Performance of the LHCb Vertex Locator

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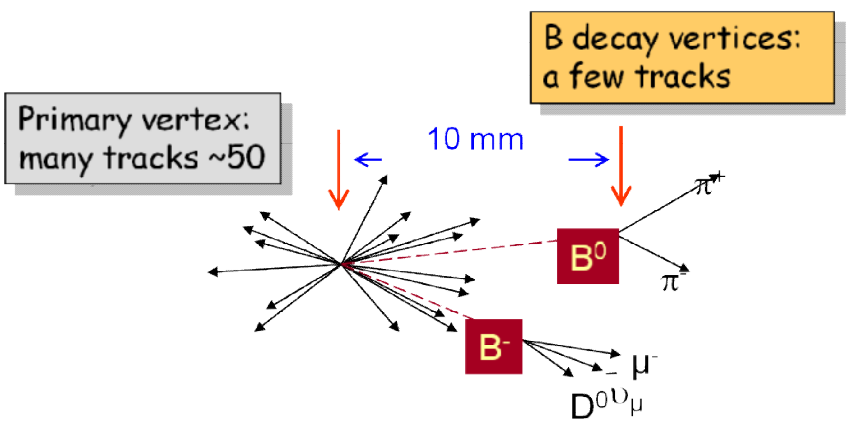
Introduction to LHCb

- LHCb is a dedicated experiment for flavour physics at the LHC, in particular:
  - Study of *CP* violation in beauty and charm decays
  - Search for New Physics in loop processes
  - Complementary to direct searches at ATLAS and CMS

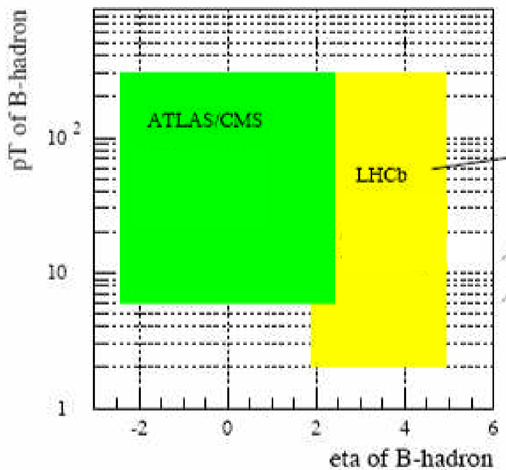


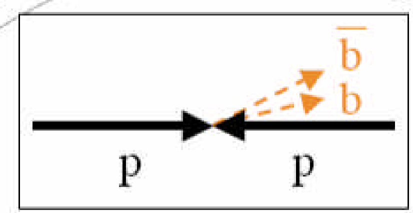
Detector requirements:

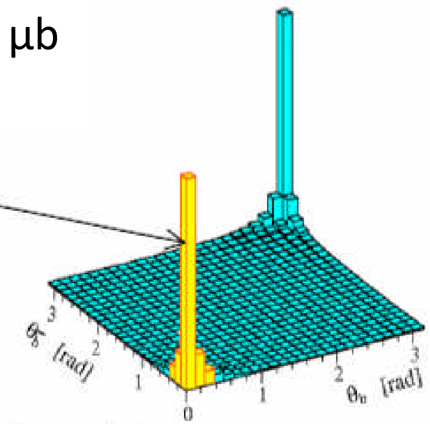
- ✓ Efficient trigger for leptonic and hadronic final states
- ✓ Excellent vertex finding ability
- ✓ Extremely good tracking efficiency and particle identification

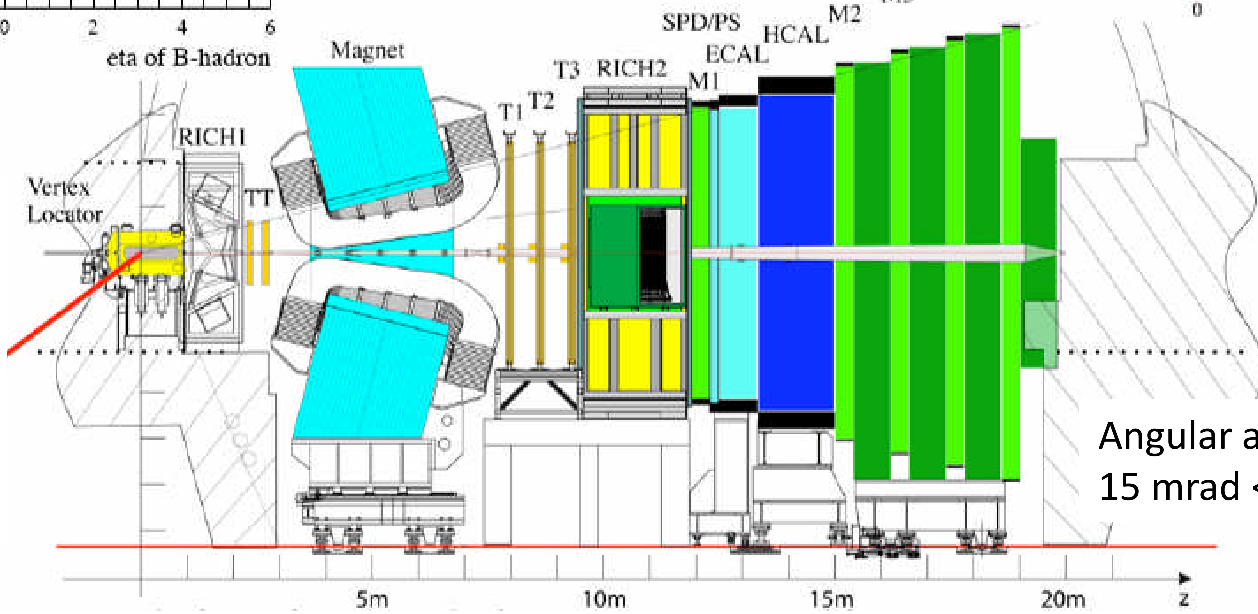
The LHCb detector

LHCb $\sigma(pp \rightarrow H_b X) = (75 \pm 5 \pm 13)\ \mu b$
Phys. Lett. B 694, 209-216 (2010)







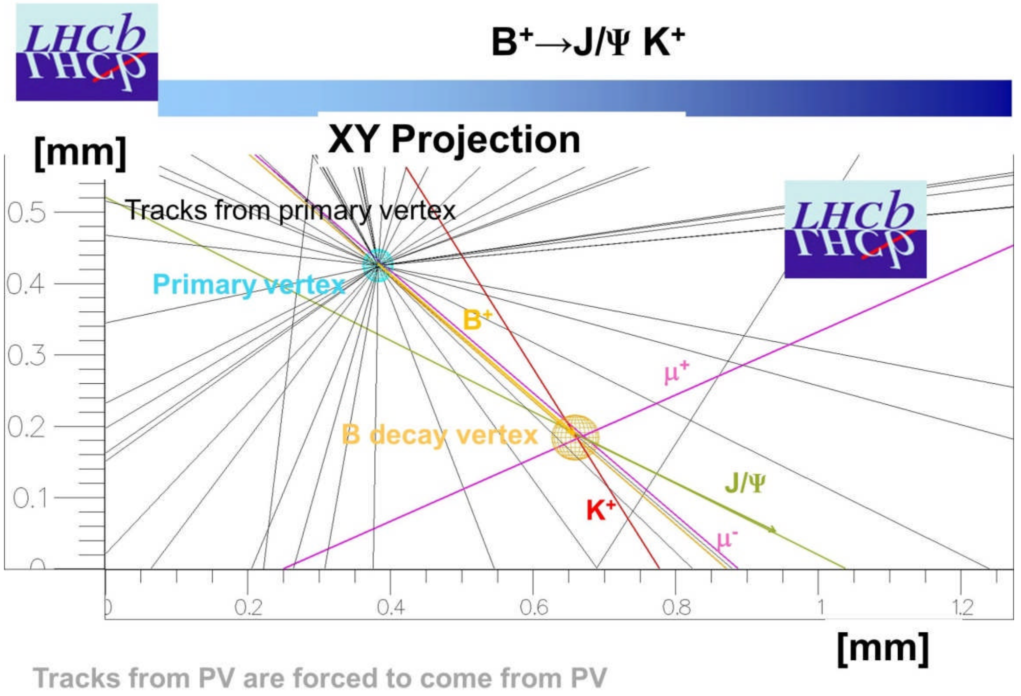


Interaction Point in the VELO

Angular acceptance:
15 mrad < θ < 250 mrad

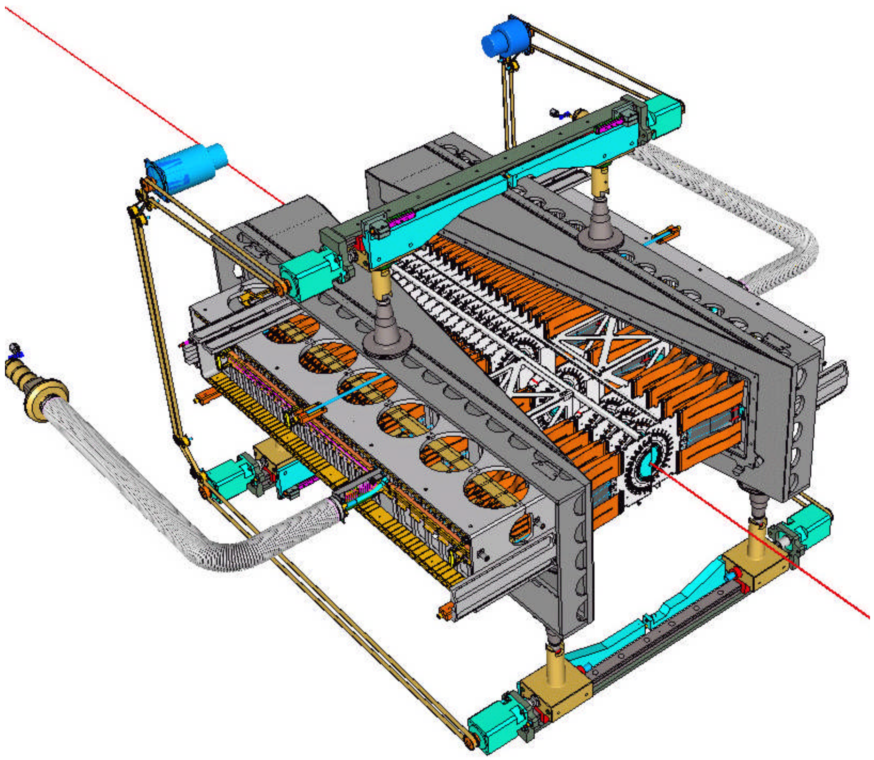
The Role of the

- b-hadrons have lifetime of O(10^{-12})s
- Relativistic boost means average flight distance of ~1cm
- VELO has to precisely locate both primary and secondary vertices
- Forms essential part of higher level trigger
- Also a principal tracking device



