# CMS luminosity measurement for nucleus-nucleus collisions at 5.02 TeV


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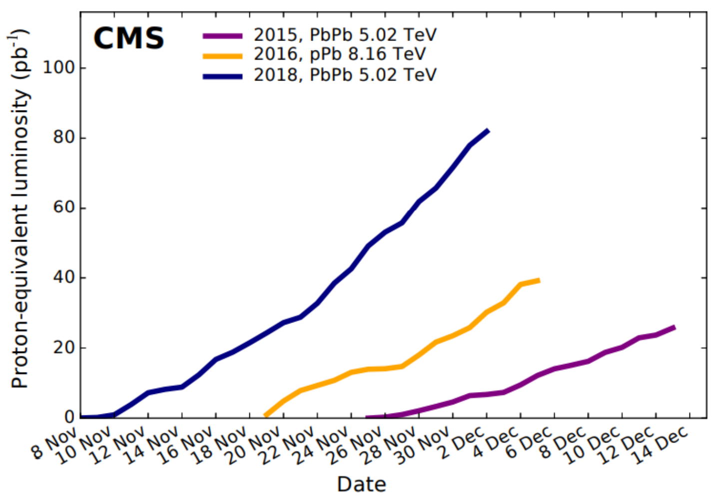
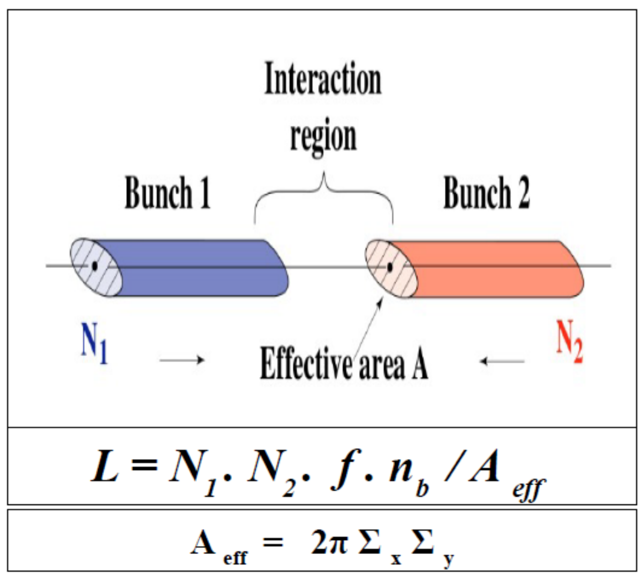
## Luminosity and its determination

- Determines the rate of particle collisions
- Relates the cross section of the process to the observed rate

$$R(t) = \frac{dN}{dt} = L(t) \cdot \sigma$$




Why precise luminosity measurement is important?

- Provides real-time feedback on accelerator performance and input to optimal detector operation (online)
- Essential for most physics analysis which measures / relies on cross sections (offline)

How we can measure luminosity?
Using well-known physics process if theoretical cross section is precisely known:

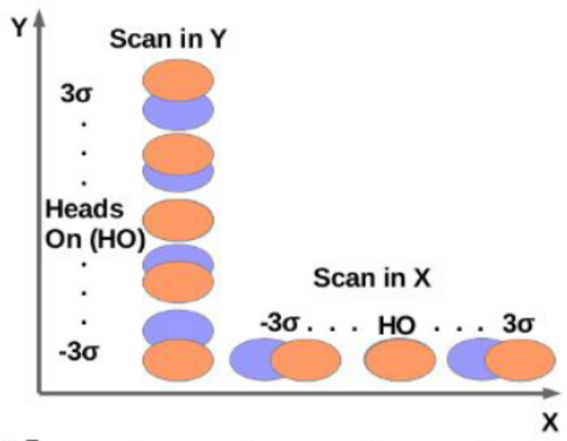
$$L(t) = \frac{R_{process}(t)}{\sigma_{process}}$$

