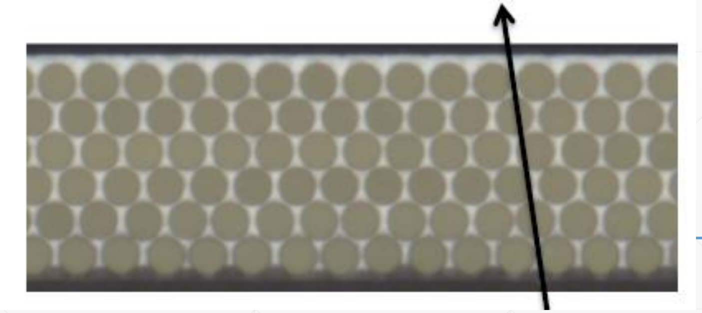




Tracking System – SciFi I

[*LHCB-TDR-015*]

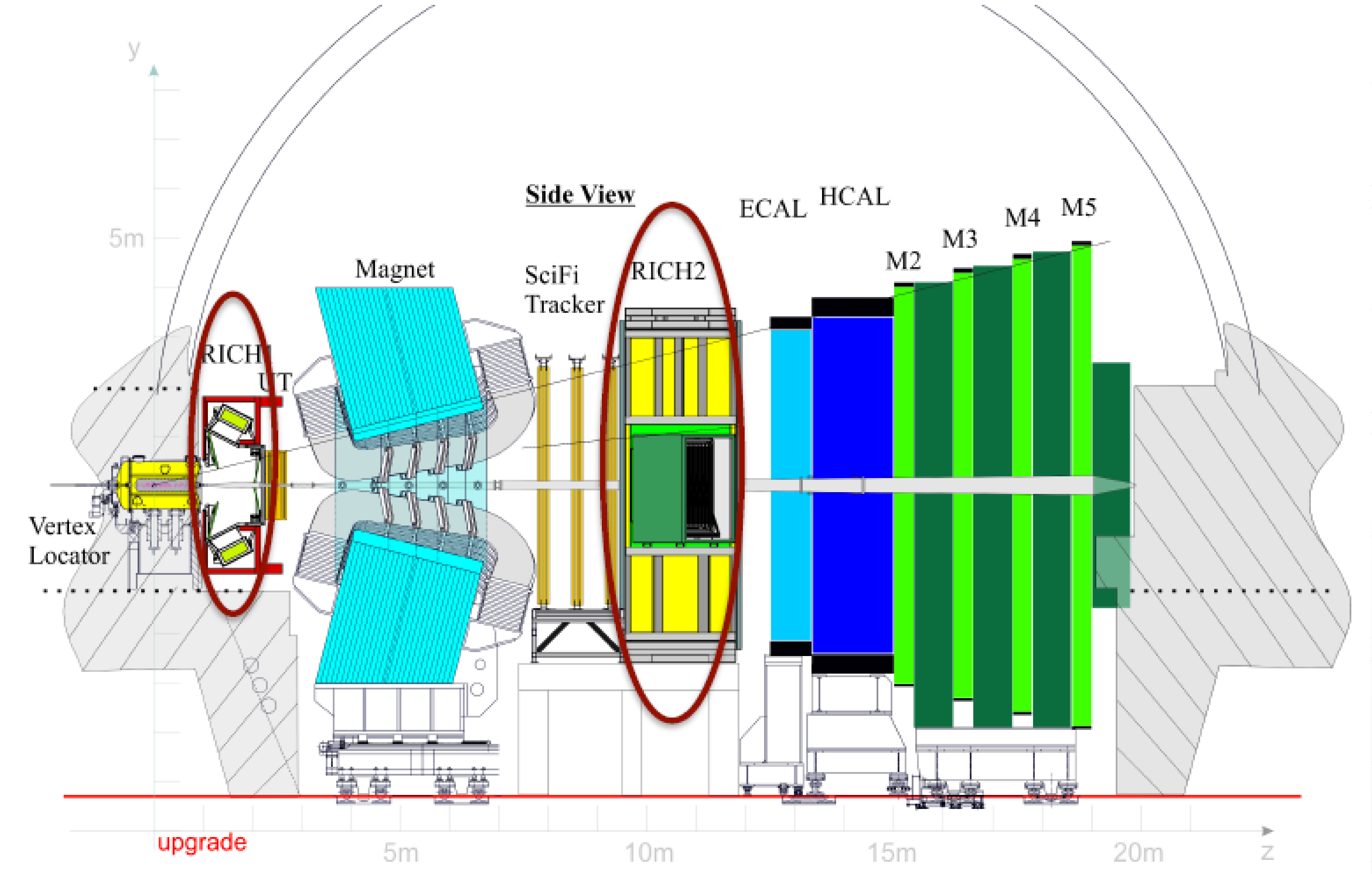




- 3 x 4 layers of scintillating fibre mats of total area close to $\mathbf{340\ m^2}$ (each mat features material thickness of $1.1\ X_0$)
- Excellent coverage up to $\mathbf{3\ m}$ from the beam pipe
- Each mat comprises 6 layers of $\mathbf{250\ \mu m}$ thick fibres (total length for SciFi $\sim \mathbf{11000\ km}$)
- 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 $\mathbf{99\%}$

RICH Detectors I

[LHCB-TDR-014]



RICH Detectors II

[*LHCB-TDR-014*]

