Real-time monitoring of the LHCb interaction region with FPGA-based hit reconstruction

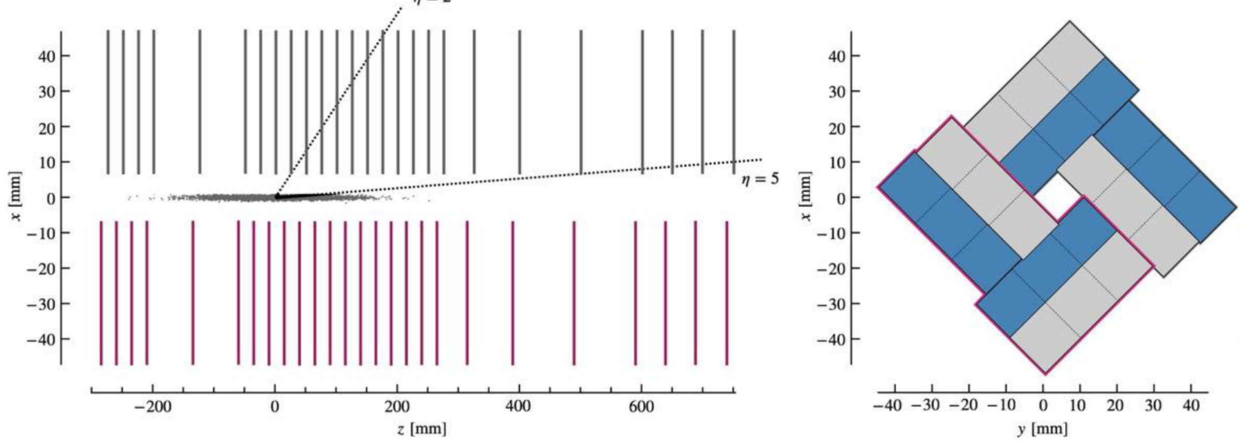
Daniele Passaro on behalf of the LHCb collaboration

Real-time processing on FPGA

Reconstructing relevant physical proxies, such as particle hits and tracks, at the earliest stages of the DAQ allows to speed up the reconstruction stages. **FPGAs** are the best suited architecture for these low-level reconstruction tasks.
The availability of **high-quality primitives** at the readout level also creates an opportunity to perform measurements in real time.

The LHCb VELO detector

The LHCb VErtex LOcator (VELO) measures Primary Vertices (PVs) with resolution of $\mathcal{O}(10\,\mu\text{m})$. It is composed of two retractable halves with 26 layers of silicon pixel sensors each (41M in total). It is positioned at 2.5 mm from the beam in nominal conditions

