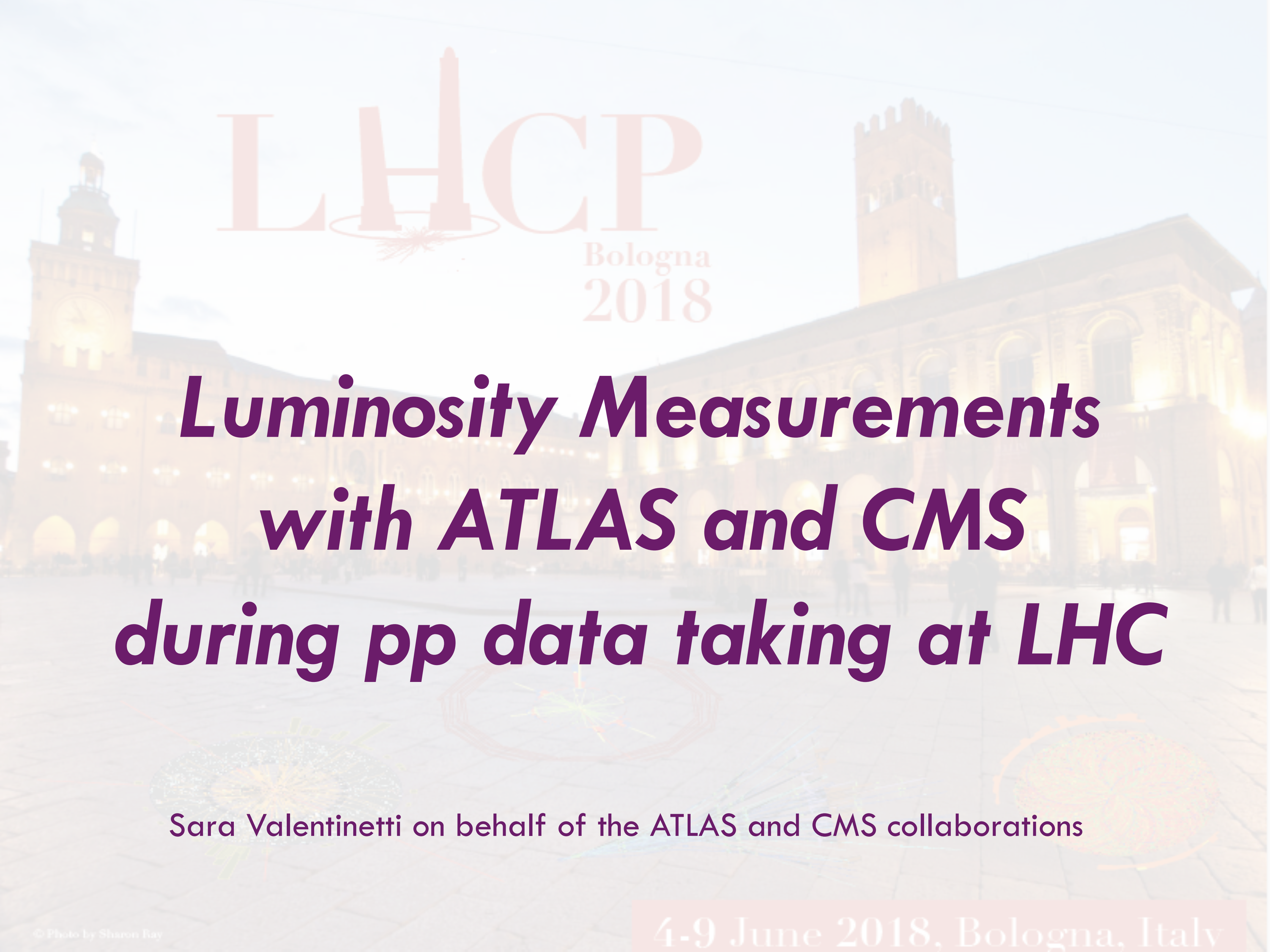

Luminosity Measurements with ATLAS and CMS during pp data taking at LHC

Sara Valentinetti on behalf of the ATLAS and CMS collaborations

4-9 June 2018, Bologna, Italy

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Outline

- Introduction: luminosity overview
- ATLAS/CMS luminosity strategy
- Absolute luminosity calibration
- Luminosity systematics
- Summary

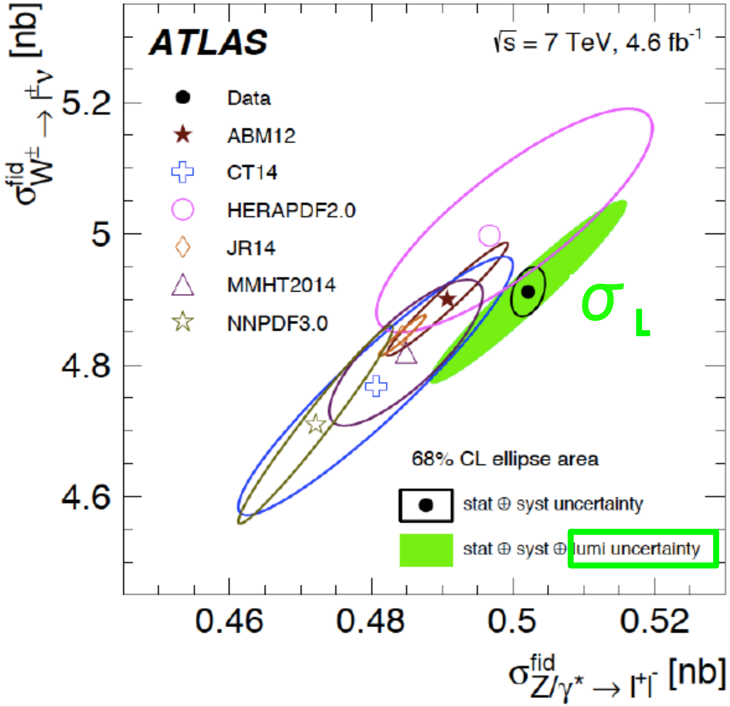
Introduction

Event rate R [events/s]: key parameter for experiments. For a physics process with cross-section σ, R is proportional to the instantaneous **luminosity** $\mathcal{L}$:

$$\boxed{R = \sigma \mathcal{L}}$$

Experiments MUST provide highly precise luminosity measurements:

- Instantaneous $\mathcal{L}$ -> online for machine monitoring: LHC performance and operation (lumi levelling, beam monitoring…). Needed precision: 3-5% or better
- Integrated L -> offline for physics: precise cross section measurements, SM test, new physics (theory often limited by PDF uncertainty, aim to have lower lumi uncertainty to better constrain PDFs'). Needed precision: below 2%, ideally 1%



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Achieved LHC uncertainty ≈2%
Quite good but still dominant for some cross section measurements

Basics of luminosity measurement

$$\mathcal{L} = \frac{\boxed{R}}{\sigma} = \frac{\boxed{\mu n_b f_r}}{\sigma_{inel}} = \frac{\boxed{\varepsilon\mu} n_b f_r}{\boxed{\varepsilon\sigma_{inel}}} = \frac{\boxed{\mu_{vis}} n_b f_r}{\boxed{\sigma_{vis}}}$$

μ = number of inelastic pp collisions per bunch crossing

n_b = number of colliding bunch pairs

f_r = LHC revolution frequency (11245 Hz)

σ_{inel} = total inelastic pp cross-section (~80 mb at 13 TeV)

ε = acceptance and efficiency of luminosity detector

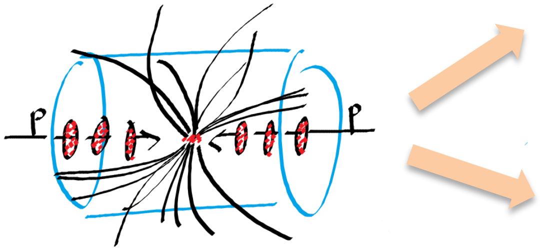
μ_{vis} = number of visible (= detected) collisions per bunch crossing

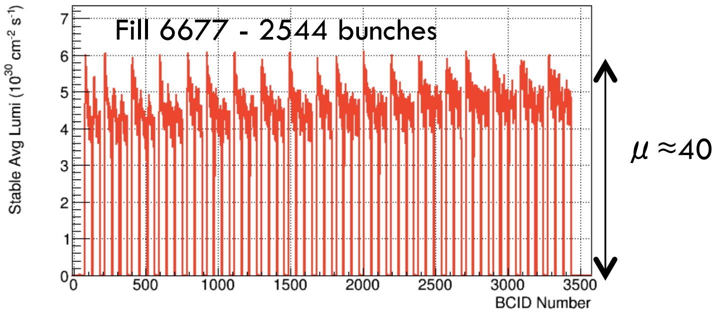
σ_{vis} = visible cross-section = luminosity calibration constant

Each detector able to provide a quantity proportional to luminosity can be considered a luminosity monitor

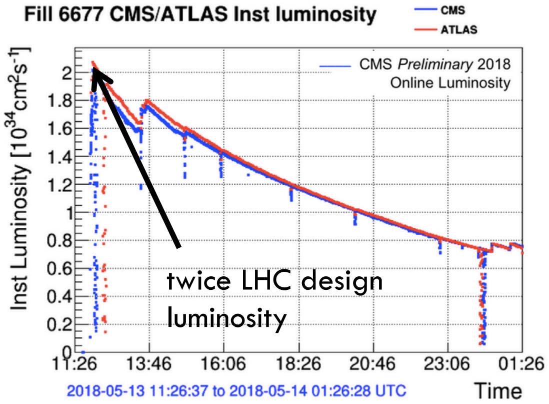
Luminosity environment at LHC

LHC 2017 running conditions: pp bunches separated by 25 ns, $\sqrt{s}$=13 TeV





Bunch-by-bunch luminosity

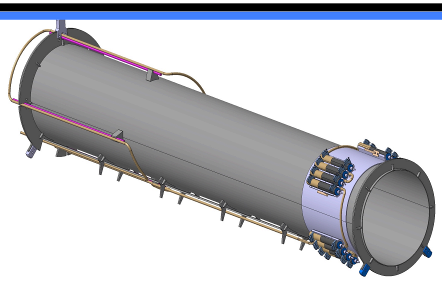


Bunch-integrated luminosity over fill (about 12 hours)

- Steps in luminosity determination and systematics assessment:
  - Absolute scale from beam-separation scans: vdM method, complemented by the luminous-region evolution (aka beam-beam imaging scans)
  - Evaluation of linearity over four orders of magnitude in luminosity
  - Stability throughout the year → redundancy between luminometers
  - All other source of systematics

ATLAS Run 2 luminosity monitors

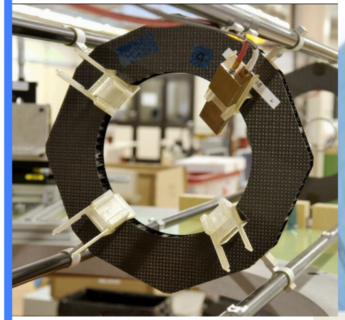
Luminosity measurement using a Cherenkov Integrating Detector (LUCID)



- **online** and **offline** measurements
- event/hit counting (aka zero-counting, based on Poisson statistics)

Online measurements

Beam Condition Monitor (BCM)



Event counting

ATLAS-preferred for Run 2: LUCID

Offline measurements

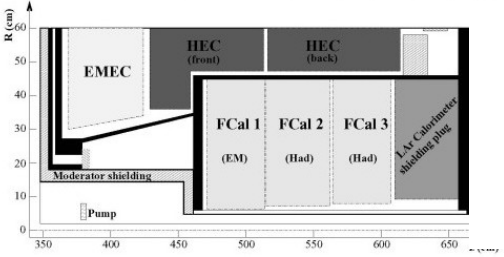
TimePix (TPX)

Hit counting

+ Z counting (relative-L checks)

+ Track counting (+ Vertex counting)

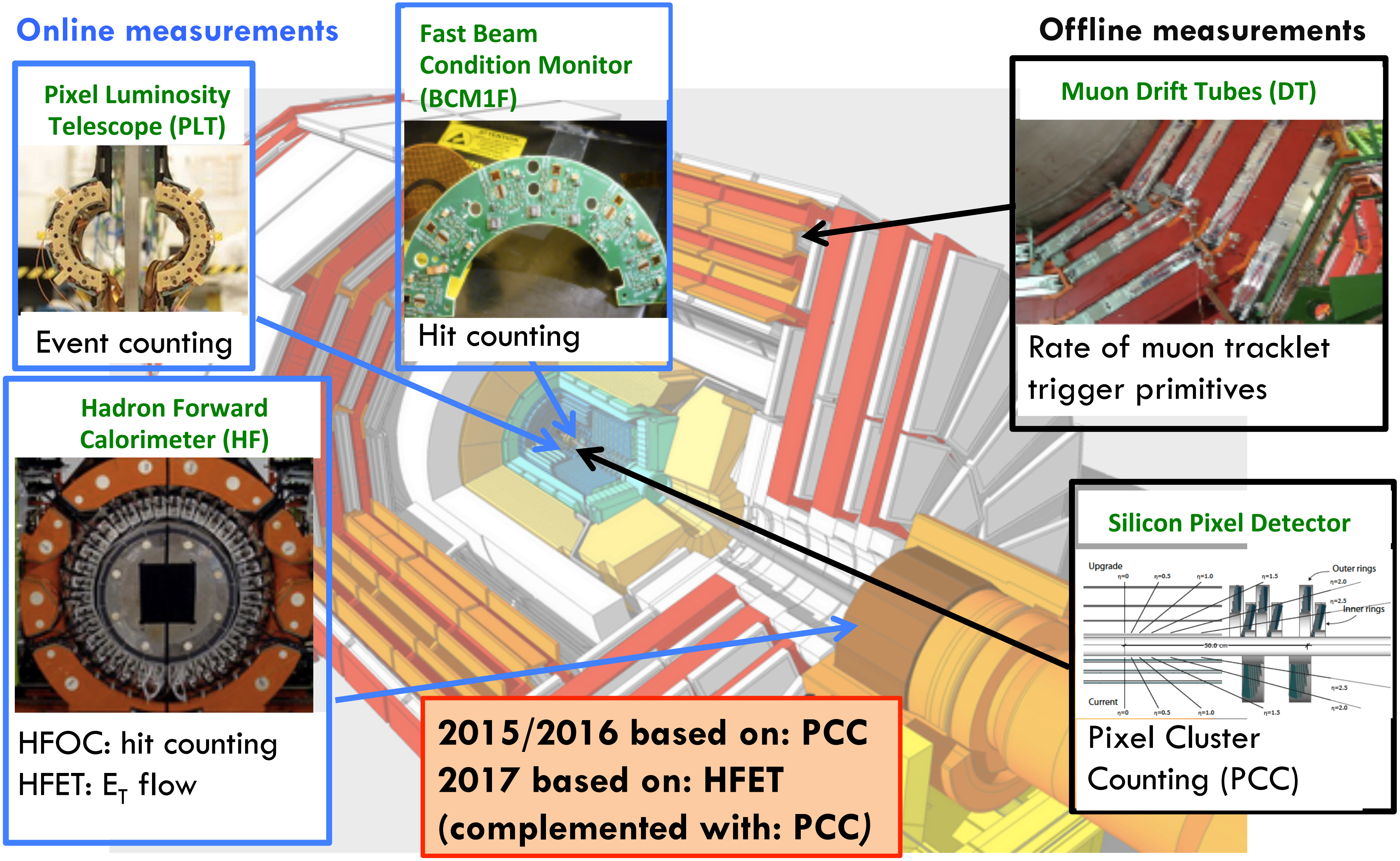
Hadronic Cal. (TILE)



