# Radiation damage in the LHCb Silicon Tracker

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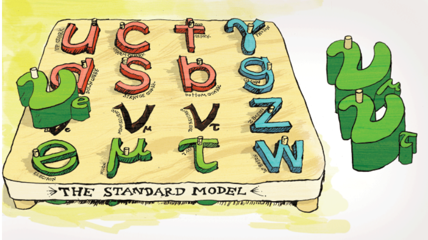
# Introduction: Standard Model open questions






- No explanation for $\nu$ masses in the SM
- What happened to antimatter? $\not{CP}$ violation is not enough!
- ....dark matter?...

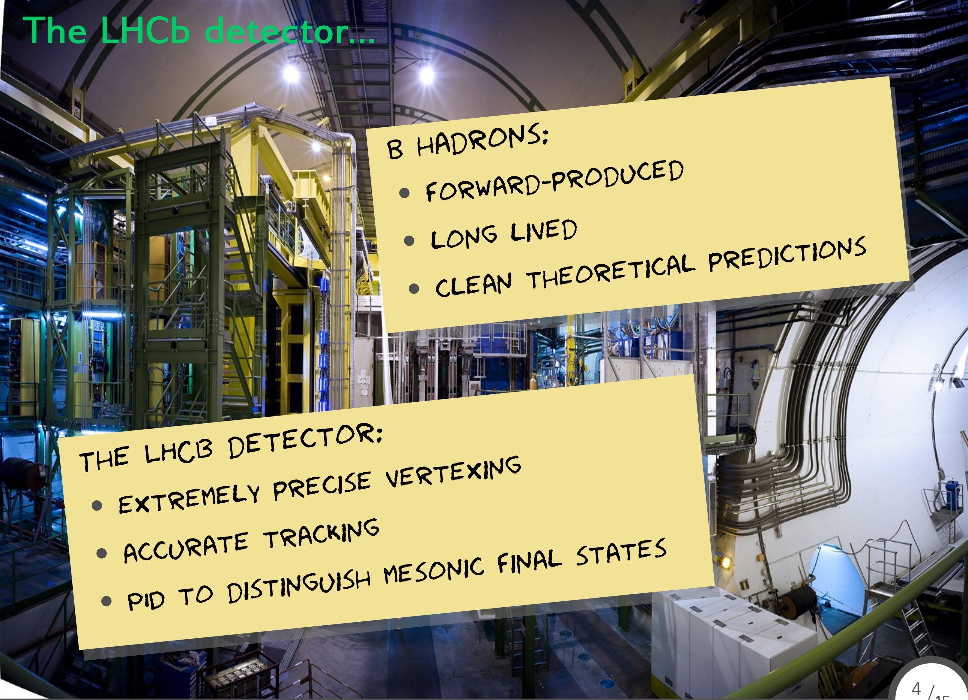
# Introduction: how to look for new physics?

- **Direct search:** production of new particles at accelerators:
  - light, small coupling: beam dump
  - heavy, larger coupling: colliders
    LHC $\longrightarrow$ CMS, ATLAS (general purpose detectors)
- **Indirect search:** probe processes sensitive to new particles intervening through loops
  - need extremely precise instruments!
    LHC $\longrightarrow$ LHCb (optimized for $b$ physics)

# The LHCb detector...

...is a single-arm forward spectrometer at the LHC, covering 15-300 mrad

# The LHCb detector...



B HADRONS:

