The LHCb VELO & ST Operational Performance Run II

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The 26th International Workshop of Vertex Detectors (VERTEX 2017)

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Overview

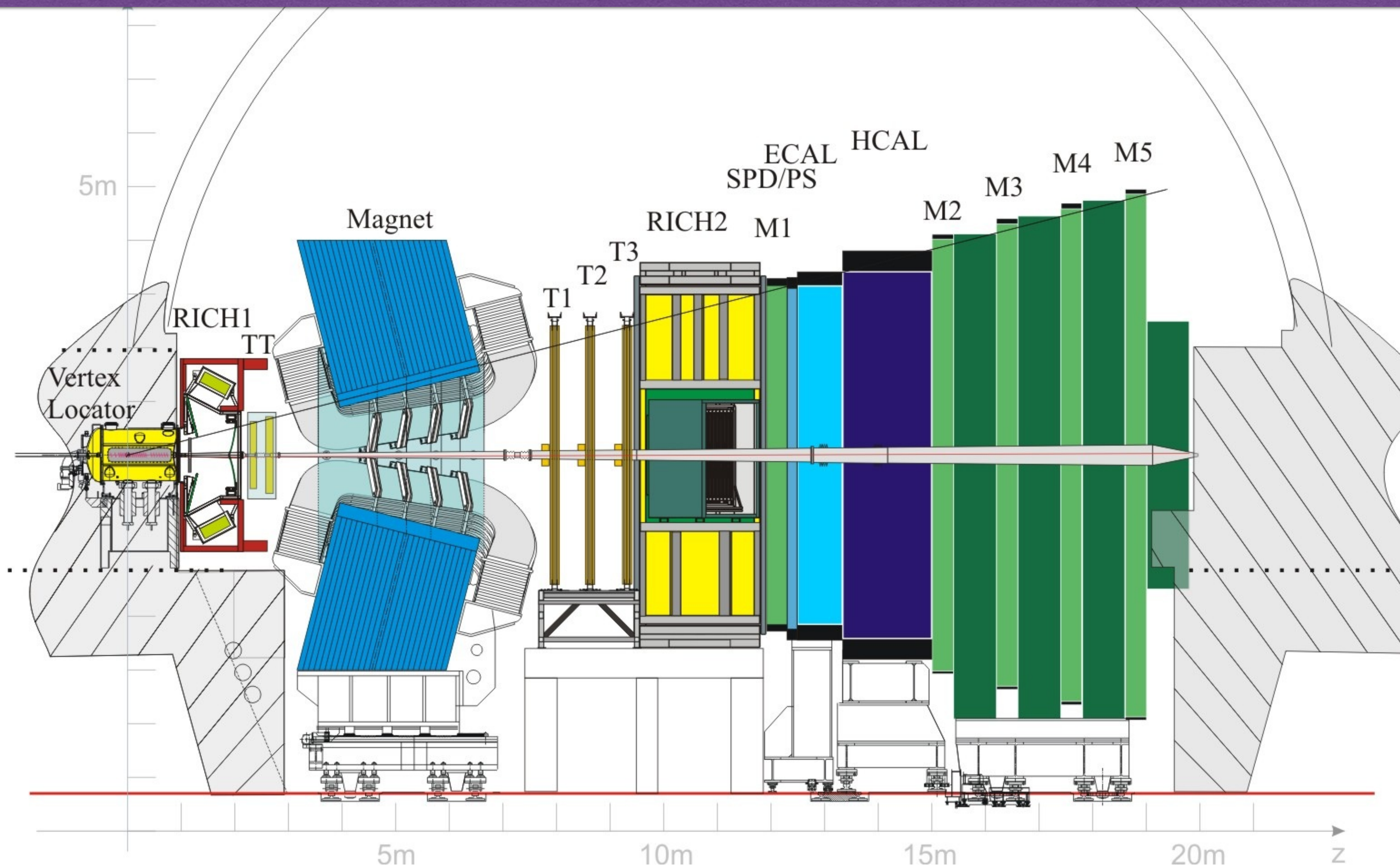
- LHCb Experiment
- The Tracking Detectors
- Expected Fluences
- Radiation Monitoring Methods
  - Leakage Current
  - Charge Collection Efficiency
- Conclusions

Presented on behalf of the LHCb VELO & ST groups

Thanks to the VERTEX Organising Committee for awarding me the young researchers grant

The Large Hadron Collider Beauty Experiment (LHCb)

Searching for New Physics through measuring CP violation and rare decays of heavy flavour mesons

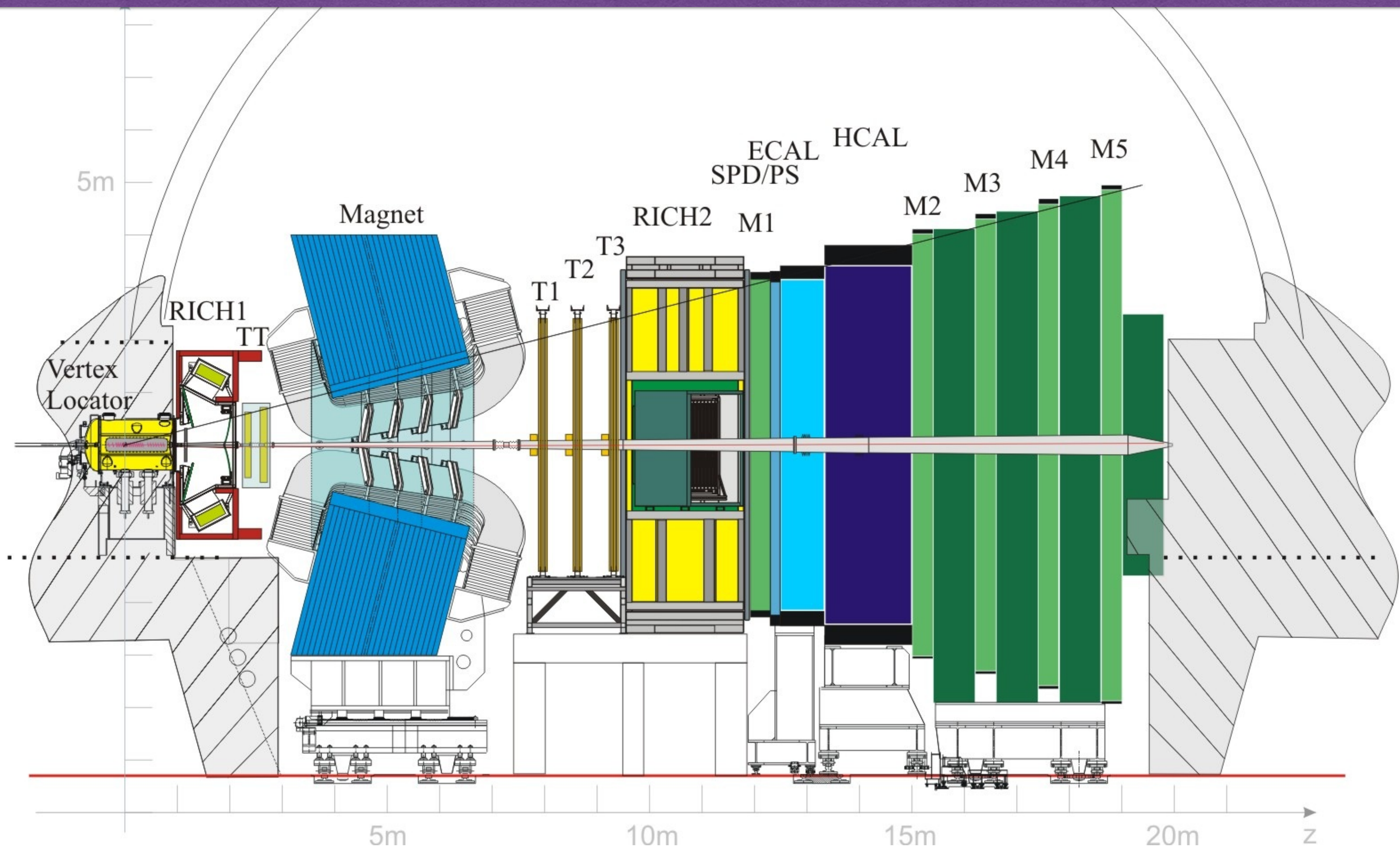


LHCb experiment: Utilising a tracking system, 2 RICH detectors for PID, Electromagnetic and Hadronic Calorimeters and a muon system.

Single arm spectrometer optimised to study particles containing b and c quarks

The Large Hadron Collider Beauty Experiment (LHCb)

Focus of this talk is on the performance of the Vertex Locator (**VELO**) and the Silicon Tracker (**ST**)



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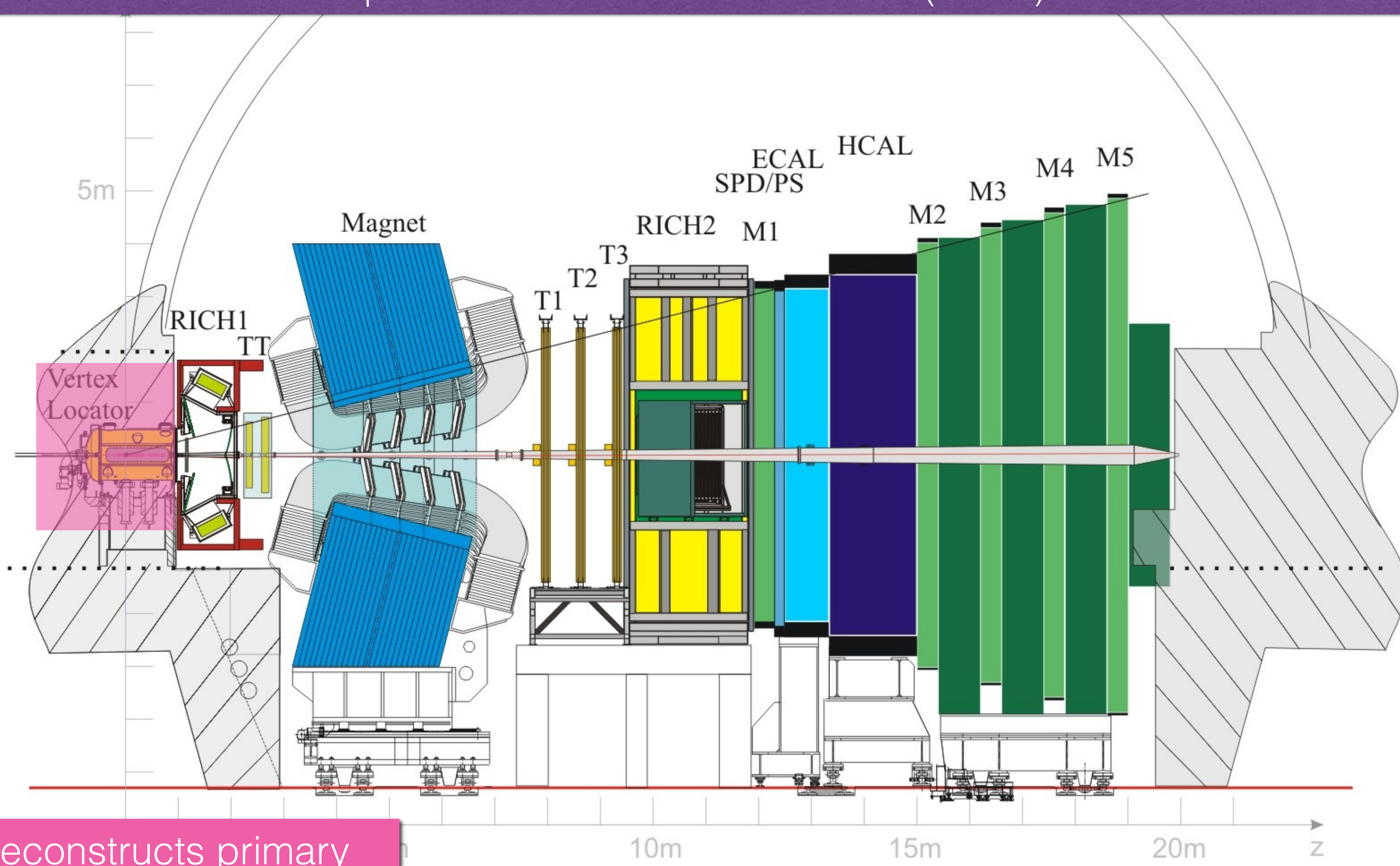

Reconstructs primary and secondary vertices

The Large Hadron Collider Beauty Experiment (LHCb)

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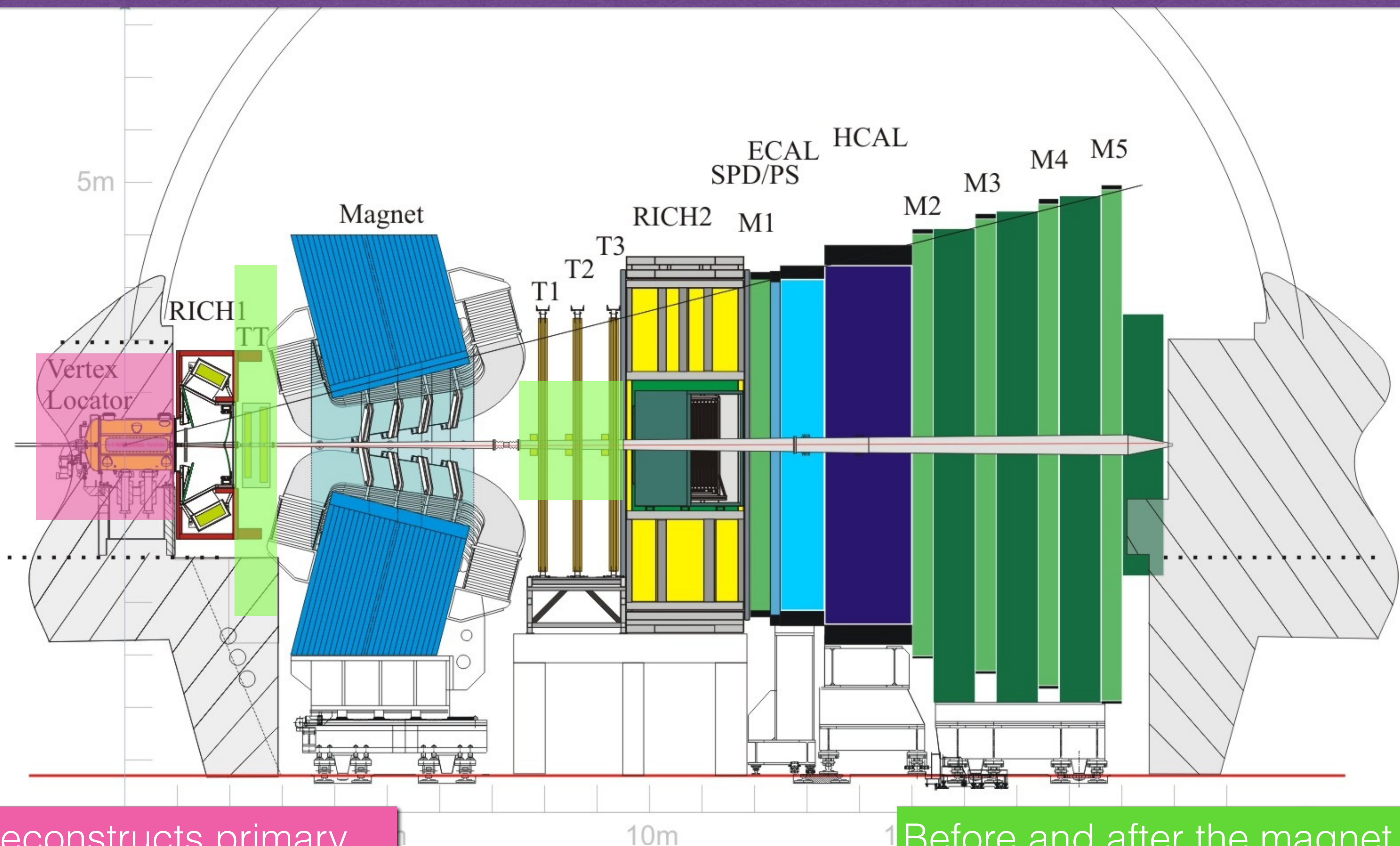

Reconstructs primary and secondary vertices

Before and after the magnet, reconstructing charged particles to determine momentum

The Large Hadron Collider Beauty Experiment (LHCb)

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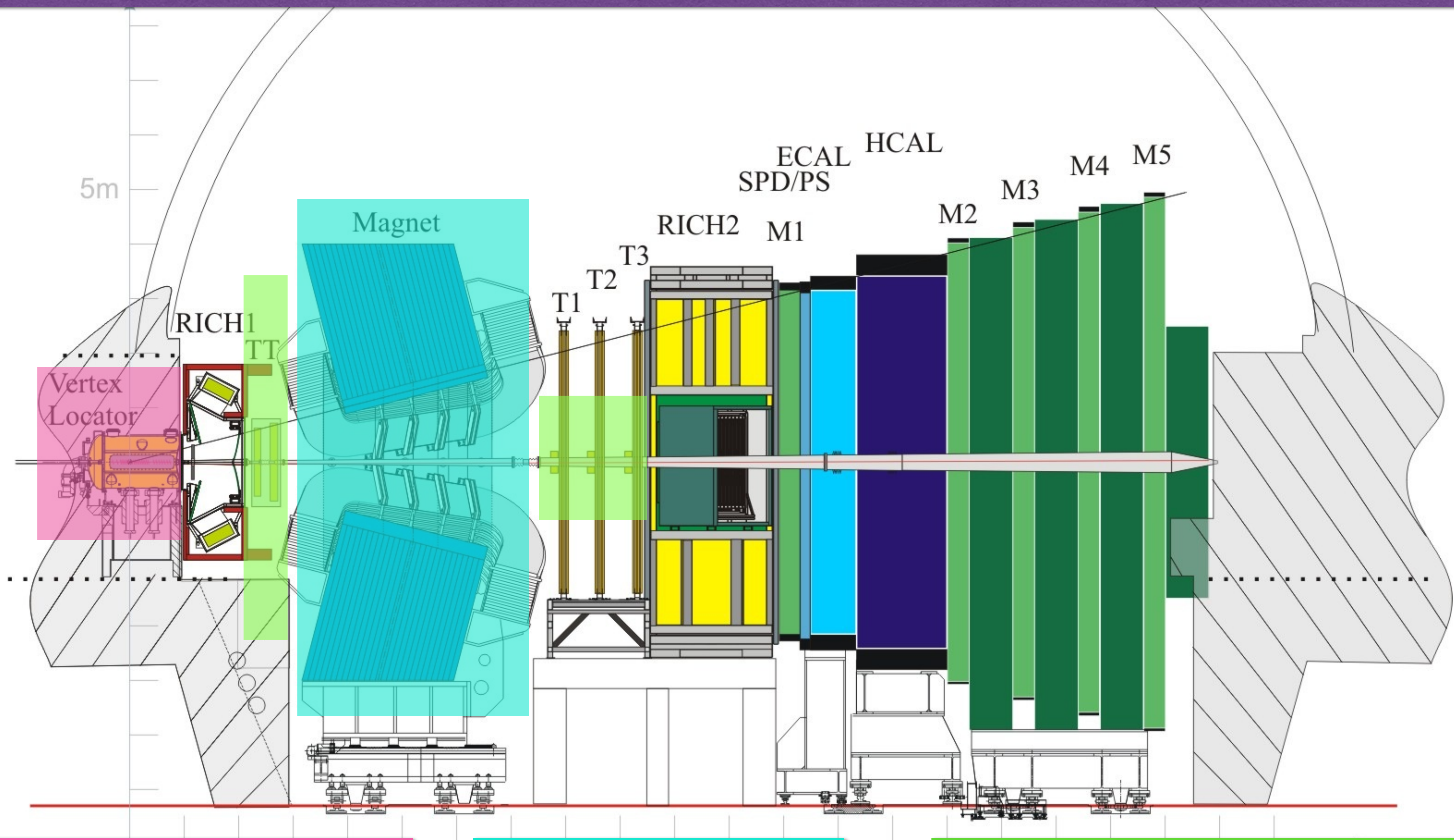


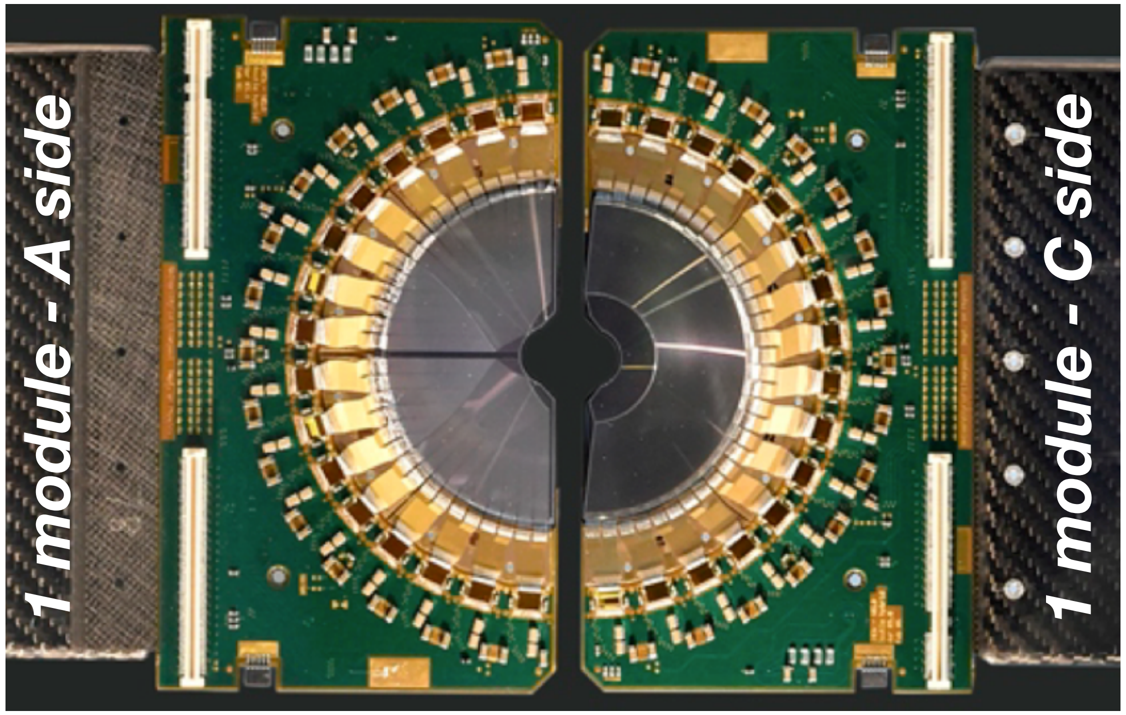
Reconstructs primary and secondary vertices

