Luminosity measurements and PLUME detector at LHCb

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Luminosity measurements

Luminosity is a fundamental parameter which needs to be known precisely for the **safety** and **optimal operation** of the detector and for the **measurement** of the **processes cross section**. Thus, its instantaneous value $\mathcal{L}_{inst}$ needs to be continuously measured during data taking and archived. The LHCb detector works at a *lower* value of $\mathcal{L}_{inst}$ with respect to GPD LHC experiments, which is kept constant through a procedure called *luminosity levelling*. Thus it is important to measure $\mathcal{L}_{inst}$ in **real time** for the LHC machine operation and for the levelling procedure [1]. The upgraded LHCb detector operates at **fivefold** $\mathcal{L}_{inst}$ in Run 3 compared to the previous runs, and it has now fully ***software-based*** trigger counters. $\mathcal{L}_{inst}$ can be computed as:

Required precision
- *Online*: < 10%
- *Offline*: best possible

$$\mathcal{L}_{inst} = \frac{N_{bb}\nu_{rev}\langle\mu\rangle}{\langle\sigma\rangle}$$

Revolution frequency
Number of interactions → **Average N interactions** per BX, evaluated in a way dependent on the specific **counter** used
Cross section → Determined for each counter from **dedicated measurements**: Van der Meer scan (vdM) [2] or Beam Gas Imaging (BGI) [3]
Number of bunch-pair

Cross section measurement

Two different methods have been used in Run 1-2 and are used also in Run 3:

1. **Van der Meer scan**
   The two beams are separated in the **transversal** plane. Then beam positions are moved in steps Δx and Δy. At every position μ_{vis} is measured with all the counters which need to be calibrated, so that the *cross section per counter* is obtained as:

$$\sigma_{vis} = \int \frac{\mu_{vis}(\Delta x, \Delta y)}{N_1 N_2} dxdy$$

   Bunch population

   Emittance scan, which consists in mini-vdM to check the linearity of counters in *physics conditions*. It will be performed once per fill. A mechanical test of the scan has been performed.
   Successfully completed data taking during *vdM scan in 2022*: → 1D, 2D and length scale calibration program *with and without* Argon injected + provided *ghost charges measurements* for the other experiments.
2. **Beam Gas Imaging**
   This method is based on reconstructing vertices of interactions between *beam* particles and *gas* nuclei which are *injected* in the Vertex Locator (VELO) primary vacuum. Those vertices can be used to measure the properties of the colliding beams such as their positions, profiles, sizes and crossing angle (Fig. 1). Luminosity is computed as:

$$\mathcal{L}_{inst} = N_1 N_2 \int \rho_1(x,t)\rho_2(x,t) d\vec{x}dt$$

   Bunch shapes

Number of interactions

There are *three* possible methods exploiting counters proportional to luminosity:

1. **Method of averaging** $\mu_{vis} \propto \langle N_C \rangle$ → Average number of hits in a counter
2. **Log0 method** (Poissonian) $\mu_{vis} = -\log P_0 = -\log \frac{N_0}{N}$ → Fraction of empty events
3. **Probability generating function** $\mu_{vis} \propto \log\langle z^{N_C}\rangle$ → Tuneable parameter (e.g. $z \to 0$ log0, $z \to 1$ linear)

Counters

To be a **good candidate**, a counter needs to:
a) Scale *linearly* with luminosity;
b) Have not too small and not too large fraction of empties, if log0 is used;
c) Have a *stable efficiency* in time.

Having more than one counter is fundamental to cross-validate the linearity and stability, to determine corrections and evaluate systematic effects.
→ Linearity of the counters has been verified with $\boldsymbol{\mu}$ **scans** ranging up to $\mu = 5.6$. Both an **online** and **offline** measurement of the luminosity is available via the *Experiment Control System* (ECS)and *High Level Trigger* (HLT). ECS counters have been newly implemented in Run 3 due to the removal of **hardware trigger** and corresponding counters. HLT1 and HLT2 counters have been completely re-designed based on the new subdetectors.

