Measurement of the luminosity at LHC

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On behalf of the ALICE, ATLAS, CMS and LHCb collaborations

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Physics at LHC and beyond (Quy Nhon, Vietnam)

Luminosity

- Fundamental relationships

Integrated luminosity

$$N = L_{int}\sigma$$

Number of events

Process cross section

$$L_{int} = \int \mathcal{L} dt$$

Instantaneous luminosity

- Luminosity from beam parameters

Bunch current product

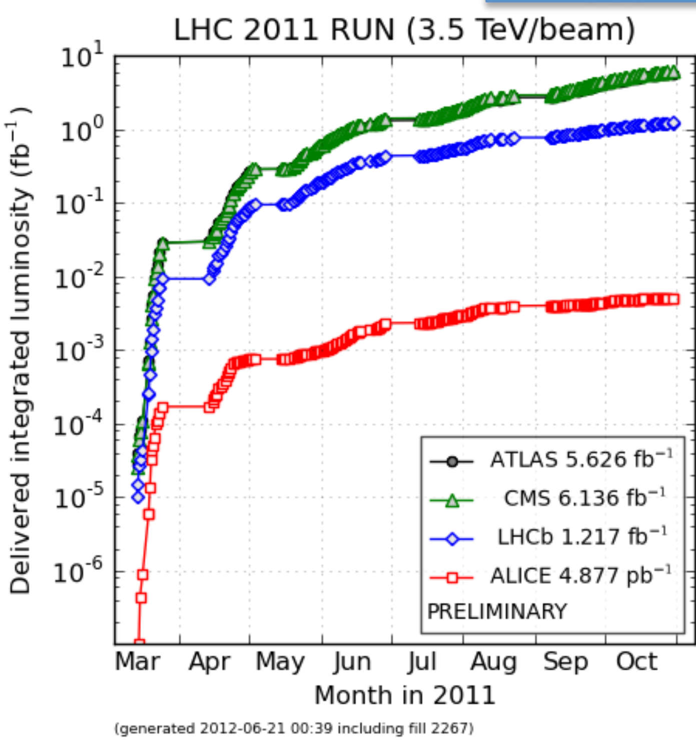
$$\mathcal{L} \propto f_r n_b n_1 n_2 \iiiint \rho_1(x,y,z,t)\rho_2(x,y,z,t) dxdydzdt$$

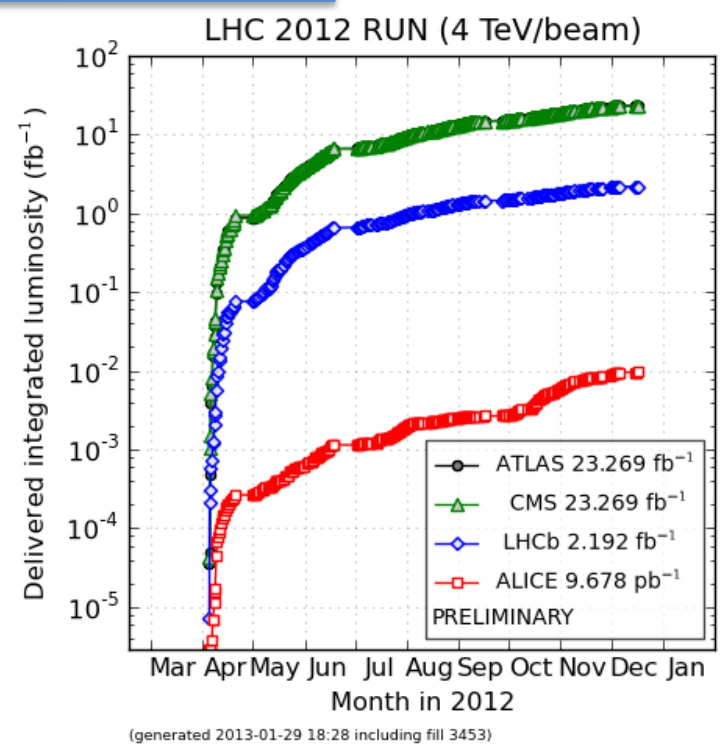
Number of bunches and revolution frequency

Spatial beam densities

LHC Run I – pp integrated luminosity

Only pp-luminosity shown here





- So far LHC delivered
  - about 30 fb^{-1} to ATLAS and CMS
  - about 3 fb^{-1} to LHCb (low μ)
  - about 15 pb^{-1} to ALICE (at very low μ)

μ is approx. number of interactions per bunch crossing

Luminosity measurements

1. Direct bunch profile and intensity measurements
   - Van der Meer scan (VdM) ALICE, ATLAS, CMS, LHCb
   - Beam-Gas-Imaging (BGI) LHCb
2. Based on optical theorem ATLAS with ALFA, CMS with TOTEM
   - Forward scattering at very low angles
   - Cross-calibration of luminosity detectors
   - Challenging, program ongoing

Luminosity calibration basics

Mean number of inelastic interactions per BX

ε*μ = Mean number of interactions per BX seen by detector

$$\mathcal{L} = \frac{R_{inel}}{\sigma_{inel}} = \frac{\mu n_b f_r}{\sigma_{inel}} = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}}$$

Inelastic cross section (not known precisely enough)

Cross section seen by detector

If beam densities factorize in x and y, i.e. $\rho(x,y) = \rho_x(x)\rho_y(y)$,then

$$\mathcal{L} = f_r n_b n_1 n_2 \Omega_x(\rho_{x1}, \rho_{x2}) \Omega_y(\rho_{y1}, \rho_{y2})$$

(No crossing angle)

where $\Omega_x = \int \rho_{x1}(x)\rho_{x2}(x)dx$ is the **beam overlap integral** in x.