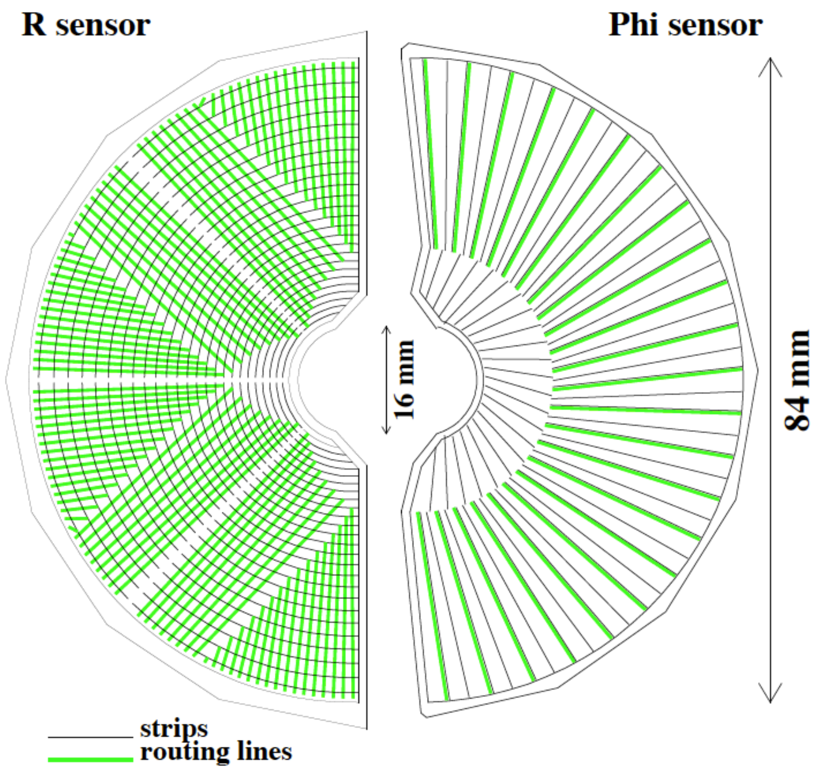
Reversible room temperature dipole magnet, ~4T

Before and after the magnet, reconstructing charged particles to determine momentum

The VErtex LOcator (**VELO**)

Silicon strip detector surrounding the interaction point





The sensors

- 42 double sided modules
  - 1 **R** sensor & 1 **ϕ** sensor per module
  - 300 μm Micron n^+-on-n
    - exception of 2 models with n^+-on-p
    - 2048 strips per sensor

R sensor

- 45 degree quadrants
- Pitch 40-101.6 μm

ϕ sensor

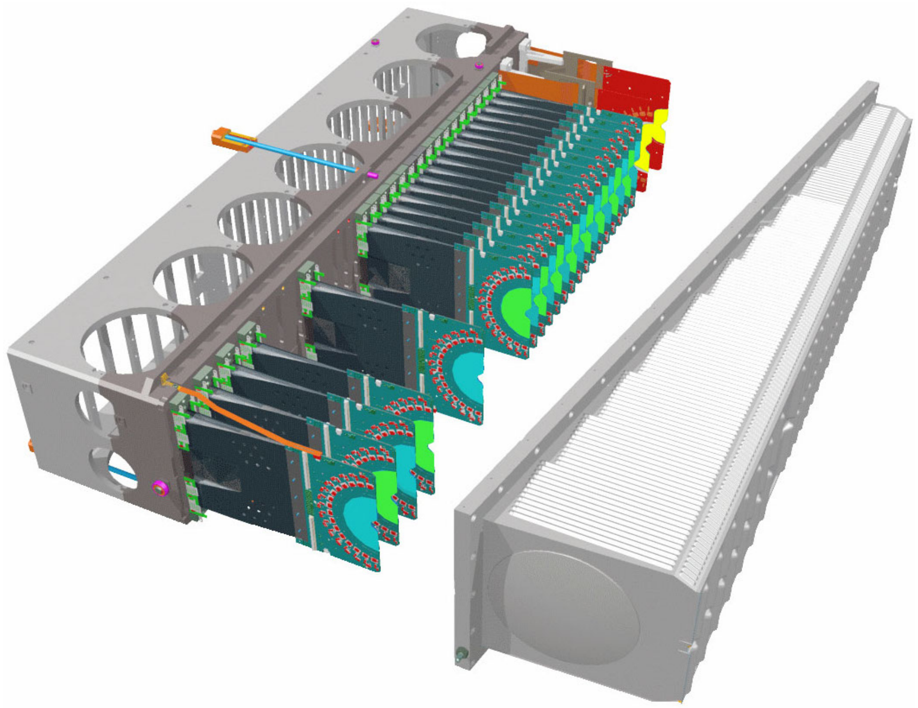
- 2 regions (inner & outer)
- Pitch 35.5-96.6 μm

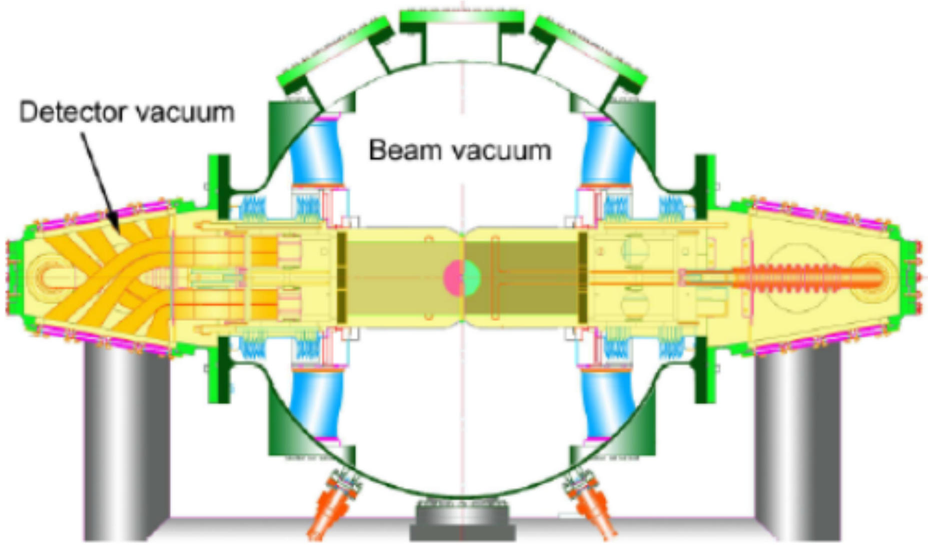
Readout

- Analogue readout by custom made "Beatle" ASICs in the periphery
- Routing lines to carry signal from inner strips

The VErtex LOcator (**VELO**)

Silicon strip detector surrounding the interaction point





Bi-phase CO_2 cooling

- Sensors mounted either side of a thermally conductive spine
- Operation at -30°C with sensors -10°C

Separated in two retraceable halves, situated inside LHC Vacuum

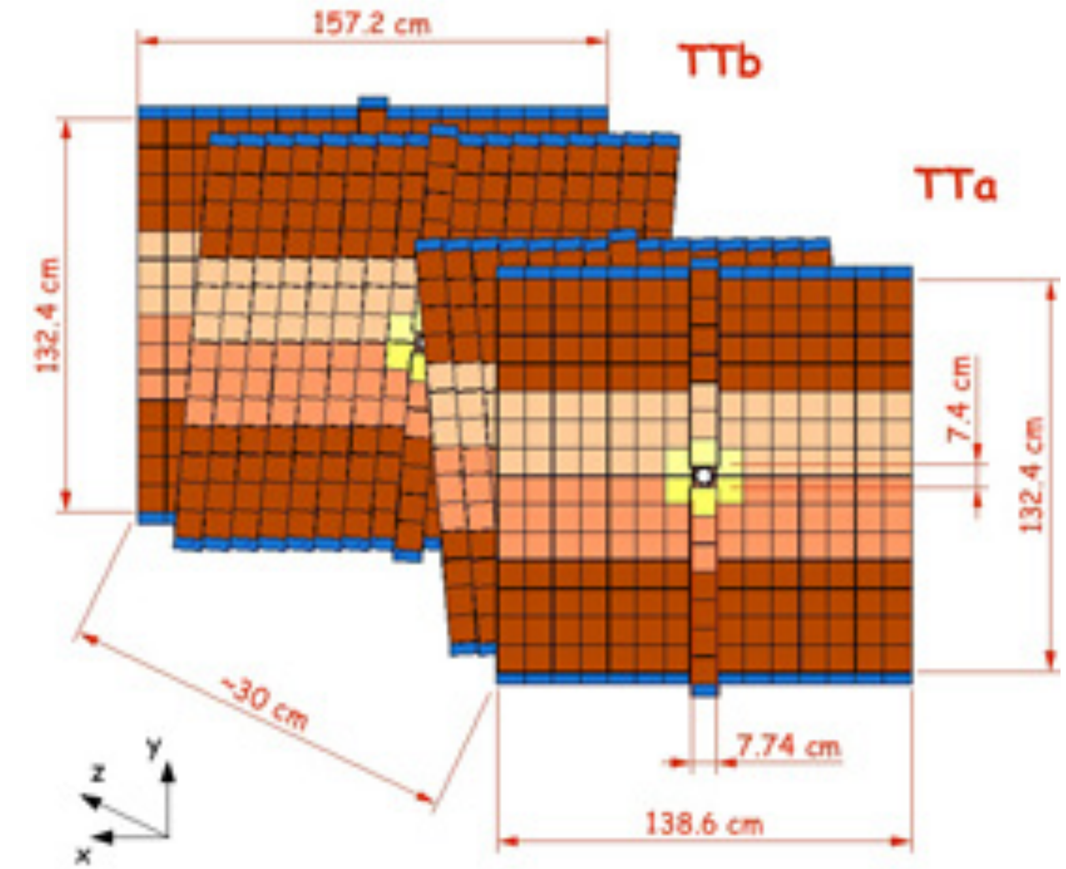
- Secondary VELO vacuum, separated by 300 μm Al RF foil
- Retractable halves
  - Open during beam injection
  - Closed during stable beam
    - Closest active strip 8 mm from the beam

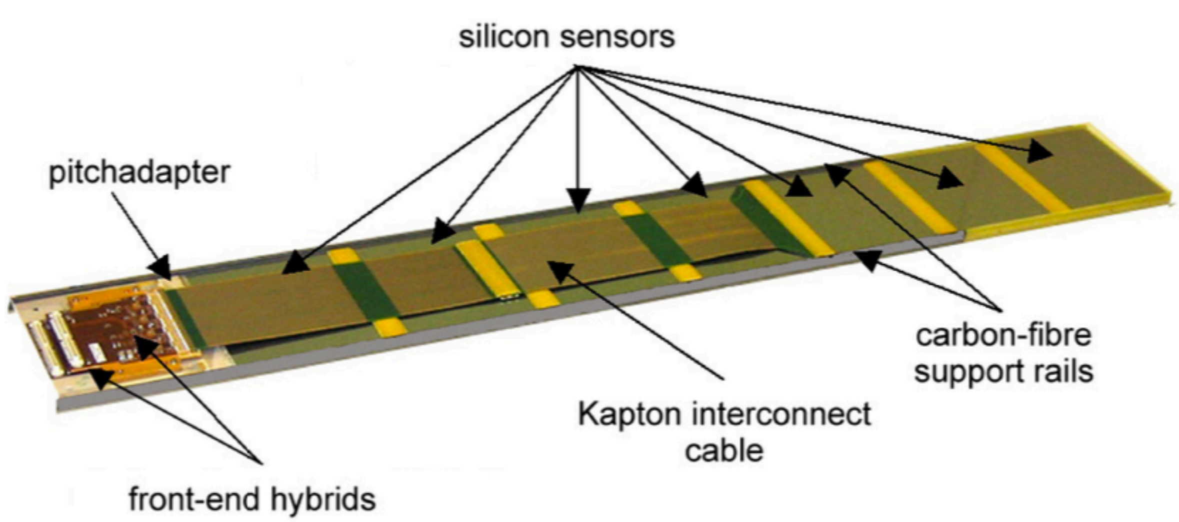
Silicon Tracker (**ST**) - Turicensis Tracker (**TT**)

Silicon strip detector upstream of the magnet

The sensors

- 4 planar detector planes
  - titled at 0°, +5°, -5° & 0°
- 500 μm p+-on-n HPK
  - pitch 183 μm
- Grouped readout sectors
  - depending on location w.r.t beam
  - readout range up to 37 cm
  - Beatle ASICs outside acceptance of LHCb



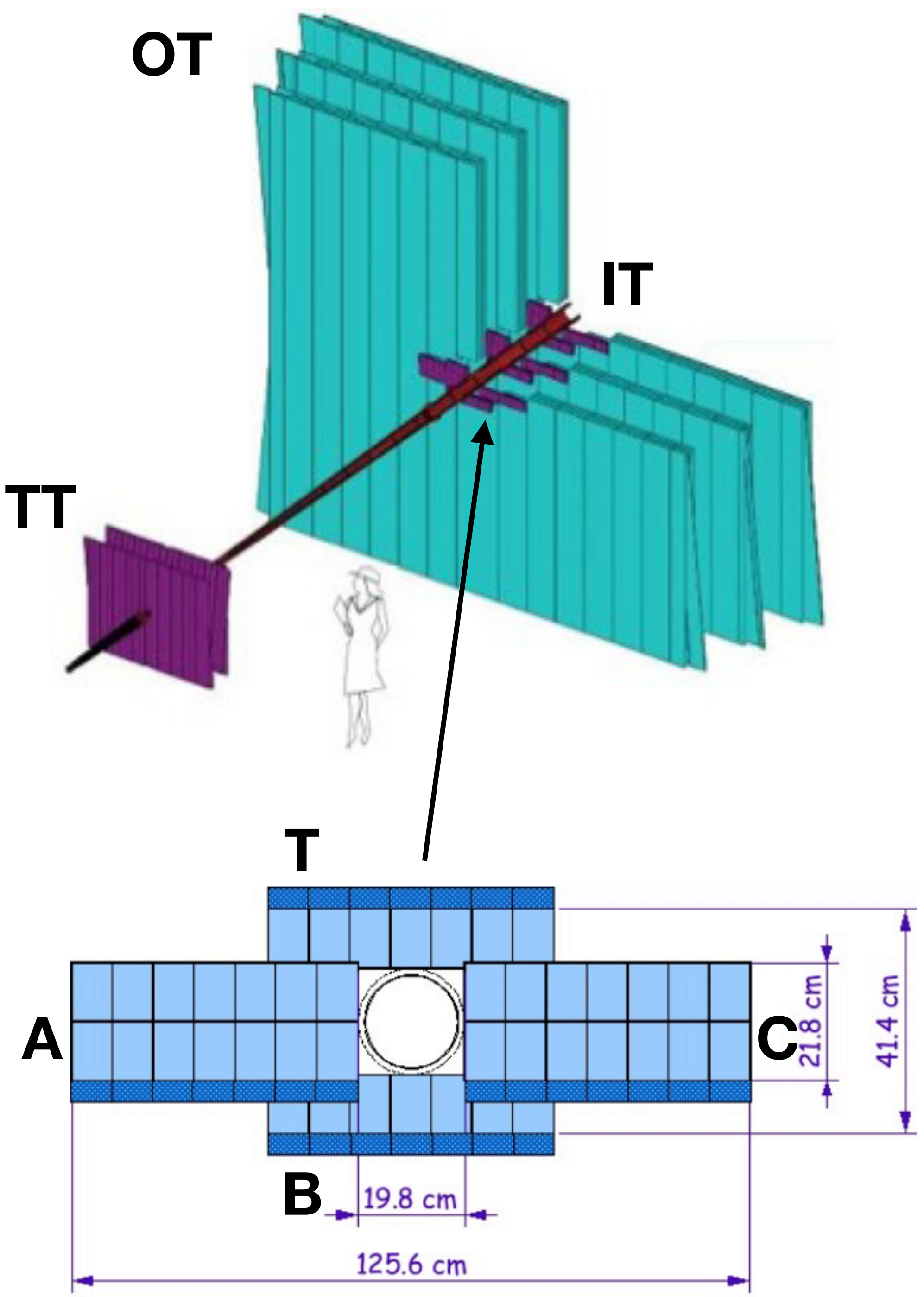


Cooling

- Mounted on common cooling plate
  - plant operates at 0°C.
  - sensors maintained at 8°C

Silicon Tracker (**ST**) - Inner Tracker (**IT**)

Silicon strip detector downstream of the magnet



The sensors

- Three stations in z
  - 4 detector planes
  - titled at 0°, +5°, -5° & 0°
- p^+-on-n HPK sensors
  - 198 μm pitch

Photograph of A & C side style module

A & C side

- 410 μm thick
- 2 sensors bonded together
- 22 cm long readout

Top & Bottom

- 320 μm thick
- 1 sensor
- 11cm long readout

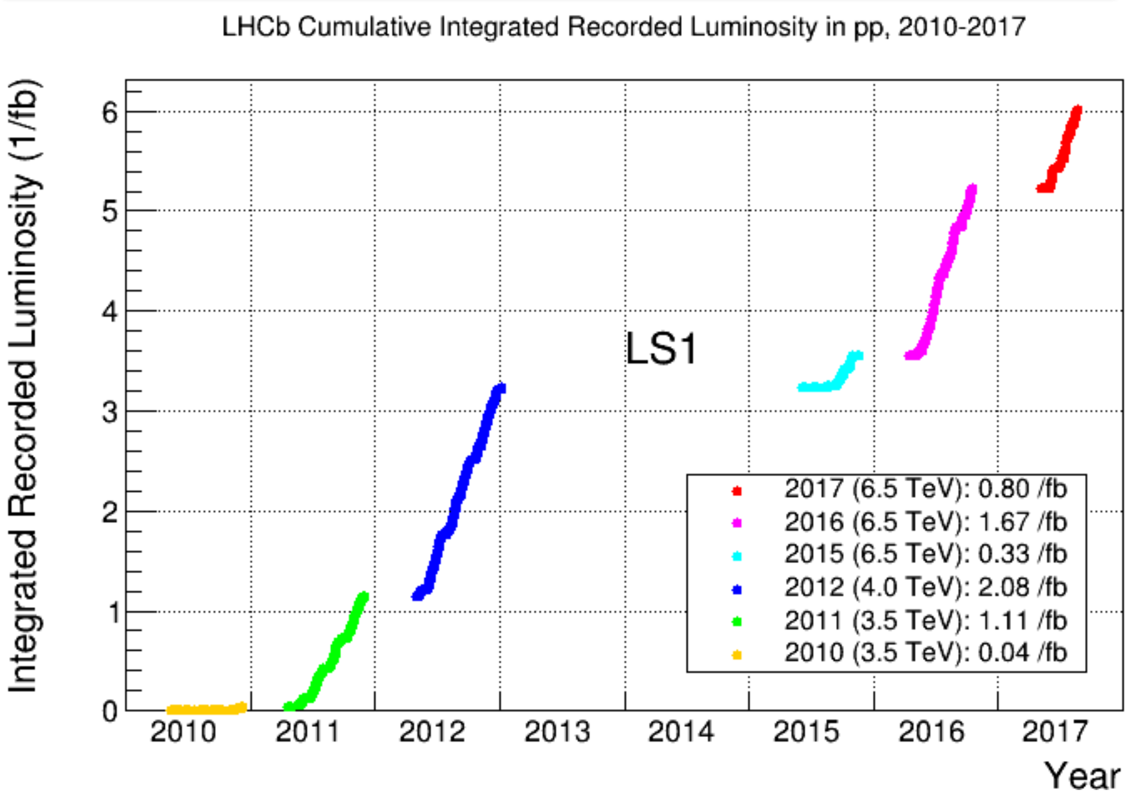
Cooling

- Same as TT

Challenges and Monitoring Methods

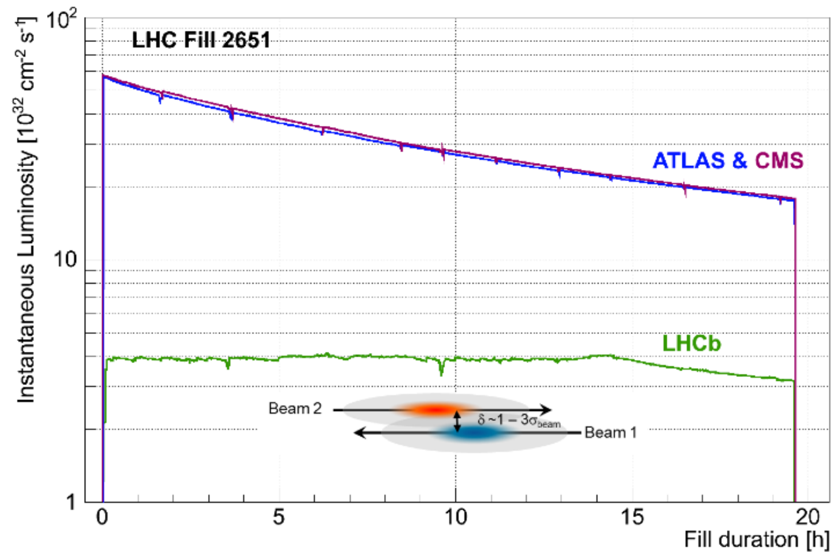
Increasing luminosity has damaging effects on our detectors, therefore we need to monitor and adjust running conditions to achieve the best performance.

