LHCb: Lessons learned from operation of the VELO

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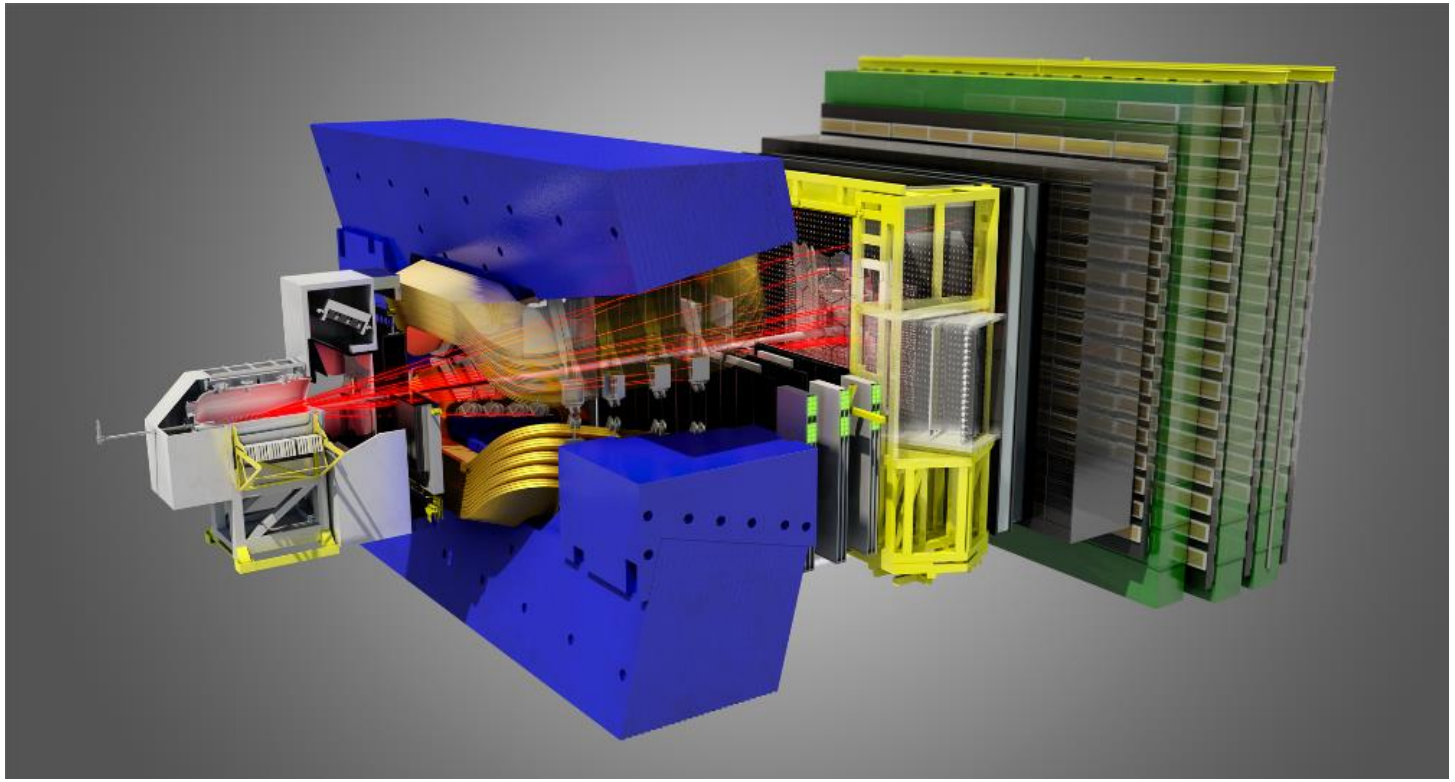
on behalf of the LHCb collaboration

The LHCb experiment

- LHCb is a dedicated heavy flavour experiment at the LHC

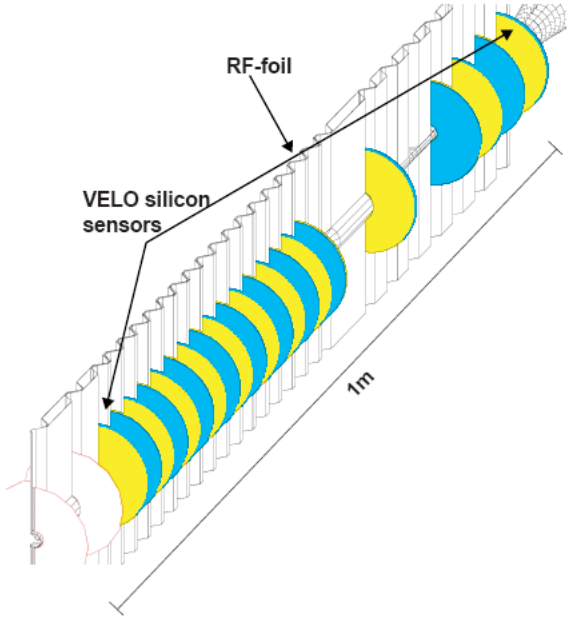


- Very precise vertex detector (VELO)
- One tracking stations before and three after a vertical dipole magnet
- Two ring imaging Cherenkov detectors
- Three layers of calorimetry
- Five of muon detectors interspersed with iron shielding walls

The LHCb Detector at the LHC, JINST 3 (2008) S08005

VELO parameters

- 42 modules with pairs of sensors all n-in-n
  - Except one n-in-p (module 0 in later plots)
- R/ϕ geometry strip detector
  - Inner most strips are 8mm from the beam, outer most 42mm from the beam
- Designed to tolerate 5 years running at LHC: we're above that now…



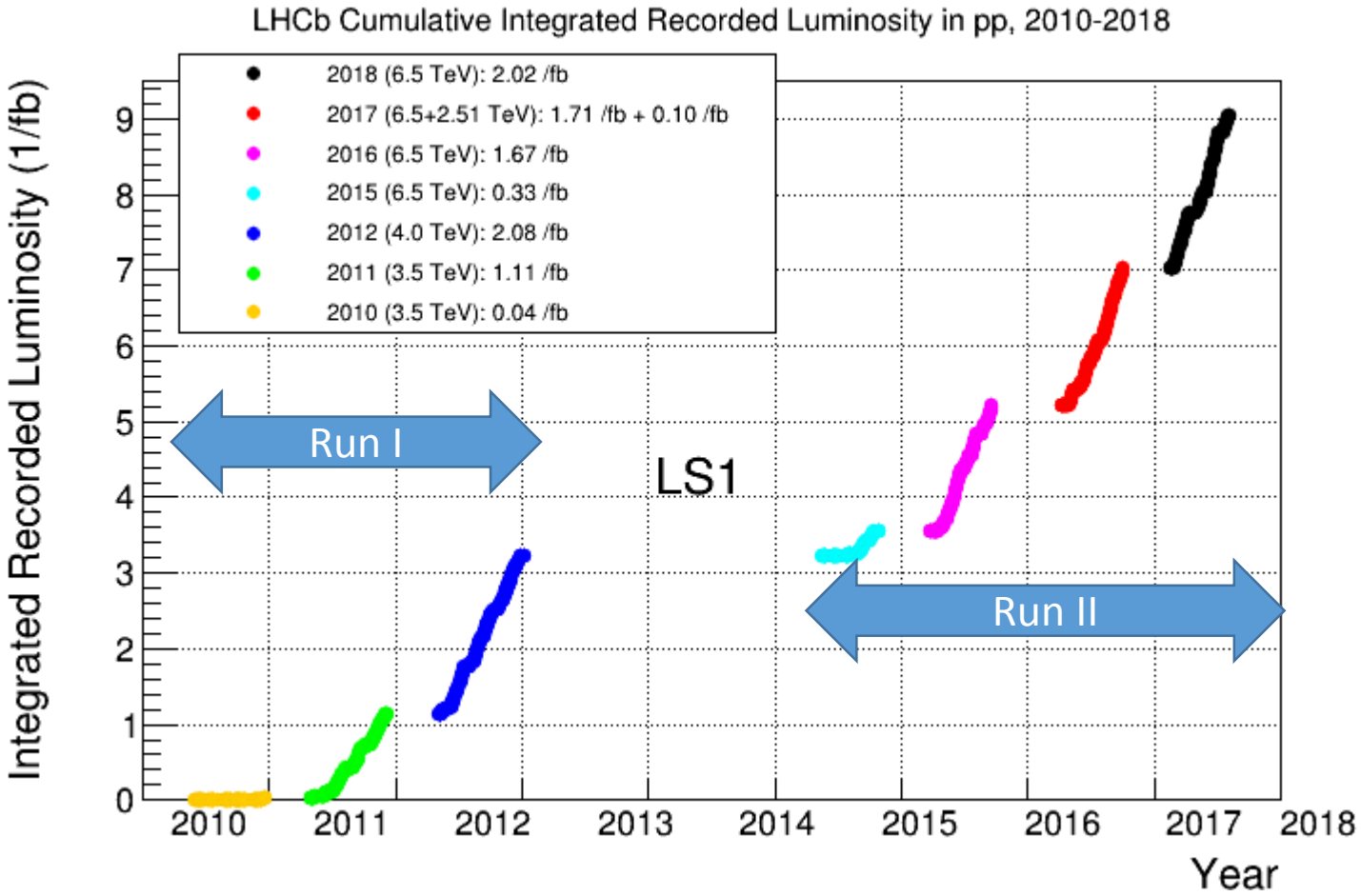
- Sufficiently radiation hard to be used without modification in a proton therapy beam at Clatterbridge Oncology centre

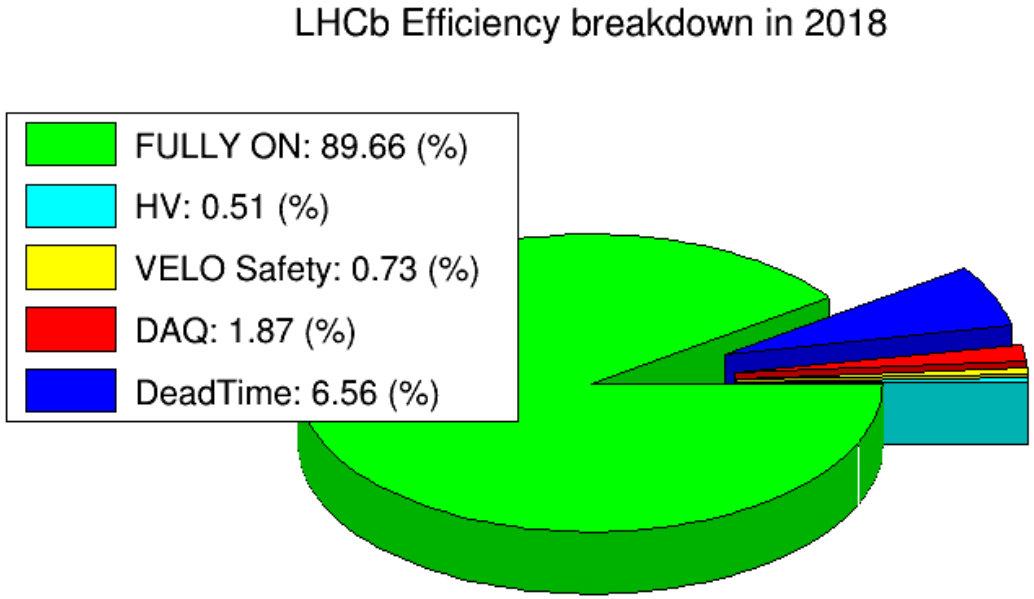
LHCb data taking

Results are quoted on

Year	$\sqrt{s}$	Luminosity
2010 & 2011	7 TeV	1.1 fb^{-1}
2012	8 TeV	2.1 fb^{-1}
2015 - 2018	13 TeV	5.7 fb^{-1}