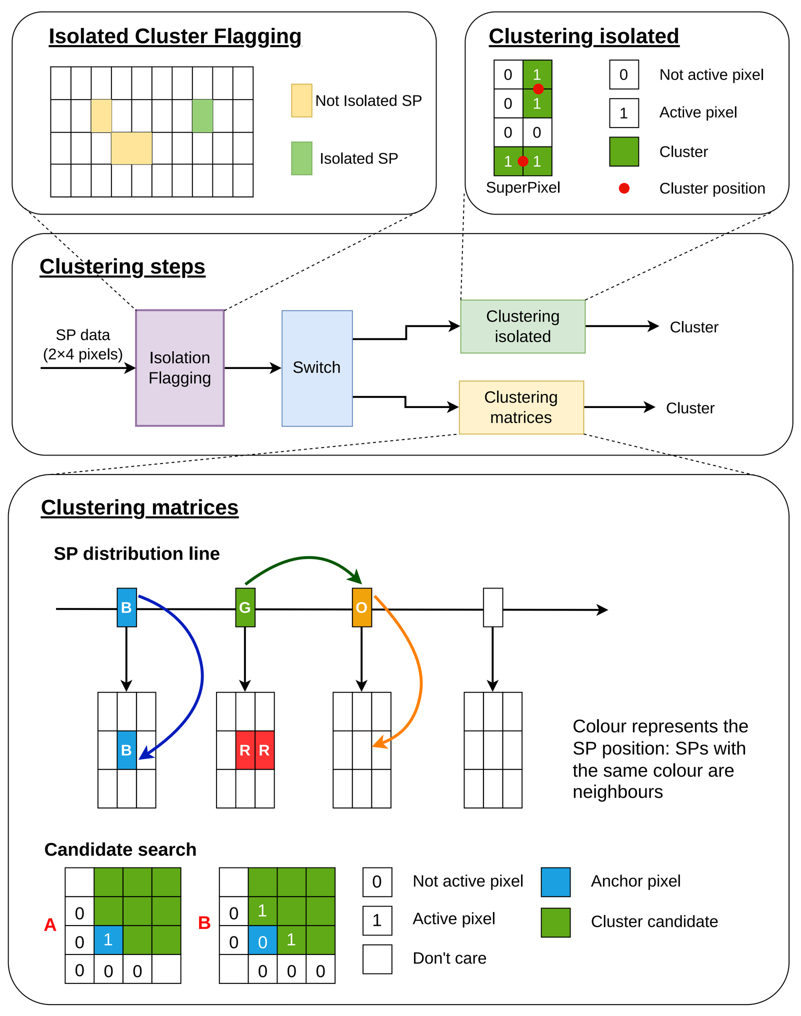


Cluster-finding algorithm on FPGA

The VELO is the first LHC detector to implement **clustering**[2;3] **at 30 MHz** directly on the FPGAs of the readout boards.

- improves the software trigger throughput by $\geq 11\%$
- reduces the VELO readout bandwidth by $\sim 30\%$
- requires $\mathcal{O}(50\times)$ less power than the HLT (GPU-based) clustering

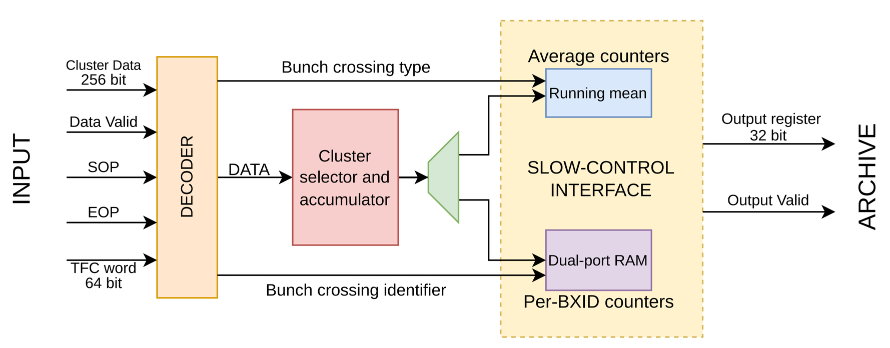
Clustering on FPGA results in the same tracking efficiency of the software-based reconstruction



Hit counters as interaction region monitors

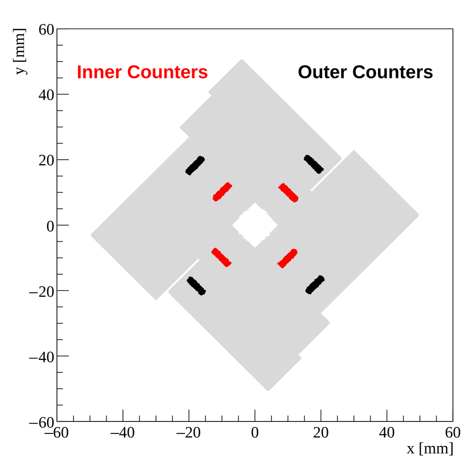
The occupancy on the VELO sensors depends on: **1.** the number of collisions *i.e.* luminosity **2.** beam spot spatial parameters. Counting the number of hits provides a **powerful tool** to perform a **real-time diagnostic of the luminous region, without the need for tracking**.