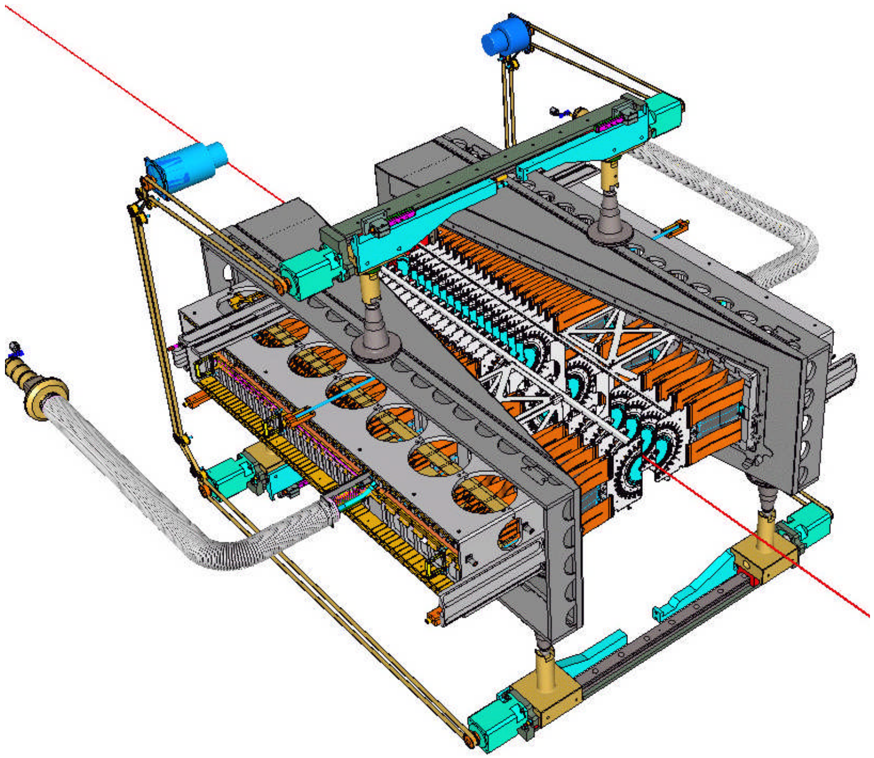
Design

- 2 retractable detector halves



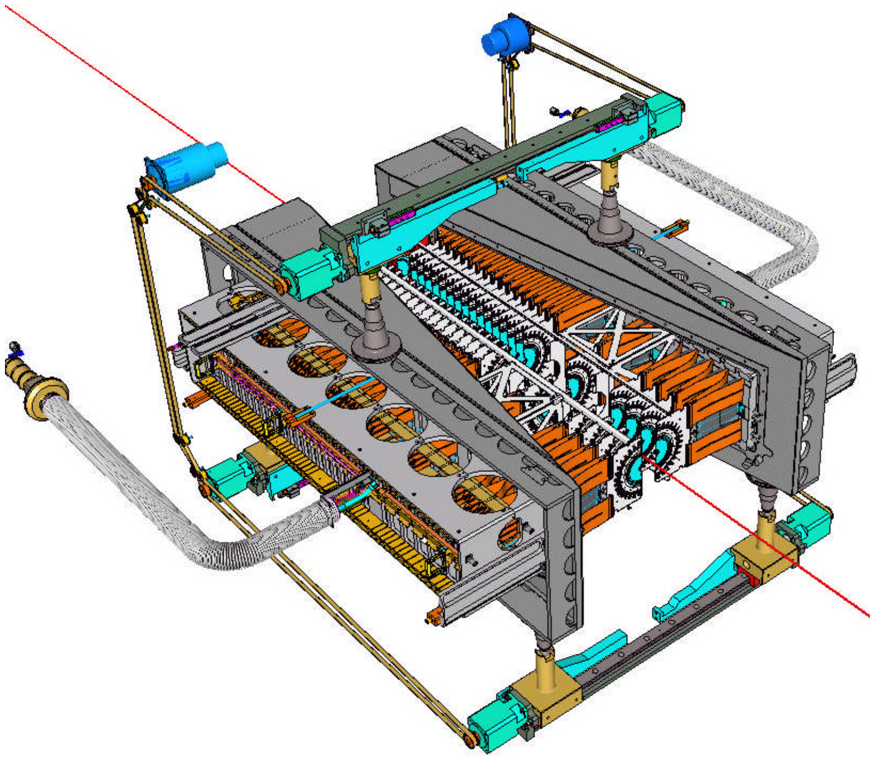
Design

- 2 retractable detector halves



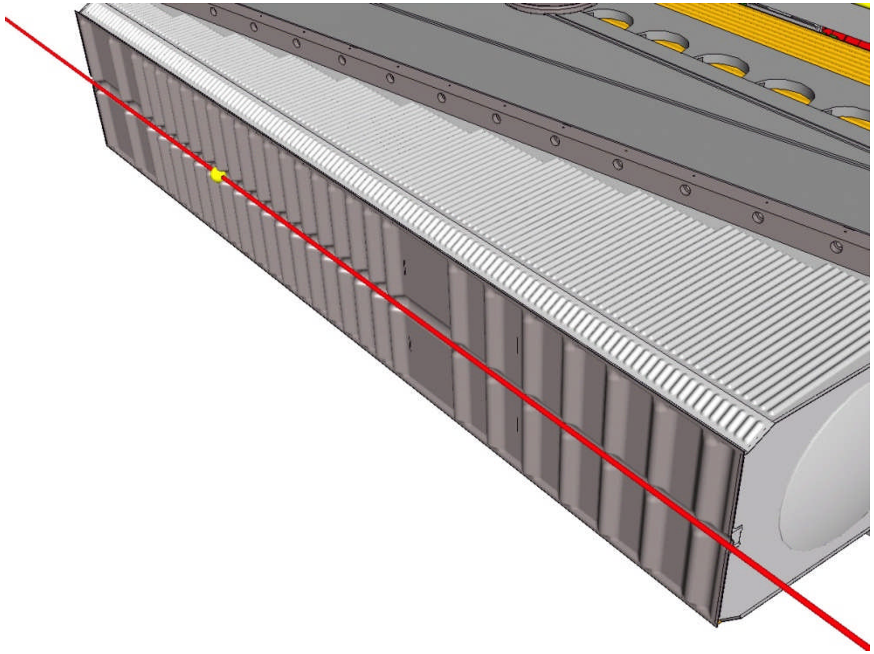
Design

- 2 retractable detector halves
- 21 modules (+ 2 pile-up) per half
- Each module has r and ϕ sensor
- Detectors in secondary vacuum

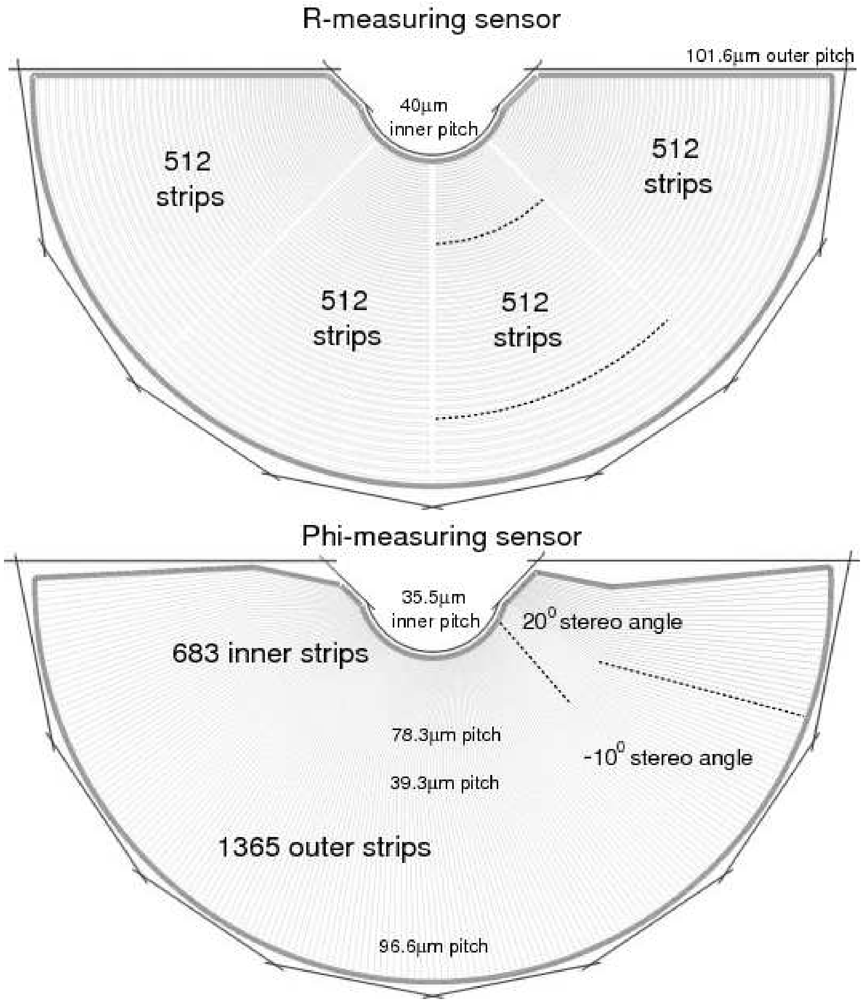


Design

- 2 retractable detector halves
- 21 modules (+ 2 pile-up) per half
- Each module has r and ϕ sensor
- Detectors in secondary vacuum
- Separated from LHC vacuum by 300μm foil
- Foil also guards against RF pickup from beam