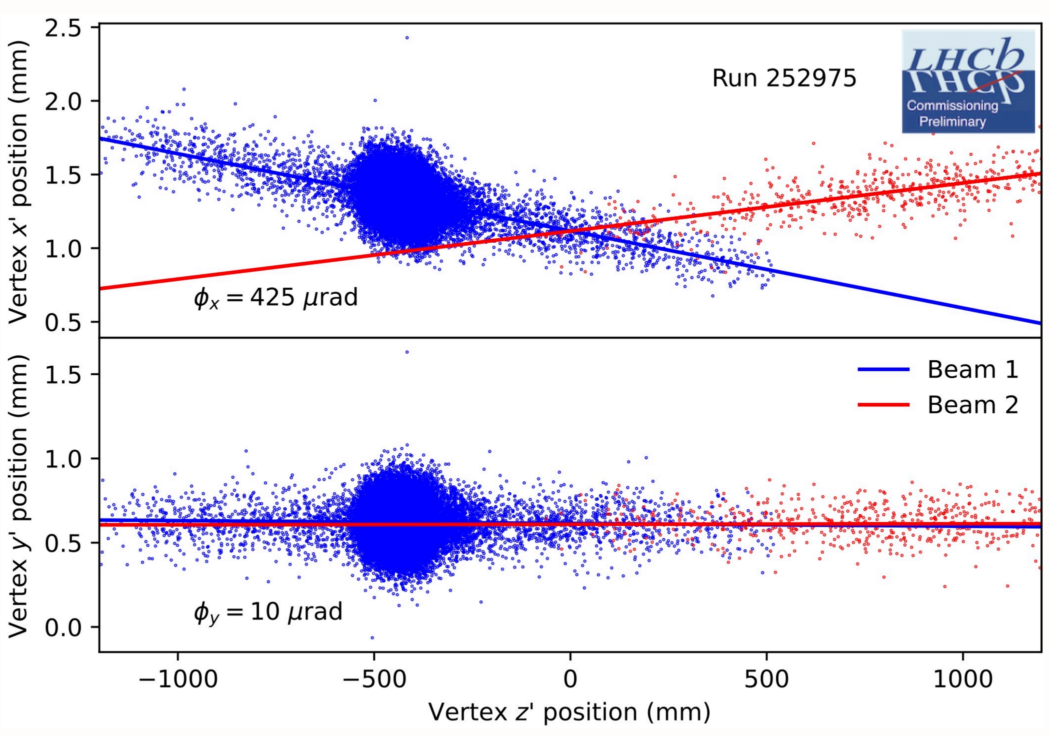


Figure 1: Crossing angles of the two beams from the BGI of **November 2022**. Gas was injected in Smog2 cell, this explains the blue blob between $[-340, -540]$ mm.

