Radiation damage studies in LHCb vertex detector

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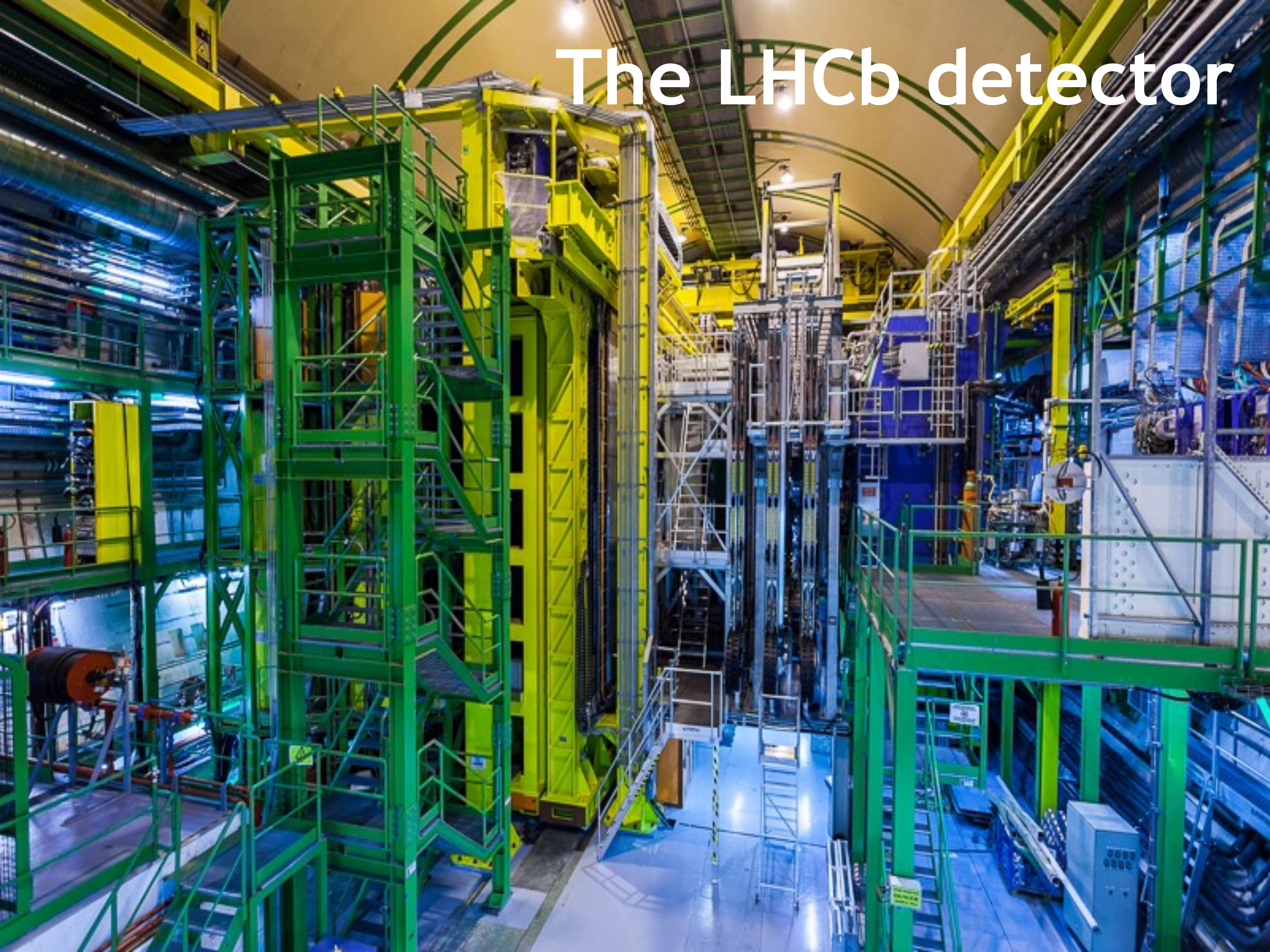
IHEP seminar

8 January 2019

The LHCb detector



LHCb

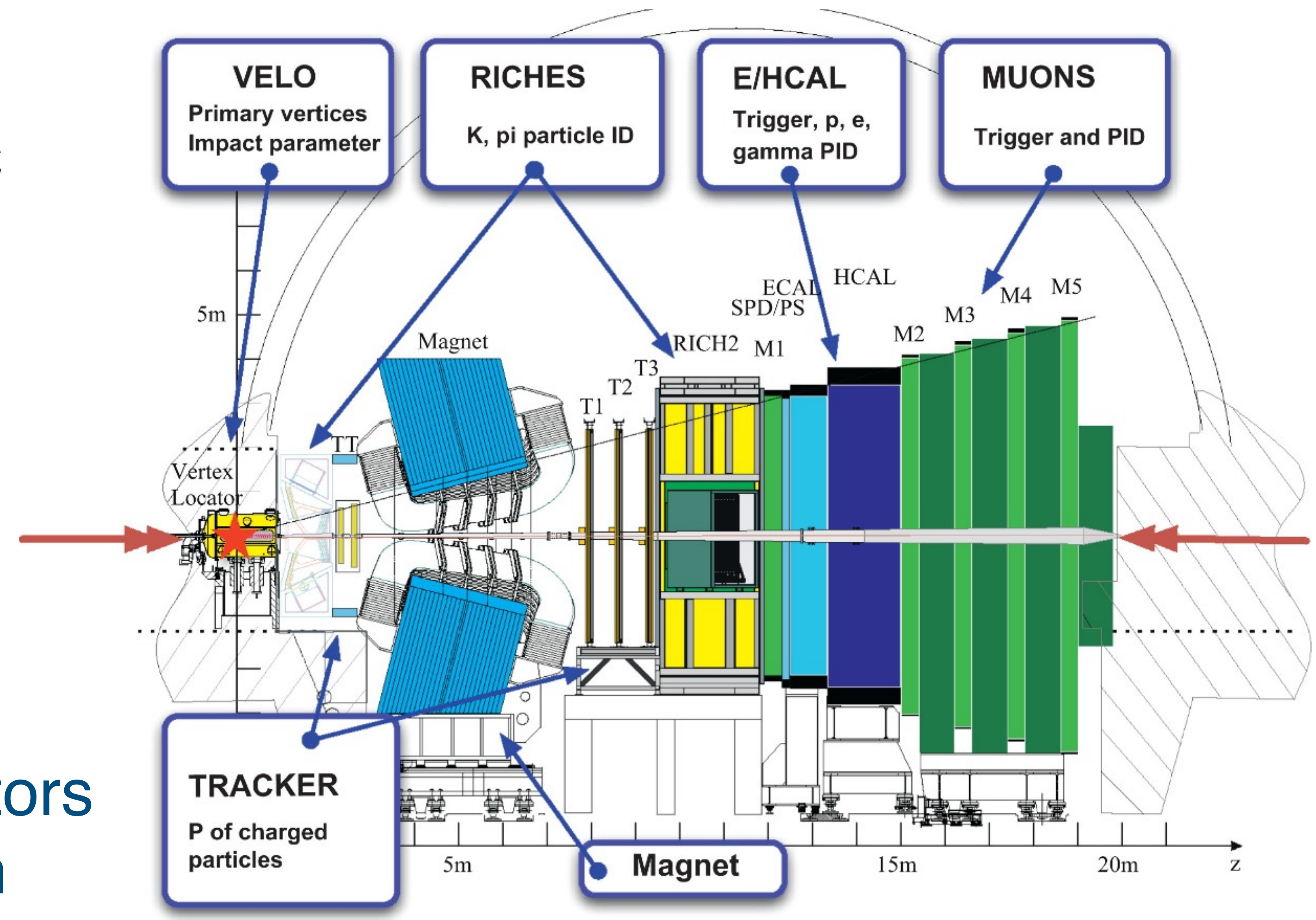
LHCb - single armed forward spectrometer, located at LHC

Acceptance: $2 < \eta < 5$

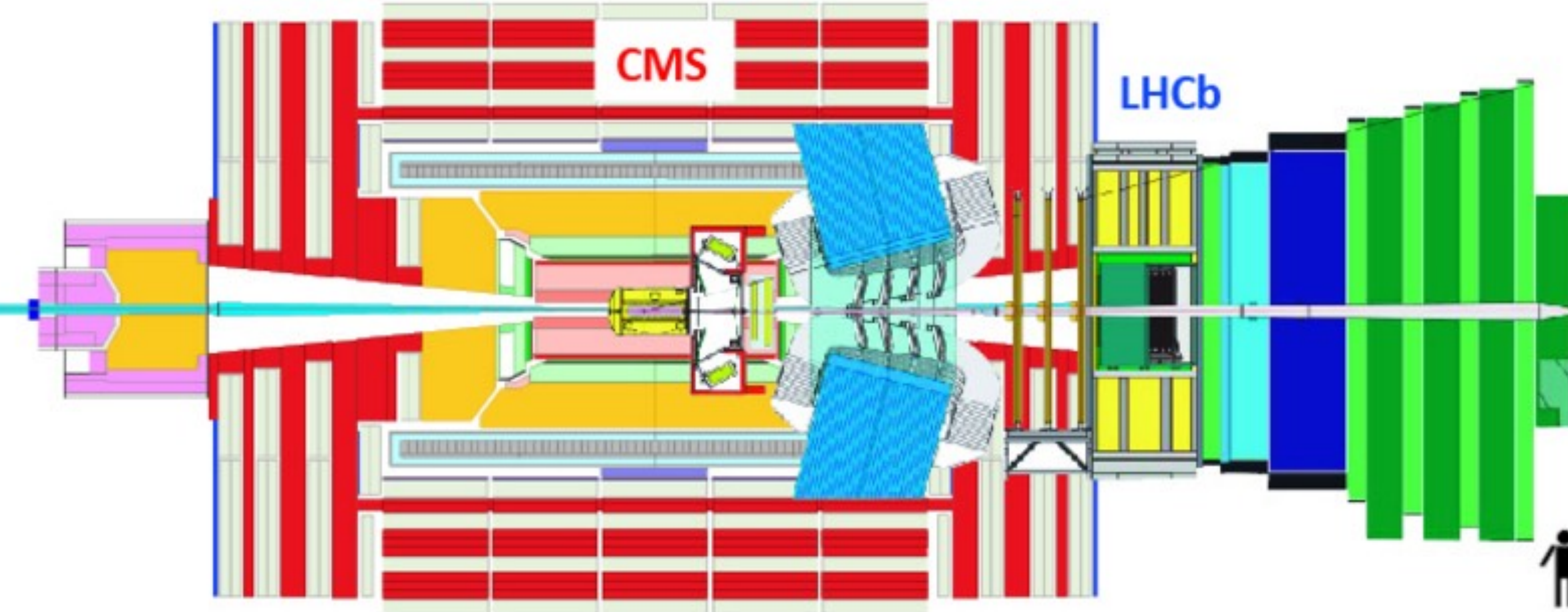
Proton-proton interaction at up to 13 TeV

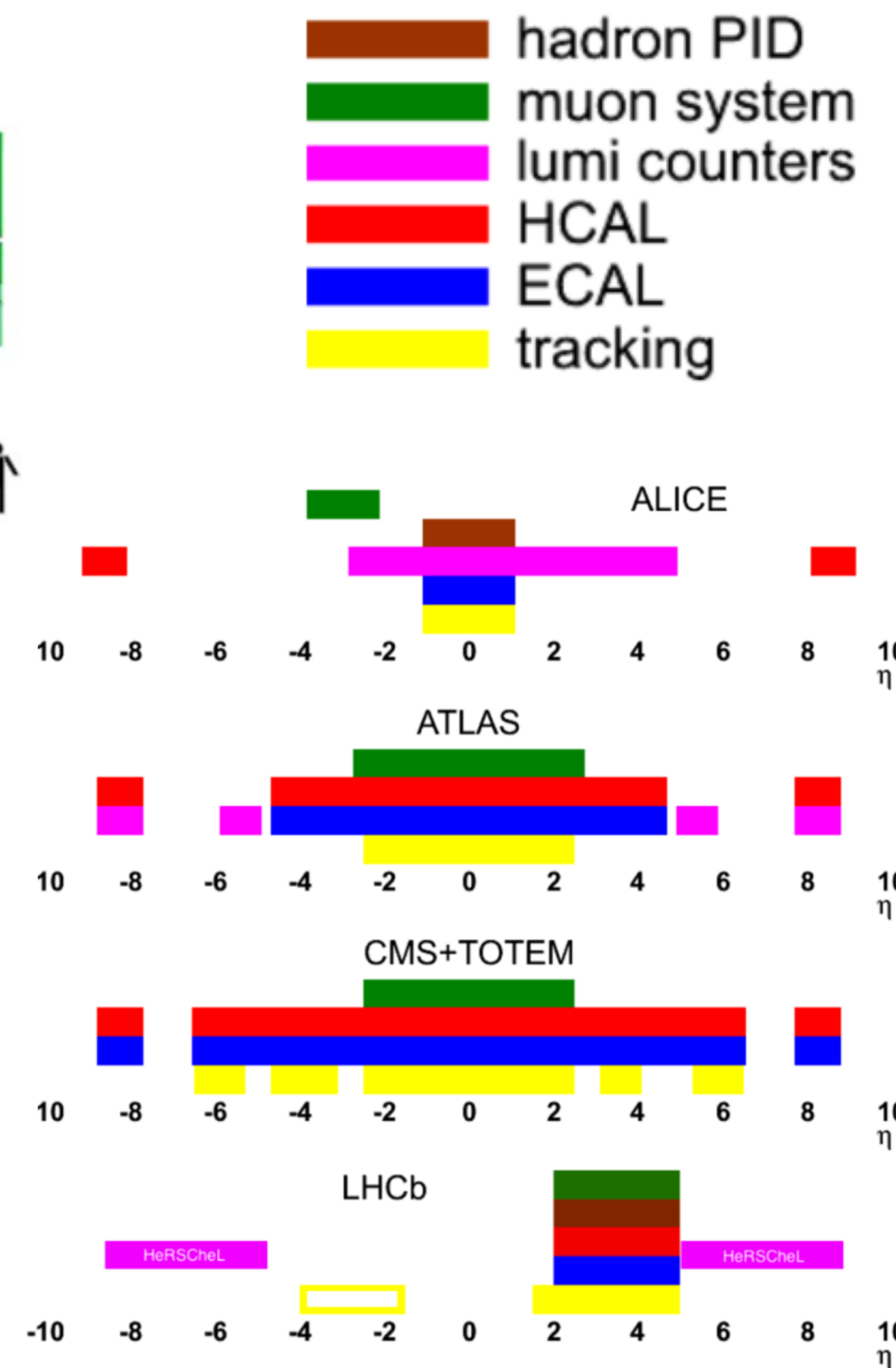
Physics goals:

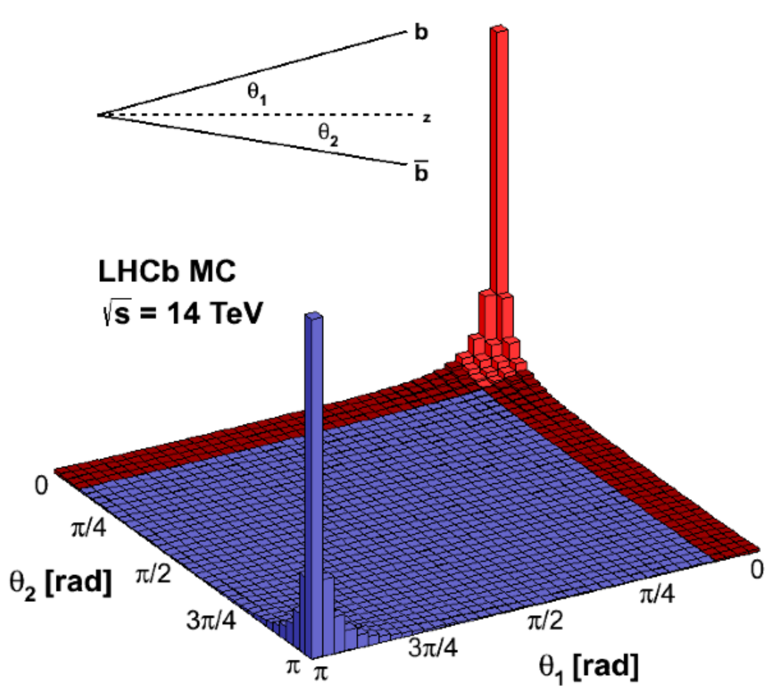
- CP violation in b and c sectors
- General purpose physics in forward region

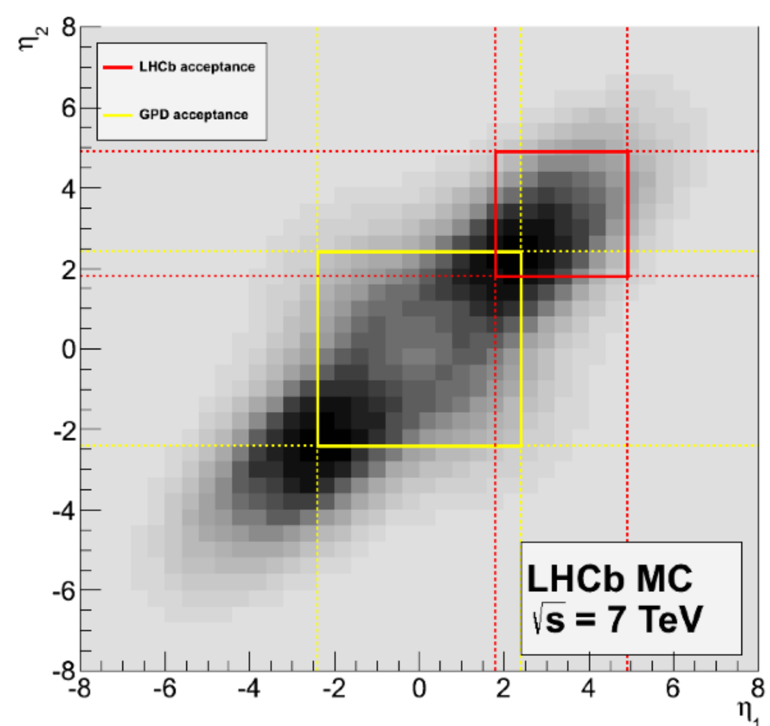


LHCb - Compare with other experiments

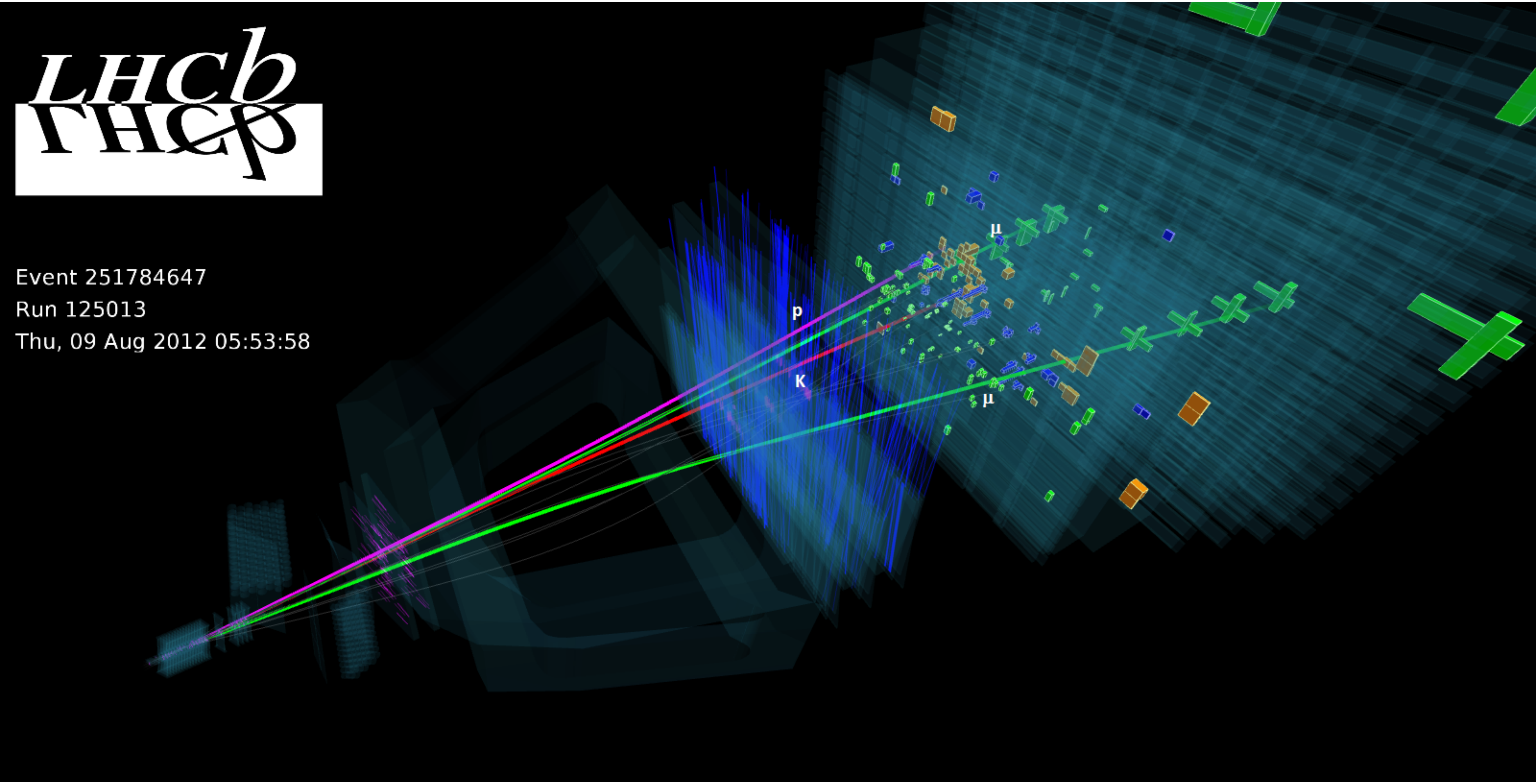




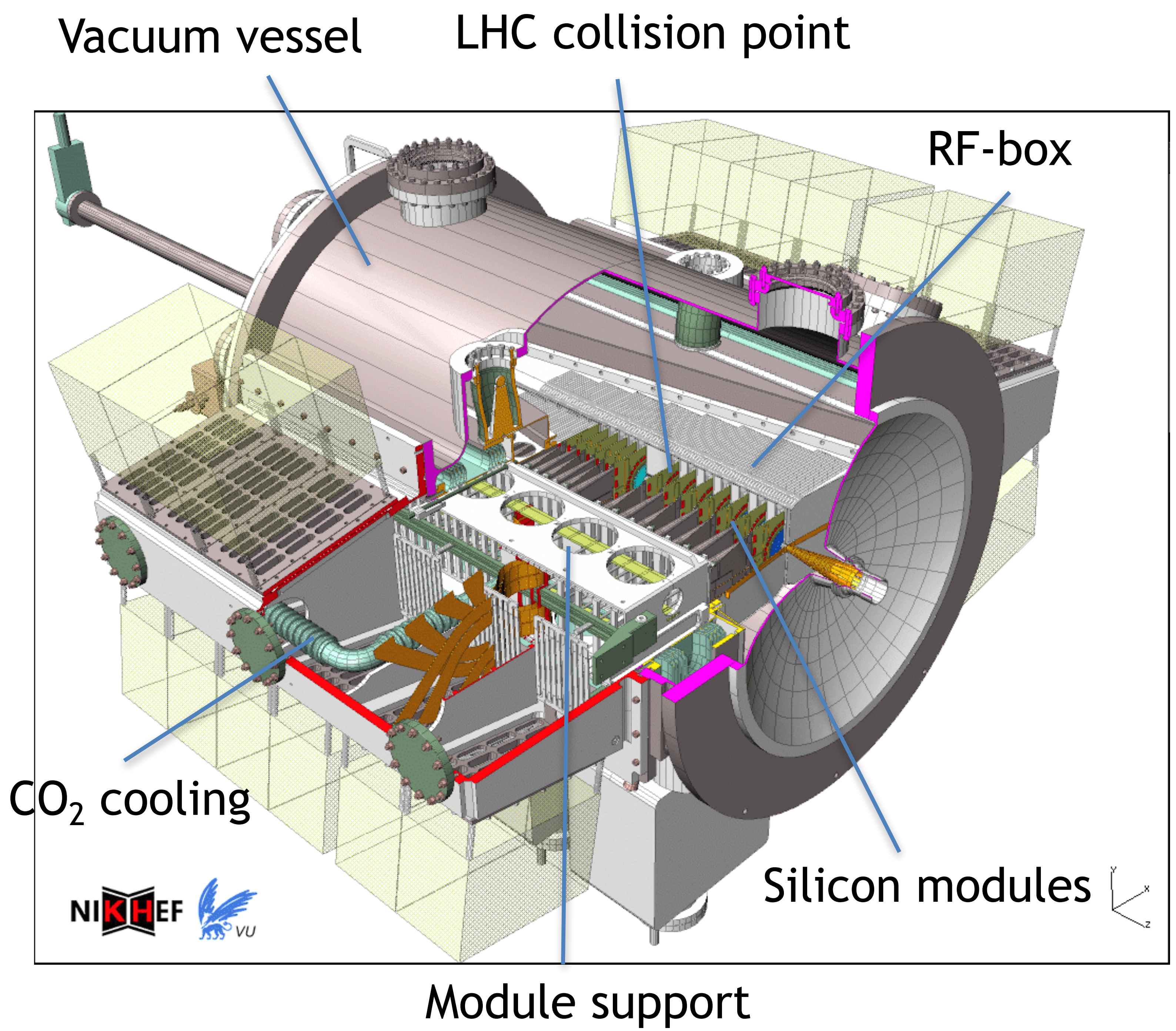




Event reconstruction: $\Lambda_b \to J/\psi pK$

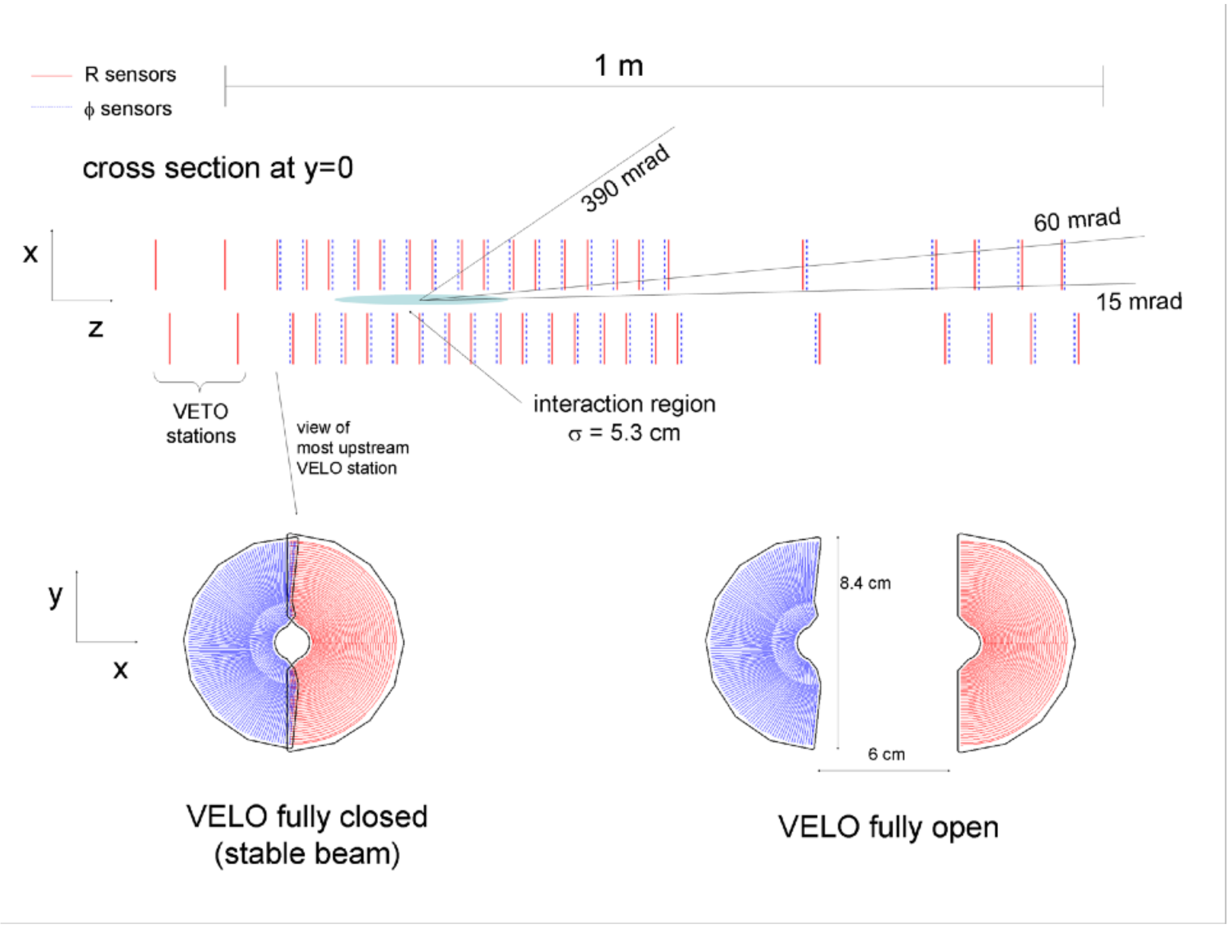


VELO

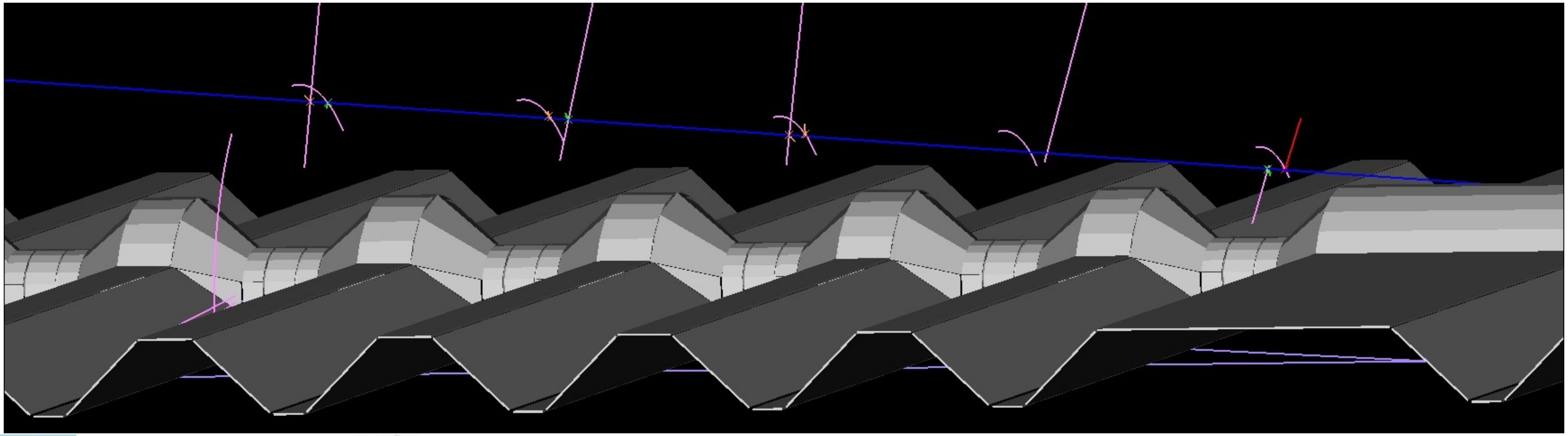


- Closest to collision point among all LHC detectors
  - First strip at 8.2 mm
- Operated in a secondary vacuum
- A 300 μm thick Al foil separates the VELO vacuum from the LHC
- Bi-phase CO_2 cooling system operates at -30 °C
  - sensors at -10 °C

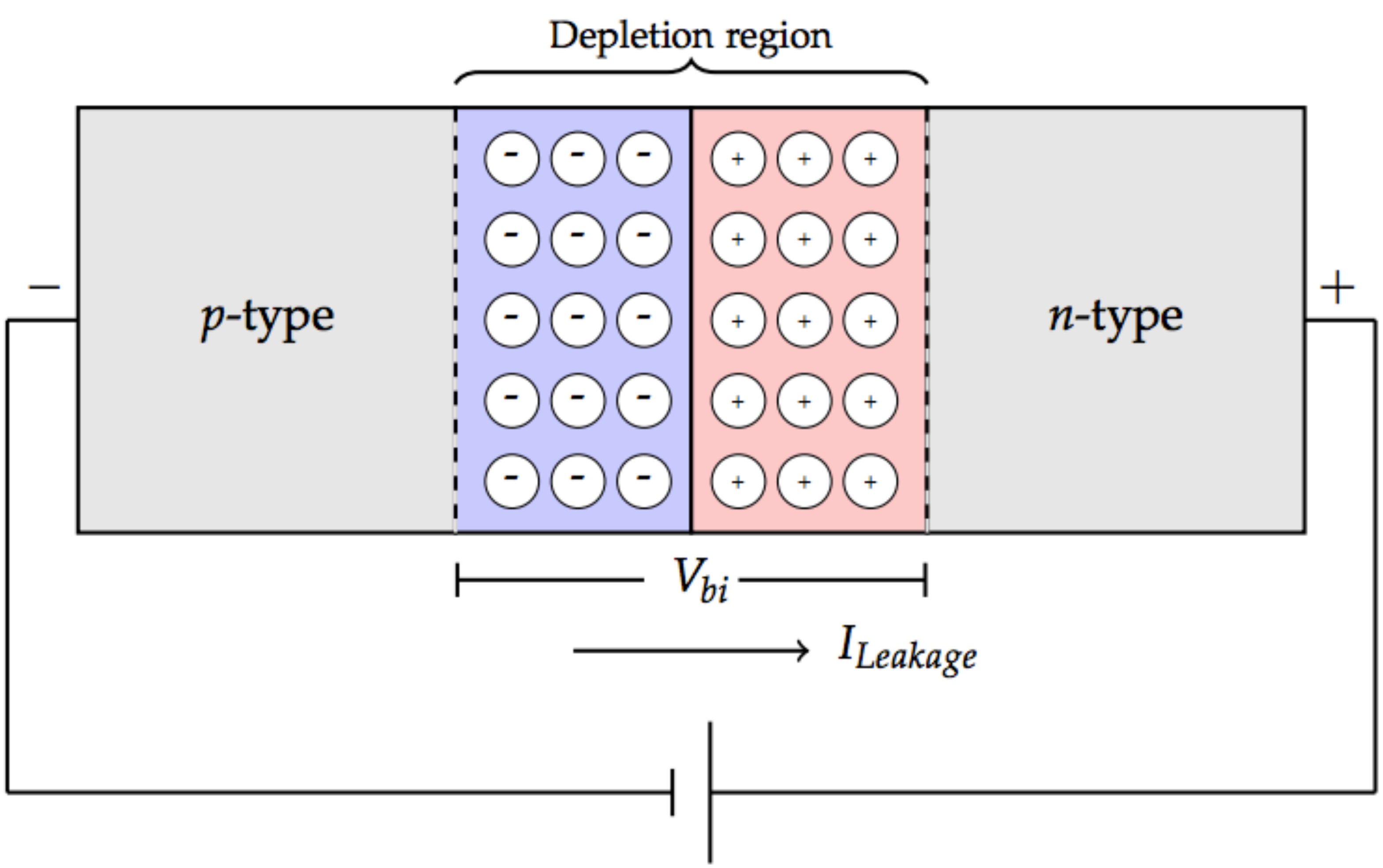
VELO sensors

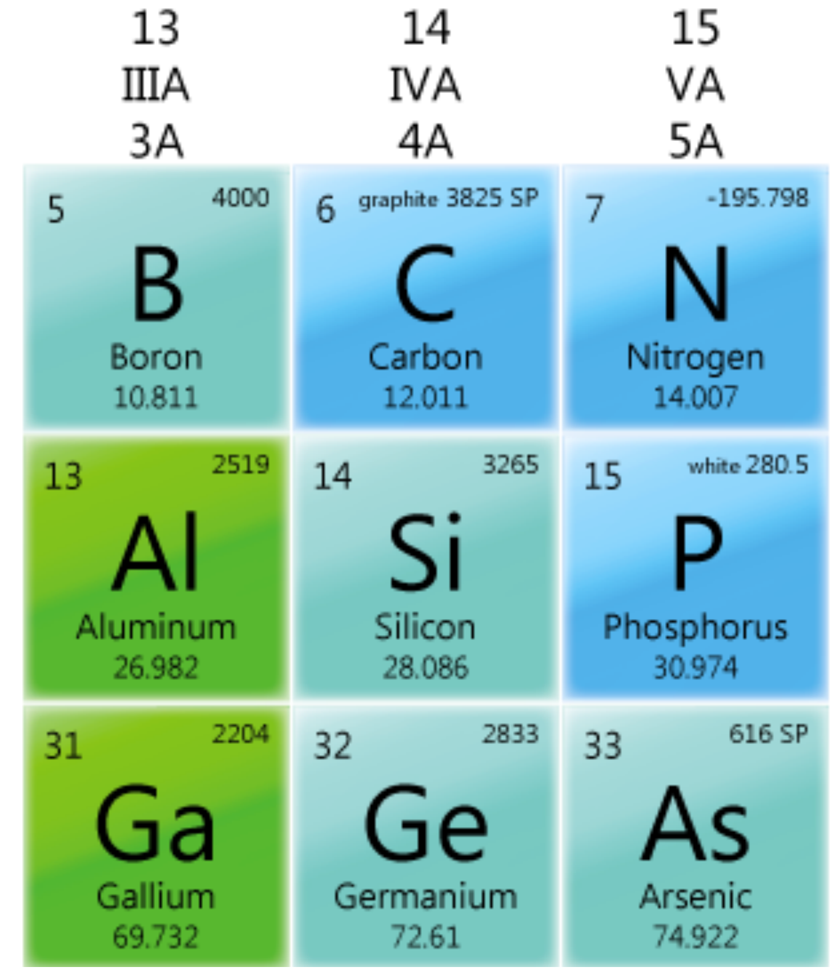


- Two retractable detector halves
- 42 modules
- each module contains 1 R-type + 1 φ-type sensor



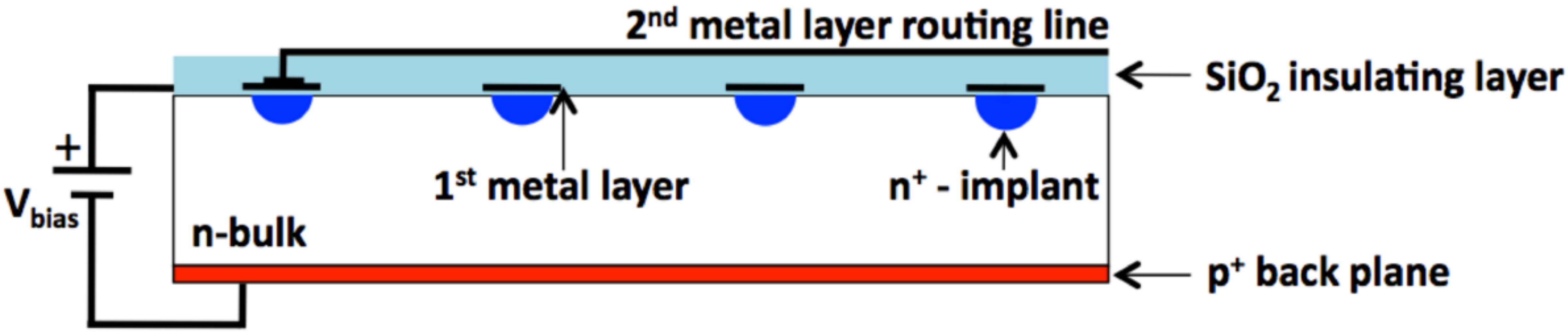
p-n junction in a silicon sensor

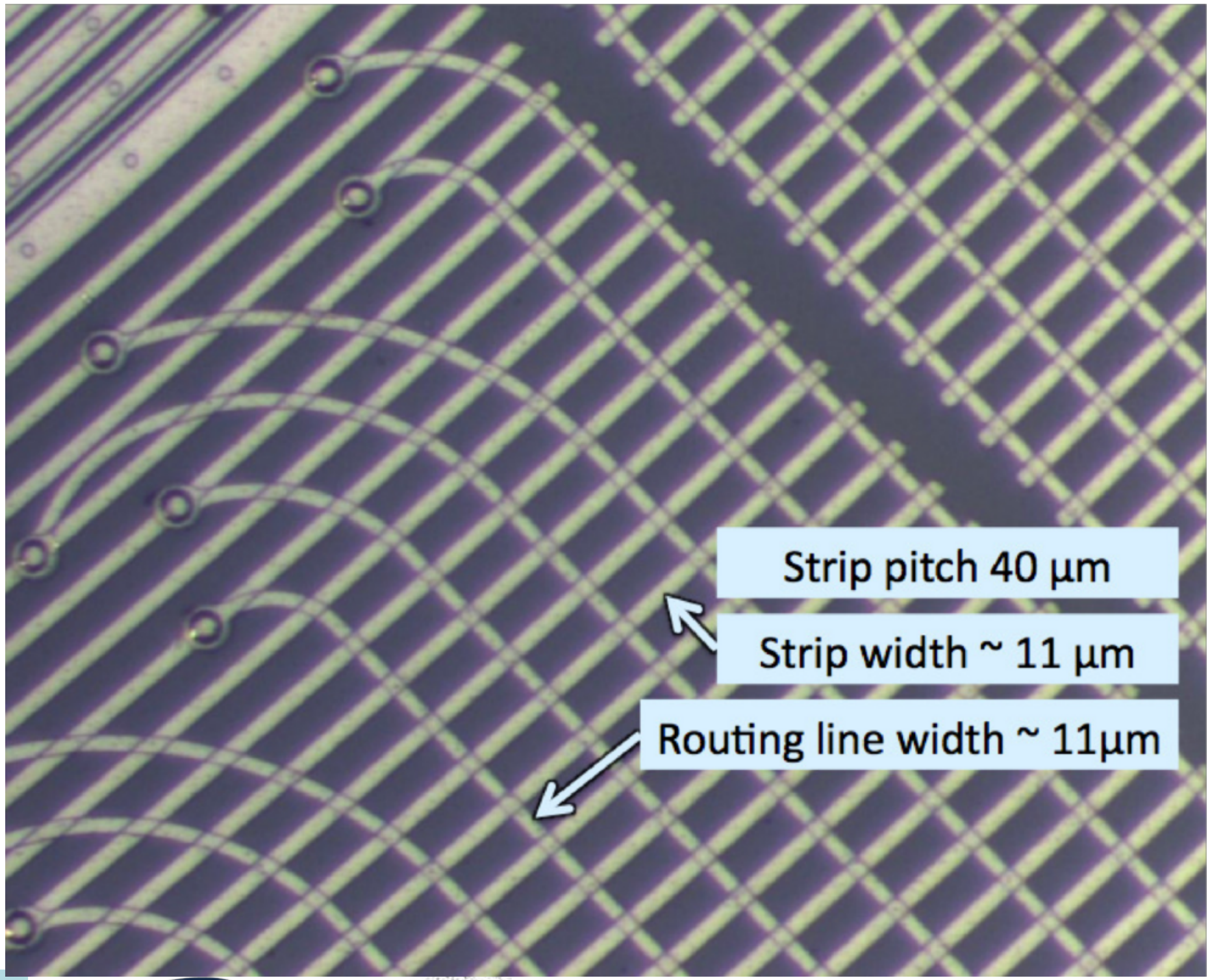




- Silicon doped with group 13 elements (p-type) or group 15 elements (n-type)
- Bias voltage applied on p-n junction can increase the depletion region to the whole junction
- Charged particle traversing silicon will create election-hole pairs and deposit energy
- Energy deposit within depletion region will be collected at the edge of the silicon