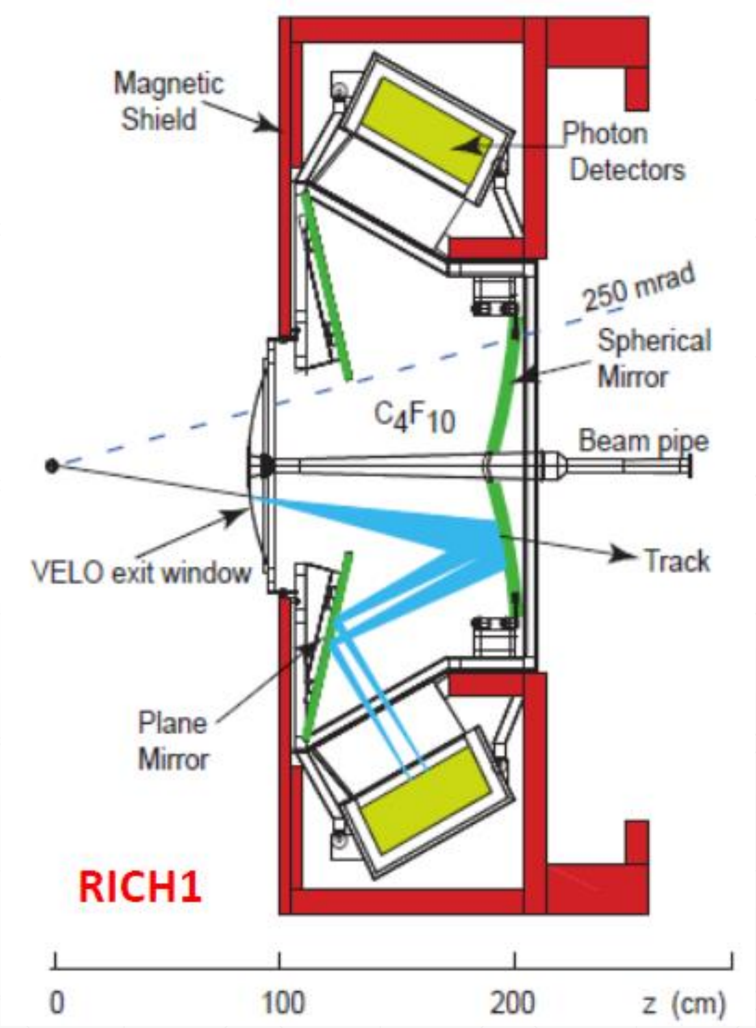
- **Currently LHCb features two of these**:
  - Upstream RICH1: 2 $GeV/c - 40\ GeV/c$ over 25 $mrad - 300\ mrad$
  - Downstream RICH2: 30 $GeV/c - 100\ GeV/c$ over 15 $mrad - 120\ mrad$
- Excellent performance in Run 1 and Run 2

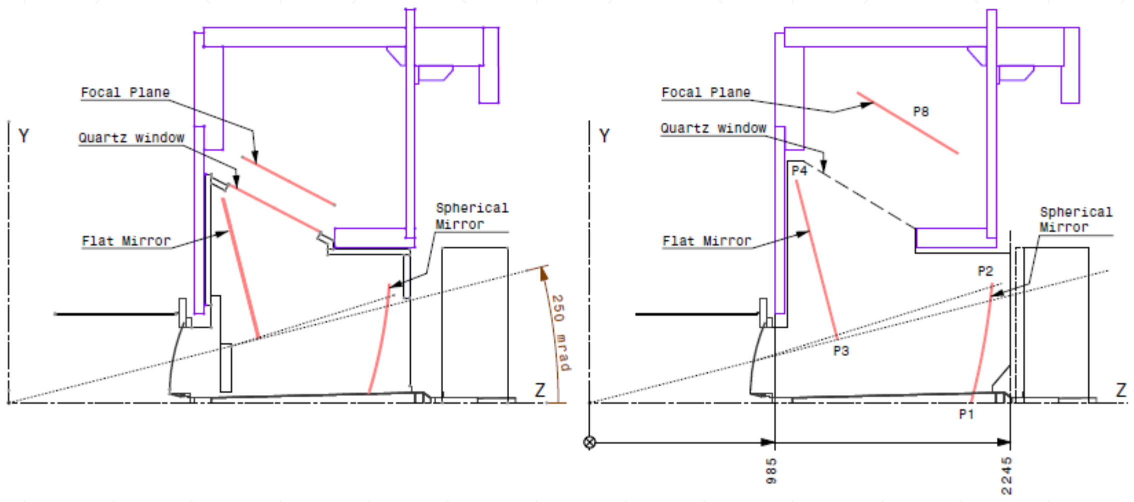
- Charged hadrons interact with gaseous radiator and produce Cherenkov photons, that in turn are focused on Hybrid Photon Detectors (HPD)

- 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*]