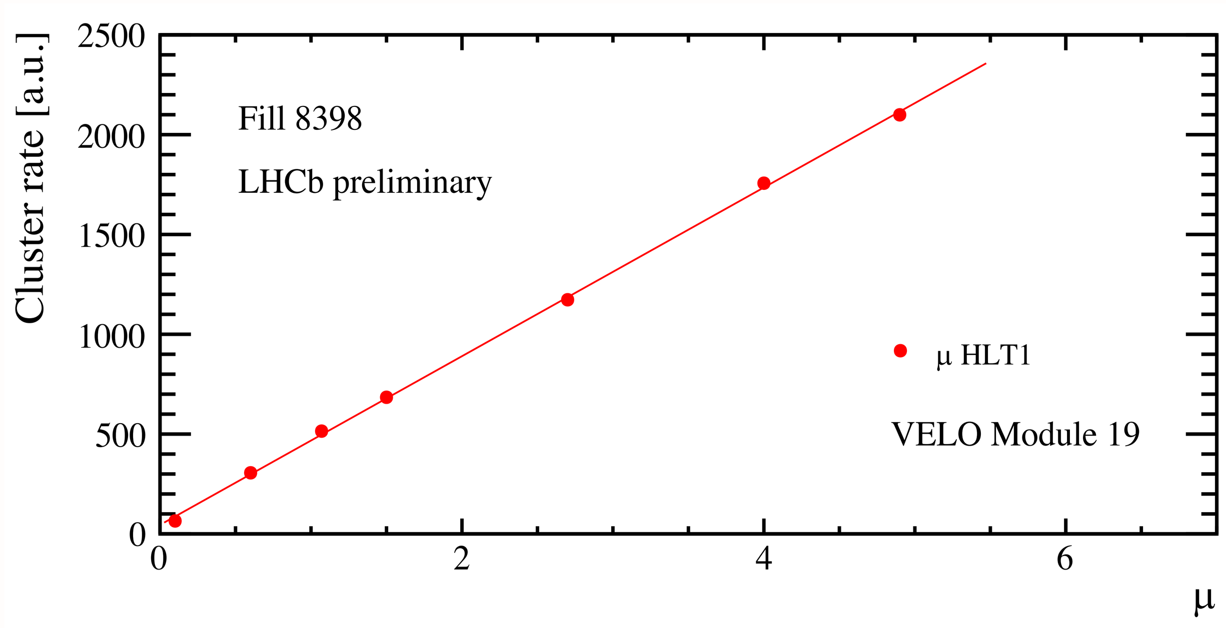
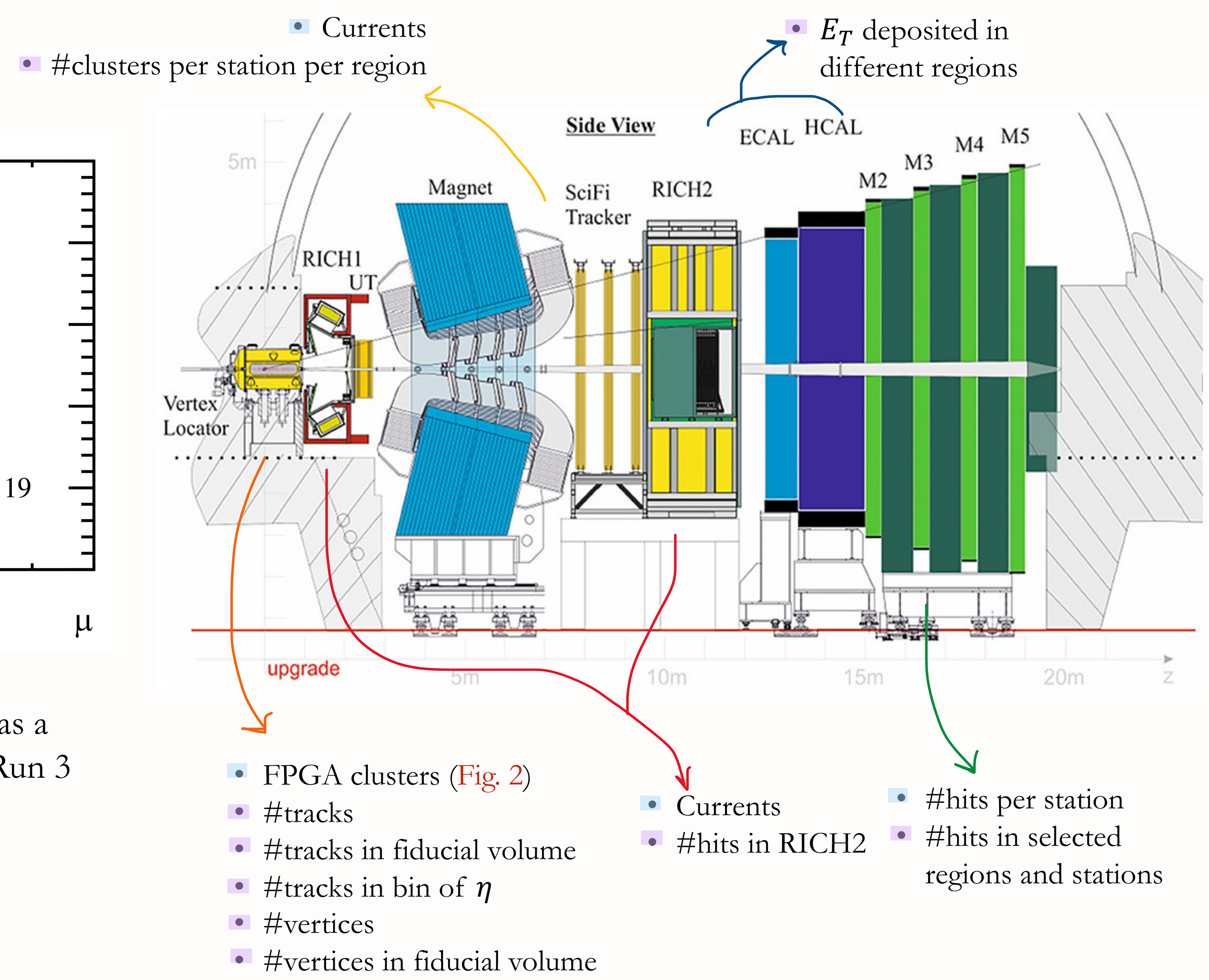


