Luminosity at LHCb in Run 3

Elena Graverini, on behalf of the LHCb collaboration

École Polytechnique Fédérale Lausanne

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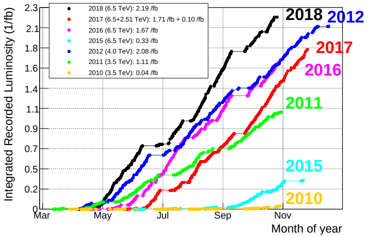
Luminosity: basics

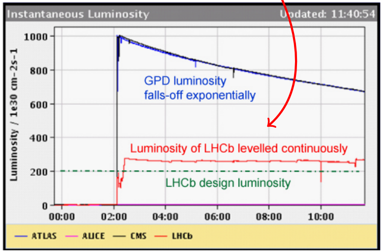
Luminosity answers the question: *at what rate will process j happen at my experimental location?*

$$R_j = \mathcal{L}\sigma_j$$

- time-integrated luminosity: necessary to calculate cross sections
- instantaneous luminosity at LHCb: continuous luminosity levelling
  - steer beams to operate the detector in optimal conditions at constant rates

time-integrated luminosity at LHCb





Measuring luminosity

- from visible number of interactions μ_{vis} and effective cross section σ_{vis}:

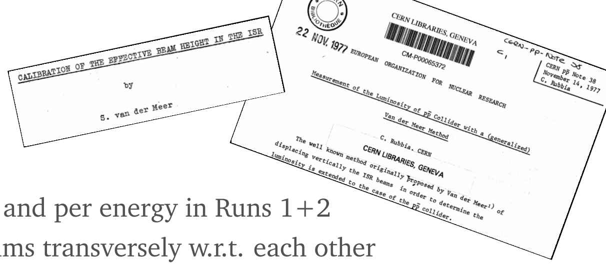
$$\mathcal{L} = f \frac{\mu_{vis}}{\sigma_{vis}}$$

  (where f = LHC revolution frequency)

- μ_{vis} measures relative luminosity
  - can be monitored continuously
  - depends on chosen luminometer

- σ_{vis} measures absolute luminosity
  - determined in dedicated scans
  - at LHCb: beam gas imaging (Run 1, 3), van der Meer scans (Runs 1, 2, 3)

Absolute luminosity


CALIBRATION OF THE EFFECTIVE BEAM HEIGHT IN THE ISR

by

S. van der Meer

22 NOV. 1977

CERN LIBRARIES, GENEVA

CM-P00065372

CERN-PP-Note

CERN $p\bar{p}$ Note 38
November 14, 1977
C. Rubbia

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Measurement of the Luminosity of $p\bar{p}$ Collider with a (generalized) Van der Meer Method

C. Rubbia. CERN

CERN LIBRARIES, GENEVA

The well known method originally proposed by Van der Meer[1]) of displacing vertically the ISR beams in order to determine the luminosity is extended to the case of the $p\bar{p}$ collider.

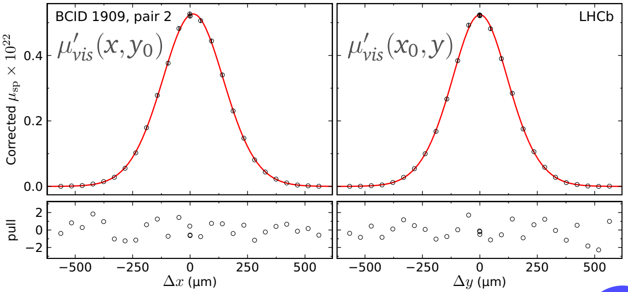
- van der Meer scans performed once per year and per energy in Runs 1+2
- measure beam size by displacing the two beams transversely w.r.t. each other
- μ_{vis} measured per step with all available counters

$$\sigma_{vis} = \frac{\int \mu'_{vis}(x,y_0)\,dx \int \mu'_{vis}(x_0,y)\,dy}{\mu'_{vis}(x_0,y_0)}$$

where $\mu'_{vis} \equiv \mu_{vis}/N_1N_2$ and $N_{1,2}$ = populations of colliding bunches at the considered step

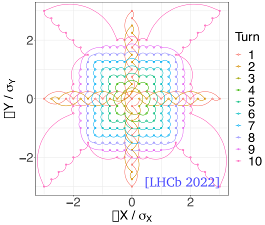
[EPJC (2021) 81:26]

