Luminosity Measurements

Toni Baroncelli

Luminosity @ LHC

How to measure cross sections ...

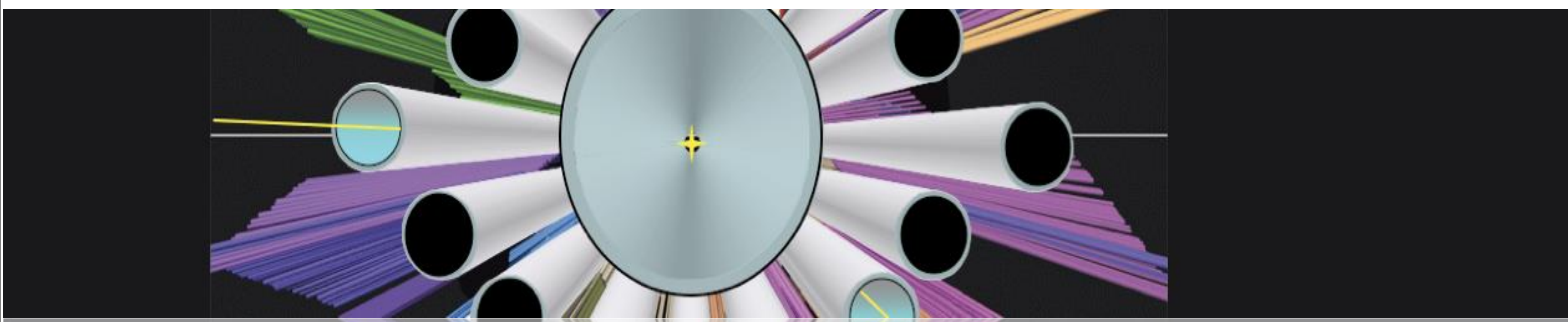
event rate (integrated # events)

Cross section

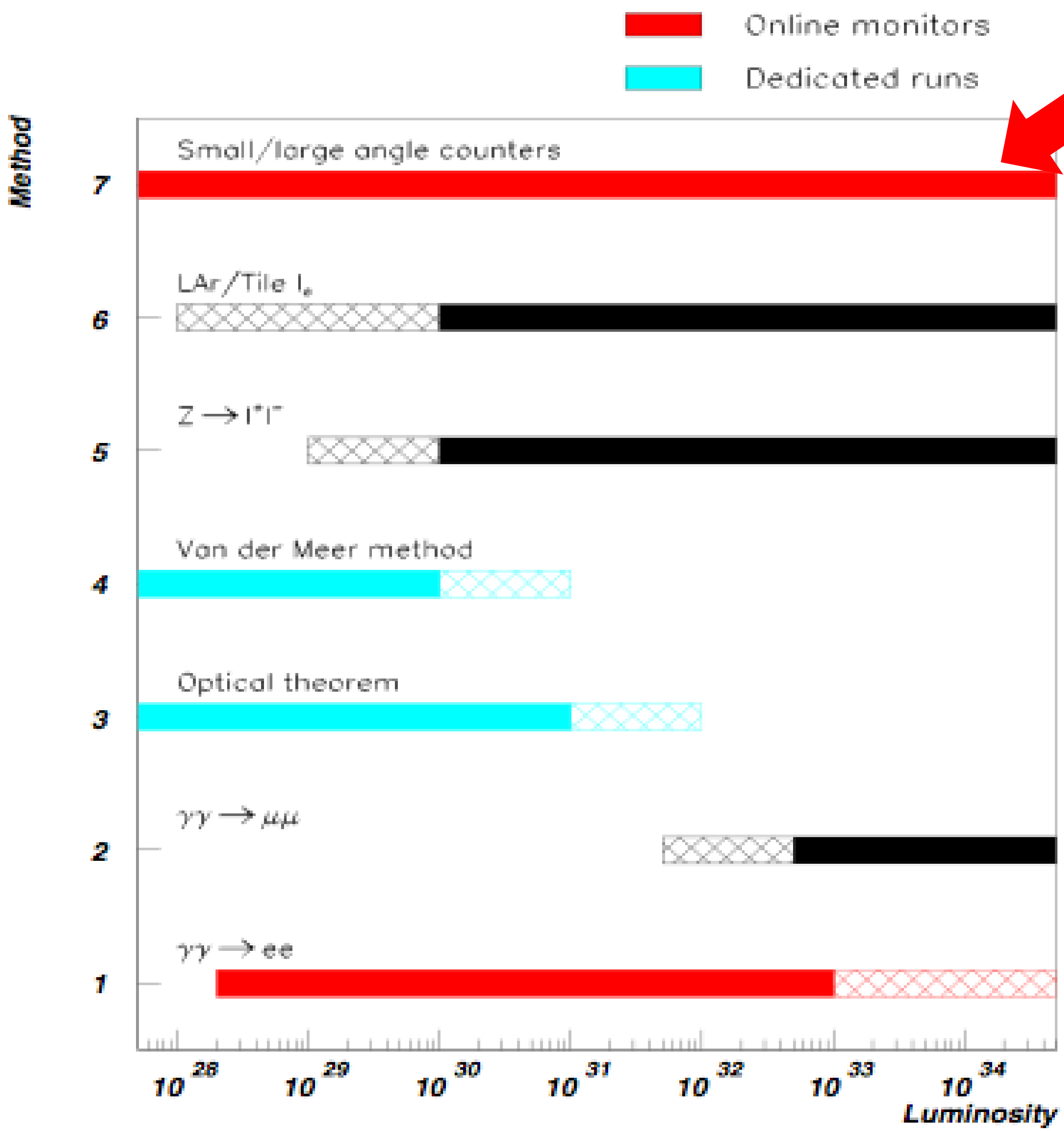
$$N = L \times \sigma \quad (\text{also } R = \sigma \cdot \mathcal{L})$$

Luminosity
(Machine parameter)

L: not only conversion factor ($\sigma = N/L$) but also monitoring



Luminosity Determination at the LHC (history)



ATLAS with ALFA,
CMS with TOTEM

Methods as
summarized in ATLAS TDR

[ATLAS Technical Design Report, Vol. I]

Red → Monitors
Light blue → Measurements

$\mathcal{L}$: Measurements and Monitoring

We have to distinguish between

- Absolute measurements of Luminosity in special low intensity conditions

  Van der Meer scan (compute luminosity using beam parameters, a few times per year)
  Low angle measurements (measure cross section and normalise to luminosity)(difficult, not precise enough → monitoring?)

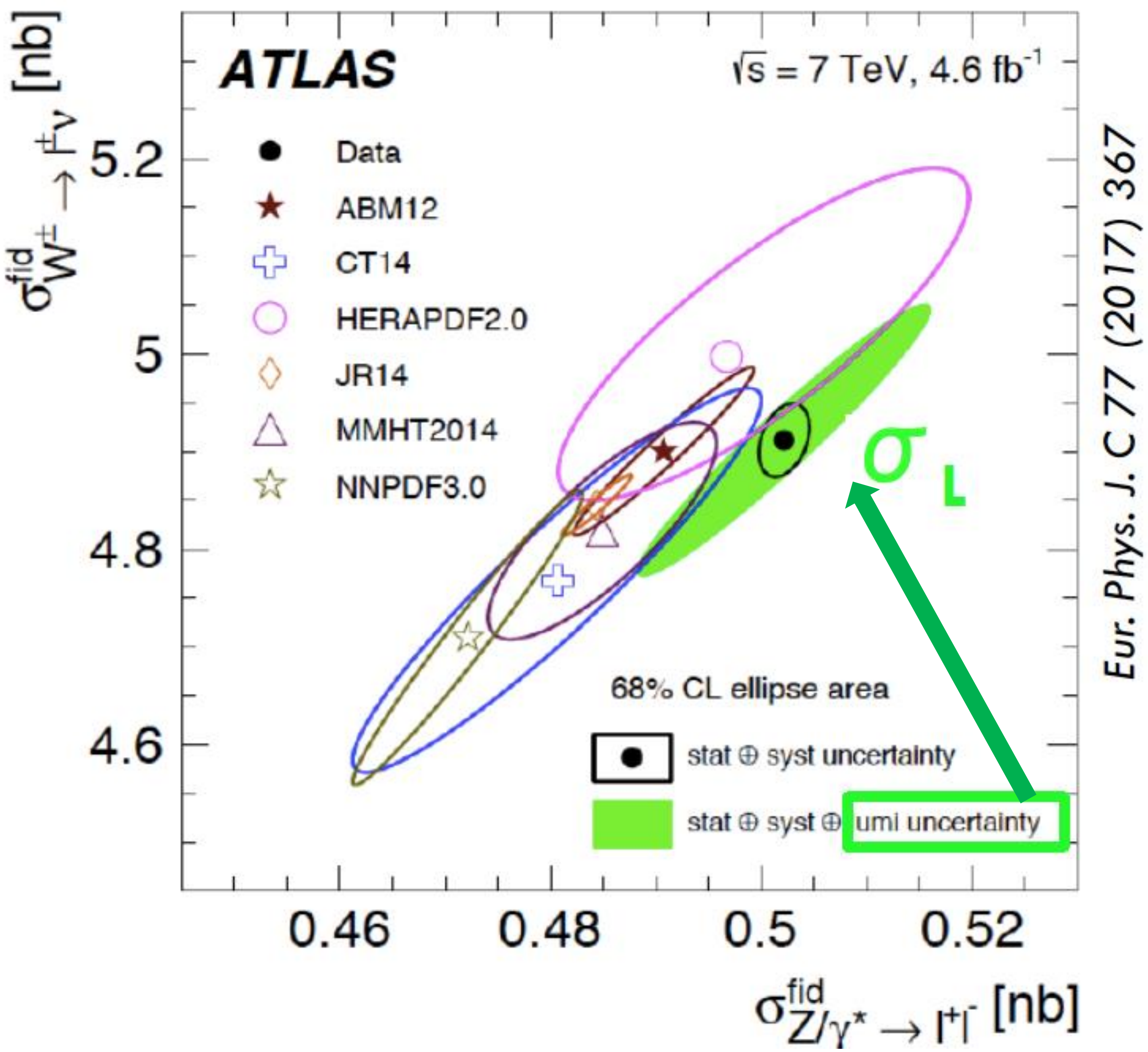
- Measurement of Luminosity @ running conditons
  Any detector sensitive to intensity of beams (tracking, calorimeters, continuous measurements during time)

The second mode has to be normalised to the absolute value of the luminosity → extrapolation

Instantaneous & Integrated Luminosity

Experiments MUST provide highly precise luminosity measurements:

- Instantaneous L -> online for machine monitoring: LHC performance and operation (luminosity 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 luminosity uncertainty to better constrain PDFs'). Needed precision: below 2%, ideally 1%



Luminosity Measurements: basic

$\sigma \rightarrow R(t)$ rate of events

$$R(t) = \mathcal{L}(t) \cdot \sigma$$

$$\mathcal{L}(t) = R(t)/\sigma$$

$$N = \int_{t_1}^{t_2} R(t)dt$$

$$L = \int_{t_1}^{t_2} \mathcal{L}(t)dt$$

$$\sigma = R(t)/\mathcal{L}(t)$$

$$\sigma = N/L$$

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

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)

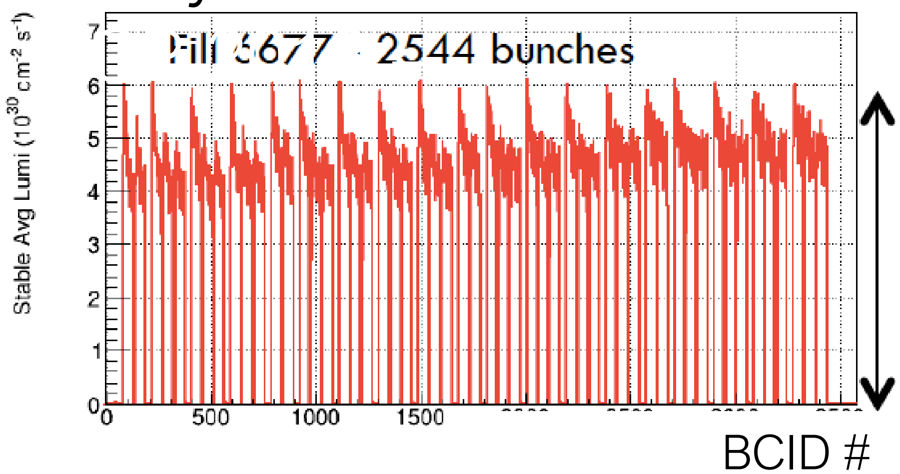
ε = acceptance and efficiency of luminosity detector

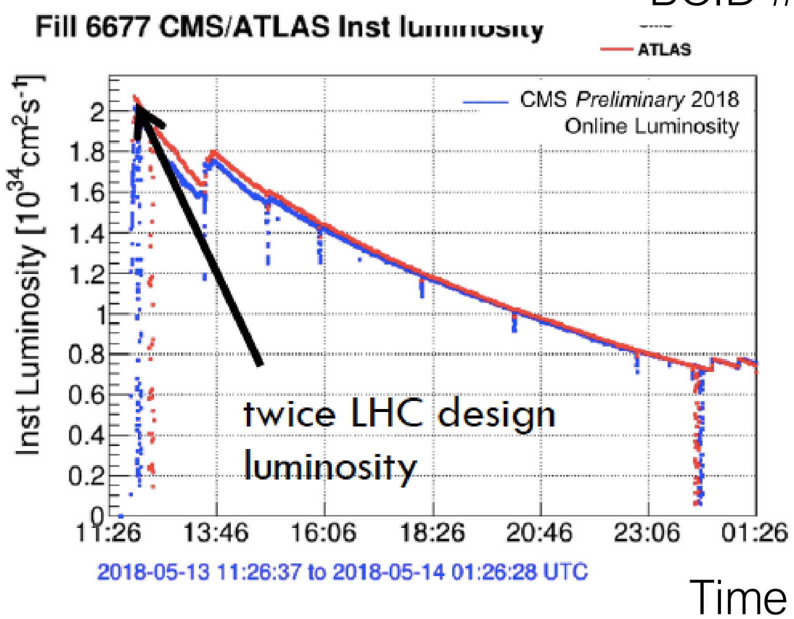
μ_{vis} = number of visible (= detected) collisions per bunch crossing