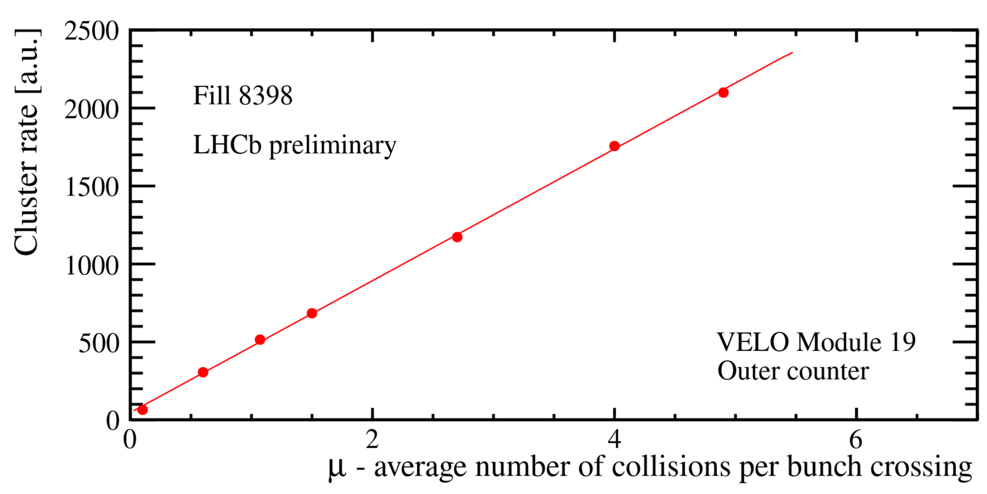
We implemented a set of programmable hit counters on each readout FPGA board of the VELO[7]:



- **Averaged counters** as feedback to the LHC beam control
- **Per-bunch-crossing counters** as feedback to the LHC injection operations

Good linearity $\Rightarrow$ suitable and robust for beam spot measurements





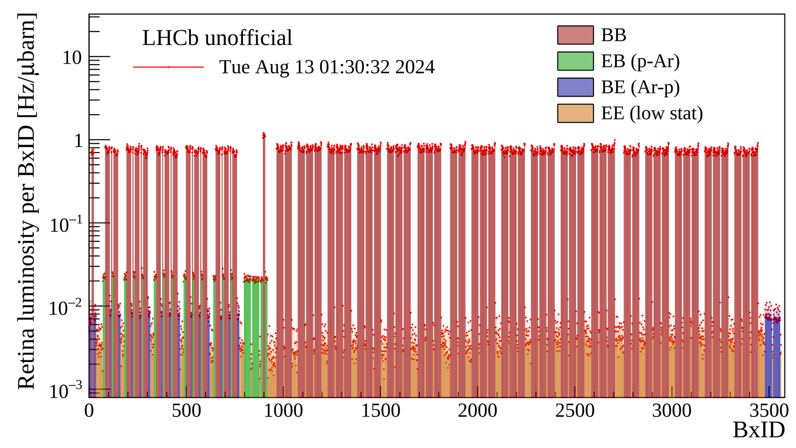
Online luminosity measurement

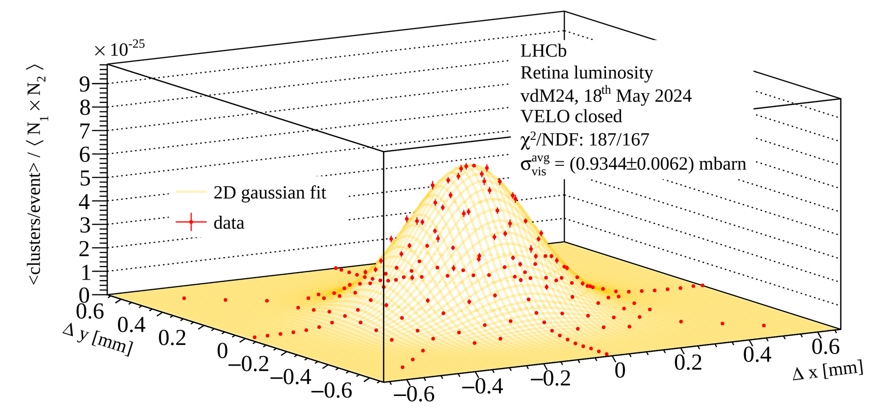
The instantaneous luminosity is defined as:

$$\mathcal{L}_{\text{inst}} = N_{\text{bb}}\frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}}f_{\text{LHC}}$$

