The LHCb Experiment Upgrade Programme

Mark Williams, on behalf of the LHCb Collaboration

INSTR17: Instrumentation for Colliding Beam Physics
Novosibirsk, Russia, 3rd March 2017

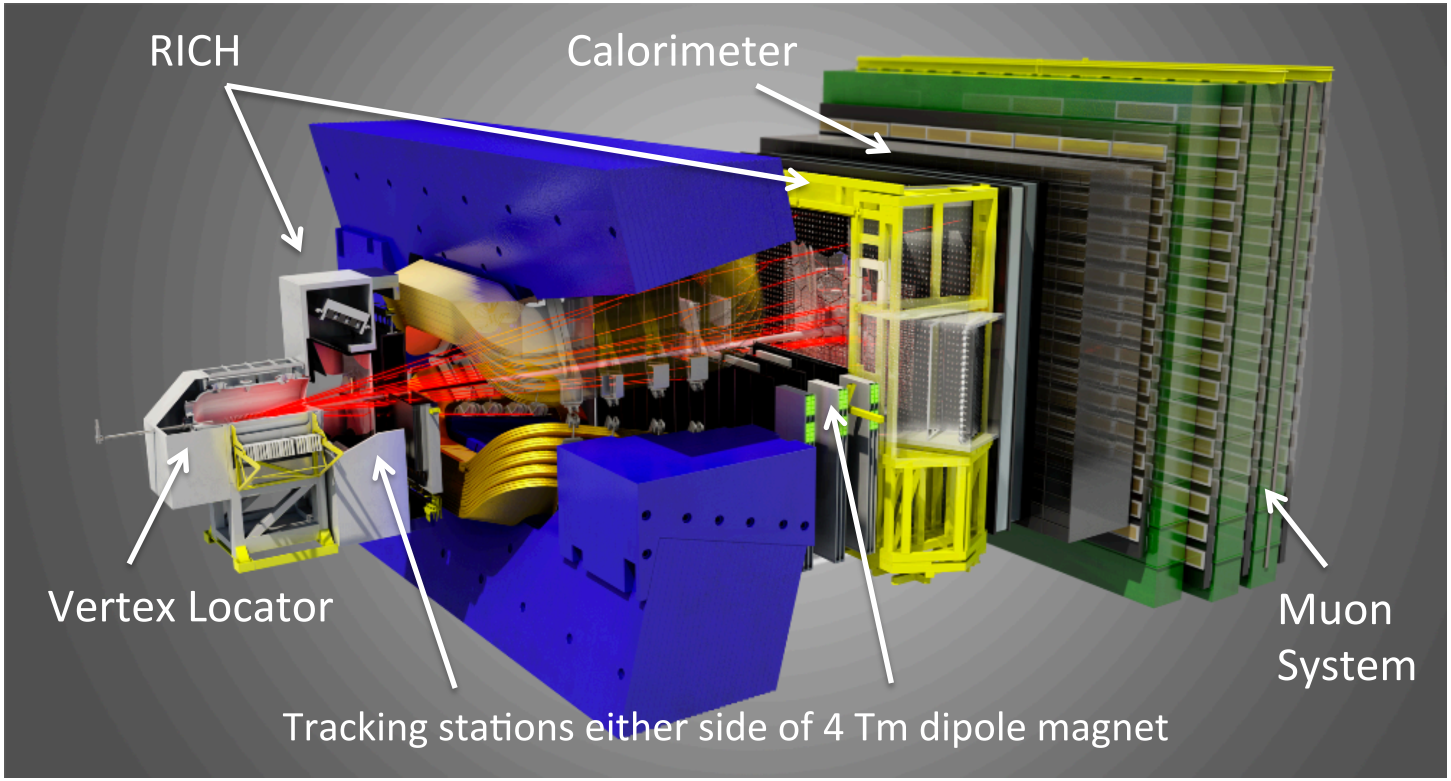
MANCHESTER 1824
The University of Manchester

Context: current LHCb Detector

Single-arm forward spectrometer (2<η<5)

Optimised for high precision heavy-flavour physics measurements.

Broad programme including EW, QCD, heavy-ion, top



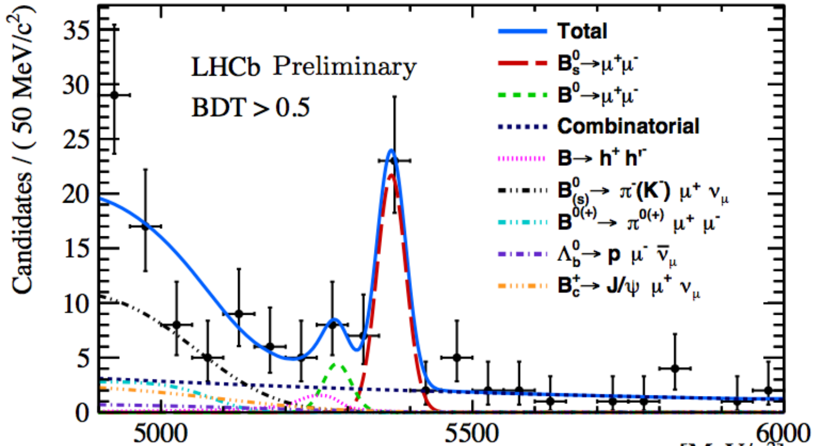
Run 1 (2010-2012) and Run 2 (2015-2018) will deliver 3+5 fb^{-1}

Already collected unprecedented samples of bottom and charm hadrons

Very successful physics program (360+ papers)

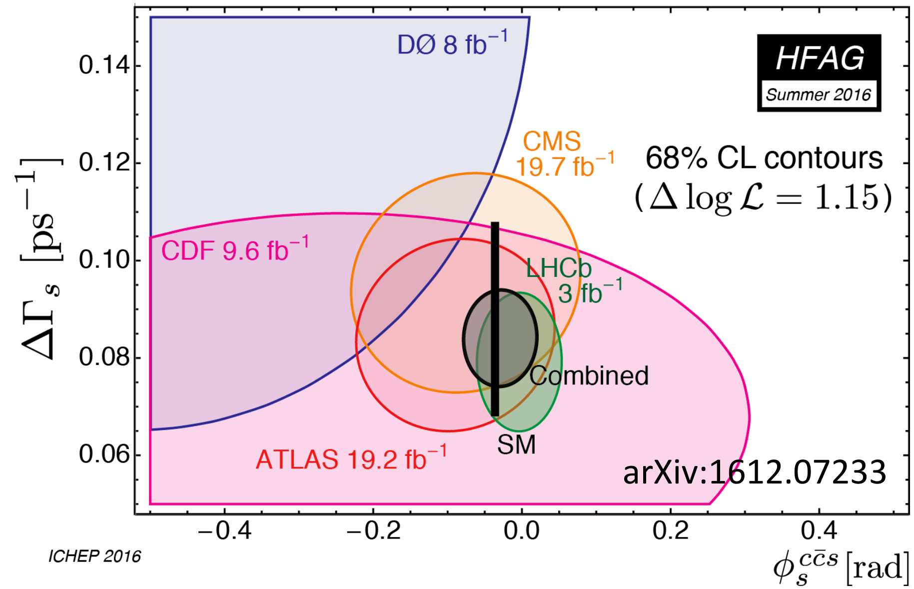
Why upgrade?

Observation of $B_s^0 \to \mu^+\mu^-$, and lifetime measurement



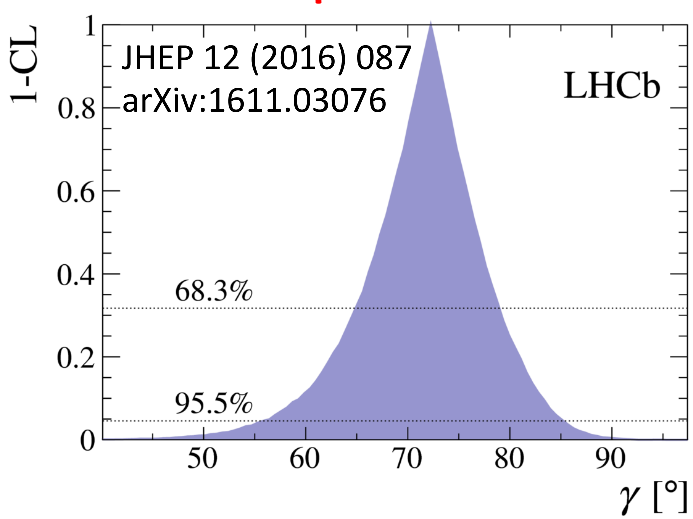
LHCb-PAPER-2017-001

Search for CPV in B meson mixing



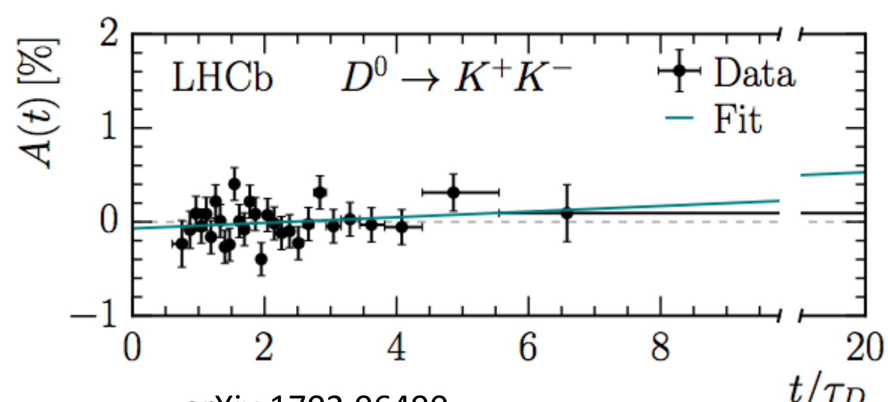
arXiv:1612.07233

Combination of γ measurements



JHEP 12 (2016) 087
arXiv:1611.03076

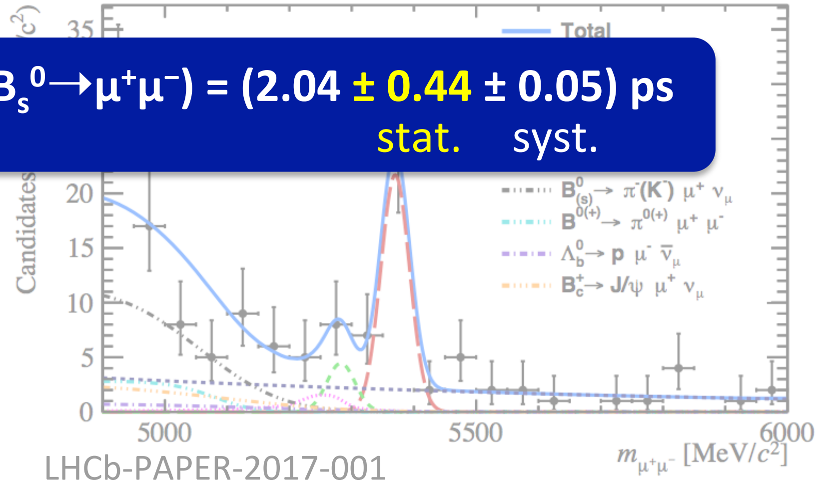
High-precision charm CPV measurements



arXiv:1702.06490

Why upgrade? Precision limited by signal yields

Observation of $B_s^0 \to \mu^+\mu^-$, and lifetime measurement



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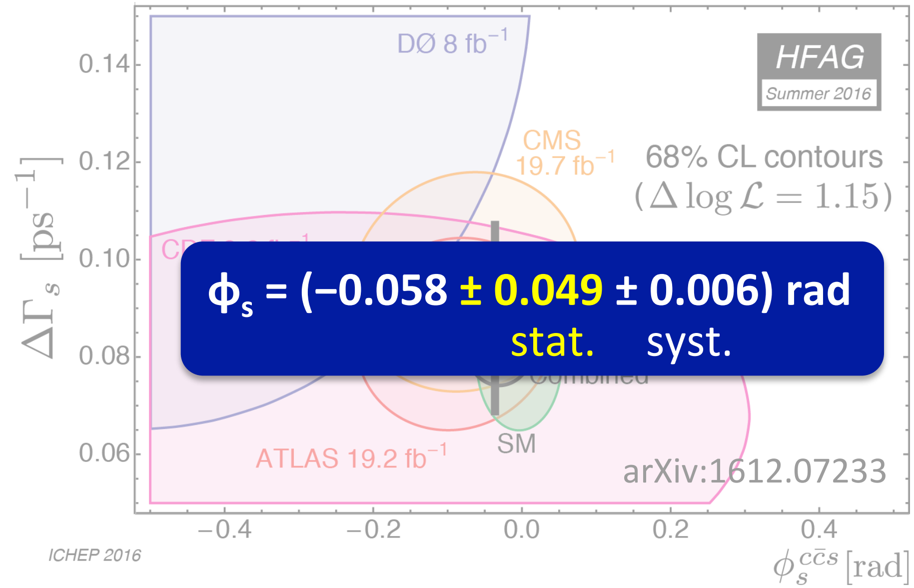
$\tau(B_s^0 \to \mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)$ ps

stat. syst.

Search for CPV in B meson mixing



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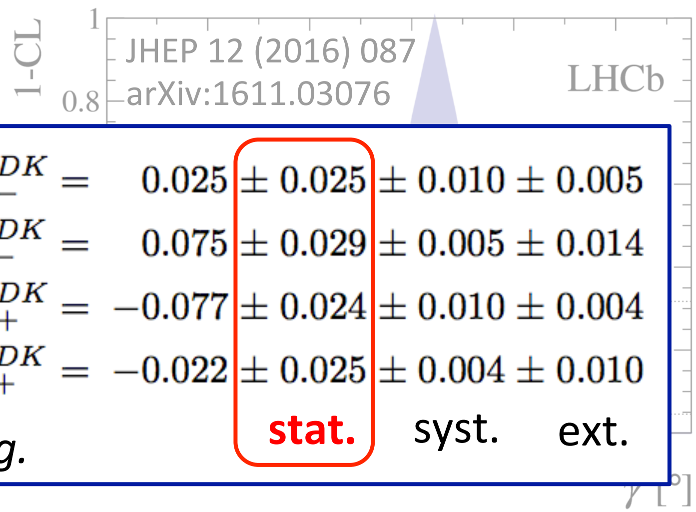
$\phi_s = (-0.058 \pm 0.049 \pm 0.006)$ rad

stat. syst.

Combination of γ measurements



JHEP 12 (2016) 087
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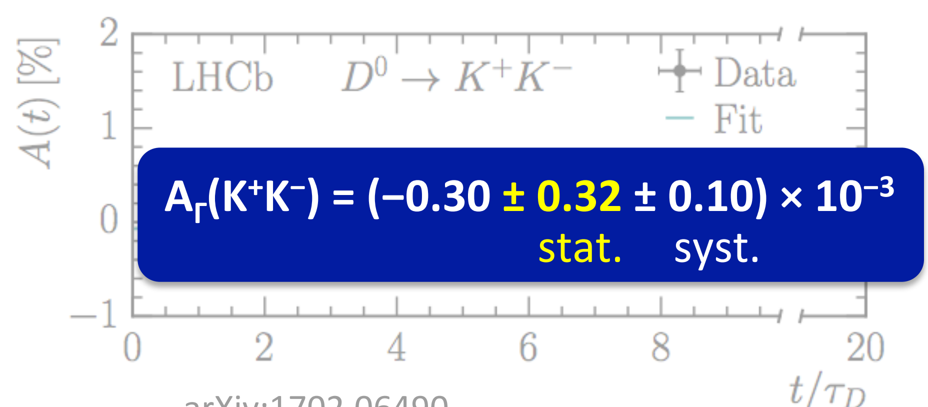
$$x_-^{DK} = 0.025 \pm 0.025 \pm 0.010 \pm 0.005$$
$$y_-^{DK} = 0.075 \pm 0.029 \pm 0.005 \pm 0.014$$
$$x_+^{DK} = -0.077 \pm 0.024 \pm 0.010 \pm 0.004$$
$$y_+^{DK} = -0.022 \pm 0.025 \pm 0.004 \pm 0.010$$

e.g. stat. syst. ext.

High-precision charm CPV measurements

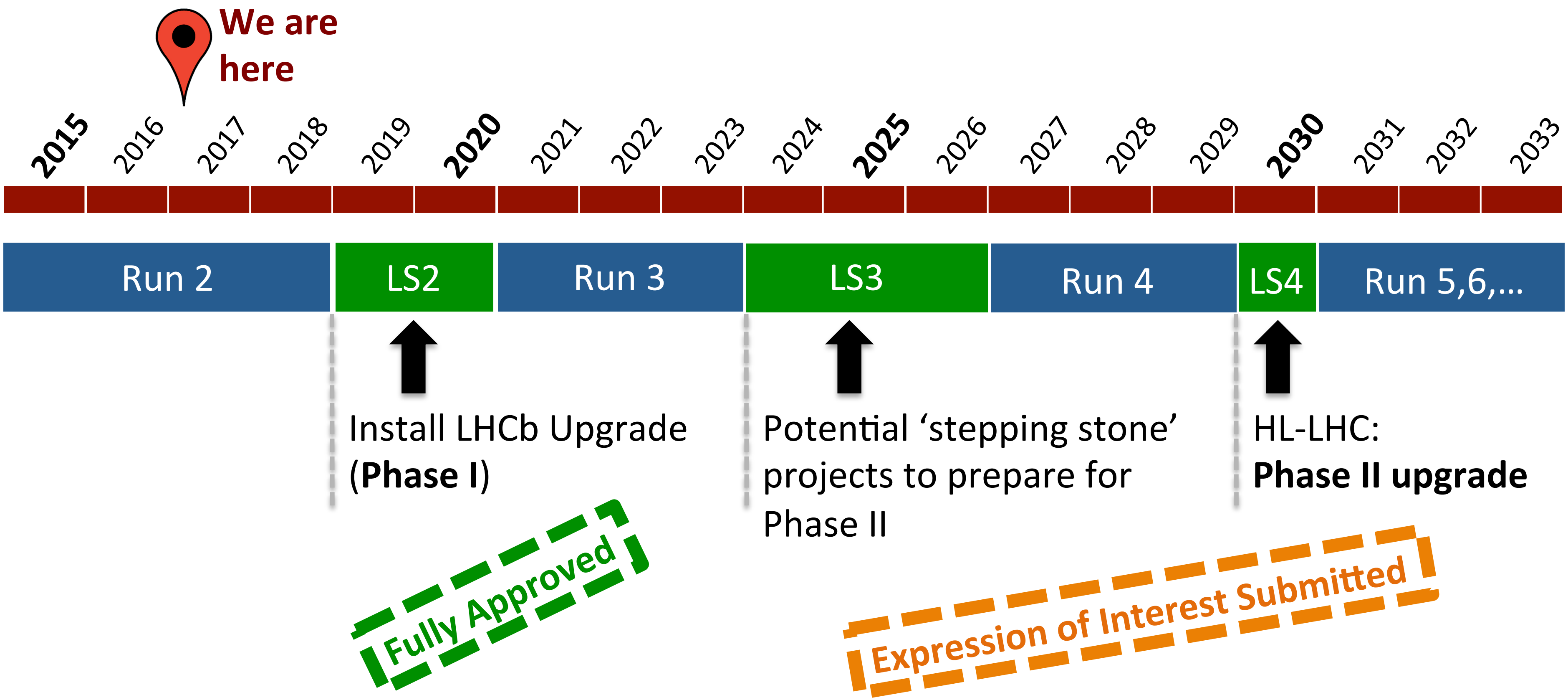


arXiv:1702.06490

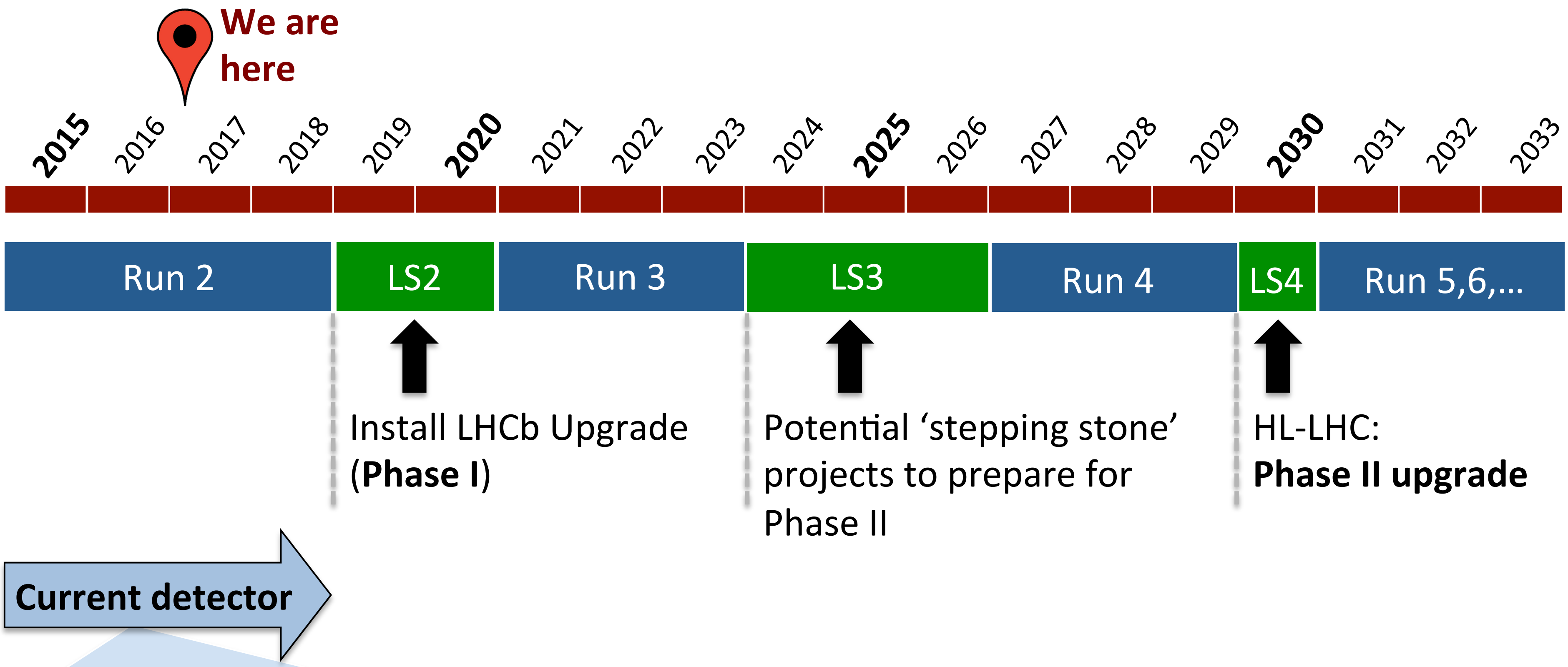
$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$

stat. syst.