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

The Devil is in the Details

- Absolute scale from beam-separation scans: vdM method, complemented by the luminous-region evolution (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





How to measure luminosity

1. Measure machine parameters → Direct bunch shape and intensity measurements
   - Van der Meer scan (VdM) — ALICE, ATLAS, CMS, LHCb
   - Beam-Gas-Imaging (BGI) — LHCb

~real option for now

2. Use processes with known cross section.

$$N = L\,\sigma \rightarrow L = N / \sigma$$

ATLAS with ALFA, CMS with TOTEM

Improving

   - Forward scattering at very low angles based on optical theorem
   - Cross-calibrated luminosity detectors

… and to monitor it with time

use of tracking detectors & calorimeters

Online luminosity detectors

Device	Algorithms	Technology	BCID-aware	ACR desk
LUCID	Event (Hit) Counting	Cherenkov quartz windows + PMTs	Y	Calo+Fwd
BCM	Event Counting	Diamond semi-conductors	Y	Inner Detector
FCAL	Particle Flux	LAr under HV	N	Calo+Fwd
MBTS	Event Counting	Scintillators + PMTs	Y	Trigger/ Calo+Fwd
TILE	Particle Flux	Scintillating Tiles + PMTs	N	Calo+Fwd
EMEC	Particle Flux	LAr under HV	N	Calo+Fwd

Each subsystem can provide more luminosity algorithms and among those, one, defined as ***preferred,*** is chosen and used online.

Precision of Luminosity measurements

Run 1 (years 2015–2018) uncertainties in the total integrated luminosities

- $\frac{\Delta\mathcal{L}}{\mathcal{L}} = 1.8\%\ for\ \sqrt{s} = 7\ TeV$
- $\frac{\Delta\mathcal{L}}{\mathcal{L}} = 1.9\%\ for\ \sqrt{s} = 8\ TeV$

Run 2 uncertainties (years 2017-2018) in the total integrated luminosities

Data sample	2017	2018	Comb.
Integrated luminosity [pb^{-1}]	147.1	191.1	338.1
Total uncertainty [pb^{-1}]	1.7	2.1	3.1
Uncertainty contributions [%]:			
Subtotal vdM calibration	0.99	0.93	0.75
Calibration transfer*	0.50	0.50	0.50
Calibration anchoring	0.14	0.14	0.10
Long-term stability	0.26	0.13	0.13
Total uncertainty [%]	1.15	1.08	0.92

Basic Mechanism

Two steps procedure:

- van der Meer (VdM) method gives the absolute luminosity in low luminosity runs with specially tailored LHC conditions. The VdM calibration was performed in dedicated fills once per year during Run 2;
- A calibration transfer procedure was then used to transport this calibration to the physics data-taking regime measurements by different detectors at high luminosity;
- The relative comparisons of the luminosities measured by different detectors were used to set limits on any possible change in the calibration during the year.

Basic Formulas - 1

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

$$\mathcal{L}_\mathrm{b} = \frac{R}{\sigma}$$

R = rate of a process with cross-section σ.

In inelastic pp collisions

- $\sigma \rightarrow \sigma_{inel}$;
- μ <inelastic interactions per bunch crossing>
- f_r is the LHC bunch revolution frequency

$$\mathcal{L}_\mathrm{b} = \frac{\mu f_\mathrm{r}}{\sigma_\mathrm{inel}}$$

The total instantaneous luminosity is given by

$$\mathcal{L}_\mathrm{inst} = \sum_{b=1}^{n_\mathrm{b}} \mathcal{L}_\mathrm{b} = n_\mathrm{b}\langle\mathcal{L}_\mathrm{b}\rangle = n_\mathrm{b}\frac{\langle\mu\rangle f_\mathrm{r}}{\sigma_\mathrm{inel}}$$

$\mathcal{L}_b$ can be computed as

- μ_{vis}, the *visible* interaction rate per bunch-crossing
- σ_{vis} ‘visible cross-section’ is a calibration constant (absolute luminosity) determined via the vdM calibration method

$$\mathcal{L}_\mathrm{b} = \frac{\mu_\mathrm{vis} f_\mathrm{r}}{\sigma_\mathrm{vis}}$$

Basic Formulas - 2

σ_{vis} is measured/scaled by VdM → the pileup parameter μ

$$\mu = \mu_{vis}\sigma_{inel}/\sigma_{vis}.$$

a reference value of σ_{inel} = 80mb is used by convention by all LHC experiments for pp collisions at $\sqrt{s}$ = 13TeV.

Assumptions:

- The calibration constant σ_{vis} 'visible cross-section' of the slide before is stable in time;
- The calibration constant σ_{vis} 'visible cross-section' of the slide before doesn't depend on LHC conditions;

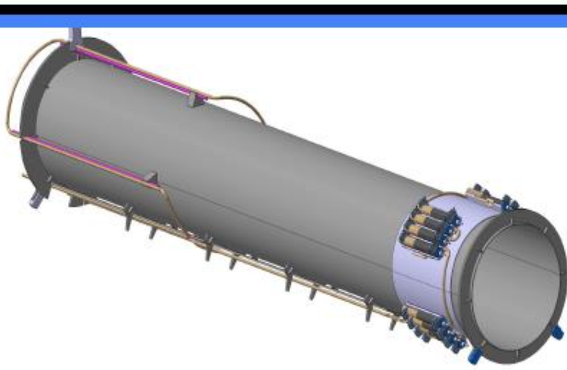
Not (fully) satisfied → comparisons between many different algorithms and detectors are essential to produce a precise luminosity measurement with a robust uncertainty estimate.

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

- Measured in 1 minute interval ('Luminosity Block')
- Varies during the course of one fill
- Integrate

ATLAS Luminosity Detectors

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

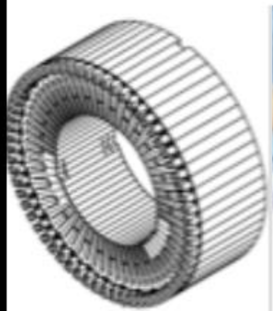
TimePix (TPX)

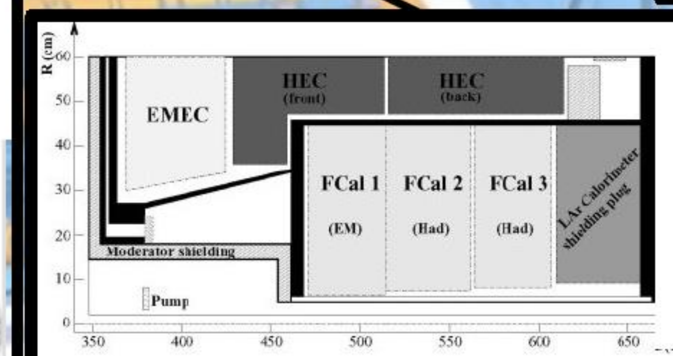
Hit counting

+ Z counting (relative-L checks)

+ Track counting (+ Vertex counting)

Hadronic Cal. (TILE)



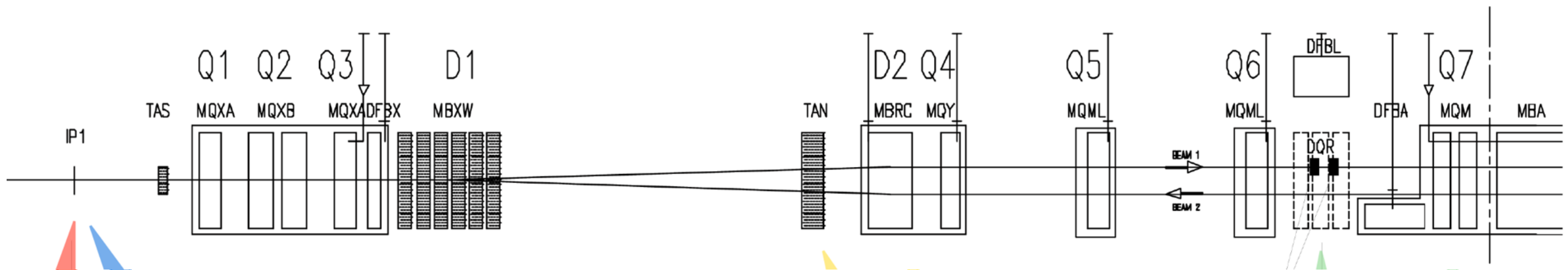


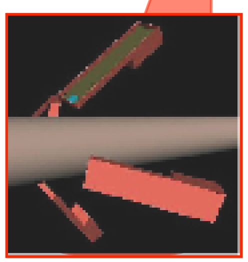
EM:
- **Forward Calorimeter (FCAL)**
- **EndCap Calorimeter (EMEC)**

Particle flux algorithms

Luminosity (monitoring) via Forward Scattering

The more forward you go → the more events you have → lower stat error



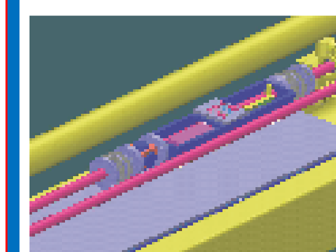


BCM
[Beam Condition Monitor]
Diamond sensors at z = ±184 cm
4 modules per side

LUCID
[Luminosity Monitor]
Cherenkov gas tubes, at ~17 m from IP.

ZDC
[Forward Neutrals]
W^{74} /Quartz calo at 140 m and at 0° toIP.

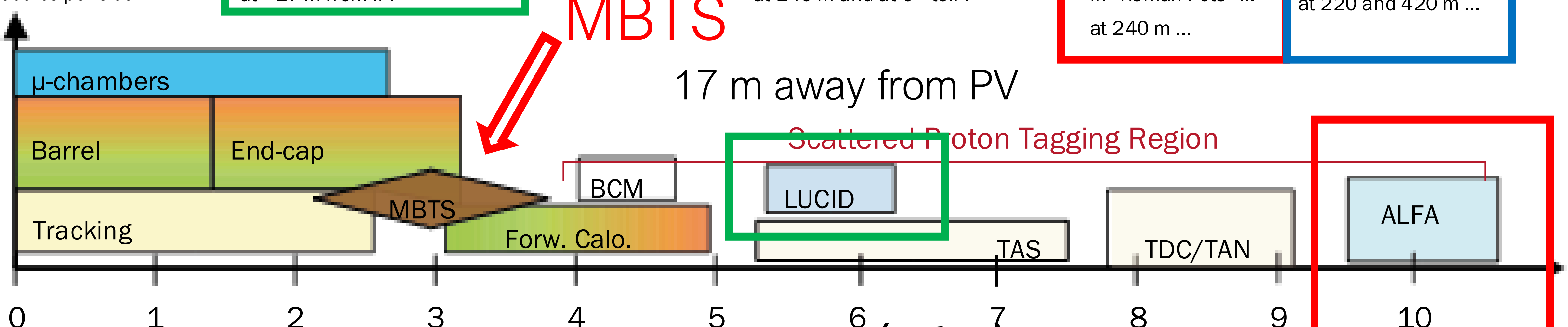
ALFA
[Absolute Lumi ...]
Fiber trackers in "Roman Pots" ...
at 240 m ...



AFP
[Track & ToF System]
LHC Upgrade ...
at 220 and 420 m ...

