

Luminosity measurement in LHCb

Vladislav Balagura
LLR, CNRS, École Polytechnique, Institut Polytechnique de Paris

13 Oct 2026

French - Ukrainian workshop in 2016:

<https://indico.ijclab.in2p3.fr/event/3300>



Same talk but 10 years ago →
(on Run 1 experience / analysis)

Luminosity at LHCb

Vladislav Balagura (CNRS / IN2P3 / LLR – Ecole polytechnique)

Today:

- upgrade of luminometers for Run 3
- analysis of Run 2

Outline:

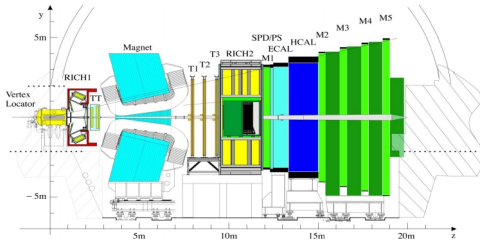
- LHCb experiment and trigger
- **Relative** luminosity monitoring during physics data taking
- Methods of **absolute** luminosity measurement
 - Beam-gas imaging (BGI)
 - Van-der-Meer scans (VDM)

8 TeV: luminosity accuracy=**1.16%**, **record at bunch-beam hadron colliders** (eg. among 4 LHC experiments), published in

"Precision luminosity measurements at LHCb", J. Instrum. 9 (2014) P12005, arXiv:1410.0149.

- Conclusions

Luminometers in Run 1, 2



9 counters
from L0-hardware and software triggers

Luminometer	
online	Calorimetric E_T from L0
offline	N VELO vertices and tracks

N interactions per bunch-crossing (pile-up) is measured as $\mu = -\log P_0$, P_0 = fraction of *empty events*,
 $P_n = \frac{\mu^n}{n!} e^{-\mu}$. Even if counter is not linear in “busy” events, P_0 remains correct.

Backgrounds:

$$P_0 = P_0^{\text{signal}} P_0^{\text{bgr}}, \quad \mu^{\text{signal}} = \mu - \mu^{\text{bgr}}.$$

μ^{bgr} : only beam-gas ($\lesssim 1\%$ without SMOG), subtracted using non-colliding bunches

$$\mu^{\text{signal}} = \mu^{\text{bb}} - \mu^{\text{be}} - \mu^{\text{eb}}.$$

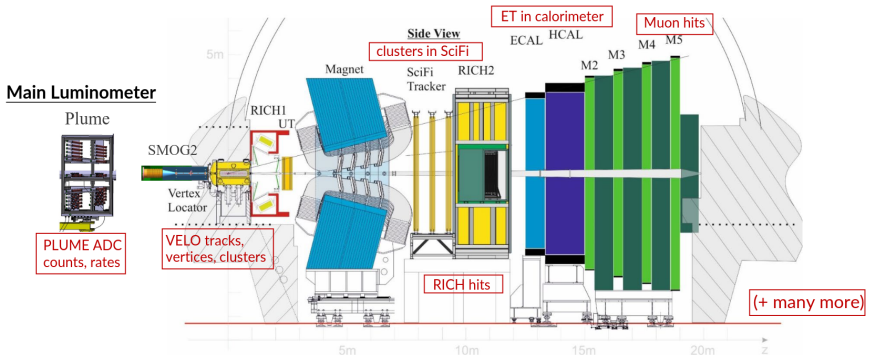
Contrary to beam-beam (bb), be and eb-crossings, in empty-empty: no Calo E_T counts, VELO tracks, vertices.

