Long-term monitoring of delivered luminosity & calibration stability in LHCb

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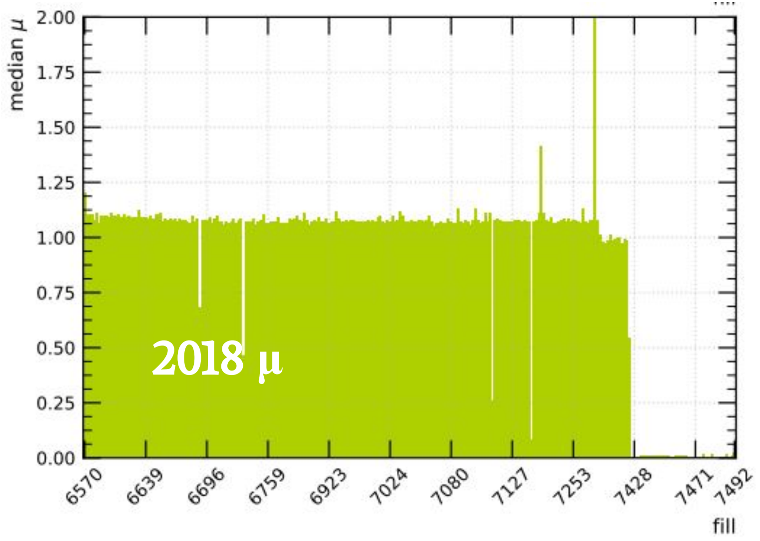
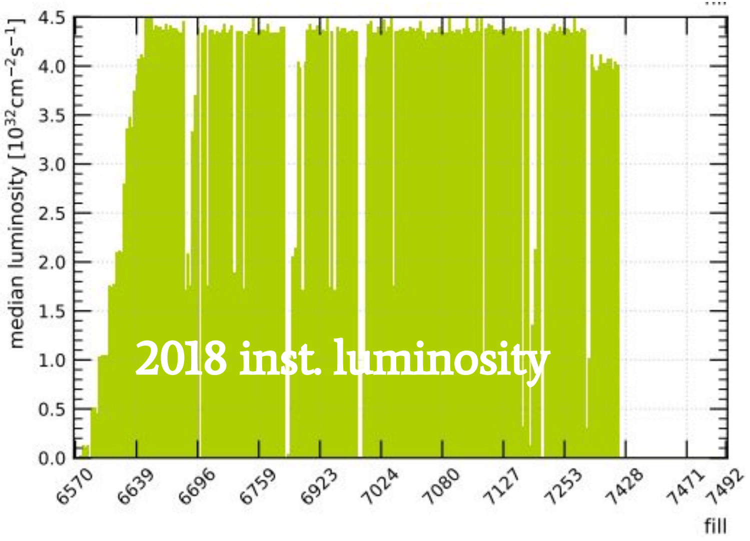
LHC Lumi Days 2019, 4–5 June 2019

What’s special in LHCb?

median mu and instantaneous luminosity per fill using online CALO-based measurement





Leveling at μ of 1.1 is a blessing for propagation of luminosity calibration!

Simply count the events

$$\int L\,dt = \frac{1}{\sigma_{eff}} \sum_i N_{\mathrm{int}}^i$$

Absolute calibration
determined from dedicated measurement using BGI and van der Meer methods

Relative luminosity
(interaction counting) determined using randomly triggered crossings and “-log0” method

Relative luminosity

$$N_{\text{int}} = \frac{f_{rev}}{R_{trig}} \sum_j N_j^{trig} \mu_j \approx \frac{f_{rev}}{R_{trig}} n_{bb} N^{trig} \mu$$

$$\mu = \frac{\mu_{bb} - \mu_{be} - \mu_{eb}}{1 - I(0)}$$

$$\mu_{bb} = -\log P(0) = -\log \frac{N_0^{trig}}{N^{trig}}$$

"log0" method works really well at mu of 1.1 to get a value proportional to L

In Run 2, typically 1000 Hz of random "bb" events acquired, "nanofied" to O(100) bytes and stored in physics data. Aggregated in prompt offline processing and calibration applied in analysis jobs

f_{rev} = LHC revolution frequency
R_{trig} = random trigger rate (bb crossings)
j runs over all colliding BCIDs

Relative luminosity (2)

Method equivalent to Run 1
2014 JINST 9 P12005

$$N_{\text{int}} = \frac{f_{rev}}{R_{trig}} \sum_j N_j^{trig} \mu_j \approx \frac{f_{rev}}{R_{trig}} n_{bb} N^{trig} \mu$$

Bias is introduced due to spread of μ over bunches
- correction is needed

$$\mu = \frac{\mu_{bb} - \mu_{be} - \mu_{eb}}{1 - I(0)}$$

I is the detector response to one interaction.
I(0) is the probability to get an "empty" event if one interaction took place. Depends on Z position of luminous region (LR) for VELO counters.
- correction is needed

