Outline:

(1) Luminosity measurement in general
(2) LHC luminometers, comparison
(3) Absolute calibration
    - from beam-gas “photos” of colliding bunches
    - van der Meer (vdM) scans
    - from reaction with known cross-section (fixed-target)
(4) Novelties in two last vdM LHCb scans

Conclusions
How to measure luminosity?

1) Relative luminosity measurement can use any linear detector:

\[ R = \sigma_{\text{vis}} L \]

where \( R \) is event rate, \( \sigma_{\text{vis}} \) - « visible » cross section and \( L \) – instantaneous luminosity. Having several luminometers crucial for systematics estimation.

2) Absolute luminosity calibration, ie. \( \sigma_{\text{vis}} \), from :

\[ L = \frac{N_1 N_2 f}{A_{\text{eff}}}, \]

\[ A_{\text{eff}} = \iint \rho_1(x, y) \rho_2(x, y) \, dx \, dy \]

where \( N_{1,2} \) are number of protons in colliding bunches, \( f \) -frequency of collisions, \( A_{\text{eff}} \) – overlap integral of two bunches.

TOTEM and ALFA measurements based on optical theorem will not be covered.
Where do we need luminosity?

Online – to optimize performance of detectors, monitor beams and for adjusting luminosity (leveling)

Offline – ultimate precision for physics analyses

- Integrated Luminosity uncertainty already is the dominant in (some) SM measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section $\sigma^{\text{fid},\mu}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \rightarrow \mu^+\nu$</td>
<td>$2839 \pm 1,\text{(stat)} \pm 17,\text{(syst)} \pm 51,\text{(lumi)}$</td>
</tr>
<tr>
<td>$W^- \rightarrow \mu^-\bar{\nu}$</td>
<td>$1901 \pm 1,\text{(stat)} \pm 11,\text{(syst)} \pm 34,\text{(lumi)}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu^+\mu^-$</td>
<td>$477.8 \pm 0.4,\text{(stat)} \pm 2.0,\text{(syst)} \pm 8.6,\text{(lumi)}$</td>
</tr>
</tbody>
</table>

(2011 data, $\sqrt{s} = 7\,\text{TeV}$, 4.6 fb$^{-1}$)

- Theorists are pushing for a $\sim1\%$ Luminosity measurement at HL-LHC
  - see e.g. G. Salam @ ECFA 2016 (https://indico.cern.ch/event/524795/contributions/2235443/attachments/1347759/2034269/HL-LHC-SMHiggs-theory.pdf)

- Total Higgs production cross-section uncertainty estimated to be $\sim3\%$ given a luminosity uncertainty of 1.5%
LHCb luminometers

**N vertices**
**N Velo tracks** (best)
**N backward tracks**
**N upstream hits**

**N hits in preshower (SPD)**
**Calorimetric transverse energy**

**N muons**

Measured in ≈1 kHz **random** stream of « nano-events » containing only “luminometers”.

N interactions per bunch crossing: $\mu \sim 1-2$, calculated from Poisson law, $\mu = -\log(P(0))$, $P(0)$=fraction of “empty” events (eg. N vertexes = 0 or N tracks < 2). Less systematics as no strict linearity required.

Small **beam-gas backgrounds** (≤1-3%): estimated from non-colliding bunches and subtracted

Level 0 CALO trigger (or BCM when L0CALO is OFF) for online luminosity monitoring

$\mu$ is stored per smallest data unit (~10 sec running): low level “mixing” of physics and lumi-data <<1 % load to DAQ in CPU, data traffic and disk space.
1. **BCM** (diamond sensors) from LHC – best in Run I, train dependency in Run II
2. **LUCID** – newly installed and best in Run II: provides offline + online luminosity
3. Inner Detector (tracks) – bunch-by-bunch, but rate limited
4. Calorimeters: bunch integrating, currents in TileCal PMT, in EMEC and FCAL LAr gaps
Fractional stability between LUCID and other ATLAS luminometers versus time, LUCID run-to-run stability = 1.3%
- 3 luminometers independent of central DAQ ("always" operational):
  a) Pixel Luminosity Telescope (PLT),
  b) Fast Beam Conditions Monitor (BCM1F), with a) uses zero-counting method,
  c) dedicated readout on hadronic forward calorimeter (HF), afterglow correction, best online+offline

