Luminosity determination in pp collisions using the ATLAS detector at the LHC

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March 23, 2017

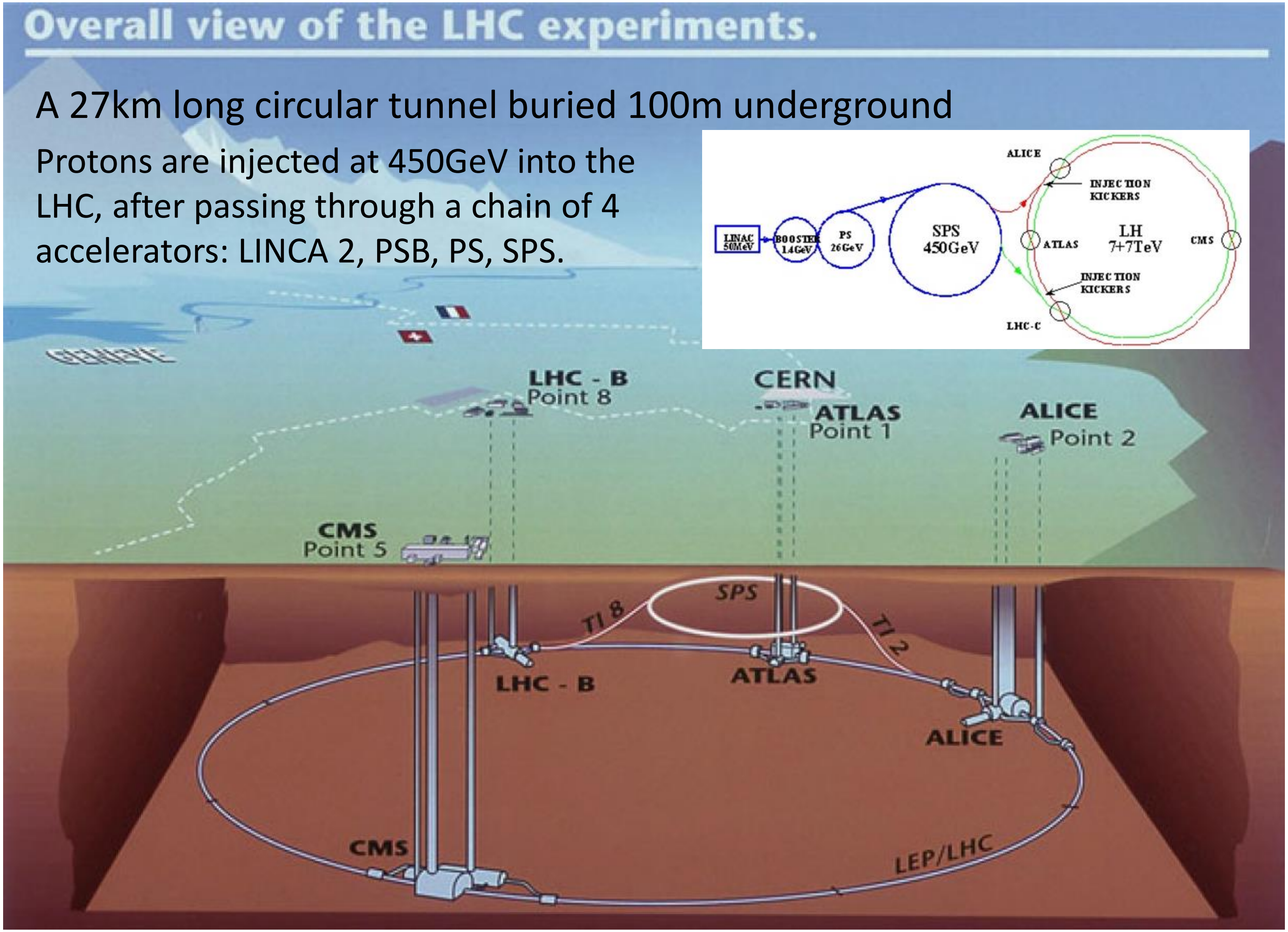
OutLine

- **ATLAS experiment at LHC**
  - The past, present and future of the ATLAS experiment
- **Luminosity measurement**
  - Bunch-by-bunch luminometers
  - Bunch-integrating luminometers
  - Luminosity uncertainty
- **Summary**

Overall view of the LHC experiments

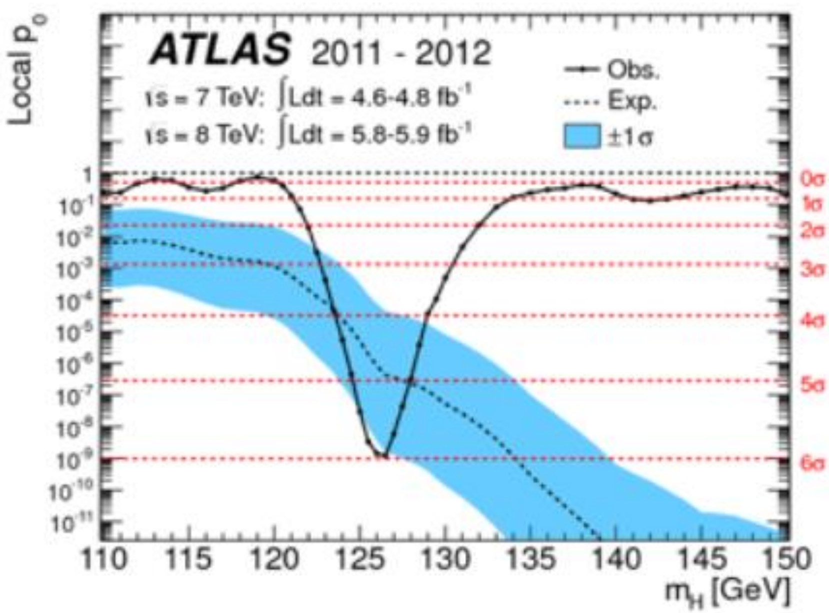
A 27km long circular tunnel buried 100m underground

Protons are injected at 450GeV into the LHC, after passing through a chain of 4 accelerators: LINCA 2, PSB, PS, SPS.



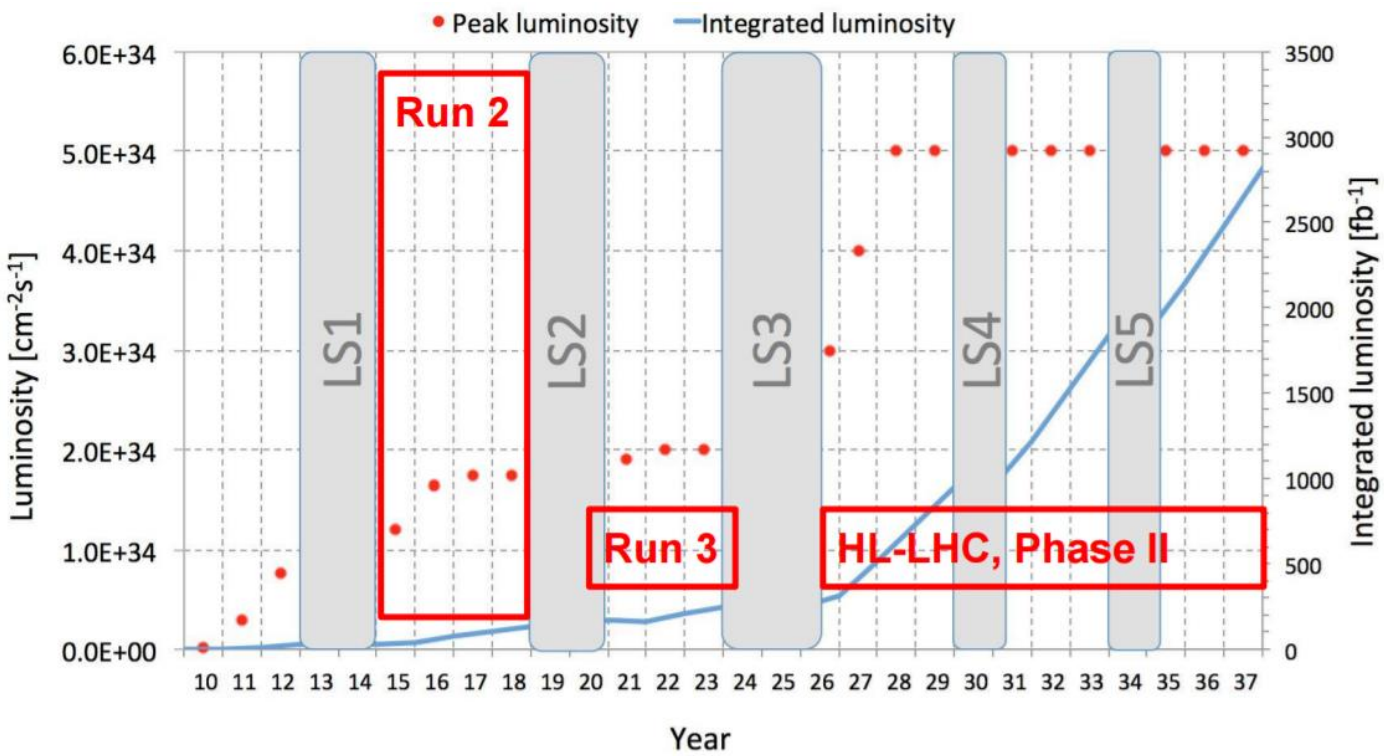
LHC Roadmap

- The LHC is built to collide 7 TeV protons/heavy-ions
- An incident in one of the main dipole circuits during the first commissioning in 2008
- The operation restarted at lower beam energy to minimize the risk
- LHC **Run 1** with pp collisions at $\sqrt{s}$ =**7-8 TeV** (2011-2012, $26fb^{-1}$)



Higgs Boson discovered on July 4th, 2012

LHC Roadmap



- Currently in a high-energy phase $\sqrt{s}$ =**13-14 TeV**, **Run2** (2015-2018, $\sim 100 fb^{-1}$)
- LHC exceeded design luminosity ($10^{34} cm^{-2} s^{-1}$)
- Run3: a bit higher luminosity ($\sim 300 fb^{-1}$)
- High-Luminosity LHC (HL-LHC) is planned (2026-, $\sim 300 fb^{-1}$/year)

Motivation

- Luminosity measurement is essential input to most LHC measurements and searches
  - Understanding of the nature of the observed Higgs particle
  - Searches for new physics beyond the Standard Model

- Some precision measurements are limited by the accuracy of integrated luminosity

Physics measurement	$\sqrt{s}$ (TeV)	$\sigma_{sys.}$(%) No lumi.	$\sigma_{lumi.}$(%)
Z fiducial cross section	13	2.1	2.1
Inelastic pp cross section	13	0.9	1.9
Inclusive $t\bar{t}$ cross section	13	3.6	2.3