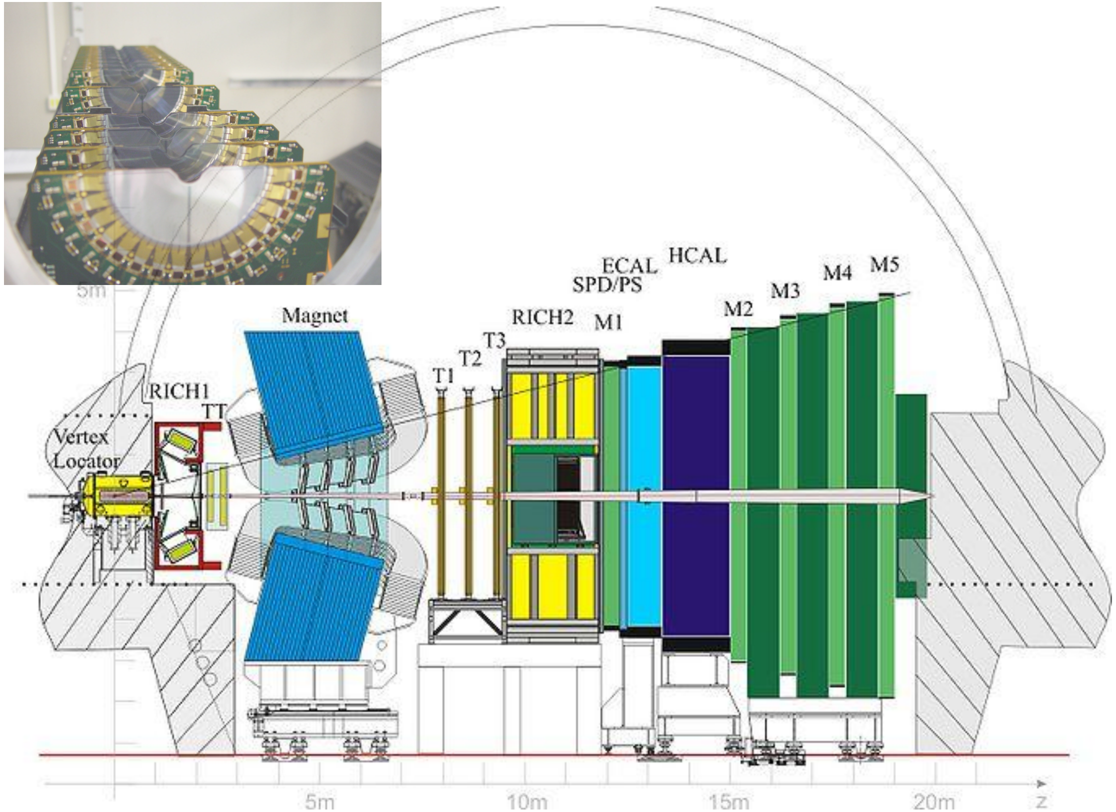
$$\mu_{bb} = -\log P(0) = -\log \frac{N_0^{trig}}{N^{trig}}$$

Number of "empty" events.
We can use various definitions of "empty" event (various lumi counters/observables).

- number of VELO tracks < 2
- number of PV < 1
- …

f_{rev} = LHC revolution frequency
R_{trig} = random trigger rate (bb crossings)
j runs over all colliding BCIDs

Counting events



CALO (L0)

- SPD: # hits in 6k scintillators
- HCAL: max ET
- online: & of the two

MUON (L0)

- # muon candidates

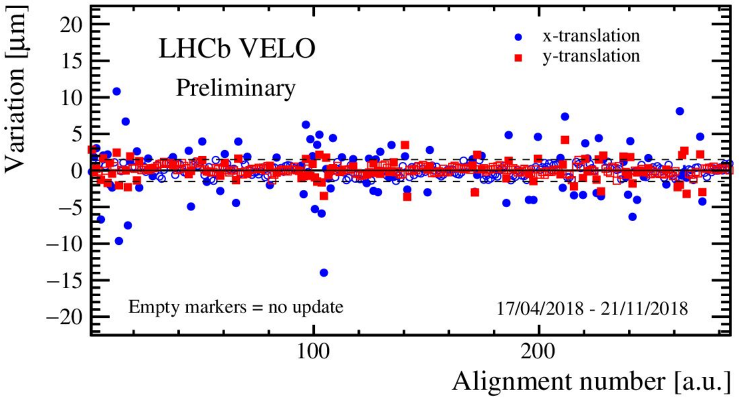
PU (L0)

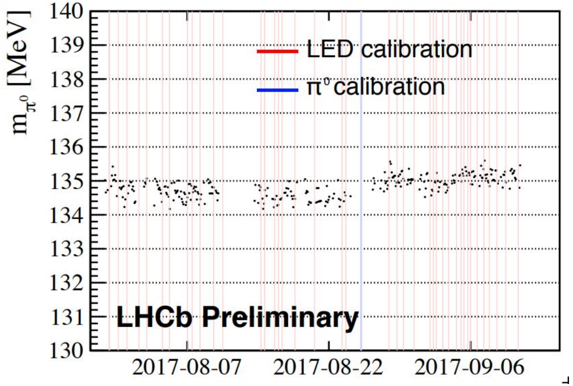
- # hits

VELO (HLT)

- # tracks (baseline counter)
- # vertices
- variations of the above

Well calibrated!