MBTS

17 m away from PV



(eta)

240 m away from PV

TAS: Target Absorber Secondaries
TAN: Target Absorber Neutrals

Cross Section & Luminosity

Vocabulary: efficiency ε is fraction of reconstructed objects measured by a detector; acceptance fraction of instrumented solid angle

Number of observed events
just count …

Background
measured from data or calculated from theory

$$N = L \times \sigma \Rightarrow \sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\,dt \cdot \varepsilon\, A}$$

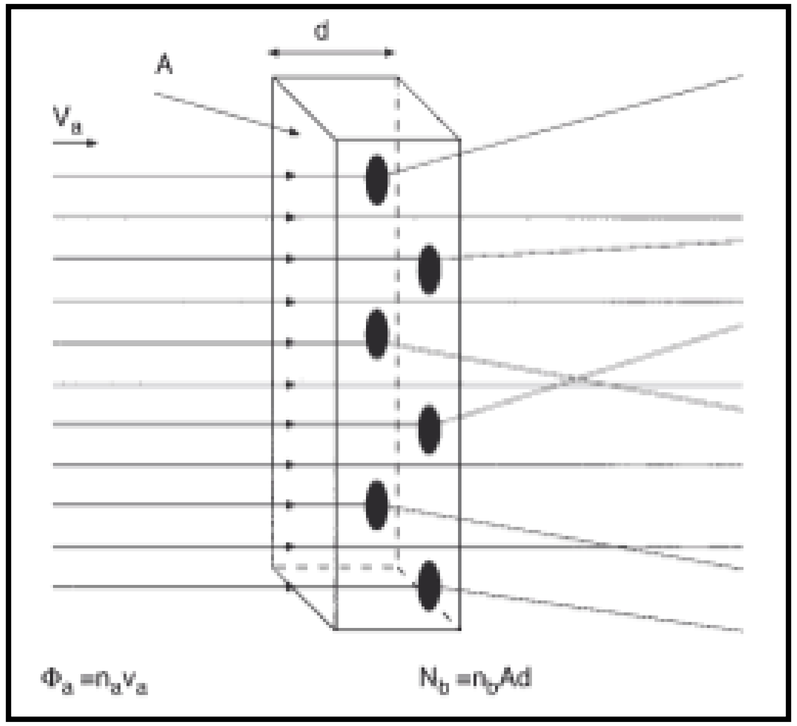
Efficiency
many factors, optimized by experimentalist

Luminosity
determined by accelerator, triggers, …

But also acceptance: correct for the fact all detectors are not full coverage

Cross Section & Luminosity

Colliders



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

- Φ_a : flux
- n_a : density of particle beam
- v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

- $\dot{N}$: reaction rate
- N_b : target particles within beam area
- σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

- L : luminosity

Instantaneous Luminosity

rate of events $\dot{N} \equiv L \cdot \sigma$

$$N = \sigma \cdot \underbrace{\int L\, dt} \qquad \sigma = N/L$$

integrated luminosity

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f\frac{nN_aN_b}{A} = f\frac{nN_aN_b}{4\pi\sigma_x\sigma_y}$$

σ_x, σ_y : not well known

LHC:

N_x	~	10^{11}
A	~	.0005 mm^2
n	~	2800
f	~	11 kHz
L	~	10^{34} cm^{-2} s^{-1}

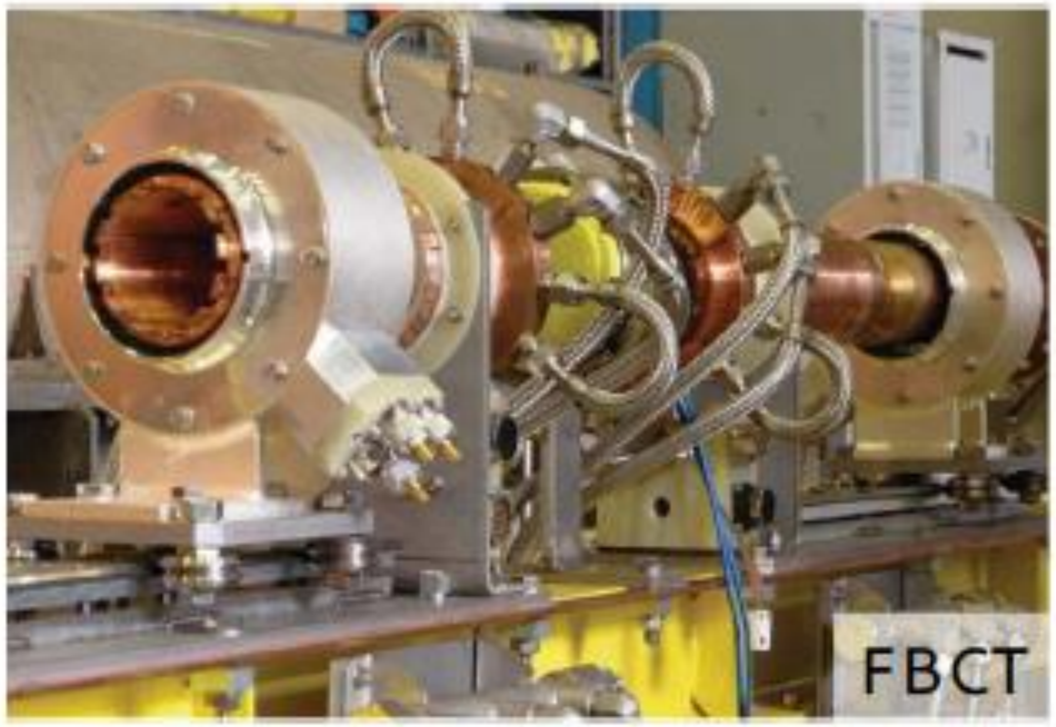
- N_a : number of particles per bunch (beam A)
- N_b : number of particles per bunch (beam B)
- U : circumference of ring
- n : number of bunches per beam
- v : velocity of beam particles
- *f* : revolution frequency
- A : beam cross-section
- σ_x : standard deviation of beam profile in x
- σ_y : standard deviation of beam profile in y

Measuring beam populations → N_1 N_2

DC Current Transformer

- total current measurement with high accuracy
- two in each beam

Fast Beam Current Transformer



- bunch-by-bunch current measurement
- two in each beam

bunch

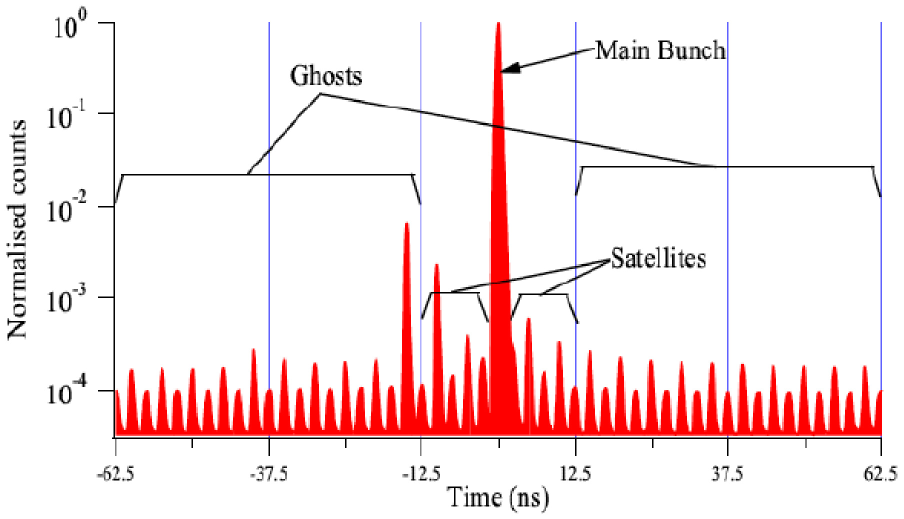
- Relative fraction of total current in each BCID from FBCT
- Normalization to overall current scale provided by DCCT

CERN-ATS-Note-2012-026
CERN-ATS-Note-2012-028
CERN-ATS-Note-2012-029

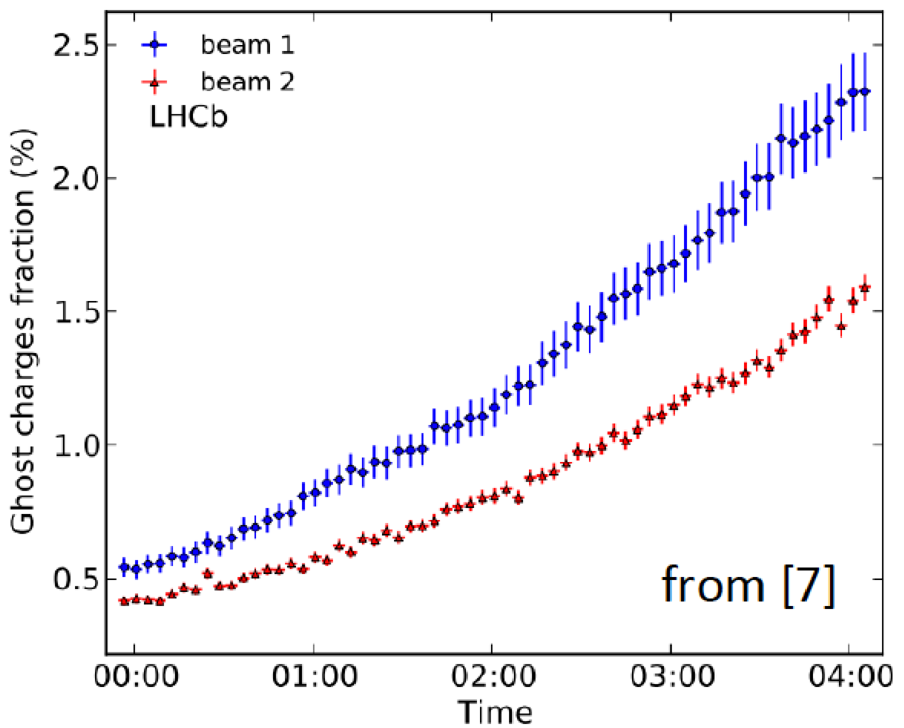
Kristof Kreutzfeldt, U. Gießen 15

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]

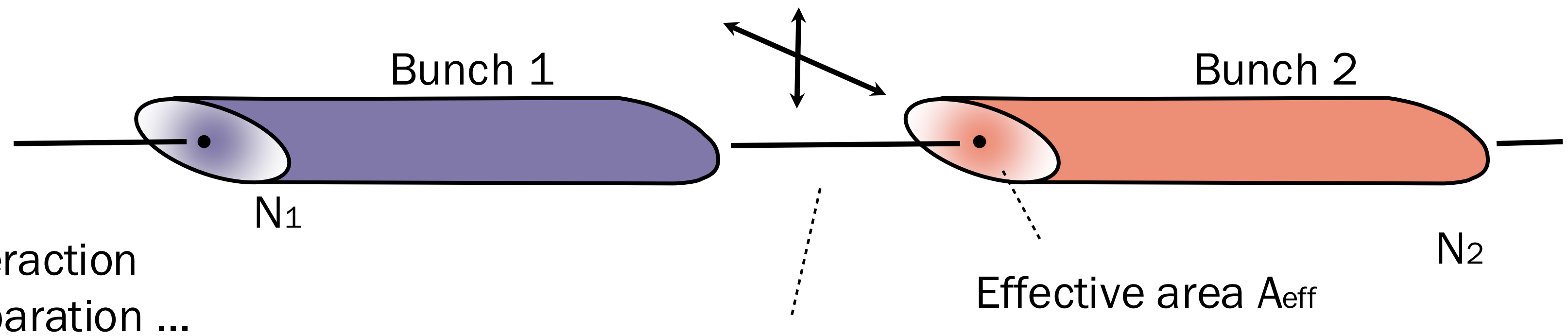


Van-der-Meer Separation Scan→ σ_x, σ_y

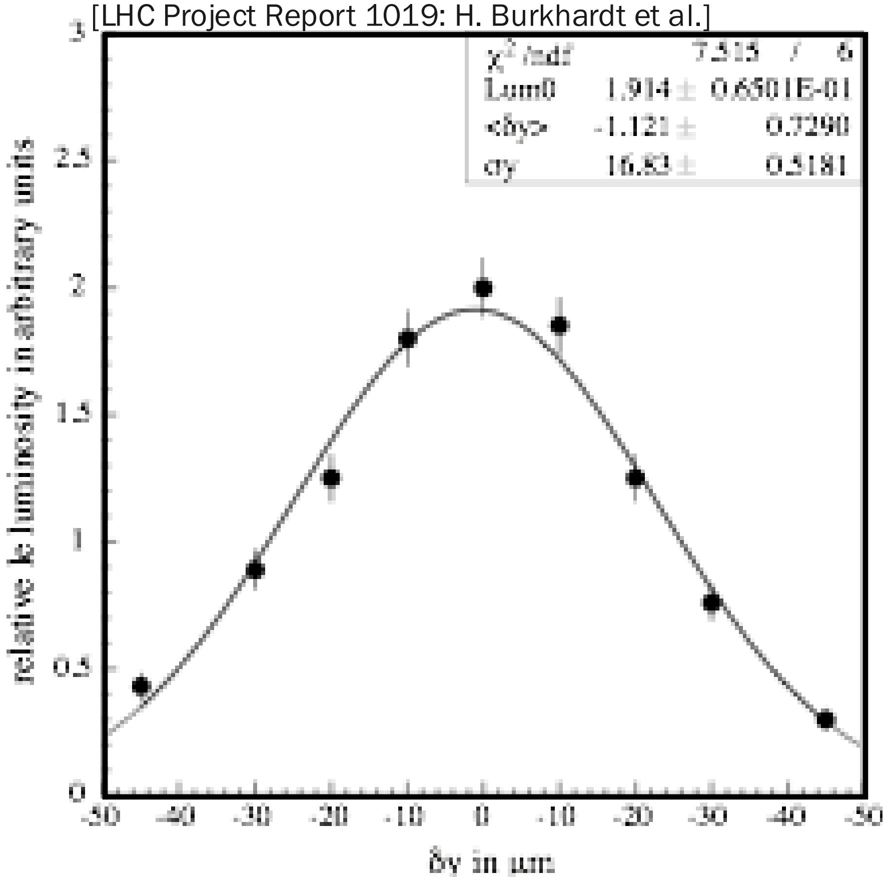
Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...

Move one beam wrt the other



[LHC Project Report 1019: H. Burkhardt et al.]



$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2\right]$$

Assumption: the two beams have the same profile!

[IPAC 2010, S. White et al.]

[November 2009].