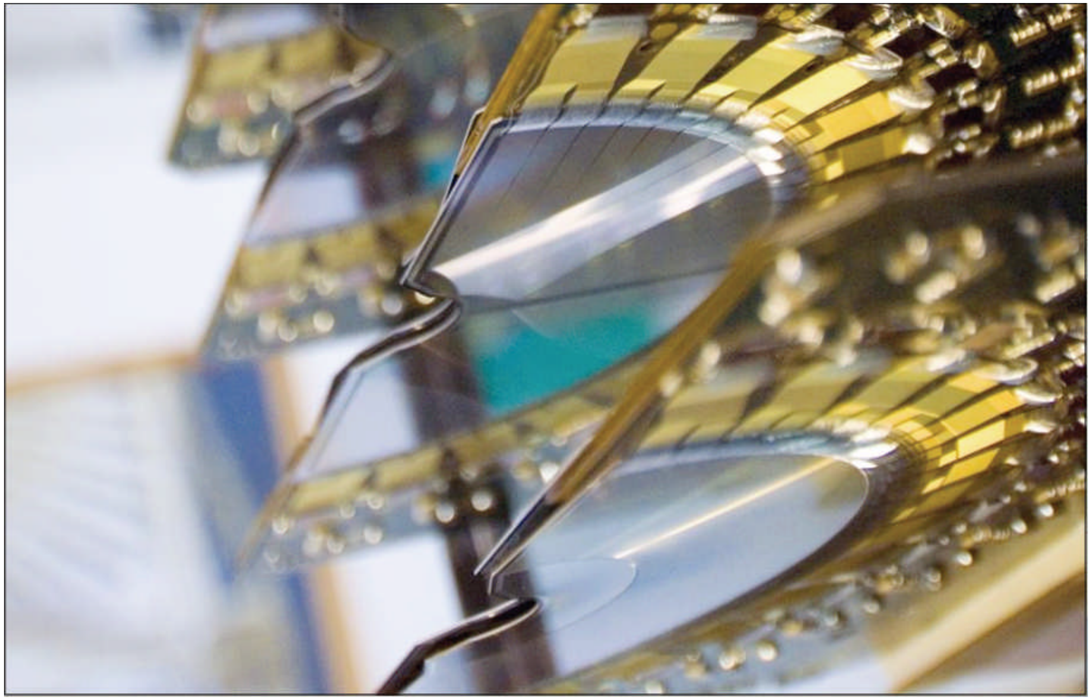


Sensor Design

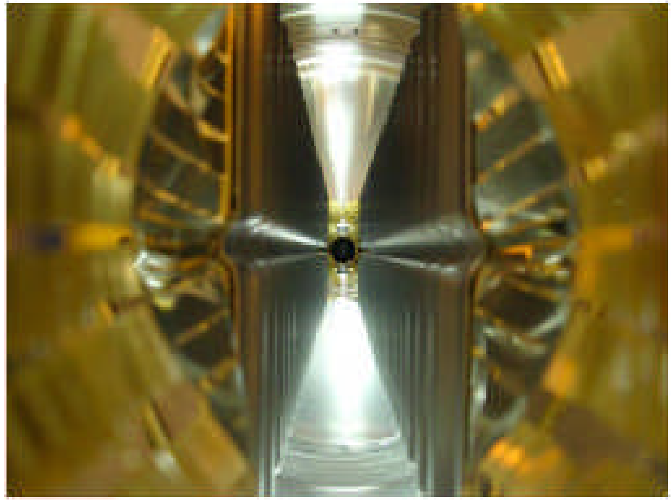


- 2 semi-circular sensor designs
  - r and ϕ measuring
- 300µm n-on-n silicon
- 2048 strips per sensor
- 8.2mm inner radius of active silicon
- Cooled by evaporative CO_2 system
  - Operating temperature of -30°C

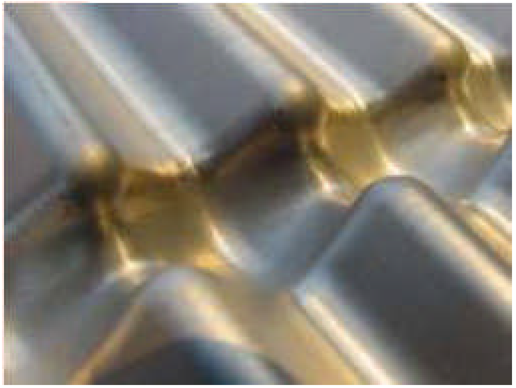
Views



VELO modules



Beam-eye view of open VELO

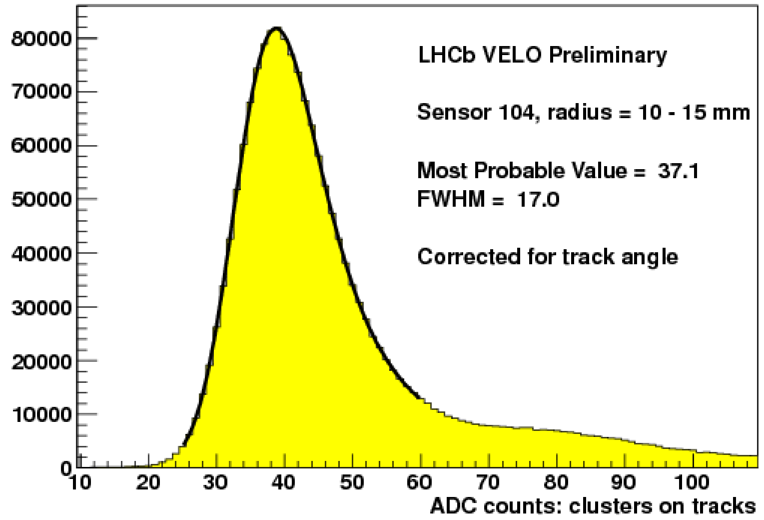


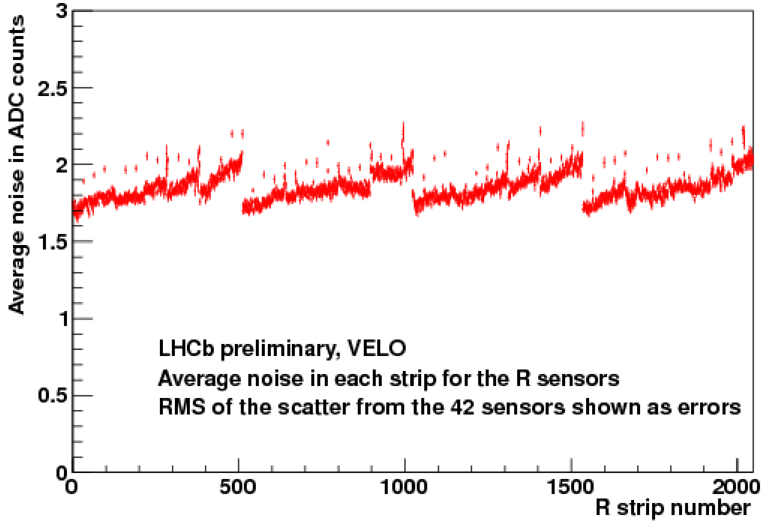
Close-up of RF foil

VELO Performance!

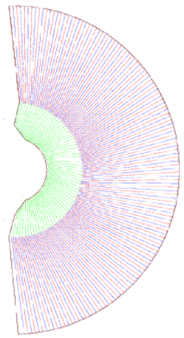
2011 Data !