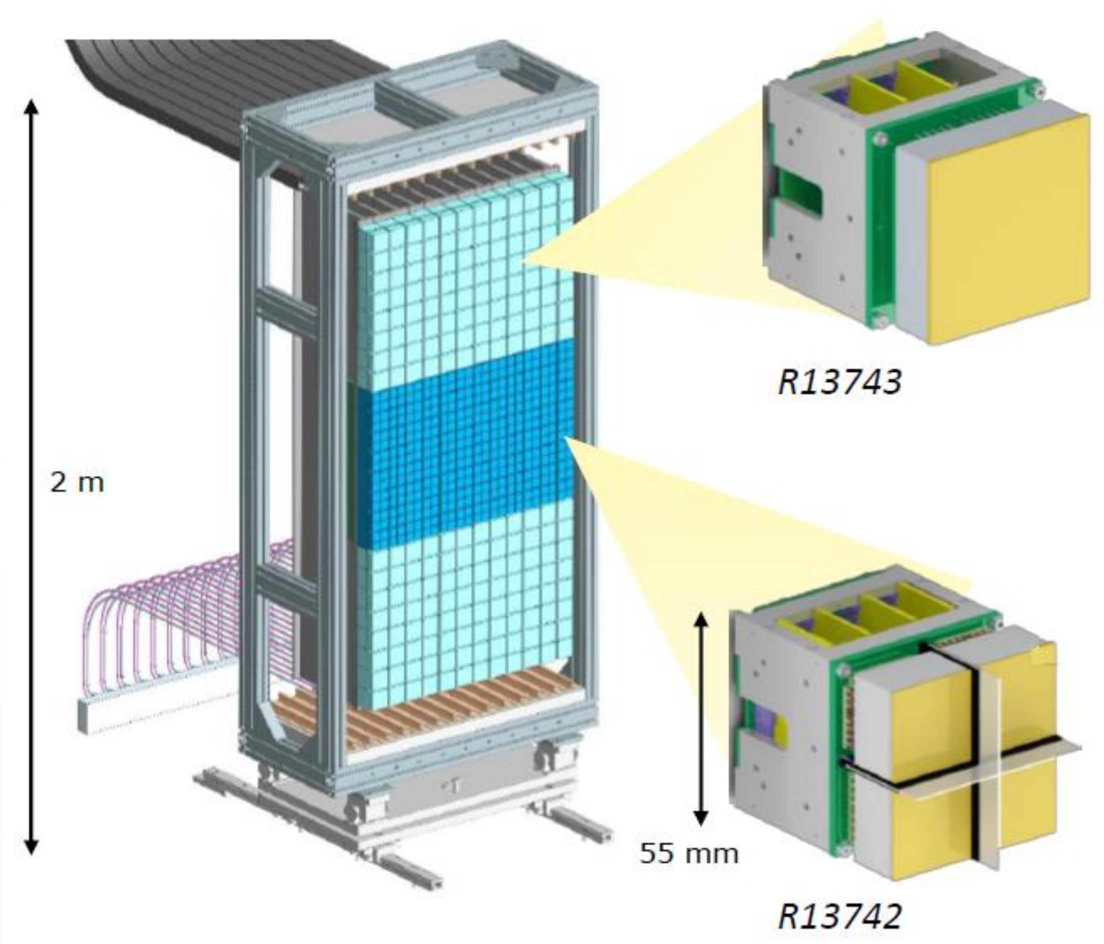




- **Upgrade plans for RICH detectors** :
  - New optics for RICH 1
  - Increase image area and bring down the occupancy
  - We need new mirrors, mechanics and radiator box
  - Simulation studies show drop in occupancy from 40% (current) to 27% (upgraded)

RICH Detectors IV

[LHCB-TDR-014]



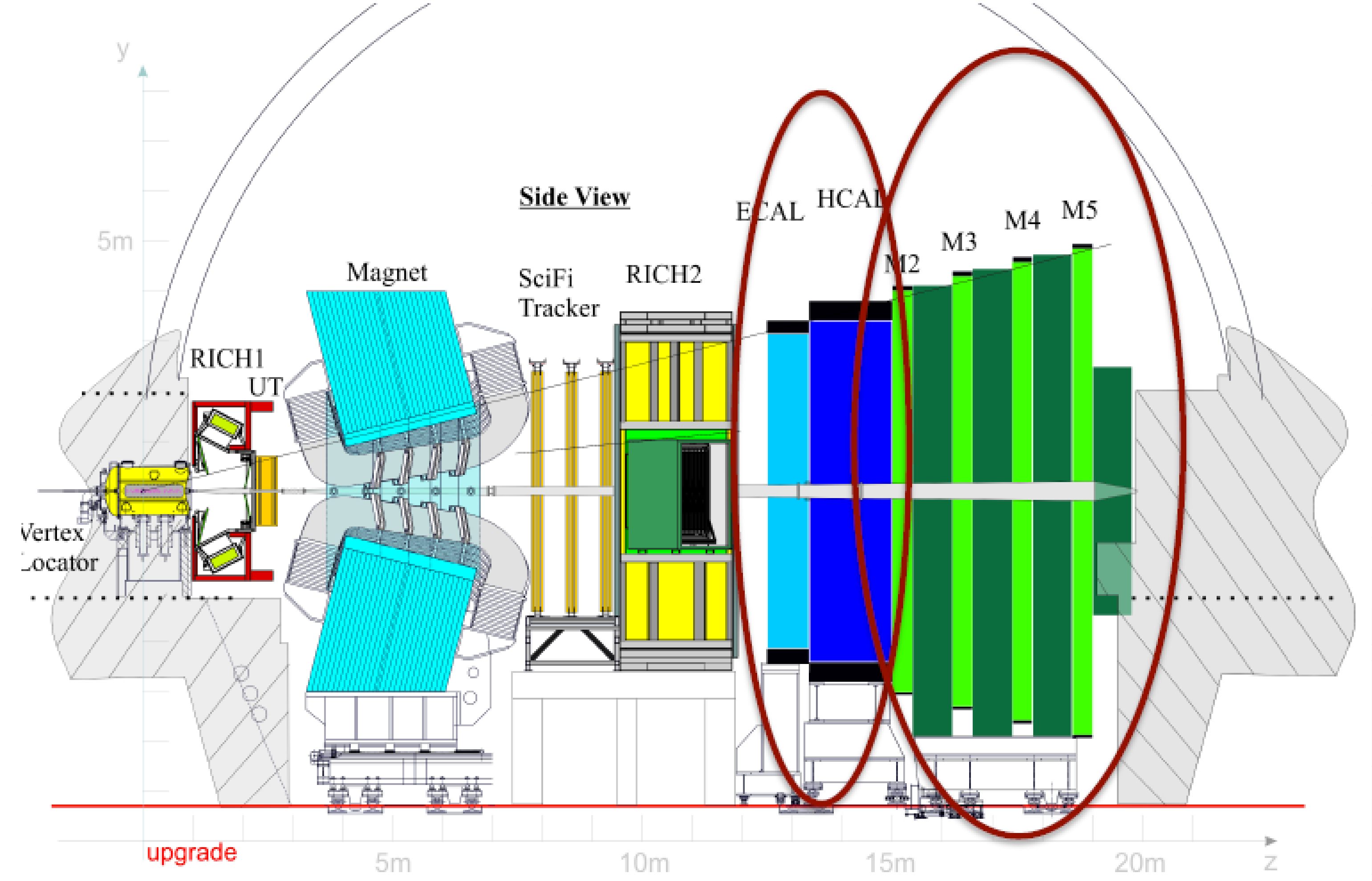
- **Upgrade plans for RICH detectors** :
  - New photon detectors
  - Allow 40 MHz read-out
  - Finer granularity
  - Improvement in single photon angular resolution by 50% (RICH1) and 20% (RICH2)