Luminosity Measurement

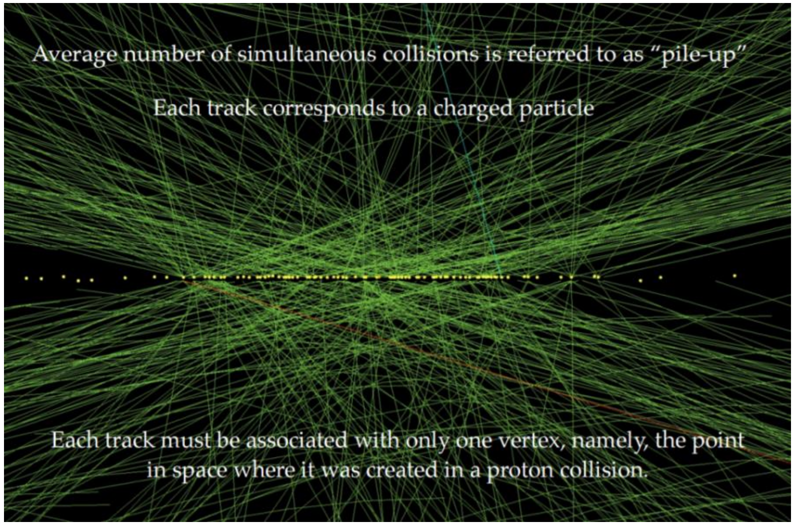
- The bunch luminosity $\mathcal{L}_b$ produced by a single pair of colliding bunches

$$\mathcal{L}_b = \frac{\mu \cdot f_r}{\sigma_{inel}}$$

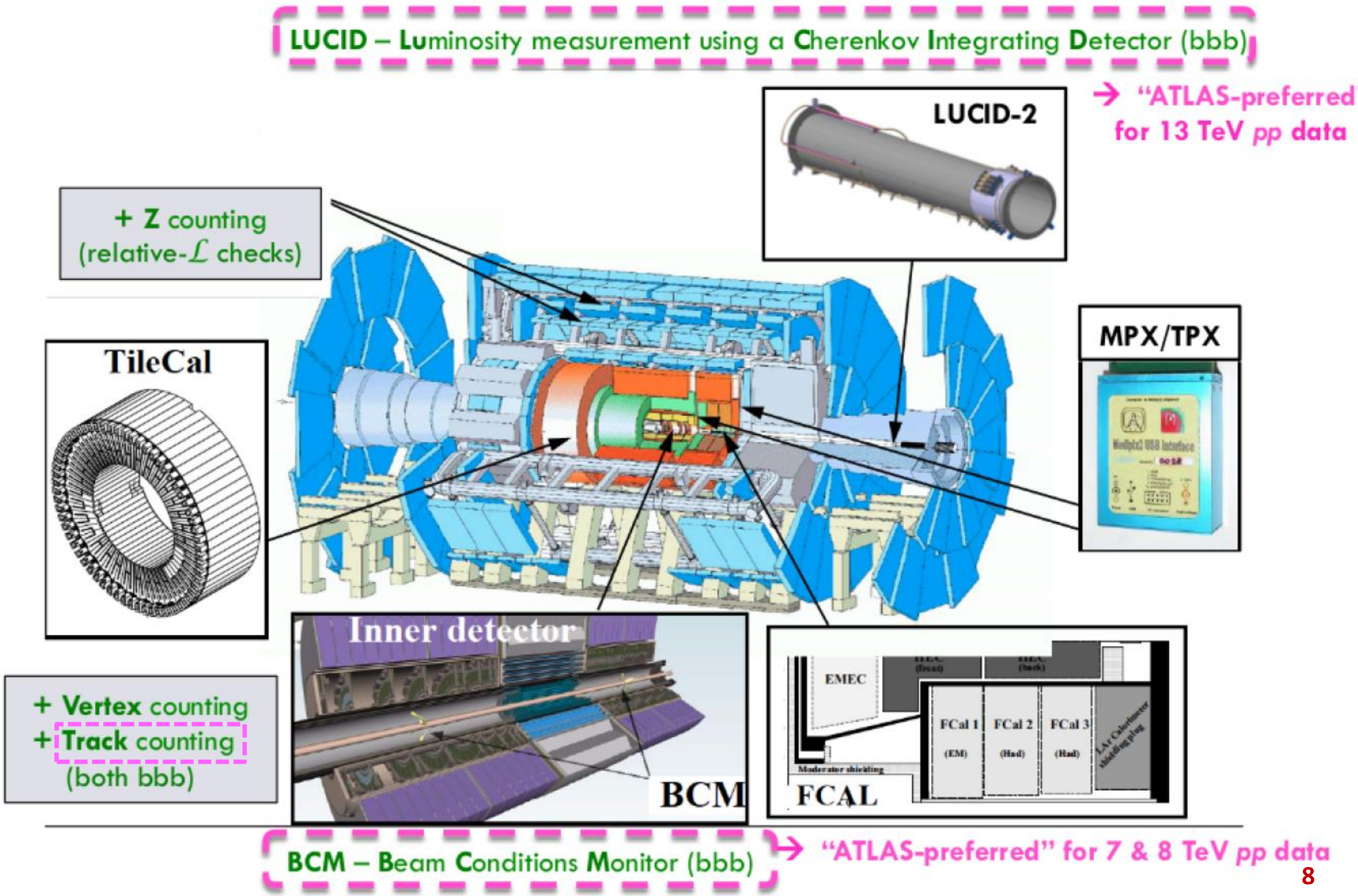
- ✓ μ : number of inelastic interactions per bunch crossing (BC)
- ✓ f_r : bunch revolution frequency (11245.5Hz at LHC)
- ✓ σ_{inel} = pp inelastic cross section

- ATLAS monitors $\mathcal{L}_b$ by measuring the visible interaction rate μ_{vis}
  - $\boldsymbol{\mu_{vis} = \epsilon \cdot \mu}$ is directly measurable (proportional to μ)
    - ϵ is the efficiency of the detector and algorithm (could be more than 1)
  - $\boldsymbol{\sigma_{vis} = \epsilon \cdot \sigma_{inel}}$: the visible cross section for the same detector and algorithm

$$\boxed{\rightarrow \mathcal{L}_b = \frac{\mu_{vis} \cdot f_r}{\sigma_{vis}}}$$



Luminometers



Bunch-by-bunch luminometers

- Dedicated two primary luminometers
  - BCM
  - LUCID
- Track-counting

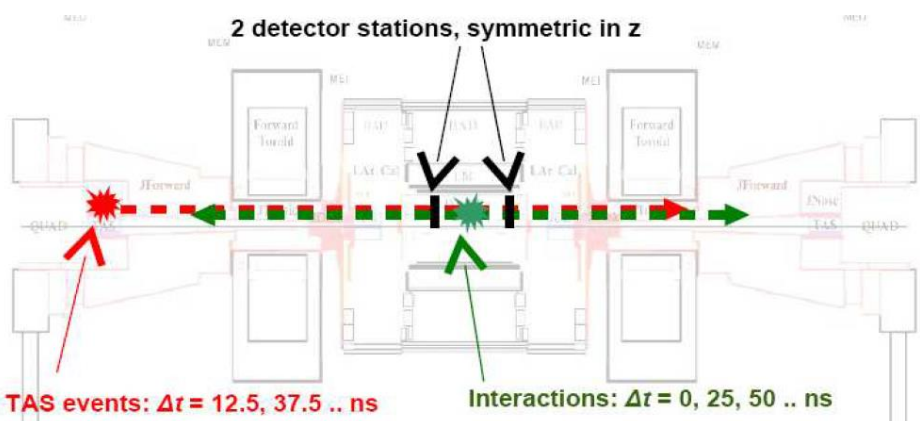
BCM
(Beam Conditions Monitor)

- BCM is designed to detect accidents which might cause detector damage
  - Enormous instantaneous radiation dose if lost protons hit the TAS collimator
- **Conditions monitor**
  - Two symmetric stations at $z = \pm 184\ cm$

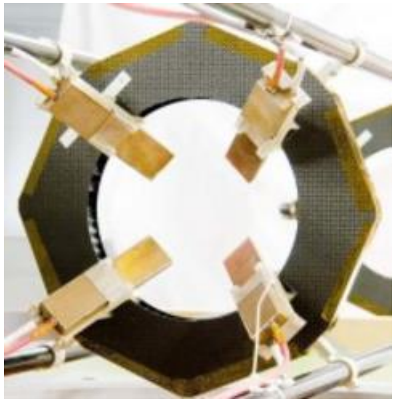
❖ Lost protons hit the two stations with $\Delta t = 2 * z/c = 12.5\ ns$

❖ Bunch spacing $= 25\ ns$

→**optimally distinguish these two classes of events**



- $R = 5.5\ cm$
- 4 diamond sensors × 2

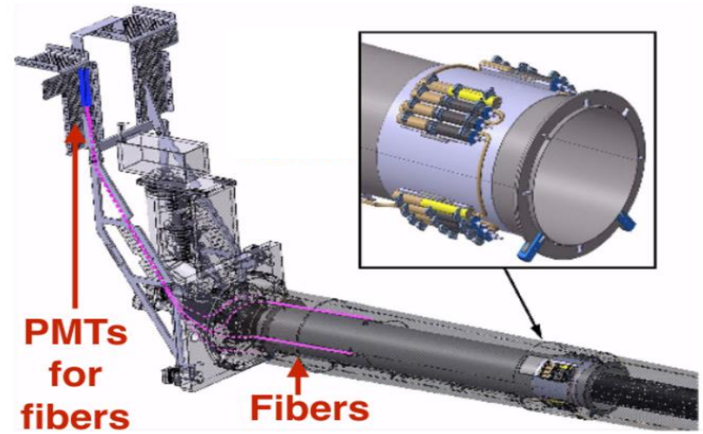


- **Luminosity measurement at $|\eta| = 4.2$**
  - Counting hits in the sensors

$$\boxed{\eta = -\ln \tan(\theta/2)}$$

LUCID
(LUminosity measurement using a Cherenkov Integrating Detector)

- **LUCID** is a Cherenkov detector specifically designed to measure the luminosity
  - Aluminium tubes surround the beampipe
  - $z = \pm 17m$
  - Counting "hits" in PMTs
  - $5.6 < |\eta| < 6.0$



- **BCM and LUCID are bunch-by-bunch luminometers**
  - **Fast** detectors with electronics capable of reading out the signals for each BC
  - Both consist of two symmetric arms in the forward ("A") and backward ("C") direction
  - **Independent measurements on A/C side**

Determination of μ_{vis} with BCM and LUCID

- μ_{vis} in a bunch crossing obeys a Poisson distribution

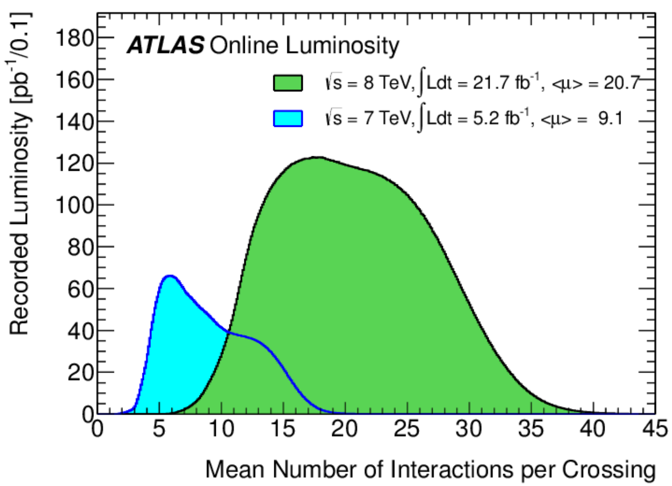
  $P(k\ events\ in\ interval\ ) = \frac{\mu_{vis}^{k} e^{-\mu_{vis}}}{k!}$