- N_{bb} = number of colliding bunches
- $f_{\text{LHC}} = 11.245\,\text{kHz}$

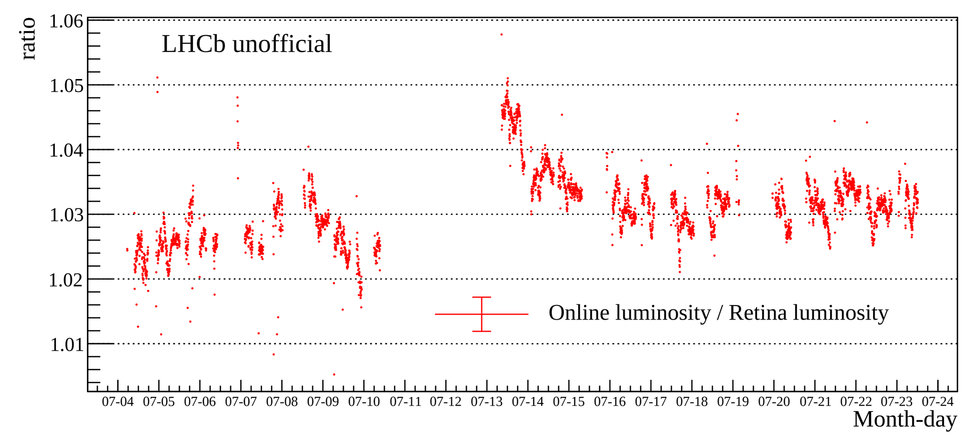
- μ_{vis} = number of visible interactions $= \langle\text{hits per event}\rangle$ or $= -\ln(\text{Prob(empty event)})$
- σ_{vis} = visible cross section specific to each counter, calibrated via *van der Meer scans*[1;5] $= \int \frac{\mu(\Delta x, \Delta y)}{N_1 N_2} d(\Delta x) d(\Delta y)$





Good stability:

- $\mathcal{O}(‰)$ in the same fill
- $\mathcal{O}(\%)$ in between fills. The main deviations are due to beam spot shifts along z.

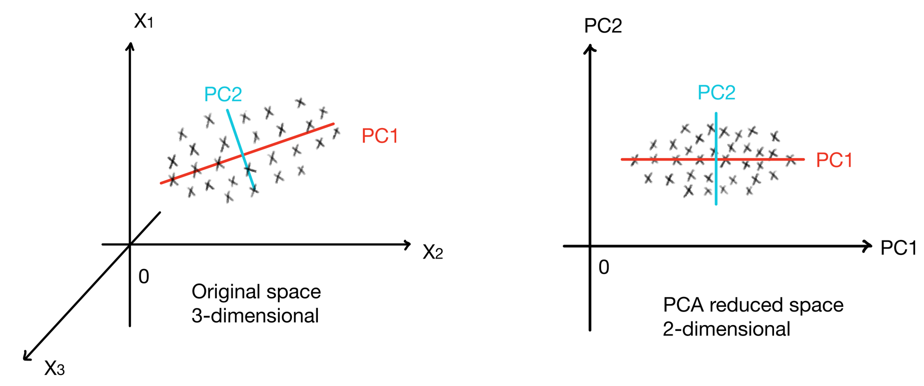


The hit-based luminosity estimator is now **used as backup** of the LHCb luminometer for **luminosity-levelling** feedback to LHC.

