The (LHC) luminosity measurements

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

The Fifth Annual Large Hadron Collider Physics conference (LHCP 2017) Shanghai, May 19th, 2017

Luminosity: does it matter?

arXiv:1612.03016 [hep-ex]

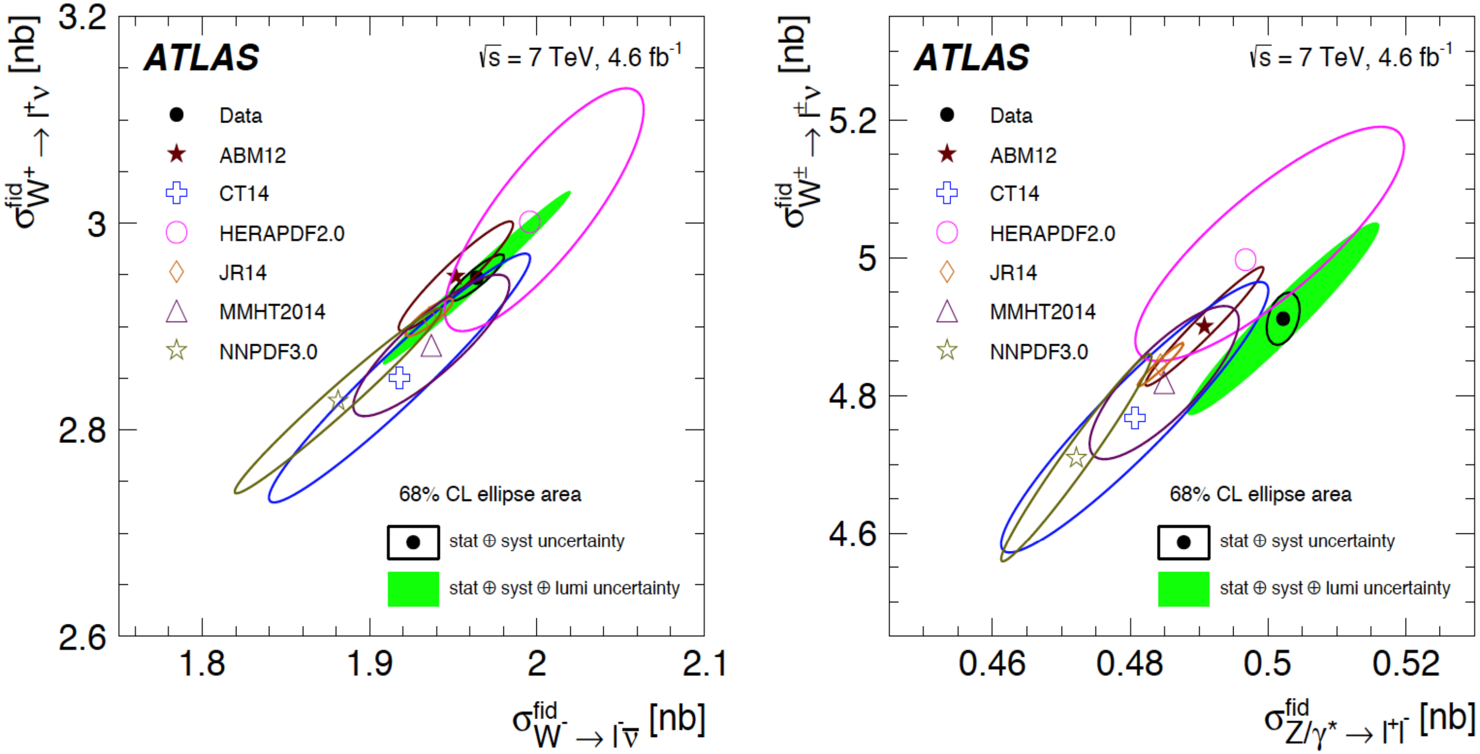

Figure 19: Integrated fiducial cross sections times leptonic branching ratios of $\sigma^{\mathrm{fid}}_{W^+\to\ell^+\nu}$ vs. $\sigma^{\mathrm{fid}}_{W^-\to\ell^-\bar{\nu}}$ (left) and $\sigma^{\mathrm{fid}}_{W^\pm\to\ell^\pm\nu}$ vs. $\sigma^{\mathrm{fid}}_{Z/\gamma^*\to\ell^+\ell^-}$ (right). The data ellipses illustrate the 68% CL coverage for the total uncertainties (full green) and total excluding the luminosity uncertainty (open black).

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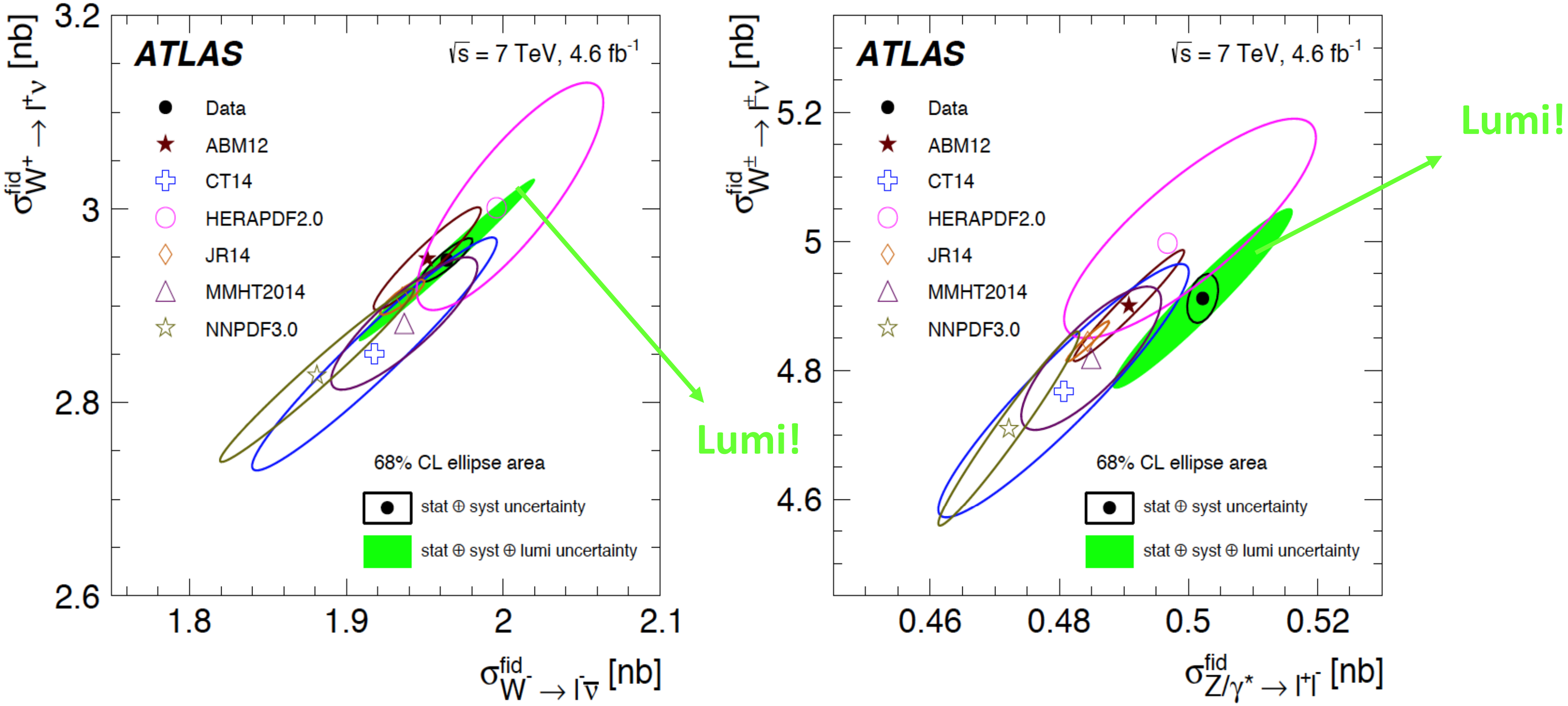


Figure 19: Integrated fiducial cross sections times leptonic branching ratios of $\sigma^{\rm fid}_{W^+\to\ell^+\nu}$ vs. $\sigma^{\rm fid}_{W^-\to\ell^-\bar{\nu}}$ (left) and $\sigma^{\rm fid}_{W^\pm\to\ell^\pm\nu}$ vs. $\sigma^{\rm fid}_{Z/\gamma^*\to\ell^+\ell^-}$ (right). The data ellipses illustrate the 68% CL coverage for the total uncertainties (full green) and total excluding the luminosity uncertainty (open black).