Luminosity



- ~**6 fb^{-1}** recorded in total
- <**1 fb^{-1}** recorded this year

Luminosity Levelling



Monitoring of Radiation Effects

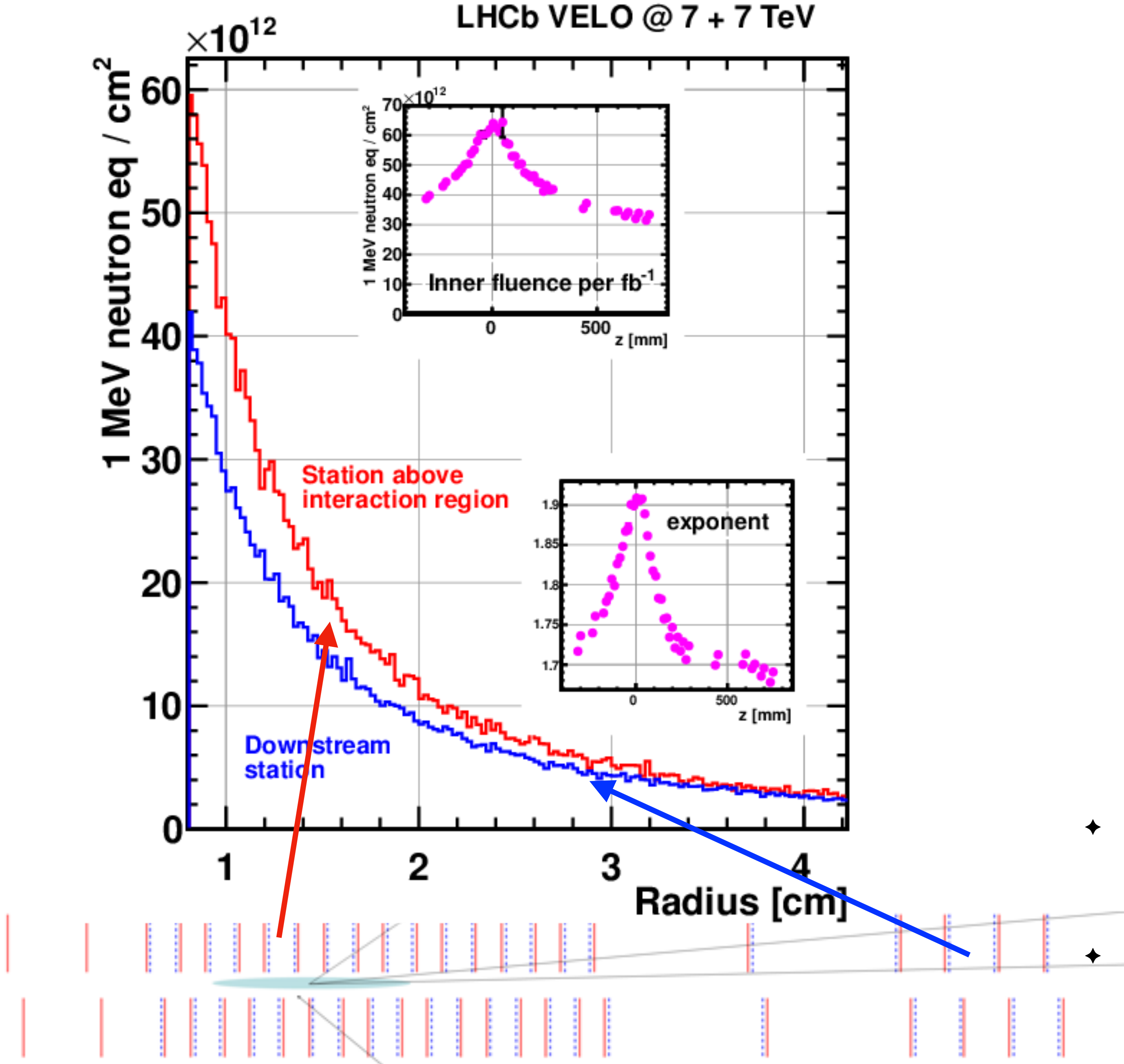
- Weekly IV scans
- Four Charge Collection Efficiency scans per year
  - Effective Depletion Voltage
  - Cluster Finding efficiency

Forward geometry of the LHCb detector leads to a highly non uniform radiation environment

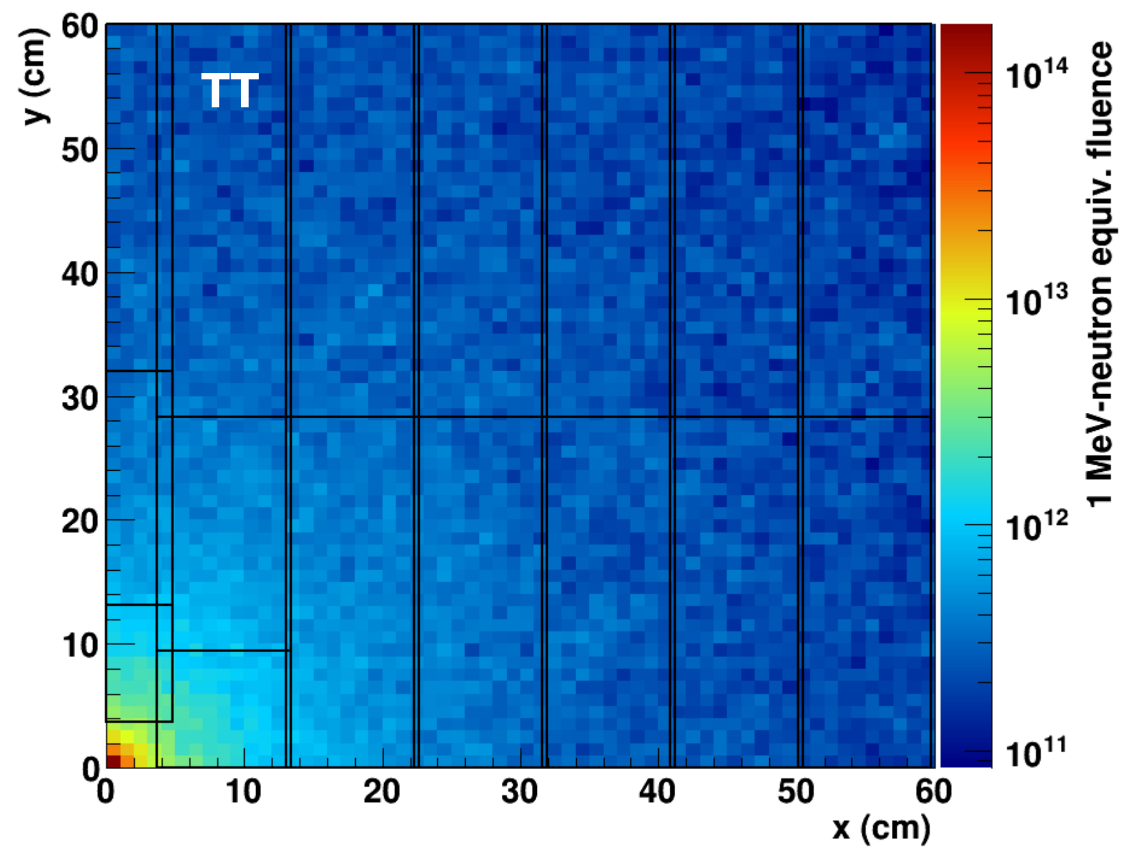
Particle Fluences

VELO exposed to a fluence of the order of 5×10^{13} 1MeV n_{eq}/cm^2 per fb^{-1}

Fluence per fb^{-1} expected in Run II



ST can expect ~10^{12} 1MeV n_{eq}/cm^2 per fb^{-1}



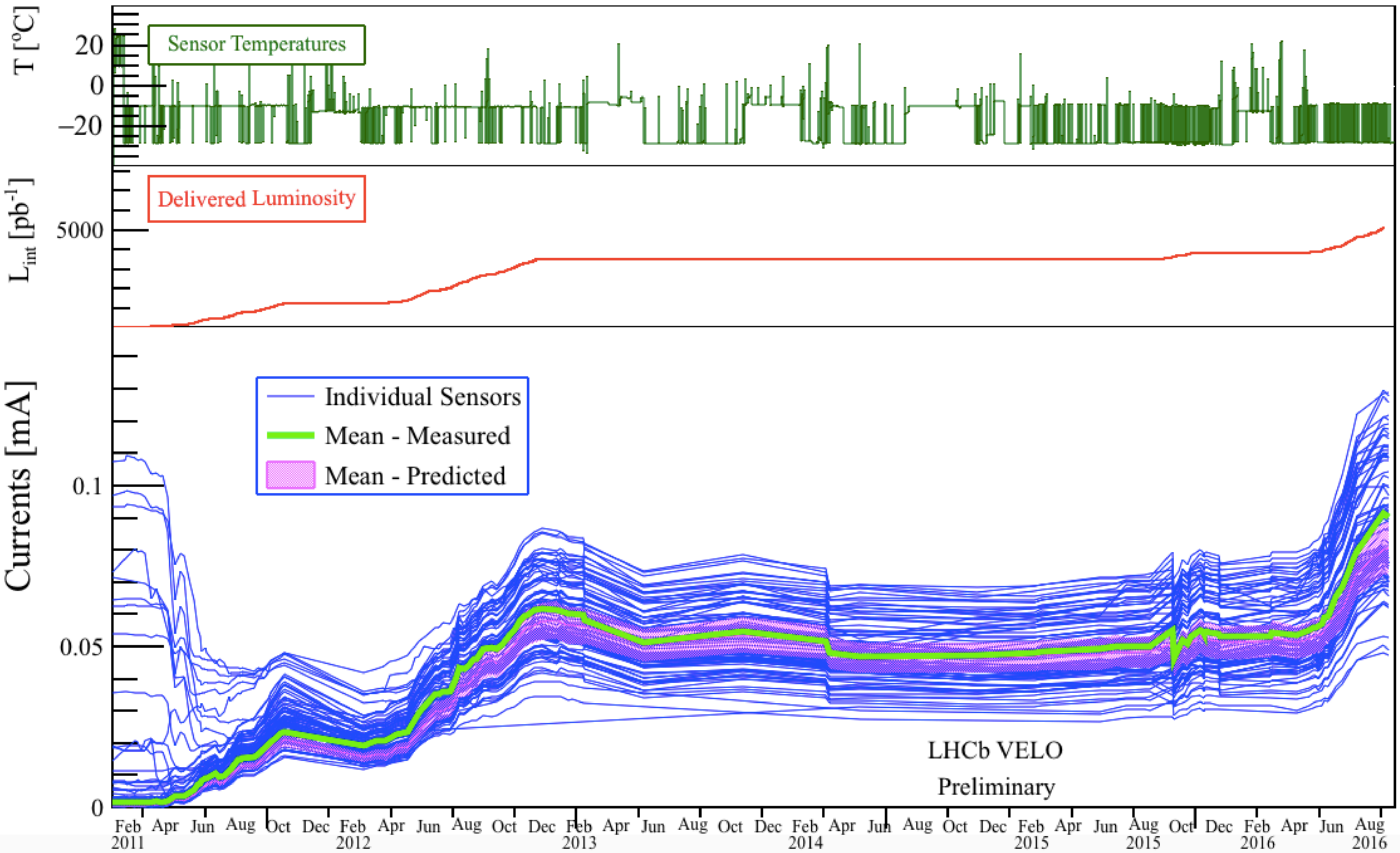
Fluence map in TT after 10 years if running (2 fb^{-1}/ year)

- **TT** - three orders of magnitude between highest and lowest flux regions
- **IT** - Expects one order of magnitude smaller than the peak fluence of **TT** and the profile differs due to the magnetic field

- **VELO** - Fluence varies exponentially with radius

Leakage Currents - **VELO**

Linear increase in leakage currents as a luminosity increases



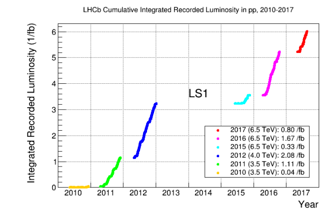
Variations in currents:

- Partly due to the different sensor positions relative to the interaction point
- Dominated by temperature variations between the sensors

Leakage Currents - **VELO**

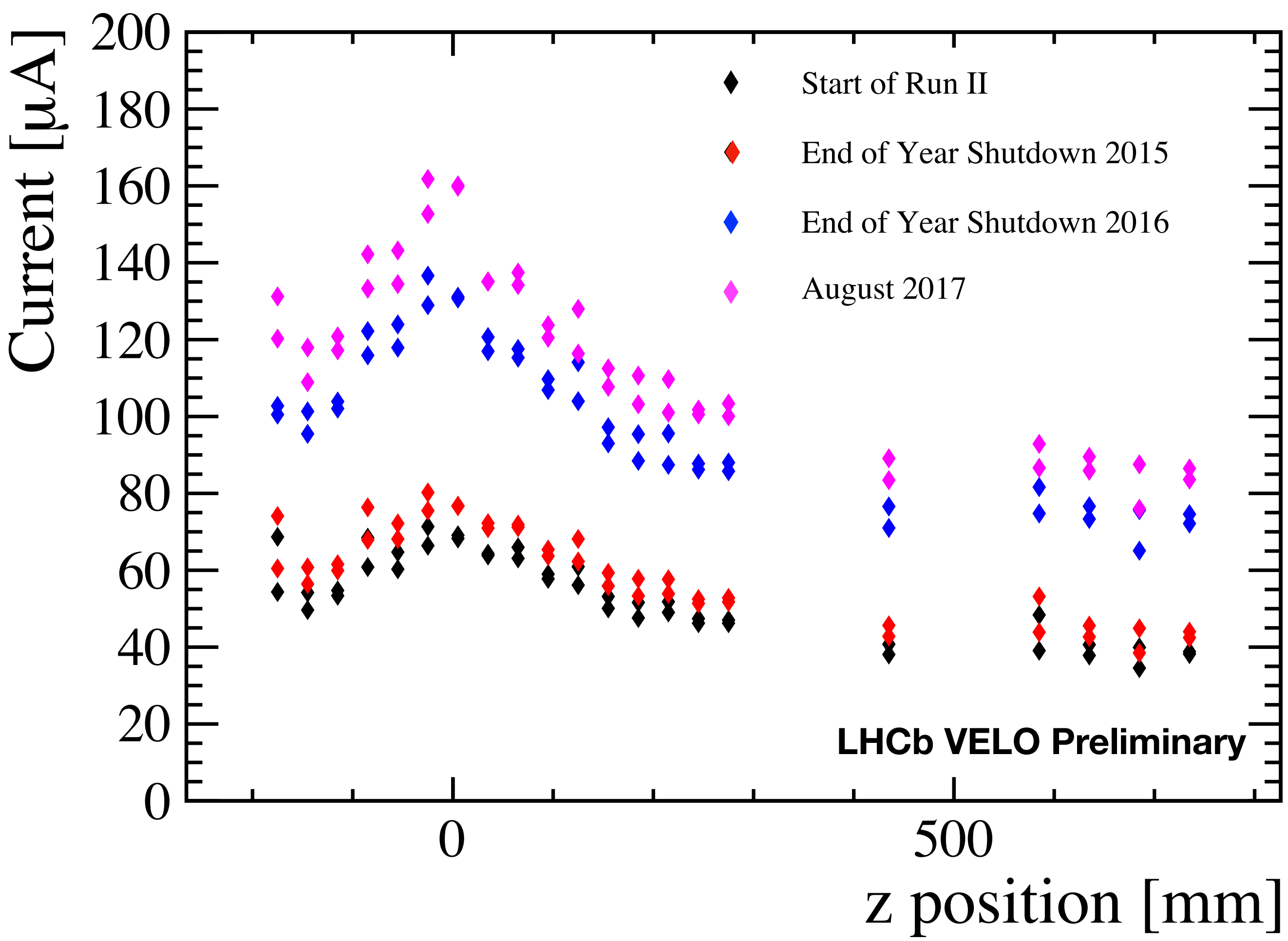
Leakage current as a function of the sensor z position

- The current is higher for sensors closest to the interaction region

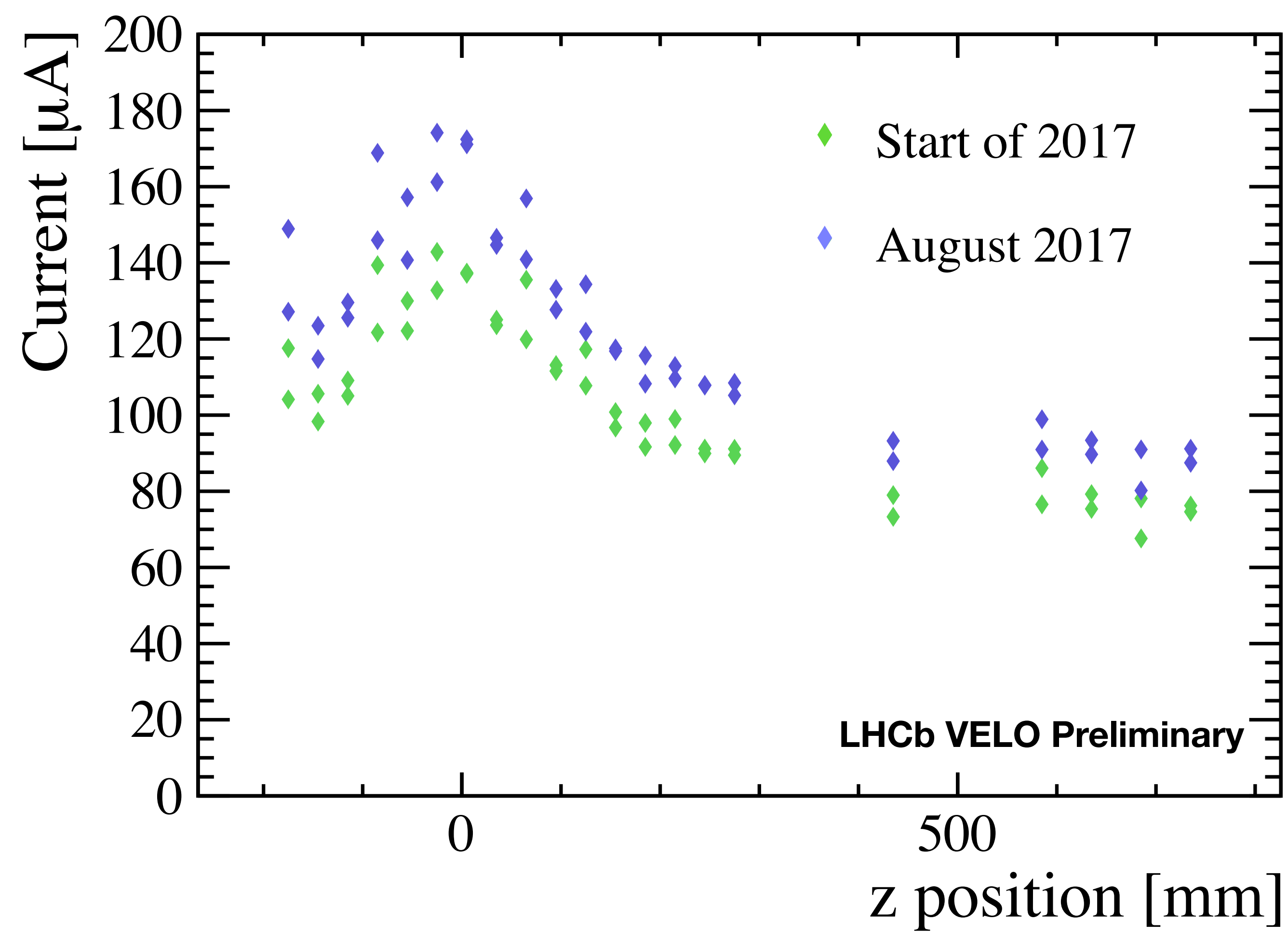


2017 (6.5 TeV): 0.80 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb

200V normalised to -10°C

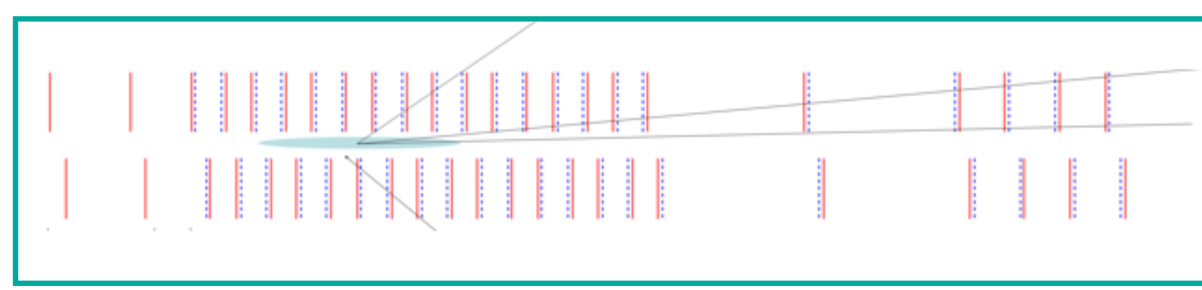


300V normalised to -10°C



Operation Voltages

- **2016**: 150-200V (250V for n-on-p) depending on proximity to interaction region
- **2017**: 300V for all sensors

