Real-time monitoring of LHCb interaction region with a fast trackless methodology

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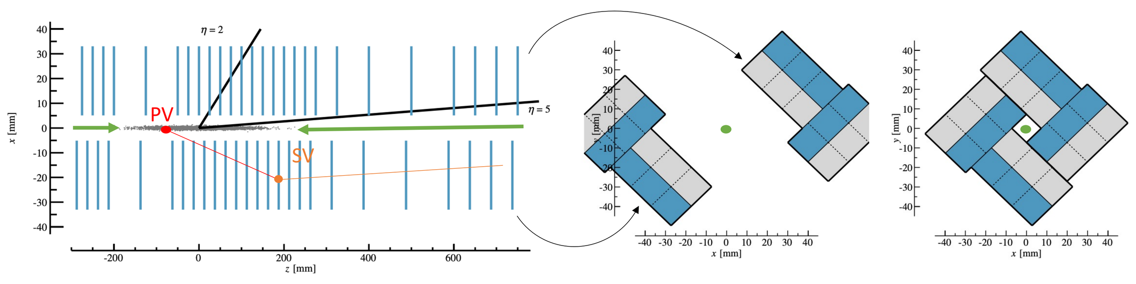
Pushing the real-time frontier

The LHCb experiment [1] precisely measures heavy hadron decay properties, in order to look for hints of new physics. To overcome hardware trigger limitations in flavour physics, LHCb employs 30 MHz real-time event reconstruction, relying on heterogeneous computing. The experiment now uses a cluster-finder FPGA architecture to reconstruct hits in the pixel detector. The triggerless readout of LHCb makes these hit positions available for every collision, generating a flow of 10^{11} hits per second.

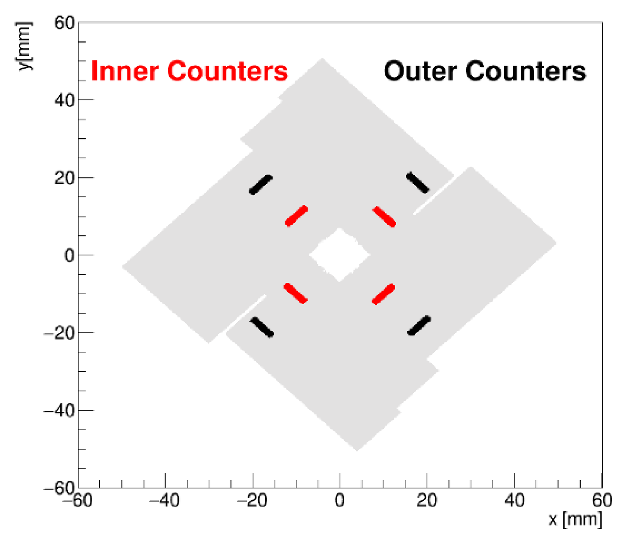
This info is used to reconstruct complex quantities at the detector readout level.

Real-time cluster counters on the VELO

The VErtex LOcator (VELO) measures Primary Vertices (PVs) with resolution of $\mathcal{O}(10\,\mu\mathrm{m})$. It consists of 26 stations of pairs of retractable modules of silicon sensors. It moves in up to 5 mm close to the beams, in normal running conditions.



An FPGA-based clustering architecture [2] reconstructs hits on the VELO in real-time at 30 MHz.



We implemented programmable counters [3] to count hit rates on-the-fly at multiple locations of the detector, with 8 counters per VELO station. The counters are available for every collision. The integration time is flexible and is currently set at 90 ms.

We used these counters to implement, directly on the readout boards, real-time estimators for:

- Luminosity
- Luminous region position

Relative luminosity estimation

Luminosity is defined as:

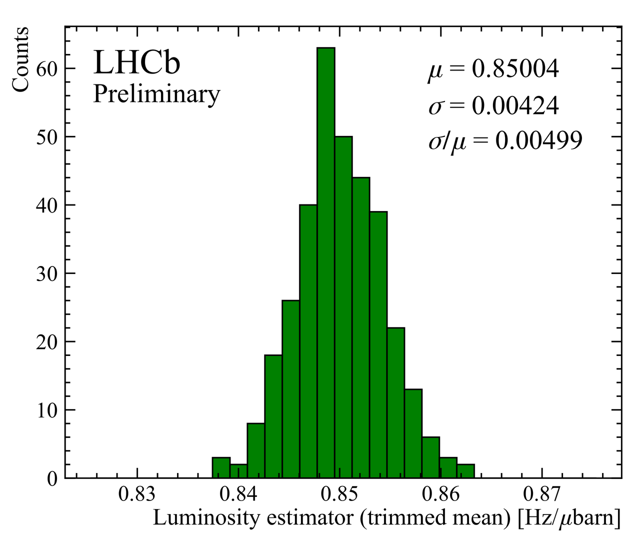
$$L = f N_b \frac{\mu_{vis}}{\sigma_{vis}}, \qquad \text{where}$$

