Operation of the LHCb silicon tracking and vertexing systems in LHC Run-2

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Outline

Introduction

Large Hadron Collider beauty (LHCb) experiment in a nutshell

[Int. J. Mod. Phys. A 30, 1530022 (2015)]

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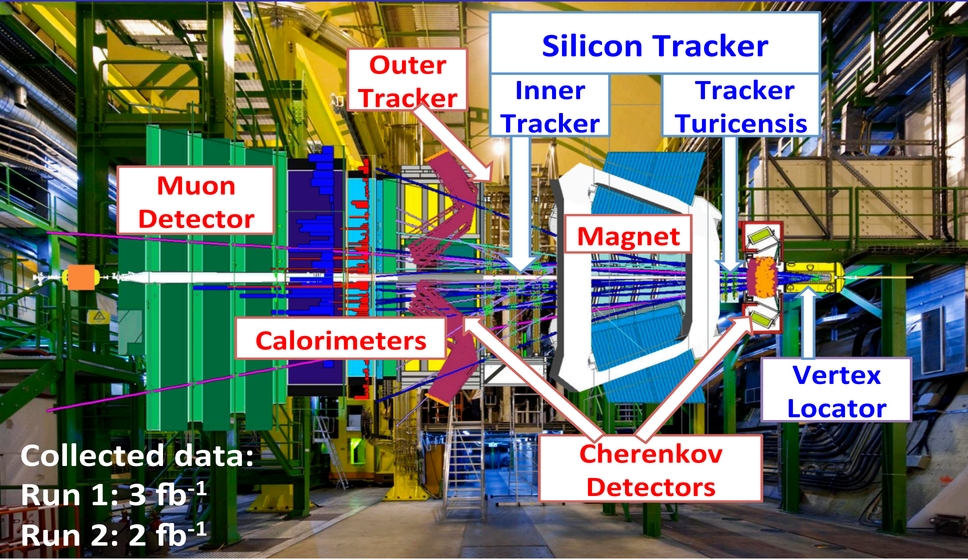


42 silicon n^+-on-n microstrip modules.

2048 strips per module:

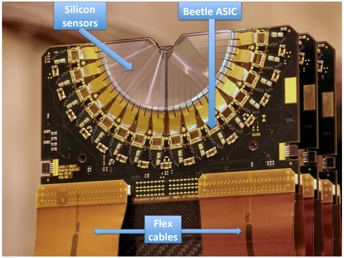
- thickness 300 μm;
- pitch $30 - 100$ μm.

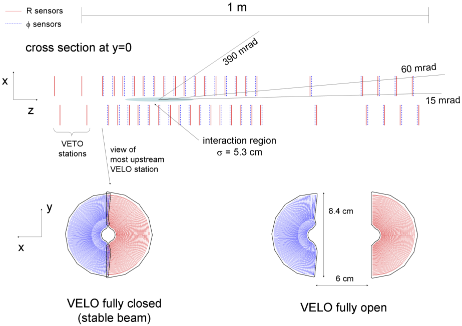
Hit resolution $\sim 5 - 25$ μm.

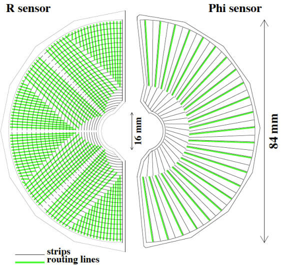
172k channels.

Crucial for:

- b and c-hadron vertices and lifetime;
- high-level trigger (rate reduction from 1 MHz to few KHz).
  - fast pattern recognition!







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

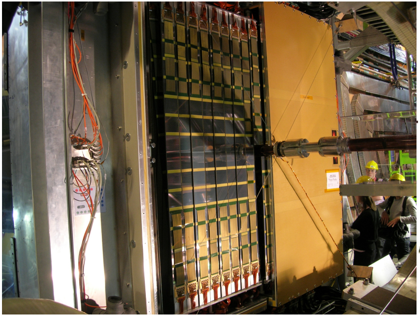
p^+-on-n, 9.64 cm × 9.44 cm × 500 μm silicon sensors.

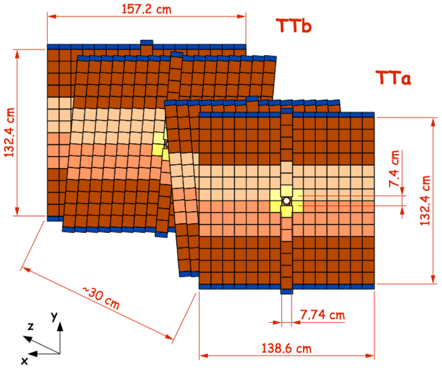
$\sim$ 143k channels, 8.4 m^2 of active area.