Luminometers in Run 3

LHCb upgrade between Run 2 and 3:

- pile-up μ increased from 1 to ~ 5 ,
- 40 MHz readout
- L0 hardware trigger removed, only software trigger on 1) GPU, 2) CPU
- efficiency improved (eg. x2)

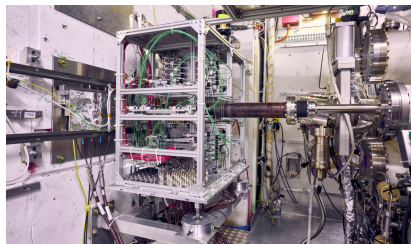
~ 350 (!!) different counters for cross-checks and studies of systematics



Run 3 online luminometers: PLUME

Proposed and initiated by IJCLab, with contributions from KIPT, TSNUK and ISMA

- Main, dedicated online luminometer.
- Cherenkov light in quartz tablet + window of 2×24 PMTs.
- Modified front-ends from calorimeter to count hits per bunch-crossing online.
- PMT gain adjusted to keep $\sim 1\%$ constant response to tracks from IP.
- Fast quasi-automatic calibration, available 30 min after vdM scan
- 4 PMTs are dedicated to timing measurements.



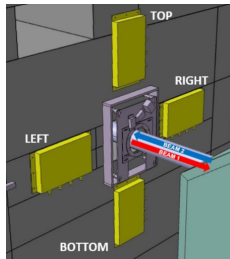
Availability: $> 99\%$ of time in all LHCb Run 3 operations (pp at different energies, $PbPb$, light ions).

pre-TDR (2020): [CERN-LHCb-PUB-2020-008](#), TDR (2021): [CERN-LHCC-2021-002](#),
performance (2026): [JINST 21 \(2026\) P09003](#)

Run 3 online luminometers: RMS-R3, JINST 20 P07027 (2025)

4 × 2 metal foil detectors, KINR

- Constantly calibrated by PLUME, took over when PLUME was not available (until other online luminometers were implemented)
- Secondary electron emission from 50 μm Cu foils
- Charge-to-frequency converter VFC110 sensitive **at fC level** (but at ~ 100 m in counting room)



BCM beam background monitor

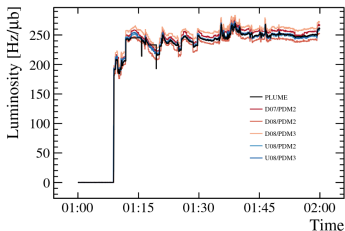
- polycrystalline Chemical Vapor Deposited (pCVD) diamond sensors, 8 up- and 8 down-stream of LHCb, FPGA-based readout
- Protects LHCb: 6 justified beam dumps in Run 3



Online luminometers developed in Run 3: RICH currents

JINST 20 (2025) P08001

- Currents through Multianode PMTs (MaPMTs)
- Runs independently of LHCb DAQ
- Within $\pm 5\%$ from PLUME (required online accuracy)

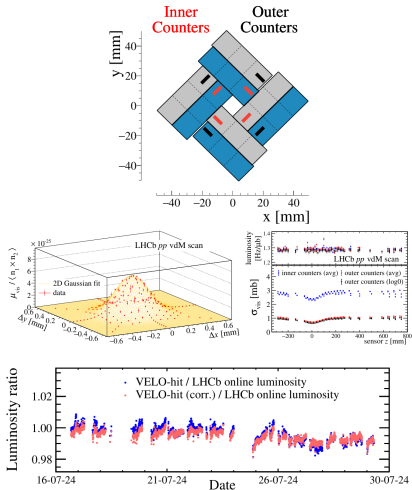


Currents in muon chambers

- Currents through multi-wire proportional chambers
- Independent of LHCb DAQ
- Correction for SMOG bgr. ($O(1\%)$) and atmospheric pressure ($< 1\%$).
- $\sim 7\%$ accurate luminosity

Run 3 online luminometers: VELO clusters, JINST 21 (2026) P04011

- VELO upgrade: strips $\rightarrow$ pixels.
FPGAs group hits to clusters
- In each of 26 VELO z-planes:
4 inner + 4 outer zones of cluster counting
 $\rightarrow$ 208 independent online counters
- Running mean of N clusters per
bb,be,eb,ee every 3 sec
- For 104 outer counters: fraction of
empties in 40 sec period per
bunch-crossing every 3 min
- Efficiencies depend on z of interaction
region (and to less extent on x, y)
- Good agreement with PLUME:



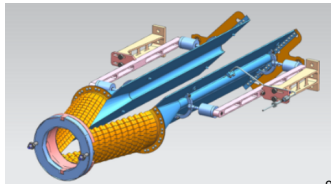
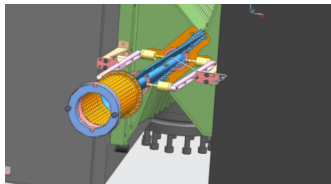
The best alternative to PLUME when VELO is closed and LHCb DAQ is running

>350 (!) new counters in trigger

- From all LHCb subdetectors (except UT at the moment), with fine segmentation: N hits, clusters, energy depositions, tracks, vertices
- Random lumi-event rate is increased from 1 kHz to 30 kHz
- **Very important** in offline systematics studies (cross-checks of different counters), and to understand subdetector performances

Gas injection system SMOG2, JINST 21 (2026) P04011

- Upgrade: SMOG = gas in VELO vessel
→ **SMOG2** = gas in narrow $\varnothing 1$ cm pipe
($z = [-50, -30]$ cm), x100 local pressure
- SMOG - originally for beam-gas imaging (BGI) for lumi, fixed-target physics was a spin-off.
SMOG2: x100 in fixed-target statistics (!),
BGI for beam 1 (only): spin-off.
- Fixed-target lumi:
 - N p -scatterings on atomic e^- with theoretical cross-section → SMOG pressure → luminosity
 - SMOG2 pressure from gas flux, temperature and simulated geometry (new in Run 3)
- Measures parasitic charges (“ghosts”) in LHC during van der Meer luminosity calibrations



LumiBMS project

Luminosity and Beam Monitoring System for the LHCb experiment, from Jan 2026.

Will provide online and offline luminosity, and protect LHCb from high backgrounds

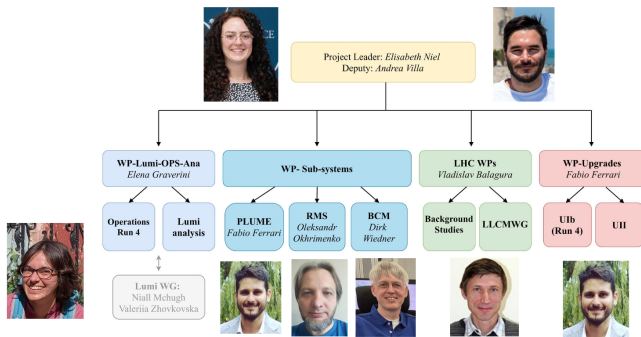
Institute	Country	Main contribution	Contact
EPFL	Switzerland	PLUME monitoring software	Lesya Shchutska
INFN-Bologna	Italy	PLUME calibration and data management	Fabio Ferrari
INFN-Firenze	Italy	Fixed-target luminosity analysis	Giacomo Graziani
INFN-LNF	Italy	Fixed-target luminosity analysis	Pasquali Di Nezza
INFN-Pisa	Italy	VELO luminosity firmware	Elena Graverini
ISMA	Ukraine	Offline luminosity analysis	Andriy Boyaryntsev
KINR	Ukraine	Radiation Monitoring System	Oleksandr Okhrimenko
TU Dortmund	Germany	Beam Conditions Monitor	Dirk Wiedner
LLR / IN2P3-CNRS	France	Offline luminosity supervision	Elisaebth Maria Niel

Others are welcome to join!

LumiBMS project

Luminosity and Beam Monitoring System for the LHCb experiment, from Jan 2026.

Will provide online and offline luminosity, and protect LHCb from high backgrounds



Others are welcome to join!