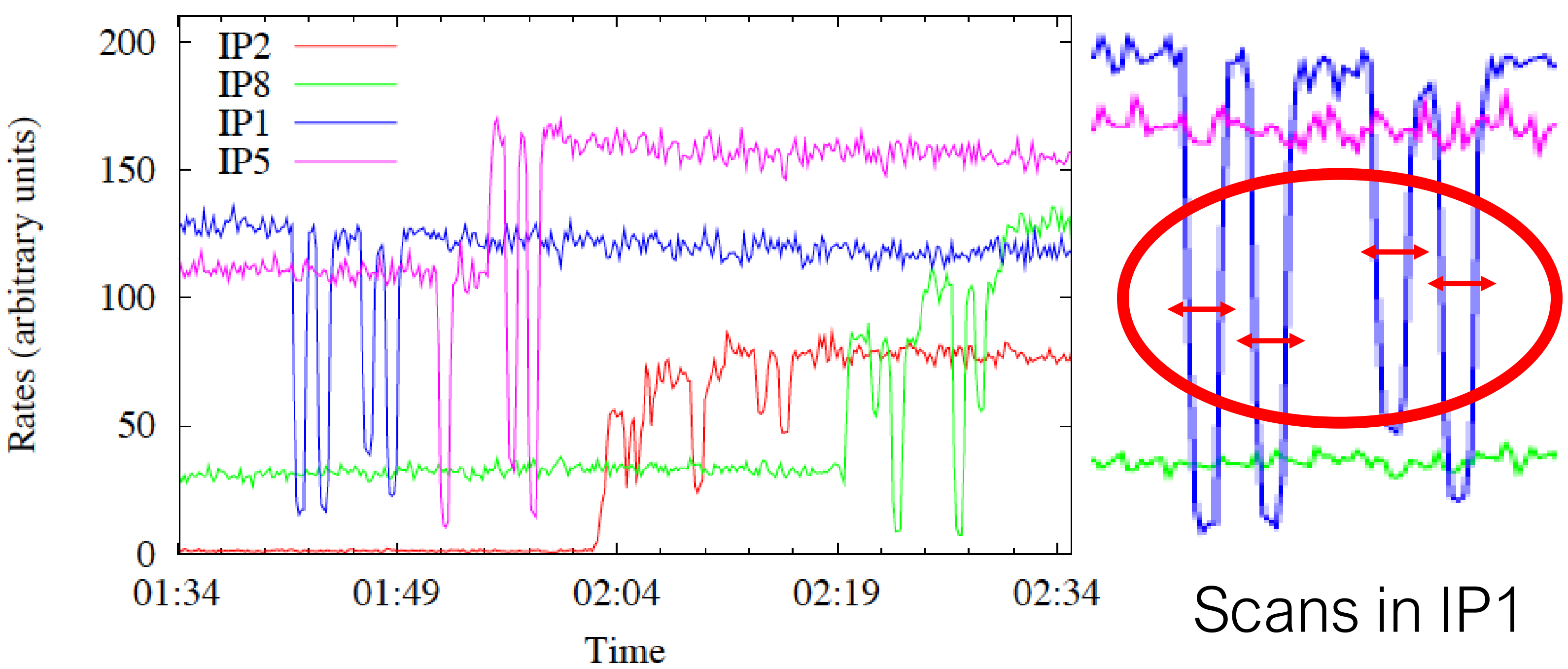


Figure 2: Optimization scans performed for squeezed optics in all IPs.

σ_x σ_y of the beam : factorability!

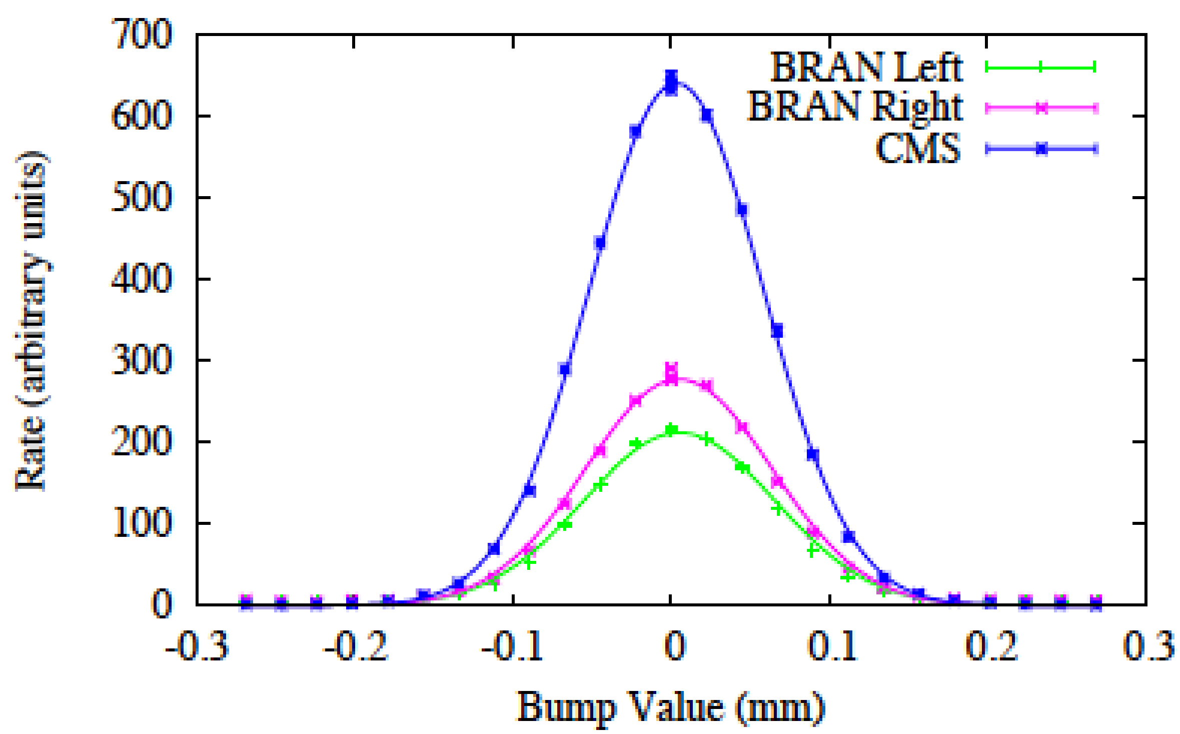
Assumption: factorization of beam density function: $\mathcal{L}(\delta_x, \delta_y) = f_x(\delta_x) \cdot f_y(\delta_y)$

$$\mathcal{L}_0 = \frac{N_1 N_2 f N_b}{2\pi\sqrt{(\sigma_{1x}^2 + \sigma_{2x}^2)(\sigma_{1y}^2 + \sigma_{2y}^2)}}$$

Factorizability

$$\sigma_u = \sqrt{\sigma_{1u}^2 + \sigma_{2u}^2} \text{ with } u = x, y$$

HP: particle densities in each bunch = product of two independent functions of x and y.



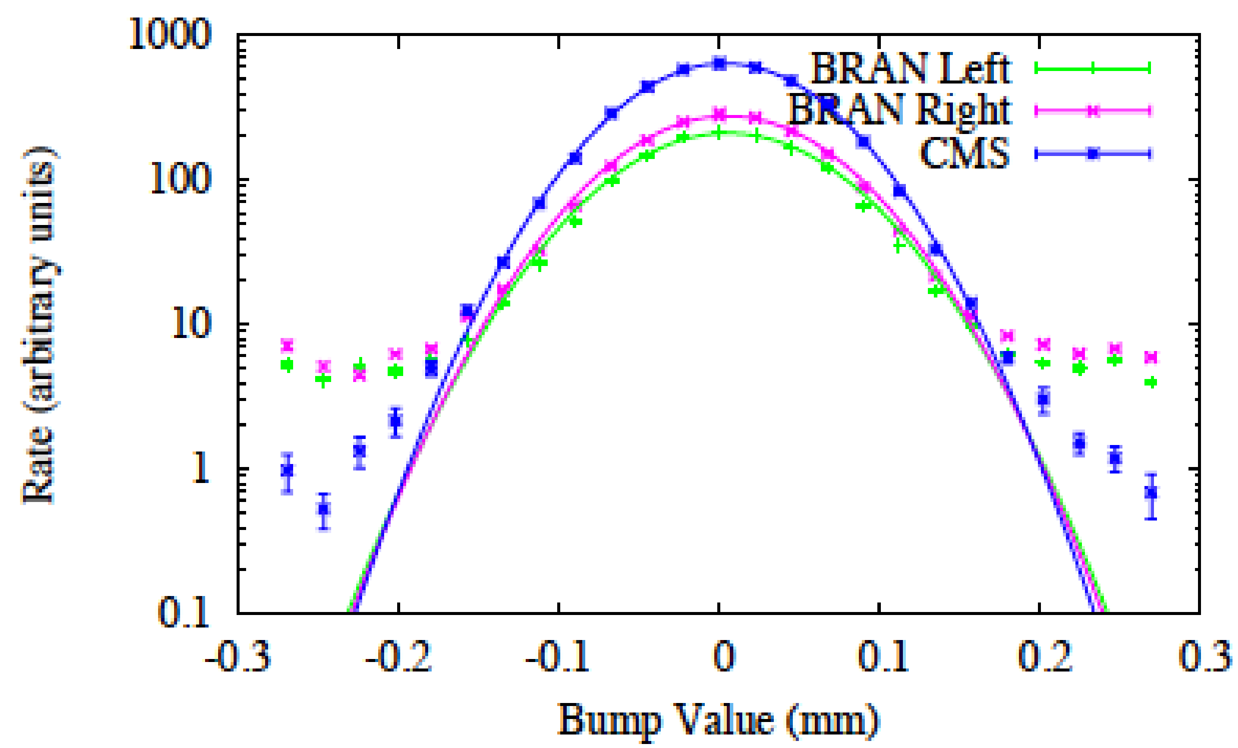
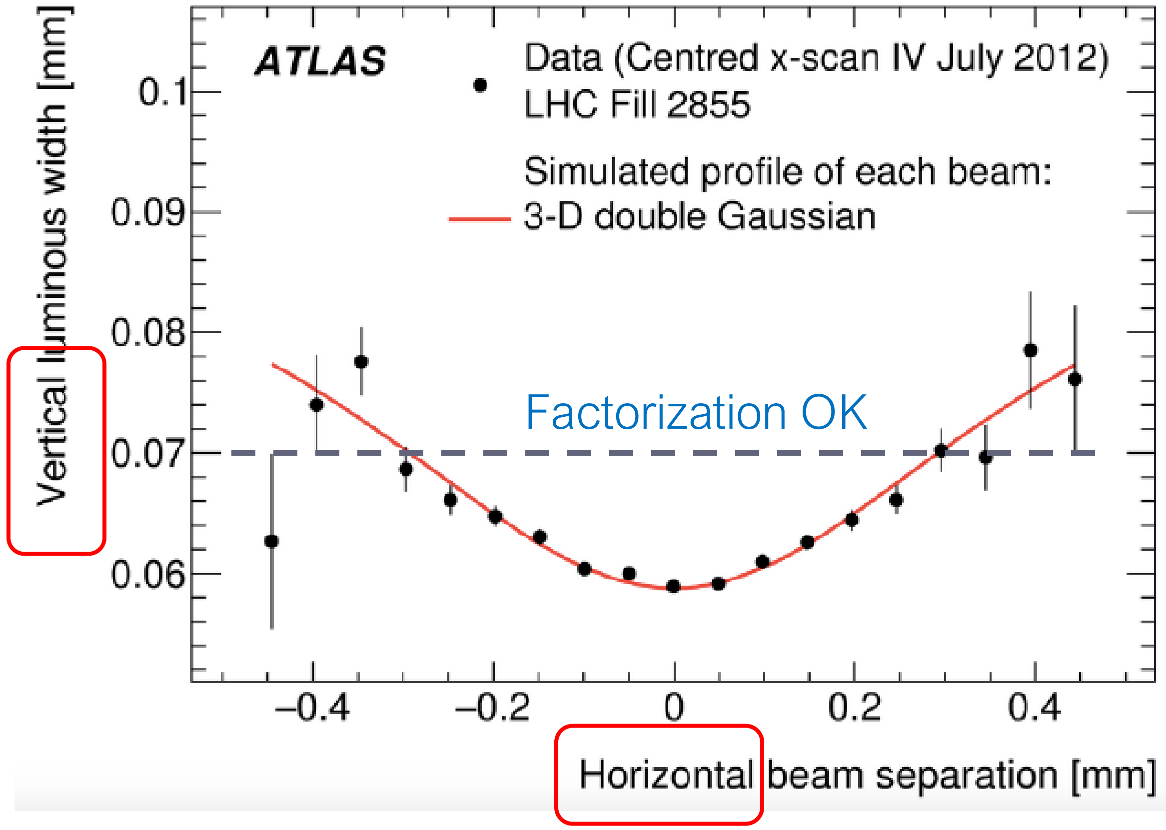


Figure 4: Same horizontal scan in IP5 shown in logarithmic scale with pure Gaussian fits.