EM:
- **Forward Calorimeter (FCAL)**
- **EndCap Calorimeter (EMEC)**

Particle flux algorithms

CMS Run 2 luminosity monitors



Online measurements

Pixel Luminosity Telescope (PLT)

Event counting

Fast Beam Condition Monitor (BCM1F)

Hit counting

Hadron Forward Calorimeter (HF)

HFOC: hit counting
HFET: E_T flow

Offline measurements

Muon Drift Tubes (DT)

Rate of muon tracklet trigger primitives

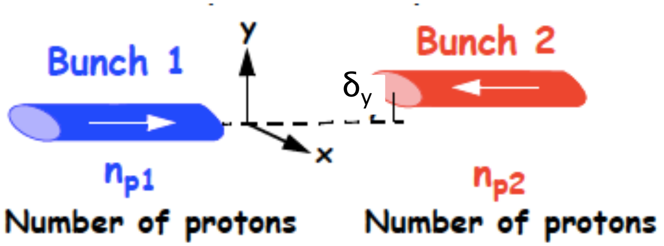
Silicon Pixel Detector

Pixel Cluster Counting (PCC)

2015/2016 based on: PCC
2017 based on: HFET
(complemented with: PCC)

vdM scan calibration: principle

- Visible interaction rate μ_{vis} measured as a function of beam separation $\delta_{x(y)}$
- Visible rate calibrated to the reference luminosity computed from measured beam parameters



$$\mathcal{L} = \frac{n_b f_r \boxed{n_{p1} n_{p2}}}{2\pi \boxed{\Sigma_x \Sigma_y}}$$

Current measurements (from LHC)

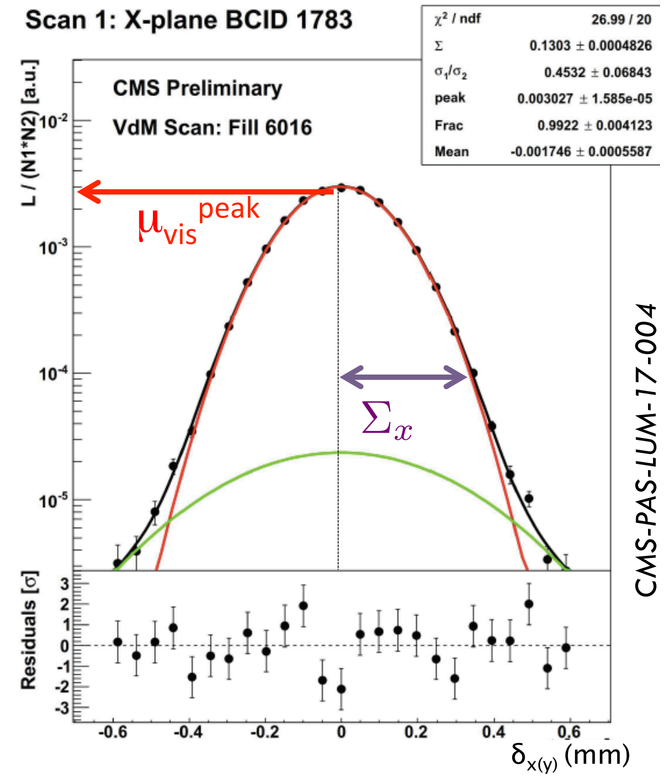
Beam overlap width: integral under the scan curve/peak (σ if Gaussian)

- Direct calibration of the visible cross section σ_{vis} for each luminosity detector/algorithm

$$\boxed{\sigma_{vis}} = \frac{R}{\mathcal{L}} = \frac{\mu f_r n_b}{\mathcal{L}} = \boxed{\mu_{vis}^{peak}} \frac{2\pi \Sigma_x \Sigma_y}{n_{p1} n_{p2}}$$

- Key assumption: factorization of bunch proton density function

$$\mathscr{L}(\delta_x, \delta_y) = f_x(\delta_x)\, f_y(\delta_y)$$



CMS-PAS-LUM-17-004

Dominant uncertainties in vdM calibration

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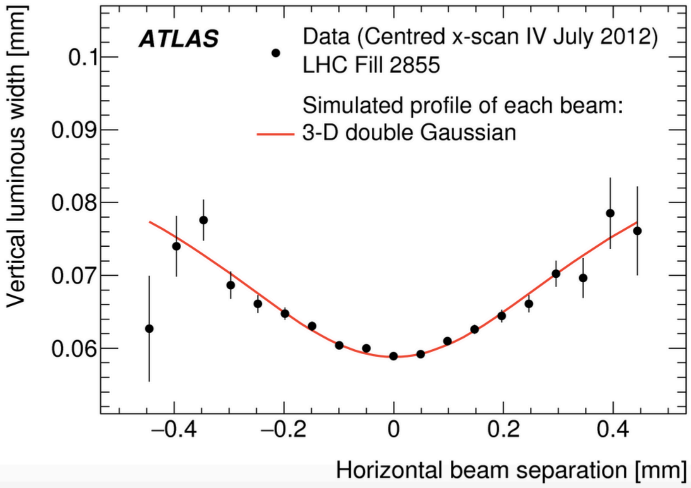
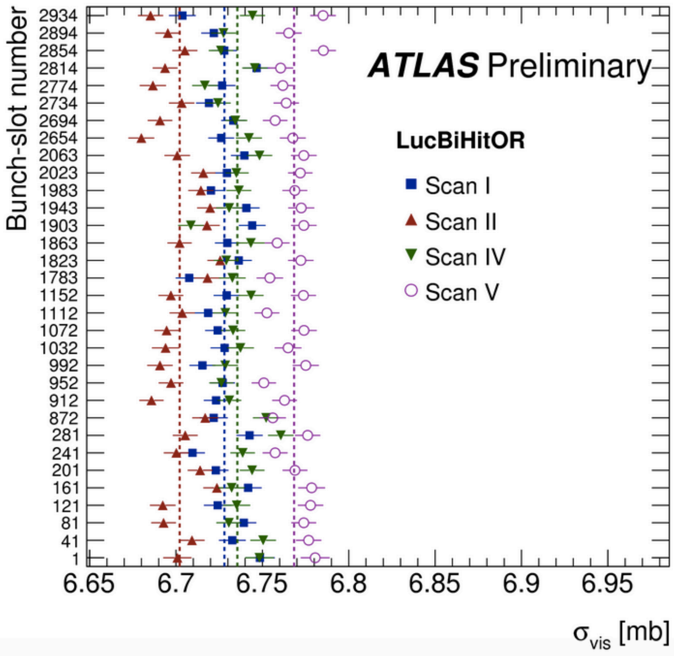




http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/

Non-factorization correction:

- Signature of non-factorization effects: dependence of vertical convolved beam size and/or vertical luminous width on horizontal separation (and vice-versa)
- Combination of factorizable vdM analysis with non-factorization correction from luminous-region data
    - CMS in 2017: 0.8 ± 0.8 %
    - ATLAS in 2017: 0.2 ± 0.2 %

Scan-to-scan reproducibility of vdM calibration:

- CMS in 2017: ± 0.9 %
- ATLAS in 2017: ± 1.2 %

CMS-PAS-LUM-17-004

https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics

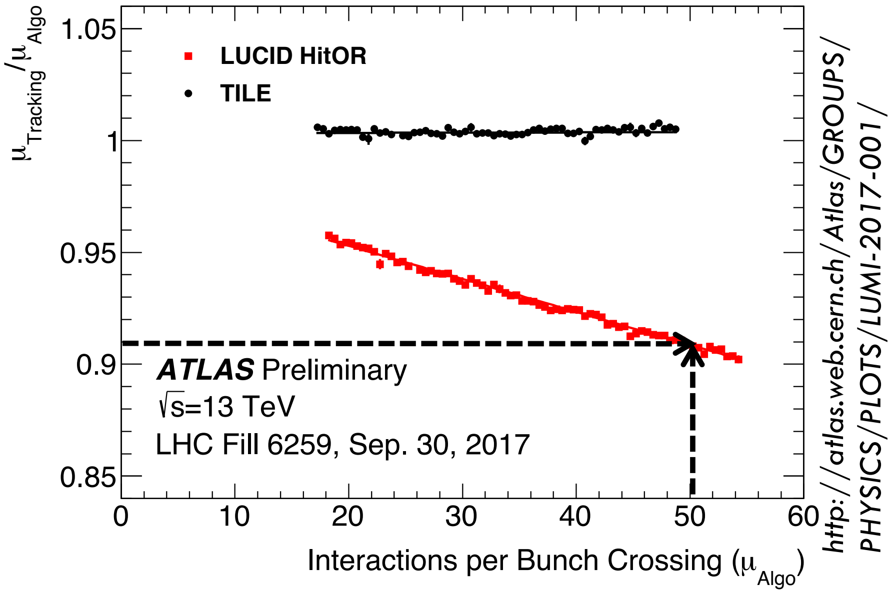
NB: somewhat different recipes to evaluate this and some others uncertainties between the two collaborations

Calibration transfer: vdM to physics

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

➢ ATLAS:

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



http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/

➢ 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: ±1.5%

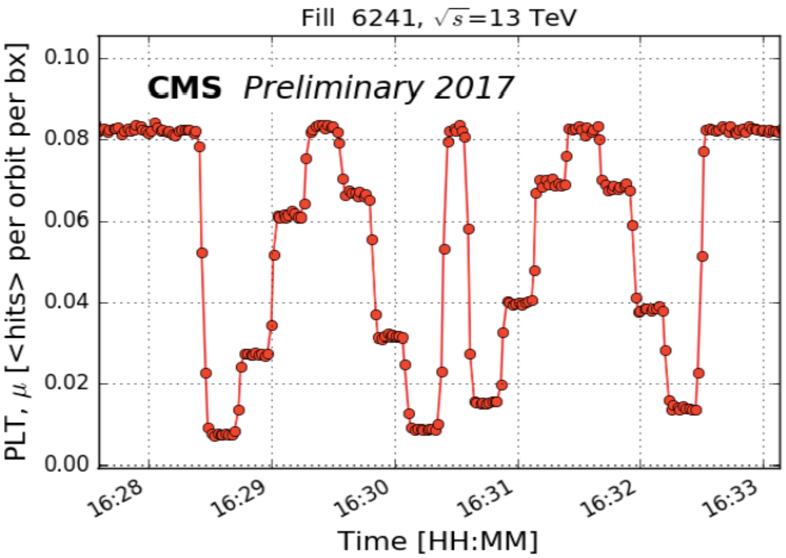
ATLAS Ref.: https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics
CMS Ref.: *CMS-PAS-LUM-17-004*

CMS emittance scans

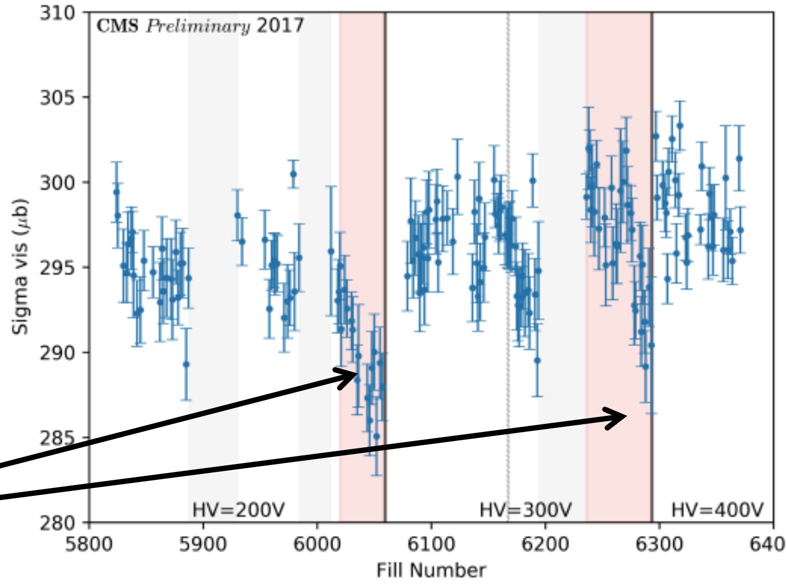
$$\Sigma_x^2 = 2\boxed{\langle \varepsilon_x \rangle}\beta_x^*$$

At zero crossing angle

- Short vdM-like scans performed at the beginning and at the end of LHC fills in standard physics conditions
  - Beams scanned in X and Y planes in 7/9 displacement steps of 10s/point
  - Lower level of precision than vdM scan due to: limited scanning range (insensitive to tails), possible non factorization biases (different bunch-production mode), beam dynamics effects (e.g. beam-beam effects)
  - useful for relative measurements
- Very powerful tool to assess linearity and stability effects:
  - Used to determine non-linearity corrections for HF, BCM1F and PLT
- Used for LHC diagnostics and for cross check of luminosity performance
  - Correct for ageing in HF
  - Correct for PLT efficiency drifts