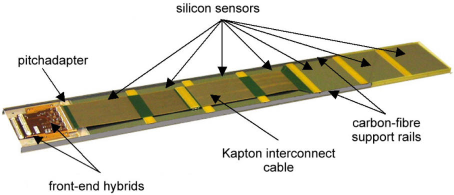
Stereo angle $\sim$ 5° in intermediate layers.

Hit resolution $\sim$ 52.6μm.

Trajectory and momentum of charged particles upstream the magnet.







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

p^+-on-n, 7.6 cm wide and 11 cm long silicon strips.

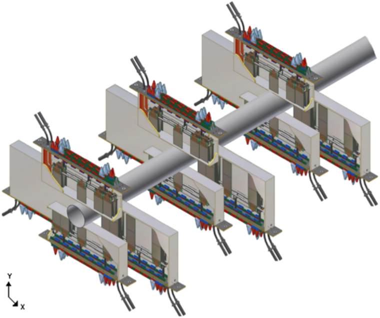
Thickness $320 - 410\ \mu$m.

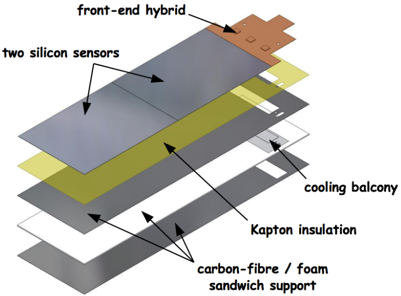
Four layers (x-u-v-x) per station (stereo angle $\sim 5^\circ$).

$\sim 129k$ channels, 4 m^2 of active area

Hit resolution $\sim 50.3\mu$m.

Trajectory and momentum of charged particles downstream the magnet.





Radiation damage

The Hamburg model

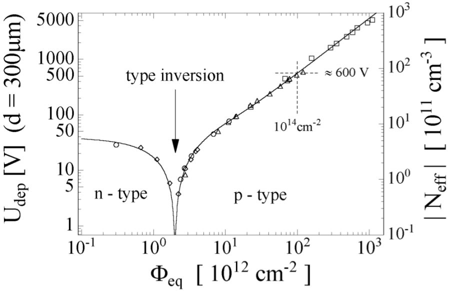
M. Moll, *"Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties"*, Phd thesis, Hamburg U., 1999

Depletion voltage depends on effective doping level N_{eff}, collection efficiency ϵ and thickness d:

$$V_{\text{depl}} = \frac{e}{2\epsilon}|N_{\text{eff}}|d^2$$

Hamburg model: variation of N_{eff} depends on time, temperature and 1-MeV neutron equivalent fluence:

$$\Delta N_{\text{eff}} = N_A(\Phi_{\text{eq}}, t, T) + N_C(\Phi_{\text{eq}}) + N_R(\Phi_{\text{eq}}, t, T)$$



Stable damage. Removal of donors, increase of stable acceptors:

$$N_C = N_{C,0}\left[1 - \exp\left(-c\Phi_{\text{eq}}\right)\right] + g_C\Phi_{\text{eq}}$$

Annealing of defects (e.g. recombination):

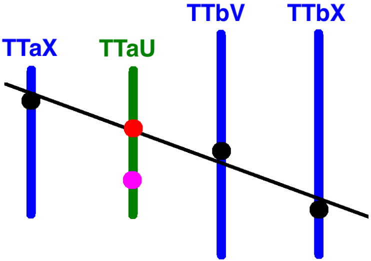
$$N_A = g_A\Phi_{\text{eq}}\exp\left(-\frac{t}{\tau_A(T)}\right)$$

Reverse annealing. Combination of individual defects:

$$N_R = g_R\Phi_{\text{eq}}\left(1 - \frac{1}{1+\frac{t}{\tau_R(T)}}\right)$$

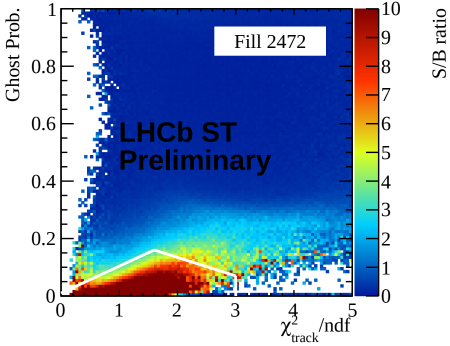
Reconstruct tracks with subset of layers and find clusters on "ignored" layers for different V_{bias} values.