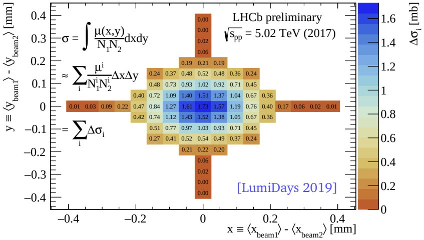
[JINST 9 (2014) P12005]



More on van der Meer scans

- previous formula assumes factorizability of x and y beam profiles!
- associated systematics proved nonnegligible [JINST 9 (2014) P12005]
- new: 2-dimensional scan in the central region [V. Balagura, LumiDays 2019]
  - pioneered at LHCb in Run 2, proved most accurate calibration method
  - will be used by other LHC experiments in Run 3



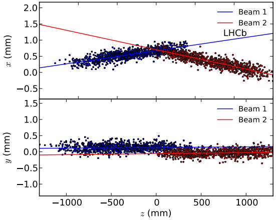


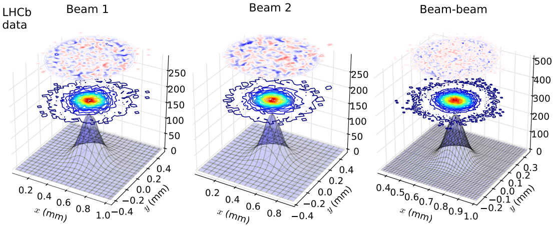
86% of full integral measured directly; extrapolated to the whole plane

- $\langle\mu\rangle$ from 1 (Run 2) $\rightarrow$ 5 (Run 3)
  - counters must be linear to extrapolate calibration from vdM scans ($\mu < 0.5$–1)
  - mini-vdM scan (emittance scan) at physics μ at the start/end of fill, like by CMS, ATLAS

Beam-gas imaging and SMOG2

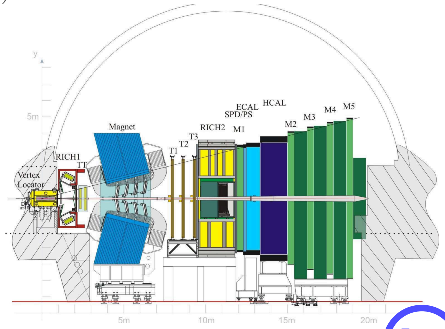
- excellent spacial resolution of LHCb VErtex LOcator (VELO)
  - reconstruct interactions between LHC beam and residual or injected gas molecules
  - calibrate DOROS beam position monitors from LHC
- SMOG: initially conceived to calibrate luminosity measurement
  - Beam Gas Imaging (BGI) alternative method for absolute lumi calibration, unique to LHCb
  - demonstrated potential for fixed-target physics
- new **SMOG2** storage cell installed for Run 3: LHCb can operate efficiently as both a **collider** and a **fixed-target** experiment!
- check BGI video at `this link`





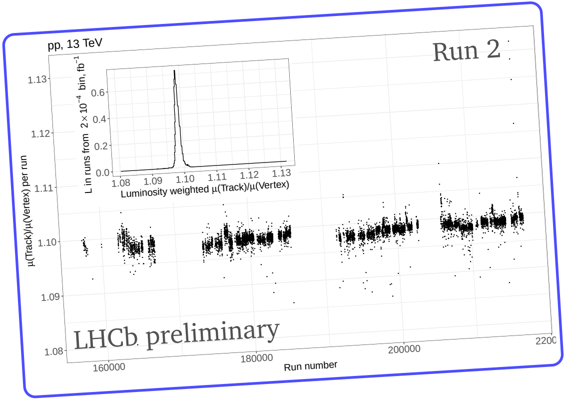
Relative luminosity

- count interactions during data taking
- use quantities proportional to $\mathcal{L}$, with efficiency stable in time
- `log0` method
  - uses Poisson statistics: $\mu_{vis} = -\log P(0) = -\log\left(N_{empty}/N_{tot}\right)$
  - mitigates non-linearity and instability
  - in Run 3 $\mu \sim 5$ might prove challenging
- in Runs 1+2:
  - online luminosity: calorimeter E_T, scintillating pad hits, n muon candidates, upstream VELO hits
  - offline luminosity: tracks and vertices in VELO + other counters as cross-checks