- The **probability of observing $\geq$ 1 hit** anywhere in BCM/LUCID

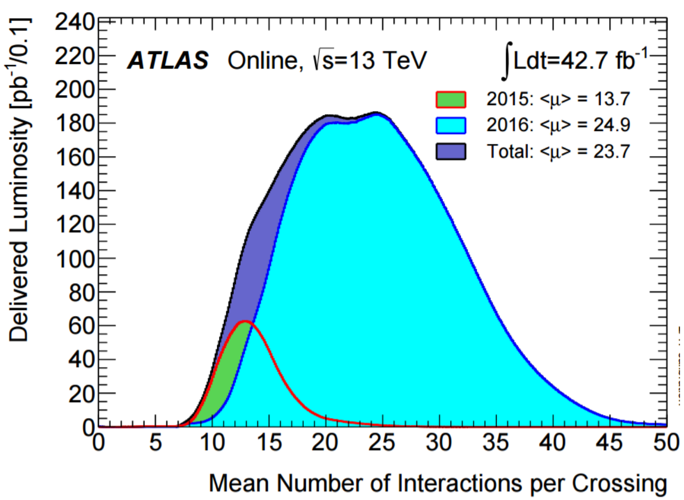
  $P(k \geq 1) = 1 - P(k{=}0\ ) = 1 - e^{-\mu_{vis}}$

- Obtained $\boldsymbol{\mu_{vis} = -\ln(1 - \frac{N_{OR}}{N_{BC}})}$
  - N_{OR} is the number of BCs in which at least one hit observed
  - N_{BC} is the total number of BCs
  - ***Saturation*** when $N_{OR}/N_{BC} = 1$

- Need *low acceptance* and *high-sensitivity* luminometers
  - **Run1: BCM is preferred**

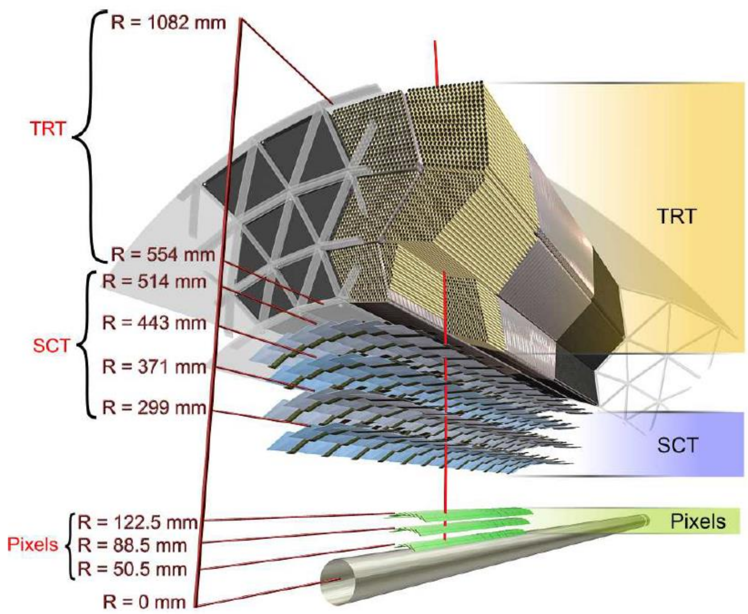


  - **Run2: LUCID is preferred**



Track-counting luminometer

- ATLAS inner Detector (ID)
  - $|\eta| < 2.5$
  - Pixel + Silicon micro-strip (SCT) + straw-tube transition-radiation (TRT)
- Counting charged tracks inside ID
  - Reconstructed with silicon detector only (**Pixel + SCT**)

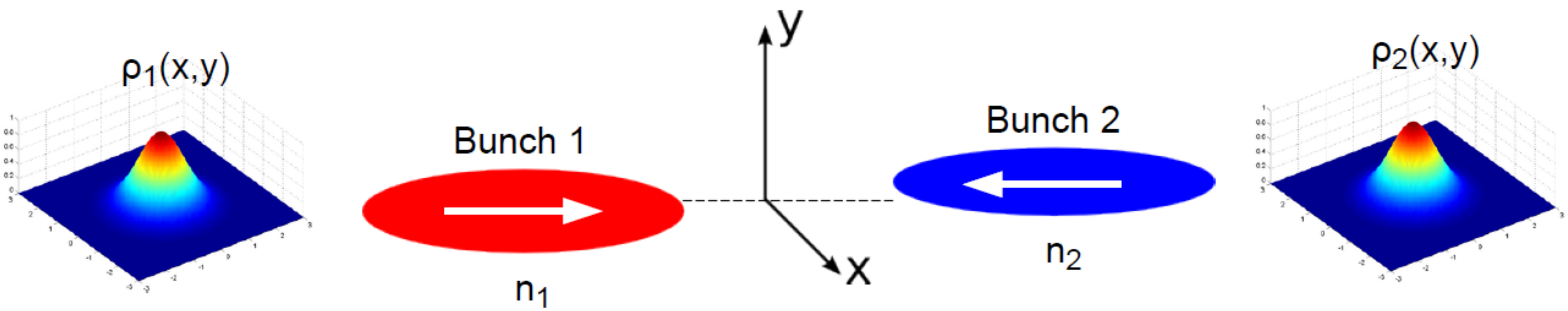


❖ **Track-counting**: $\boldsymbol{\mu_{vis}}$ **= Number of tracks**

- BCM/LUCID: $P(\geq 1\ hits) = 1 - e^{-\mu_{vis}}$

Determination of σ_{vis}

- To use μ_{vis} as a luminosity monitor, each detector & algorithm must be calibrated by determining its σ_{vis}
- σ_{vis} is determined by calibration of **absolute luminosity**



- The bunch luminosity $\mathcal{L}_b$ in terms of colliding-beam parameters

$$\mathcal{L}_b = f_r n_1 n_2 \int \hat{\rho}_1(x,y)\, \hat{\rho}_2(x,y) dxdy$$

  - n_1, n_2 : bunch population
  - $\hat{\rho}_1, \hat{\rho}_2$: normalized particle density in x-y plane

❖ beam-overlap integral $\Omega_x(\rho_{x1}, \rho_{x2}) = \int \rho_{x1}(x)\, \rho_{x2}(x) dx$ (assume $\hat{\rho}(x,y) = \rho_x(x)\rho_y(y)$)

$$\left.\begin{aligned} \mathcal{L}_b &= f_r n_1 n_2 \Omega_x \Omega_y \\ \mathcal{L}_b &= \frac{\mu_{vis} \cdot f_r}{\sigma_{vis}} \end{aligned}\right\} \Rightarrow \sigma_{vis} = \mu_{vis} \frac{\Omega_x \Omega_y}{n_1 n_2}$$

Determination of $\sigma_{vis}(\Omega_x, \Omega_y)$

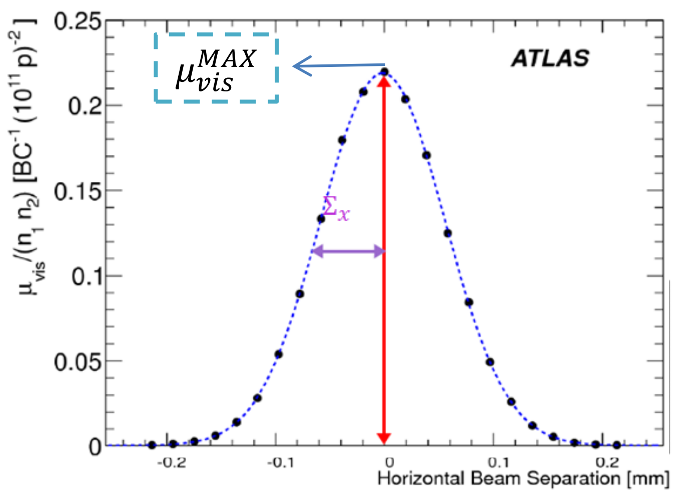
- $\sigma_{vis} = \mu_{vis} \dfrac{\Omega_x \Omega_y}{n_1 n_2}$
  - Beam-overlap integral $\Omega_x(\rho_{x1}, \rho_{x2}) = \int \rho_{x1}(x)\, \rho_{x2}(x) dx$
- Proposed by van der Meer
  - The overlap integral $\Omega_x(\rho_{x1}, \rho_{x2}) = \dfrac{R_x(0)}{\int R_x(\delta) d\delta}$
  - $R_x(\delta)$ is the luminosity when two beams are separated horizontally by the distance δ
- Ω_x and Ω_y are determined by measuring the specific visible interaction rate $\boldsymbol{\mu_{vis}/(n_1 n_2)}$ for each colliding-bunch pair, as a function of the nominal beam separation δ → vdM scan
- If $R_x(\delta)$ is Gaussian, $\Omega_x = \dfrac{1}{\sqrt{2\pi}\Sigma_x}$ (Σ_x is the width)
- Defining the convolved beam size $\boldsymbol{\Sigma_x} = \dfrac{1}{\sqrt{2\pi} \cdot \Omega_x}$

$$\boldsymbol{\Sigma_y} = \frac{1}{\sqrt{2\pi} \cdot \Omega_y}$$

$$\rightarrow \boldsymbol{\mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}}$$