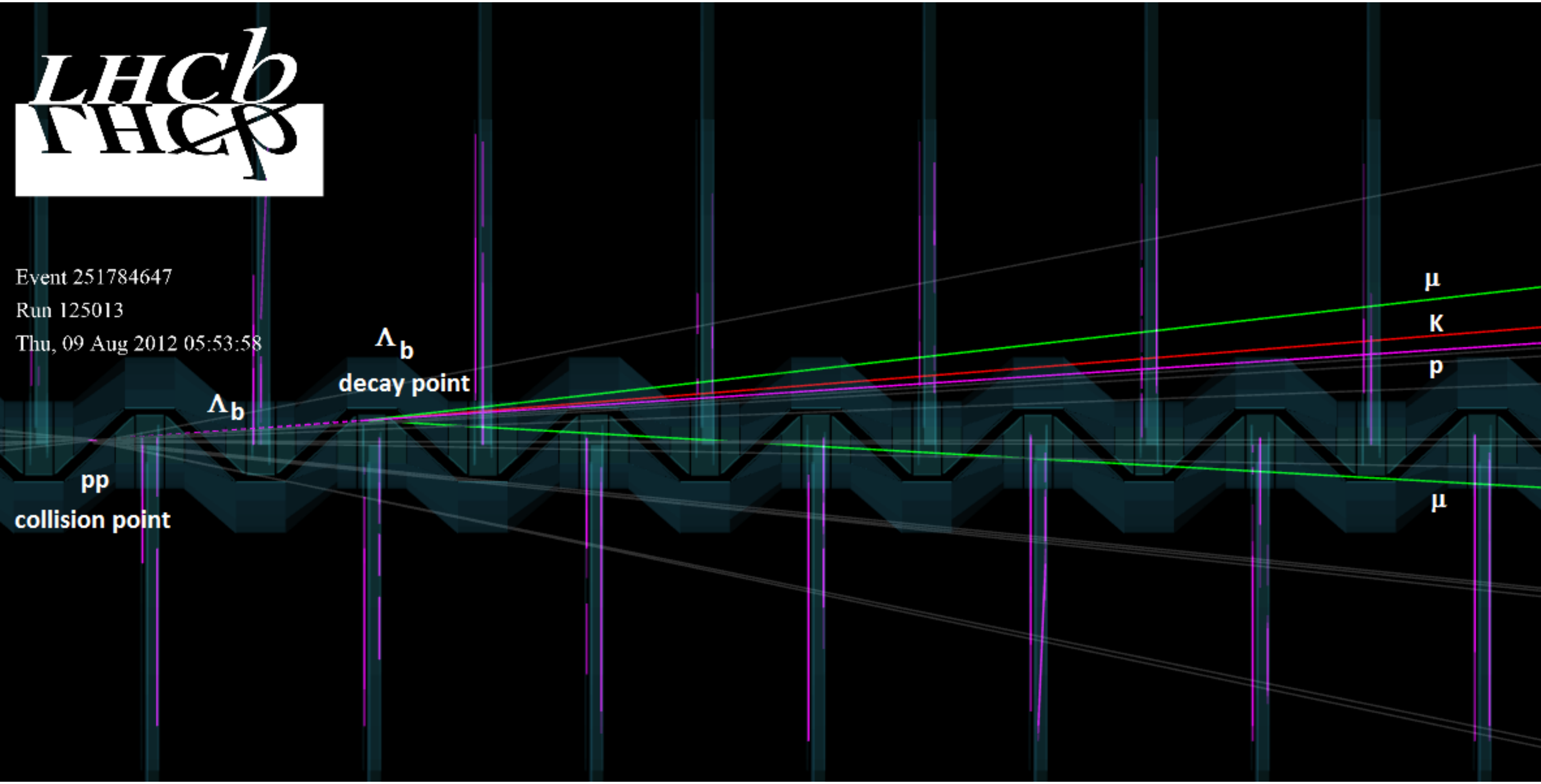
VELO sensors strips



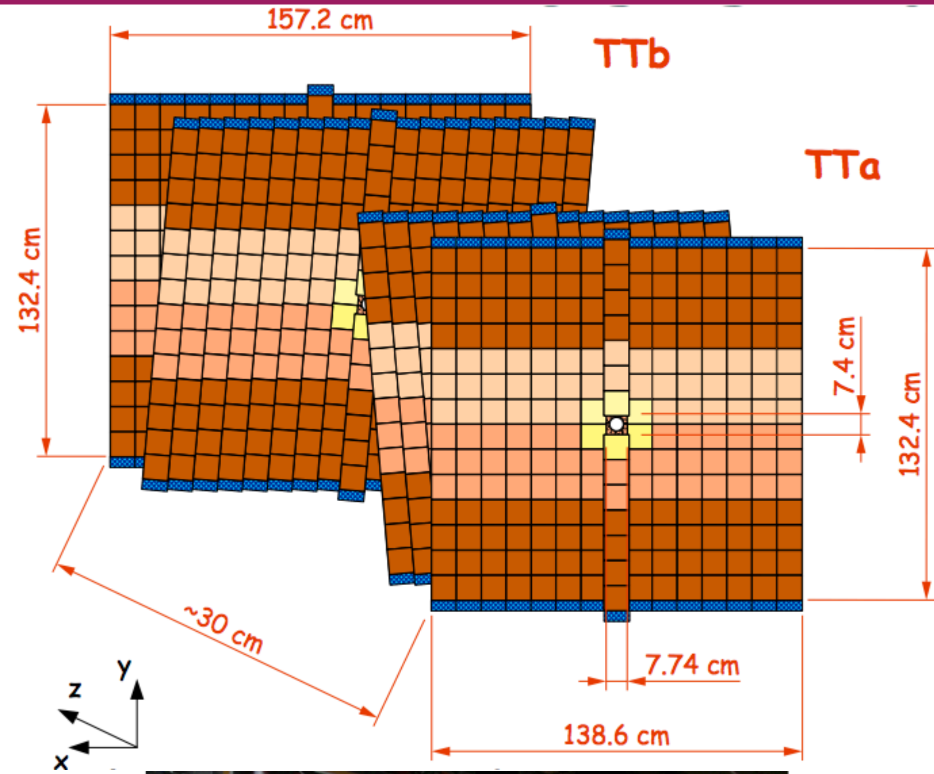


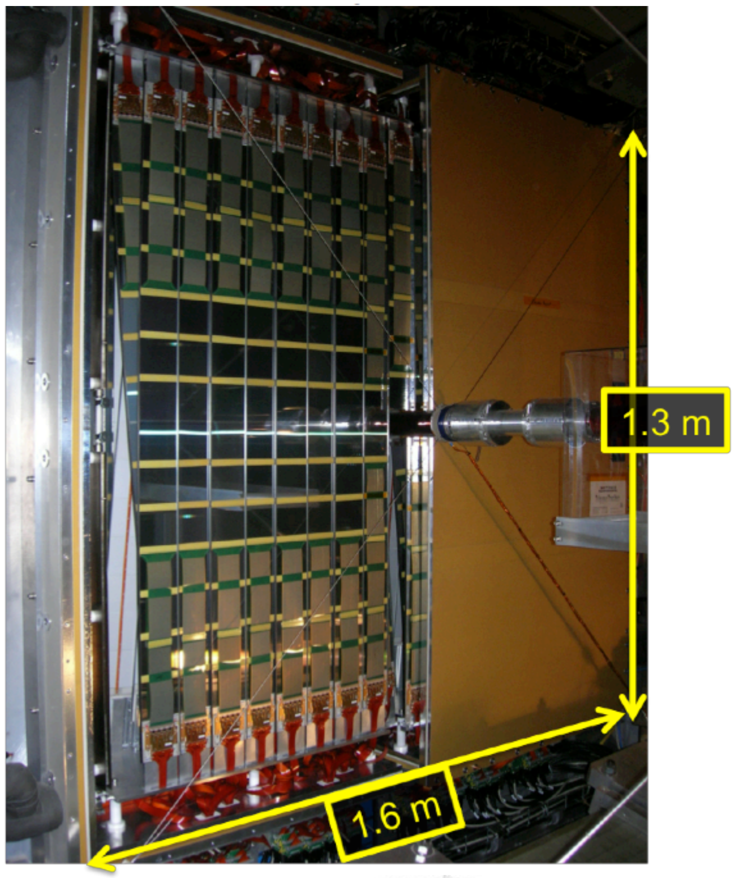
- 82 n^+-on-n sensors + 2 n^+-on-p sensors
- 2048 strips on each sensor
- Pitch varies from 40 µm to 100 µm
- Best hit resolution 4 µm

$\Lambda_b \to J/\psi pK$: inside VELO



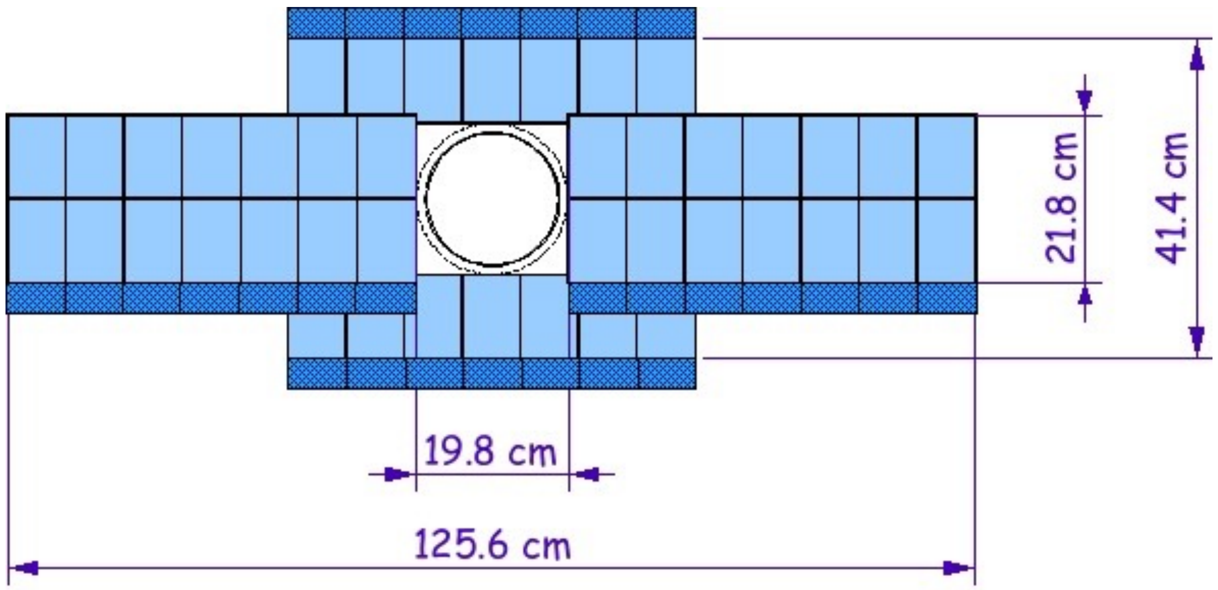
Silicon trackers - Tracker Turicensis (TT)

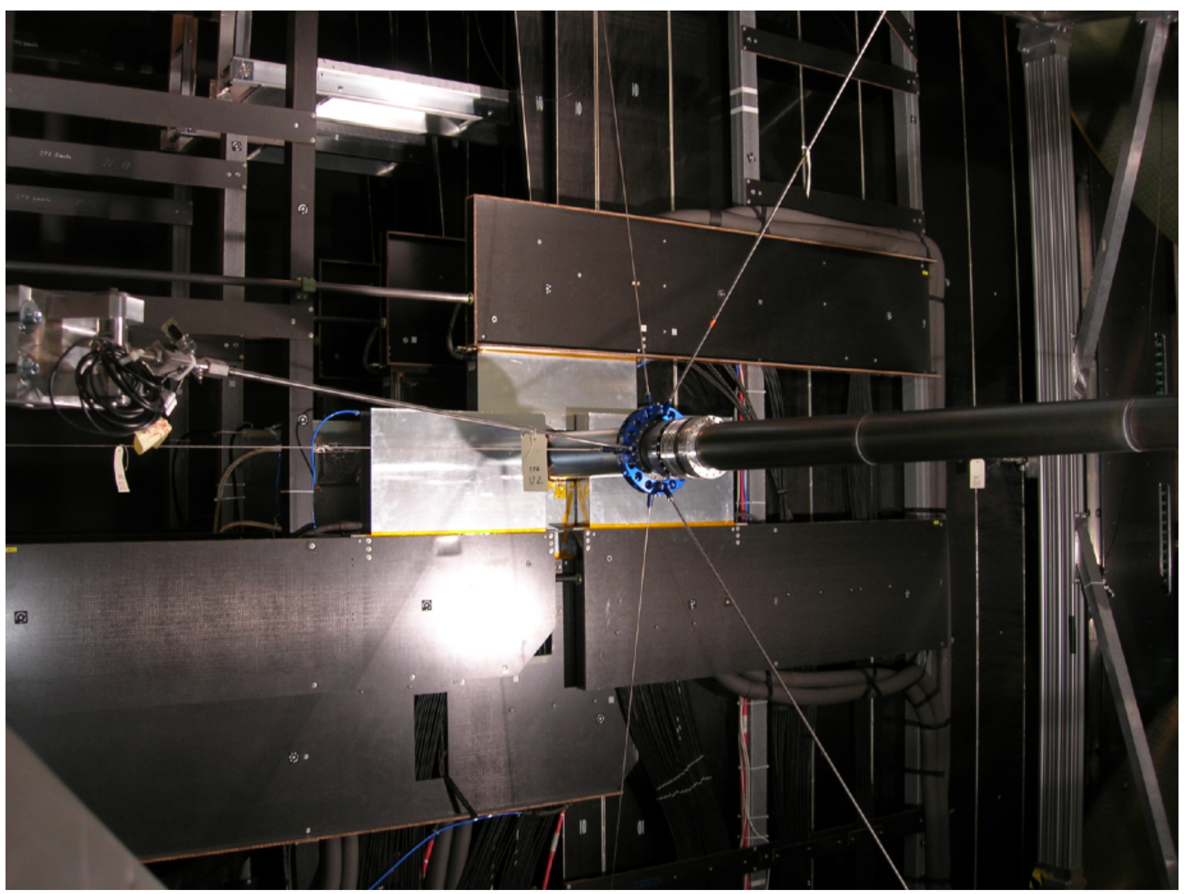




- Silicon micro-strip detectors.
  - p^+-on-n from Hamamatsu Photonics K.K.
- Four planes (0°, +5°, -5°, 0°).
- Pitch: 183 μm; Thickness: 500 μm.
- Long read-out strips (up to 37 cm).
- 143360 read-out channels.
- Total Silicon area is 8 m^2.
  - Covers full acceptance before magnet.
- Cooling plant operates at 0°C.
  - Sensors @ 8°C.

Silicon trackers - Inner Tracker (IT)

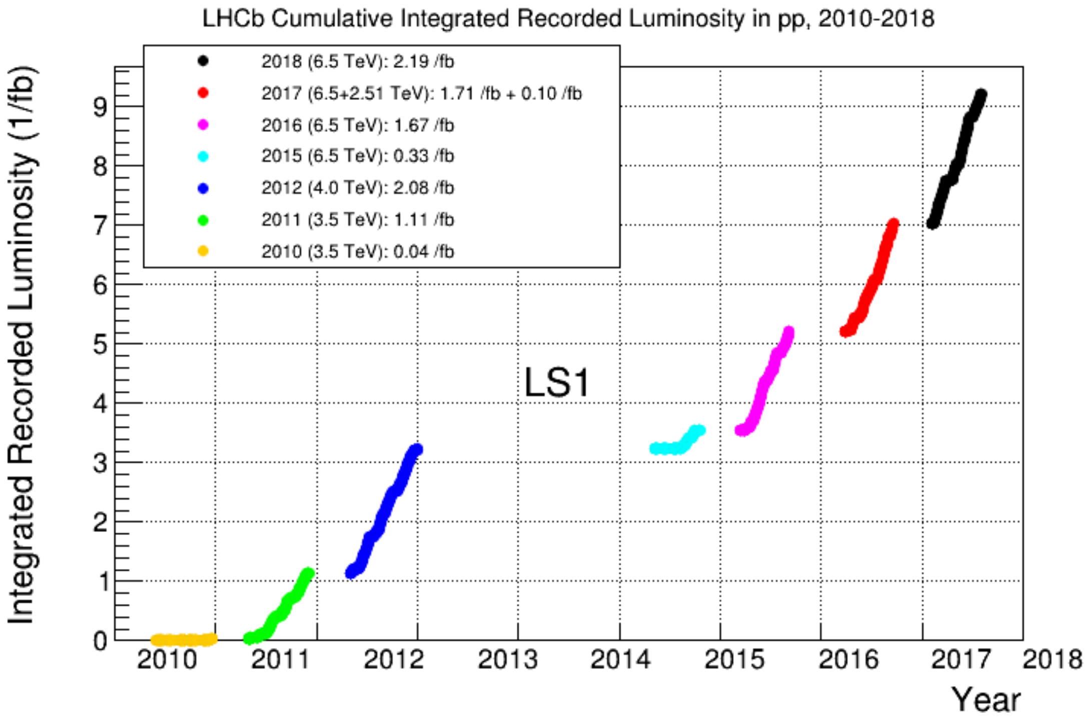




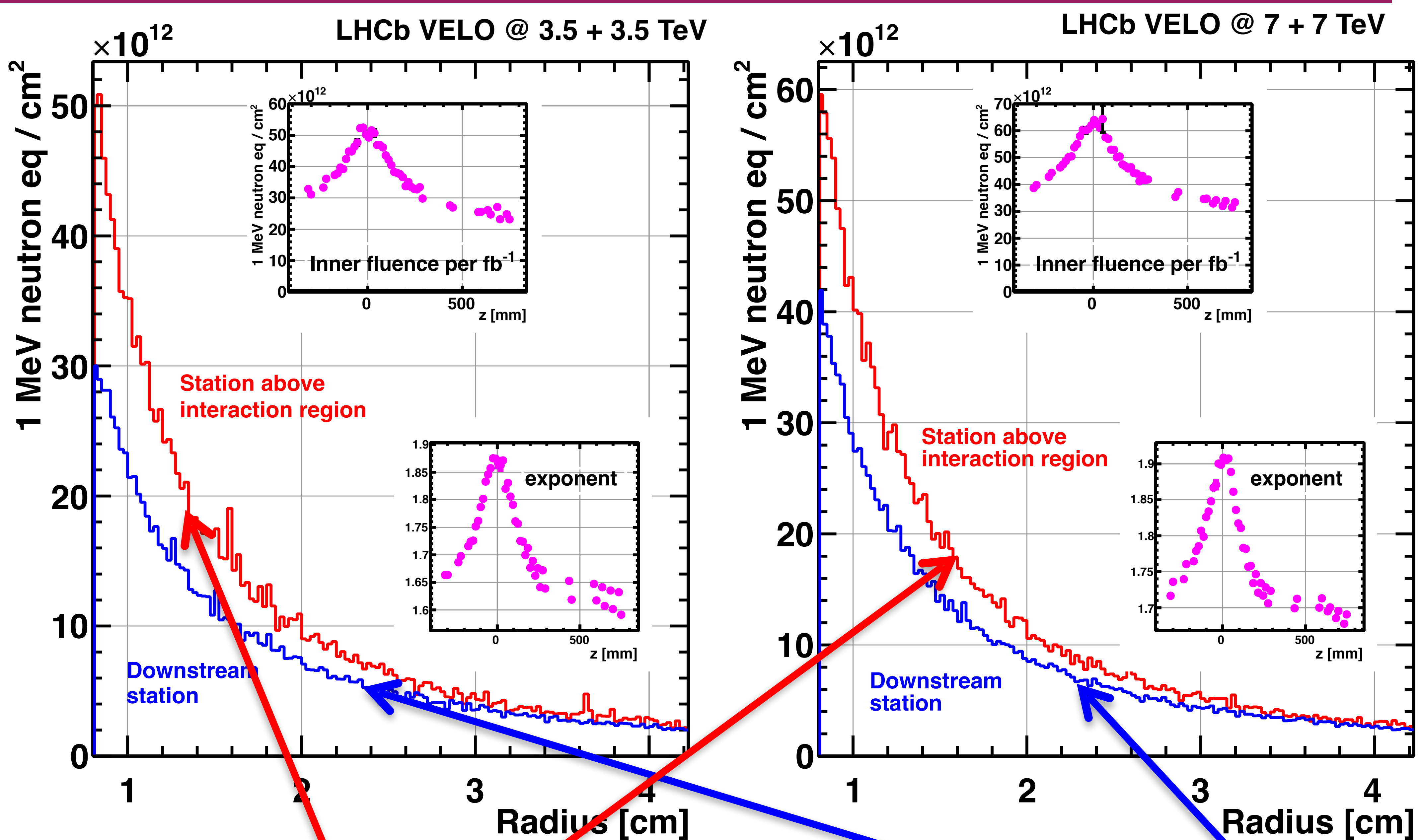
- Silicon micro-strip detectors.
  - p^+-on-n from Hamamatsu Photonics K.K.
- Three stations in z.
  - Four boxes in each station.
  - Four planes (0°, +5°, -5°, 0°)
- Pitch: 198 μm
- Thickness: 320 or 410 μm
- 129024 read-out channels.
- Total Silicon area is 4.2 m^2.
  - Covers region around beam with highest flux.
- Cooling plant operates at 0°C.
  - Sensors @ 8°C.

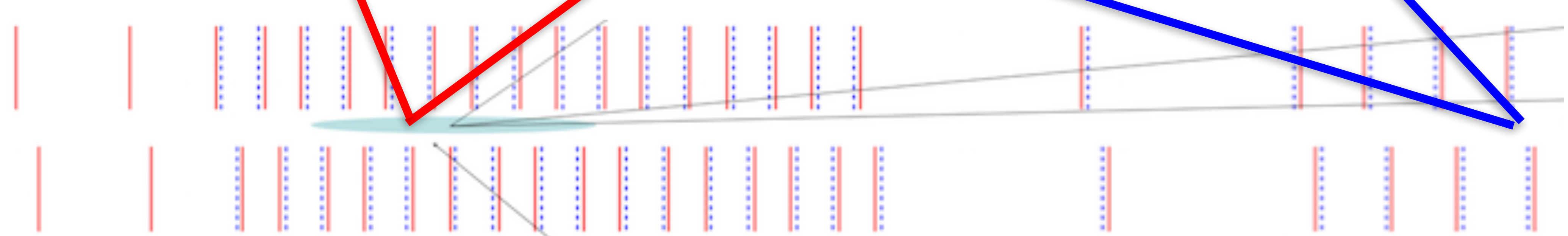
From Run-I to Run-II

- Higher rate, higher energy, higher luminosity
  - Bunch spacing 25 ns, twice as fast as Run-I
  - 6.5+6.5 TeV
  - 3 fb^{-1} of data collected by LHCb in Run-I, 6 fb^{-1} collected in Run-II
- Careful operation
  - Monitoring radiation damage
  - Attention to cooling and annealing

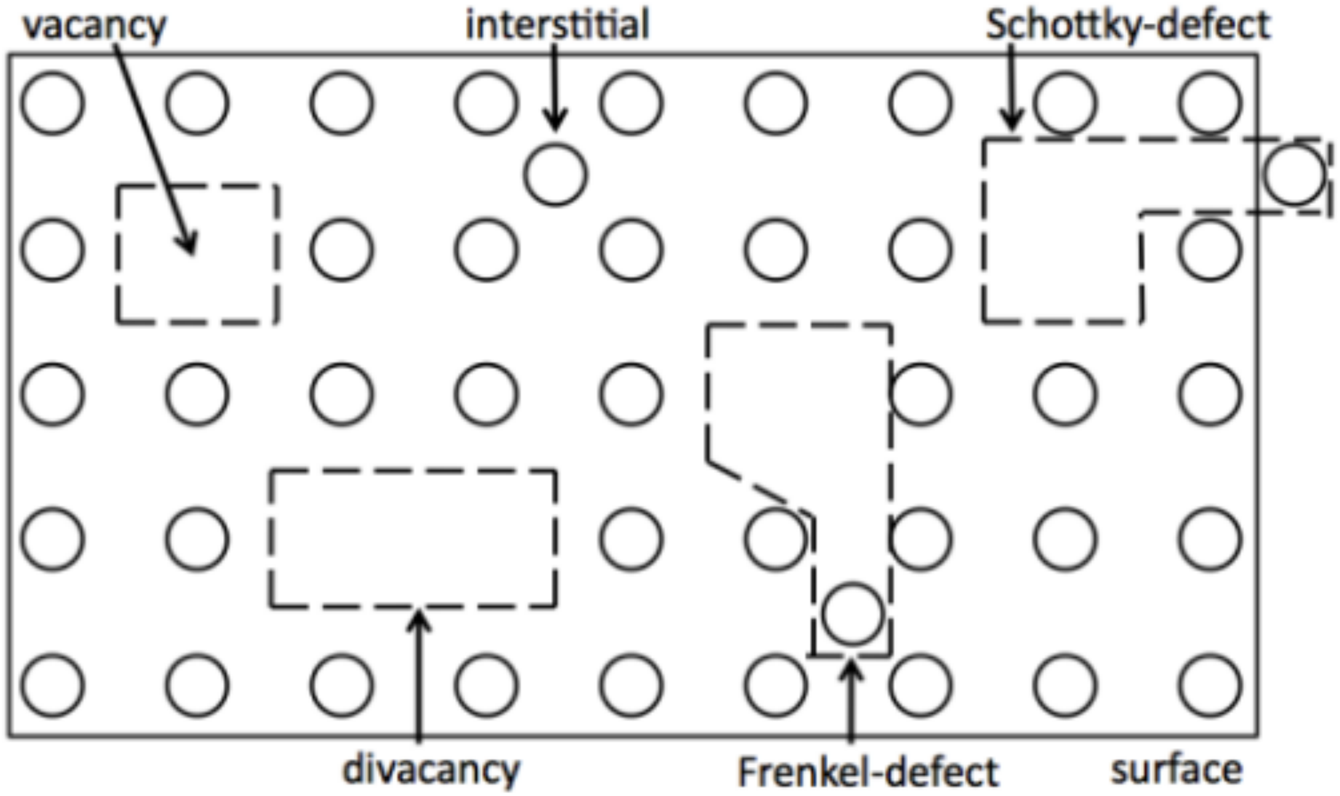


Expected increase in fluence





Radiation damage effects



- Particles transverse the silicon detectors interact with lattice atoms via a non- ionising energy loss (NIEL) process
- Majority of vacancies can recombine with interstitials due to thermal motion - **annealing**
- Remaining defects can combine with each other, and form a more complex defect structure

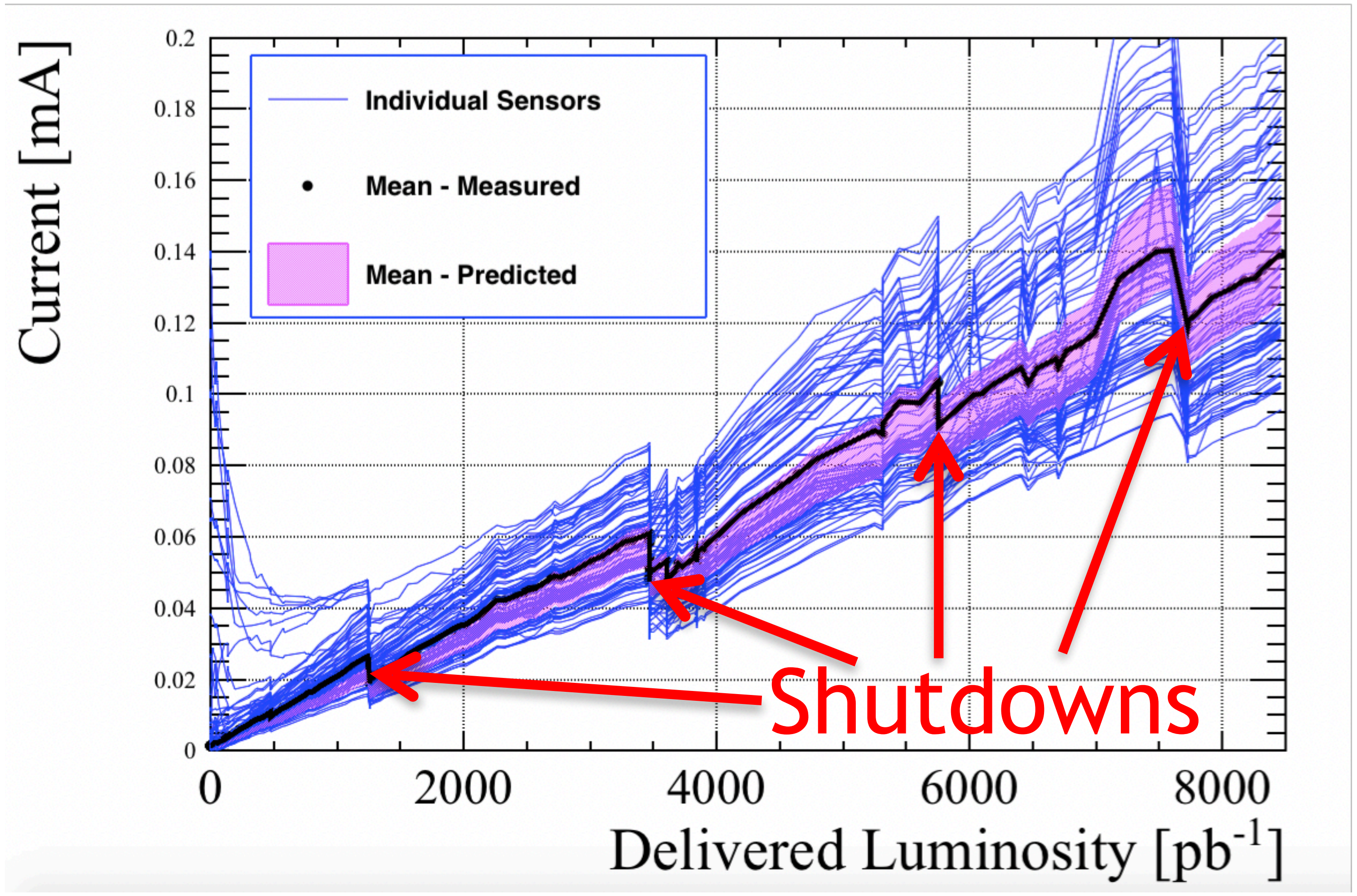
Radiation damage studies

- Radiation damage is measured with a few approaches, mainly:
  - Monitoring currents and compare to expected values
    - Constant IV curves and occasional IT curves
  - Measurement of the collected charge
    - Dictates the operational voltage
    - Regular HV scans taken with beam
- Unforeseen effect for VELO: second metal layer

Leakage current

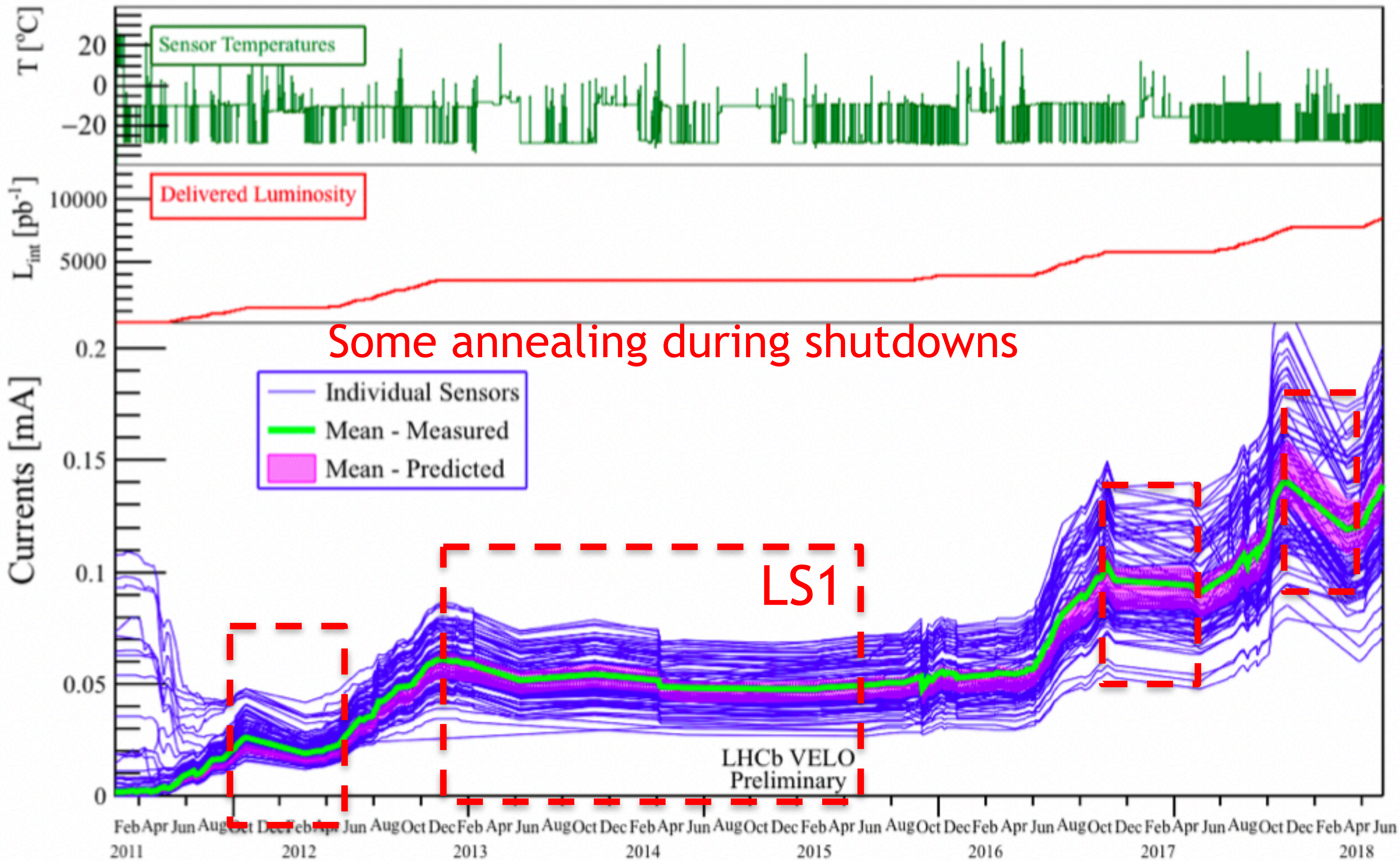
- Continue to observe the linear increase in bulk leakage currents with delivered luminosity
  - Different slopes reflect particle densities in different parts of detector
- As expected, significant decrease after shut downs due to annealing of radiation damage

LHCb VELO preliminary



IV curves are taken semi-automatically at the end of fills

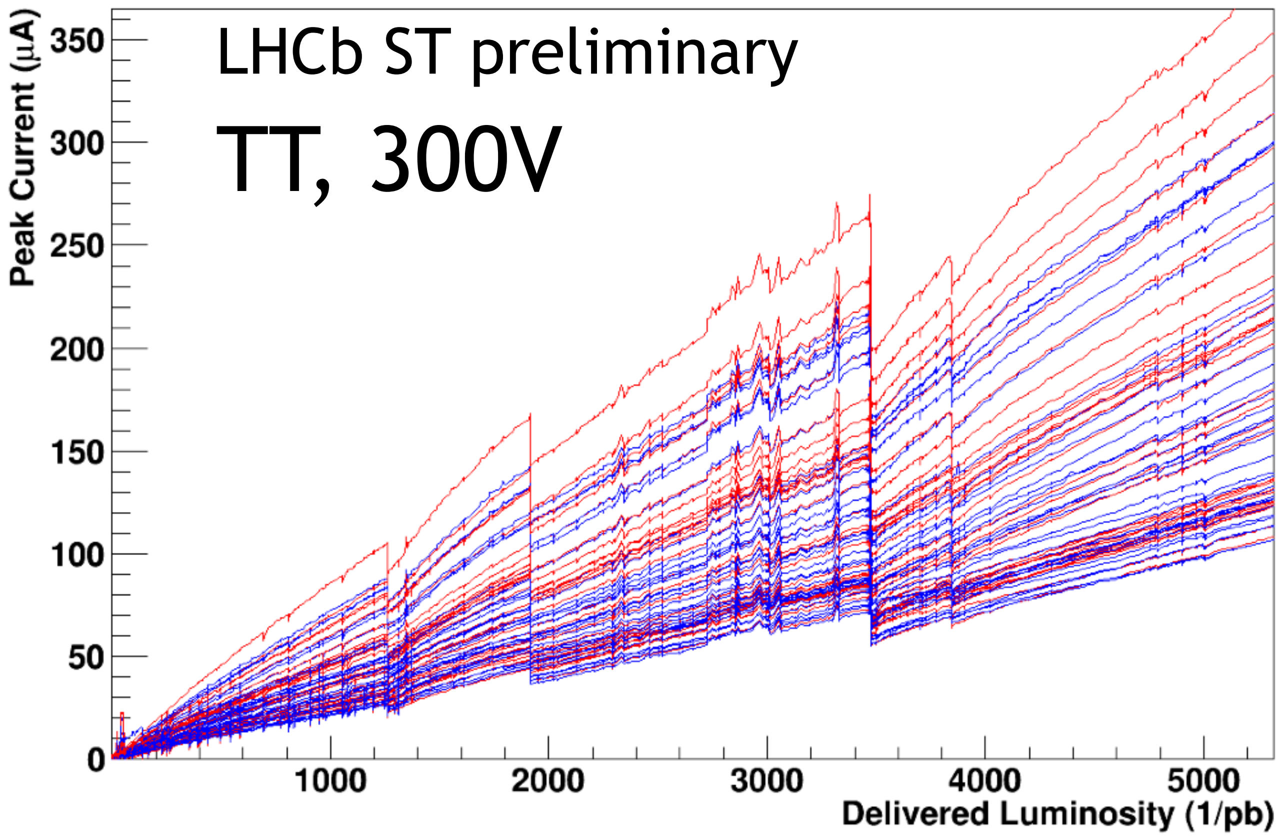
Leakage current

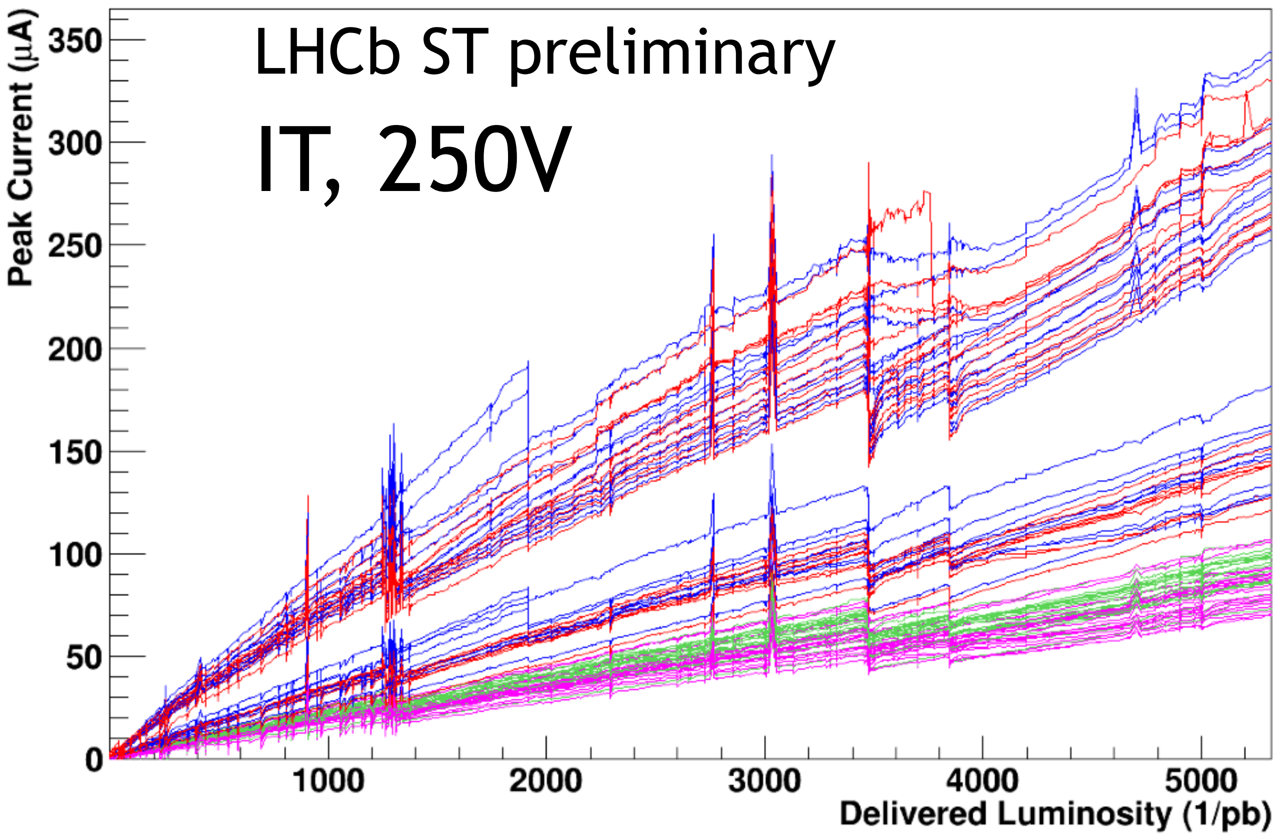


LHCb VELO preliminary

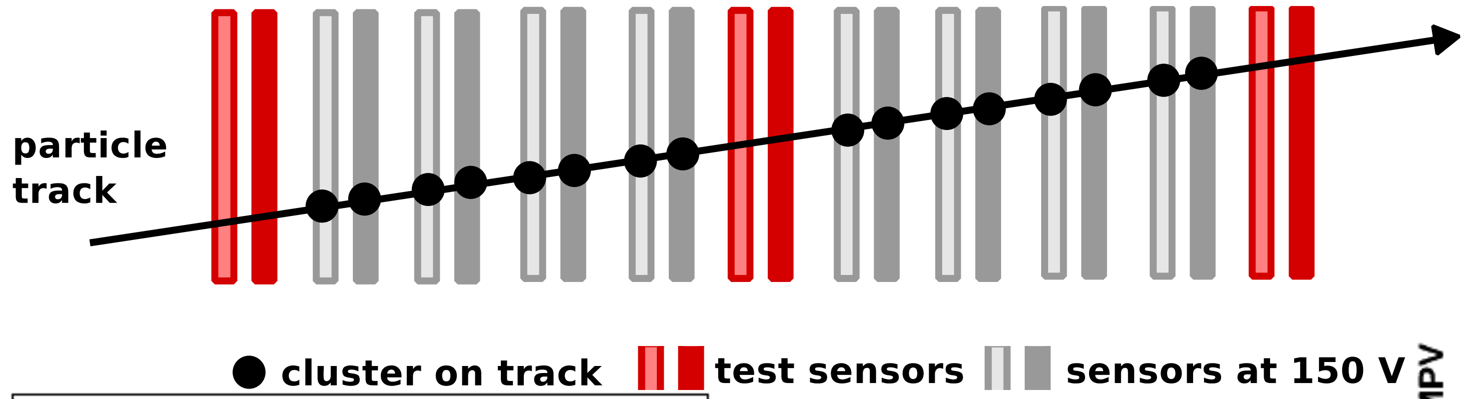
Leakage currents (ST)

- Similar trend for silicon trackers
- Linear increase of leakage currents as function of delivered luminosity, with drops during shutdowns

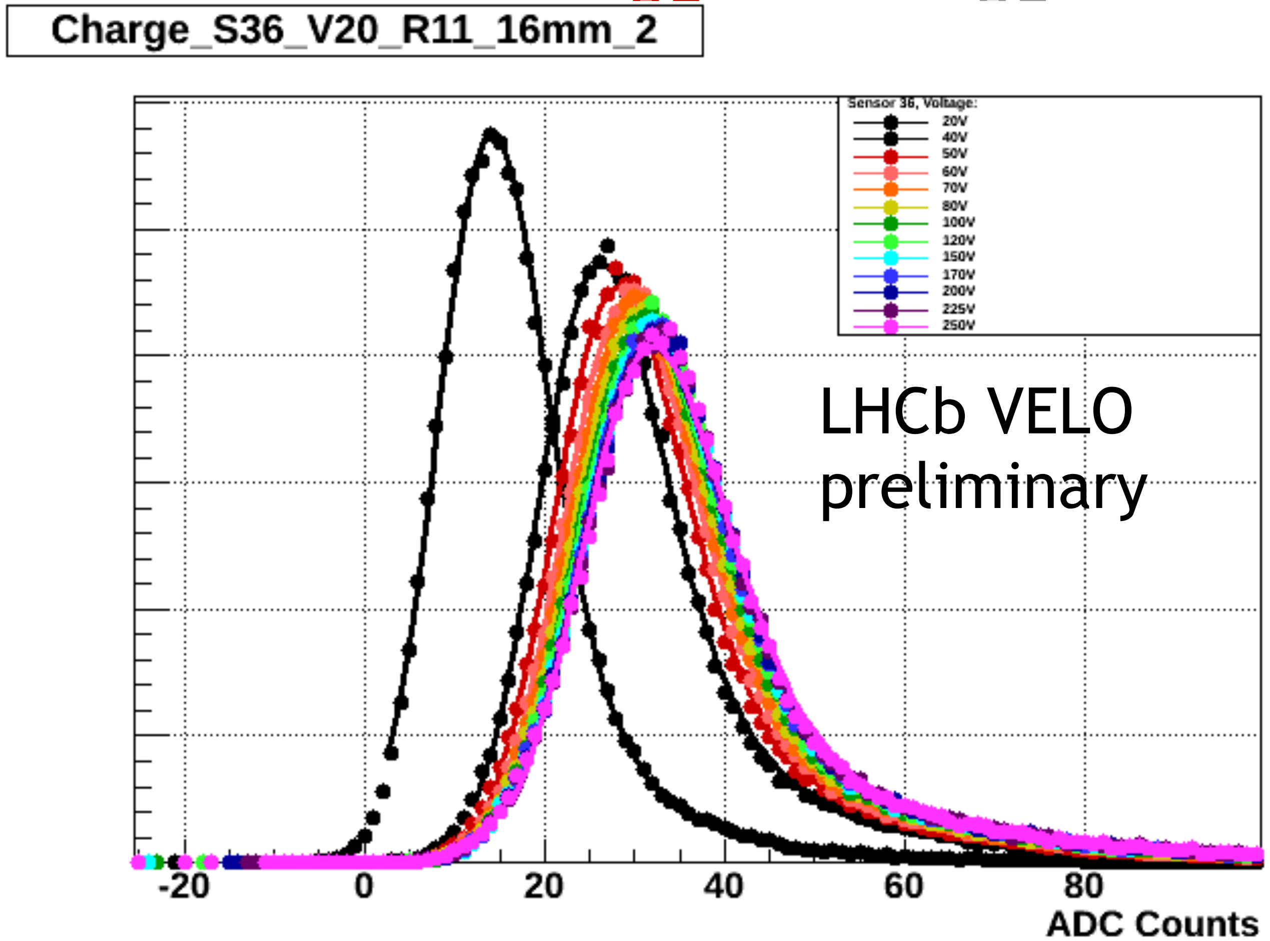




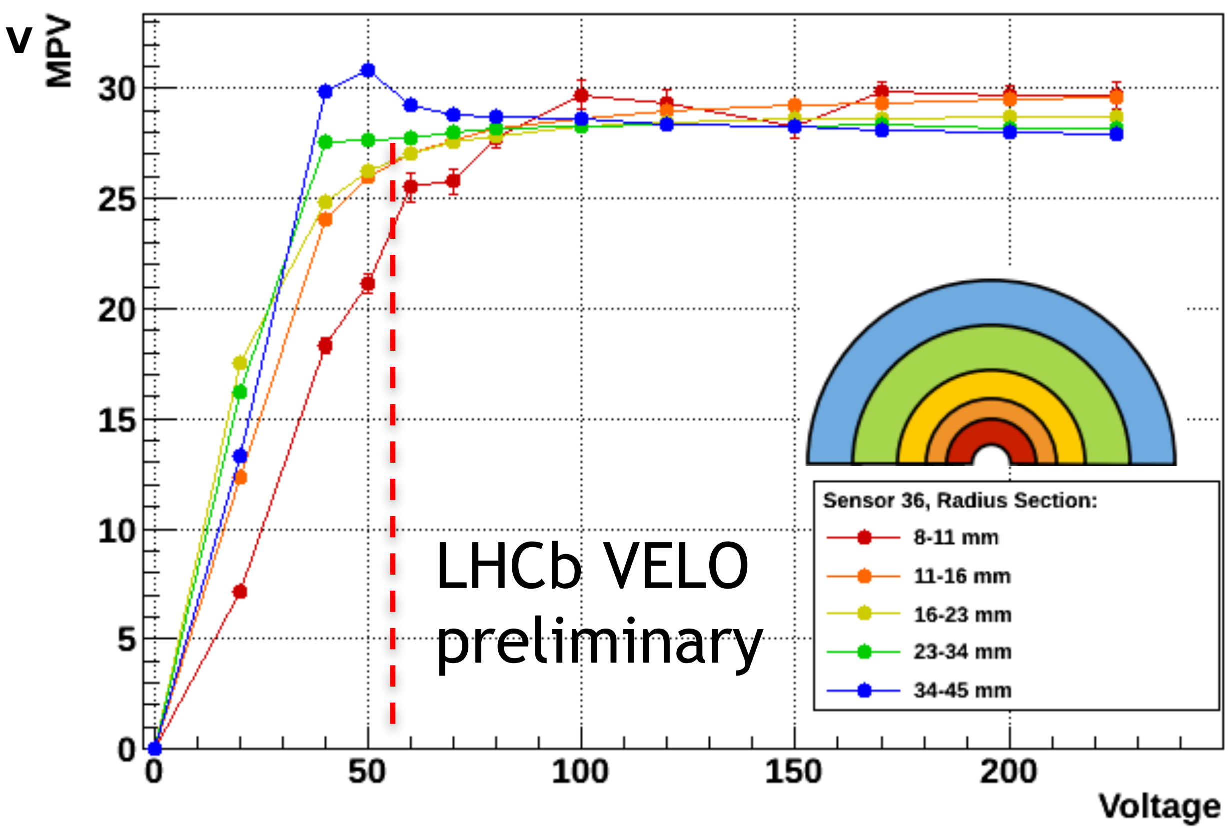
Charge collection efficiency (CCE)