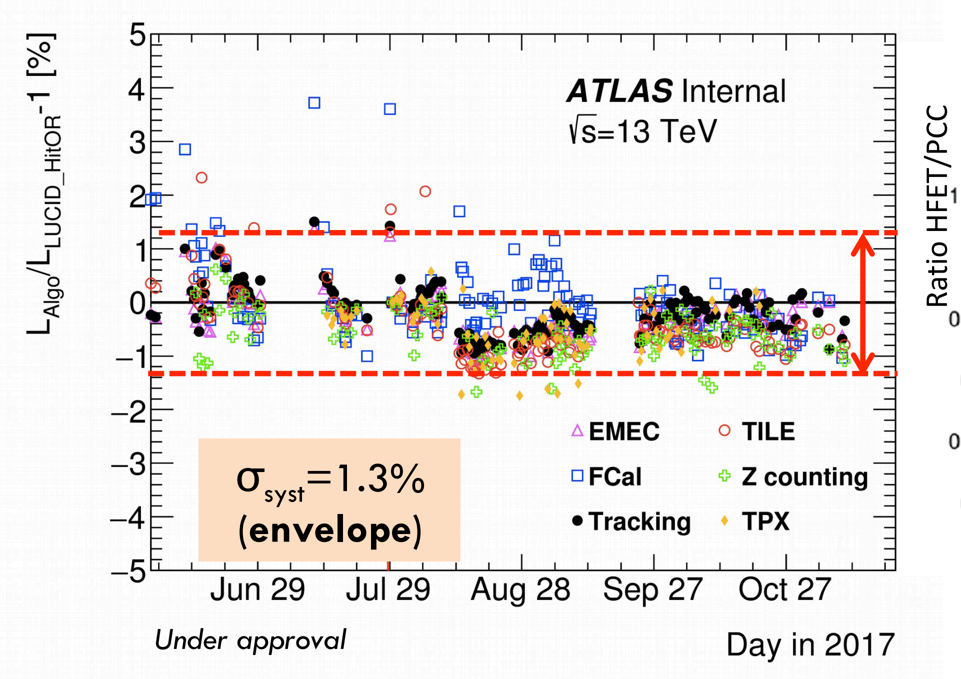


CMS-DP-2018-011

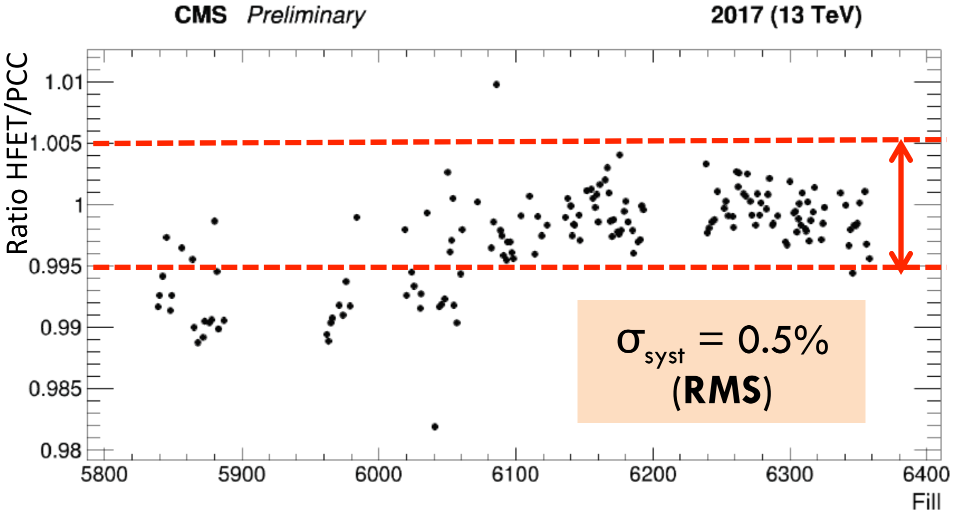


CMS-DP-2018-011

Stability during data taking



Under approval



CMS-PAS-LUM-17-004

Stability uncertainty:

- ATLAS: from comparison of all available relative-luminosity monitors over the entire data-taking period, including Z-counting (not used to asses uncertainty) ±1.3% in 2017
- CMS: RMS of HFET/PCC ratio (providing 99.4% of 2017 luminosity) ±0.5% in 2017

CAVEAT: different way to assess the stability uncertainty!

ATLAS/CMS uncertainties overview

ATLAS	Systematics: vdM calibration	CMS	Systematics:vdM calibration
Bunch-charge product	Beam current calibration	Bunch-charge product	Beam current calibration
	Ghost and satellites		Ghost and satellites
	Orbit-drift correction		Orbit-drift correction
	Beam position jitter		-
	Emittance growth correction		-
Beam conditions	Scan-to-scan reproducibility 1.2%	Beam conditions	Scan-to-scan reproducibility 0.9%
	Bunch-to-bunch consistency		Bunch-to-bunch consistency
	Fit model		-
	Non-factorization effects		Non-factorization effects 0.8%
	Beam-beam effects		Beam-beam effects 0.6%
	Cross-detector consistency		Cross-detector consistency 0.6%
	Background subtraction		-
Instrumental effects	Length scale calibration	Instrumental effects	Length scale calibration
	ID length scale 0.6%		-

Dominant

https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics

CMS-PAS-LUM-17-004

ATLAS/CMS uncertainties overview

ATLAS	Systematics: L monitoring	
Monitoring	Internal stability	1.3%
	Linearity	1.3%
	Afterglow	
	-	
	-	

https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics

Dominant

CMS	Systematics: L monitoring	
Monitoring	Internal stability	0.5%
	Linearity	1.5%
	Afterglow	
	Afterpulses	
	Dead time	0.5%

CMS-PAS-LUM-17-004

Total systematic uncertainty for 2017 (preliminary):

ATLAS: 2.4%

CMS: 2.3%

Luminosity performance summary

High luminosity i.e. Standard data taking

	ATLAS	**CMS**	**ATLAS**	**CMS**	**ATLAS**	**CMS**	**ATLAS**	**CMS**
Running period	2012 pp	2012 pp	2015 pp	2015 pp	2016 pp	2016 pp	2017 pp	2017 pp
$\sqrt{s}$ [TeV]	8	8	13	13	13	13	13	13
σ_L/L [%]	1.9	2.6	2.1	2.3	2.2	2.5	2.4 *preliminary*	2.3

Low luminosity i.e. ALFA runs for total pp cross section

Year	**c.m.s (TeV)**	**β^* (m)**	**L_Inst ($10^{30}c^{-2}s^{-1}$)**	**Tot Sys Unc. (%)**	**vdM Sys. Unc.(%)**	**Reference detector**
2011	7	90	$5*10^{-3}$	2.3	1.5	ATLAS- BCM
2012	8	90	$5*10^{-2}$	1.5	1.2	ATLAS - BCM
2012	8	1000	$0.8*10^{-3}$	1.4	1.2	ATLAS - Lucid

ATLAS Ref: https://twiki.cern.ch/twiki/bin/viewauth/Atlas/LuminosityForPhysics

CMS Ref: CMS-PAS-LUM-17-004/17-004/15-001/13-001

Conclusions

- Luminosity determination is a key parameter for all physics analyses and a challenging measurement at hadron colliders
  - accelerator issues: reproducibility of beam conditions, accounting for beam dynamics (non factorization biases, beam-beam corrections, ghosts & satellites)
  - detector issues: linearity of luminosity measurements vs pile-up and number of filled bunches, stability over different data taking conditions, ageing…

- Redundancy of luminometers crucial for cross check of performances and systematics assessment: typical total systematics around 2-2.5%!

- Z-counting for relative-luminosity monitoring: highly valuable! (validate non-linearity corrections, confirm long-term consistency estimates)

- Luminosity project at LHC great success over all Run 1 and Run 2 data taking
  ➔ precise test of Standard Model and search for new physics

- Future perspective (LHC Phase II): expected to be even harder!

Back up

Luminosity algorithms

- Event- (or zero-) counting algorithms:
  - Based on Poisson statistics: count of events with at least one hit

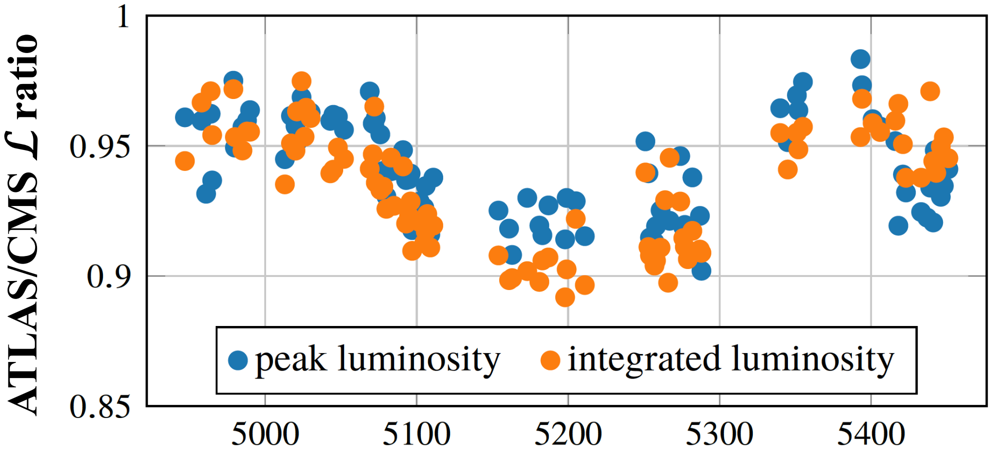
$$P_{OR} = \frac{N_{OR}}{N_{orbits}} = 1 - e^{-\mu\varepsilon_{OR}} \Rightarrow \mu = -\ln(1 - \frac{N_{OR}}{N_{orbits}})$$

  - If μ too large → "zero starvation" or "saturation"
- Hit-counting algorithms: *Now: ATLAS: # LUCID hits. CMS: # pixel clusters.*
  - Count of total hits in a given BX
  - based on Poisson statistics but saturation at higher μ
- Track- (& vertex-) counting algorithms:
  - conceptually similar to hit-counting. Examples: ATLAS.
- Particle-counting algorithms (summed over all bunches)
  - Examples in ATLAS: current in hadronic-calorimeter photomultipliers or charge measurements (LUCID).

Lumi from	Detector type	Data flow	Name	Lumi Algo
ATLAS	P-CVD diamond pads	Bunch-by-bunch (bbb)	BCM	Event counting
	Quartz Cherenkov tubes	bbb	LUCID	Event counting Hit counting
	Si strip + pixel tracker: #vertices	bbb	“Vtx”	Vtx counting
	Si strip + pixel tracker: #tracks	bbb	“Trks”	Trks counting
	Fwd LAr / E.M. EndCap calo: gap currents	Bunch-averaged (ba)	FCal	Particle flux
	TILE calorimeter	ba	TILE	Particle flux
	Pixelated radiation monitor	ba	TPX	Hit counting
CMS	Pixel trk: #clusters	bbb	PCC	Hit counting
	Fwd Fe/quartz calo	bbb	HFET	E_T flow (analog)
	Fwd Fe/quartz calo.	bbb	HFOC	Hit counting
	Pixel telescope	bbb	PLT	Hit counting
	Fast Beam Conditions Monitor	bbb	BCM1f	Trk segment counting
	Muon drift tube	ba	DT	Rate counting

ATLAS/CMS luminosity ratio

☐ Significant (~ 10%) ATLAS-CMS L difference across 2016



- ❖ Largest contribution: emittance$_x$ > emittance$_y$, coupled with horizontal (x) crossing in CMS vs. vertical (y) crossing in ATLAS
- ❖ Analysis complicated by residual μ- or time-dependence of reported L, that could be different in the two experiments
    - ➢ most trusted offline algorithms: track-cntg (ATLAS), pixel-cluster cntg (CMS)
    - → dedicated experiment: crossing-angle scan

Vdm Scan calibration: difficulties

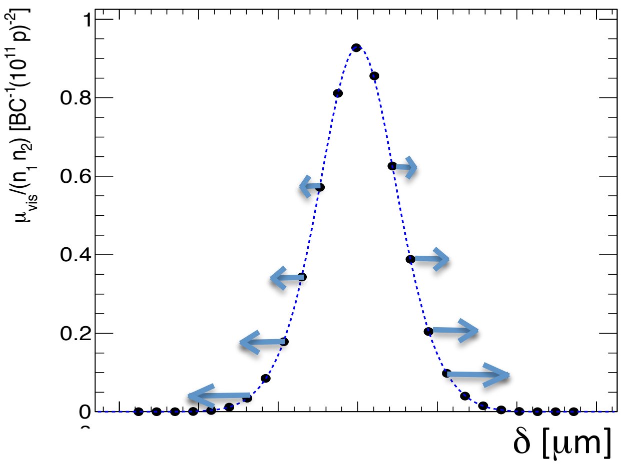
Central role of beam dynamics -> two beam-beam effects:

1) beam-beam deflection: if bunches not exactly centred ➔ angular kick due to e.m repulsion;
2) dynamic β : mutual (de)focusing of the two colliding bunches;

Effect: < 0.5% PbPb, 1 - 2% for 7/8/13 TeV pp and around 4% for 5 TeV pp.

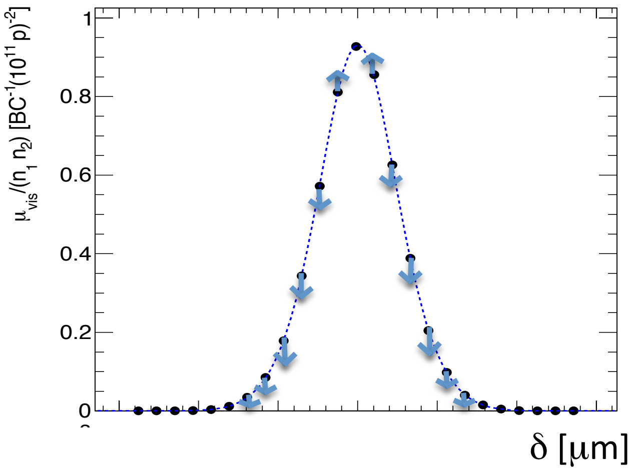
Scan curve distorted by interactions of the two beams during a scan.