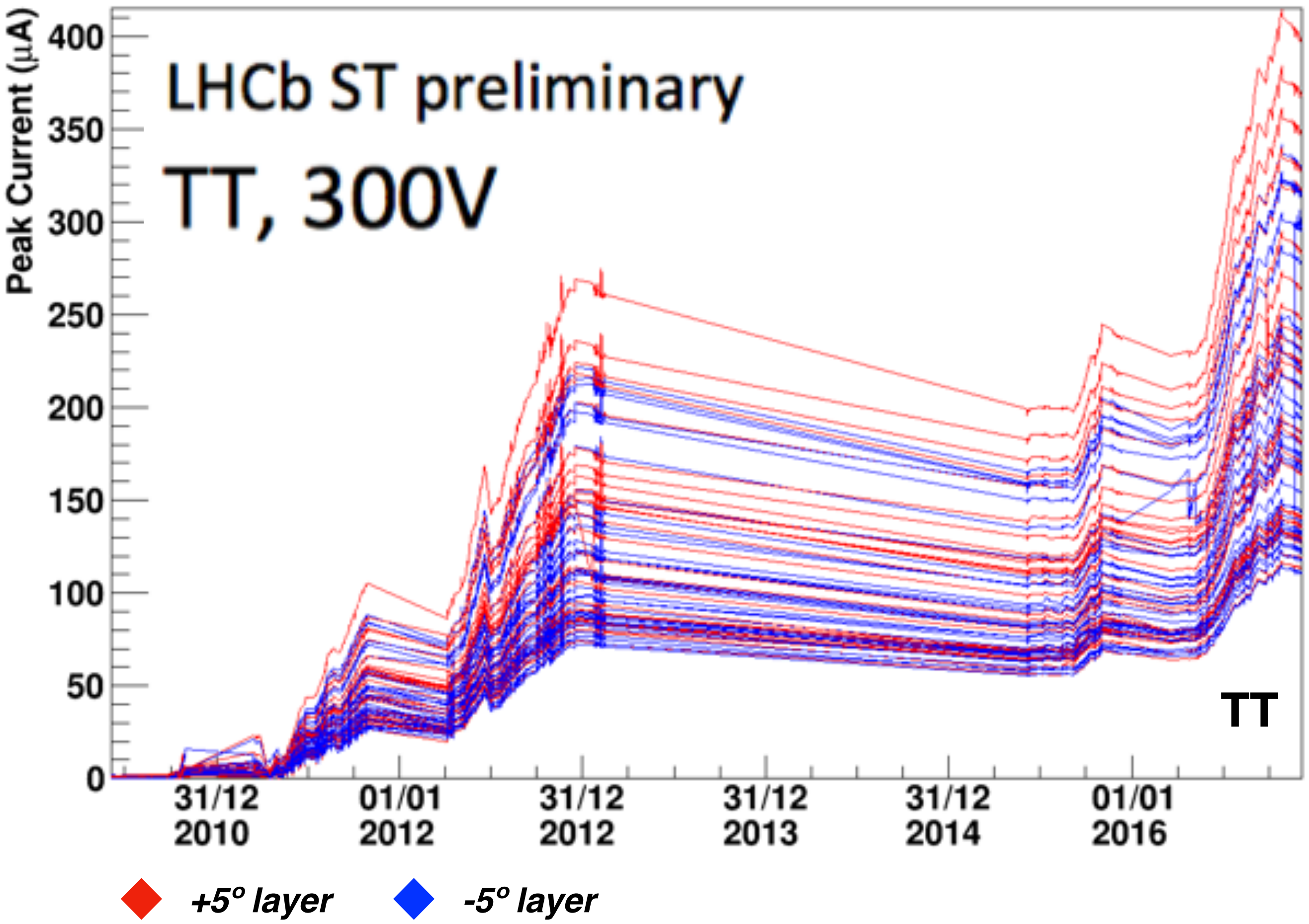


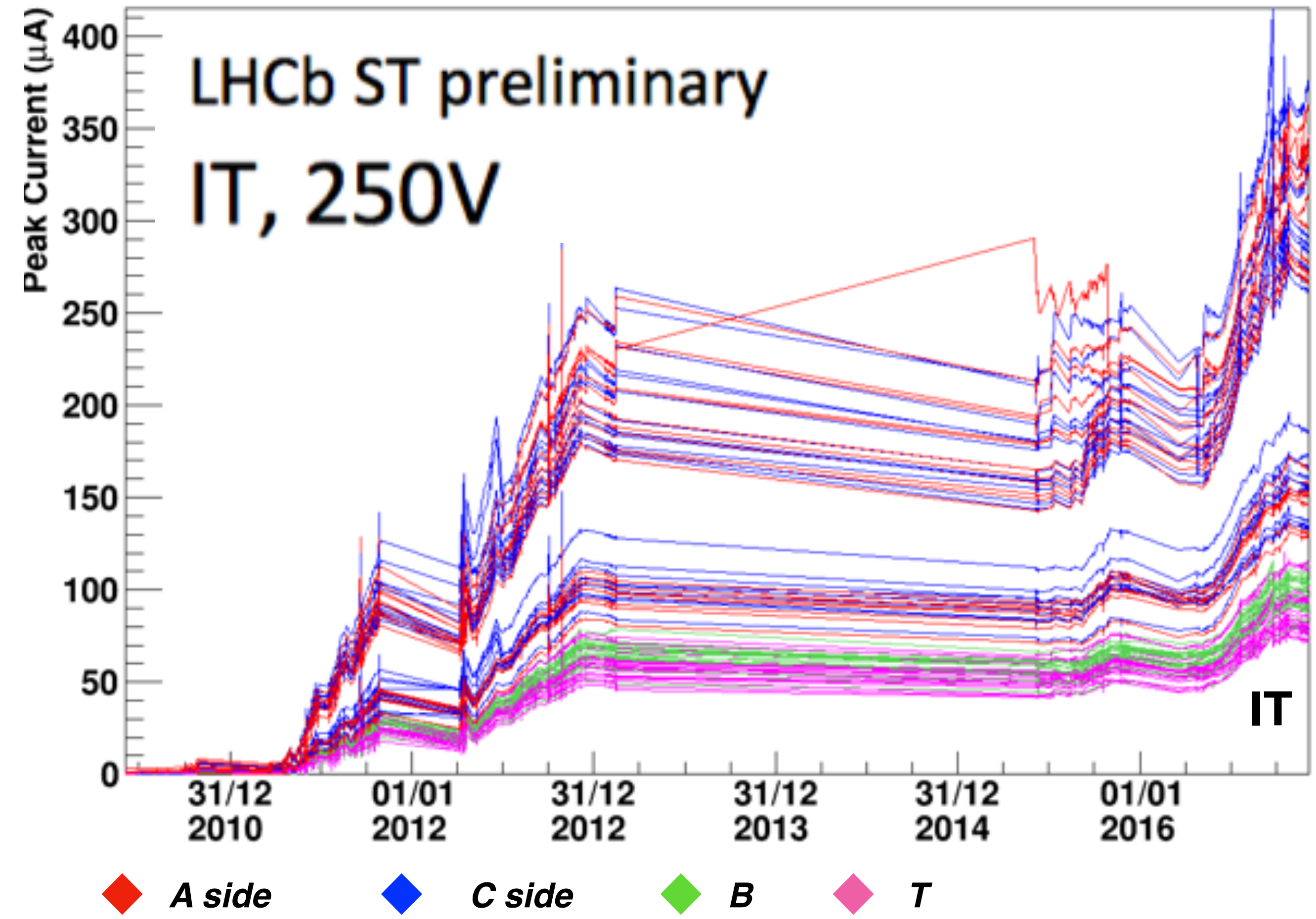
Layout of the VELO modules, interaction region shown in the shaded area

Leakage Currents - **ST**

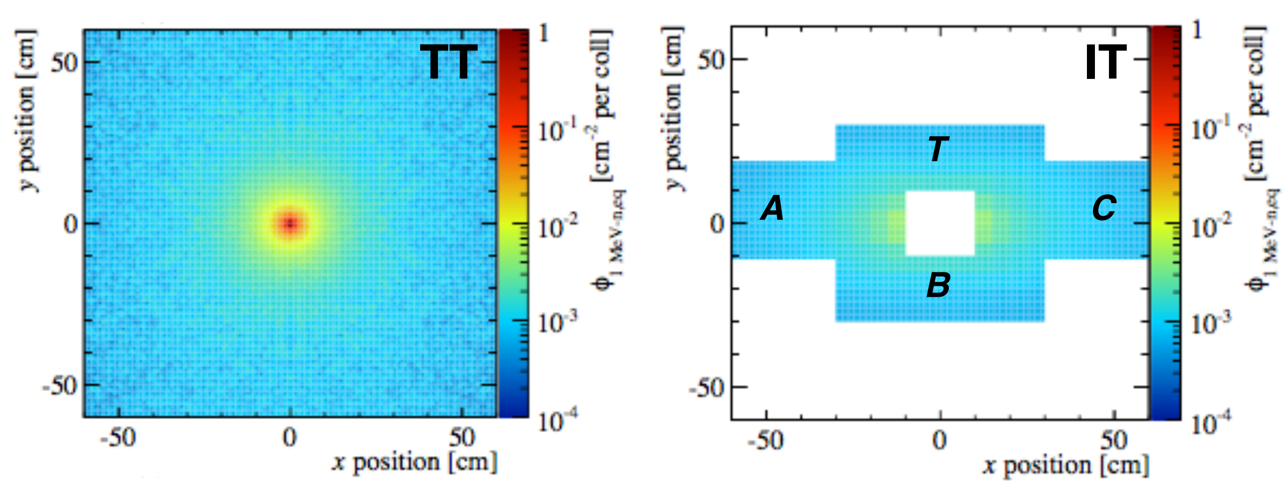
Linear increase in leakage currents as luminosity increases

Normalised to 8°C





- Similar leakage currents to the **VELO**
- Visible dips in currents due to Long Shutdowns and Technical Stops
- **TT** operates at a higher bias than **IT** due to differences in sensor thicknesses

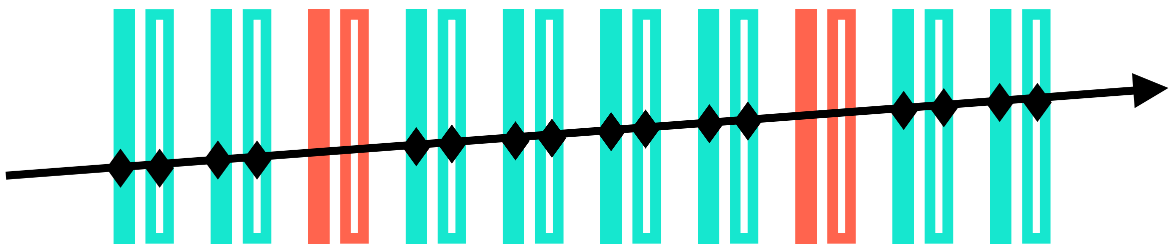


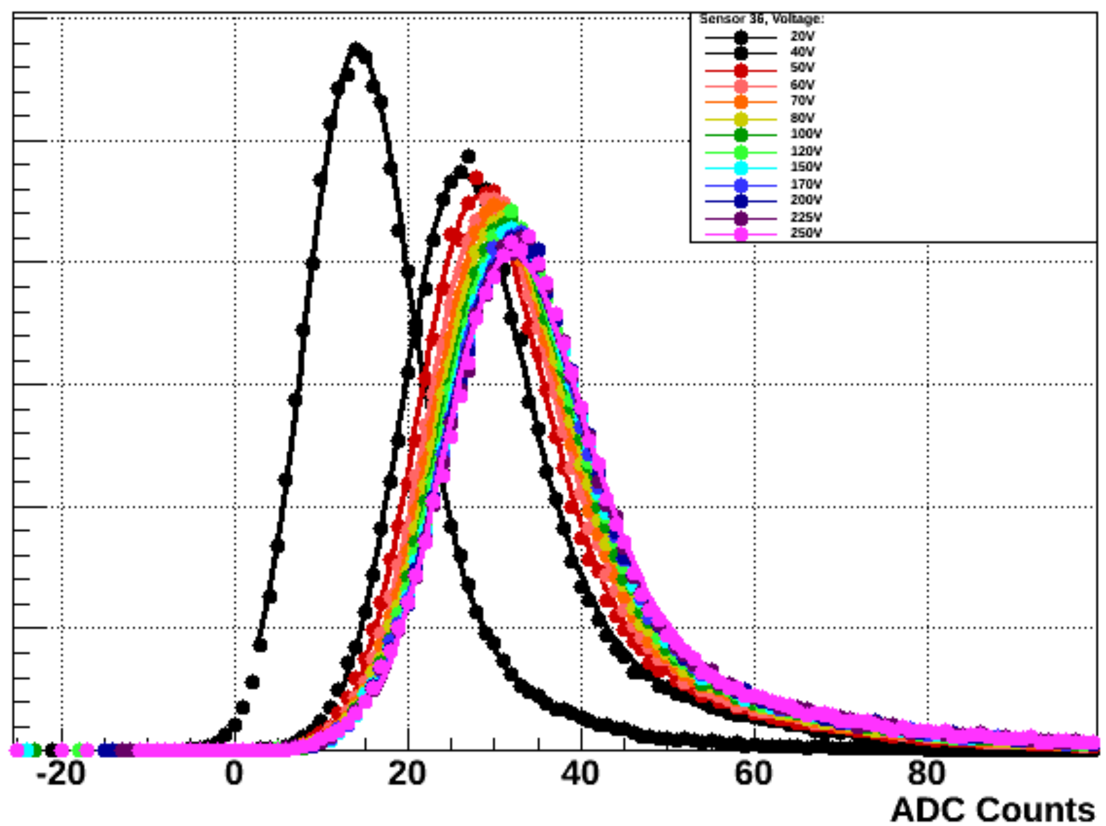
Simulation showing the fluence variations across the sensor planes

Charge Collection Efficiency - EDV - **VELO**

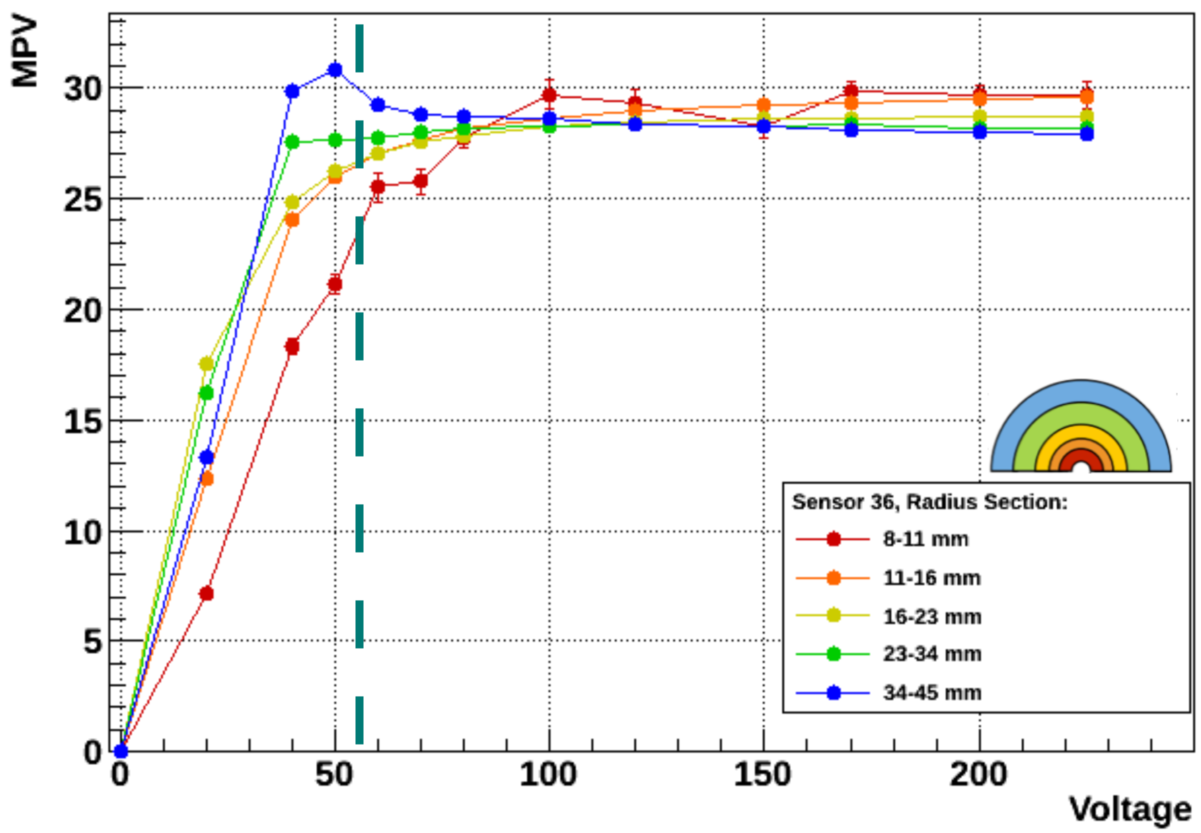
Charge Collection Efficiency Scans used to measure Effective Depletion Voltage

- Collision data recorded for every 5th module operated at a range of voltages, all other modules run at nominal voltage
- MPV is calculated using the Landau fit to the ADC distribution





ADC distributions for increasing bias voltage steps



MPV as a function of bias depending on radial bin

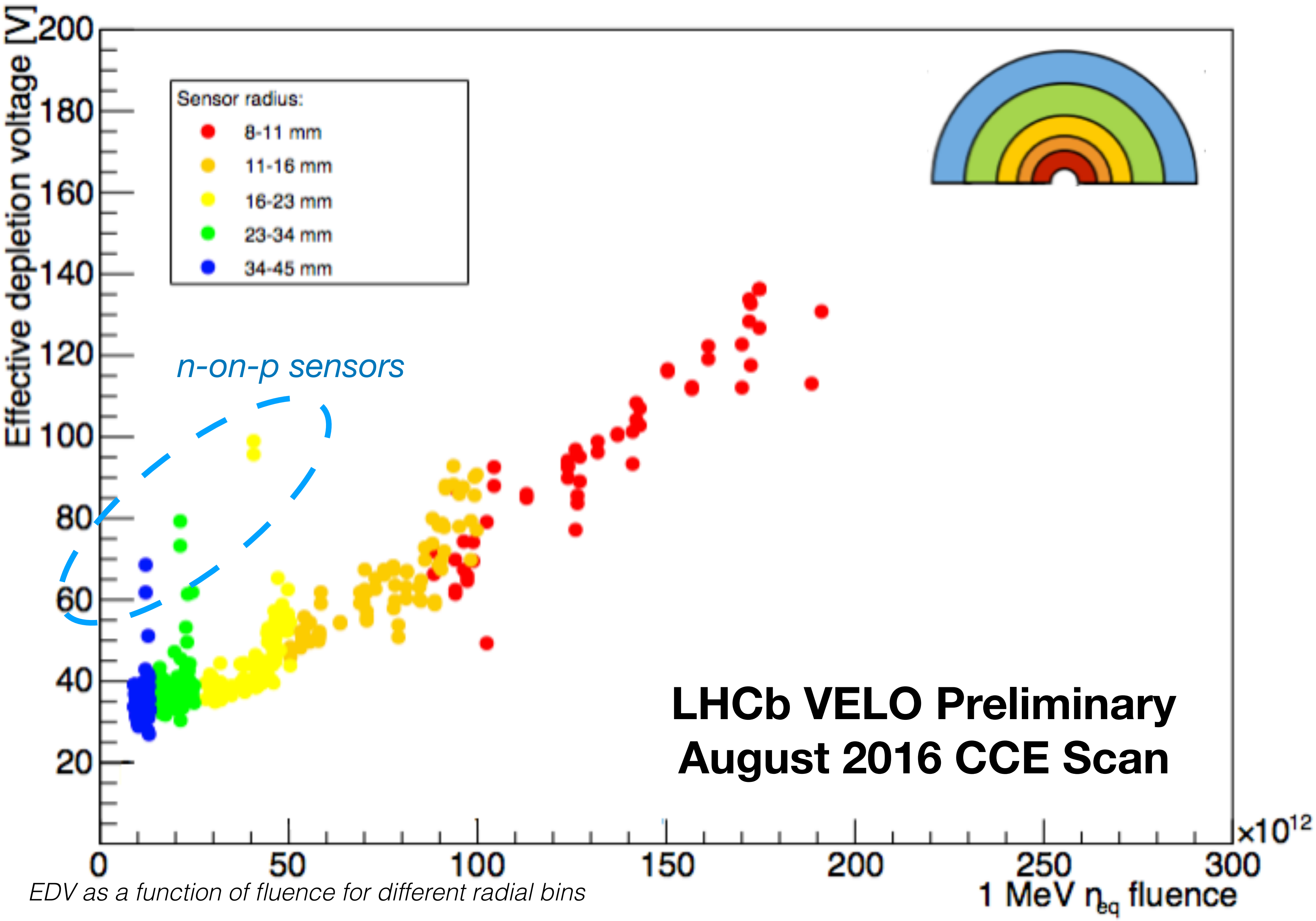
EDV is the voltage at which the MPV of a sensor is equal to 80% of the maximum