LHCb Timeline



LHCb Timeline

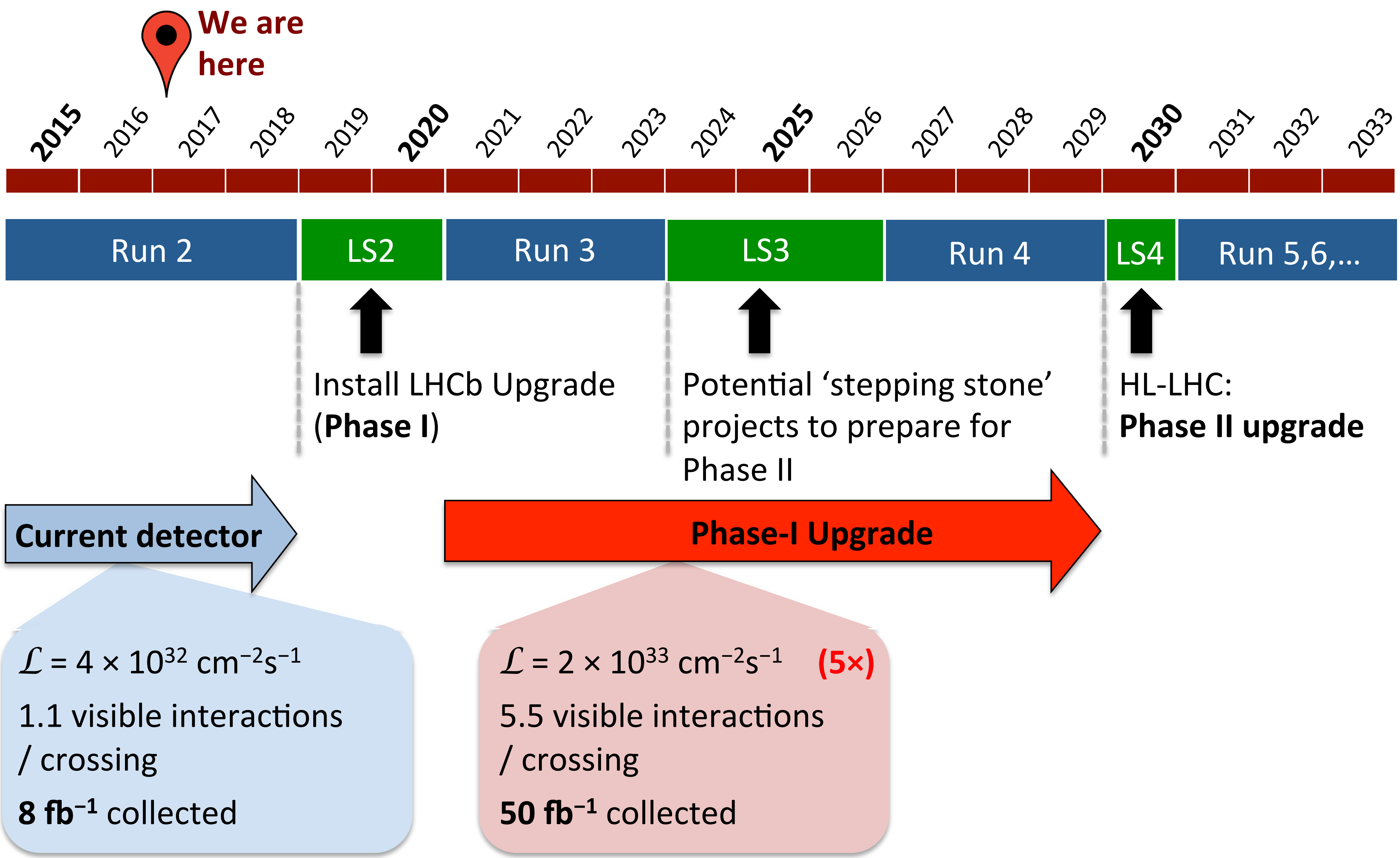


$\mathcal{L} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

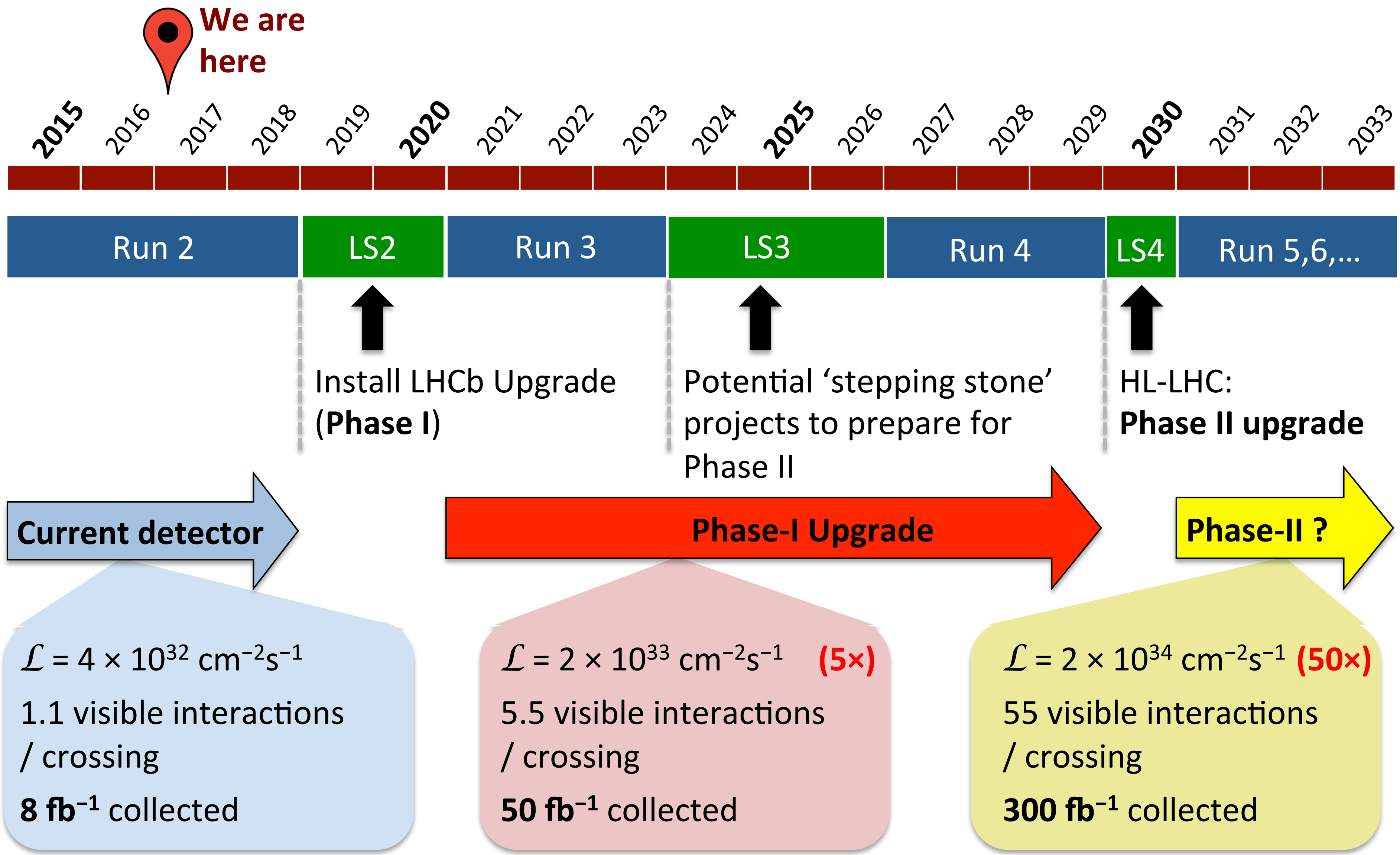
1.1 visible interactions / crossing

8 fb^{-1} collected

LHCb Timeline



LHCb Timeline



Reaching the limits: Phase I Upgrade

Now: beams offset to deliberately reduce luminosity (= cleaner collision environment)

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

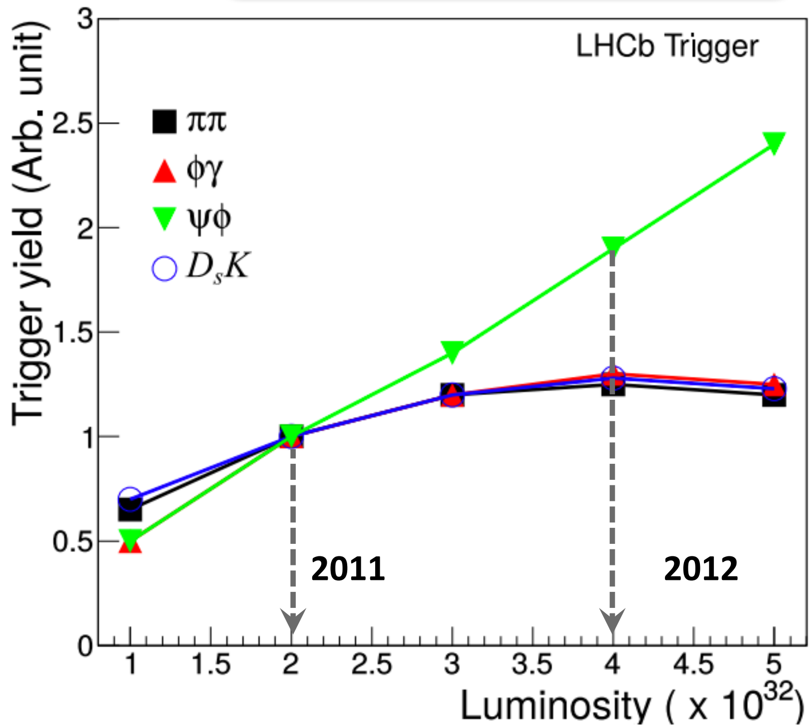
Phase I Upgrade →

Potential LHC luminosity:
$\mathcal{L} = 20 \times 10^{32}\ \mathrm{cm^{-2}s^{-1}}$

Next limit : "Level-0" hardware trigger:

Signal rates for hadronic channels saturate well below maximum luminosity

(already in Run 1)



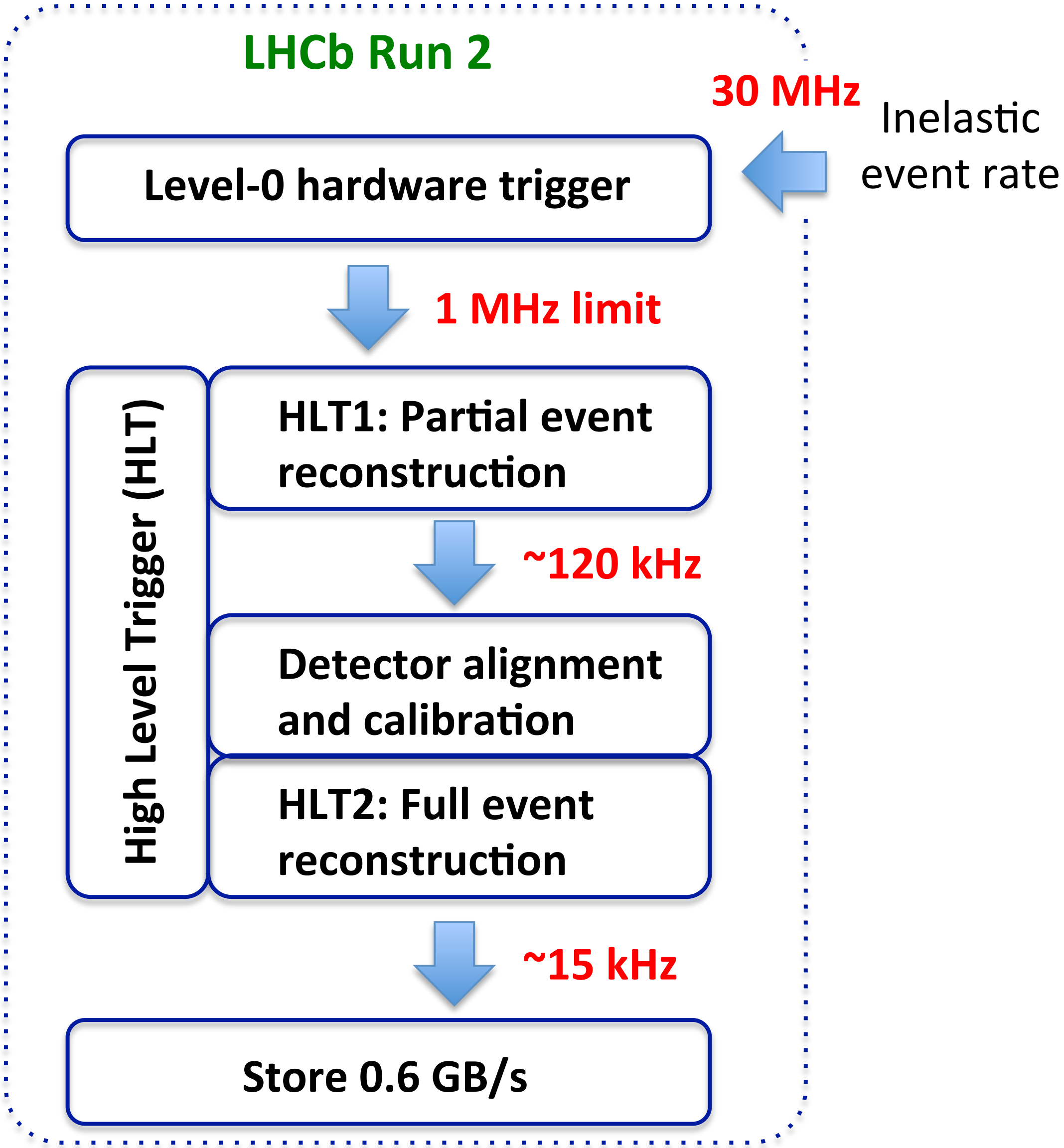
Solution: replace hardware trigger with fully-reconstructed software trigger:

Better handles to select hadronic channels using topology/PID/kinematics

Boost in yields will outstrip luminosity gains for all hadronic final states

Upgrade Trigger

LHCB-TDR-016



Upgrade Trigger

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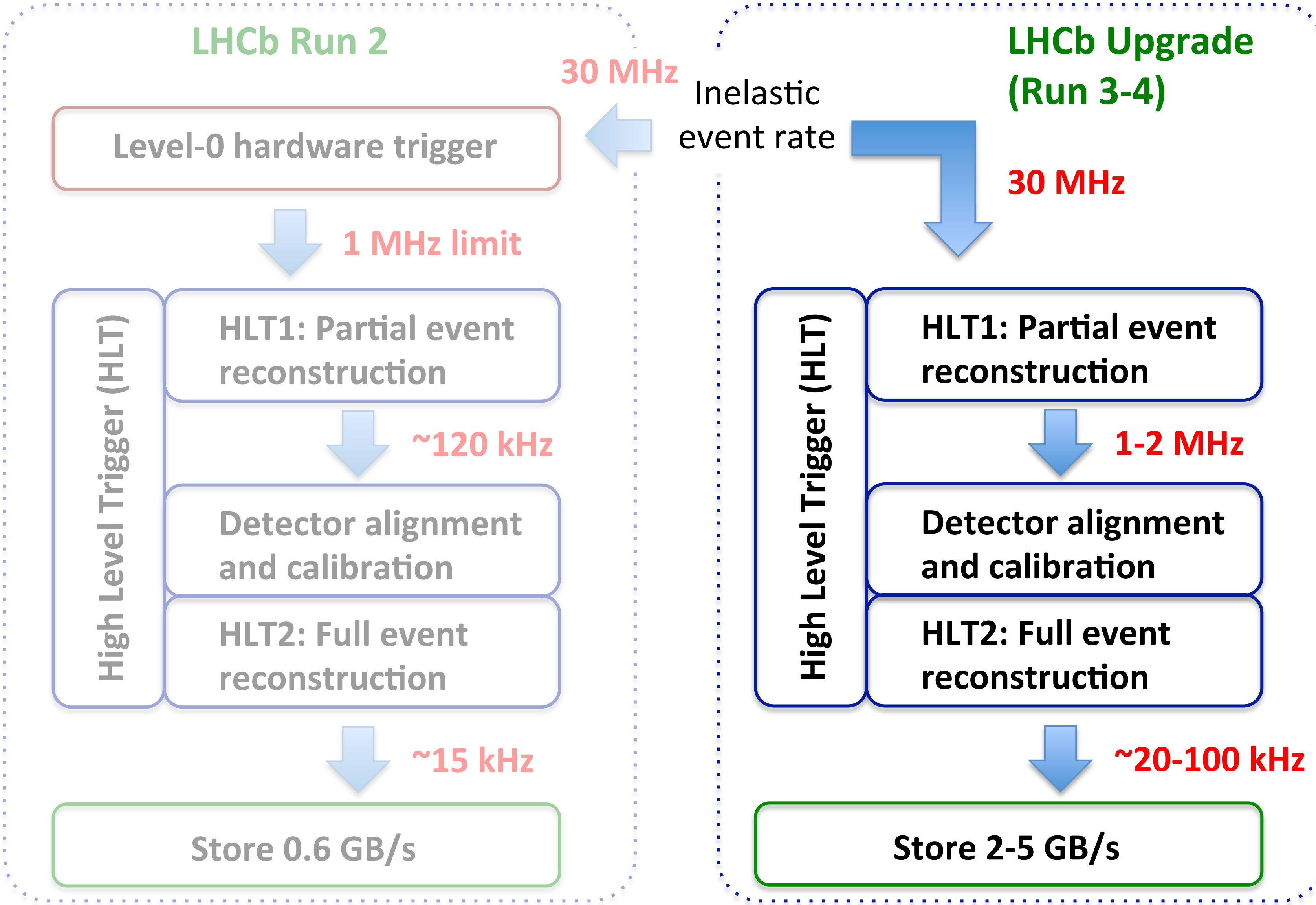
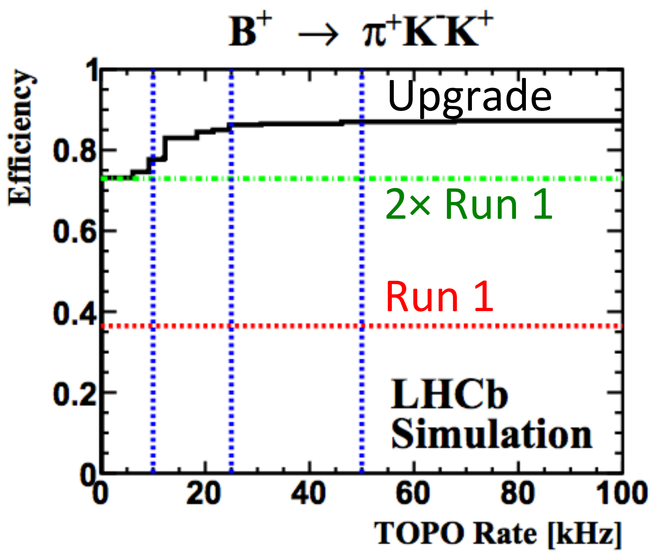


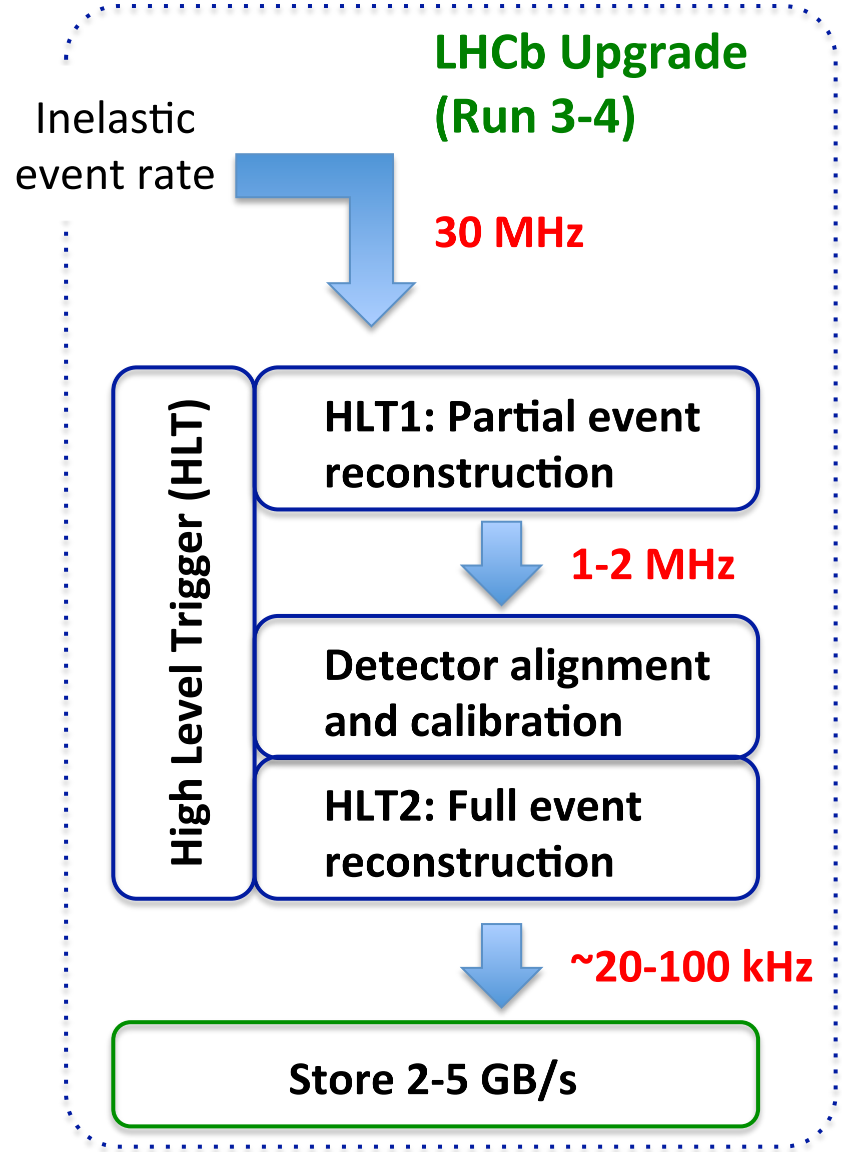
Upgrade Trigger

LHCB-TDR-016

Clear performance gains:

All upgrade rate scenarios (blue vertical lines) give significant efficiency gains compared to Run 1

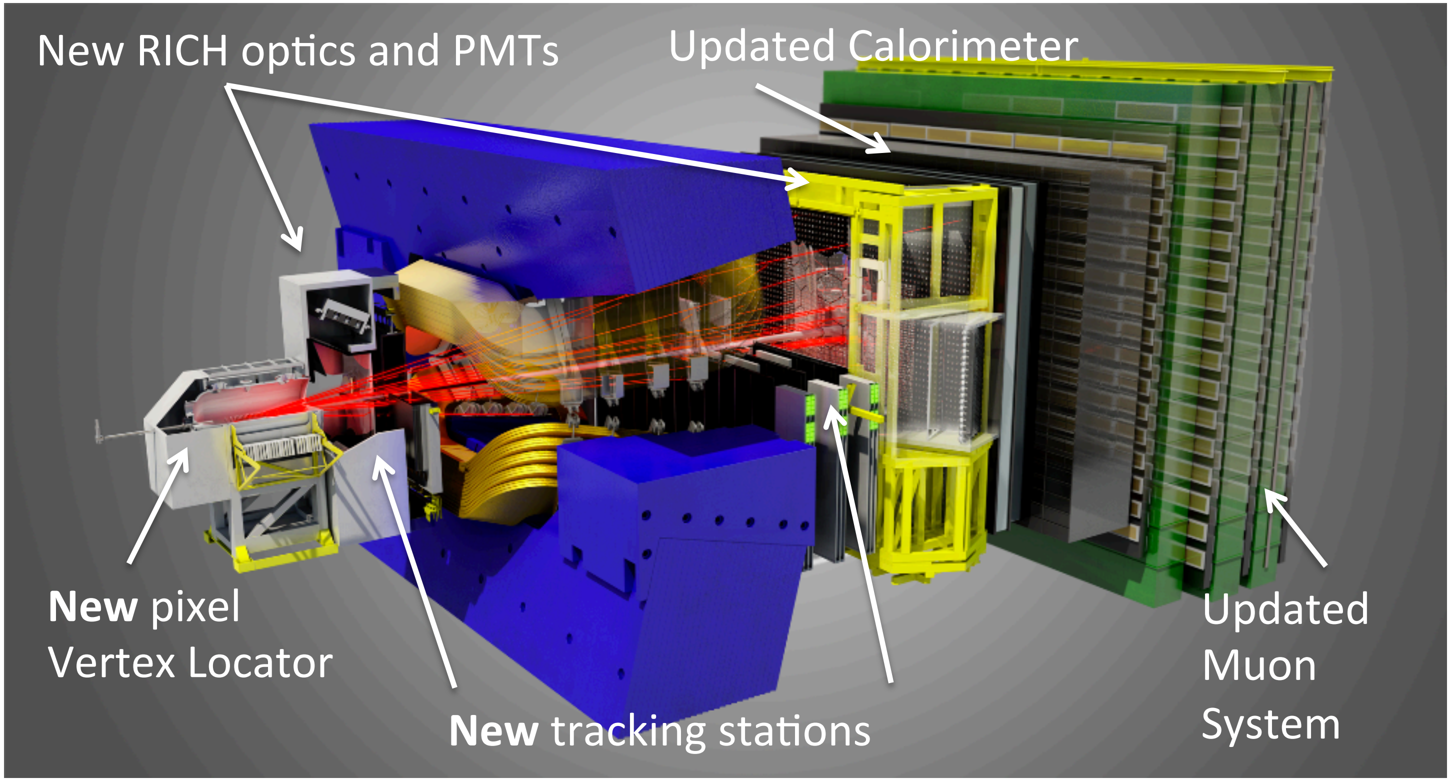




Hardware: themes

Common technology themes:

Full software trigger	⇒	Read-out all detector sub-systems at 40 MHz
Increased particle multiplicity	⇒	Finer granularity detectors
		Improved radiation hardness



VErtex LOcator (VELO) Upgrade

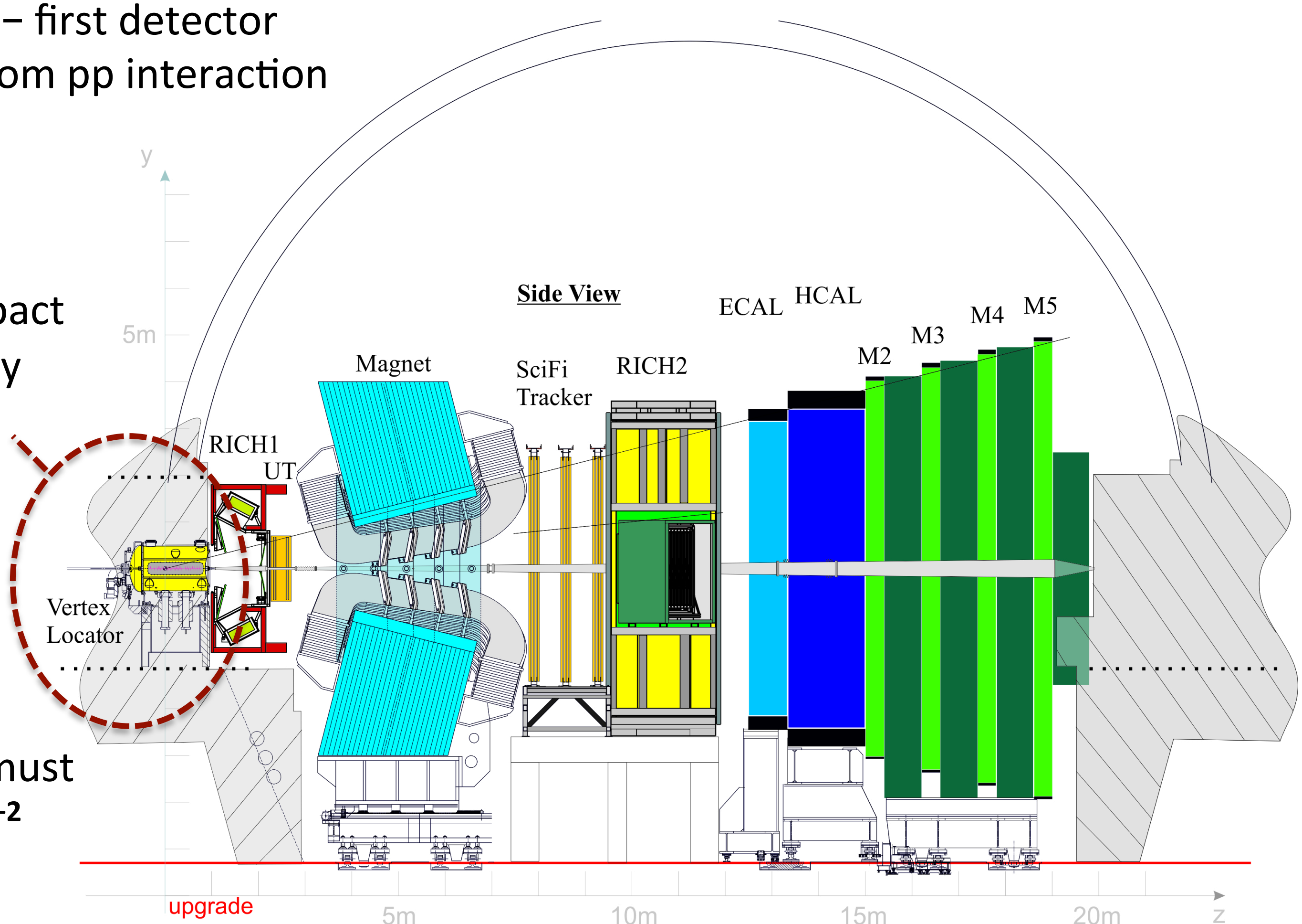
LHCB-TDR-013

Surrounds beam region – first detector traversed by particles from pp interaction