- $f = 11.245$ kHz is the LHC revolution frequency
- N_b is the number of colliding bunches
- μ_{vis} is the mean number of hits per event in a counter
- σ_{vis} is the visible cross section [4] specific to each counter

Hit counters have demonstrated to be linear with the pile-up μ, i.e. they are suitable observables for measuring luminosity. Each counter provides an independent luminosity estimation.

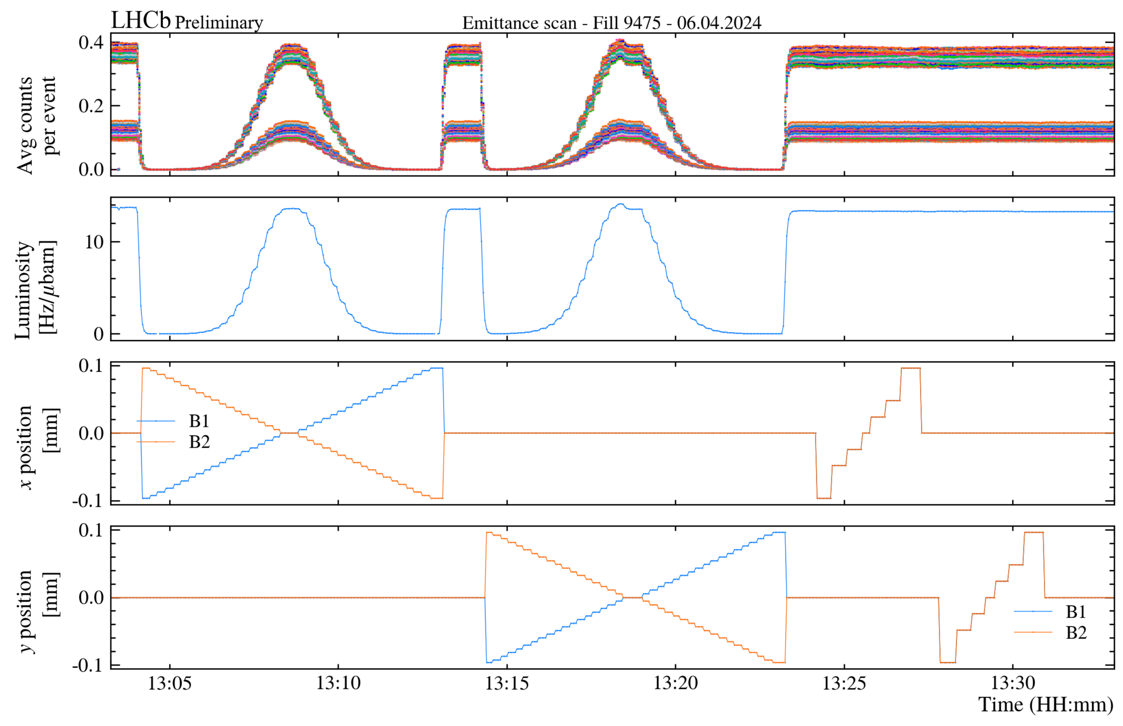
A real-time luminosity estimator

Luminosity measurements from each counter are combined in one estimator using a trimmed mean. This method is particularly robust to fluctuations or local conditions of the detector. We estimated a relative statistical uncertainty of 0.5% by observing the estimator in a 15 minute period of constant luminosity.



The van der Meer (vdM) and LSC scan

The vdM scan is a technique used to compute the visible cross-section σ_{vis} [5] of each counter by shifting beams and measuring the variation of the rates of counters. In the second panel we report our luminosity estimation during the vdM.



The vdM routine includes a Length Scale Calibration (LSC) scan during which the beams are shifted head-to-head. The LSC is used to calibrate the luminous region position estimators.

