Tracking and alignment performance of LHCb silicon detectors

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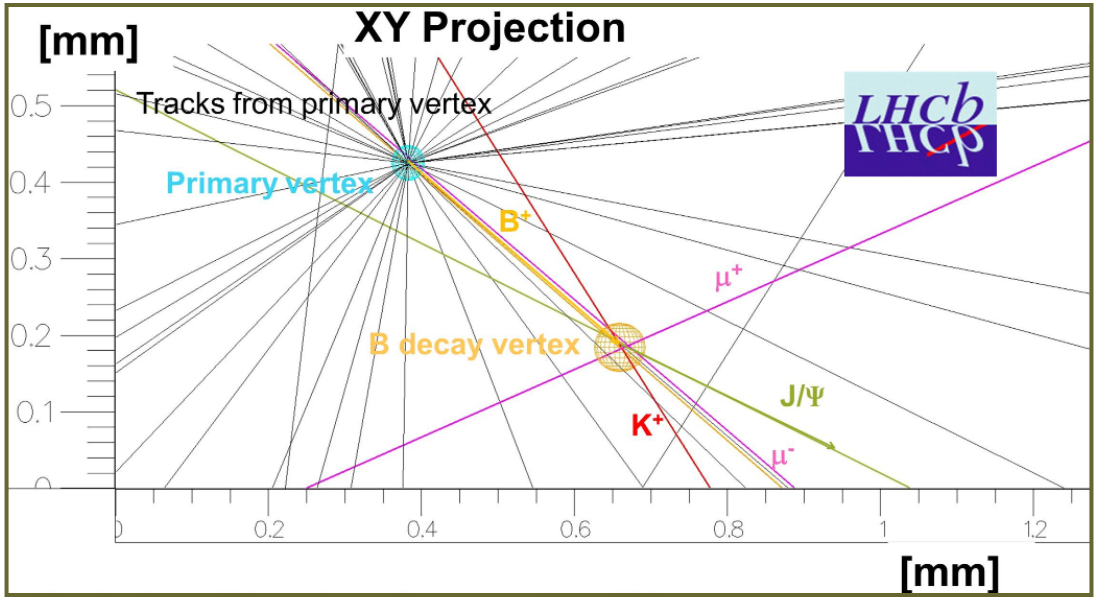
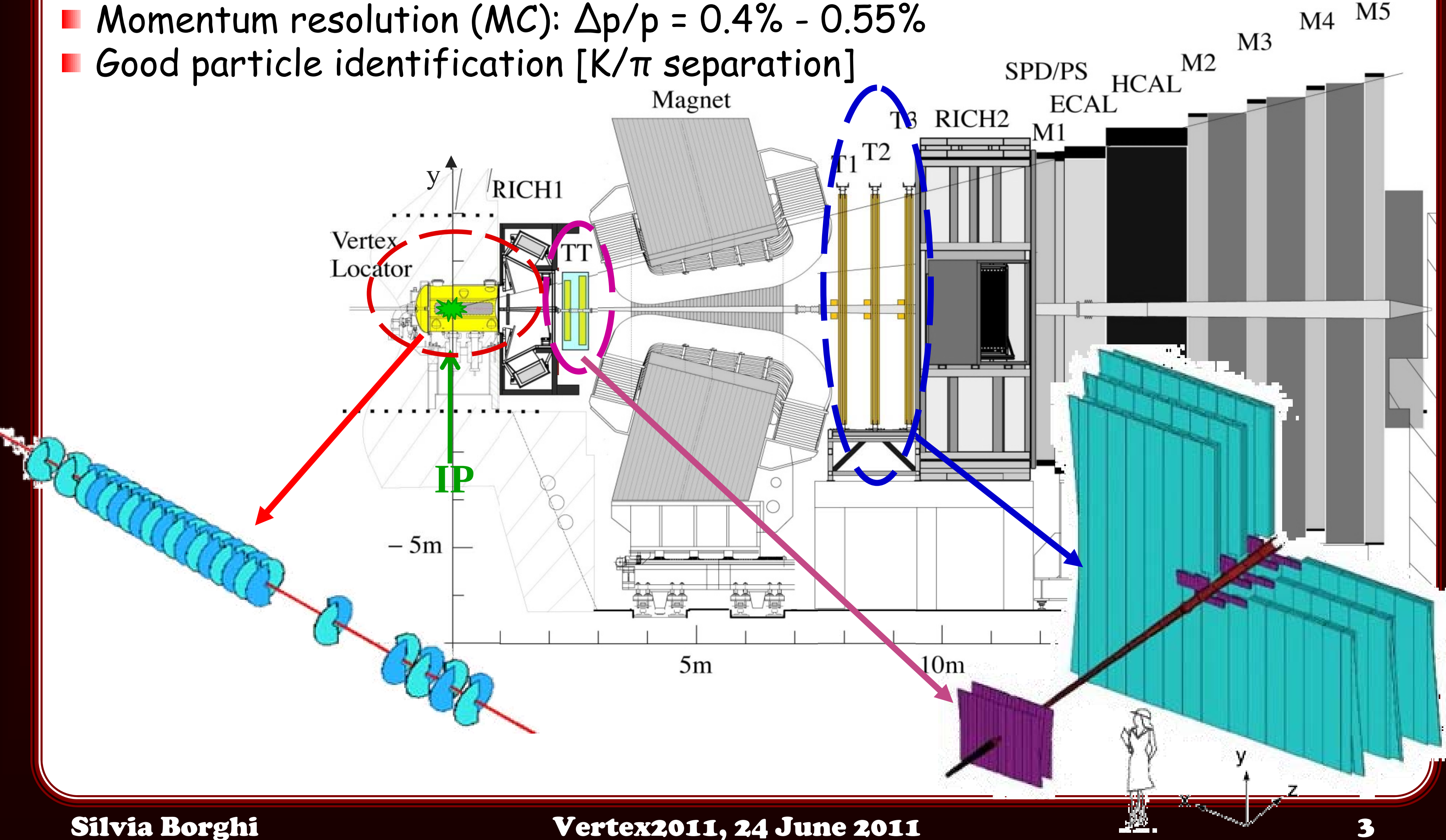
The LHCb experiment

- LHCb is an experiment dedicated to heavy flavour physics at the LHC.
- Its primary goal to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.
- $b\bar{b}$ – pairs produced predominantly close to beam direction ⇨Forward spectrometer: $1.9 < \eta < 4.9$
- Requirements:
  - High precision measurement of primary and secondary vertex ➔ proper time
  - Good momentum resolution $\Delta p/p$ = 0.4% - 0.55%
  - Good particle ID



Main detector requirements

- Good vertex resolution [proper time]
- Momentum resolution (MC): $\Delta p/p$ = 0.4% - 0.55%
- Good particle identification [K/π separation]



Overview of LHCb detector

Main detector requirements

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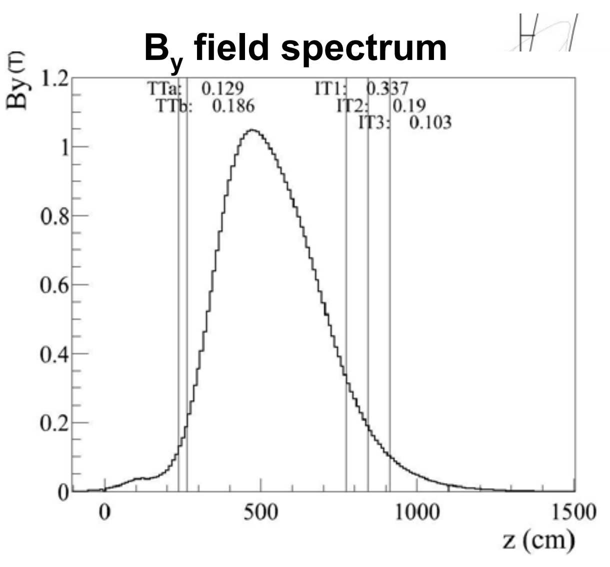
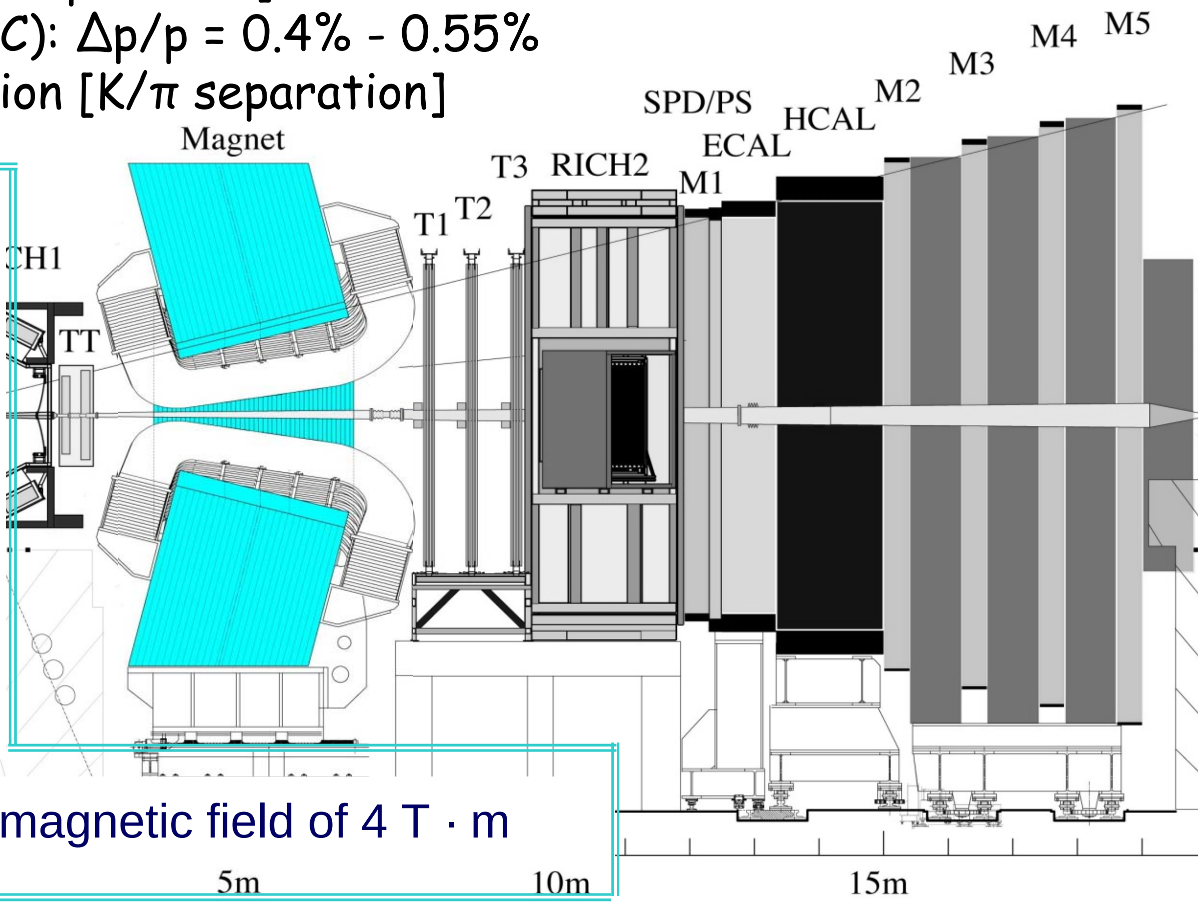
- Good particle identification [K/π separation]