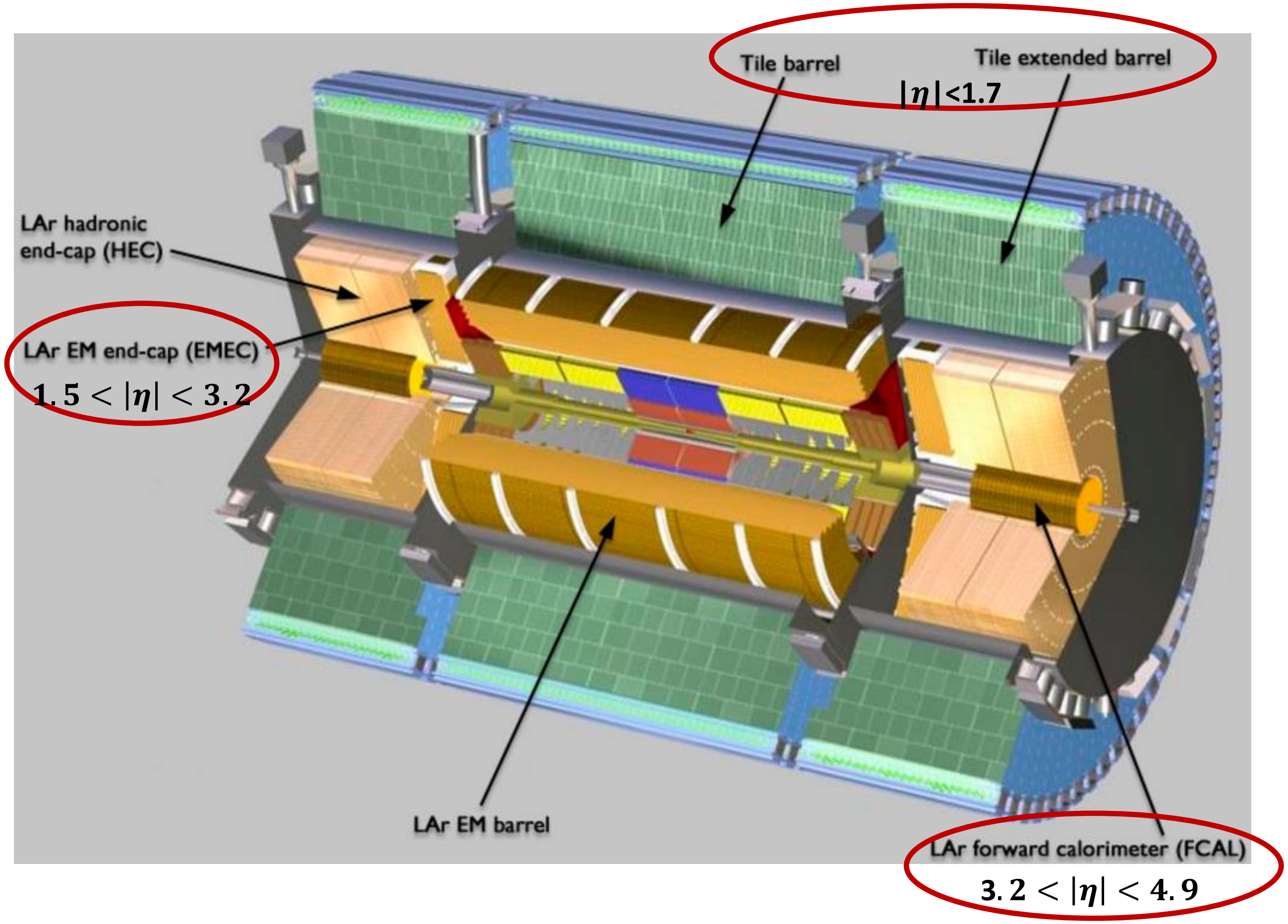
$$\mathcal{L}_b = \frac{\mu_{vis} \cdot f_r}{\sigma_{vis}}$$

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

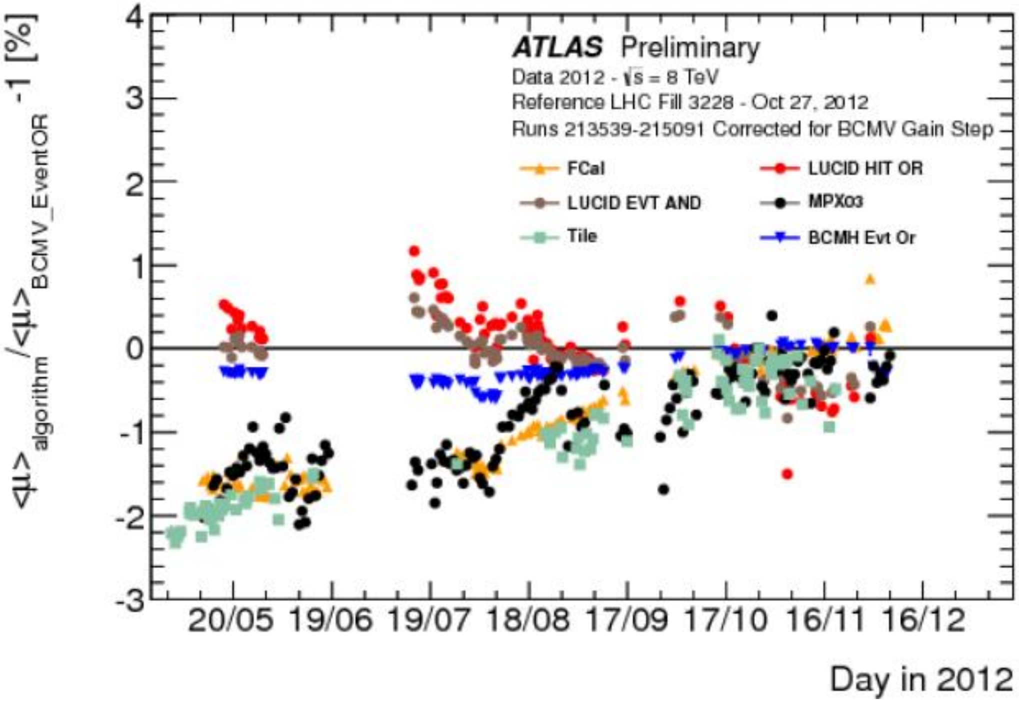


Bunch-integrating luminometers

- **TileCal** the barrel **hadronic** calorimeter
- The **electromagnetic** endcap (**EMEC**) and forward (**FCal**) calorimeters



Why Bunch-integrating algorithms?

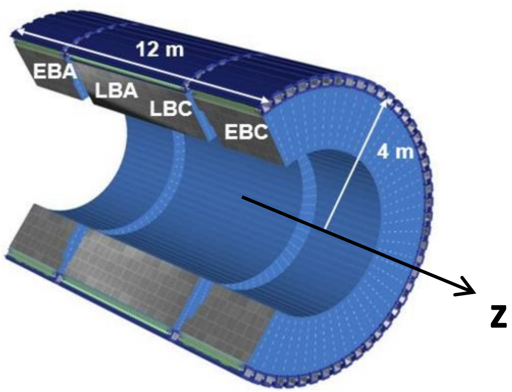


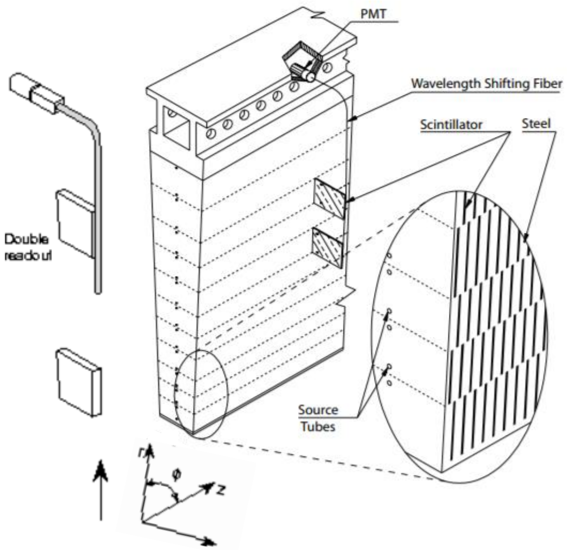
- Fractional deviation in $<\mu>$ **Deviation between bunch-by-bunch algorithms and bunch-integrating algorithms**

- Provide relative-luminosity monitoring on time scales of a few seconds rather than of a bunch crossing
- Allow independent checks of the linearity and long-term stability of the bunch-by-bunch algorithms

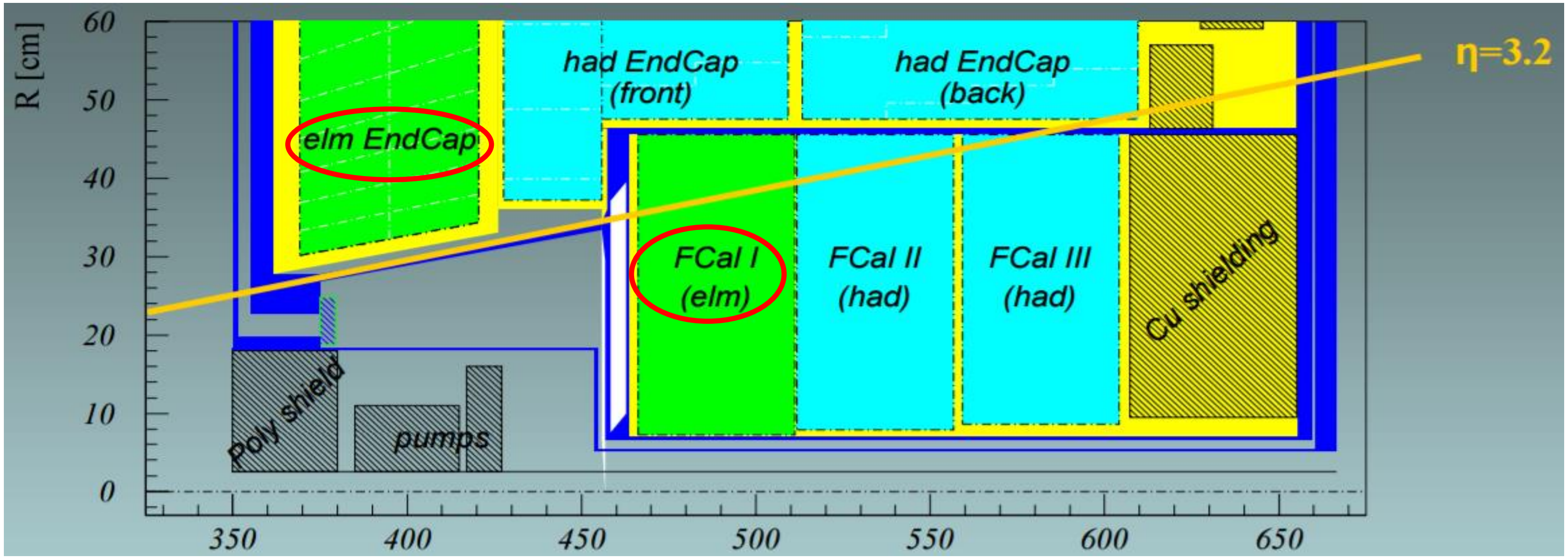
TileCal

- TileCal
  - $|\eta| < 1.7$
  - Consists of **a long central barrel (LB)** and **two smaller extended barrels (EB)**
  - Plastic-tile scintillators as the active medium separated by steel absorber plates
  - Each cell is connected by fibers to two PMTs
- μ_{vis} = Current drawn by each PMT