Requirements:

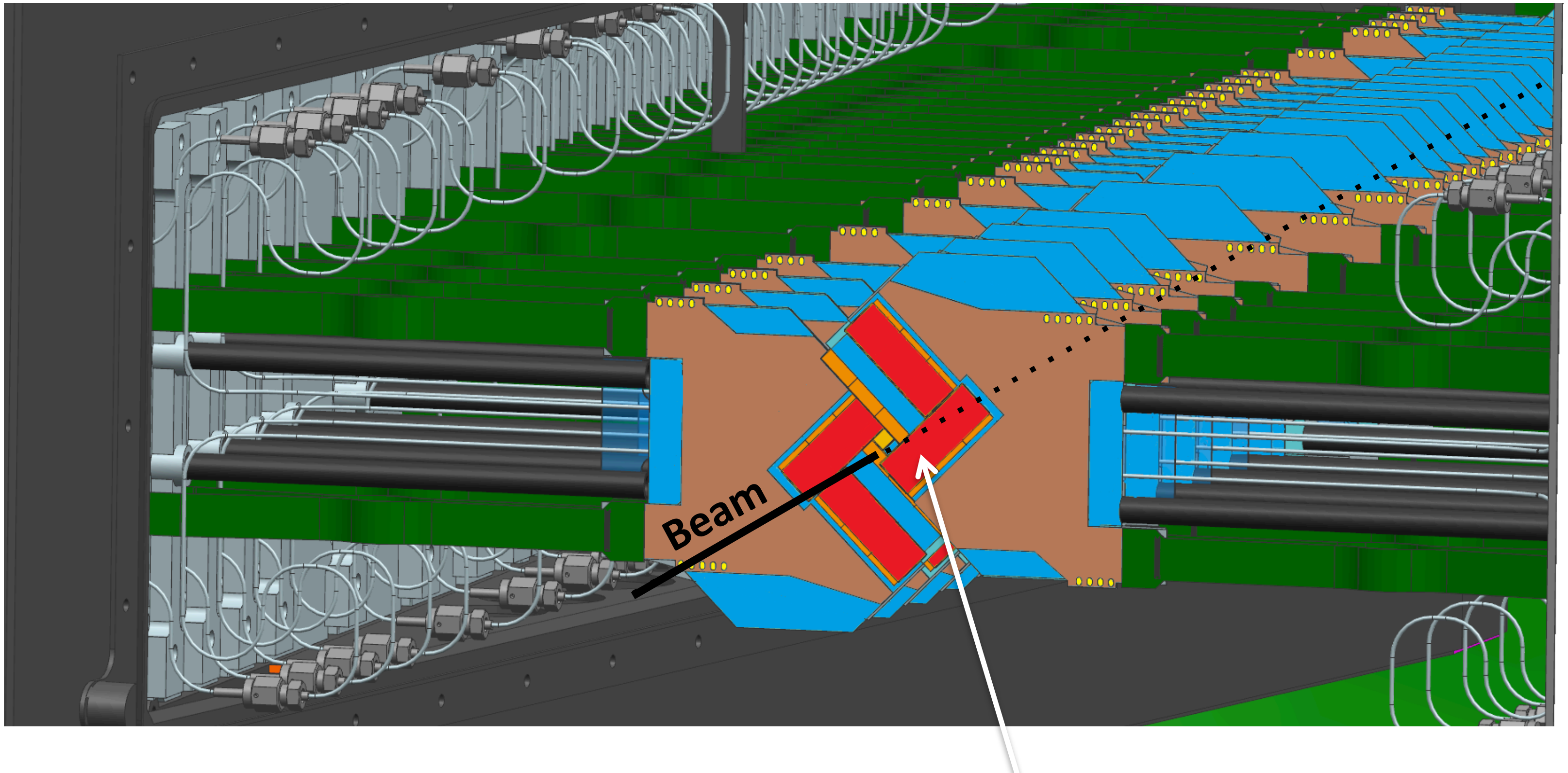
- Measure particle impact parameter (IP) to very high precision
- High track-finding efficiency

In upgrade conditions, must tolerate **8×10^{15} n_{eq} cm^{-2}** over lifetime
(10× current VELO)
Highly non-uniform dose



VELO Upgrade

LHCB-TDR-013



52 modules in total (26 per half), perpendicular to beam

Separated from beam vacuum by thin (0.25mm) aluminium foil

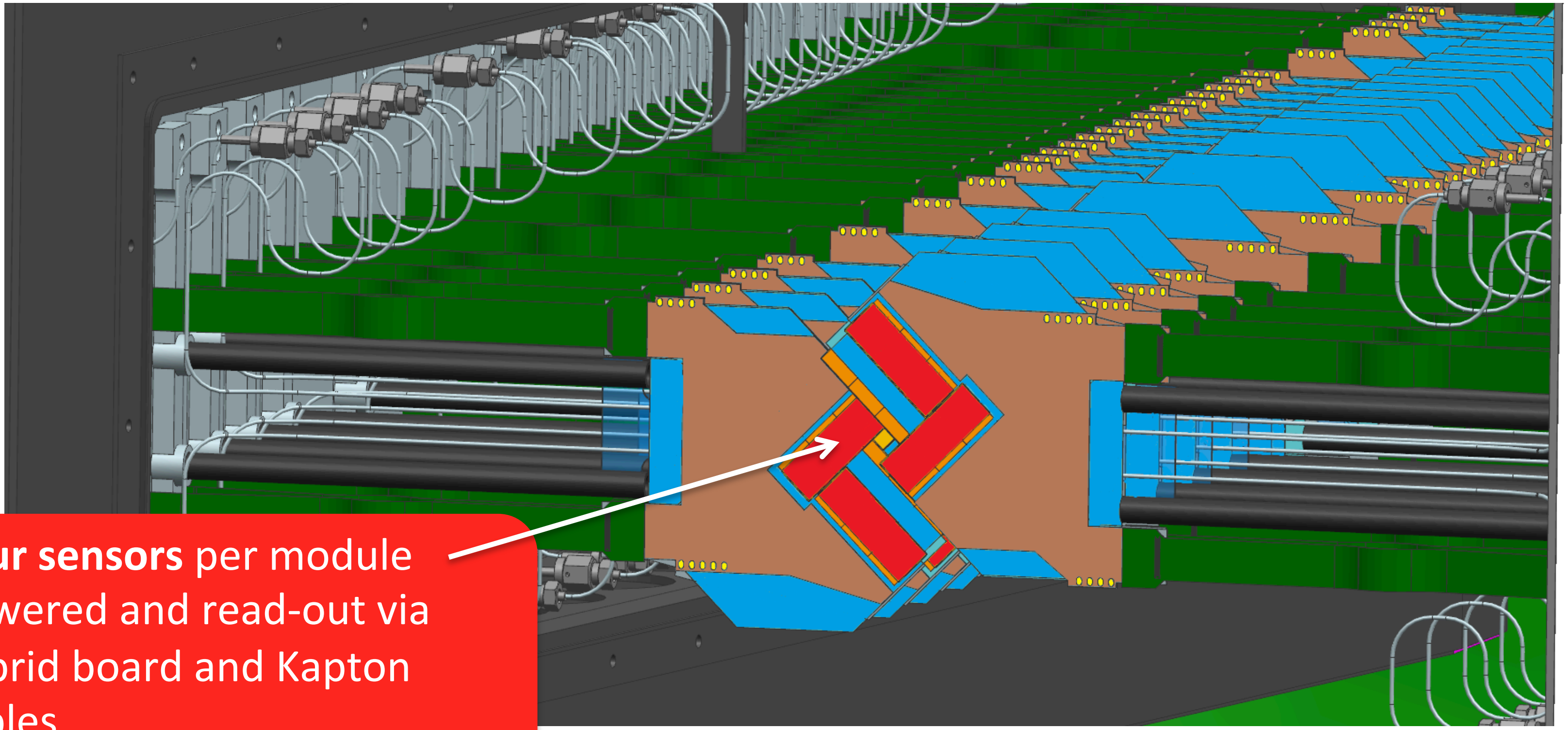
Retractable for safe operations outside of stable beam conditions

Closer!

Active area just **5.1mm** from beams (now 8.2mm)

VELO Upgrade: Sensors

LHCB-TDR-013



Four sensors per module powered and read-out via hybrid board and Kapton cables

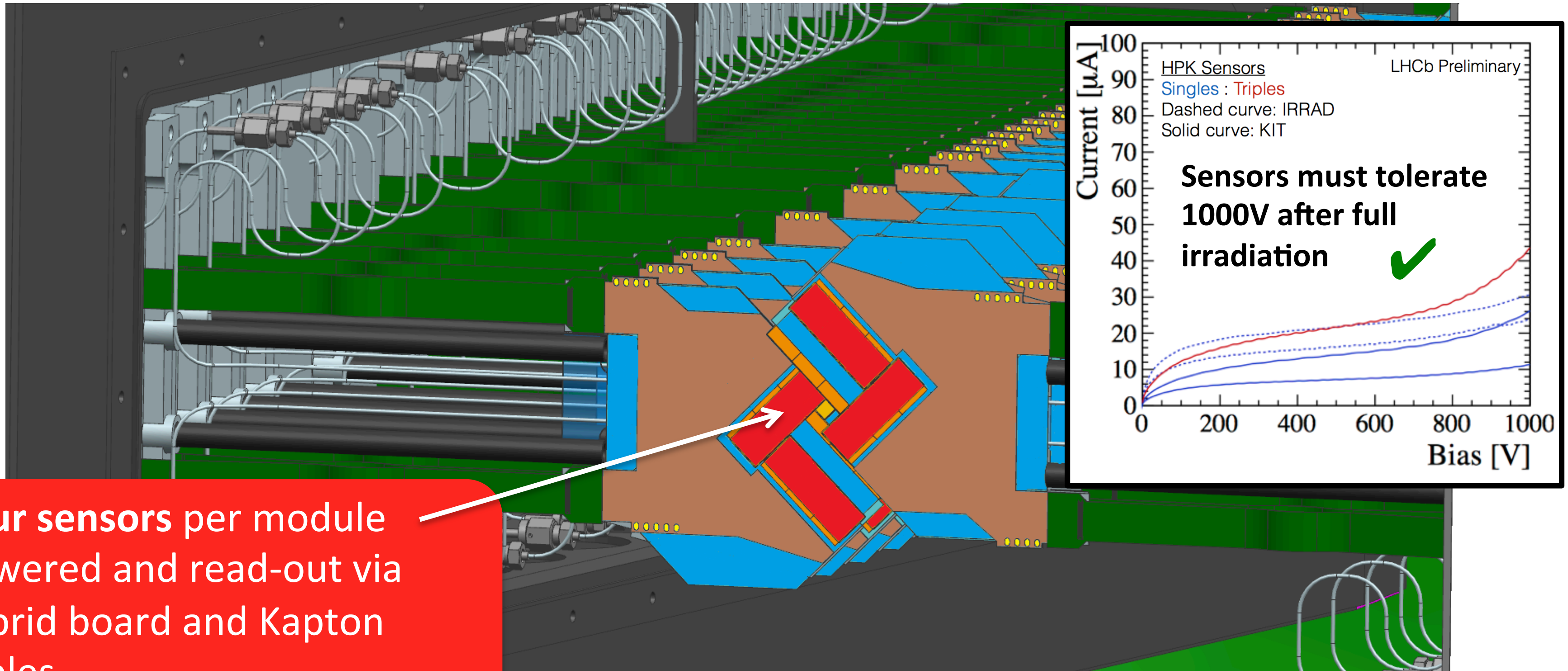
Extensive sensor evaluation program using test beam, source, and lab data

- **55µm pixel size** (current velo: strips)

Finer granularity!

VELO Upgrade: Sensors

LHCB-TDR-013



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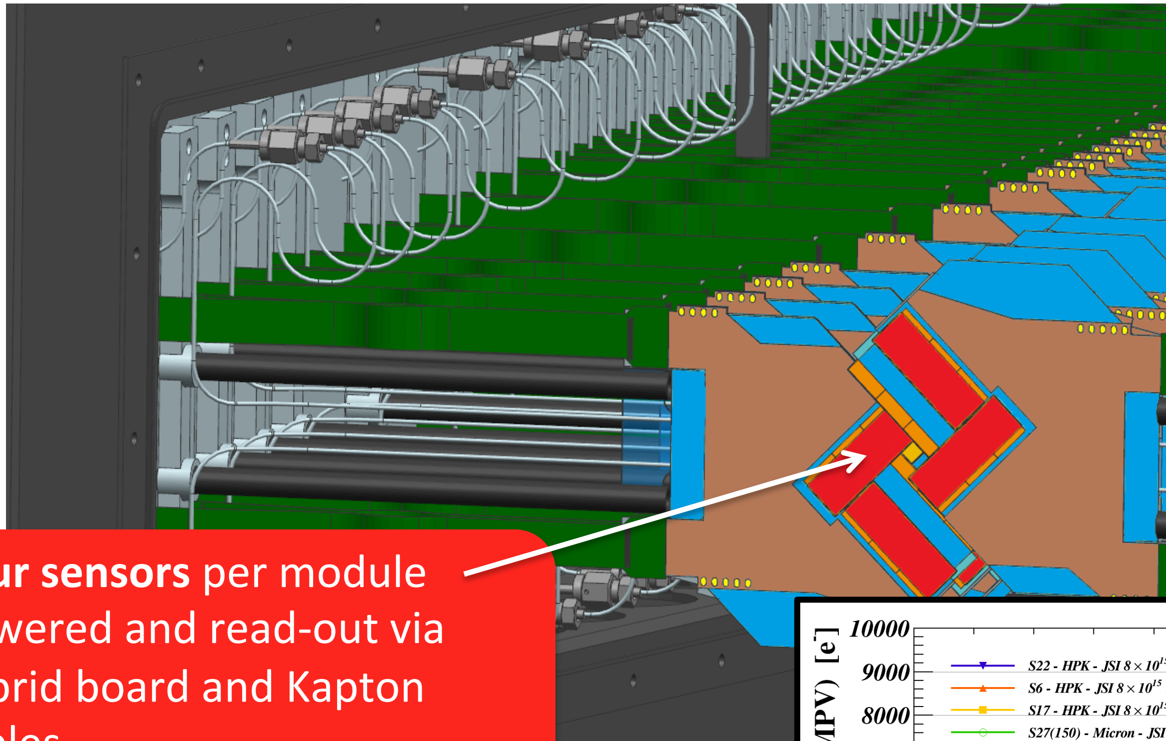

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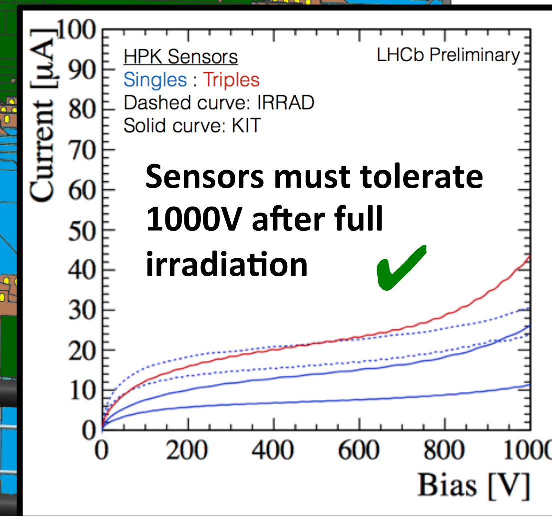

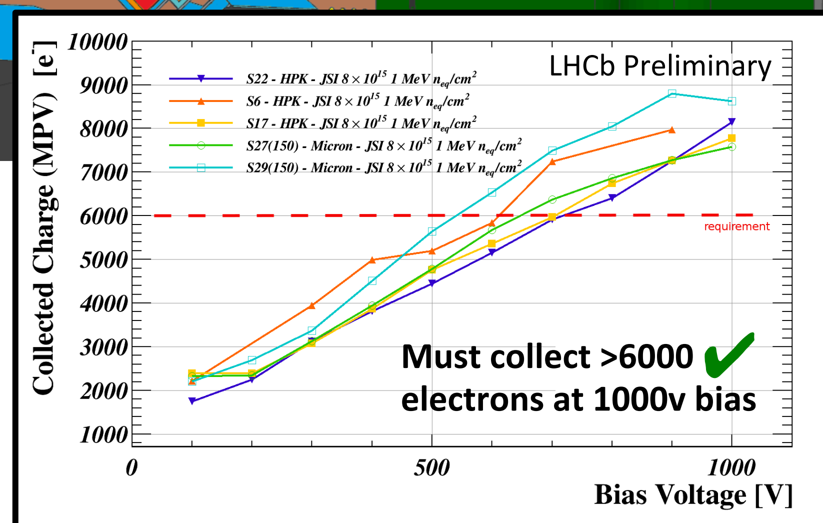

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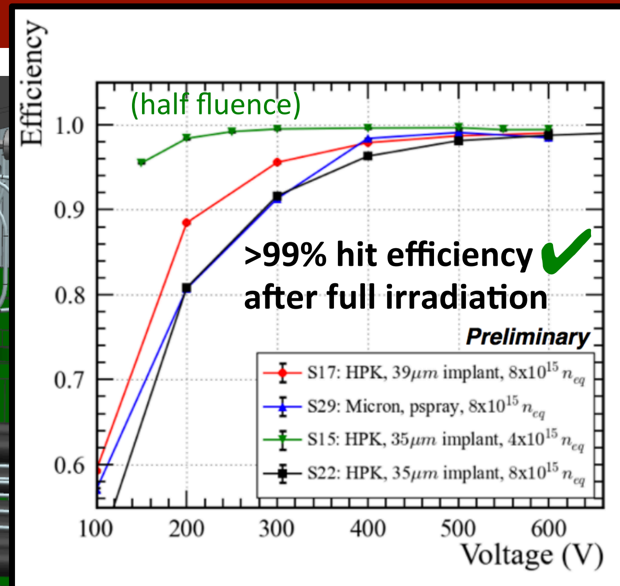

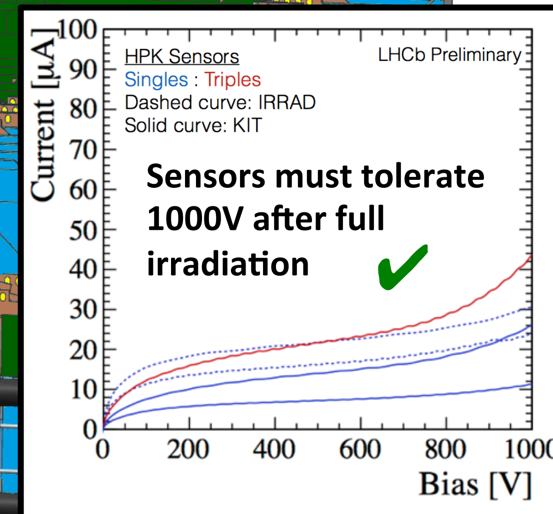

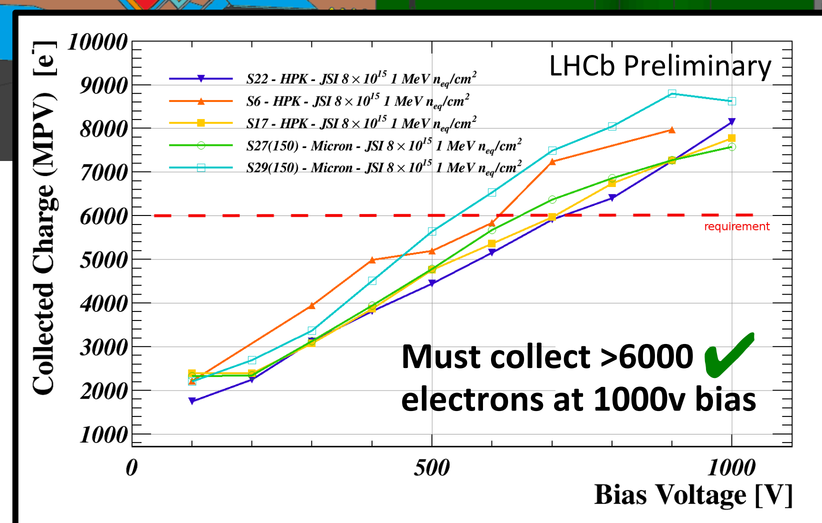

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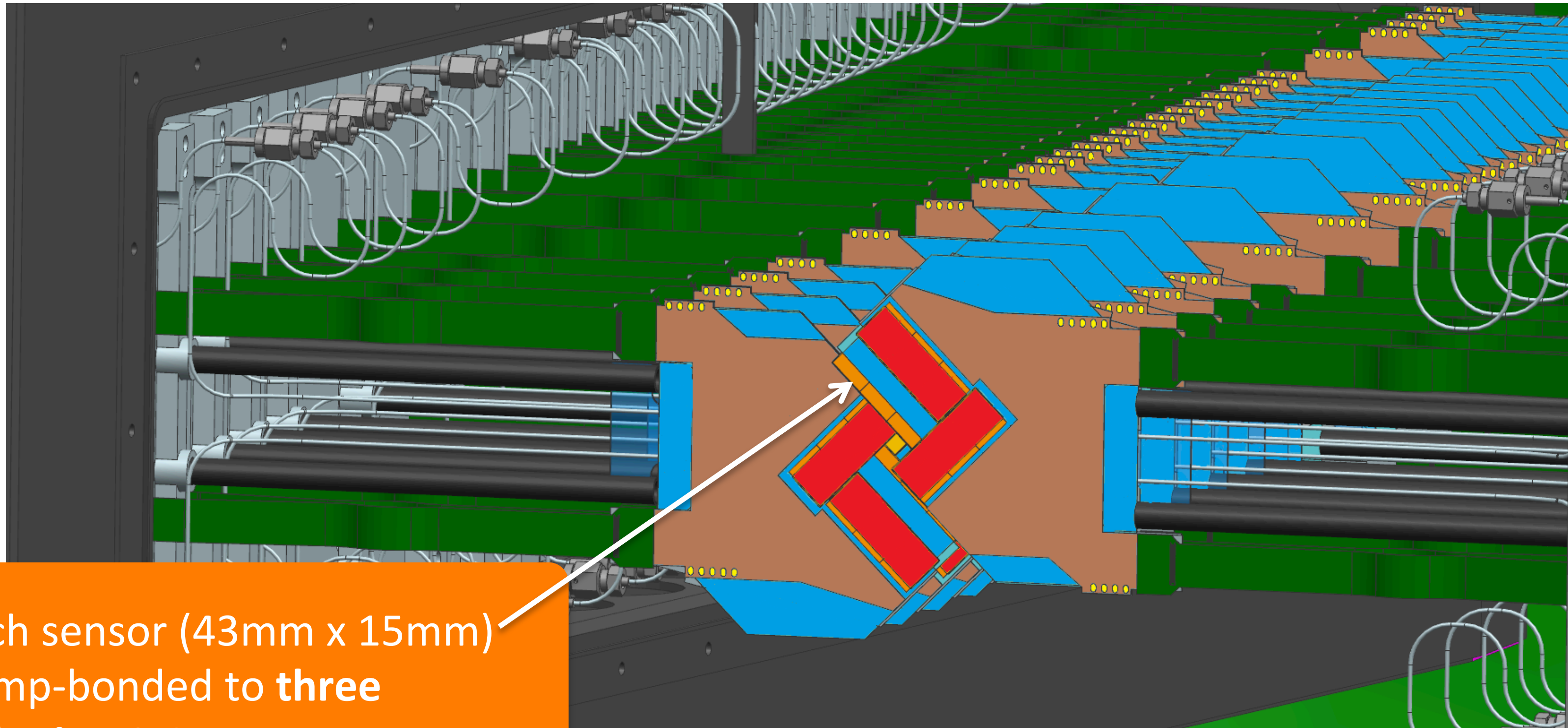
VELO Upgrade: VeloPix ASIC

LHCB-TDR-013



Each sensor (43mm x 15mm) bump-bonded to **three VeloPix ASICs**

VeloPix ASIC	VeloPix ASIC	VeloPix ASIC

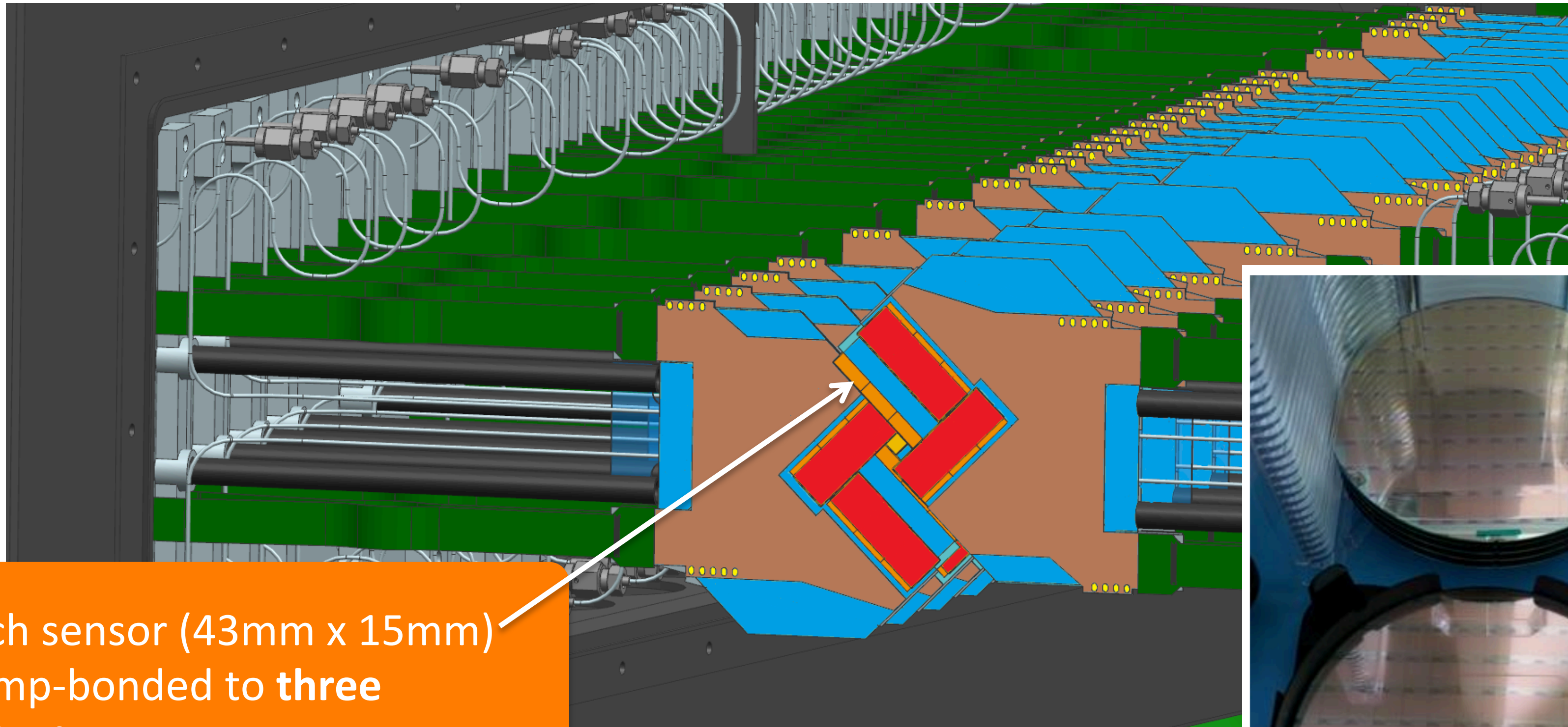
Timepix family. Highlights:

- High data rate (800 Mhits/s)
- Power-efficient (~1.5 W/ASIC)

Faster!