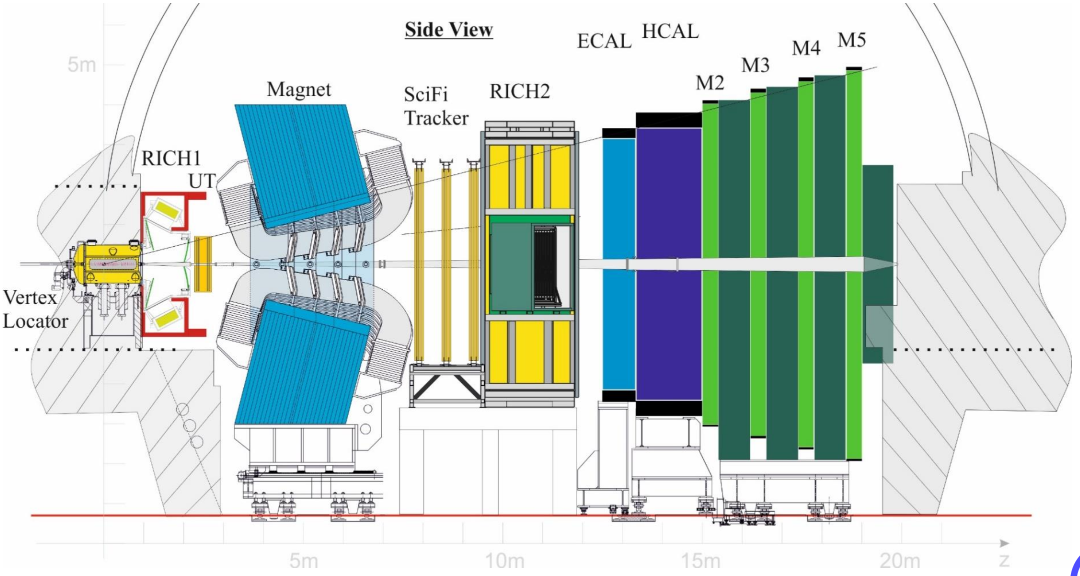


Example: VELO counters

- tracks and vertices recorded in LHCb's VErtex LOcator
- `log0` method, *pp*: events with less than 2 tracks or 1 vertex are empty
- luminosity-corrected ratio $\mu_{vis,track}/\mu_{vis,vtx}$ stable to within 0.08% across *pp*, 13 TeV (Run 2)
  - uncertainty on relative lumi $\leq 0.2\%$
  - best in LHC



The LHCb detector in Run 3



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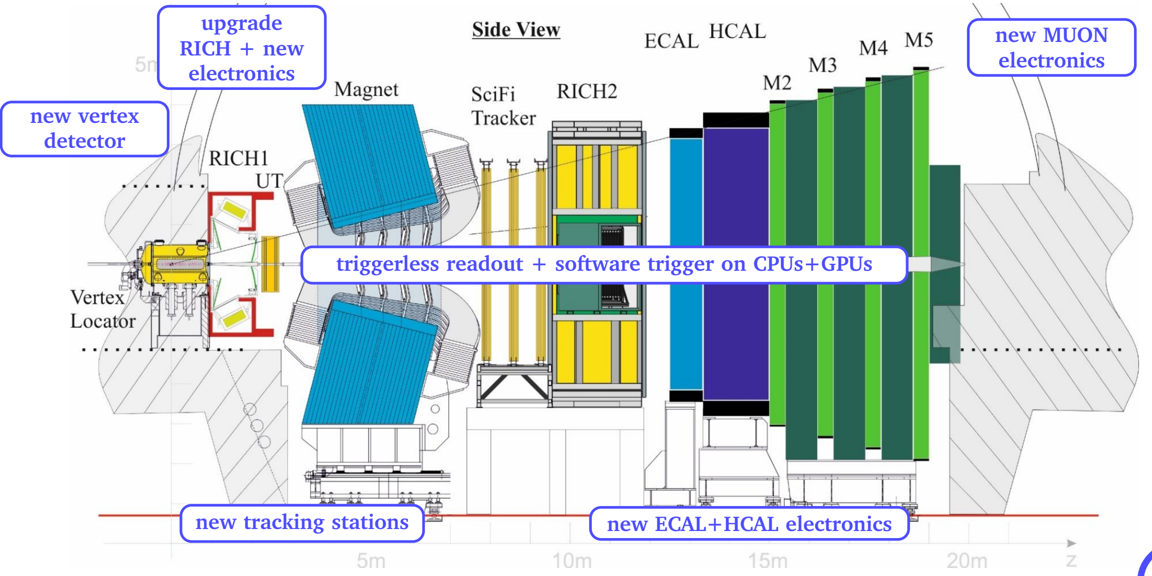
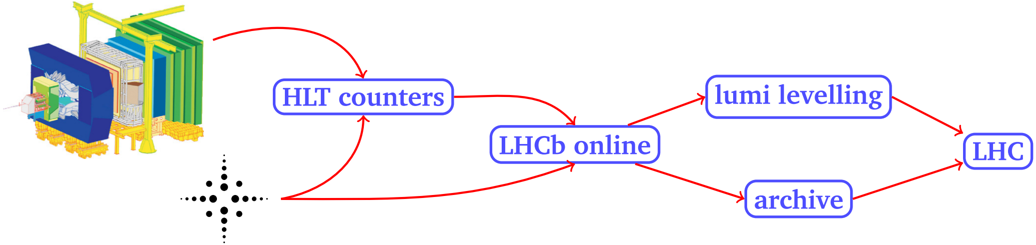
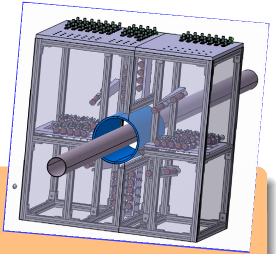


