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

$$\mathcal{L}_{\text{inst}} = \frac{N_{\text{coll}} \cdot \mathcal{L}_{\text{inst}}(\text{bx}) \cdot \Delta \mathcal{L}_{\text{inst}}}{\langle \mathcal{L}_{\text{inst}} \rangle}$$

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 $\Delta x$ and $\Delta y$. At every position $\mu_{\text{inst}}$ is measured with all the counters which need to be calibrated, so that the cross section per counter is obtained as:
     $$\sigma_{\text{inst}} = \frac{\mu_{\text{inst}}(\text{bx}, \Delta x, \Delta y)}{N_{1} N_{2} \cdot \Delta x \cdot \Delta y}$$
   - Bunch population

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:
     $$\mathcal{L}_{\text{inst}} = N_{1} N_{2} \int \rho_{x}(x, t) \rho_{y}(y, t) dt$$

![Figure 1: Crossing angles of the two beams from the BGI of November 2022. Gas was injected in Smog2 cell, this explains the blue blobs between [-340, -540] mm.](image1)

![Figure 2: ECS counter of clusters in a VELO module as a function of $\mu$ averaged on all the HLT1 counters with Run 3 data (LHCb preliminary).](image2)

PLUME detector

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

The detector

- a) It is installed upstream of the LHCb collision area.
- b) The elementary module is a PMT - O(196) occupancy - with a quartz entrance window and attached tablet acting as radiators of Cerenkov light.
- c) The full layout counts 48 PMTs arranged in two-layer hodoscope, around the beam, forming a cross (Fig. 3).

Online luminosity

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 $\mu$. For PLUME the log$\mu$ method is used.

![Figure 3: Photo of PLUME detector](image3)

![Figure 4: Top: x and y positions of the beams during vmd 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.](image4)

Number of interactions

There are three possible methods exploiting counters proportional to luminosity:

1. Method of averaging:
   - $\mu_{\text{inst}} \propto \langle \mathcal{L} \rangle$ - Average number of hits in a counter

2. Log$\mu$ method (Poissonian):
   - $\mu_{\text{inst}} = -\log(1 - \frac{N_{\text{coll}} \cdot \mathcal{L_{\text{inst}}(\text{bx}) \cdot \Delta \mathcal{L_{\text{inst}}}}{\langle \mathcal{L}_{\text{inst}} \rangle})$ - Fraction of empty events

3. Probability generating function $\mu_{\text{inst}} \propto \log(e^{\mathcal{L}_{\text{inst}}} - 1)$ - Tunable parameter $e = \{0 \text{ (p}}, \text{ 2 \text{ (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 log$\mu$ is used;
- c) Have a stable efficiency in time.

Having more than one counter is fundamental to cross-validate the linearity and validate to determination corrections and evaluate systematics.

Centrality and crossing angle

- Linearity of the counters has been verified with mc scan 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.

Run 3 counters in the upgraded LHCb detector:

- $E_{\text{dep}}$ deposited in different regions
- $\mu$ in bins of $E_{\text{dep}}$
- Bins on different regions and stations
- Bins per station

Offline luminosity

Two PLUME counters are also implemented in High Level Trigger:

1. Over-threshold bins for all PMTs
2. $\Delta E_{\text{dep}}$ values averaged over all PMTs

Offline HLT data will allow more detailed analysis.

![Figure 5: Values of $\mu$ normalized by average product of numbers of protons in colliding bunch pairs from 2-D scan.](image5)

References