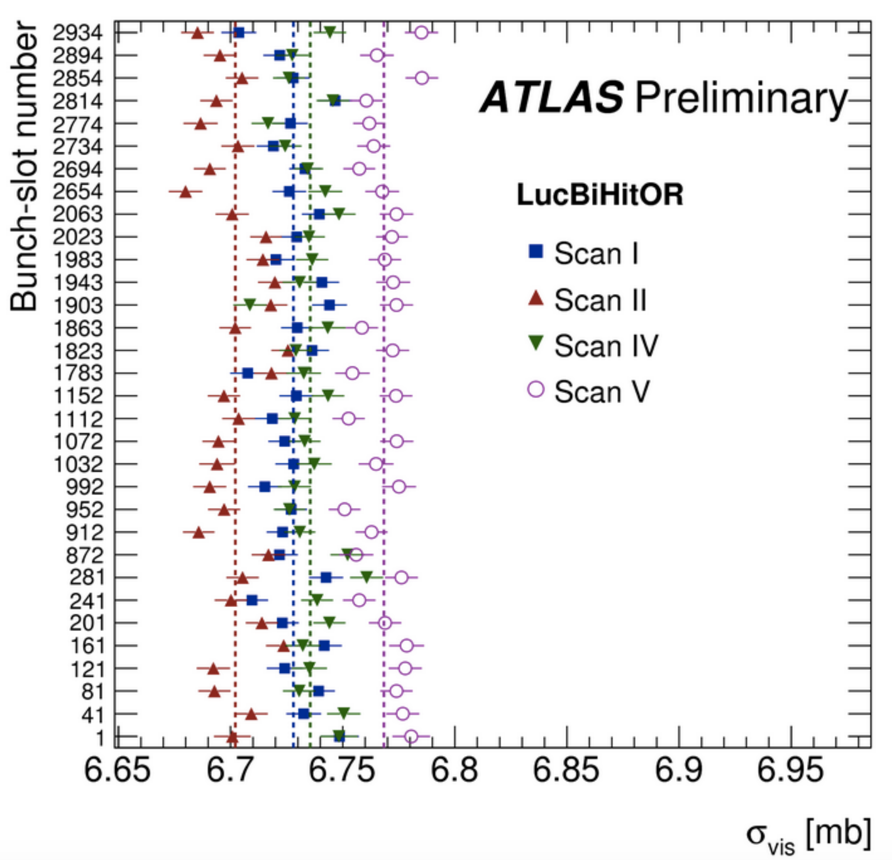
Systematic effects



Factorization

Signature of non-factorization effects: dependence of vertical convolved beam size and/or vertical luminous width on horizontal separation (and vice-versa).

- 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 %

Effect of non-factorizability

Date	Fill	n_{tot}	n_b	Scans
24/8/2015	4266	44	30	S1, S2, S3-off
25/8/2015	4269	51	8	S4, LSC
17/5/2016	4937	55	11	LSC
18/5/2016	4945	52	32	S1,S2, S3-off, S4, S5-diag
27/5/2016	4954	52	32	S6
28/7/2017	6016	52	32	S1, S2, S3-off, S4, S5, LSC
29/6/2018	6864	70	58	LSC
30/6/2018	6868	140	124	S1, S2, S3-off, S4, S5-off, S6

List of VdM scans in 2015/16/17/18

- n_{tot} total # of bunches in LHC
- n_b # colliding bunches

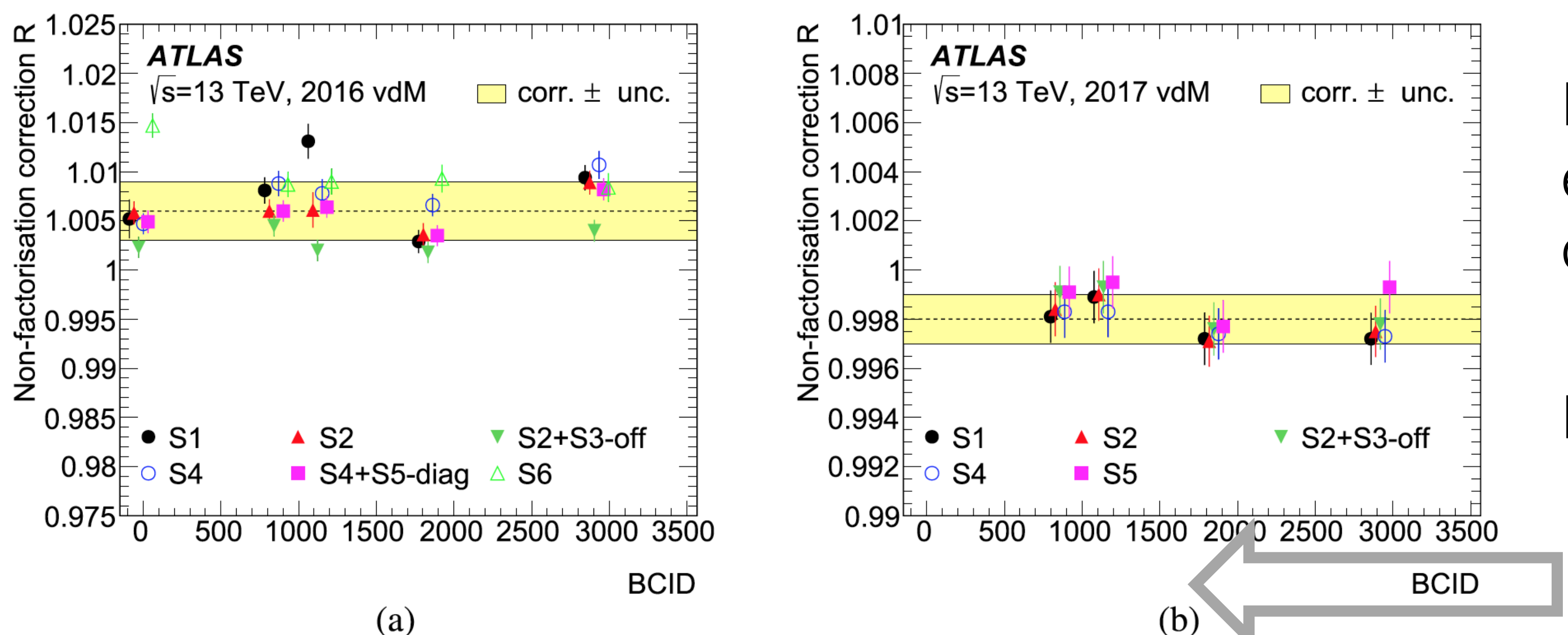


Fig. 2 Non-factorisation correction factors R for several colliding bunch pairs (BCID) and vdM scan sets in the (**a**) 2016 and (**b**) 2017 vdM sessions. The results were extracted from combined fits to the vdM luminosity scan curves and reconstructed primary vertex data, using either on-axis scans alone or combined fits to an on-axis scan and an off-axis or diagonal scan. The uncertainties are statistical. The dashed horizontal lines show the error-weighted mean corrections, and the yellow bands the uncertainties assigned from the RMS of the measured R values. The results from the different scans for each colliding bunch pair are slightly offset on the horizontal axis for clarity

Non-factorizability has the effect to modify slightly the computed luminosity

$\rightarrow R$

Effect is between .5 and 1%

Bunch # evenly distributed along LHC ring

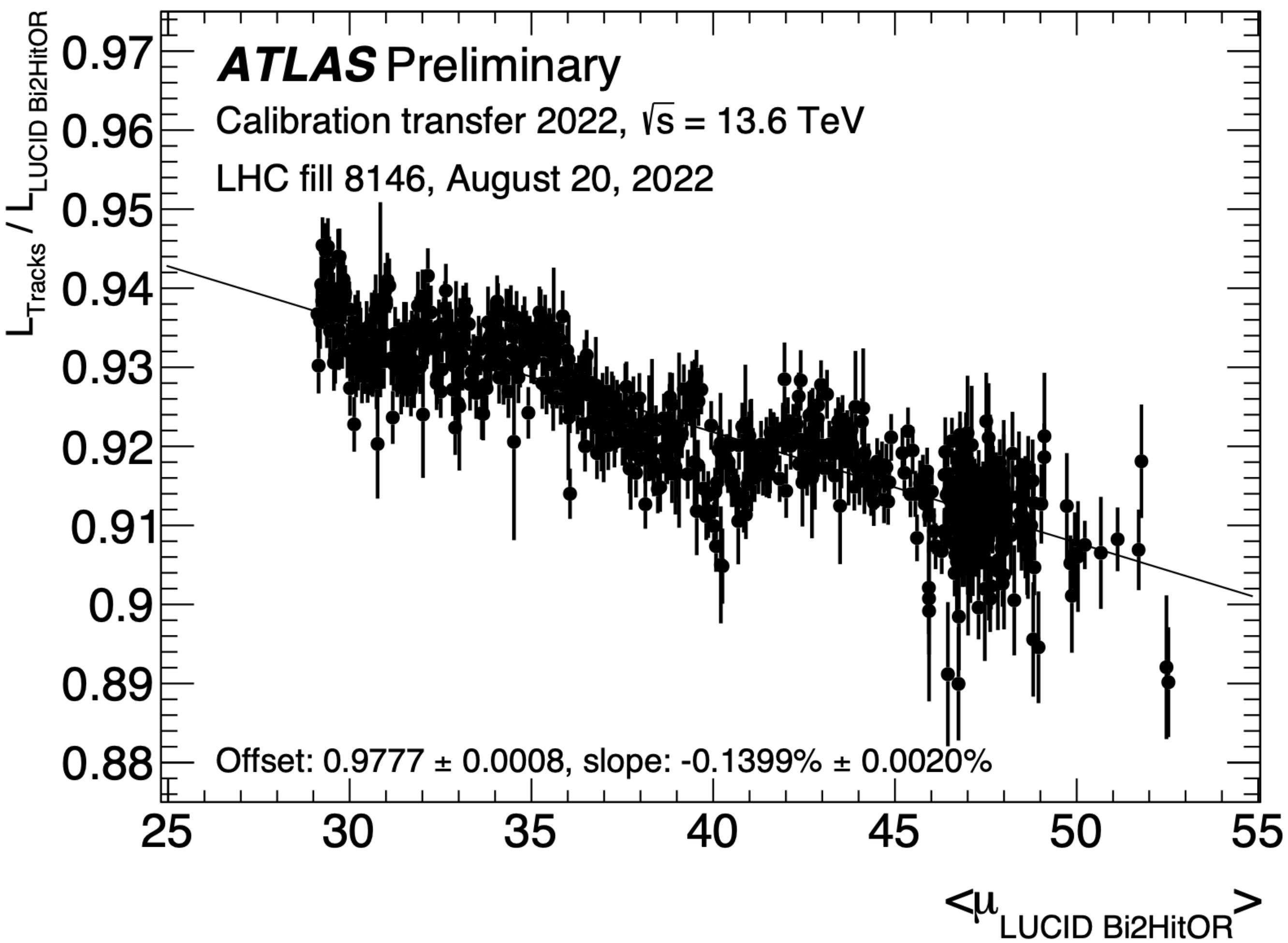
VdM scans in ATLAS

Table 2 Summary of the main characteristics of the 2010 and 2011 *vdM* scans performed at the ATLAS interaction point. Scan directions are indicated by "H" for horizontal and "V" for vertical. The values of luminosity/bunch and μ are given for zero beam separation.

Scan Number	I	II–III	IV–V	VII–IX
LHC Fill Number	1059	1089	1386	1783
Date	26 Apr., 2010	9 May, 2010	1 Oct., 2010	15 May, 2011
Scan Directions	1 H scan followed by 1 V scan	2 H scans followed by 2 V scans	2 sets of H plus V scans	3 sets of H plus V scans (scan IX offset)
Total Scan Steps per Plane	27 ($\pm 6\sigma_b$)	27 ($\pm 6\sigma_b$)	25 ($\pm 6\sigma_b$)	25 ($\pm 6\sigma_b$)
Scan Duration per Step	30 s	30 s	20 s	20 s
Bunches colliding in ATLAS & CMS	1	1	6	14
Total number of bunches per beam	2	2	19	38
Typical number of protons per bunch ($\times 10^{11}$)	0.1	0.2	0.9	0.8
Nominal β-function at IP [$\beta^\star$] (m)	2	2	3.5	1.5
Approx. transverse single beam size σ_b (μm)	45	45	57	40
Nominal half crossing angle (μrad)	0	0	± 100	± 120
Typical luminosity/bunch ($\mu b^{-1}/s$)	$4.5 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$	0.22	0.38
μ (interactions/crossing)	0.03	0.11	1.3	2.3

Low luminosity runs, clean measurement

Extrapolating the VdM $\mathcal{L}$ ⇢ *LUCID*



Extrapolation depends on

- Number of bunches
- Number of superimposed interactions

$$\mathcal{L}_{\text{inst}} = \sum_{b=1}^{n_b} \mathcal{L}_b = n_b \langle \mathcal{L}_b \rangle = n_b \frac{\langle \mu \rangle f_r}{\sigma_{\text{inel}}}$$