Beam-beam deflection



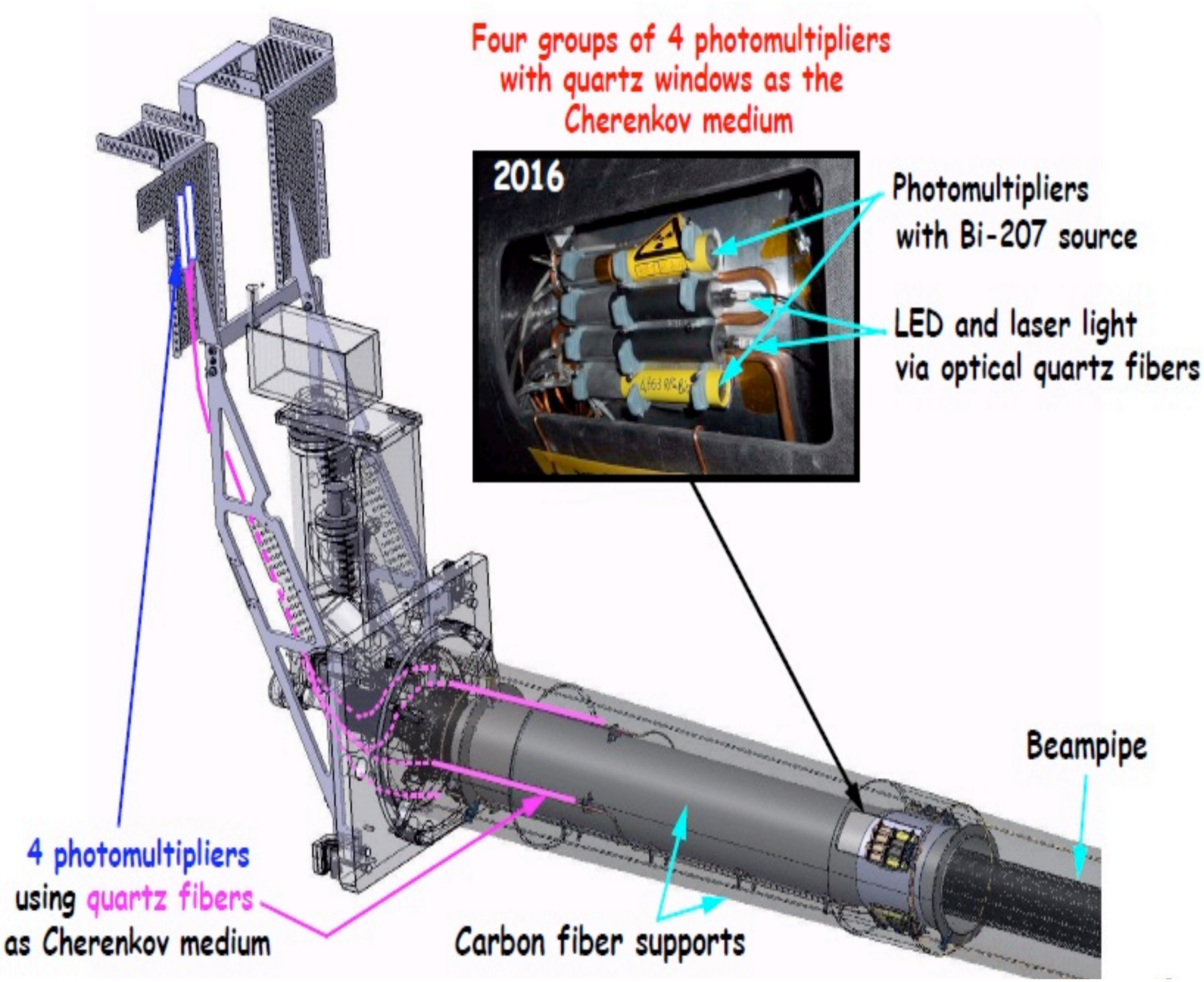
beam separation larger than nominal separation

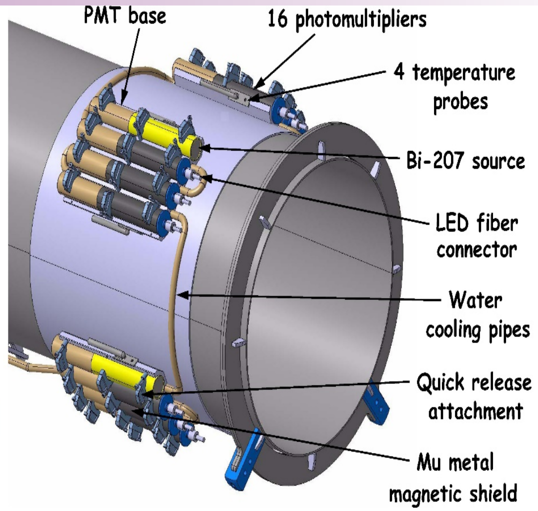
Dynamic-β



Beams focus/defocus each other by an amount that is a function of separation

ATLAS reference luminometer: LUCID-2





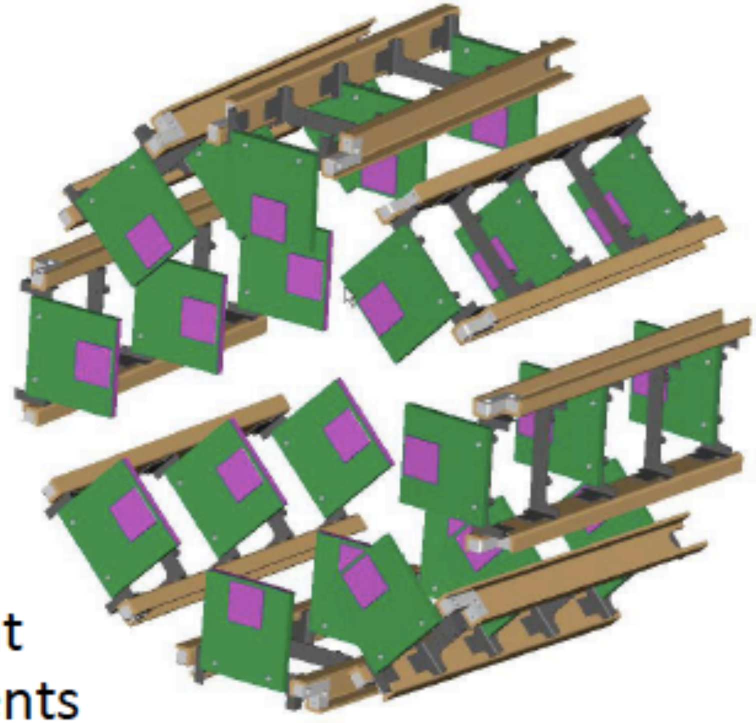
17 meters from IP – 13 cm from beam-line

ATLAS Luminosity performance summary

Year	c.m. energy (TeV)	Mu max	L_max (10^{33} $cm^{-2}s^{-1}$)	L_int (fb^{-1})	NBCID	Dt (ns)	Tot Sys Unc. (%)	vdM Sys. Unc. (%)	Reference Detector (online & offline)
2010	7	5	0.2	0.047	348	150	3.5	3.4	LUCID-I
2011	7	20	3.6	5.5	1331	50	1.8	1.5	BCM
2012	8	40	7.7	22.7	1368	50	1.9	1.2	BCM
2015	13	28	5	4.2	2232	25	2.1	1.7	LUCID-2
2016	13	45	14	38.5	2208	25	2.2	1.2	LUCID-2
2017	13	80	20	40	2544	25	2.4	ongoing	LUCID-2

Year	c.m. energy (TeV)	β * (m)	L_Inst ($10^{30}c^{-2}s^{-1}$)	L_Int (μ b^{-1})	Tot Sys Unc. (%)	vdM Sys. Unc.(%)	Reference detector
2011	7	90	$5*10^{-3}$	80	2.3	1.5	BCM
2012	8	90	$5*10^{-2}$	500	1.5	1.2	BCM
2012	8	1000	$0.8*10^{-3}$	22	1.4	1.2	LUCID

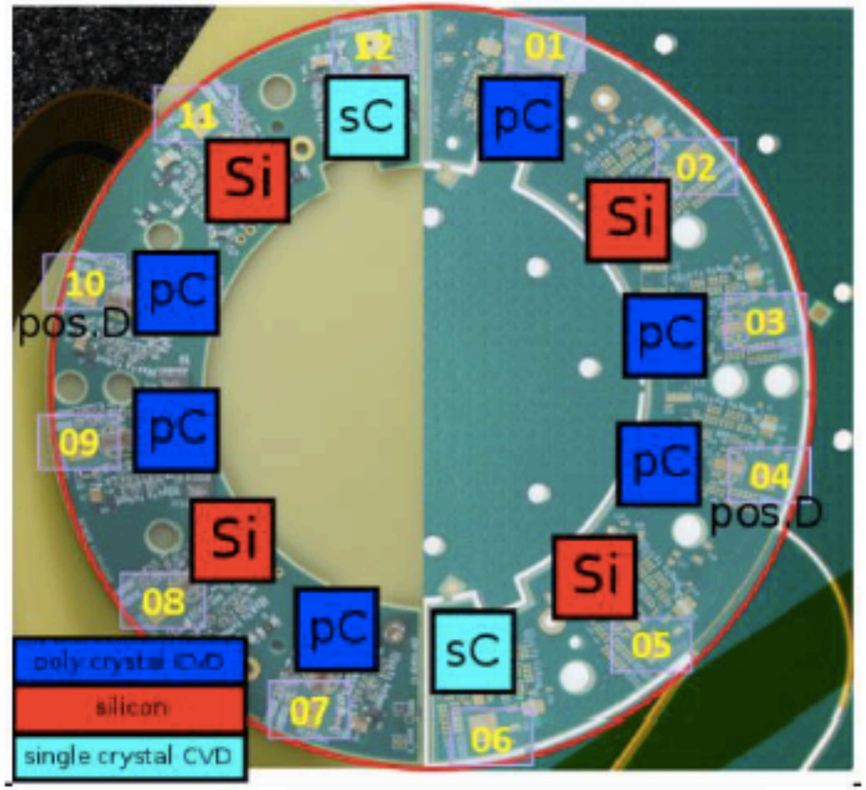
CMS: PLT



- Uses same pixel sensors and readout chips as phase-0 pixel detector
- 48 silicon sensor planes arranged in 16 “telescopes” (8 on either side of CMS) outside the pixel endcap ($|\eta|\sim 4.2$)
- Use special “fast-or” readout mode of chip to look for events where all three planes in a telescope register a hit (“threefold coincidence”) to measure luminosity
- Provide online bunch-by-bunch measurements to LHC and CMS with a statistical precision of 1% every 1.5s to allow for fast feedback (e.g., for beam optimizations)

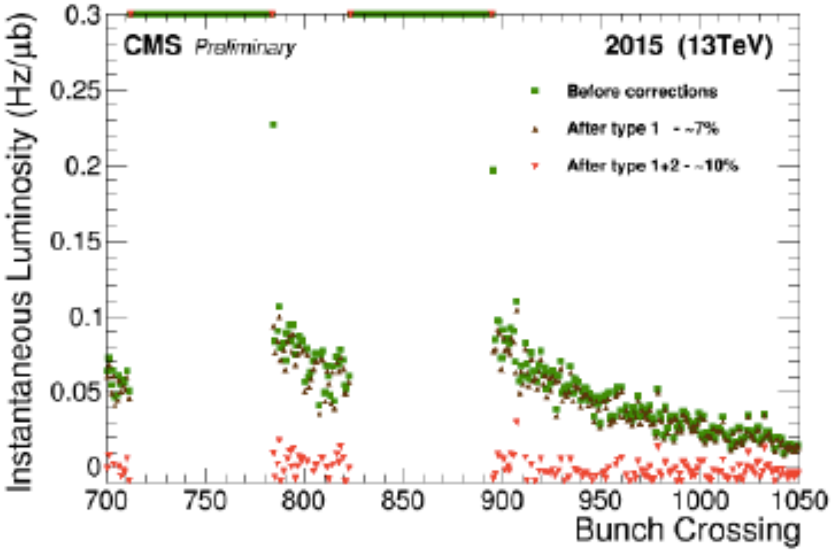
CMS: BCM1F

- 24 sensors located on face of PLT/BCM1F carriage with fast readout (6.25 ns) to distinguish luminosity from machine background
- 2015-2016 all sensors were diamond, but severe problems with efficiency loss in 2016
- EYETS 16/17 In EYETS sensors were replaced and upgraded to a mix of polycrystalline diamond, single crystal diamond, and silicon



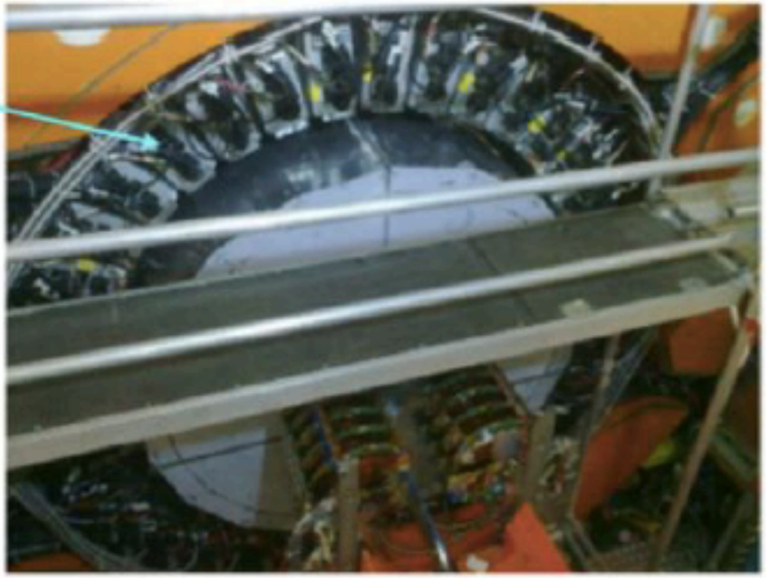
CMS: PCC

- Pixel cluster counting uses the raw rates of pixel clusters in the main CMS pixel detector
    - Primary offline measurement in 2015 and 2016 (Phase 0 pixel detector)
    - Limited by CMS DAQ and trigger for online practicality
- Two major corrections necessary:
    - “Type 1” affect the next BX after a colliding BX for signal spillover
    - “Type 2” affect several BXes after for material activation



CMS-PAS-LUM-15-001

CMS: HF



36 PMT boxes each end

- Uses existing HF calorimeter with dedicated readout for luminosity information
- Two algorithms used:
  - HFOC: uses raw occupancy rate in HF (fraction of towers with hit energy above noise threshold). Standard in 2015-16 but some nonlinearities at higher pileup.
  - HFET: uses sum of E_T deposited in all HF towers. Commissioned during 2016 and is now the primary algorithm for 2017-2018 running.