Figure 2 ECS counter of clusters in a VELO module as a function of μ averaged on all the HLT1 counters with Run 3 data (LHCb preliminary)

Run 3 counters in the upgraded LHCb detector:



PLUME detector

PLUME [4] is the **first dedicated luminosity counter** at LHCb.

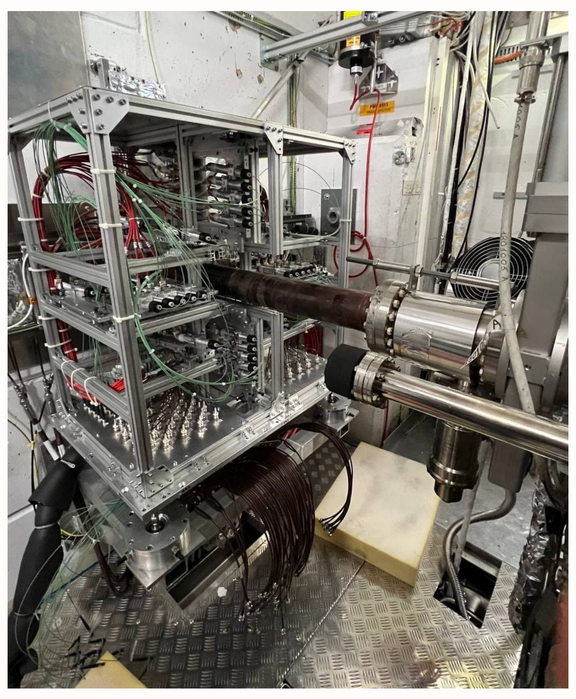
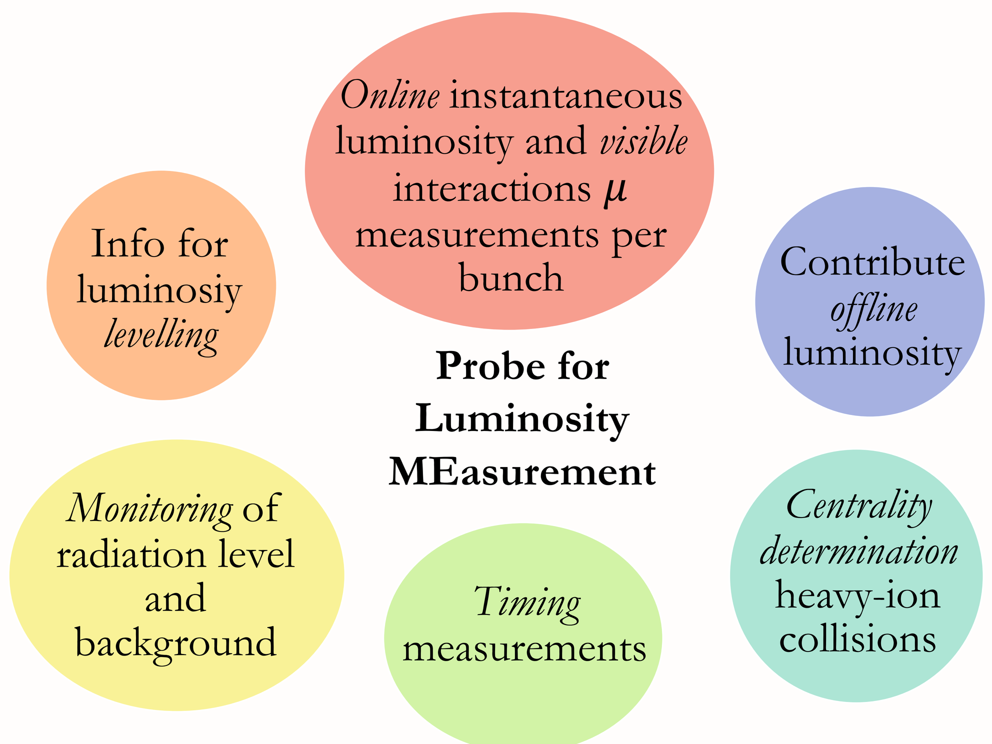