Luminosity: does it matter?

Table 1: Relative systematic uncertainties (in %) on the J/ψ cross-section measurements. The uncertainty from the t_z fit only affects J/ψ-from-b mesons. Most of the uncertainties are fully correlated between bins, with the exception of the p_T, y spectrum dependence and the simulation statistics, which are considered uncorrelated.

pp 13 TeV

Source	Systematic uncertainty (%)
Luminosity	3.9
Hardware trigger	0.1 – 5.9
Software trigger	1.5
Muon ID	1.8
Tracking	1.1 – 3.4
Radiative tail	1.0
J/ψ vertex fit	0.4
Signal mass shape	1.0
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.6
p_T, y spectrum	0.1 – 5.0
Simulation statistics	0.3 – 5.0
t_z fit (J/ψ-from-b only)	0.1

LHCb, arXiv:1509.00771 [hep-ex]

ALICE, arXiv:1702.00557 [hep-ex]

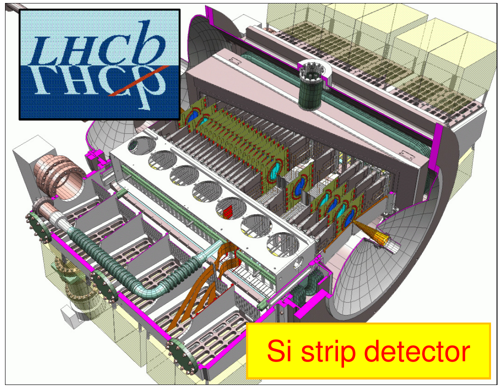
	$\sqrt{s} = 5.02$ TeV		$\sqrt{s} = 13$ TeV	
Source	J/ψ (%)	ψ(2S) (%)	J/ψ (%)	ψ(2S) (%)
Branching ratio	0.6	11	0.6	11
Luminosity	2.1	2.1	3.4	3.4
Signal extraction	3 (1.5 – 10)	8	3 (3 – 8)	5 (5 – 9)
MC input	2 (0.5 – 2.5)	2.5	0.5 (0.5 – 1.5)	1 (0.5 – 4)
MCH efficiency	1	1	4	4
MTR efficiency	2 (1.5 – 2)	2	4 (1.5 – 4)	4 (1.5 – 4)
Matching	1	1	1	1

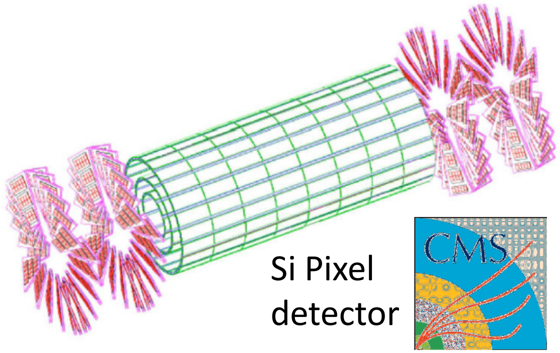
Table 1: Relative systematic uncertainties associated to the J/ψ and ψ(2S) cross section measurements at $\sqrt{s}$ = 5.02 and 13 TeV. Values in parenthesis correspond to the minimum and maximum values as a function of p_T and y. For ψ(2S) at $\sqrt{s} = 5.02$ TeV, only the p_T-integrated values are reported.

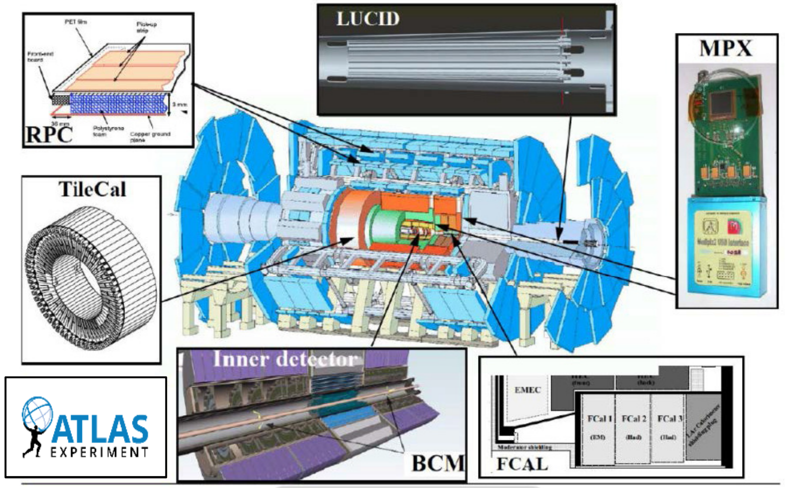
Luminosity is still **a non-negligible uncertainty source** for precision measurements at the LHC!

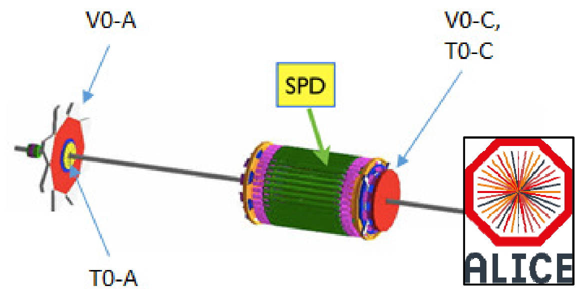
Outline

- Luminosity and its measurement
- Selected analysis details
- Current precision in luminosity determination with proton beams
- Luminosity determination for heavy-ion beams
- Conclusions









What's new

Published and updated luminosity documents since LHCP 2016

- ALICE-PUBLIC-2016-005	ALICE, pp $\sqrt{s}$ = 5 TeV (2015)
- CMS-PAS-LUM-16-001	CMS, pp $\sqrt{s}$ = 5 TeV (2015)
- Eur. Phys. J. C 76 (2016) 653	ATLAS, pp $\sqrt{s}$ = 8 TeV (2012)
- ALICE-PUBLIC-2017-002	ALICE, pp $\sqrt{s}$ = 8 TeV (2012)
- CMS-PAS-LUM-17-001	CMS, pp $\sqrt{s}$ = 13 TeV (2016)
- CMS-PAS-LUM-15-001	CMS, pp $\sqrt{s}$ = 13 TeV (2015)

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Results from Run I still coming up

→ an evolving field of study!