- HV scan
- Testing a group of sensors while using others as a telescope



- Fit the ADC distribution to get MPV

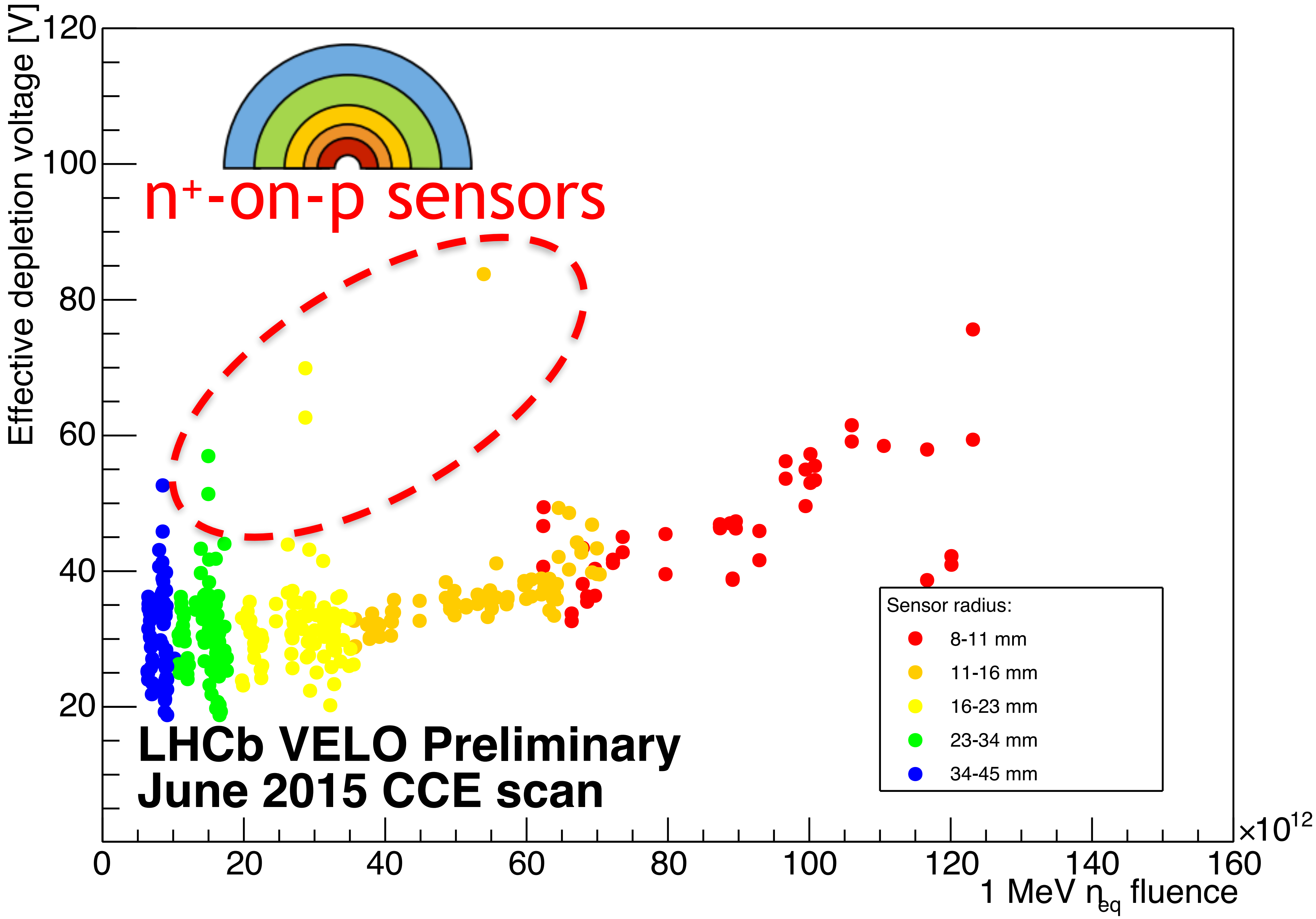


- Define effective depletion voltage (EDV) as the voltage where MPV is 80% of maximum

ST shares the same concept, scans are taken simultaneously

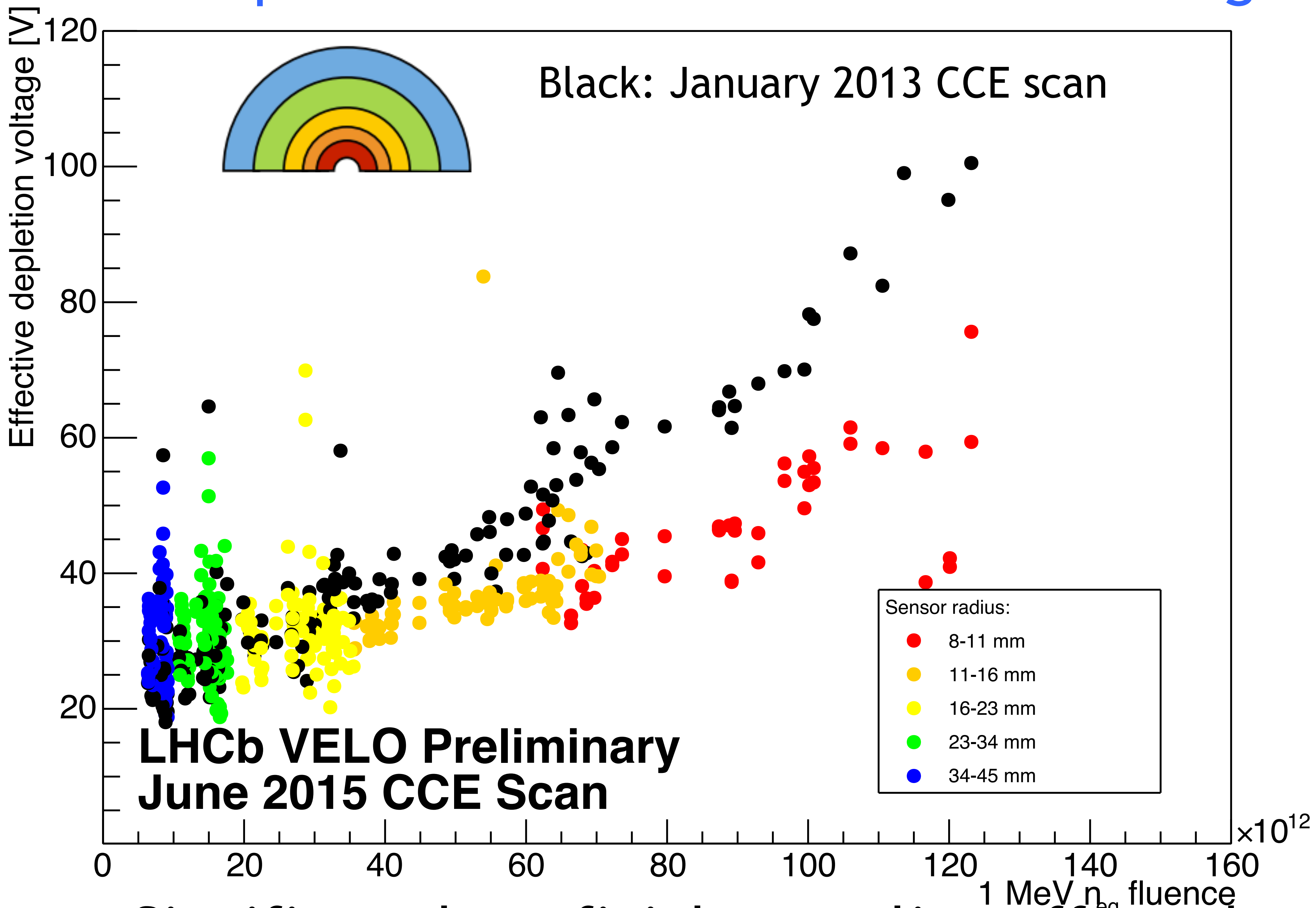
Effective depletion voltages

First CCE scan from Run 2



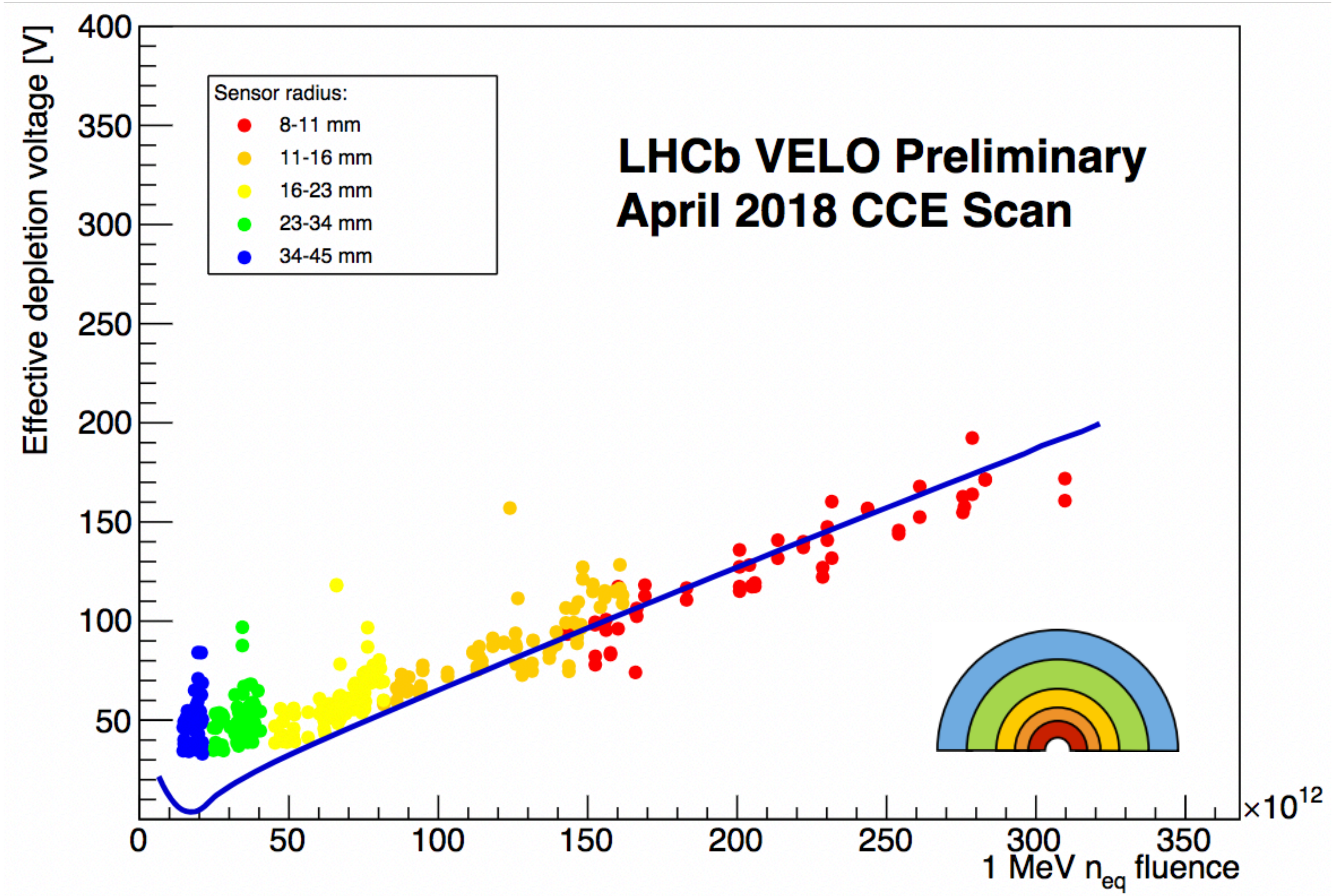
Effective depletion voltages

Compare it with the last CCE before long shutdown-I

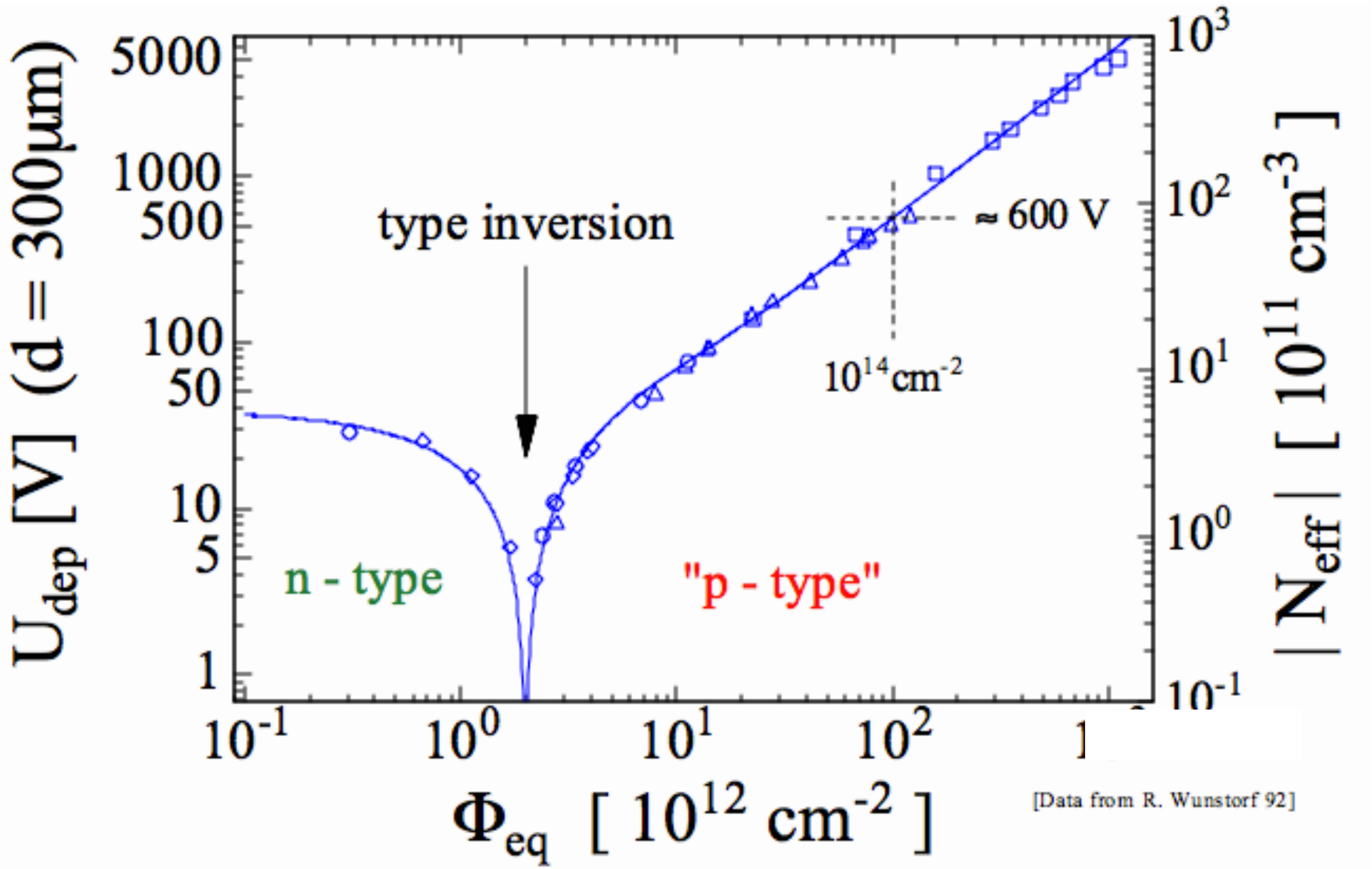


Significant beneficial annealing effect observed

Overlaid with Hamburg model

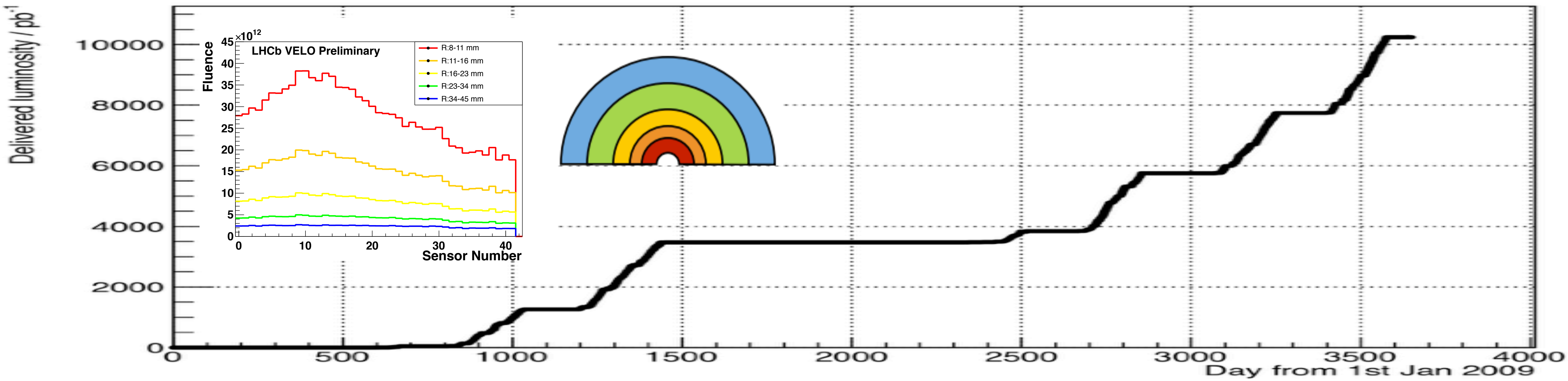


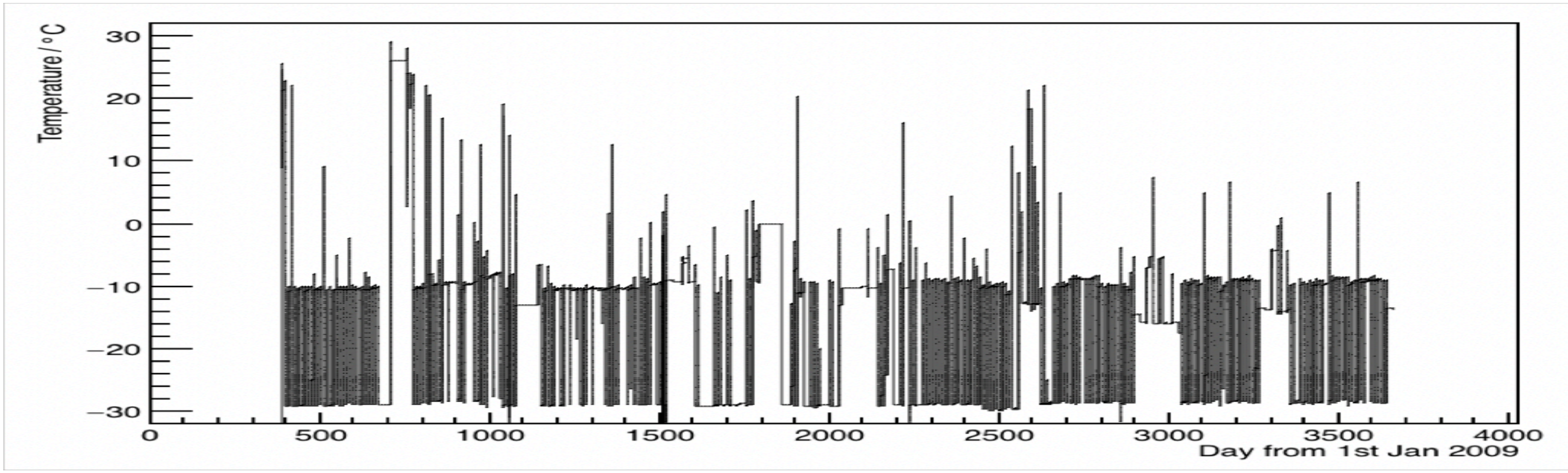
Hamburg model



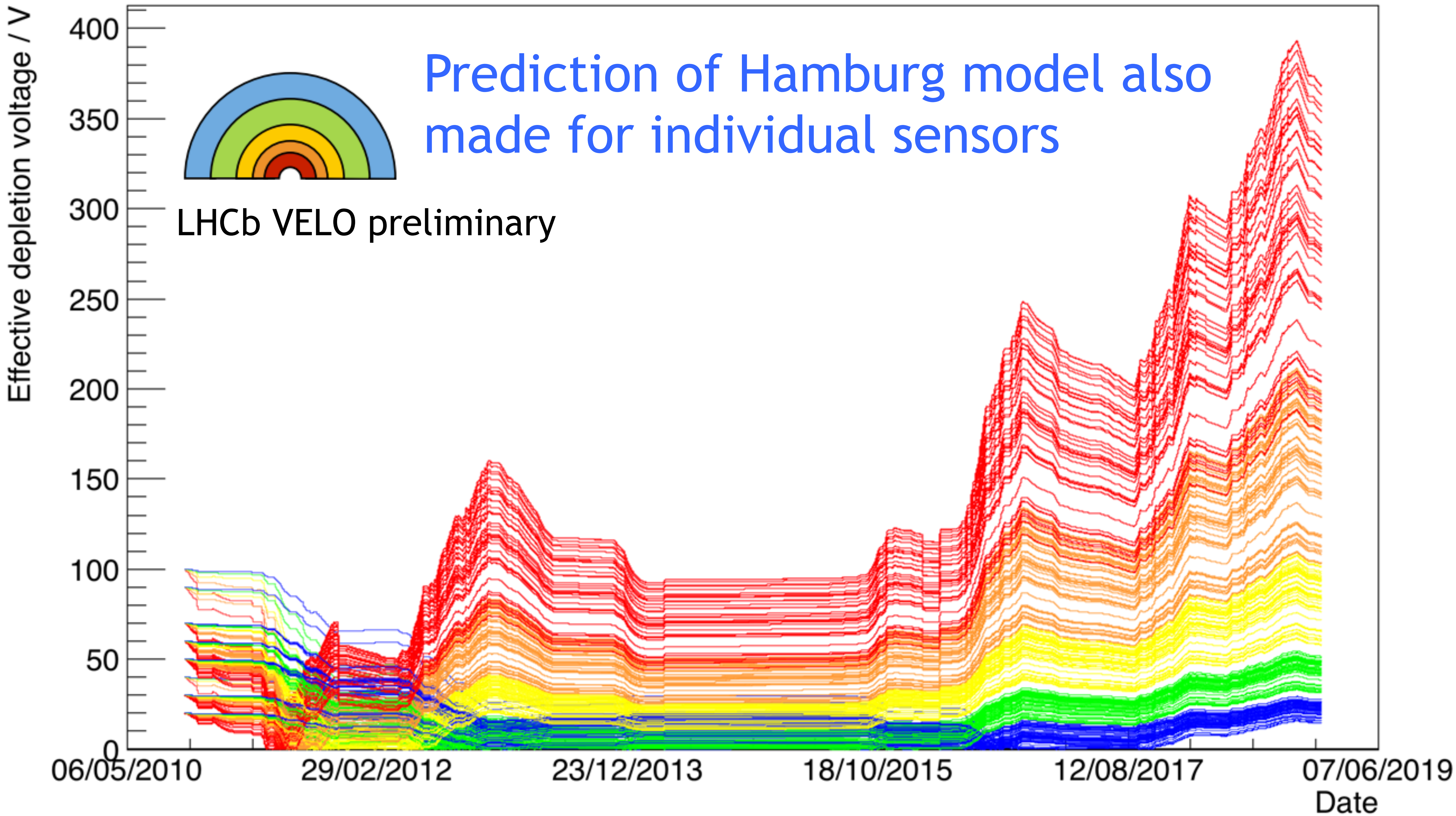
Effective doping concentration of the silicon changed due to radiation
n-type silicon: acceptor defects are introduced whilst donor defects are removed
Type inverted after irradiation

Luminosity and temperature profile



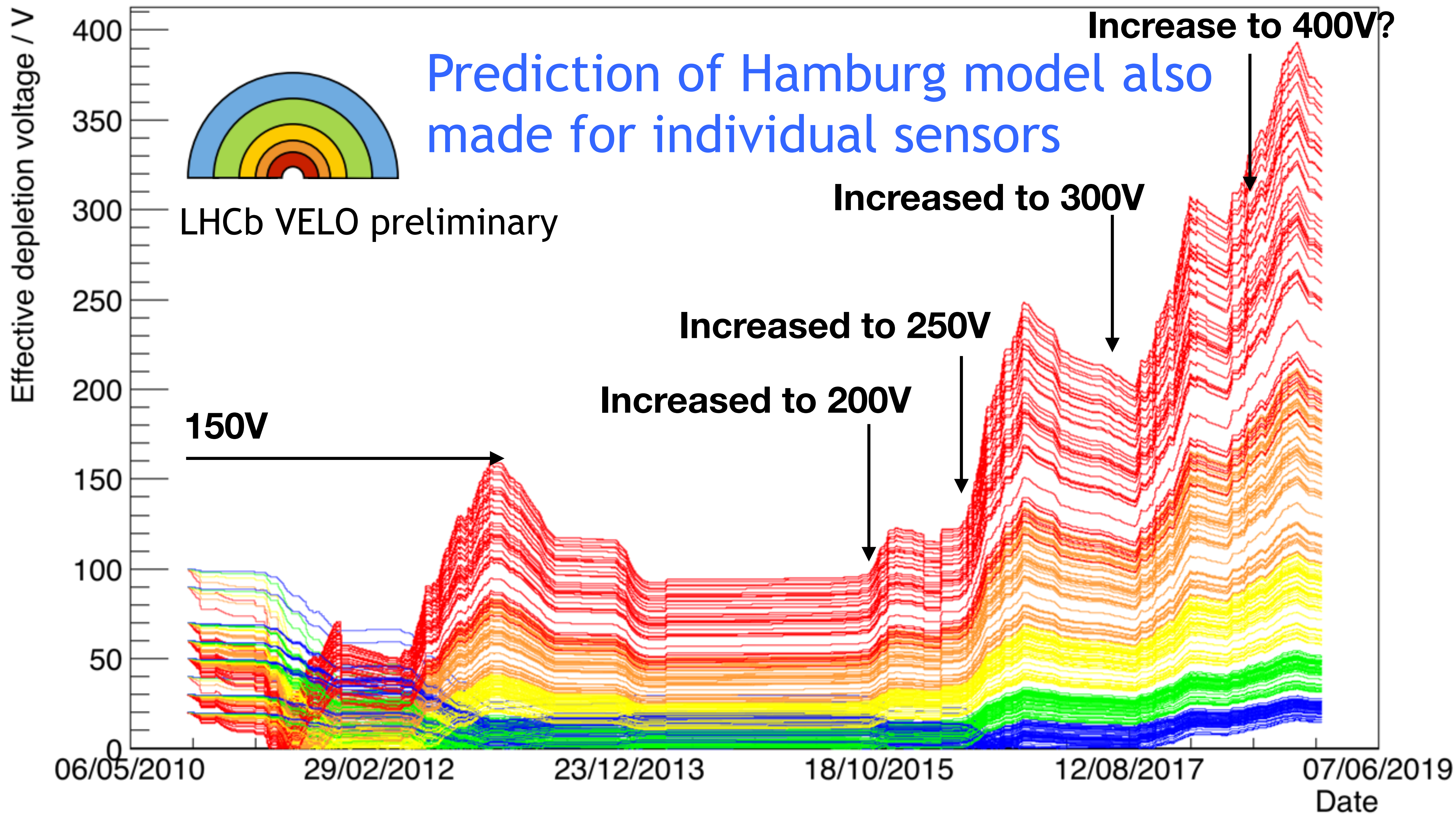


Hamburg model prediction - innermost tips

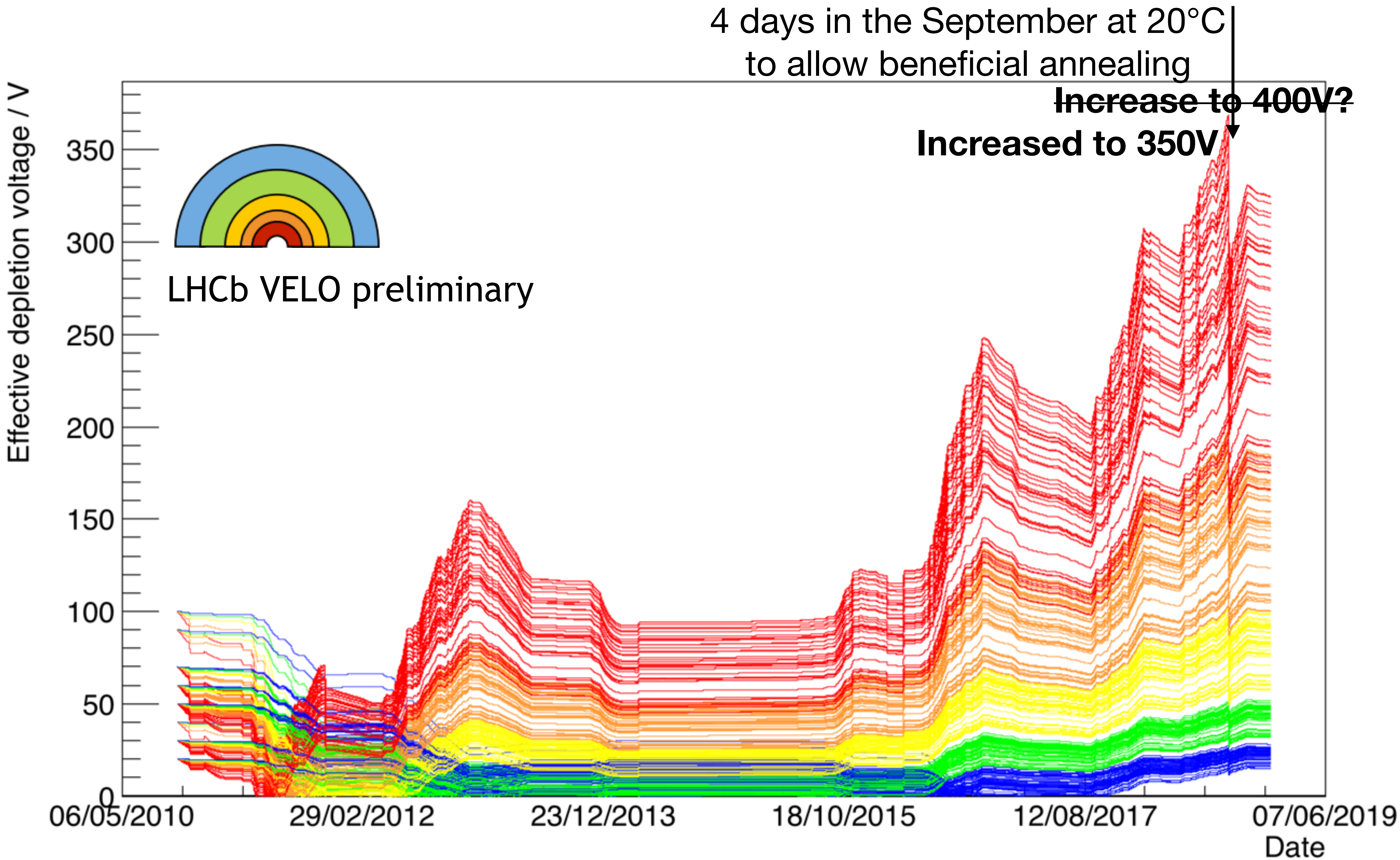


Hamburg model prediction - innermost tips

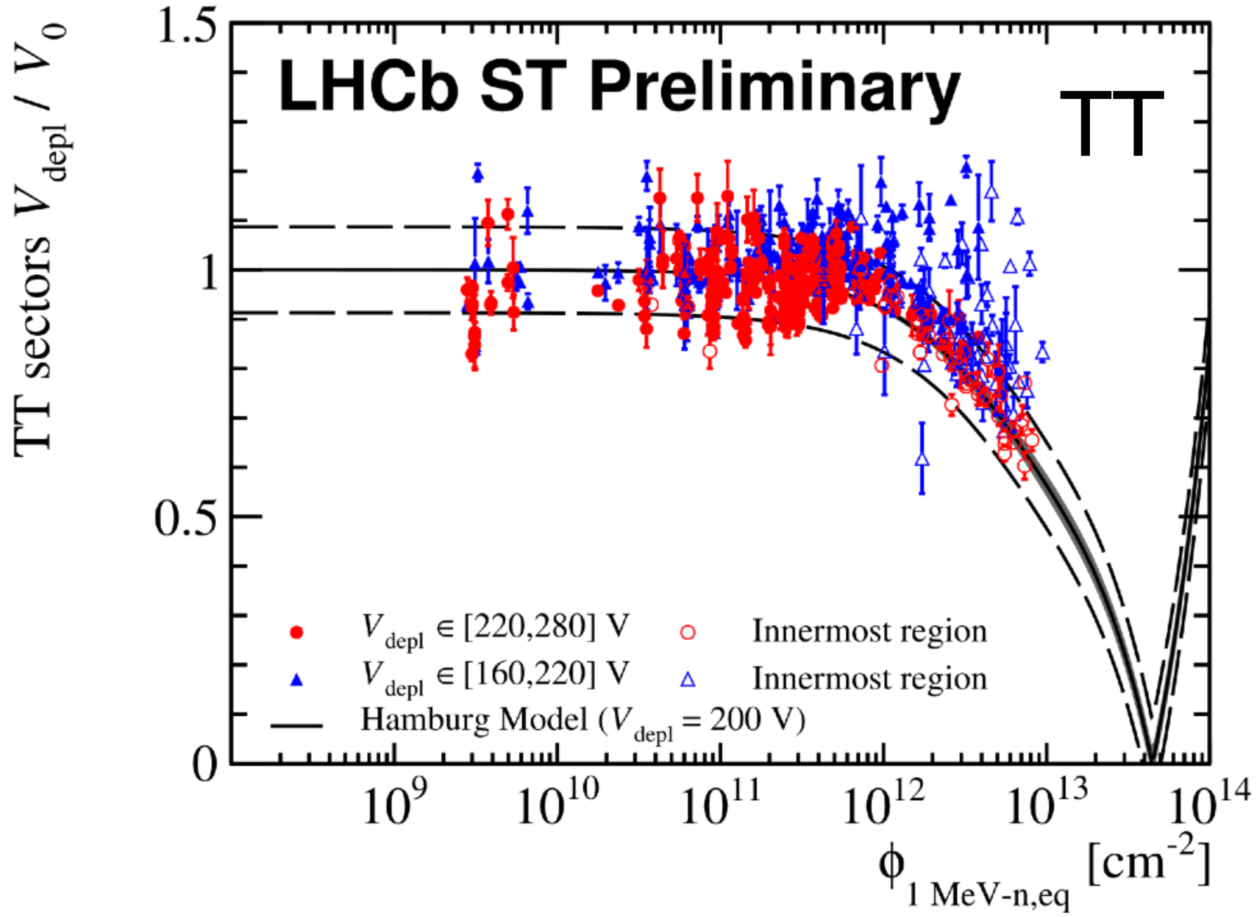
(designed breakdown voltage: 500V)

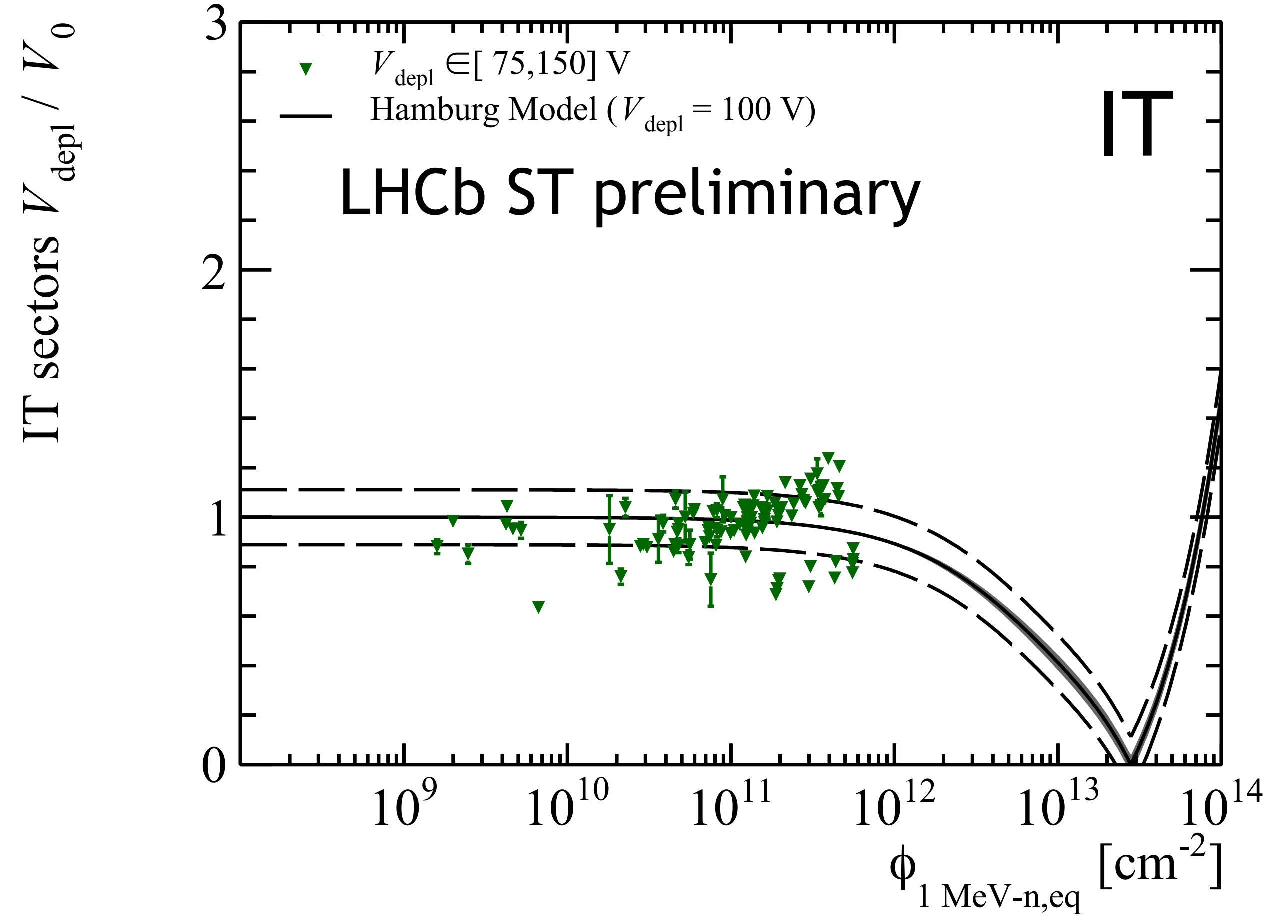


Beneficial annealing



Effective depletion voltages (ST)

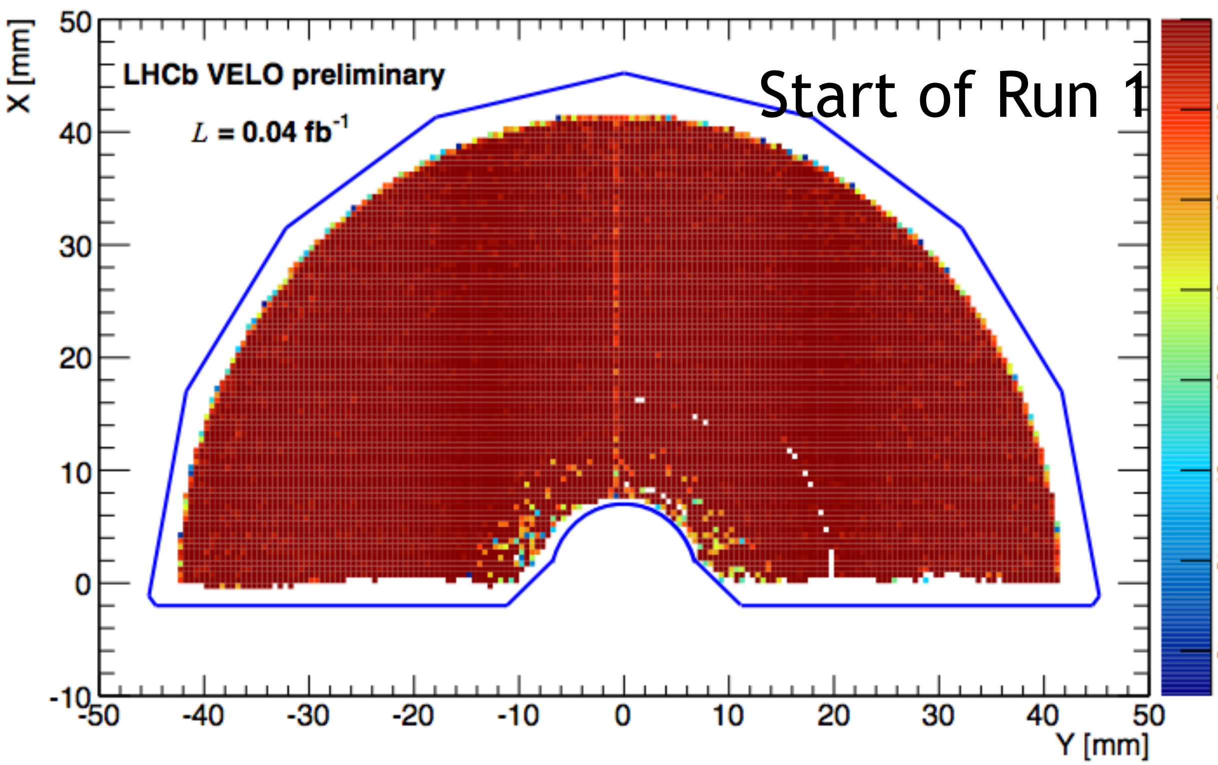


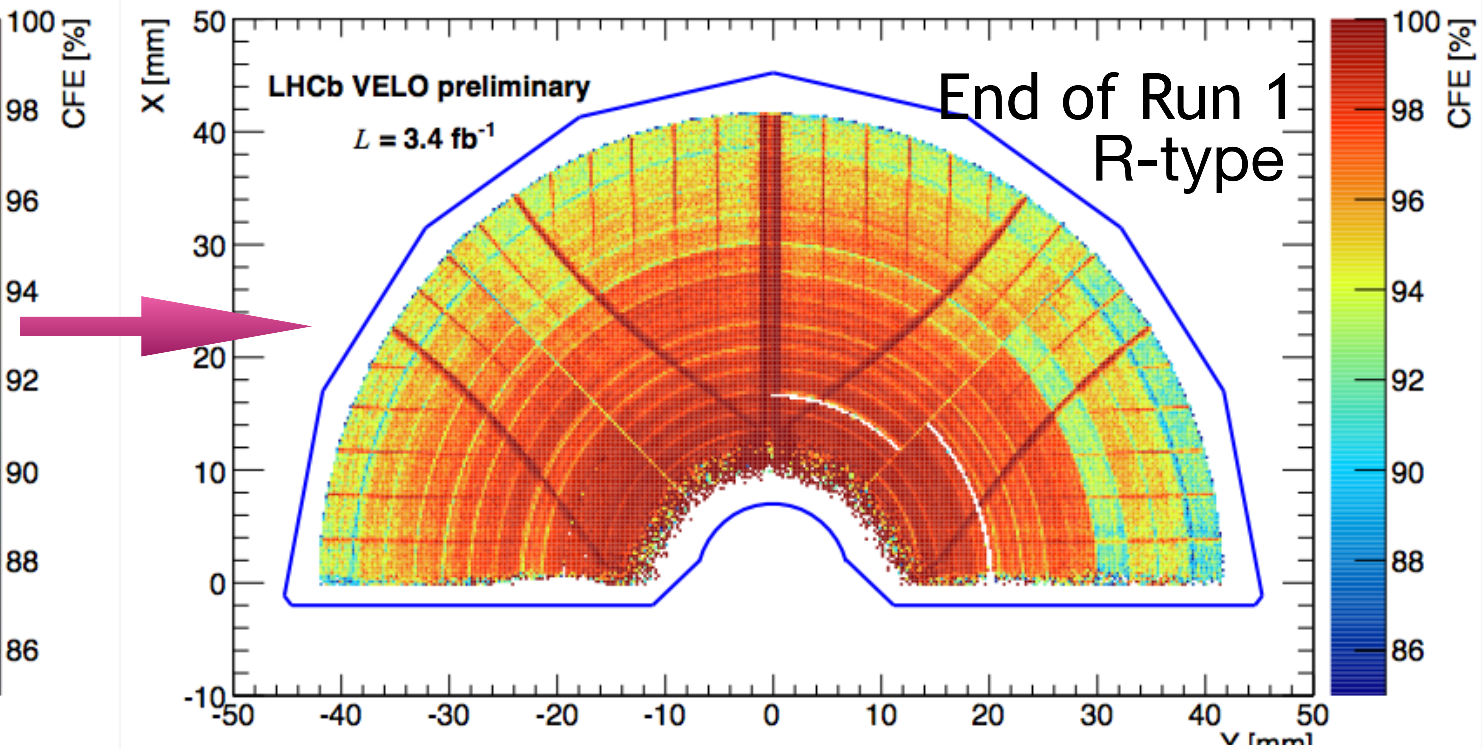


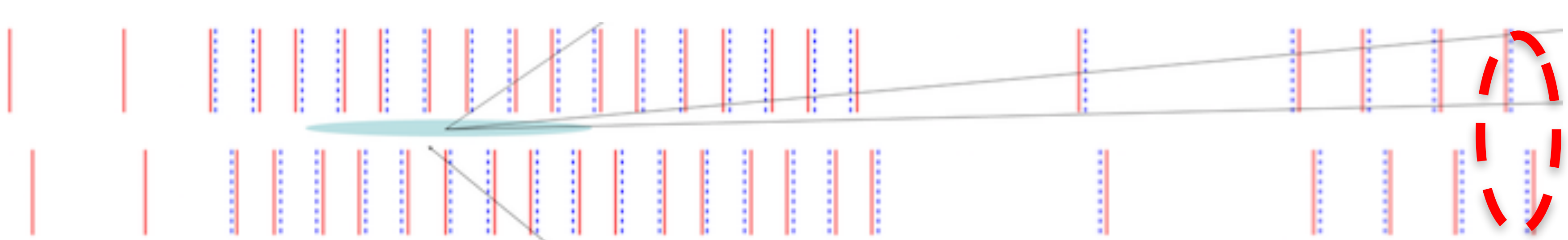
Silicon tracker sensors has not reach type-inversion