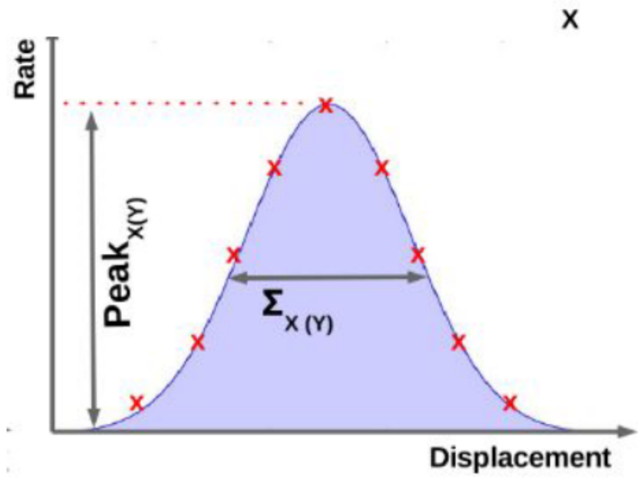
Using machine parameters → beam overlap widths obtained from vdM scans

### vdM method

- Measure the rate while beams are separated in X, Y in discrete steps
- Use fills with special beam conditions
- Assume proton density function is factorizable in x and y
  $$h(x, y) = f(x) \cdot g(y)$$
- Apply various corrections
- Use multiple luminometers
- Measure detector dependent calibration constant $\sigma_{vis}$, then use it during physics fills to convert rate to luminosity

$$\sigma_{vis} = \frac{2\pi \cdot \Sigma_x \cdot \Sigma_y}{N_1 \cdot N_2 \cdot f \cdot n_b} \cdot R_{peak}$$




## CMS luminometers and LHC beam instrumentation

Requirements for CMS detectors: stable operation, linear rate-luminosity response, a way to measure and correct for deviation from ideal behaviour

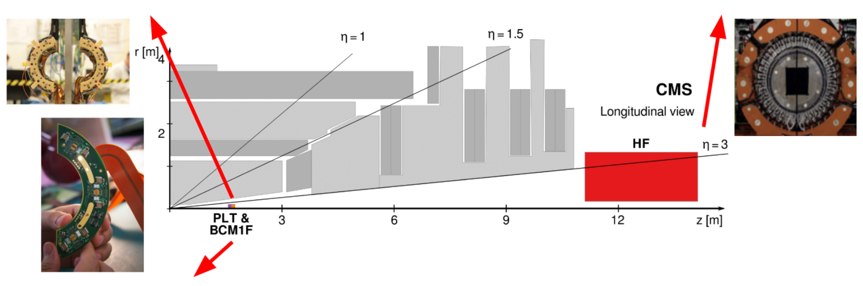
Several real-time bunch-by-bunch luminosity monitors used in PbPb collisions, relying on zero-counting assuming Poisson probability distribution of signal

#### Pixel Luminosity Telescope

- Three pixel detector planes in a telescope arrangement
- Counting triple coincidences of hits in planes

#### Hadron Forward Calorimeters

- Two rings (3.15 < η < 3.50)
- Dedicated luminosity back end
- Occupancy-based counting method