VELO Upgrade: VeloPix ASIC

LHCB-TDR-013



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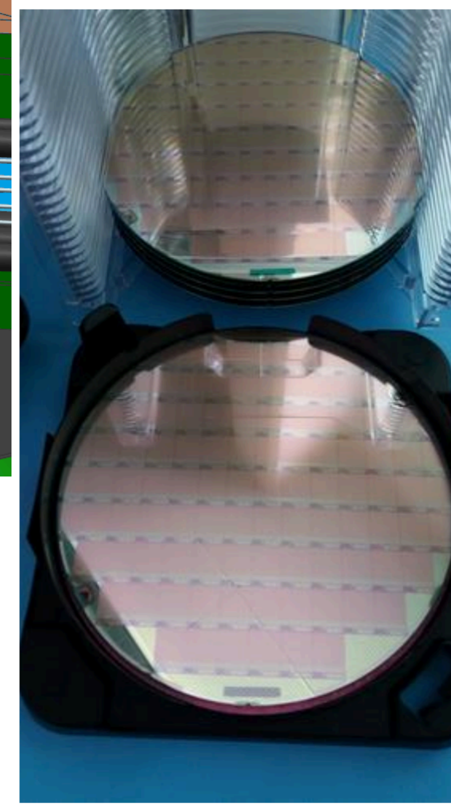
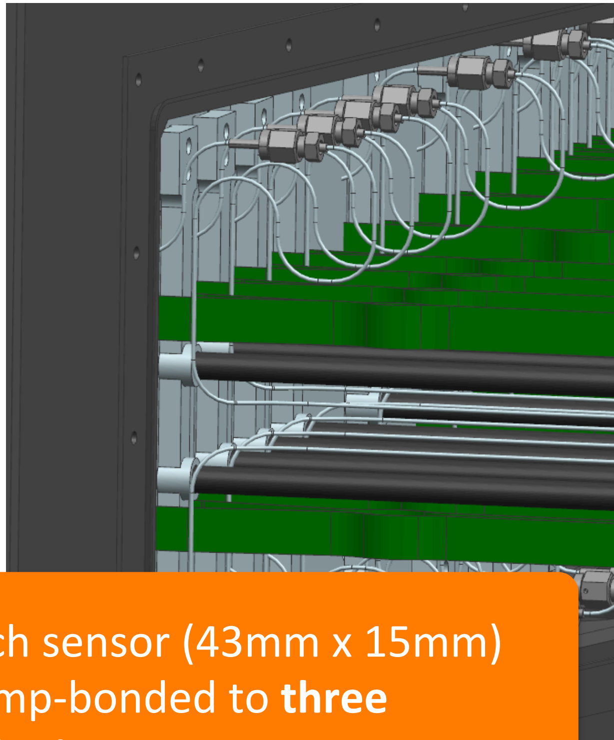
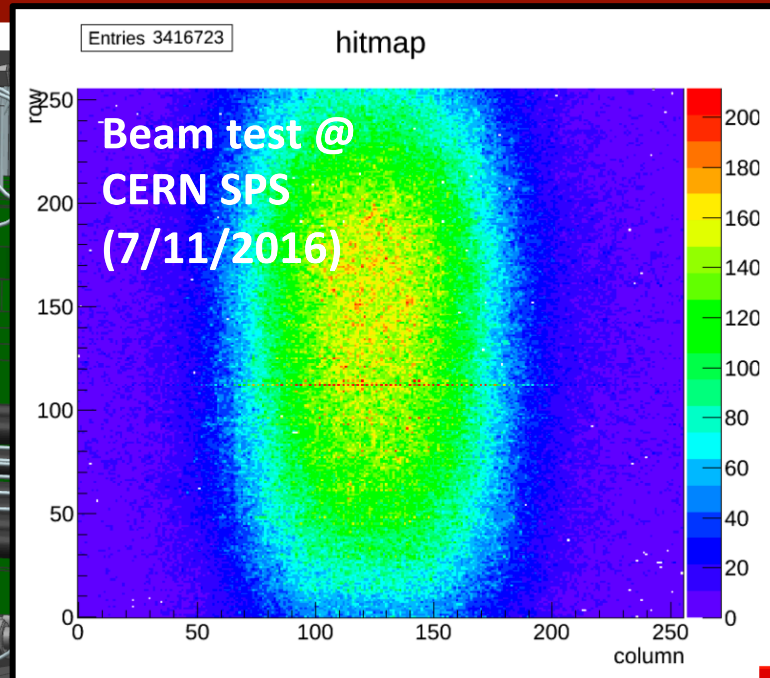
First wafers received **31/8/2016**
Intense testing programme – all results look good

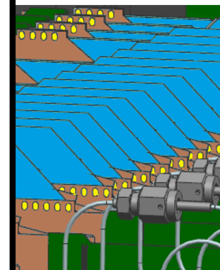


VELO Upgrade: VeloPix ASIC

LHCB-TDR-013







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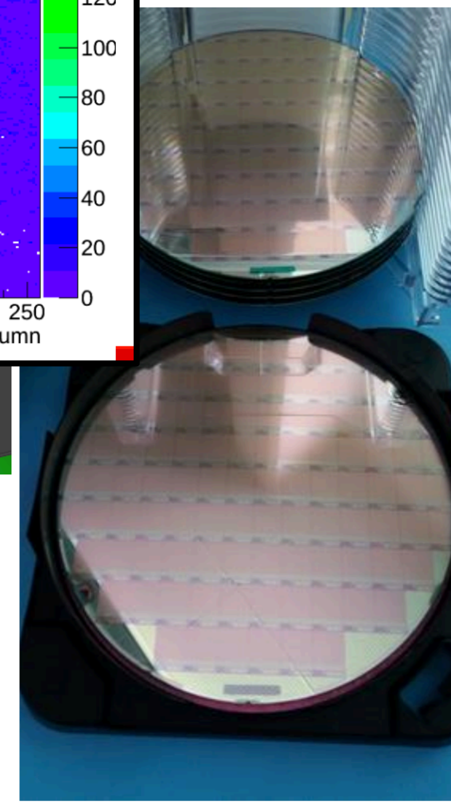
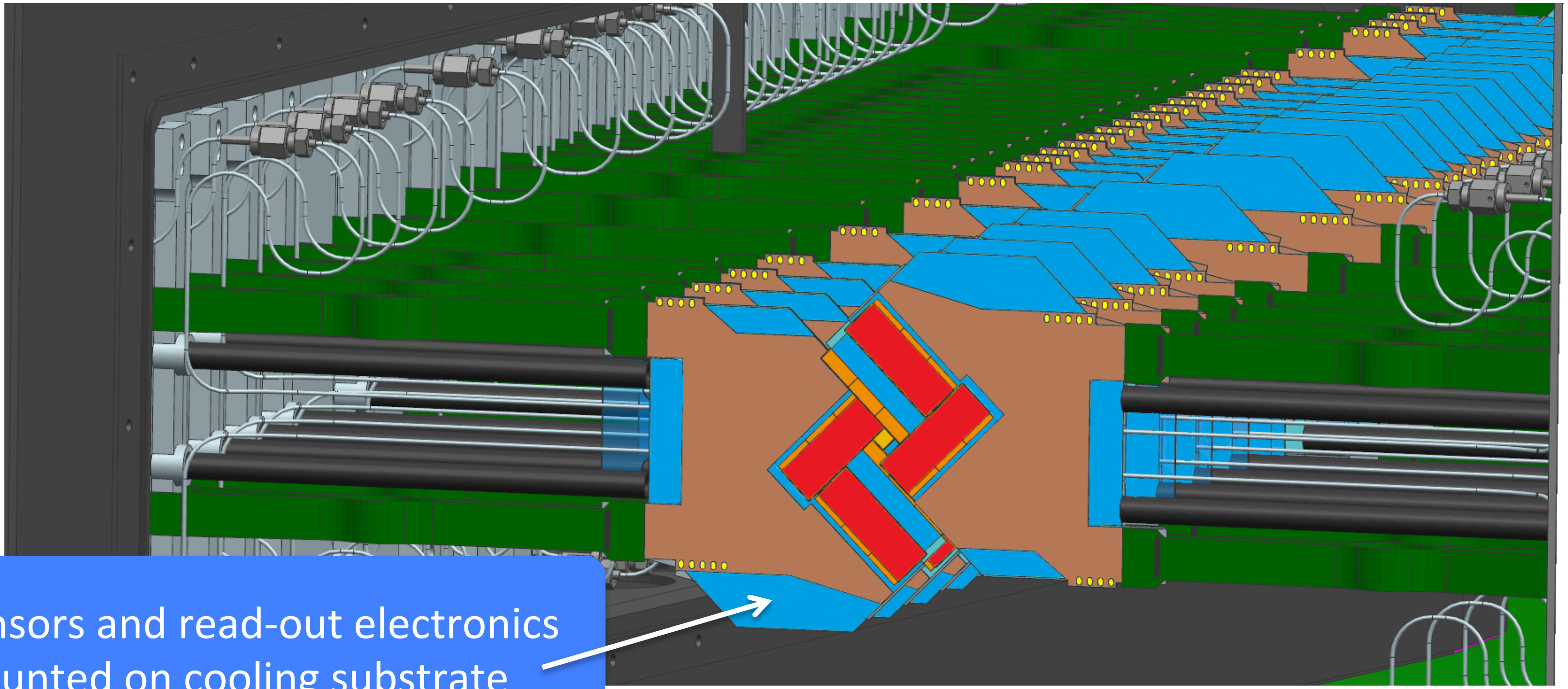
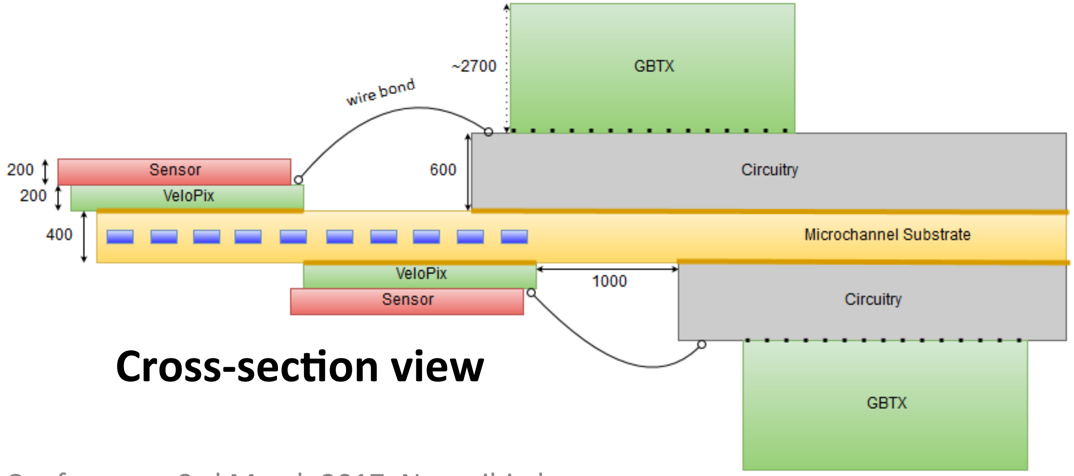


VELO Upgrade: Cooling

LHCB-TDR-013



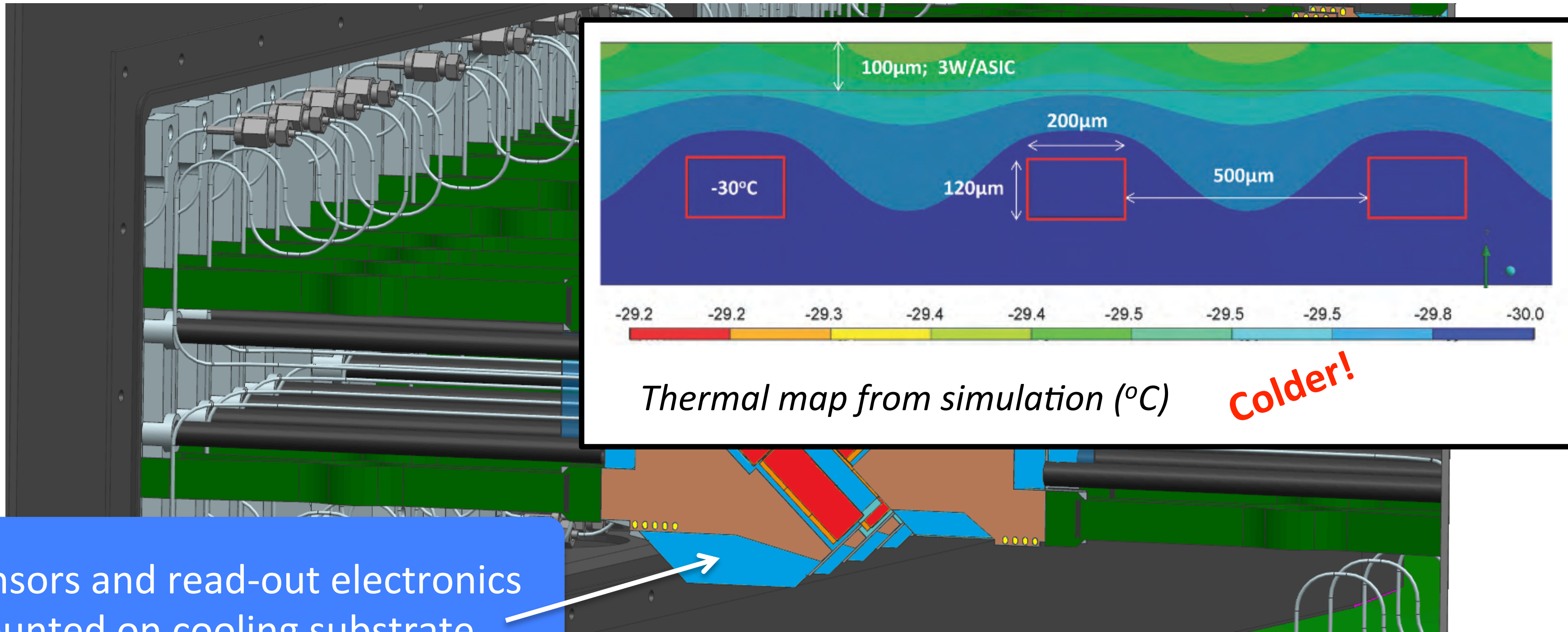
Sensors and read-out electronics mounted on cooling substrate etched with CO_2 micro-channels



Cross-section view

VELO Upgrade: Cooling

LHCB-TDR-013

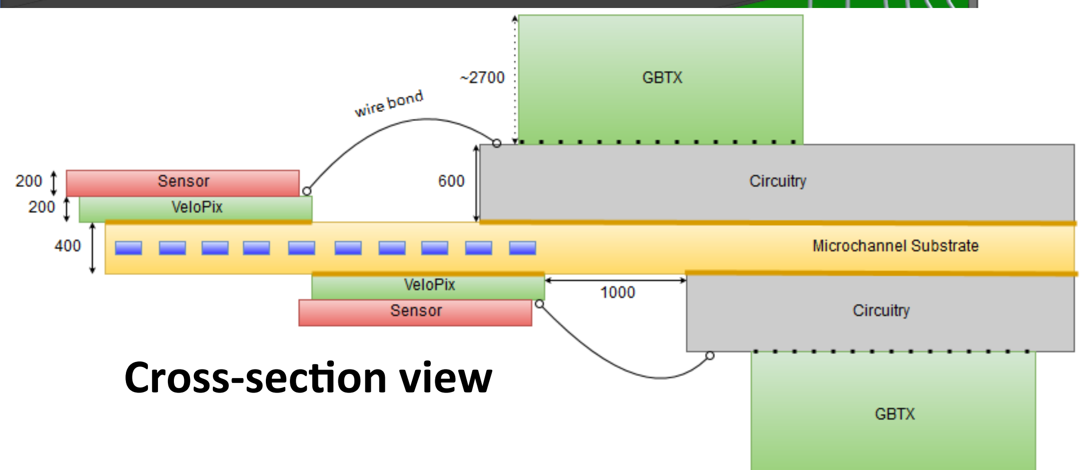


Thermal map from simulation (°C) **Colder!**

Sensors and read-out electronics mounted on cooling substrate etched with CO_2 micro-channels

Minimum material, excellent cooling performance

Now in full production – will see first wafers in April



Cross-section view

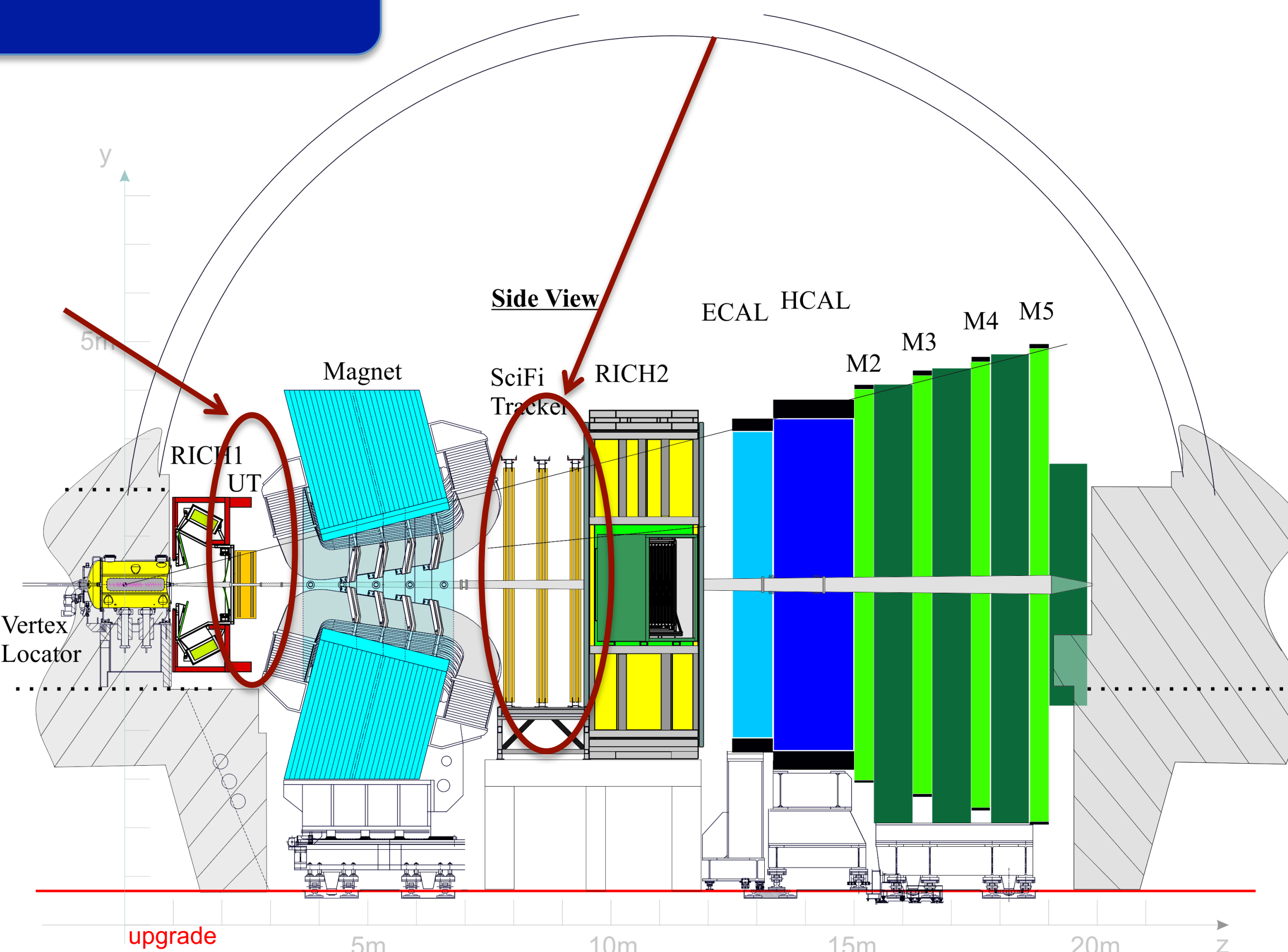
Tracking System Upgrades: UT and SciFi

LHCB-TDR-015

Current trackers (silicon strips + straw tubes) will be entirely replaced

Scintillating Fibre Tracker (SciFi): 3x4 detection planes after magnet

Upstream Tracker (UT): 4 planes of silicon strip detectors before magnet

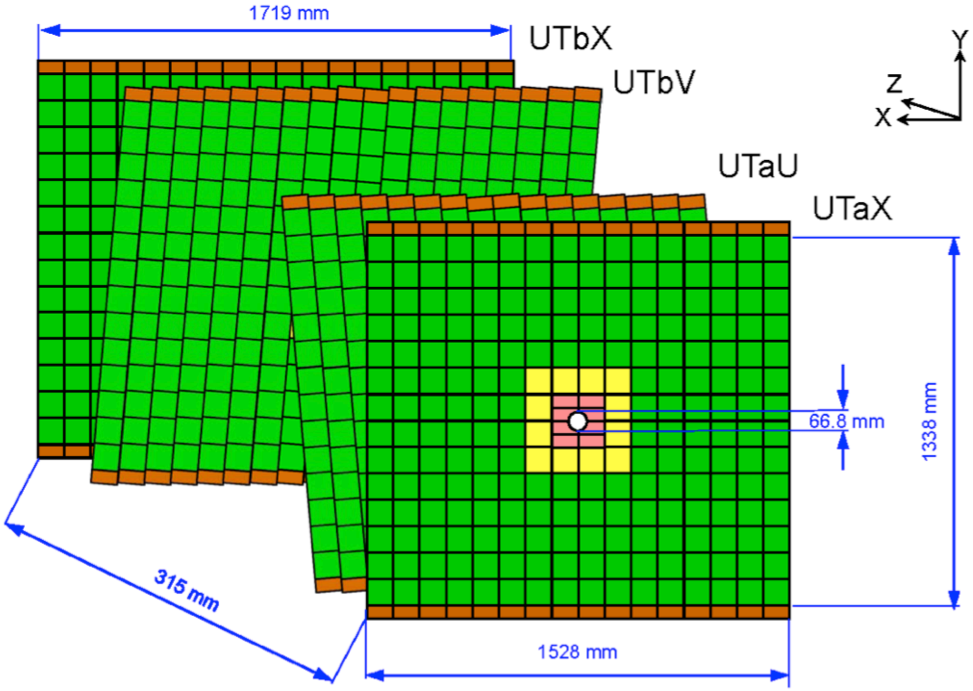


Requirements:

- High precision momentum measurement
- Match VELO tracks to downstream detectors
- Reconstruct particles decaying outside VELO (K_S^0, Λ^0)

Upstream Tracker

LHCB-TDR-015



4 detection planes, each built from lightweight staves — **Less material**

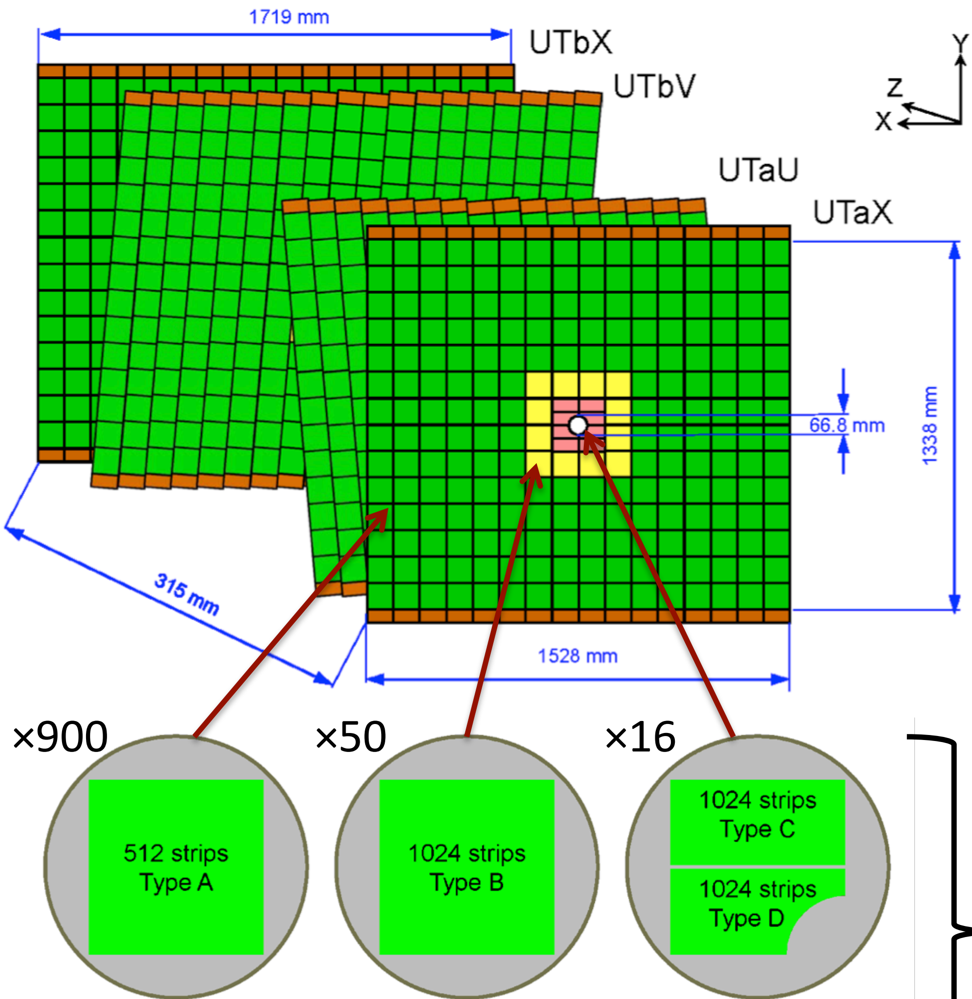
Sensors mounted on both front and back of staves — **No gaps**