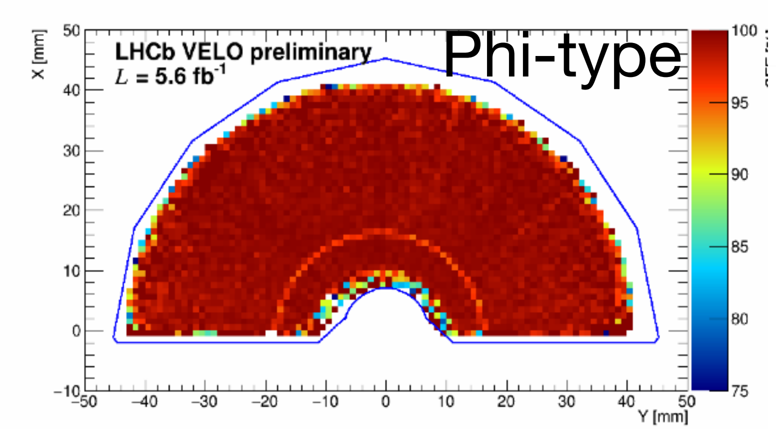
Cluster finding efficiency (CFE)

- **R type** sensors (especially **downstream** sensors) have very clear CFE drop in the outer region, and CFE has the pattern of routing line
  - Effect seems to reduce after type inversion
- Phi type sensors have a drop at the boundary between inner strips and outer strips

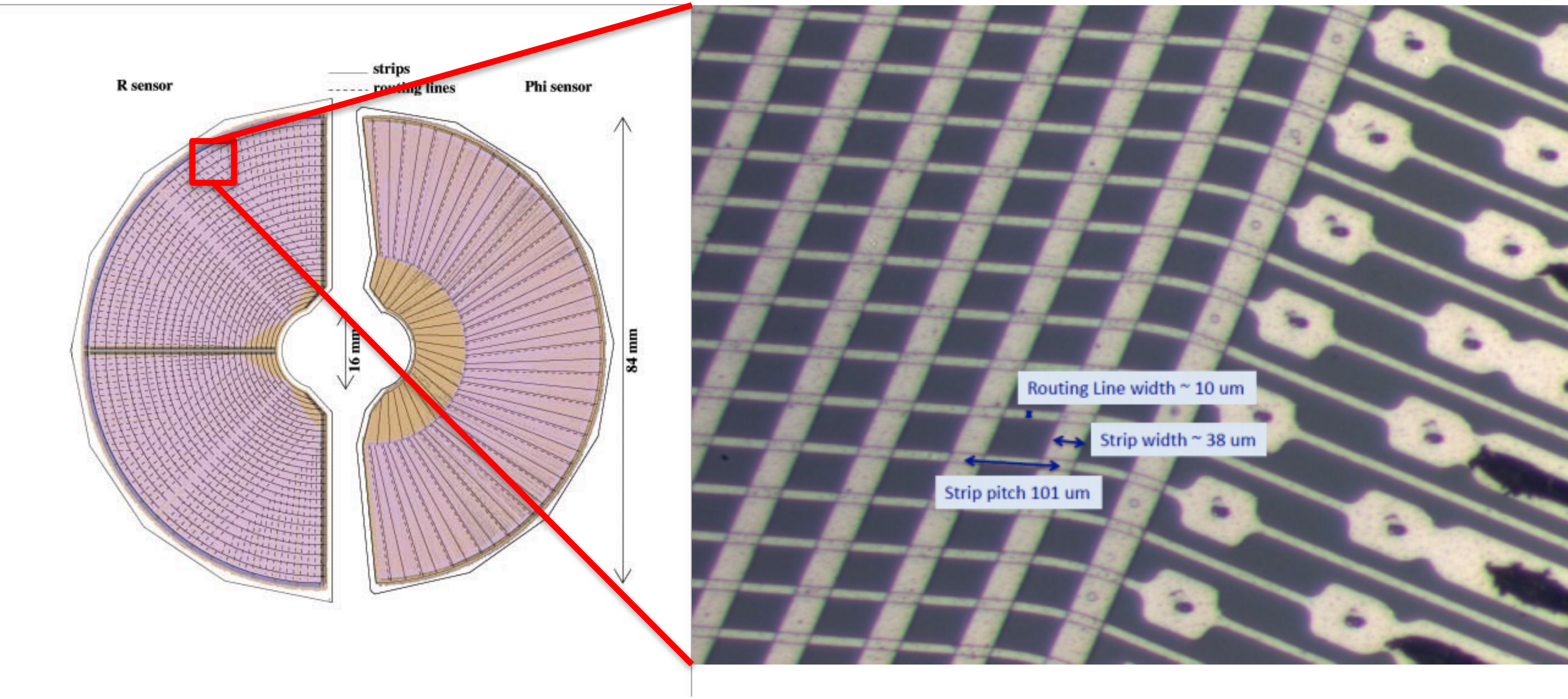








Second metal layer



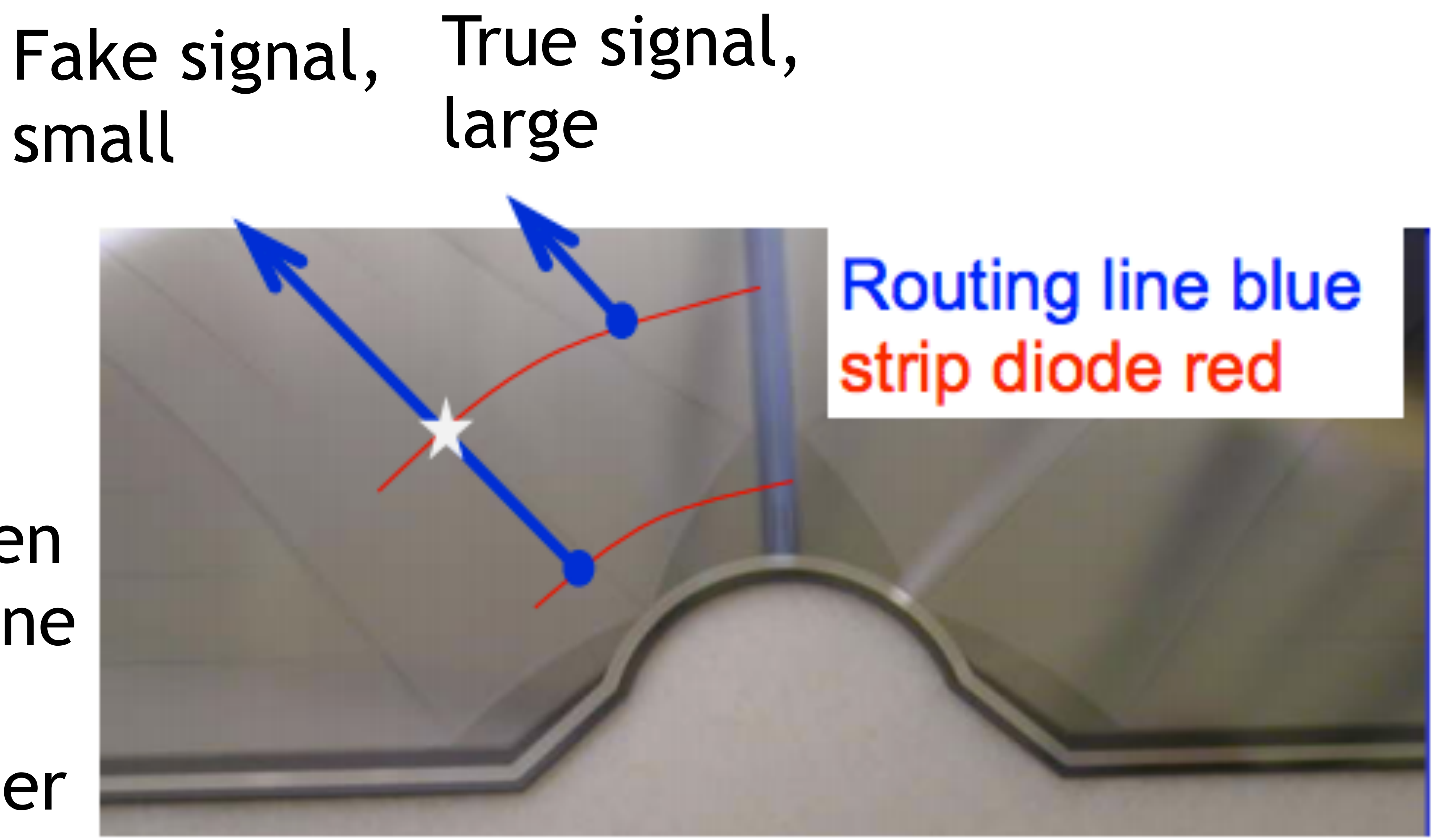
- Sensors are AC coupled, one metal layer couples to the strip and the other routes the signal to the edge of the sensor
- Routing lines are perpendicular to the strips in R-sensors and parallel to and overlain by strips in φ-sensors

Second metal layer effect

Track impacts at star

Small signal is seen on blue routing line

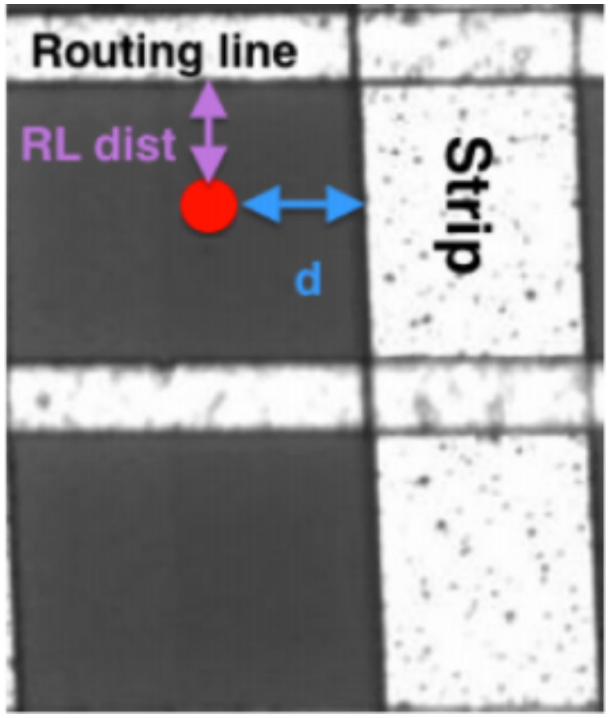
This fakes a cluster on inner strip

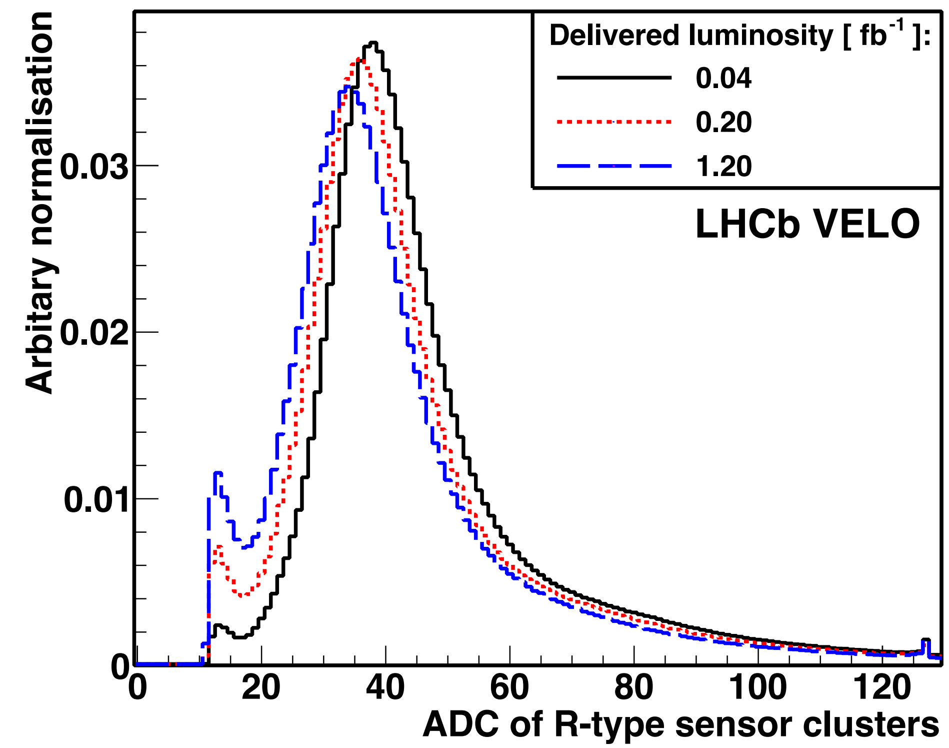


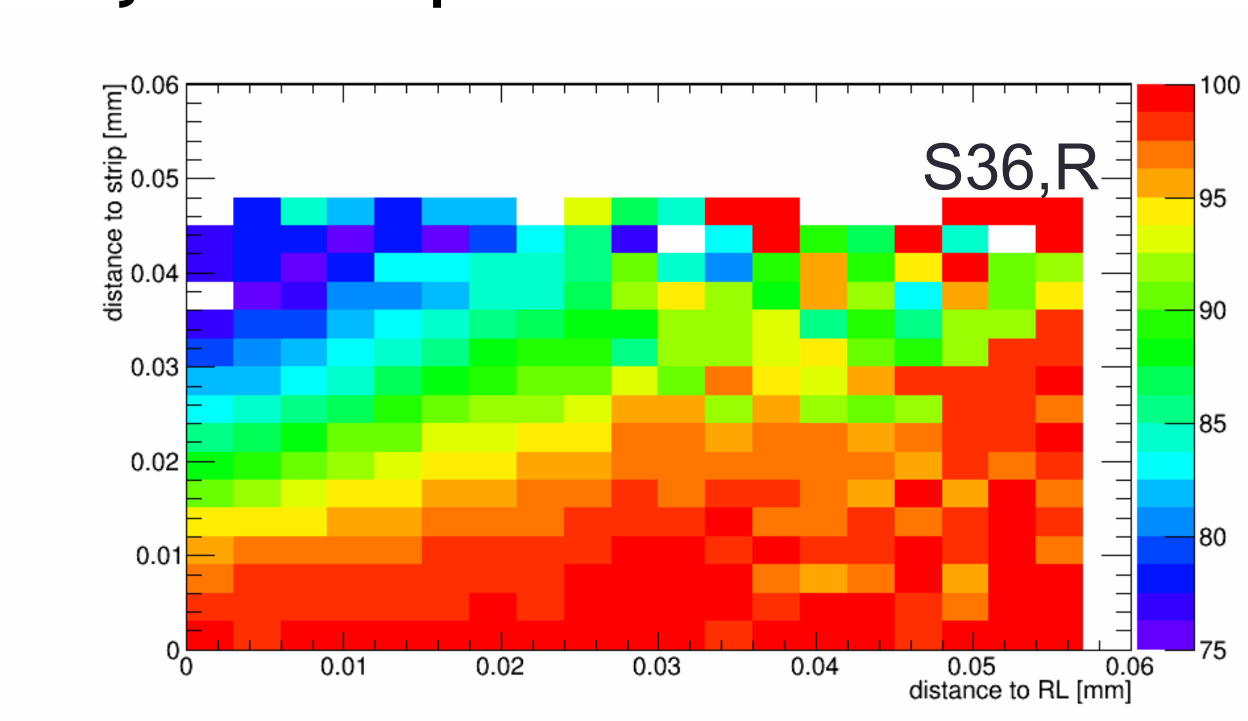
Losing charge

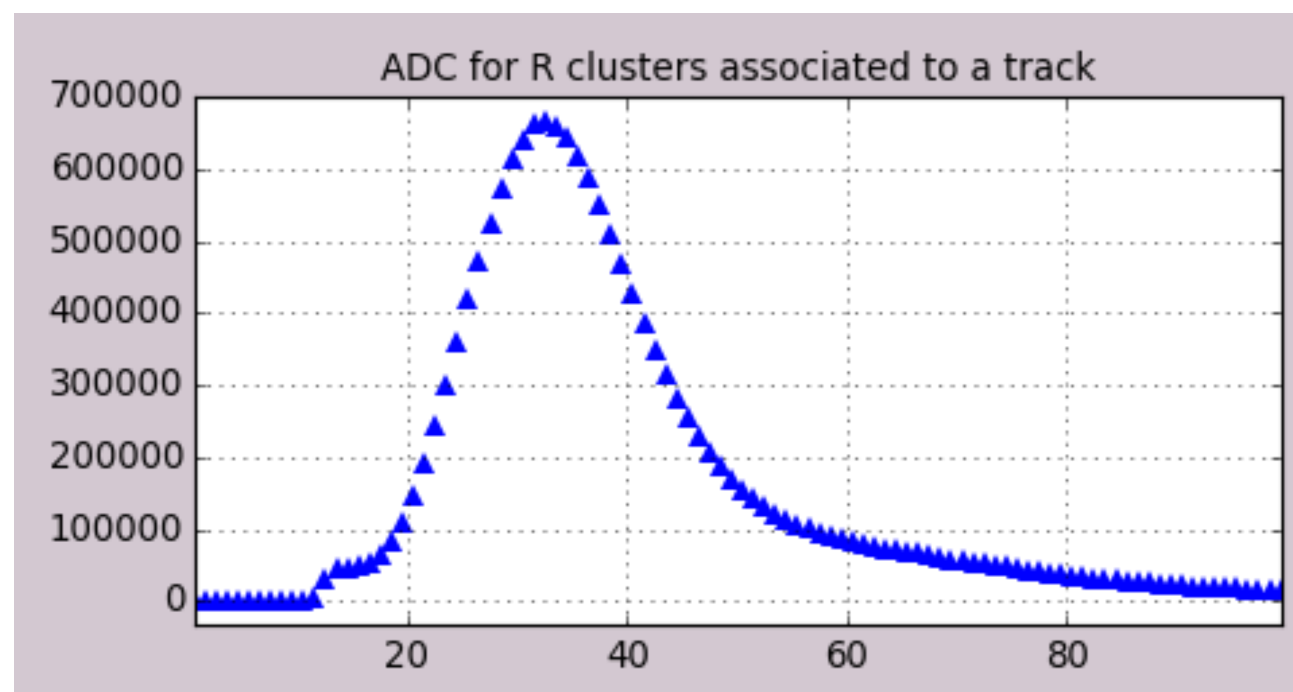
Effect depend on the distance to the routing lines

CFE low for regions that close to RL but far away from strips







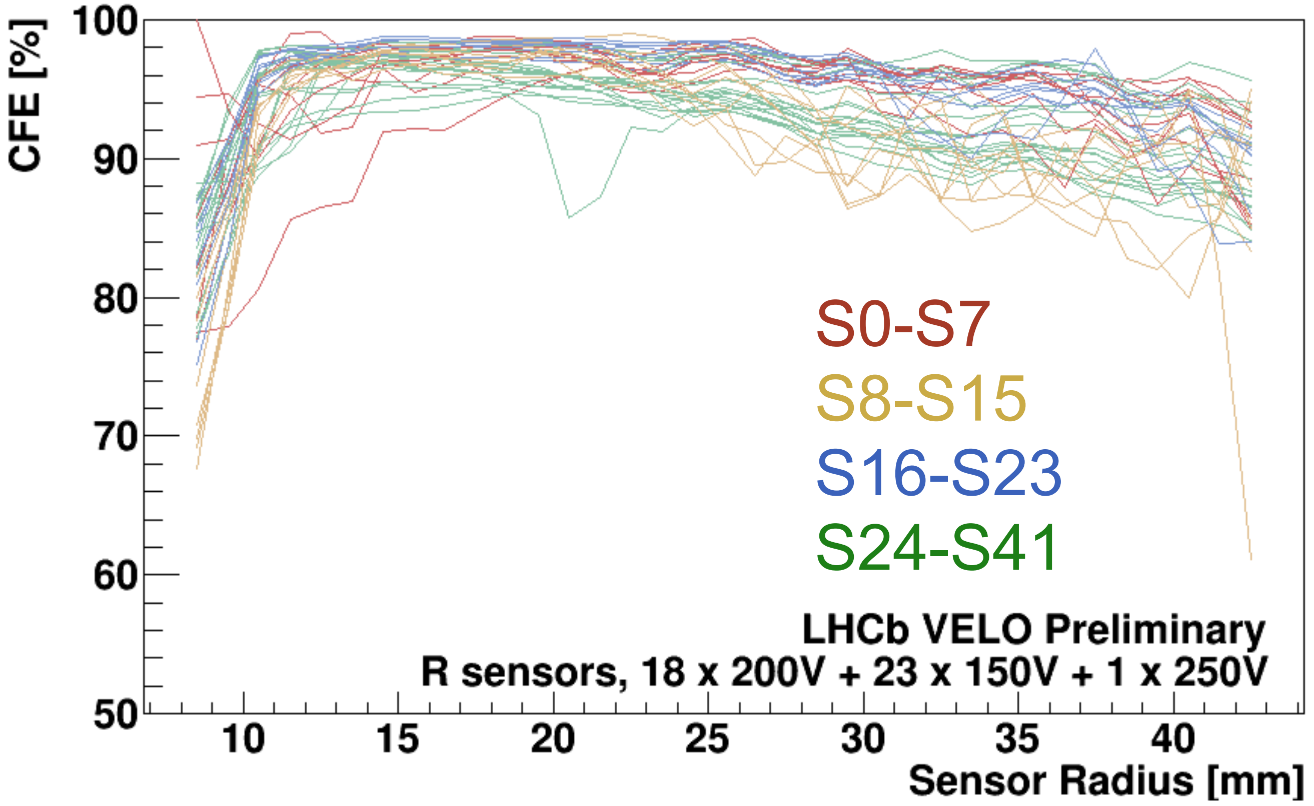


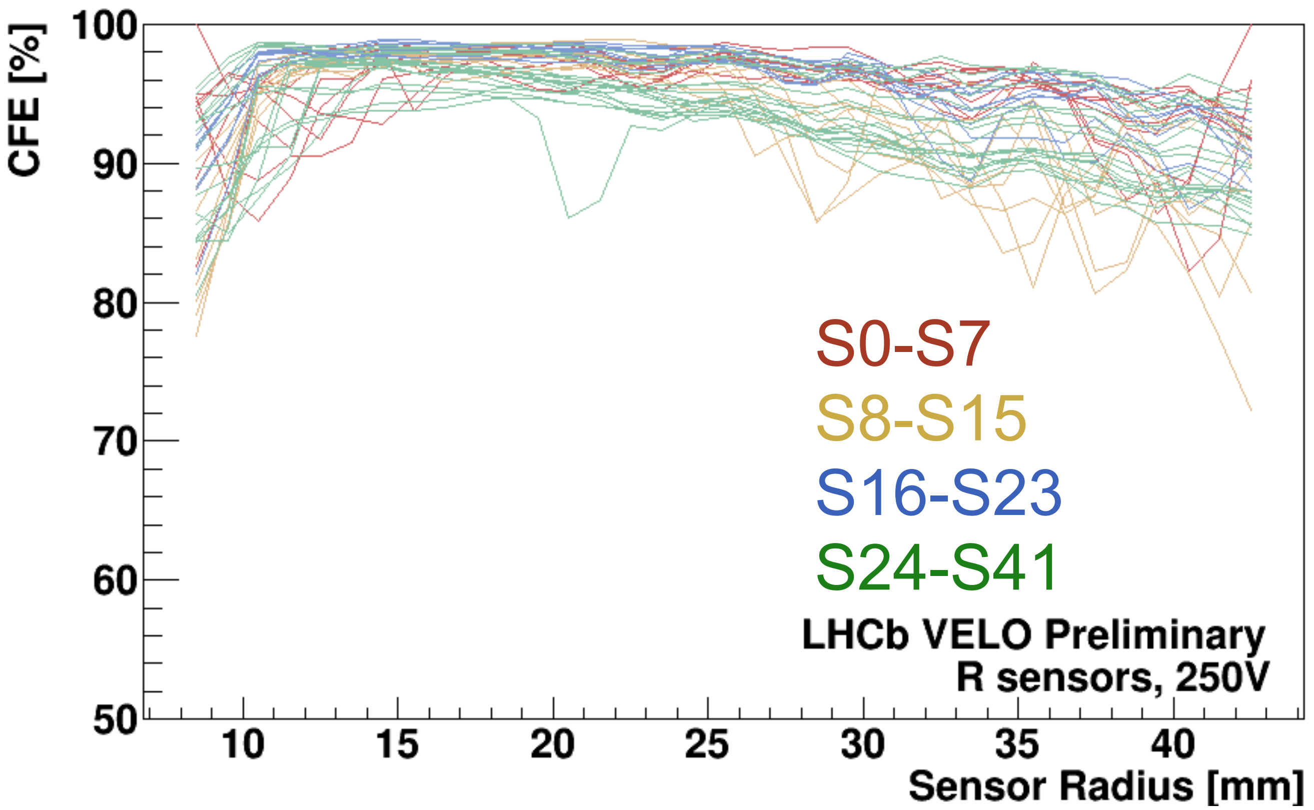
Does not affect tracking performance

CFE vs Radius

- R sensors:
- Drop at low radius due to the increased radiation damage in that region, with the most damaged sensors being around the interaction region.
- This drop can be partially recovered by increasing the operation voltage

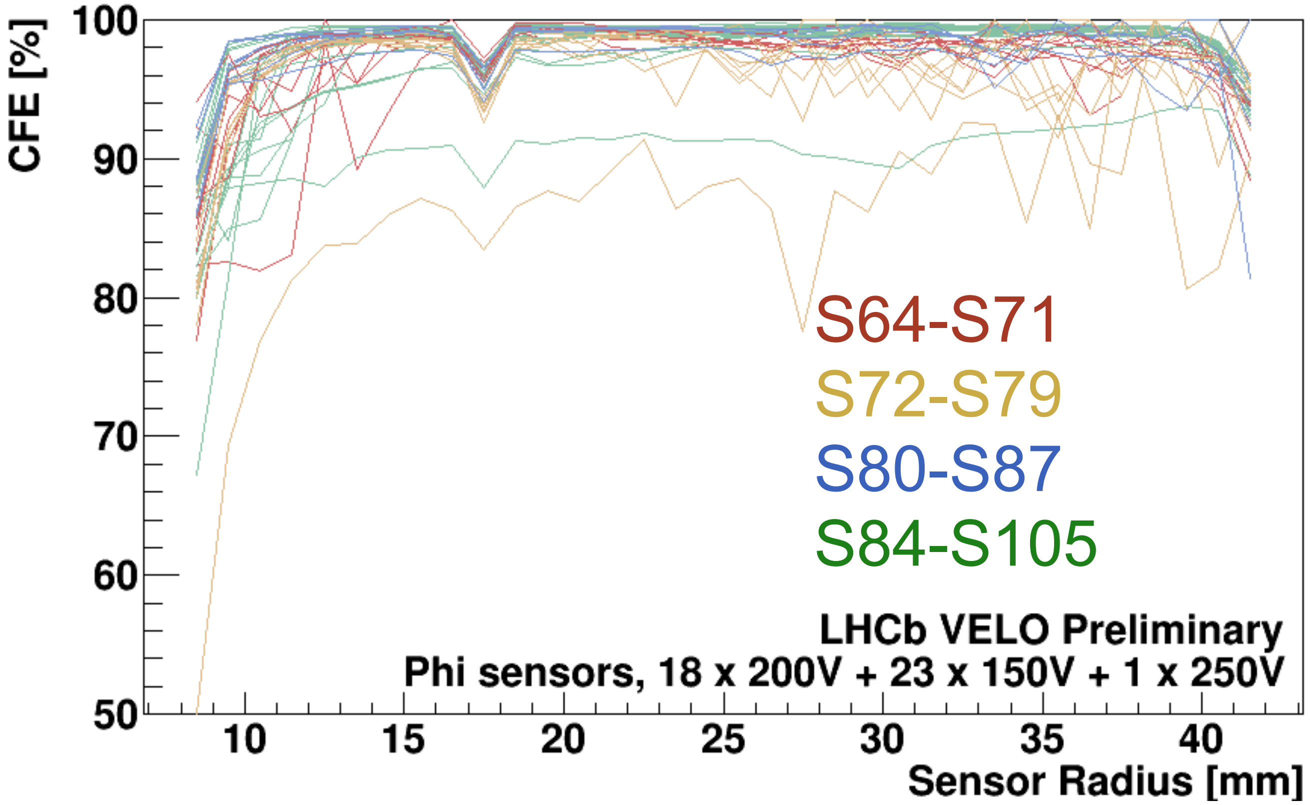
- Wide spread in efficiencies at high radius with most inefficient sensors in the downstream part of the VELO. Increasing the operation voltage does not help

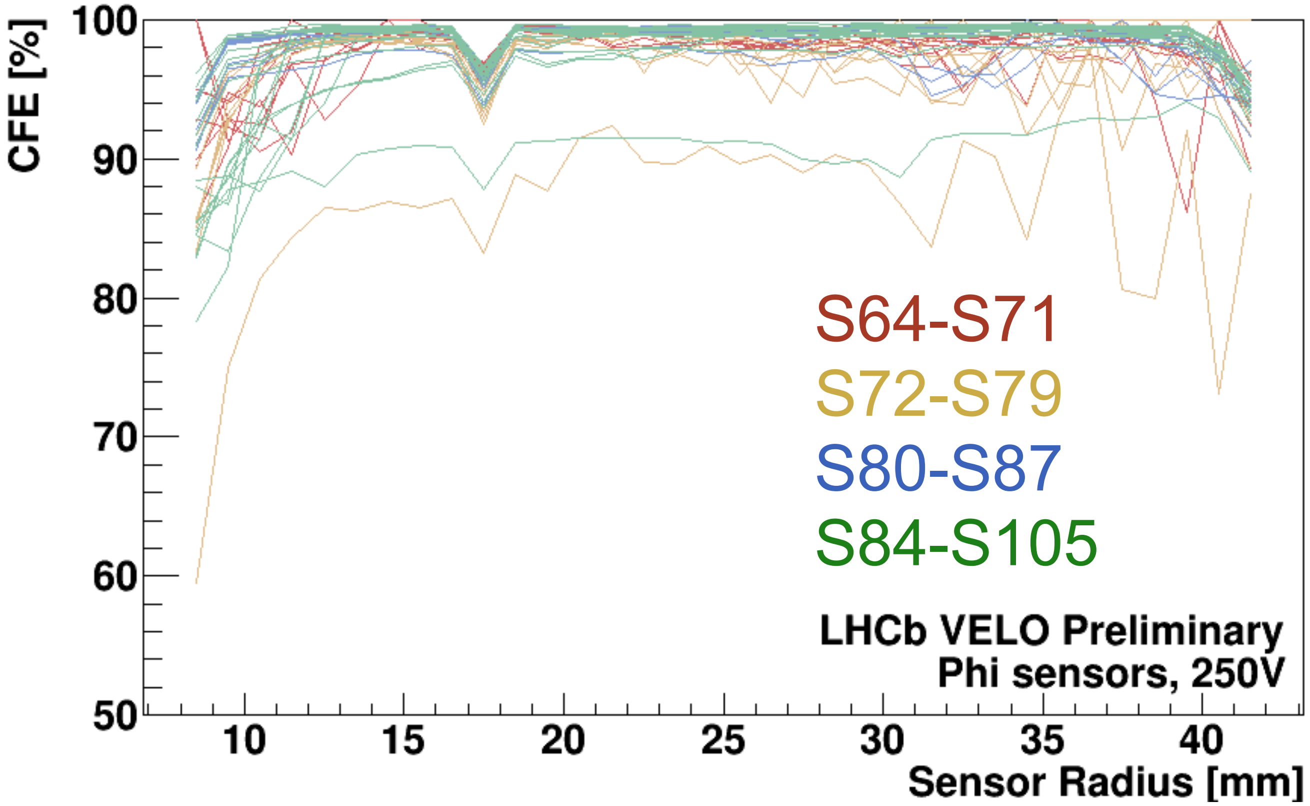




CFE vs Radius

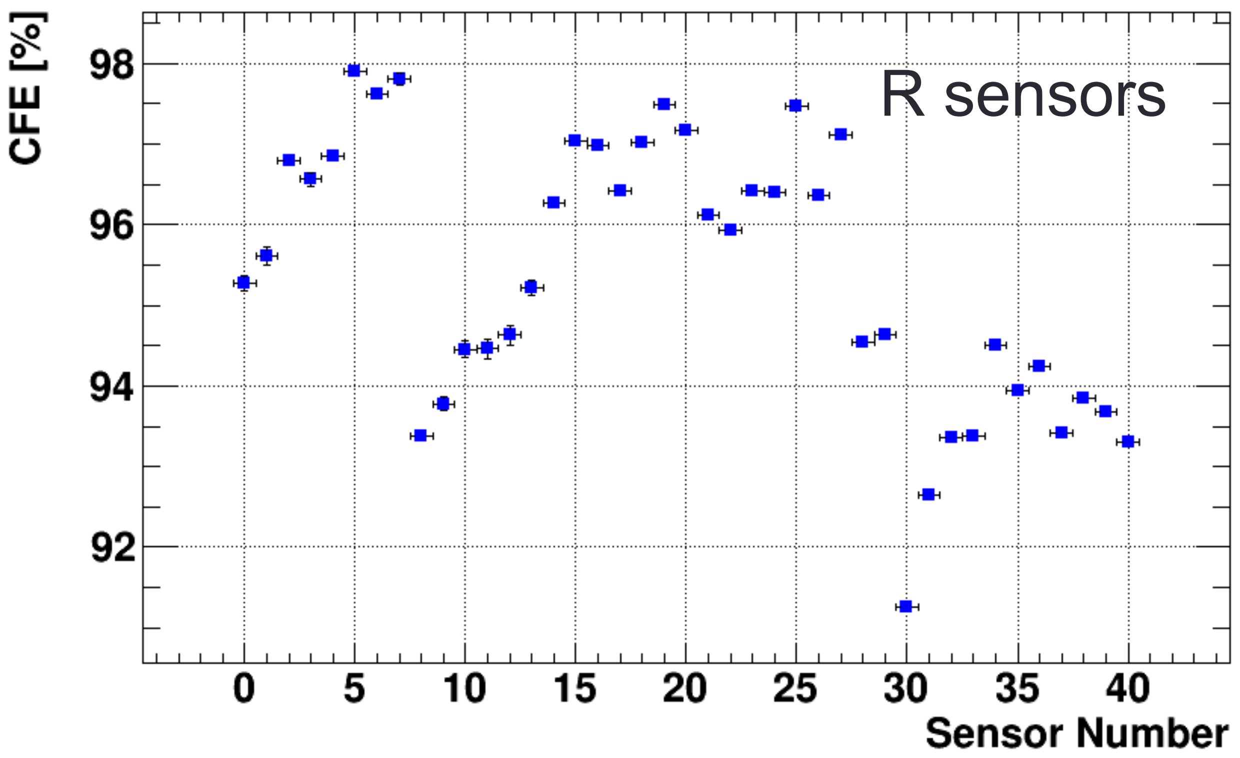
- Phi sensors:
- Drop at low radius due to the increased radiation damage in that region, with the most damaged sensors being around the interaction region.
- This drop can be partially recovered by increasing the operation voltage
- Drop at 17mm due to the boundary between inner strips and outer strips

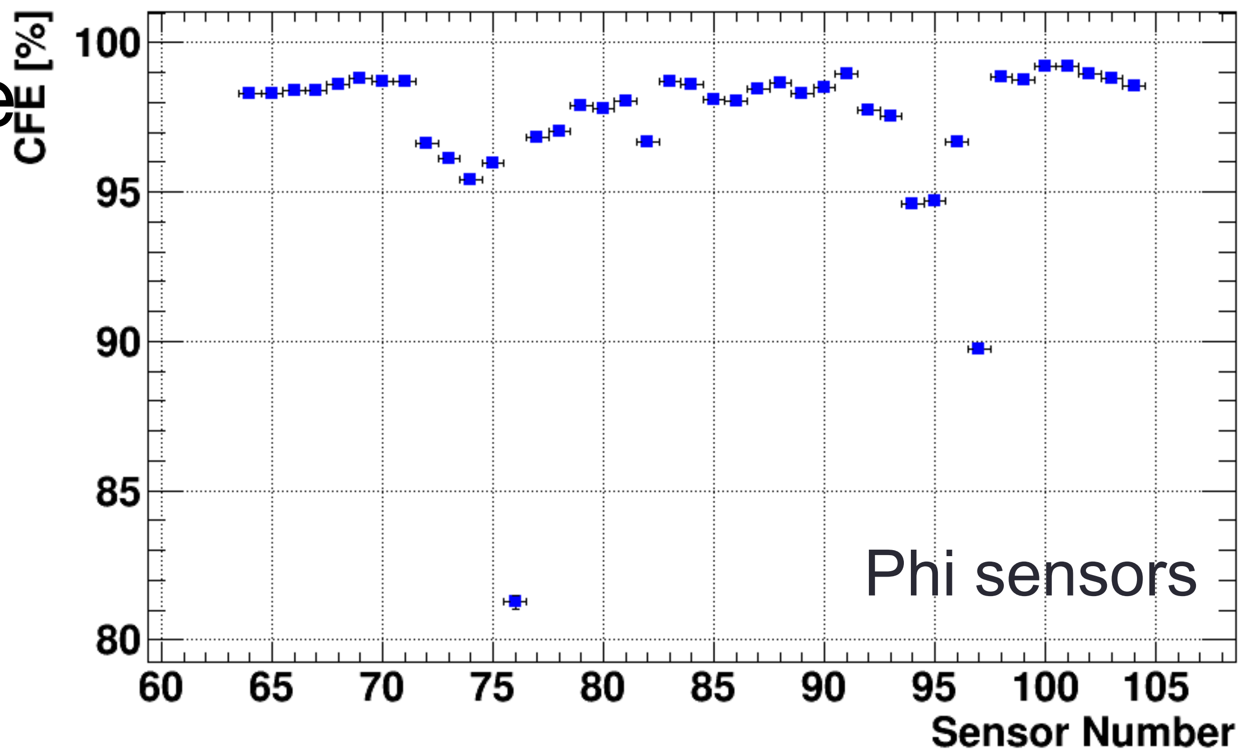




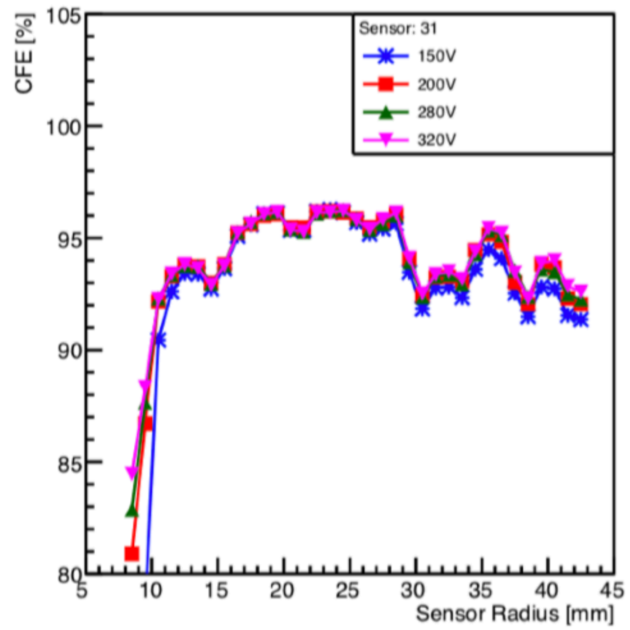
CFE vs Sensor number

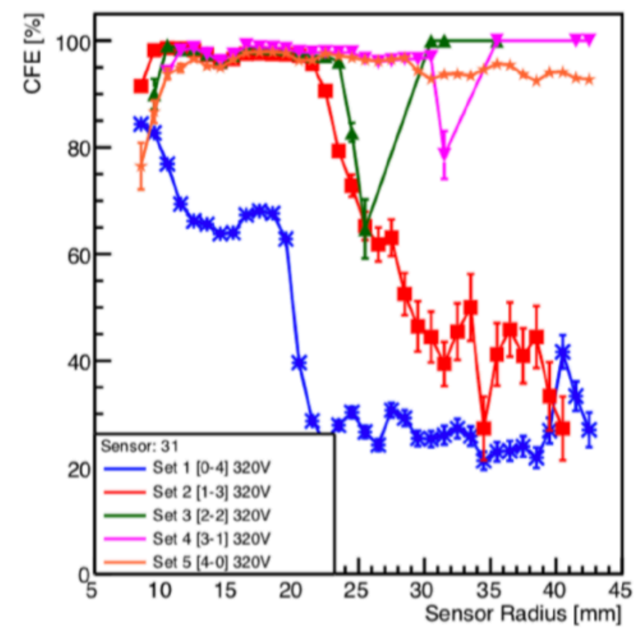
- On R type sensors, CFE drops suddenly at sensor 8
- On Phi sensors, we can see CFE of S76 and S97 are much lower than others