- 2 luminometers in main CMS DAQ:
  a) muon drift tube "track" counter (DT), integrates bunches,
  b) pixel cluster counting (PCC) with "zero-bias" trigger, after exclusion of some modules and time dependent afterglow corrections – similar precision to offline HF
ATLAS and CMS

- high pile-up $\mu \sim 40$: fraction of “empty” bunch crossings is essentially zero, $\mu = -\log(P(0))$ method directly not applicable (but can be recovered by redefining “visible” event as occupying 1/40 phase space eg. in acceptance, having muon etc.)

- without $\mu = -\log(P(0))$: luminometer linearity = dominating source of systematics: dependence on pile-up, LHC filling scheme (eg. bunch spacing) etc.

- in vdM calibration fills: $\mu \sim 1$, large linear dynamic range required to extrapolate to physics $\mu \sim 40$

- special emphasis (not really justified?) to have precise luminometer independent of common detector DAQ

- ageing of luminometers and other instrumental instabilities require
  a) corrections and
  b) vdM re-calibrations every year.
  In LHCb measured visible cross-section is stable.

- CMS: beam-gas background can not be estimated from be, eb crossings and subtracted (by luminometers design), parameterized in vdM scan fits.

- CMS: a few minutes, short vdM scans (called “emittance”) in beginning / end of every fill. Take physics time, but necessary to (approximately) re-calibrate luminometers, measure ageing effects and pile-up dependences
## CMS luminosity in 2017

Table 4: Summary of the systematic uncertainties entering the CMS luminosity measurement for $\sqrt{s} = 13$ TeV pp collisions. When applicable, the percentage correction is shown.

<table>
<thead>
<tr>
<th></th>
<th>Systematic</th>
<th>Correction (%)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normalization</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length scale</td>
<td>-0.9</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Orbit drift</td>
<td>—</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>$x$-$y$ correlations</td>
<td>+0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Beam-beam deflection</td>
<td>+1.6</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Dynamic-$\beta^*$</td>
<td>—</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Beam current calibration</td>
<td>—</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Ghosts and satellites</td>
<td>—</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Scan to scan variation</td>
<td>—</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Bunch to bunch variation</td>
<td>—</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Cross-detector consistency</td>
<td>0.4–0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td><strong>Integration</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Afterglow (HF)</td>
<td>—</td>
<td>0.2$\pm$0.3</td>
<td></td>
</tr>
<tr>
<td>Cross-detector stability</td>
<td>—</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>—</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>CMS deadtime</td>
<td>—</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>
ATLAS and CMS overall precision

High luminosity i.e. Standard data taking

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
<td>pp</td>
</tr>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>8</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>$\sigma_{L}/L$ [%]</td>
<td>1.9</td>
<td>2.6</td>
<td>2.1</td>
<td>2.3</td>
<td>2.2</td>
<td>2.5</td>
<td>2.4</td>
<td>preliminary 2.3</td>
</tr>
</tbody>
</table>

ATLAS Ref: https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics
CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001

Excellent precision!
Extrapolating from vdM to physics

Shift in luminometer response between vdM (low $L$, low $\mu$, few bunches far apart) and physics (high $L$, high $\mu$, more than 2000 bunches in trains of 25 ns)

- **ATLAS:**
  - Non-linearity correction from Track-based $L$
    - typical correction @ $\mu = 50$ for LUCID hit counting in 2017: -9%
  - Systematic uncertainty evaluated by comparing with calorimeter-based correction in 2017: $\pm 1.3\%$

- **CMS:**
  - Non-linearity correction from emittance-scan analysis (i.e. "absolute")
    - typical correction @ $\mu = 50$ for HFET in 2017: 1.5%
  - Systematic uncertainty evaluated by comparing residual relative non-linearity of luminometers on 2017: $\pm 1.5\%$