Math: probability generating function instead of $\mu = -\log P_0$

Reported at this [French-Ukrainian workshop in 2020](#), [link](#)

2 methods: lumi from $\mu = -\log P_0$ ("logZero") or from average $\frac{\sum N_i}{n}$.

LogZero is better: no bias if counter non-linear at large N_i (non-empty anyway)

After upgrade, $\mu = 1 \rightarrow 5$ and $P_0 = e^{-1} \rightarrow e^{-5} = 0.007$ – **low stat. of empties!**

Solution: **new method of luminosity measurement** (to be published):

Let $N_1, N_2, N_3, \dots$ - counter values in events 1, 2, 3, $\dots$

			limit: $\epsilon \rightarrow 0$
LogZero	$-\log P_0 = -\log \frac{(N_1==0?1:0)+(N_2==0?1:0)+\dots}{n}$	$= -\log \frac{\epsilon^{N_1} + \epsilon^{N_2} + \dots}{n}$	
Average	$\frac{N_1 + N_2 + \dots}{n}$	$= -\frac{1}{\epsilon} \log \frac{\epsilon^{N_1} + \epsilon^{N_2} + \dots}{n}$	$= -\frac{1}{\epsilon} \log \frac{\sum (1-\epsilon)^{N_i}}{n}$
PGF method	For any $z \in \mathbb{C}$:	Luminosity $\propto$	$-\log \frac{z^{N_1} + z^{N_2} + \dots}{n}$

If p_K – probability that counter = K :

$$\sum \frac{z^{N_1} + z^{N_2} + \dots}{n} = \sum p_K z^K = \text{probability generating function (PGF) of } p_K.$$

For $0 < z < 1$: "busy" events with non-linearity exponentially, $\propto z^N$, suppressed.

Tuning z btw. 0 (logZero) and 1 (average) allows PGF **to have statistics + remain linear**.

Already applied in Run 3 preliminary analyses

Back to Run 2: pp luminosity

Race for luminosity accuracy, main drivers: Z , W , t cross-sections.

Records at bunched hadron colliders:

- 8 TeV, Run 1, LHCb: **1.16%**, JINST 9 P12005 (2014)
- 13 TeV, ATLAS: **0.83%**, Eur. Phys. J. C 83, 982 (2023)
- 13 TeV, CMS: **0.73%**, arXiv:2606.26832 (Aug-Sep 2026)

LHCb unique advantages:

- Calibrated $\mu \sim 0.5$ (in vdM fills) is close to physics $\mu^{\text{LHCb}} \sim 1$ (in Run 2) and $\mu \approx \text{const}$ (“leveled”) most of the time; while $\mu^{\text{ATLAS/CMS}} \sim 30$ in LHCb “units”
- Beam-gas imaging (BGI): determines bunch shapes, overlap and luminosity. Complementary to van der Meer (vdM) calibration, used by all LHC experiments.

$$L = N_1 N_2 \int \rho_1(x, y) \rho_2(x, y) dx dy$$

BGI bunch $\rho_{1,2}$ “photos” are blurred by VELO resolution, which should be measured and de-convolved. Run 2 novelties:

BGI Run 2 calibration will soon be public.

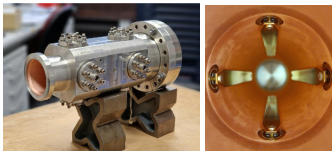
- Much larger BGI statistics due to SMOG injection, sufficient to measure $\rho_{1,2}$ every 15 min without fits of pp interaction overlap $\rightarrow$ simpler.
- Selection of vertices with more tracks $\rightarrow$ better resolution.
- Bunch deformations due to bunch electromagnetic repulsions are modeled.