TT example:



Layers used for clusters/tracks reconstr
Reconstructed clusters and tracks.
Layer with varying V_{bias}.
Cluster found on search window.
Noise cluster (used for noise estimation).

TT track (quality) selection:

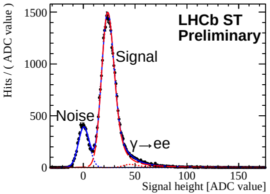


Cluster is signal if charge > 12 ADC.

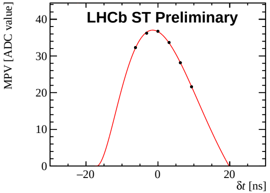
Charge Collection Efficiency (CCE) Scans

How to obtain V_{depl}:

Obtain the signal MPV from the ADC Landau distribution.

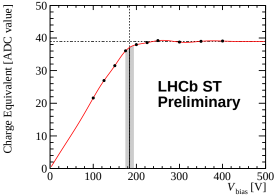


Repeat for many time shifts from the nominal sampling time to obtain the pulse shape. Get the charge by integrating the pulse shape.



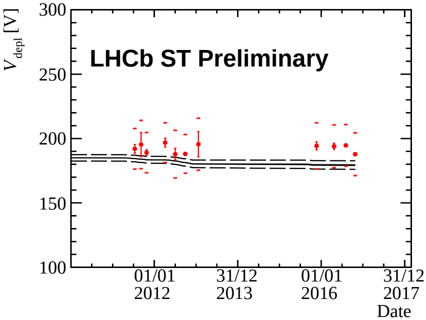
Repeat for different V_{bias}. The charge is saturated when:

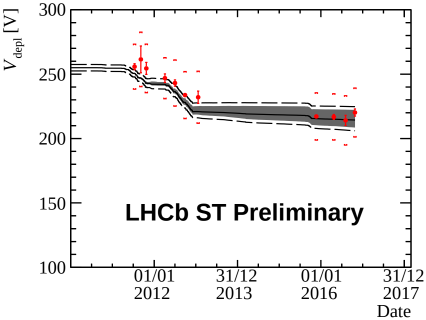
$$V_{\text{bias}} \sim V_{\text{depl}}$$



Depletion voltage VS time for TT

Results for an outer (left) and an inner (right) TT sector.

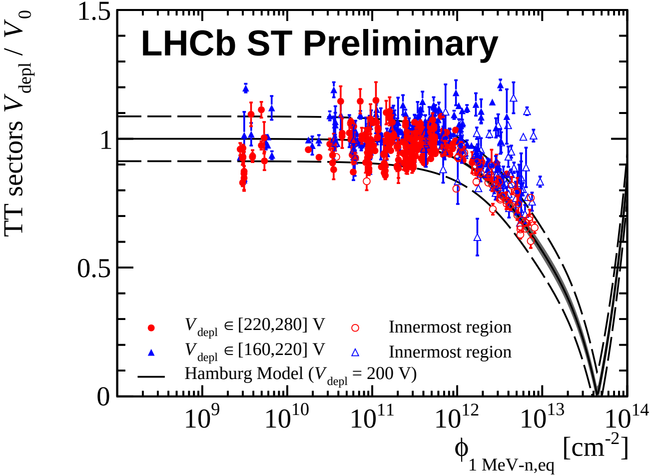




Good agreement between measurement from CCE scans and Hamburg model prediction.

Depletion voltage VS fluence for TT

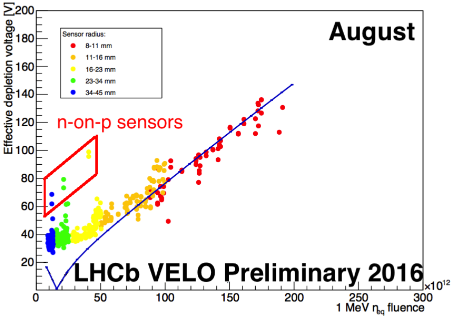
Comparison between CCE scan results and stable damage term of Hamburg model.



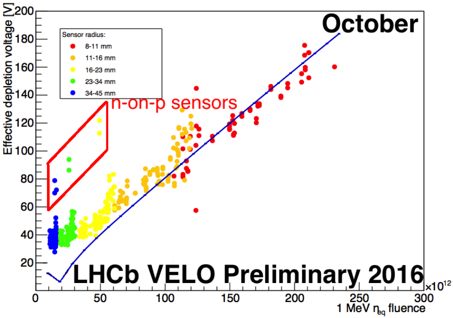
V_0 from CCE scans performed before detector installation.
Good agreement data/prediction from Hamburg model. Type inversion not yet occurred.