95-190μm pitch — **Finer segmentation**

Closer to beam pipe — **Better coverage**

Upstream Tracker

LHCB-TDR-015



320 µm thick, p-in-n,
190 µm pitch

250 µm thick, n-in-p,
80 µm pitch

4 detection planes, each built from lightweight staves — *Less material*

Sensors mounted on both front and back of staves — *No gaps*

95-190µm pitch — *Finer segmentation*

Closer to beam pipe — *Better coverage*

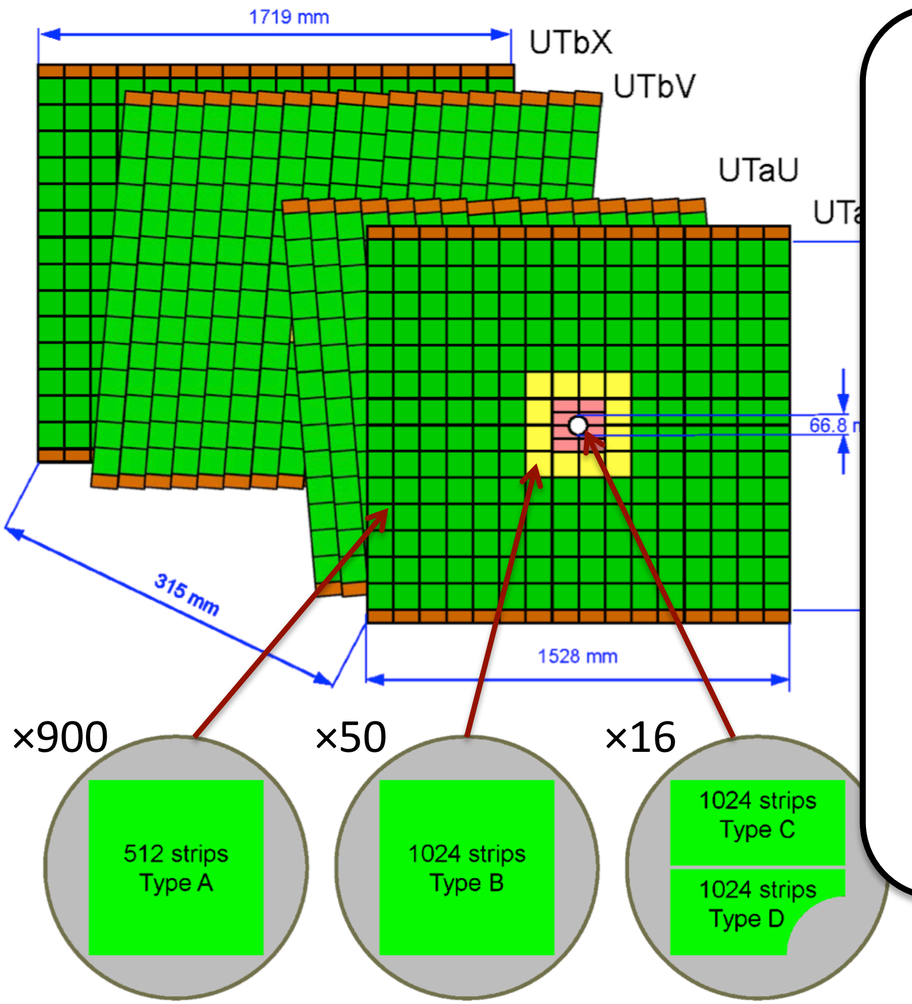
Sensors in 4 designs:

- Embedded pitch adapters (to ASICS @ 73µm pitch)
- Cut-outs in beam-pipe region

More radiation hard

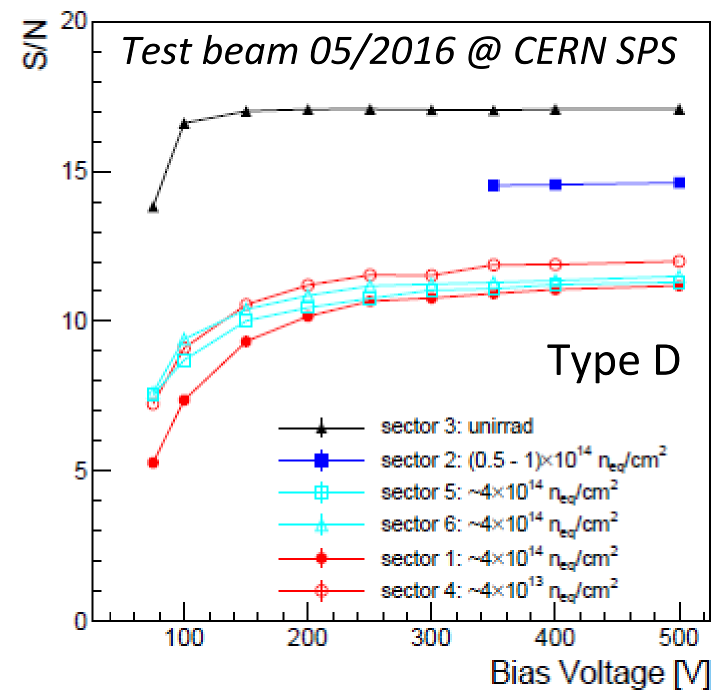
Upstream Tracker

LHCB-TDR-015



320 µm thick, p-in-n, 190 µm pitch

250 µm thick, n-in-p, 80 µm pitch



Signal/noise 16 before irradiation, 11 after full irradiation

material

No gaps

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e radiation hard

Sensors in 4 designs:

- Embedded pitch adapters (to ASICS @ 73µm pitch)
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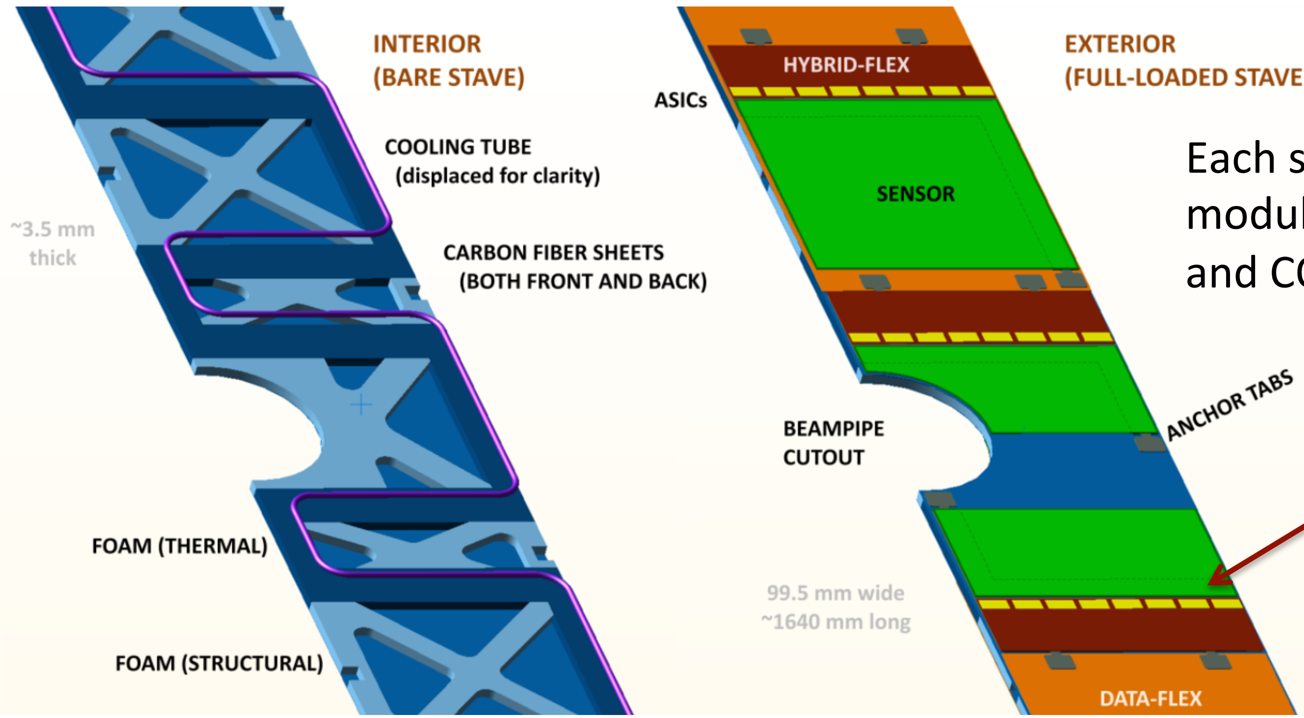
Upstream Tracker

LHCB-TDR-015

Stave design well advanced − now transitioning to construction phase



Each stave supports 14-16 hybrid modules, data-flex connectors, and CO_2 cooling tube

Dedicated SALT128 chips being developed: "**S**ilicon **A**SIC for **L**HCb **T**racking"

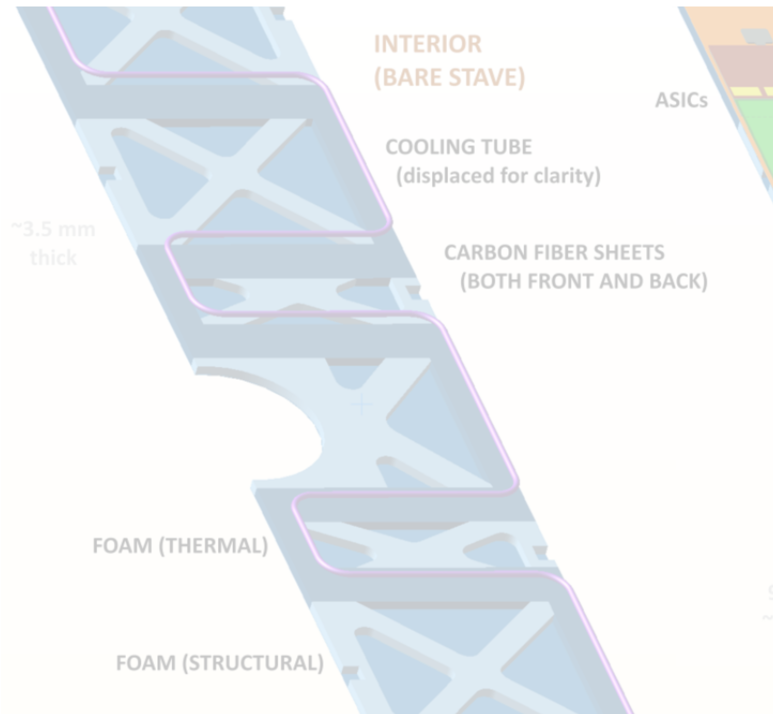
Tests ongoing, engineering run is imminent.

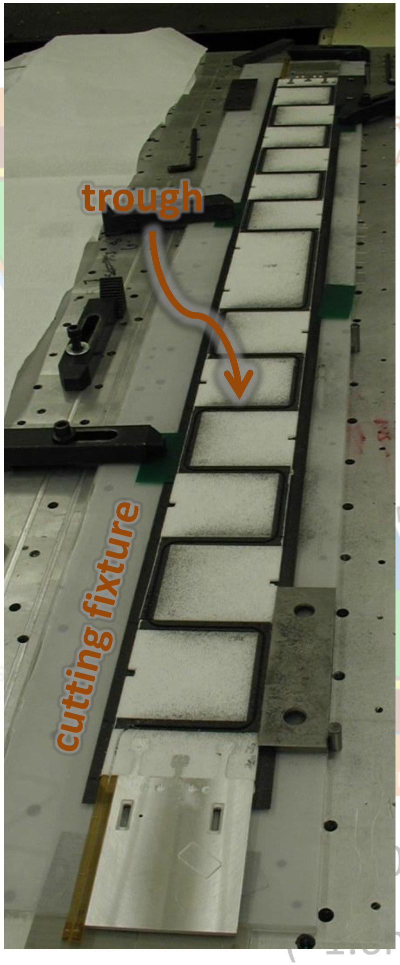
⇤ ~10cm ⇥

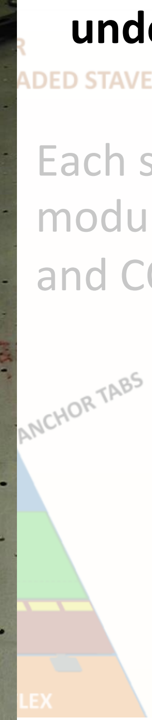
(~1.6m long)

Upstream Tracker

Stave design well advanced – now transitioning to construction phase







cm →

m long)

Bare stave prototype under construction

Each stave supports 14-16 hybrid modules, data-flex connectors, and CO_2 cooling tube

Dedicated SALT128 chips being developed: "**S**ilicon **A**SIC for **L**HCb **T**racking"

Tests ongoing, engineering run is imminent.

Scintillating Fibre Tracker (SciFi)

LHCB-TDR-015

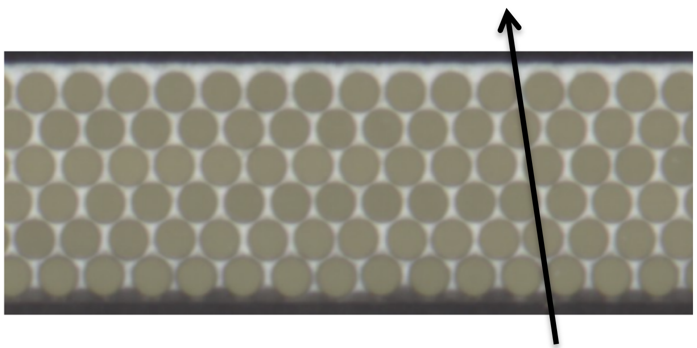
LHCb-PUB-2015-025

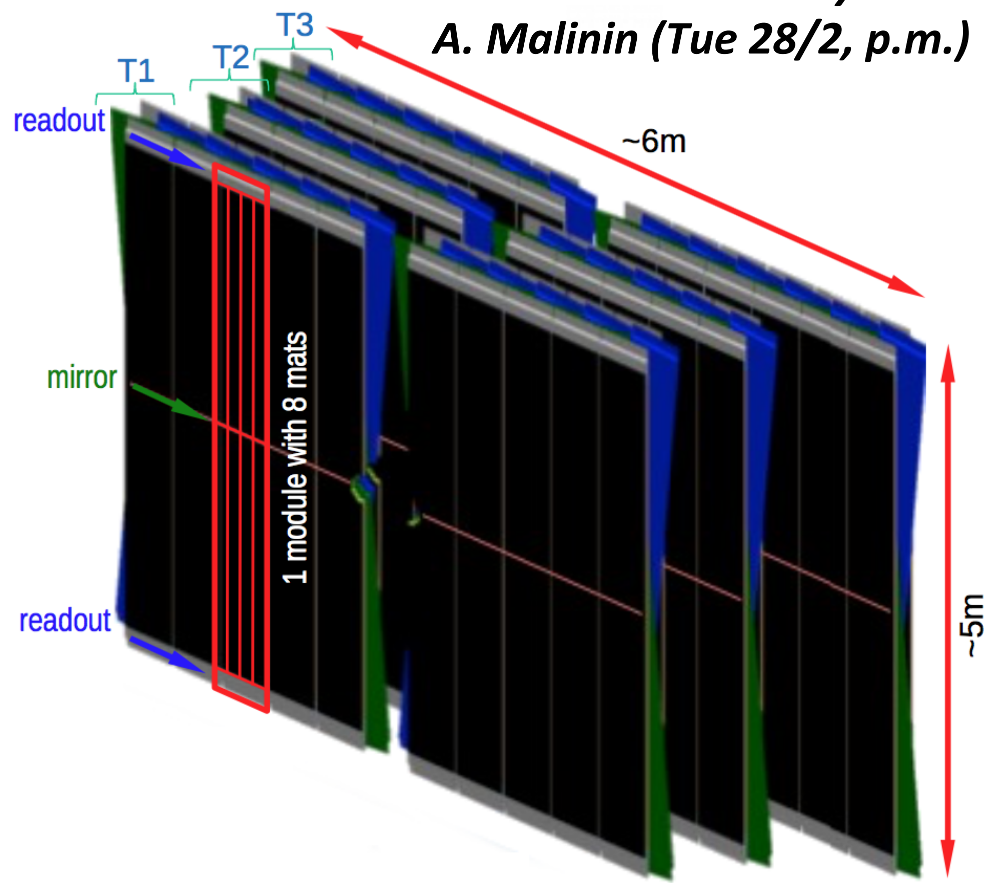
See dedicated talk by A. Malinin (Tue 28/2, p.m.)

3x4 planes (340m^2) of scintillating fibre mats (each mat: **1.1 X_0** thickness)

Homogeneous coverage from beampipe to distance of 3m

Each mat: 6 layers of 250μm fibres (total length: 10,000km)





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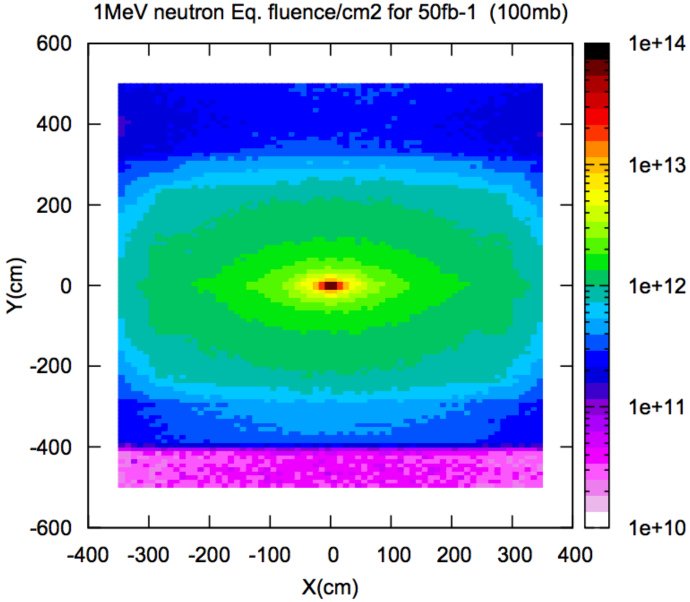
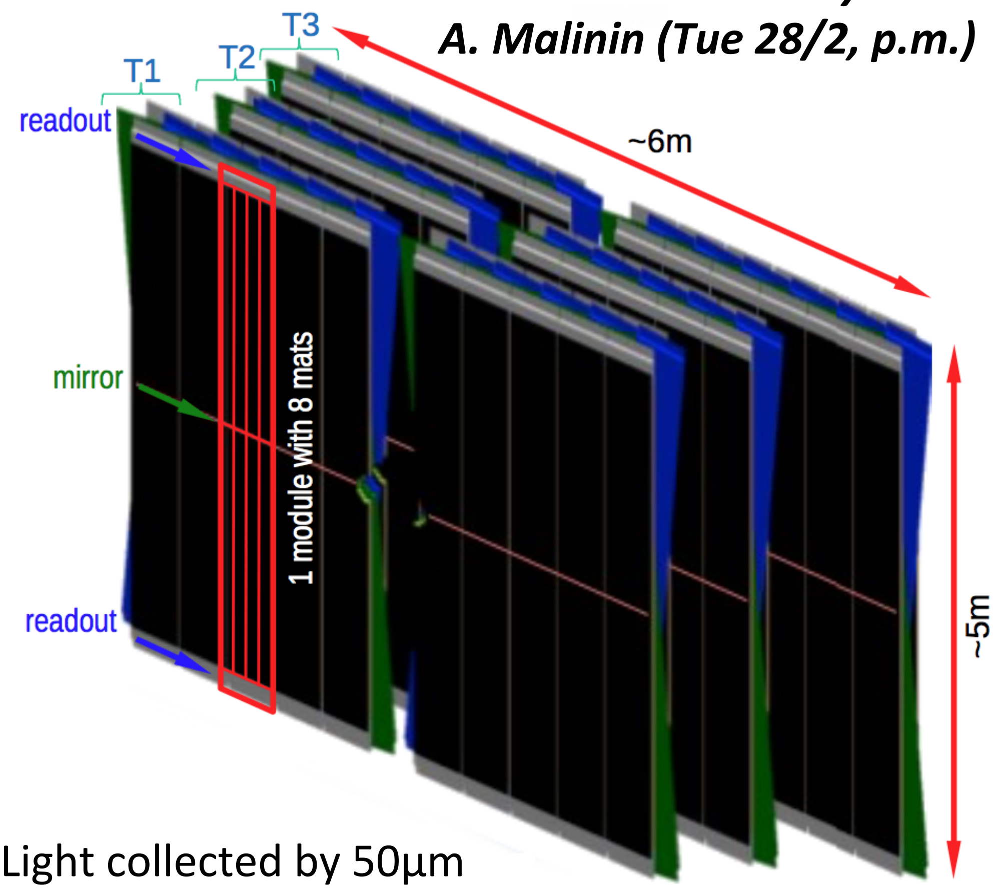
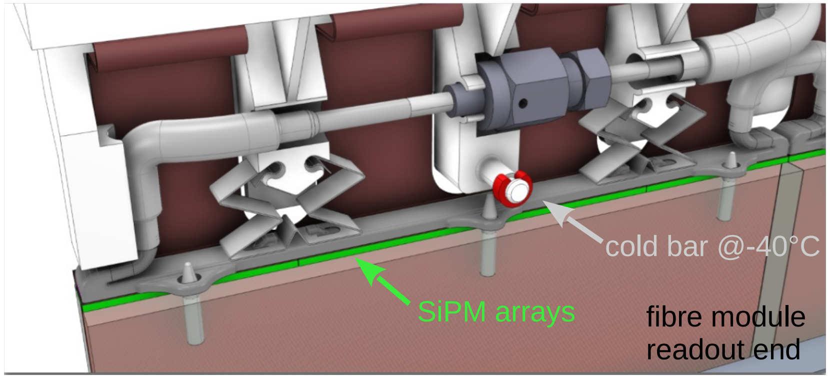


Significant radiation levels and neutron fluence

See dedicated talk by A. Malinin (Tue 28/2, p.m.)



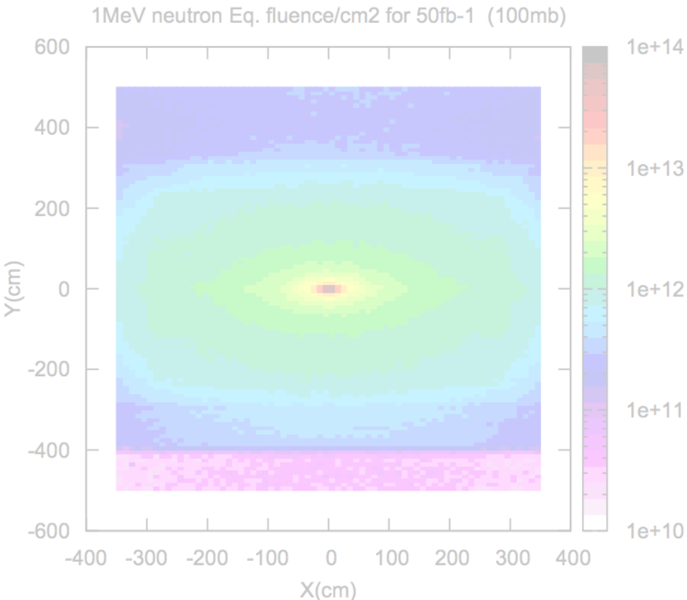


Light collected by 50μm pitch SiPMs, cooled to -40°C to reduce dark counting rate.