Luminosity: the basics

For **cross-section measurements,**

$\sigma = N \,/\, \mathscr{L}_{\mathbf{int}}$,

where:

- N is the efficiency-corrected, bkg-subtracted yield for a given physics process

- $\mathscr{L}_{\mathbf{int}} = \int \mathscr{L}(t)\mathrm{d}t$ is the integrated luminosity

Luminosity: the basics

For two counter-rotating bunches at a collider:

$$\mathscr{L} = f_{rev} N_1 N_2 \iint \rho_1(x,y)\rho_2(x,y)\,dxdy$$

Factorisation assumption:

$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

where:

$$1/\Sigma_x = \sqrt{2\pi} \int \rho_{1x}(x)\rho_{2x}(x)\,dx$$

$$1/\Sigma_y = \sqrt{2\pi} \int \rho_{1y}(y)\rho_{2y}(y)\,dy$$

Σ_x and Σ_y are the effective widths of the beam overlap region in the two transverse directions

Measuring the luminosity

$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

$N_1 N_2$: Measured by the accelerator instrumentation

$\Sigma_x \Sigma_y$:

- Can be derived from **nominal machine parameters with uncertainty > 10%**
- Can only be **measured directly in dedicated sessions**

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In standard physics data-taking,
the **luminosity is measured indirectly**:

$$\mathcal{L} = \frac{R_{ref}}{\sigma_{ref}}$$

σ_{ref} is the cross section for a suitable reference process

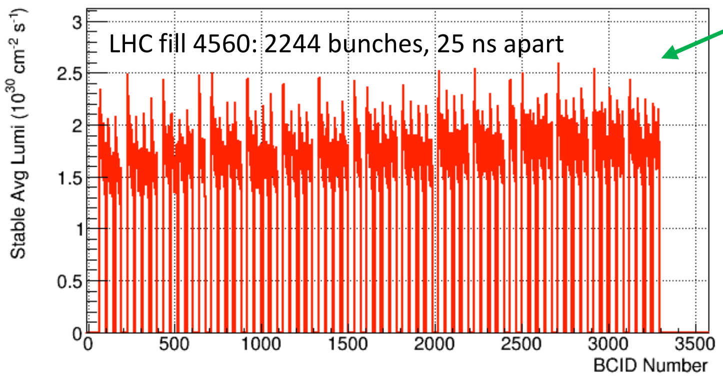
- Known physical cross section (es. *Z* boson, inelastic..)
- **Visible cross section (σ_{vis})** measured in a dedicated calibration experiment → Main solution at the LHC

Luminosity monitoring

$$\mathscr{L} = \frac{R_{vis}}{\sigma_{vis}} = \frac{\mu_{vis} f_{rev}}{\sigma_{vis}}$$

μ_{vis} = average number of «visible» interactions per bunch crossing

Bunch-by-bunch luminosity measurement



- **Event counting:** $\mu_{vis} = \varepsilon_{trig}\, \mu_{inel}$
  - count number of inelastic events satisfying a given trigger condition
  - not too sensitive to detector response if condition is loose enough
  - saturates at μ_{vis} ~ 1-5 (pile-up!)

- **Track, hit, vertex counting:** $\mu_{vis} = \langle N_{track,hit,vertex}\rangle\ \mu_{inel}$
  - count number of tracks, hits or vertices
  - saturates at much larger μ (<-> granularity)
  - sensitive to drifts and dead channels

- **Flux-counting**:
  - measure some bunch-integrated quantity (e.g. current), proportional to the total luminosity

Luminometers use a **wide range of technologies**:
scintillators, silicon, calorimeters, diamond sensors...

Calibrating the luminometers

$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y} \qquad \sigma_{vis} = \frac{\mu_{vis} f_{rev}}{\mathscr{L}}$$

To measure σ_{vis}:

Measure μ_{vis} and $\Sigma_x \Sigma_y$ simultaneously in a dedicated calibration session

$$\sigma_{vis} = \frac{2\pi \mu_{vis} \Sigma_x \Sigma_y}{N_1 N_2}$$

How to measure $\Sigma_x \Sigma_y$?

Beam-gas imaging (BGI):

use the **distribution of beam-gas vertices** to directly measure ρ(x,y) for each beam

- **does not assume factorisation**

- requires exquisite vertex resolution and possibly a dedicated gas injection system → **LHCb**

van der Meer (vdM) scan:

measure μ_{vis} vs beam separation in the transverse plane, and determine Σ from the area of the resulting curve

- **assumes factorisation**

- used by a**ll four large LHC experiments**

→ **will focus on vdM in the following**

Bunch intensity measurement

$$\mathscr{L} = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}$$

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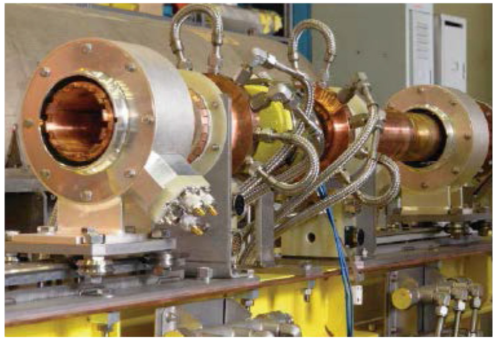
- LHC **current transformers**:
  - **DCCT** for the total beam intensity
  - **fastBCT** for relative bunch populations

DCCT

fBCT



Bunch intensity measurement

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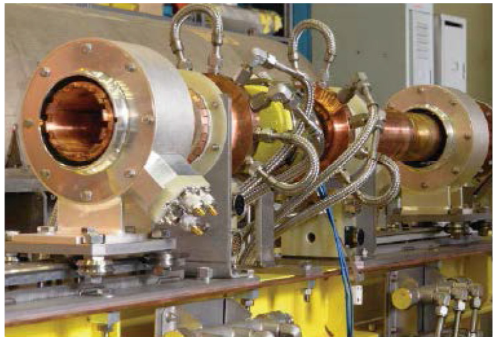
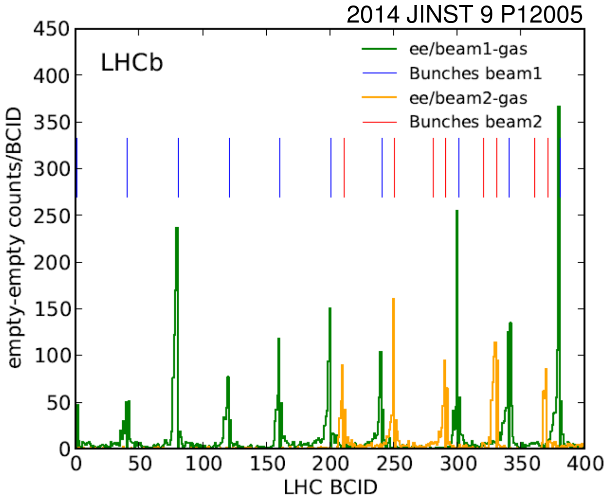


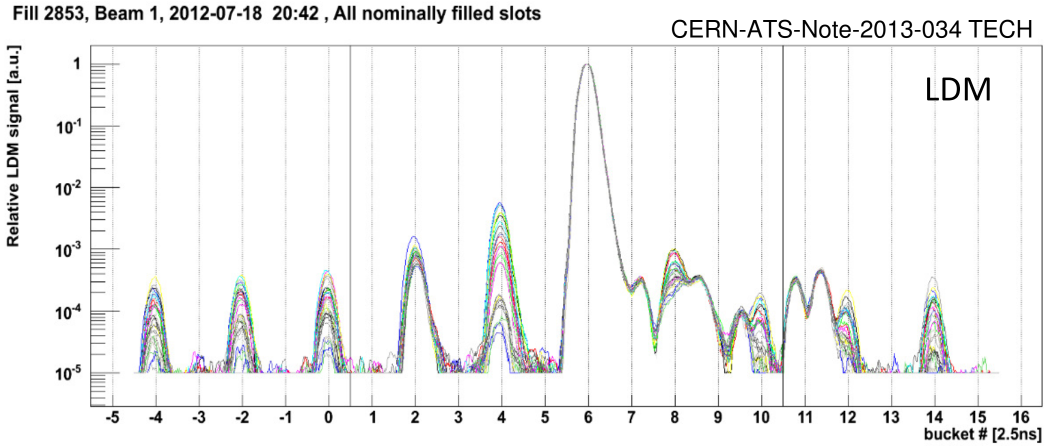
- Correction for
  ghost and satellite charge:

LHCb (as a by-product of beam-gas imaging)



Ghost charge-induced counts vs LHC bunch slot

LHC Longitudinal Density Monitor (LDM)