LHCb uses luminosity levelling so we get less luminosity than ATLAS & CMS

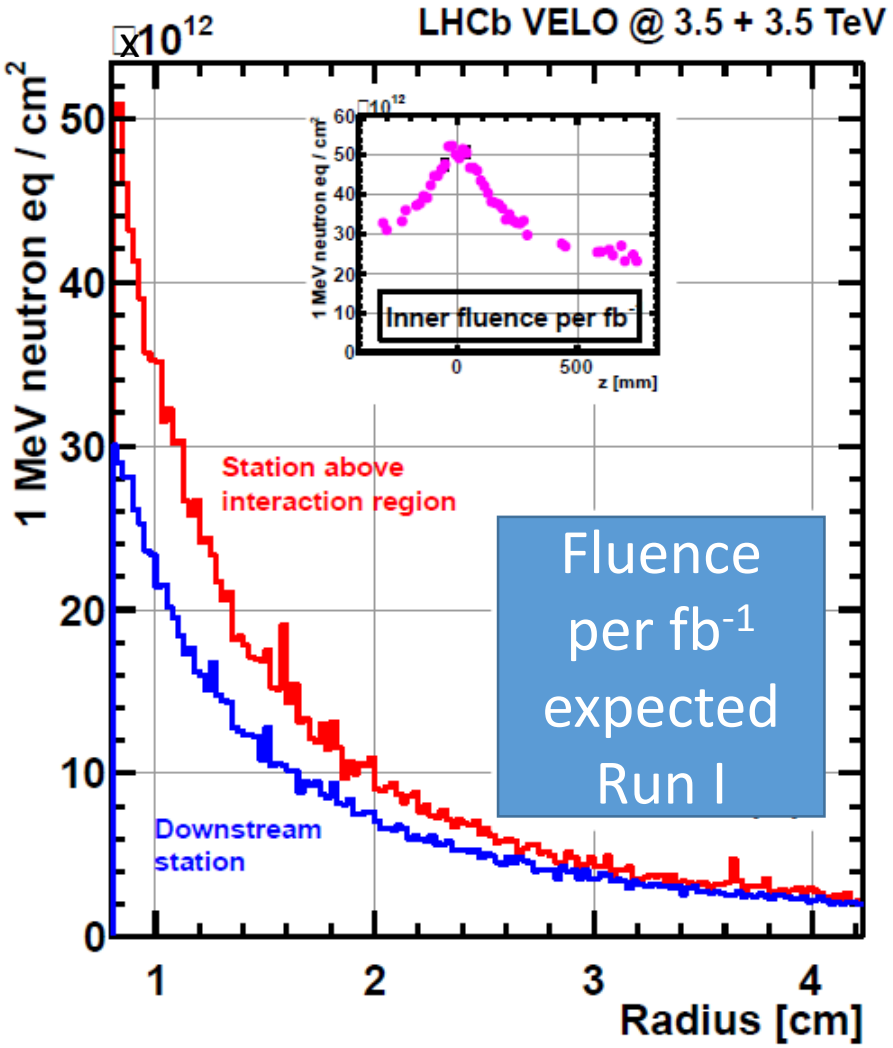


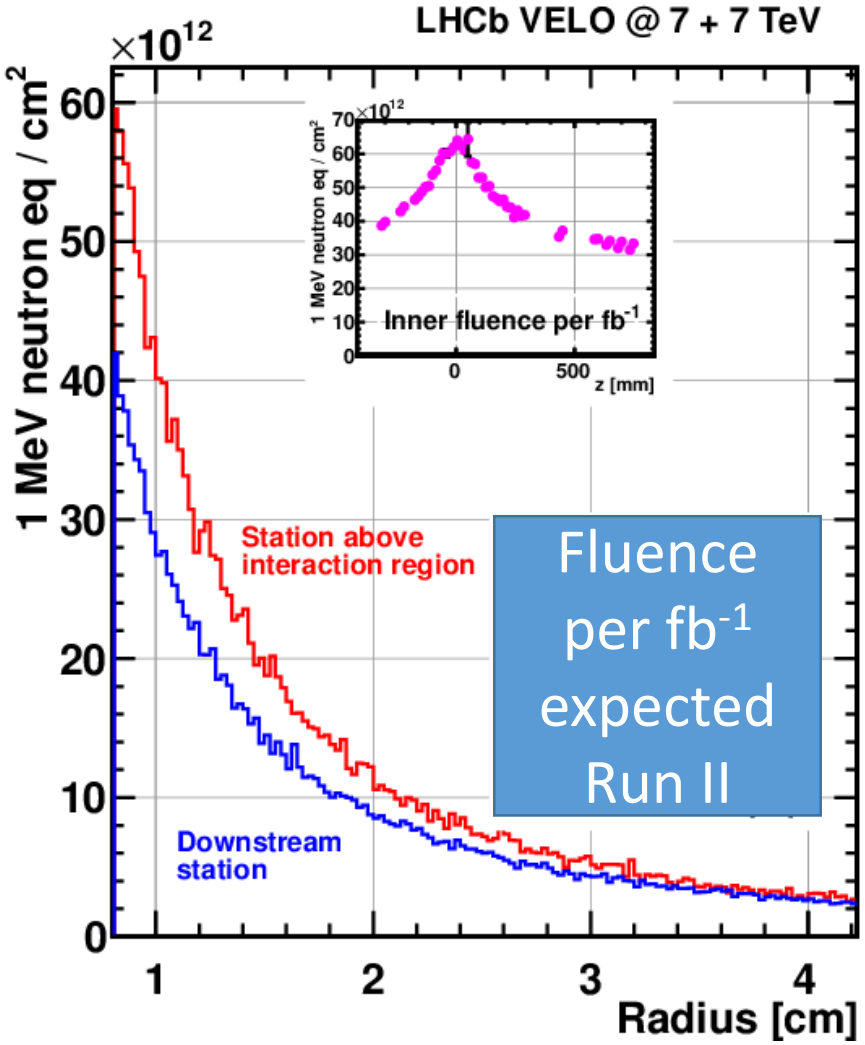


http://lhcb-operationsplots.web.cern.ch/lhcb-operationsplots/index.htm

Plus a small amount of beam-beam p-Pb, Pb-p, Pb-Pb collisions and also p-A where A is Helium or Argon for beam gas events

Radiation dose delivered





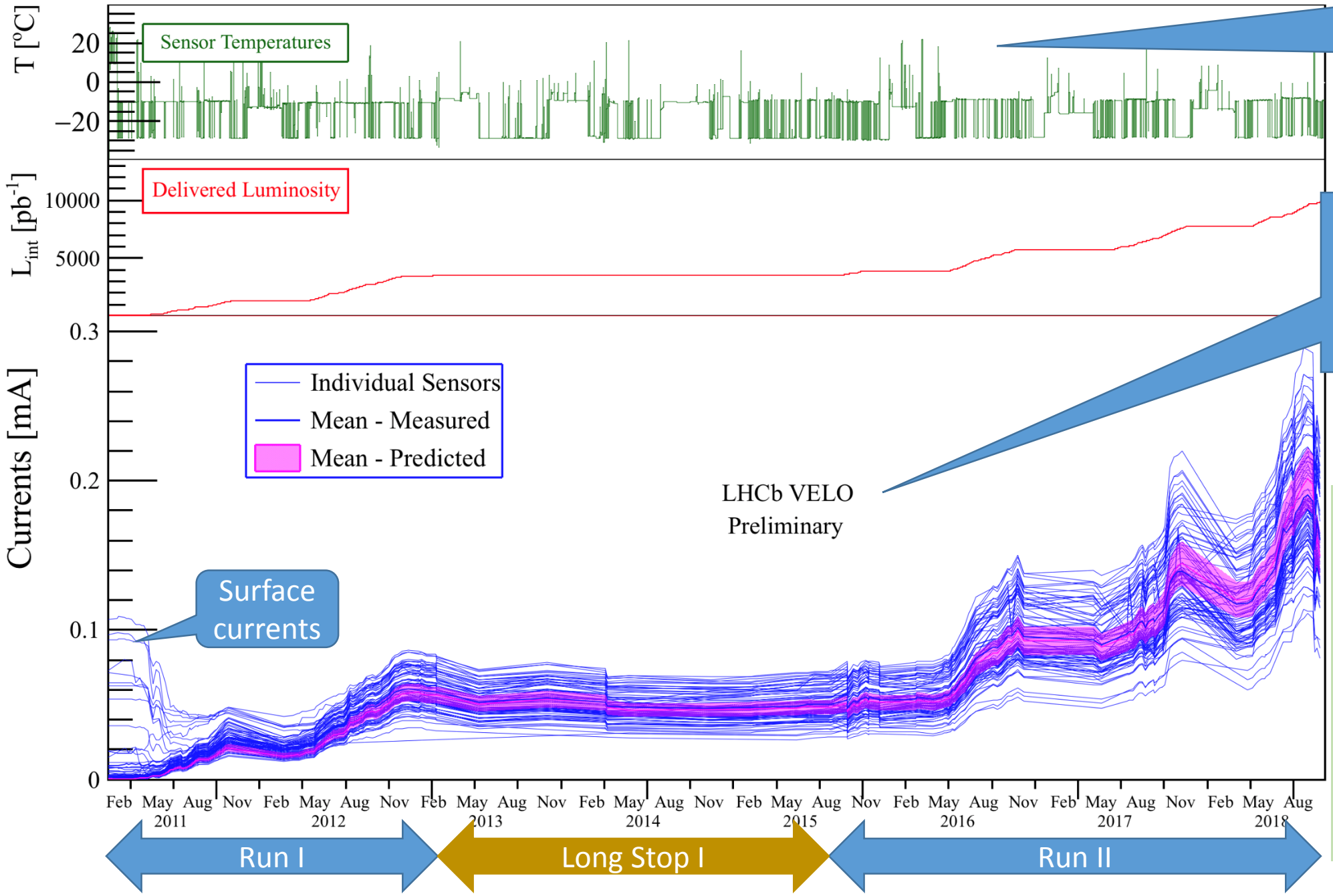
Fluence varies exponentially with radius and by x2 between stations

Effects of $\sqrt{s}$ are smaller, about 30% between Run I and Run II

x3 this for Run I total dose

x5.5 this for Run II dose so far

LHCb VELO (VErtex LOcator) : Technical Design Report
CERN-LHCC-2001-011

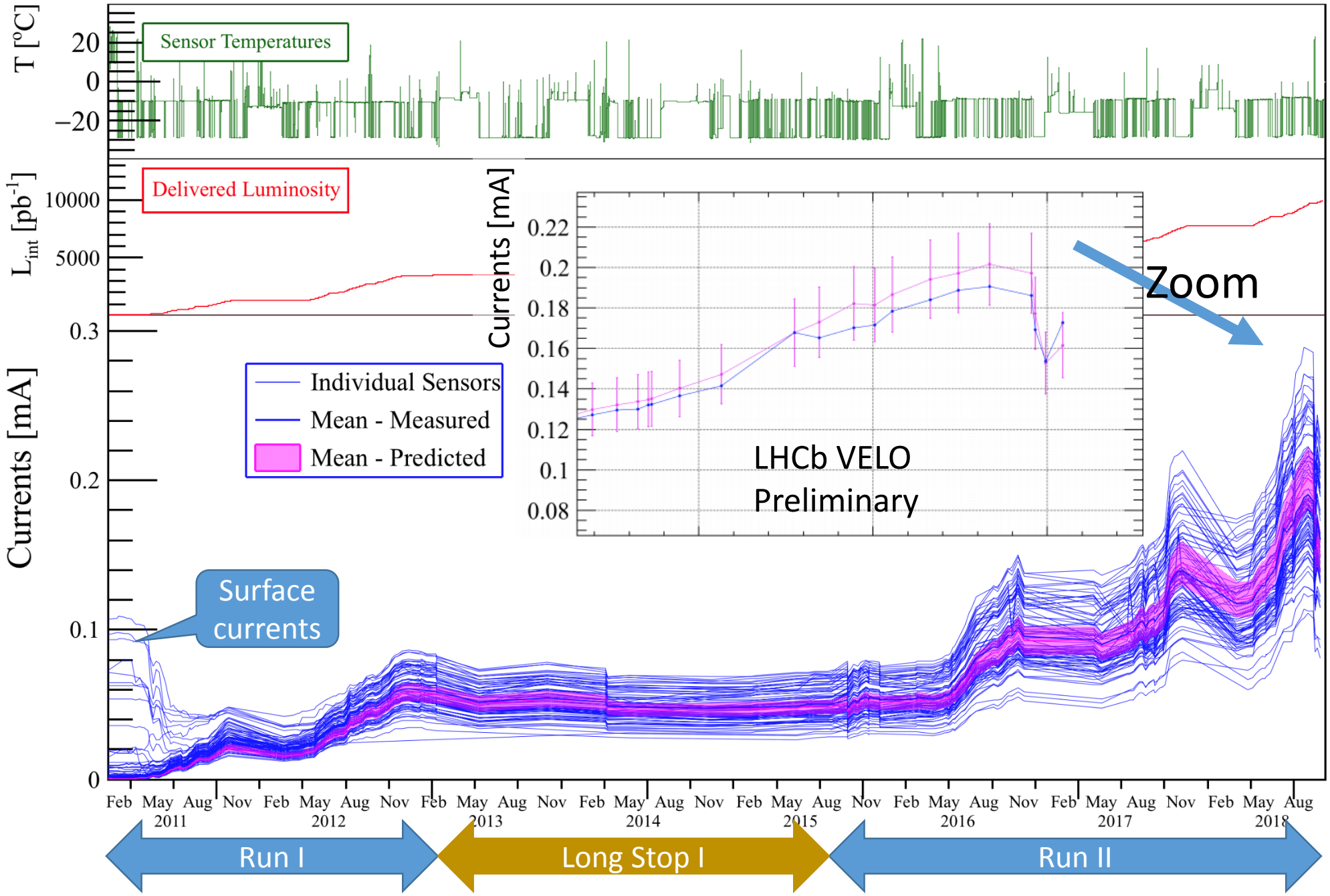


Operational temperature is about -8°C. Sensors at -30°C when the chips are unpowered

Long periods between data taking due to LS1 and end of year shutdowns
Need to avoid annealing

Currents measured at approx –8°C without beam and sensors at 150V

Typical increase was 1.9 μA per 100 pb^{-1}



Deliberate annealing

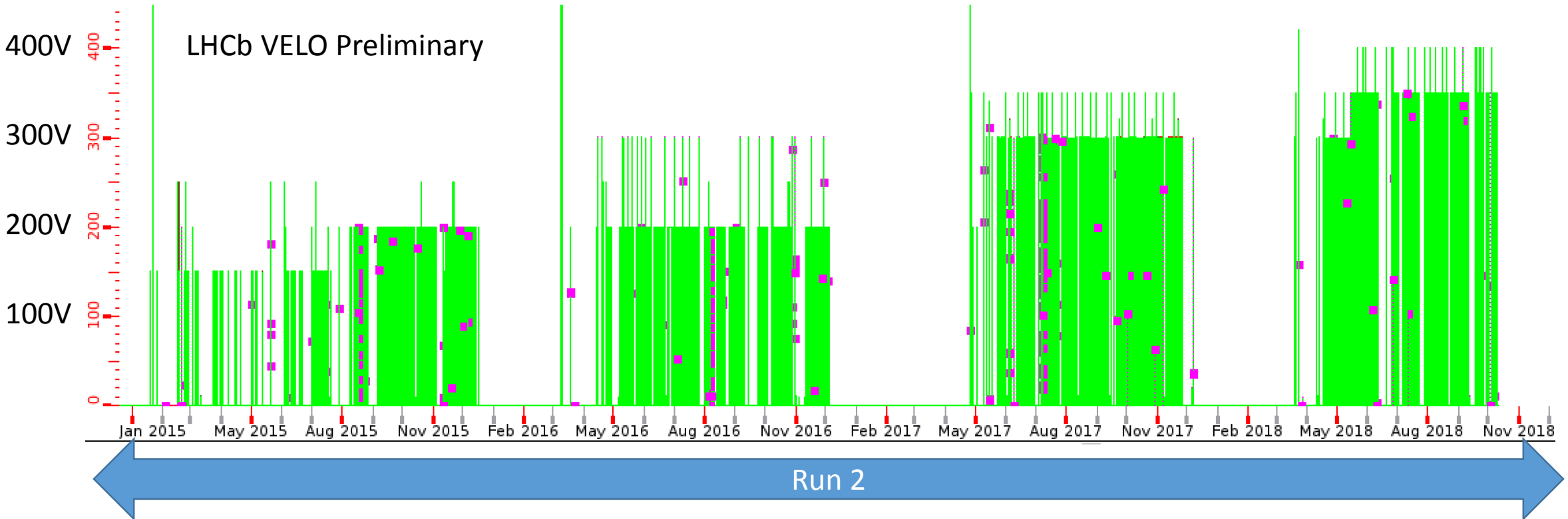
Set the temperature to 20°C for 40 hours

Dropped average sensor currents from 190 μA to 150 μA at 150 V

Possible as the detectors only have to work to the end of the year and the excellent performance of the cyro-plant