Endcap Calorimeters

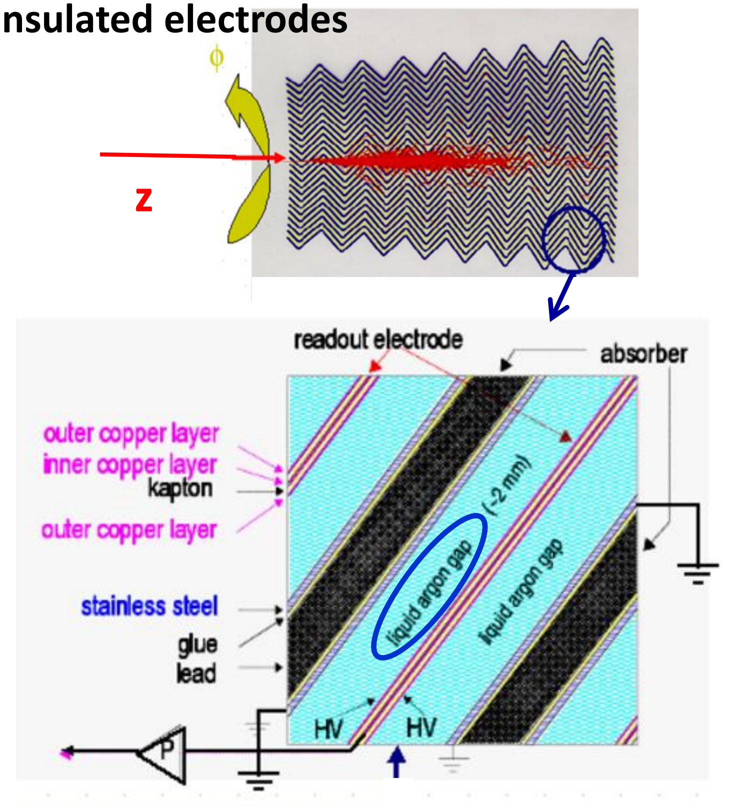


- Two endcap calorimeters used as luminometers
  - ElectroMagnetic Endcap Calorimeter (**EMEC**)
  - Forward Calorimeter (**FCal1**)

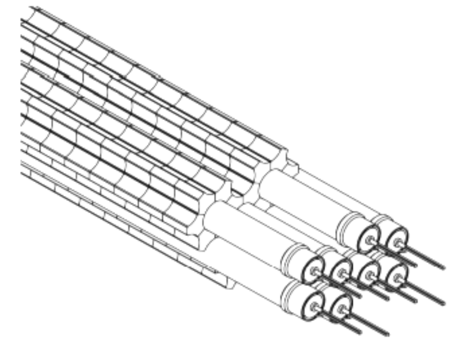
    Only the first sampling is used for luminosity measurement.

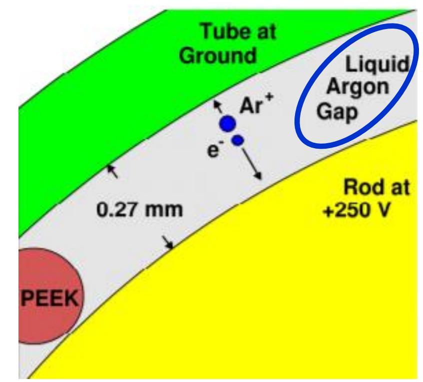
EMEC and FCal1

- **EMEC** **Lead/steel absorbers** and **Honeycomb-insulated electrodes**



- **FCal1** **Copper absorber matrix** containing **cylindrical electrodes**





- μ_{vis} = **LAr-gap currents**
  - Voltage drop induced by the particle flux through a given HV sector is counterbalanced by a continuous injection of electrical current (to keep the electric field across each LAr gap constant)
  - The LAr-gap current is proportional to the particle flux

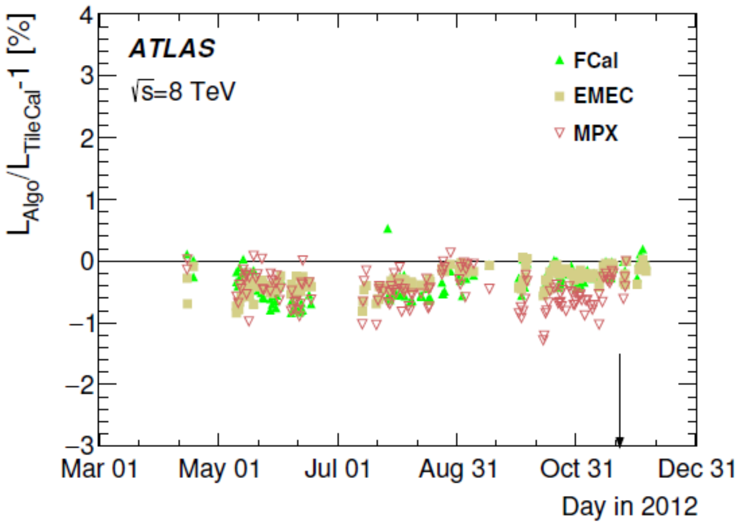
Calibration of bunch-integrating luminometers

Calibration of $\boldsymbol{\mu_{vis}}$ obtained TileCal and Endcap EM Calorimeters

- σ_{vis} not determined by vdM scan
  - Slow readout
  - Low-sensitivity under the low-luminosity conditions of *vdM* scans
- μ_{vis} obtained with the bunch-integrating luminometer are cross-calibrated to the luminosity reported by the baseline algorithm from *vdM* scan
  - $\mathcal{L} = \frac{\mu_{vis}^{LUCID} \cdot f_r \cdot n_b}{\sigma_{vis}^{LUCID}}$; $\mathcal{L} = \frac{\mu_{vis}^{TileCal} \cdot f_r \cdot n_b}{\sigma_{vis}^{TileCal}}$ → $\boldsymbol{\sigma_{vis}^{TileCal} = \frac{\sigma_{vis}^{LUCID}}{\mu_{vis}^{LUCID}} \cdot \mu_{vis}^{TileCal}}$
  - luminosity reported by the baseline algorithm are integrated over one high-luminosity reference physics run
  - $\boldsymbol{\sigma_{vis}^{TileCal}}$ are used for other physics runs

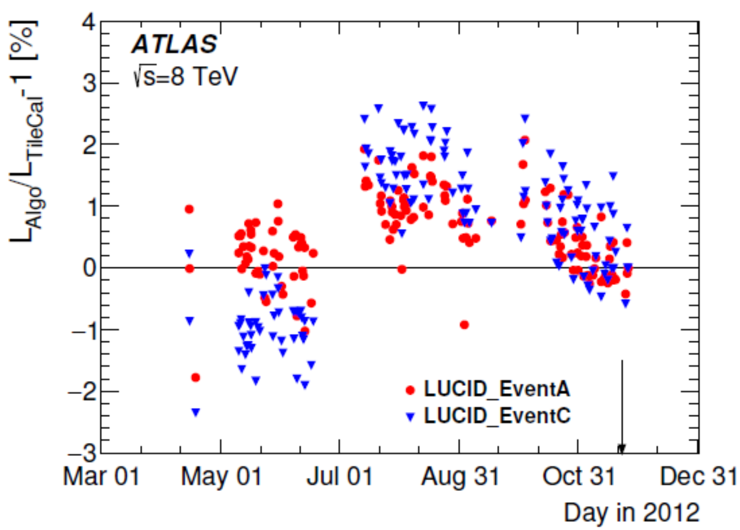
Uncertainties in the luminosity

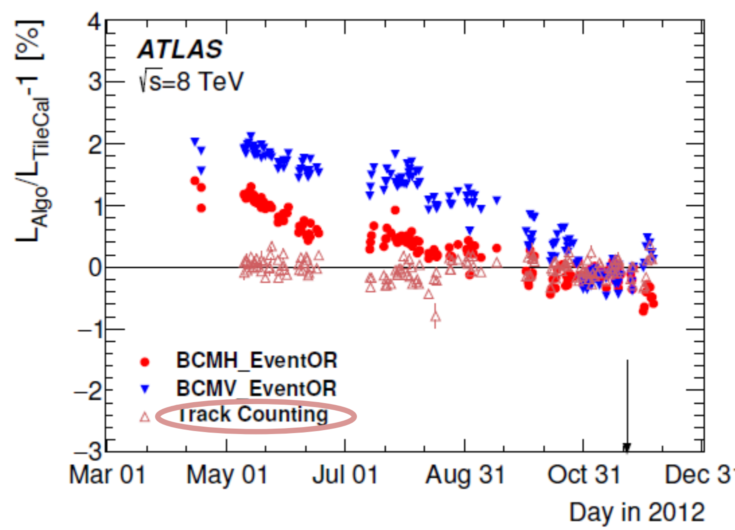
Long-term stability $\mathcal{L}_{Alg}/\mathcal{L}_{TileCal}$



- **Bunch-integrating** algorithms
  Consistent with each other and all stable along time

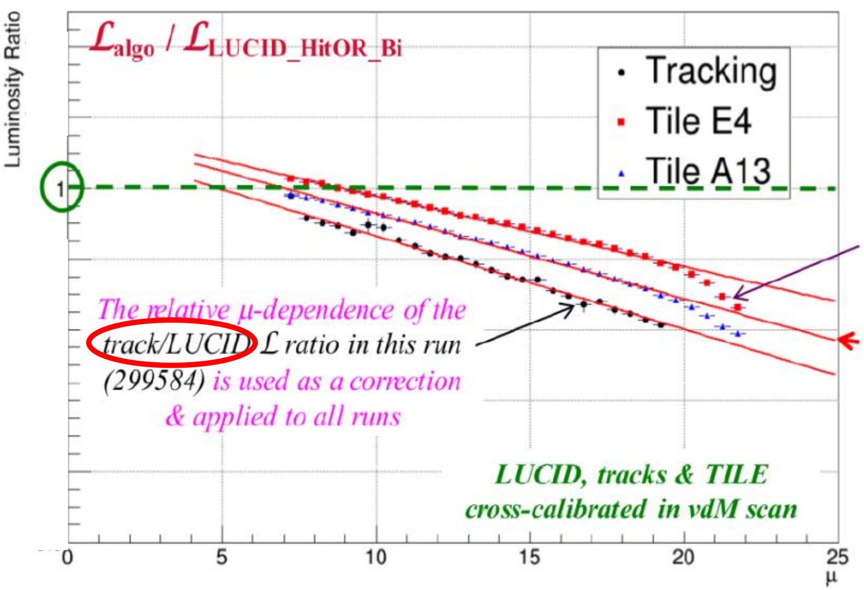
- **Bunch-by-bunch** algorithms
  Track counting is stable along time, but BCM and LUCID are not





Calibration transfer

- Different beam conditions of ***vdM* scan** and **physics fills**
  - **Low pile-up** (μ) in *vdM* scan
  - **Isolated bunches** in *vdM* scan while bunch trains in physics fills
- Use runs with nominal conditions near the vdM scans and derive corrections/uncertianties based on comparisons



Track counting is the reference algorithm to correct LUCID

- Stable and provides bunch-by-bunch luminosity

Summary of the luminosity measurement at ATLAS

- Bunch-by-bunch luminosity
  - LUCID
  - BCM

  μ_{vis} **is inferred from the 0-count rate (**$R_0 = e^{-\mu_{vis}}$**)**
  - Inner tracker → μ_{vis} **= number of tracks**

    Track counting is vital to transfer low luminosity to high luminosity calibration

luminosity scale σ_{vis} **is obtained from dedicated beam-separation scans (*vdM* scan)**

- Bunch-integrating luminosity (in a few seconds rather than of each BC)
  - Particle fulx in the PMTs of the hadronic calorimeter (TileCal)
  - Total ionization current flowing through a set of liquid-argon(LAr) calorimeter cells

- **Uncertainties** (%) in the luminosity values provided for physics analyses

Source	ICHEP 2016
vdM calibration	1.9
Calibration transfer	0.9
Long-term consistency	3.0
Others	0.1
Total $\Delta\mathcal{L}/\mathcal{L}$	3.7