Satellite charge-induced counts vs LHC RF bucket
(1 bunch slot = 10 RF buckets)

Bunch intensity measurement

$$\mathcal{L} = \frac{f_{rev} N_1 N_2}{2\pi\Sigma_x\Sigma_y}$$

- LHC **current transformers**:
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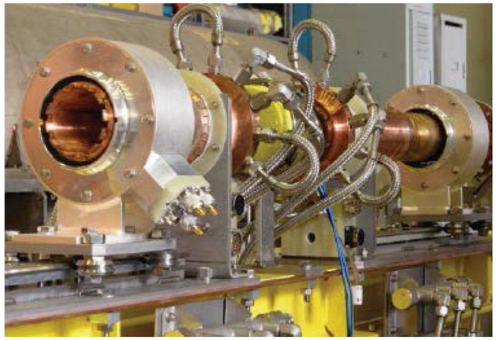
DCCT

fBCT



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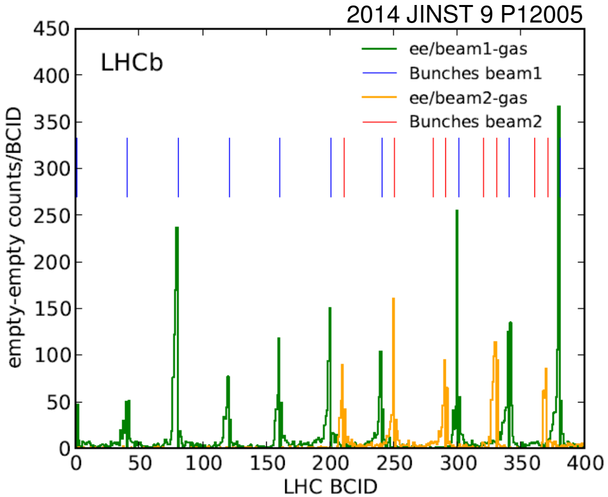

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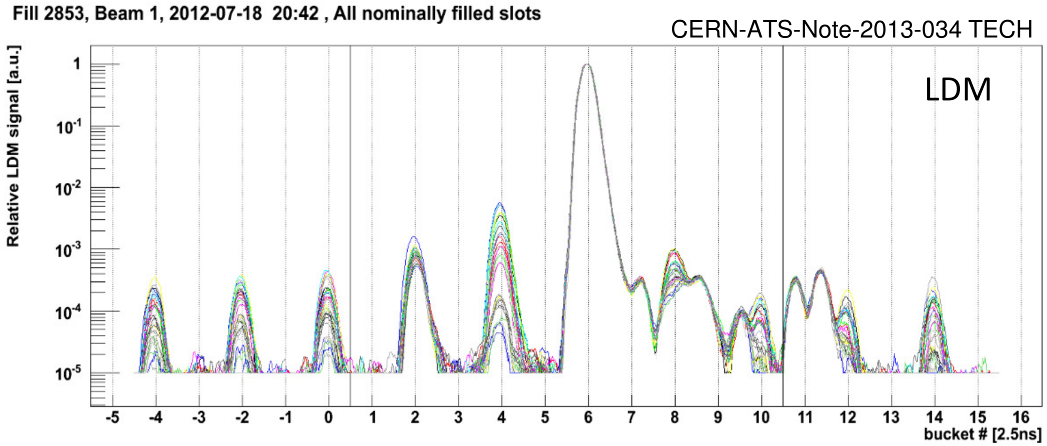
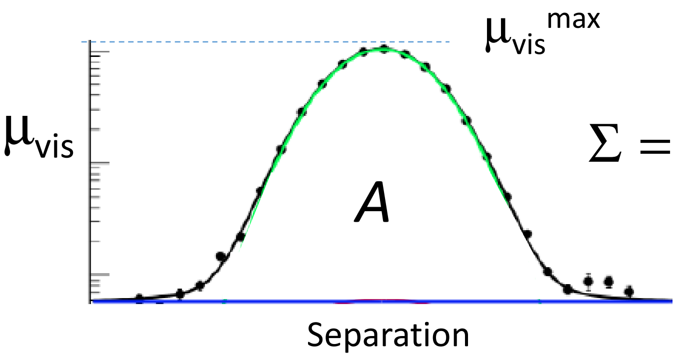


Satellite charge-induced counts vs LHC RF bucket
(1 bunch slot = 10 RF buckets)

Bunch intensity was **initially dominating the luminosity uncertainty** → **great effort** in calibrating and understanding these devices → per-mil level uncertainties

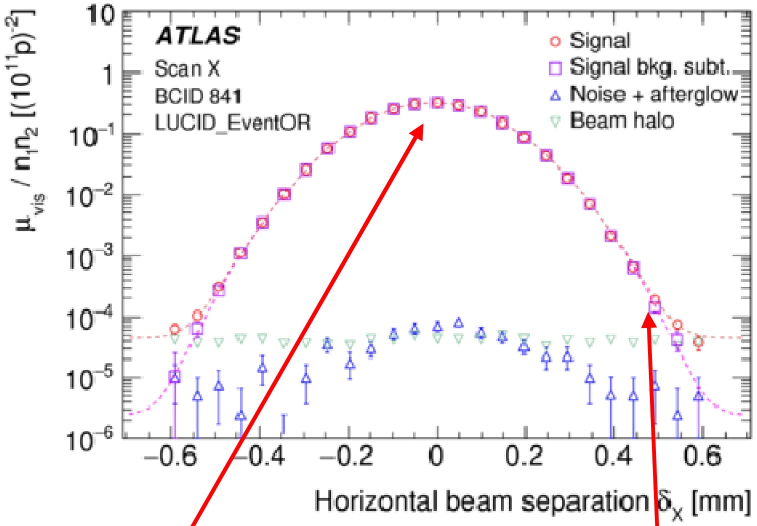
The vdM scan method

- **Measure μ_{vis} vs separation** in a dedicated session

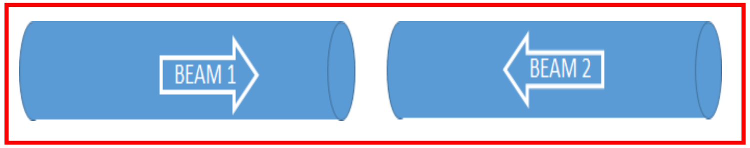


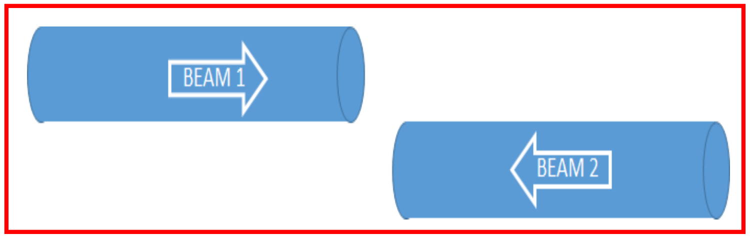
$$\Sigma = \frac{A}{\sqrt{2\pi}\,\mu_{vis}^{max}}$$

Eur. Phys. J. C 76 (2016) 653



– μ_{vis} needs to be corrected for both detector- and beam-related effects:
  - noise + afterglow
  - separation-dependent acceptance
  - beam-gas and beam-satellite collisions





- vdM scans prefer tailored running conditions (low μ_{vis}, low intensity, well-spaced bunches..)