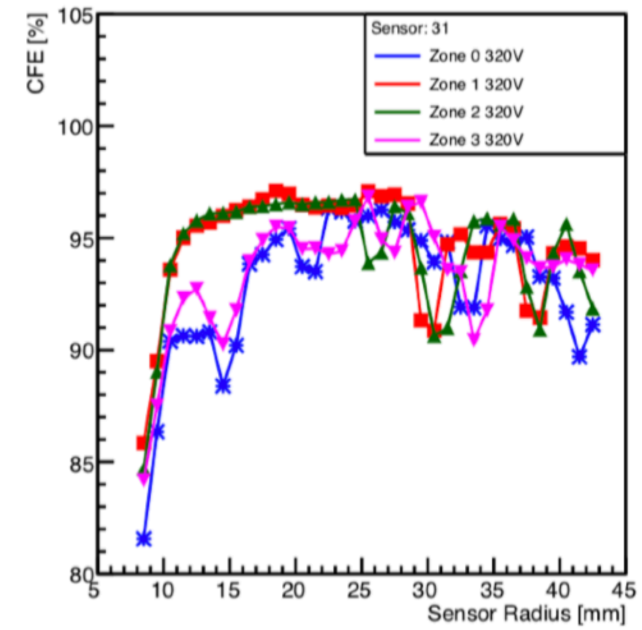


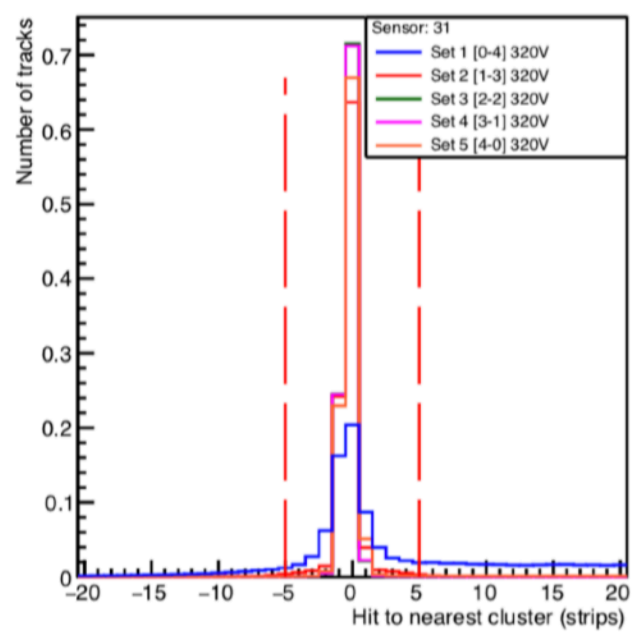


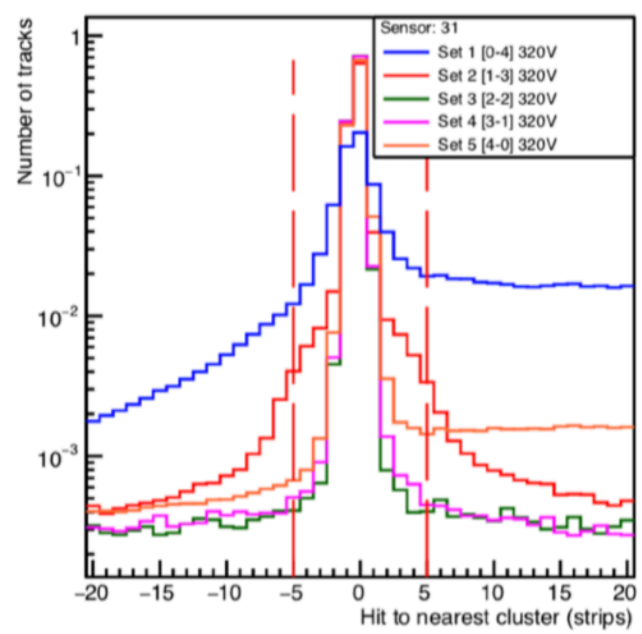
CFE - with bad strips

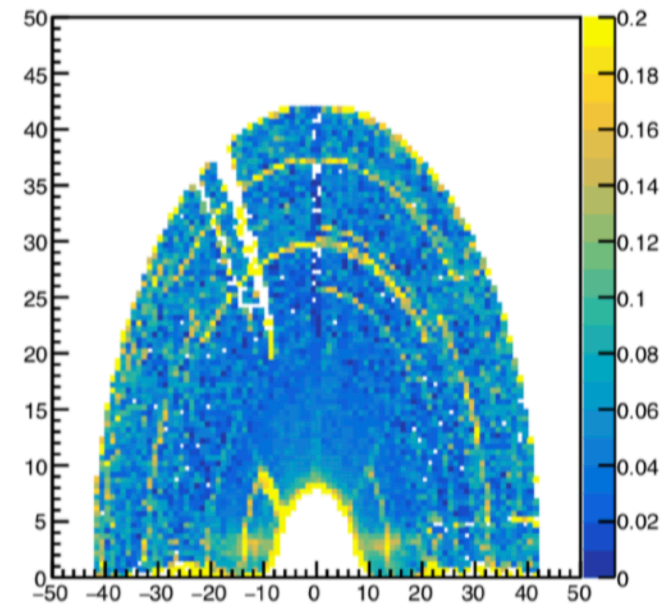




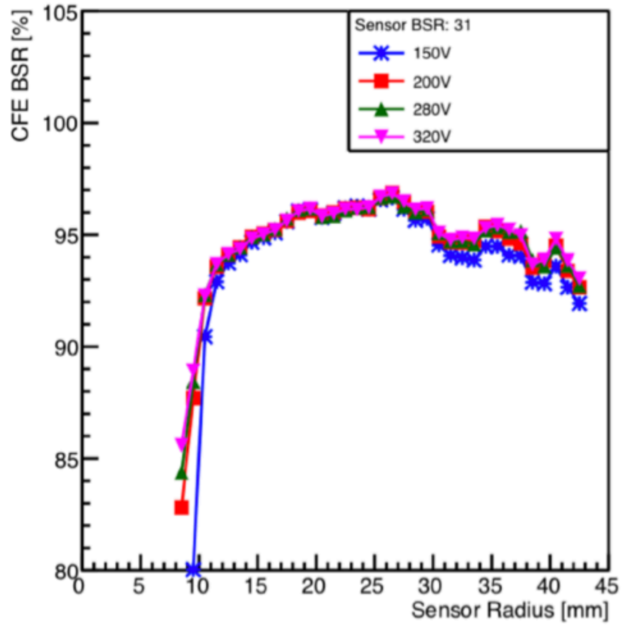


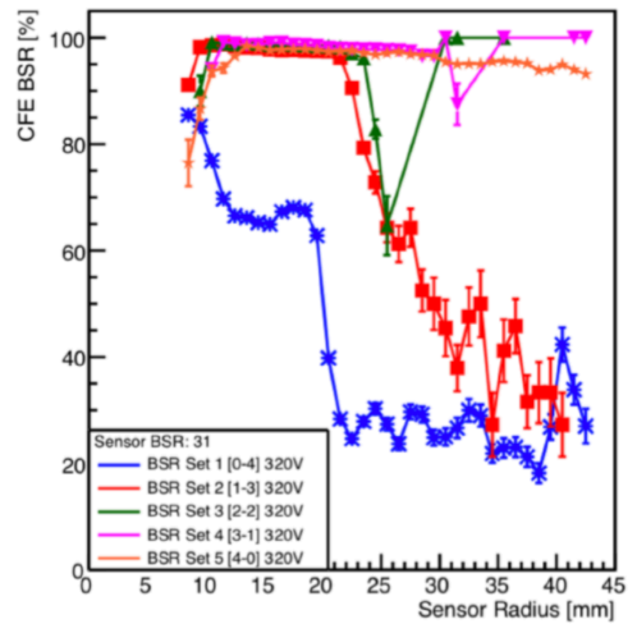


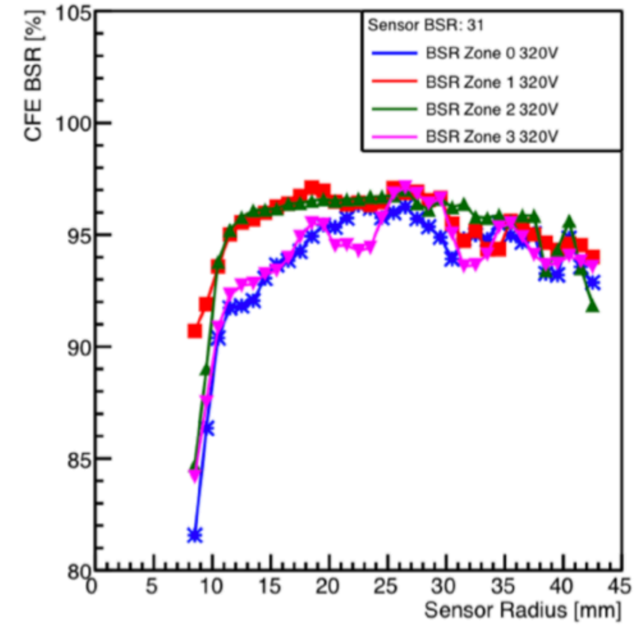


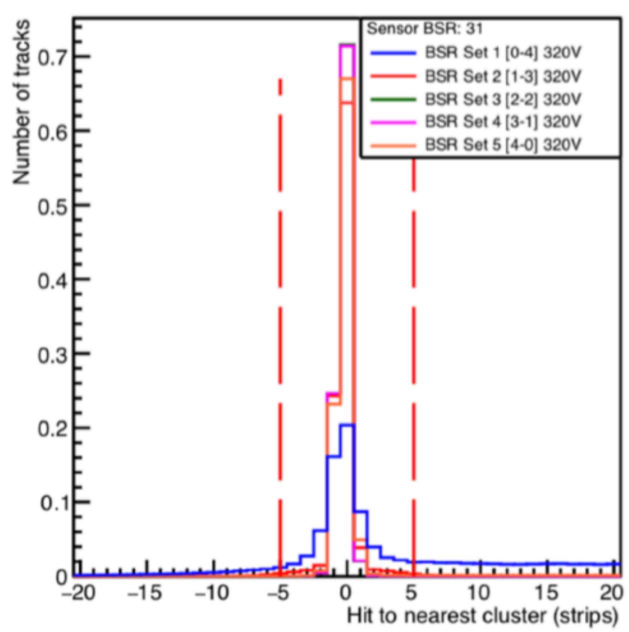


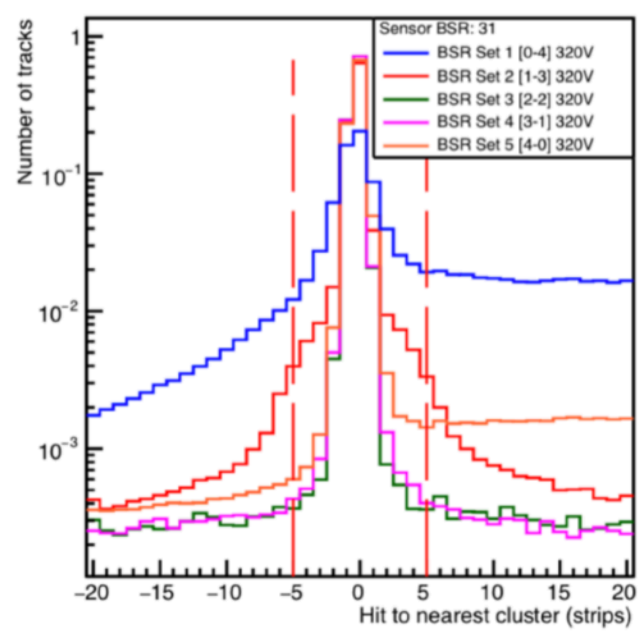
CFE - bad strips removed

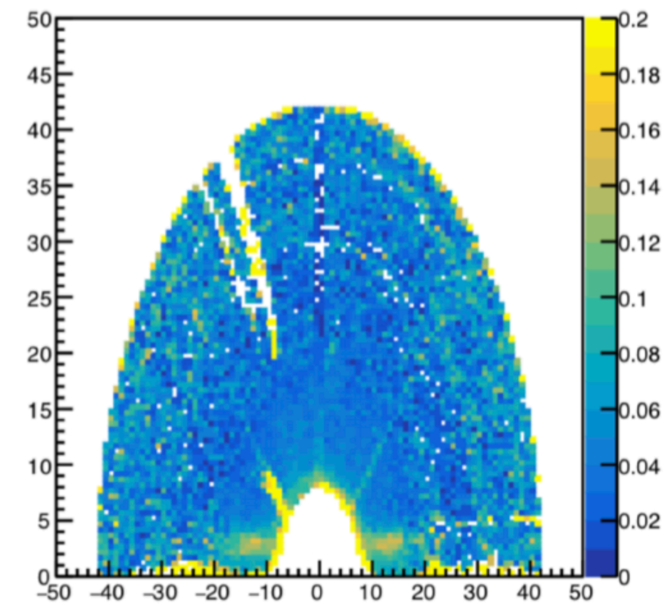




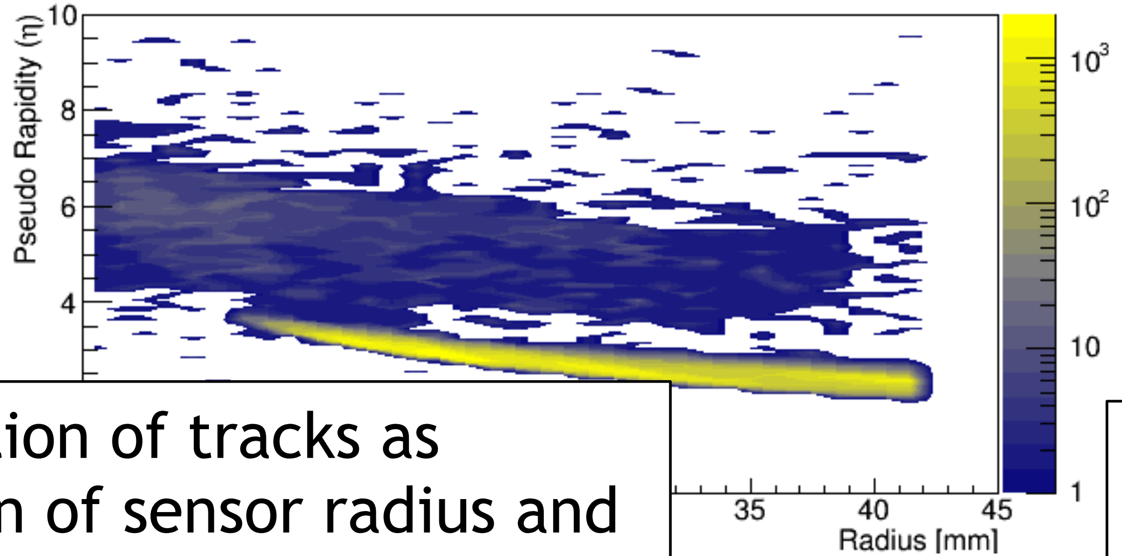




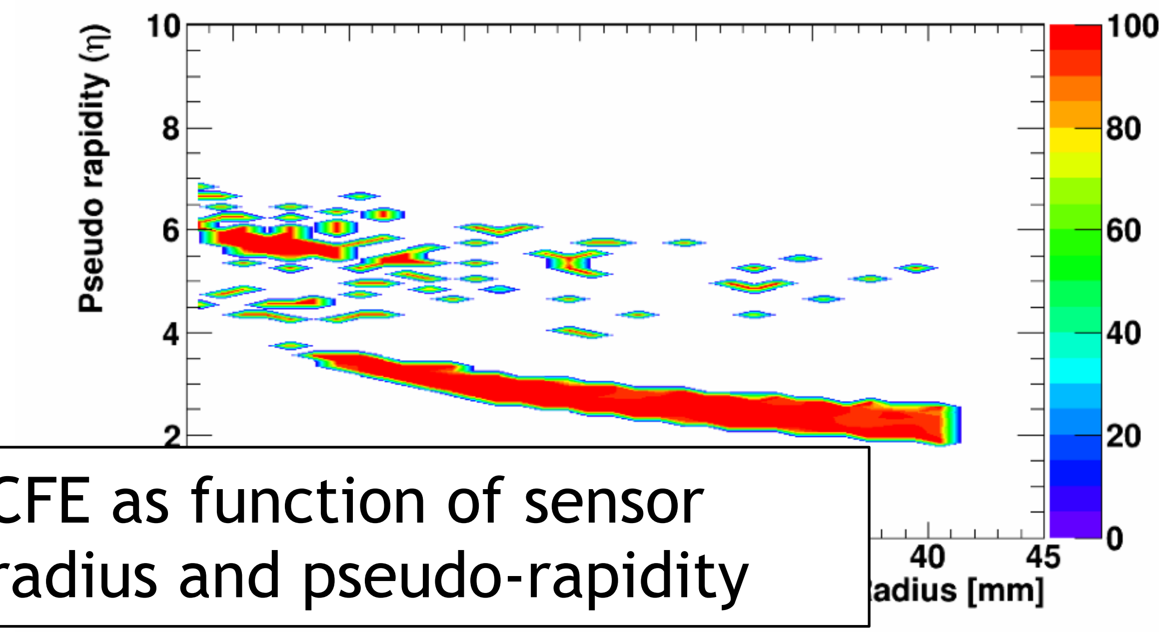




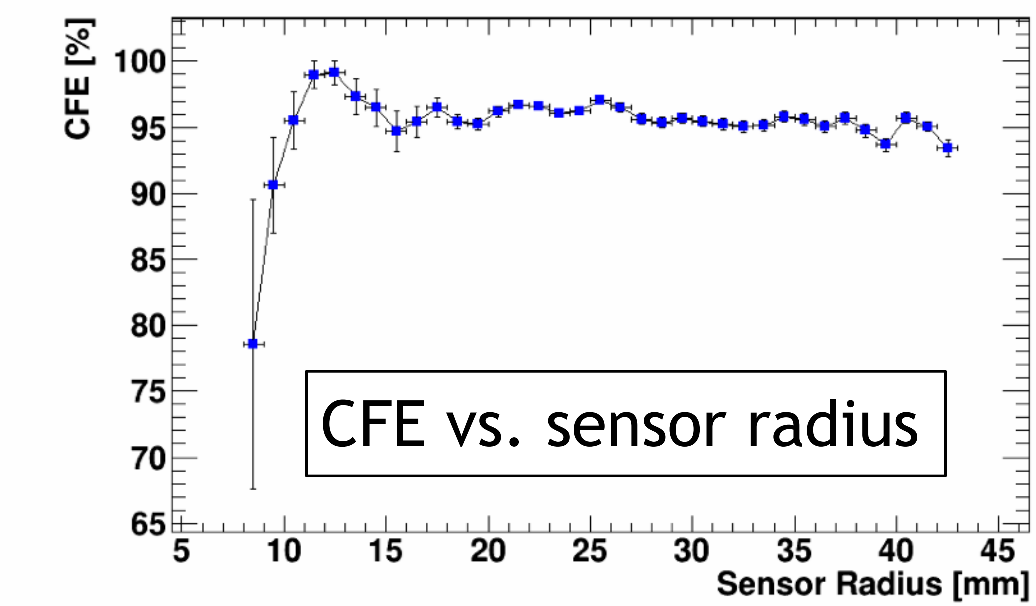
Backward sensors – S1



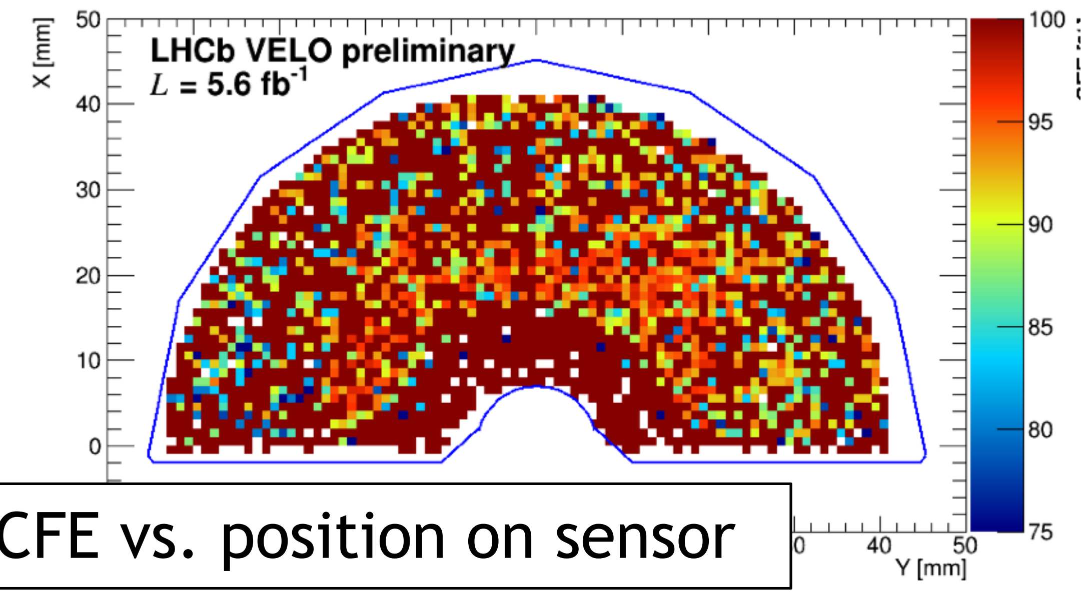
Population of tracks as function of sensor radius and pseudo-rapidity



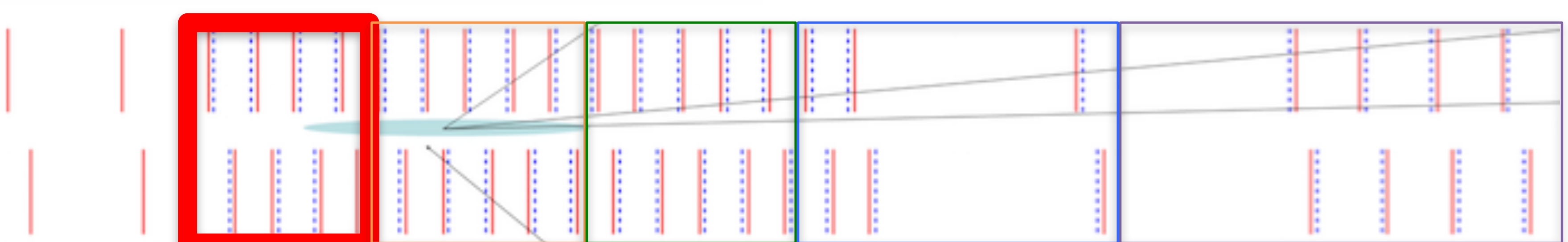
CFE as function of sensor radius and pseudo-rapidity