- Measuring the beam overlap integral yields the absolute luminosity and thus σ_{vis}
- Beam overlap integral can be measured in VdM scans or with BGI (in case of BGI: crossing angle correction)

VdM scan basics

- The key idea of the VdM scan is to relate the overlap integral to the rate integral [12]:

$$\Omega_x = \frac{R_x(0)}{\int R_x(\delta)\, d\delta}$$

Rate measured by detector

Beam separation

- Defining the convolved beam size Σ_x as

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{1}{\Omega_x}$$

the luminosity becomes

$$\mathcal{L} = \frac{n_b \, f_r \, n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

Convolved beam sizes

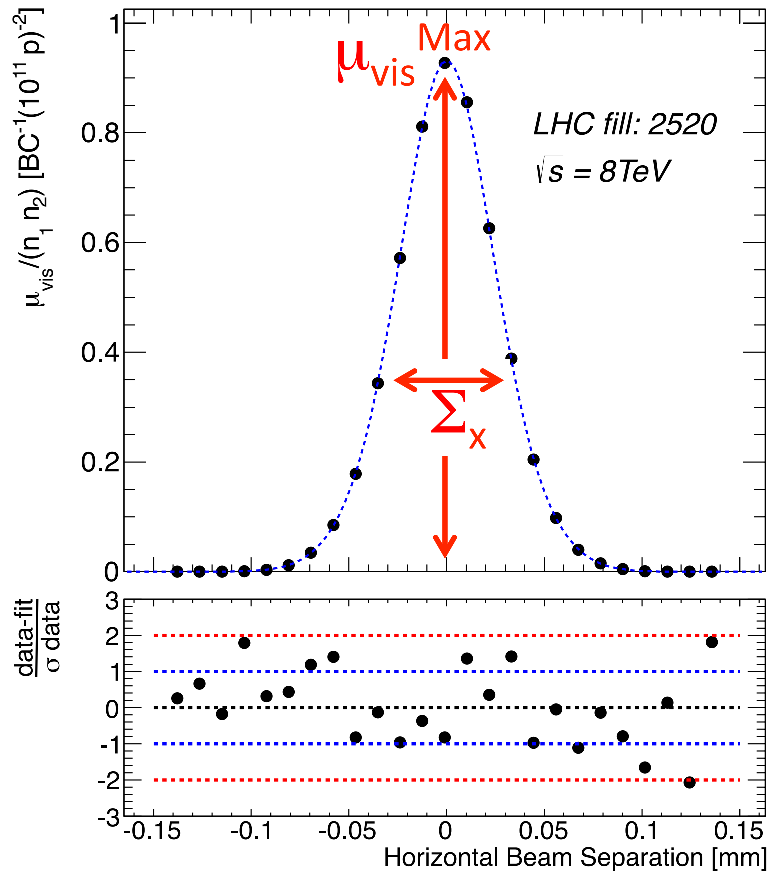
Measured in vdM scan

$$\sigma_{vis} = \mu_{vis}^{Max} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