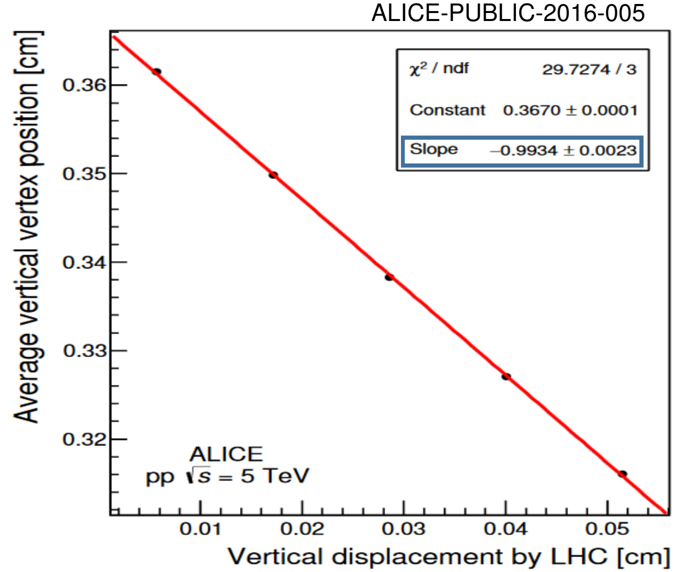
  → **1-2 sessions / year**

A number of subtle details..

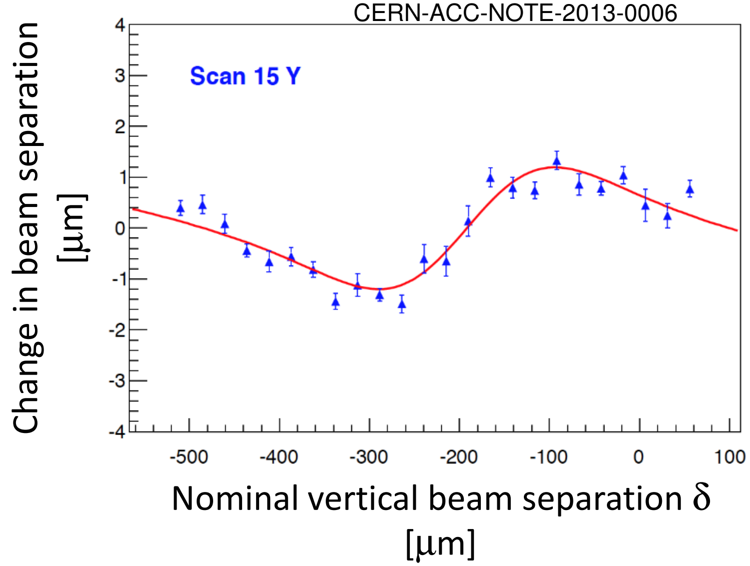
The «raw» scan curves need **a number of corrections**:

- **Drifts** of the reference orbit
  (typically a per-mil effect, but can reach per-cent levels)

- Length-scale calibration:
  measure vertex displacement vs nominal beam displacement in a dedicated scan
  (few per-mil to **~3%** effect)



- **Beam-beam effects**:
  - up to ~2% bias if not accounted for
  - scale with the bunch intensity and beam size
  - separation-dependent
    - **beam-beam deflection**:
      mutual repulsion between charged beams, affects the beam separation
    - **dynamic β***:
      mutual (de-)focusing between beams, affects the widths (hence μ_{vis})



The non-factorisation issue

Main vdM assumption: $\rho(x, y) = \rho(x)\rho(y)$

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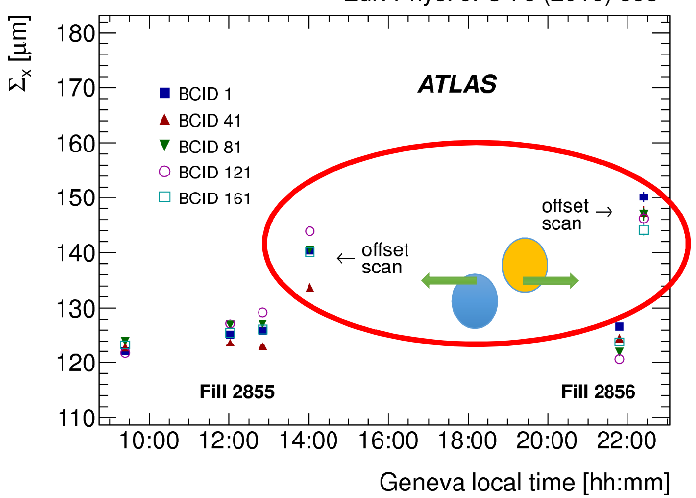
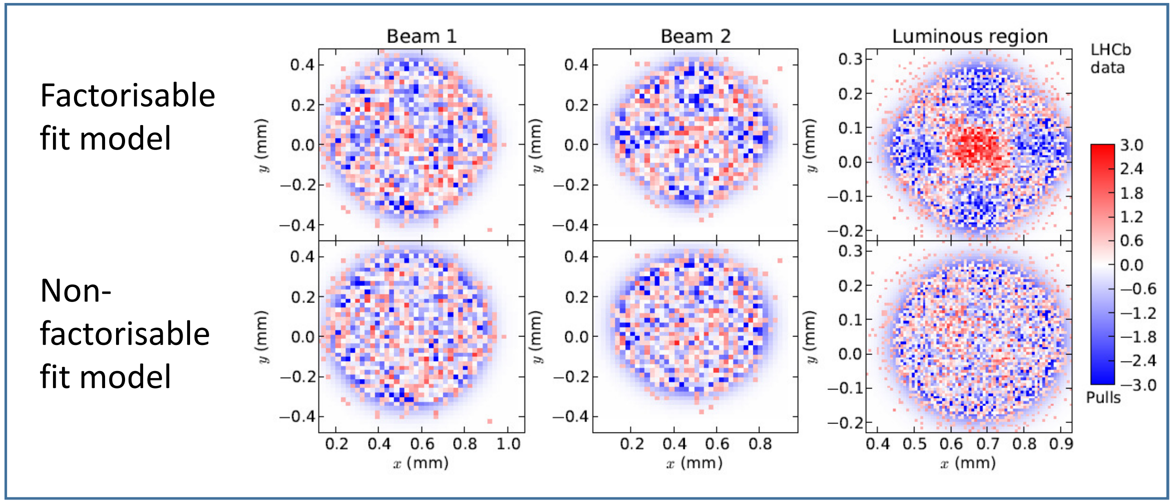
Evidence for broken factorisation in 2012 vdM scans → **up to ~5% effect on σ_{vis}!**

Discrepancy between Σ values in offset and centred scans



LHCb beam-gas imaging

2014 JINST 9 P12005



Non-factorisation effects were **first observed at the LHC**:

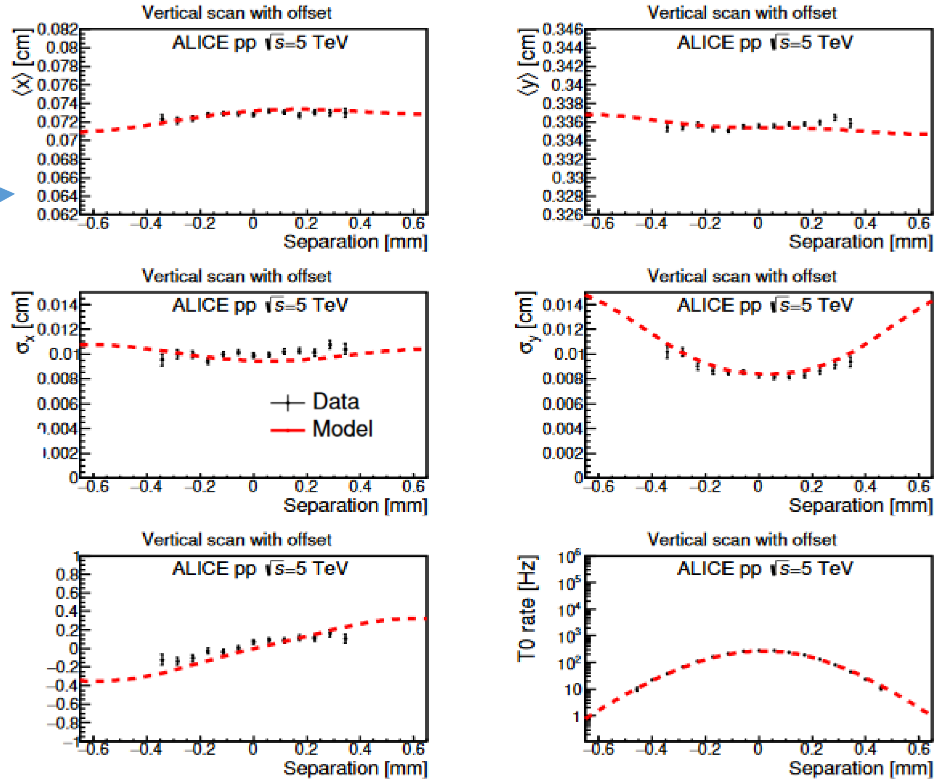
- by all four experiments, although at different stages and in different ways
- co-operation and info exchange among Collaborations were crucial for a «fast» solution of the puzzle