- Operational bias voltage is always set higher than the EDV

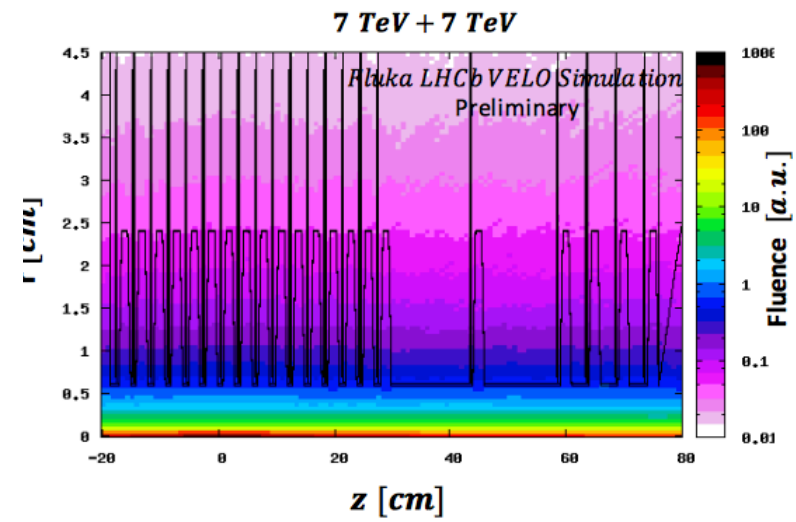
Charge Collection Efficiency - EDV - **VELO**

Effective Depletion Voltage as a function of radius

August 2016



EDV as a function of fluence for different radial bins



Simulated fluence profile

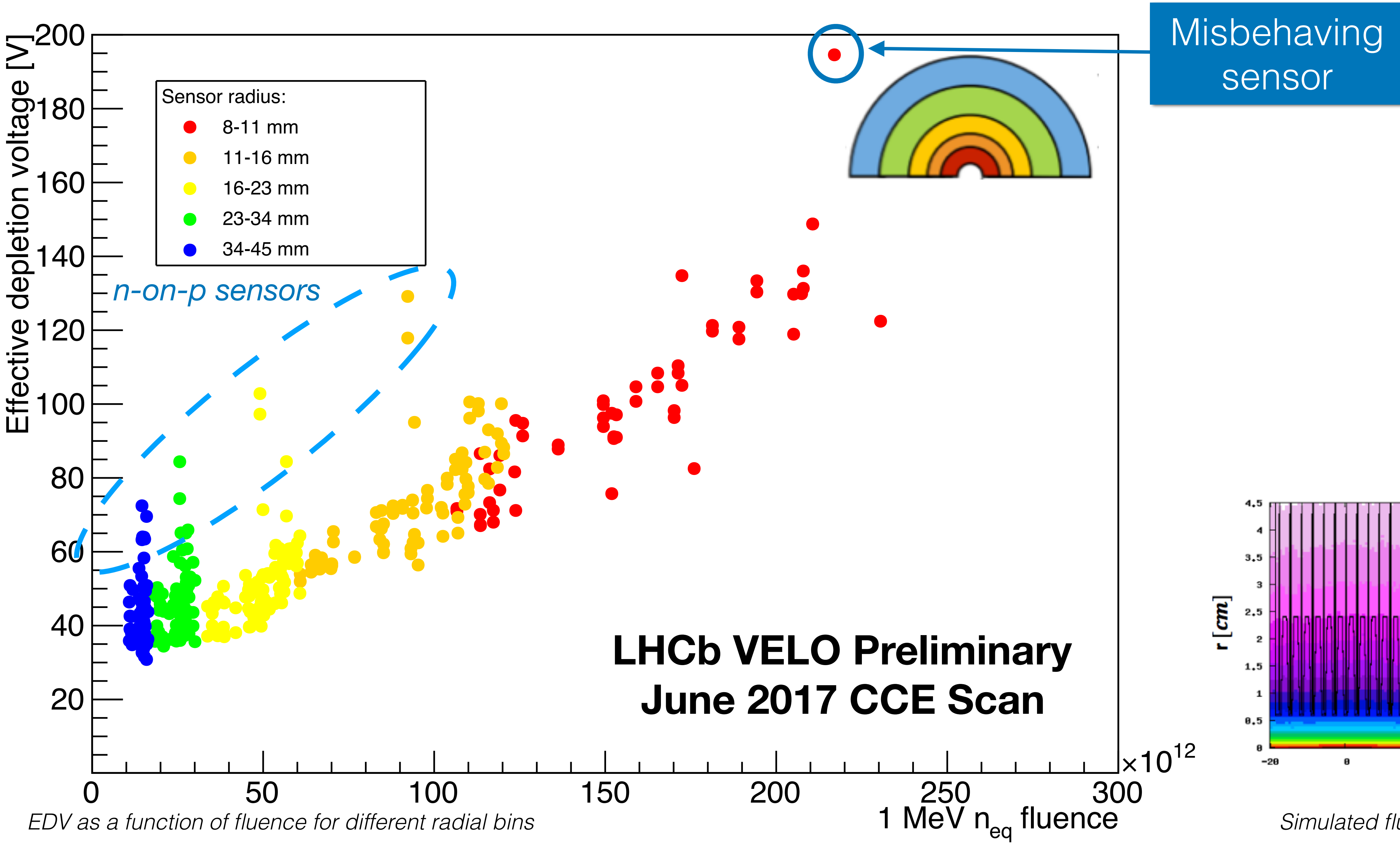
Highly non unform irradiation profile across the sensors

- The effective depletion voltage is higher in the inner most regions, where the dose is higher

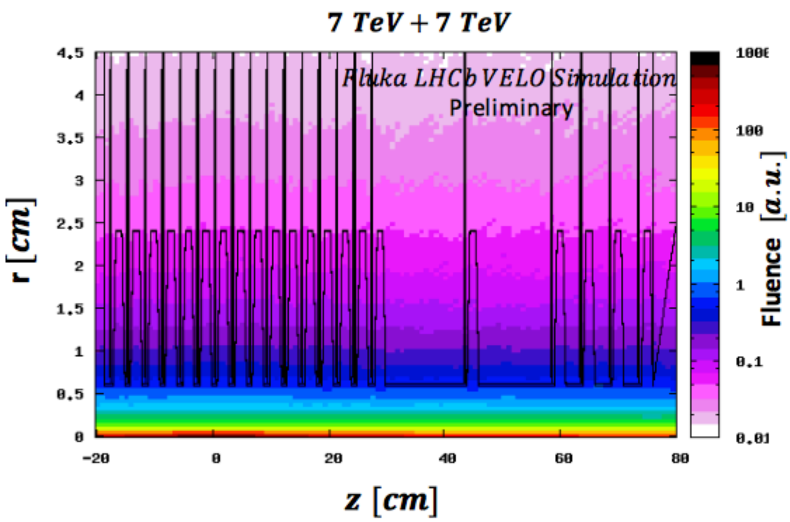
Charge Collection Efficiency - EDV - **VELO**

Effective Depletion Voltage as a function of radius

June 2017



EDV as a function of fluence for different radial bins



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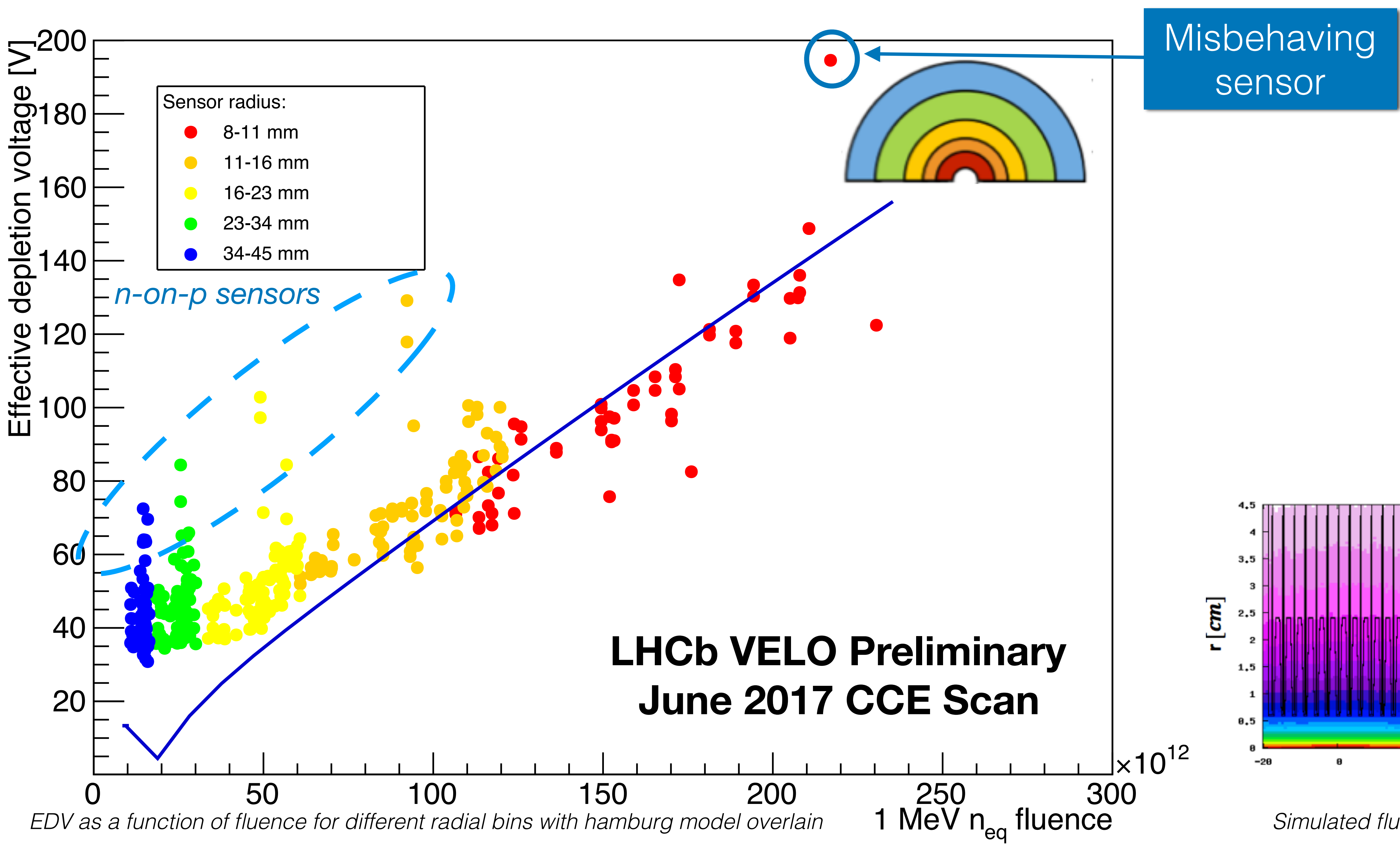
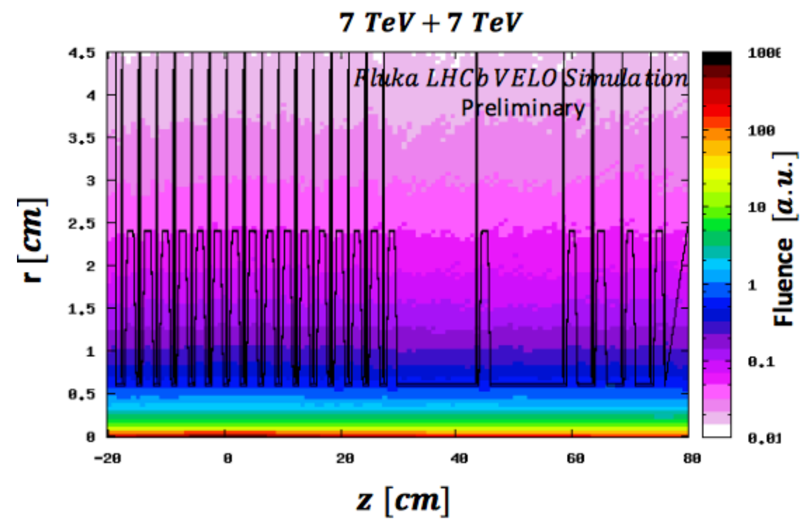
Charge Collection Efficiency - EDV - **VELO**

Effective Depletion Voltage as a function of radius

June 2017



EDV as a function of fluence for different radial bins with hamburg model overlain



Simulated fluence profile

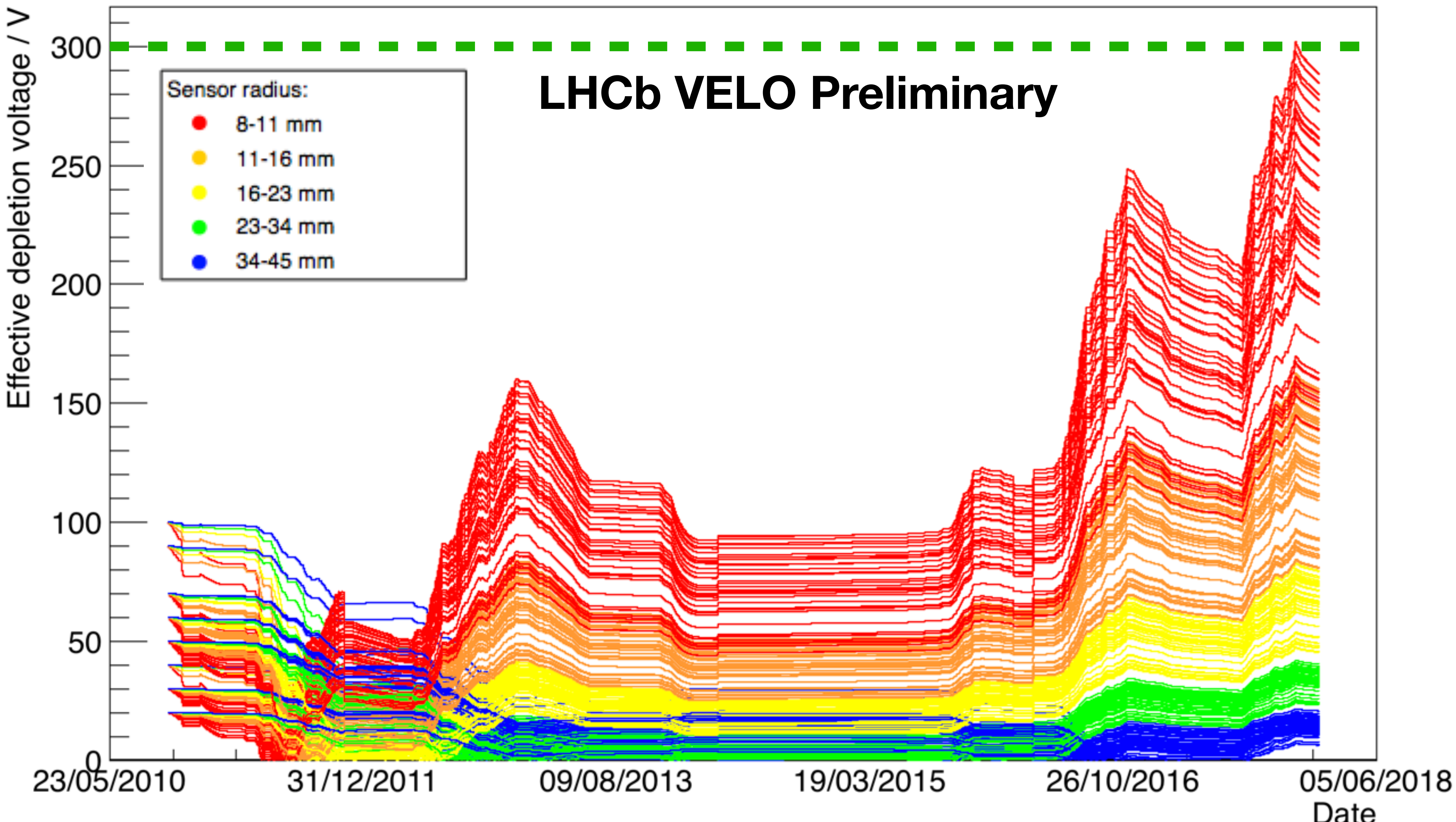
The Hamburg model and data are in reasonable agreement in the high fluence region

- Which can be used to predict the voltages required for future periods of operation

Charge Collection Efficiency - EDV - **VELO**

Prediction of Hamburg model also made for individual sensors to estimate EDV

- Simulated using the expected fluence at the tip of each sensor region (fluence is 1.4 times higher than middle)



Predicted Effective Depletion Voltage over time

This lead to the operational bias voltage of all sensors being set to 300V

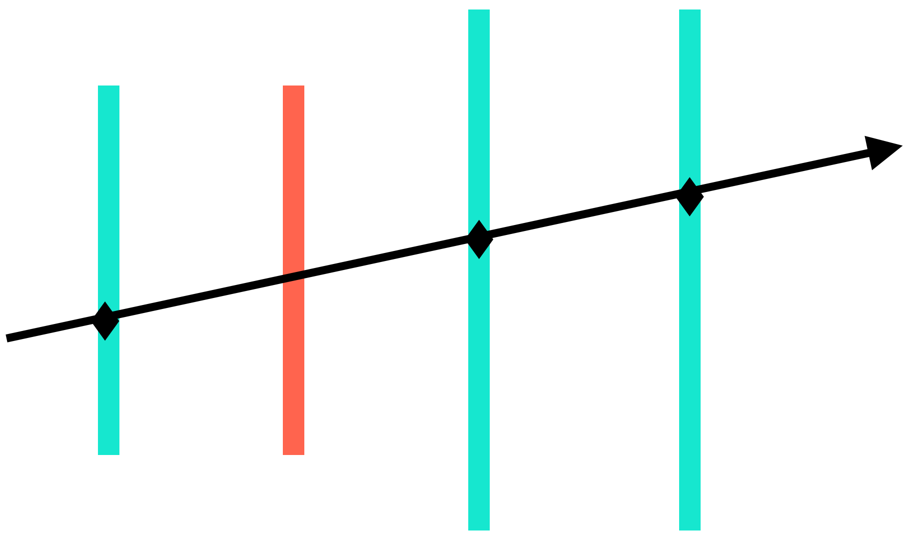
- VELO sensors can be operated up to 500V
- Expect to be able to fully deplete the sensors until the end of Run II

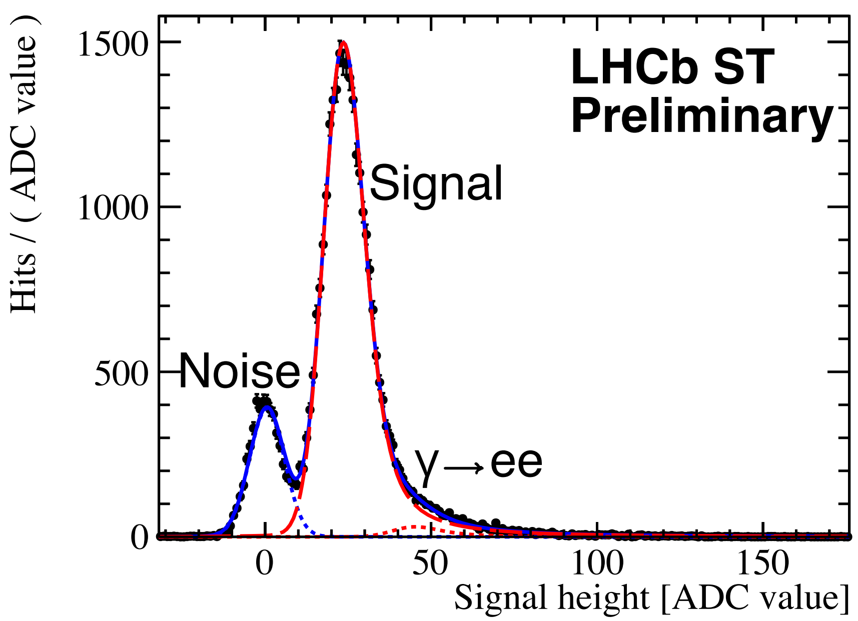
Charge Collection Efficiency - EDV - **ST**

Charge Collection Efficiency Scans for **TT** and **IT** are similar in method to **VELO**

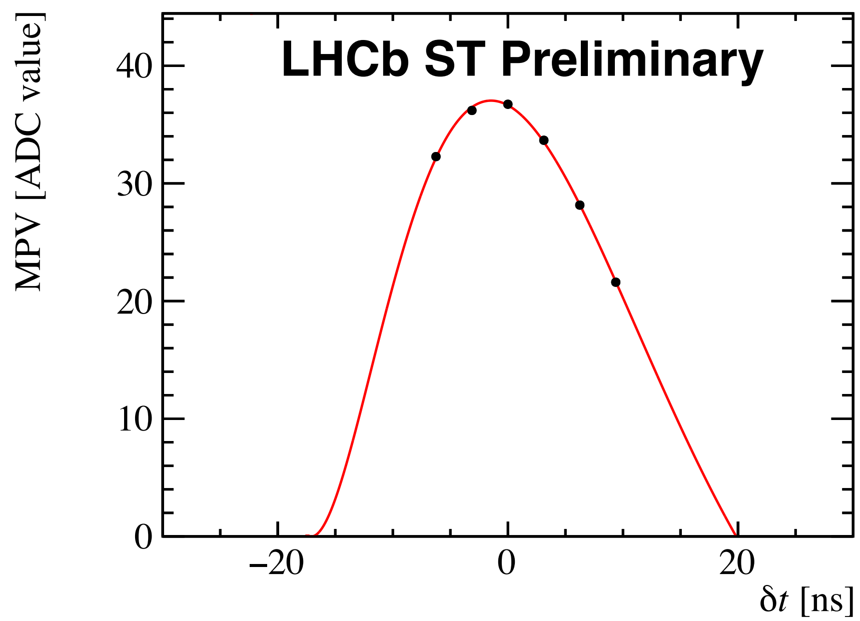
Example for **TT**

- Collision data recorded with one test module operated at a range of voltages
- MPV measured using the Landau fit to the ADC distribution
- Repeat for different time shifts to obtain the pulse shape.
- Charge calculated by integrating the pulse shape.