New challenges!

- no hardware trigger (L0) $\longrightarrow$ completely redesigned data taking flow
  - offline-quality CPU+GPU real-time reconstruction
- Run 1+2: calorimeter E_T from L0 provided real-time μ
- re-invent new luminometers for Run 3
- including a new dedicated detector
  - real-time luminosity for lumi-levelling
  - integrated with, but independent from LHCb



A new Probe for LUminosity MEasurements



- new LHCb detector, conceived in 2019, now installed and taking data
- ongoing intense commissioning phase

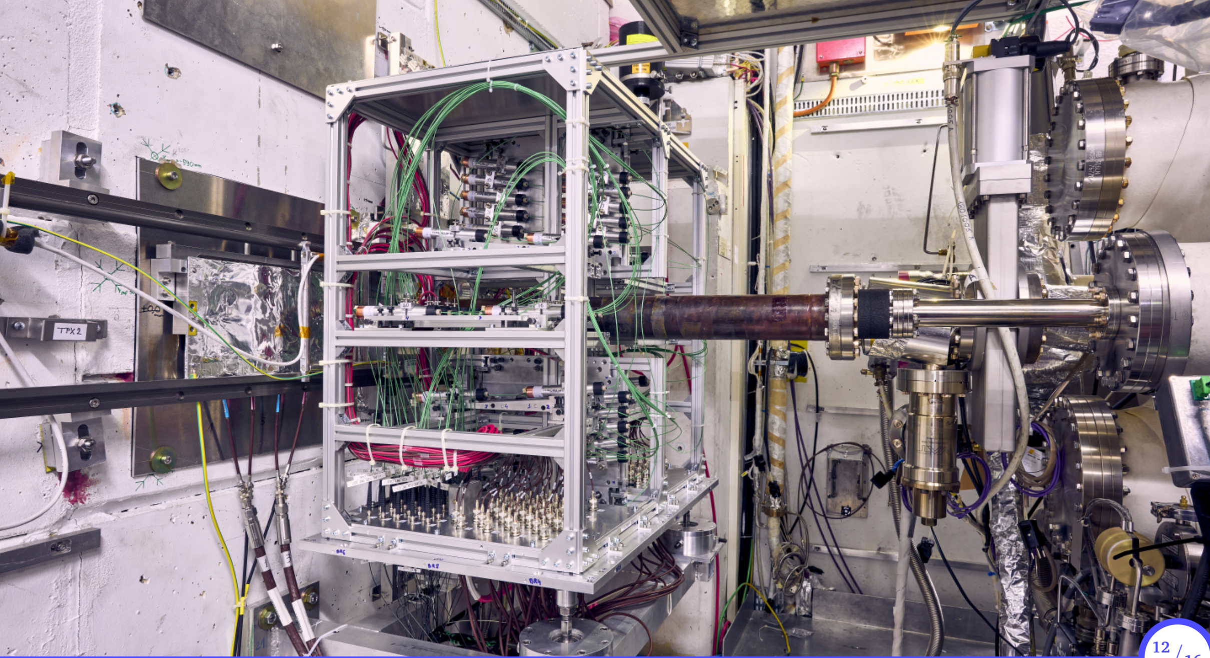
design requirements

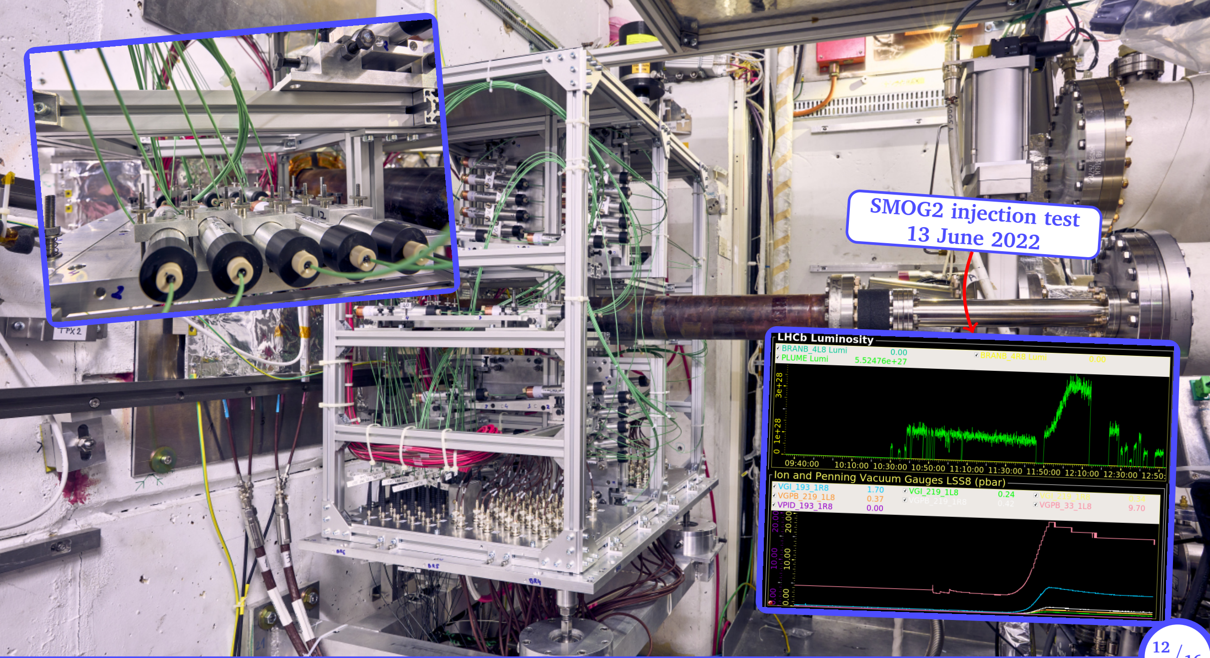
- large signal (high precision) + fast signal (avoid *spillover*)
- radiation resistant (10^{14} neutrons/cm^2)
- occupancy $\mathcal{O}(1\%)$

PLUME