- Warm Magnet integrated magnetic field of 4 T · m

Silicon Vertex and Tracker detectors

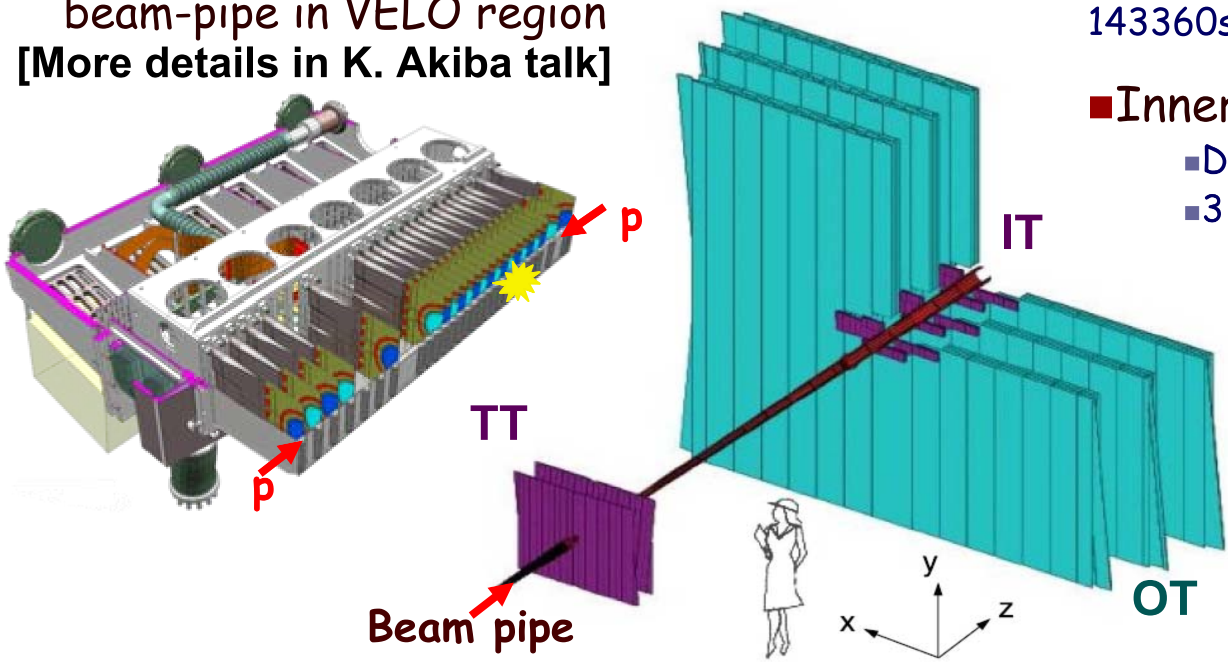
Vertex detector

- 21 silicon micro-strip stations with r-ϕ geometry
- 2 retractable detector halves:
  - 8.2 mm from beam with stable beam condition,
  - 30mm from beam during injection and MD
- 300µm foil separates detector vacuum from beam vacuum and constitutes beam-pipe in VELO region

[More details in K. Akiba talk]

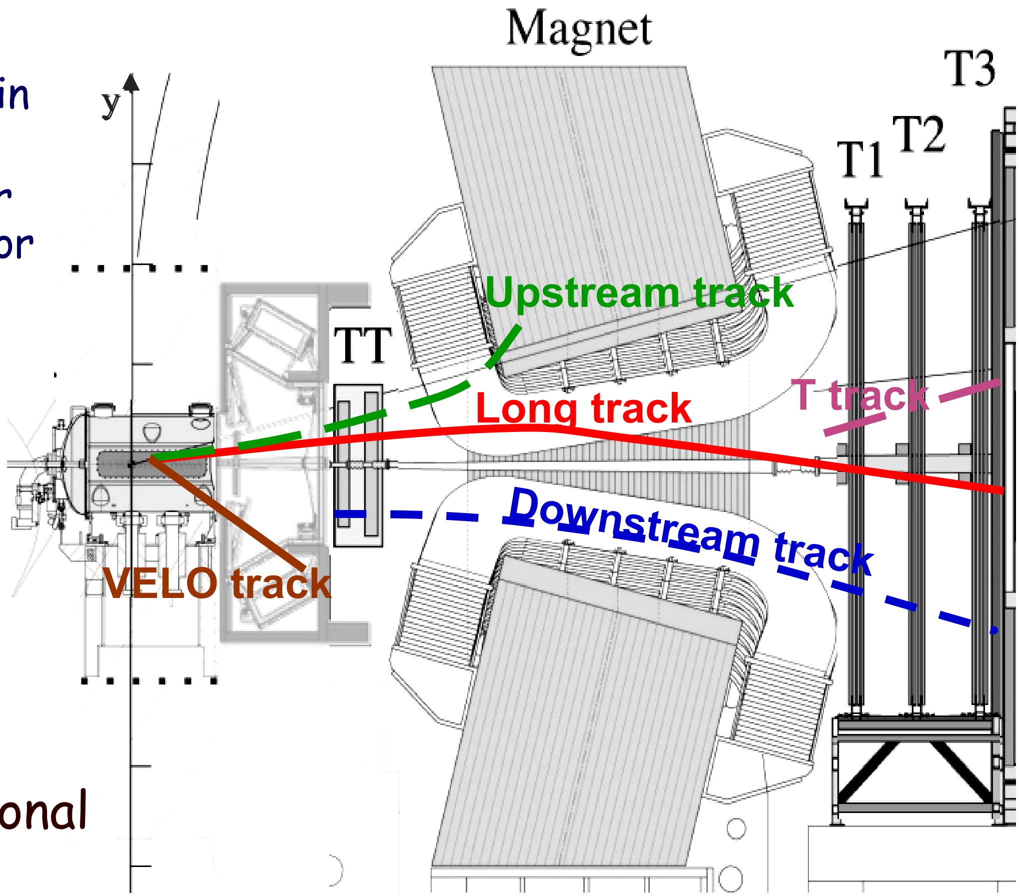
Silicon tracker

- Track Turicensis (TT) detector
  - Upstream of the magnet
  - Four planes of silicon micro-strip (p on n) sensors (0°, +5°, -5°, 0°)
  - Readout pitch 183 µm pitch
  - 500 µm thickness
  - strip length from 9 to 37 cm
  - Area of 8.2 m2 covered by Silicon, 143360strips
- Inner Tracker (IT) detector
  - Downstream of the magnet
  - 3 stations with 4 layers (0°, 5°, -5°, 0°)
    - Readout pitch 198 µm
    - 320/410 µm thickness for 1/2 sensor ladders
    - Area of 4.2 m^2 covered 129024 readout strips



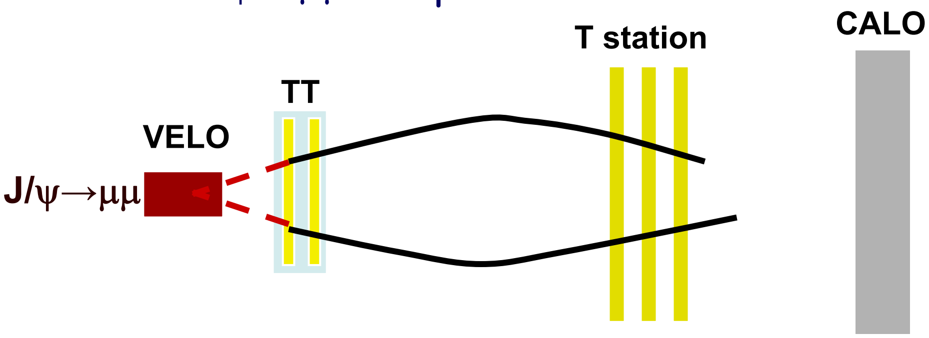
LHCb Tracking

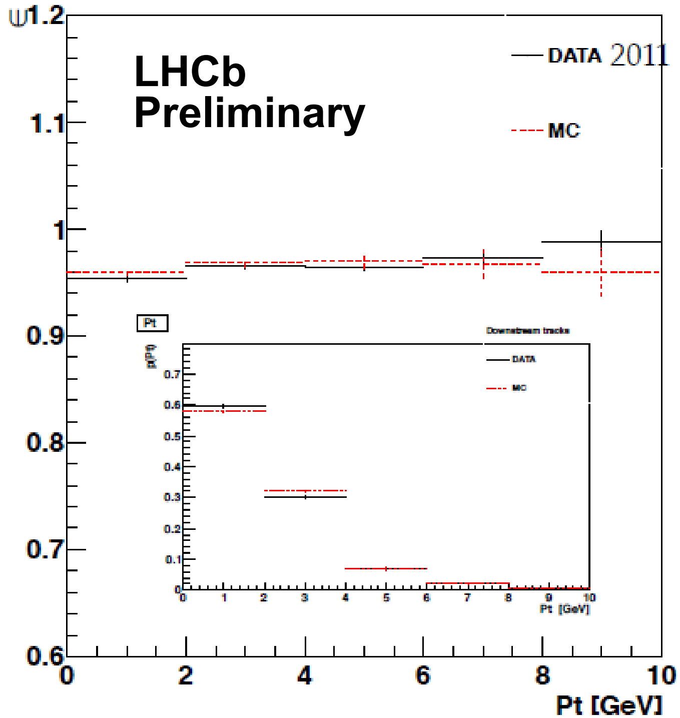
- VELO tracking using r and ϕ hits
  - Same tracking in trigger and in offline data processing
  - No momentum information for backward tracks ➔ needed for improving PV resolution
- Long tracks
  - Extrapolate VELO tracks and associate hits in T-stations
  - Combine VELO tracks with seeds from T-station
  - Add TT hits for resolution
- Track fitting with bi-directional Kalman filter and detailed material map



Track efficiency

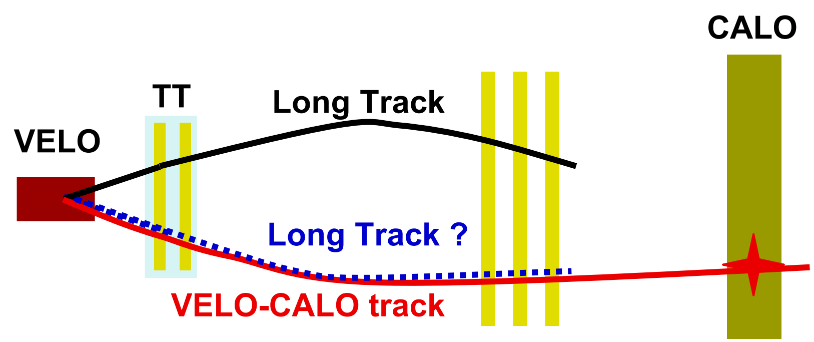
- Efficiency of VELO tracking:
  - Using Tag and Probe method with $J/\psi \to \mu\mu$ sample





Good agreement between data and MC

- Similar method can be used to evaluate the efficiency of the tracking system
  - Selecting $K \to \pi\pi$ or $J/\psi \to \mu\mu$



Alignment

VELO: sensor module alignment

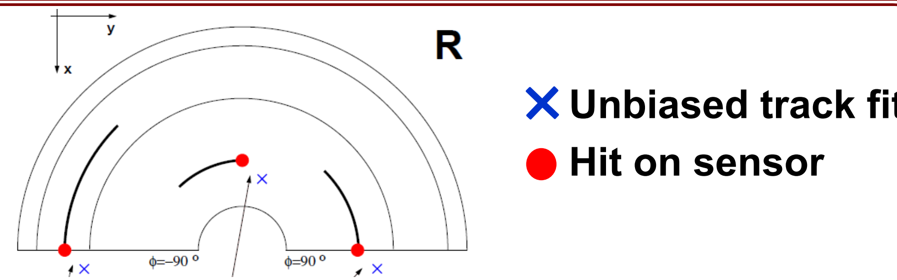
First method

- Module and 2 half alignment by method based on Millepede
- Sensor alignment by an histogram method, used also for monitoring

Second method

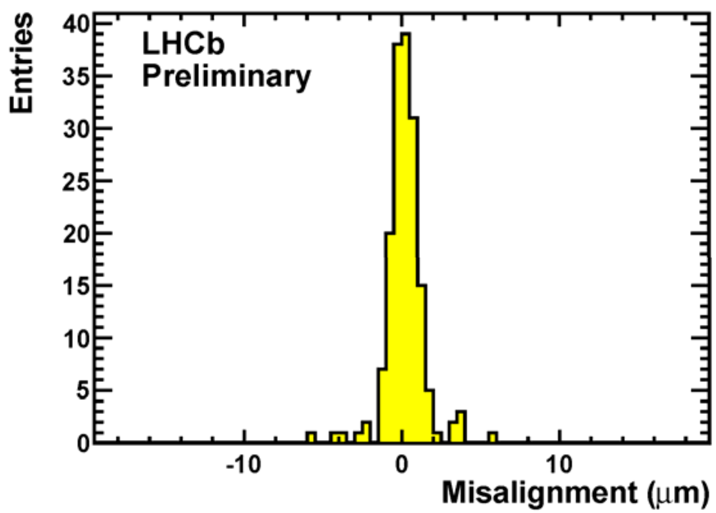
- Global χ^2 minimisation based on Kalman track fit residuals.