Further Run 2 improvements

Van der Meer idea in two dimensions:

$$\iint \frac{\mu(\Delta x, \Delta y)}{N_1 N_2} d\Delta x d\Delta y = \sigma \iint \rho_1(x_2 + \Delta x, y_2 + \Delta y) \rho_2(x_2, y_2) dx_2 dy_2 d\Delta x d\Delta y = \sigma$$

- LHCb pioneered **two-dimensional vdM scans** at LHC: no need to assume $\rho_{1,2}$ x - y factorization, avoid $\sim 1\%$ associated systematics
- LHC gained accurate ($< 1\mu\text{m}$), per-second beam position monitors (DOROS) in 2016. But require calibration, **the best is performed with LHCb BGI**.



- Electromagnetic repulsion of bunches modeled in LHC publications before 2019 was oversimplified, cross-sections biased by $\sim 1\%$. New accelerator simulation **BxB** is developed, **EPJC 81, 26 (2021)**.
- **Data-driven** eff. of lumi-counters, N VELO vertices and tracks, no MC dependence
- Low stat. of lumi-events (only 1 kHz rate in physics): solved using rolling windows per bunch-crossing and 2d-order logZero correction

$$\mu = -\log \frac{n_0}{n} - \frac{1}{2} \left(\frac{1}{n_0} - \frac{1}{n} \right)$$

Run 2 LHCb luminosity *is not yet public*

Race for luminosity accuracy, main drivers: Z , W , t cross-sections.

Records at bunched hadron colliders:

- 8 TeV, Run 1, LHCb: **1.16%**, JINST 9 P12005 (2014)
- 13 TeV, ATLAS: **0.83%**, Eur. Phys. J. C 83, 982 (2023)
- 13 TeV, CMS: **0.73%**, arXiv:2606.26832 (Aug-Sep 2026)

LHCb Run 2: conservative 2% from 2020.

New numbers at 13 TeV preliminarily converge to:

- BGI calibration accuracy: $\approx 0.91\%$
- vdM calibration: $\approx 0.56\%$
- counting vertices in physics: $\approx 0.2\%$

Total: $\approx 0.53\%$

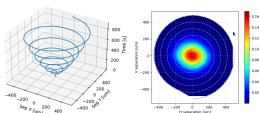
LHCb luminosity: a story of success and innovation continues

Currently, 6% for “early Run 3 publications”, but will be improved during LHC shutdown.

New ideas and improvements:

- > 350 new counters in LHCb (instead of 9 in Run 2)
- $2 \times 2 \times 4 = 16$ vdM magnets: 4 required to parallel-shift one beam in one direction. Before 2025, vdM scans at discrete points: no data-taking in between, until currents in all magnets reach new values.

In 2025, LHC pioneered “**spiral**” **continuous scans** specifically for LHCb.



Saves beam time and allows continuous vdM integration.

If validated by LHCb, other experiments will follow.

- Dominating Run 2 systematics is due to LHC tune uncertainty, affecting beam-beam repulsion and bunch deformations (this was not known in Run 2). In Run 3, LHC performed a dedicated tune measurement in vdM fills.
- LHC increased bunch sizes by $\sqrt{2}$ in both x and y in ATLAS/CMS vdM fills when LHCb performs BGI calibration $\rightarrow$ simplifies deconvolution with VELO resolution.

A lot of places to contribute to Run 3 analysis!

Conclusions

LHCb collaboration < ATLAS, CMS: less people for luminosity measurements.
However, this is (over)compensated by innovations:

- unique **Beam-Gas Imaging**,
- **Beam-Beam Imaging** (not mentioned, used now in CMS),
- **two-dimensional scans**,
- modeling of **beam-beam** repulsions,
- usage of the **best analysis methods**
 - logZero, with 2d-order correction
 - Gauss-Hermite quadrature to convolve Gaussian bunch with polynomial efficiency
 - probability generating functions in Run 3
- new promising **spiral vdM** scans
- new online luminometers (**PLUME, VELO clusters, currents**), by far the largest (> 350) number of lumi-counters per experiment in Run 3
- **LHCb Run 2 pp luminosity** will set a new record at bunched hadron colliders

A lot of places to contribute to Run 3 analyses !