Non-factorisation correction

Main strategy for ALICE, ATLAS, CMS:
«standard» vdM analysis + non-fact. correction

- simultaneous **fit of μ_{vis} and luminous region parameters** vs beam separation
- constrain single beam parameters via single-beam scan (beam-beam imaging)

ALICE-PUBLIC-2016-005



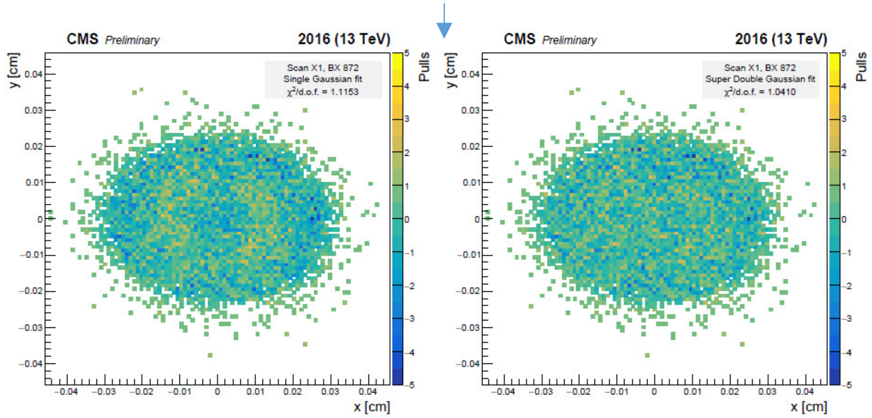


Figure 7: Example of the pull distributions of the fitted model of Single Gaussian type (left) and Super Double Gaussian type (right) with respect to the vertex distribution accumulated during scan X3 of BCID 872.

CMS-PAS-LUM-17-001

→ **vertexing capabilities are crucial!**

LHCb: directly obtain non-factorisation information via beam-gas imaging

Run 2 vdM scans:

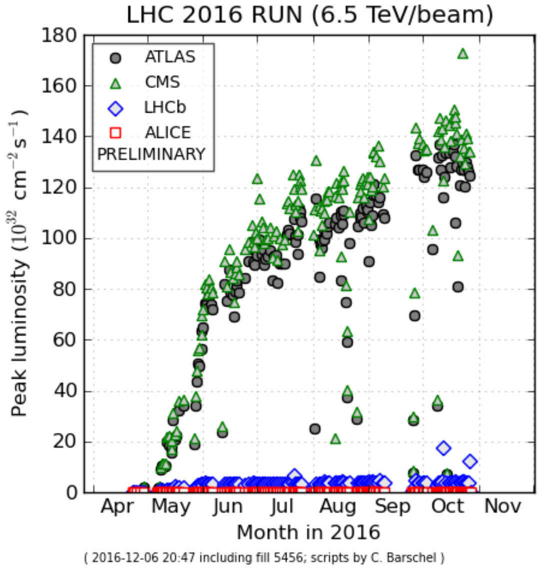
- so far, <2% corrections and/or uncertainties from non-factorisation

(effect of beam tailoring in the injectors?)

From the vdM scan to physics runs

- **Luminometers are calibrated at one point in time** in the vdM scan (or BGI) session:
  - μ_{vis}^{max} ~ 0.5-1, isolated bunches, low total lumi

- **Physics data** is taken throughout ~1 year:
  - at (slightly) much larger μ_{vis} for (LHCb) ATLAS, CMS (1-2 orders of magnitude)
  - at smaller μ_{vis} (<-> smaller signal/bkg) for ALICE
  - with much smaller bunch spacing (25-50 ns)

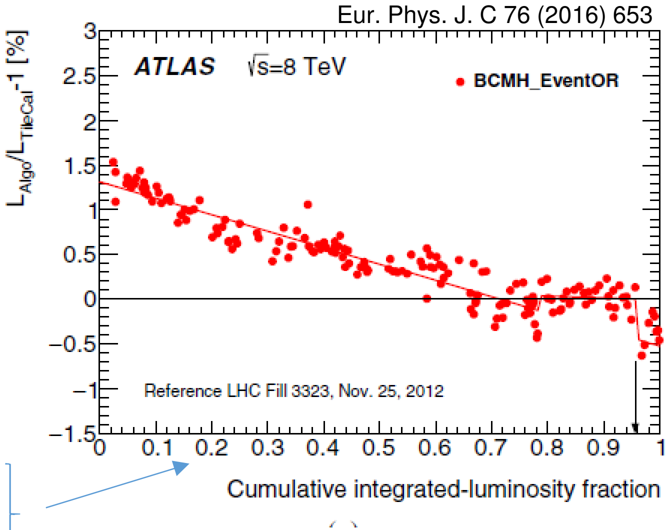


- **Two main issues:**
  - linearity of detector response in different μ_{vis} regimes
  - long-term stability (ageing, drifts...)

Solution: **redundancy!!**

→ use several luminometers, cross-calibrate them at different luminosity scales

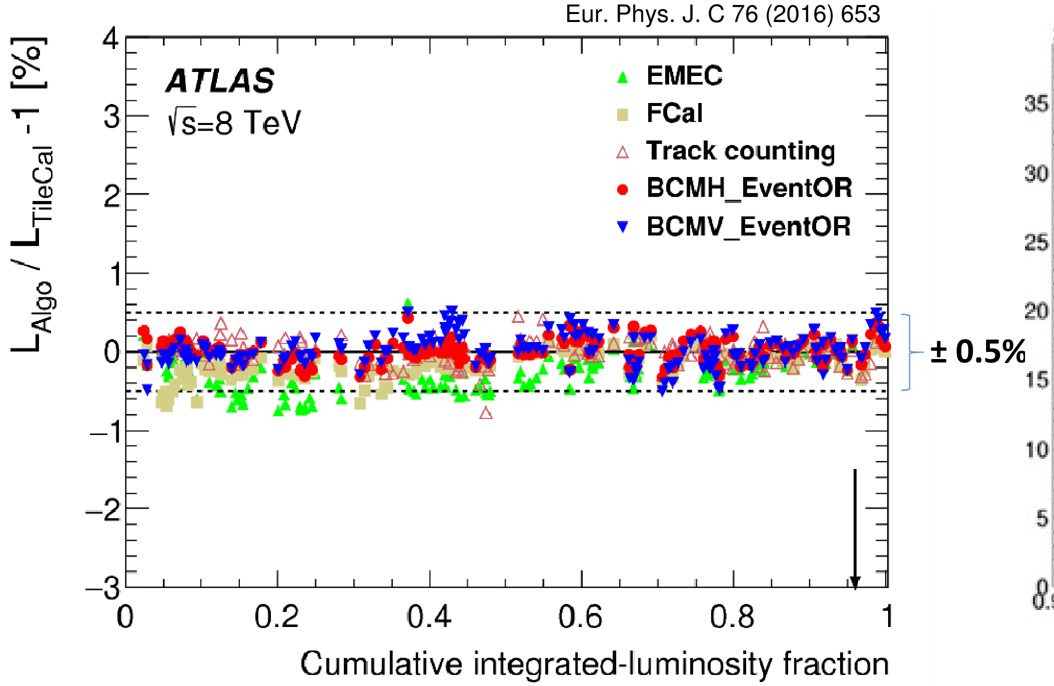
→ use consistency among different luminosity measurements to estimate corrections and/or uncertainties