On-detector cluster-finding and compression

Scintillating Fibre Tracker (SciFi)

LHCB-TDR-015
LHCb-PUB-2015-025



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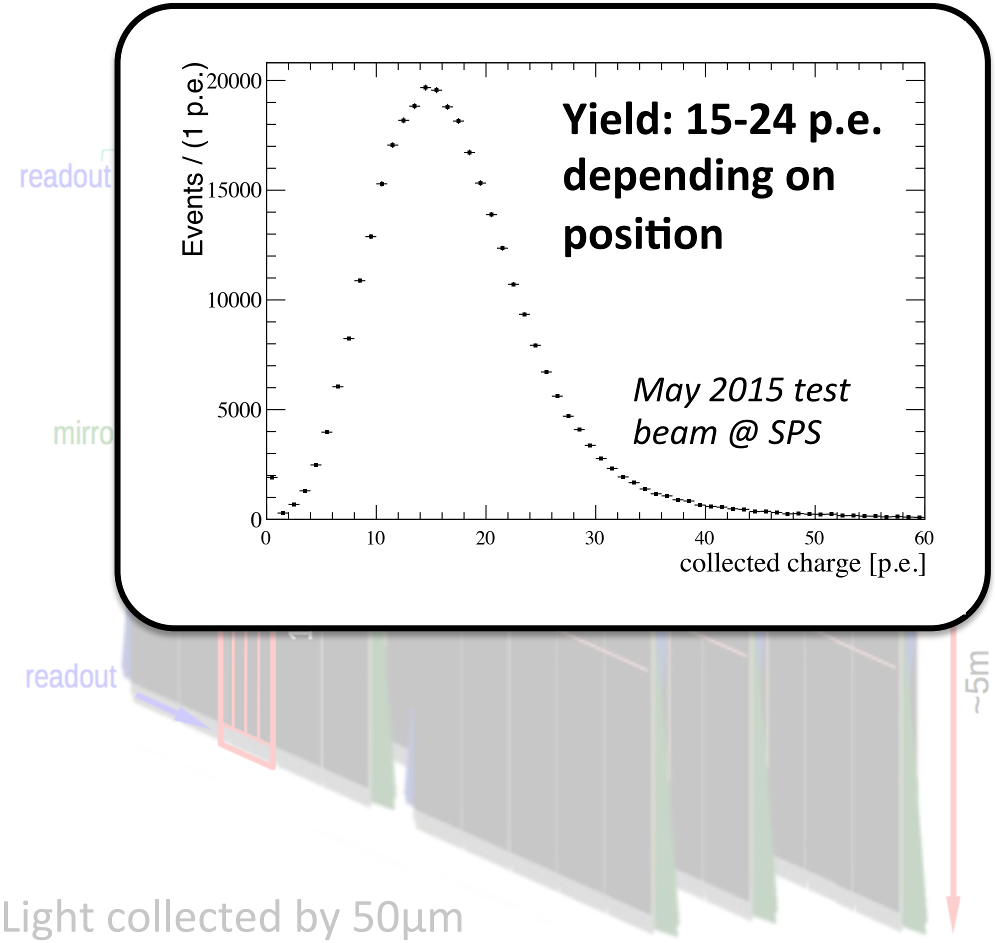

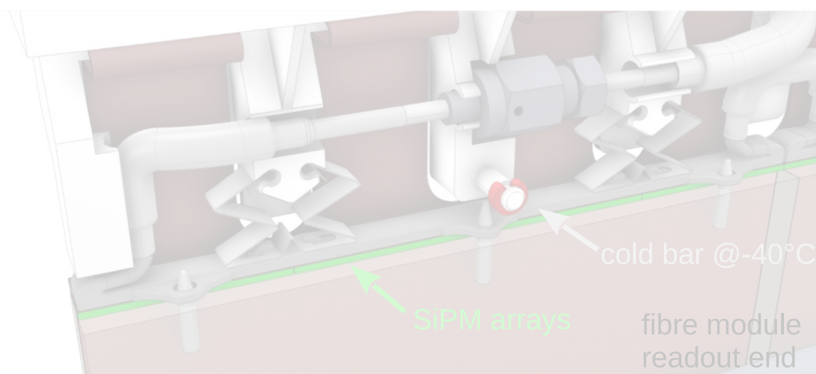

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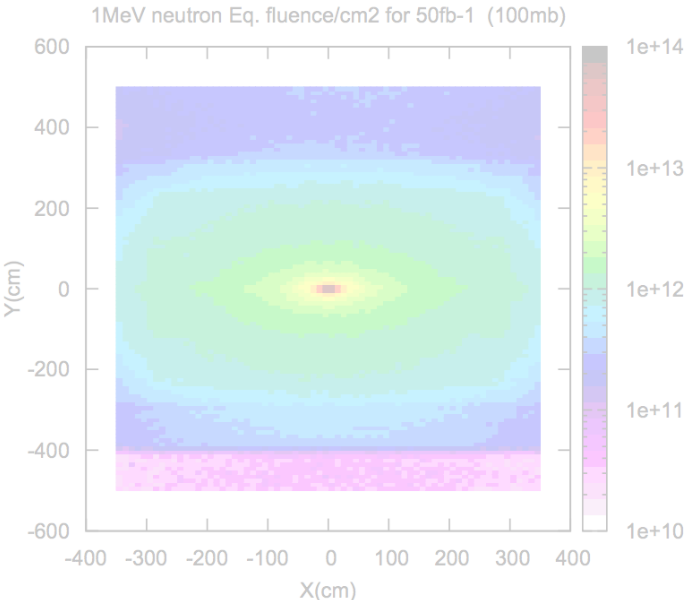

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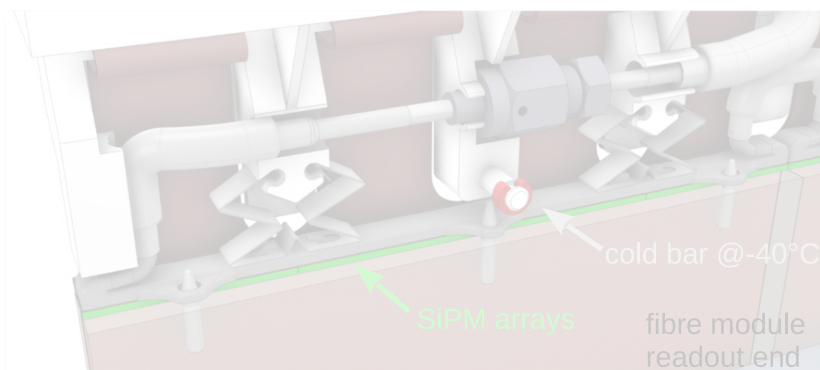

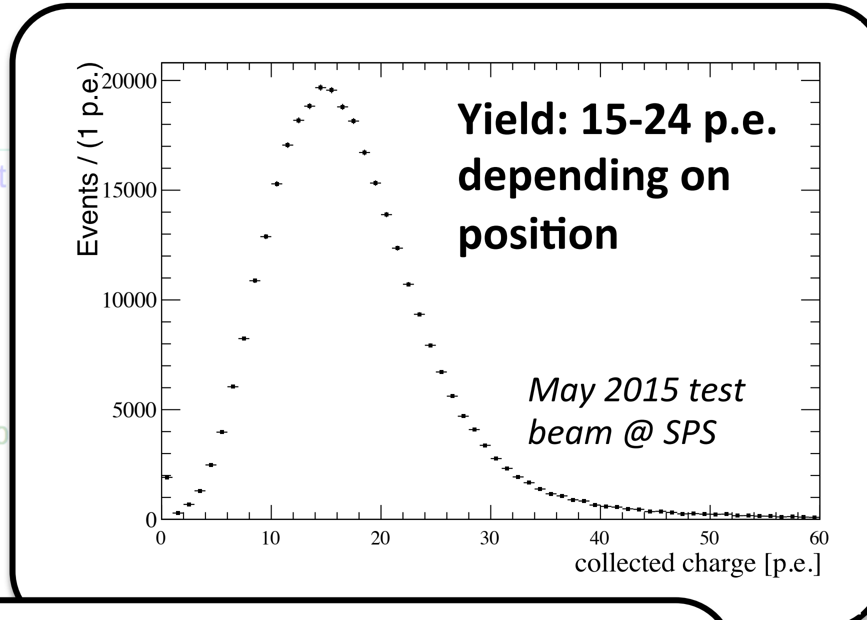

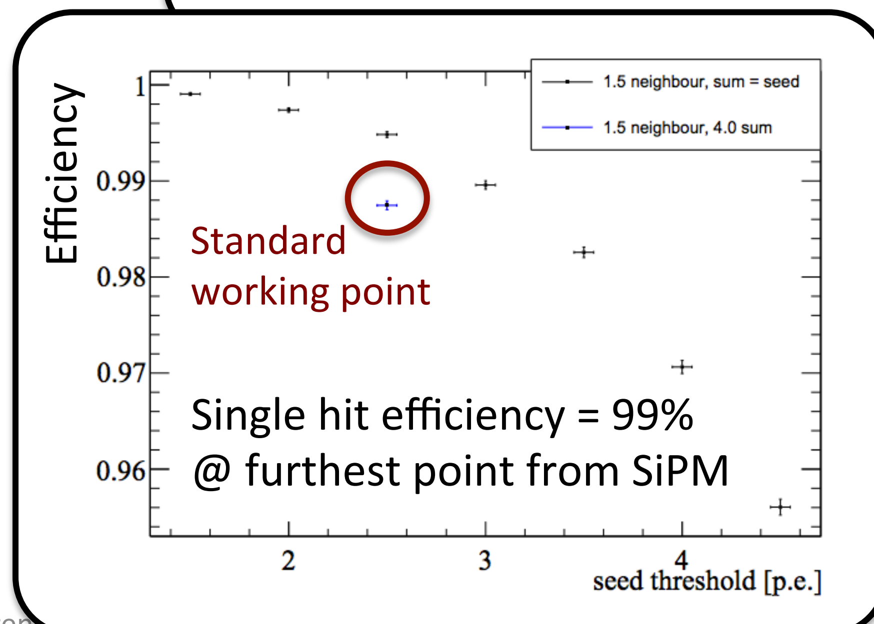

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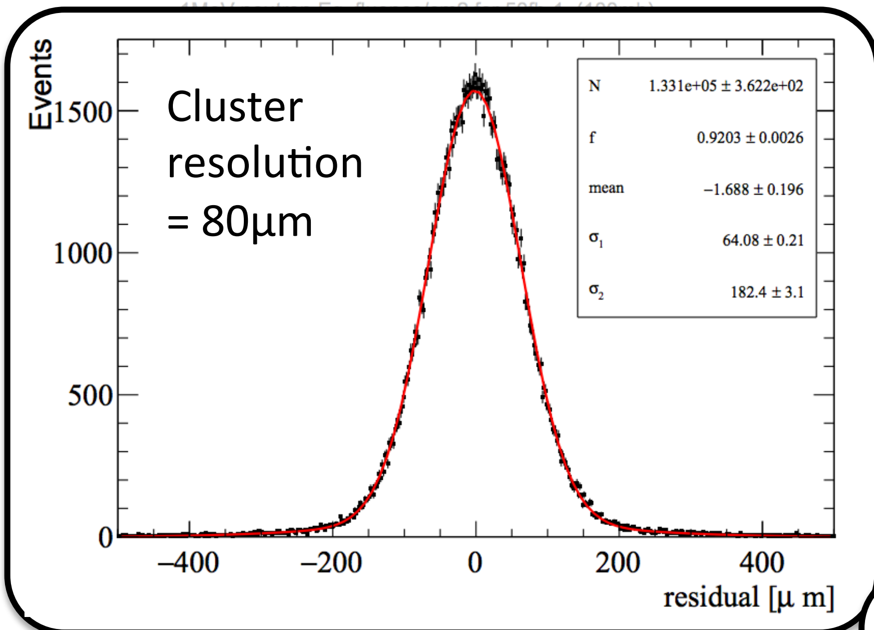

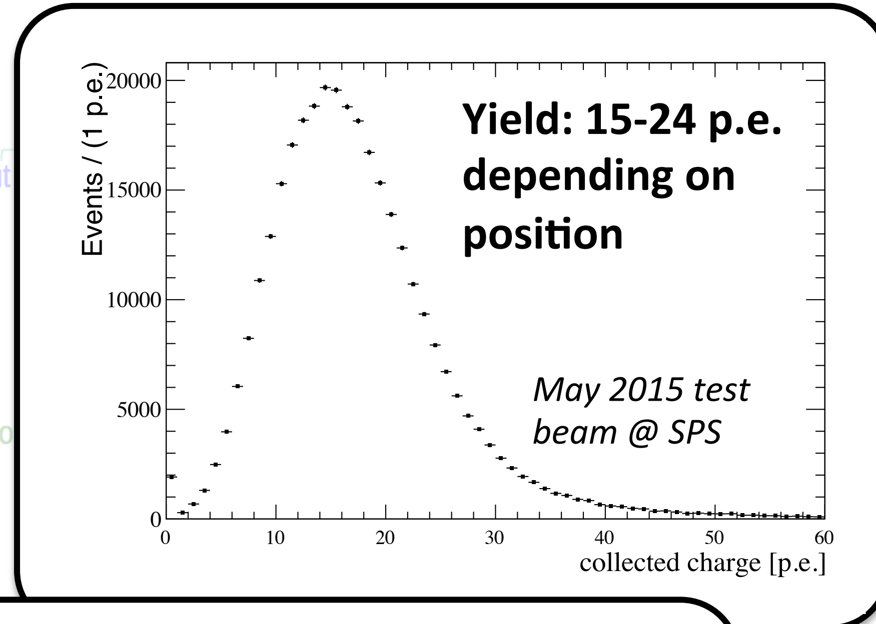

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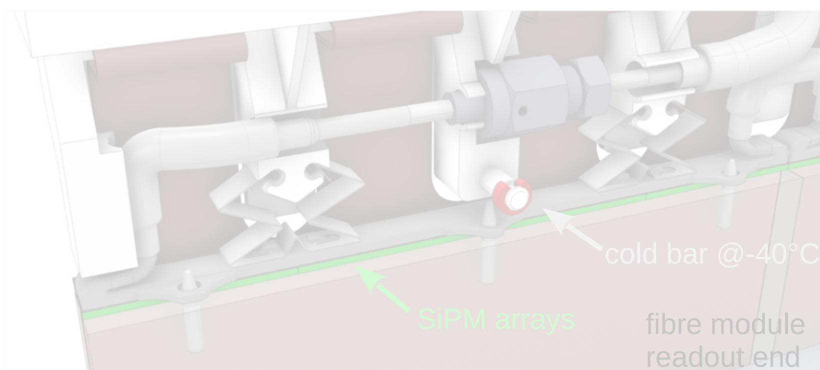
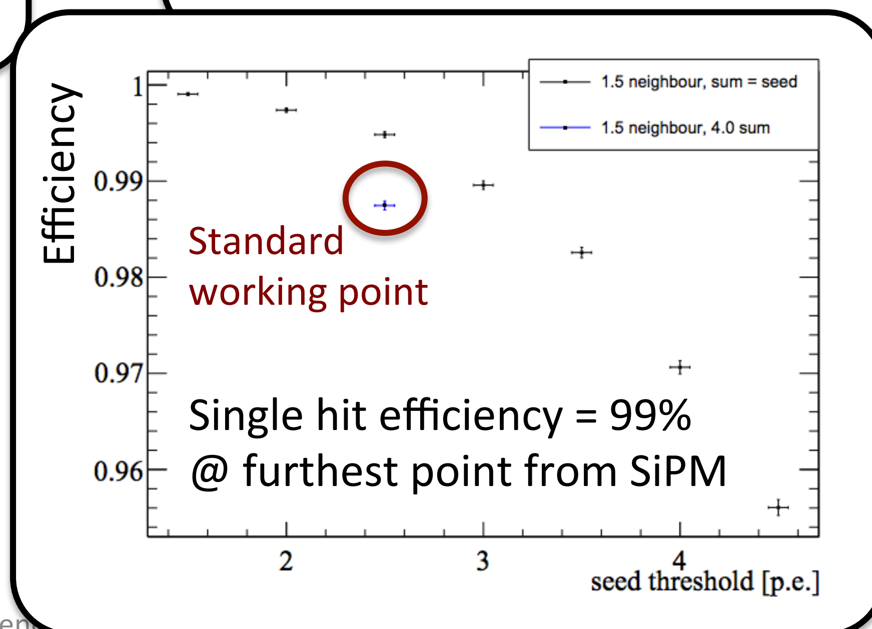
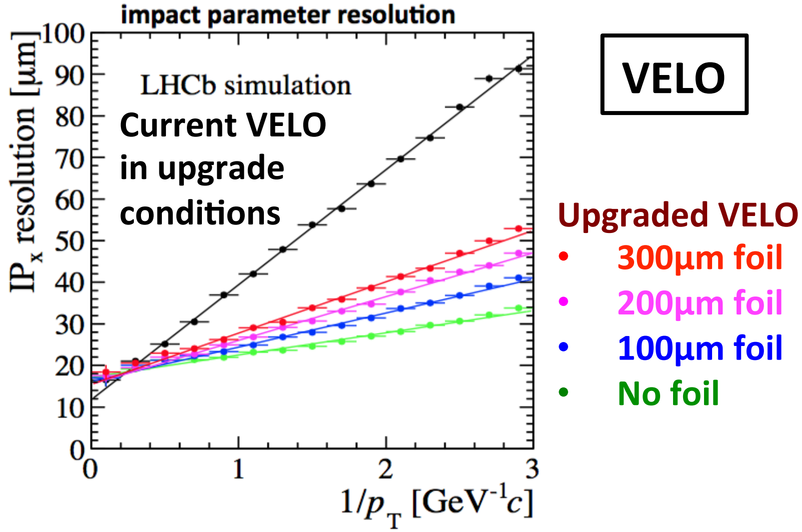


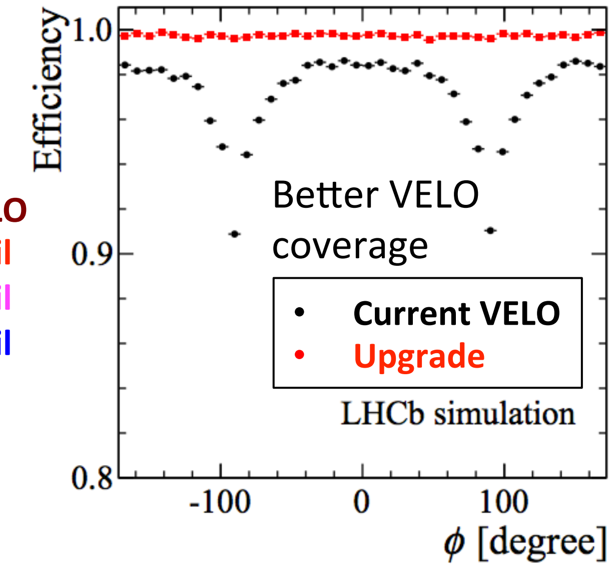


Simulated Tracking Performance

LHCB-TDR-013
LHCB-TDR-015

Surpass current performance in all metrics, even with higher luminosity





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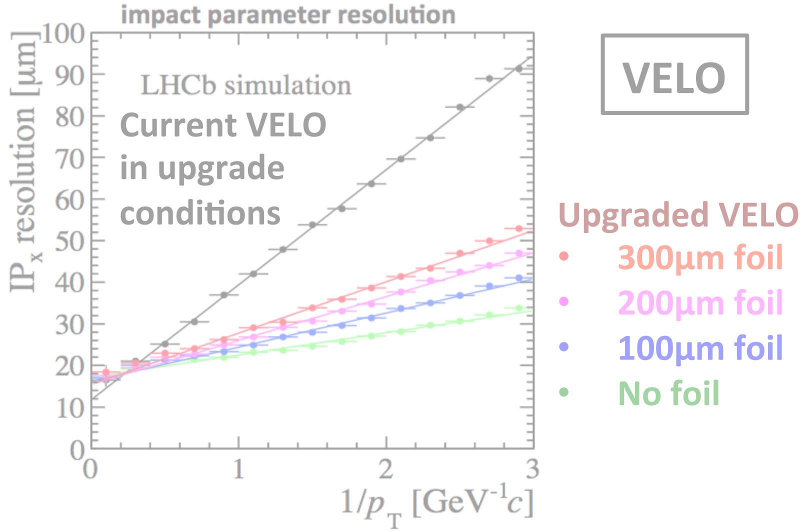
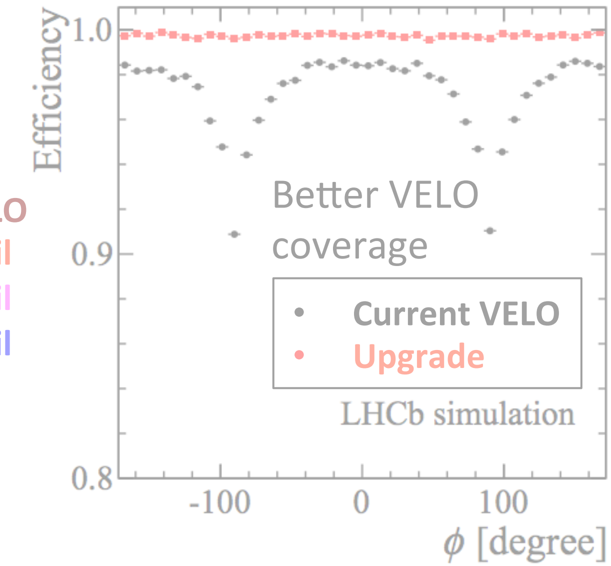
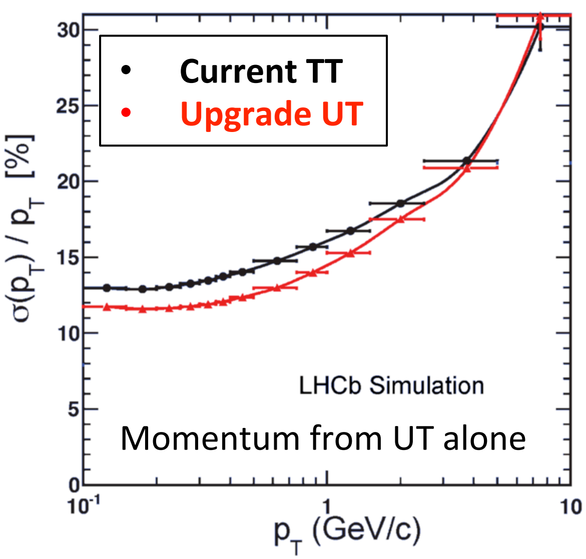
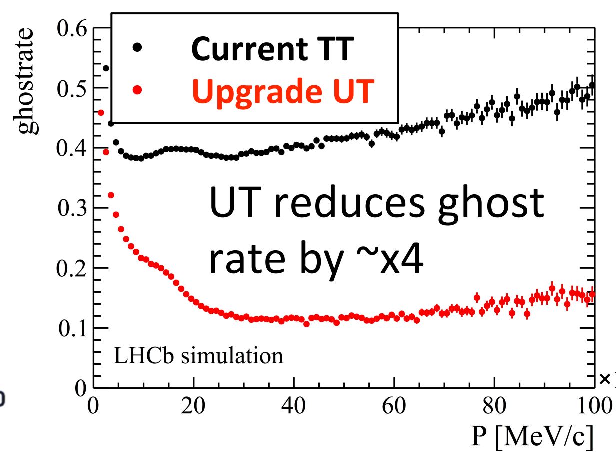


VELO





UT



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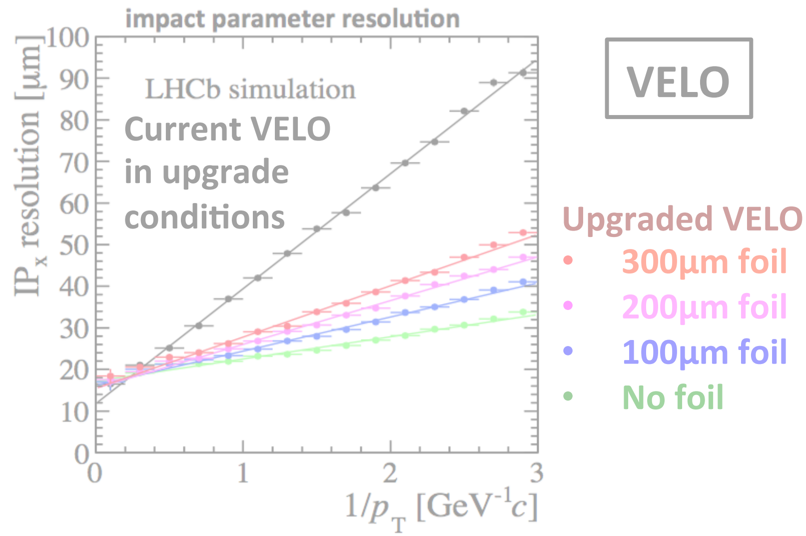

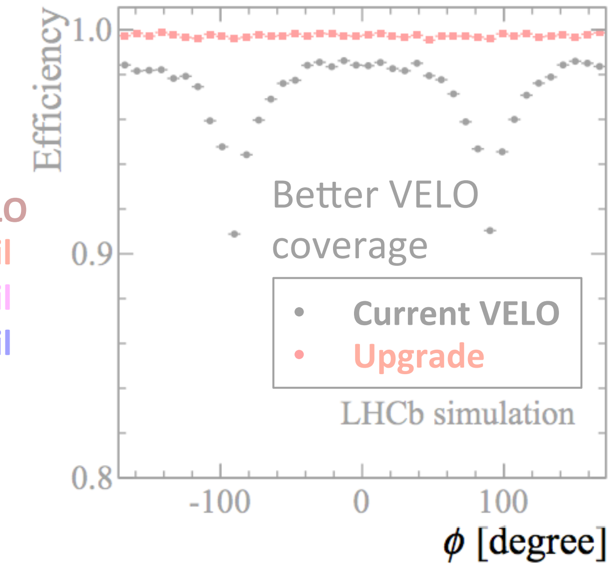

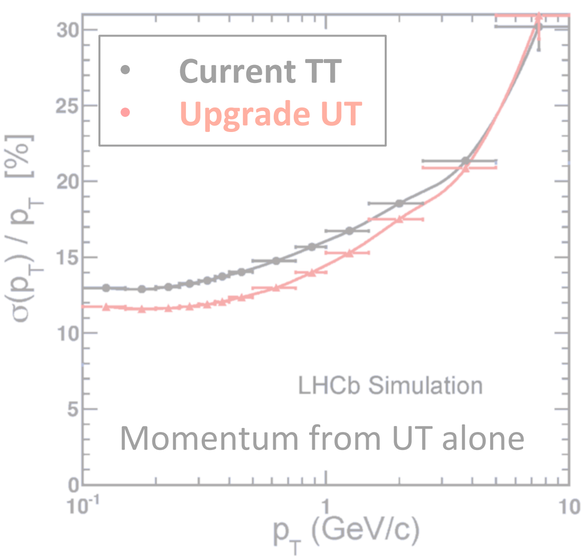

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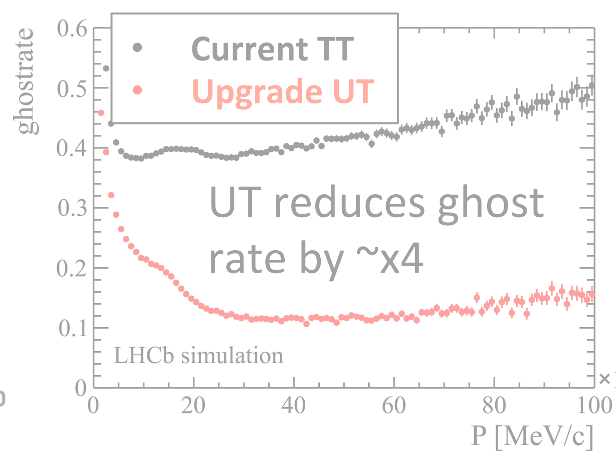
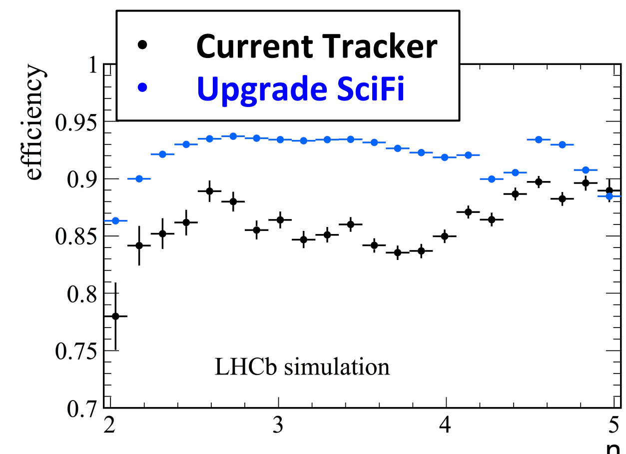