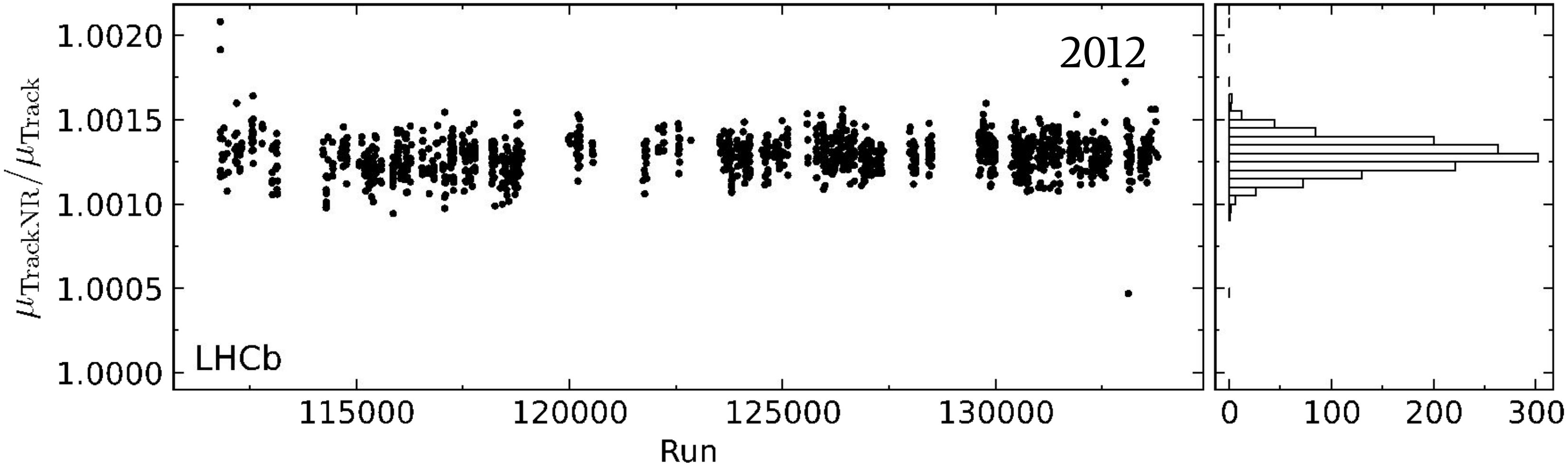
I like LHCb a lot, too!

Luminosity wouldn't be so easy without all calibrations.

VELO: Regular IV, CCE scans, HV adjustments; align every fill!

CALO: timing; caesium scan every TS for HCAL, π^0-based for ECAL; update HV every fill based on a LED system

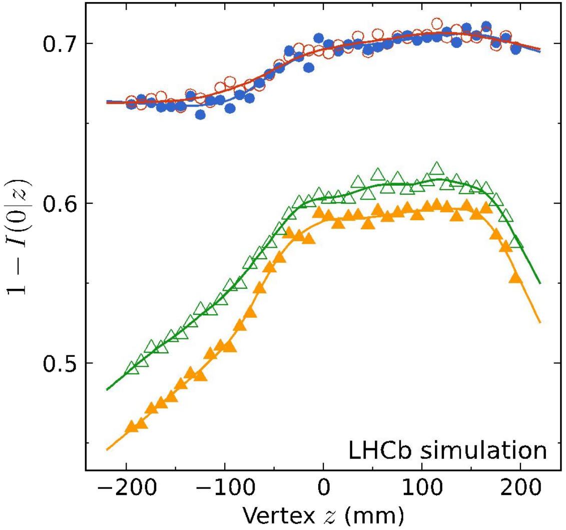
Background

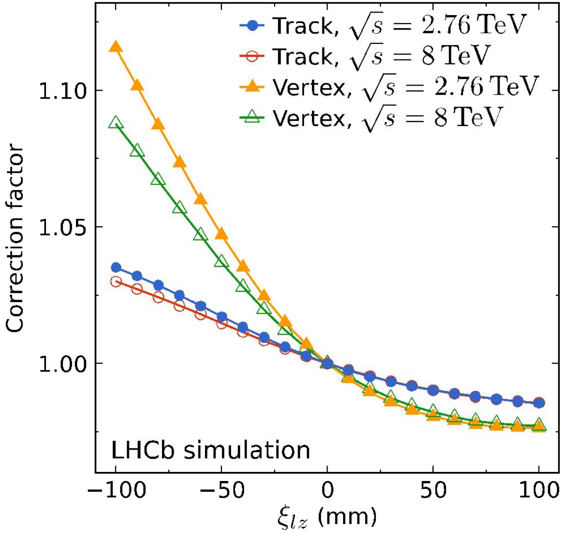


- Beam-gas background is well understood and subtracted (small)
- Beam-beam related background is estimated (e.g. main-satellite collisions)
  - take the difference between counting VELO tracks with and w/o fiducial volume cut around the luminous region as a systematic
  - the restricted observable is used for calibration