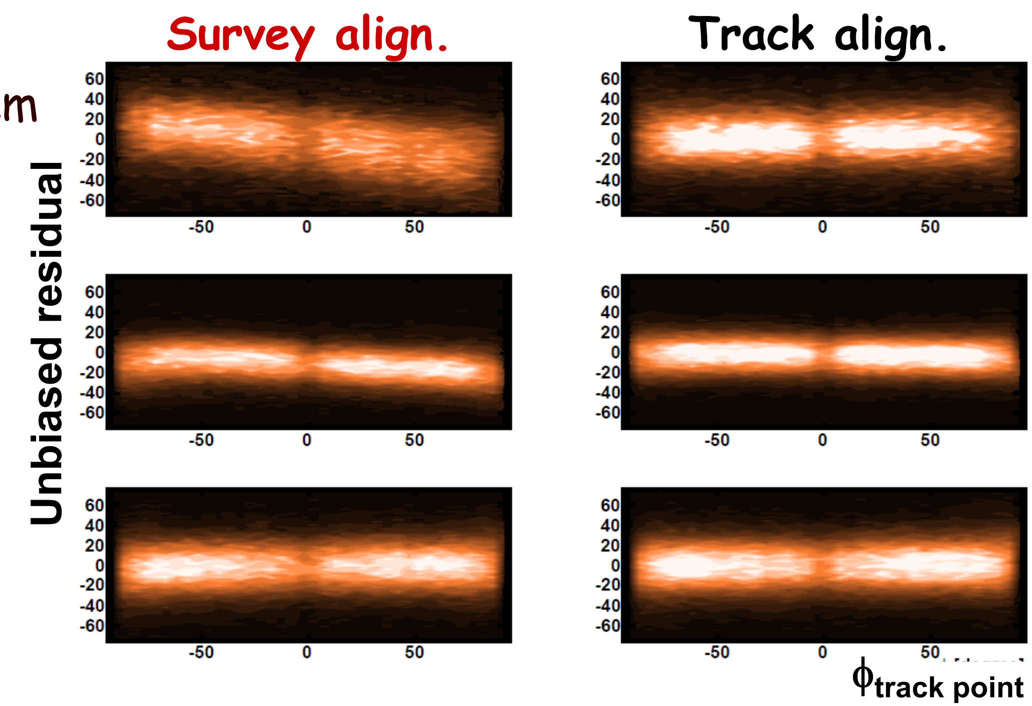
Sensor alignment better than 4 μm



$$res.(R) = -\Delta x \cos\phi_{track} + \Delta y \sin\phi_{track}$$

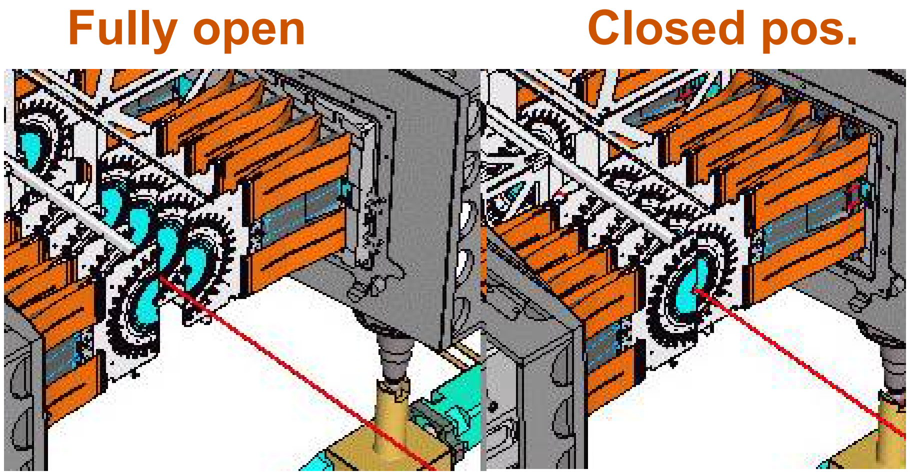
$$res.(\Phi) = \Delta x \sin\phi_{track} + \Delta y \cos\phi_{track} + \Delta\gamma\, r_{track}$$

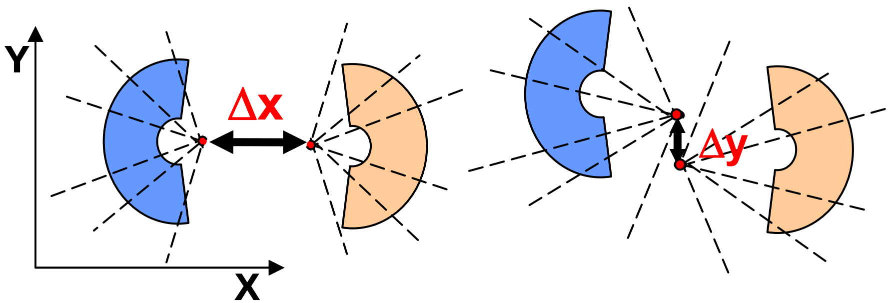


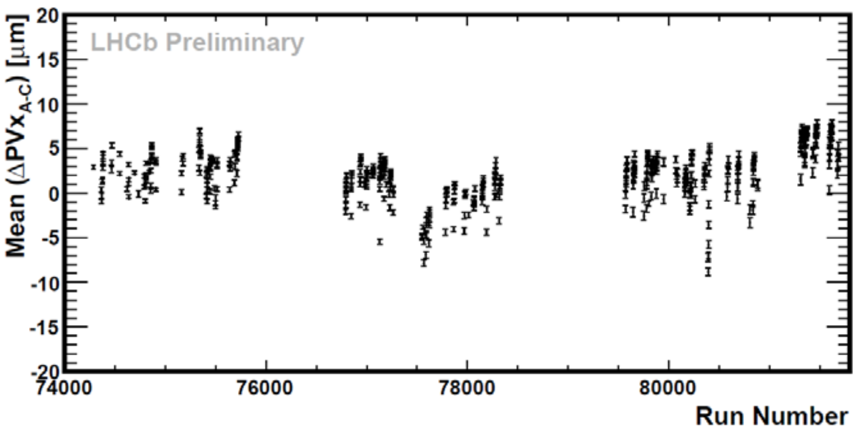


VELO: 2 half alignment

- VELO centred around the beam for each fill when the beam declared stable
- PV method:
  - Reconstruct PV using tracks in left or in the right side
  - Evaluation of misalignment by the distance between the 2 vertices
- Stability of 2 half alignment by PV method:
  - within ± 5 μm for Tx
  - within ± 2 μm for Ty



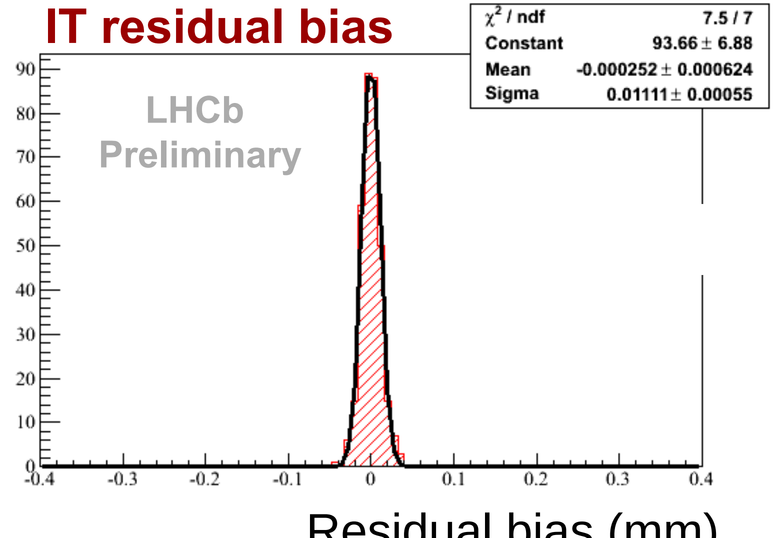




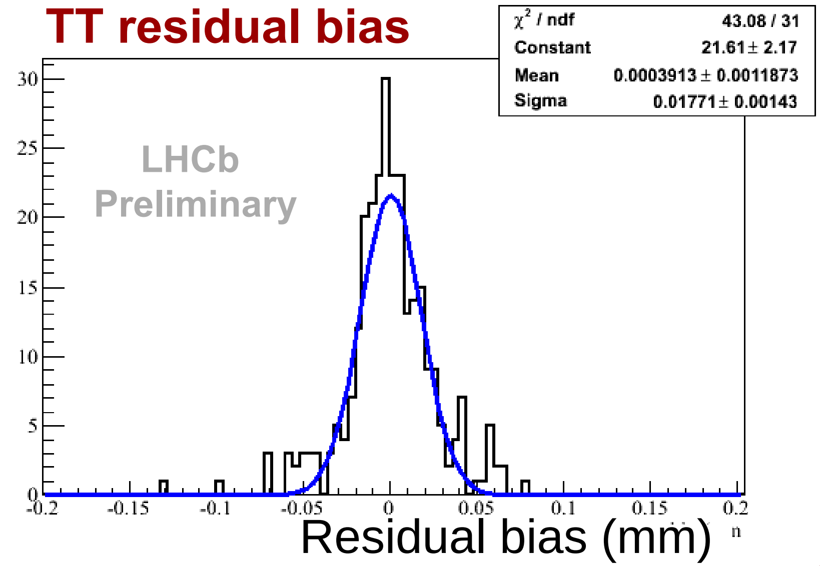
ST: alignment

- Method:
  - Global χ^2 minimisation based on Kalman track fit residuals
  - track t residual
  - applying also mass constraints (J/Ψ and D^0 masses)
  - No sensitive to Ty alignment
- Alignment precision evaluated by the bias of the residuals
  - IT Misalignment 11.1 μm
  - TT Misalignment 17.7 μm

IT residual bias

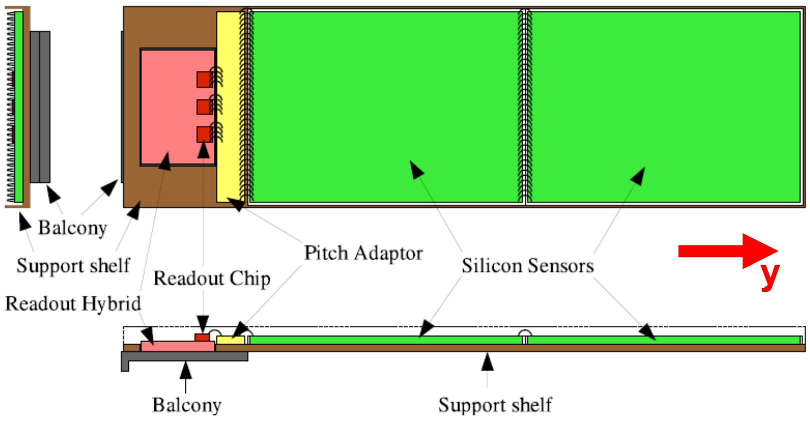


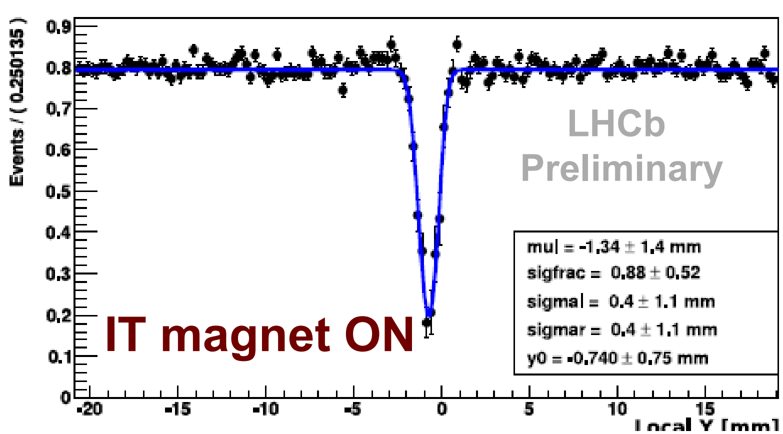
TT residual bias

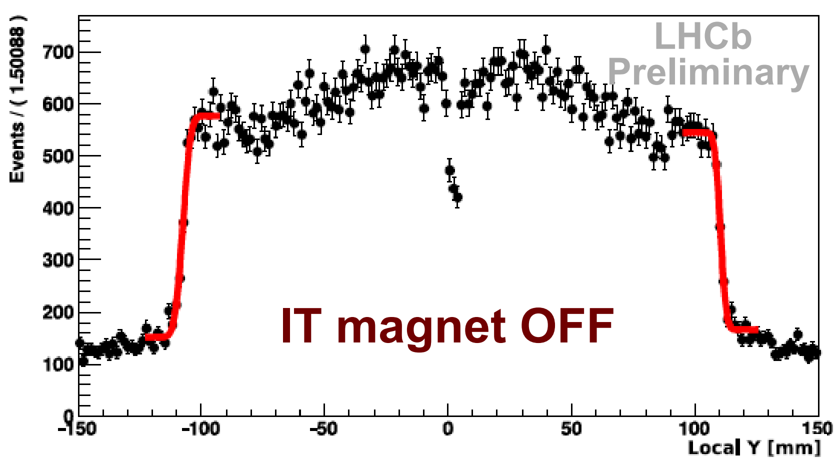


ST: alignment

- ST modules have gaps due to insensitive Guard Rings and edges in Y hits distributions.
- Extrapolation VELO tracks to the IT and TT stations
  → evaluation of y misalignment
- To disentangle y misalignment and effect due the magnetic field
  → magnet off data for alignment
  → magnet on data for validation