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

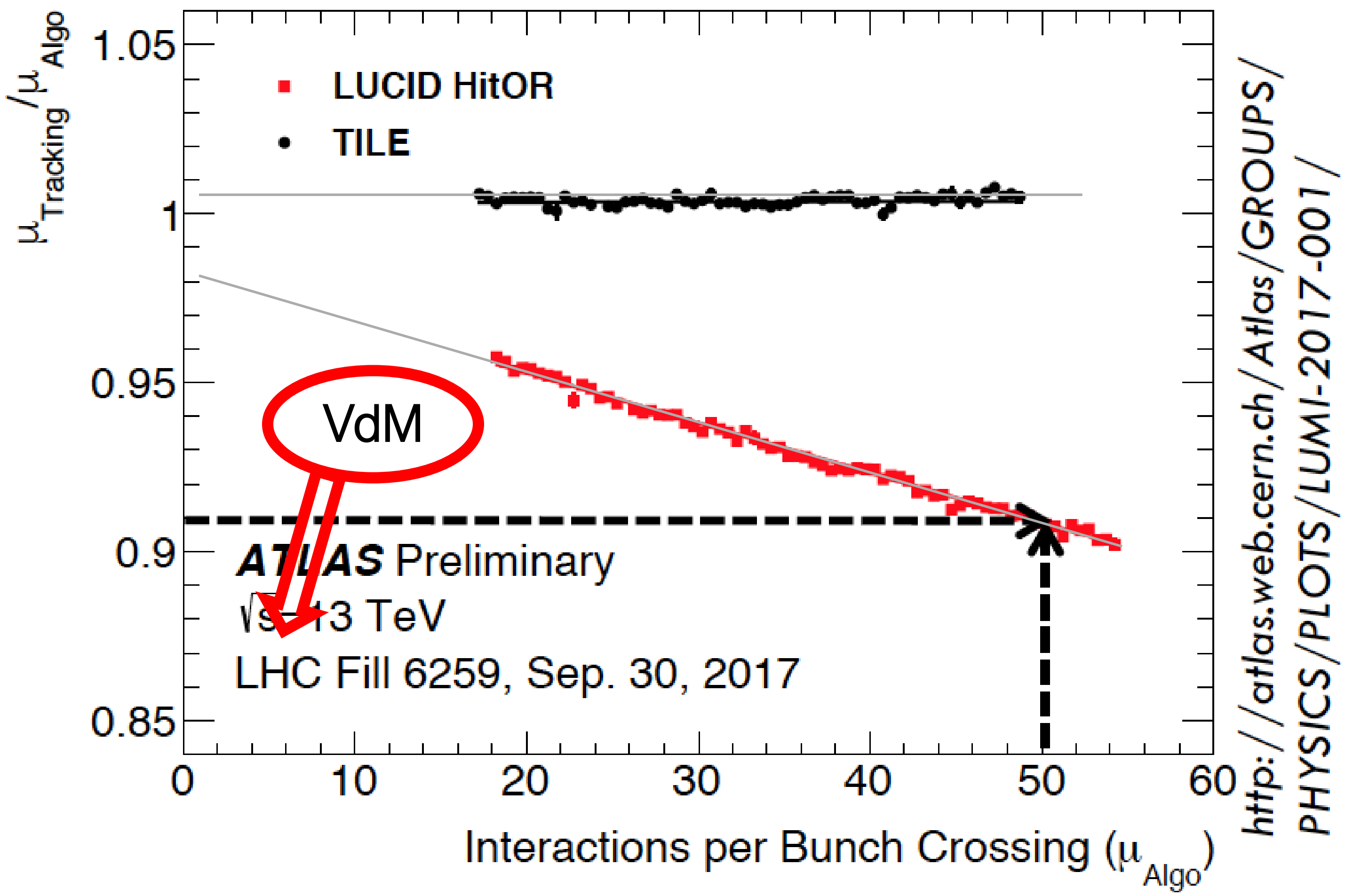
Extrapolation of luminosity calibration	**Used cell families**	**Range of shifts across used cell families**
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 40$, 1154b, trains)	A13, A14	[-0.1, 0.8]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 45$, 144b, trains)	A13, A14, E3, E4	[0.1, 0.7]%
($\mu \approx 45$, 144b, trains) → ($\mu \approx 40$, 1154b, trains) (*)	A13, A14	[0.0, 0.4]%
Combined 2-step extrapolation		[0.1, 1.1]%
Upper limit on extrapolation impact (rounded)		< 1%
Effect of missing laser corrections (linearly added)	A14	0.5%
Upper limit on total extrapolation impact		**< 1.5%**

1 step extrapolation: # bunches & μ

2 steps extrapolation:

bunches first and then μ

Calibration Transfer



- Van der Meer scan (low L, low μ, few bunches far apart)
- Physics (high L, high μ, more than 2000 bunches in trains of 25 ns)

Q: how to extrapolate ?

A: tracking luminosity (~#tracks) is not (or very little) sensitive to bunches and pile-up.

Non-linearity correction from Tracking

ATLAS: typical correction @ μ = 50 for LUCID hit counting in 2017: - 9%

Systematic uncertainty evaluated by comparing with calorimeter-based correction in 2017: ±1.3%

CMS: Non-linearity correction from emittance-scan analysis (i.e. "absolute")

typical correction @ μ = 50 for HFET in 2017: 1.5 %

Systematic uncertainty evaluated by comparing residual relative non-linearity of luminometers on 2017: ±1.5%

Some details on the bunch structure

- One LHC bunch is a sum of 'buckets' 1–1.5 ns long
- Ideally, all particles should be contained within the nominally filled bunches;
- Experience: correct to about 1–2% (for LHC p beams and about 5%for LHC Pb)

Luminosity needs the total bunch populations of the two rings:

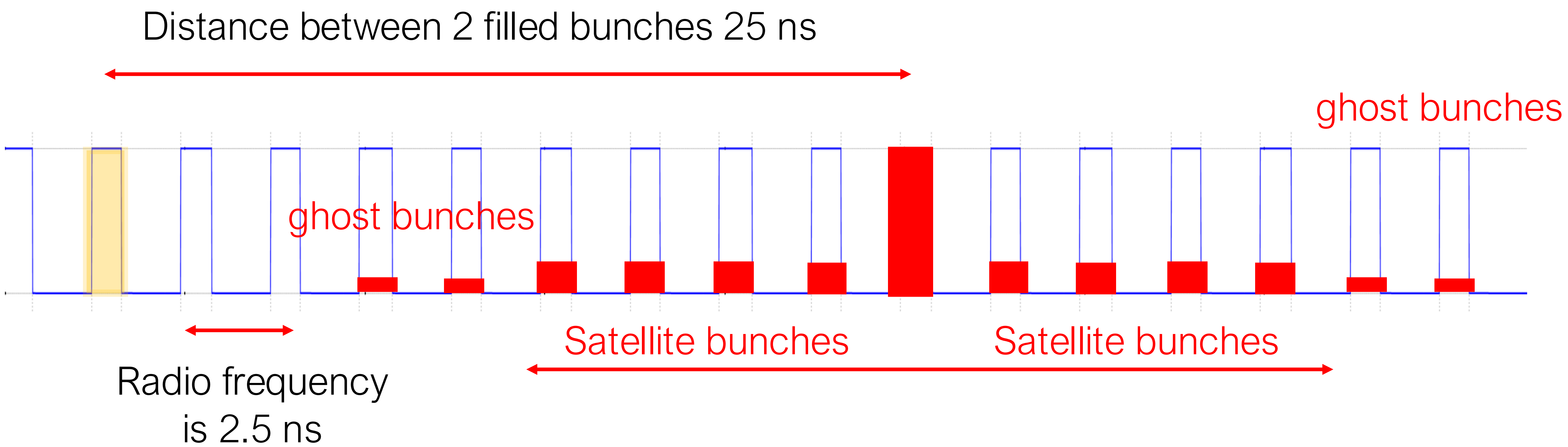
- Nominal bunches (main)
- satellite bunches
- ghost charge.

The total beam population of beam j = 1 or 2 (measured with the DCCTs [3]) is assumed to be the sum of the following components

$$N_{tot}^{j=1,2} = N_{main}^{j=1,2} + N_{ghost}^{j=1,2} + N_{pilot}^{j=1,2}$$

where N_{main}, j is the charge of all slots nominally filled with a high intensity bunch (a 'main' bunch), N_{ghost}, j is the ghost charge and N_{pilots}, j the charge of all slots containing a 'pilot' bunch (not used in all fills, see below). In our definition, **the term N_{main}, j is what is needed to determine the scale of the cross section, after correcting for the effects of satellite bunches.**

Some details on the bunch structure



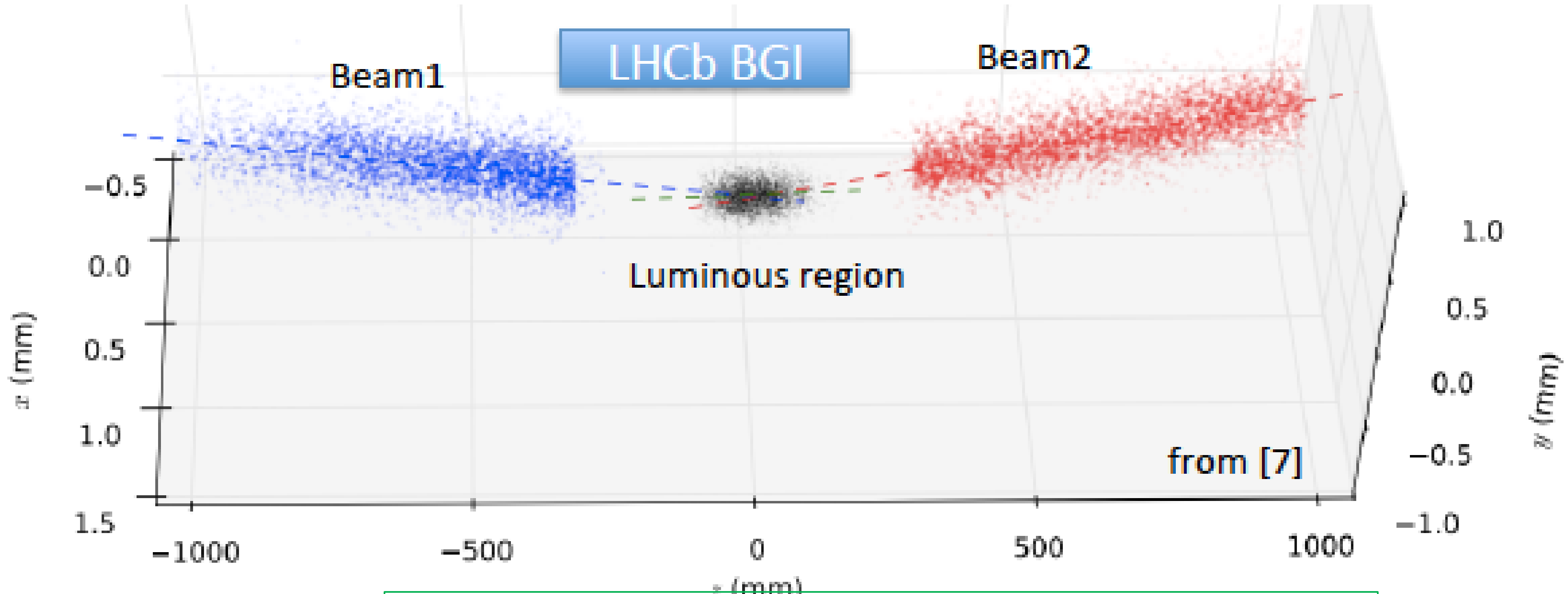
The particles of an LHC bunch are contained within a bucket 1–1.5 ns long. Ideally, all particles should be contained within the nominally filled RF bins. Experience has shown that this is typically correct to an accuracy of about 1–2%

In the phase of filling beams also *pilot* bunches are injected to check the orbit of a fill

$$N_{tot}^{j=1,2} = N_{main}^{j=1,2} + N_{ghost}^{j=1,2} + N_{pilot}^{j=1,2}, j = beam\#$$

An alternative approach: BGI

- **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



The direction of tracks (forward backward)
→ vertices to a beam 1 or 2.

Uncertainties - 1

- 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	

Key assumption: factorization of bunch proton density function → Factorizability

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

Snapshot of Luminosities uncertainties

Parts of table reproduced from [11]

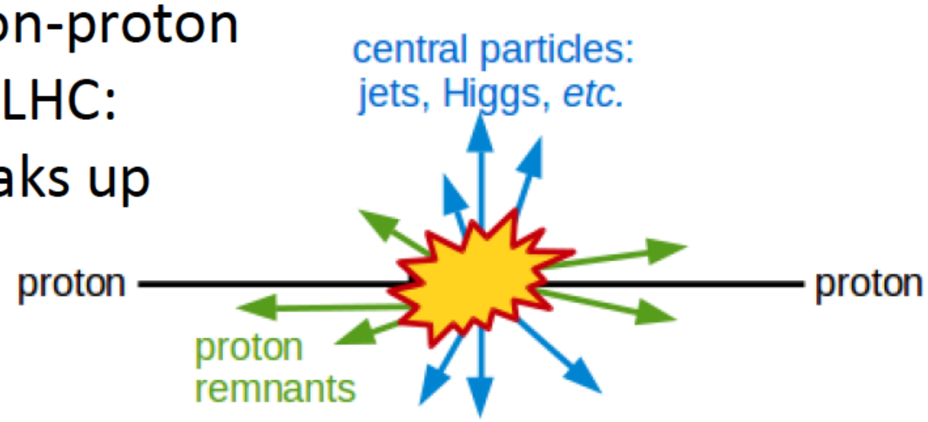
	ALICE	ATLAS	CMS	LHCb
Running period	2013	2011	2012	2012
Sqrt(s) [TeV]	5.02	7	8	8
Running mode	**Pb-p**	**p-p**	**p-p**	**p-p**
Reference	[8]	[9]	[10]	In the process of being made publicly available
Absolute calibration method	VdM	VdM	VdM	VdM + BGI *
$\Delta\sigma_{vis}/\sigma_{vis}$ [%]	**2.8**	**1.53**	**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**