- FORWARD-PRODUCED
- LONG LIVED
- CLEAN THEORETICAL PREDICTIONS

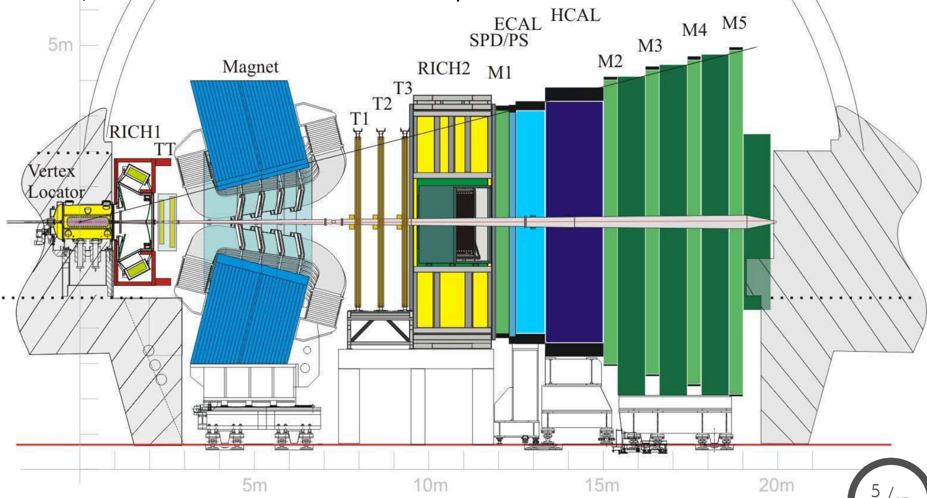
THE LHCB DETECTOR:

- EXTREMELY PRECISE VERTEXING
- ACCURATE TRACKING
- PID TO DISTINGUISH MESONIC FINAL STATES

# The LHCb detector

**Vertexing:** two halves closing up to few mm from the beam line

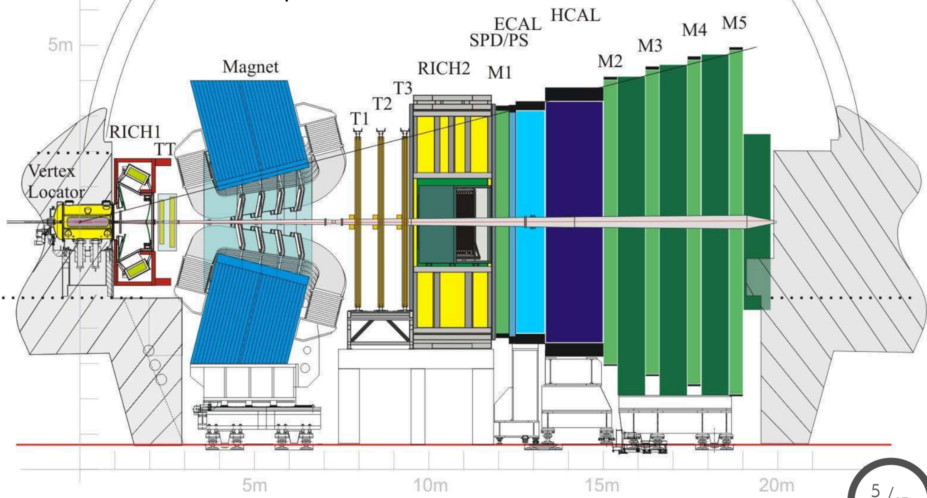
- silicon strips, $r$ and $\phi$ information
- 20$\mu$m IP resolution $\Longrightarrow$ PV-SV separation



# The LHCb detector

**Tracking system:** $\sigma_m \sim 30$ MeV/$c^2$, 96% efficiency

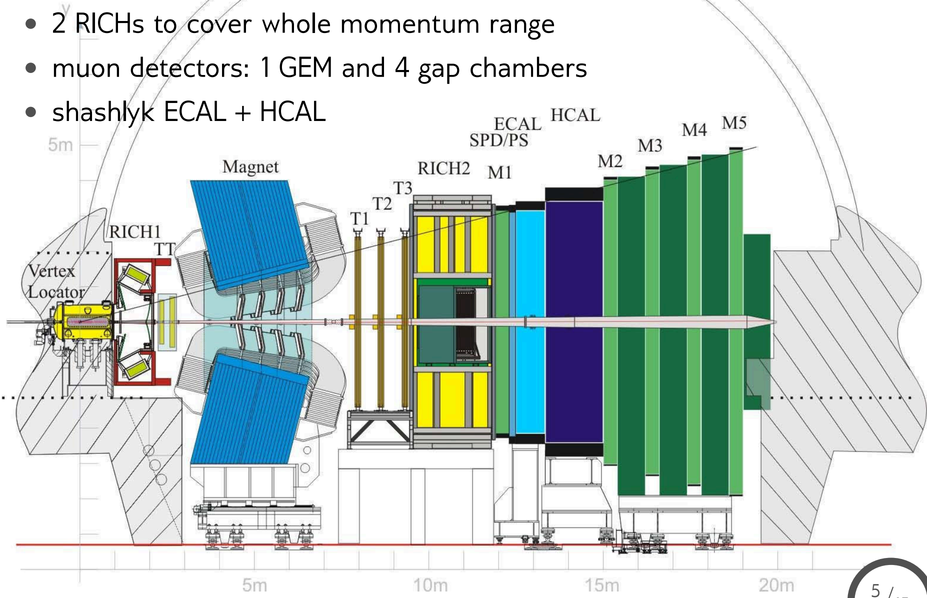
- silicon (TT + inner part of downstream tracker)
- straw tubes (outer part of downstream tracker)