Detector independent

Detector dependent

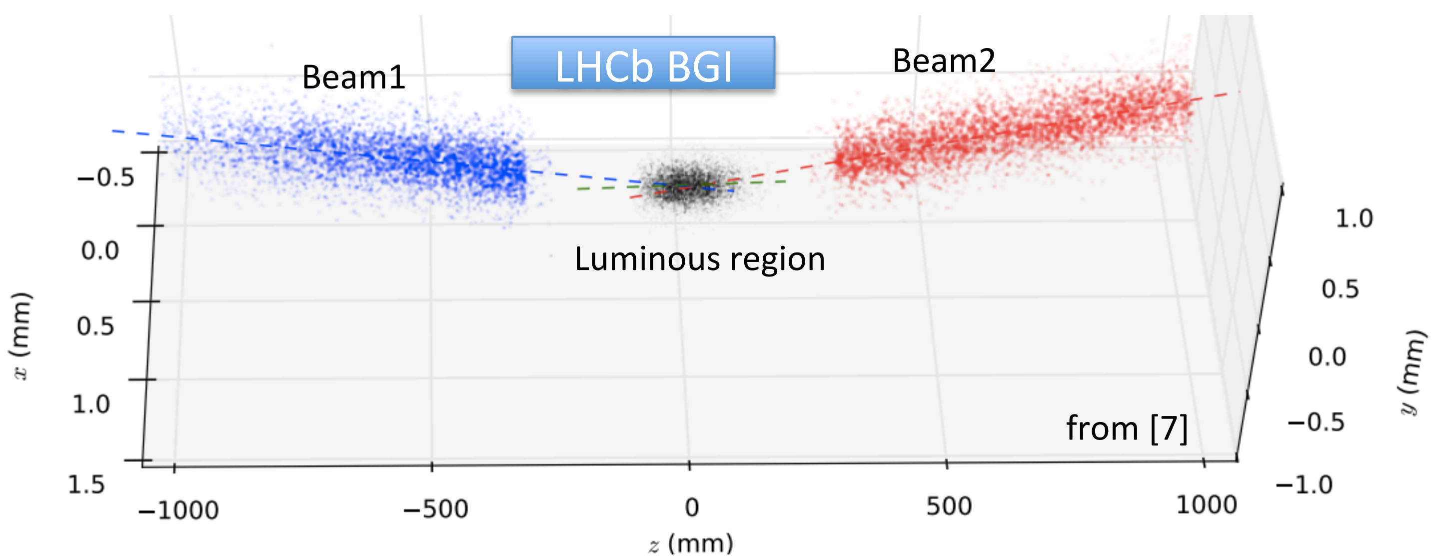
Measured by beam instrumentation



δ →

BGI basics

- **Beam-Gas imaging** (pioneered by LHCb) [1]
  - Reconstruct interaction vertices of protons with residual gas
  - Infer beam shape near interaction point (IP) and extrapolate to IP
- **Combination** of Beam-Gas and Beam-Beam vertices
  - Simultaneous fit to individual beam and luminous region shapes yields beam overlap integral and then luminosity
  - Beams do not need to be moved (hence no beam-beam corrections, etc.)
  - Overall calibration uncertainty dominated by vertex resolution
  - Several important systematic uncertainties are independent from VdM scan analysis



ALICE luminosity detectors [2]

- V0 detector
  - 32 scintillator tiles on each side of IP
    - Coincidence counters
  - $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$,

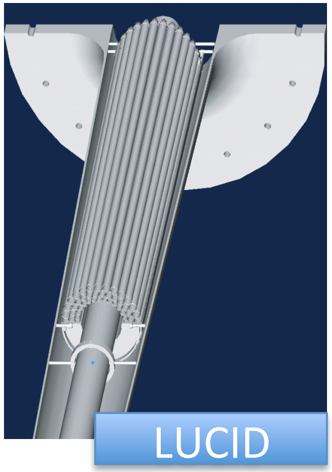
- T0 detector
  - 12 Cherenkov counters on each side of the IP
    - Coincidence counters
  - $4.6 < \eta < 4.9$ and $-3.3 < \eta < -3.0$

- ZDC detector
  - two calorimeters on opposite sides of the IP
  - detect forward neutrons in p-Pb and Pb-Pb collisions
  - $|\eta| > 8.8$

V0 arrays on C-side

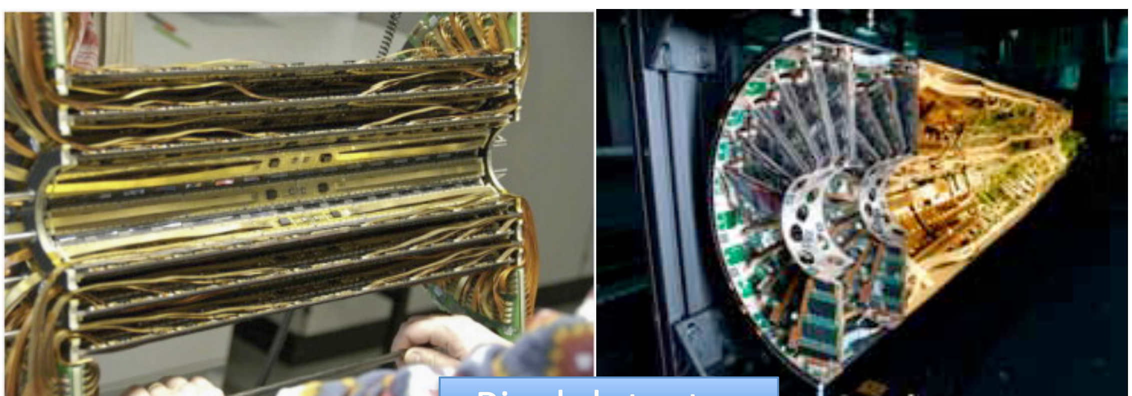
ATLAS luminosity detectors [3]

- LUCID
  - Dedicated luminosity monitor (5.6 < | η | < 6.0)
  - Cherenkov tubes
  - Zero-counting and hit-counting algorithms
- Beam Condition Monitor (BCM)
  - Designed as beam protection system
  - Diamond-based sensor (| η | ~ 4.2)
  - Zero-counting algorithms
- Silicon detectors
  - Track counting in Pixel and SCT
- Calorimeter currents (bunch-integrating)
  - TileCal PMT currents
  - LAr HV currents: ECC, FCal



CMS luminosity detectors [4]

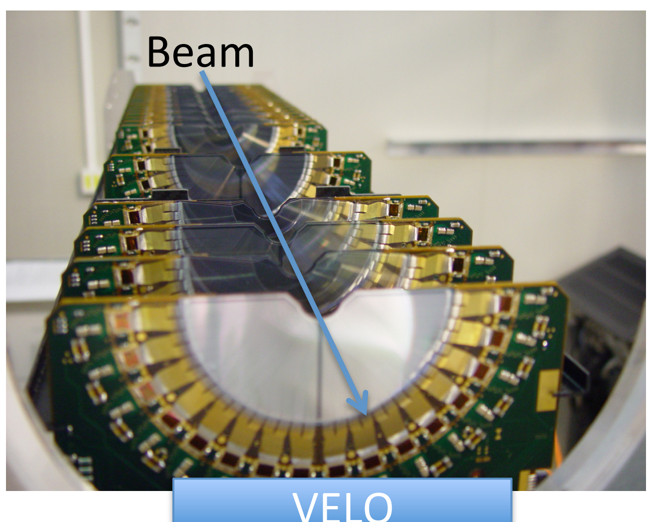
- Forward iron-quartz calorimeter (hit counting) for online measurements
- Silicon Pixel detector used offline
  - providing the most stable luminosity measurement
  - Luminosity through Pixel Clusters Counting (PCC)
  - Linear response till very high pileup