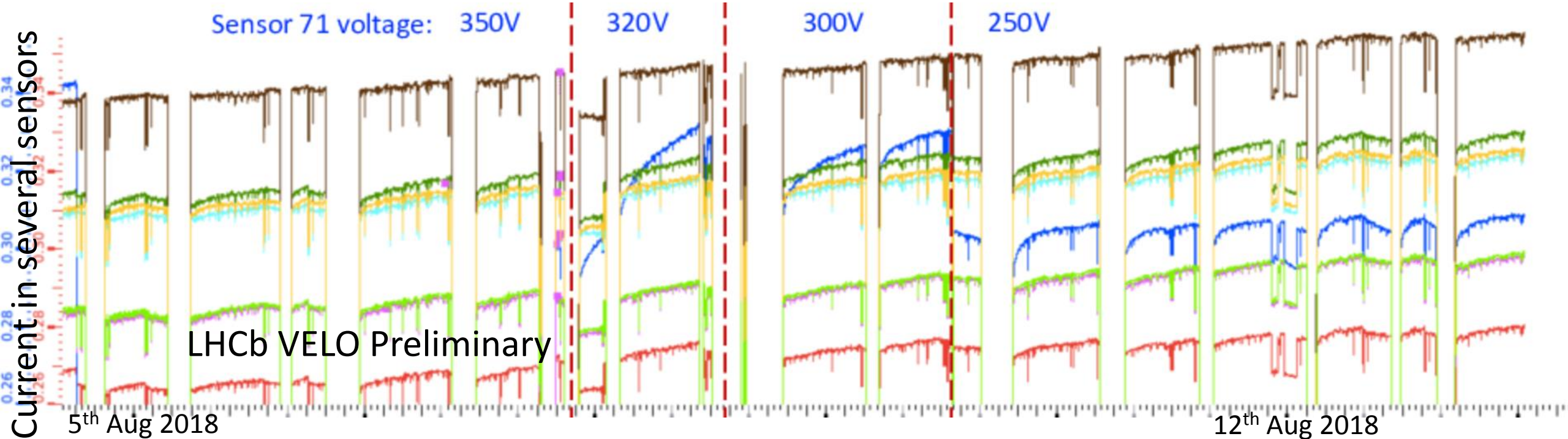
HV changes are necessary

Major HV changes due to increasing effective depletion voltage (see later)
However IV curves for specific sensors must be monitored and adjusted to manage currents
Through out the data taking we have been able to fully deplete the sensors, even through now above design luminosity

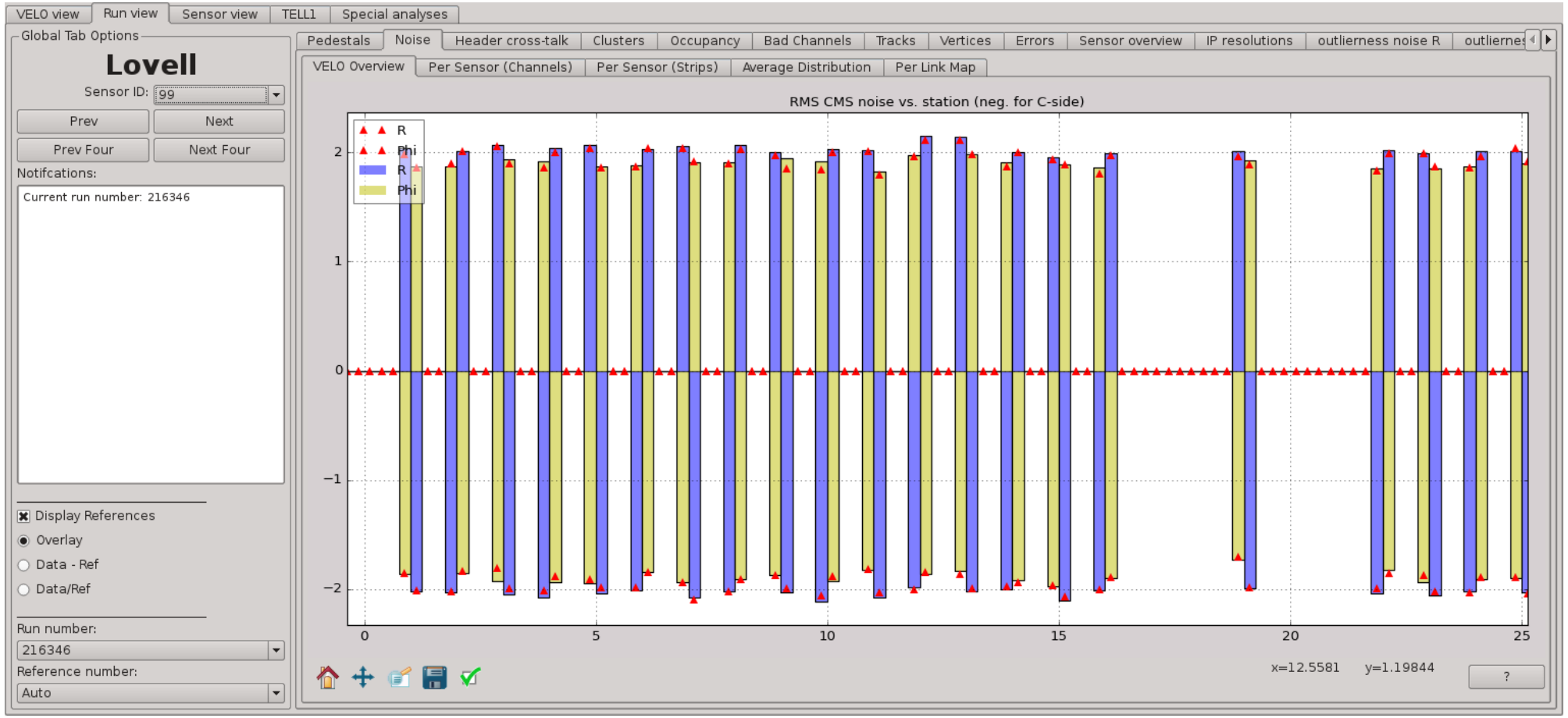


Monitoring is critical

Occasional small effects in one sensor; such as current increase during a fill need to be caught and mitigated early



Monitoring: both people and software are critical

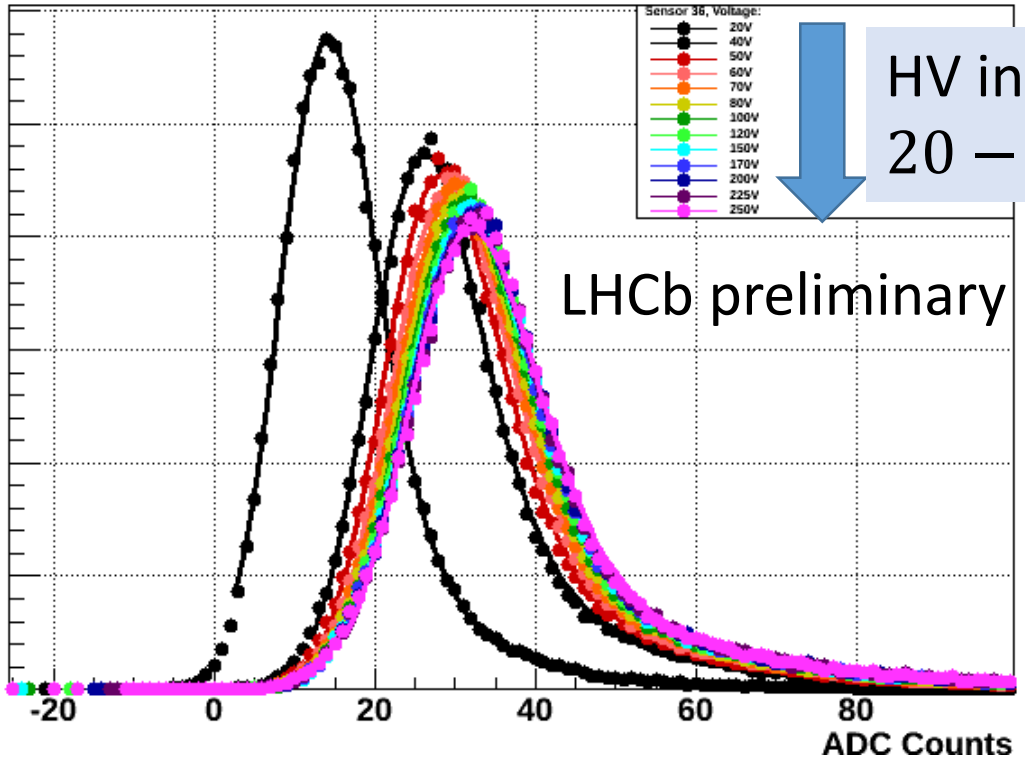


The detector is checked daily during data taking on data taken and in the hardware status

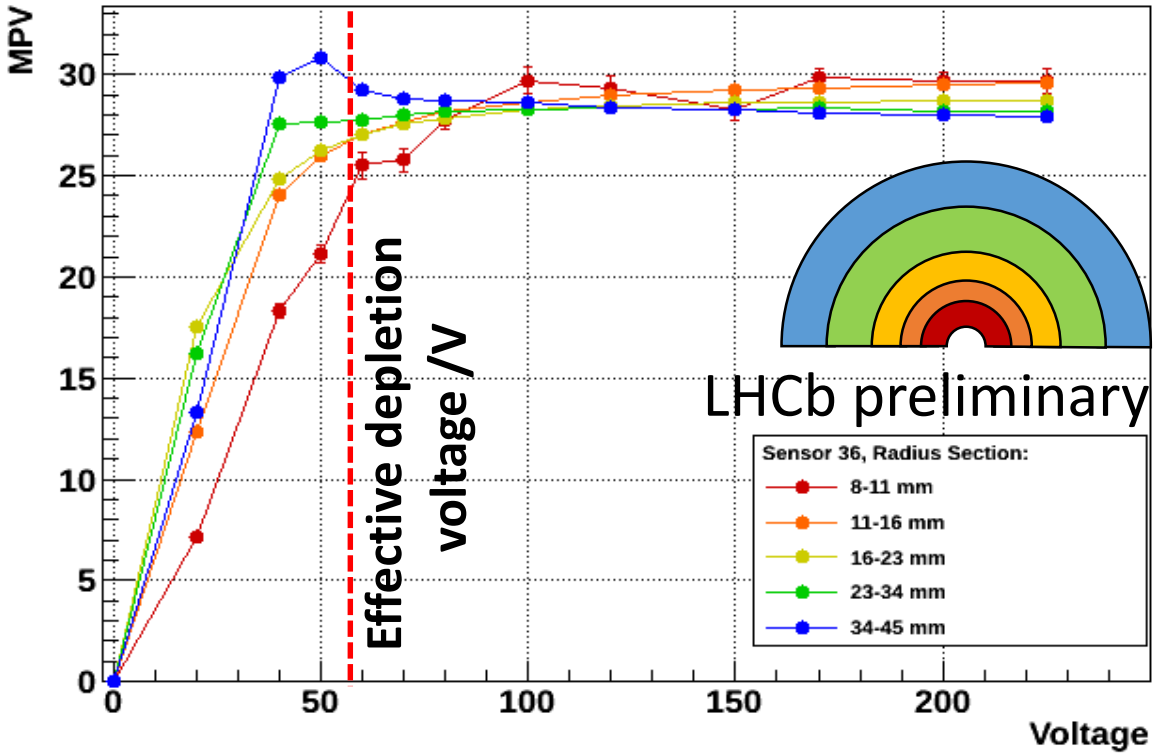
Lot of effects seen, almost all corrected before any impact on data for physics

Effective depletion voltage

An R sensor toward the end of the detector

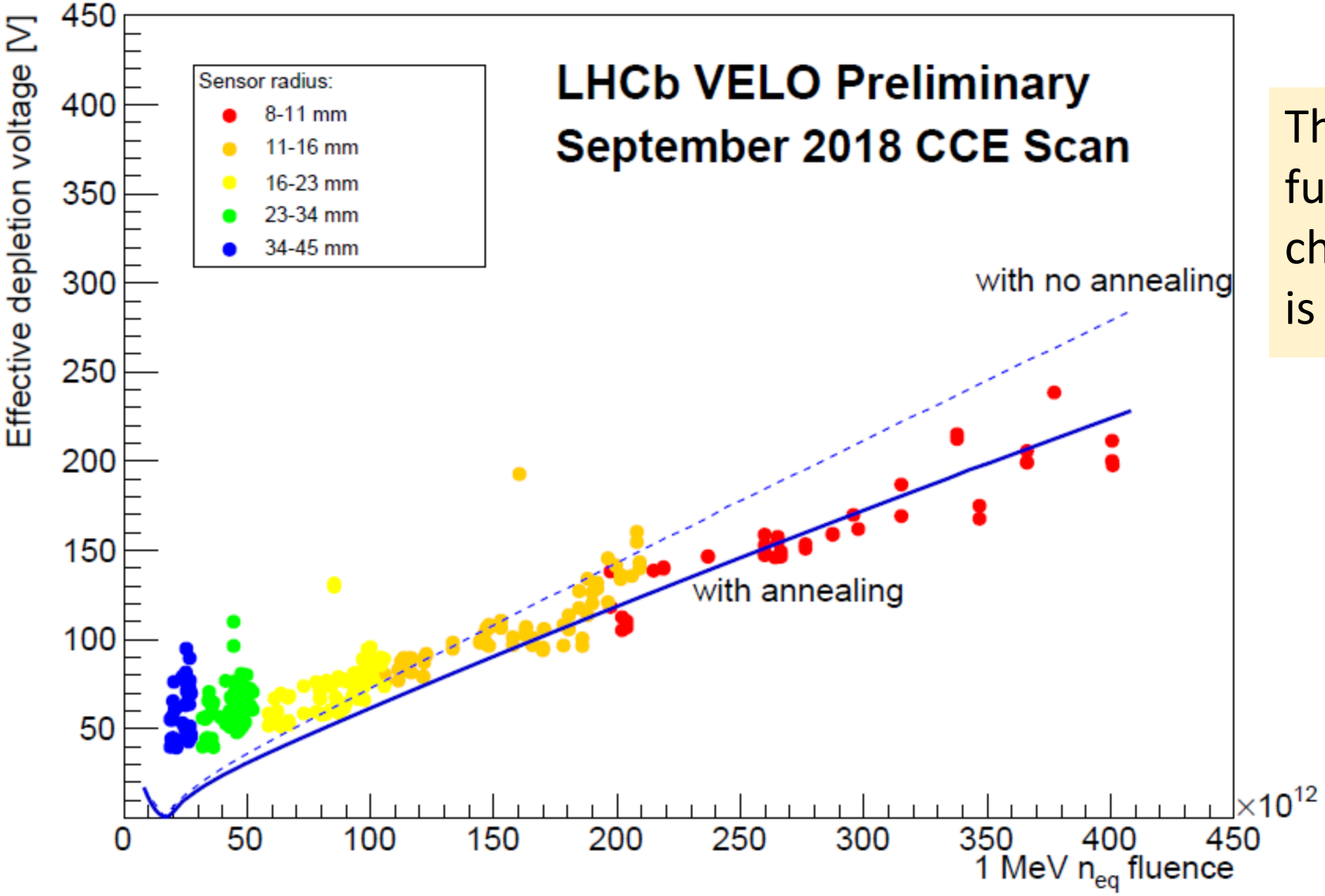


HV increasing
20 – 250 V



Measure EDV during HV scans in data taking by looking at the charge collection efficiency vs Voltage curves