Efficiency correction

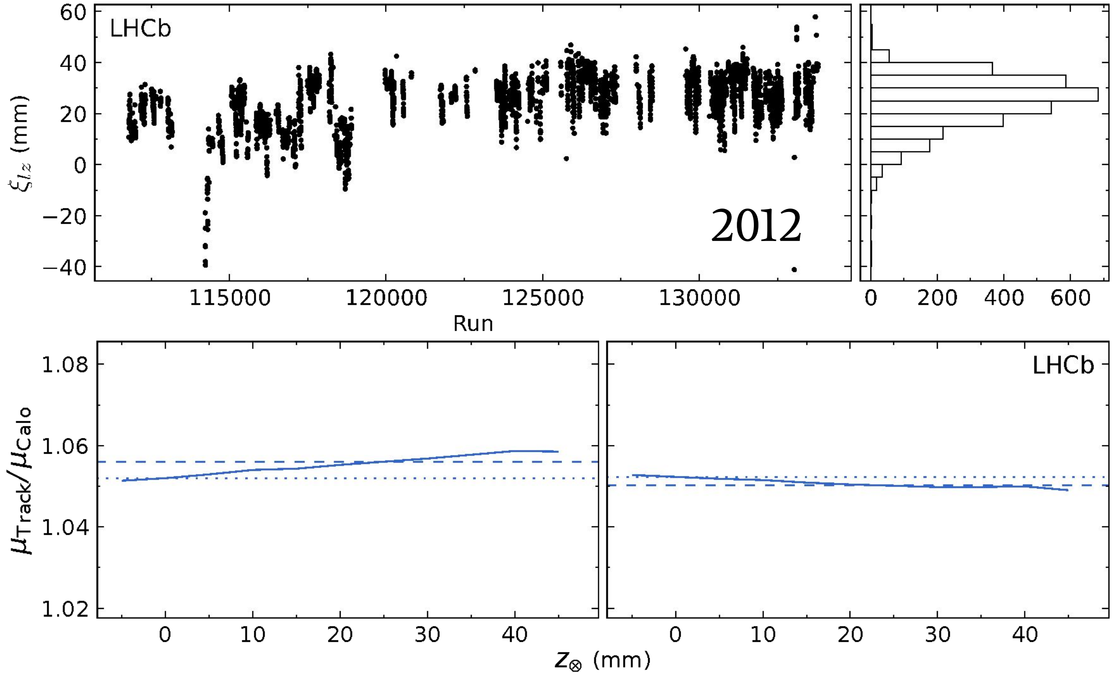
assuming σ_{LR} = 50 mm





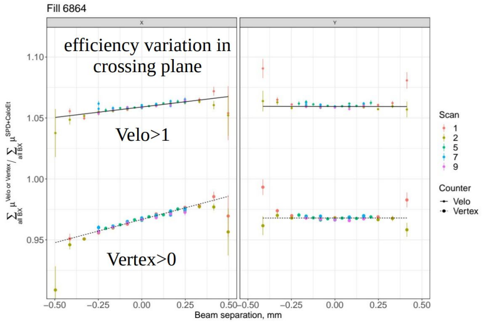
- Longitudinal luminous region (LR) movements not negligible compared to VELO length (worse in 2012, leveling in bad plane)
- The z-dependence of the efficiency is estimated from simulation
- Correction based on measured z position and length of LR

Efficiency correction (2)



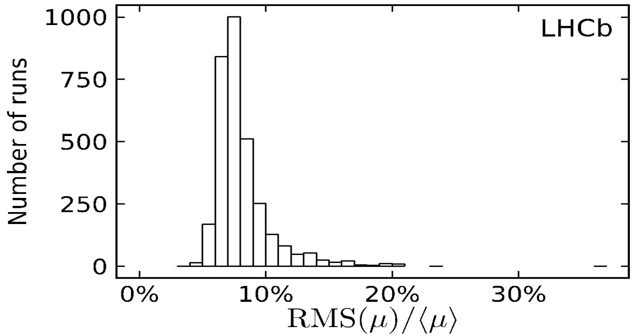
Cross check with an unaffected observable: online luminometer based on HCAL+SPD

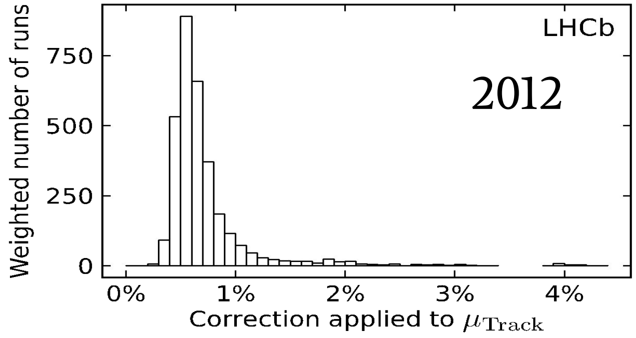
Same procedure in VDM (bigger lever arm)



Spread of μ over bunches

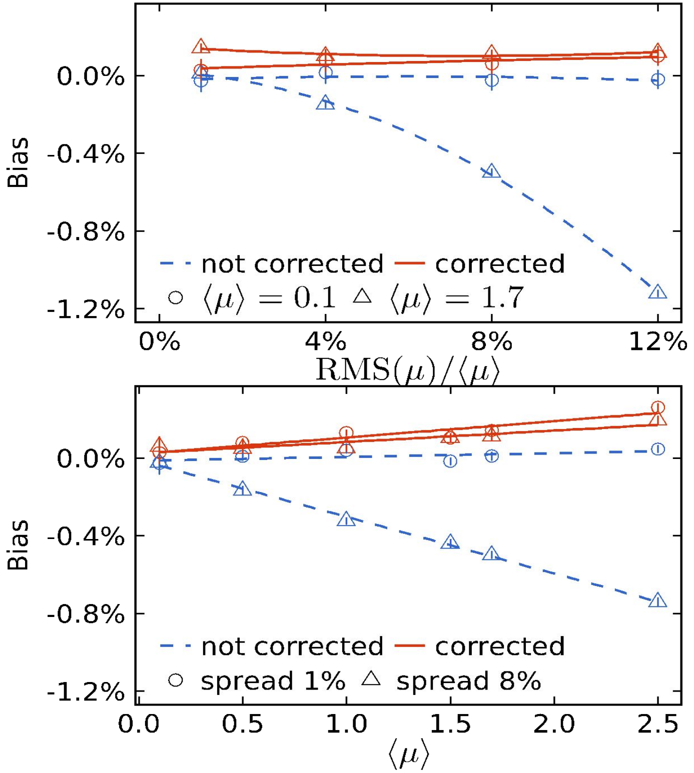
- Random triggers rate insufficient to measure μ for each bunch in a short period of time
- First, assume all bunches have the same μ
- Then, correct using long time periods (30m)
  - assume μ does not change during the period
  - measure relative μ values of bunches
  - calculate correction factor for each long period
  - estimate residual bias after such correction using a MC technique
- Run 3: more spread expected ⇒ to be revised
  - with distinct groups of bunches