CMS: summary of 2017 uncertainties

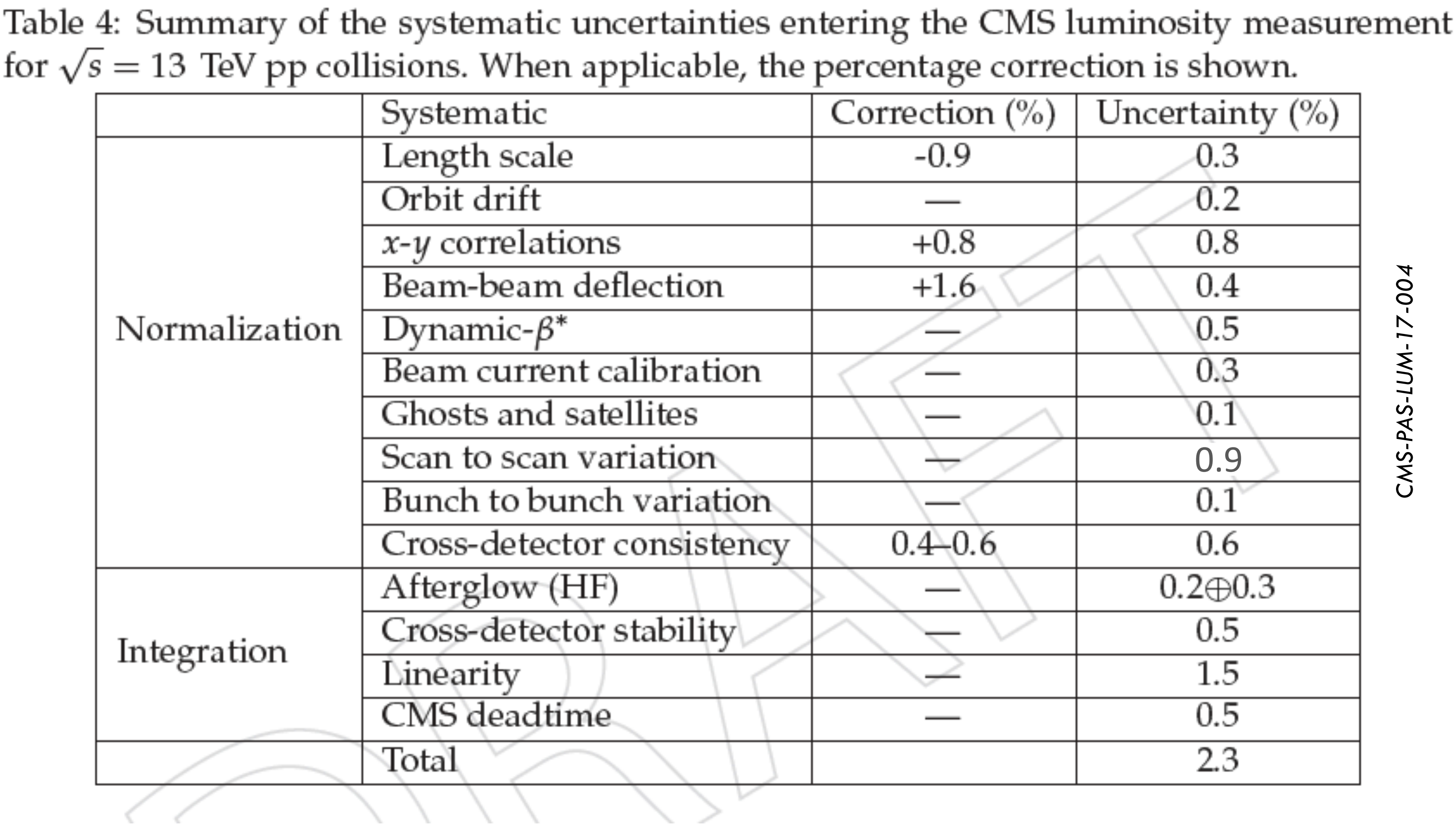
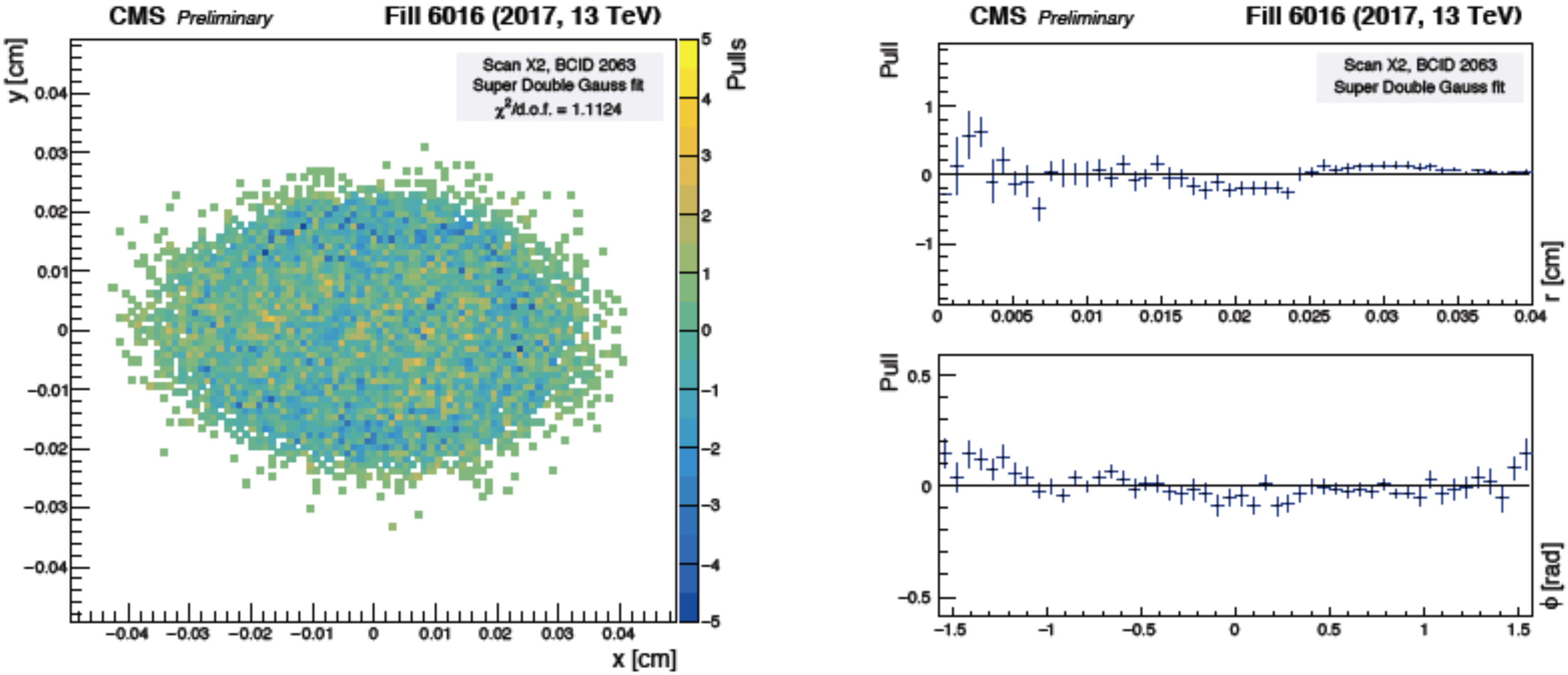


Table 4: Summary of the systematic uncertainties entering the CMS luminosity measurement for $\sqrt{s} = 13$ TeV pp collisions. When applicable, the percentage correction is shown.

	Systematic	Correction (%)	Uncertainty (%)
Normalization	Length scale	-0.9	0.3
	Orbit drift	—	0.2
	x-y correlations	+0.8	0.8
	Beam-beam deflection	+1.6	0.4
	Dynamic-β^*	—	0.5
	Beam current calibration	—	0.3
	Ghosts and satellites	—	0.1
	Scan to scan variation	—	0.9
	Bunch to bunch variation	—	0.1
	Cross-detector consistency	0.4–0.6	0.6
Integration	Afterglow (HF)	—	$0.2 \oplus 0.3$
	Cross-detector stability	—	0.5
	Linearity	—	1.5
	CMS deadtime	—	0.5
	Total		2.3

CMS-PAS-LUM-17-004

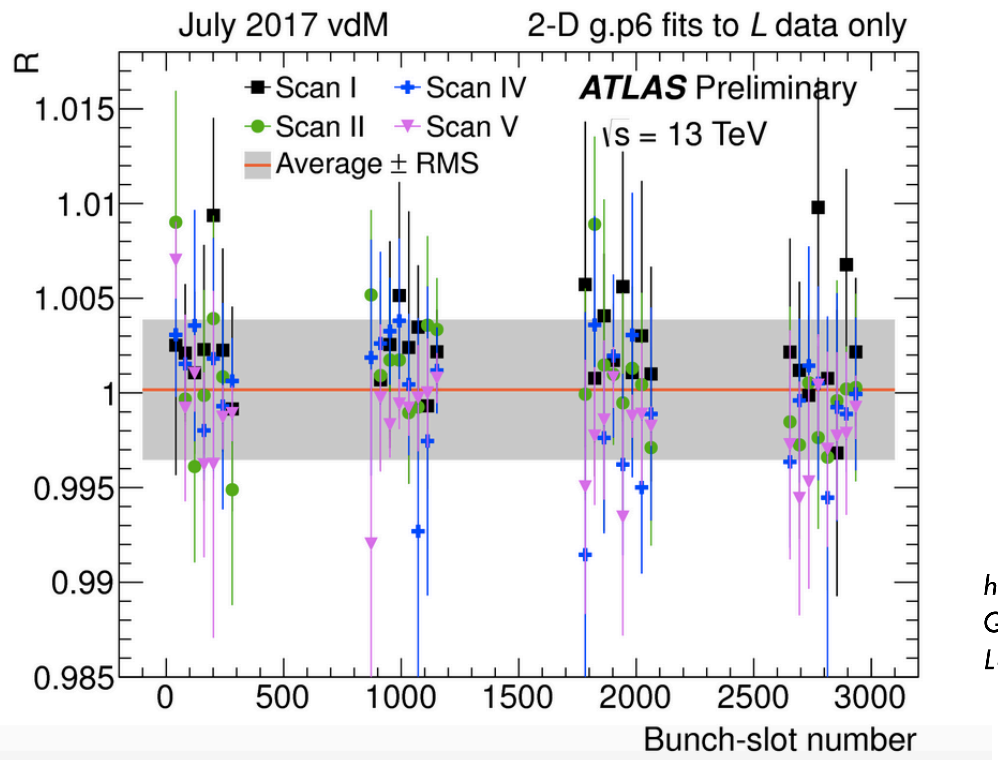
CMS: Non factorization evidence



CMS-PAS-LUM-17-004

Figure 6: Pull distributions using the Super Double Gaussian fit model. The pull is defined as the difference between the number of measured vertices and the number of vertices predicted by the fit, divided by the statistical uncertainty of the measurement. These plots show the results from the scan constraining beam 1 in x. Left: 2-D pull distribution as a function of x and y position. Right: 1-D projections of the 2-D pull distribution, in slices of constant radius (top) and constant azimuthal angle (bottom).

ATLAS: Non factorization evidence

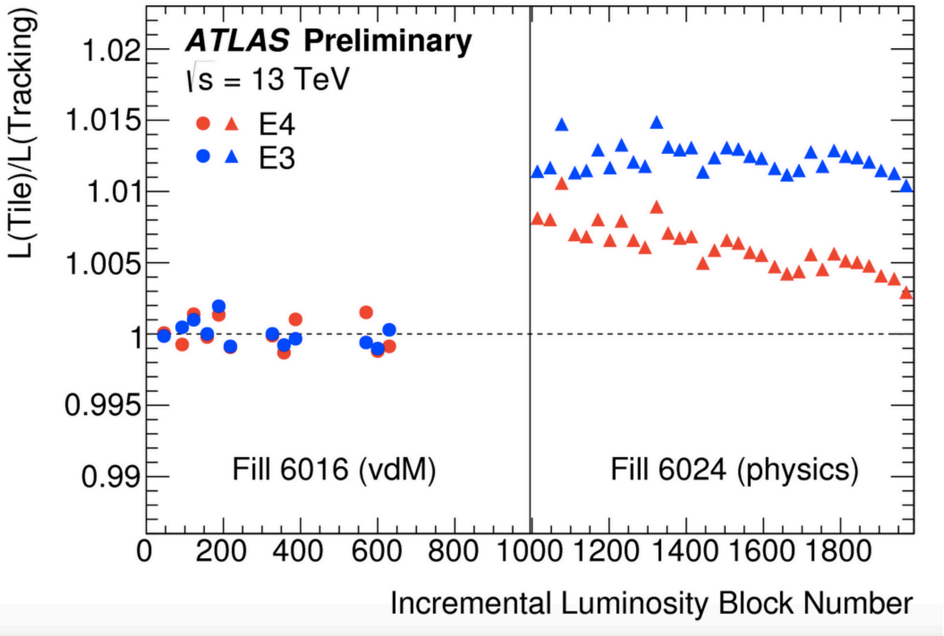


http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/

Figure 3a:

Non-factorization correction factor R ($\sigma_{vis}^{corr}=\sigma_{vis}/R$) for several colliding-bunch pairs and scan sets (I-V), extracted from fits to the beam-separation dependence, during van der Meer (vdM) scans, of only the luminosity L. The beam-separation dependence of the luminosity is modeled by a two-dimensional (2-D) Gaussian function multiplied by a sixth-order polynomial (g.p6). The error bars are statistical only. The horizontal red lines represent the weighted average over all colliding-bunch pairs and scan sets, with the shaded bands indicating the RMS spread of the individual R values associated with each colliding-bunch pair.