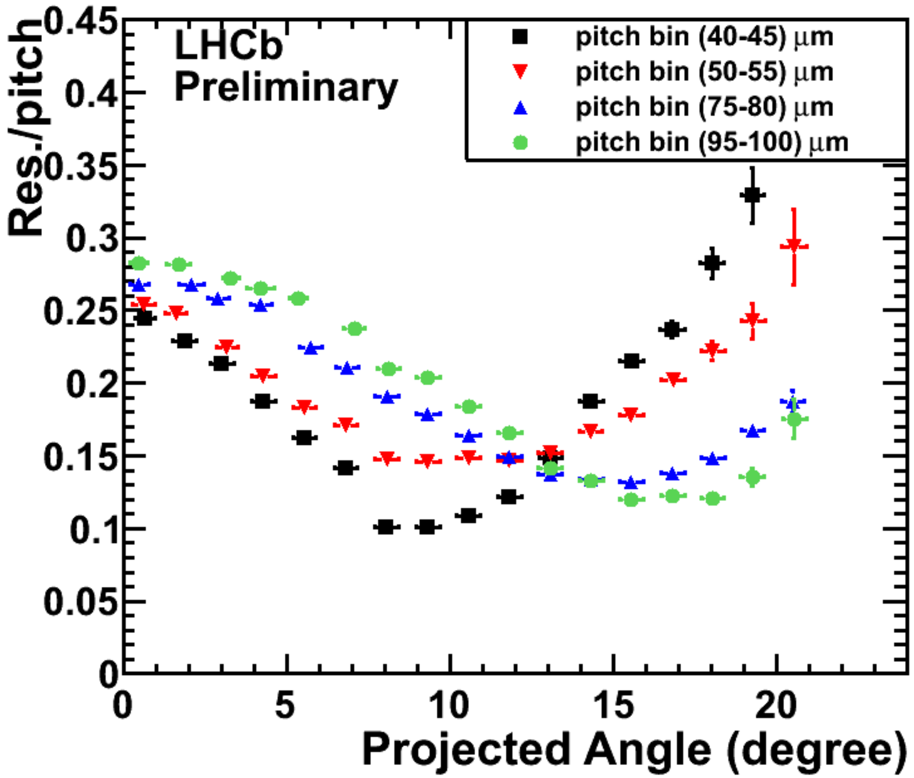




Hit resolution

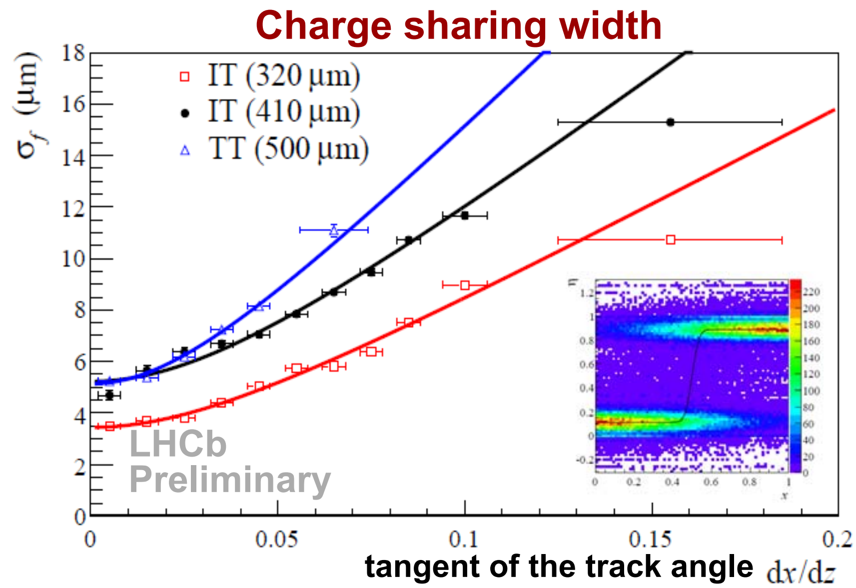
VELO: hit resolution

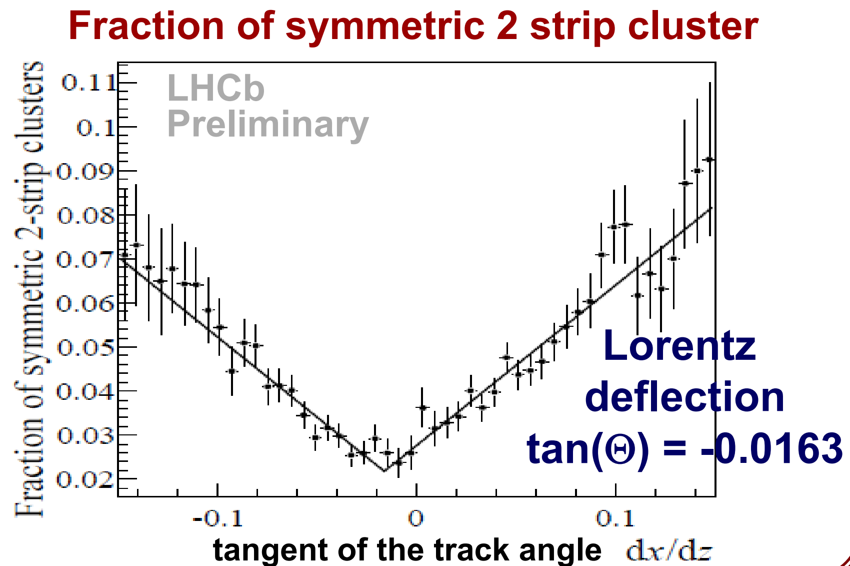
- Main dependence:
  - strip pitch
  - projected angle (the angle between the track and the strip in the plane perpendicular to the sensor).
- Other factors:
  - Charge sharing as function of fractional strip position (η)
    ➔ work on progress for η correction implementation
- Hit resolution:
  - Best hit resolution 4 μm
  - Good agreement with MC
  - Improvements expected with η correction



ST: hit resolution

- Dependency:
  - Strip pitch
  - Charge sharing
  - Cross talk due to capacitive coupling between the strips
  - Lorentz angle: bias of cluster position due to the presence of B_{field}
- Tuning of Monte Carlo with the measured parameters



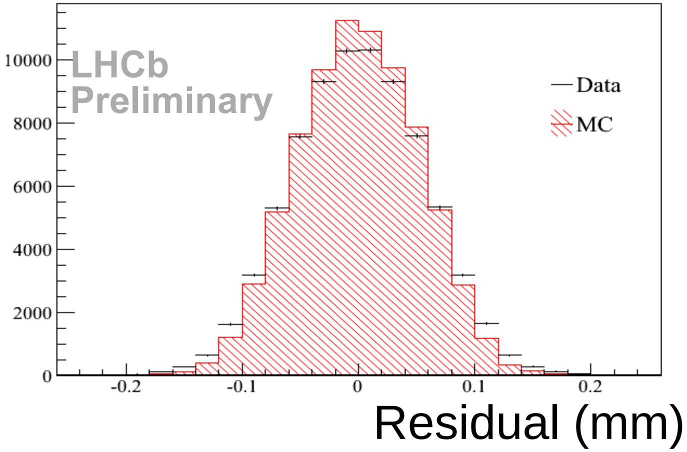


ST: hit resolution

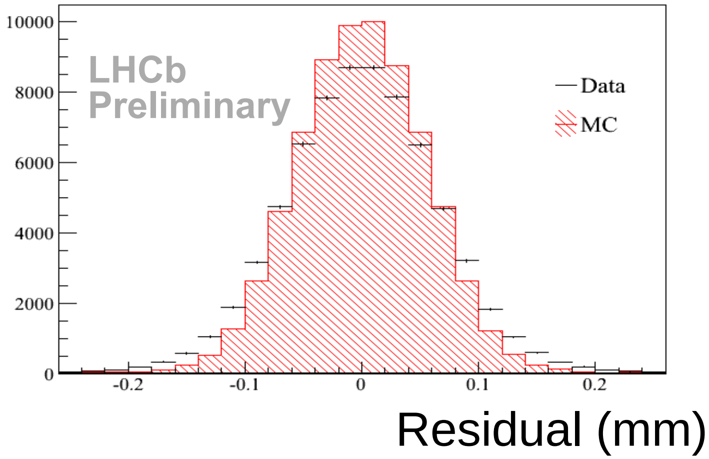
- Hit resolution
  - IT : 58 μm, strip pitch 190 μm
  - TT : 62 μm, strip pitch 183 μm

- The difference with respect to Monte Carlo due to:
  - some difference in the gain
  - status of the alignment

Residuals of IT



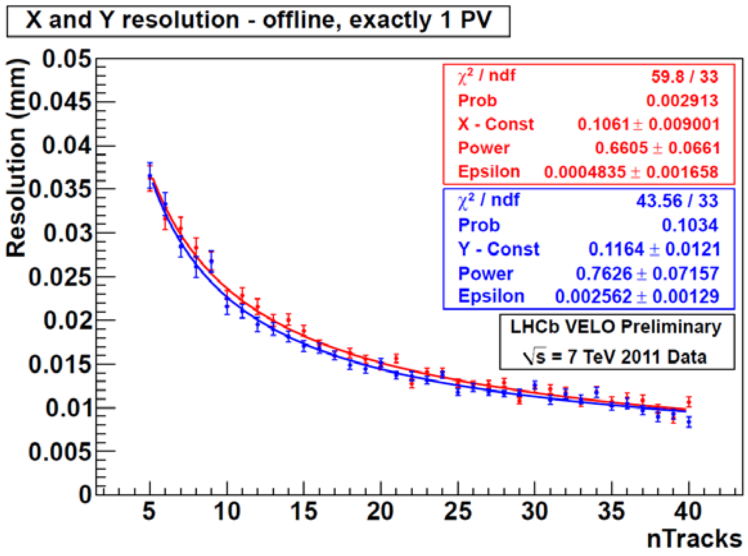
Residuals of TT

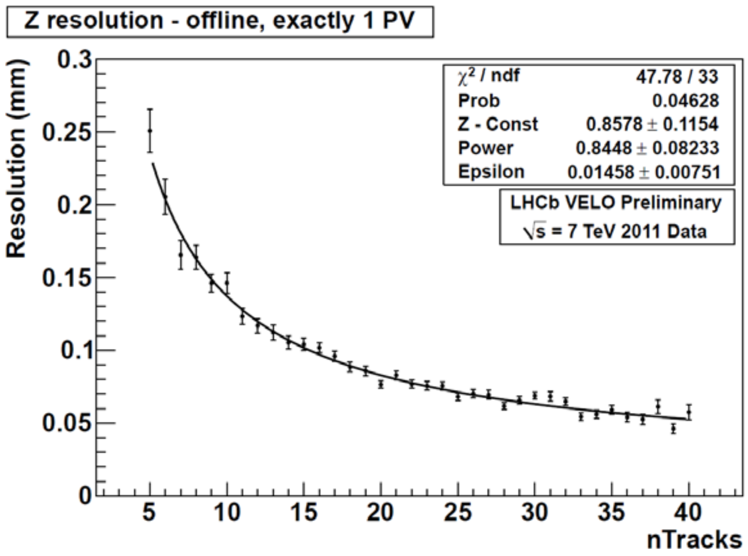


Physics Performance

Primary Vertex Resolution

- Vertex resolution
  - Measure resolutions by randomly splitting track sample in two
  - Compare split vertices of equal multiplicity
  - Method validated with MC
- PV resolution (x,y,z) with 25 tracks:
  - Data (13.0, 12.5, 68.5) µm
  - MC (10.7, 10.9, 58.1) µm
- Room for improvement