- hodoscope of 24 projective pairs of quartz-window PMTs with quartz tablet in front
  - profit from ATLAS-LUCID experience
  - fast Cherenkov light signal
  - 22 PMT pairs for lumi, 2 for timing
- read out with LHCb calorimeter electronics
- reconstructed tracks + LED light injection system for gain stabilization

CERN-LHCC-2021-002


TPX2



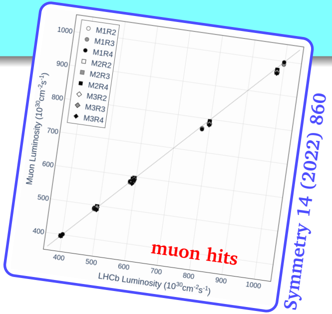
SMOG2 injection test
13 June 2022
LHCb Luminosity
BRANB_4L8 Lumi 0.00
PLUME Lumi 5.52476e+27
BRANB_4R8 Lumi 0.00
3e+28
1e+28
0
09:40:00 10:10:00 10:30:00 10:50:00 11:10:00 11:30:00 11:50:00 12:10:00 12:30:00 12:50:
Ion and Penning Vacuum Gauges LSS8 (pbar)
VGI_193_1R8 1.70
VGPB_219_1L8 0.37
VPID_193_1R8 0.00
VGI_219_1L8 0.24
VGPB_219_1R8 0.42
VGI_219_1R8 0.34
VGPB_33_1L8 9.70
20.00
10.00
0.00