ATLAS: Calibration transfer



http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/LUMI-2017-001/

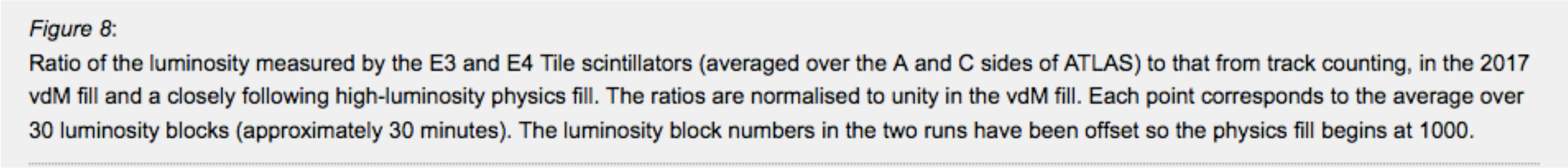
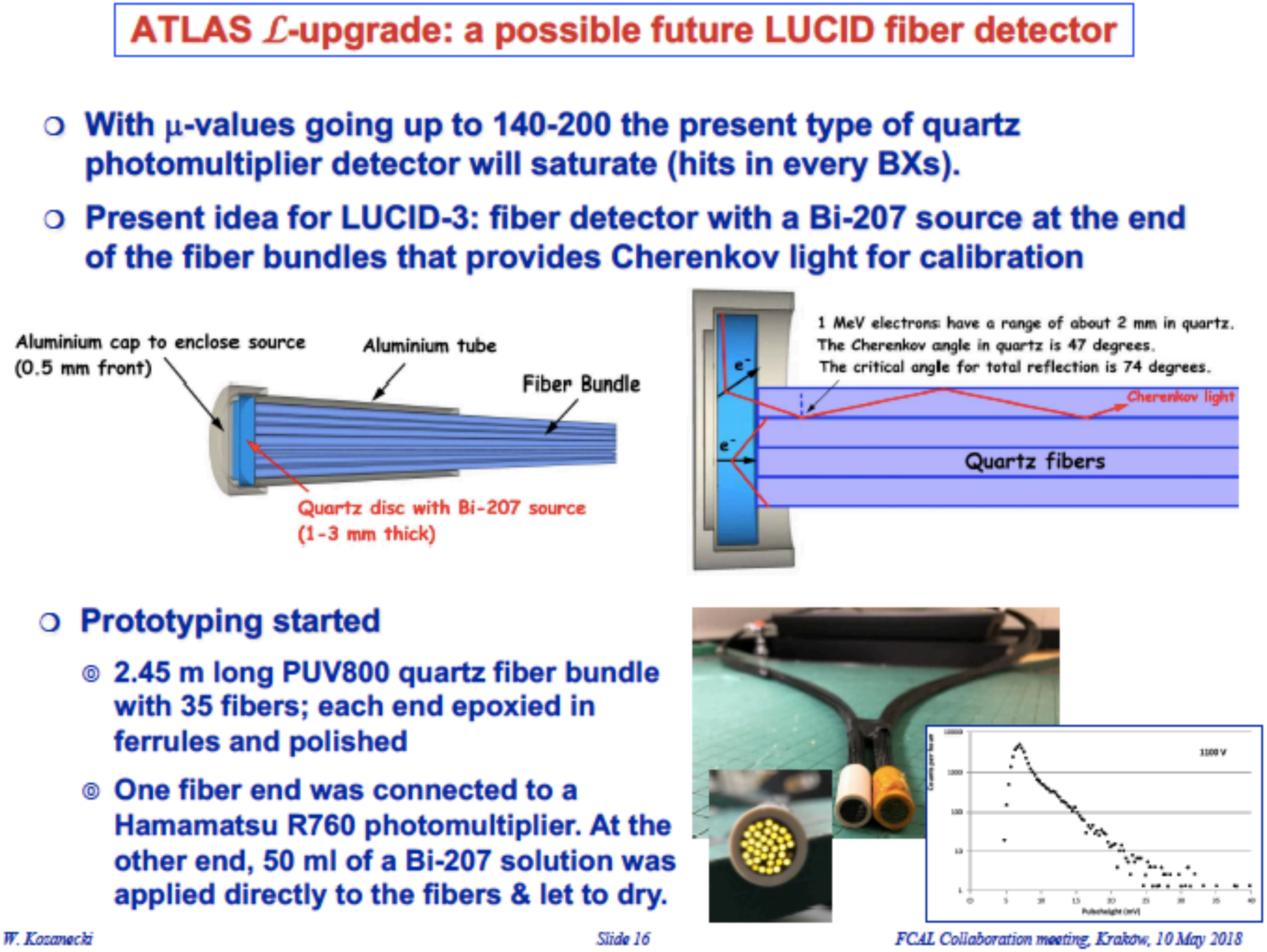


Figure 8:

Ratio of the luminosity measured by the E3 and E4 Tile scintillators (averaged over the A and C sides of ATLAS) to that from track counting, in the 2017 vdM fill and a closely following high-luminosity physics fill. The ratios are normalised to unity in the vdM fill. Each point corresponds to the average over 30 luminosity blocks (approximately 30 minutes). The luminosity block numbers in the two runs have been offset so the physics fill begins at 1000.

HL-LHC: ATLAS



ATLAS $\mathcal{L}$-upgrade: a possible future LUCID fiber detector

- With μ-values going up to 140-200 the present type of quartz photomultiplier detector will saturate (hits in every BXs).
- Present idea for LUCID-3: fiber detector with a Bi-207 source at the end of the fiber bundles that provides Cherenkov light for calibration

1 MeV electrons have a range of about 2 mm in quartz.
The Cherenkov angle in quartz is 47 degrees.
The critical angle for total reflection is 74 degrees.

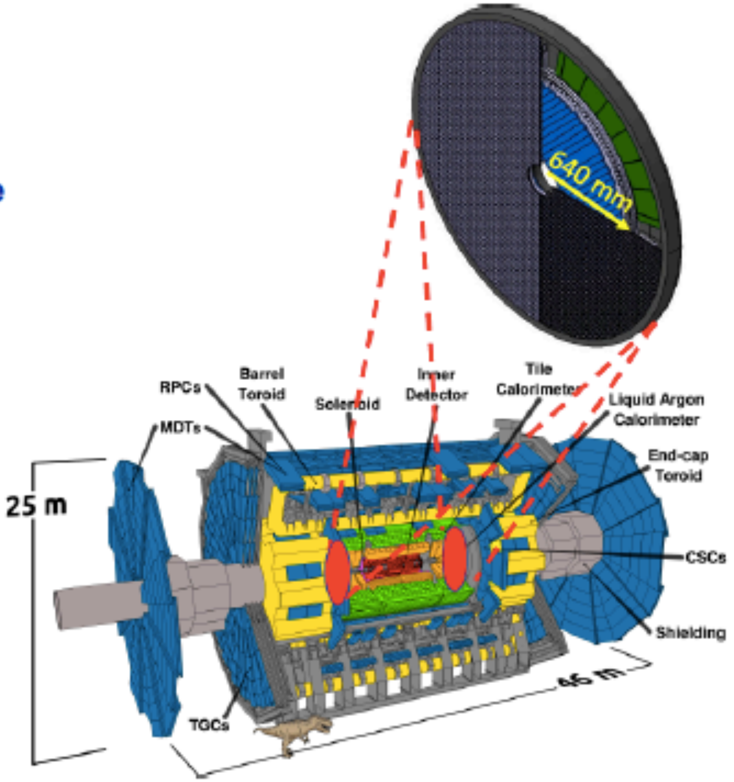
- Prototyping started
  - 2.45 m long PUV800 quartz fiber bundle with 35 fibers; each end epoxied in ferrules and polished
  - One fiber end was connected to a Hamamatsu R760 photomultiplier. At the other end, 50 ml of a Bi-207 solution was applied directly to the fibers & let to dry.

W. Kozanecki *Slide 16* *FCAL Collaboration meeting, Kraków, 10 May 2018*

HL-LHC: ATLAS

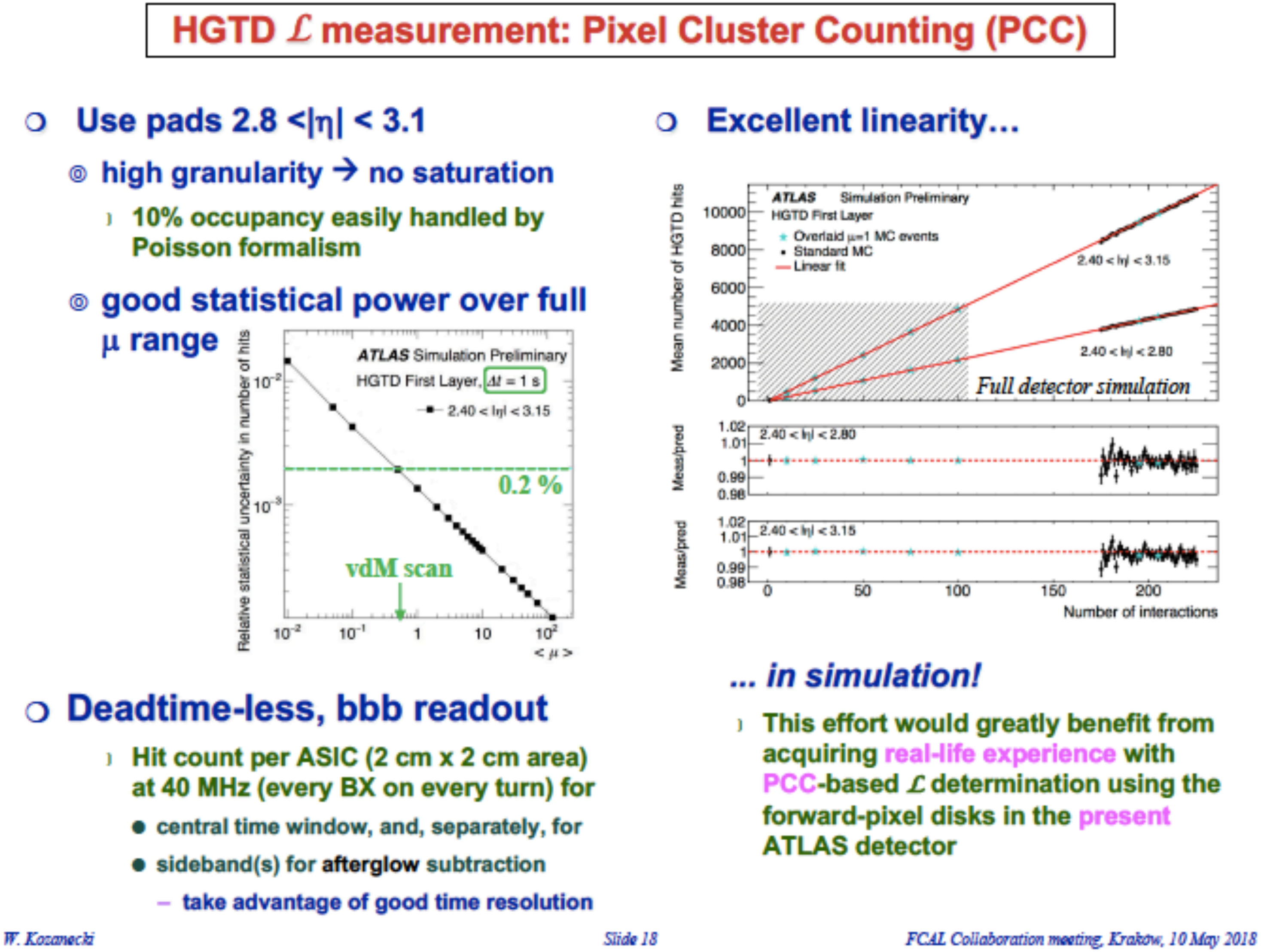
ATLAS $\mathcal{L}$-upgrade: (one of the applications of) the HGTD [High-Granularity Timing Detector]

- **Original (& primary) motivation**
  - High vertex density & degraded z_0-resolution at high η → ambiguous track-to-vertex association
  - Spatially overlapping vertices can be resolved in the time dimension using accurate vertex timing measurements
- **HGTD in a nushell**
  - two endcap disks at $z = \pm 3.5$ m
  - Active area: $120 \text{ mm} < R < 640 \text{ mm}$ $\Rightarrow 2.4 < |\eta| < 4.0$
  - Si-based Low-Gain Avalanche Detector (LGAD) technology $\Rightarrow \sigma_t = 30$ ps/track over the lifetime of HL-LHC
  - 2 Si layers per disk
  - RQ < 10% occupancy @ $\mu = 200$ $\Rightarrow$ 1.3 mm x 1.3 mm pixels



W. Kozanecki *Slide 17* *FCAL Collaboration meeting, Kraków, 10 May 2018*

HL-LHC: ATLAS from CMS experience



HGTD $\mathcal{L}$ measurement: Pixel Cluster Counting (PCC)

- **Use pads $2.8 < |\eta| < 3.1$**
  - **high granularity → no saturation**
    - **10% occupancy easily handled by Poisson formalism**
  - **good statistical power over full μ range**
- **Deadtime-less, bbb readout**
  - **Hit count per ASIC (2 cm x 2 cm area) at 40 MHz (every BX on every turn) for**
    - **central time window, and, separately, for**
    - **sideband(s) for afterglow subtraction**
      - **take advantage of good time resolution**
- **Excellent linearity…**

… in simulation!