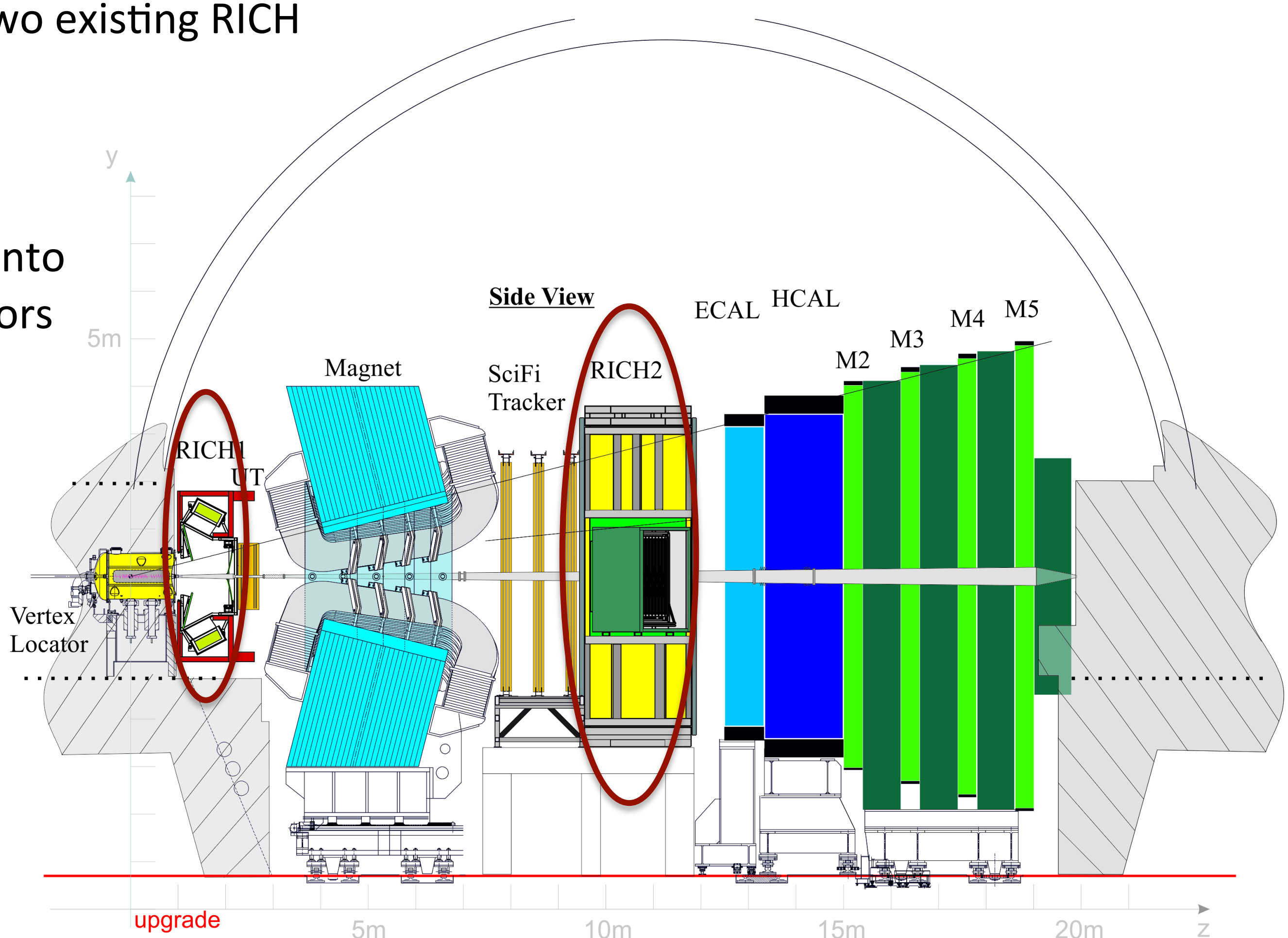
SciFi higher efficiency, lower ghost rate

RICH Detectors: Hadronic Particle ID

LHCB-TDR-014

Updated technology for two existing RICH stations

Gaseous detectors with Cherenkov light focused onto photon detectors via mirrors



Requirements:

- Differentiate $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ with high efficiency and low backgrounds
- Operate under much higher particle multiplicity

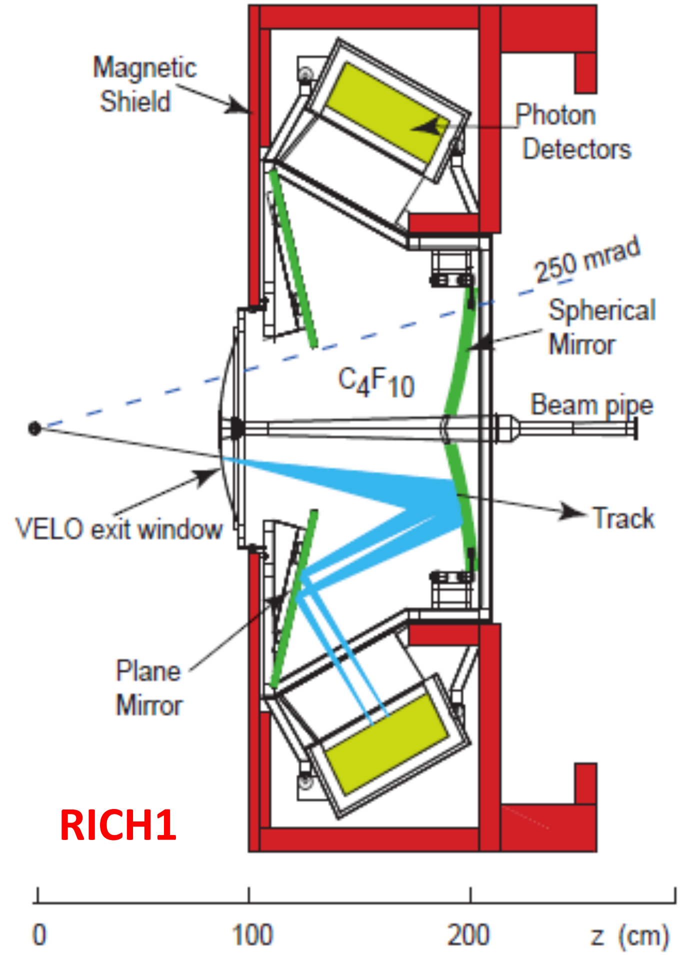
RICH Detectors: Hadronic Particle ID

LHCB-TDR-014

Two main changes for upgrade RICH:

(1) Update **RICH1** optics to increase image area and reduce occupancy − new mirrors, mechanics, radiator box

- 30% higher yield, 50% lower emission-point error



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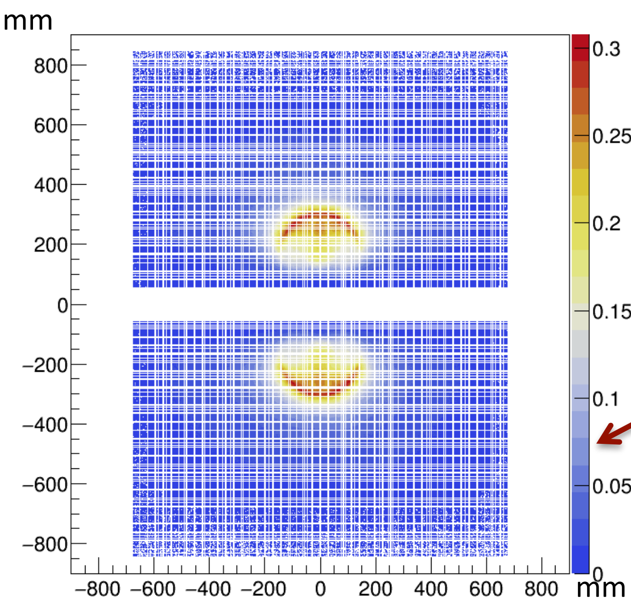
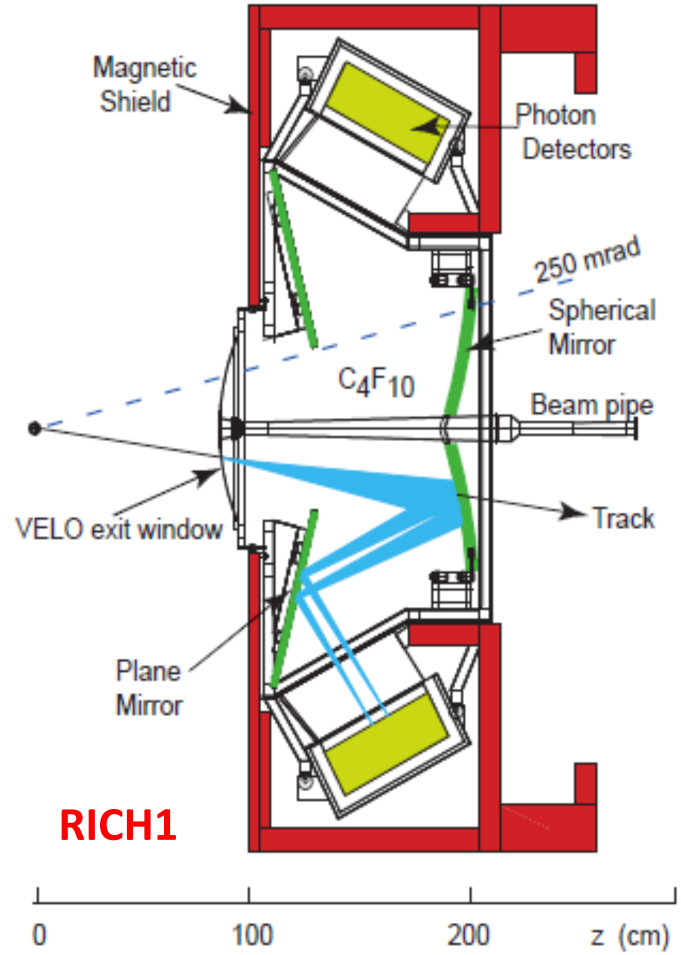


Peak upgrade RICH1 occupancy:

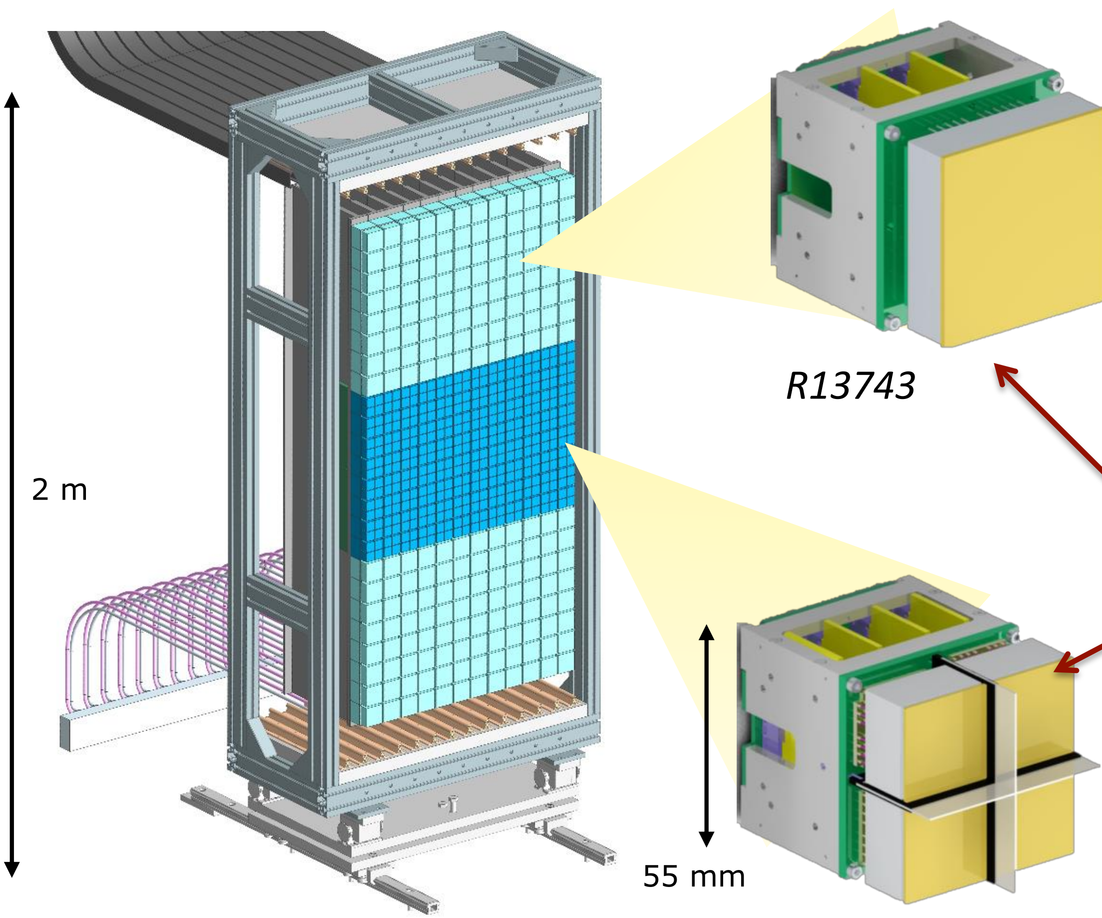
- Old geometry: **40%**
- New geometry: **27%**



RICH1

RICH Detectors: Hadronic Particle ID

LHCB-TDR-014



R13742

Photosensitive plane of the RICH-2 detector

(2) Replace photon detectors to allow 40 MHz readout, and provide finer granularity

- Overall single-photon angular resolutions improve by 50% (RICH1), 20% (RICH2)

Hamamatsu MaPMTs:

- 48x48mm (periphery of RICH2)
- 23x23mm (central region)

Both types have 8x8 pixels

RICH Detectors: Hadronic Particle ID

LHCB-TDR-014

(2) Replace photon detectors to allow
readout, and provide finer
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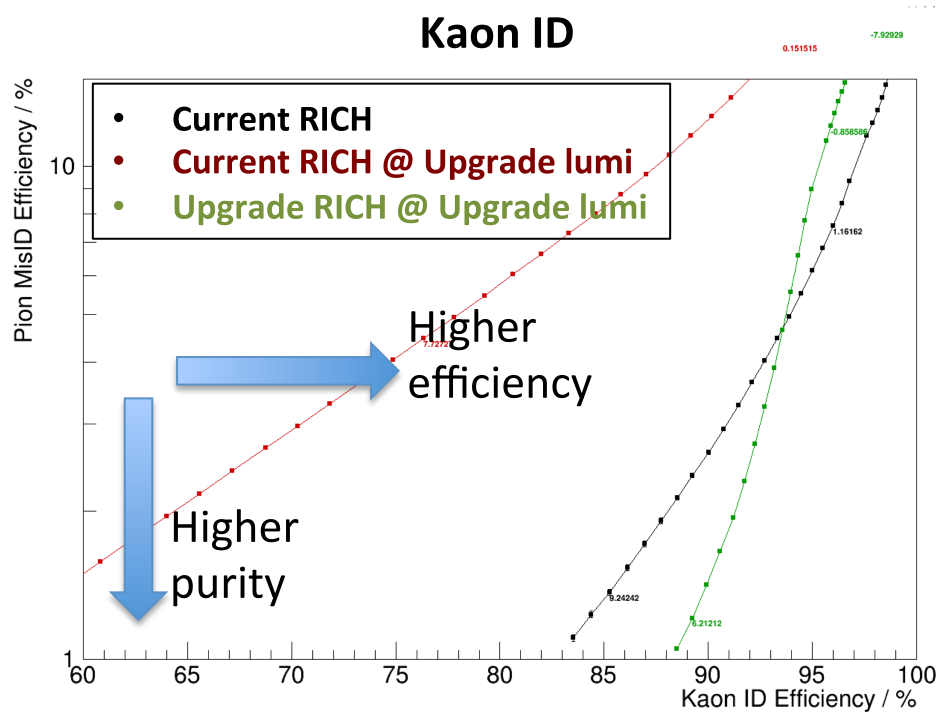
atsu MaPMTs:

8mm (periphery of RICH2)

3mm (central region)

pes have 8x8 pixels

2 m



Upgraded detector gives significantly improved PID at upgrade luminosities

55 mm

Photosensitive plane of the RICH-2 detector

Calorimeter and Muon System

LHCB-TDR-014

See dedicated talk by Y. Guz (Wed 1/3, a.m.)

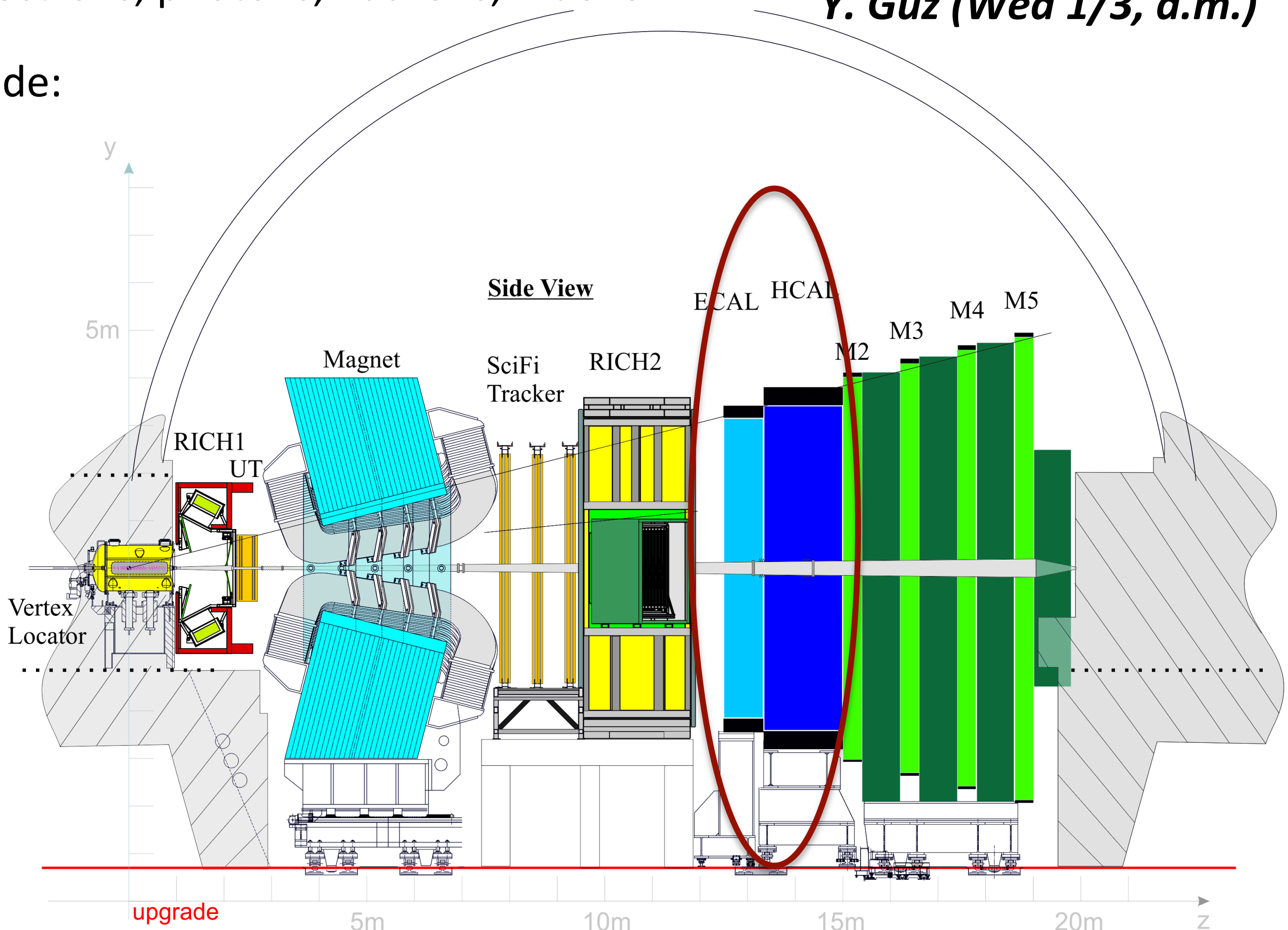
Requirements: Identify electrons, photons, hadrons, muons

Modest updates for upgrade:

Calorimeter:

- New readout electronics
- Remove scintillating pad detector (SPD)
- Remove pre-shower (PS) detector

(both now used in L0 trigger)



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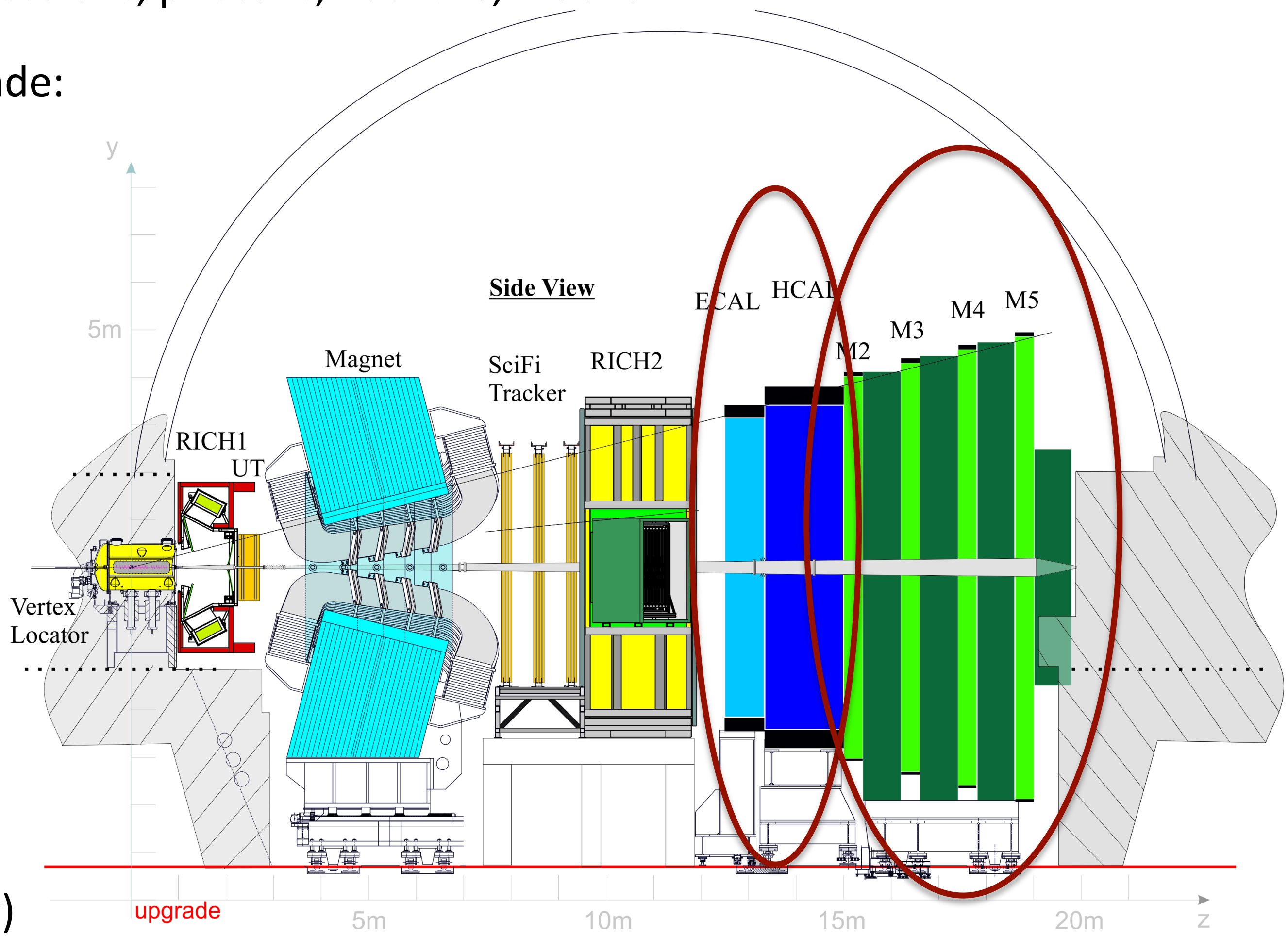
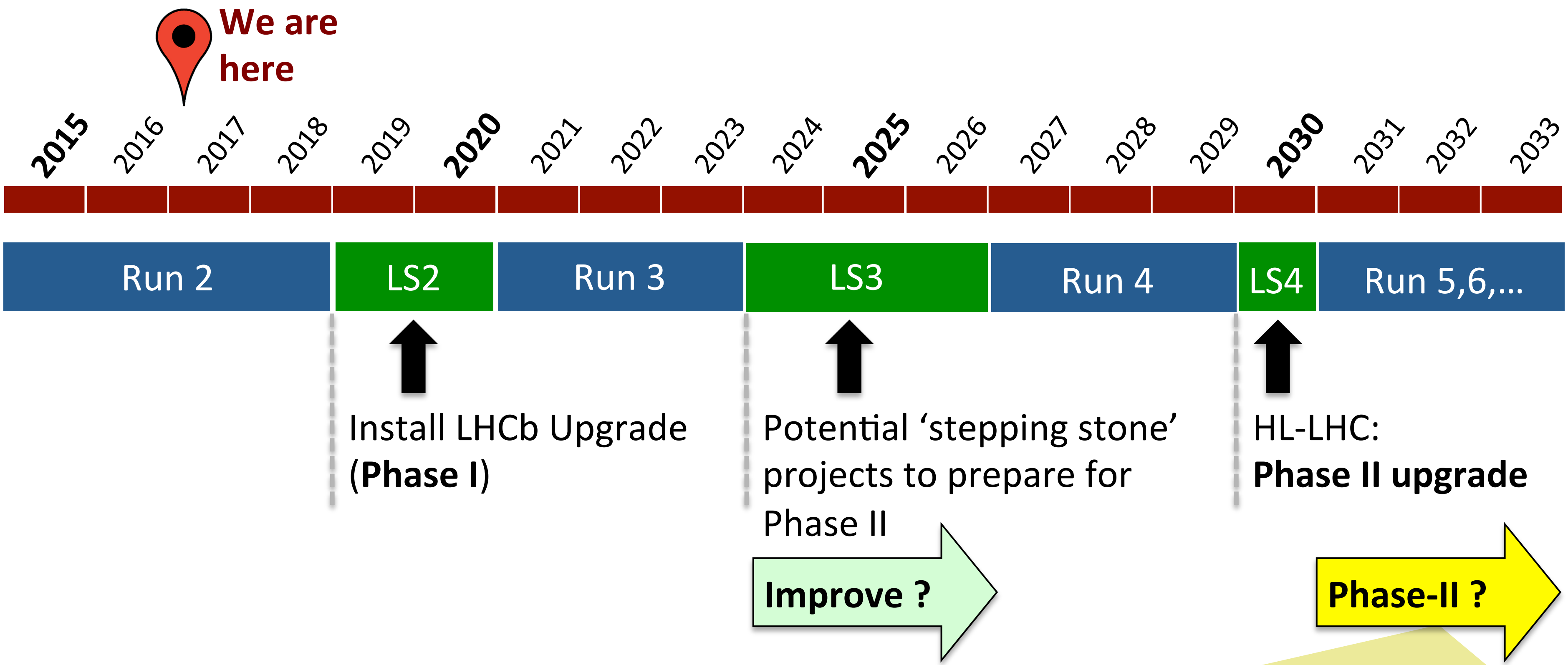
Muon:

- New readout electronics
- Remove M1 plane (upstream of calorimeter)
- Increase shielding to reduce fake hit rate



Pushing the limits: Future Upgrades



$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(50×)**

55 visible interactions / crossing

300 fb^{-1} collected

Pushing the limits: Future Upgrades

In 2030, LHCb likely the only collider detector designed for flavour physics

Now is the time to start planning:

- What will we need / want to measure?
- Can we operate at 10x upgrade luminosity and maintain (or improve) performance?
- What are the principle technological challenges?
- Can we extend physics reach with innovative solutions?