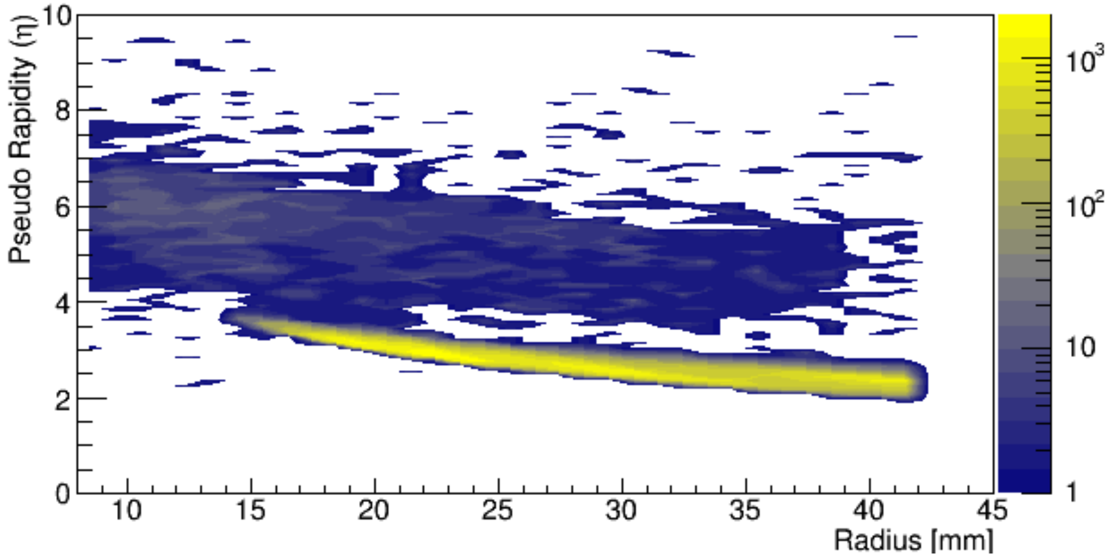
CFE vs. sensor radius

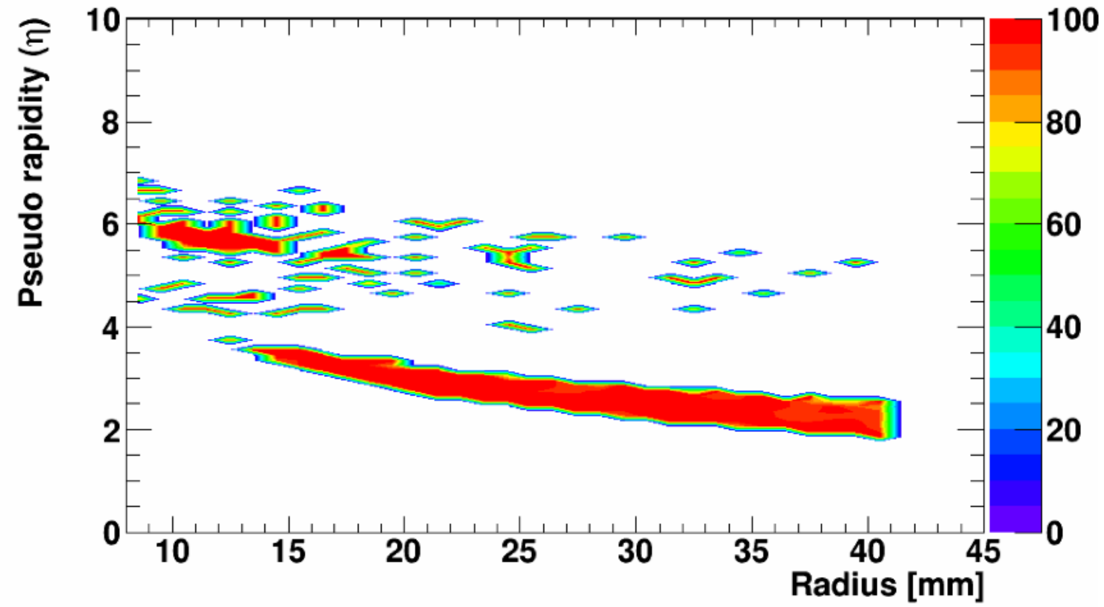


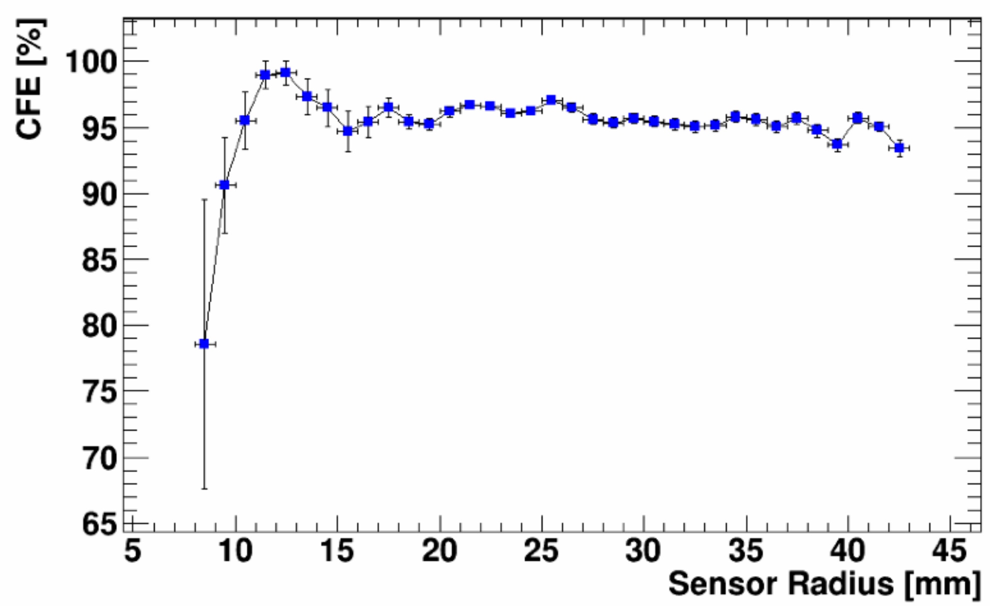
CFE vs. position on sensor

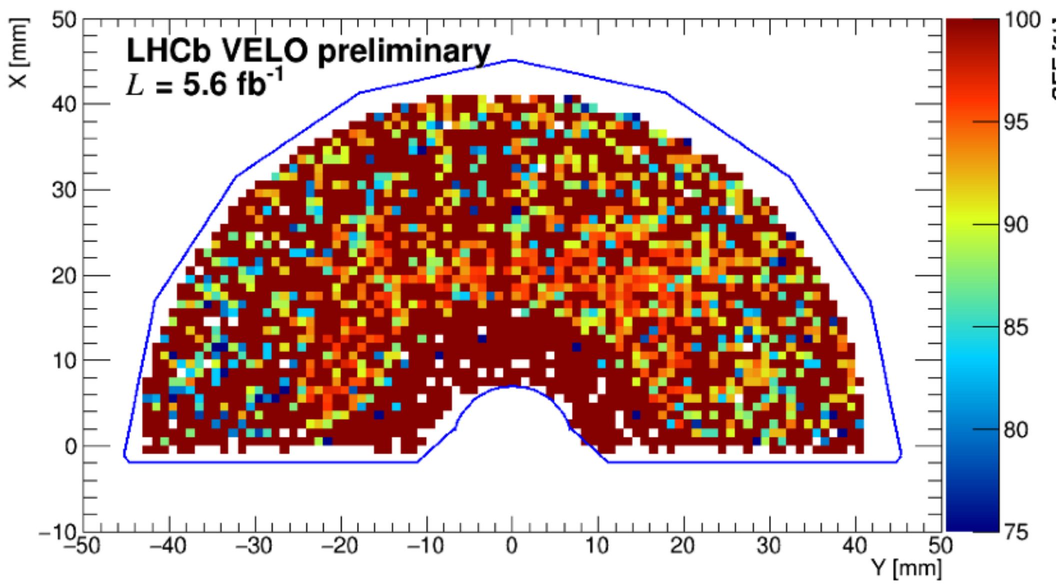


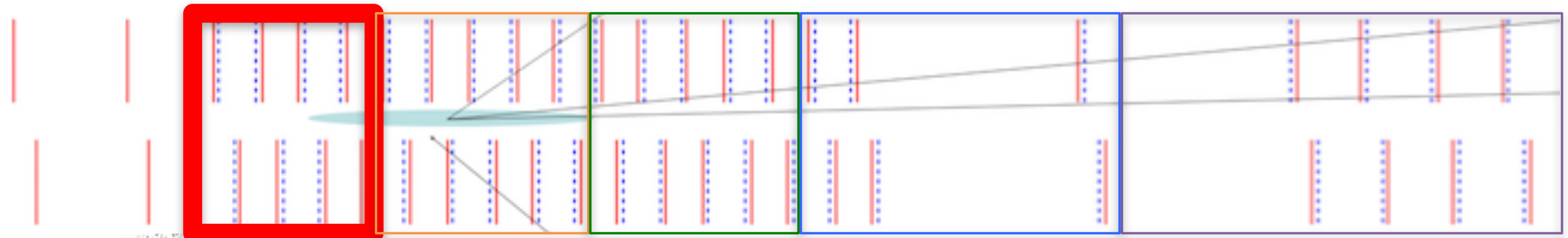
Backward sensors – S1



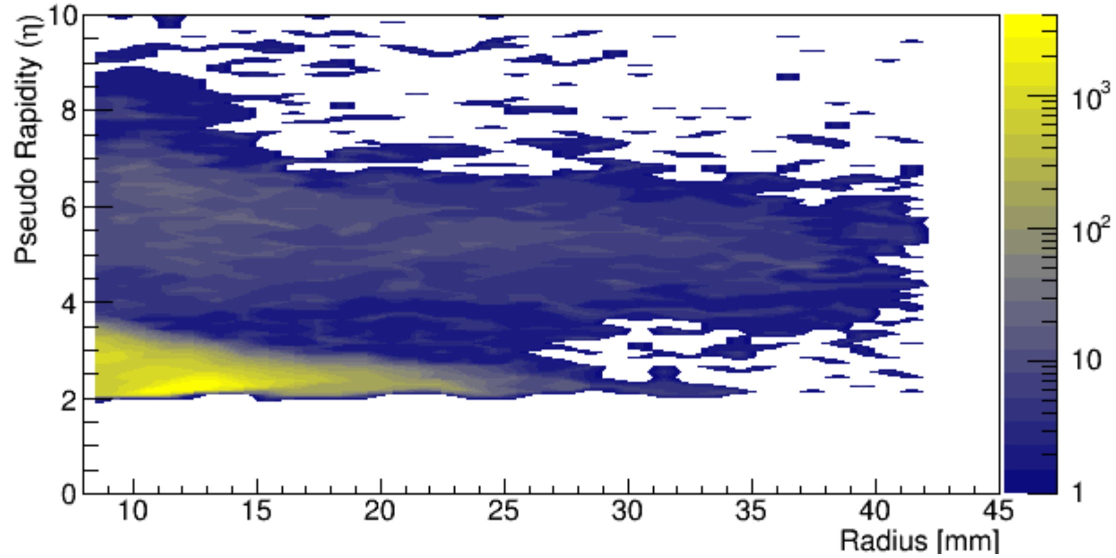


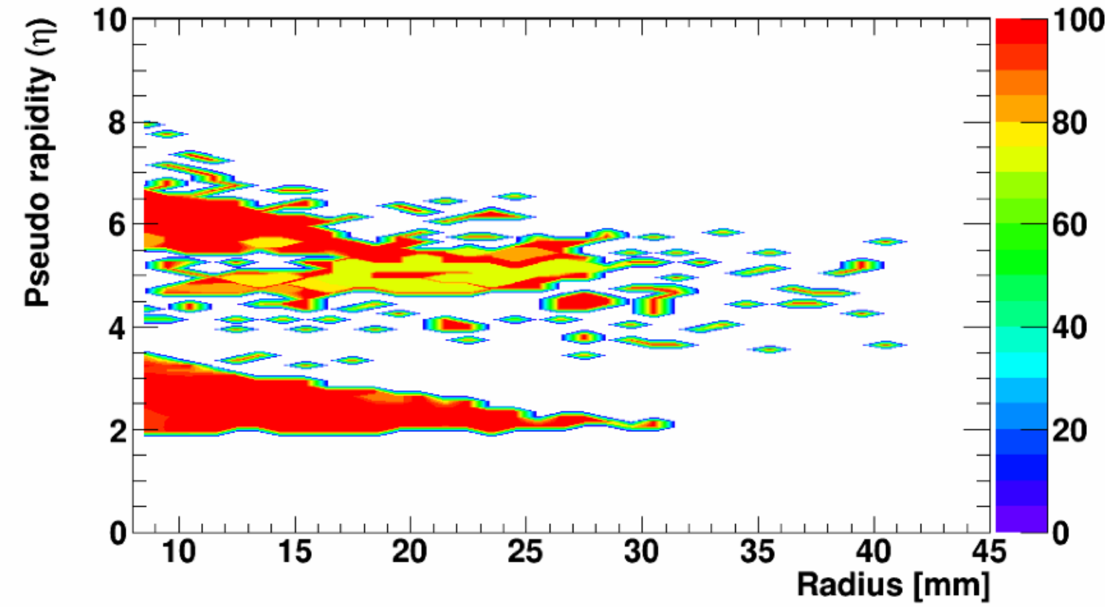


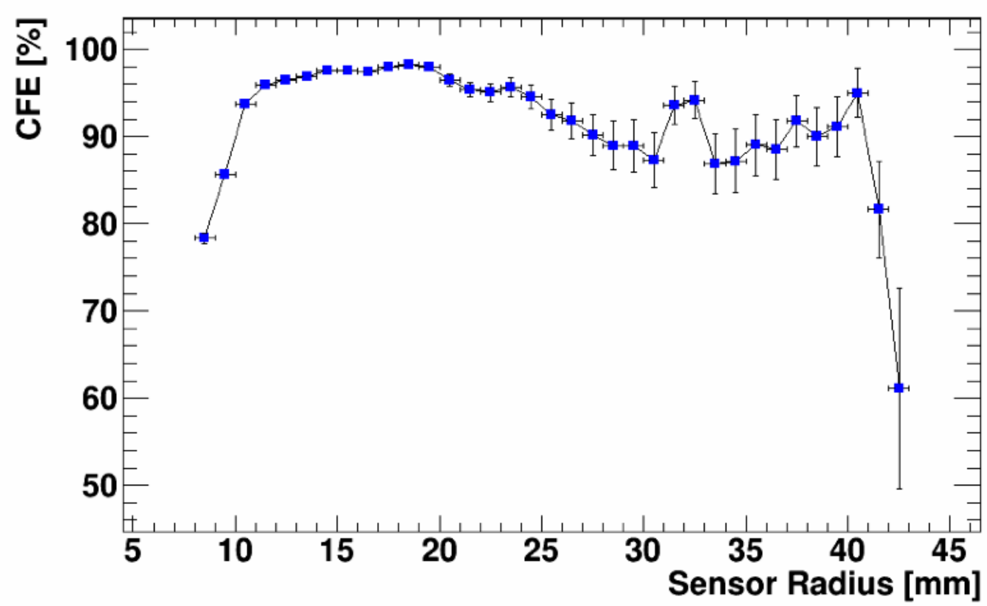


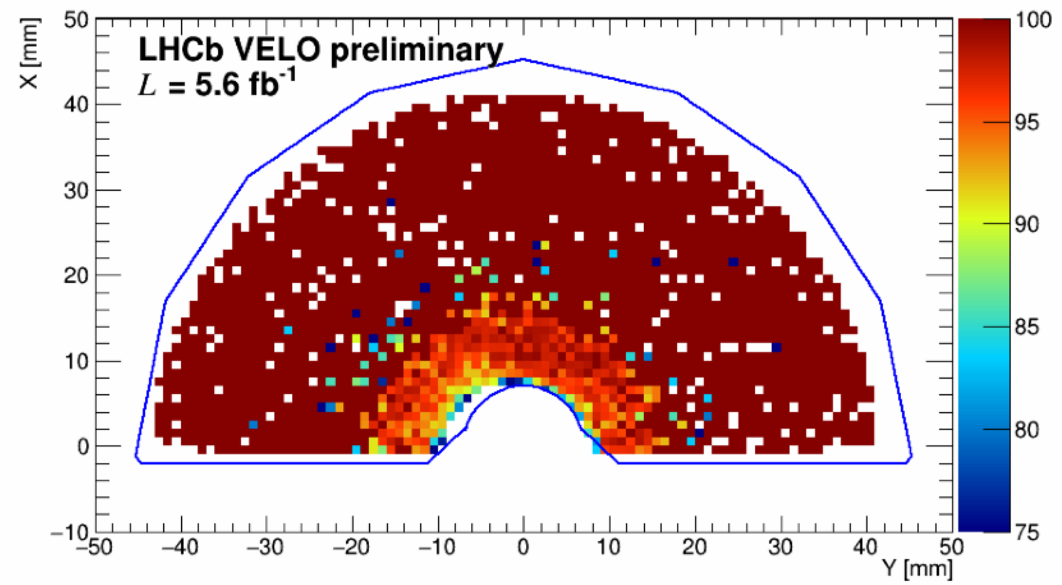


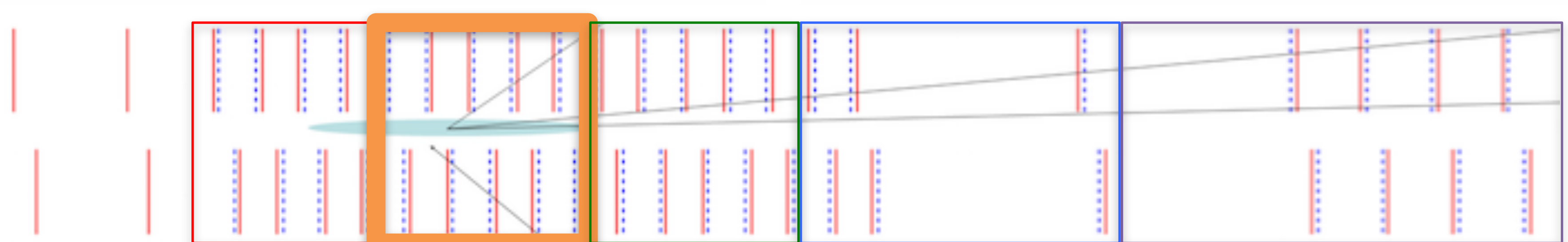
Interaction region – S10



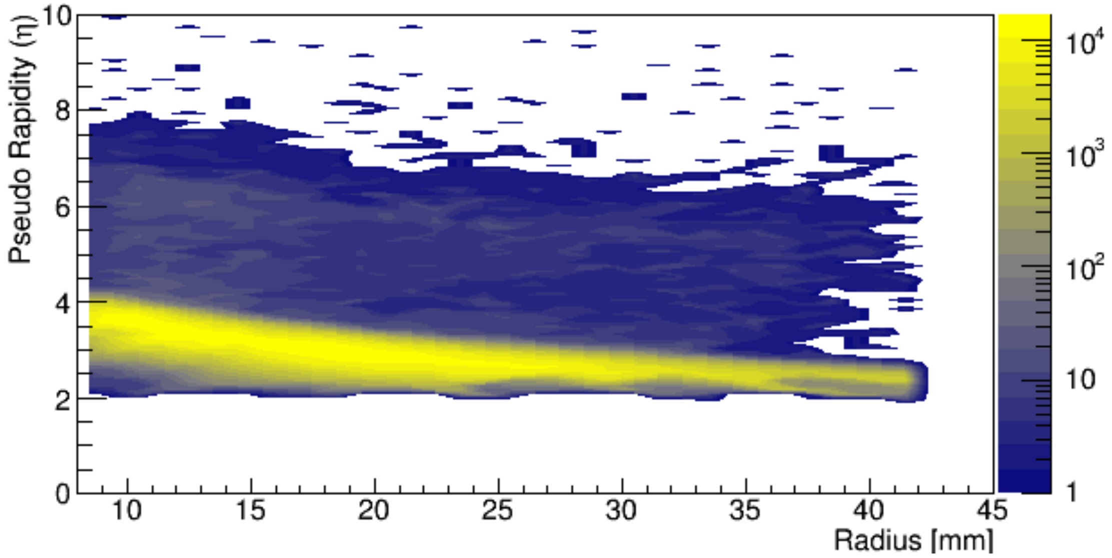


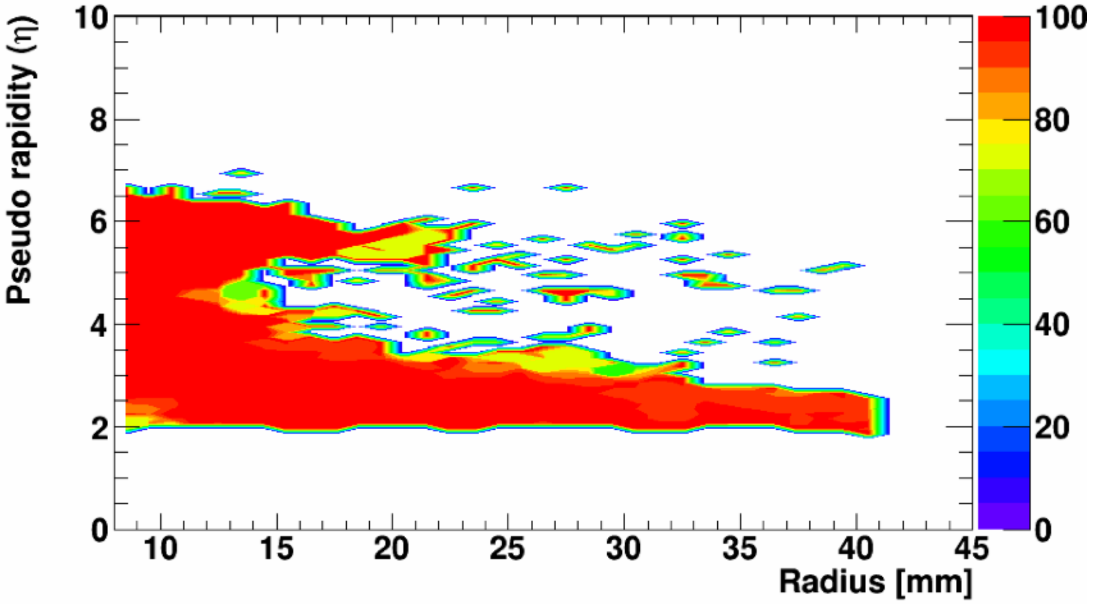


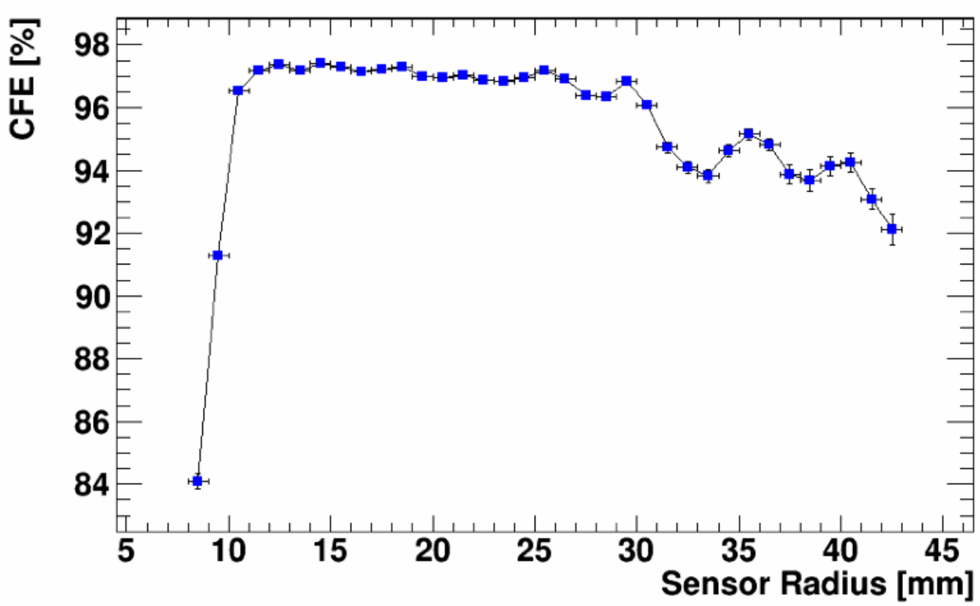


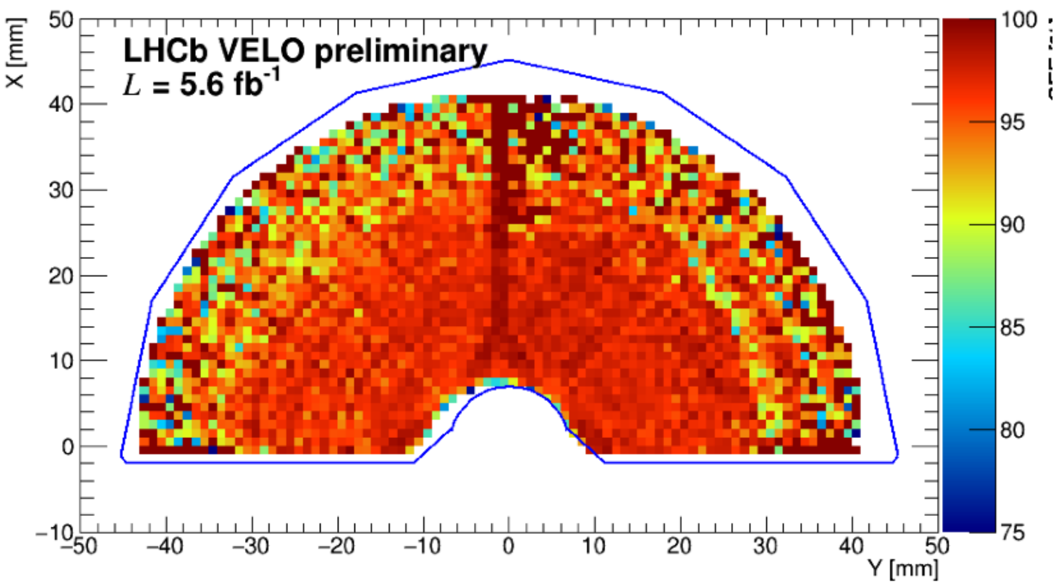


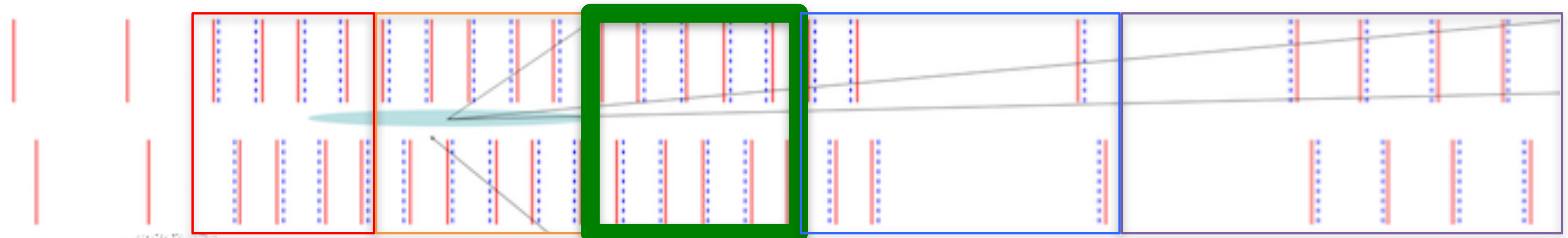
Forward sensors – S23



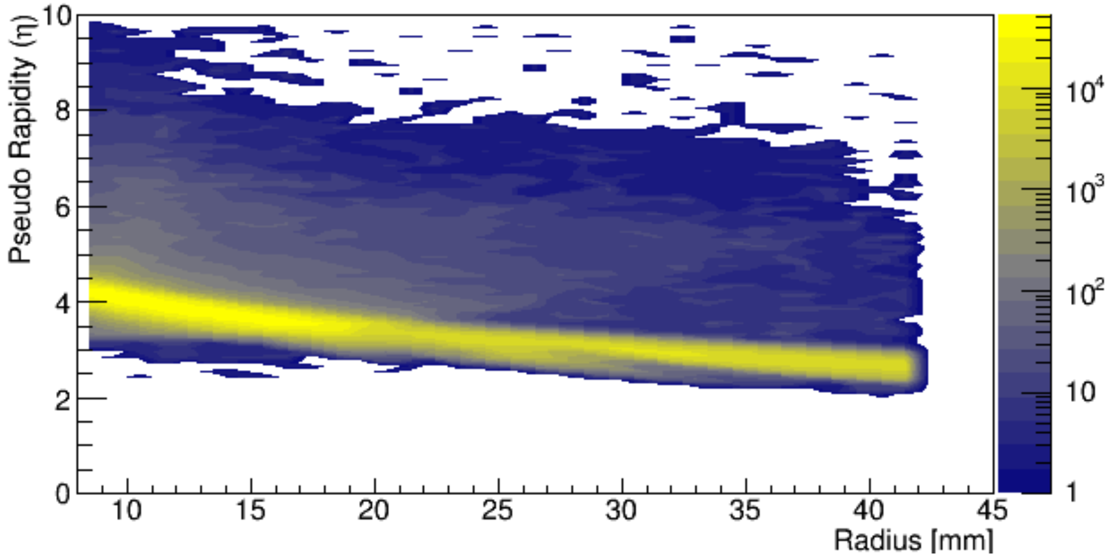


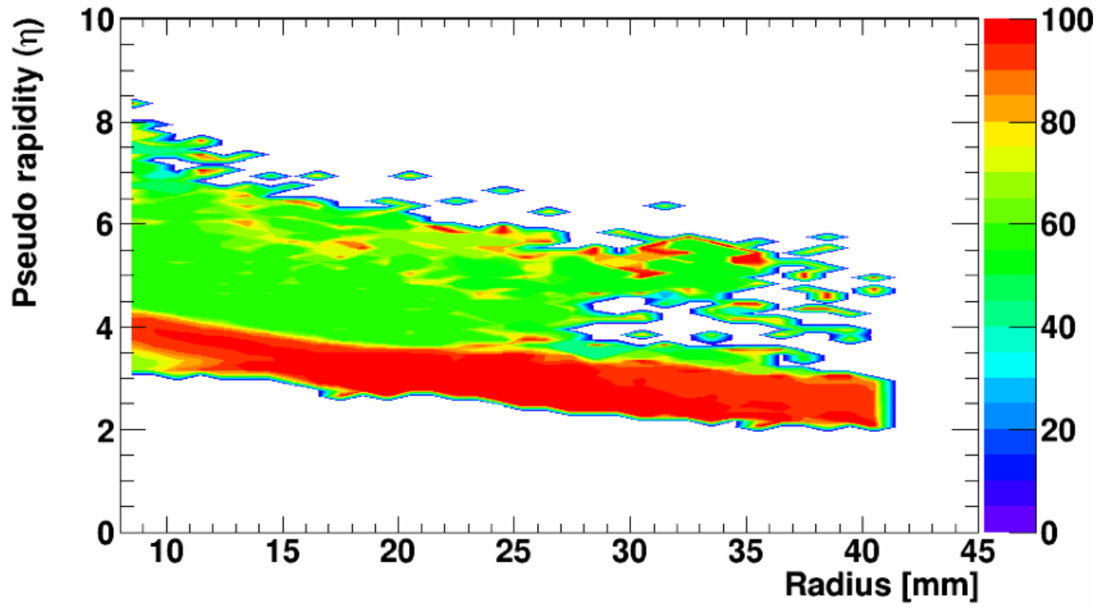


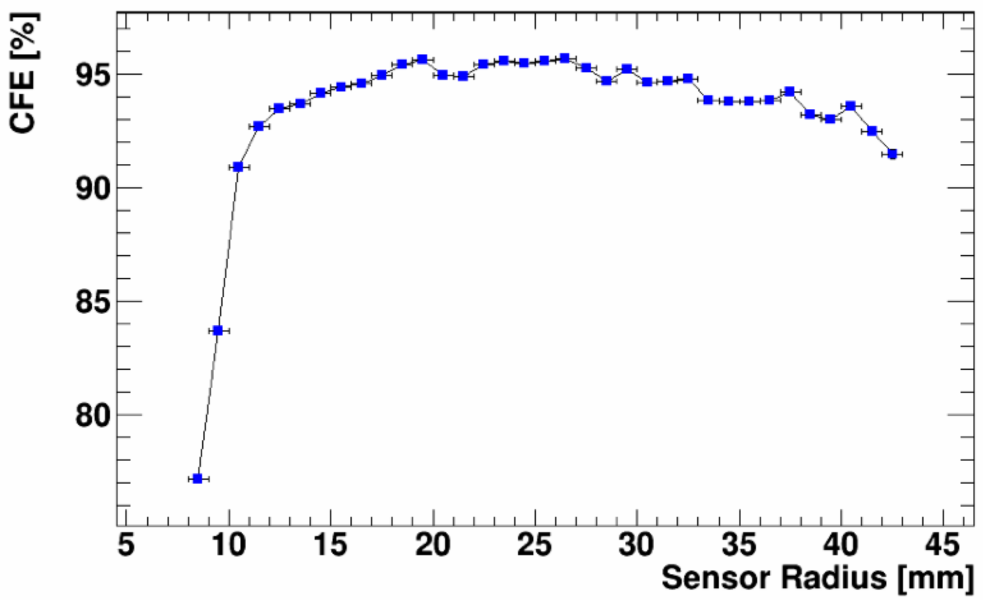


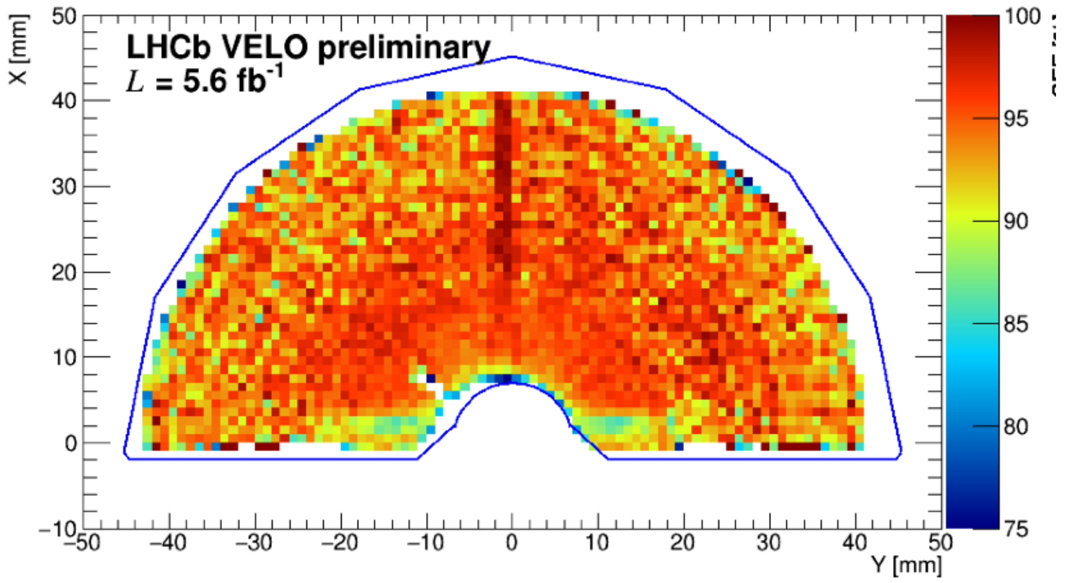


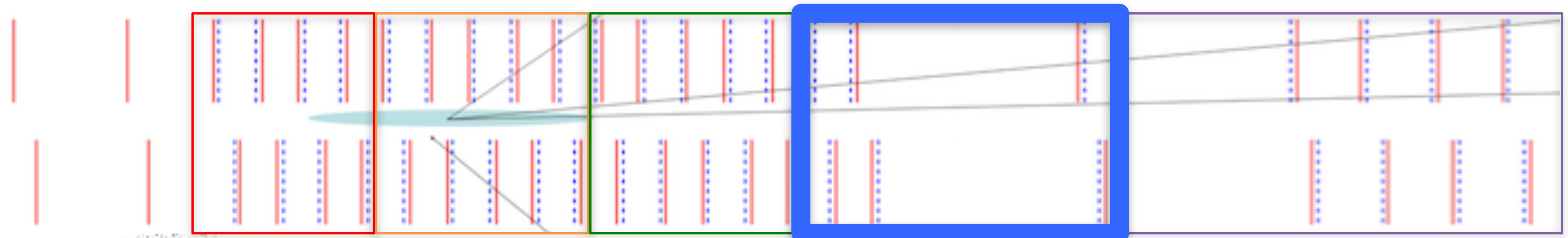
Very forward sensors – S31



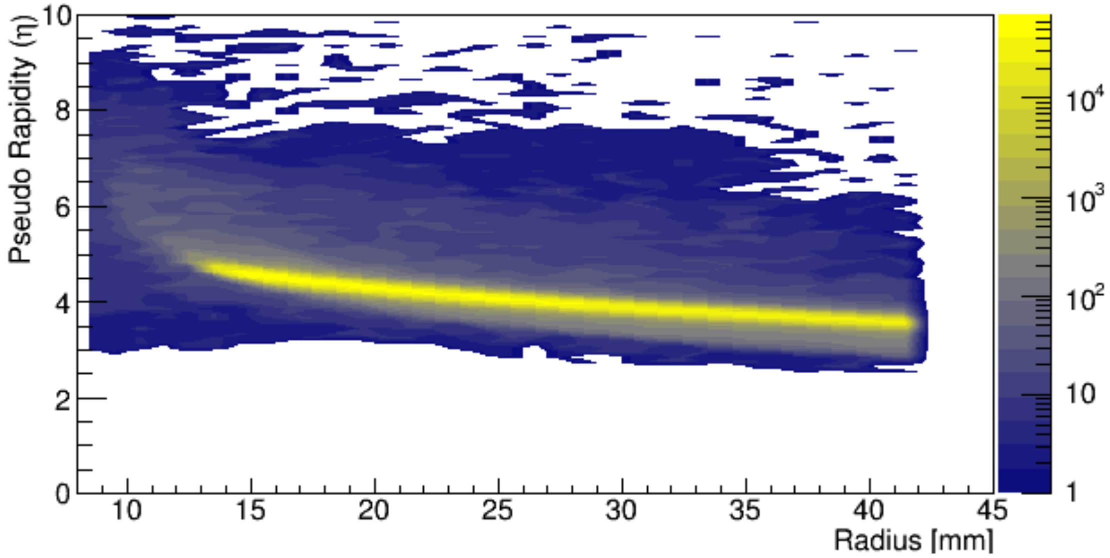


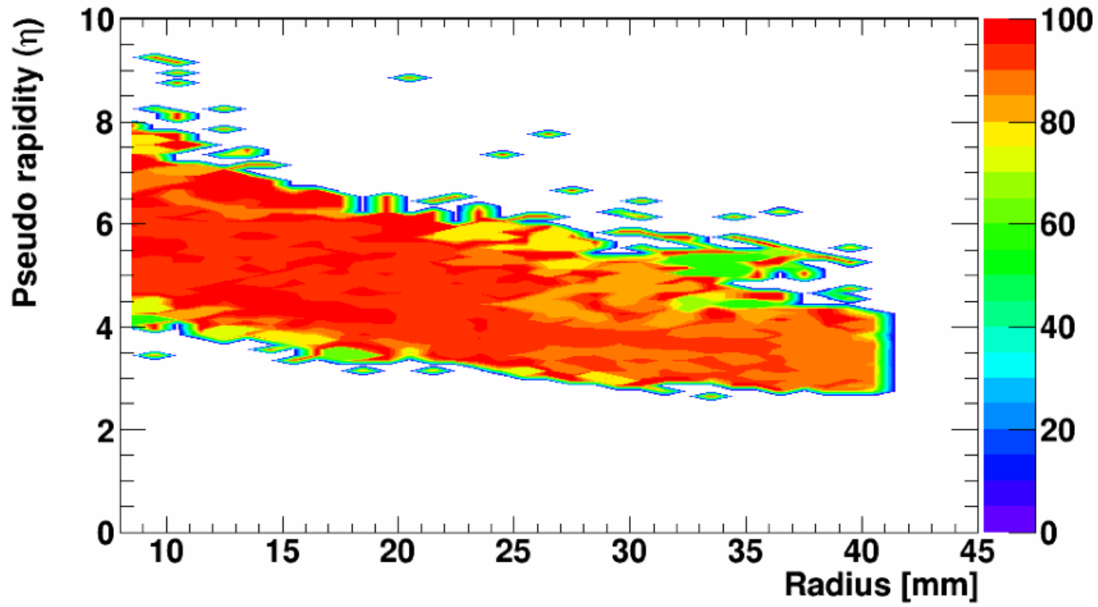


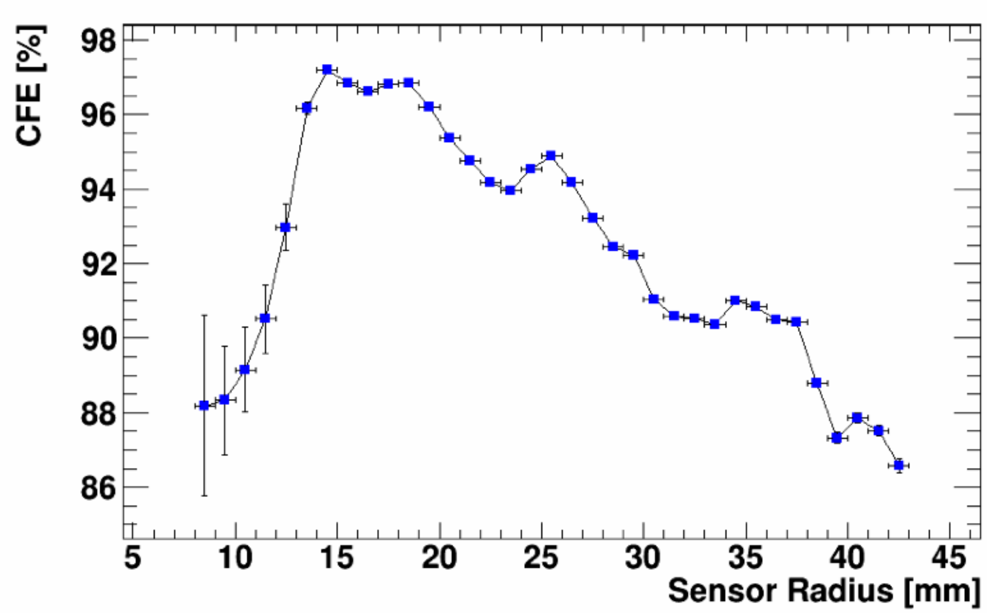


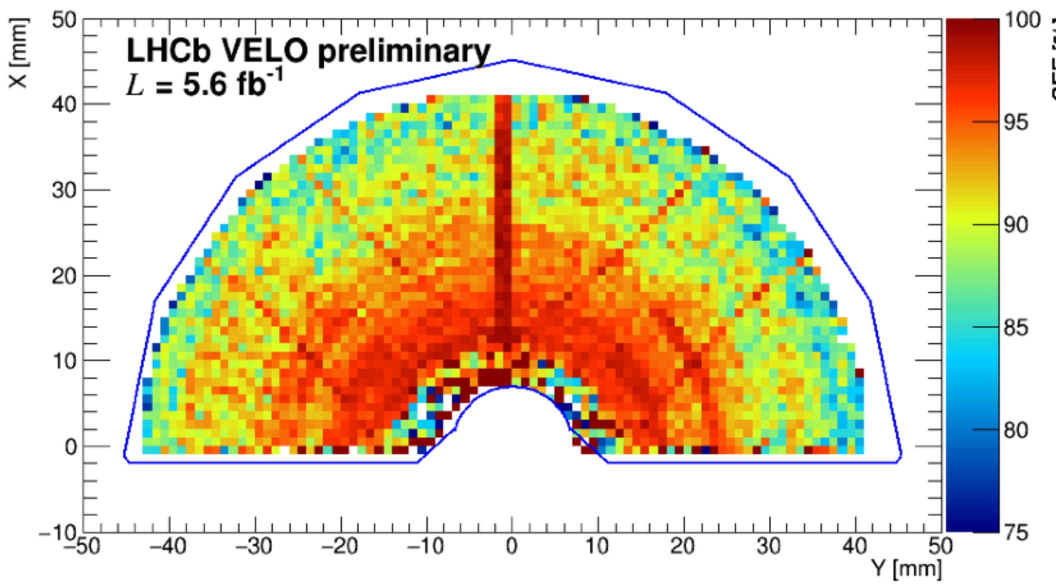


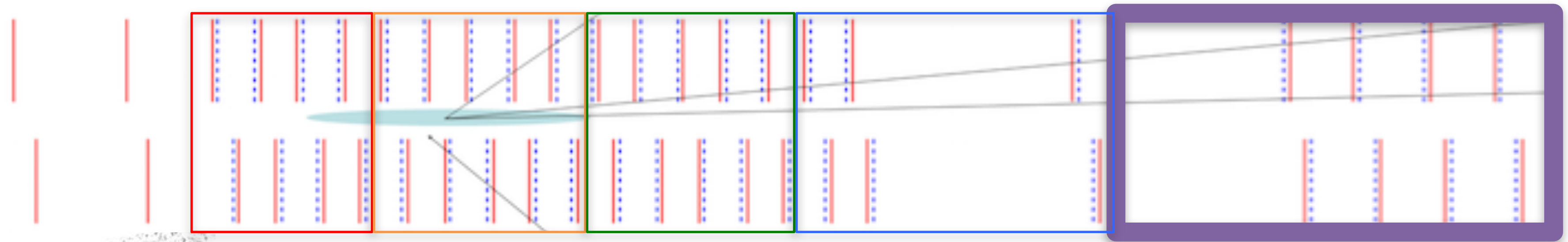
Downstream sensors – S40



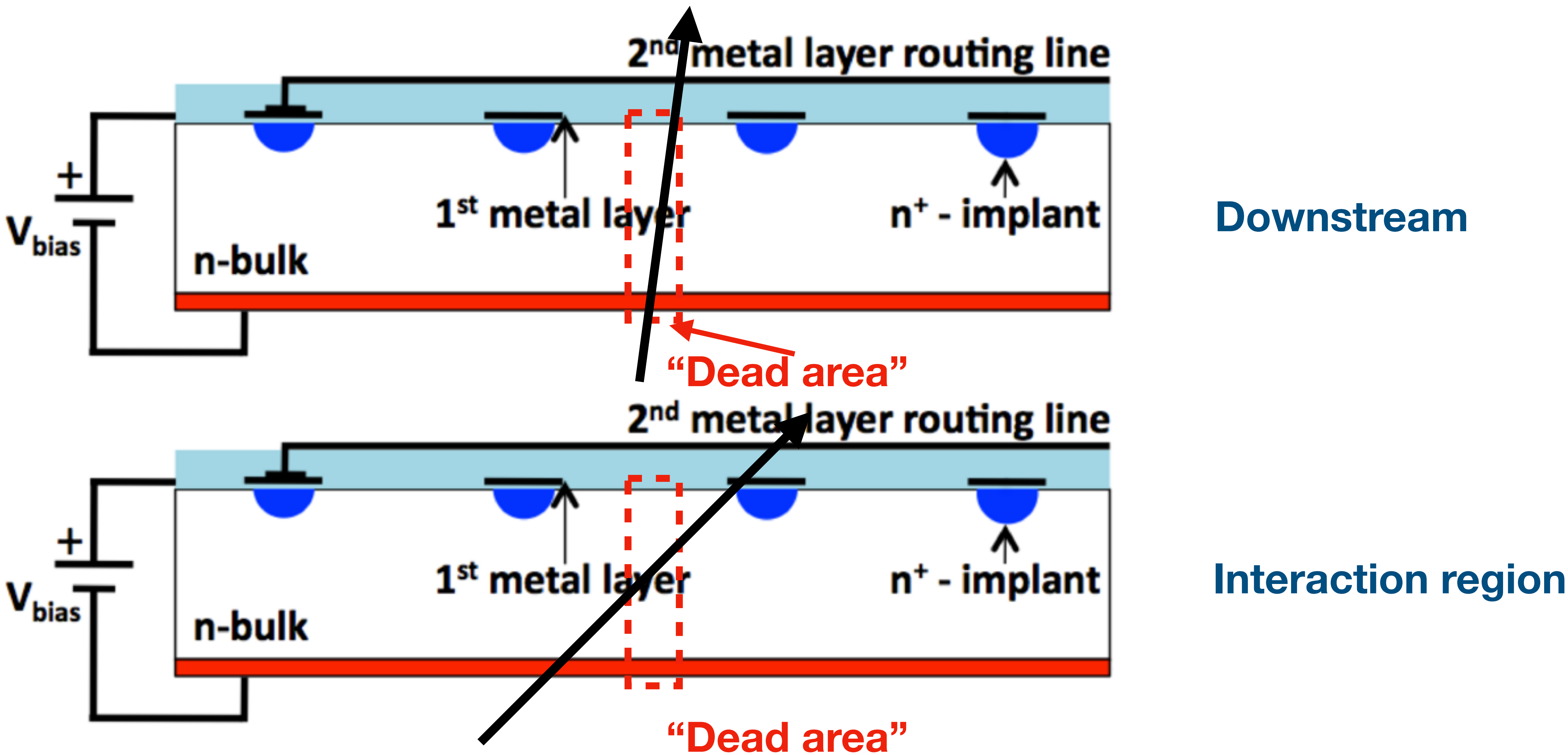






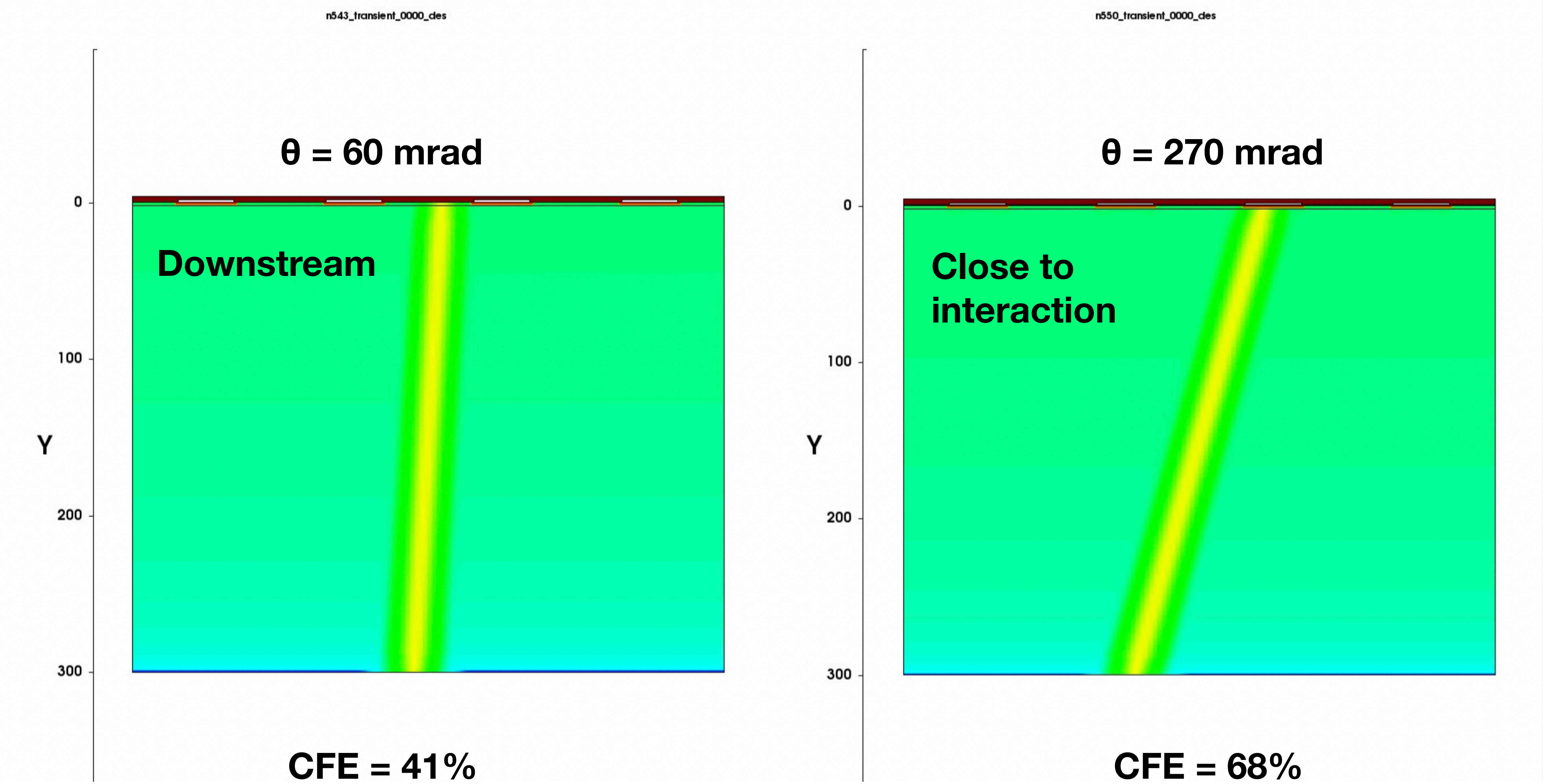


Geometry effects



- Dead areas should have a more detrimental effect in downstream sensors, as lower angles are probed there
- With high angles it is impossible to hit only inside a dead area

Geometry effects - TCAD simulations



End of Run-II calibration

- Very last physics fill in LHC run-II is for “burning off” VELO
- Most of the sensors survived at 700V(!)
  - VELO sensors are stronger than we expected…

Shift

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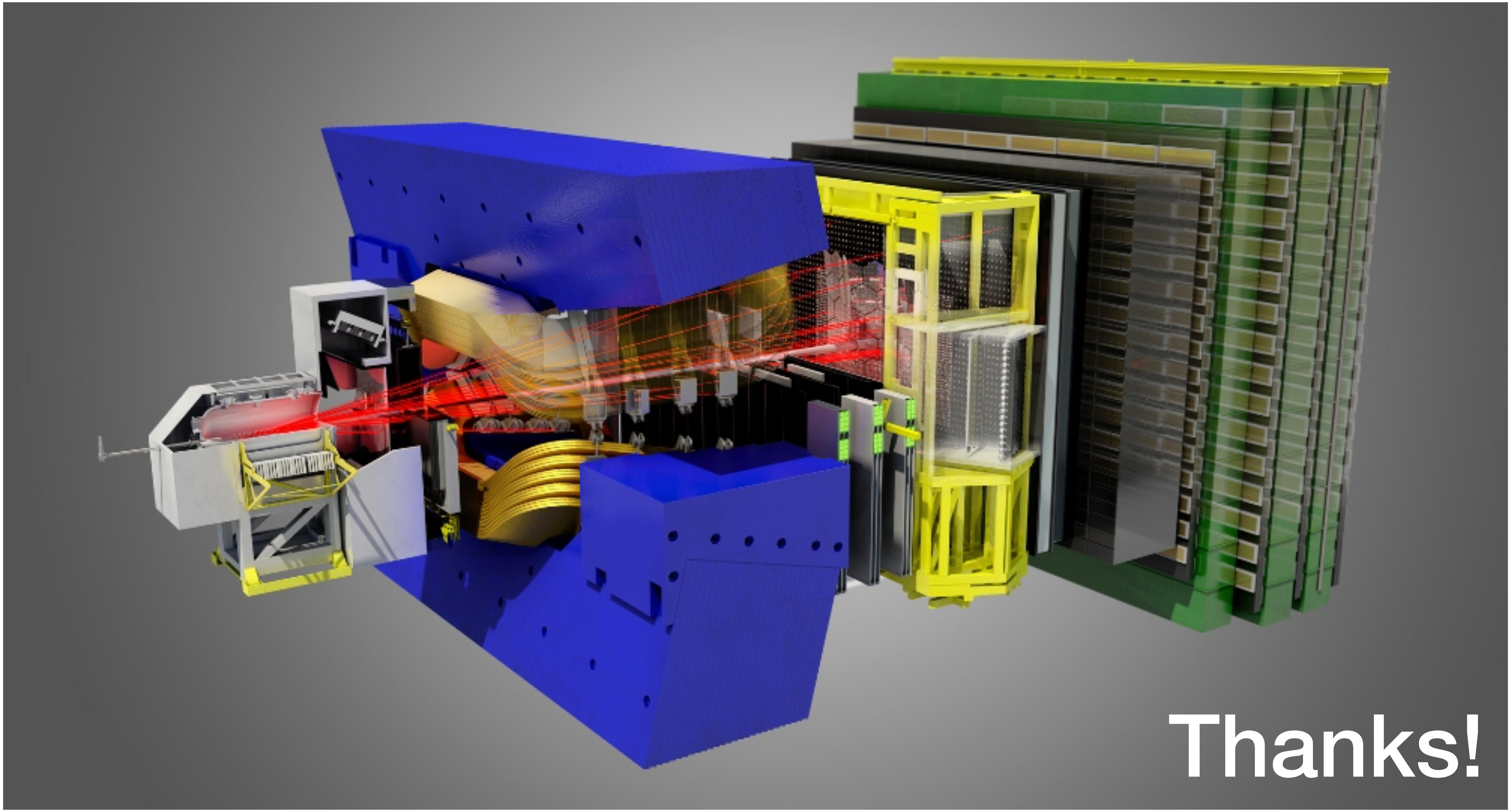
Message ID: **147386** Entry time: **02-Dec-2018 15:55**

Run:	
System:	LHCb
Author:	Niels Tuning

```
LHC re-filled to finish our VELO test...
Speed up of injection, leaving us with 313b(271b) in B1 (B2).
MEP factor at 5, NZS at 20%.

16:00 Step 0: run 219106 (2'), nominal 350V, L0 rate 123 kHz (physics 92 kHz).
              16:03 Raise to 500V. Ramping off? OPC server crashed?
              16:08 continue running (219108) unknown voltage ... seems off.
              16:09 VELO alignment failed? Chris Burr is here.
              16:10 ramping again to 500V...
16:14 Step 4: run 219109 (2') 500V.
              16:16 ramp to 600V.
              16:18 run 219111 (12') (most sensors at 600V, ~10% tripped). OPC server keep dying... (forceClear?)
16:31 Step 6: run 219113 (2') 600 V (A side good, C-side bad). After 1'30" OPC server crashed again...
              16:33 ramping to 700V!
              16:35 run 219114 (7') 700V (some sensors made it to 700V). OPC server keep dying!
              16:45 LV C-side off, restarted. 3x.
              16:49 Excluded VELOC_DCSLV EB01, and DAQ_M04
16:51 Step 7: run 219117 700V (A side made it to 700V). Typical currents 300 uA

              16:58 run 219118, increase T from -30 to -26 C.
              17:01 run 219119, changed run to separate increasing temperature.
              17:05 run 219120 Ramping down to 350V

17:07 Step 0: run 219121 350V reference step.
```

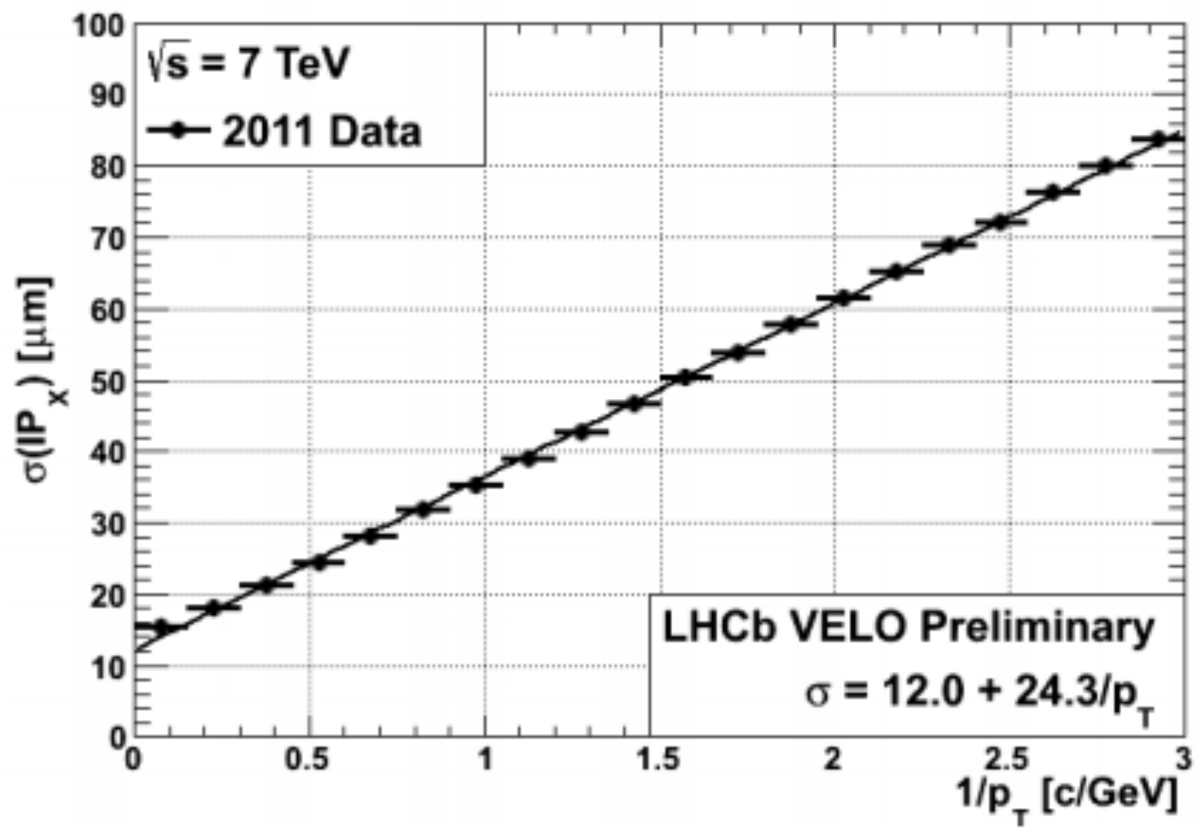
Conclusions

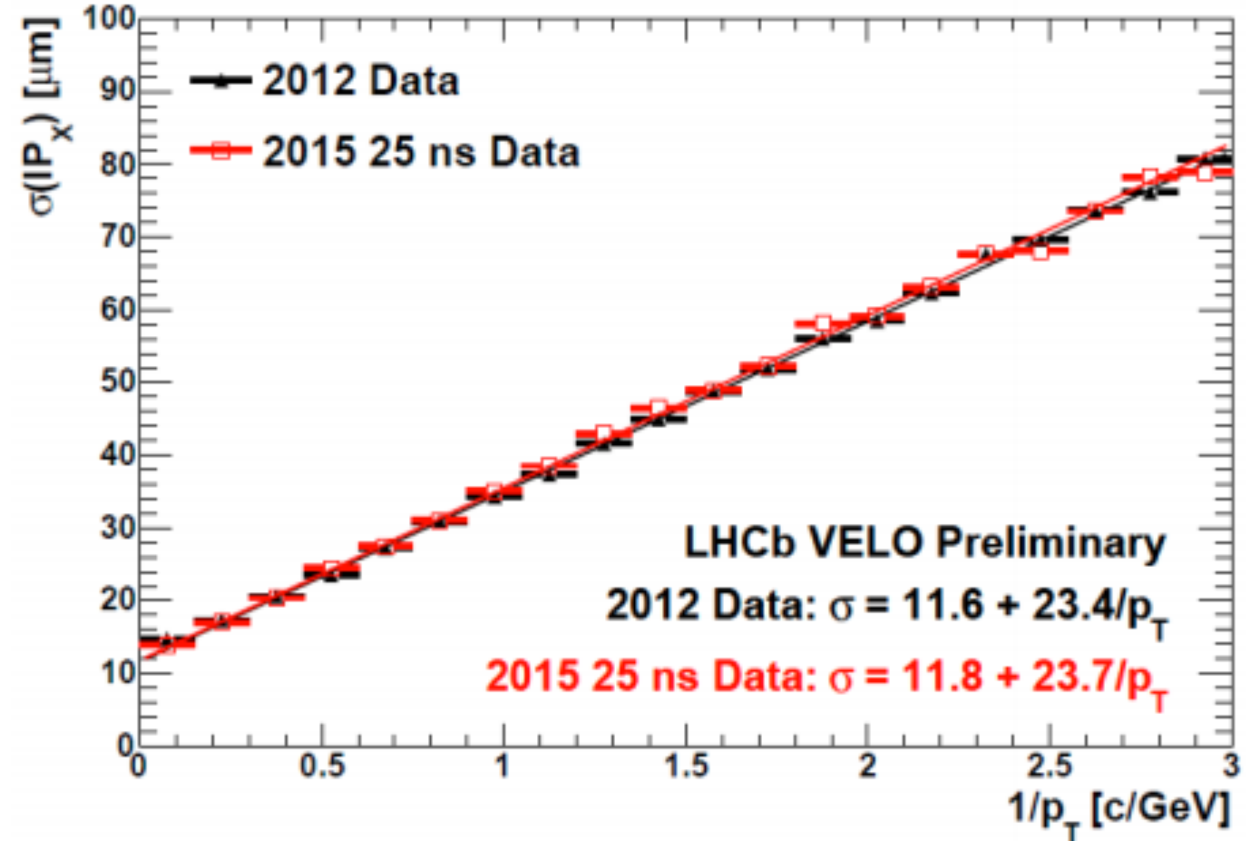
- The detectors performed well during Run-II data taking
- VELO operation voltages are under the design range up to 9 fb^{-1}
  - Much safer for ST, as they have much less fluence and just reached the type inversion
- Upgrade of silicon detectors in progress


Thanks!

Back up

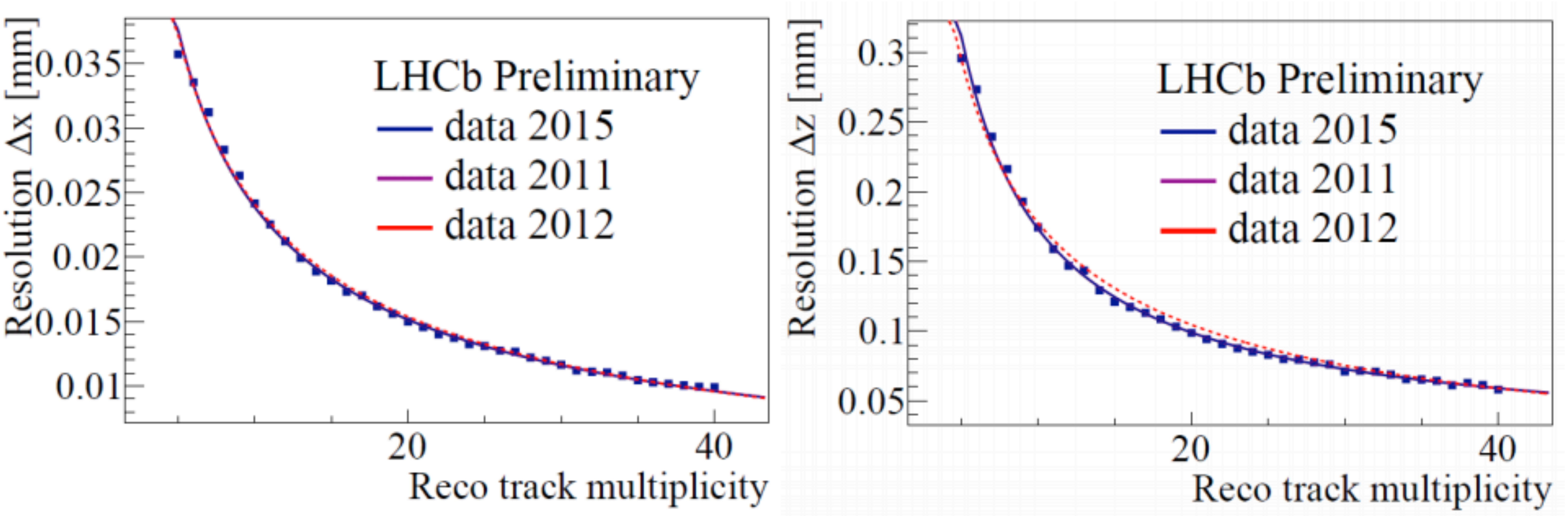
VELO impact parameter resolution



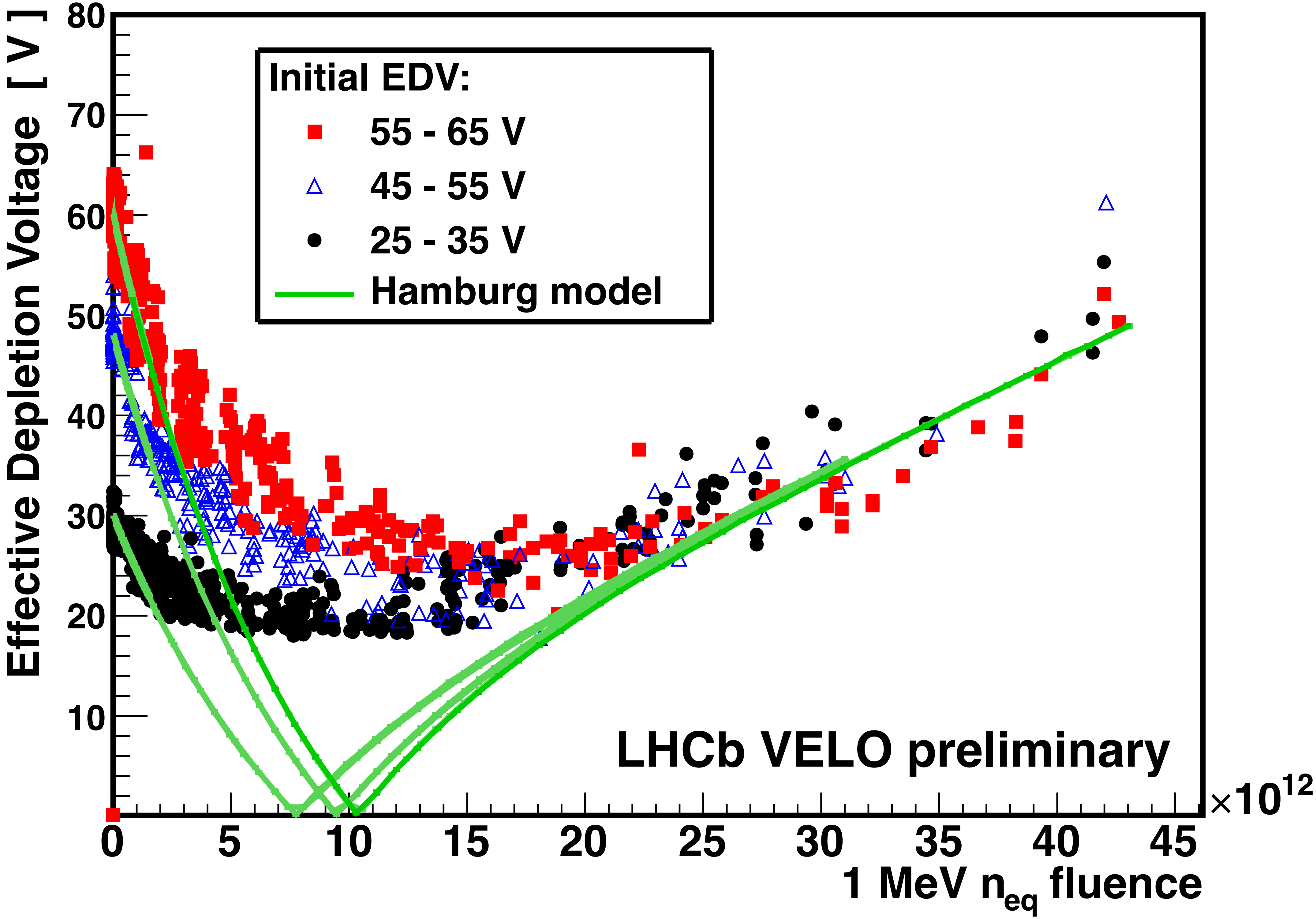


Degradation due to radiation damage still negligible

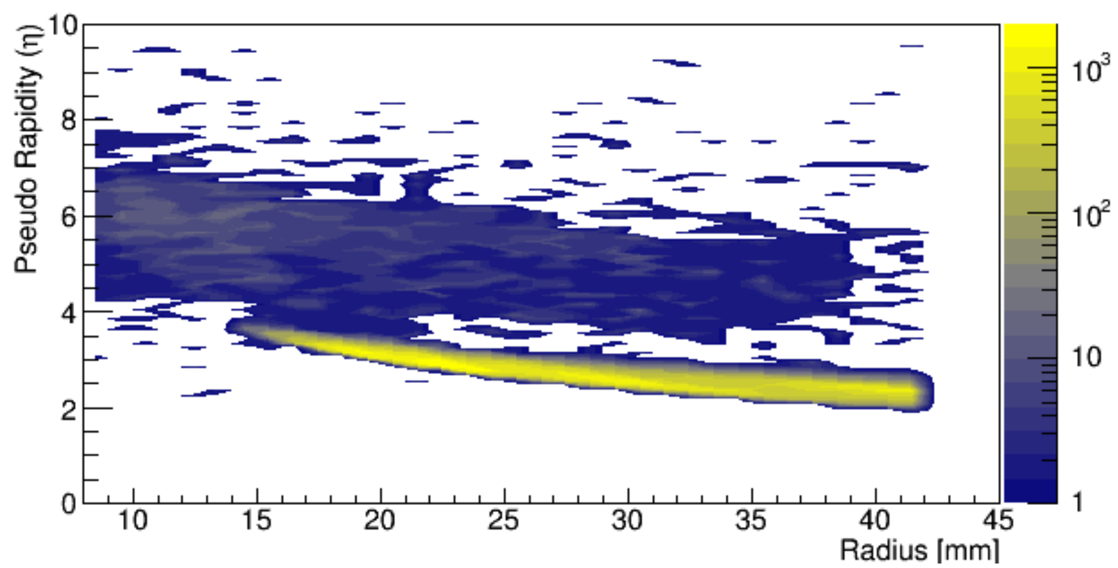
VELO primary vertex resolution

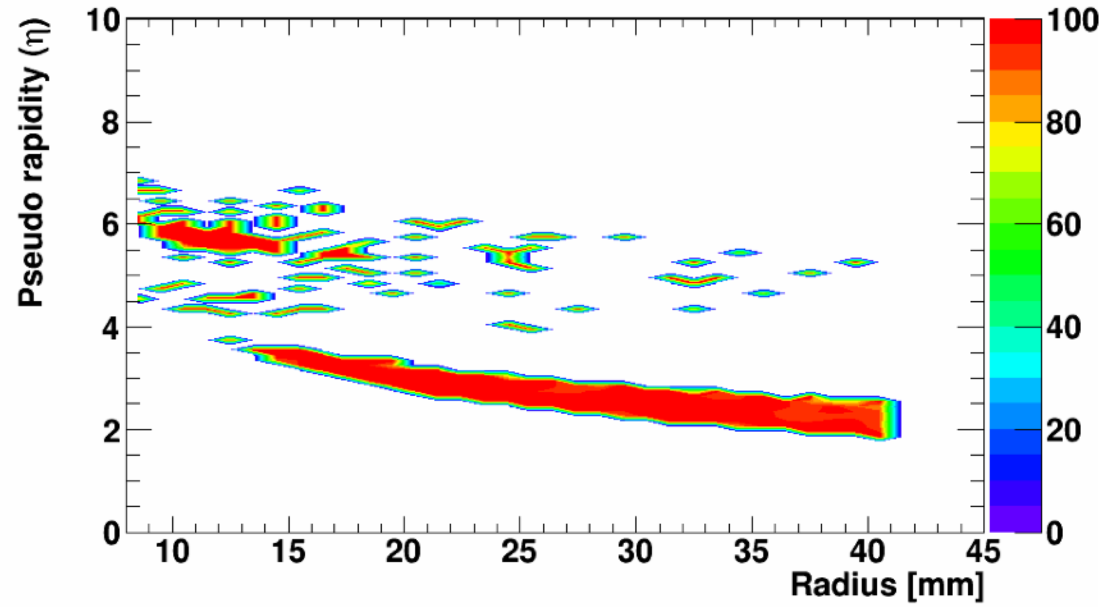


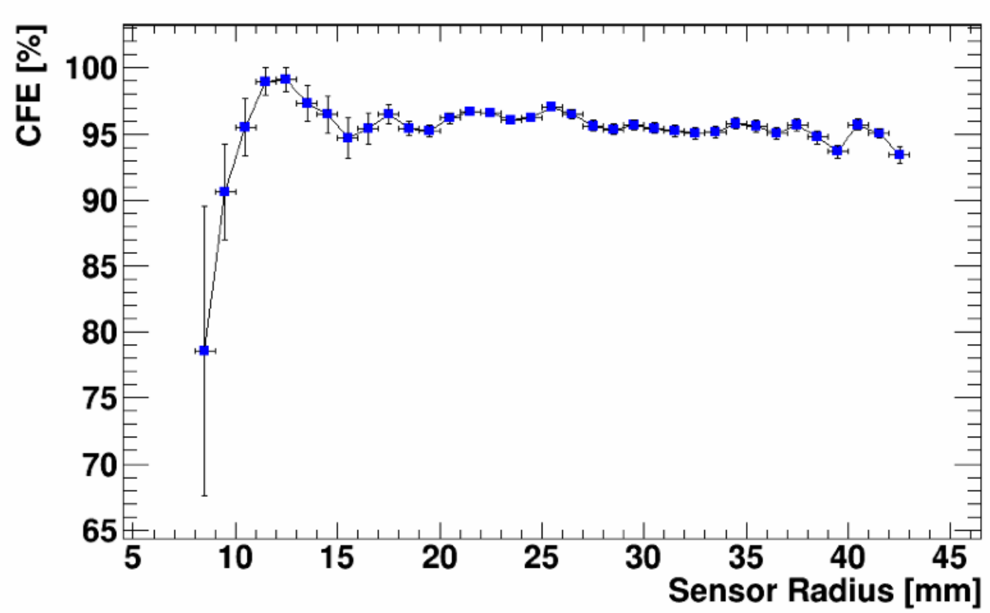
Although some degradation was observed through Run I,
High level physics quantities remain with good resolution