- **This effort would greatly benefit from acquiring real-life experience with PCC-based $\mathcal{L}$ determination using the forward-pixel disks in the present ATLAS detector**

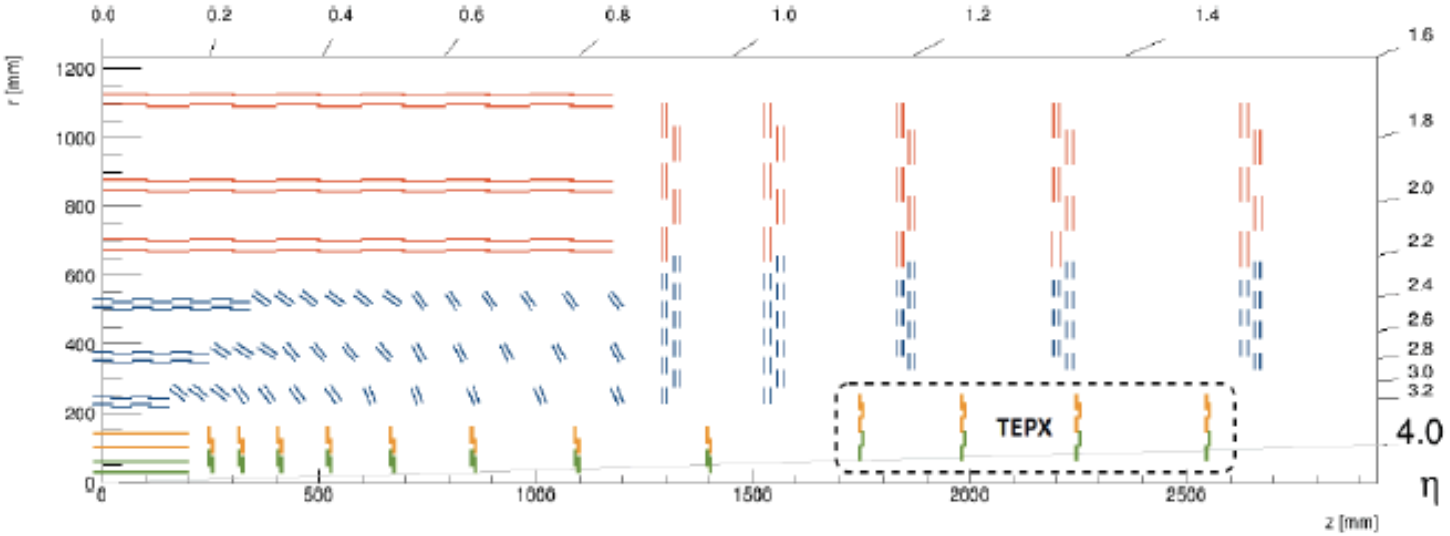
W. Kozanecki *Slide 18* *FCAL Collaboration meeting, Kraków, 10 May 2018*

CMS: special read out of Inner Tracker

HL-LHC: CMS

Inner Tracker Endcap

- The larger tracker for HL-LHC will take up the space currently occupied by PLT & BCM1F
- However the endcap disks (TEPX) are in a perfect position to do a similar luminosity measurement

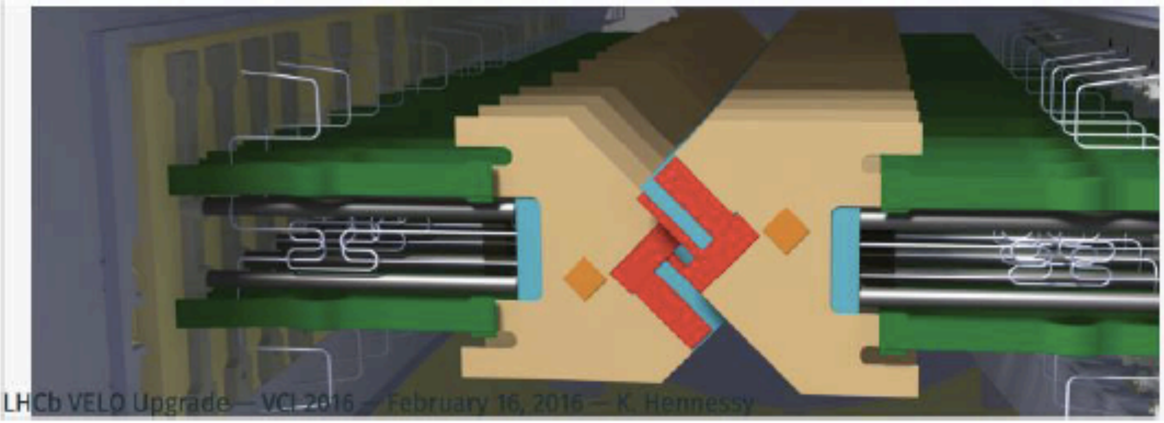


https://indico.cern.ch/event/697164/contributions/2987411/attachments/1647549/2633730/CMSLuminosity-FCALWorkshop.pdf

HL-LHC: CMS

Standalone Lumi Detector

- It is also desirable to have a completely independent lumi system
- Promising approach using VeloPix: very radiation-hard pixel chip being developed for LHCb VELO upgrade
- Could squeeze a single layer in the space outside the tracker



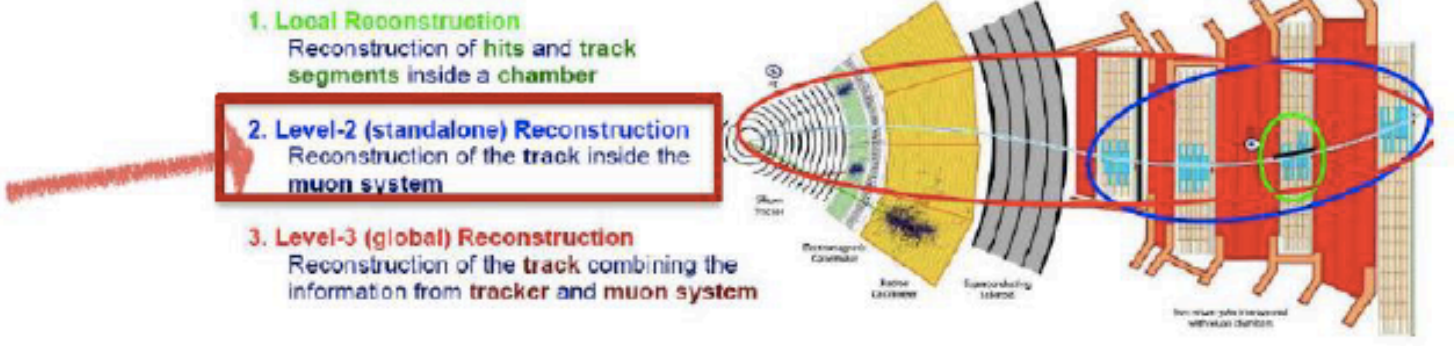
LHCb VELO Upgrade — VCI 2016 — February 16, 2016 — K. Hennessy

HL-LHC: CMS

DT Lumi

- As currently, it looks like the most advantageous approach to using the muon chambers is to take advantage of tracks reconstructed at trigger level
- Should be possible in principle to make bunch-by-bunch measurements available (may even be possible, at least as a prototype, in Run3 after LS2)
- Overall occupancy should remain quite low even at HL-LHC levels

HLT TRACK RECONSTRUCTION

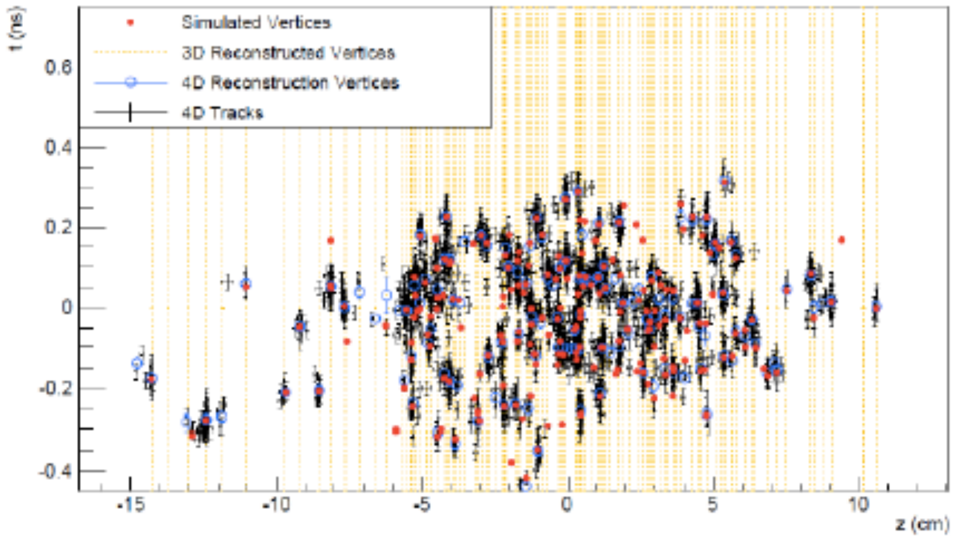


1. Local Reconstruction
   Reconstruction of hits and track segments inside a chamber
2. Level-2 (standalone) Reconstruction
   Reconstruction of the track inside the muon system
3. Level-3 (global) Reconstruction
   Reconstruction of the track combining the information from tracker and muon system

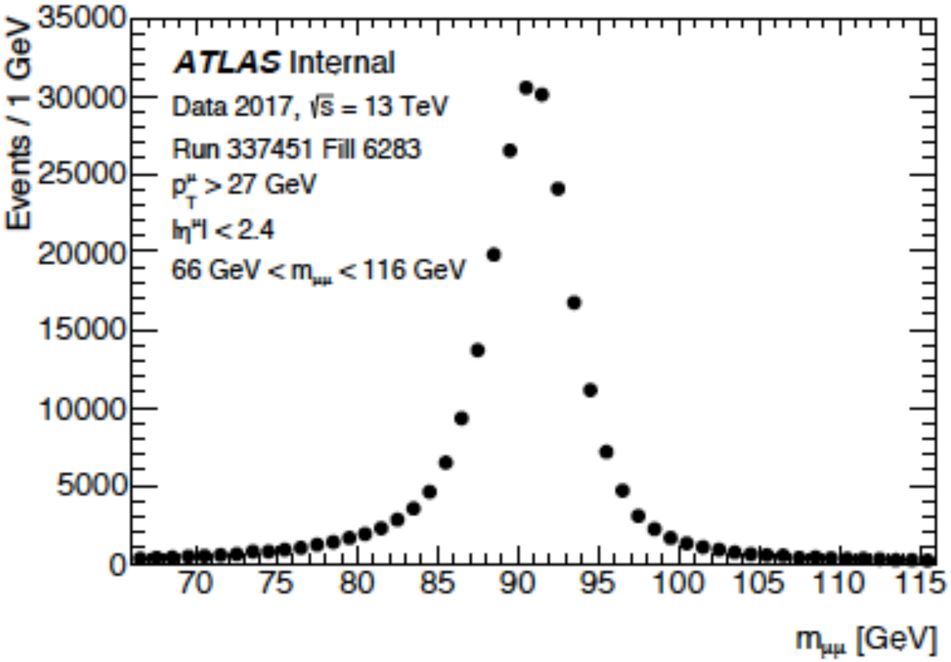
HL-LHC: CMS

Lumi with Timing Detectors

- Timing layer outside tracker to provide high-precision time measurements to improve PF reconstruction
- High time resolution (30-50ps) makes this promising as a luminosity measurement also
- Still just an idea at this point…will need much more development



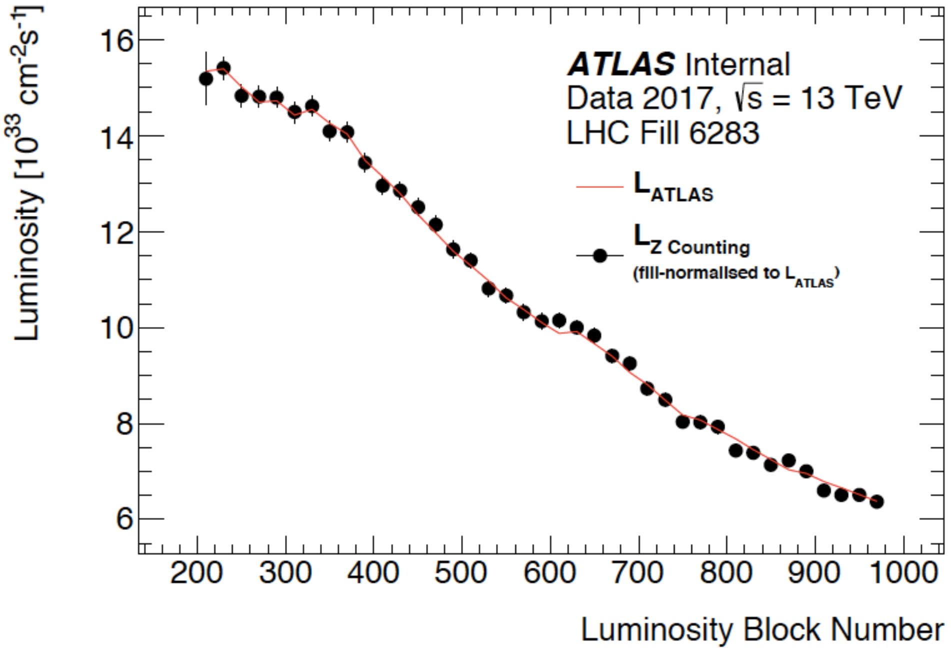
ATLAS Z-counting



ATL-COM-DAPR-2018-011

The invariant mass distribution of the muon pairs of the 240,000 Z ->mumu boson events selecting two muons with pT> 27 GeV, pseudorapidity < 2.4 and 66 < m(mumu) < 116 GeV. The statistical errors are smaller than the symbol size.