- 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

Summary

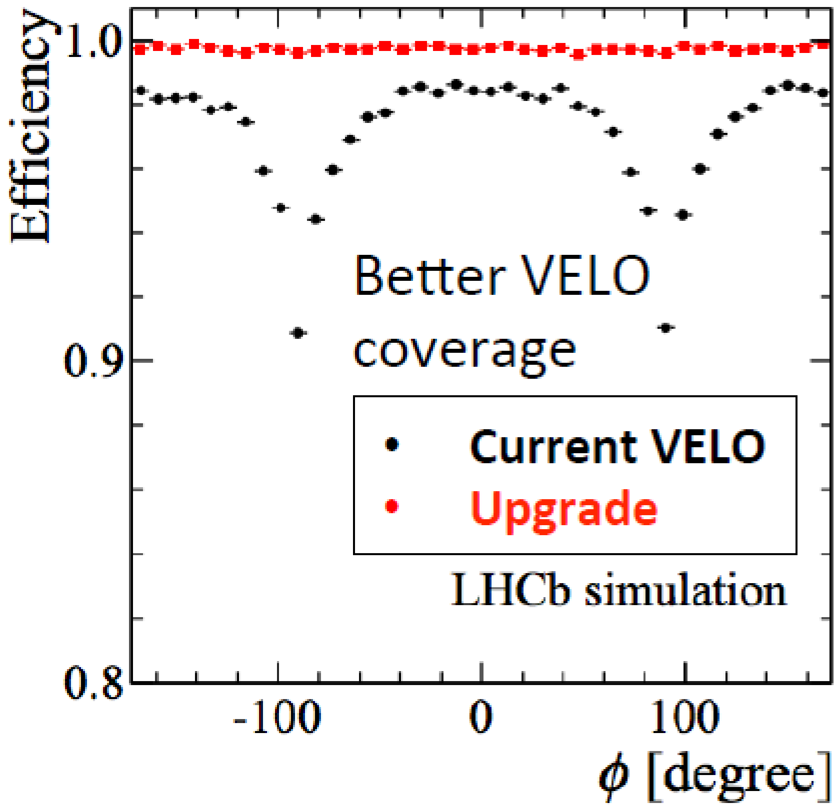
- **Ambitious plans for LHCb Upgrade I**
- R&D well underway – transition to construction phase
- Development of advanced and sophisticated r/o electronics (e.g. SALT chip)
- Trigger and computing model is being tested during Run 2
- Major changes to the LHCb spectrometer – new VELO, UT and SciFi, also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

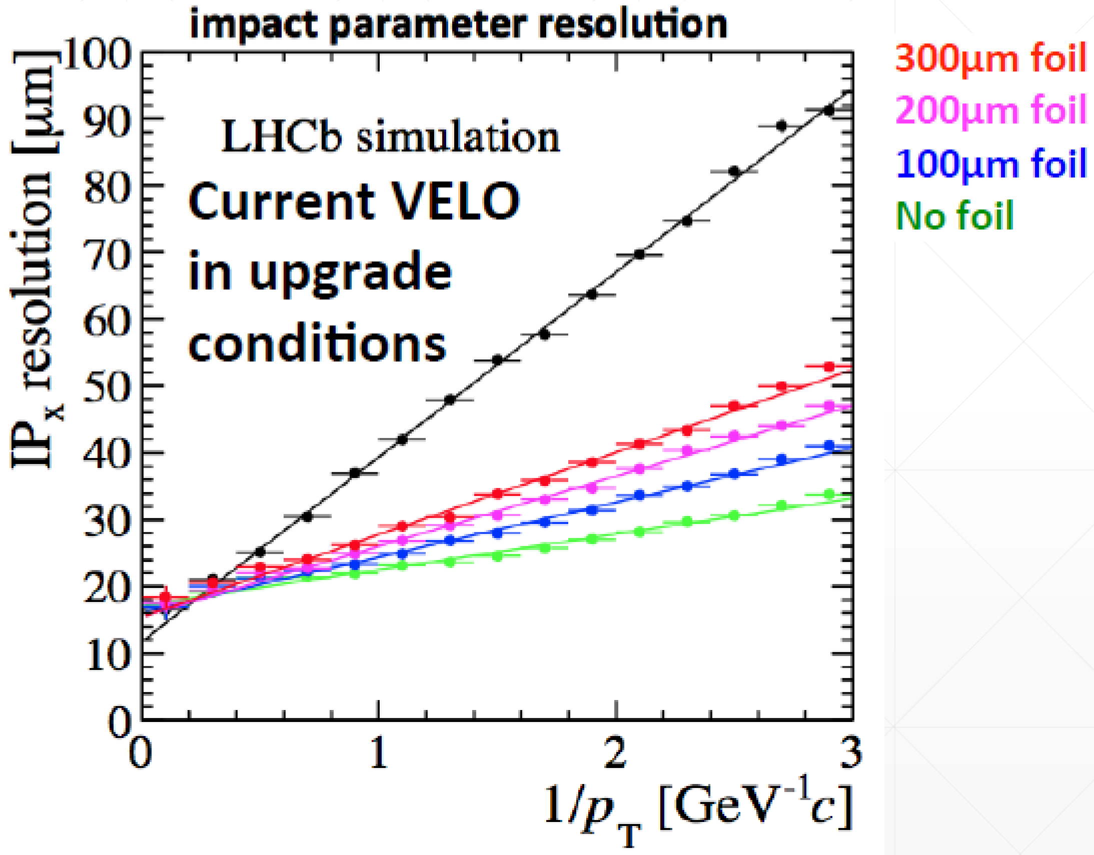
- **Future upgrades to exploit HL LHC era possible (Upgrade II)**
- Potential huge data samples
- Major challenge for detector design
- Timing information and radiation hardness critical