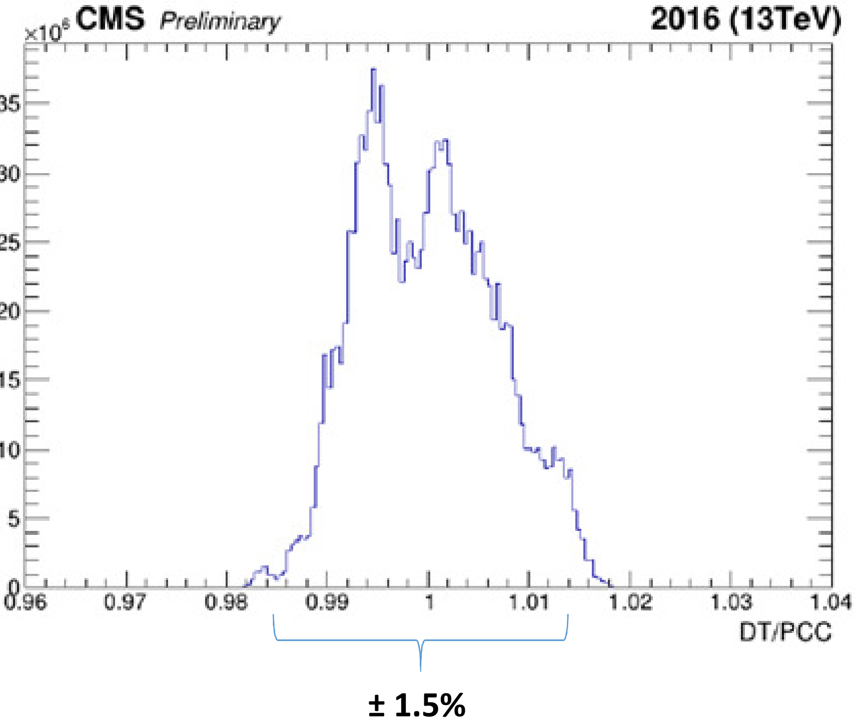
Long-term stability and consistency

Some recent results:

Relative difference of luminosities measured by several ATLAS luminometers



Ratio of luminosities measured by two of the CMS luminometers

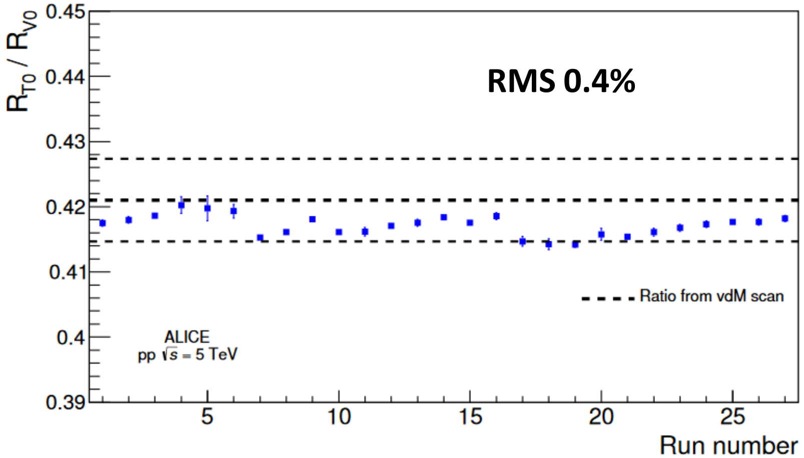


Long-term stability and consistency

Some recent results:

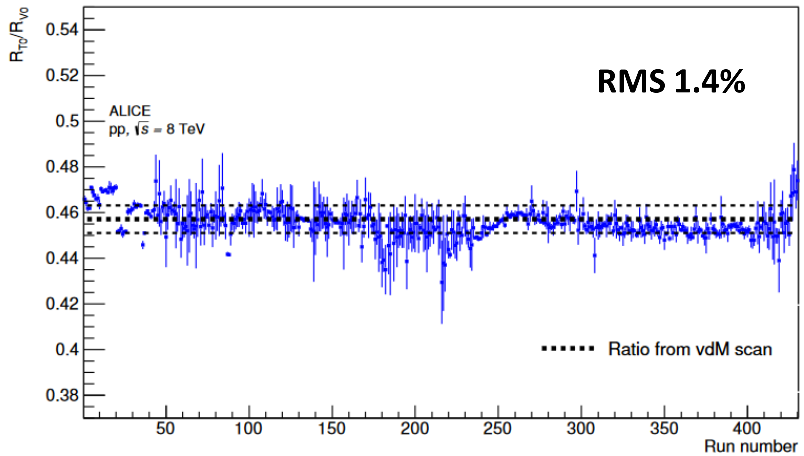
Ratio of counting rates for two of the ALICE luminometers

ALICE-PUBLIC-2016-005



pp 5 TeV, **5 days** of data-taking

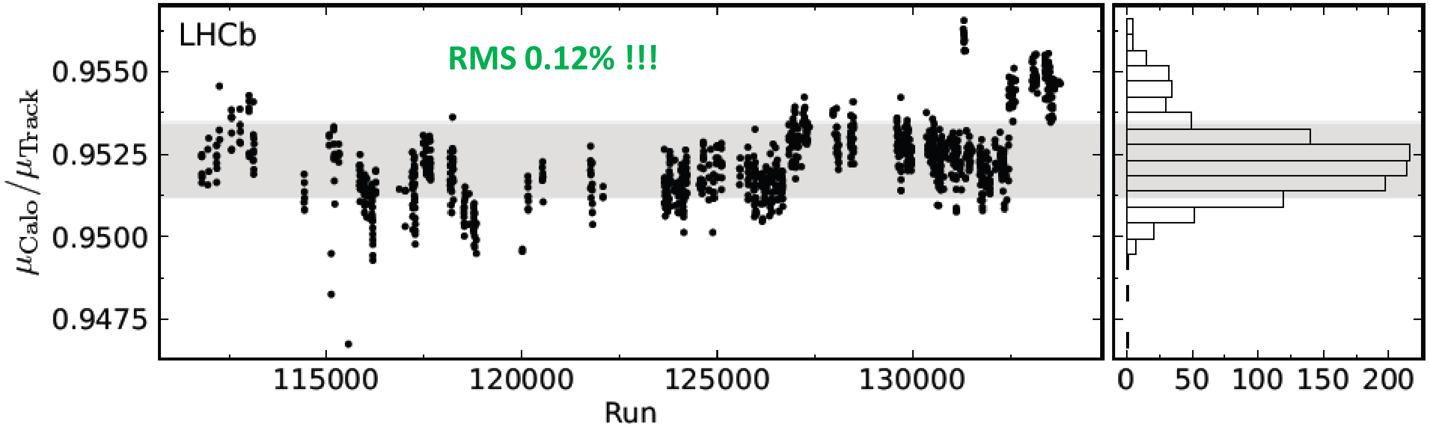
ALICE-PUBLIC-2017-002



pp 8 TeV, **7 months** of data-taking

2014 JINST 9 P12005

Ratio of counting rates for two of the LHCb luminometers (pp 8 TeV)



Current precision in pp luminosity determination

(2012 and later)