Depletion voltage VS fluence for VELO

2016 delivered luminosity (up to August): 1.36 fb^{-1}



2016 delivered luminosity (up to October): 2.25 fb^{-1}



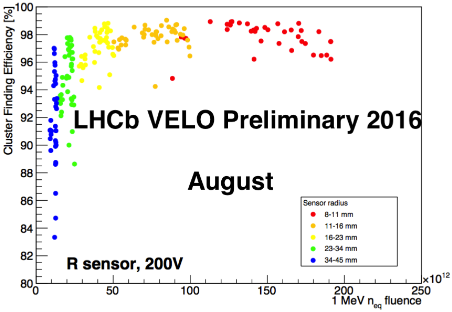
Innermost regions are more exposed to radiation.

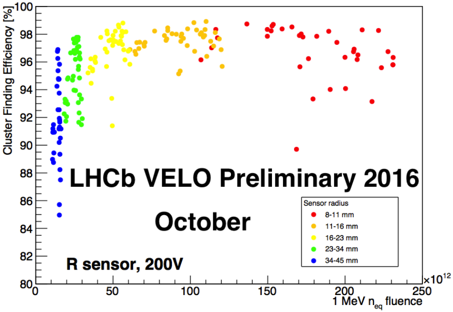
Good agrement data/prediction from Hamburg model.

Cluster finding (pseudo)efficiency for VELO - R sensors

2016 delivered luminosity (up to August): 1.36 fb^{-1}

2016 delivered luminosity (up to October): 2.25 fb^{-1}

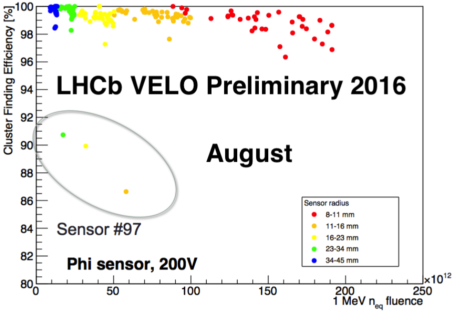




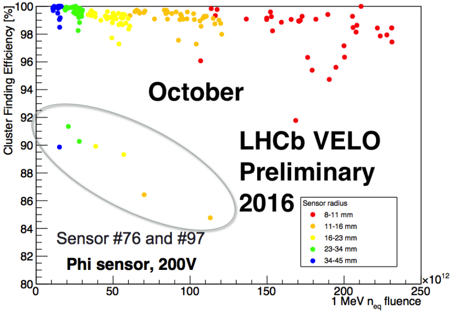
"Pseudoefficiency": no ghost track suppression.

Cluster finding (pseudo)efficiency for VELO - ϕ sensors

2016 delivered luminosity (up to August): 1.36 fb^{-1}



2016 delivered luminosity (up to October): 2.25 fb^{-1}



"Pseudoefficiency": no ghost track suppression.

Understood readout problems for sensors 76 and 97.

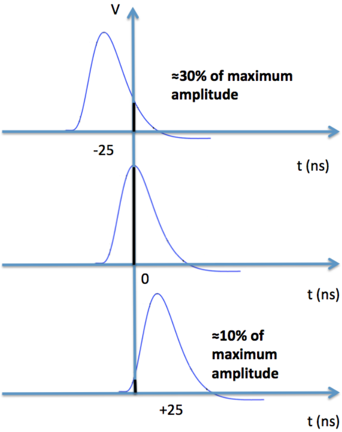
Timing and spillover

Beetle chip and spillover

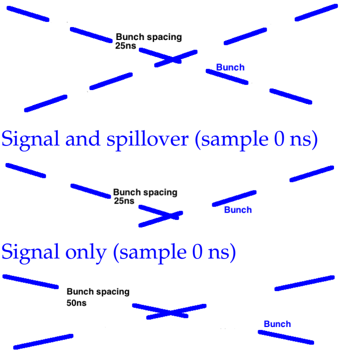
M. Agari *et al, "Beetle: a radiation hard readout chip for the LHCb experiment"*, NIM A518 (2004)

Beetle chip analogue output gives spillover clusters with 25 ns bunch spacing (Run 2).

Beetle sampling time.