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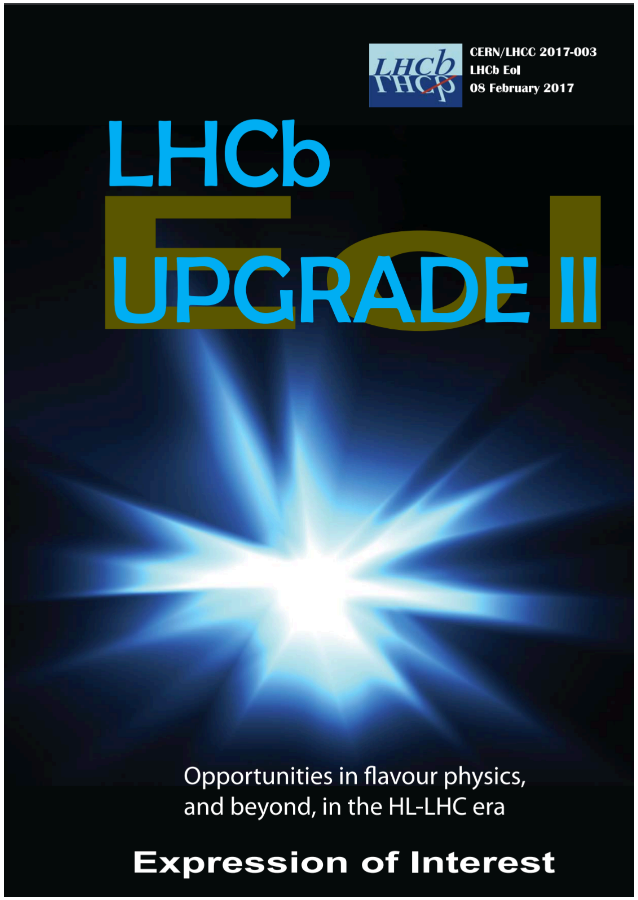
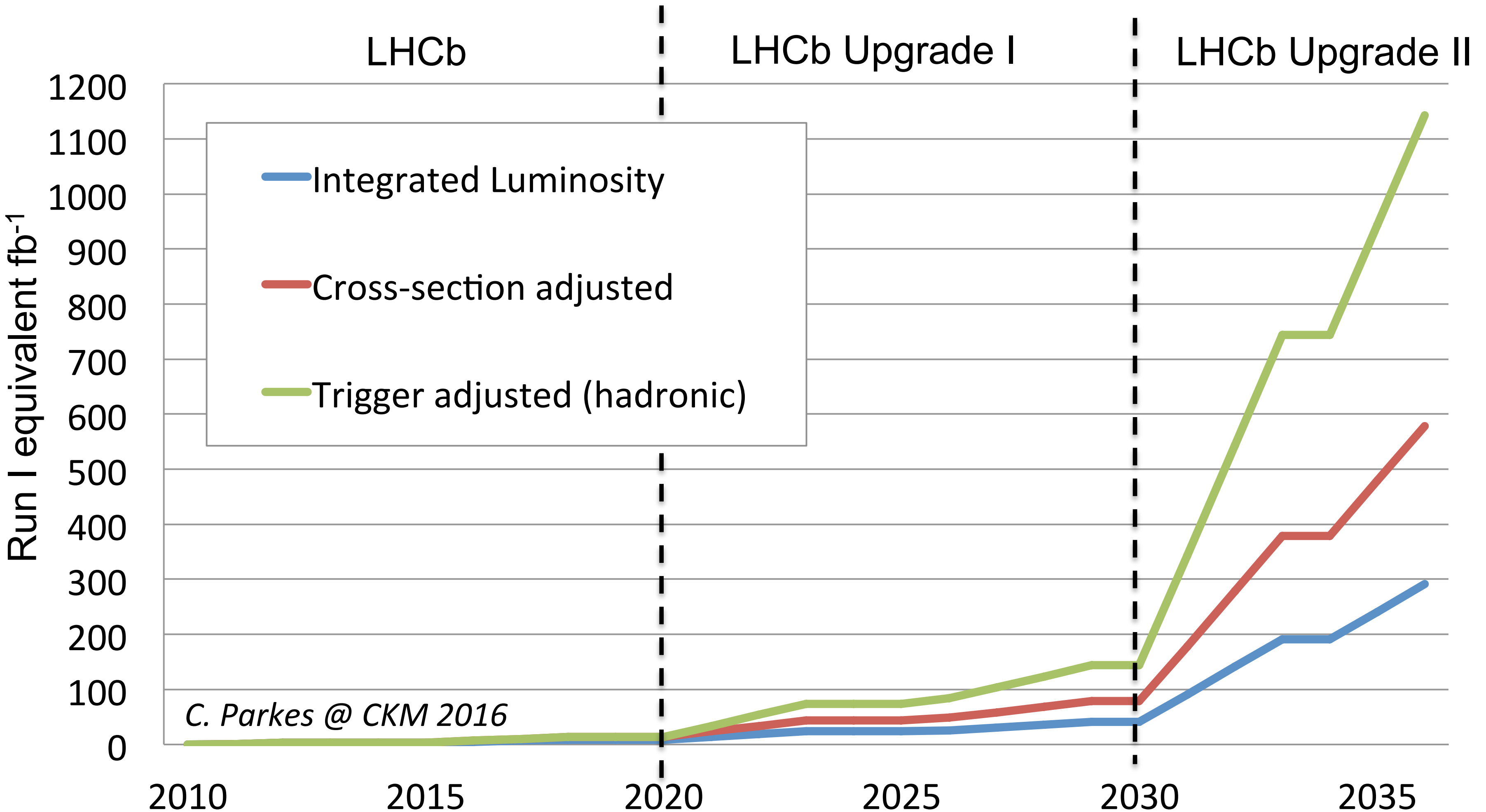
Hot off the Press: Expression of Interest document: CERN-LHCC-2017-003
https://cds.cern.ch/record/2244311/



Major themes:
Radiation hardness, finer granularity, timing information

Pushing the limits: Future Upgrades

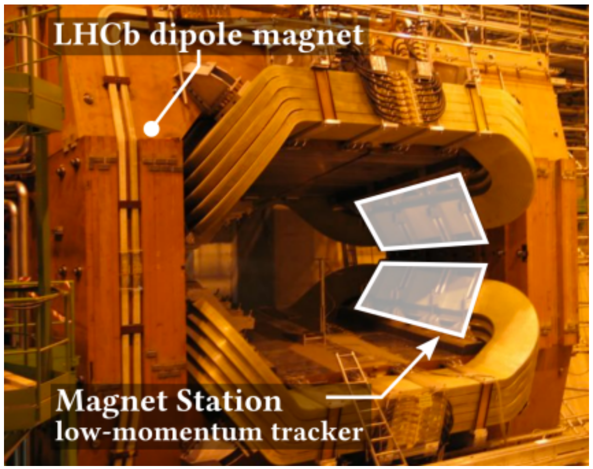
Potentially huge yield gains if we can take advantage of the HL-LHC

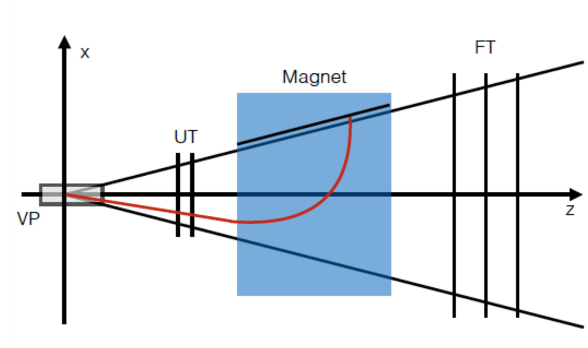


* Extrapolated trigger efficiencies have significant uncertainties at this stage

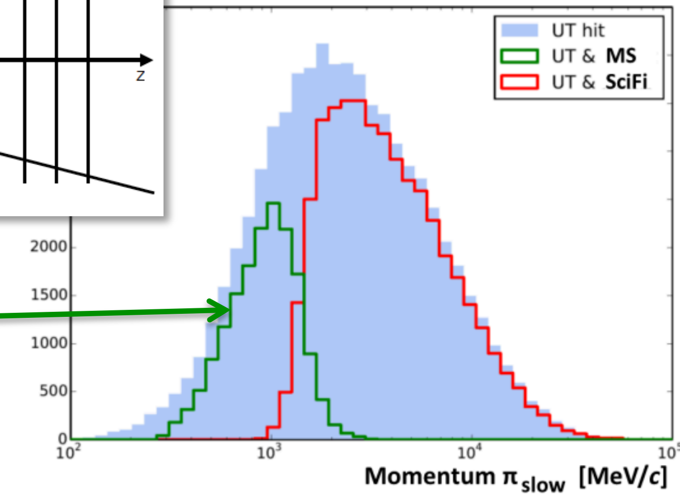
Options for Detector Improvements in LS3

Install tracking stations
inside magnet (outside acceptance)





40% gain in slow pion
yield from $D^{*\pm} \rightarrow D\,\pi^{\pm}$



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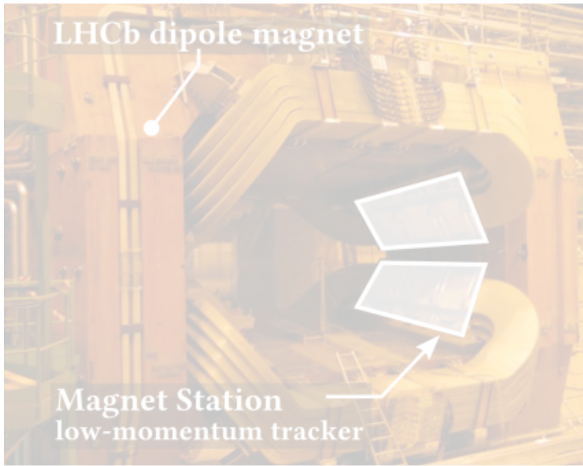

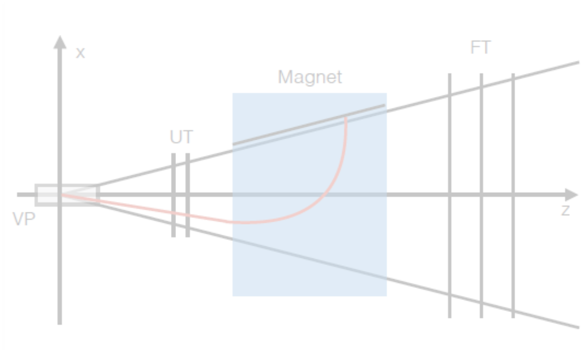

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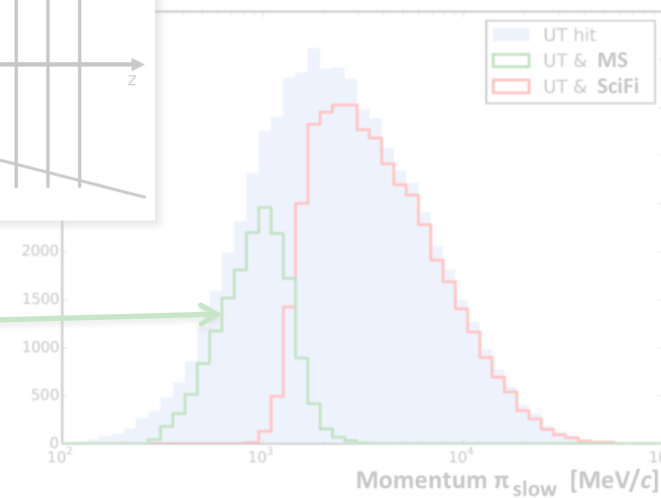
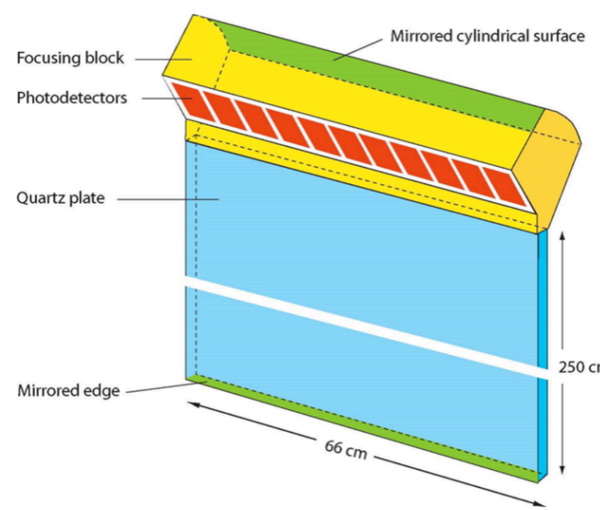


Other possibilities:

- Install TORCH detector for high-precision timing (~15ps per track) – low momentum PID and track-matching between subsystems and to vertices
- Improved technology in most-irradiated / highest occupancy regions of Calorimeter, tracker, RICH, and Muon systems

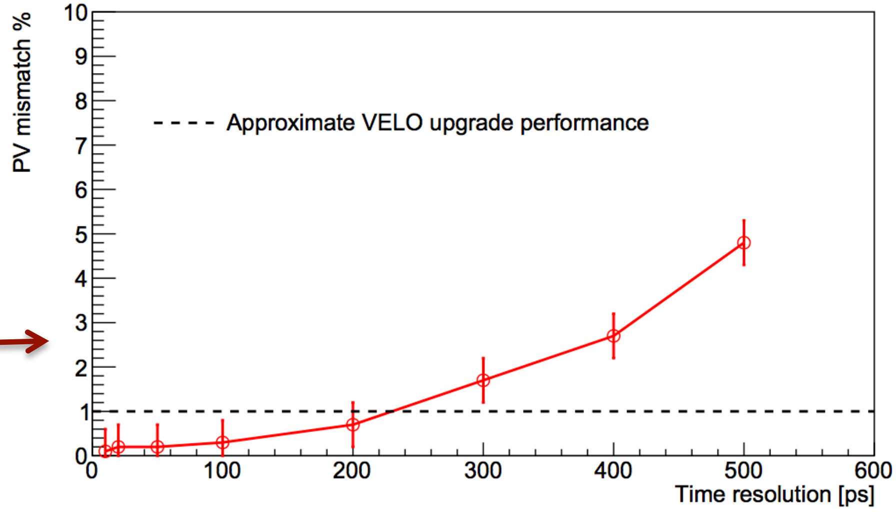


Phase II options

Vertex Locator with timing:

At HL-LHC luminosity, time stamps needed to correctly associate tracks to PVs for long-lived particles

- ~200ps resolution sufficient to recover current VELO performance
- More precise timing detectors could be used in Pattern Recognition and PID



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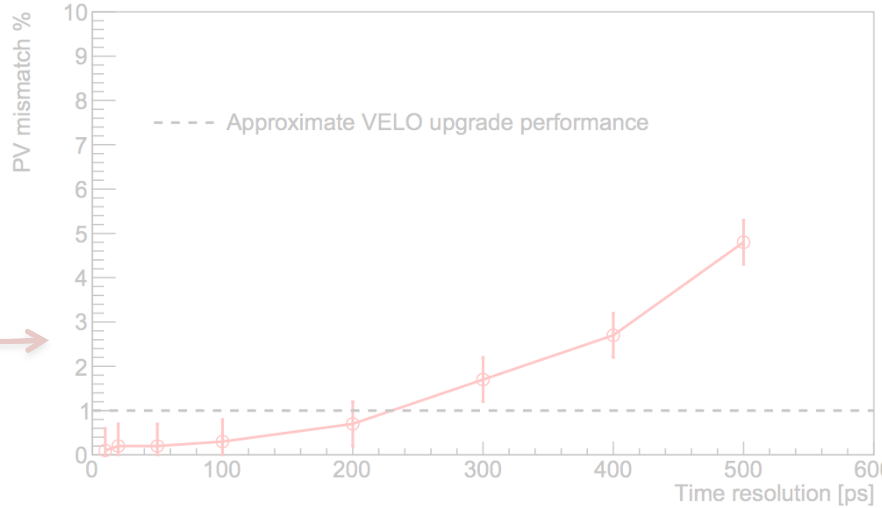
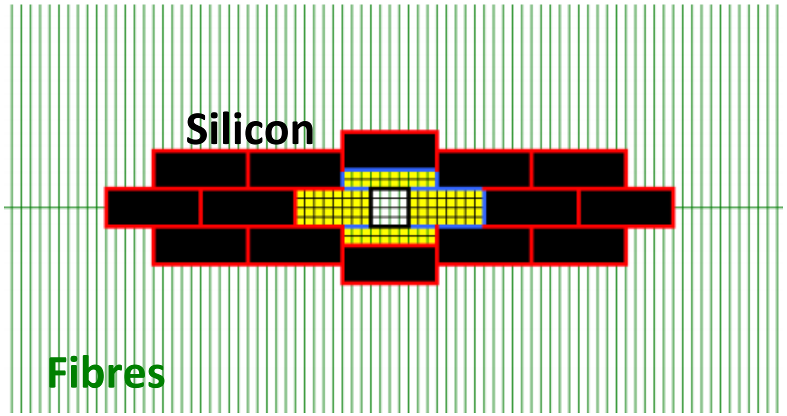
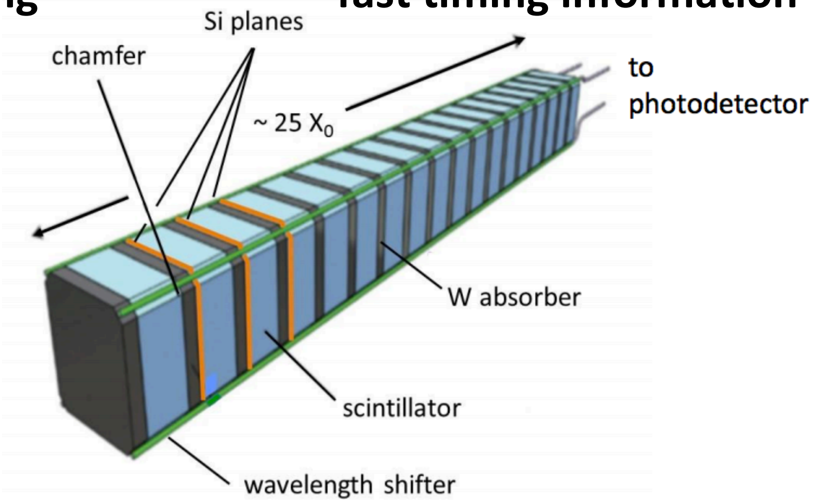


Hybrid SciFi / Silicon detector for downstream tracking



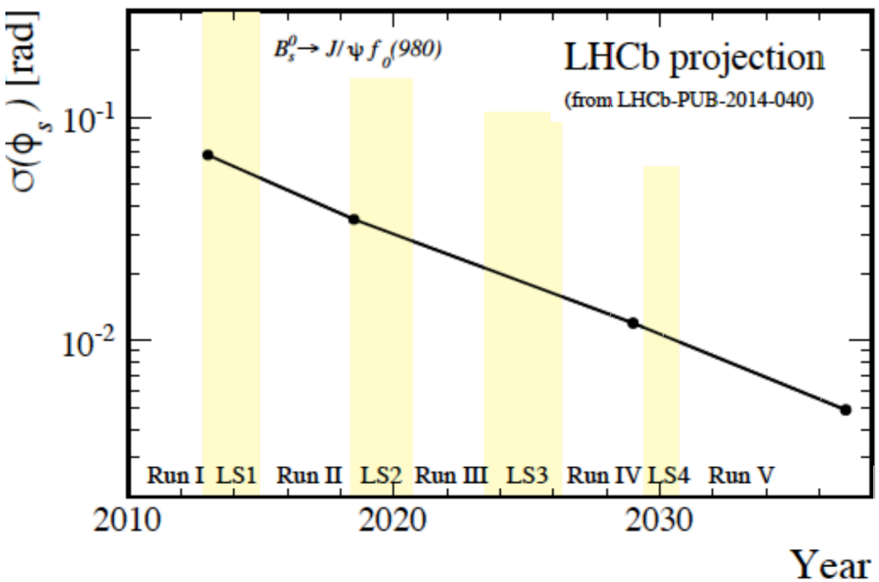
New ECAL: Smaller cells, add fast timing information



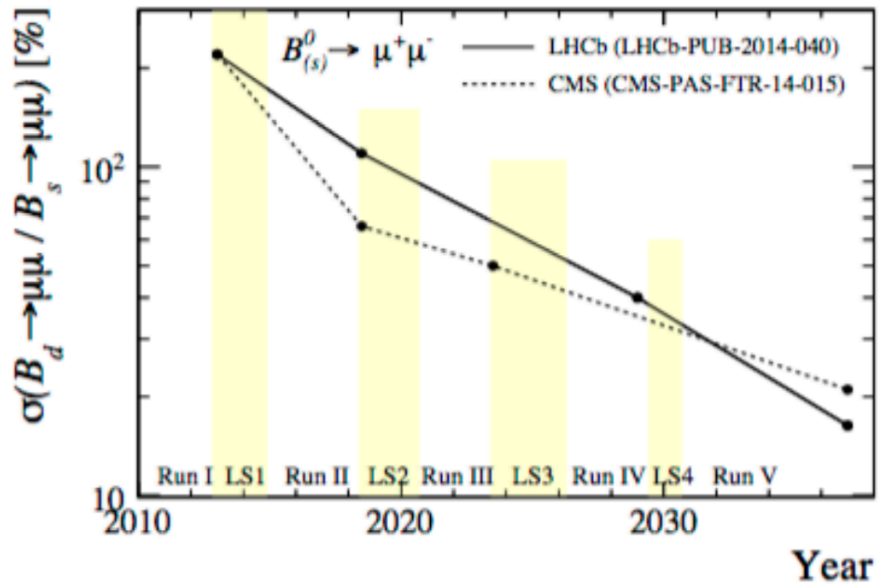
Physics Gains

Example precision projections from Run 1 – Run 5

ϕ_s from $B_s^0 \to J/\psi f_0(980)$



$B_{(s)}^0 \to \mu^+\mu^-$

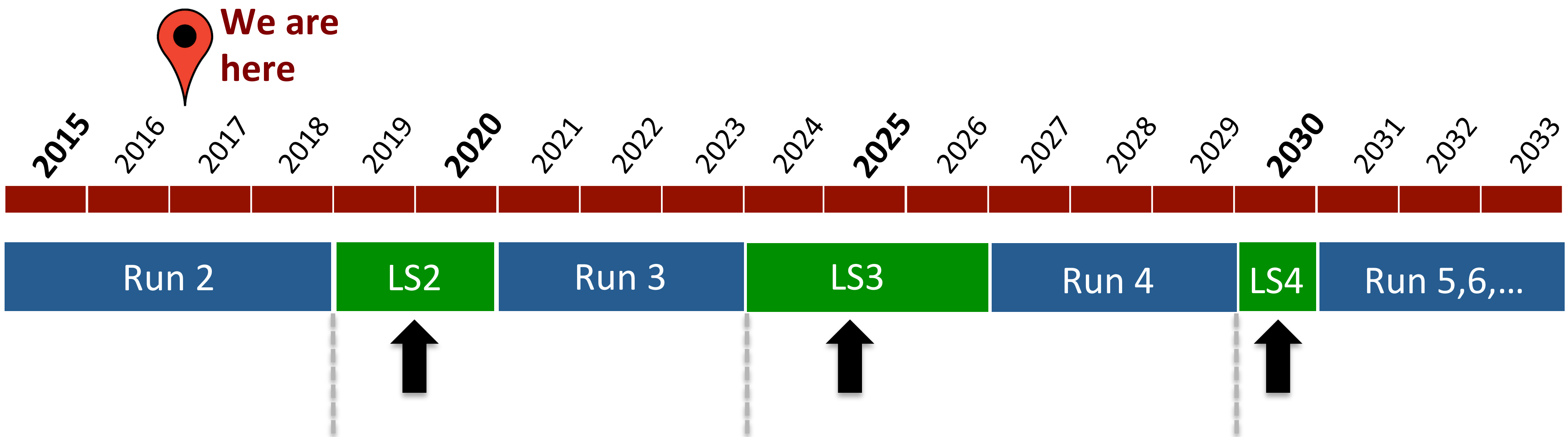


Current detector

Phase I upgrade

Phase II upgrade ?

Summary



Phase-I upgrade : R&D well-advanced. Now transitioning to production phase.

- Trigger/computing model already evolving in Run 2
- New read-out electronics throughout detector
- Major new detectors (VELO, UT, SciFi) and significant technology upgrade for RICH

Future Phase-II HL-LHC upgrade offers major gains in physics reach

- New technology and ideas essential to get most from the data
- Key areas: Timing capabilities & radiation hardness