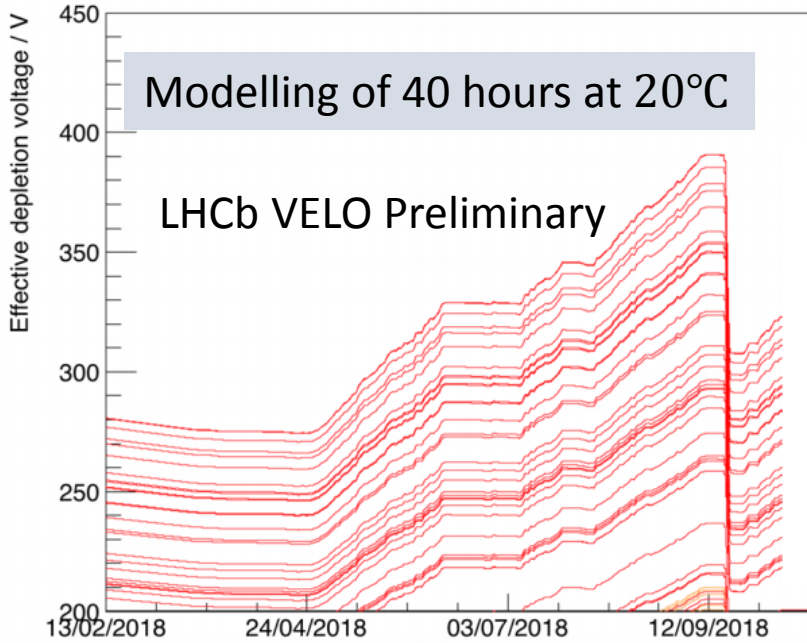
Effective depletion voltage in 2018

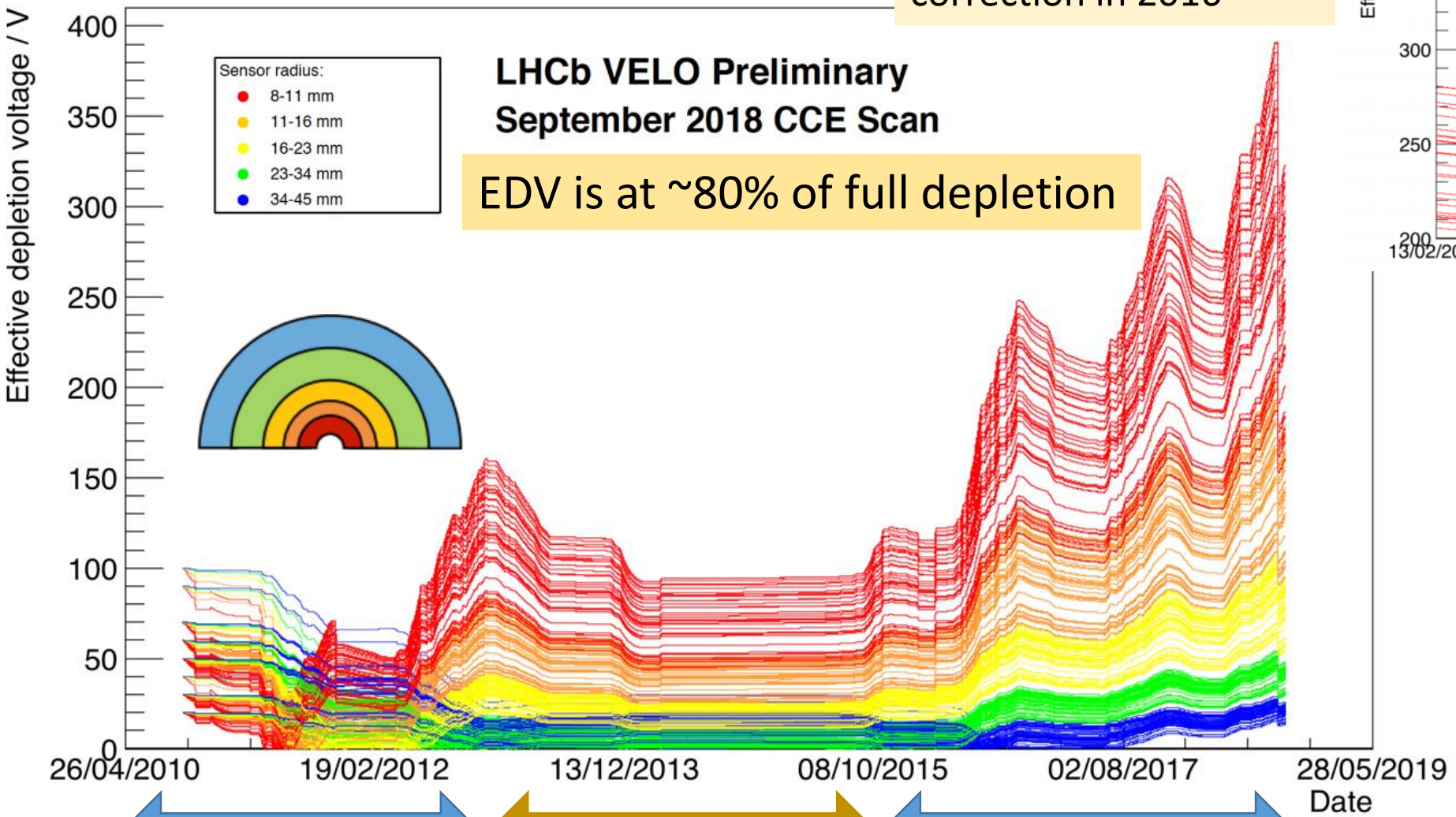


The detector can still be fully depleted so the charge collection efficiency is still excellent

Predicting the EDV by the end of Run II

Predictions of Hamburg model, last parameter correction in 2016





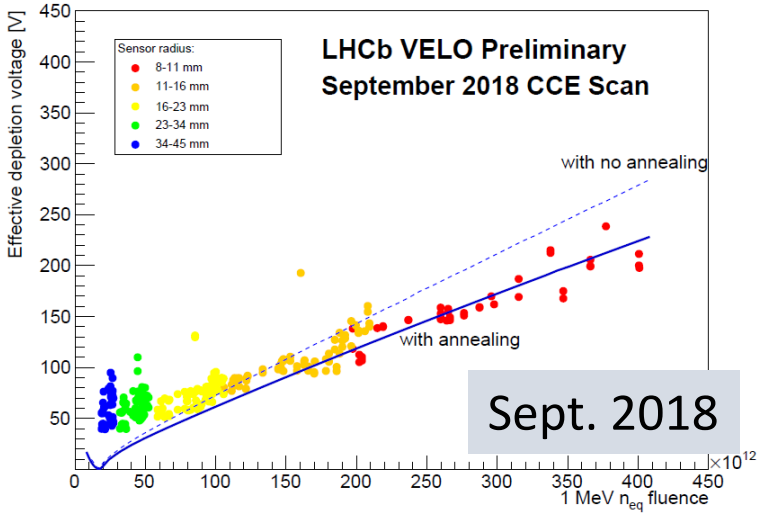
EDV is at ~80% of full depletion

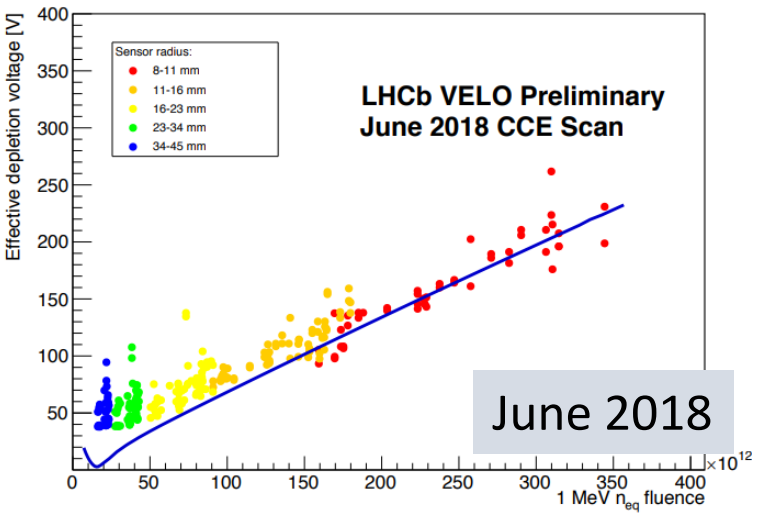
Run I | Long Stop I | Run II

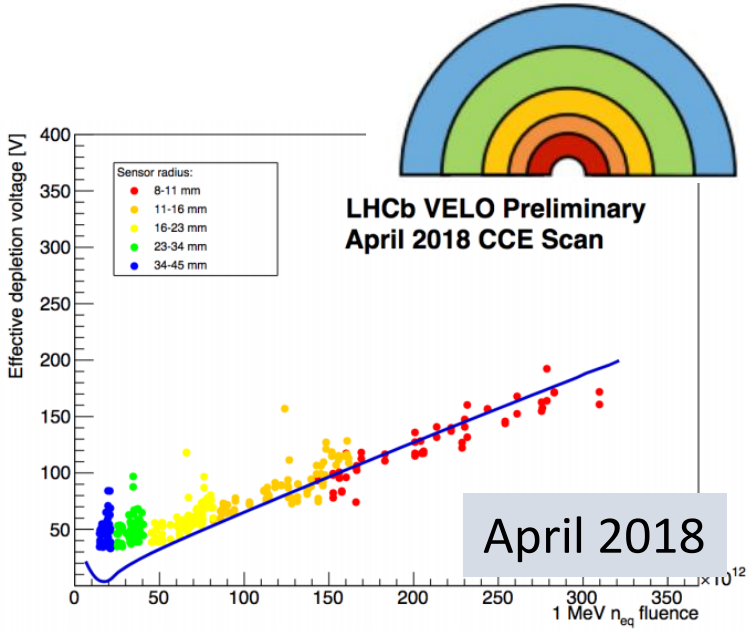
We expect to be able to fully deplete the sensors up to the end of Run II

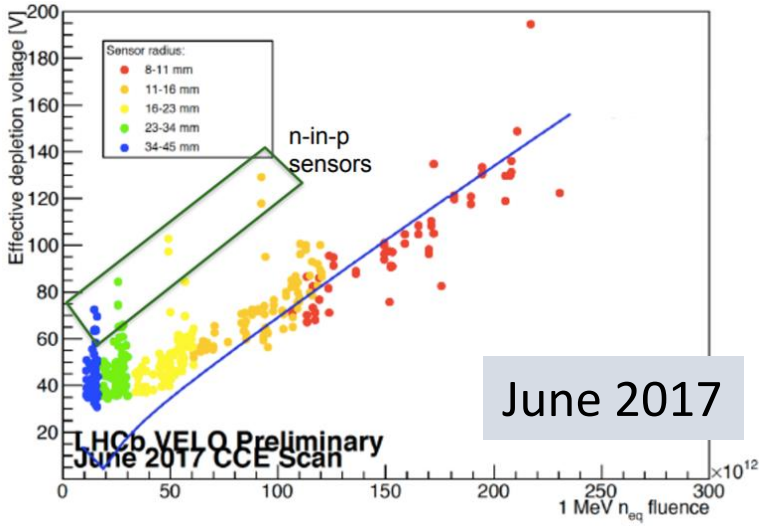
If run at 1.5°C warmer max HV lower by 15V

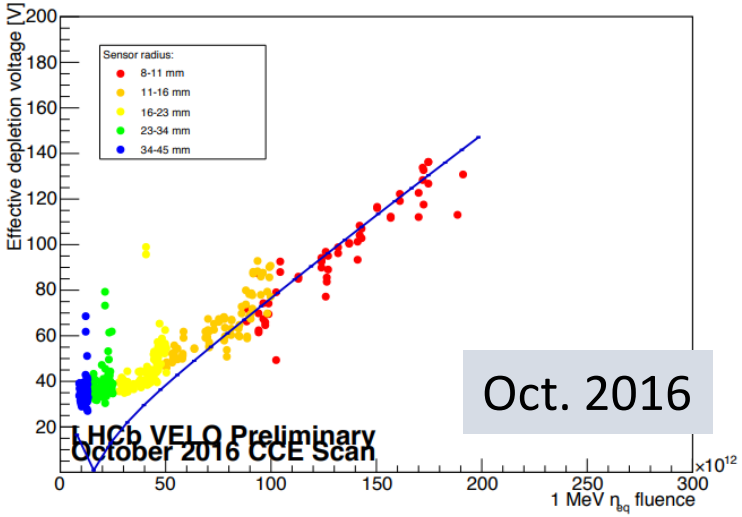
Hamburg model: consistent with LHCb VELO data