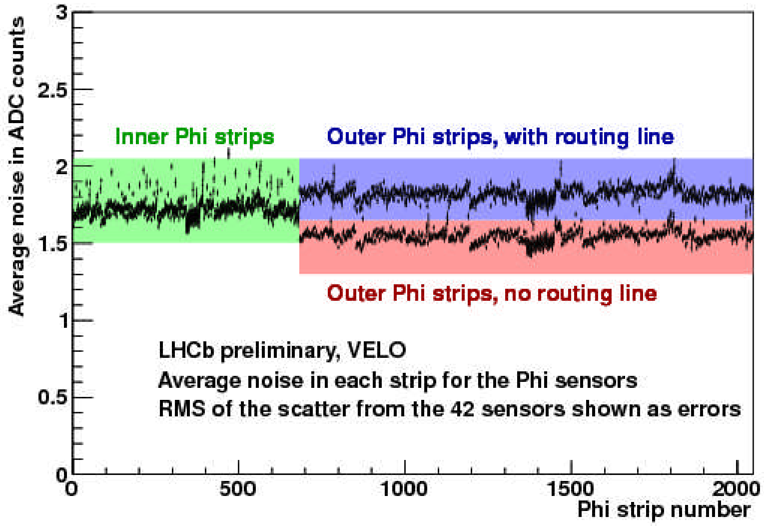
Signal and Noise





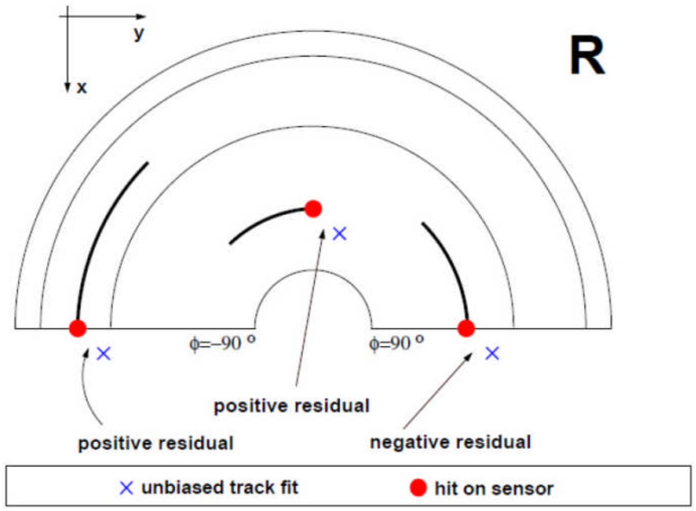
- Overall S/N as per design, > 20
- Noise on strips increases with strip length, hence with radius of r strips
- Noise levels also differ between 3 different types of ϕ strips:
  - inner – routed over outer strips
  - outer – w/ overlaid routing lines
  - outer – no overlaid routing lines

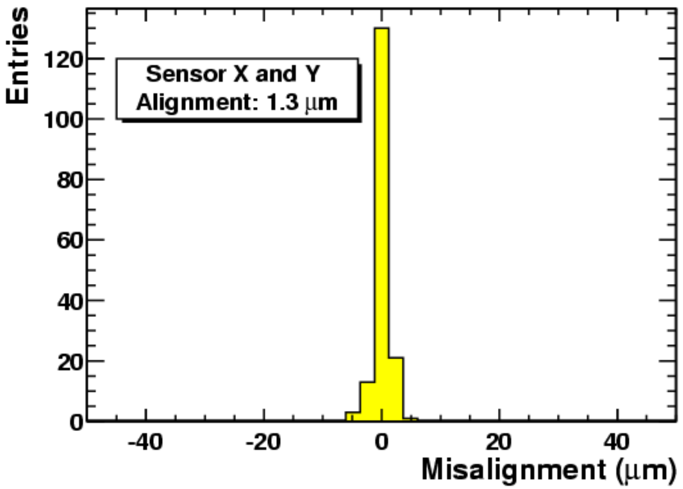




Spatial Alignment

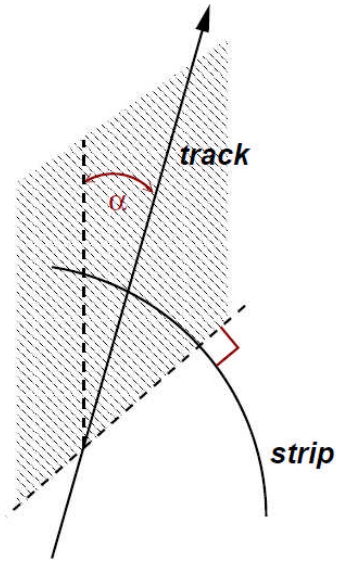
- VELO moved for each LHC injection
- Precise knowledge of alignment critical for lifetime measurements
- Proceeds in 3 stages:
  - Sensors within modules
  - Module to module within half
  - Inter-half alignment
- Uses residuals from track fit
- Module and sensor alignment known to better than 4µm
- Inter-half stable over time to better than 5µm

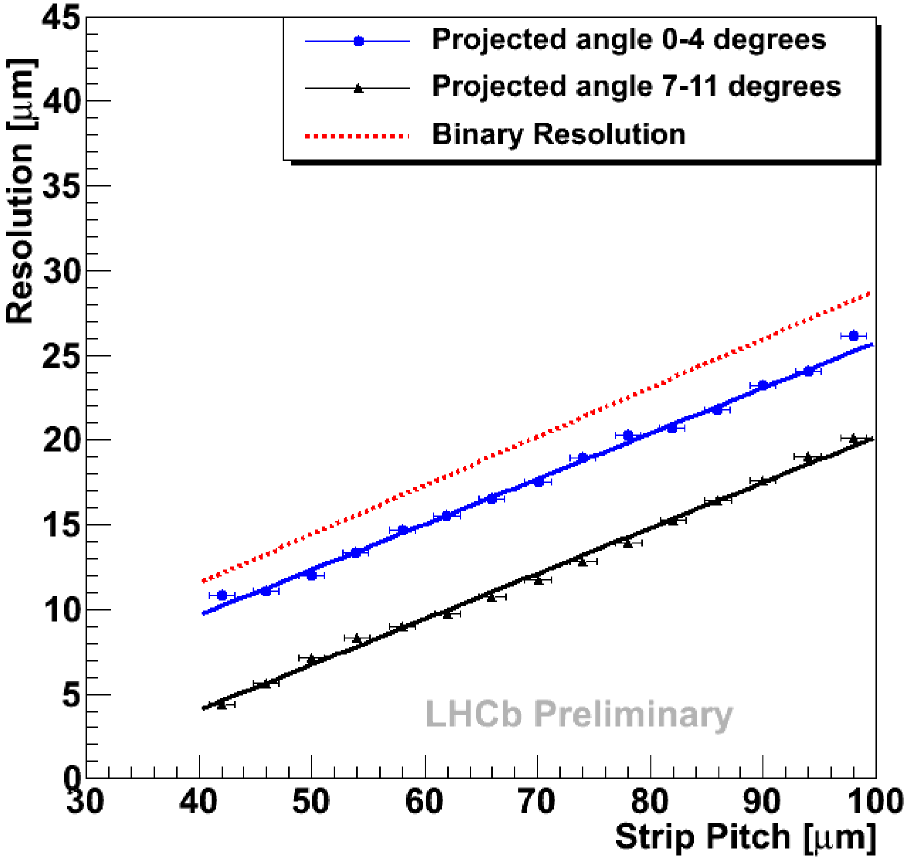




Hit Resolution

- Measure residual of cluster to track made without that cluster
- Correct for track uncertainty
- Bin in both strip pitch and projected track angle
- Best resolution < 4μm !

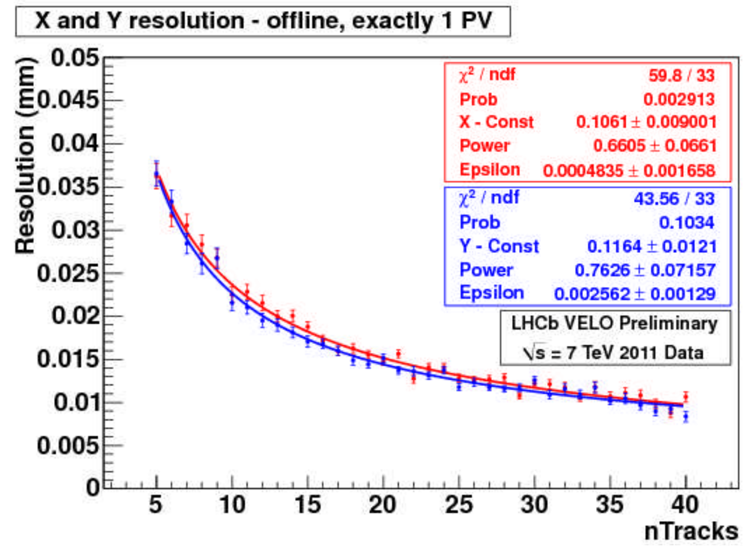


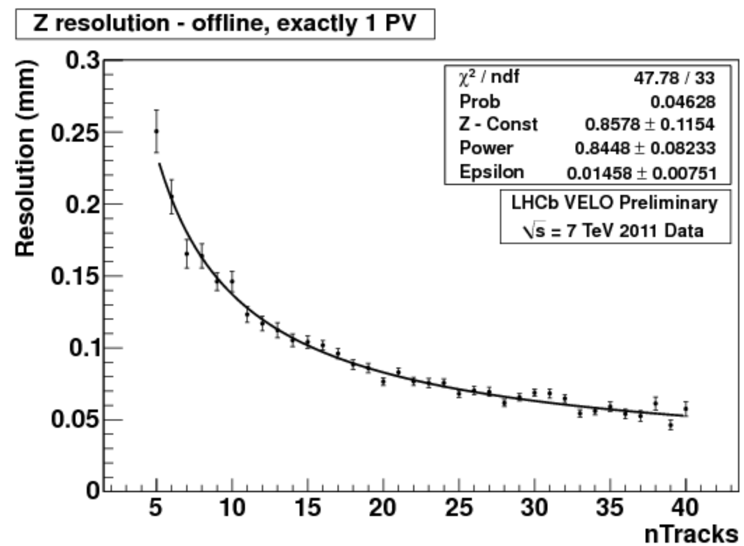


2011 Data !

Primary Vertex Resolution

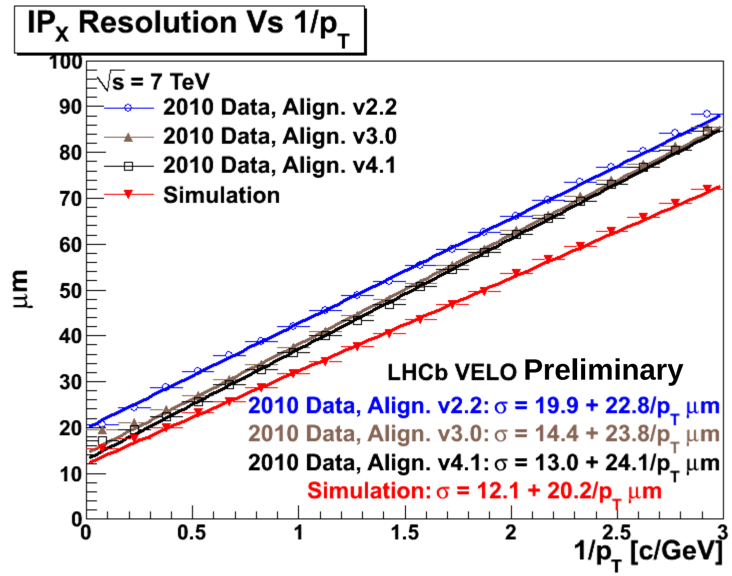
- Randomly split tracks into two sets
- Fit two vertices and measure their separation
- With 25 tracks per vertex:
  - x resolution = 13.1μm
  - y resolution = 12.5μm
  - z resolution = 71.1μm
- Approaching design levels