Pixel detector

LHCb luminosity detectors [5]

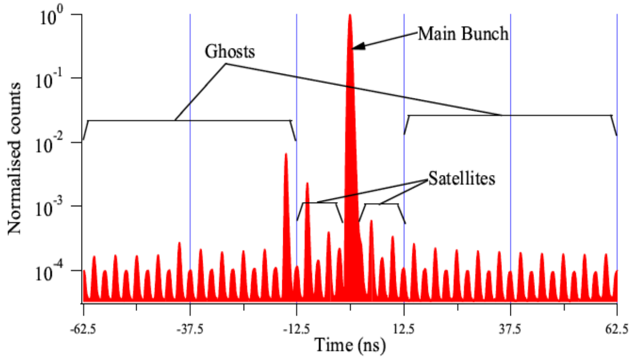
- Vertex/track monitoring with vertex locator (VELO)
  - VELO built around the IP and contained within vacuum
  - VELO approaches the beam if safe conditions
  - high precision in order to separate primary and secondary vertices
  - covers $1.6 < \eta < 4.9$ and $-3.3 < \eta < -1.6$



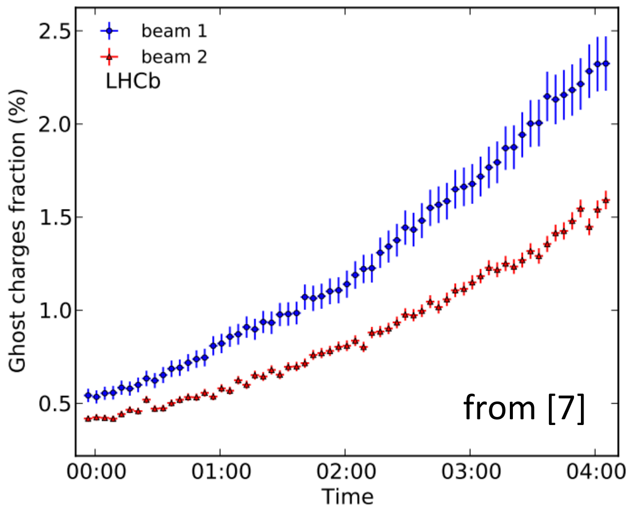
+ neon gas injection system for BGI (SMOG)

Bunch current measurements

- Currents are crucial input to VdM scan analysis
  - DC Beam Current Transformer (DCCT)
    - total circulating charges
  - Fast Beam Current Transformer (FBCT)
    - fraction of charge in each bunch
  - In 2010 uncertainty on bunch current product (10%) dominated luminosity uncertainty, due to major effort this uncertainty is well below 0.5% today [13]



- Corrections for ghost and satellite bunches
  - Fill dependent, but typically < 1%
  - Measured with various methods
    - Synchrotron radiation by LDM (for satellite bunches) [6]
    - BGI in LHCb VELO with SMOG (for ghost charge) [7]



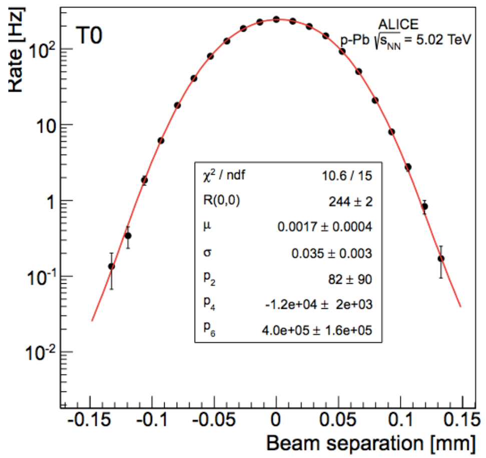
Luminosity uncertainties

- Only a selection of the most important systematic uncertainties is listed in the following

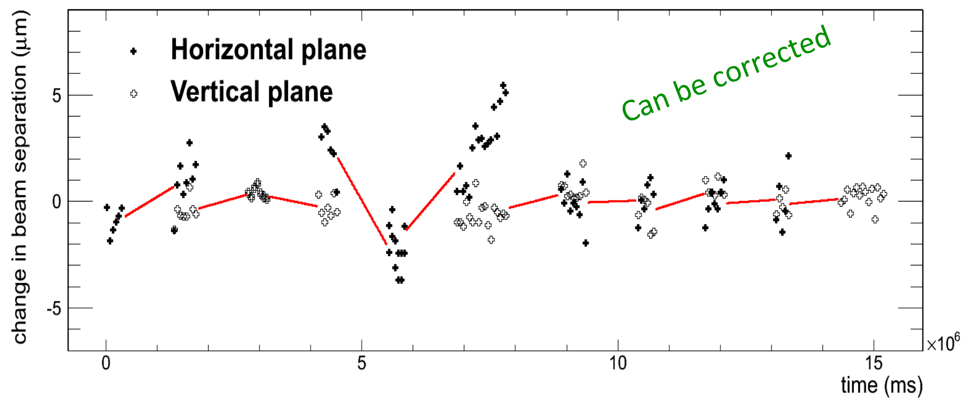
Calibration uncertainties	**VdM scan**	**BGI**
	Scan curve model	Bunch shape model (accounts for factorizability)
	Factorizability	
	Beam-Beam effects	Vertexing resolution
	Orbit drifts	Detector alignment & crossing angle
	Reproducibility	
Calibration transfer uncertainties from low $\mathcal{L}$ calibration to high $\mathcal{L}$ physics	μ-dependence	
	Radiation effects	
Monitoring uncertainty	Long-term stability	