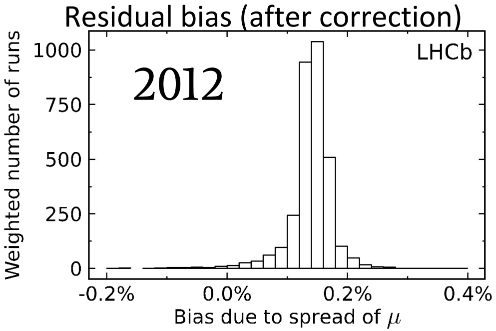


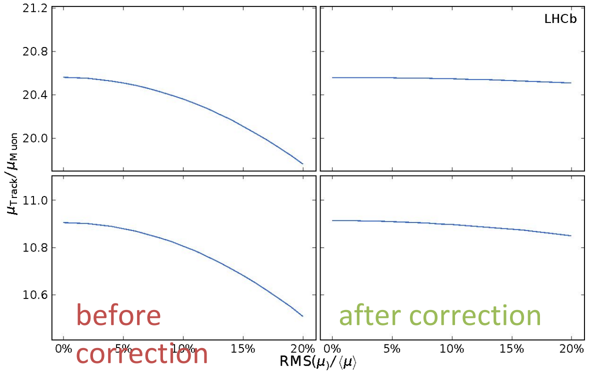


Spread of μ over bunches (2)

- Estimate residual bias using toy simulations
- Cross-check using a less affected counter
  - i.e. one with smaller efficiency (μ values)

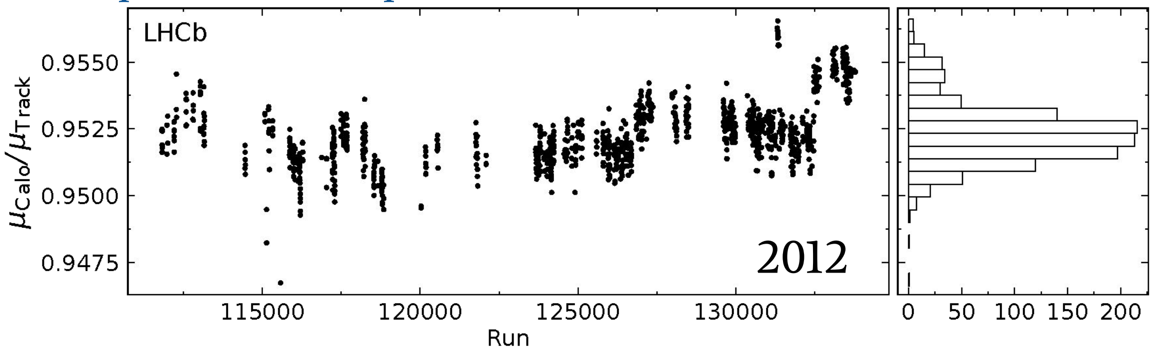




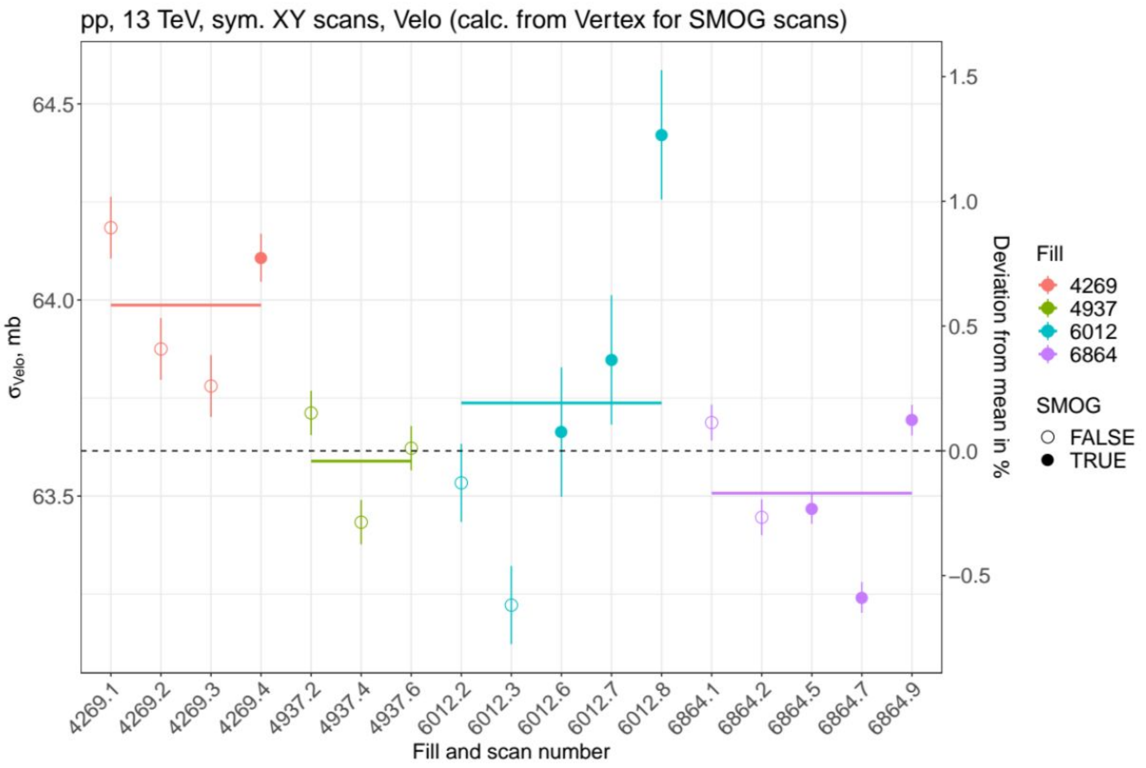


Stability of the effective process

- Compare Track counter with the CALO-based (online) counter
- Take the RMS of the ratio as an uncertainty on the Track counter
    - conservative, we “know” Tracks are inherently more stable
    - threshold changes in the calo correlate with steps in the ratio
- Analogous comparison with Vertex counter (# vertices ≥ 1)
    - Vertices composed of >4(5) tracks ⇒ ratio sensitive to VELO efficiency
    - RMS compatible with expected statistical fluctuations