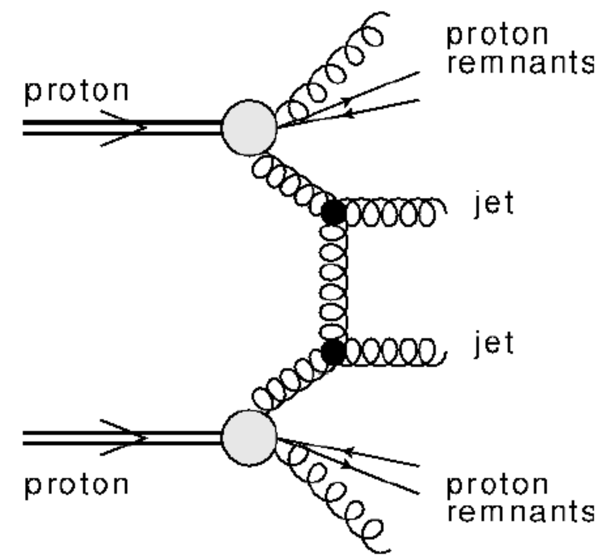
*uncertainties of both methods almost equal in size

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

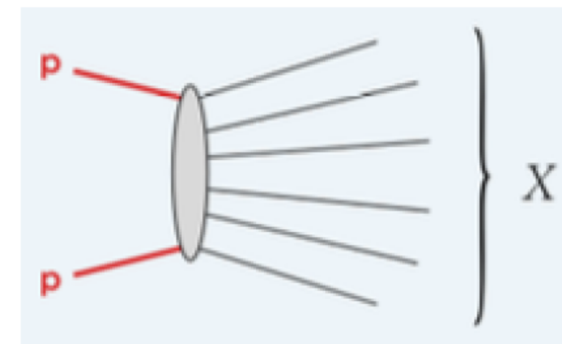
Collisions at LHC

- Usual proton-proton collision at LHC: proton breaks up



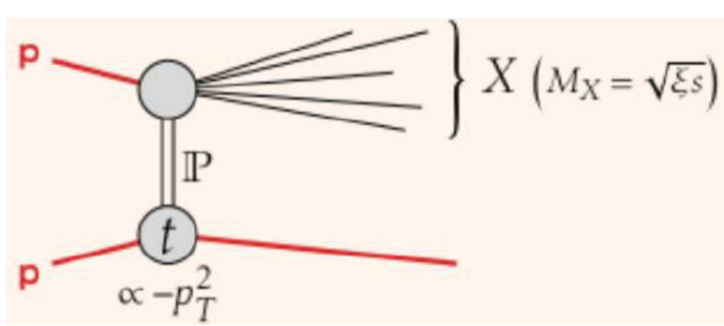


Non-diffractive

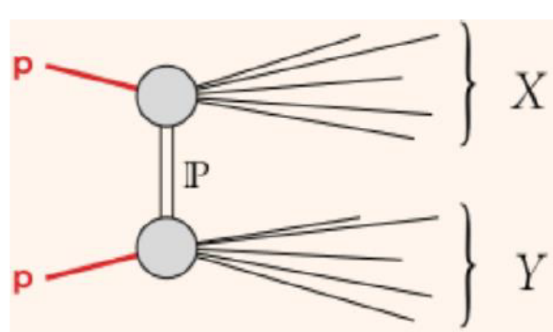


- Proton-proton interaction via photon (γ), electromagnetic force, or pomeron (P) exchange, strong force: proton can remain intact

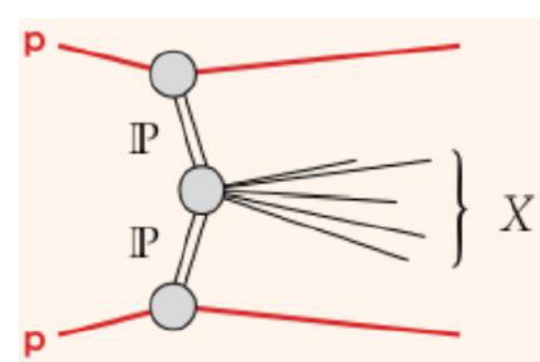
Single diffractive



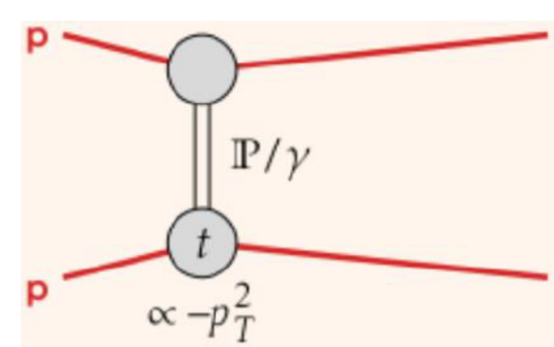
Double diffractive



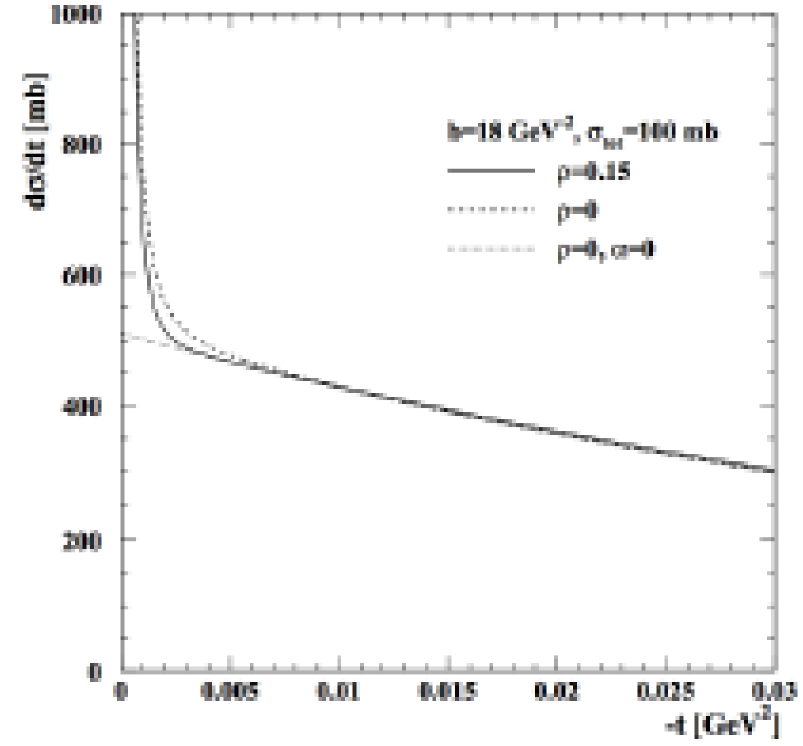
Central diffractive



Elastic scattering



Optical theorem basics



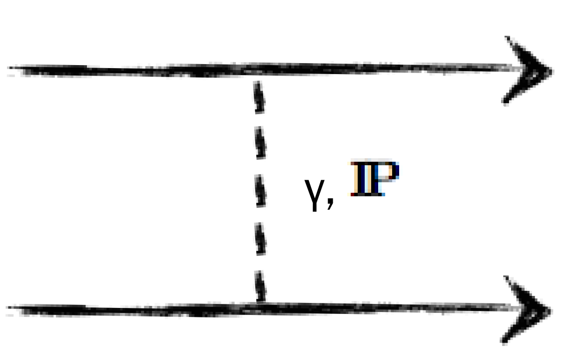
- TOTEM for CMS and ALFA for ATLAS are able to perform absolute luminosity measurements
- Based on Optical theorem
  - Measurements of the total rate in combination with the t-dependence of the elastic cross section (TOTEM)
  - Measurements of elastic scattering rates in the Coulomb interference region(ALFA)

$$N = L\,\sigma \rightarrow L = N / \sigma$$

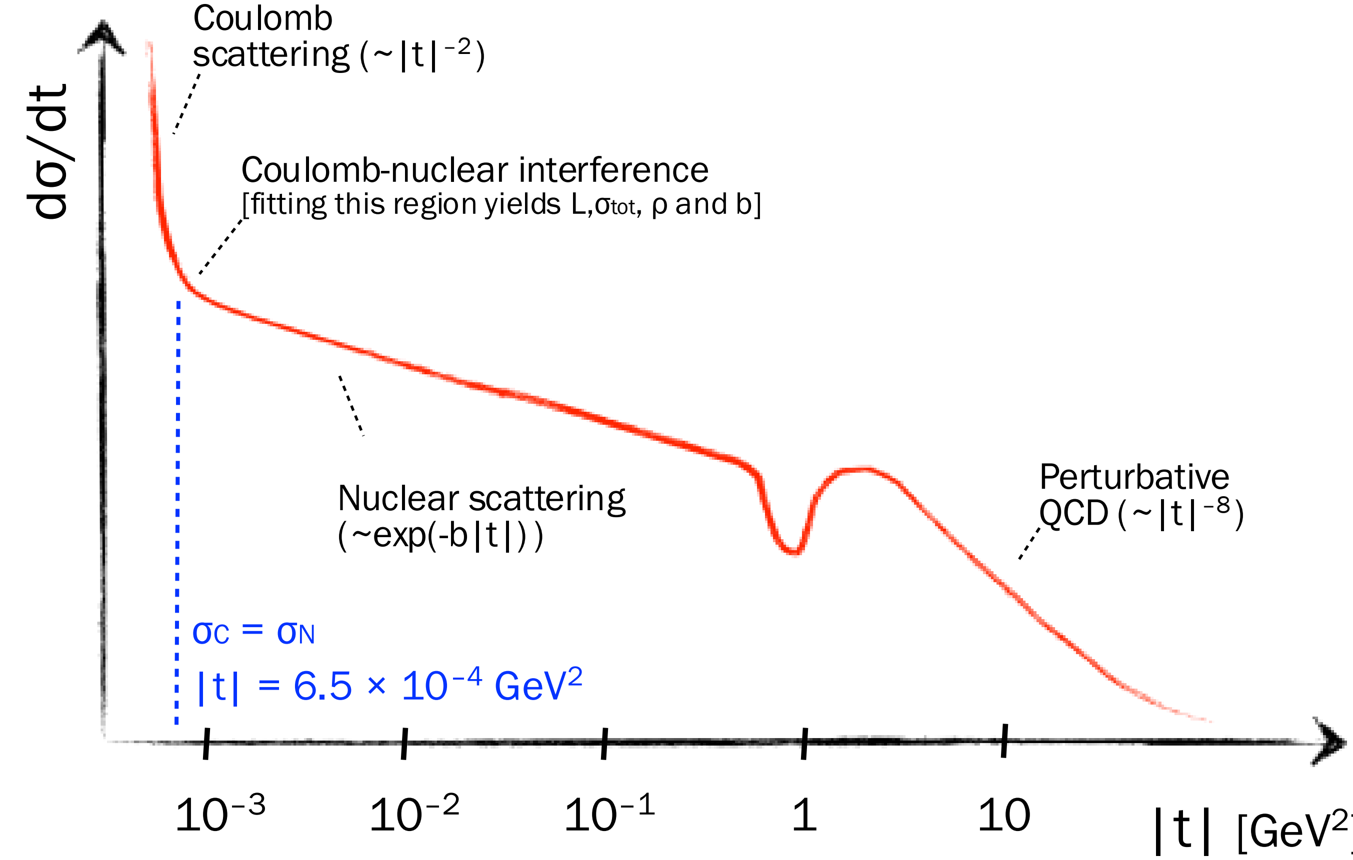
- Requires dedicated LHC fills with special magnet settings
- Roman pots far from the interaction points (about 200 m)
- Measurements at very low interaction rates
  - Cross-calibration of dedicated luminosity detectors
  - Extrapolation of calibration to typical physics conditions introduces big uncertainties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

ALFA – Absolute Luminosity for ATLAS

Elastic Scattering:



$$t = (p_i - p_i') \sim p^2\theta^2$$



Elastic Scattering at low t is sensitive to exactly known Coulomb amplitude ...

Shape of elastic scattering distribution can also be used to determine total cross section, σ_{tot}, and the parameters ρ and b ...