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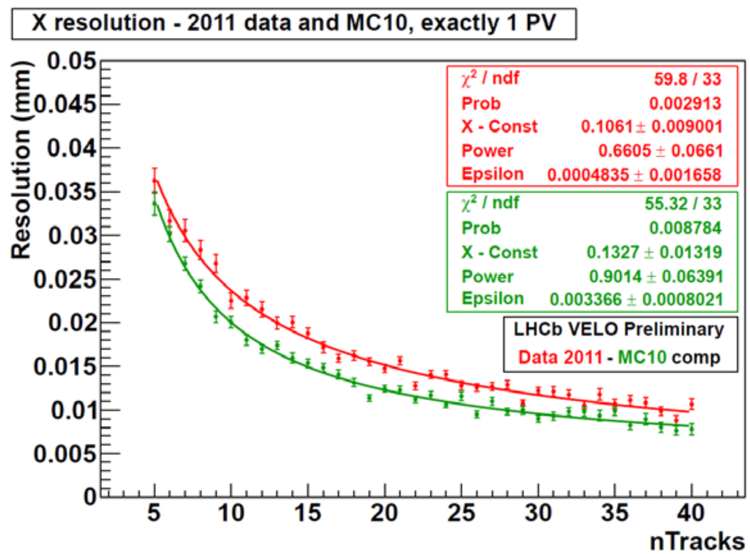
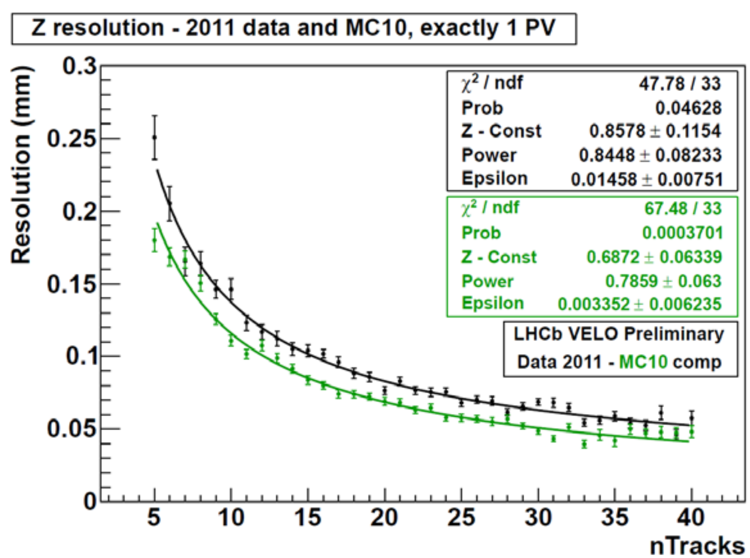
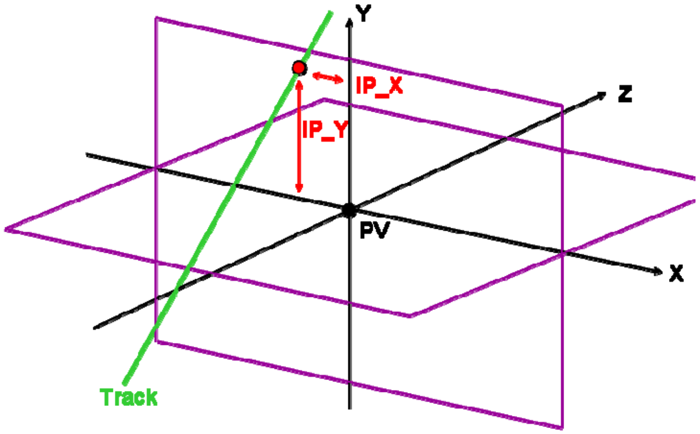
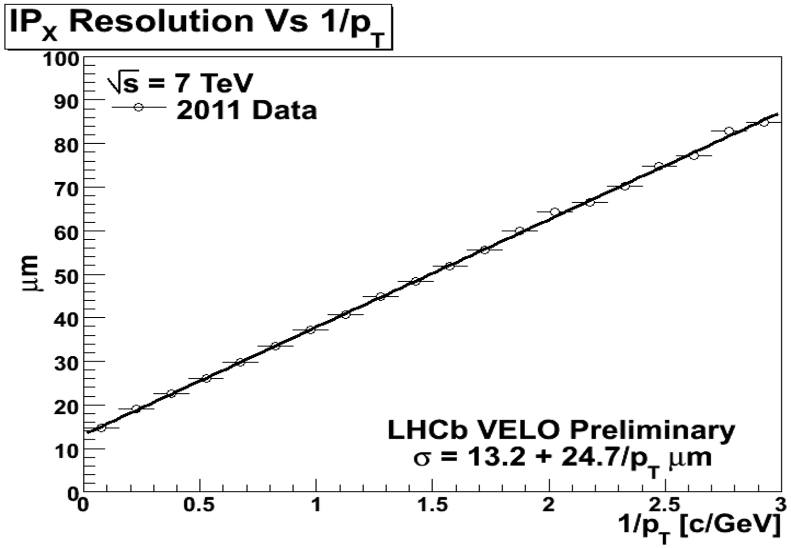


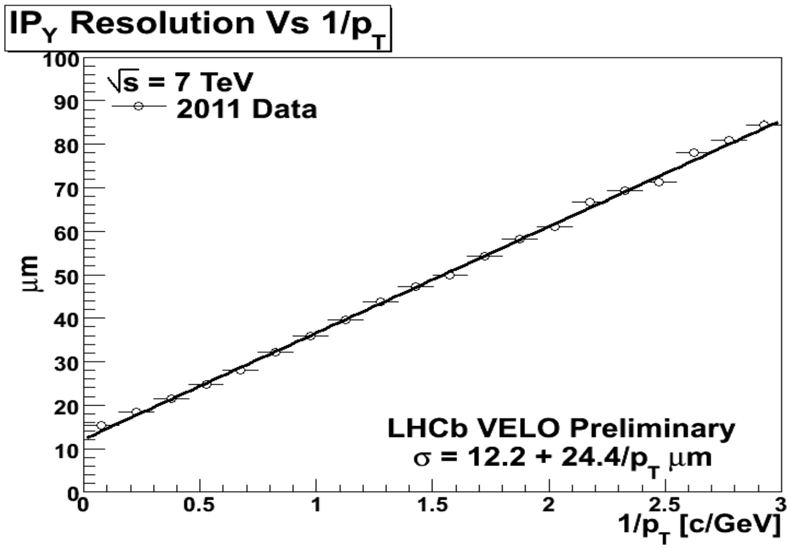


Impact Parameter resolution

- IP resolution:
  - defined as the closest distance of each track to the primary vertex
  - Measure x and y component of impact parameter
  - Assume all tracks originate from primary interaction point
  - Measure resolution as spread of IP distribution
- **IP resolution down to 13 μm for high p_t**







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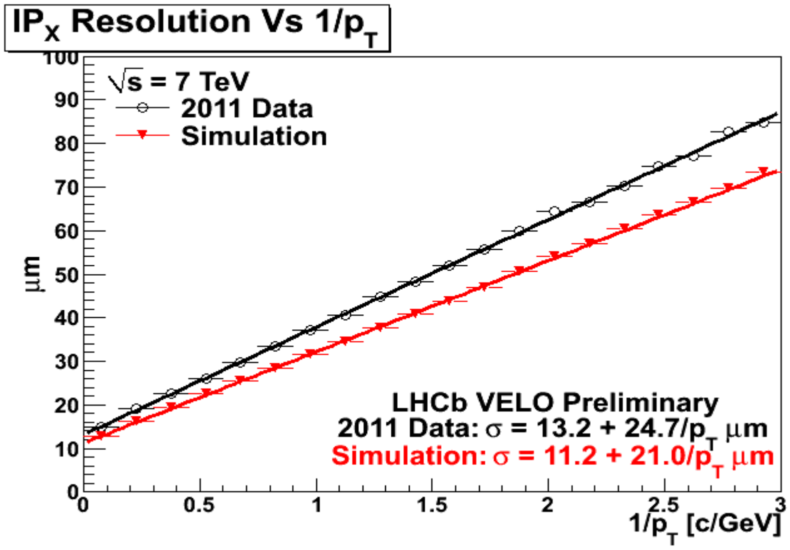
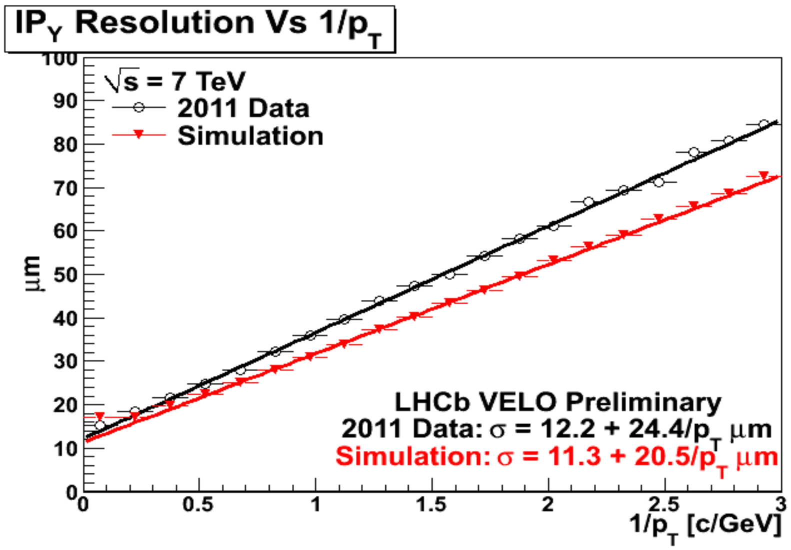
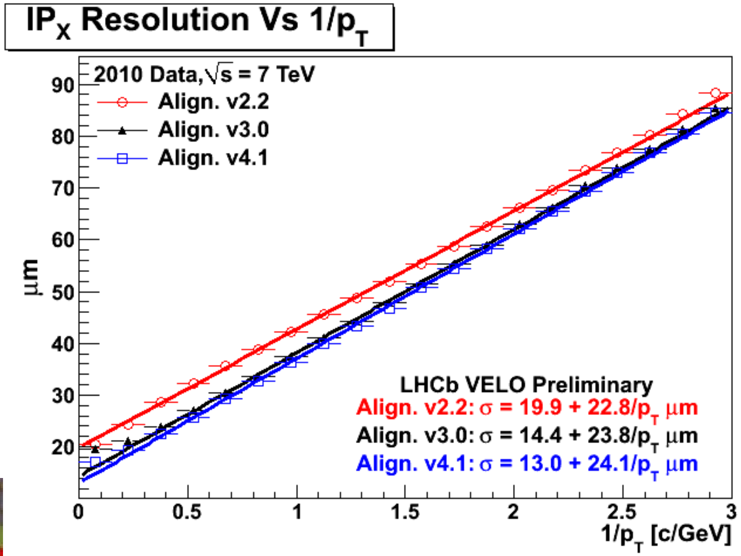
  - Measure resolution as spread of IP distribution
- **IP resolution down to 13 μm for high p_t**
- MC resolution down to 11 μm
- Possible cause of discrepancy
  - Alignment effect
  - Material description