Uncertainties: calibration

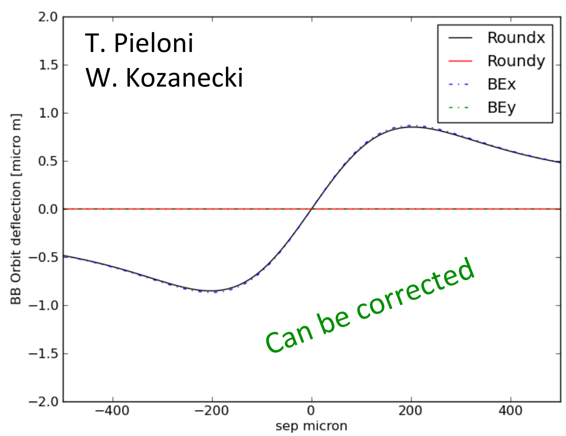
Choice of scan curve model



Orbit drifts



Beam-beam effects



Beam-beam deflection

- Orbit shift dependent on beam separation

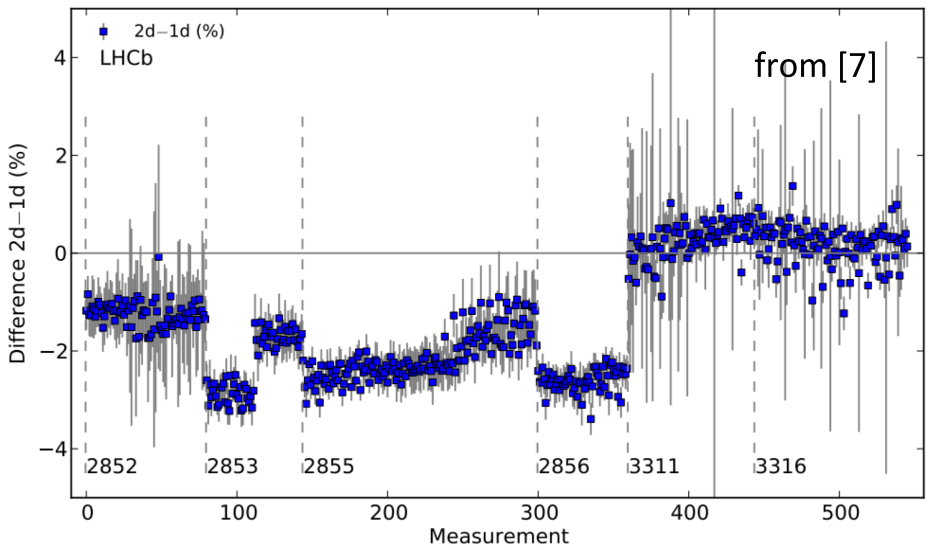
Dynamic β

- Beam sizes vary during VdM scan since beams exert focussing/ defocussing force on each other

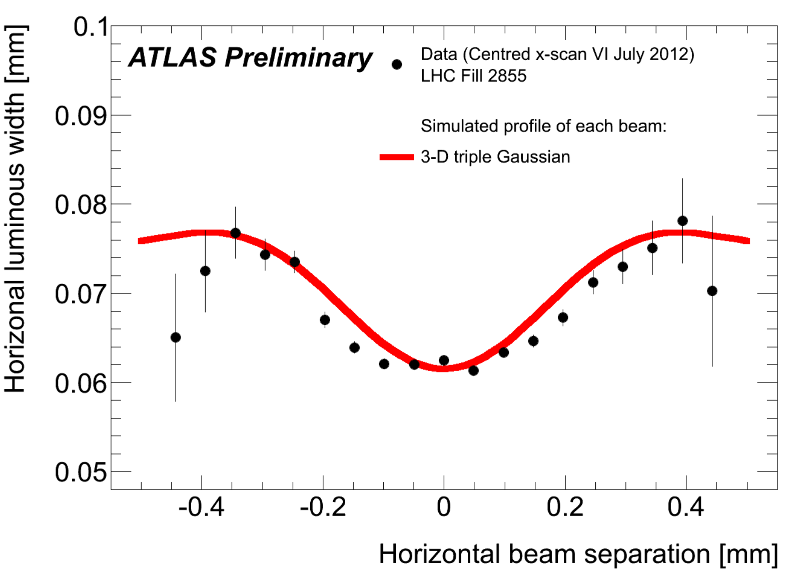
Uncertainties: non-factorizability

- Non-factorizability of beam densities could be tracked down as the source for significant inconsistencies in some VdM scans
  - Its effect on VdM scans is new territory and was first studied at LHC
- Two approaches to deal with the factorizability problem
  - Accelerator experts prepare good beams which have approx. factorizable densities
  - Experiments measure the non-factorizability and develop new methods to correct for it (based on BGI, luminous-region evolution during scan)

Difference between factorizable and non-factorizable model



Monitoring the luminous region during VdM scans



L_{int} : correlations between experiments

- Assessment difficult since uncertainty accounting and grouping varies among experiments
- Each uncertainty must be treated individually and often there are arguments for both view points (correlated vs uncorrelated)
- Preliminary (and not final!) statement
  - Calibrations done in different fills, mostly uncorrelated
  - If VdM calibrations done in the same fill, to some extend correlated