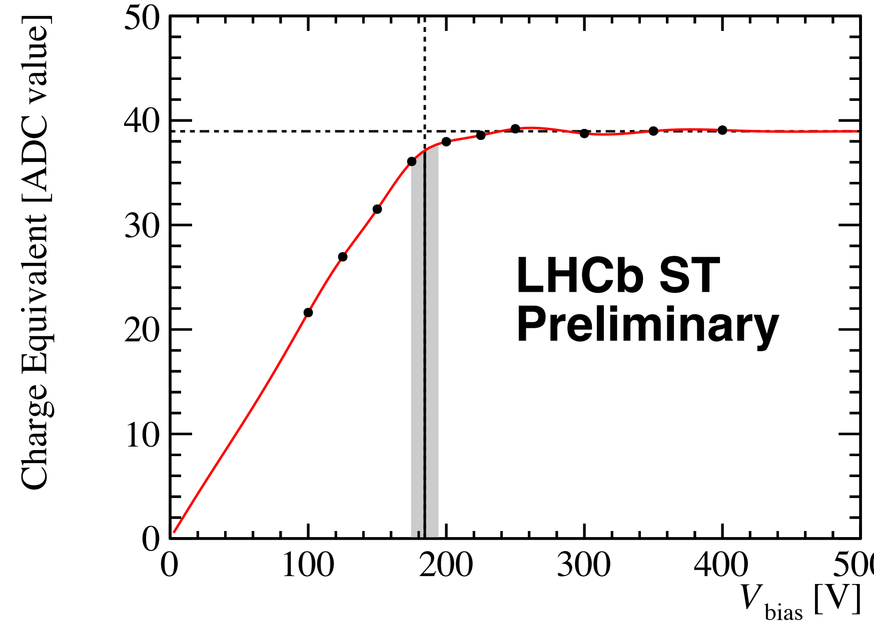




ADC distribution



MVP with varying signal sampling time, where the charge is estimated by integrating the pulse shape



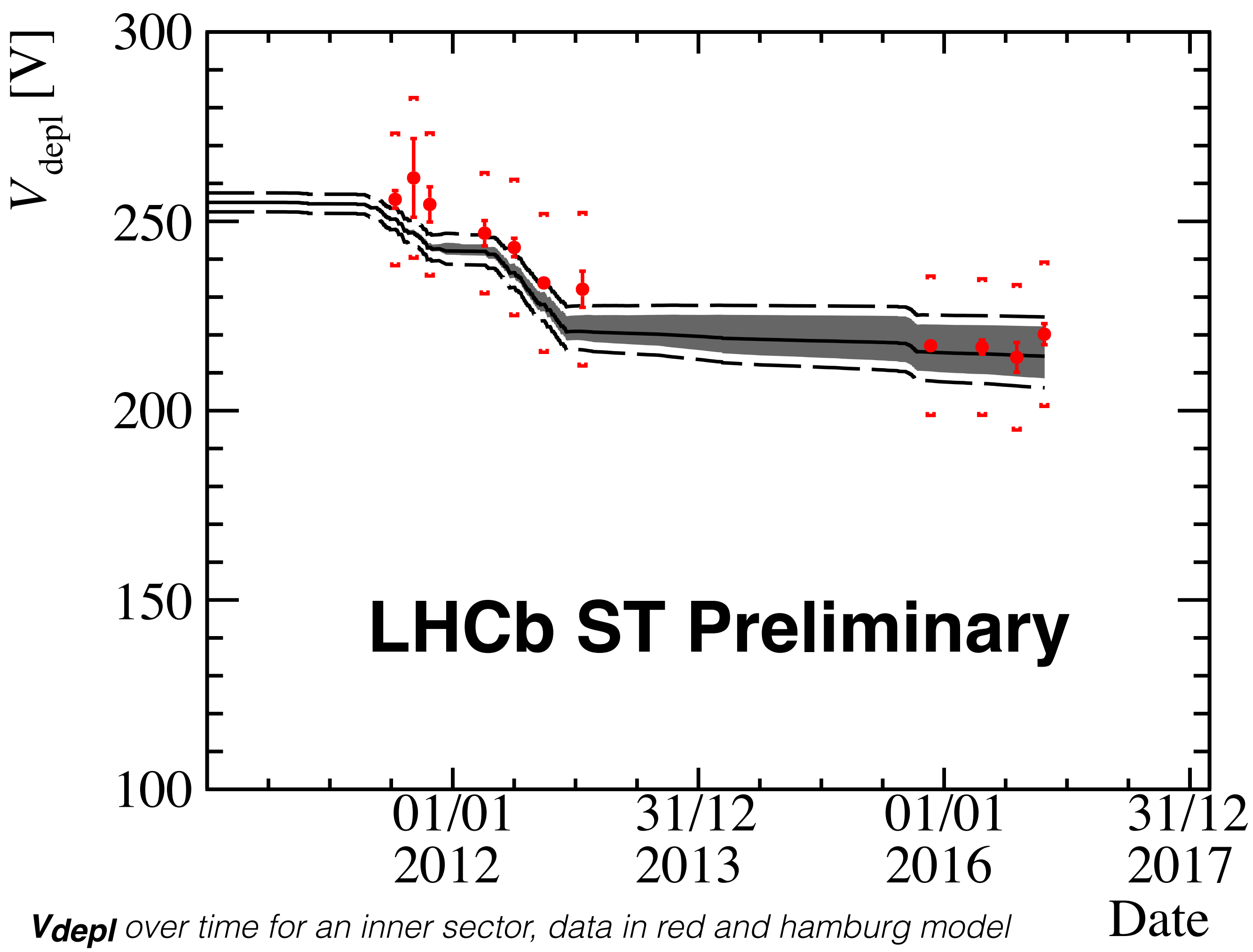
Charge vs bias voltage, fitted with a 3rd order spline

V_{depl} is the bias voltage at which the fit reaches 95% of its maximum value

Charge Collection Efficiency - EDV - **ST**

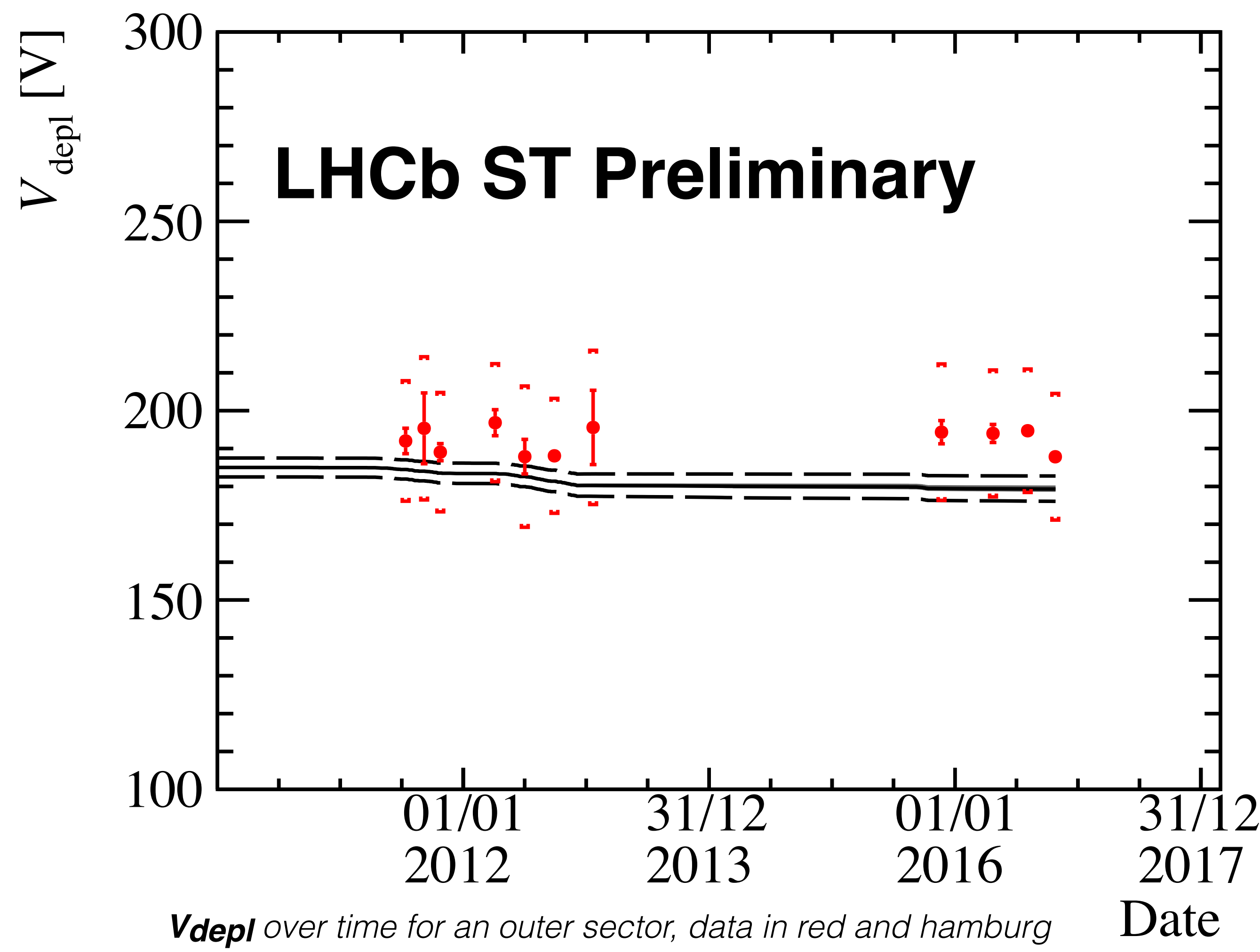
Effective Depletion Voltage over time for **TT**

Inner sector, closest to beam



V_{depl} *over time for an inner sector, data in red and hamburg model shown in grey*

Outer sector, further from the beam



V_{depl} *over time for an outer sector, data in red and hamburg model shown in grey*

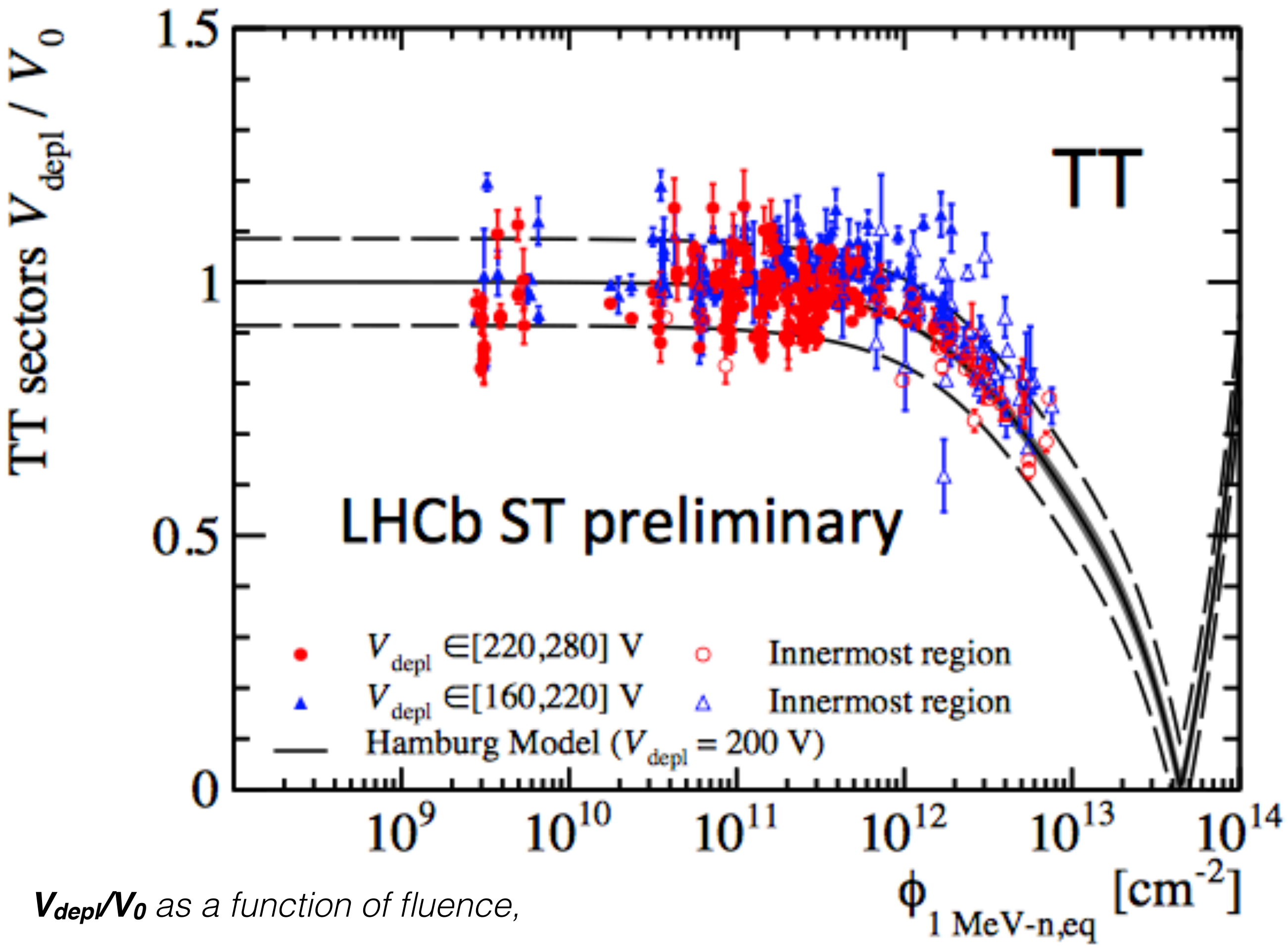
- Reasonably good agreement between $\mathbf{V_{depl}}$ from data and the Hamburg model prediction.

Depletion voltages decrease with increasing fluence

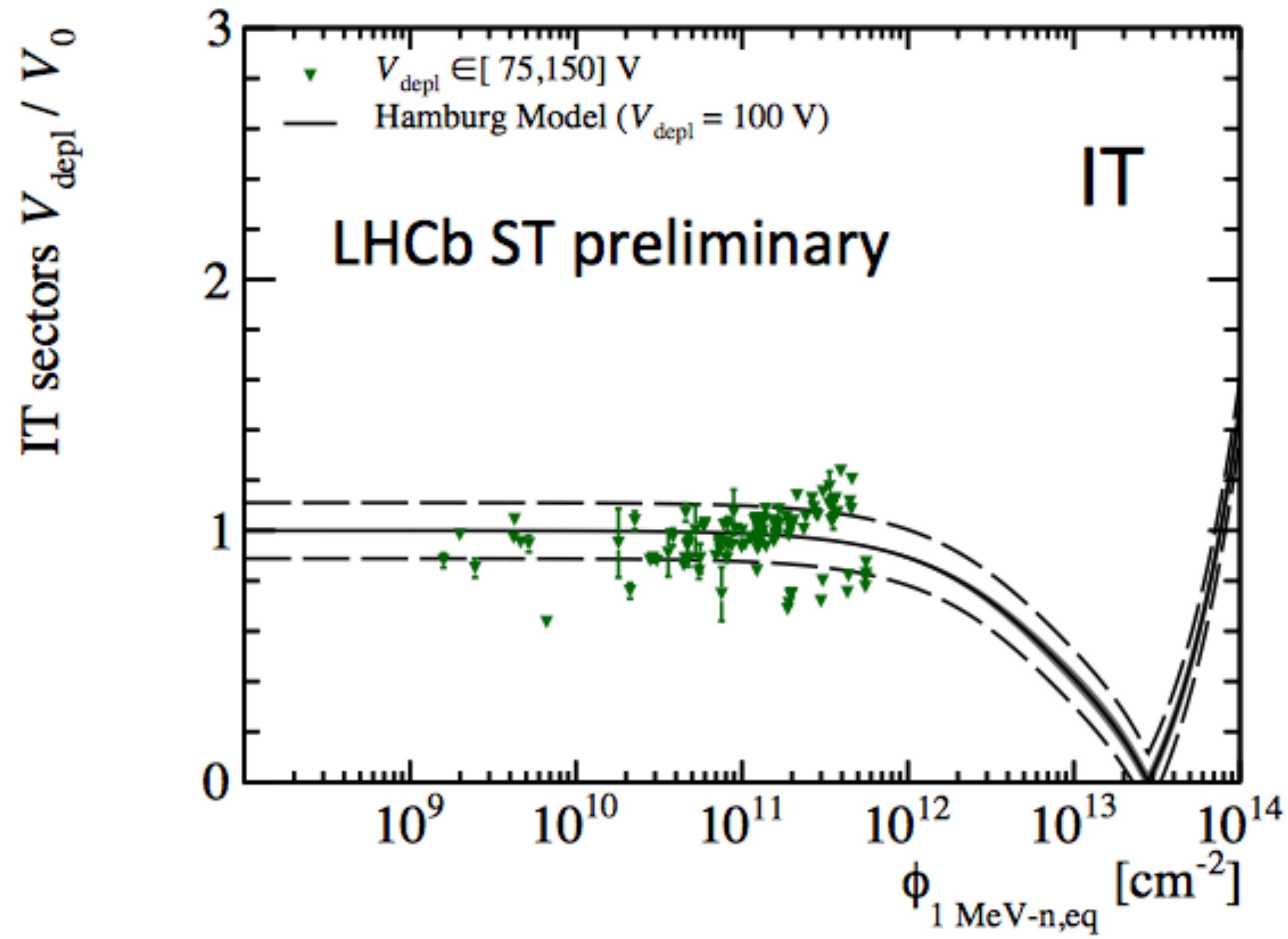
Charge Collection Efficiency - EDV - **ST**

Effective Depletion Voltage as a function of fluence

Normalised to V_0 - the depletion voltage before installation



***V_{depl}/V_0* as a function of fluence,**



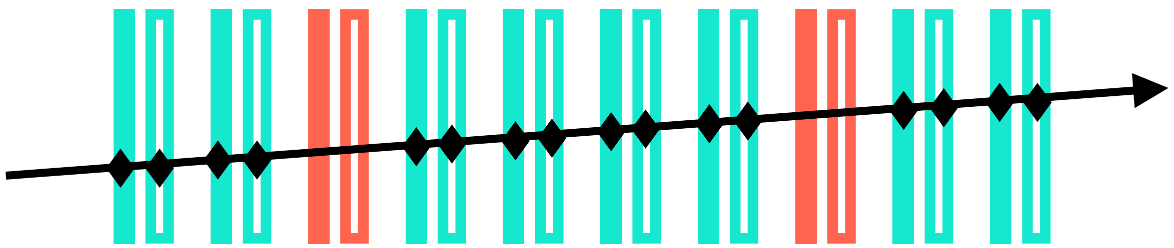
- Reasonably good agreement between $\mathbf{V_{depl}}$ from data and the Hamburg model prediction.