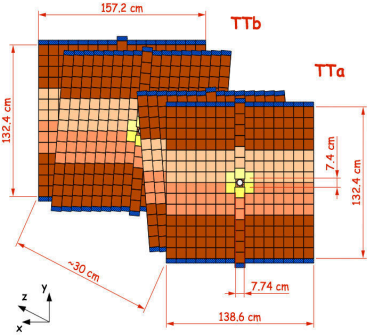
# The LHCb detector

**PID:** need good separation for $\pi$, $K$ etc.

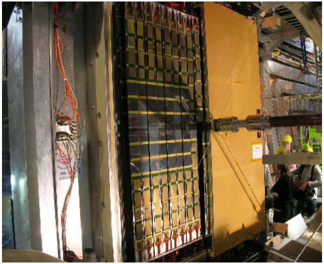
- 2 RICHs to cover whole momentum range
- muon detectors: 1 GEM and 4 gap chambers
- shashlyk ECAL + HCAL

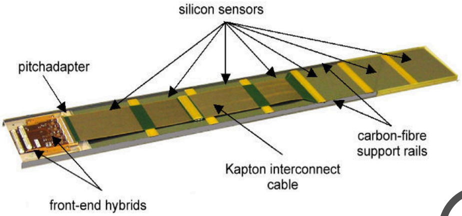


# The Silicon Tracker (ST): Tracker Turicensis (TT)




- 8.4 $m^2$ active area in front of the magnet
- two $x$ layers, two 5°stereo layers
- $\sigma_{\text{hit}} \sim 50\mu$m
- staves made of 7 sensors wire-bonded according to occupancy (“sectors”)
- TT feels the “tail” of the **B** field $\Longrightarrow$ allows for preliminary momentum estimate





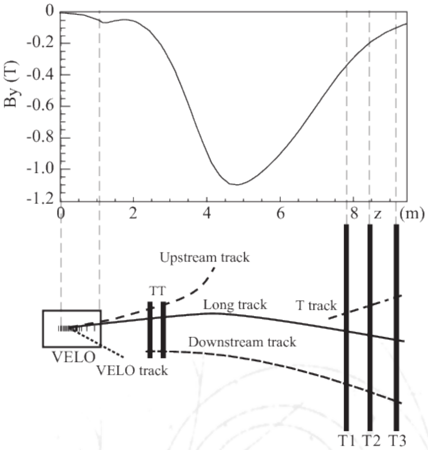
# Track reconstruction at LHCb

**Run II:** introduction of **VELO-TT** tracking algorithm in the trigger.

⇒ Tracking became 3× faster, allowing for:

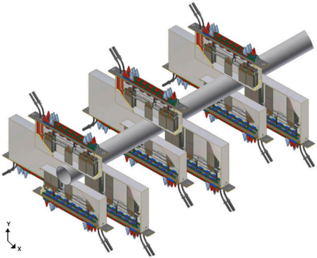
- more refined trigger selections
- available resources to perform online calibration & alignment

⇒ **Offline** performances achieved in **real time**!