Snapshot of luminosity uncertainties

Parts of table reproduced from [11]

	ALICE	ATLAS	CMS	LHCb
Running period	2013	2011	2012	2012
Sqrt(s) [TeV]	5.02	7	8	8
Running mode	**Pb-p**	**p-p**	**p-p**	**p-p**
Reference	[8]	[9]	[10]	In the process of being made publicly available
Absolute calibration method	VdM	VdM	VdM	VdM + BGI *
$\Delta\sigma_{vis}/\sigma_{vis}$ **[%]**	**2.8**	**1.53**	**2.3**	**1.12**
μ-dependence [%]	1.0	0.50	<0.1	0.17
Long-term stability [%]		0.70	1.0	0.22
Subtraction of luminosity backgrounds [%]		0.20	0.5	0.13
Other luminosity-dependent effects [%]		0.25	0.5	-
Total luminosity uncertainty [%]	**3.0**	**1.8**	**2.6**	**1.2**

*uncertainties of both methods almost equal in size

This snapshot represents a selection of the latest luminosity calibration results publicly available

Summary

- VdM scans are the one & only luminosity-calibration method (so far) for ALICE, ATLAS, CMS (and until recently for LHCb as well)
- BGI pioneered by LHCb is a new contender in the game and looks very promising
  - Several important systematic uncertainties are independent from the ones of a VdM scan
- Beam-Beam effects and orbit drifts are non-negligible and need to be taken into account
- Bunch density factorization crucial for luminosity calibration
  - New methods to monitor non-factorization and to correct for it
- Redundancy is key for monitoring long-term stability of detectors
- Integrated luminosity uncertainty for all experiments about 1-4 %
  - Depending on beam conditions, rate environment, instrumental capabilities, ..
  - Do not expect much improvements on these numbers ..

Future Challenges

- More difficult pile-up and radiation conditions at LHC will impose new challenges to detector hardware and data acquisition
  - Long-term stability of luminosity detectors will need to be closely monitored
- Preparation of good and factorizable beams for VdM scans by accelerator colleagues

- Successful VdM calibrations will rely on very close collaboration between LHC experiments, beam instrumentation experts and accelerator physicists

References

[1] M. Ferro-Luzzi, Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions, Nucl. Instr. Meth. A 553 (2005) 388–399

[2] The ALICE Collaboration, "The ALICE experiment at the CERN LHC," Journal of Instrumentation, vol. 3, no. 08, p. S08002, 2008.

[3] The ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," Journal of Instrumentation, vol. 3, no. 08, p. S08003, 2008.

[4] The CMS Collaboration, "The CMS experiment at the CERN LHC," Journal of Instrumentation, vol. 3, no. 08, p. S08004, 2008.

[5] The LHCb Collaboration, "The LHCb Detector at the LHC," Journal of Instrumentation, vol. 3, no. 08, p. S08005, 2008.

[6] A. Boccardi, et al., LHC Luminosity calibration using the Longitudinal Density Monitor, CERN-ATS-Note-2013-034 TECH, https://cds.cern.ch/record/1556087

[7] C. Barschel, Precision Luminosity Measurement at LHCb with Beam-gas Imaging, CERN-THESIS-2013-301.

[8] The ALICE Collaboration, Measurement of visible cross sections in proton-lead collisions at sqrt(s) = 5.02 TeV in van der Meer scans with the ALICE detector, arXiv:1405.1849 ,version 1

[9] ATLAS Collaboration, Improved Luminosity Determination in pp Collisions at sqrt(s)=7 TeV Using the ATLAS Detector at the LHC , Eur. Phys. J. C73 (2013) 2518.

[10] CMS Collaboration, CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update, CMS-PAS-LUM-13-001, 2013.

[11] P. Grafstrom and W. Kozanecki, Luminosity Determination at Proton Colliders, submitted to Progress in Particle & Nuclear Physics

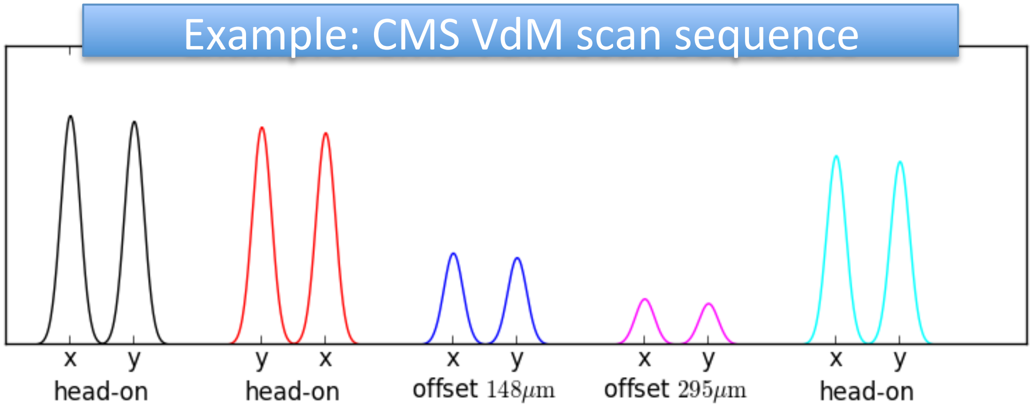
[12] S. Van der Meer, "Calibration of the Effective Beam Height in the ISR," Tech. Rep. CERN-ISR-PO-68-31, CERN, Geneva, 1968.