#### Fast Beam Condition Monitor

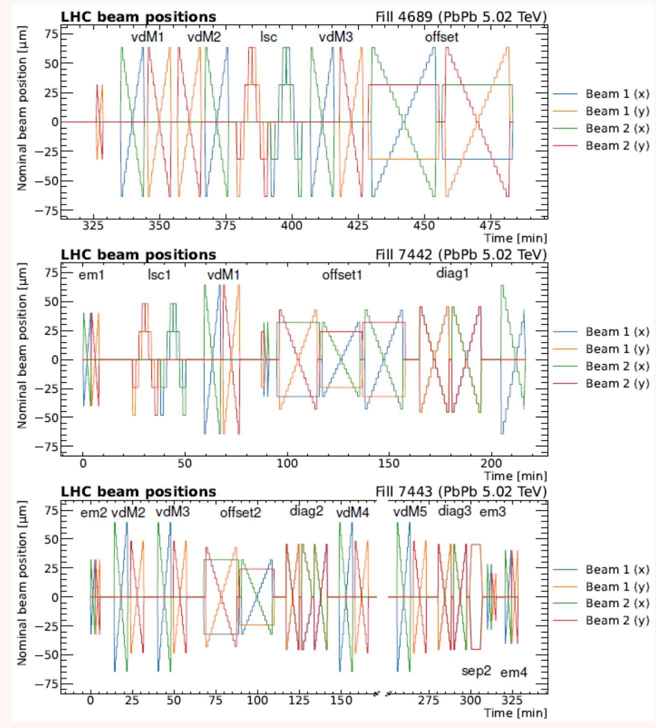
- Silicon and diamond sensors mounted on a C-shape holder (24 altogether)
- Hit counting

#### LHC beam position monitors

- measure the orbit of the circulating beams, based on image charges
- Diode ORbit and OScillation (DOROS) detectors
- Arc BPM detectors

## Run II luminosity scan program

- Measured in two parts: 2015 and 2018
- <u>vdM scan:</u> ±5.5(7.5)$\sigma_b$ in x (y) in 2015 and ±4(3)$\sigma_b$ in x (y) in 2018 maximal displacement in each direction
- <u>Offset scan:</u> like VdM, but ±3$\sigma_b$ transverse displacement both 2015 and 2018
- <u>Diagonal scan:</u> beams separated in both x and y at the same time with $\Delta x = \pm\Delta y$, ±3$\sigma_b$ in 2018
- <u>Length-scale scan:</u> two beams move together in the same direction ±1.4(1.8)$\sigma_b$ in x (y) in 2015




| Year | Fill | $\sqrt{s_{NN}}$ [TeV] | $n_b$ | $\phi$ [$\mu$rad] | $\beta^*$ [m] | $N_1/N_2$ [$\times 10^{11}$charges] | $\mathcal{L}_{init}$ [$\times 10^{27}$ cm$^{-2}$ s$^{-1}$] | Number of scan pairs: vdM | length scale | off-axis | emittance | super sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 4689 | 5.02 | 400 | 0 | 0.8 | 43.0 / 44.7 | 1.25 | 3 | 1 | 1 | 0 | 0 |
| 2018 | 7442 | 5.02 | 288 | 160 | 0.5 | 97.3 / 98.7 | 2.11 | 1 | 1 | 2 | 1 | 0 |
| | 7443 | 5.02 | 288 | 160 | 0.5 | 91.2 / 92.8 | 1.91 | 4 | 0 | 3 | 3 | 2 |
| | 7483 | 5.02 | 620 | 160 | 0.5 | 96.6 / 98.5 | 3.98 | 0 | 1 | 0 | 1 | 0 |

## Corrections to absolute luminosity

### Bunch current normalization

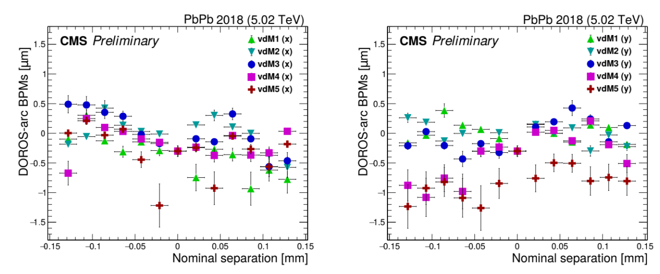
- bunch-by-bunch corrected for ghosts (charges in nominally empty BCIDs) and satellites (charges leaking out of the main RF bucket into nearby buckets)