Figure 3: Photo of PLUME detector

The detector

a) It is installed **upstream** of the LHCb collision area.
b) The *elementary module* is a PMT - $\mathcal{O}(1\%)$ occupancy- with a quartz entrance window and attached tablet acting as radiators of Cherenkov light.
c) The overall layout counts **48** PMTs arranged in *two-layers* hodoscope, around the beam, forming a cross (Fig. 3).



Offline luminosity

Two PLUME counters are also implemented in High Level Trigger:
1. Over-threshold bits for all PMTs;
2. ADC value averaged over all PMTs.

Offline HLT data will allow more detailed analysis.

Online luminosity

Now, the value **stored** is the number of events with *coincidences* in PMT *pairs*. This will change in the future due to non-linearities observed at higher μ. For PLUME the **Log0** method is used.
The first vdM scan has been made in June 2022 during which PLUME was calibrated at $\sqrt{900}$ GeV (Fig. 4-5) [5]. Another one has been made in July at 13 TeV and now PLUME can provide **luminosity measurements** at this energy. Both were in physics conditions, while the first scan in nominal vdM conditions has been performed in *November 2022*.

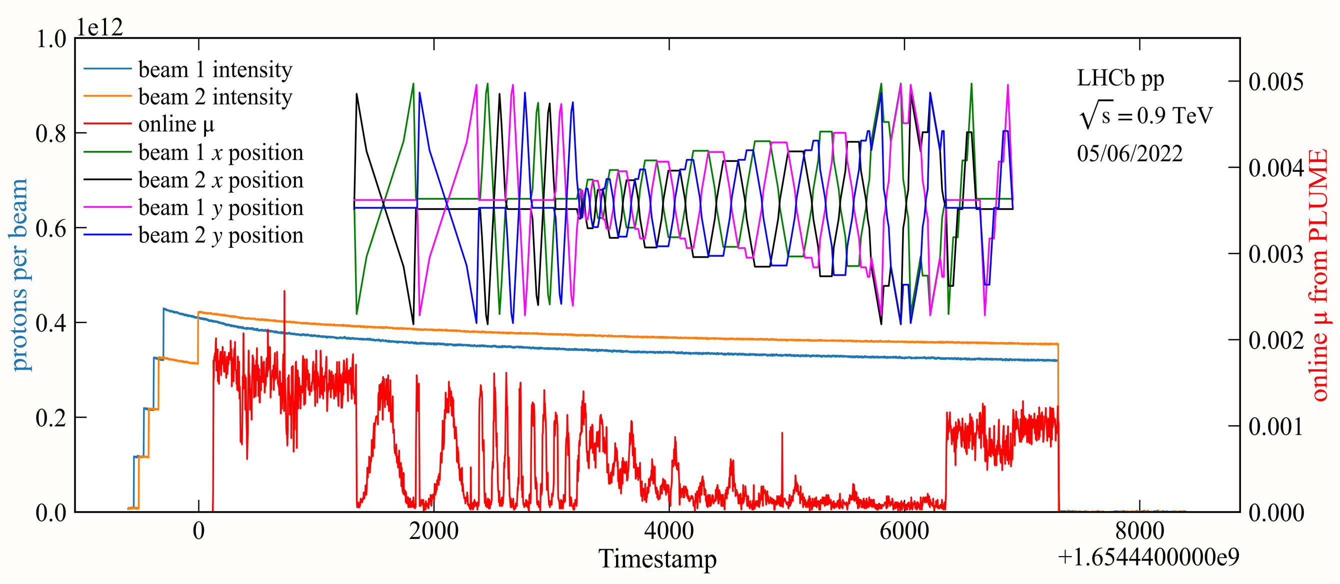


Figure 4: **Top**: x and y positions of the beams during vdM scan. **Bottom**: protons per beam are shown, while the visible interactions seen by PLUME are reported in red. The larger the beams are separated, the lower the luminosity is. [5]

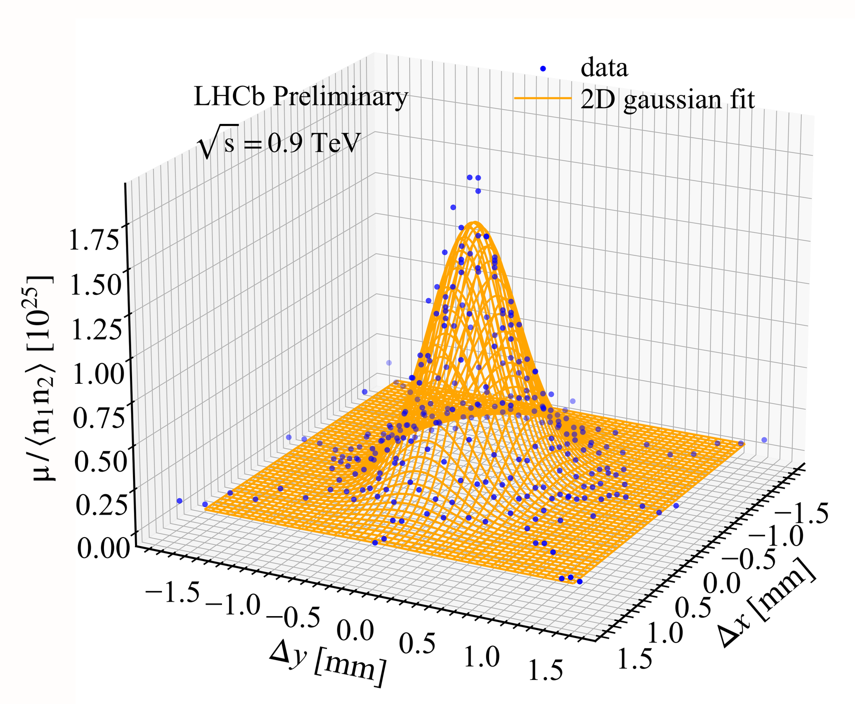


Figure 5: Values of PLUME μ normalized by average product of numbers of protons in colliding bunch pairs from 2-D scan. [5]

References:
[1] JINST 9 (2014), P12005
[2] Eur.Phys.J.C 81 (2021) 1, 26, 2012.07752
[3] IBIC2018-WEPB13 (2018), 978-3-95450-201-1
[4] CERN-LHCC-2021-002, LHCB-TDR-022 (2021), 2750034 [5] LHCb-FIGURE-2022-012 (2022), 2813388