New counters

Requirements

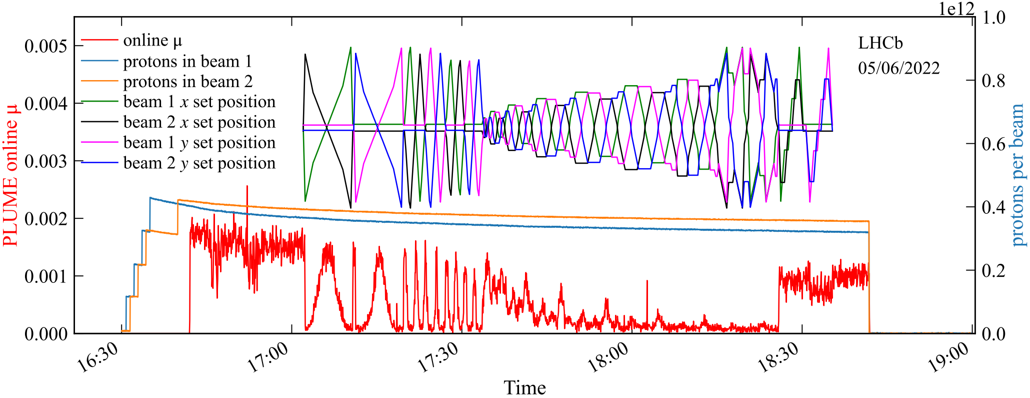
- many counters! cross-check stability + reduce systematics
- response scales linearly with luminosity
- efficiency is stable in time

- number of VELO tracks and vertices
- number of hits in any detector
- number of clusters in SciFi
- number of coincidences in PLUME
- E_T in calorimeter
- physics channels such as $Z \to \mu\mu$
- **these and more observables under study!**



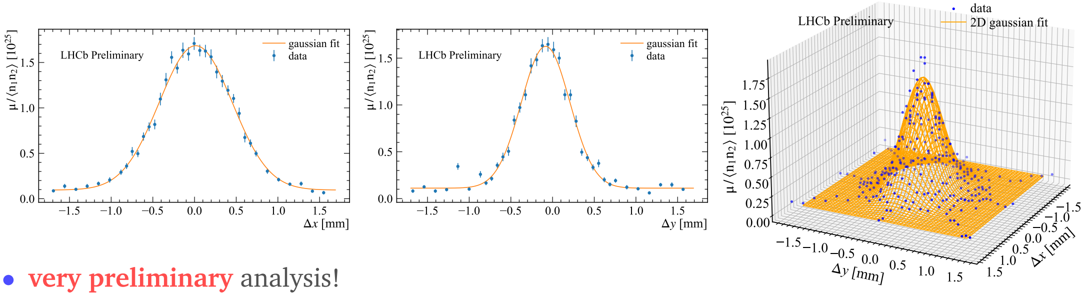
First lights...

First LHCb vdM scan on June 5: absolute calibration of PLUME for $\sqrt{s} = 900$ GeV



- PLUME online μ from coincidences in any of 22 lumi PMT pairs
- beam movements shown in arbitrary scale at corresponding time
- two 1D vdM scan followed by 2D scan and length scale calibration

First lights...



- **very preliminary** analysis!
- many simplifications:
  - positions of beams: LHC set values
  - bunch populations (from LHC) are averaged
  - use PLUME coincidences recorded online every 3 seconds
  - no background subtraction
- 1D and 2D σ_{vis} compatible, beam size $\approx 300 \times 200\ \mu$m

Conclusions

LHCb luminosity track record

- record accuracy (1.16%) for luminosity at a bunched hadron collider in Run 1 [JINST 9 (2014) P12005]
  - use of unique beam-gas imaging capabilities
- pioneered 2D van der Meer scans in Run 2
- best time stability of lumi counters in Run 2
  - lumi available at 2% accuracy for Run 2 (*pp* 13 TeV) [see R. Lavička, LHCP 2022]

new LHCb subdetectors & new electronics for Run 3

- switch to software trigger imposes new challenges for real time luminosity
- re-invent a set of luminosity counters
  - observables from HLT and from experiment control system
  - linear response and stable efficiency are crucial
  - will be calibrated with vdM and cross-checked against each other
- new dedicated detector (**PLUME**) installed and functioning, being commissioned
  - very preliminary calibration of absolute luminosity at injection energy
- extremely lively commissioning phase :)

Spare slides