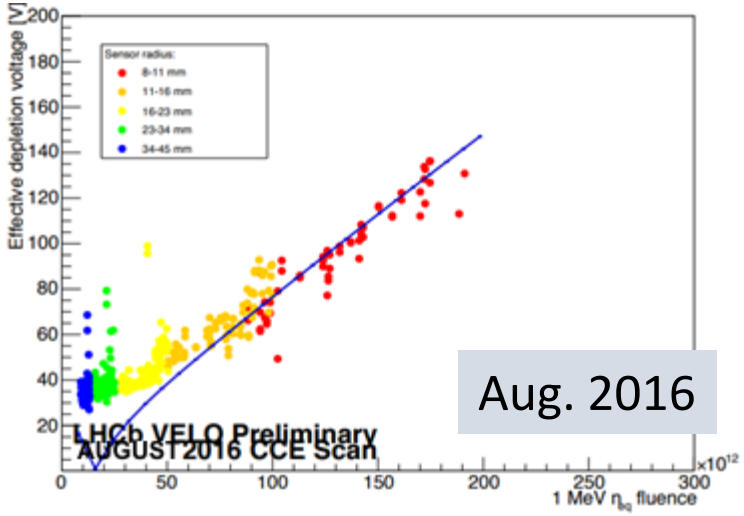












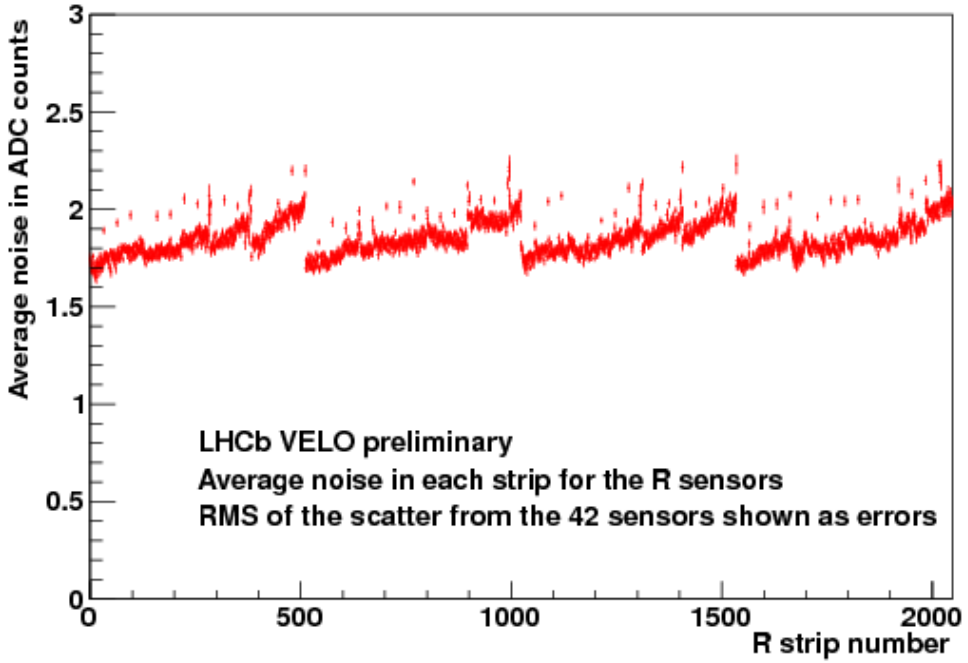
Signal to noise of the sensors

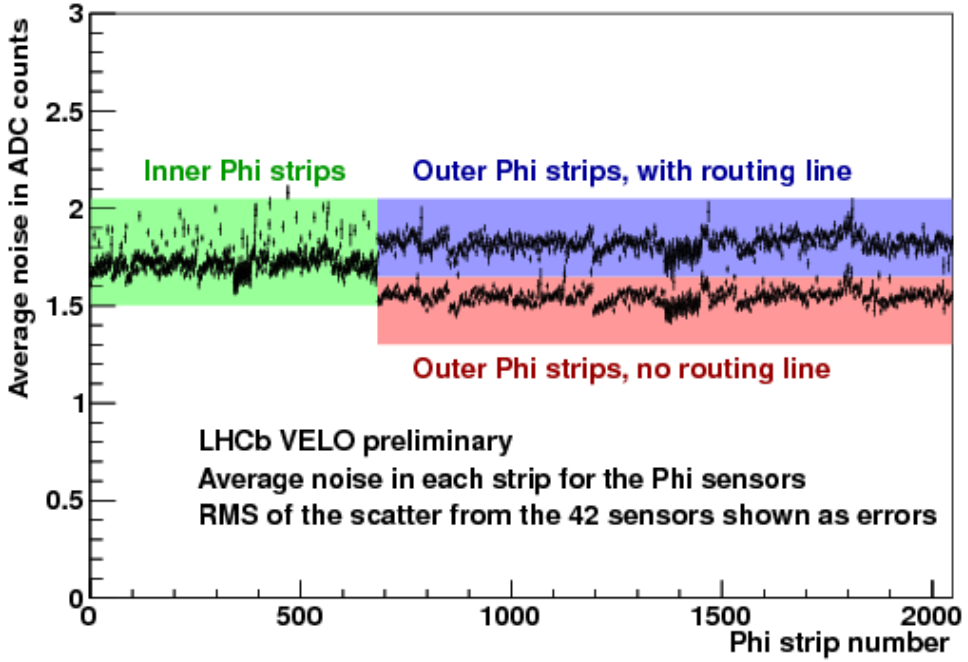
The MPV of the signals are 30-40 ADC counts after irradiation

The noise is ≤ 2 ADC count, and has been stable

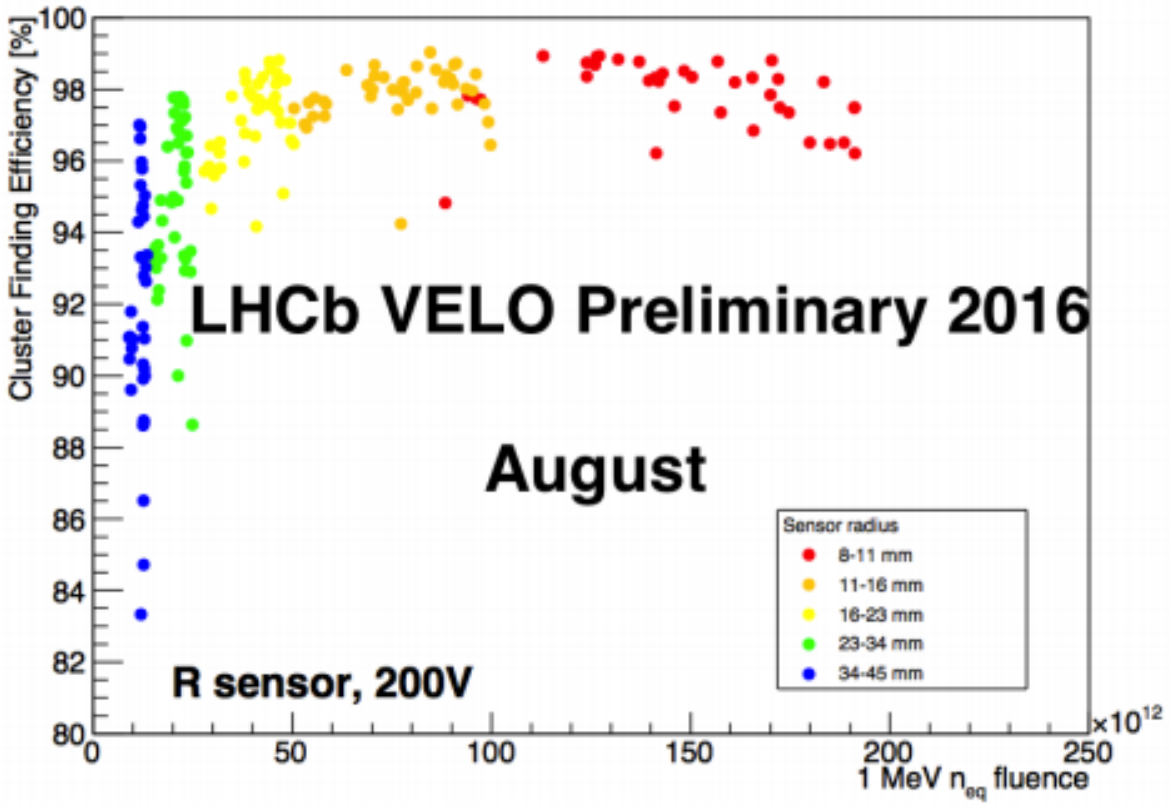
This huge Signal/Noise ratio means we have had no classical radiation damage induced inefficiency

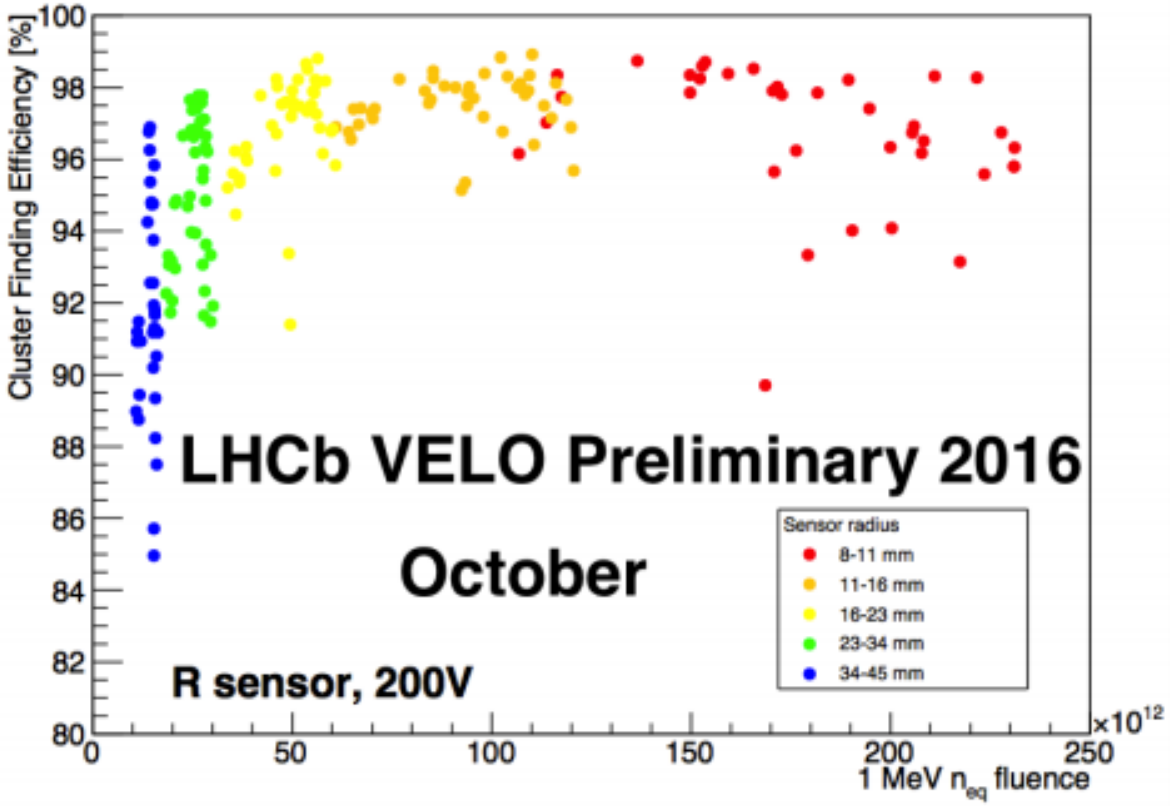
We set the clustering thresholds to get almost no noise in the detector: still have previous and next bunch spillover though