# The Silicon Tracker (ST): Inner Tracker (IT)

- 3 stations of 2 $x$ layers and 2 stereo layers each
- 4 $m^2$ active area, inner part of the downstream tracker
- $\sigma_{\text{hit}} \sim 50\mu$m
- magnetic field bends charged particles out of IT acceptance $\Longrightarrow$ less occupancy than the TT

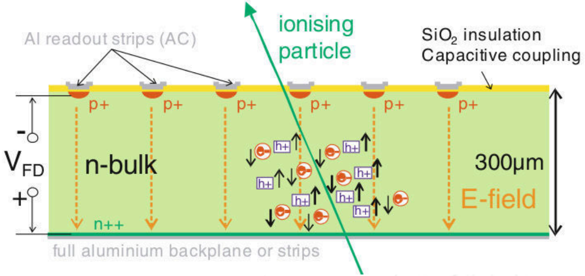


# Silicon detectors: basics

- The amount of free charge carriers in standard silicon sensors is $10^5$ times higher than the amount of charge carriers generated by a ionizing particle
- Depletion of the p-n junction volume via a reverse-biased configuration: $w = \sqrt{2\,\varepsilon\,\mu\,\rho\,V_{bias}}$, $w$ thickness of the depleted region
- Minimal working point: full depletion voltage $V_{fd}$ such that $w = d$

$$V_{fd} = \frac{d^2}{2\,\mu\,\varepsilon\,\rho}$$

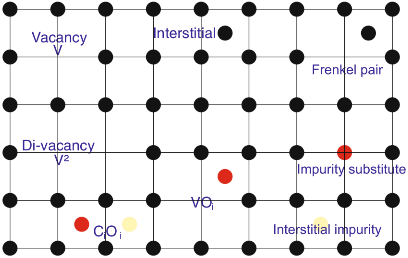
where $\rho = \frac{1}{\mu\,e\,N}$ is the silicon resistivity for a doping concentration $N$, $\mu$ is the pairs mobility and $d$ the thickness of the sensor.



# Radiation damage in silicon sensors

Atoms may be displaced from their lattice positions, and subsequently diffuse. The creation of interstitials and vacancies (space charge) leads to:

- increase of $I_{leak}$ due to the creation of additional energy levels
- increase of the voltage needed to transport charges through the full sensor thickness: $V_{fd} = \frac{e}{2\,\varepsilon}\,|N_{eff}|\,d^2$, where $N_{eff}$ is the effective doping level

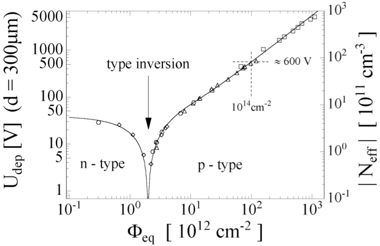



- the defects in the lattice may act as traps for charged particles: decrease in collection efficiency. At effecting fluences above $10^{15}$ equivalent 1 MeV neutrons per cm$^2$, charges may no longer arrive at the collecting electrodes in 300 $\mu$m thick sensors.

# The Hamburg model

Variation of $V_{fd} \Longleftrightarrow$ Variation of $N_{eff}$ (time, temperature, fluence)

$$\Delta N_{eff} = \boldsymbol{N_C}(\phi) + \boldsymbol{N_A}(\phi, t, T) + \boldsymbol{N_R}(\phi, t, T)$$




## Stable damage:

- removal of donors $\propto 1 - e^{-c\phi}$
- increase of acceptors $\propto \phi$

## Annealing:

- recombination of defects $\propto \phi \times e^{-t/\tau_A(T)}$

## Reverse annealing:

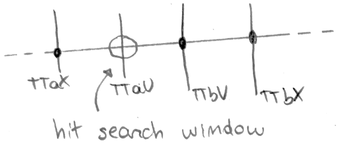
- combination of individual defects $\propto \phi \times \left(1 - \frac{1}{1+t/\tau_R(T)}\right)$

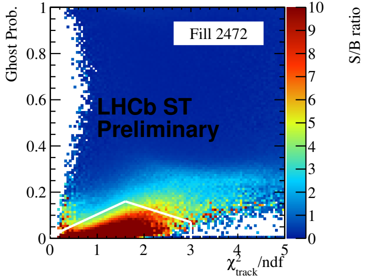
# Charge Collection Efficiency (CCE) scans

Monitoring of the ST radiation damage. Detector installed in the LHCb cavern $\Longrightarrow$ in-situ CV, IV scans not possible!