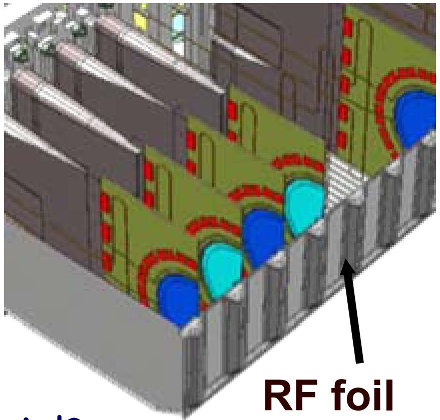


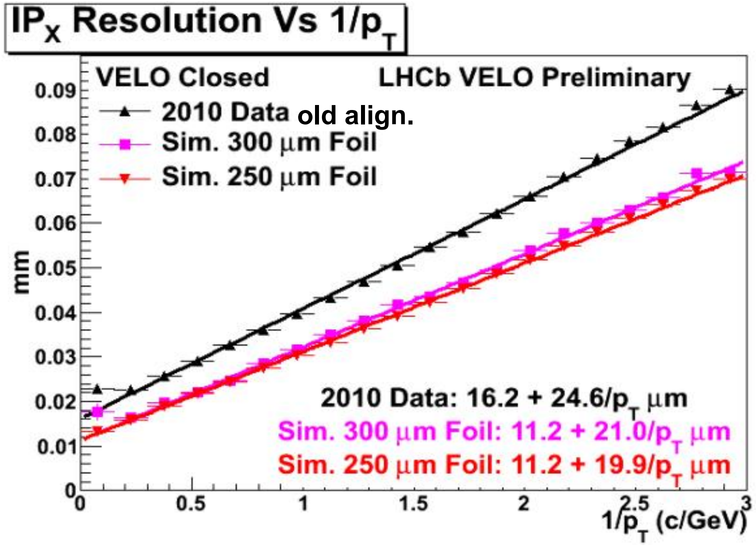
Impact Parameter resolution

- Alignment effect:
  - Improving alignment closed the gap between data & MC at high p_T.
  - Difference between gradients remains roughly constant.



- Material effect:
  - RF foil thickness 250 μm instead of 300 μm
    ➔ small change in the slope

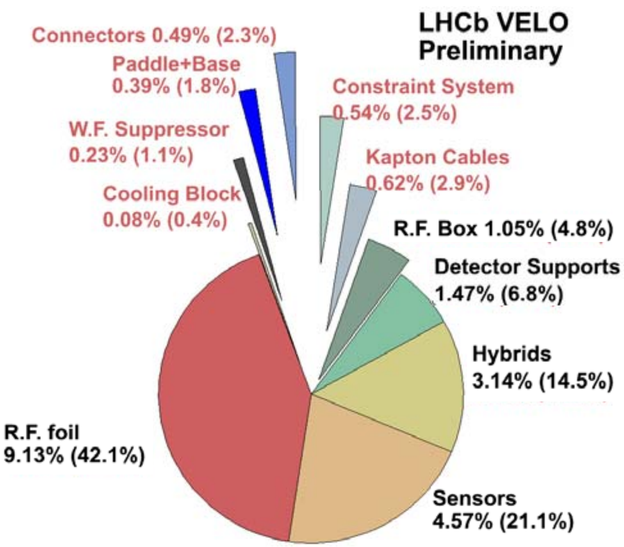


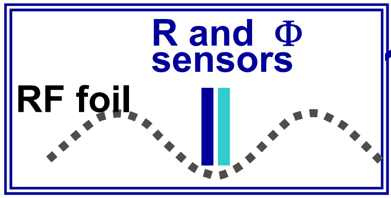


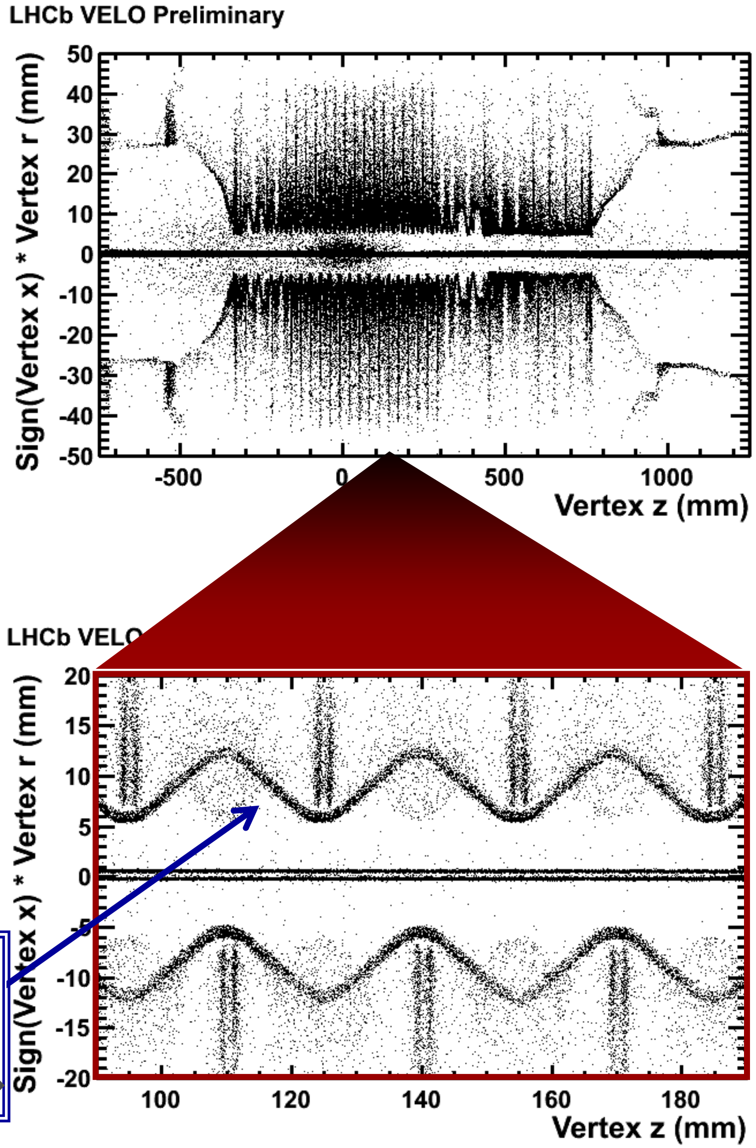
  - Missing other material?
    ➔ detailed material scan study by vertex interaction

Material study

- Use detector model in simulation to estimate material budget
  - Largest contribution from RF foil (~42%)
- Use vertices of hadronic interactions with material to map VELO
- The $\frac{\#\text{interaction}(Si)}{\#\text{interaction}(RF)}$ has good agreement between data and MC
  - Good description of total material
- Changing the Geant setting, size of multiple scattering is changing

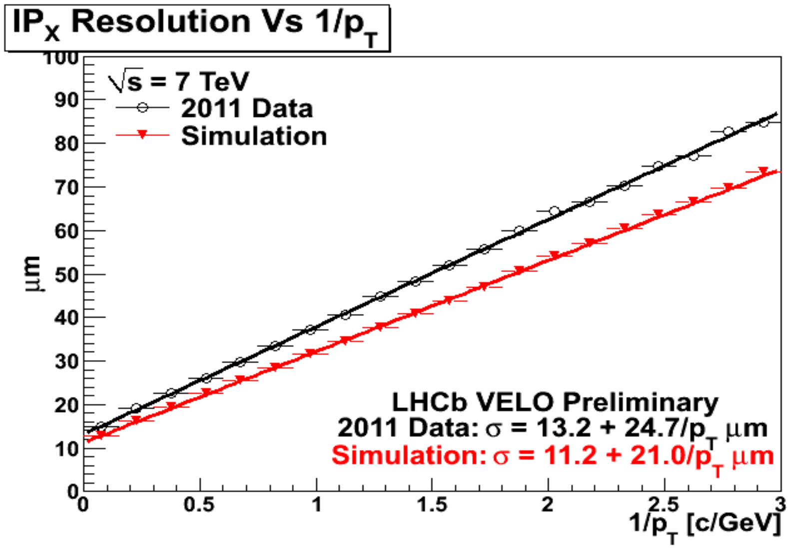


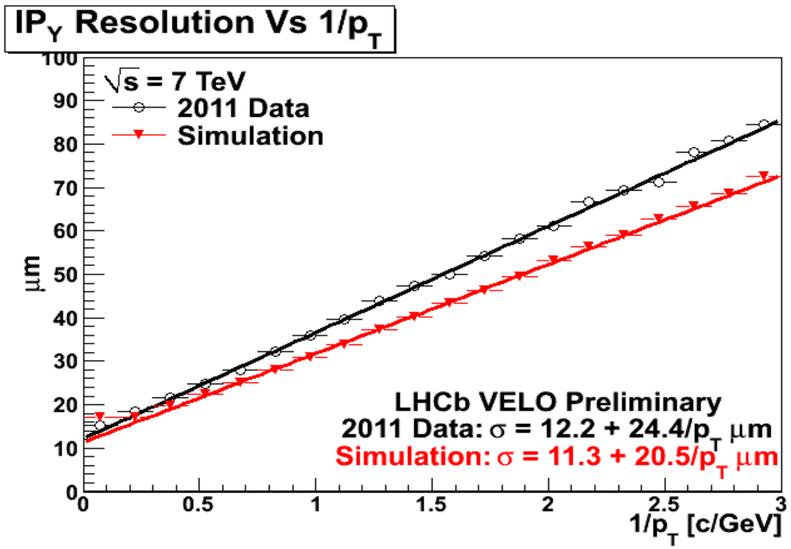




Impact Parameter resolution

- IP resolution:
  - Impact Parameter (IP) is defined as the closest distance of each track to the primary vertex:
  - Measure x and y component of impact parameter
  - Assume all tracks originate from primary interaction point
  - Measure resolution as spread of IP distribution
- **IP resolution up to 13 μm for high p_t**
- MC resolution up to 11 μm
- Still under investigation the discrepancy between data and Monte Carlo

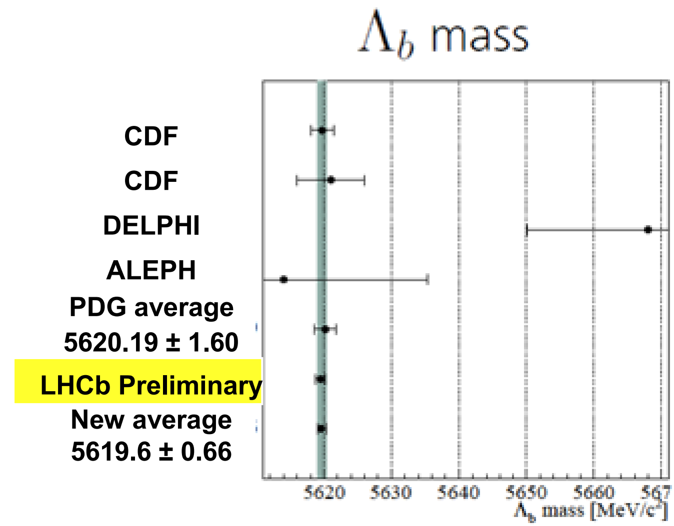


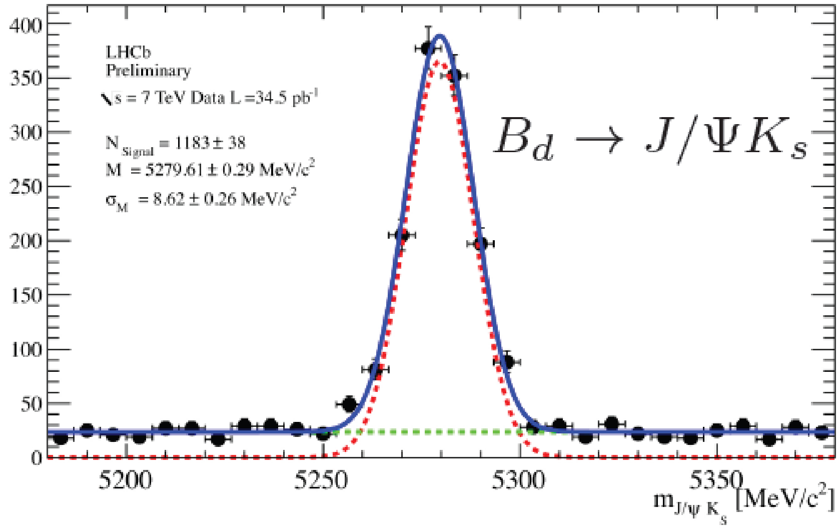


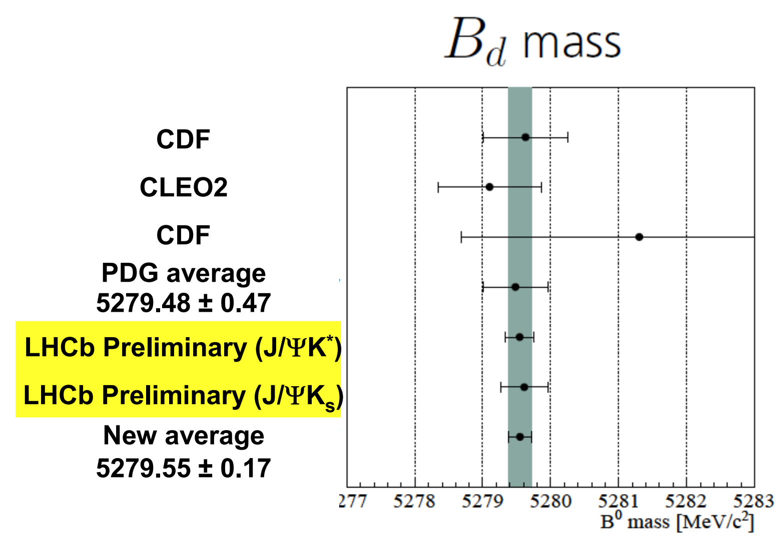
Mass measurement

- Very precise momentum and mass resolution
- Mass measurement:

→ world best measurements for B_u,B_d,B_s and Λ_b after one year of data taking

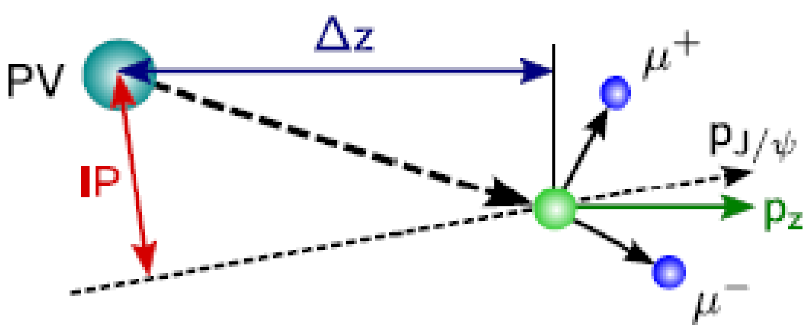




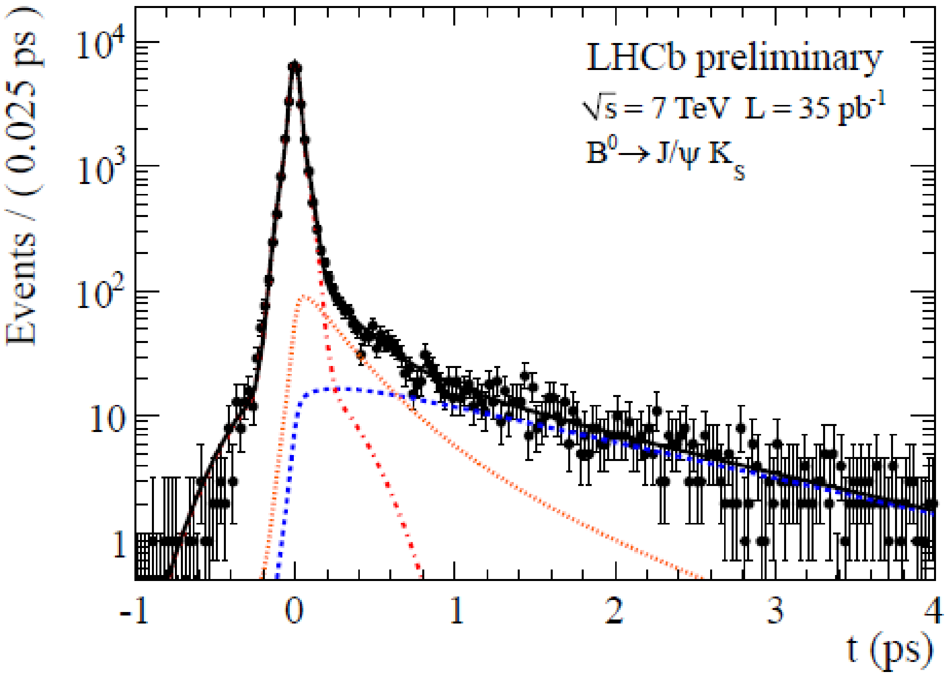


Proper time resolution

- Proper time resolution ~50 fs
- Many physics results, one example:
  - Competitive measurement of $B_s^0 - \overline{B}_s^0$ mixing frequency Δm_s with 36 pb^{-1} $\Delta m_s = 17.63 \pm 0.11$ (stat.) ± 0.04 (syst.) ps^{-1} **LHCb Preliminary**



$$t_{J/\psi} = \frac{\Delta z}{p_z} m_{J/\psi}$$



Conclusion

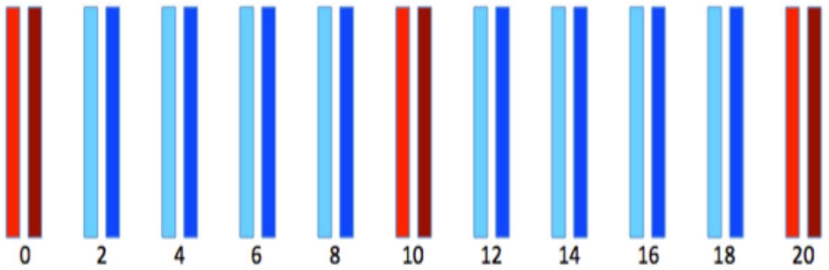
- Excellent performance of the vertex and tracker detectors in LHCb experiment:
  - Good understanding of tracking and alignment
  - High track efficiency
  - Hit resolution for VELO down to 4 μm and for ST ~190 μm
  - PV resolution at ~13 μm
  - IP resolution down to 13 μm
  - Good momentum and mass resolution
  - Proper time resolution 50 fs
- Given a powerful tool to obtain a lot of new physics results …

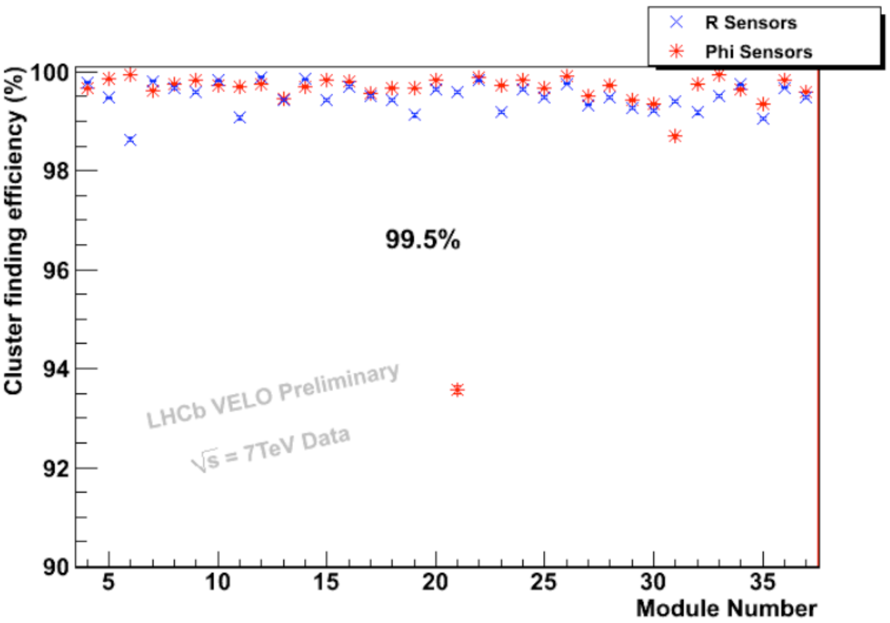
  and maybe also observation of New Physics!

Backup

VELO: Cluster finding efficiency

- Evaluation of efficiency in the test module, not used in the tracking
  - 1 module test each 5 modules
  - Same method as Charge Collection Efficiency
- Extrapolate each track to the test sensor
- If the extrapolated point in the sensitive area
- Check the cluster in the neighboring strip
- Overall efficiency is 99.5% including the known bad and dead strips





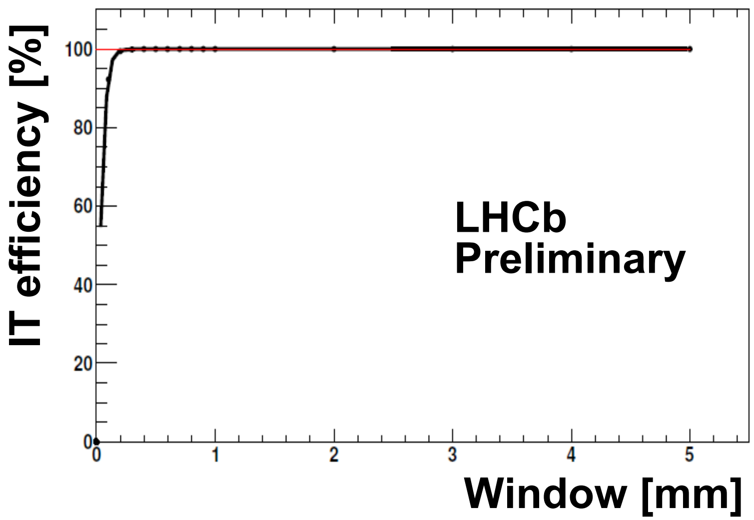
ST: Hit efficiency

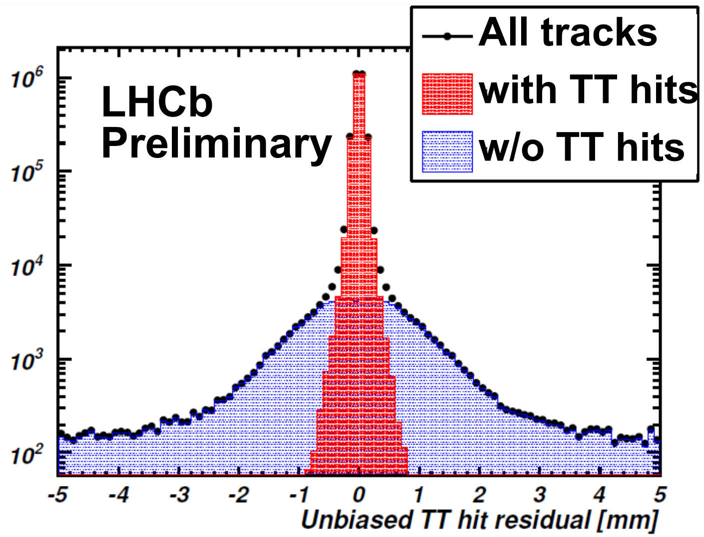
- Measure efficiency with tracks p > 10 GeV.
  - Isolation criteria to reject ghosts.
  - Efficiency varies as function of window size: 2.5 mm (TT) and 1 mm (IT).

$$\text{Efficiency} = \frac{\text{Num. found hits}}{\text{Num. expected hits}}$$

  - Noise cluster rate : $O(10^{-5})$

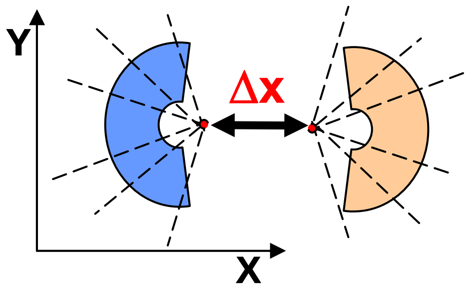
- Overall efficiencies :
  - IT : 99.7 %.
  - TT : 99.3 %.