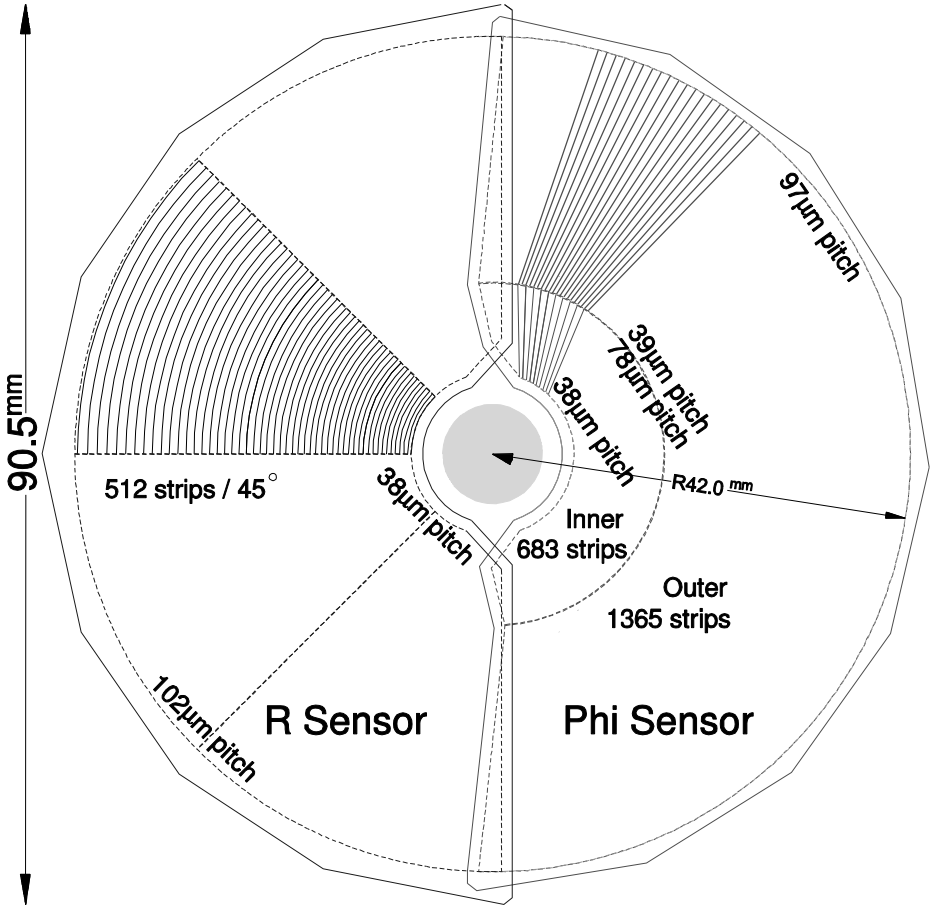
Cluster finding (pseudo) efficiency

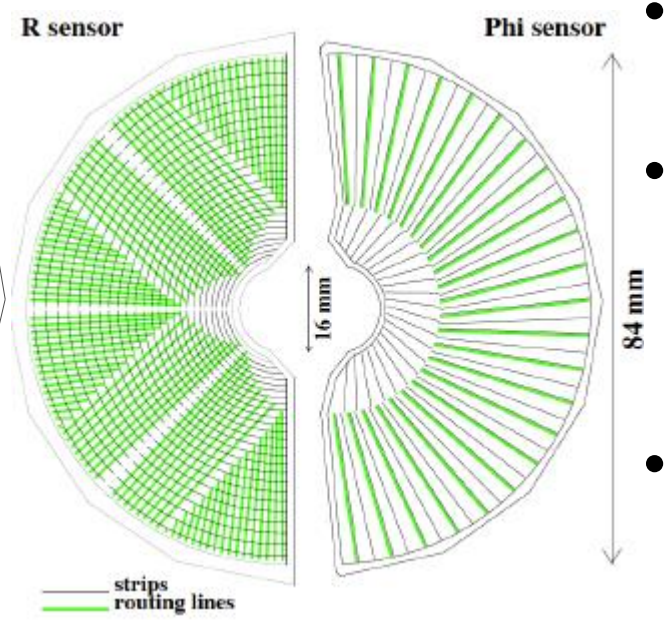




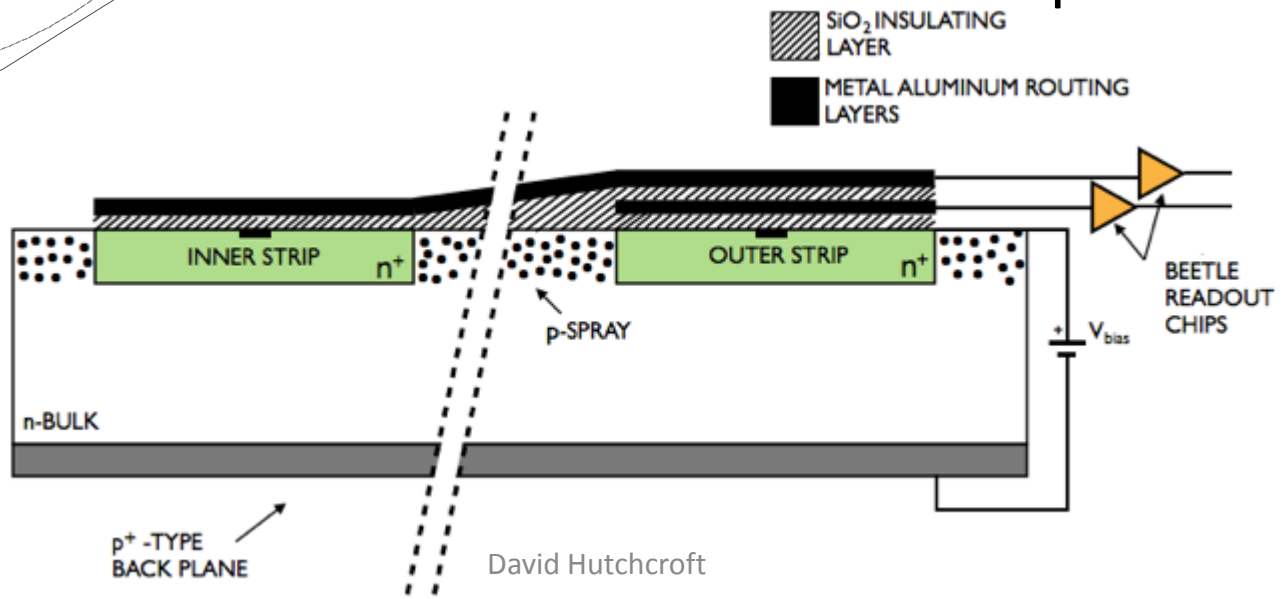
Note: these points are affected by fake tracks, reducing the apparent efficiency

Double metal effects





- R and phi sensors need two sets of metal lines
- One to capacitively couple to the strips, the other carrying the signal to the amplifiers over the outer strips
- Phi sensors (below) second metal routing is over the outer strips

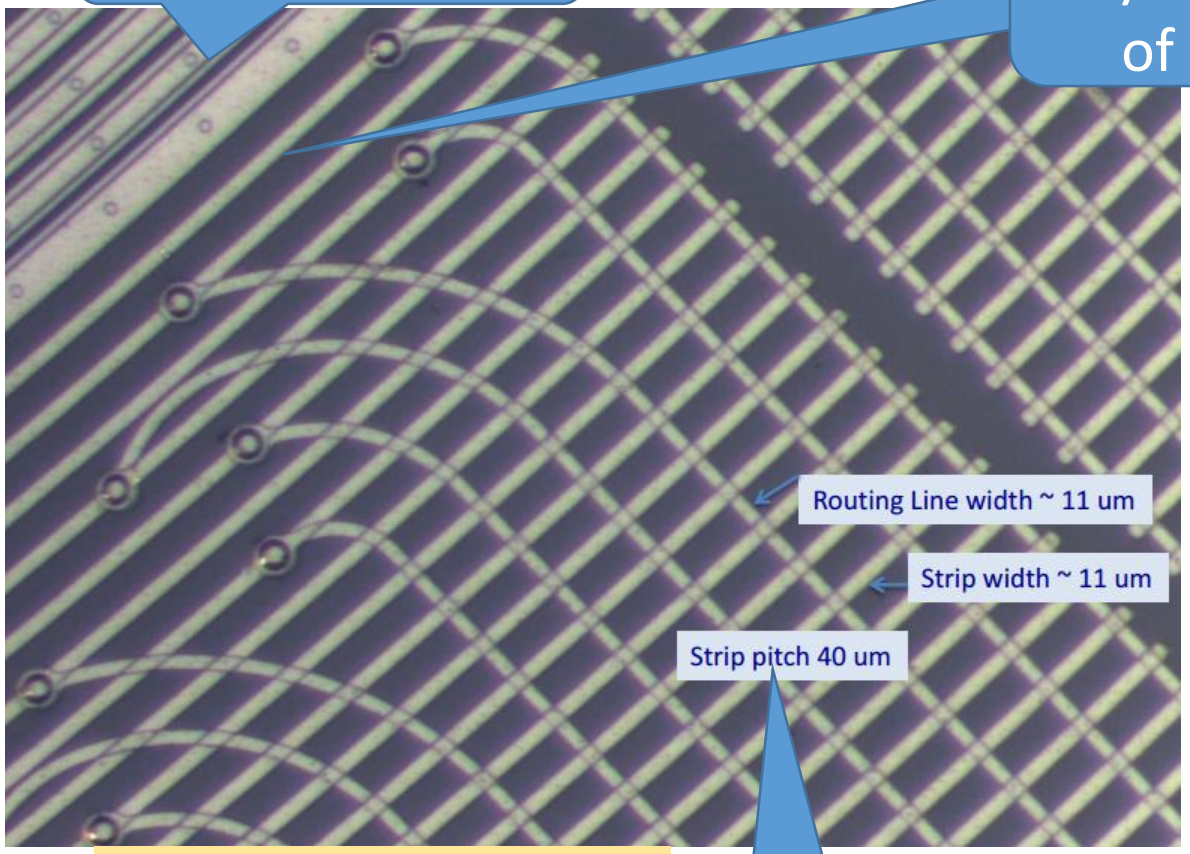


R sensors route across the outer strips

Picture of the R sensor's active area

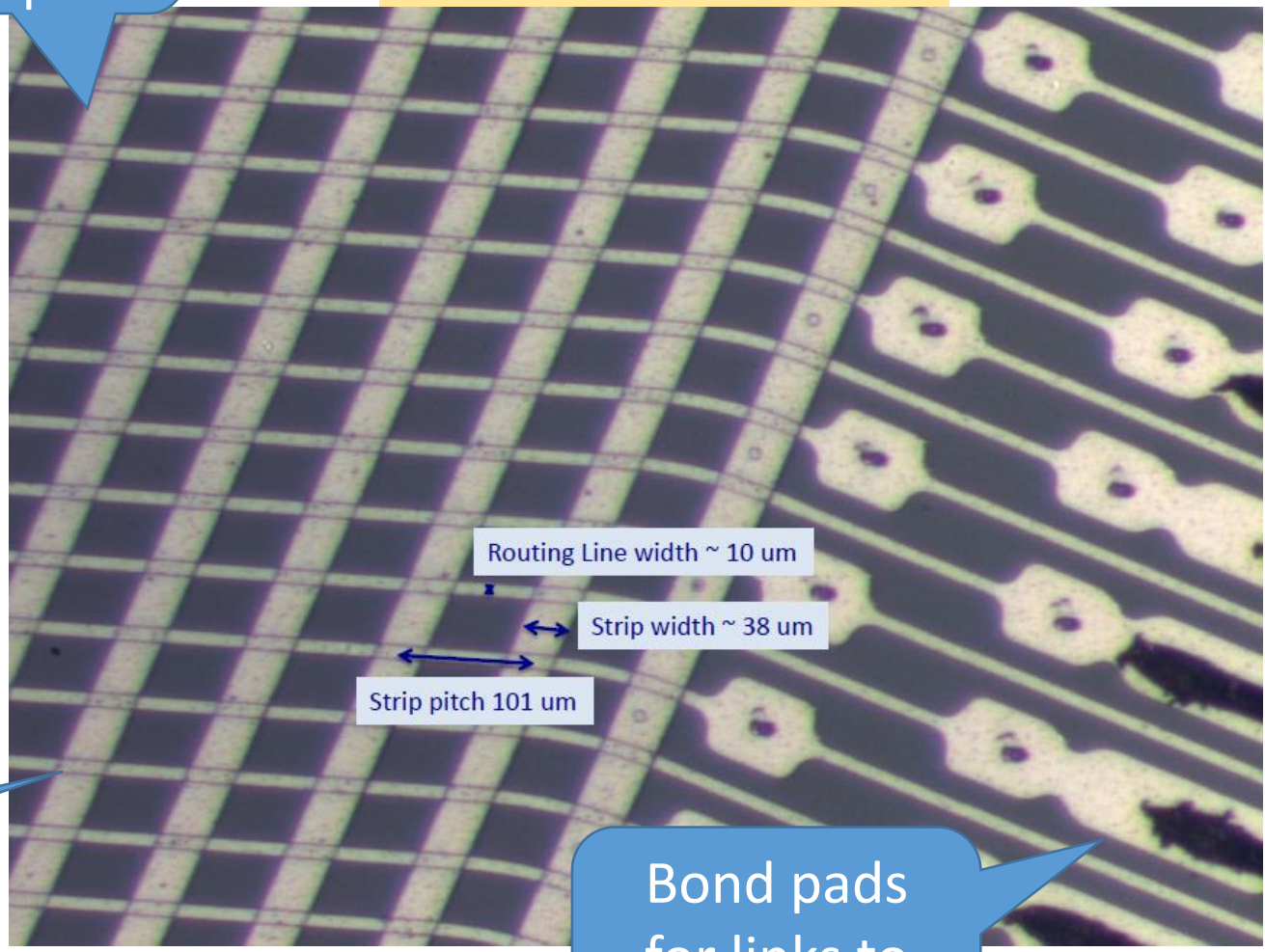
Guard rings

First Metal layer on top of strips



Inner edge of sensor

Outer edge of sensor

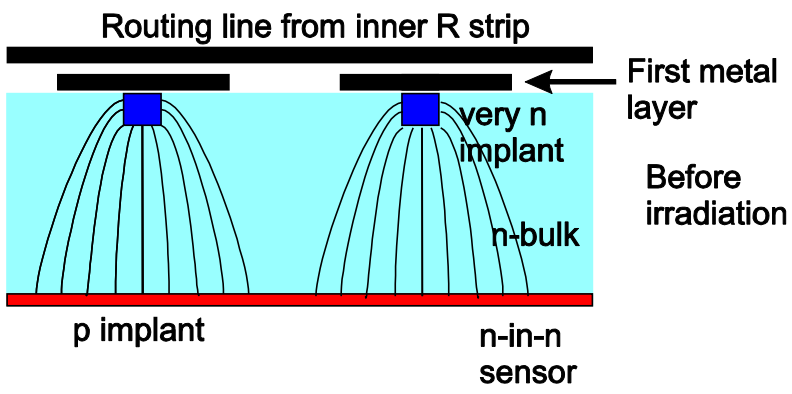


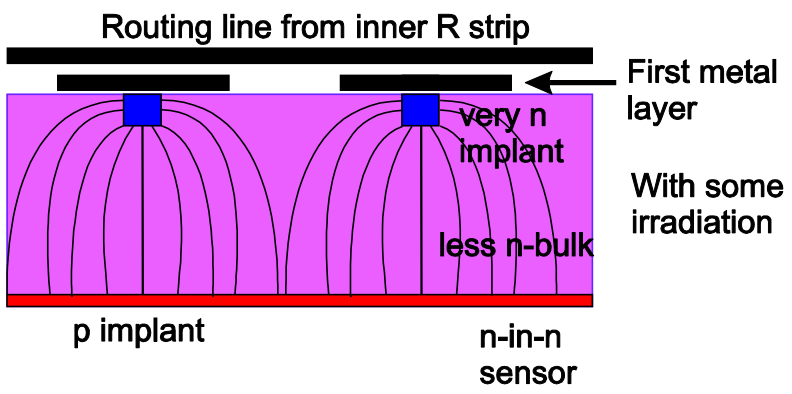
Second metal layer running across the strips

Bond pads for links to readout chips

Coupling effects of signals in R sensors

- Before irradiation there was no visible coupling to between inner and outer strips
- When a signal passes between the strips both layers of routing lines couple to the moving charge
- Before irradiation free surface charges can act as a shield as does the 1st metal layer
- After irradiation we see phantom signals in the inner strips