[13] Notes of the Bunch Current Normalization Working Group (BCNWG notes), http://lpc.web.cern.ch/lpc/bcnwg.htm

Backup

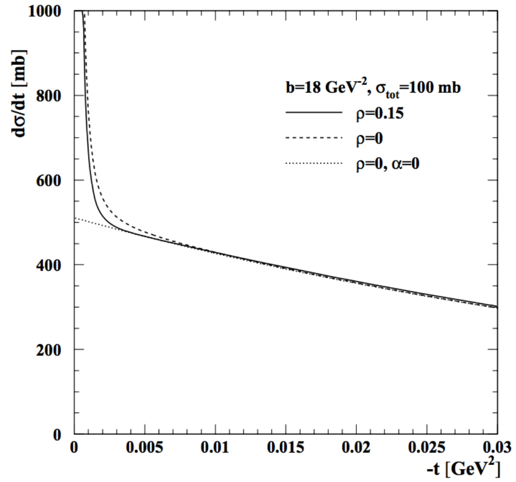
Typical VdM scan at LHC

- Horizontal and vertical beam separation
  - ~25 steps per scan plane, ~30 sec per separation step
- Dedicated machine setup for optimal conditions
  - Reduced number of bunches
  - Reduced bunch intensity
  - Larger β^*
- Combined effort from all experiments and LHC experts to achieve maximum precision
- VdM scans are time-consuming and need to be carefully planned
  - Only two or three scan sessions per year



Optical theorem basics

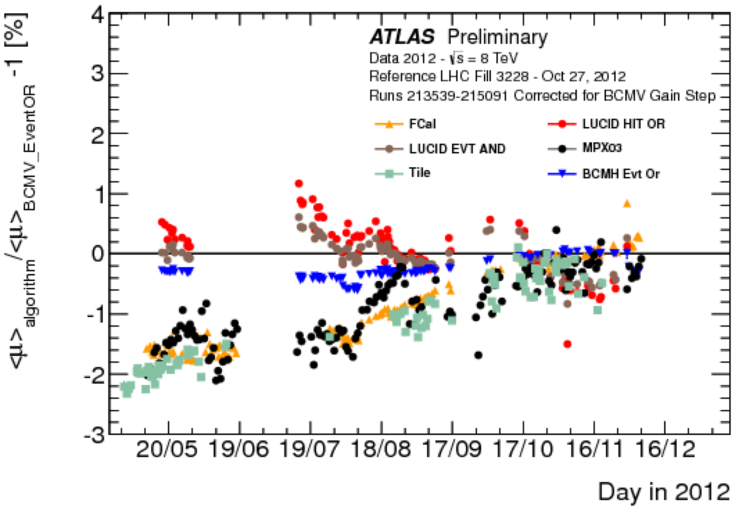
- TOTEM for CMS and ALFA for ATLAS are able to perform absolute luminosity measurements
- Based on Optical theorem
  - Measurements of the total rate in combination with the *t*-dependence of the elastic cross section (TOTEM)
  - Measurements of elastic scattering rates in the Coulomb interference region(ALFA)

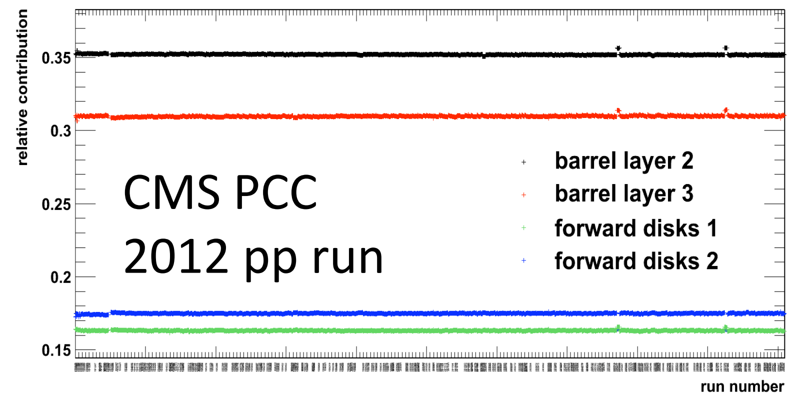


- Requires dedicated LHC fills with special magnet settings
- Roman pots far from the interaction points (about 200 m)
- Measurements at very low interaction rates
  - Cross-calibration of dedicated luminosity detectors
  - Extrapolation of calibration to typical physics conditions introduces big uncertainties
- Valuable cross check but at LHC not competitive to VdM scans for integrated luminosity measurements