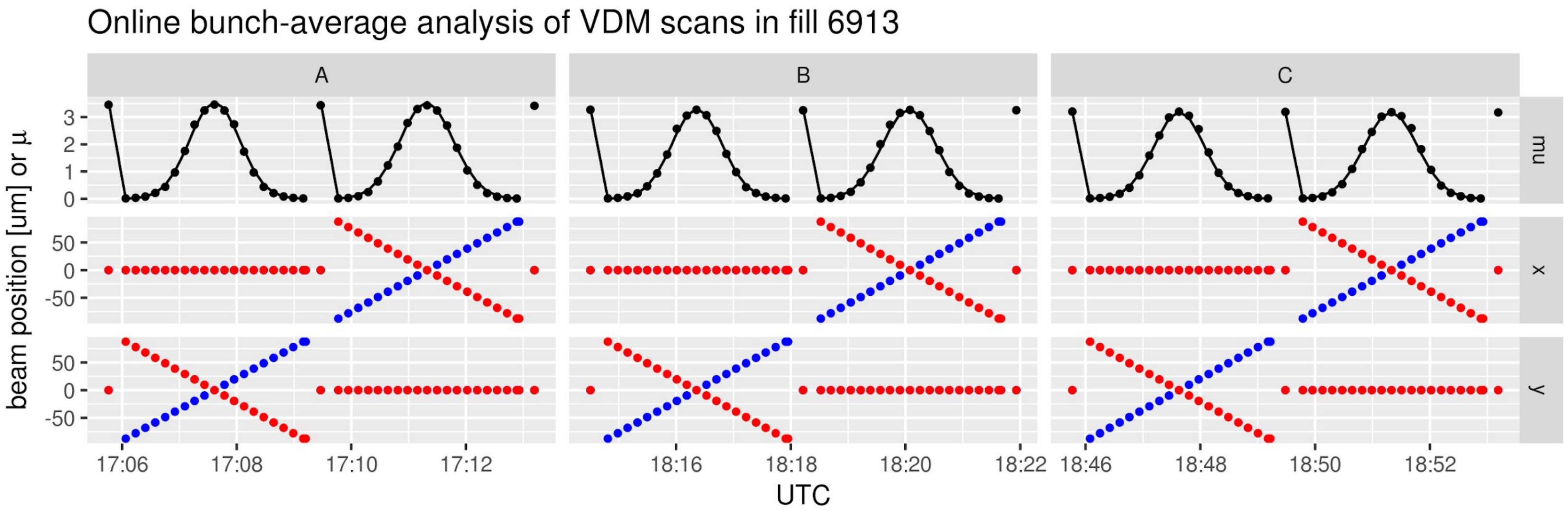


Ultimate stability check



The absolute calibration for each year of Run 2 yields stable values across different counters

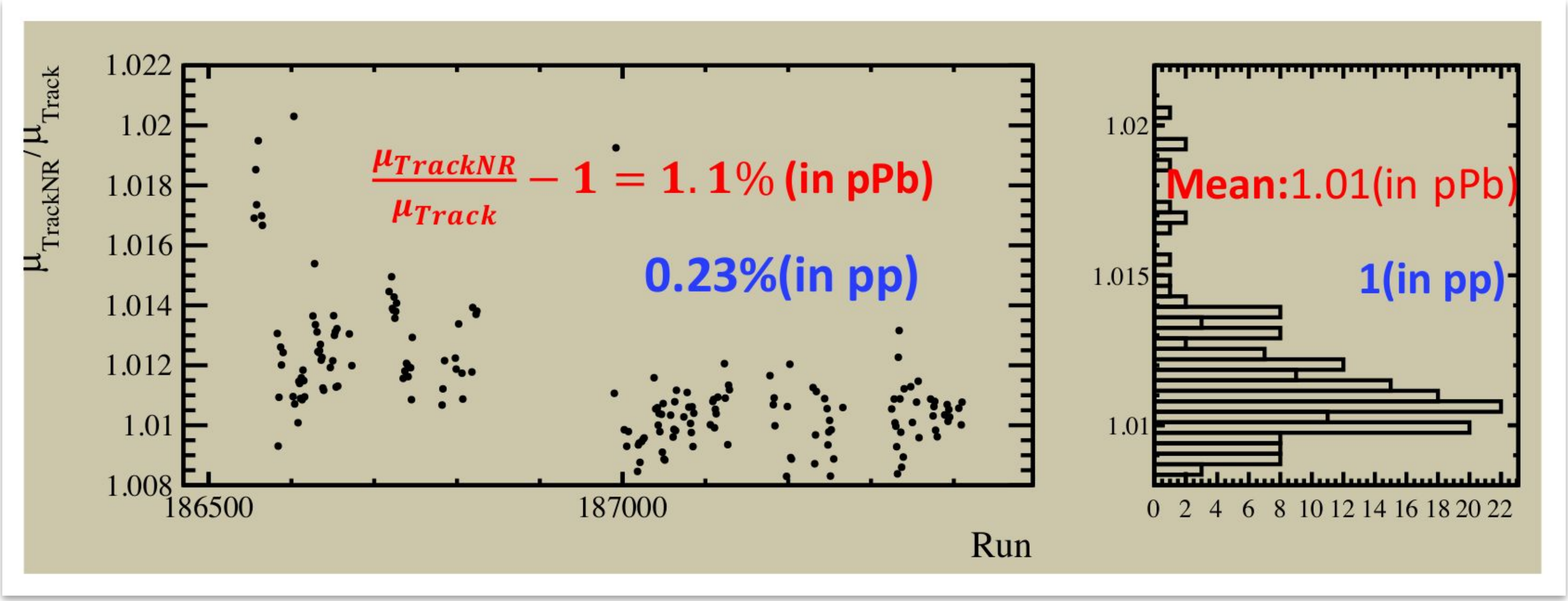
Emittance scans?