ATLAS Ref.: [https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics](https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics)

CMS Ref.: CMS-PAS-LUM-17-004
ALICE luminometers

- **V0**
  - two scintillator arrays on opposite side (A and C) of the IP (2.8 < η < 5.1 ; -3.7 < η < -1.7)
  - coincidence of A and C side

- **T0**
  - two Cherenkov detector arrays on opposite sides of the IP (4.61 < η < 4.92 ; -3.28 < η < -2.97)
  - coincidence of A and C side
  - with hardware cut on the signal arrival time difference

- Very low μ = 0.001 - 1
- Only two detectors (no redundancy)
- In 2015 overall luminosity measurement precision = 2.3% for isolated bunches, 3.4% for bunch trains (because of non-trivial systematics in V0)
Absolute calibration of $L$

$$L = \frac{N_1 N_2 f}{A_{\text{eff}}} = N_1 N_2 f \iint \rho_1(x, y) \rho_2(x, y) \, dx \, dy$$

$N_{1,2}$ are measured in three steps:

- **Total beam intensities** are determined from total beam currents (slowly) measured with high accuracy by LHC direct-current current-transformers (DCCT),
- **Background** (1-2%) in nominally empty LHC bunches or buckets is determined either with LHC equipment (BSRL) and/or with beam-gas interactions in LHCb and subtracted,
- **Charge fraction per bunch** is measured with LHC fast transformers (FBCT)

Typical $N_1 N_2$ uncertainty: ~0.2-0.3%. 
Beam-gas imaging (BGI)

Main difficulty: \[ \iiint \rho_1(x,y)\rho_2(x,y) \, dx \, dy \]

Only at LHCb: find \( \rho_{1,2} \) from beam images recorded with beam-gas interactions.

- The very first \( L \) measurement at LHC in 0.9 TeV pilot run in Dec 2009
- To increase statistics: switch off VELO pumps; from Nov 2011 on: inject a tiny amount of gas using a dedicated injection System for Measuring the Overlap with Gas (SMOG) (~50 more interactions)
- SMOG is also used as a fixed target eg. for heavy ion physics
- Beam-gas allows to measure “ghost” charge in nominally empty bunches

First 1000 vertexes in fill 2852 (Run I).

Typical \( x,y \) (z) beam widths: 0.1 (40) mm

\[ \Delta Y \text{ separation to reduce pile-up} \]
Beam-gas imaging

Beam profiles are unfolded with Velo spatial resolution, determined from data as a function of N tracks, z position and interaction type (beam-beam or beam-gas).

To improve precision: $\rho_{1,2}$ are fit to a sum of Gaussians simultaneously with the precisely measured beam-beam profile $IP(x,y) \sim \rho_1 \rho_2$.

2D fit for one bunch pair as an example. Pulls are shown by color in ±3 range in the top.

The best BGI luminosity calibration precision (8 TeV data): 1.43%  

*J. Instrum. 9 (2014) P12005*
Van der Meer scan

Idea: sweep one beam across the plane.
Van der Meer scan

Idea: sweep one beam across the plane. This integrates its $\rho$ out:

$$\iiint \rho_1(x+\Delta x, y+\Delta y)\rho_2(x, y)\,d\Delta x\,d\Delta y\,dx\,dy = 1$$

and

$$\sigma = \iiint \mu(\Delta x, \Delta y)\,d\Delta x\,d\Delta y/N_1/N_2$$

Suggested by van der Meer in 1968.
Works for any $\rho_{1,2}$ and any LHC crossing angle
(relativistic correction due to transverse velocity is negligible)
If $\rho_{1,2}$ factorize in $x,y$:

Another possibility: swept beam effectively becomes broad and uniform.
Similarly to “beam gas” it provides beam-beam imaging after unfolding with VELO resolution $V$:

$$IP = (\rho_1\rho_2)\circ V$$

$$[\rho_2\circ V](x) \propto \int IP(x, \Delta x)\,d\Delta x$$

(for $\Delta x$ in frame of fixed beam 2)