The largest contribution arises from long-term consistency

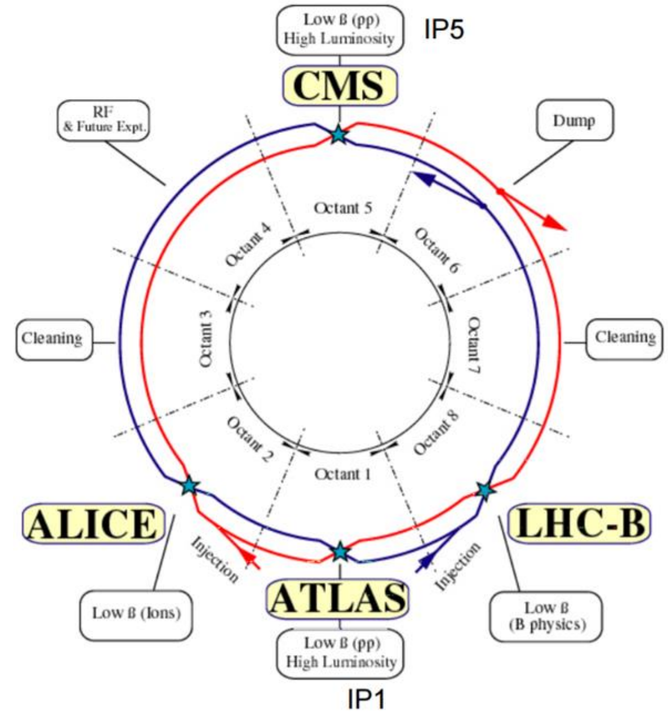
ATLAS-CMS comparison

- LHC is supposed to deliver the same luminosity to ATLAS and CMS
- **ATALS recorded smaller luminosity than CMS**
  - ❖ **Instrumental effects on ATLAS/CMS measurements**
    - – *vdM* calibration
    - – Stability vs pile-up and time
  - ❖ **Genuine imbalance of delivered luminosity**
    - – Beam parameters: $\epsilon, \beta^*, \alpha$

$$L = \frac{n_b \times N_1 \times N_2 \times f_{rev}}{4\pi\beta^\star\epsilon} \times F(\alpha, \beta^\star, \epsilon, \ldots)$$

beam size $\sigma_x\sigma_y$

crossing angle effect



    - – Crossing angle in the $y(x)$ axis at ATLAS (CMS)
    - – Ideally $\sigma_x \sim \sigma_y$ round beam: $\sigma^{IP1}(\text{ATLAS})$ **vs** $\sigma^{IP5}(\text{CMS})$

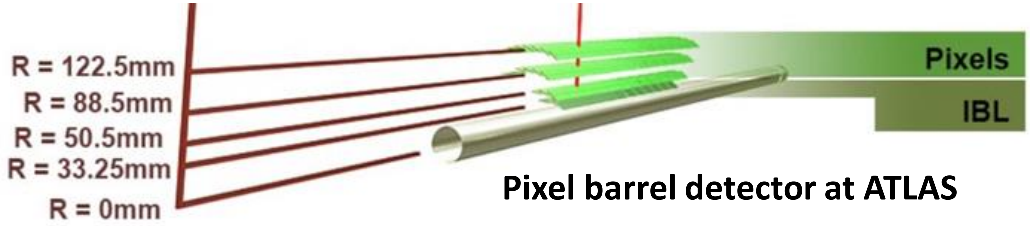
▪ **Dedicated fill to investigate luminosity dependence of crossing angle**
  - ▪ Clear effect from changing crossing angle on ATLAS/CMS luminosity ratio

Motivation of new algorithm

- Track counting is vital to transfer *vdM*-calibration scan to the high-luminosity regime
  - μ_{vis} = **number of tracks**
- **A new algorithm I am working on: Pixel Cluster Counting (PCC)**
  - μ_{vis} = **number of pixel clusters**
  - Provides independent check of tracking values
  - PCC is the baseline luminosity algorithm online for CMS

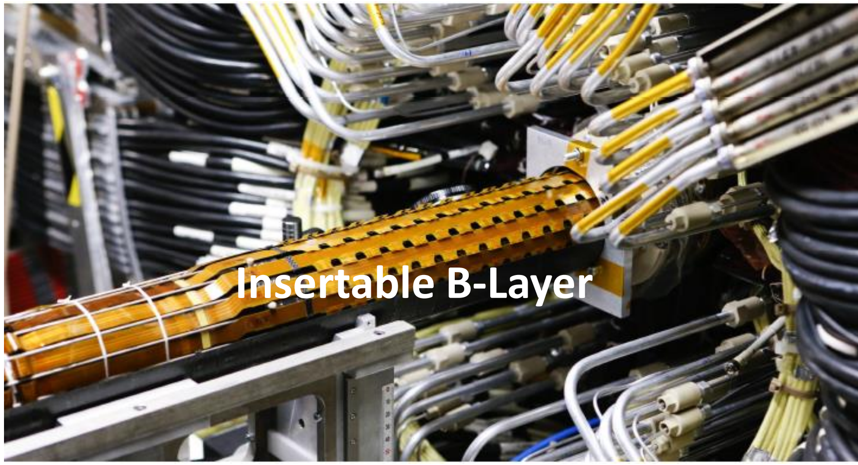
Pixel Cluster Counting in Insertable B-Layer (IBL)

- **Pixel barrel detector during Run1**
  - B-layer (closest to beam-pipe) + 2 outer layers



Pixel barrel detector at ATLAS

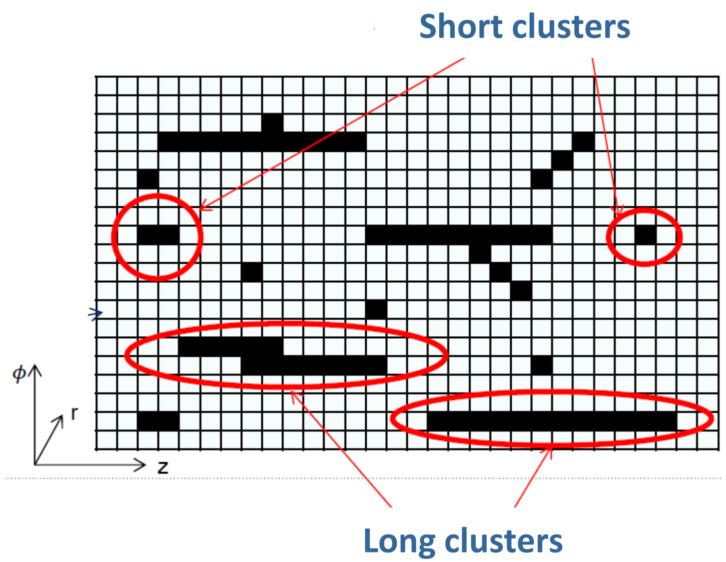
- **A new 4th layer added for Run2**
  - Increased radiation level and pixel occupancy
  - B-layer lost efficiency due to radiation damage
  - **Replacing B-layer takes $>$ 1 year** due to the long cooling down time of activated material
  - Introduce a **4th pixel layer** mounted on a new **smaller radius beam-pipe**



Why IBL? **Higher** capabilities of **tracking**, **vertexing**, and **b-tagging** !

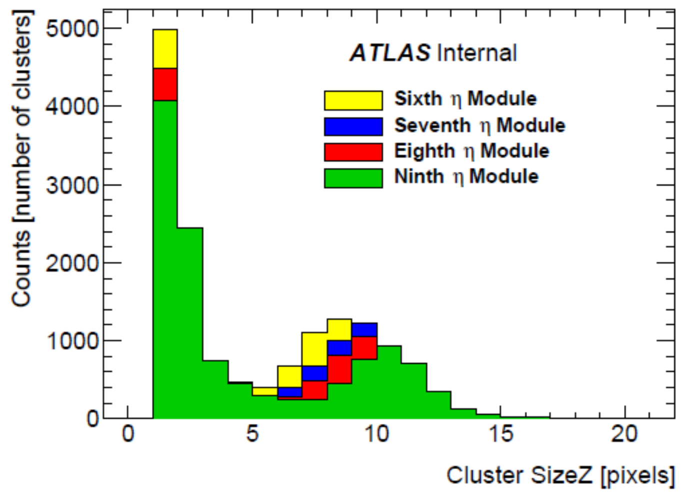
Pixel Cluster Counting in IBL

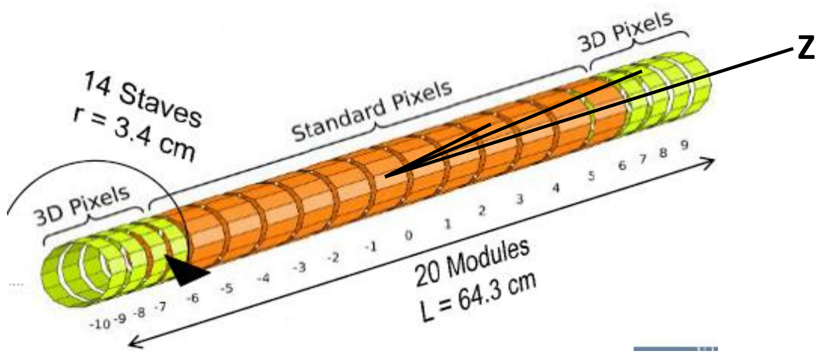
- Pixel clusters : groups of adjacent fired pixels
- $\boldsymbol{\mu_{vis}}$ = Number of **long** pixel clusters
- cluster length along Z
  - **Long clusters** from collision debris
  - **Short clusters** from material excited by charged particles, broken clusters, hot pixels, etc



- Higher η modules give better signal-background separation
  - Shallower particles result longer clusters
  - **Only count clusters in 3D sensors (8 rings) in IBL**

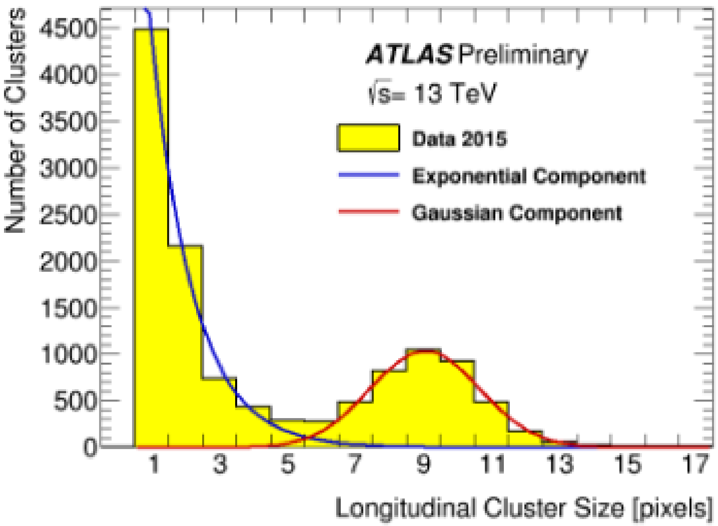
$$\boxed{\eta = -\ln \tan(\theta/2)}$$





Get number of long clusters (1)

- **Fit to clusters' size along Z in each module**
  - **Decaying exponential component** (short clusters)
  - **Gaussian component** (long clusters)
  - **Number of long clusters = Area under Gaussian**

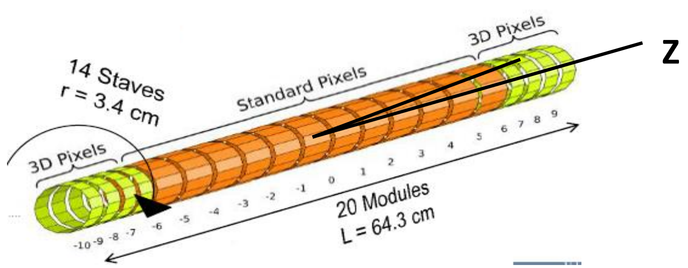


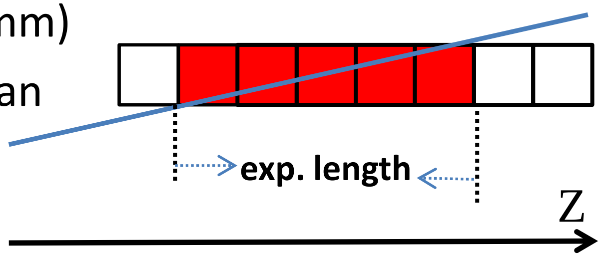
- Why the long clusters' length in Z distribute in a Gaussian?