Data-driven studies from bunch crossing:



Signal and spillover (sample 0 ns)

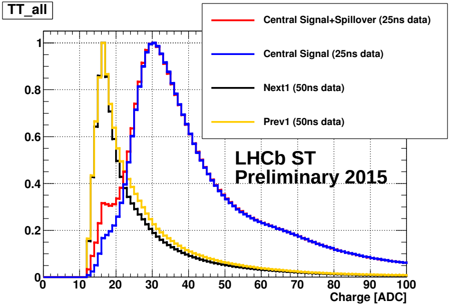
Signal only (sample 0 ns)

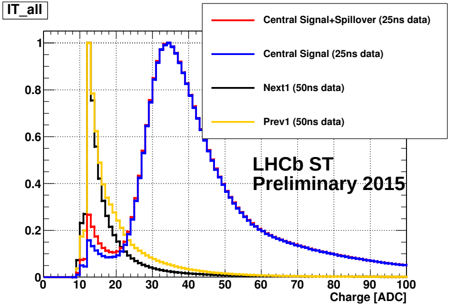
Spillover only (sample ± 25 ns)

TT and IT cluster charge distribution

Good separation between signal and spillover clusters.

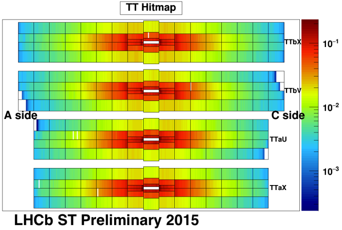
Higher overlap in TT due to higher strip capacitance.



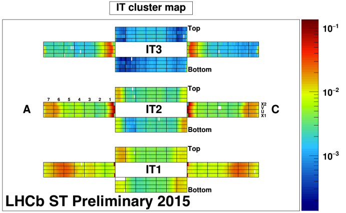


Occupancy: number of cluster normalised over number of events.
Occupancy of clusters from reconstructed tracks is almost unchanged with or without spillover.

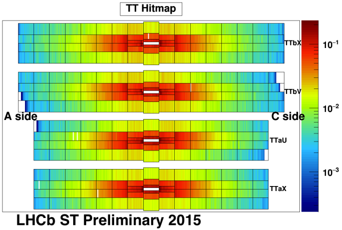
TT signal + spillover



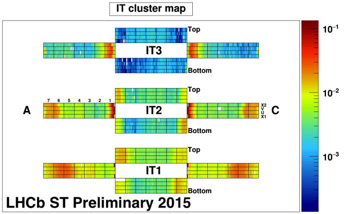
IT signal+spillover



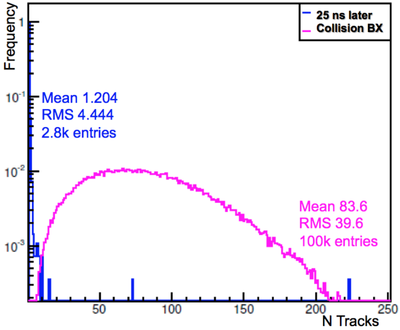
TT signal

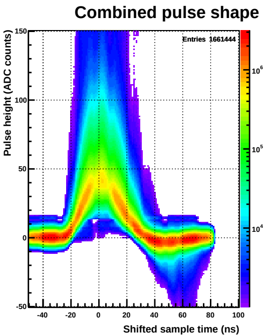


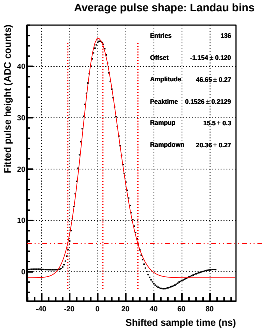
IT signal



Low temperature (-7 C°) allows fast pulse shape wich minimizes spillover.