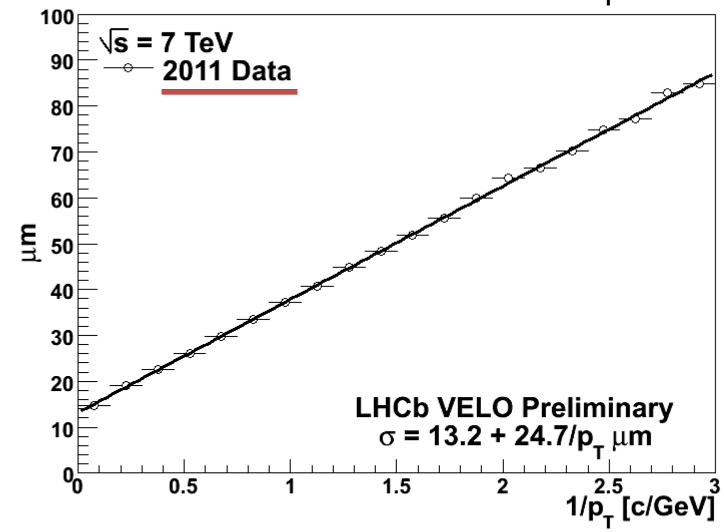




Impact Parameter Resolution

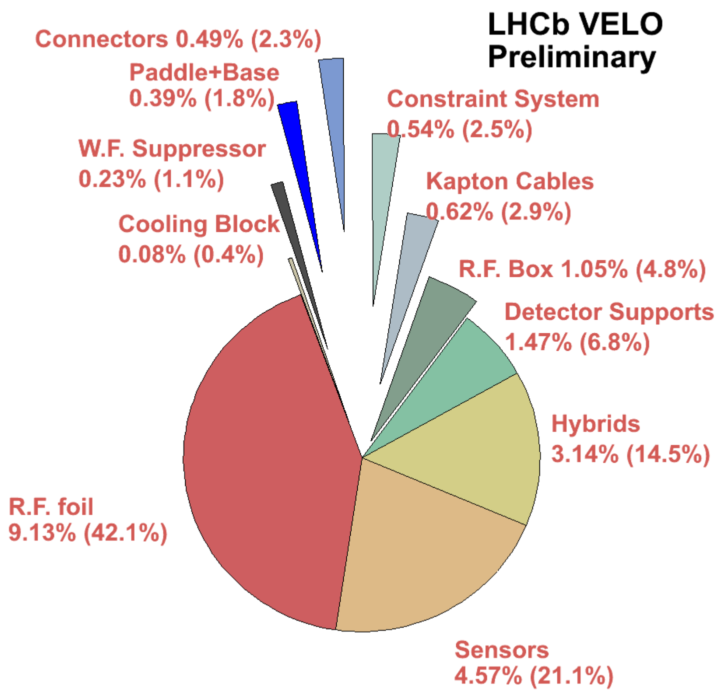
- IP = distance of closest approach of track to PV
- Important variable for identifying long lived particles such as B mesons
- Contributions from PV and hit resolutions plus multiple scattering
- IP resolution improved with data based alignment
- Some disagreement with simulation remains
  - Under investigation



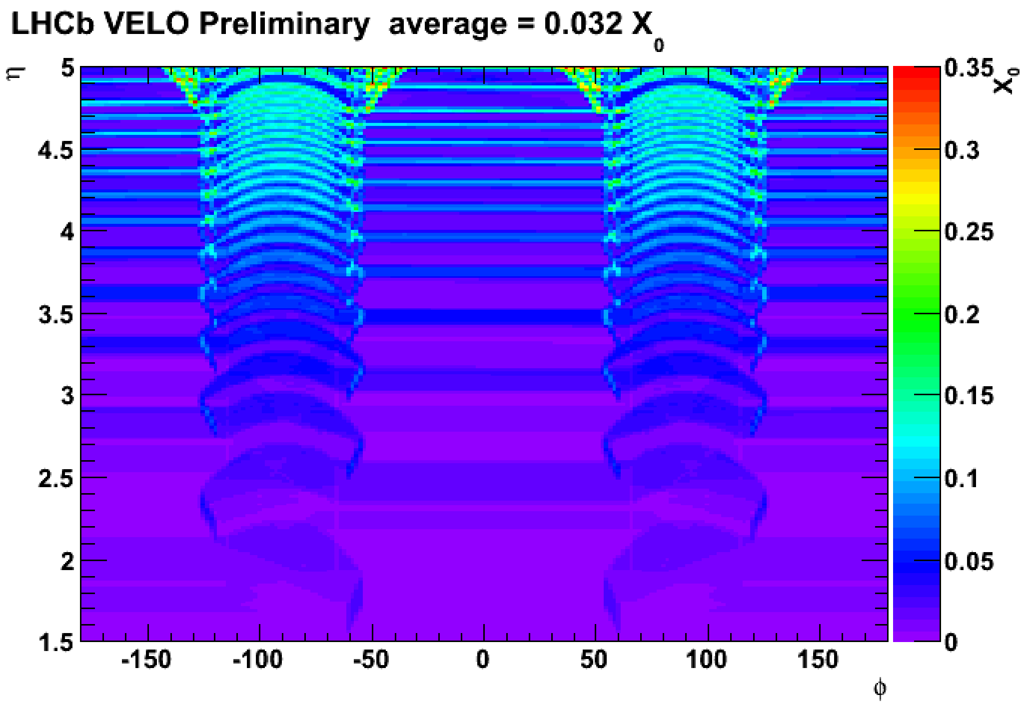


Material Budget

Total material budget $0.221X_0$



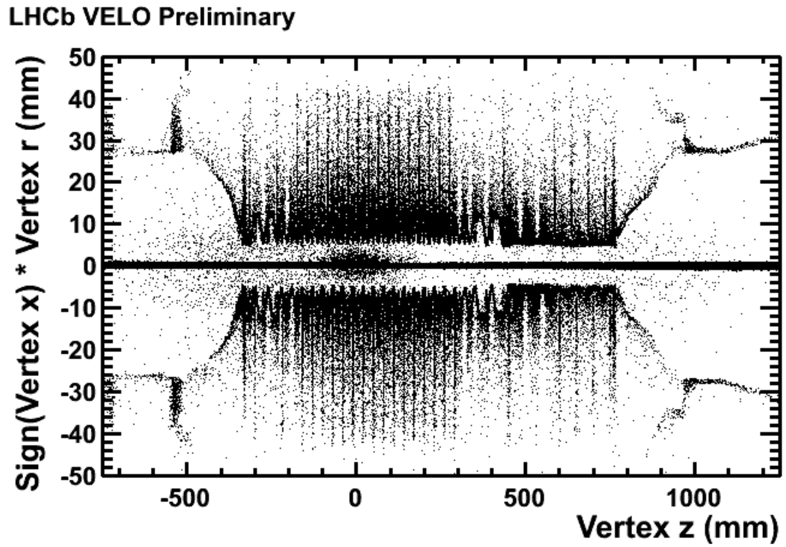
Material before 1st measurement $0.032X_0$

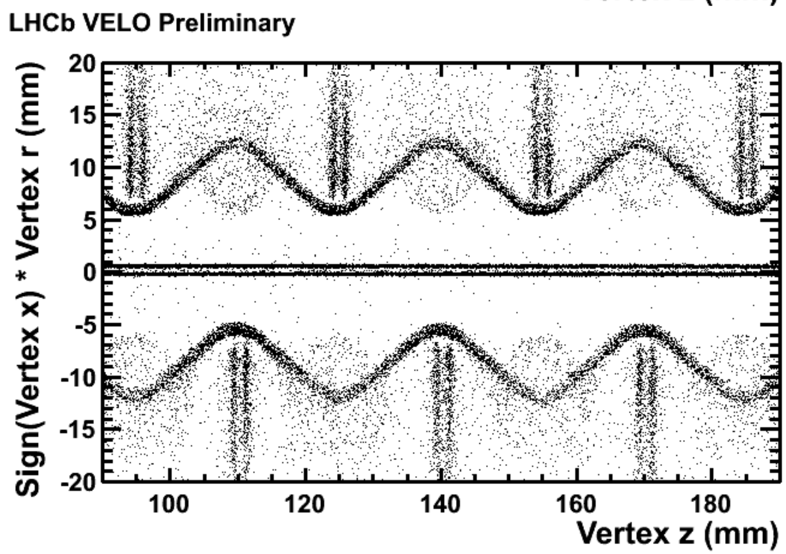


- Use detector model in simulation to estimate material budget

Self Imaging

- Use vertices of hadronic interactions with material to map VELO
- Requires precise vertex measurements
  - Exactly what VELO was designed for!
- Key features (sensors, RF foil etc.) stand out clearly
- Preliminary comparisons between data and MC indicate good agreement