Uncertainties: long-term stability

Long-term stability

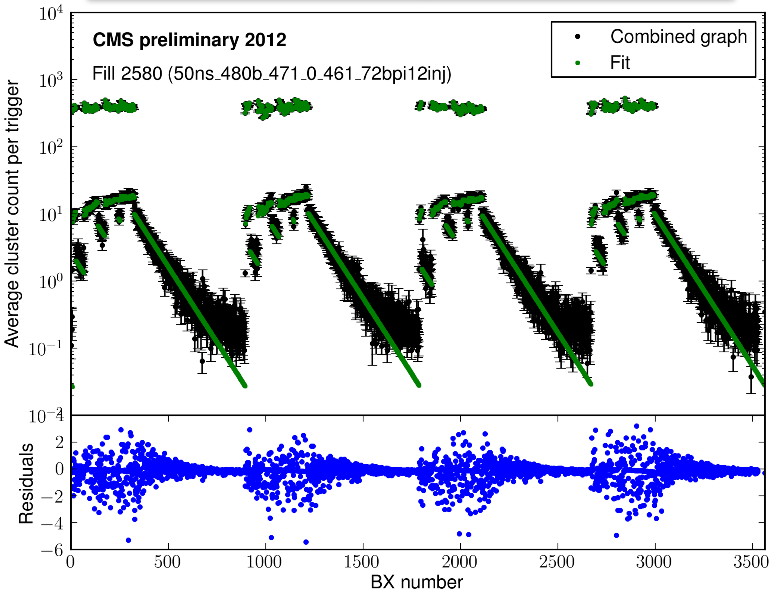




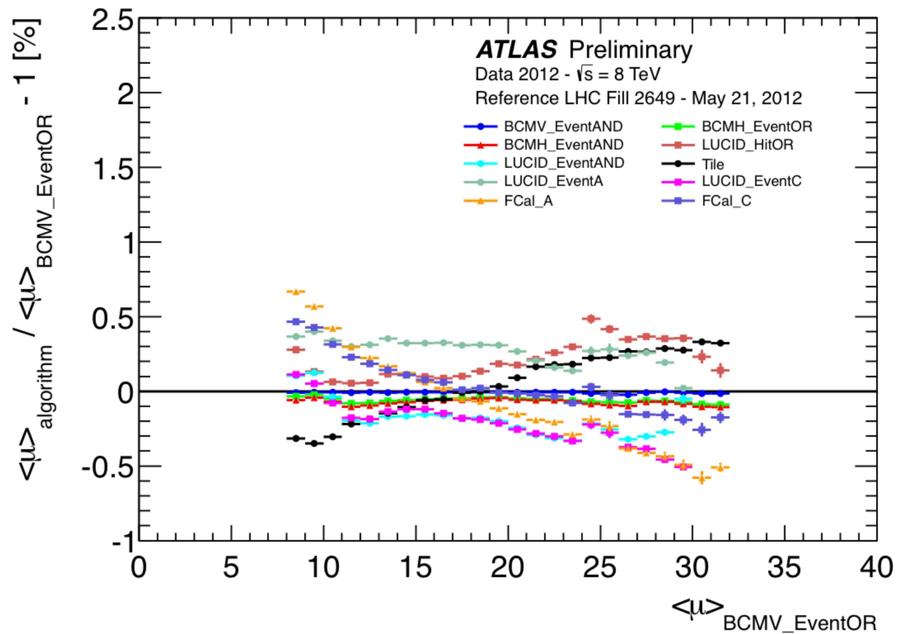
- Long-term stability is monitored by the long-term consistency of different luminosity detectors
  - Redundancy is key

Uncertainties: detector-related

Afterglow

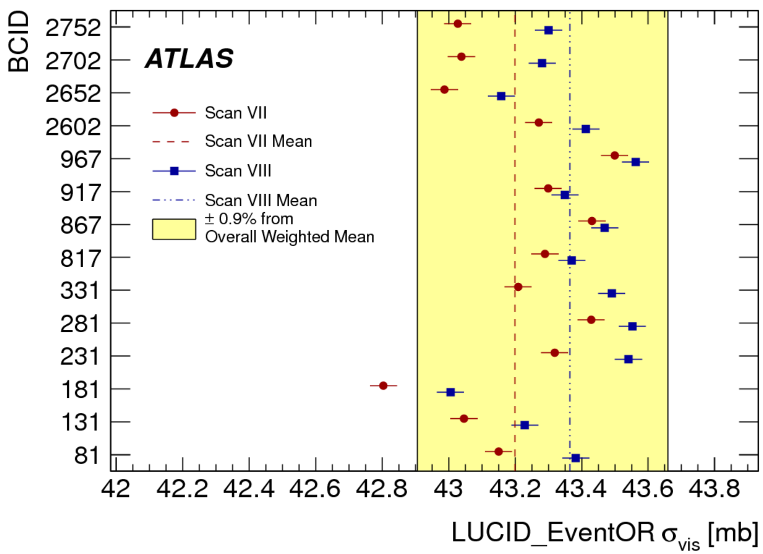


Linearity wrt luminosity

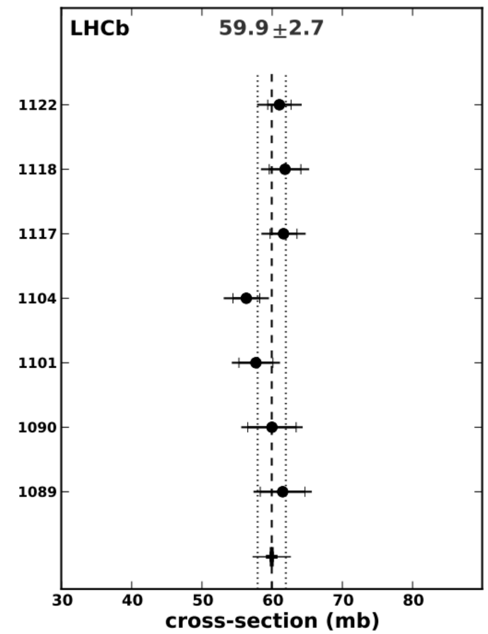


Uncertainties: reproducibility

Bunch-by-bunch consistency



Scan-to-scan consistency



- Consistency of calibration results among different bunches and among scans is used to estimate uncertainties due to unknown effects