CERN ISR-PO-68-31
Van der Meer scan

$\mu$ in one bunch crossing in X, Y scan

$$\sigma = \frac{\int \mu(\Delta x, y_0) d \Delta x \cdot \int \mu(x_0, \Delta y) d \Delta y}{\mu(x_0, y_0) N_1 N_2}$$

X-Y non-factorizability can give $\sim 1\%$ bias, not easily visible (except with BGI):
- from luminous region fits
- “offset” and “diagonal” scans

25(45) kHz rate of “lumi”- events in Run I (II)
vdM length scale calibration

\[ \sigma \propto \int \ldots d \Delta x \int \ldots d \Delta y \]
directly depends on \( \Delta x, \Delta y \) scale.

Calibration: beams move \textit{synchronously} in X or Y.
IP movement (by the same amount) is precisely measured by VELO (and can be cross-checked by BGI).

Measured deviation from LHC scale

Mismatch btw IP and BGI beam1,2
average gives systematics
Observations in recent pp vdM scans at LHCb
Recent pp vdM scans at LHCb: observations

Length Scale Calibration (LSC) in fill 4269, 25 Aug’15: LHC X- and Y-displacements were incorrectly written manually as equal. 3.5% mistake found by checking the bump magnet recordings in LHC data base. In later vdM scans the displacements were logged automatically.

FBCT measurement of N particles per bunch before 2017: 2-in-1 device for odd / even bcid, with a few % different slopes and offsets. To equalize: ATLAS BPTX (noisier but immune to odd-even difference). Bcid can be wrong by 1-4. Now: much better new FBCT
Recent pp vdM scans at LHCb: observations

Fill 6012 (Jul’17): unexpected instabilities in 3 and, after 2 scans, in 19 out of 24 bunch crossings (current drops, width increase)
Only 5 good pairs used in all scans

![Graphs showing residuals and beam separation](image)

- Changed to non-Gaussian
- Current drop
- vdm profile changed
vdM scan with beam gas imaging

SMOG during vdM scan is very attractive cross-check:
+ measures individual bunch profiles, their movements and length scale, but
- introduces huge backgrounds.

Solid points: background is **not fully subtracted** from *Velo-based track and hit counters.*
In fill 6012, Jul’17: $\mu$(head-on beam-beam) $\sim$ 0.25, $\mu$(SMOG) $\sim$ 0.13,
after background subtraction $\Delta \mu$(SMOG) $\sim$ 0.001 – 0.002 remains.

Therefore, final cross-section is obtained from $\text{Vertex} \geq 0$ by rescaling with coefficient determined without SMOG.
Preliminary 13 TeV pp cross section

Preliminary: still, a few things to finalize.
Spread between 15 scans in 2015,16,17,18:
0.5 % – excellent time stability without any corrections (!) contrary to ATLAS/CMS.
Probably, final systematics will be ~2% or less.

<table>
<thead>
<tr>
<th>$\sigma(\text{Velo}&gt;1)$, mb</th>
<th>63.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early 2015 BGI measurement</td>
<td>63.4 ± 3.9 %  (-0.6%)</td>
</tr>
<tr>
<td>preliminary BGI, fill 4937</td>
<td>65.8 (+3.1 %)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCCT</td>
</tr>
<tr>
<td>Ghost charge, BGI+LDM</td>
</tr>
<tr>
<td>FBCT A/B/BPTX</td>
</tr>
<tr>
<td>LSC</td>
</tr>
<tr>
<td>Fit model statistics</td>
</tr>
<tr>
<td>statistics</td>
</tr>
<tr>
<td>Scan-to-scan variations within one fill</td>
</tr>
<tr>
<td>Fill-to-fill variations</td>
</tr>
<tr>
<td>RZ Velo – Velo diff.</td>
</tr>
</tbody>
</table>