TT and **IT** sensors have not yet reach type-inversion

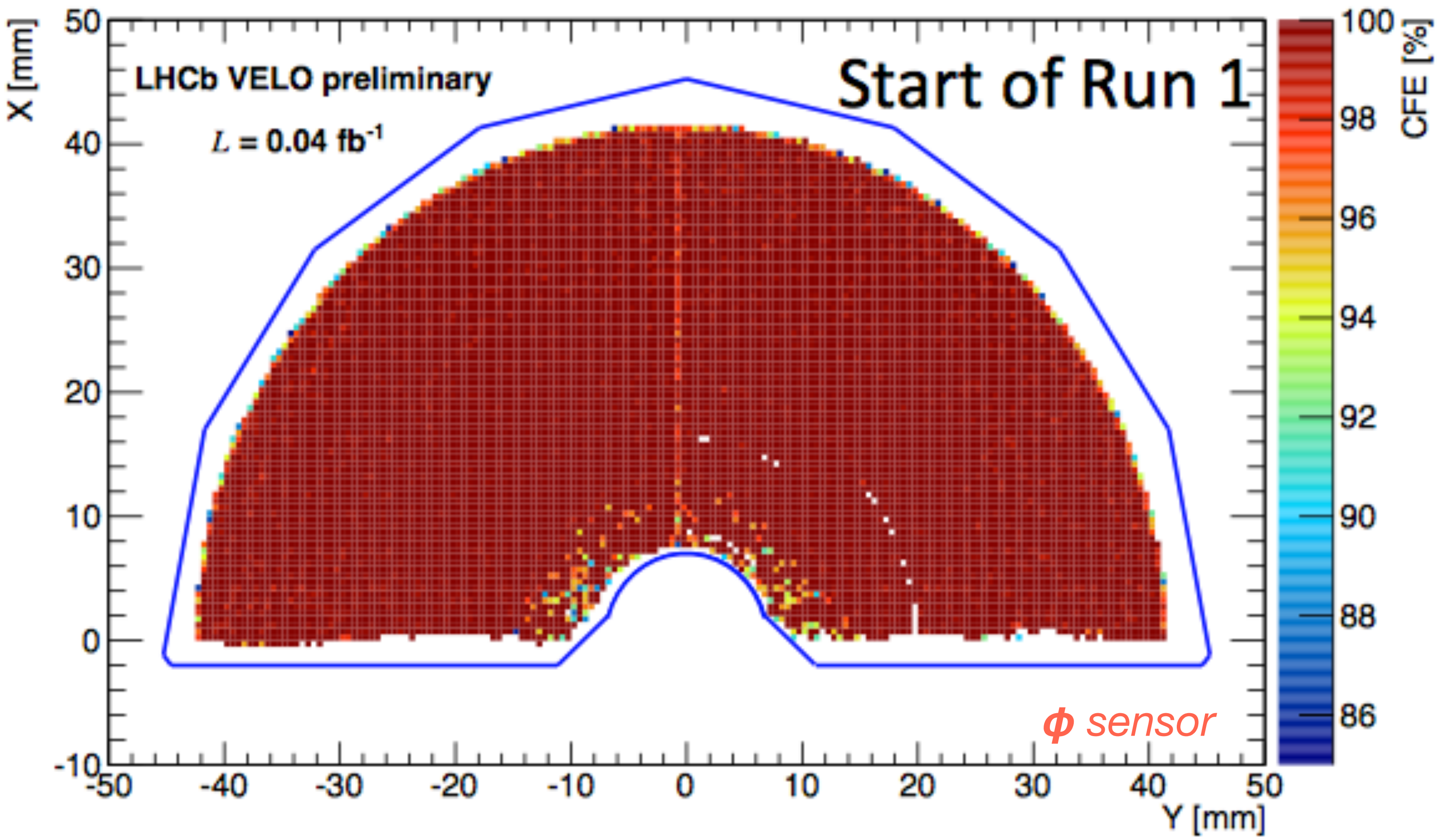
Charge Collection Efficiency - CFE - **VELO**

Charge Collection Efficiency Scans used to measure the Cluster Finding Efficiency

- Collision data recorded for every 5th module operated at a range of voltages, all other modules run at nominal voltage
- Look for the presence of a cluster near the track intercept of the test sensor



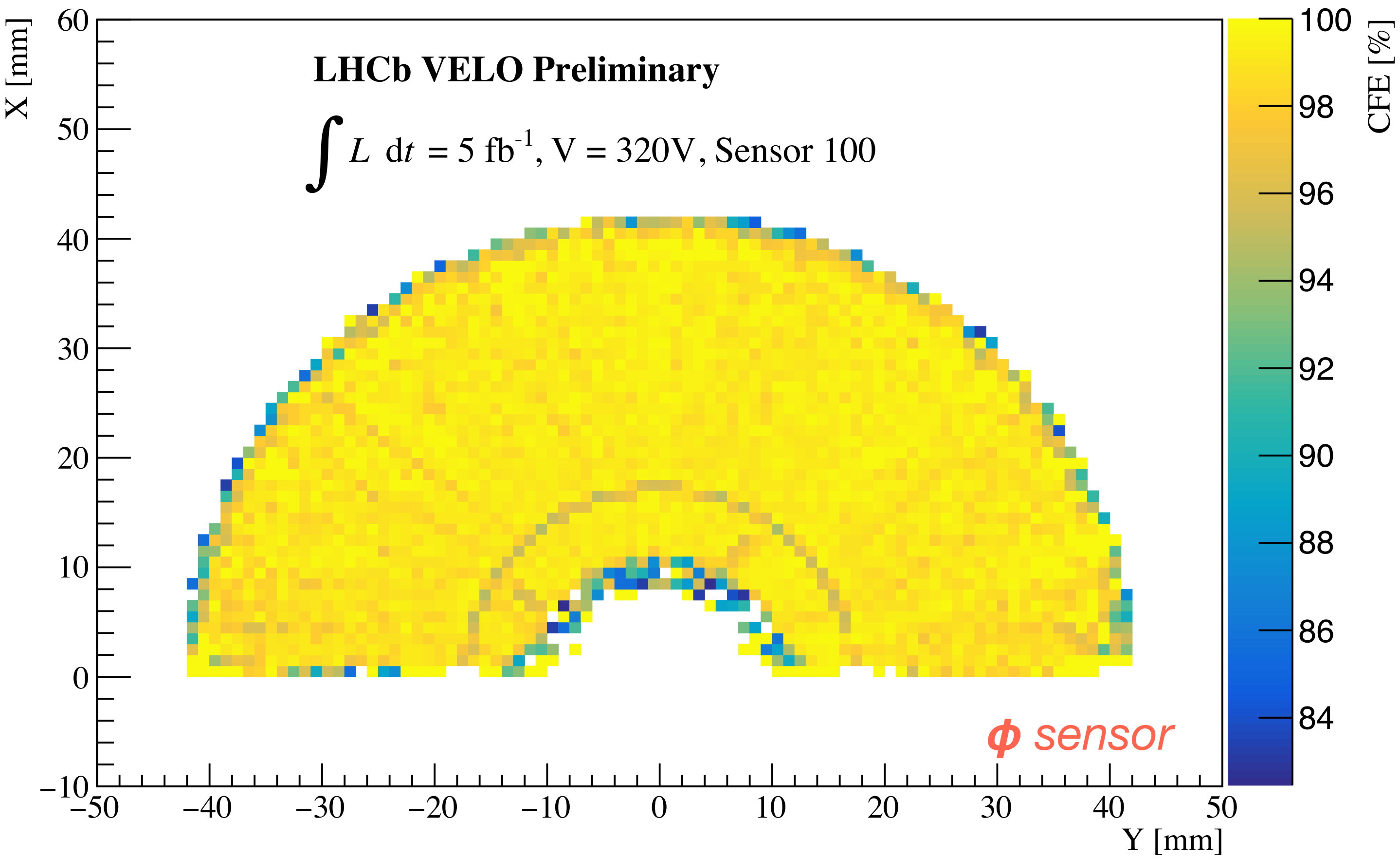
At the start of Run I, before irradiation the mean CFE was greater than 99%

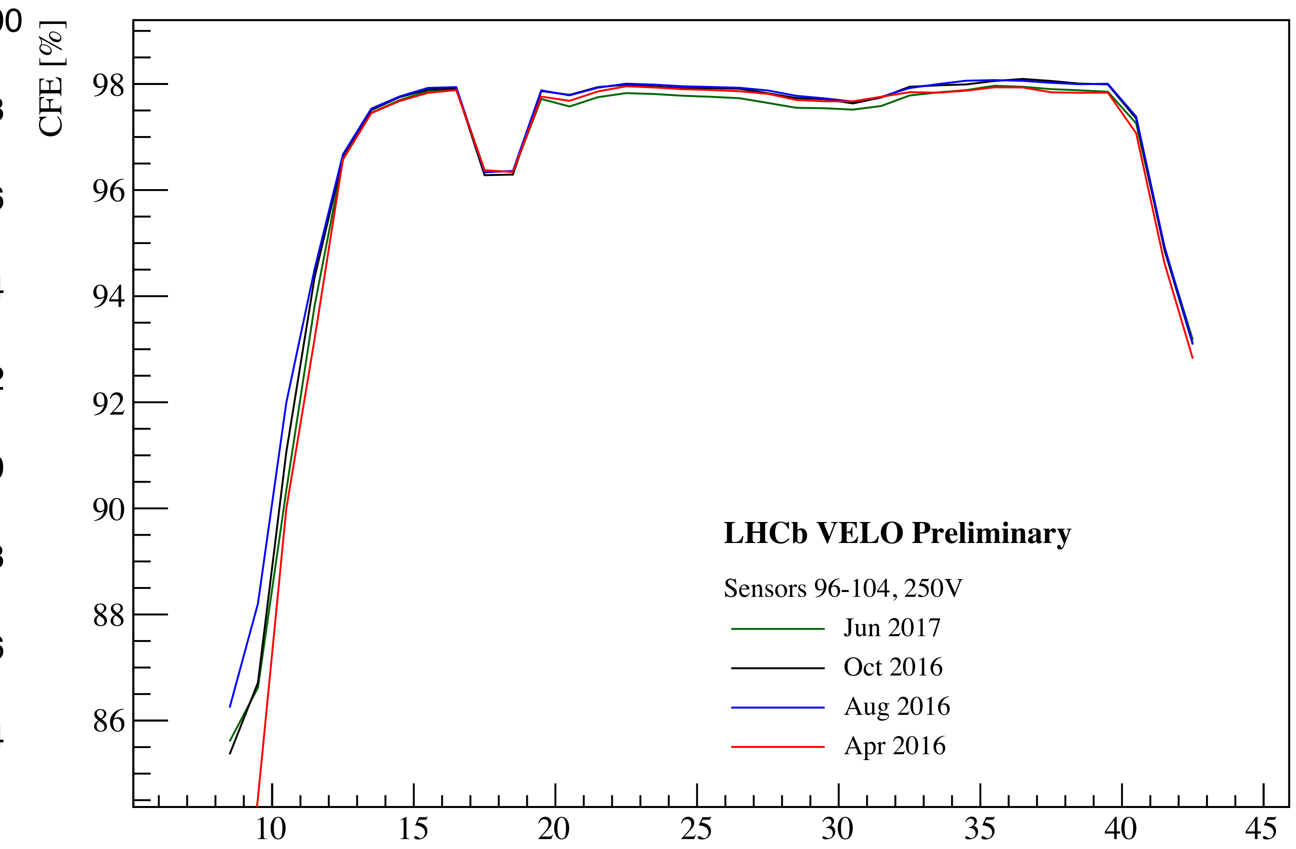


Charge Collection Efficiency - CFE - **VELO**

Cluster Finding Efficiency decreases with increasing fluence

ϕ sensor





Average efficiency for CCE scans taken at different times during Run II

- Lower CFE in the inner most irradiated areas of the sensor,
  - can be partly recovered with increased bias voltage
- Higher CFE in outer radii due to lower luminosity exposure
  - reduced at the periphery due to poorer tracking, ghosts/fakes

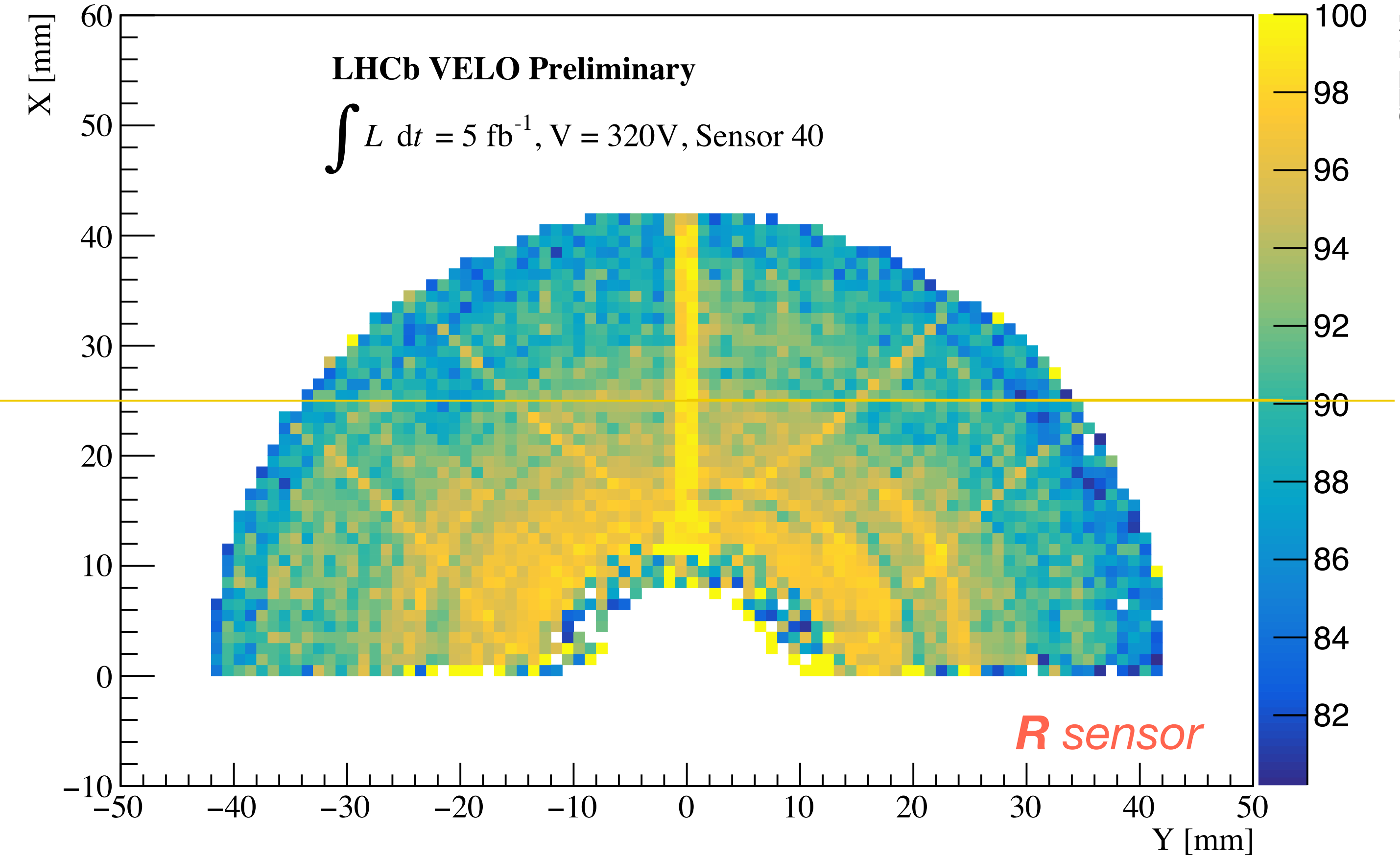
Drop in efficiency at ~18 rad boundary between inner and outer strips

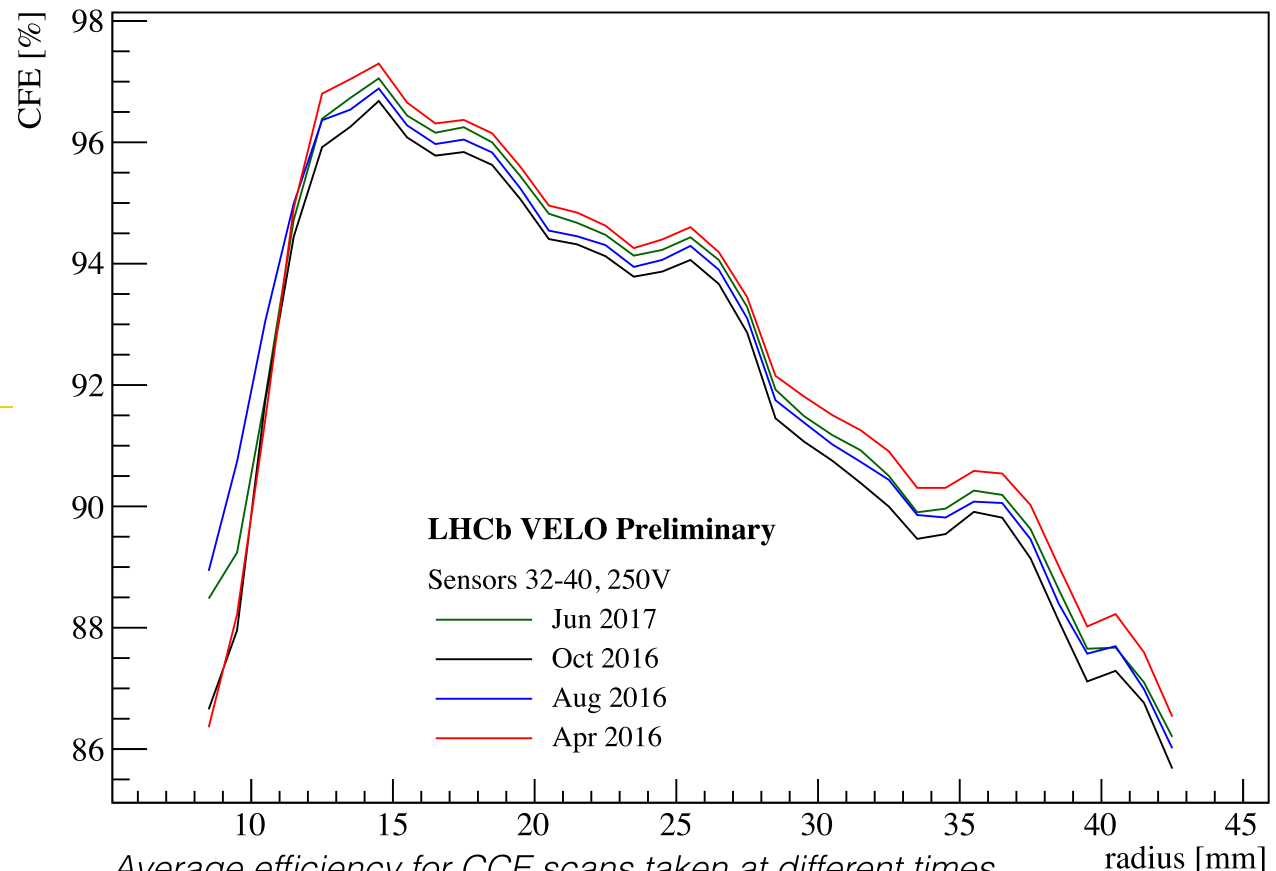
Majority of the sensor has a CFE ~98%

Charge Collection Efficiency - CFE - **VELO**

Cluster Finding Efficiency decreases with increasing fluence

R sensor





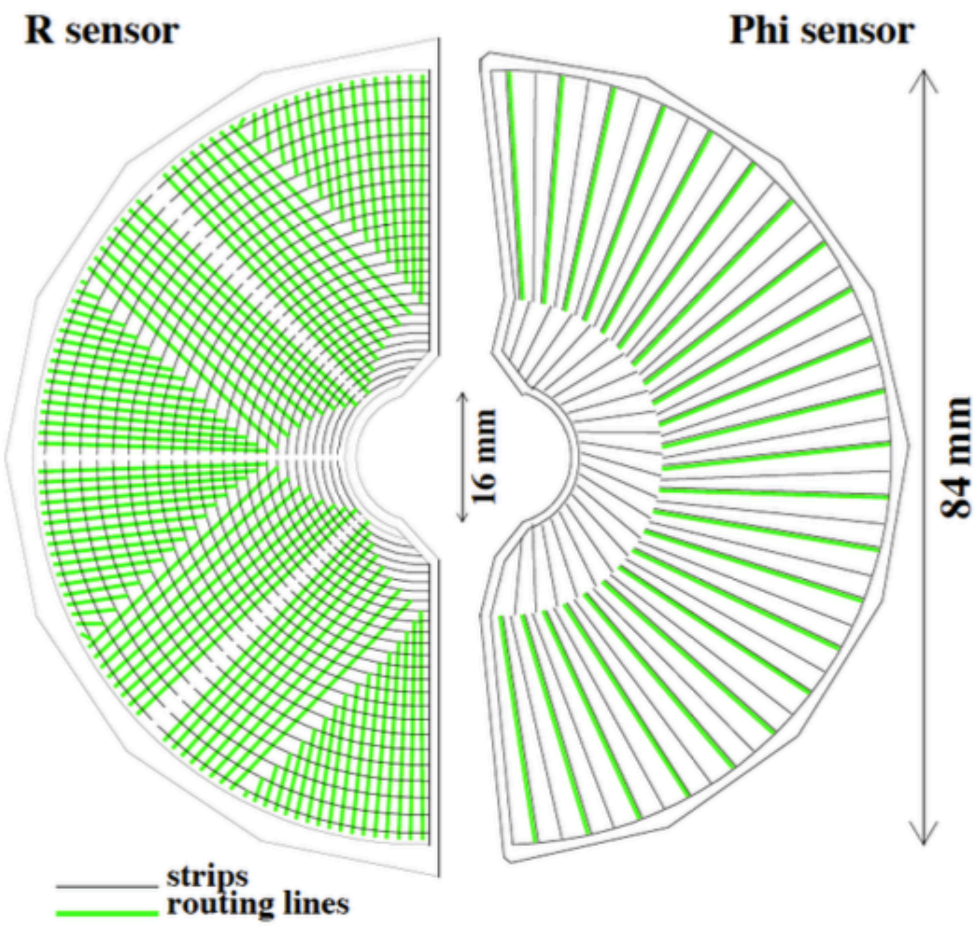
Average efficiency for CCE scans taken at different times during Run II

R sensor behaves differently to a **ϕ** sensor

- Lower CFE in the inner most irradiated areas of the sensor,
  - can be partly recovered with increased bias voltage
- **Reduced CFE in outer radii, in the lower luminosity regions**