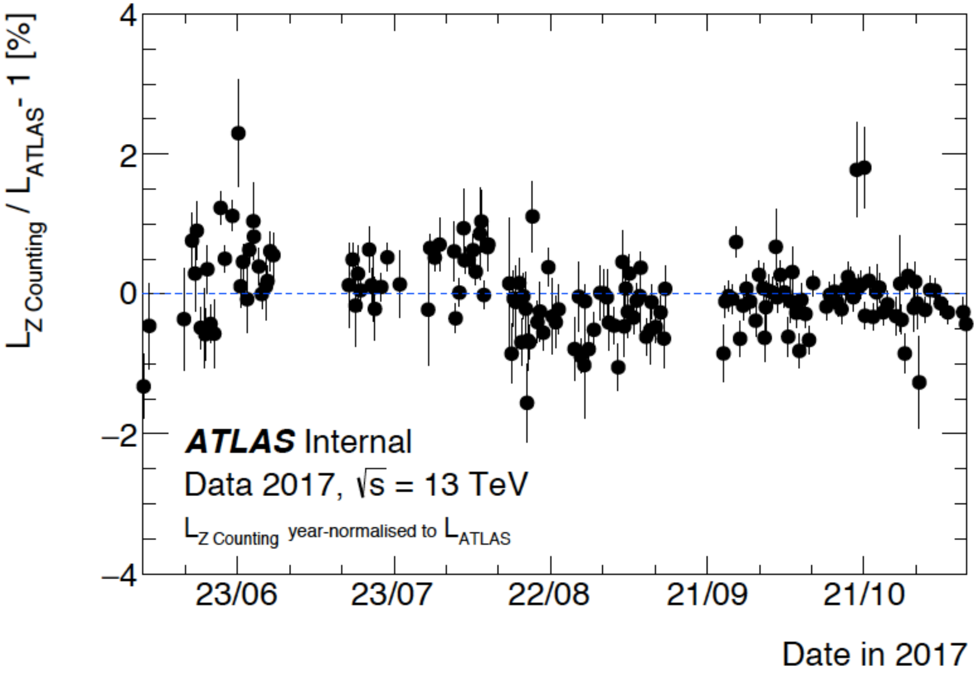
ATLAS Z-counting



ATL-COM-DAPR-2018-011

Figure 2: *Top:* The instantaneous luminosity determined from the $Z \rightarrow \mu\mu$ counting rate, $\mathsf{L}_{\mathsf{Z\,Counting}}$ (full circles), selecting two muons with $p_T^{\mu} > 27$ GeV, $|\eta^{\mu}| < 2.4$ and $66 < m_{\mu\mu} < 116$ GeV, and the ATLAS-preferred luminosity measurement $\mathsf{L}_{\mathsf{ATLAS}}$ (red line) based on the LUCID online luminometer, both averaged over 20 Luminosity Blocks (LB). The LHC fill 6283 was taken at $\sqrt{s} = 13$ TeV on October 8, 2017. The Z counting rate is corrected for in situ data-driven trigger and reconstruction efficiencies including the residual Monte Carlo correction, and is normalised to the integrated ATLAS luminosity for this fill. The x-axis represents the elapsed time in units of Luminosity Blocks with a typical length of one minute per LB. Error bars are the statistical uncertainties of the $\mathsf{L}_{\mathsf{Z\,Counting}}$ determination.

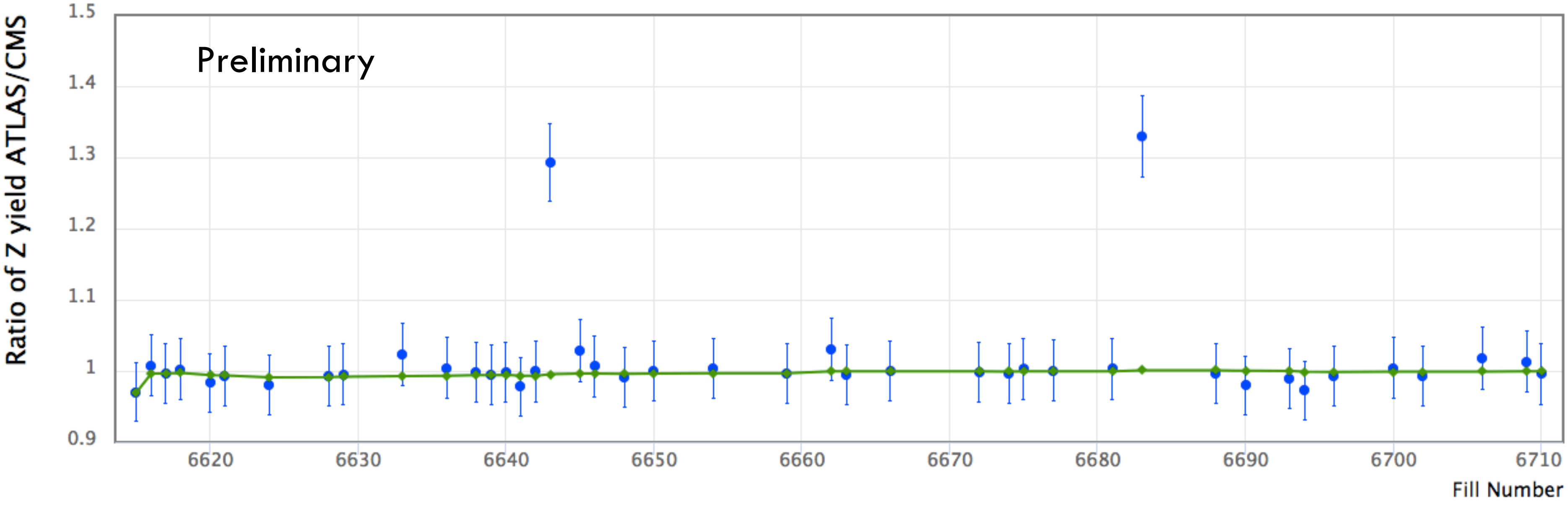
ATLAS Z-counting



ATL-COM-DAPR-2018-011

Figure 3: Fractional difference between the run-integrated luminosity determined from the $Z \to \mu\mu$ counting rate, $\mathsf{L}_{\mathsf{Z\,Counting}}$, selecting two muons with $p_T^{\mu} > 27$ GeV, $|\eta^{\mu}| < 2.4$ and $66 < m_{\mu\mu} < 116$ GeV, and the run-integrated, ATLAS-preferred luminosity measurement $\mathsf{L}_{\mathsf{ATLAS}}$ (based on the LUCID online luminometer) per LHC fill taken at $\sqrt{s} = 13$ TeV in 2017. The Z counting rate is corrected for in situ data-driven trigger and reconstruction efficiencies including the residual Monte Carlo correction, and is normalised to the integrated ATLAS luminosity of the whole 2017 data taking period. The x-axis represents the date when the fill was recorded; only runs with at least 10,000 Z counts and a minimum length of about 40 min are included. Error bars reflect the statistical uncertainties of the $\mathsf{L}_{\mathsf{Z\,Counting}}$ measurements only. The dashed line indicates zero.

ATLAS/CMS Z-counting ratio



https://lpc.web.cern.ch/cgi-bin/plots.py

Non-factorisation correction procedure

$$\mathscr{L}\left(\delta_x,\delta_y\right) = f_x\left(\delta_x\right) f_y\left(\delta_y\right) \text{ ?}$$

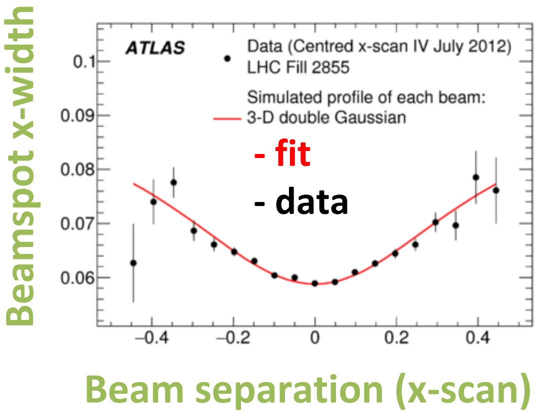
- Single beam profiles are parameterised by fitting the beam-separation dependence of the luminosity & of the beamspot displacement and width during a vdM scan.

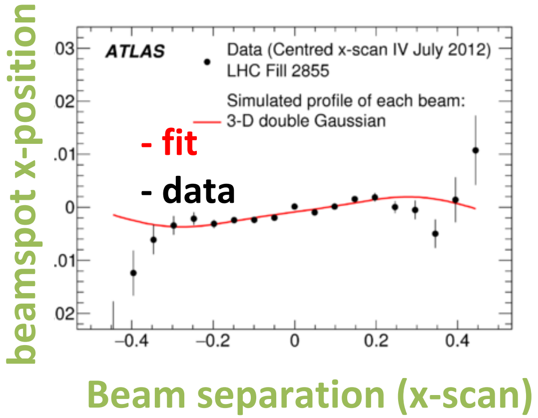
  This allows to:

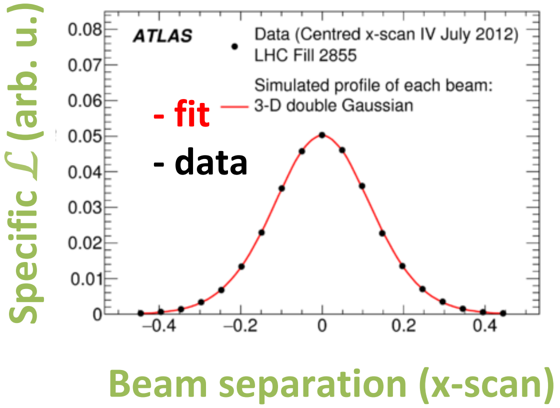
  ➜ estimate the true luminosity (i.e. unbiased by non-factorisation effects)

  ➜ estimate correction for non-factorisation, ***R***, with an associated uncertainty

$$\boldsymbol{R} = \frac{\mathscr{L}\ \text{not assuming factorisation}}{\mathscr{L}\ \text{assuming factorisation}}$$







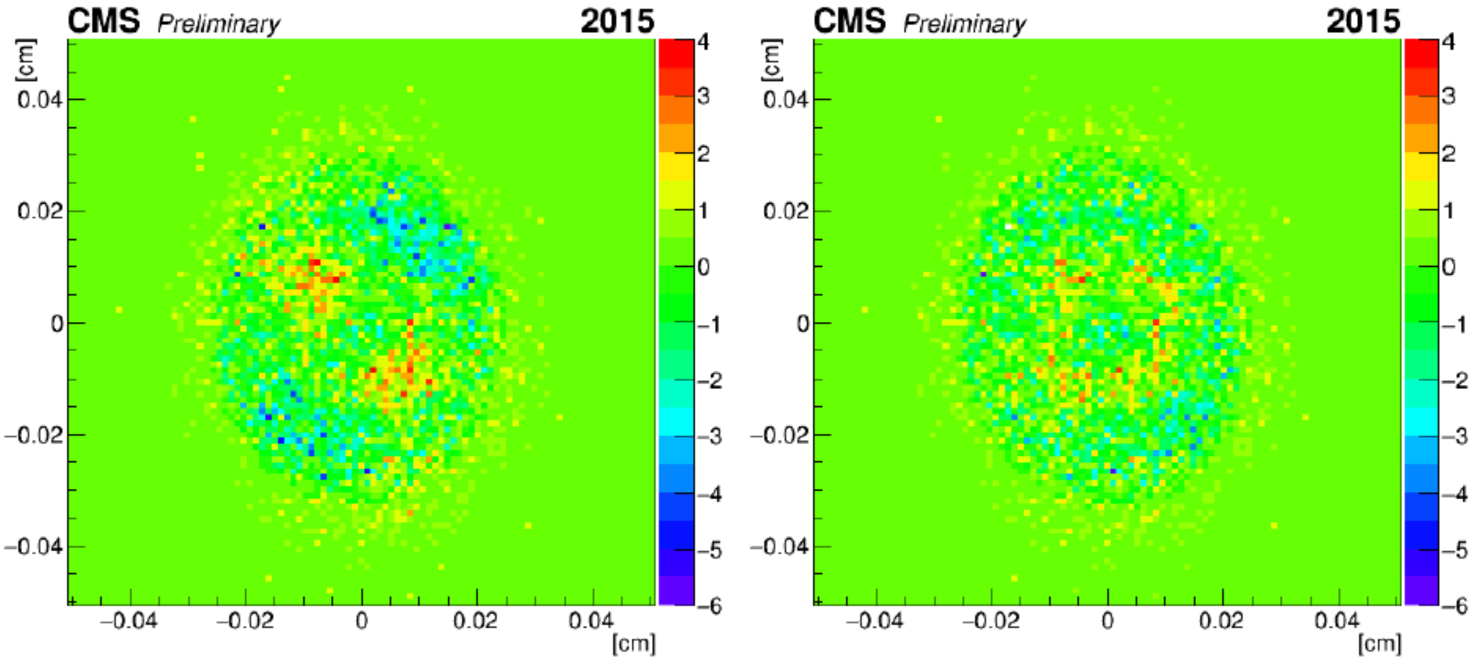
- The [ATLAS/ALICE] procedure above is closely related to the "beam-beam imaging" scans [pioneered by LHCb & now established method in CMS] in which one beam is scanned transversely as a probe across the other.

Non-factorization correction: beam-beam imaging

- Principle: use one beam (~ wire) to probe the other
  - keep witness beam (B1) stationary; scan probe beam (B2) across it in x, then in y; repeat with B1 ←→ B2
    - measure 2-d distribution of reco'd evt vertices at each step: $N_{vtx}(x, y) = \{r_{witness}(x,y) \times r_{probe}(x,y)\} \ (X) \ R_{vtx\ position}(x,y)$ (see ArXiv_1603.0356 [hep-ex])
  - extract single-beam parameters of B1 & B2 from fit to 2-d vertex distributions in the 4 scans (B1/ B2, x/y)
  - closely related to the ATLAS & ALICE luminous-region evolution method (but uses only transverse info, not L/z)
    - common key issue: vertex-position resolution $R_{vtx\ position}$
    - pros & cons of the 2 approaches to be clarified

Non-factorization correction: beam-beam imaging

Pull distribution to cumulative event-vertex distributions for 2 single-beam models:



factorizable

non-factorizable

Example of pull distributions of the fitted single-beam model of the single-gaussian (factorizable, left) and double-gaussian (non-factorizable, right) type to the vertex distribution accumulated during scan Y3 of bunch pair1631.
(Caption adapted from Fig. 11 of CMS-PAS-LUM-2015-001)