- $V_{fd}$ must be measured on data!
- **CCE scans:** probe charge collection efficiency as a function of $V_{bias}$
- CCE saturation $\equiv V_{fd}$

- dedicated data taking runs 3-4 times per year
- one TT and one IT layer probed, the others used for track reconstruction




track selection tuned on data

# Charge Collection Efficiency (CCE) scans

Charge mobility depends on $V_{bias}$.
$\Rightarrow \forall\, V_{bias}$, access the whole pulse by recording data at several $\delta t$.

- $\forall\, V_{bias}, \delta t$:

  find MPV of ADC distribution. Model:

  - noise Gaussian
  - signal Landau $\circledast$ noise Gaussian
  - $\gamma \to e^+e^-$: Landau with $2\times$MPV

- $\forall\, V_{bias}$:

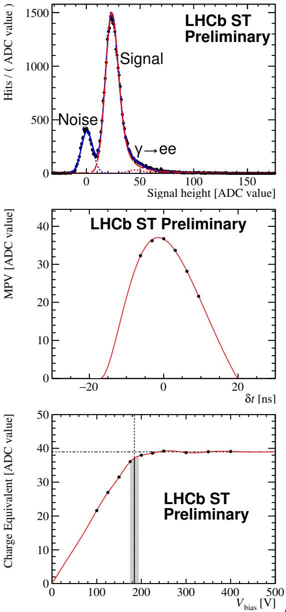
  estimate $Q_{tot} = \int_{\Delta t} q(t)\delta t$

- Plot $Q_{tot}$ against $V_{bias}$.

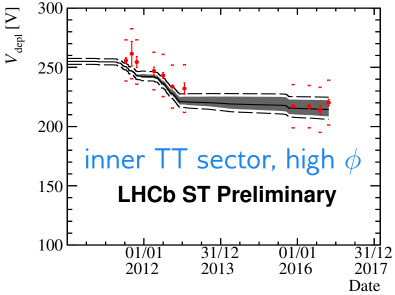
  Extract $V_{depl}$ from:

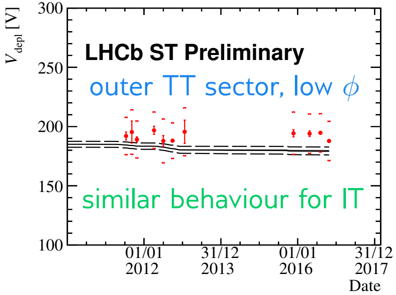
  $$Q(V_{depl}) = r \times Q_{max}$$

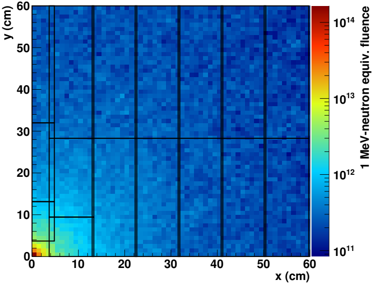
  with $r$ calibrated on post-production CV scans.

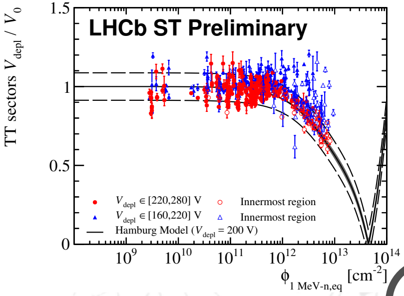


# Evolution of $V_{depl}$ compared to Hamburg predictions



# Conclusions & outlook

- The performance of the tracking system is crucial for precision physics
  - TT boosted trigger capabilities in Run 2
- A procedure was developed to monitor the ageing of the Silicon Tracker with collision data
  - procedure in place since 2011
  - dedicated data taking runs performed every few months
  - will continue until the end of Run II, then the detectors will be replaced
- Evolution of $V_{depl}$ closely follows Hamburg model predictions
- Radiation damage is well under control!

# Thanks!