Initial EDV:
55 - 65 V
45 - 55 V
25 - 35 V
Hamburg model
LHCb VELO preliminary
Effective Depletion Voltage [V]
1 MeV n_eq fluence
×10^12
0
5
10
15
20
25
30
35
40
45
10
20
30
40
50
60
70
80

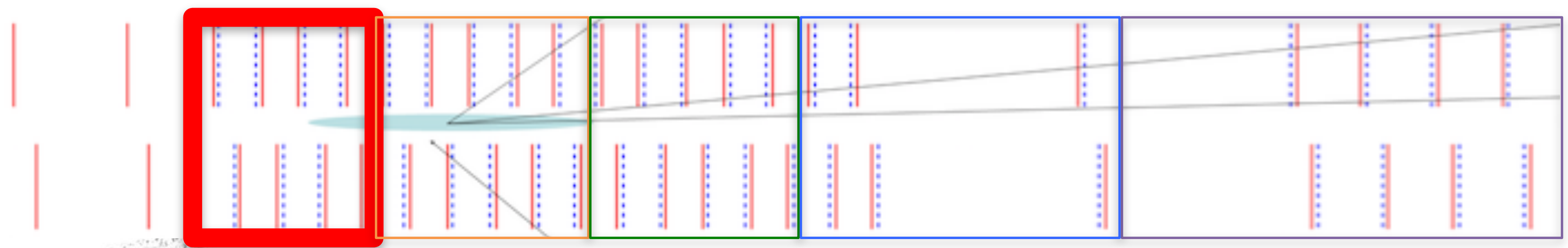
Backward sensors – S1



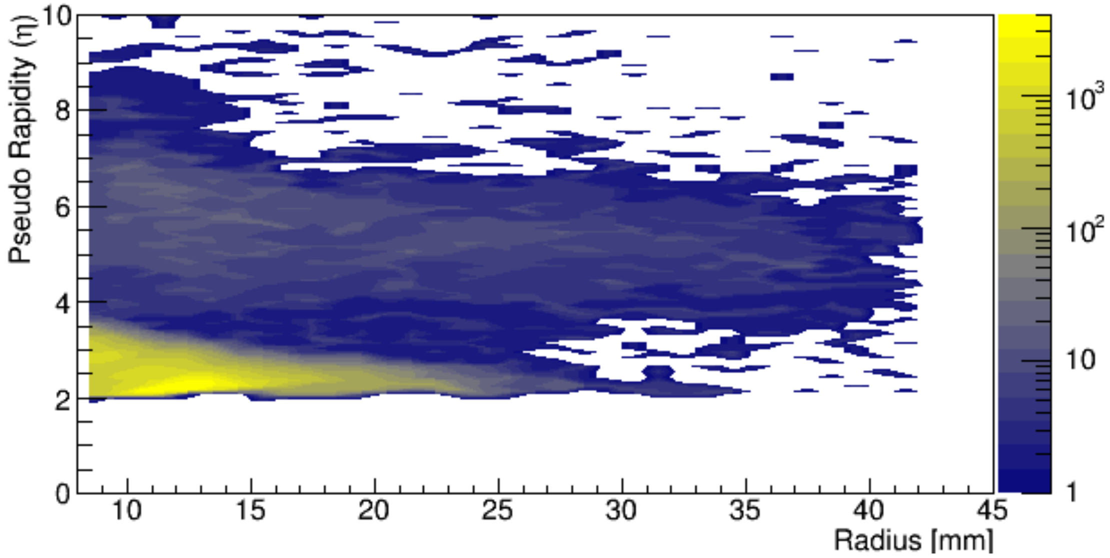


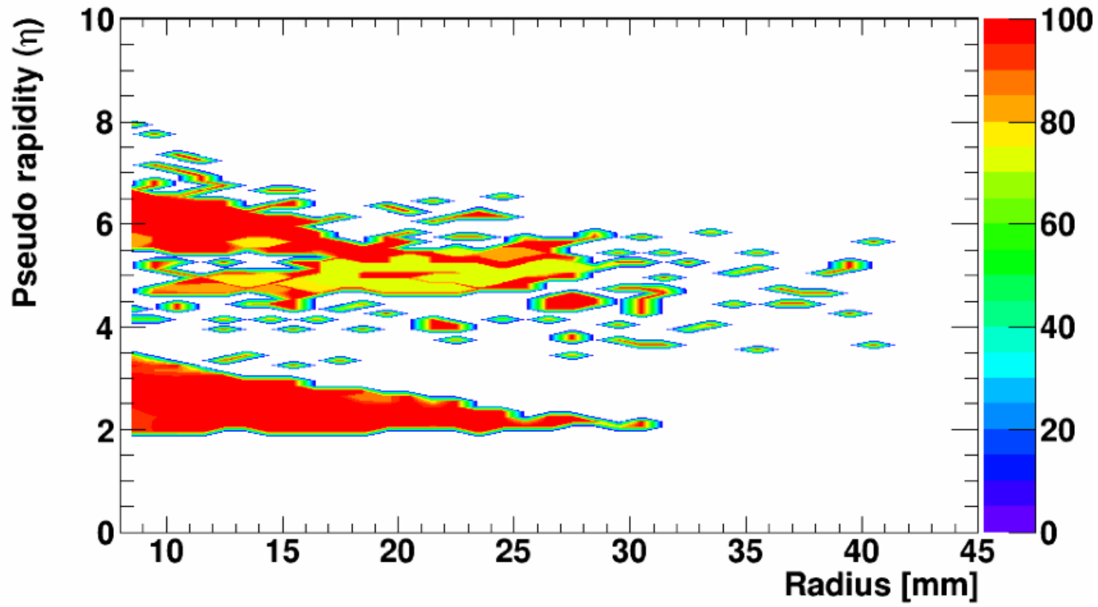


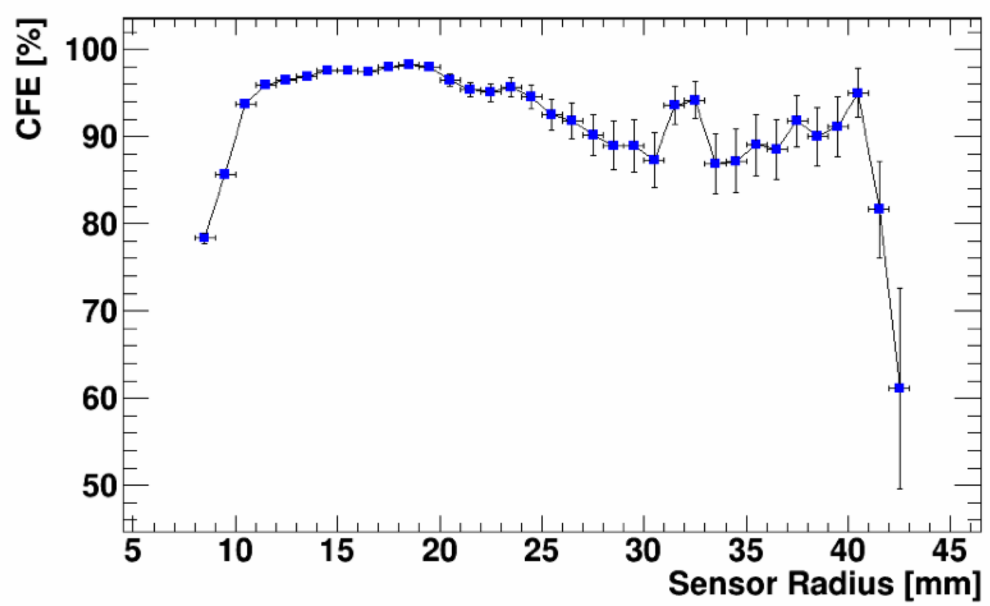
- No three other sensors ‘in front of’ the very inner part of the tested sensor
- Primary tracks reach very inner part of sensor cannot be reconstructed
- Low efficiency in the very inner part due to lack of primary tracks and present of beam halo (?) tracks



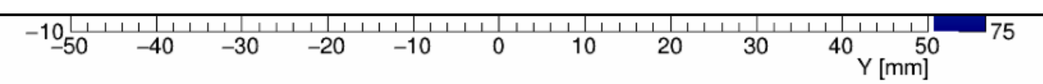
Interaction region – S10

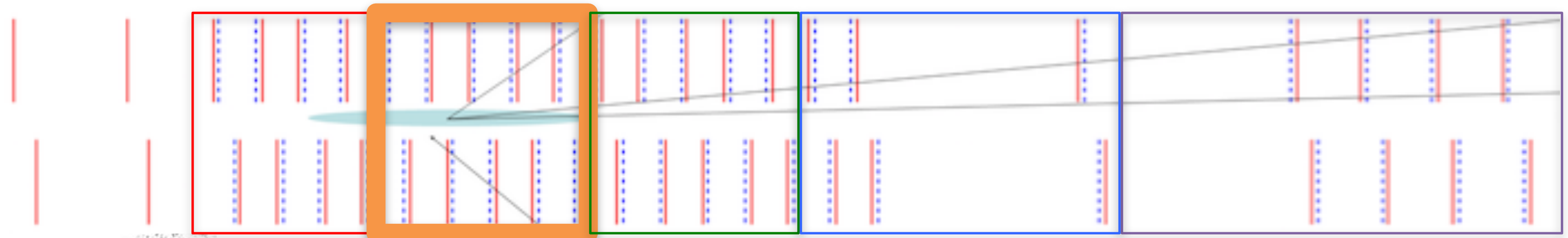




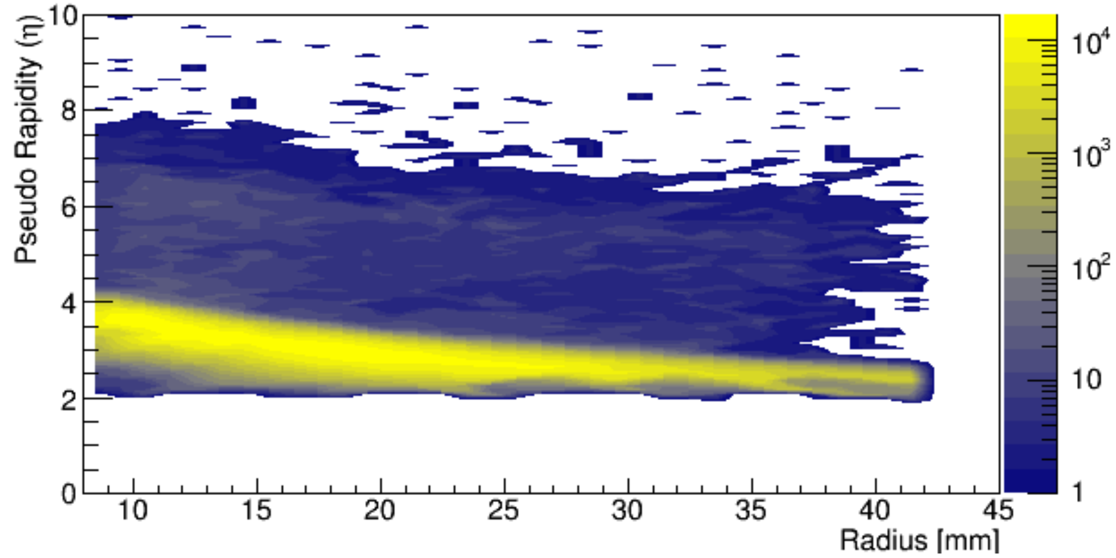


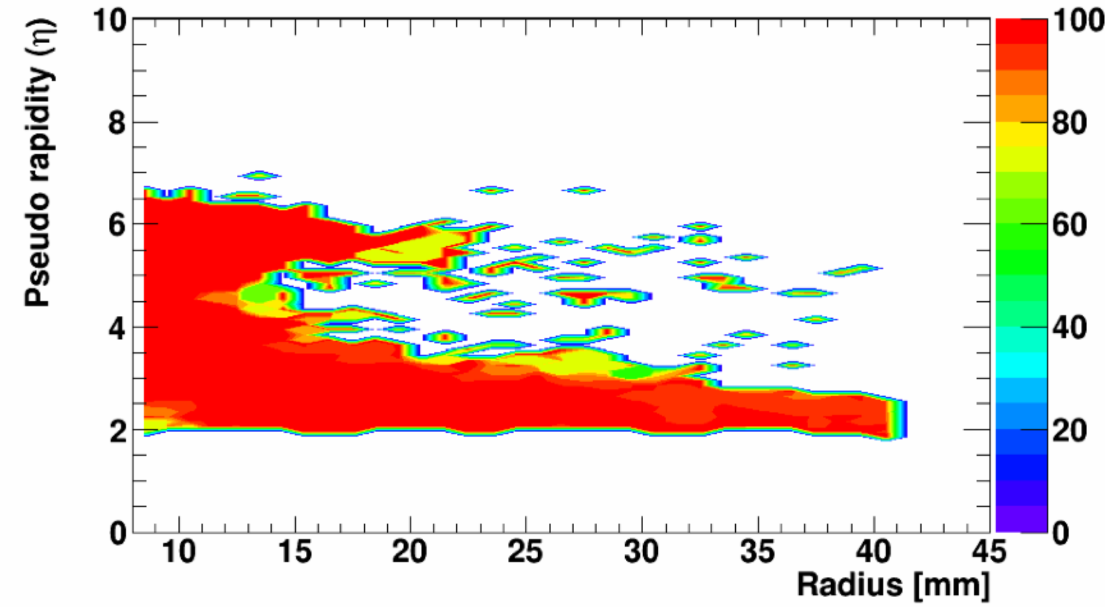
- Primary tracks reach very outer part of sensor cannot be reconstructed
- Low efficiency in the outer region mainly due to lack of primary tracks and present of beam halo (?) tracks
- Low efficiency in the very inner part due to classic radiation damage

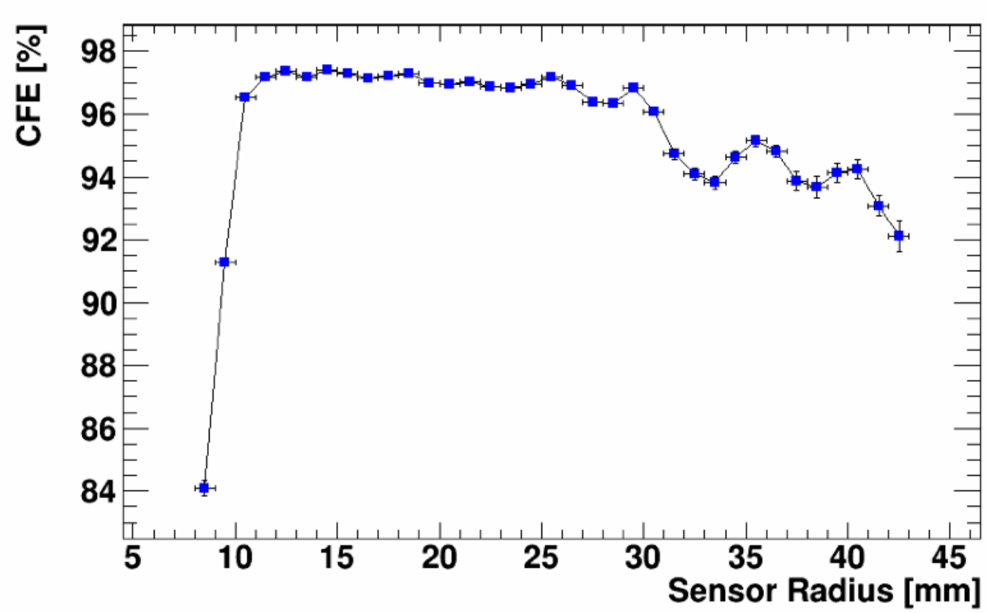




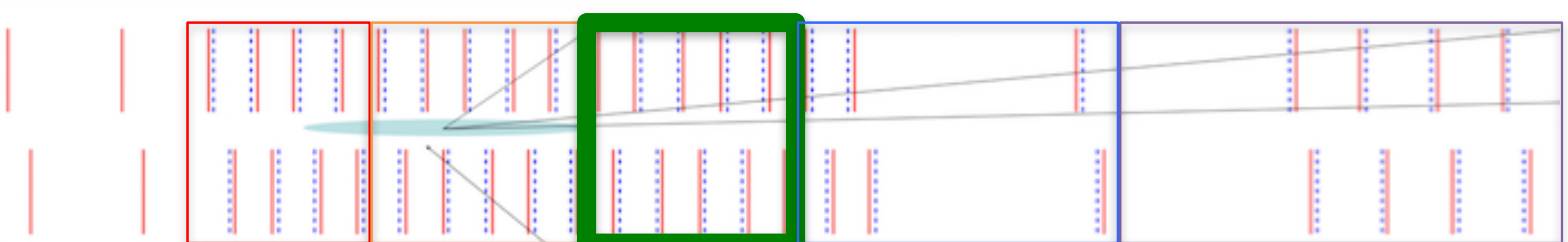
Forward sensors – S23



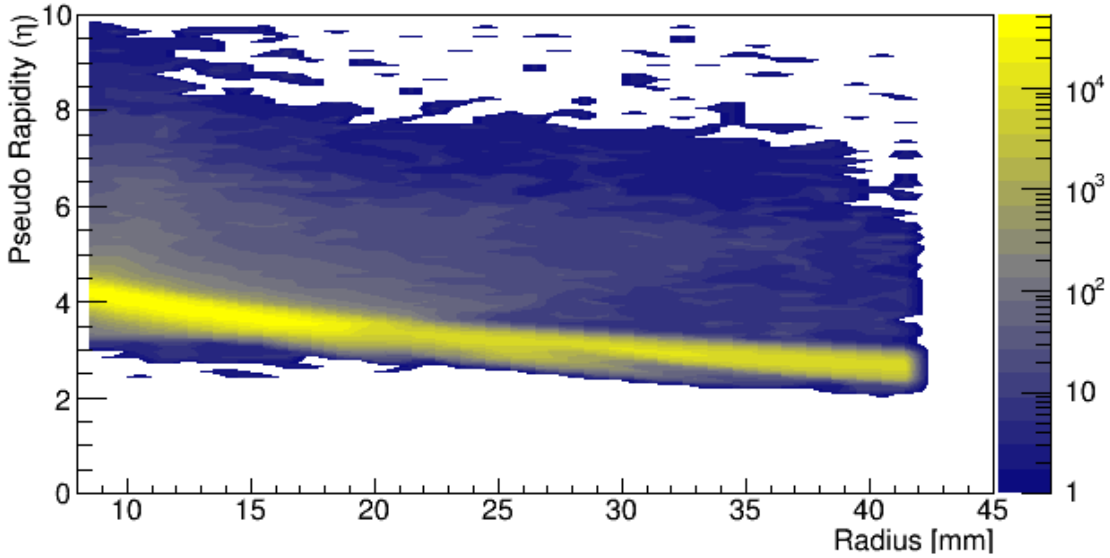


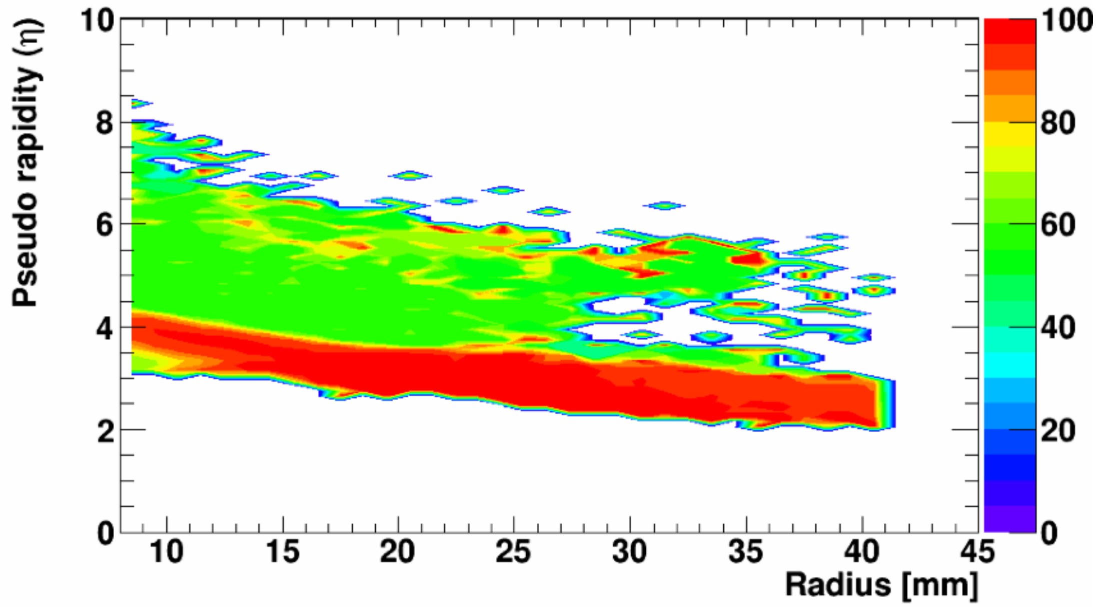


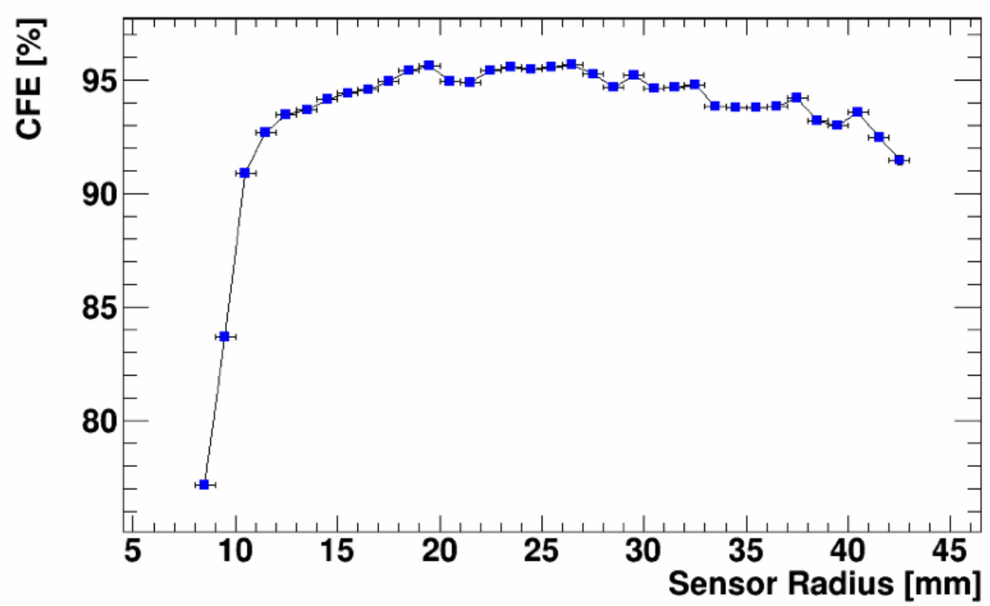
- Primary tracks can be reconstructed at all radius
- Low efficiency in the outer region contribute from second metal layer effect
- Low efficiency in the very inner part contribute from classic radiation damage



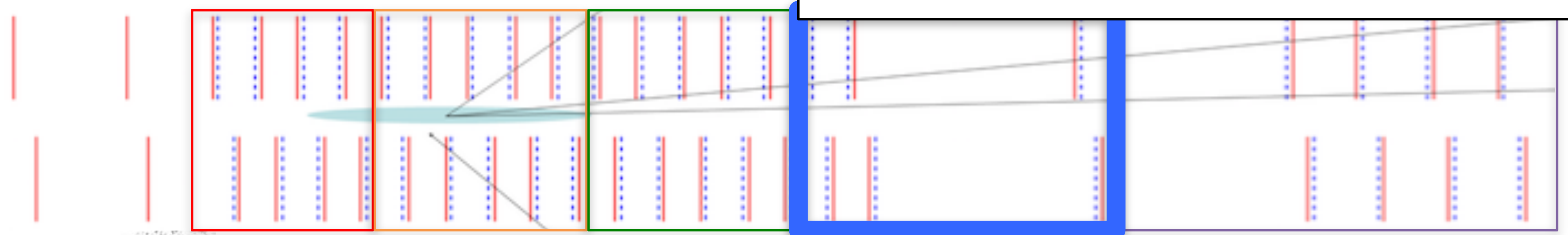
Very forward sensors – S31



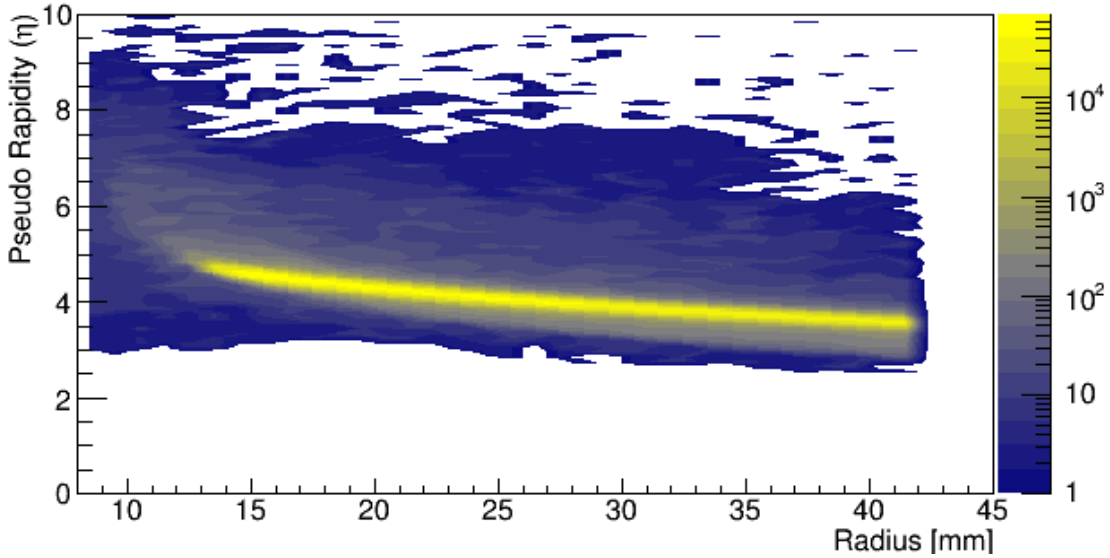


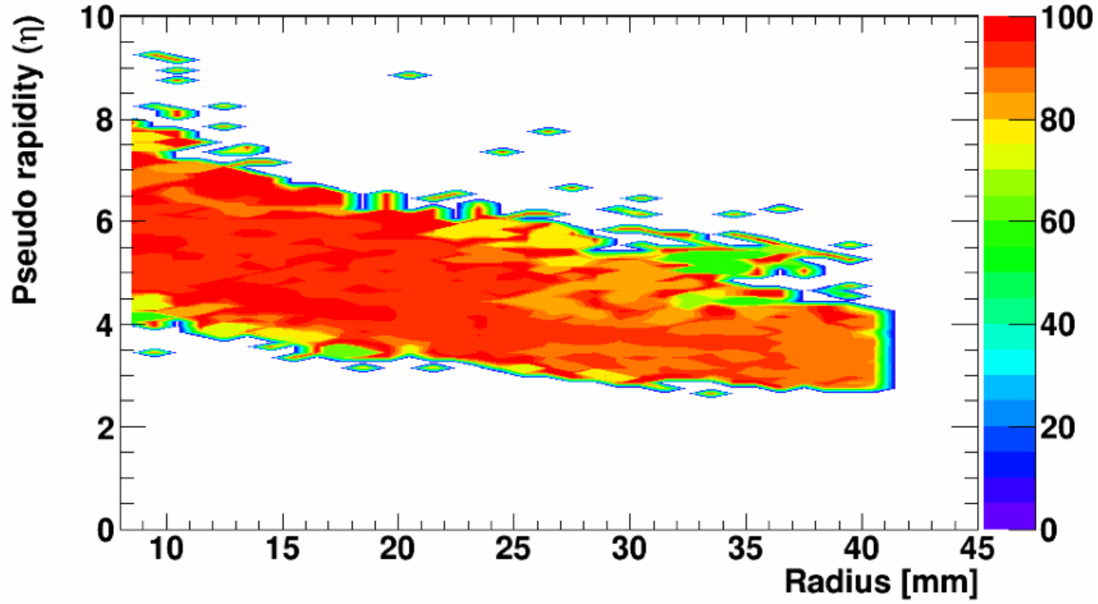


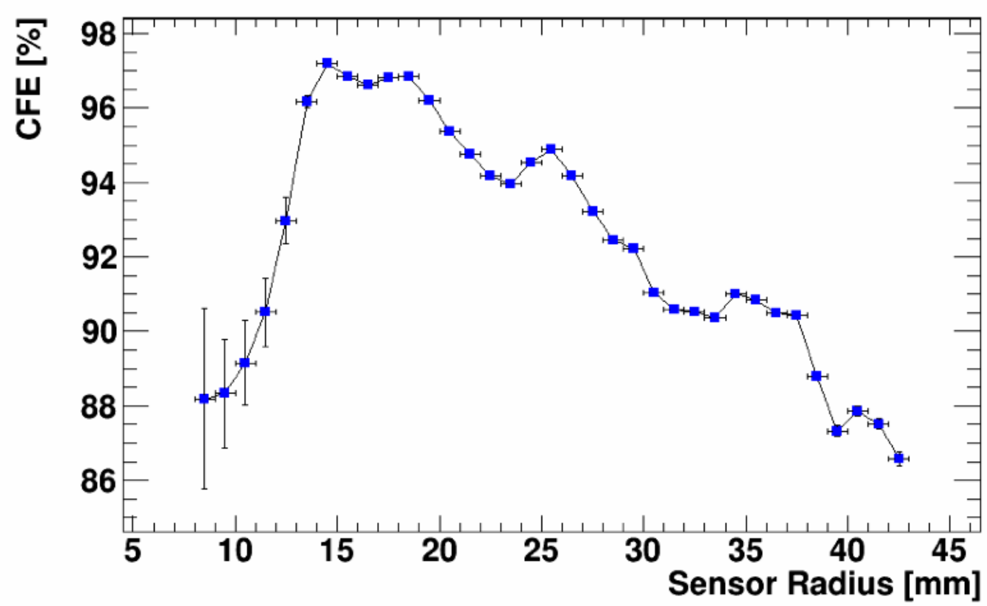
- Primary tracks can be reconstructed at all radius
- Low efficiency in the outer region due to second metal layer effect
- Low efficiency in the very inner part due to classic radiation damage
- Beam halo tracks have very low efficiency may due to the geometry of detector



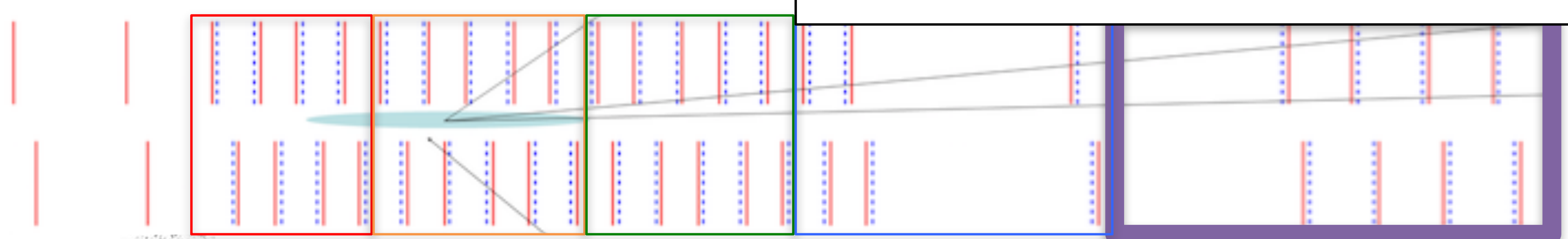
Downstream sensors – S40



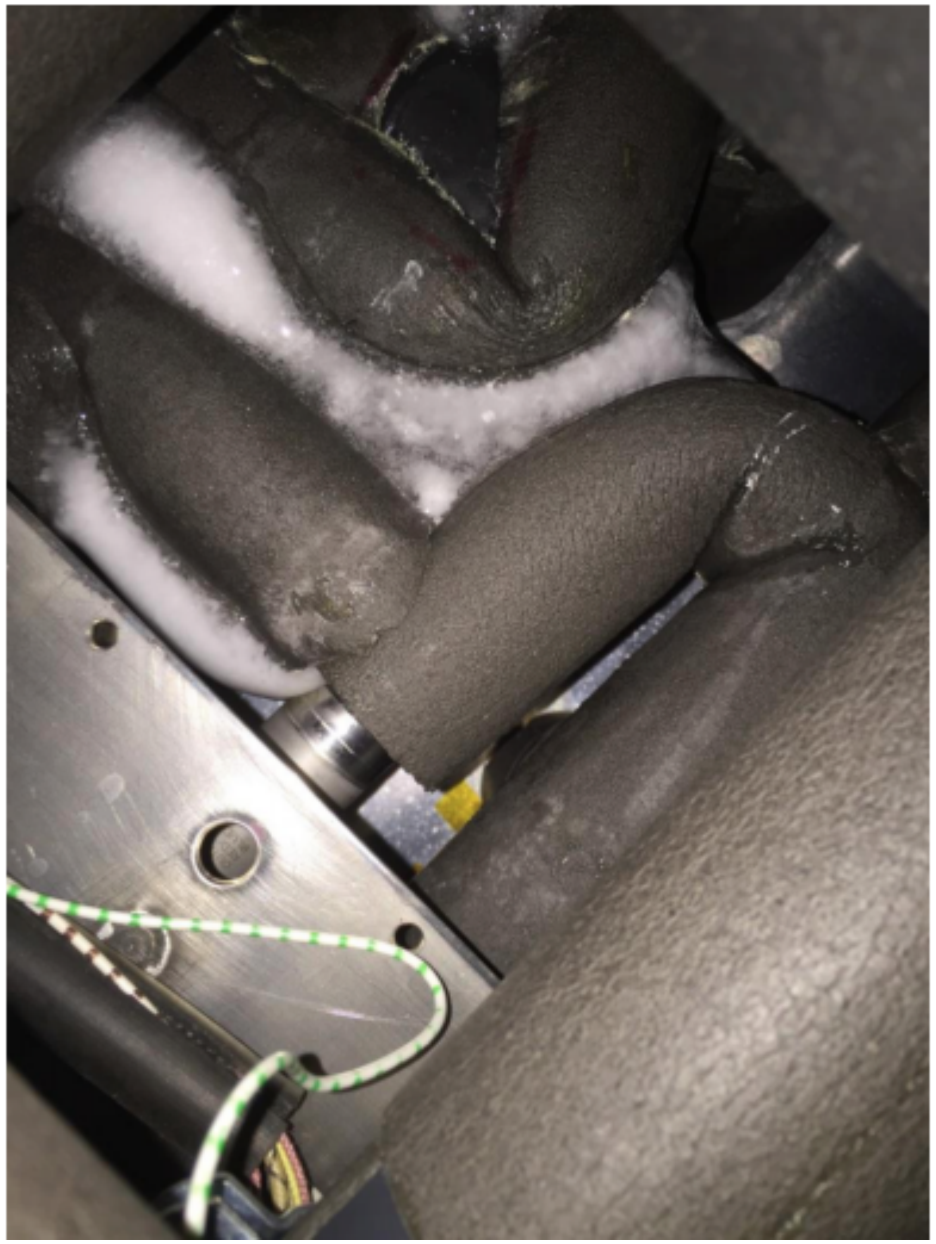




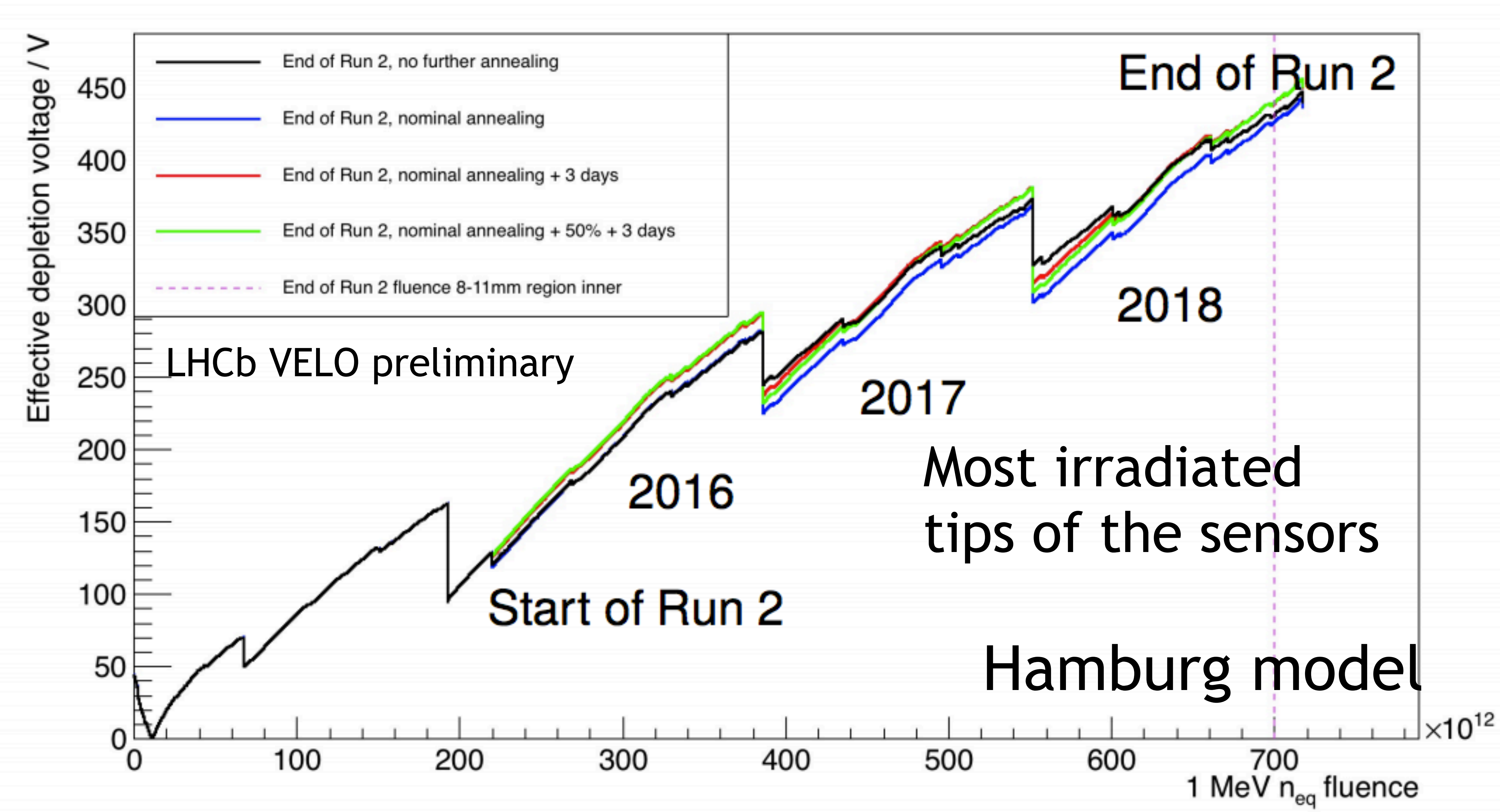
- Primary tracks reach very inner part of sensor cannot be reconstructed
- Low efficiency in the outer region contribute from second metal layer effect
- Low efficiency in the very inner part due to lack of primary tracks and present of beam halo /interaction tracks



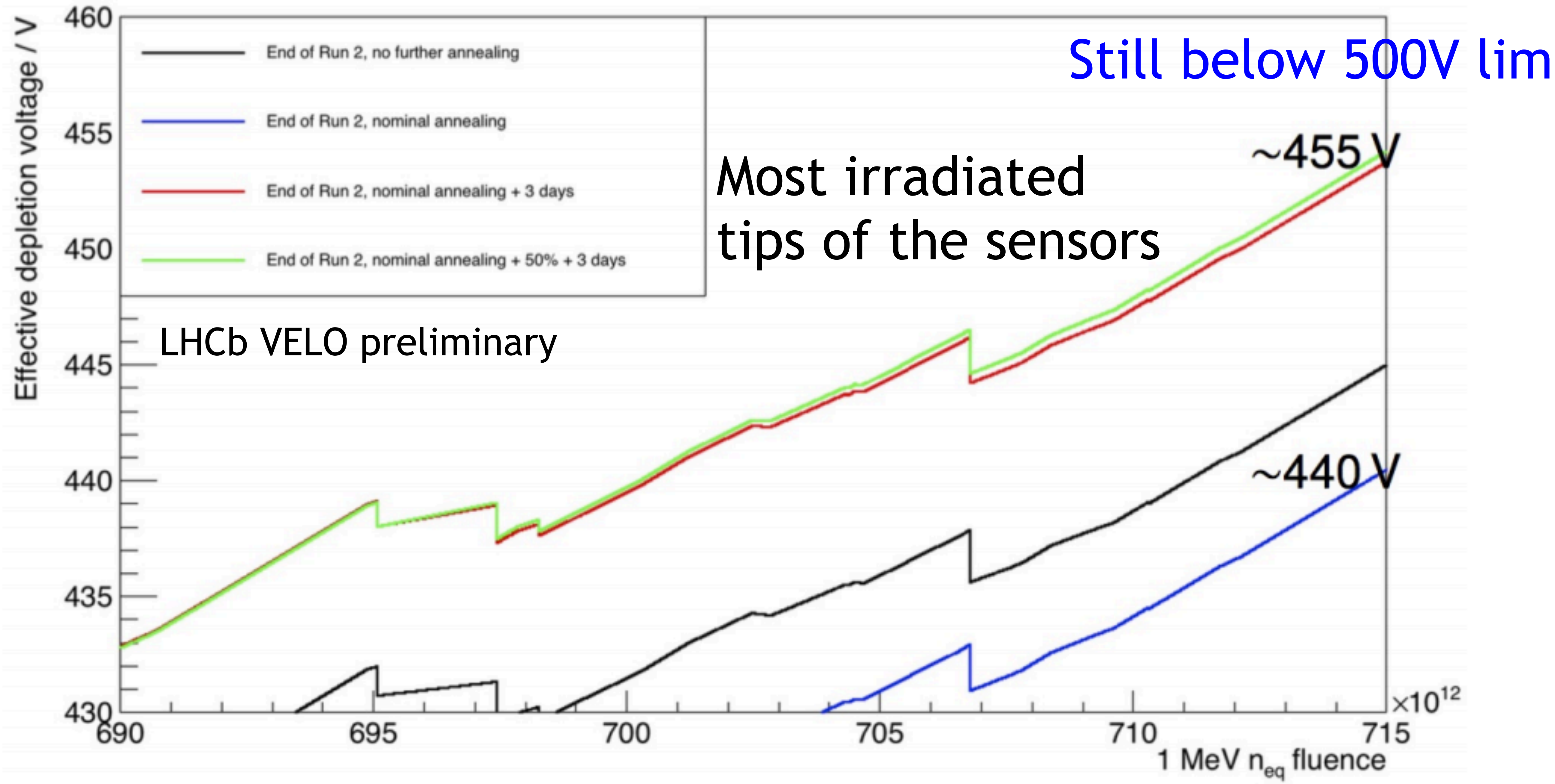
- Winter 2015: large build ups of ice found in cooling plant
- Melting of ice eventually triggered alarm due to excess water in reservoirs
- Remove ice & install new insulation
  - Warming up VELO for around 3 days
  - This would provide beneficial annealing, where the effective depletion voltage decreases
  - But, we then 'lose' beneficial annealing time available for the future
  - Pump in dry air to prevent it happen again in the future