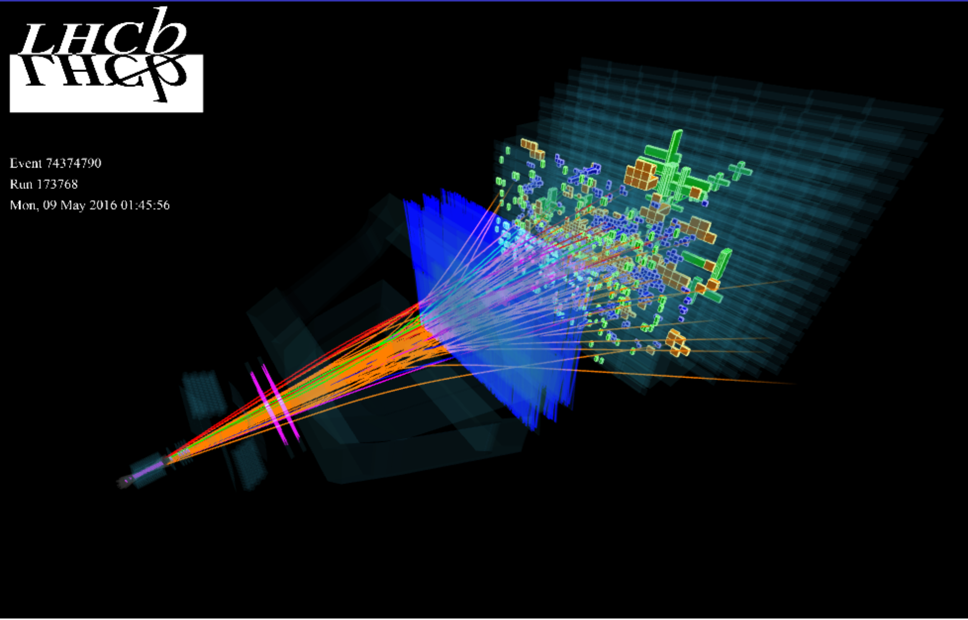




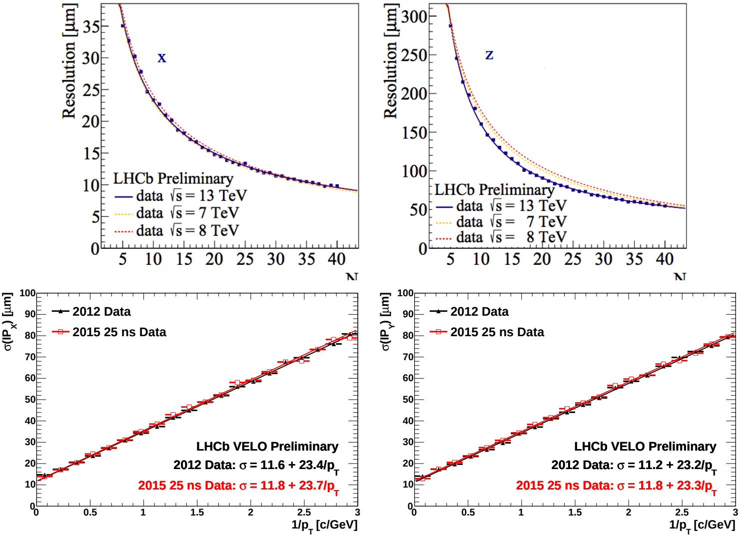
Tracks made up with spillover clusters only are $\sim 1.5\%$ of tracks from "normal" tracking.

Conclusions and summary

Putting everything together



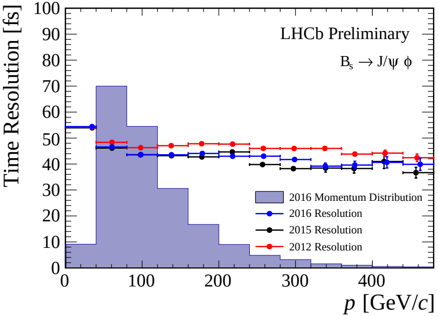
Primary Vertex (PV) and impact parameter (IP) resolution

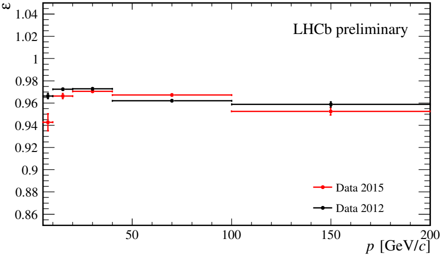


Run 2 resolution is better than (or comparable with) Run 1.

Reconstruction can cope with VELO radiation damage, spillover and higher track multiplicity.

Decay time resolution and track reconstruction efficiency





Tracking in Run 2 is similar to Run 1.

Radiation damage, spillover and higher track multiplicity are not showstoppers for LHCb physics!

Summary

Radiation damage is affecting VELO, TT and IT silicon lattice as predicted by theoretical models.

Spillover noise due to small bunch spacing in Run 2 is negligible and is not affecting track reconstruction.

Track reconstruction performance in Run 2 is better than Run 1:

- detector ageing under control.
- improvements in the reconstruction software: faster pattern recognition which allows online calibrations and alignment and better performance.
  → more details about online in talk from Artur Ukleja on 23/05.