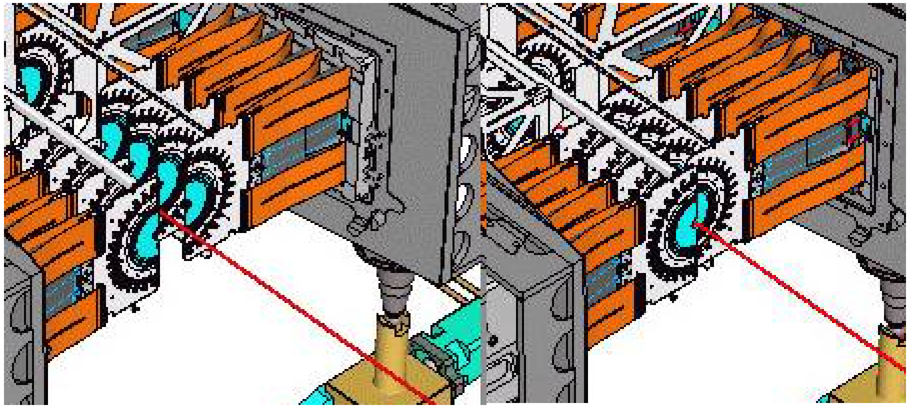


VELO: 2 half alignment

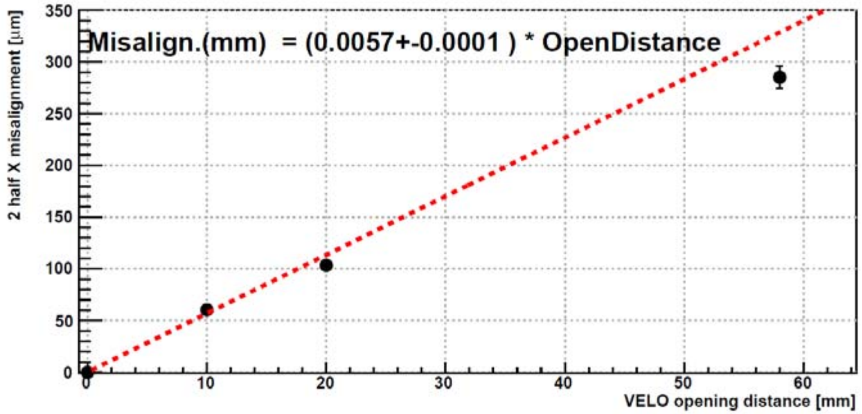
- VELO centred around the beam for each fill when the beam declared stable
- Special Data taking condition at beam energy below 7 TeV:
  - at 0.9 TeV ➔ VELO at ± 10mm
  - at 2.8 TeV ➔ VELO at ± 5mm
- Motion system high precision for opening distance < 5 mm
  - Not foreseen other positions than fully closed
  - Observed large misalignment
- Calibration of resolver position using PV method



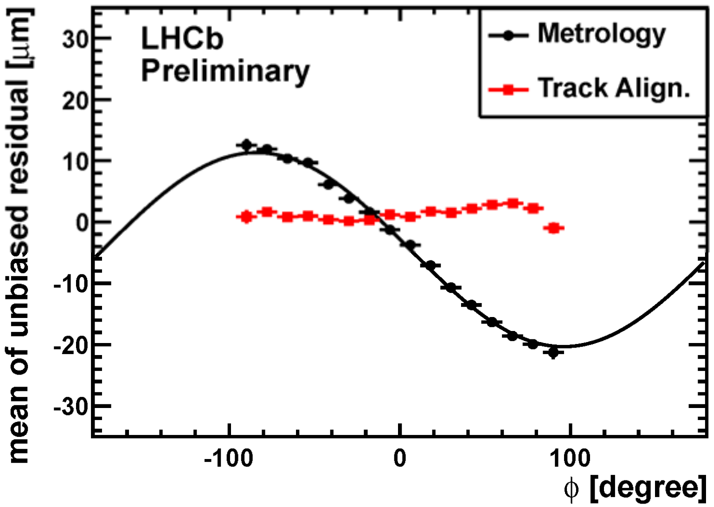
Fully open Closed pos.

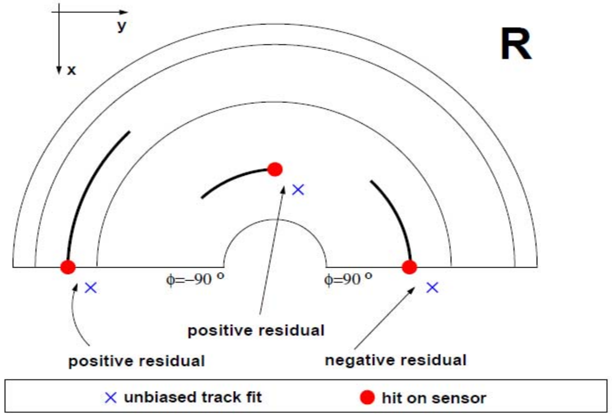


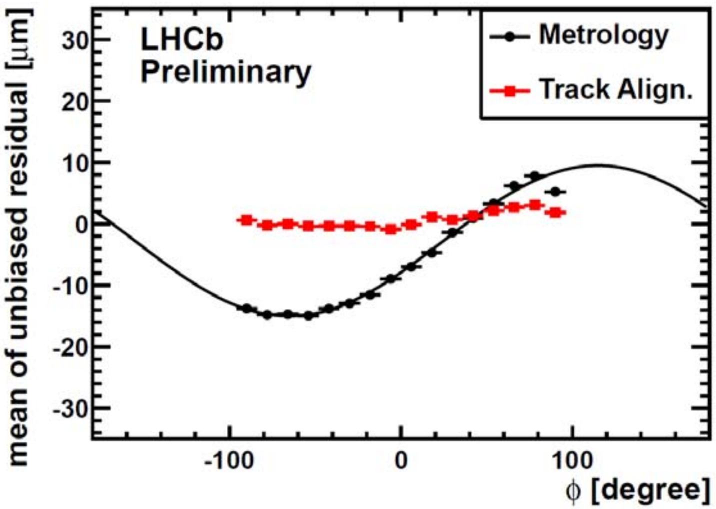
Scale factor of 0.57%

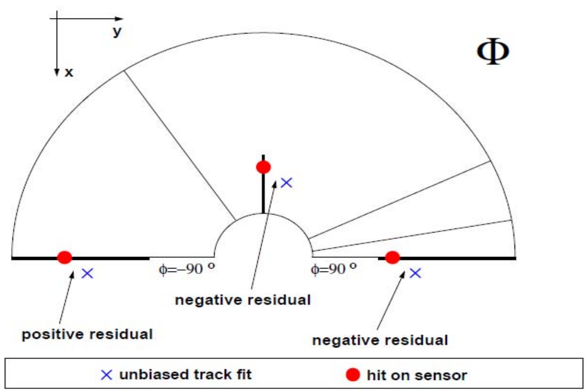


VELO: sensor module alignment



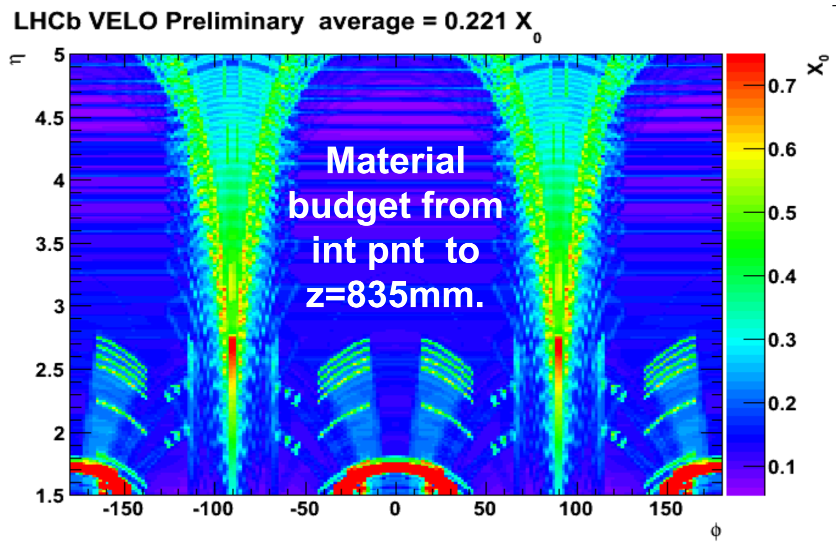


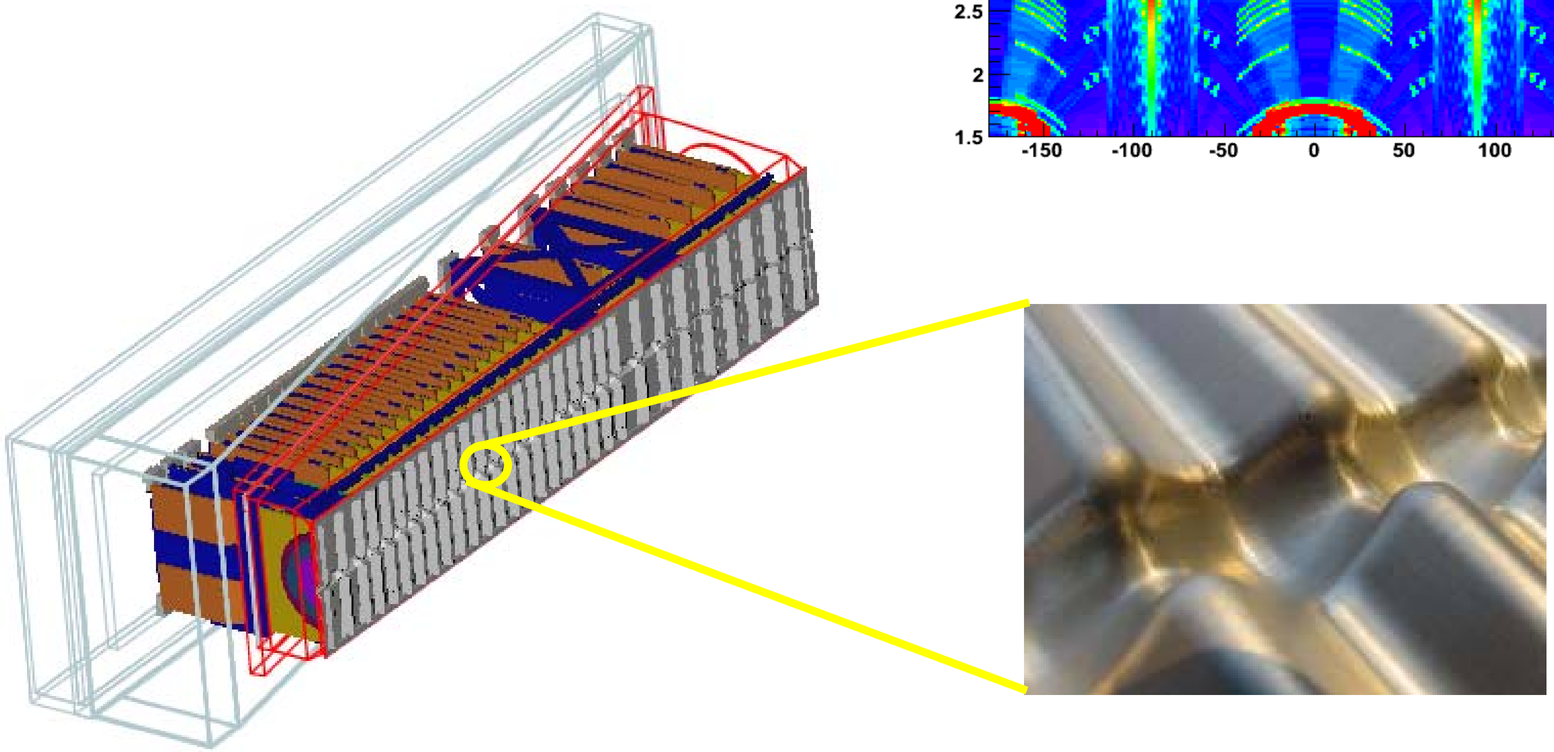




Material study

- Material budget
- Use detector model in simulation to estimate material budget
- Average particle leaving VELO sees 0.217 X_0 material for 1.6< η<4.9
- Largest contribution from RF foil (~42%)





VELO: charge sharing

Cluster size as function of the projected angle