- LHCb took part in a 2018 BSRT calibration fill. Nominal optics ⇒ high mu!
- Rudimentary online analysis gives cross-section surprisingly close to VDM
- Likely OK in Run 3 to exceed target mu as longs as total lumi is < design

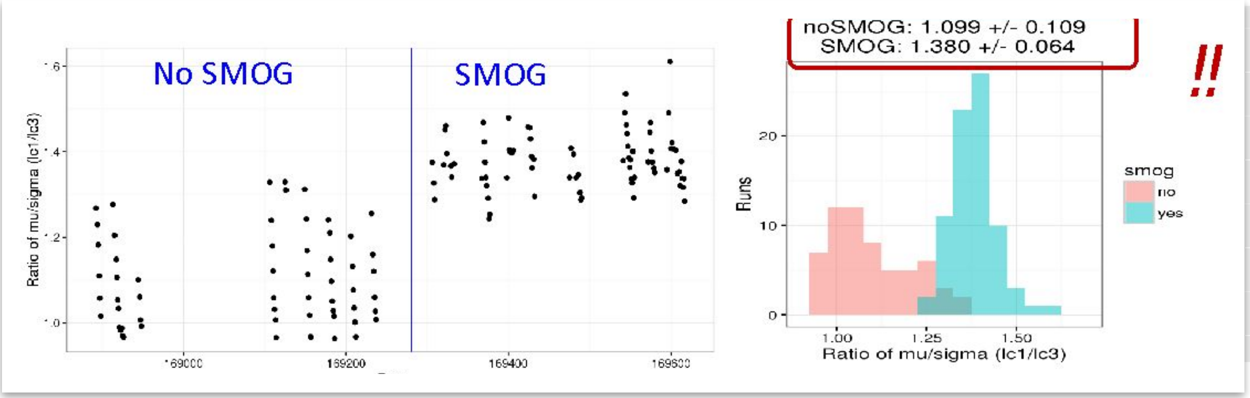
Proton-lead luminosity

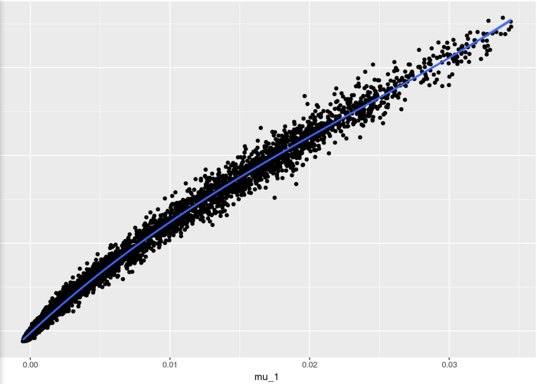
- generally straightforward
- low mu ⇒ relative backgrounds higher ⇒ larger uncertainty



Lead-lead luminosity

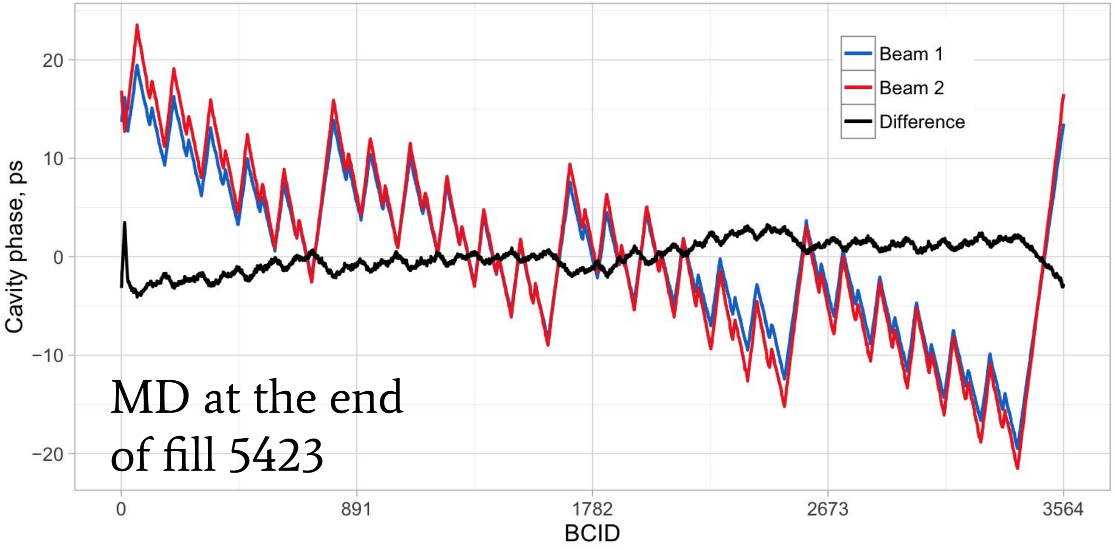
- Large time-variation (non-linearity) of luminosity counters
- ~12% uncertainty on relative measurement
- seen in both 2015 and 2018
  - 2018: record high-rate random raw data to study effect
  - now known to be due to sensitivity to EM (mu >> 1)





Fun with RF detuning

Phase modulated RF voltage to minimize klystron power



MD at the end of fill 5423

$$\mu_{LR,z} = \frac{z_1+z_2}{2} - \cos\alpha\sin\alpha\frac{x_1-x_2}{2}\frac{\sigma_z^2-\sigma_x^2}{\sigma_z^2\sin^2\alpha+\sigma_x^2\cos^2\alpha}$$

$$\Delta\mu_{LR,z} = \mu_{LR,z}(\Delta t_1,\Delta t_2) - \mu_{LR,z}(0,0) = -\frac{c\Delta t_1 - c\Delta t_2}{2}\left(1-\frac{\sigma_{LR,z}^2\sin^2\alpha}{\sigma_{LR,x}^2}\right)$$

not very visible?