Luminous region position measurement

The position of the luminous region in each Cartesian component i is determined with a linear estimator:

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

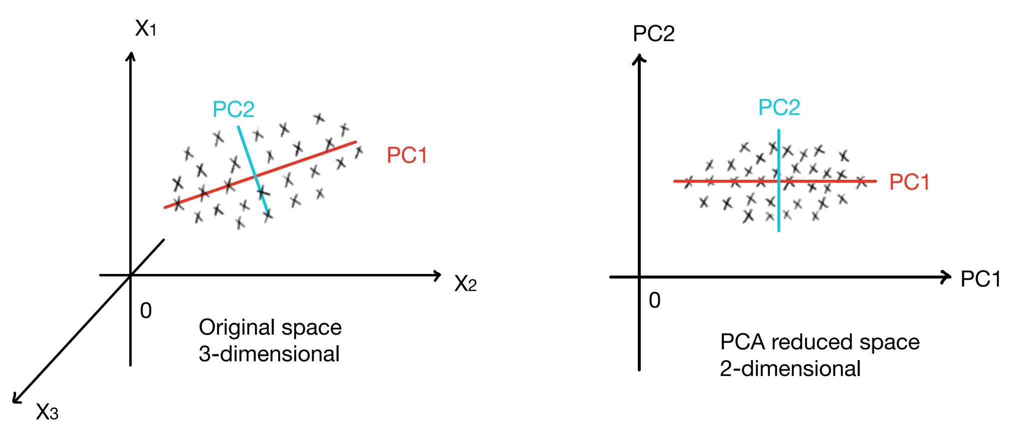
- $\vec{c}$ is the vector of counter rates normalised by the pile-up μ
- $\vec{w}_i$ are weights calculated in MC using the PCA technique [6]
- α_i and β_i are coefficients obtained from a calibration on data

Advantages of this method

- The estimate **does not rely on tracks**;
- does not depend on detector alignment;
- does not require complex computing.

Principal Component Analysis (PCA)

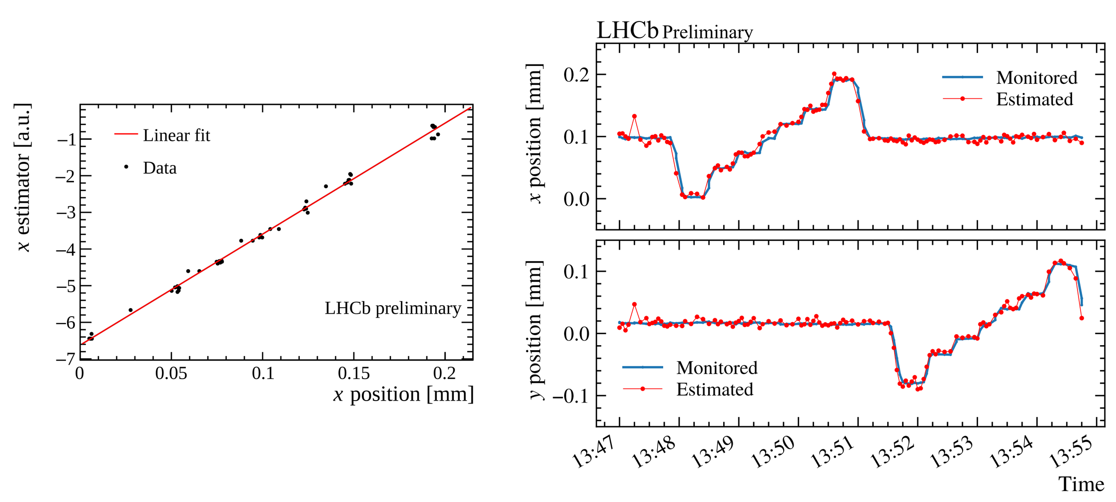
PCA is a data reduction technique, in which data is linearly transformed onto a new coordinate system such that the directions capturing the largest variation in the data can be easily identified.



Applying this transformation to a simulated dataset of counters in which the position of the luminous region is set to vary, allows to find the optimal linear combinations of the counters to estimate the luminous region position in a particular direction.