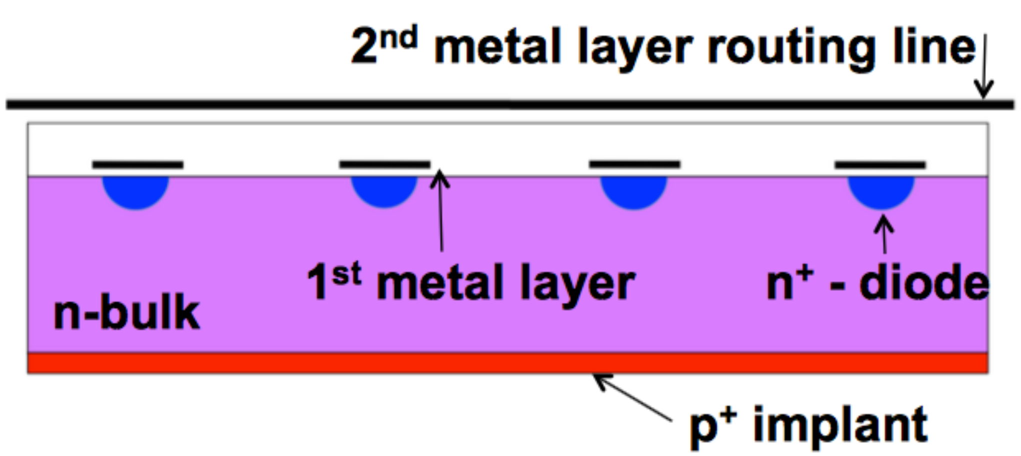
Behaviour can be explained by the "second metal layer effect"

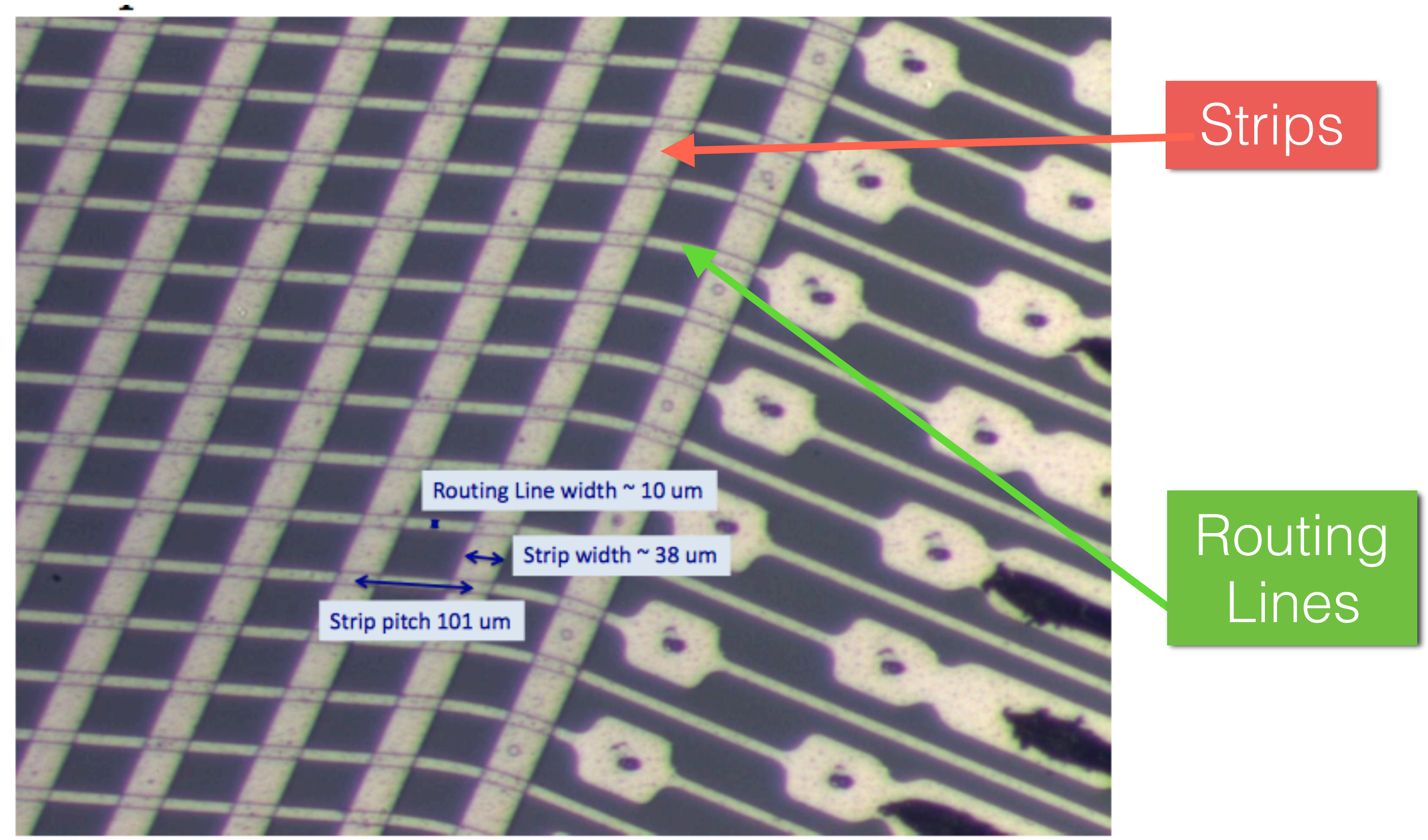
Charge Collection Studies - Double Metal Layer



R and phi sensors need two sets of metal lines

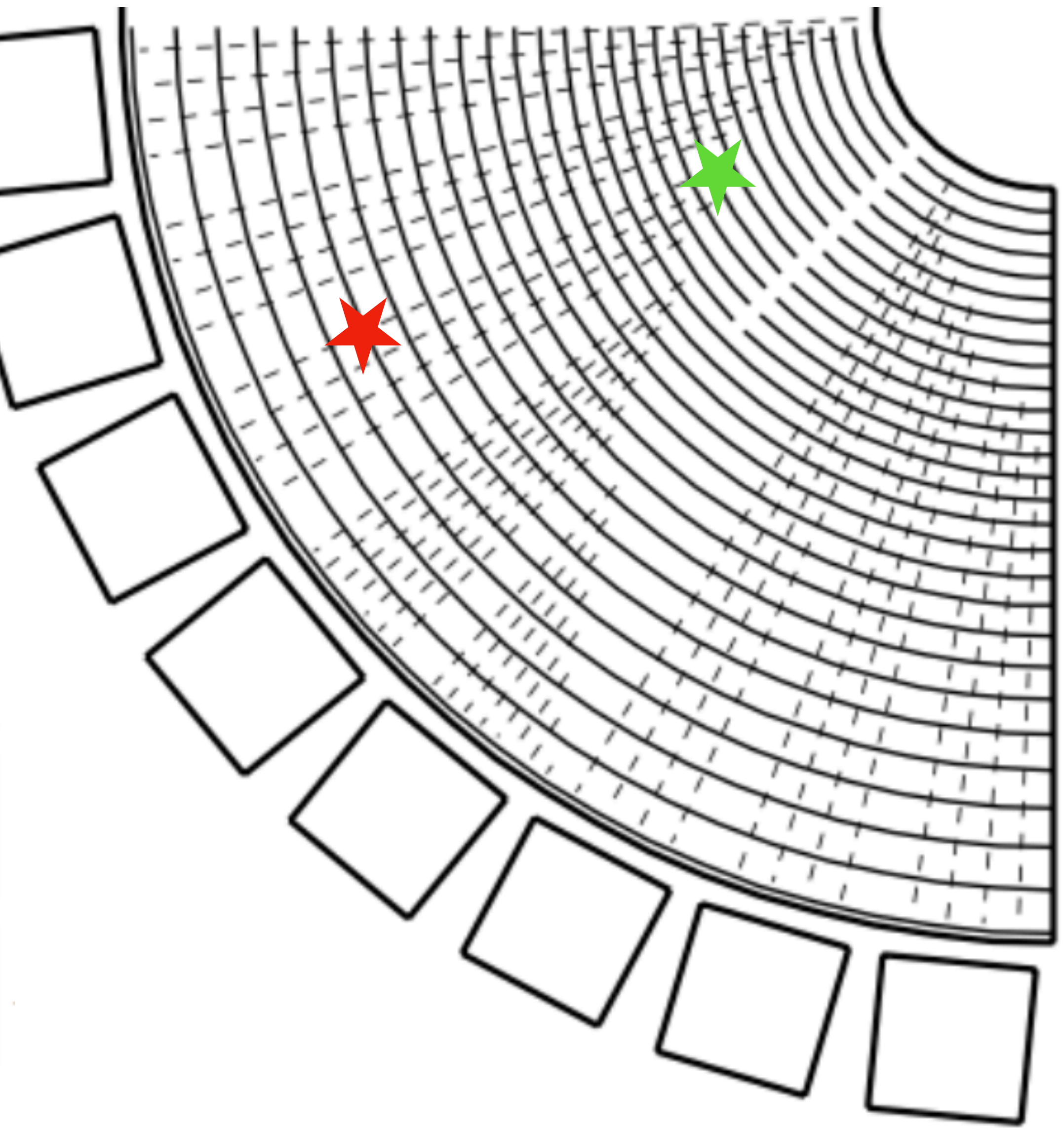
- One to capacitively couple to the strips
- One to carry the signal to the amplifier in the periphery
- **ϕ sensors** - the routing lines are parallel to the strips
- **R sensors** - the routing lines are perpendicular to and run over the outer strips





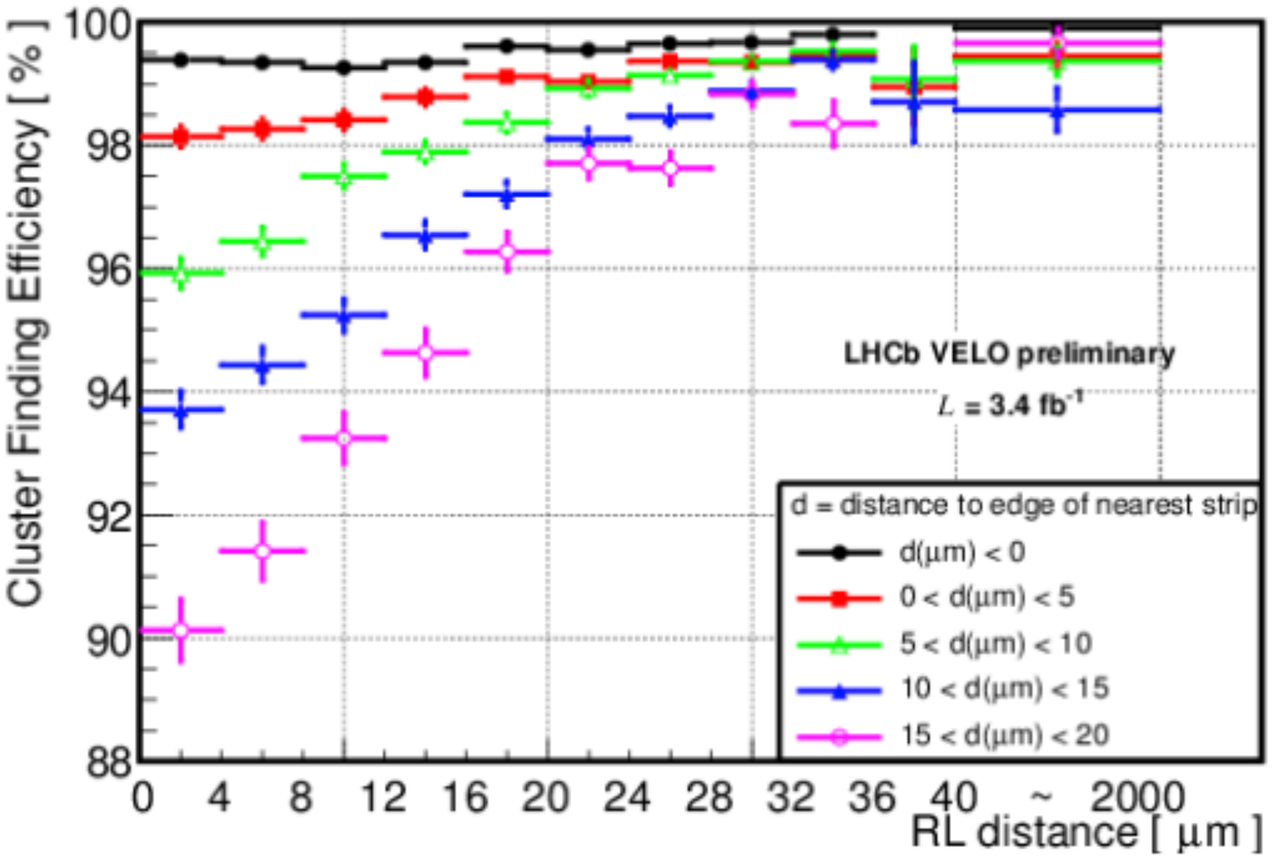
Charge Collection Studies - Double Metal Layer

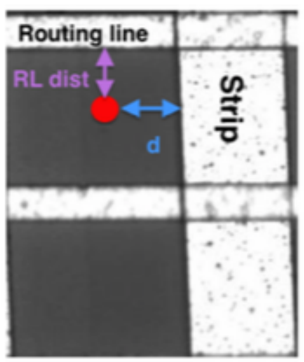
After irradiation, the routing line appears to pick up the signal, that would have been picked up by the strip pre-irradiation



A charge is induced on the routing lines

- The hit is registered in a strip far from the predicted track position





CFE is reduced for tracks far from a strip and close to a routing line

- Ongoing TCAD simulations to try recreate this effect
- Limited effect on the tracking performance

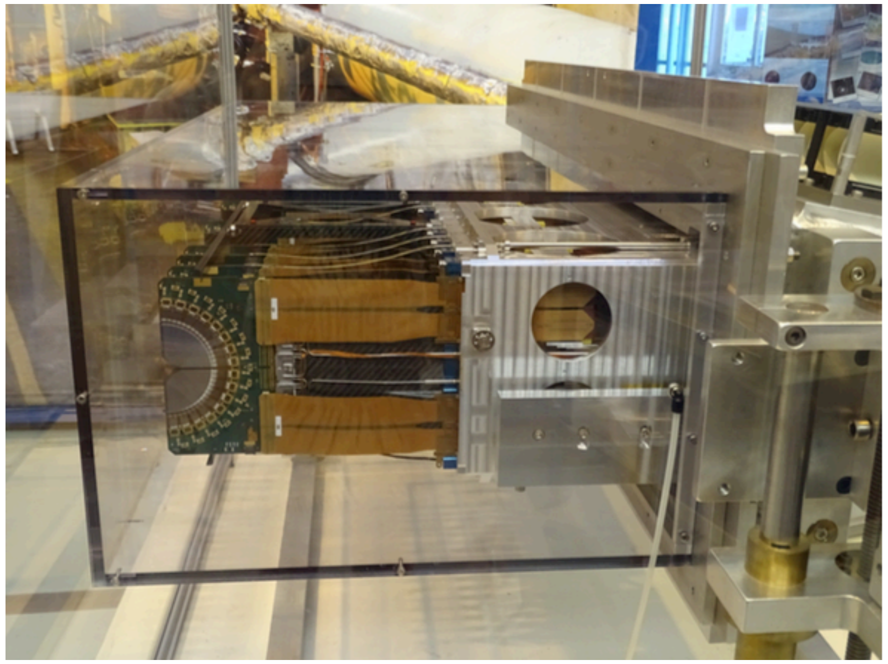
Conclusions

- Tracking detectors are showing signs of degradation due to radiation damage
- We expect to maintain a good physics performance until the end of Run II
- Second fully operational copy of the VELO incase of beam related incident
- During LS2 the tracking detectors will be upgraded
  - The LHCb Vertex Locator Upgrade by Edgar Lemos Cid
  - Microchannel Cooling techniques at LHCb by Oscar Augusto
  - Design and construction of the LHCb Upstream Tracker by Marco Petruzzo

Beam Crossing	50 ns			-		25 ns			-		25 ns		
Start up	2010	2011	2012	2013	2014	2015	2016	2017	2 18	2019	020	2021	2022+
TeV	0.9-7		8	LS 1		13-14			LS 2 LHCb Upgrade				
Instant Luminosity	10^{32}	$3\text{-}4 \times 10^{32}$				4×10^{32}					$10 – 20 \times 10^{32}$		
Integrated Luminosity	$3\ fb^{-1}$					$5\text{-}7\ fb^{-1}$					$> 50\ fb^{-1}$		

Start of LS2 upgrade delayed until 2019

Spare **VELO** in the LHCb surface area exhibition



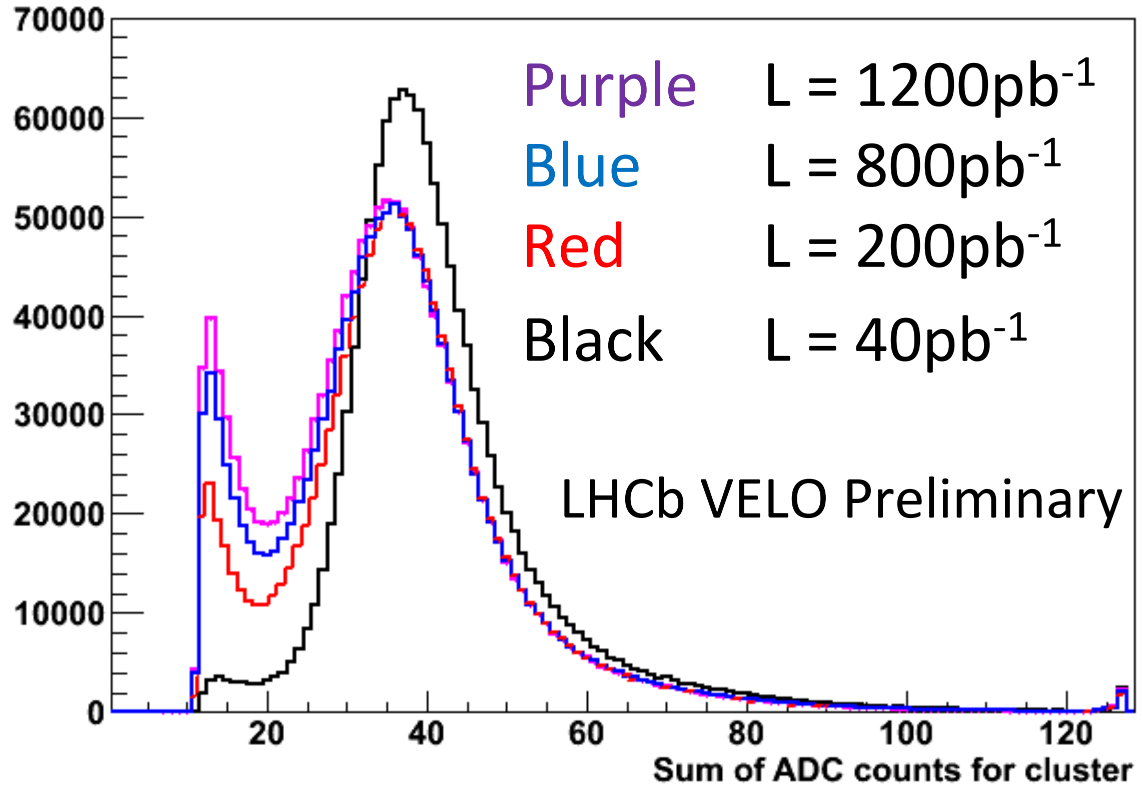
Reached **6 fb^{-1}** on September 7^{th}

Back up

Charge Collection Studies - Double Metal Layer

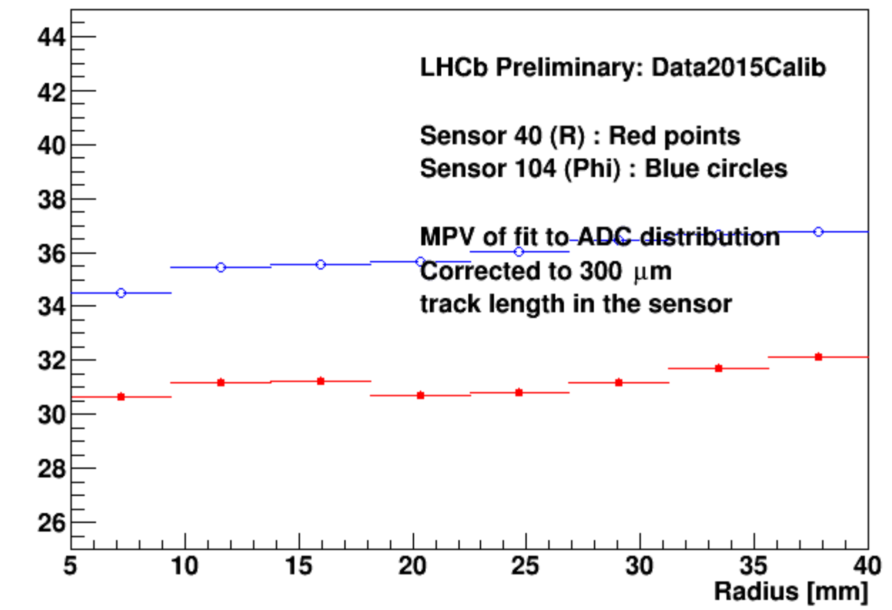
Effects on the data taking

Inner **R** strips sees an increase in lower ADC counts



- Predominately from inner regions, far from where the track crossed the sensor
- Double metal layer effect is seen in the outer edges of the sensors and for mostly perpendicular tracks, hence downstream sensors far from the interaction region
- Region with the most redundancy, so losing one cluster on a track does not effect the tracking greatly

Lower charge collected in **R** compared to **ϕ**



Wider distribution due to only some clusters losing charge