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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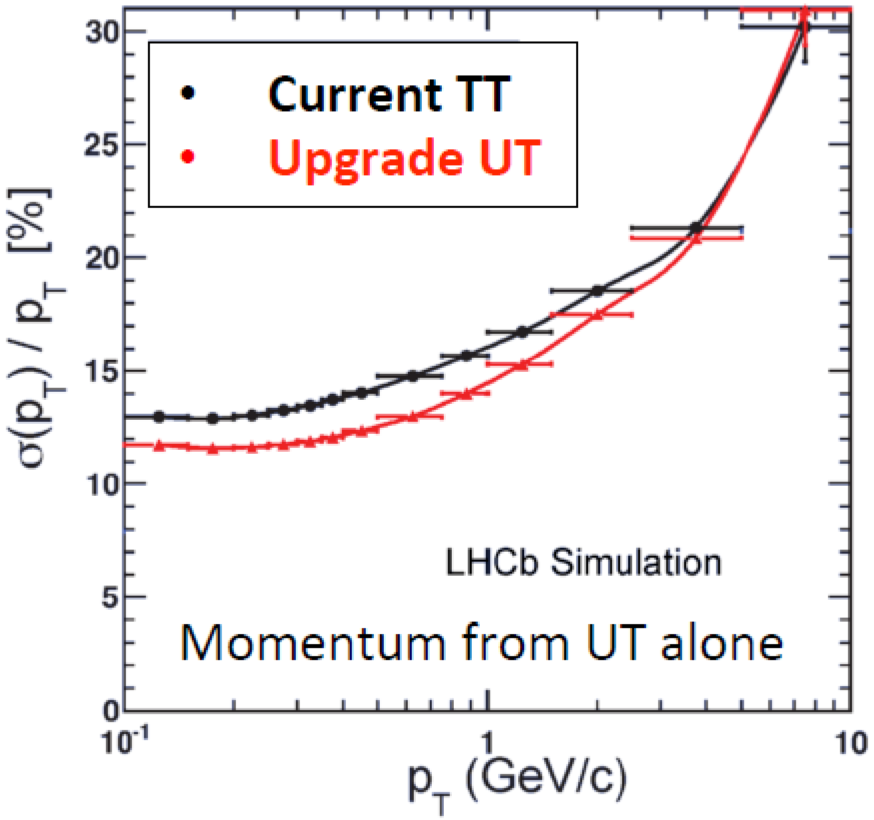
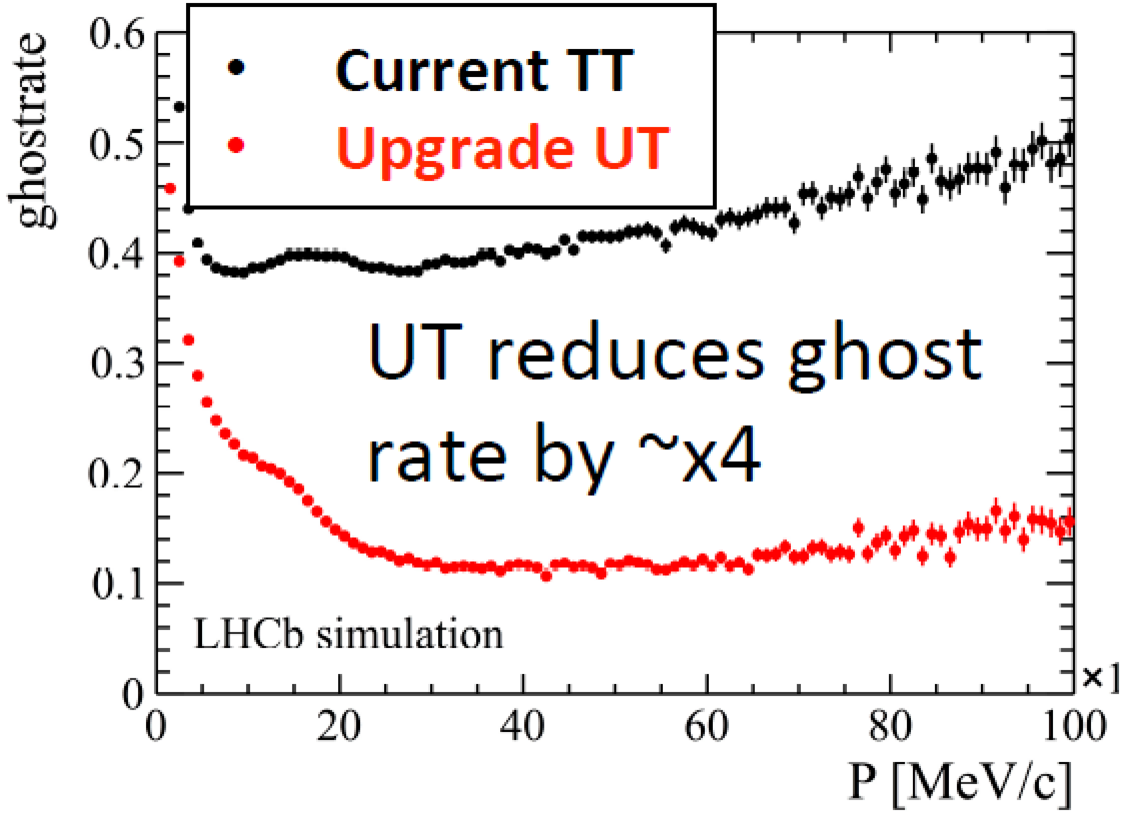
UT