MOPPC015 Proceedings of IPAC2012, New Orleans, Louisiana, USA

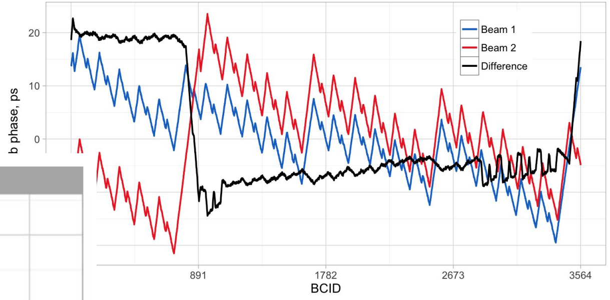
PROPOSAL FOR AN RF ROADMAP TOWARDS ULTIMATE INTENSITY IN THE LHC

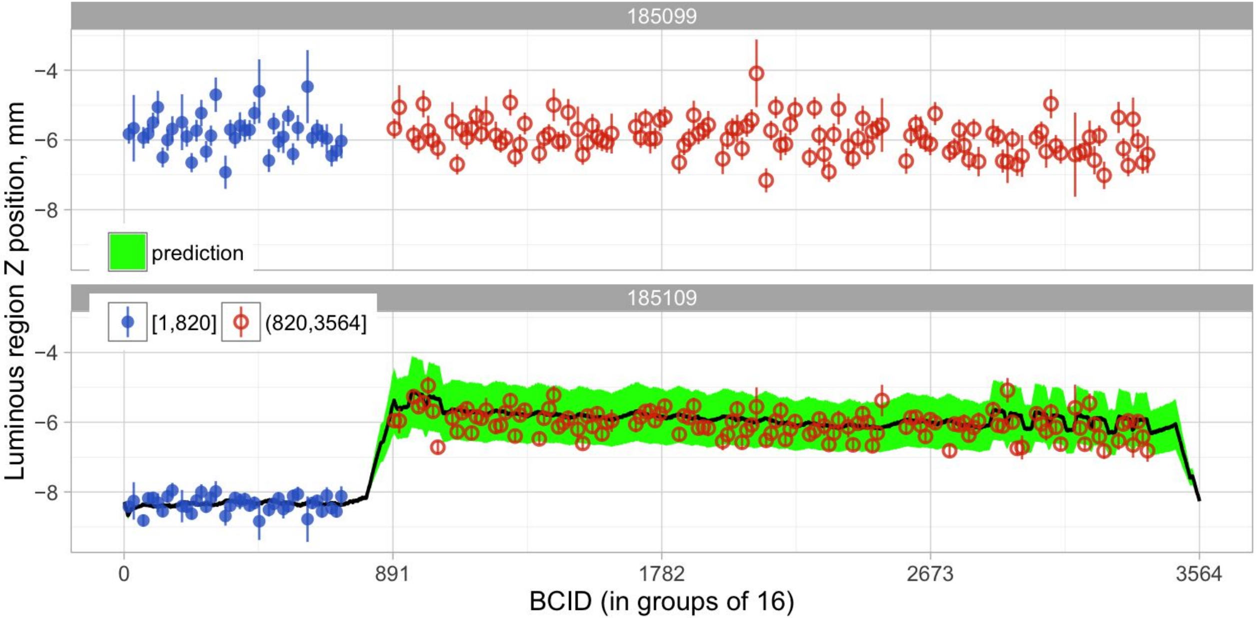
P. Baudrenghien, T. Mastoridis, CERN, Geneva, Switzerland

https://accelconf.web.cern.ch/accelconf/IPAC2012/papers/moppc015.pdf

Fun with RF detuning (2)

LHCb beam 2 shifted by 894 BCIDs!





Little impact on lumi measurement, but fun!

Outlook

- Work ongoing to finish Run 2 relative calibrations
  - promising Vertex/Tracks stability at the permil level ⇒ stable VELO efficiency
  - "out-of-the-box" stability of Tracks vs. CALO at O(1%)
  - we know we can do better: ~0.2% in Run 1
  - tedious process of understanding every significant change in ratios
- Run 3
  - at mu of 5.5, log0 still works (keep statistical power by ~10x rate increase)
  - brand new detectors => reassess choice of luminosity counters
  - larger bunch-to-bunch mu differences expected ⇒ more data per-bunch needed
  - ideas under consideration for new, dedicated luminometer hardware

Novelties in Run 2

- Readout supervisor firmware update
  - Per-BCID trigger masks for the various trigger sources: NoBias, Sequencer, L0
  - Could easily do physics + BGI at the same time (p-He + BGI, p-Pb + ghost charge)
  - Could take data efficiently for Pb VDMs, e.g. 5-8 of O(100) bunches triggered at 11kHz
- Continuous beam-shape monitoring
  - Important input for the LHC colleagues
  - Main limitation: resolution unfolding at 3m
  - Run 3: improved VELO but even smaller beta