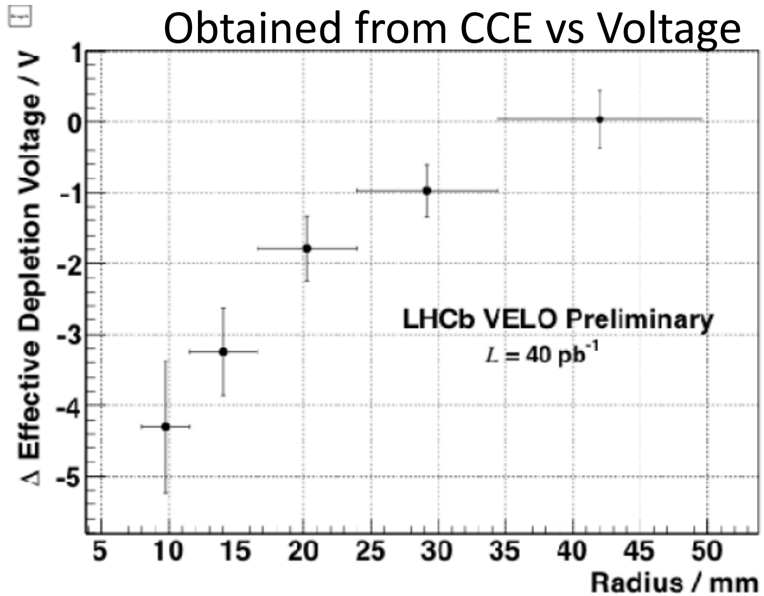


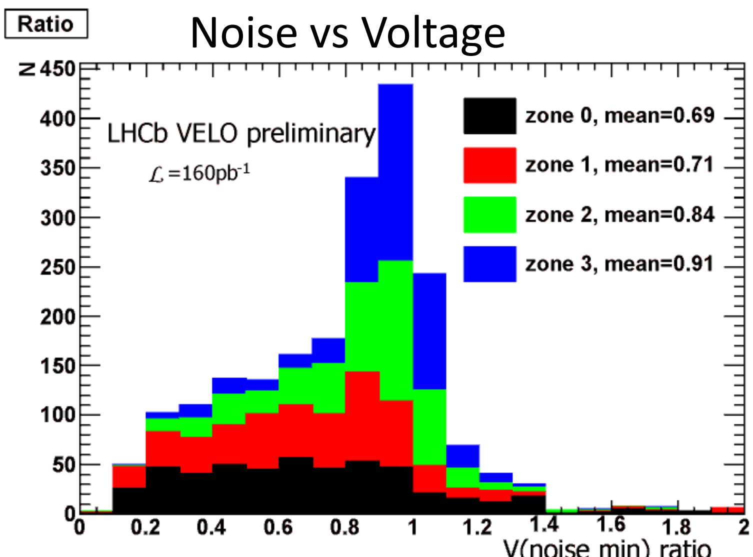
New Results !

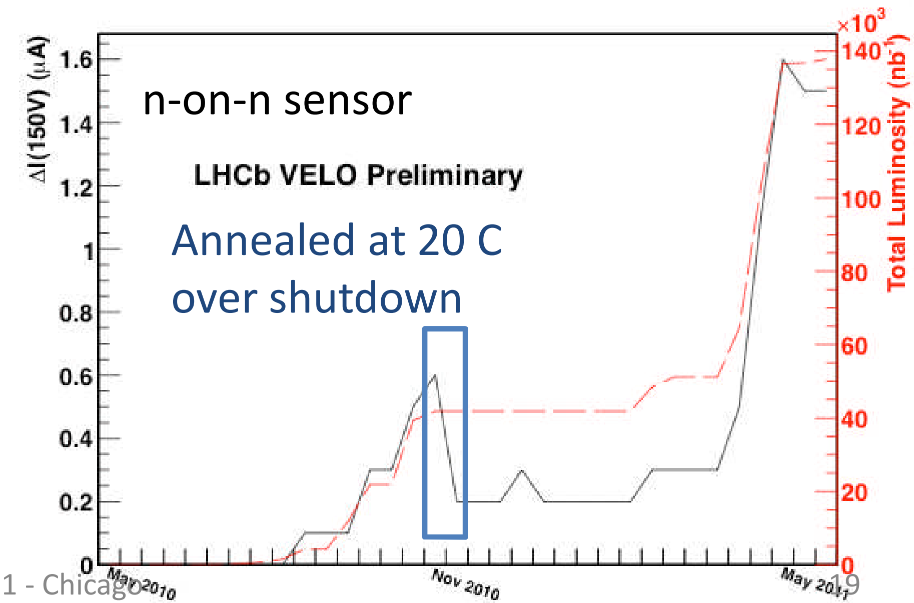
Velo Radiation Damage Studies

- LHCb VELO ***HOT!***

- First Strip only 8mm from LHC beam
  - Outer strip 40mm
- Maximum Fluence predicted at 14TeV
  - 1.3×10^{14} 1MeV $n_{eq}/cm^2/2\ fb^{-1}$
- Strongly non-uniform
  - dependence on $1/r^{1.9}$ and station (z)
- Clear observation of radiation damage
  - IV, CCE, noise versus voltage





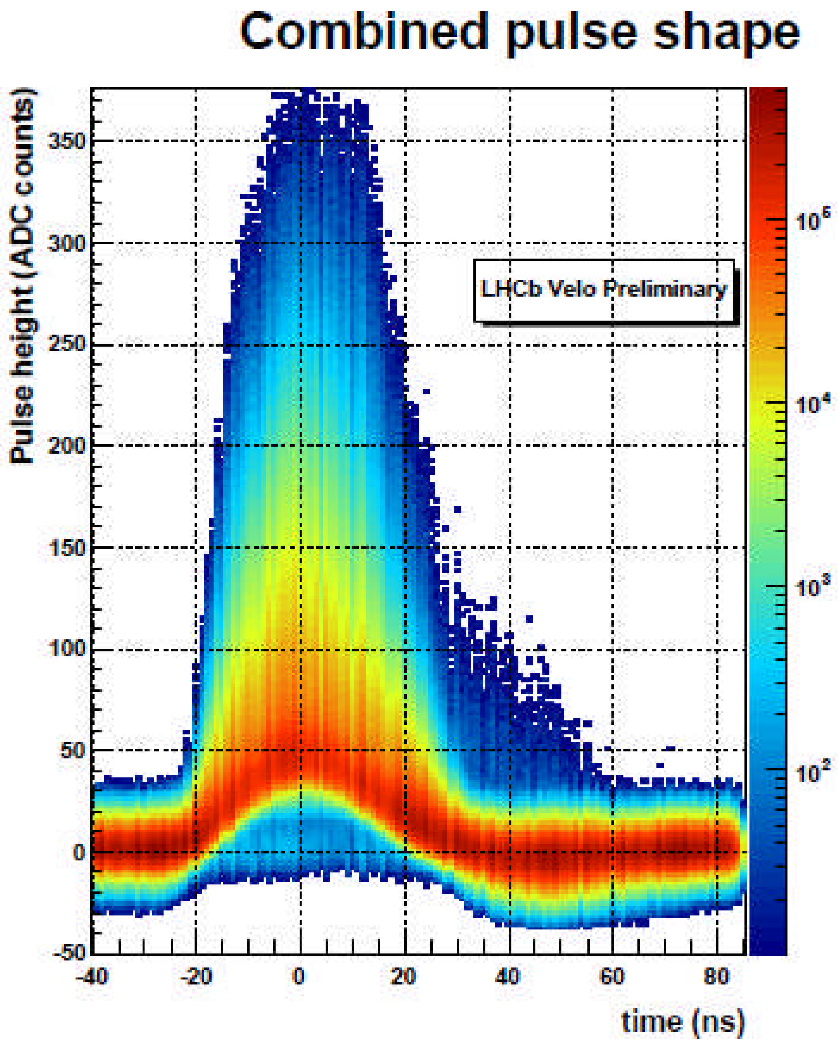


Summary

- VELO has operated extremely well from day one
- Operations becoming smoother over time
- Performance is close to design parameters
  - Best hit resolution < 4µm – best at LHC!
- Improvements already made based on 2010 data will reap further benefits for the LHCb physics programme this year
- Outlook:
  - Still some room for improvements – work ongoing
  - Challenges to come from radiation damage
    - First evidence for radiation damage now seen
  - Replacement VELO under construction