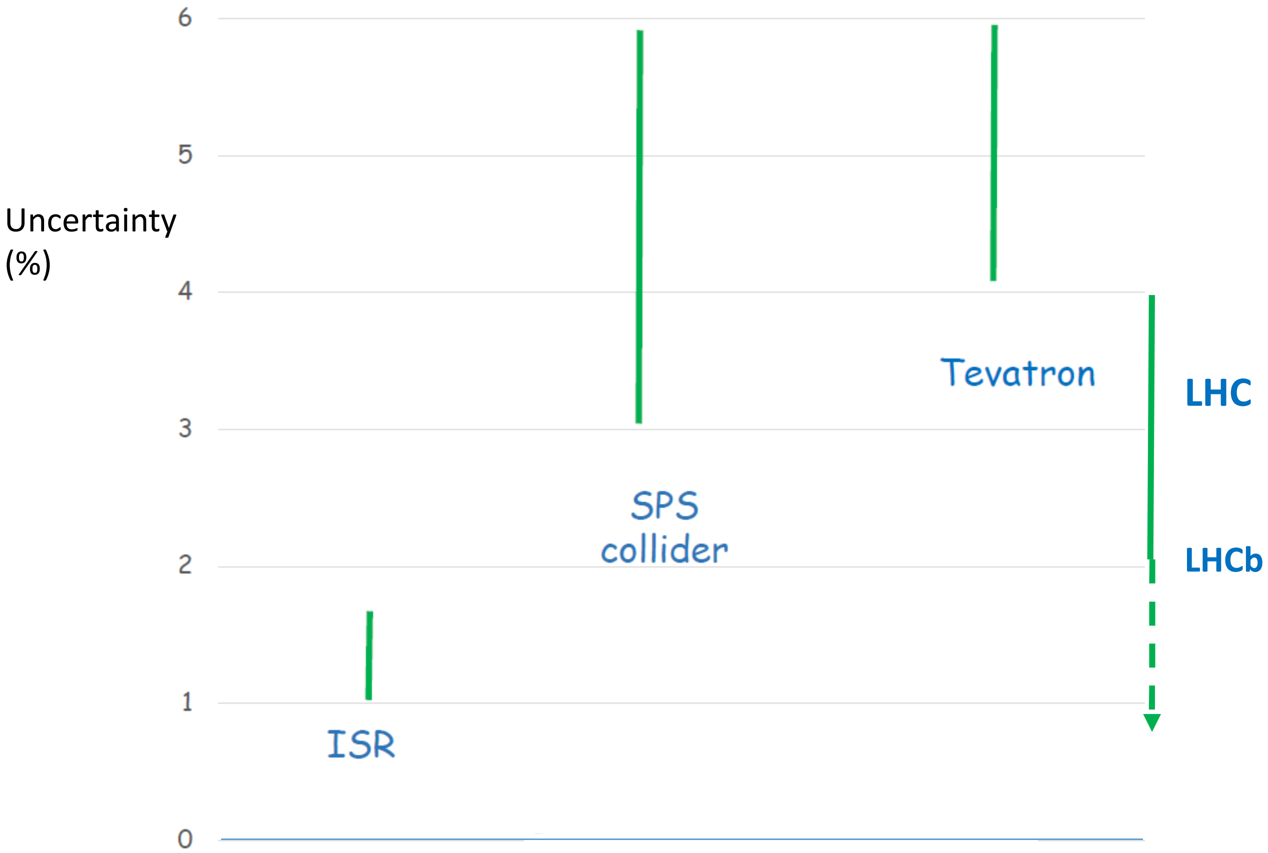
	ALICE	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS	LHCb	ATLAS	CMS
Running period	2012 pp	2012 pp	2012 pp	2012 pp	2015 pp	2015 pp	2015 pp	2015 pp	2016 pp	2016 pp
$\sqrt{s}$ [TeV]	8	8	8	8	13	13	13	13	13	13
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	2.4	1.9	2.6	1.2	3.4	2.1	2.3	3.9 Prelim.	3.4 Prelim.	2.5

	ALICE	ATLAS	CMS	LHCb	ALICE	ATLAS	CMS
Running period	2013 pp	2013 pp	2013 pp	2013 pp	2015 pp	2015 pp	2015 pp
$\sqrt{s_{NN}}$ [TeV]	2.76	2.76	2.76	2.76	5.02	5.02	5.02
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	3.8	3.1	3.7	2.2	2.1	5.4 Prelim.	2.3

Updating a table originally conceived and compiled by W. Kozanecki for LHCP 2016

LHC vs the past

Precision reached by proton colliders



ISR:
- continuous beam
- smaller μ_{vis}
- flat beam, i.e. negligible non-factorisation effects

Tevatron, SPS:

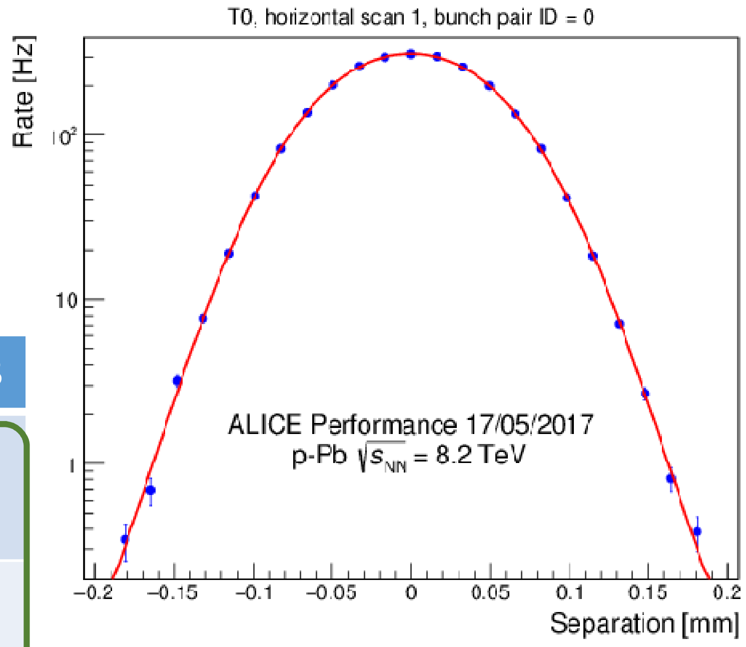
p and anti-p beams can not be separated magnetically
→ vdM method impractical

Slide partially stolen from P. Grafstrom

Luminosity determination for heavy-ion beams

- Generally larger uncertainties:
  - no time for a dedicated vdM set-up
  - larger ghost and satellite charge
  - bunch-by-bunch measurements are statistically-limited
- But:
  - smaller beam-beam effects
  - smaller μ_{vis} and total luminosity ranges

→ room for improvement, even for Pb-Pb



	ALICE	ALICE	ATLAS	CMS	LHCb	ATLAS
Running period	2010/11 PbPb	2013 p-Pb / Pb-p	2013 p-Pb / Pb-p	2013 p-Pb / Pb-p	2013 p-Pb / Pb-p	2015 PbPb
$\sqrt{s_{NN}}$ [TeV]	5	5	5	5	5	5
$\sigma_{\mathcal{L}}/\mathcal{L}$ [%]	5.8/4.2	3.7/3.4	2.7	3.6/3.4	2.3/2.5	6.1 Prelim.

Updating a table originally conceived and compiled by W. Kozanecki for LHCP 2016

Conclusions

- Luminosity is a **dominant or non-negligible source of uncertainty for precision measurements** (EW bosons, quarkonia, total cross sections...)
- The **precision of luminosity** determination at the LHC **exceeds expectations** and, for vdM-based pp measurements, it **ranges from 2% to 4%**
- Although based on a very simple principle, vdM-based calibration requires a detailed data-taking and analysis procedure to have good control of **several subtle effects**
- Main source of uncertainty as of now is connected to **the calibration transfer from the vdM scan to the standard data-taking scenario**
  → challenge for HL-LHC!
- **LHC-wide (experiments+machine) discussion of luminosity-related issues** has greatly helped progress in this field

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