### Beam-beam effects

- electromagnetic interaction between the two beams leads to a deflection from the nominal position and a distortion of the bunch shapes (dynamic beta)

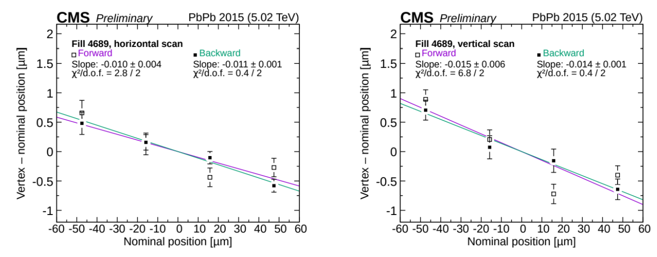
### Orbit drift

- Change of beam orbit with respect to its nominal position during scans
- Measure by DOROS & arc BPMs



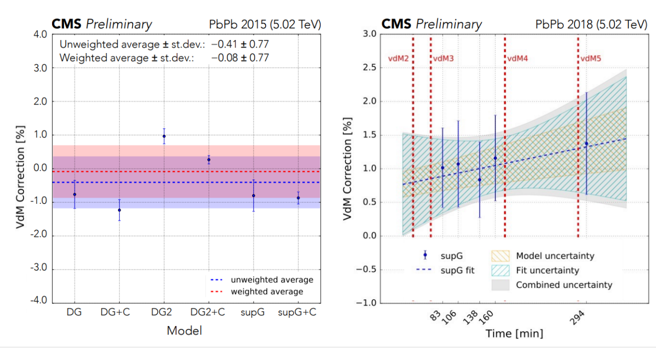

### Length scale

- Calibration of the nominal transverse beam positions wrt the CMS tracker coordinate system




### XY factorization

- Bunch proton density not perfectly factorizable into independent x and y components
- probed by constructing two dimensional luminosity distributions using on-axis (vdM) and off-axis (diagonal or offset) scans → fit with various 2D analytical models




## Results

"Normalization" concerns the visible cross section ($\sigma_{vis}$) as determined from the van der Meer scan procedure, while the "Integration" concerns the stability and quality of the measurements by the luminosity subdetectors.

Normalization uncertainty

| Source | 2015 [%] | 2018 [%] | Corr |
|---|---|---|---|
| *Bunch population* | | | |
| Ghost and satellite charge | 0.3 | 0.5 | Yes |
| Beam current calibration | 0.2 | 0.2 | Yes |
| *Noncolliding bunches* | | | |
| Noncollision rate | 0.5 | 0.2 | No |
| *Beam position monitoring* | | | |
| Random orbit drift | 0.5 | 0.1 | No |
| Systematic orbit drift | 0.2 | 0.2 | Yes |
| *Beam overlap description* | | | |
| Length scale calibration | 0.5 | 0.5 | Yes |
| Beam-beam effects | 0.2 | 0.3 | Yes |
| Transverse factorizability | 1.1 | 1.1 | No |
| *Result consistency* | | | |
| Cross-detector consistency | 2.5 | 0.4 | No |
| Scan-to-scan variation | - | 0.5 | No |
| Statistical uncertainty | 0.2 | 0.1 | No |

Integration uncertainty

| Source | 2015 [%] | 2018 [%] | Corr |
|---|---|---|---|
| *Detector performance* | | | |
| Cross-detector stability | 0.7 | 0.8 | No |
| *Noncolliding bunches* | | | |
| Noncollision rate | 0.1 | 0.1 | Yes |
| Total normalization uncertainty | 2.9 | 1.5 | - |
| Total integration uncertainty | 0.7 | 0.8 | - |
| Total uncertainty | 3.0 | 1.7 | - |

## Reference


[1] The CMS Collaboration.
Cms luminosity measurement for nucleus-nucleus collisions at 5.02 tev in run 2.
*CMS-PAS-LUM-20-002*, 2024.