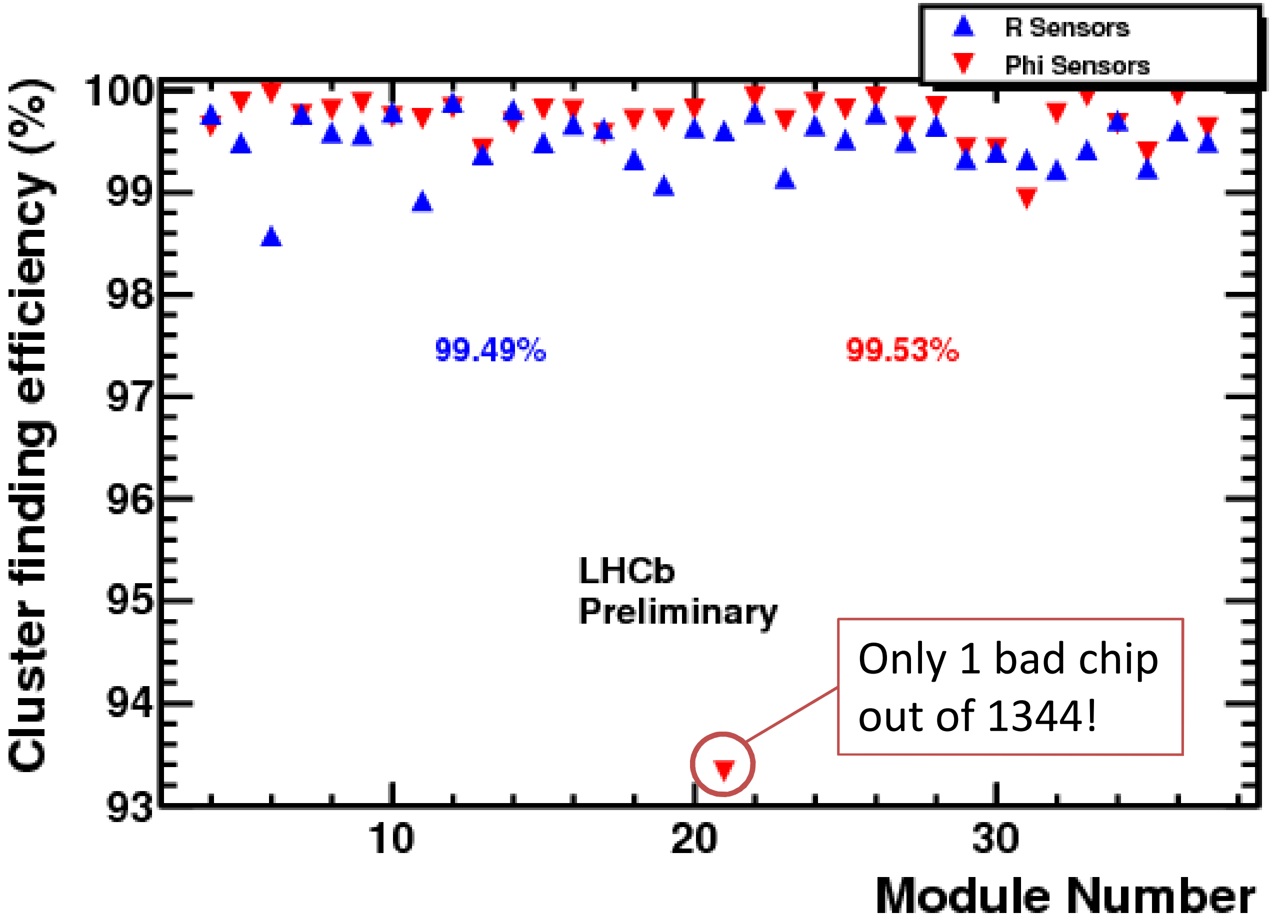
BACKUP

Time Alignment



- Nominal LHC bunch spacing 25ns
- Fine tune timings of front end chips
- Aim for
  - Maximum signal/noise
  - Minimum spillover
- Sensors individually tuned to account for differences in
  - Time of flight
  - Cable length

Cluster Finding Efficiency



- Efficiency generally extremely good
- Most inefficiencies understood

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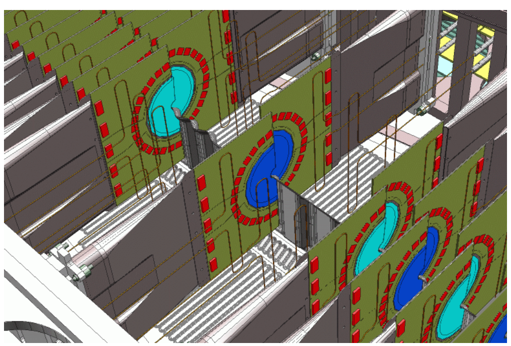
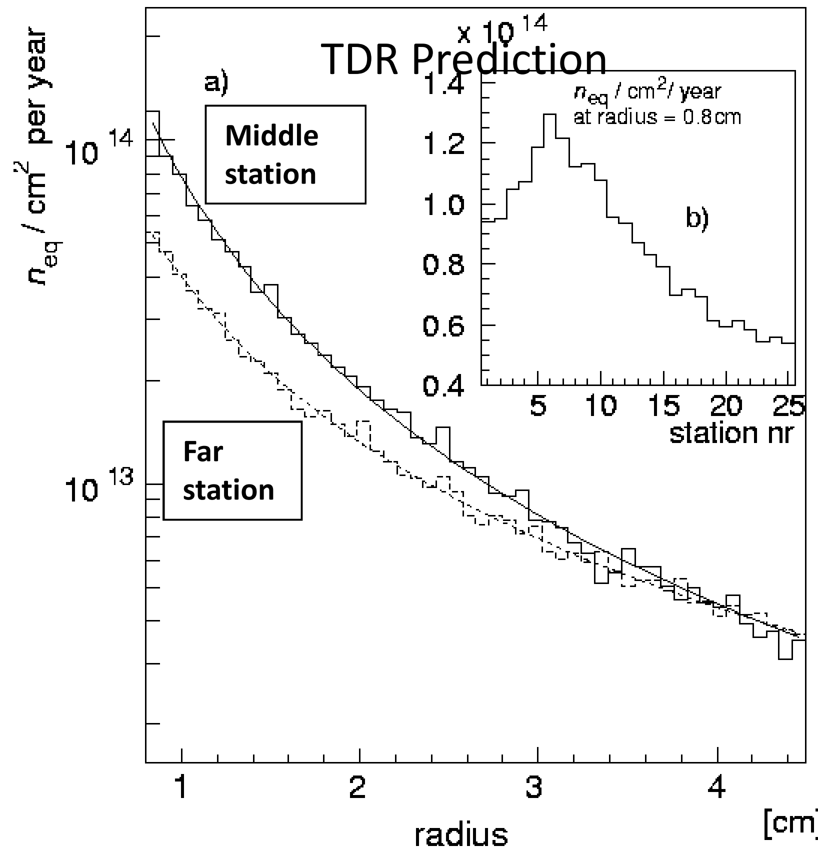




Tips of VELO sensors expected to type invert in next months of LHC running

Velo Radiation Damage Monitoring

Expectation:

Depletion voltage of VELO sensors around 40-80V originally.

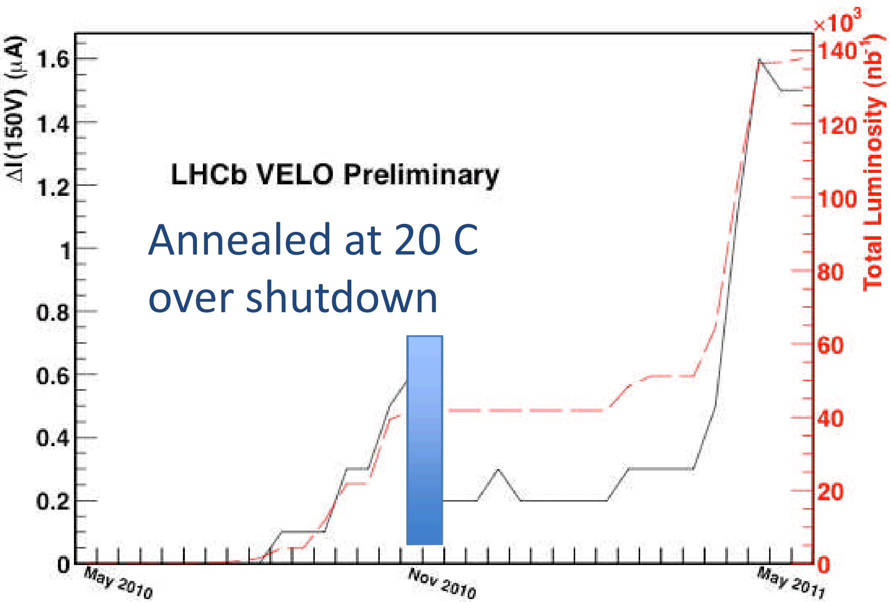
Depletion voltage decreases with fluence till type inversion

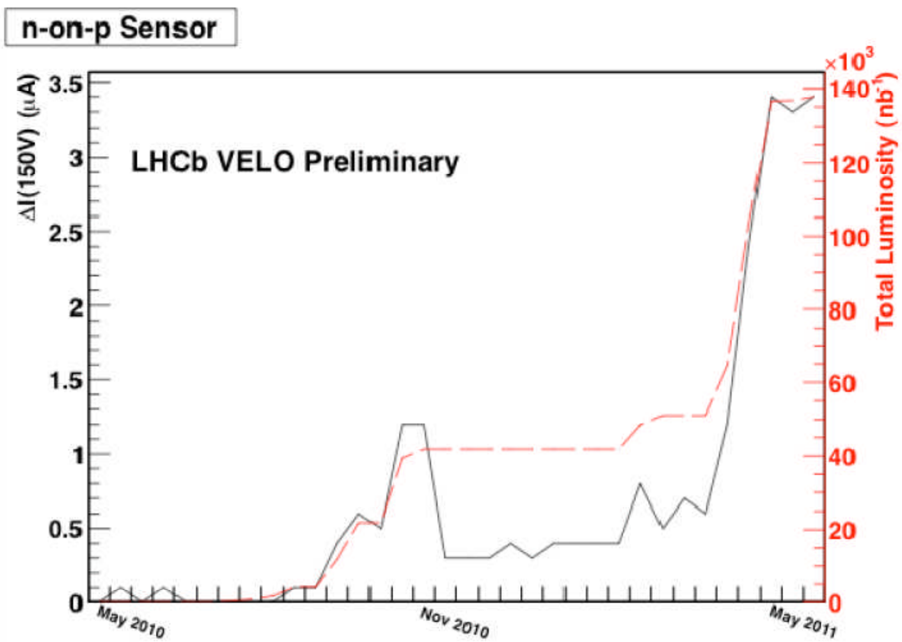
1. Current vs applied bias Voltage (IV)
   - Taken weekly
   - Current increases with bulk damage, linearly related to fluence
   - Does not study depletion voltage
2. Noise vs applied bias Voltage
   - Taken monthly
   - Sensors decrease capacitance and hence noise when depleted, so sensitive to depletion voltage at least during early running
3. Charge Collection Efficiency vs applied bias voltage
   - Direct measure of physics relevant parameter
   - Can study rad. damage as function of position
   - Requires beam data so only taken a few times per year
     - April 2010 (~0), April 2011 (40 pb^{-1})