Good performances expected for VELO, TT and IT until their replacement (end of Run 2). New detectors will be in place to cope with higher occupancy expected in Run 3:

- VELO upgrade;
- Upstream Tracker;
- Scintillating Fibre Tracker.
  - seek for dedicated talks!


Thank you

Backup

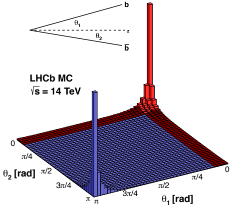
Large Hadron Collider beauty (LHCb) experiment in a nutshell

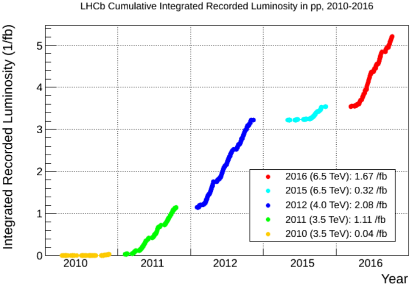
Forward spectrometer ($2 < \eta < 5$) optimized for b-hadron physics (B, Λ_b, Ω_b...).

High-precision measurements in flavour physics (CKM, beyond SM...).

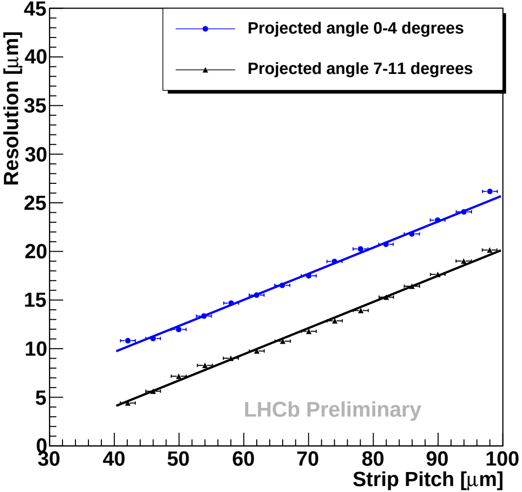
Excellent performances
[Int. J. Mod. Phys. A 30, 1530022 (2015)]:

- Momentum resolution: $\frac{\sigma_p}{p} \approx$ 0.5-0.8 % ($p <$ 100 GeV/c).
- Impact Parameter (IP) resolution: $\sigma_{IP} \approx 20\ \mu$m (at high p_T).
- Decay time resolution: $\sigma_t \approx$ 50 fs.
- Particle Identification (PID): $\epsilon(K) \approx 95\%$, π mis-ID$\approx 5\%$ ($p <$ 100 GeV/c).