Typical uncertainty of extrapolation from vdM to physics: ~ 0.5% (stability of luminometer ratios)
Other methods of luminosity calibration
LHCb: Luminosity of p-He sample $\sqrt{s} = 110$ and 86 GeV

**PAMELA + AMS-02: excess in anti-p / p fraction**
- sign of dark matter or wrong model of anti-p production in interstellar medium of galactic disk?
Largest uncertainty from $\sigma(p+\text{He} \to \text{anti-p } X)$

Measurable at LHCb as fixed target process: p – He (SMOG)

Critical to know SMOG pressure, but difficult to measure precisely because it is very low

*Take SMOG density from p - (atomic) e elastic scattering, using its known Rosenbluth cross-section.*

*Precision: 6% !*

"Measurement of antiproton production in p-He collisions at $\sqrt{s_{NN}} = 110$ GeV",

Same approach will be used for heavy flavor production measurements in p-He.
Physics reaction as a luminometer

$Z^0 \to ll$ counting (used in ATLAS and CMS) can be useful in relative luminosity debugging (validate corrections, long-term stability)

Example: $N(Z^0) / L$, should be constant, from 2015 CMS report

Earlier proposal (eg. in LHCb): two-photon $pp \to pp \mu^+\mu^-$, proton compositeness can be neglected, QED precise cross-section allows to calibrate luminosity; but very low statistics and requires very forward coverage to veto backgrounds – not competitive.
Novelties in 2 most recent vdM scans at LHCb

Experiments typically do symmetric X,Y vdM scans with minimal variations. From end 2015 LHC allows to define scan points arbitrarily, however.

1) Nov’17, 5 TeV pp, 1 hour: LHCb has tried for the first time two-dimensional vdM scan

2) Jun’18, 13 TeV pp, 3.5 hours: many novelties (on the next slides)
Cross-section $\sim$ integral over X-Y beam separation plane.
Standard vdM: along X, Y axes, assuming factorization: $\mu(\Delta x, \Delta y) = \mu(\Delta x, 0) \mu(0, \Delta y) / \mu(0, 0)$.
Factorization cross-checks up to now: diagonal scans and scans along x=const or y=const lines.

Full two-dimensional scans are expensive (too many points). In Nov’17 LHCb scanned central region giving maximal contribution to the integral.
Mismatch btw. factorization and 2D cross-section integrals

... for 22 bunch crossings. Red: average line with expected from spread error band. Mismatch for Velo: 0.11±0.10 % – excellent accuracy and agreement.

Full $\chi^2$ analysis of 44 scan points, ie. of $22 \times 44 = 968$ underdetermined factorizability equations also gives reasonable agreement (deviation at only 6σ probability in spite of excellent stat. precision).
Jun’18, 13 TeV pp vdM scan

- Same 2D scan as in Nov’17

- Special program to study beam orbit drifts (difficult to control during “standard” scans)
  a) multi-pass X,Y scans
  b) spiral 2D

4 passes (2 forward + 2 backward) instead of one, each allows to find when beams are head-on and measure drifts during the scan
every side of the spiral allows to find head-on position and measure drifts
Jun’18, 13 TeV pp vdM scan

- since beams are moving not in one direction during scan, important to check the absence of hysteresis effects in LHC magnets: forward – backward through the same points

in addition,

- more sophisticated length scale calibration

- beam-beam imaging when one beam is at rest

Lot’s of interesting and new data to analyze!
Conclusions

(1) Luminosity measurement is a technical service, but very much needed. Eg. in LHCb used in ~15% of all publications.


(3) My opinion: LHCb luminosity measurement is very well designed, excellent time stability, reference calibrations stable in 2015-2018 without need of any correction at hardware level

(4) Lack of manpower in LHCb lumi group, only 2-3 experts and having also other duties. Rosen Matev (convener) is now on CERN long duration contract fully on HLT. BGI not covered, George Coombs finishes his PhD.

(5) Many novelties in last 2 vdM scans at LHCb, data to be analyzed. First 2D scan results are very positive.

(6) Ideas for upgrade are welcome