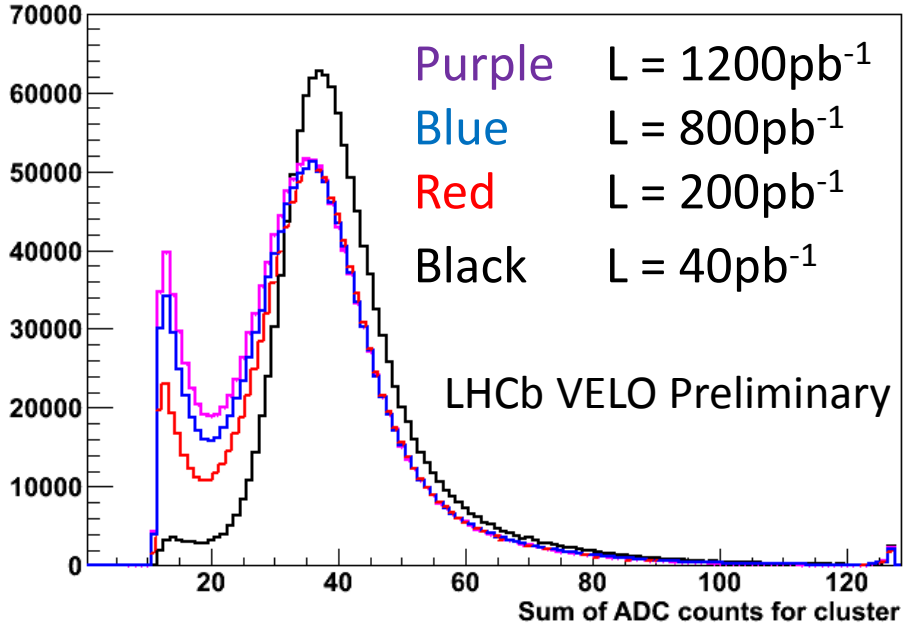




Effects see during data taking

Cluster on inner R strips at very low ADC counts appearing

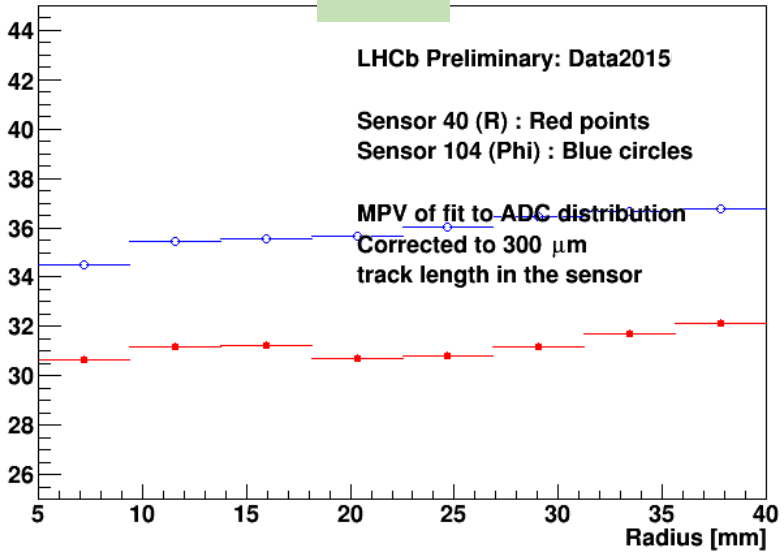
Predominately at the inner regions of the sensors, not where tracks crossed the sensors



Cluster size for R sensor clusters in ADC counts

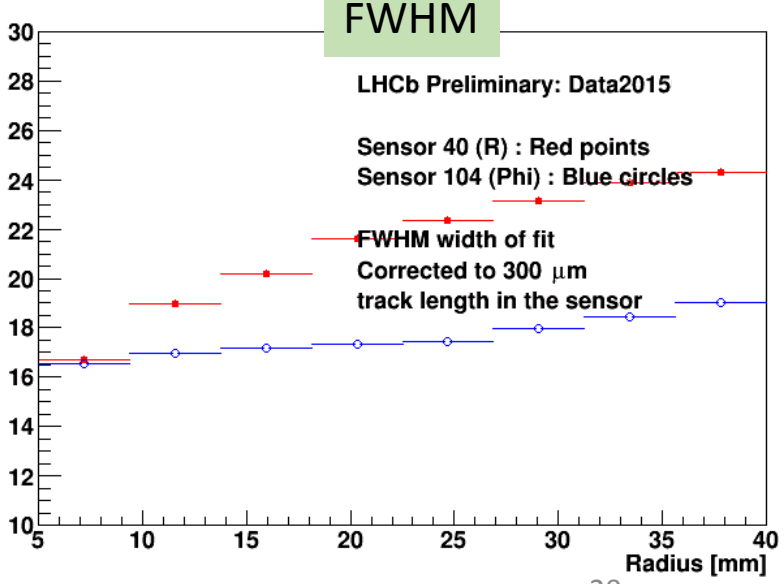
Lower charge collected in R sensors than phi sensors

MPV

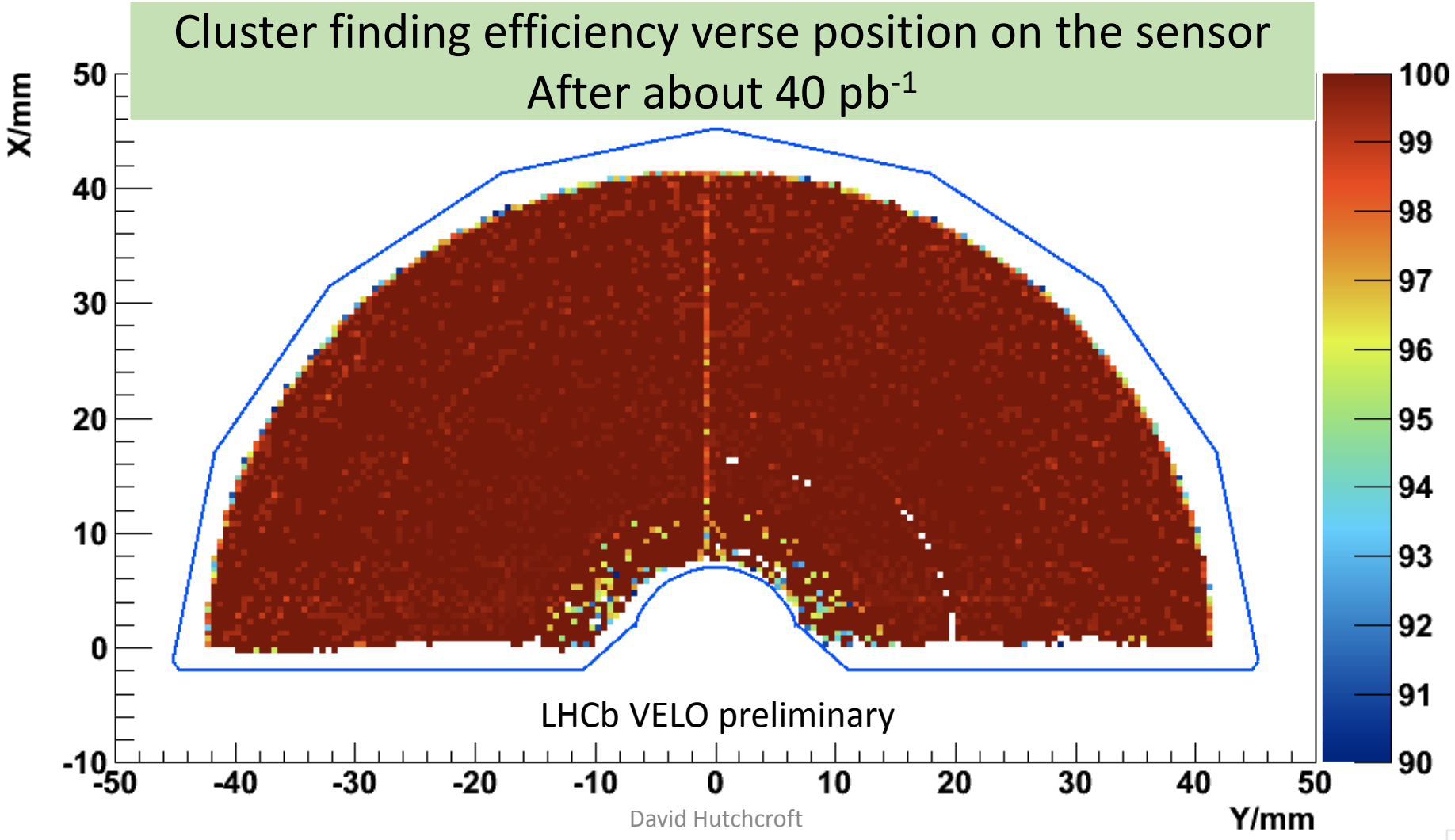


Wider distribution due to only some clusters losing charge

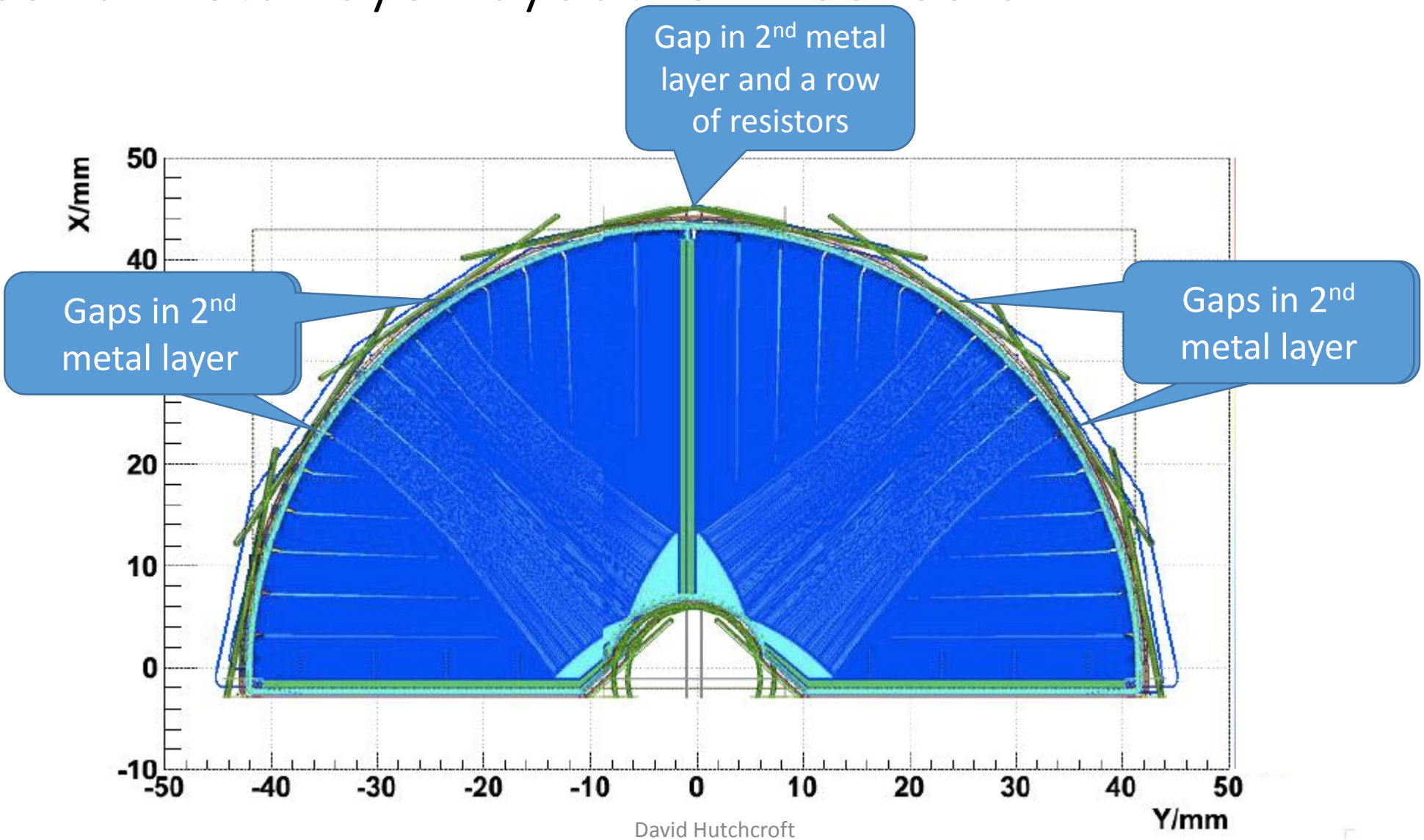
FWHM



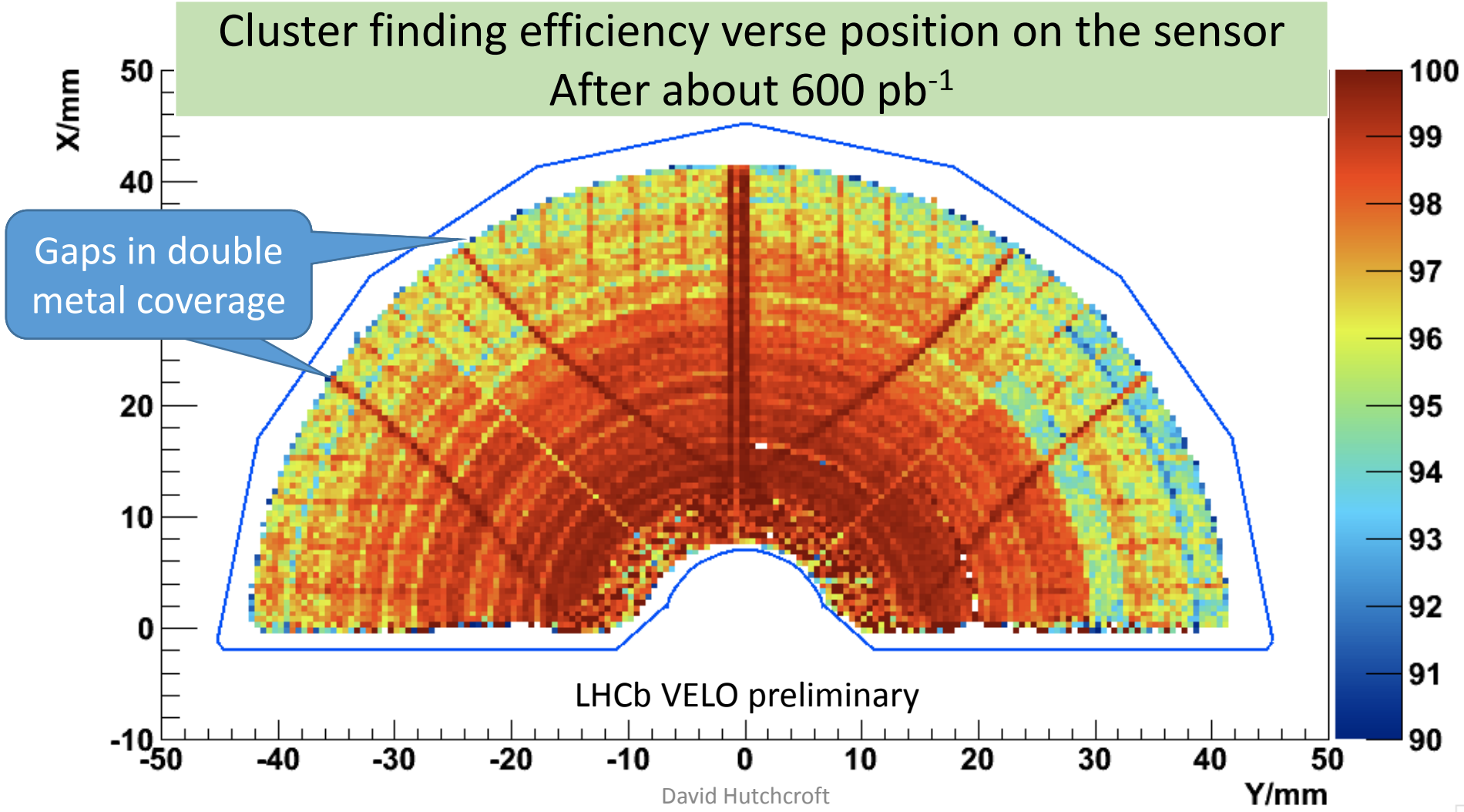
Cluster finding efficiency 2D map for one R sensor, when new…