Calibration of position estimators

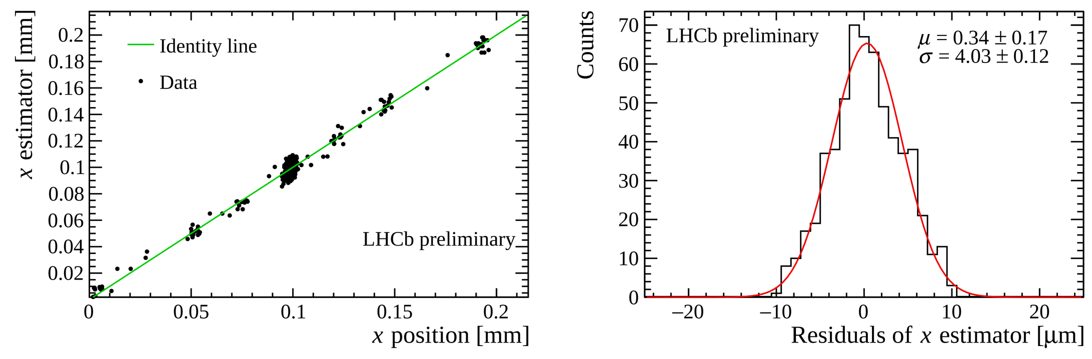
For calibration, we use independent measurements of the luminous region position during the LSC taken by the VELO monitoring tasks: PVs calculated with VELO tracks sampled every few milliseconds, with a resolution of 1 μm.



From the fit we estimate coefficients α_i and β_i. Relation is linear as expected. Estimators behave correctly during a second LSC performed 30 minutes after the calibration.

Estimator performance

On a period of 30 minutes after calibration, our estimates are compared with the ones of the VELO monitoring tasks, showing good agreement and a resolution of 4 μm for both x and y [7], compared with 3.8 μm obtained in calibration.

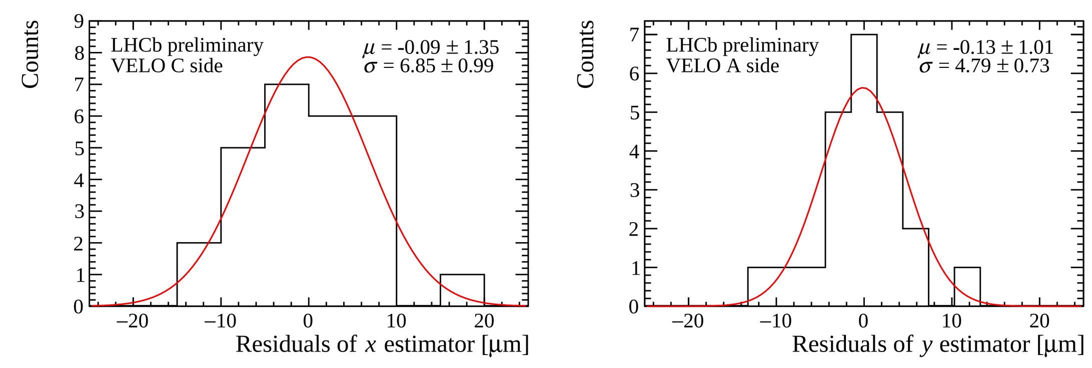


Relative position of VELO halves

Using counters $\vec{c}$ 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.
This requires recalculating $\vec{w}_i$ with another PCA on MC.
Calibration of α_i and β_i is analogously performed during LSC.

VELO halves position estimators

A period of few minutes before and after the calibration is selected for testing the performance of the VELO halves position estimators.



The resolution varies between 4 μm and 7 μm, similarly to what was obtained in calibration.

Conclusions and future prospects

This work demonstrates the implementation of on-the-fly hit counters in specific VELO regions, providing real-time information embedded in the readout at the 30 MHz collision rate. By combining these counters, we achieve precise real-time estimates of key quantities, including:

- Luminosity with a relative precision (statistical only) of 0.5%.
- trackless estimate of luminous region position with an extrapolated precision of 4 μm for a measurement every 1 ms in nominal running conditions.
- relative position of VELO halves: extrapolated resolution up to 7 μm for a measurement every 1 ms.

This tool will be further refined by including:

- z component of luminous region;
- luminous region shape;
- luminous region inclination in the horizontal and vertical plane;
- study of systematics.

This approach highlights the potential of real-time FPGA-based data processing, with low-level high-rate quantities providing essential information for event reconstruction. The potential for future applications is broad.

References

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