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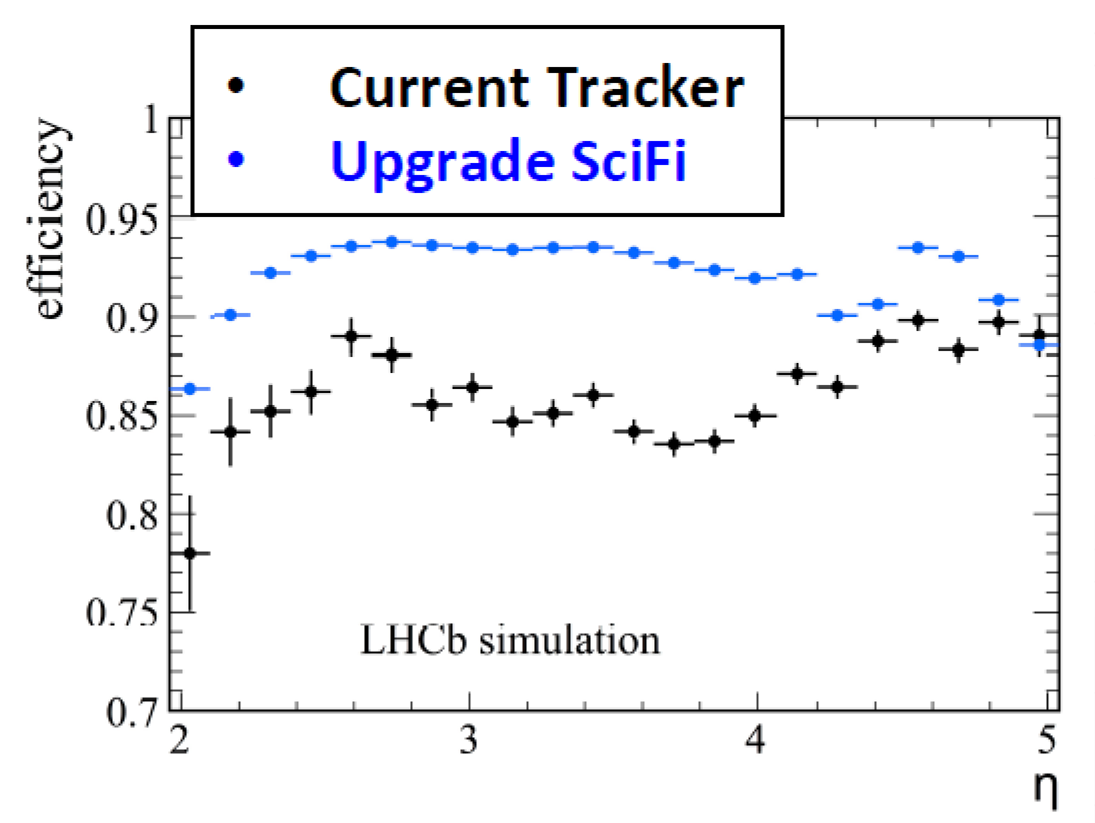
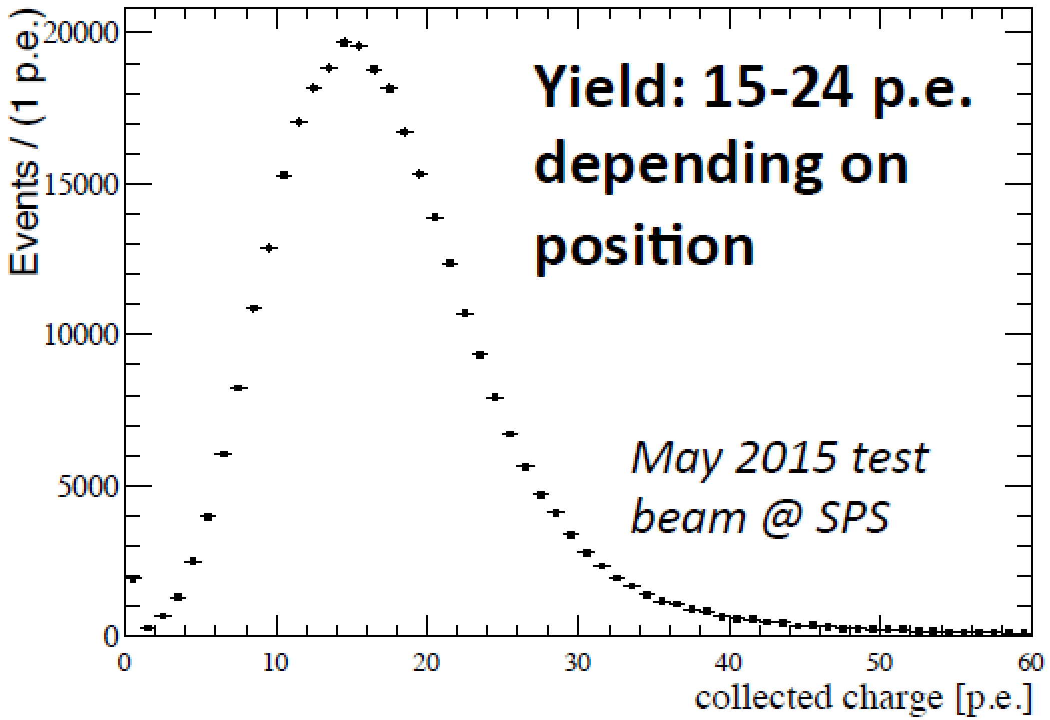
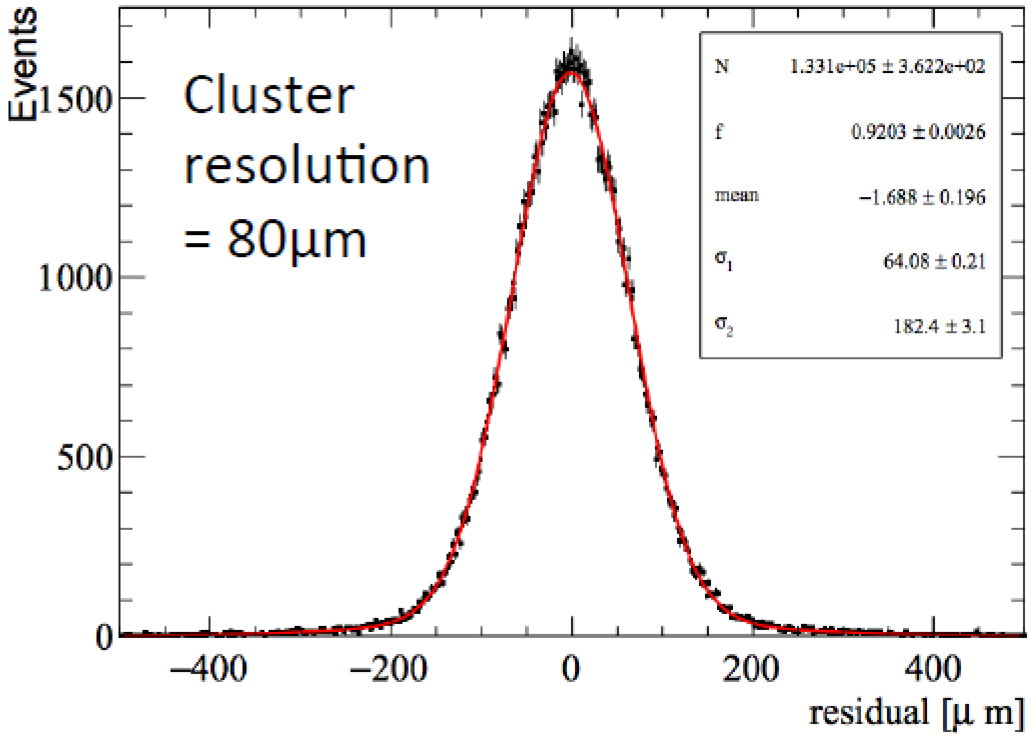
SciFi