Second metal layer layout for R sensors

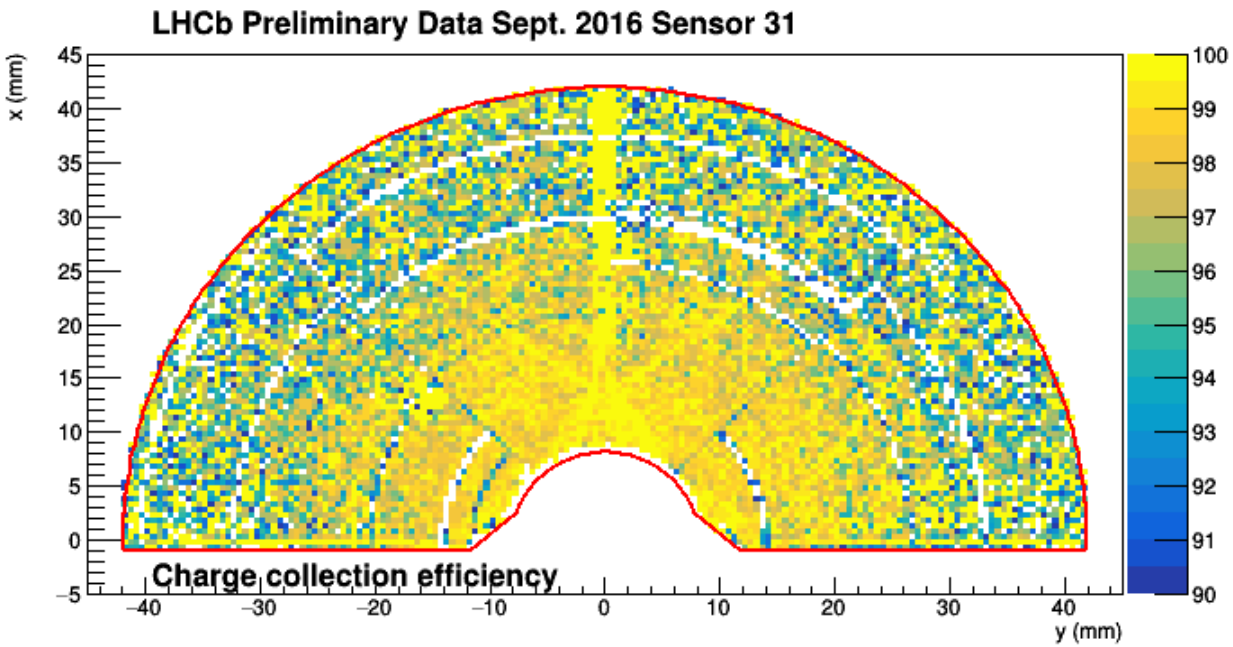


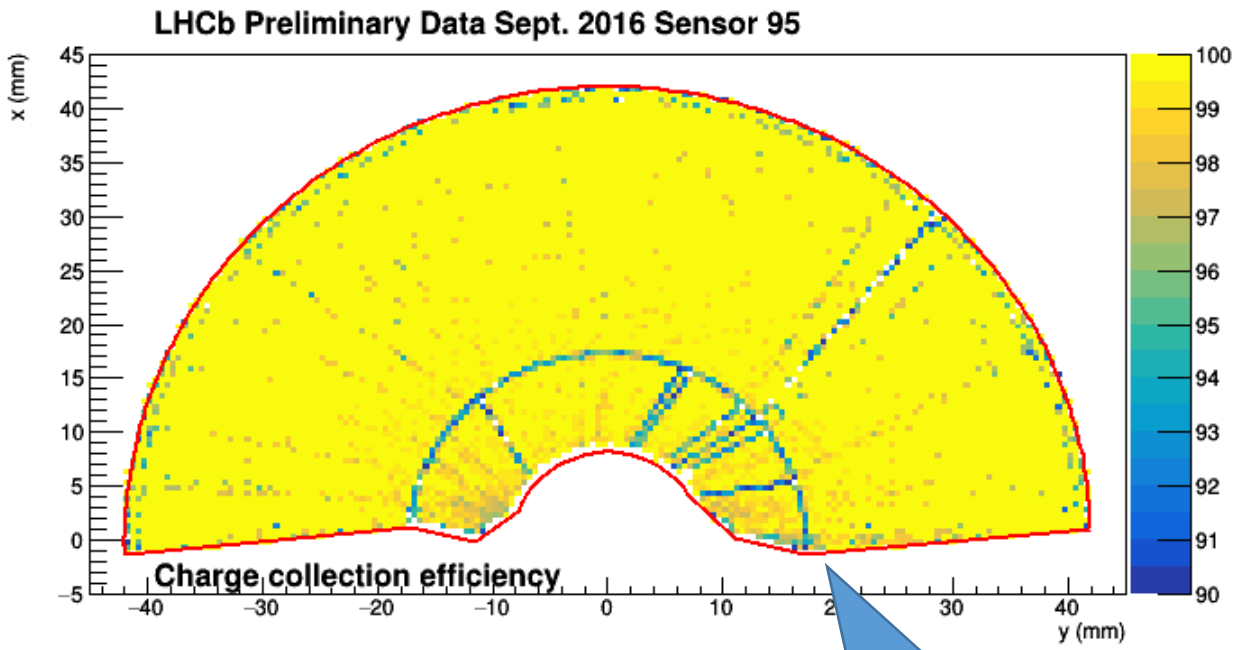
Cluster finding efficiency 2D map for one R sensor, in the second year of data taking



Cluster finding efficiency 2D map for one R & phi sensor, September 2016

After about 5000 pb^{-1}



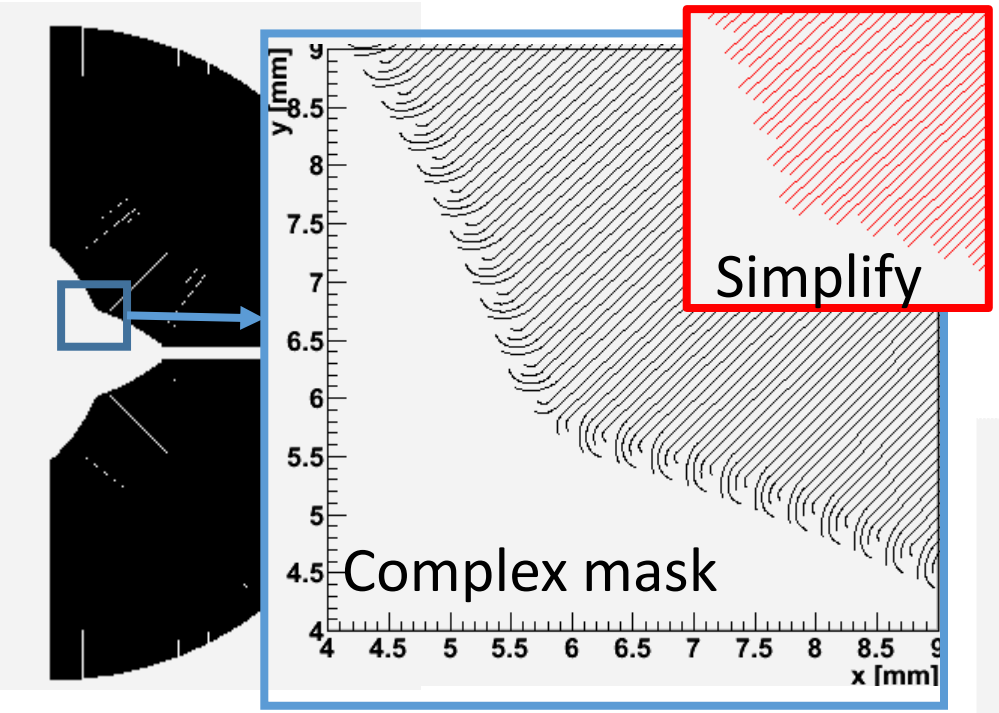


Different R sensor, so different pattern of dead strips

Inner to outer region

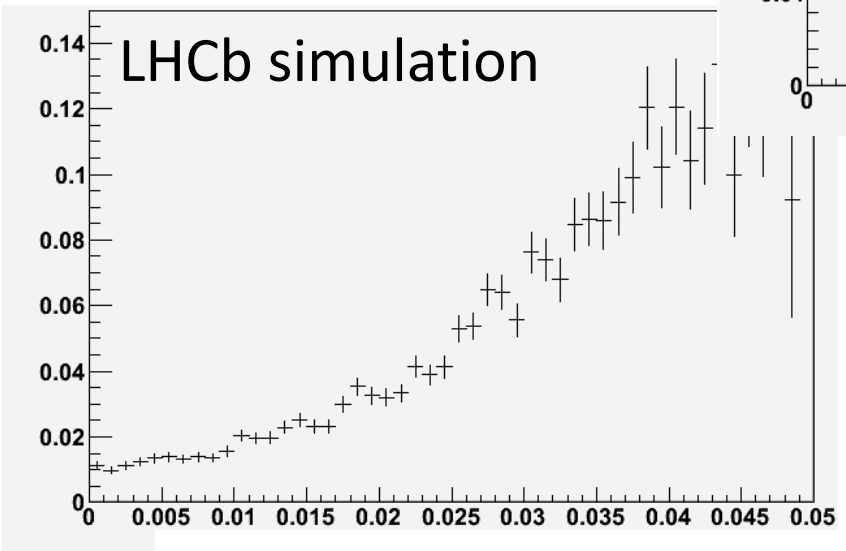
Simulation of the effects

To simulate the 2nd metal effects we had to add the 2nd metal to the detector description

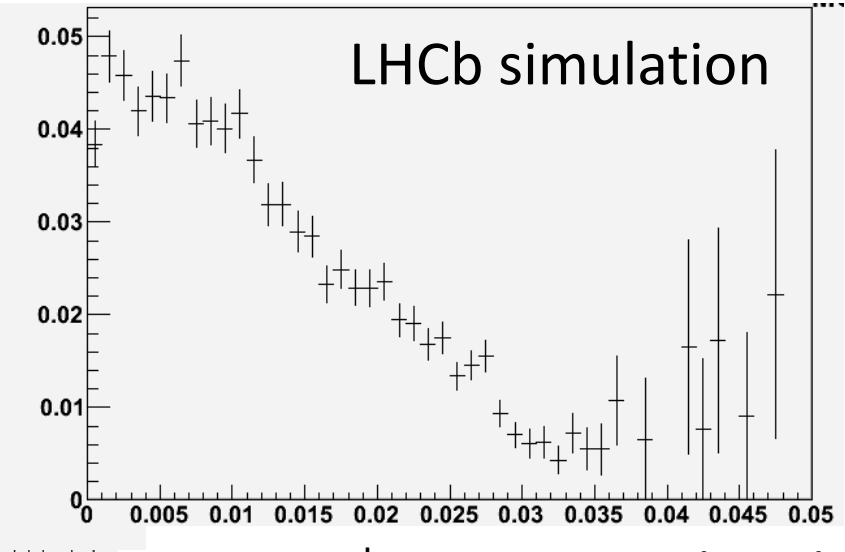


Real routing lines are complex to fit Micron's design criteria

Need to correct charge sharing for the track position wrt the 1st and 2nd metal layers



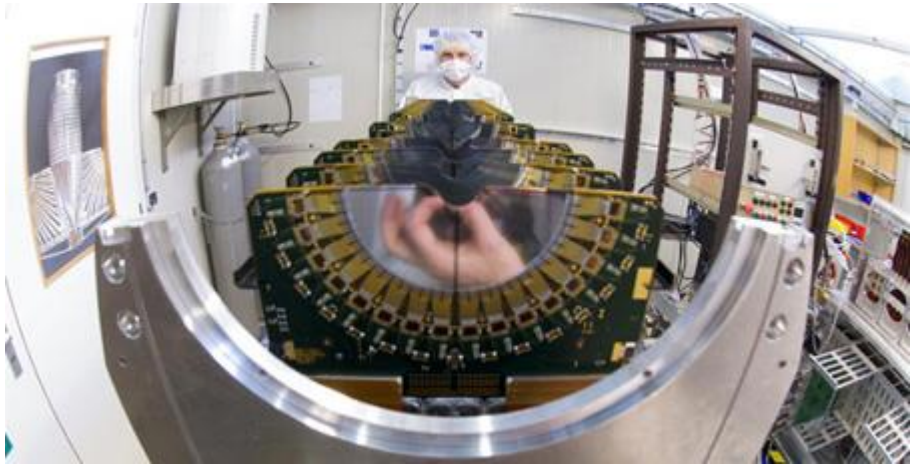
Dist. 1st metal layer (mm)



Dist. 2nd metal layer (mm)

Use rate of production of fake clusters to tune simulation

Measuring is easier than aligning



Measure the positions of your detector before installation!

Too many degrees of freedom lead to “unphysical” alignments and weak modes can not be constrained

Construction time R to Phi sensors alignments were taken with $\sim 4\mu m$ precision, these are still used as they can not be bettered using alignment fits

The VELO was measured in a metrology machine for over a week, which has significantly reduced the B decay lifetime systematics

Conclusions

- LHCb VELO detectors do see radiation damage
- Hamburg model predicted IV evolution with luminosity
- Leakage currents rising linearly with luminosity
  - We try to always keep the detector cold to avoid unwanted annealing, but in the last year we can use beneficial annealing
- R sensors show coupling to second metal layer causing a small reduction in efficiency
- Tracking efficiencies are unchanged
- Every reason to believe that we will get to the end of Run II in good shape
  - We built a full spare VELO available just in case and we've started constructing the replacement for Run III this year: listen to Deepanwita Dutta's talk tomorrow

Thank you for listening!

Any questions?