Track-less beam spot position monitoring

The position of the luminous region is determined[4;6] with a linear estimator:

$$x_i = \alpha_i \vec{c} \cdot \vec{w}_i + \beta_i$$

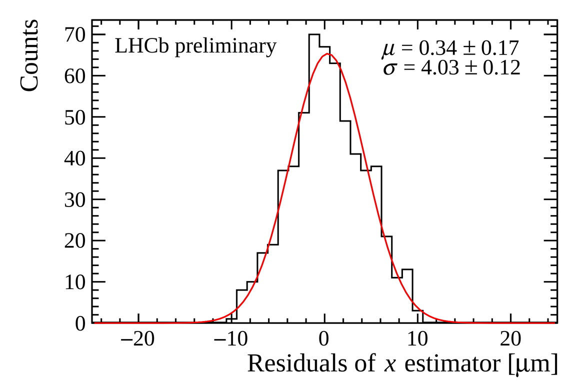


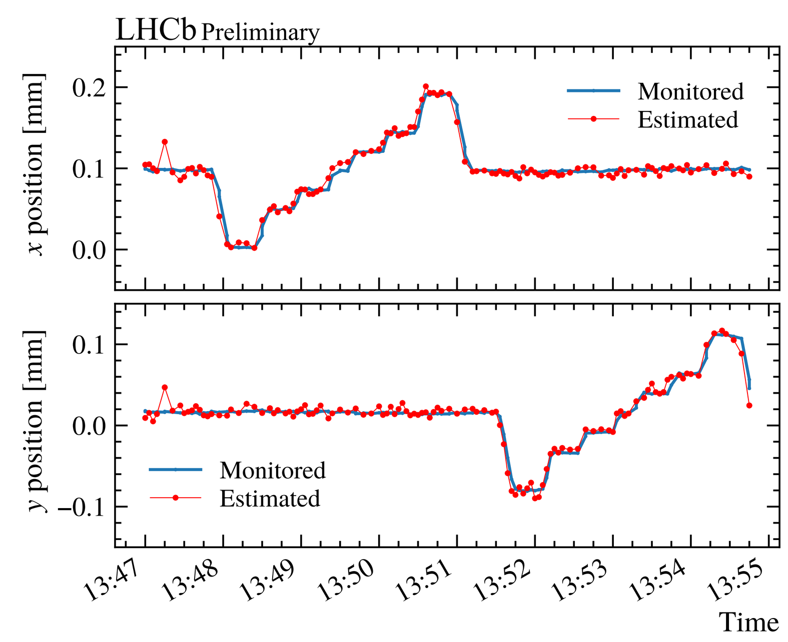
- $\vec{c}$ is the vector of counter rates normalised by the pile-up μ
- $\vec{w}_i$ are weights calculated in MC using the PCA technique[4]
- α_i and β_i are coefficients obtained from a calibration on data

Advantages of this method:

- Pre-reconstruction, immediate estimate
- Does not rely on tracks / alignment
- Does not require complex computing

Our estimates are compared with the PVs reconstructed using VELO tracks. Resolution: $\sigma_{x,y} \approx 4\mu\text{m}$.





Using the counters positioned on only one side of the VELO, it is possible to measure the relative position of the two halves with respect to the luminous region. Resolution: $\mathcal{O}(4-7)\,\mu\text{m}$.

Acknowledgements & References

These results were achieved thanks to funding from the INFN, and wide support from the LHCb VELO, Luminosity and Real Time Analysis groups.

[1] V. Balagura. Van der Meer scan luminosity measurement and beam–beam correction. *The European Physical Journal C*, 81(1), January 2021.

[2] G. Bassi. *A FPGA-based architecture for real-time cluster finding in the LHCb silicon pixel detector*. PhD thesis, Scuola Normale Superiore, 2023.

[3] G. Bassi et al. A FPGA-Based Architecture for Real-Time Cluster Finding in the LHCb Silicon Pixel Detector. *IEEE Transactions on Nuclear Science*, 70(6):1189–1201, 2023.

[4] Giulio Cordova. Real-time characterisation of the LHCb luminous region with fast FPGA-based reconstruction. Master's thesis, University of Pisa, 2024. Presented 11 Jun 2024.

[5] LHCb Collaboration. Calibration of online luminosity measurement using VELO RetinaCluster counters at LHCb, 2024.

[6] LHCb Collaboration. Real-time monitoring of the LHCb interaction region with a fast trackless methodology, 2024.

[7] Daniele Passaro. Real-time luminosity and detector monitoring using FPGAs at LHCb experiment. Master's thesis, University of Pisa, 2022. Presented 25 Oct 2022.

daniele.passaro@cern.ch