IV Studies

- Example sensors showing bulk damage

n-on-n sensor

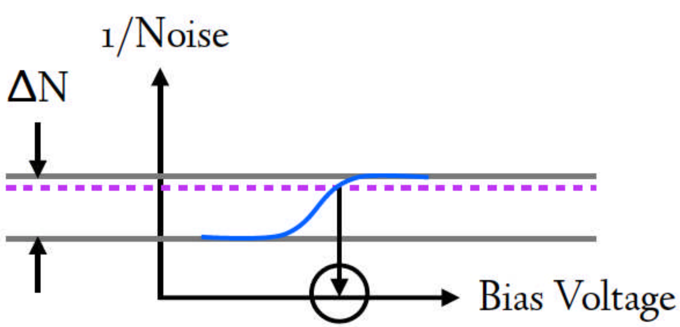


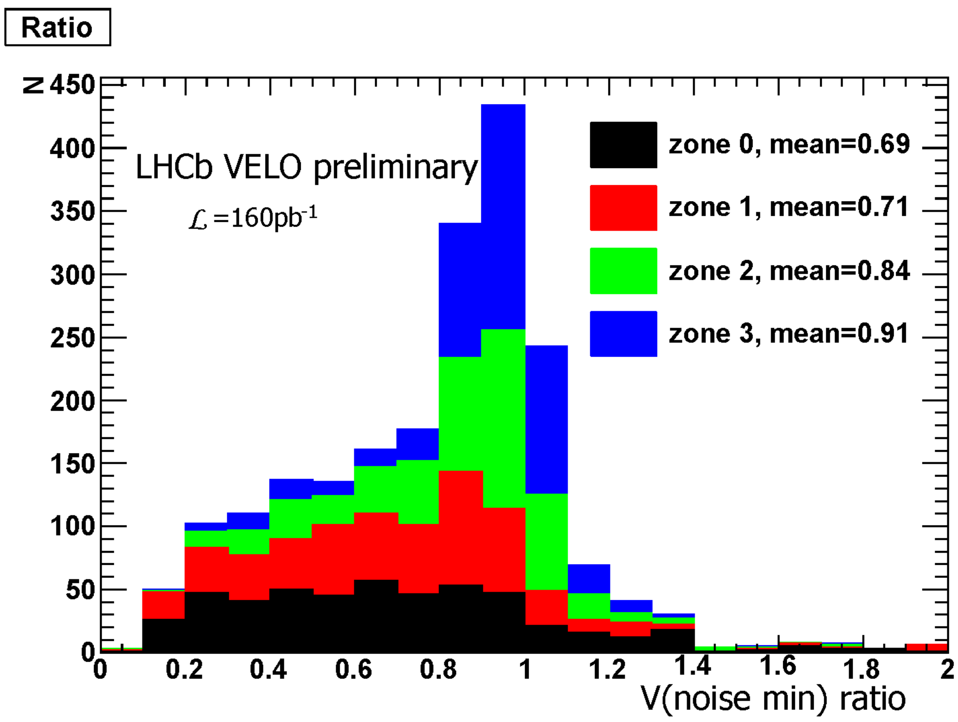


- VELO n-on-n, contains one n-on-p module

Noise vs Voltage

- **Measure voltage required to get noise to reduce by a specified fraction of the total depleted/undepleted change in noise**

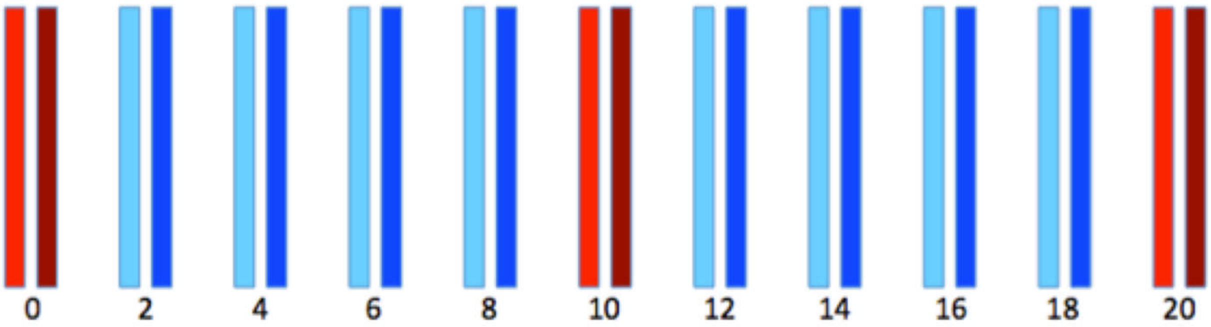




Innermost strips on R sensor
most irradiation
Ratio < 1, i.e. change in V(noise min)

Outermost strips on R sensor
less irradiation
Ratio ~ 1, i.e. no change in V (noise min)

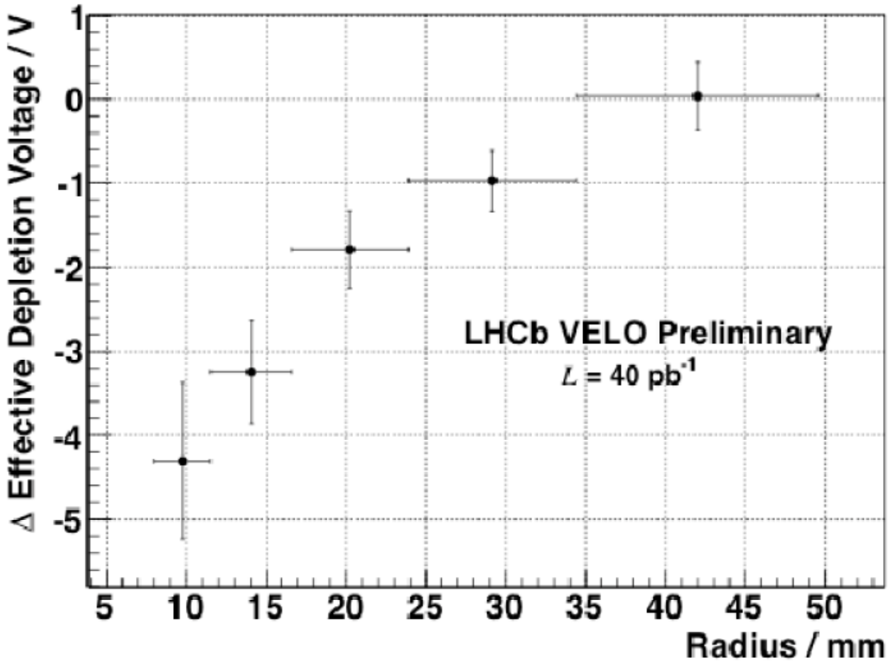
Charge Collection Efficiency (CCE)

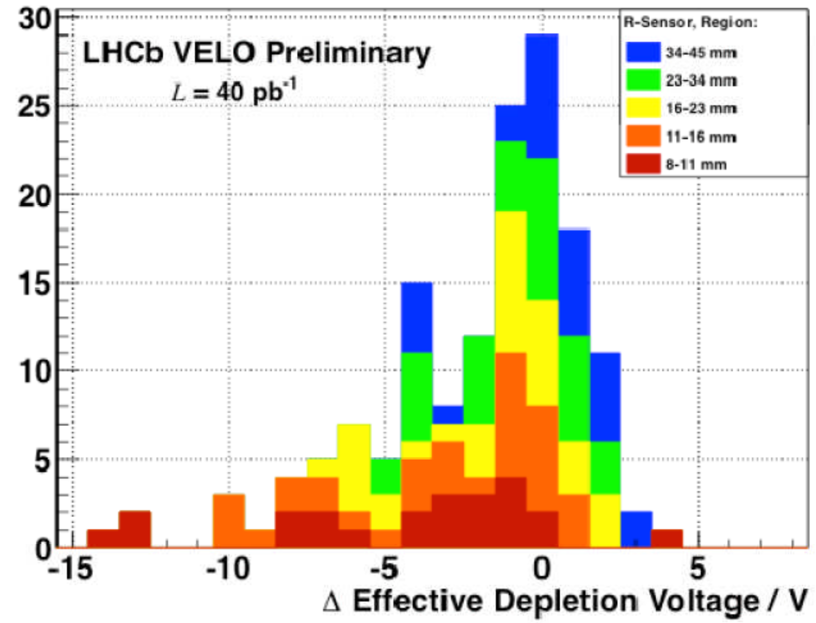


- Blue – tracking sensors – at full bias voltage
- Red – test sensors – bias voltage ramped
  - 10V steps, 0V-150V
  - Rotate through patterns, fully automatic scan procedure

- Tracks fitted through tracking sensors
  - Charge collected at intercept point on test sensors measured as function of voltage
    - Non-zero suppressed data taken so full charge recorded
  - Can study regions of sensor

Charge Collection Efficiency (CCE)





- Charge collection efficiency vs Voltage measured.
- Voltage at which CCE is 80% extracted
    - 80% chosen as gives best agreement unirradiated with depletion
- Here, averaged over all sensors, there is dependence of fluence on Z position
- Region sizes chosen so that fluence varies by factor two in each region
- Fluence expected to change as 1/r^{1.9}
- Errors on plot are error on mean from all sensor average

- Same info. plotted for all regions, all modules
- Lines are fits to all modules