Tracking System – SciFi II

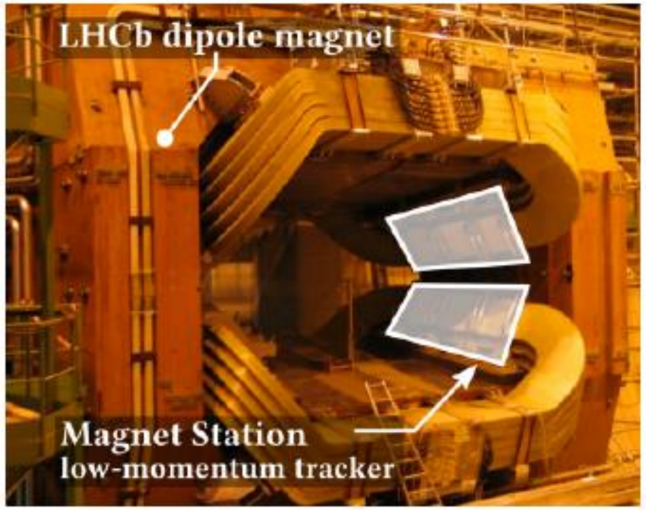
- Extensive test beam experiments

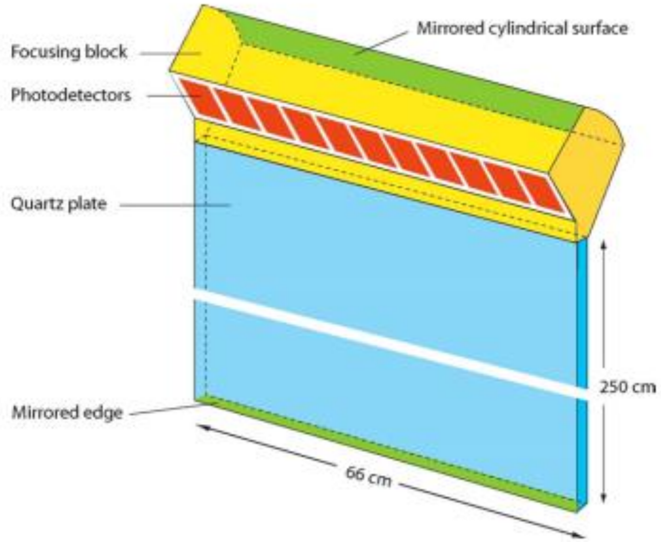




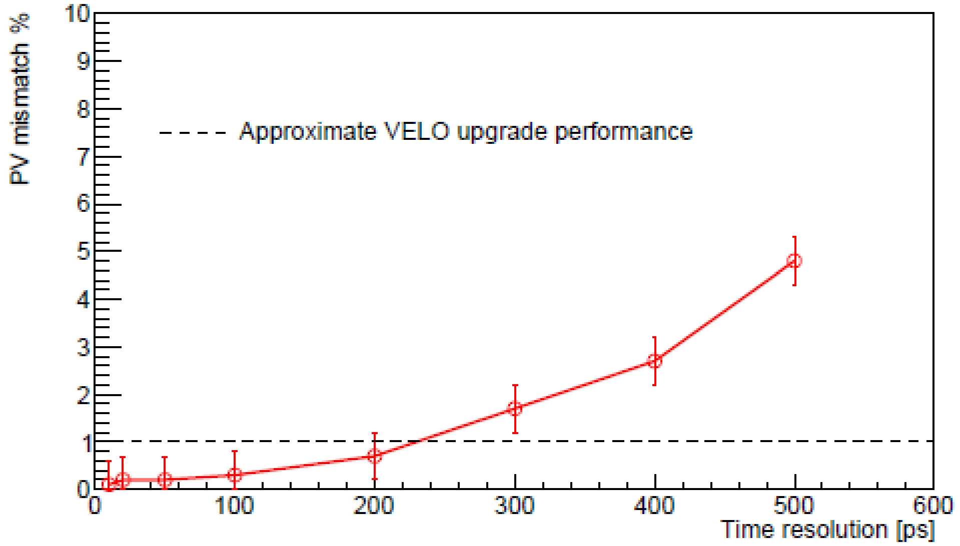
Beyond Upgrade Phase I – Phase Ib

- 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)