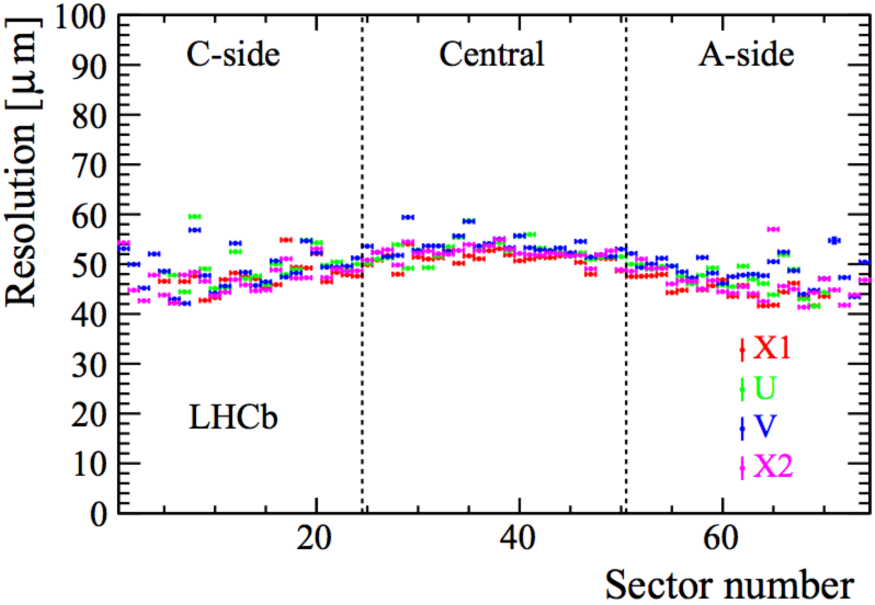




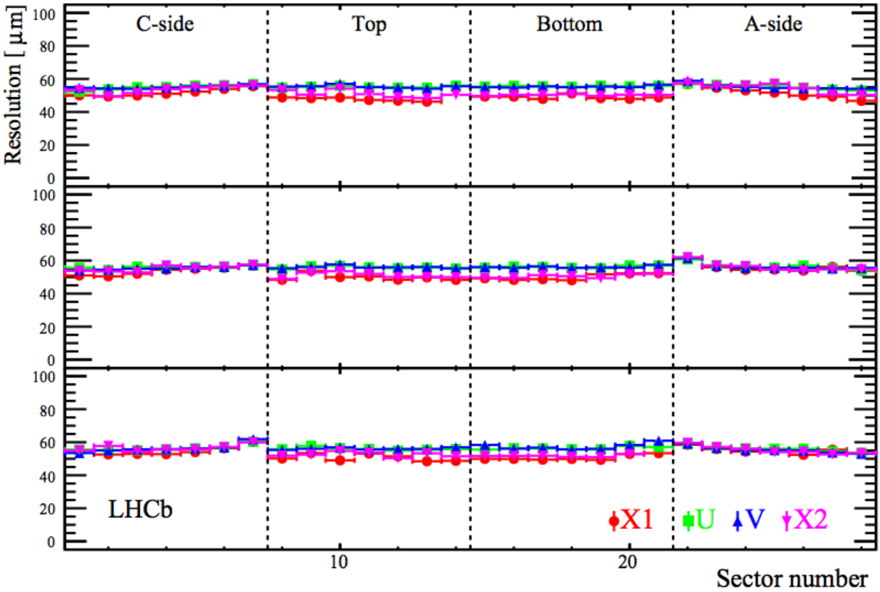
VELO hit resolution



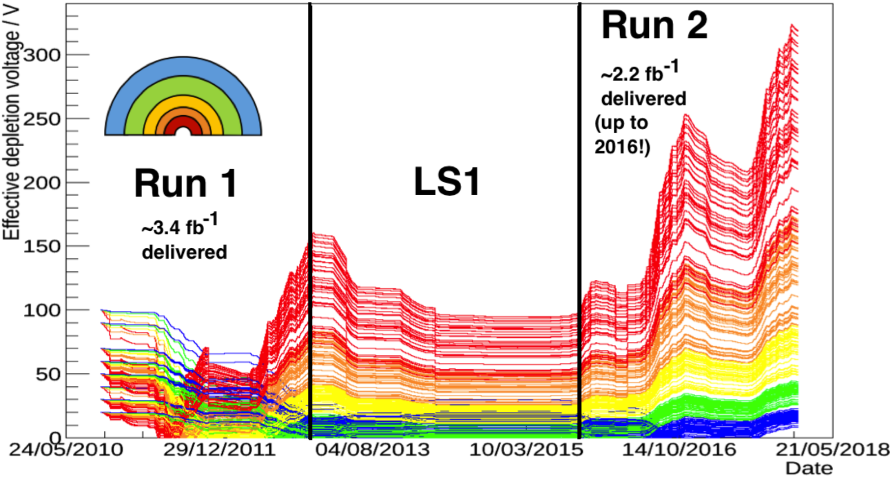
TT hit resolution



IT hit resolution



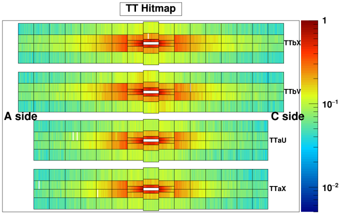
Hamburg prediction for VELO sensors



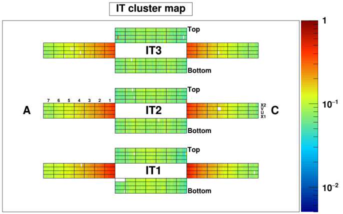
TT and IT cluster occupancy - all clusters

Occupancy: number of cluster normalised over number of events.
On average, spillover occupancy is a factor ~ 3 (TT) or ~ 8 (IT) smaller than signal.

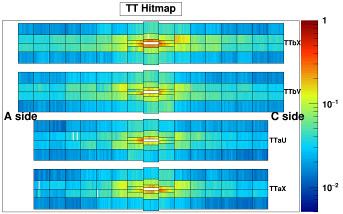
TT signal



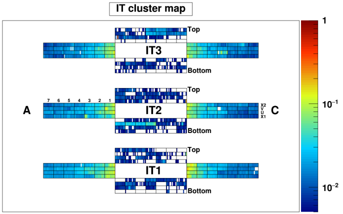
IT signal



TT spillover



IT spillover



Signal-spillover tradeoff for Beetle signal