Expected cluster length in Z $= \frac{thickness(230\mu m)}{pitch(250\mu m)} * \frac{z - IP_z}{r\ (33.25\ mm)}$

Z is the position of 3D sensors (varying between 259 and 321 mm)

IP_z is the interaction location in z, which distributes in a Gaussian



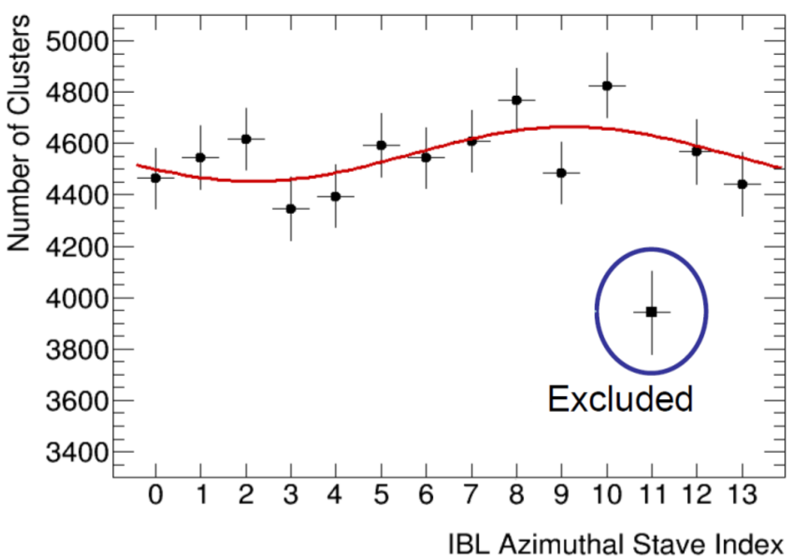


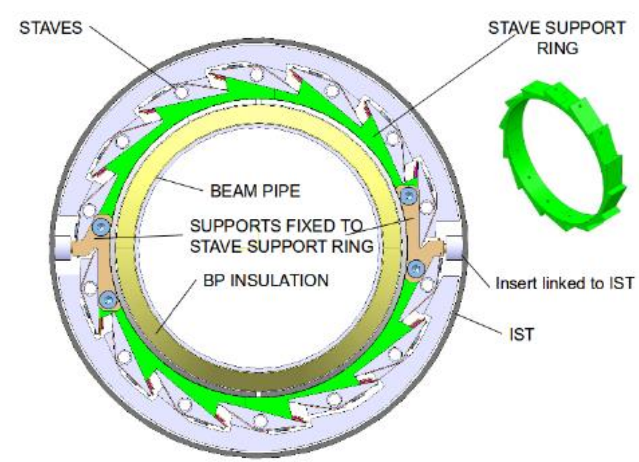
Get number of long clusters (2)

Module performance correction in each ring

- **The 14 sensors in the same ring** should perform consistently ⟵**same acceptance**
- **Find the average signal region in an ring, and exclude outliers**
- **How to find the average signal region?**
  - The IP is not always centered in x-y → **More (less) clusters in sensors closer to the IP (far away)**
  - The circular symmetry of each ring implies :

Number of long clusters in each module in the same ring $\sim A * sin\left(2 * \frac{\pi}{14}(x - B)\right) + C$



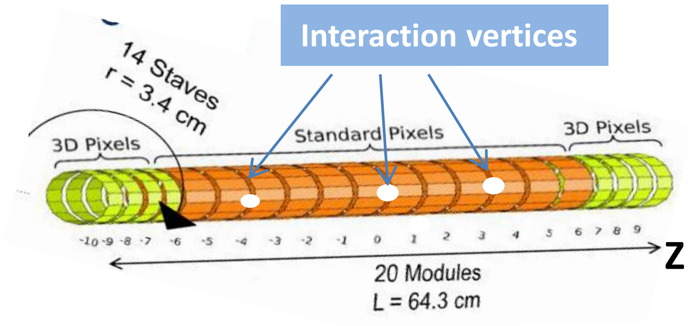


8 rings × 14 modules/ring = 112 modules

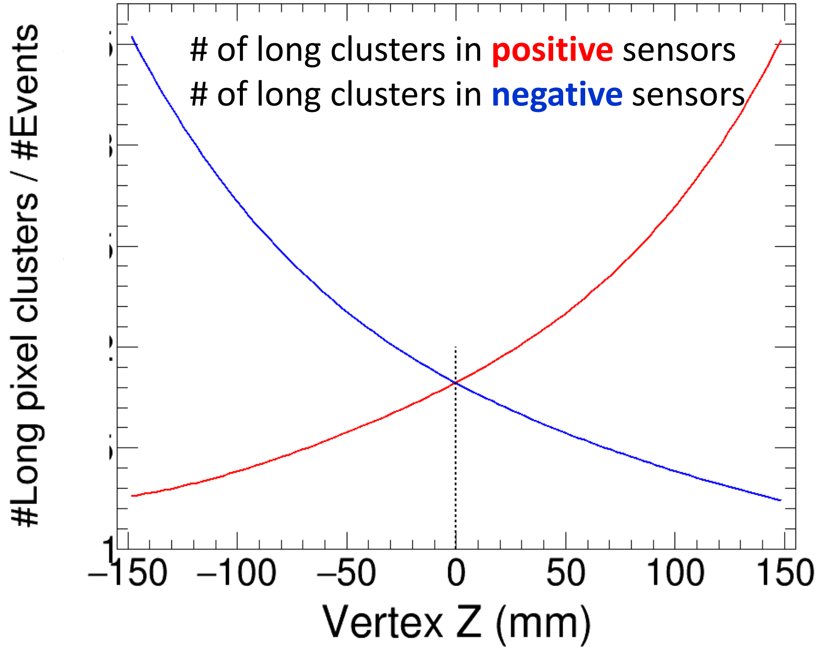
- **Total number of long clusters in each ring =** $14 * C$

IP location dependence

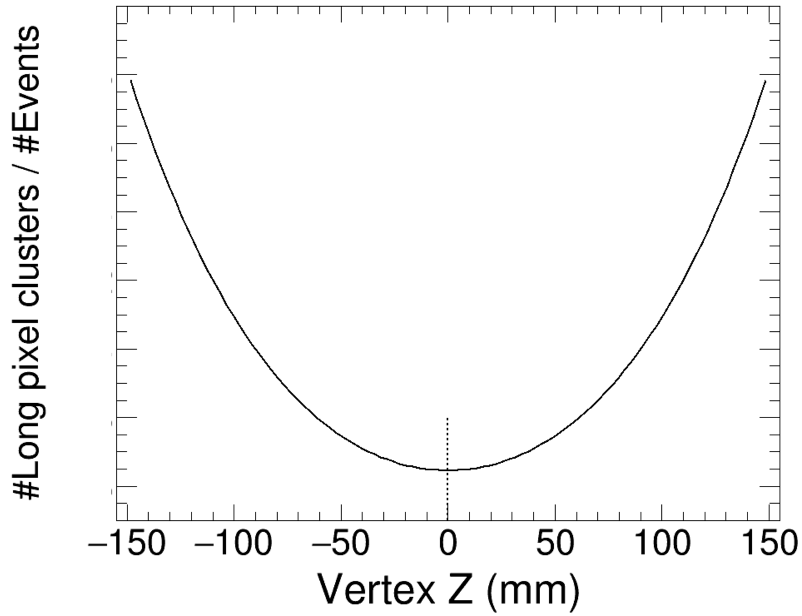
- Number of long clusters depends on where the interactions happen
  - **More clusters in modules closer to the IP**
  - **The interaction location in the transverse plan is constrained well because the transverse size of the beam is too small**



- **The positive and negative modules behave inversely**

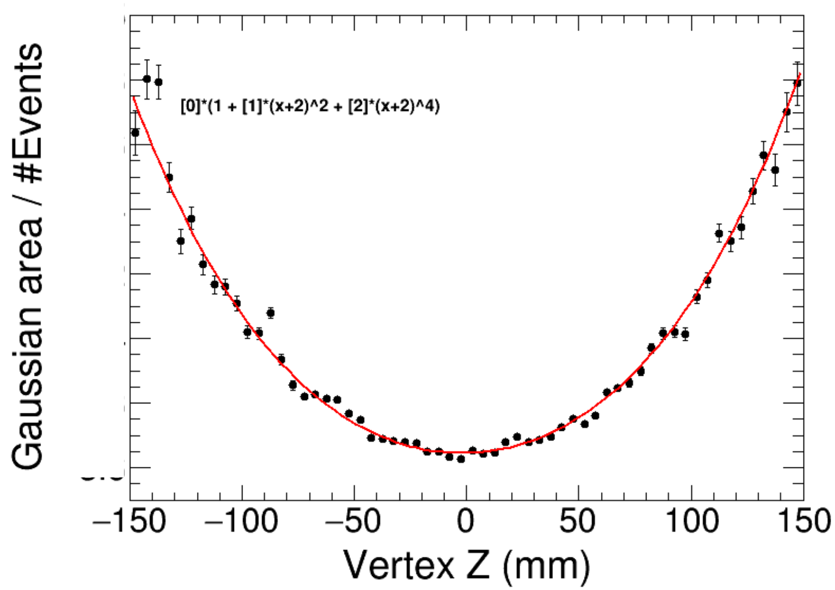


- **Total number of long clusters in all 3D sensors** $= N(\textbf{interaction vertex } z)$



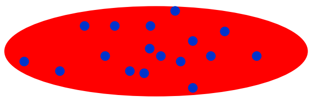
Interaction location dependence

- How the number of pixel clusters depends on the interaction location Z?
  - Counting the pixel clusters from interactions occurred at different Z
  - How to know where the interaction is ? Reconstruction of vertex (truth vertex in MC)