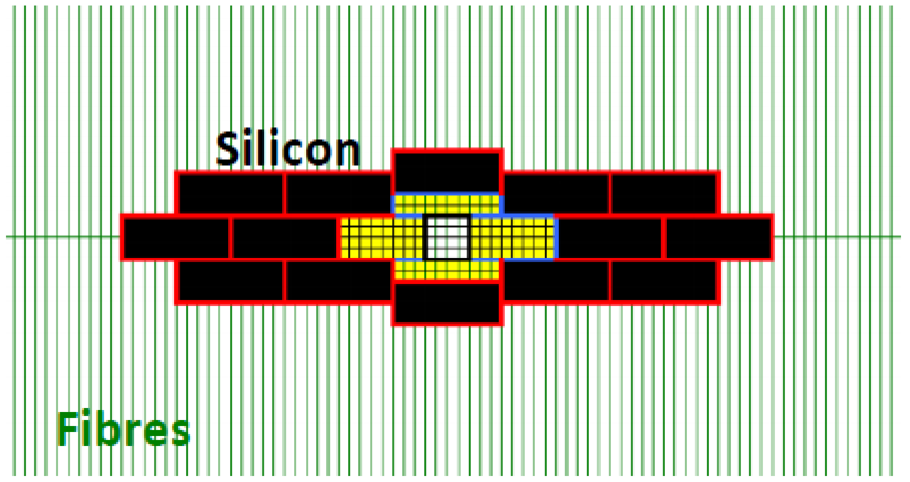


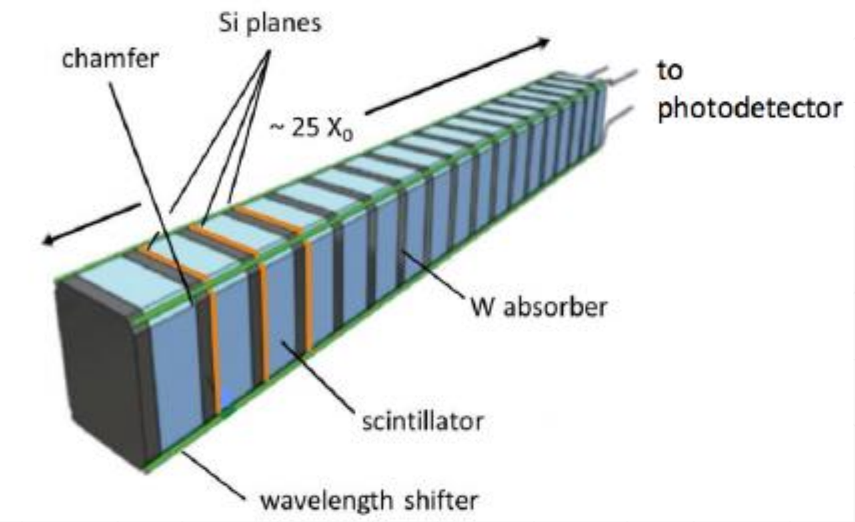


Beyond Upgrade Phase I – Phase II

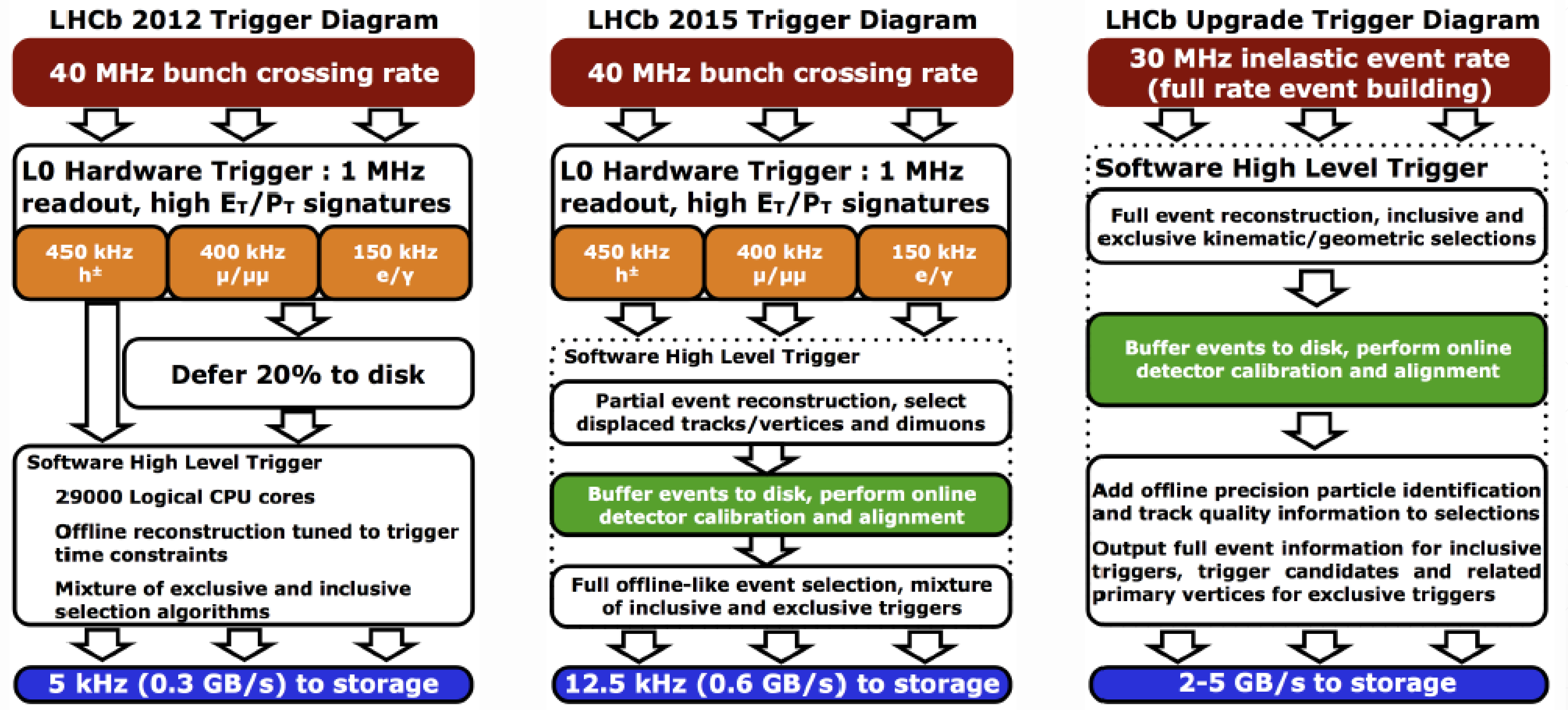


- 4D Pixels
  - Timing information needed for correct long lived tracks association to PVs
  - $\sigma_t \approx 200\ ps$ time resolution enough to match the performance of the current VELO
  - Smaller pixels $25 \times 25\ \mu m$
- Enhance fibre tracker with inner silicon detector
- Smaller cells and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





30 MHz Tracking – New Trigger [*LHCB-TDR-016*]

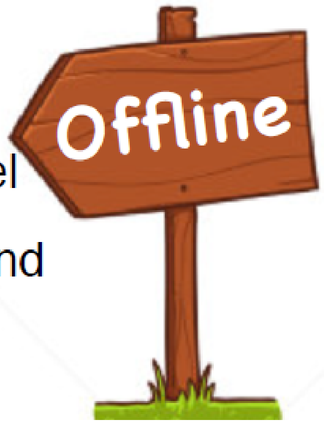


Run 1 **Run 2** **Run 3, 4**

The LHCb trigger in Run II

Online and offline as close as possible:

- PID (and its calibration) performed at the trigger level
- Same calibration and detector alignment in trigger and offline
- Same reconstruction in the trigger and offline



Possibility to perform analyses directly on the trigger output (Turbo stream):

- Candidates are saved directly after the trigger
- Only reconstructed objects saved
- Smaller events + more rate + fast data availability