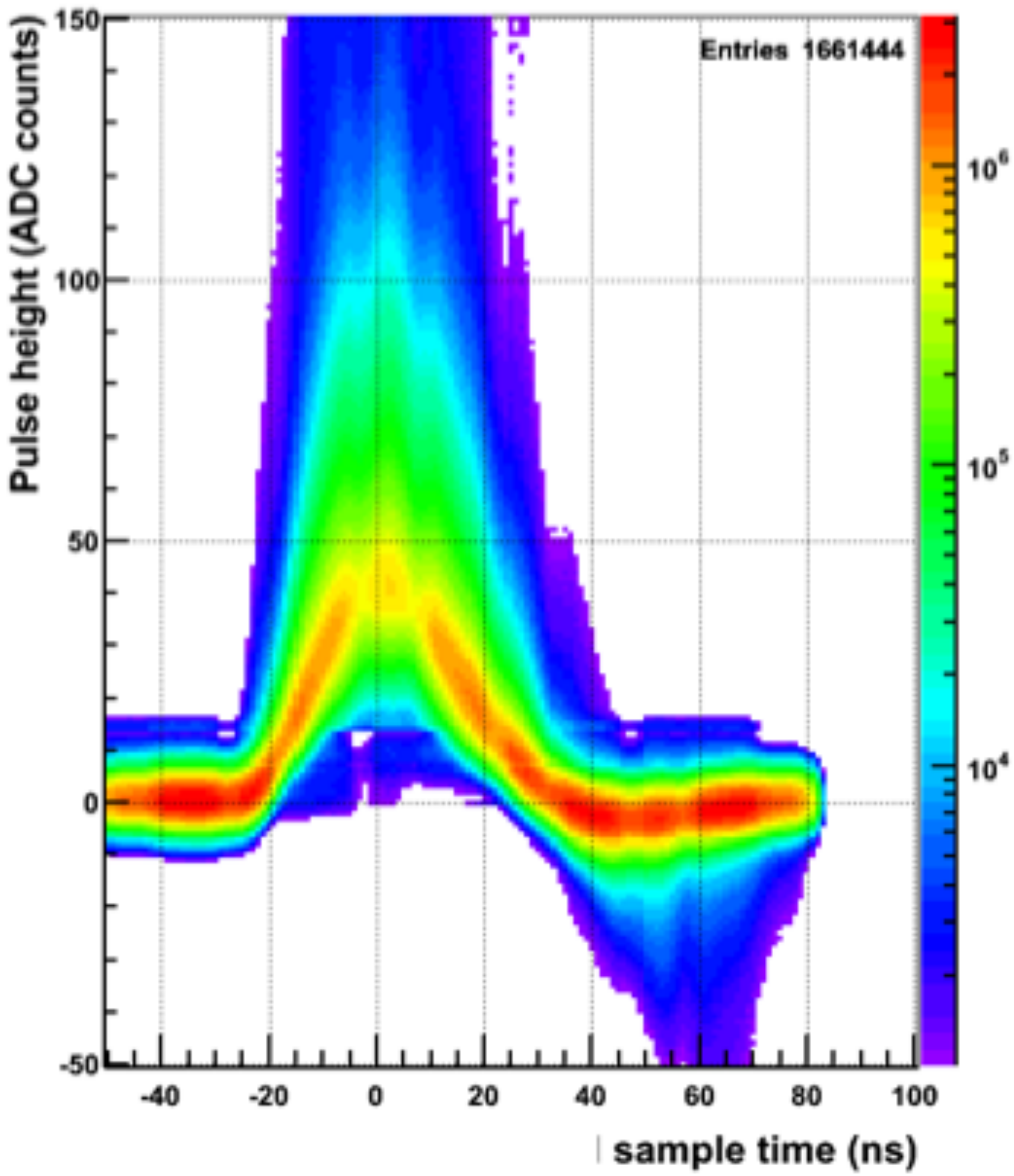
Studies on how the warming up affects future operational voltage

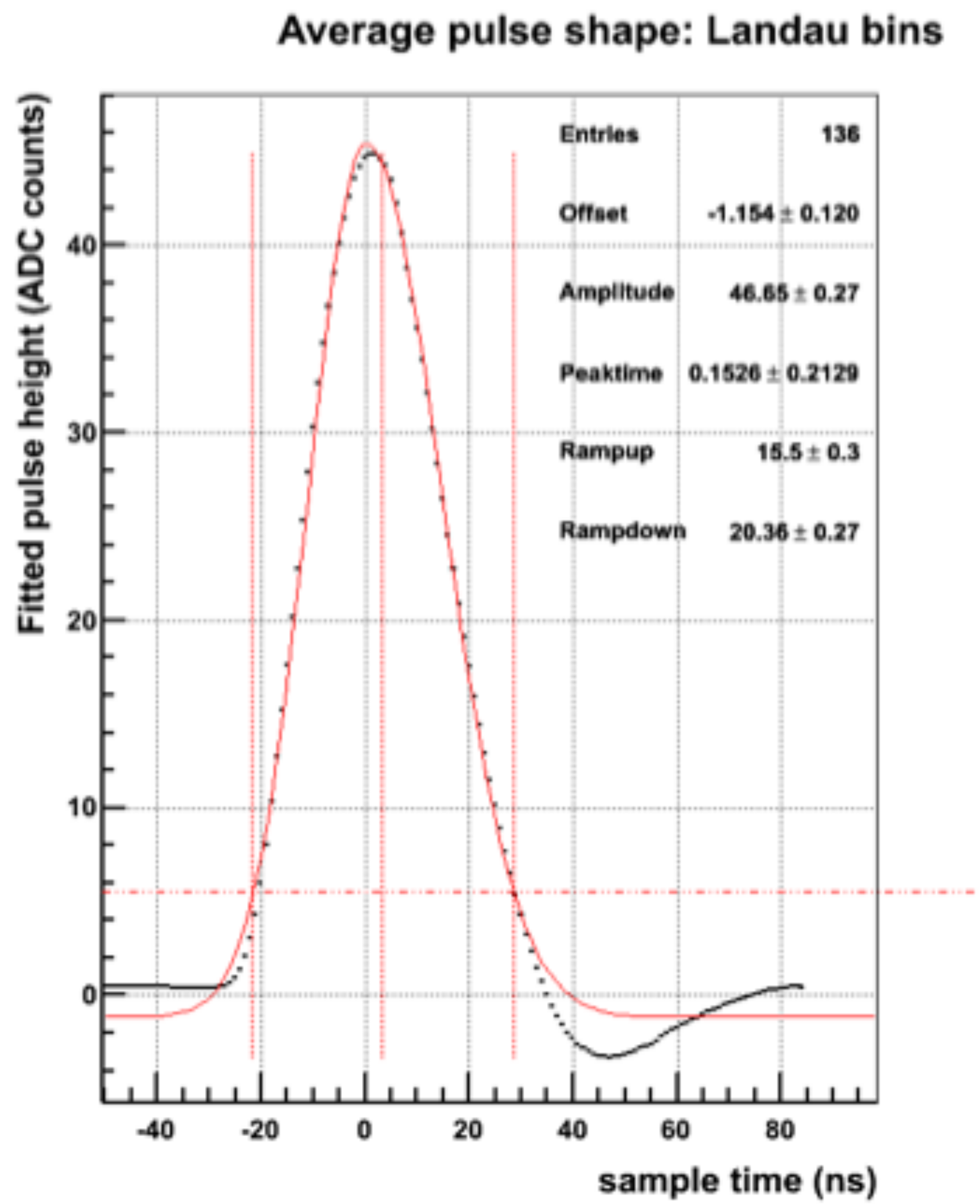


Studies on how the warming up affects future operational voltage

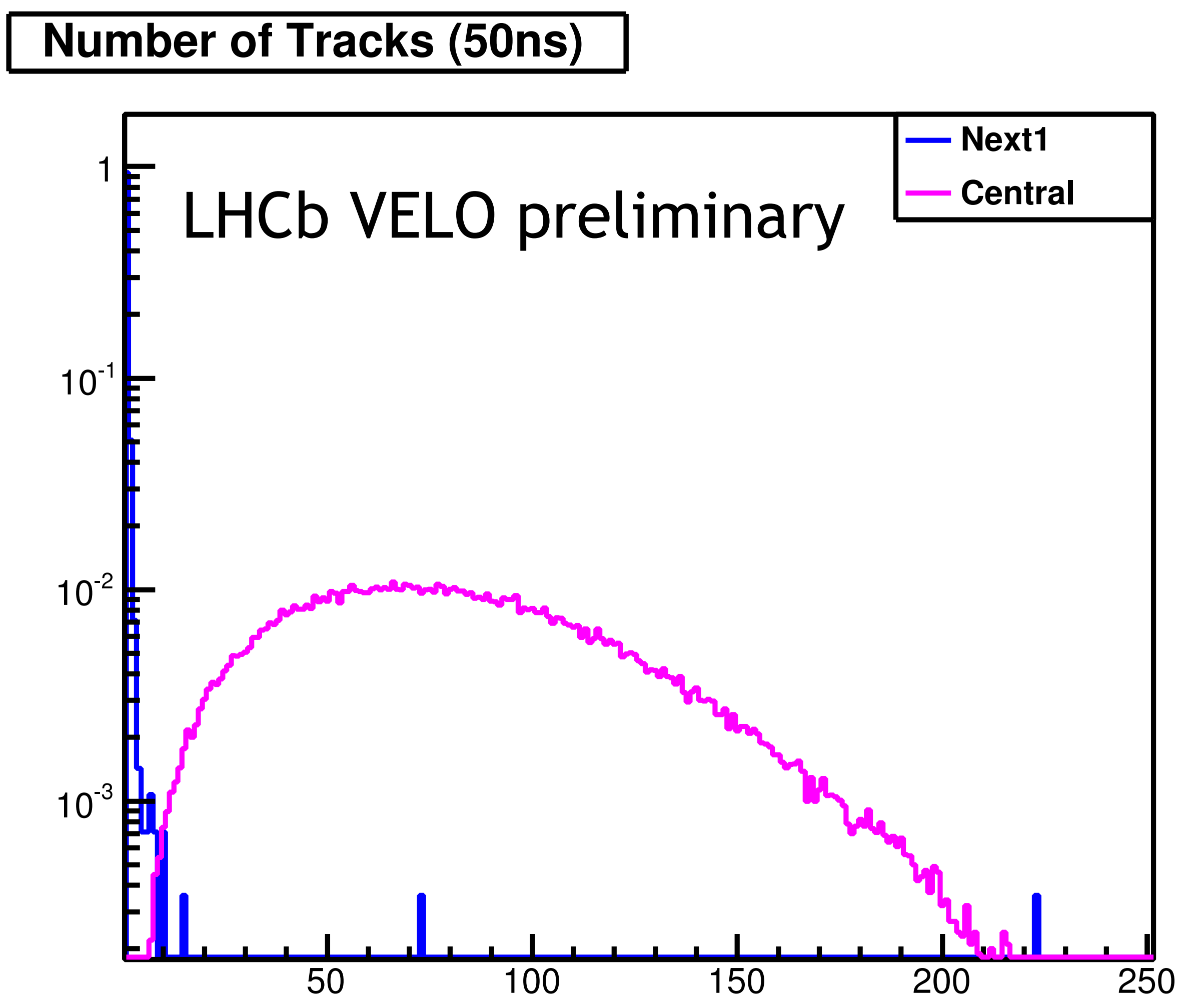


- Pulse shapes measured with beam. Each sensor is optimised for equal spill-over between bunch crossings



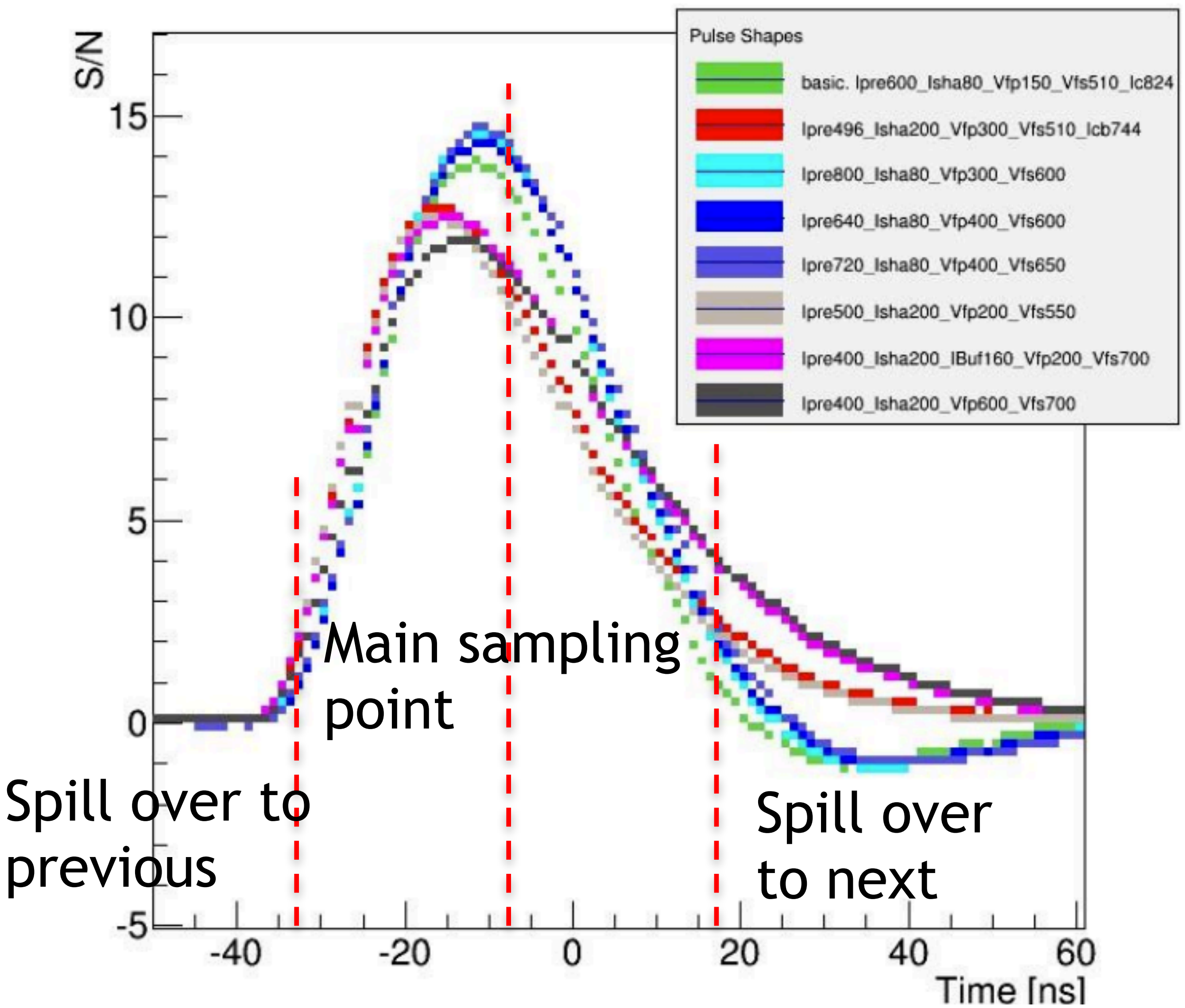


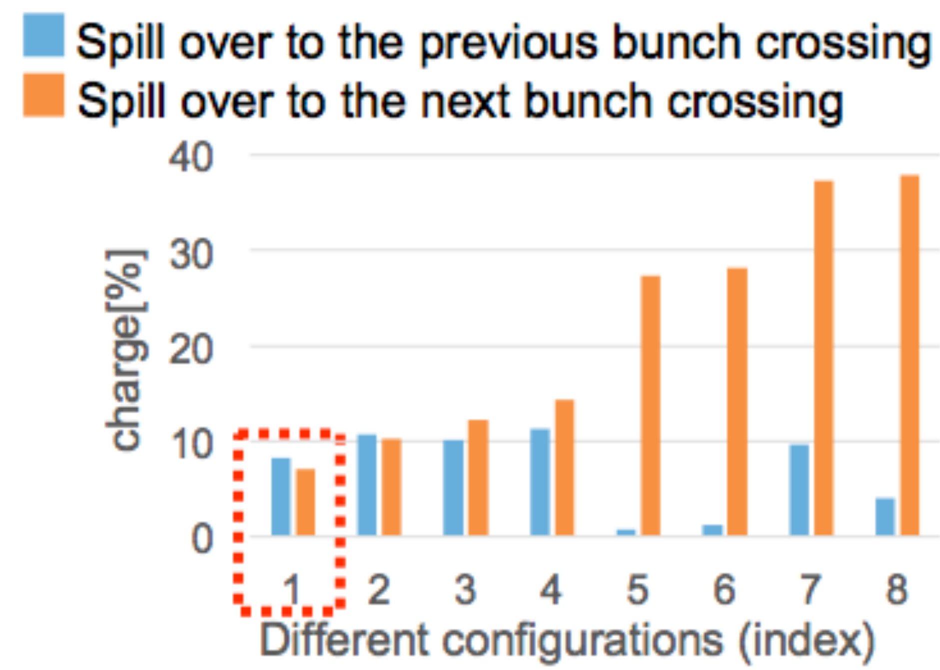
- The 25 ns bunch spacing could introduce spill-over tracks.
- Using 50 ns bunches to study the number of tracks in the empty bunches and collision bunches



- Less than one spill over track in the empty-empty crossings on average, the number of spurious tracks "spilling over" bunch crossings is negligible.

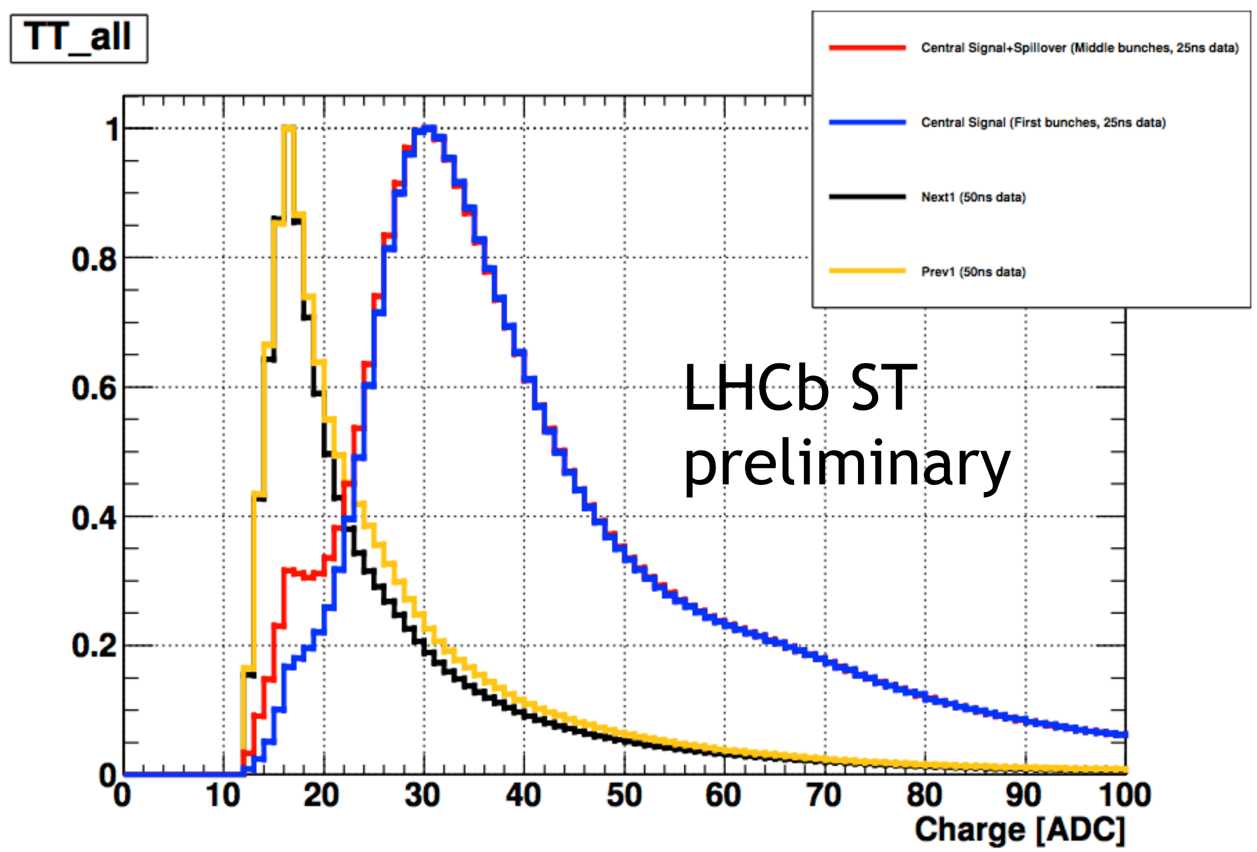
- The 25 ns bunch spacing could introduce spill-over tracks.
- The analogue pulse of the front-end chips was optimized for fast readout and signal to noise.



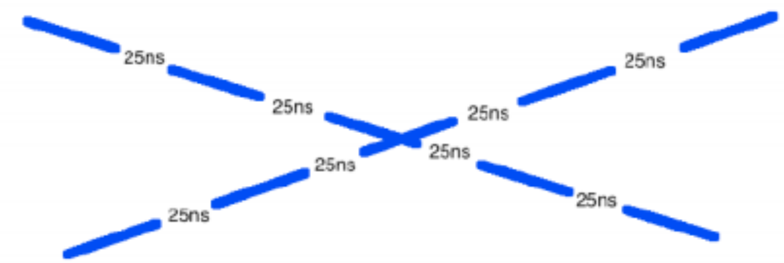


- Studies to assess the viability of lower power consumption in the VELO
- Leads to lower temperatures, higher radiation tolerance, and lower leakage current

- With 25 ns bunch crossing, expect ~ 30 % signal spillover in TT
  - less in IT (shorter strips → smaller load capacitance)



TT, data only (Central and Next1)



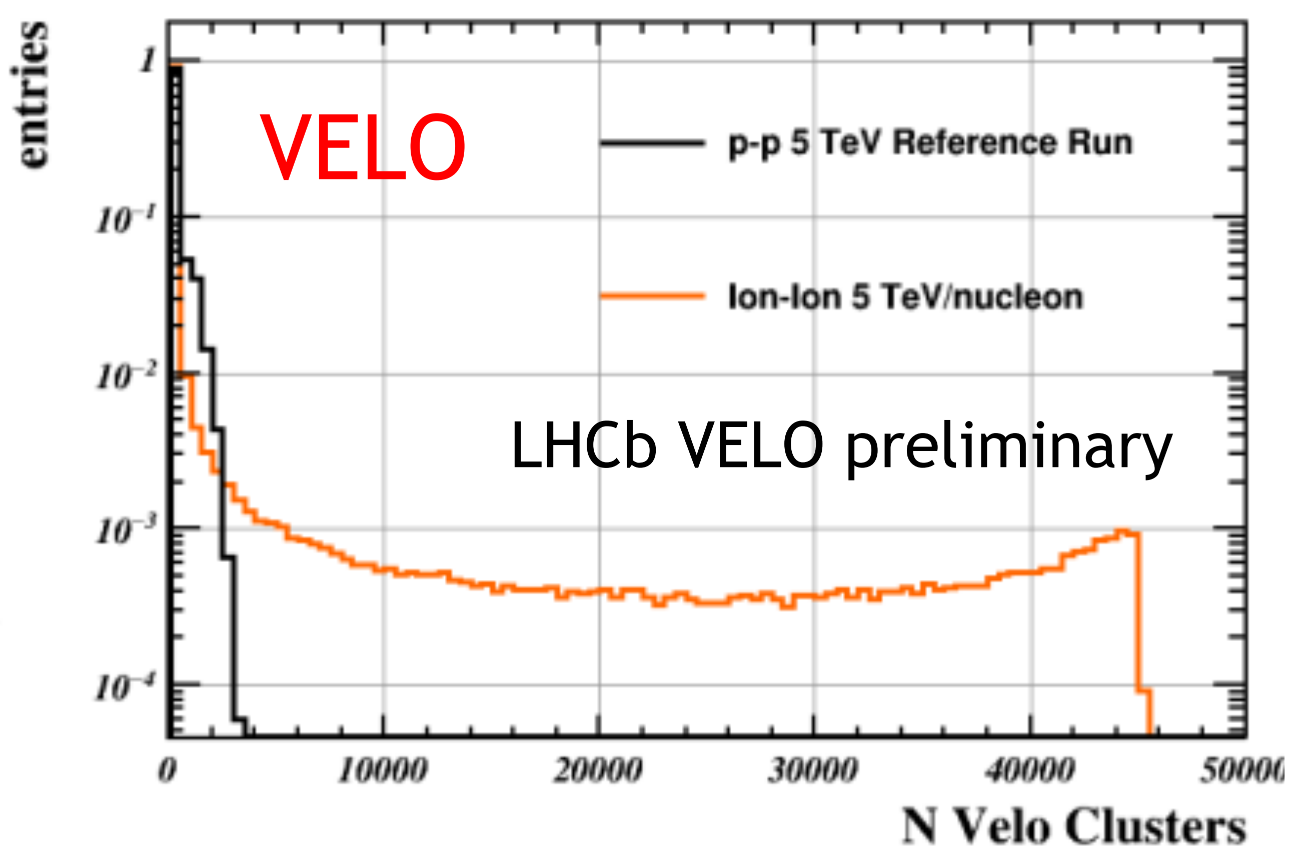
Signal+Spillover (25 ns)

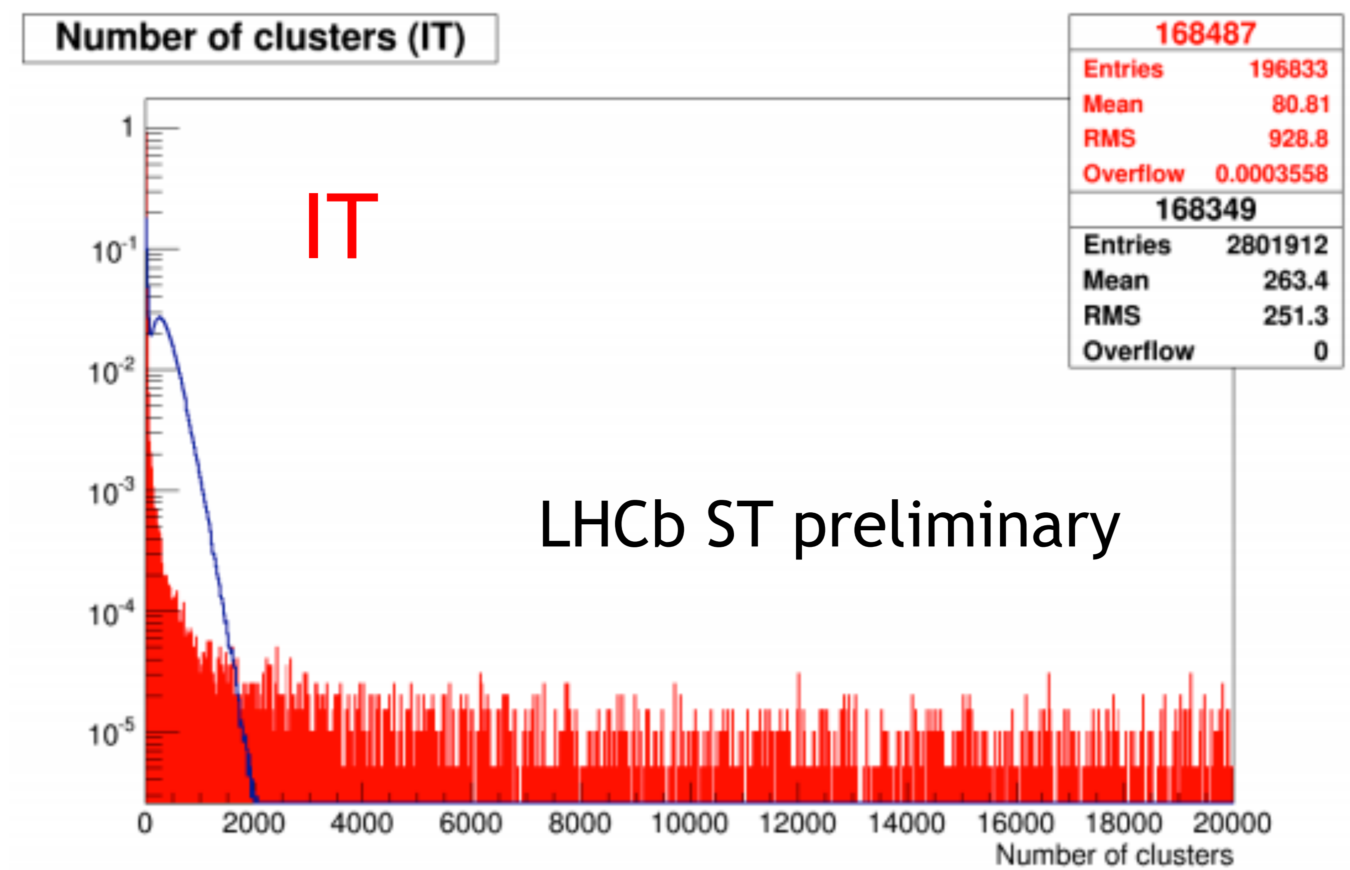
Signal (25 ns)

Spillover (TAE 50 ns)

- Bunch in middle of bunch train: signal + spill-ove.
- First bunch in bunch train: pure signal
- “Empty” bunches in 50 ns runs: pure spill-over

- Careful study taking into account the safety of the detector before ion runs
- First fill had very careful power on procedure
- Small total dose, average occupancy much lower than in pp collisions
- Too high multiplicities: busy events are really busy!





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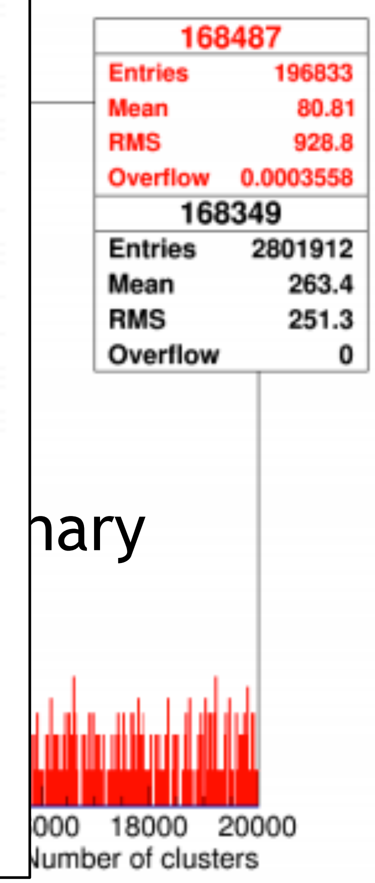
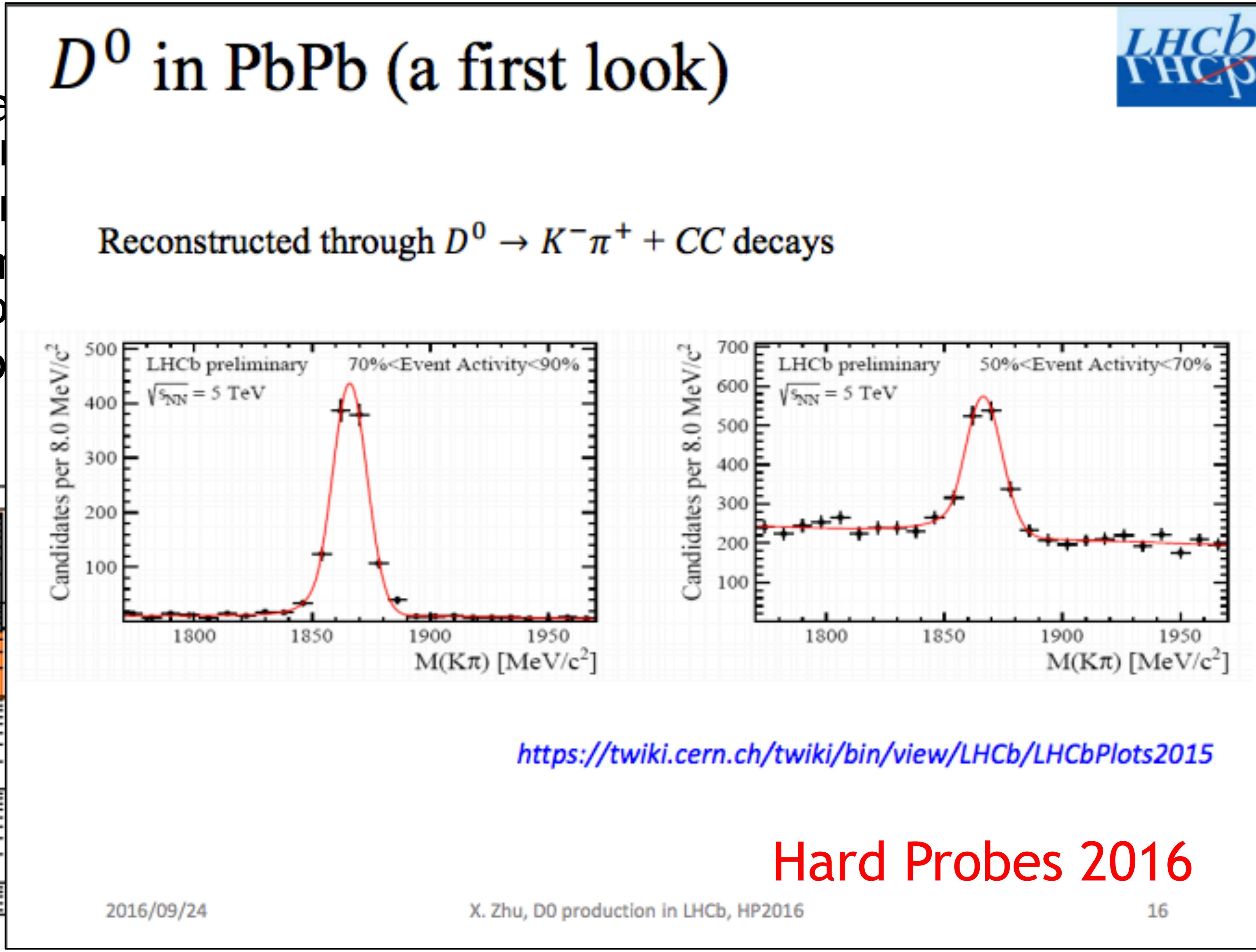
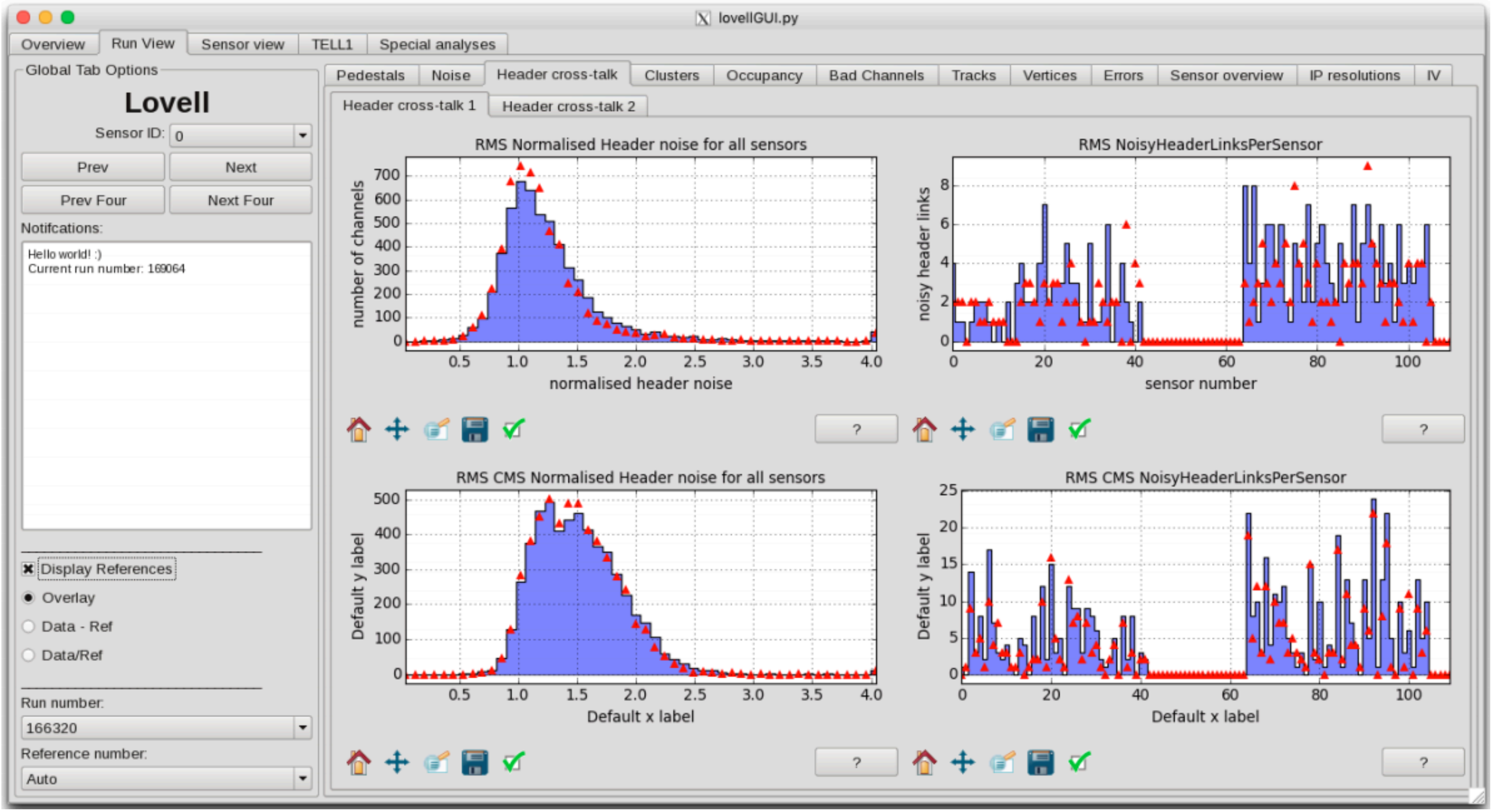
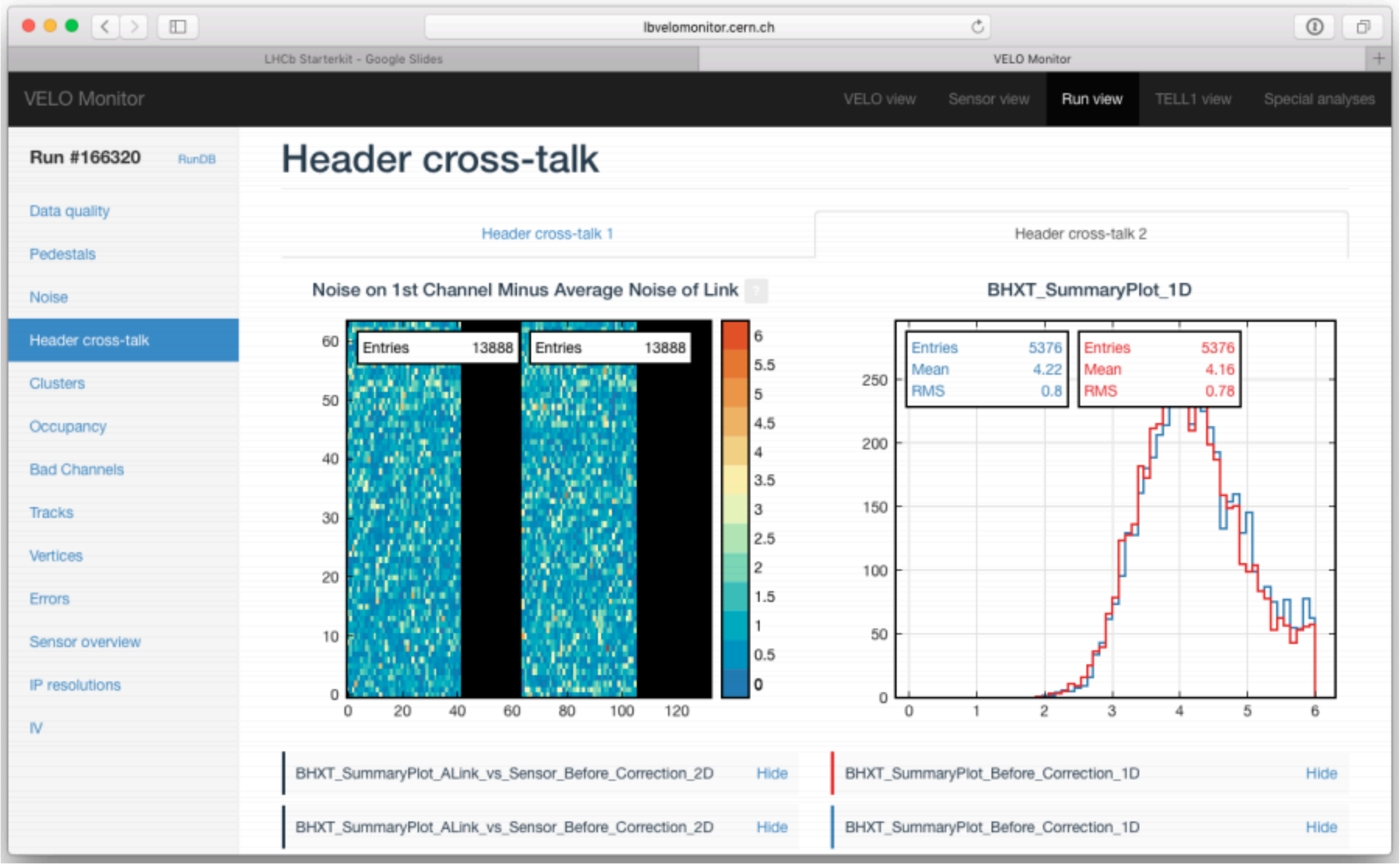




- New GUI, desktop and web
- Increase monitoring power with trends over time and automatic analysis



- Web version


lbvelomonitor.cern.ch
LHCb Starterkit - Google Slides
VELO Monitor
VELO Monitor
VELO view
Sensor view
Run view
TELL1 view
Special analyses
Run #166320
RunDB
Data quality
Pedestals
Noise
Header cross-talk
Clusters
Occupancy
Bad Channels
Tracks
Vertices
Errors
Sensor overview
IP resolutions
IV
Header cross-talk
Header cross-talk 1
Header cross-talk 2
Noise on 1st Channel Minus Average Noise of Link
Entries 13888
Entries 13888
BHXT_SummaryPlot_1D
Entries 5376
Mean 4.22
RMS 0.8
Entries 5376
Mean 4.16
RMS 0.78
BHXT_SummaryPlot_ALink_vs_Sensor_Before_Correction_2D
Hide
BHXT_SummaryPlot_Before_Correction_1D
Hide
BHXT_SummaryPlot_ALink_vs_Sensor_Before_Correction_2D
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BHXT_SummaryPlot_Before_Correction_1D
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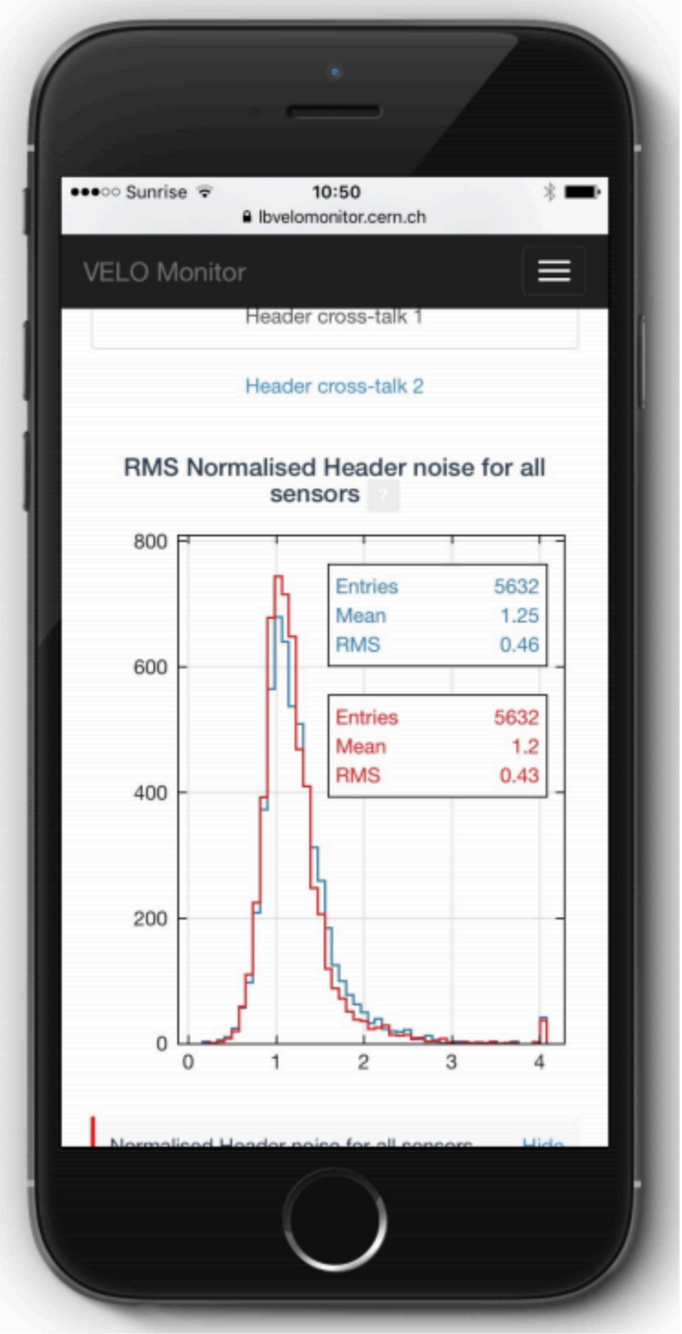
- Web version - It's everywhere!



Fully Functional and Tested spare sensors and frontend electronics

Spare to be used in case of beam related incident