- Total number of clusters in all 3D sensors from one interaction at z $= N_0 * (1 + p_1 * z^2 + p_2 * z^4)$
  - The quadratic term dominates
  - N_0 is the number of clusters when the interaction happens at $z = 0$

Beamspot shape dependence



- Multiple interactions in each bunch crossing
- The interaction vertices are in a 3D Gaussian distribution

  $\mu * Gauss(x) * Gauss(y) * Gauss(z)$

  - Number of interactions in a bunch crossing is μ
  - The interaction vertices density is a 3D Gaussian

- The total number of clusters produced by all interactions in one bunch crossing

  $$\boldsymbol{N} = \int N_0 * (1 + p_1 * z^2 + p_2 * z^4) * \mu * Gauss(z; \mu_z, \sigma_z)\, dz$$

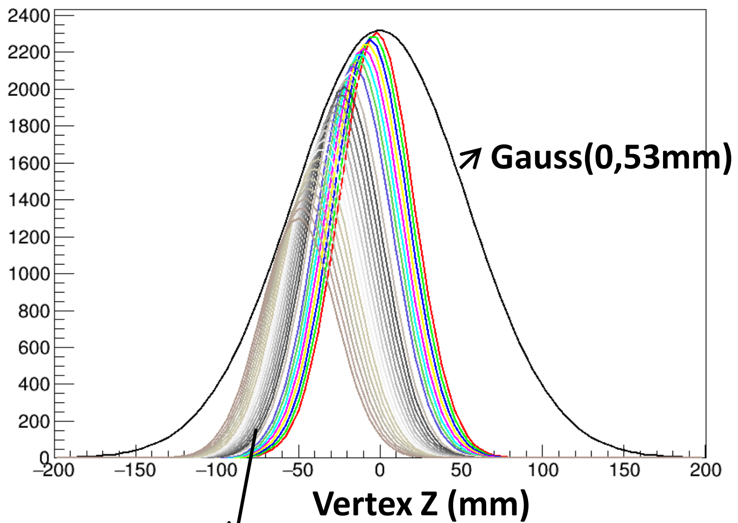
  $$= (N_0 * \mu) * \left[\mathbf{1} + \boldsymbol{p_1} * \left(\boldsymbol{\mu_z^2} + \boldsymbol{\sigma_z^2}\right) + \boldsymbol{p_2} * \left(\boldsymbol{\mu_z^4} + \mathbf{6}\boldsymbol{\mu_z^2\sigma_z^2} + \mathbf{3}\boldsymbol{\sigma_z^4}\right)\right]$$

- ***N*** should be corrected, because the interaction vertices density varies in different BC

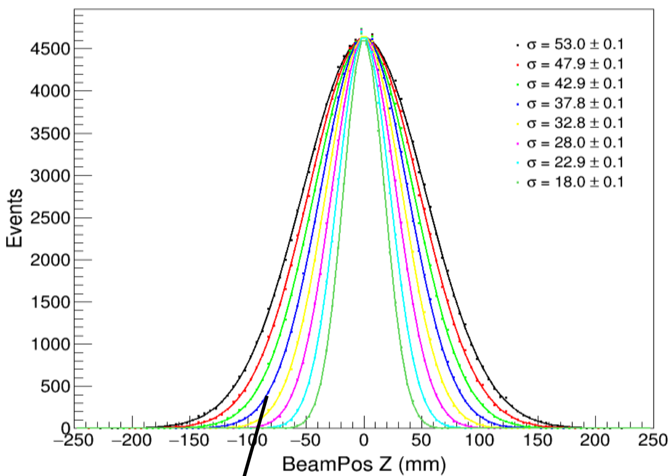
  $$\frac{\boldsymbol{N}}{\mathbf{1}+\boldsymbol{p_1}*\left(\boldsymbol{\mu_z^2}+\boldsymbol{\sigma_z^2}\right)+\boldsymbol{p_2}*\left(\boldsymbol{\mu_z^4}+\mathbf{6}\boldsymbol{\mu_z^2\sigma_z^2}+\mathbf{3}\boldsymbol{\sigma_z^4}\right)} \rightarrow \boldsymbol{N_0} * \boldsymbol{\mu} \quad \text{(all } \mu \text{ interactions at } z = 0\text{)}$$

MC samples to validate the correction

- Validate the dependence of the number of clusters on the vertices density $Gauss(z; \mu_z, \sigma_z)$
- We need several samples in which the interaction vertices distribute in a Gaussian but with different μ_z and/or σ_z
  - In the official simulated samples, the interaction vertices density in z direction = $Gauss(0{,}53mm)$, and μ varies between 1 and 60
  - Sampling new z distribution of interaction vertices
  - Only use the simulated single interaction events
    - We couldnot identify which cluster from which interaction if there are more than one interactions



Gauss(μ_z, 23mm)

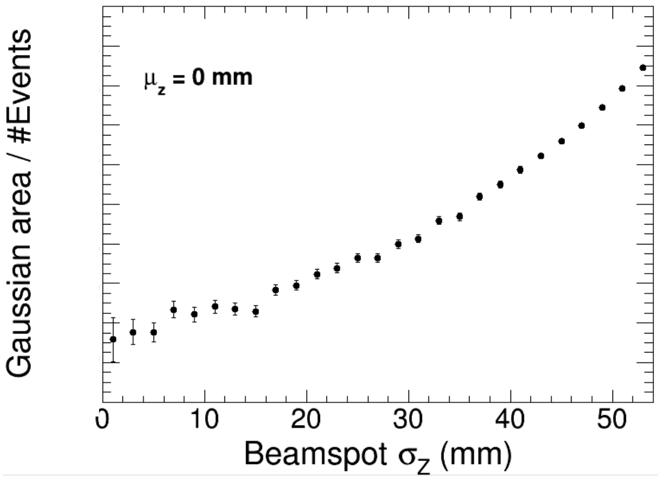


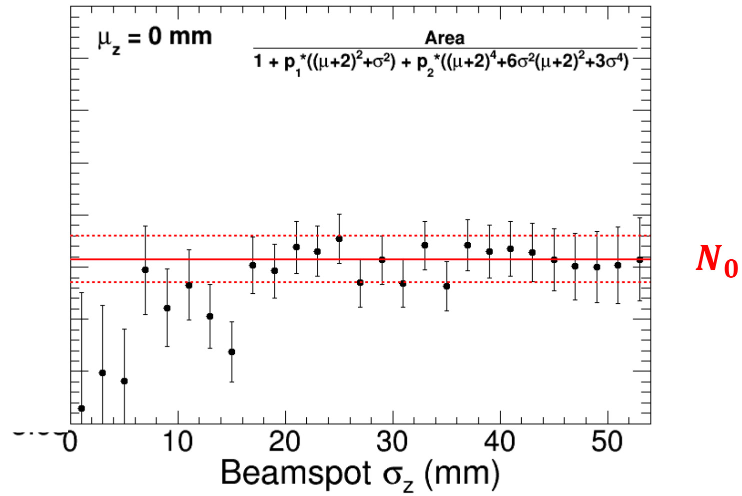
Gauss(0, σ_z)

The correction works well

– The number of clusters obtained in one bunch crossing should be corrected according to the interaction vertices density in z ~ $Gauss(\mu_z, \sigma_z)$

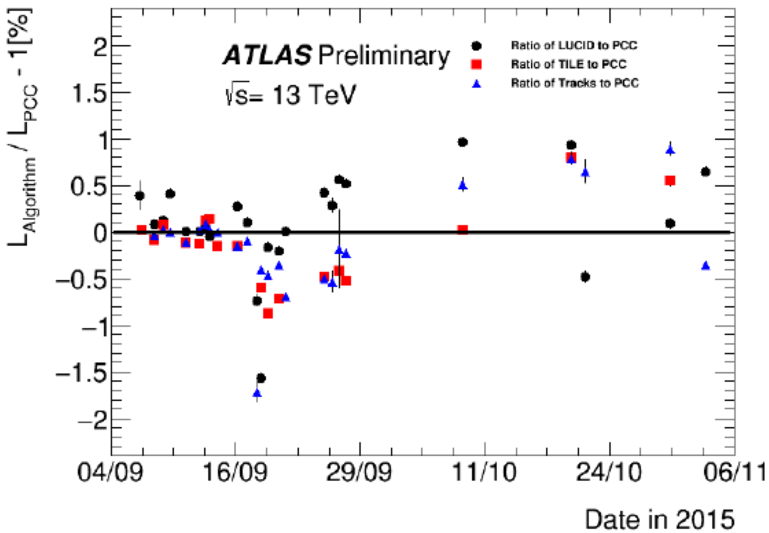
$$\frac{\boldsymbol{N}}{\mathbf{1}+\boldsymbol{p_1}*(\boldsymbol{\mu_z^2}+\boldsymbol{\sigma_z^2})+\boldsymbol{p_2}*(\boldsymbol{\mu_z^4}+\mathbf{6}\boldsymbol{\mu_z^2}\boldsymbol{\sigma_z^2}+\mathbf{3}\boldsymbol{\sigma_z^4})} \rightarrow N_0 * \mu$$

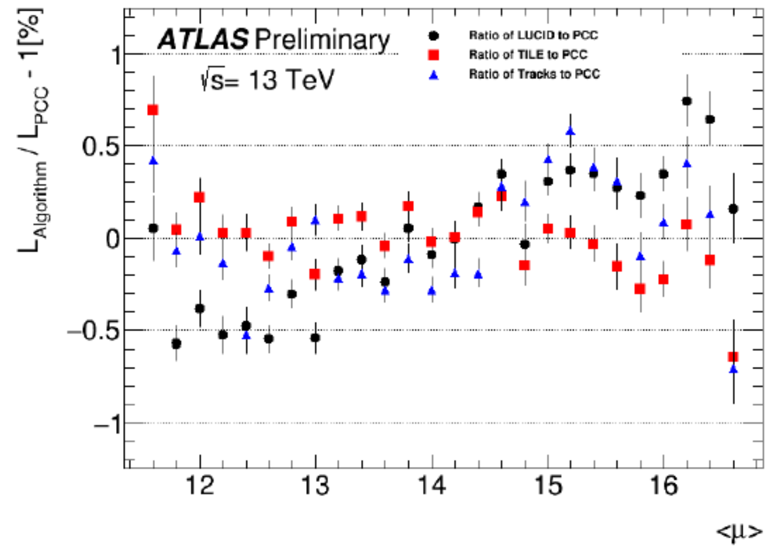




Single interaction samples ($\mu = 1$)

PCC results





- Stable along time
- Stable with respect to $< \mu >$
- Comparable with other algorithms within $\pm 1\%$

➢ Would be better after the correction of beamspot shape dependence

Plans for 2017

- Myself
  - Apply the Pixel Cluster Counting algorithm to Run2 data
- **Luminosity group**
  - Finalize understanding of ATLAS/CMS luminosity difference
  - Discussions started for a strategy to guarantee “fair” luminosity share in 2017
    - ✓ **Direct measurement of crossing angle effect**