Perform fit to:

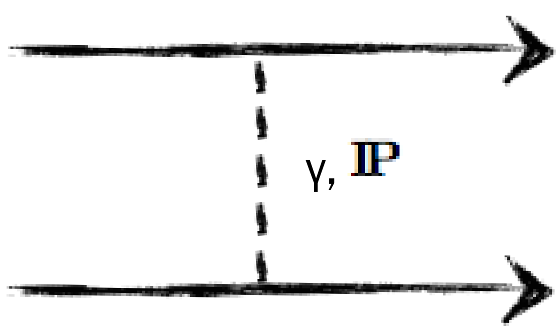
$$\frac{dN}{dt} = L\left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{\text{tot}}e^{\frac{-b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma_{\text{tot}}^2(1+\rho^2)e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}\right)$$

with:

- ρ : ratio of the real to imaginary part of the elastic forward amplitude
- b : nuclear slope
- σ_{tot} : total pp → X cross section

ALFA – Absolute Luminosity for ATLAS

Elastic Scattering:



$$t = (p_i - p_i') \sim p^2\theta^2$$

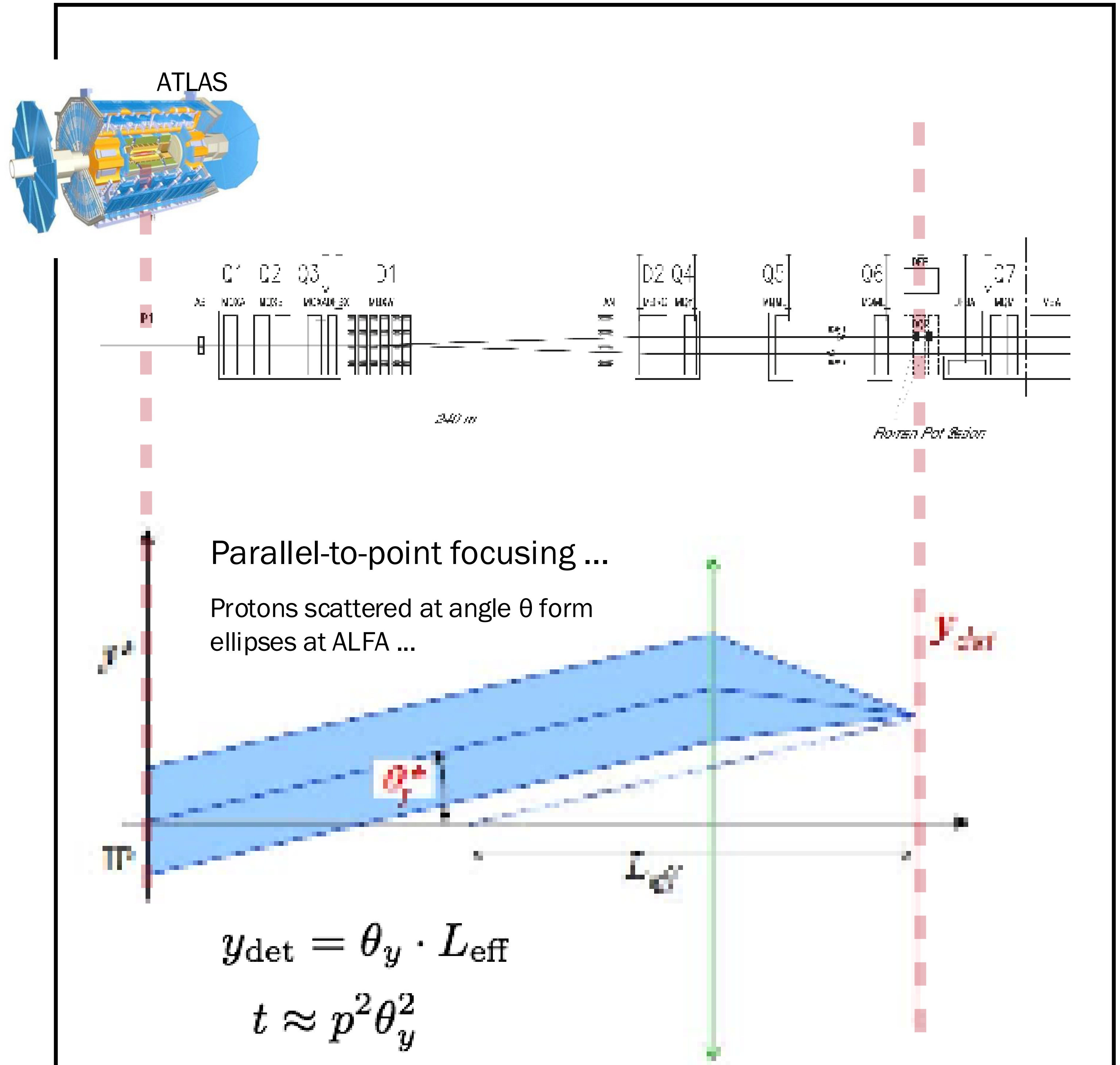
$t \approx 10^{-3}\ \mathrm{GeV}^2$

→ $\theta \approx 5 \cdot 10^{-6} = 5\ \mu\mathrm{rad}$
$L_{\mathrm{eff}} \approx 240\ \mathrm{m}$
[Depends on beam optics]

→ $y_{\mathrm{det}} \approx 1.5\ \mathrm{mm}$

→ Need proton detection 1.5 mm from beam ...

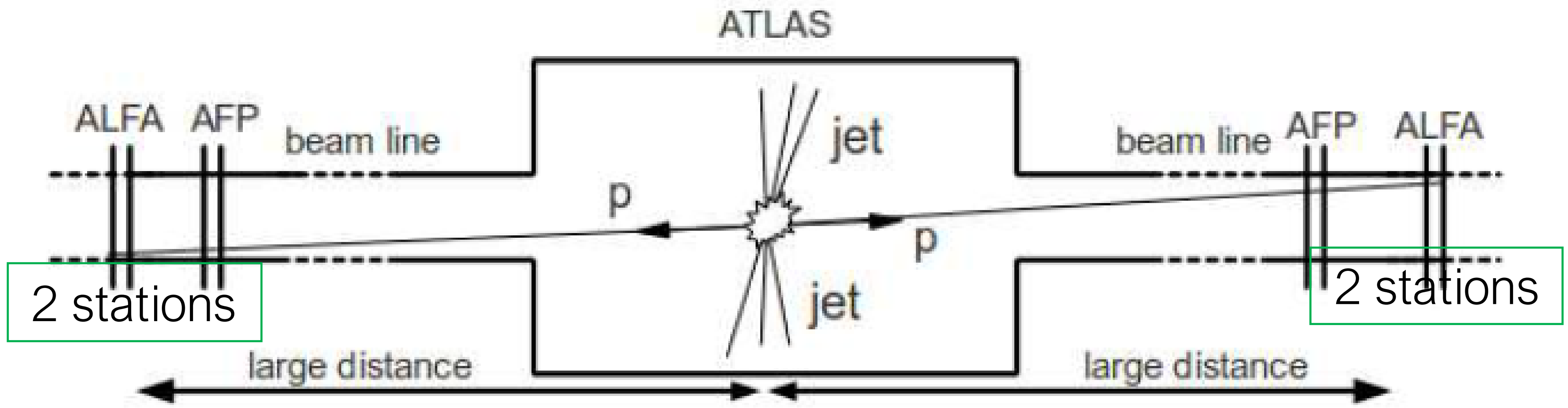
Use of Roman Pot detectors ..



AFP & ALFA : geometry

Forward Detectors @ IP1

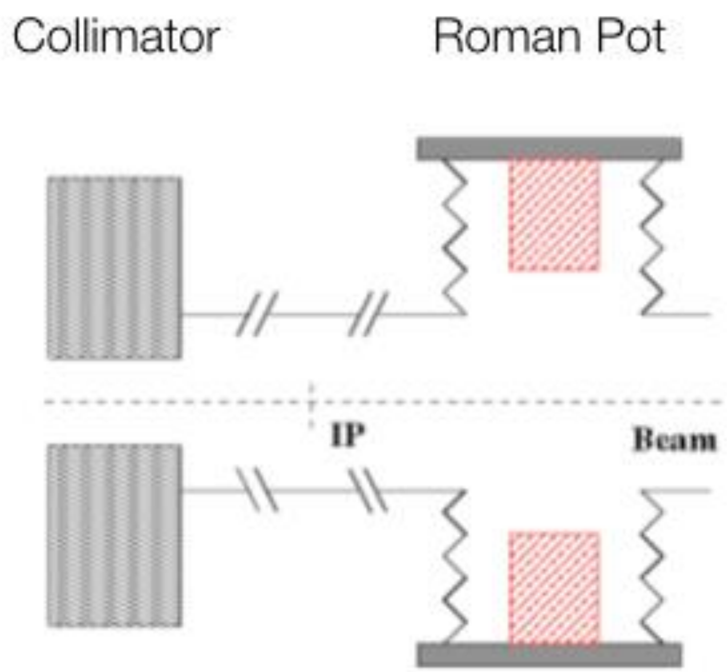
Intact protons → natural diffractive signature → usually scattered at very small angles (μrad) → detectors must be located far form the Interaction Point.

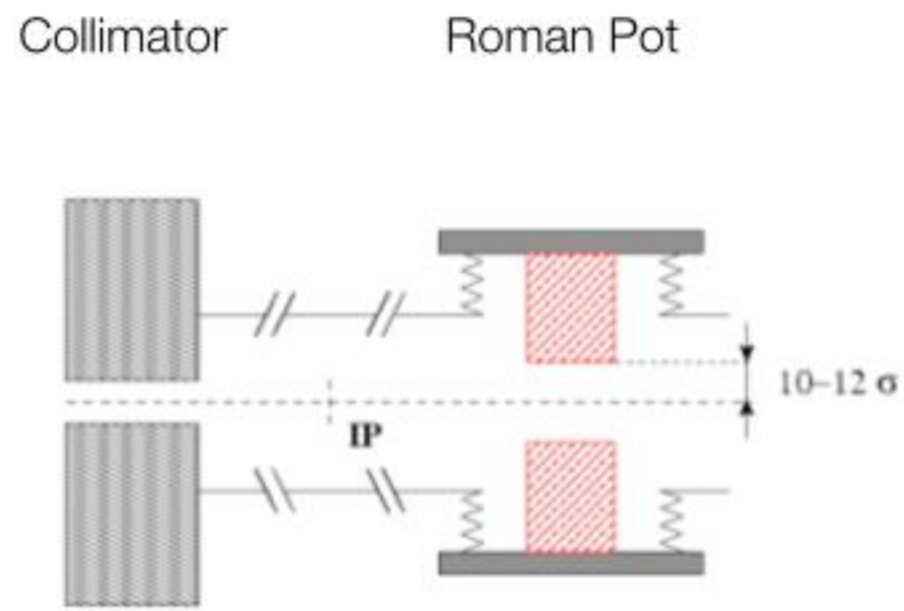


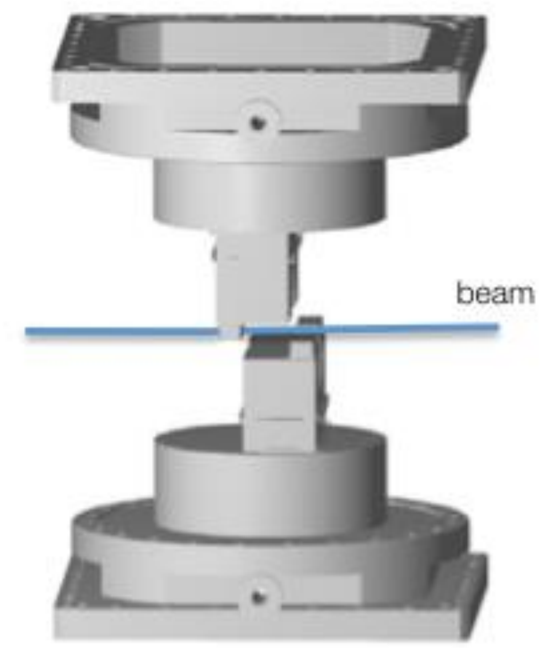
ALFA	AFP
• **A**bsolute **L**uminosity **F**or **A**TLAS	• **A**TLAS **F**orward **P**roton
• exist, 240 m from ATLAS IP	• exist 210 m from ATLAS IP
• soft diffraction (elastic scattering)	• hard diffraction
• special runs (high β^* optics)	• nominal runs (collision optics)
• vertically inserted Roman Pots	• horizontally inserted Roman Pots
• tracking detectors, resolution: $\sigma_x = \sigma_y = 30\ \mu m$	• tracking detectors, resolution: $\sigma_x = 10\ \mu m$, $\sigma_y = 30\ \mu m$
	• timing detectors, resolution: $\sigma_t \sim 20$ ps

Similar Devices @ IP5: CMS-TOTEM.

ALFA – Absolute Luminosity for ATLAS





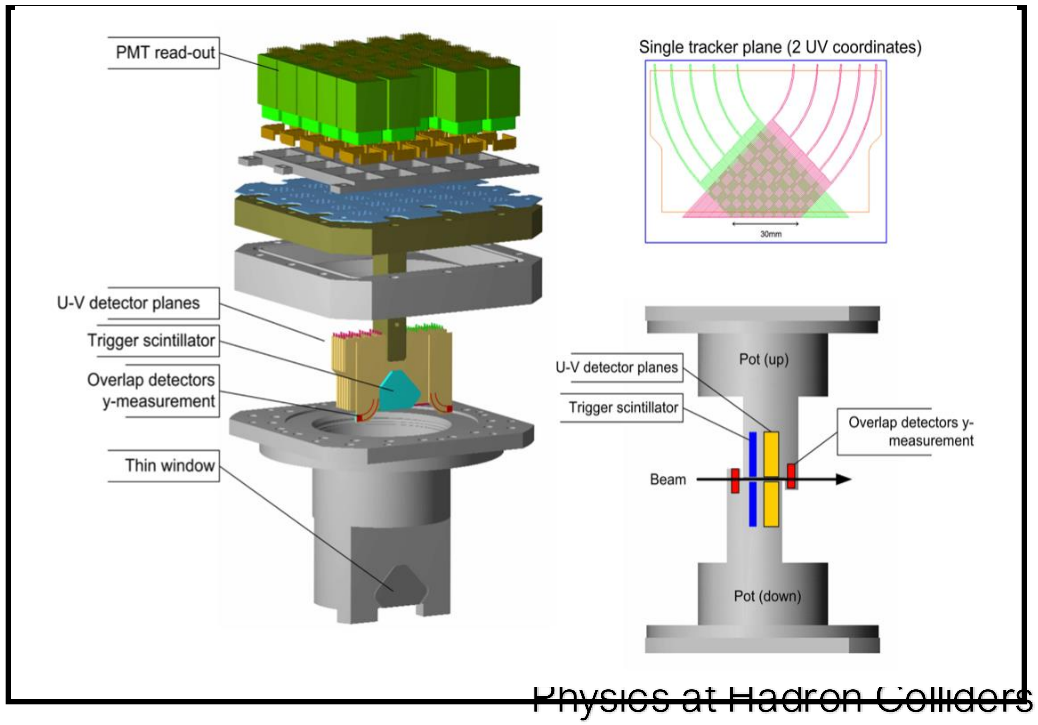


Roman Pots, based on modified Totem design, used to move detectors near to stable beam.

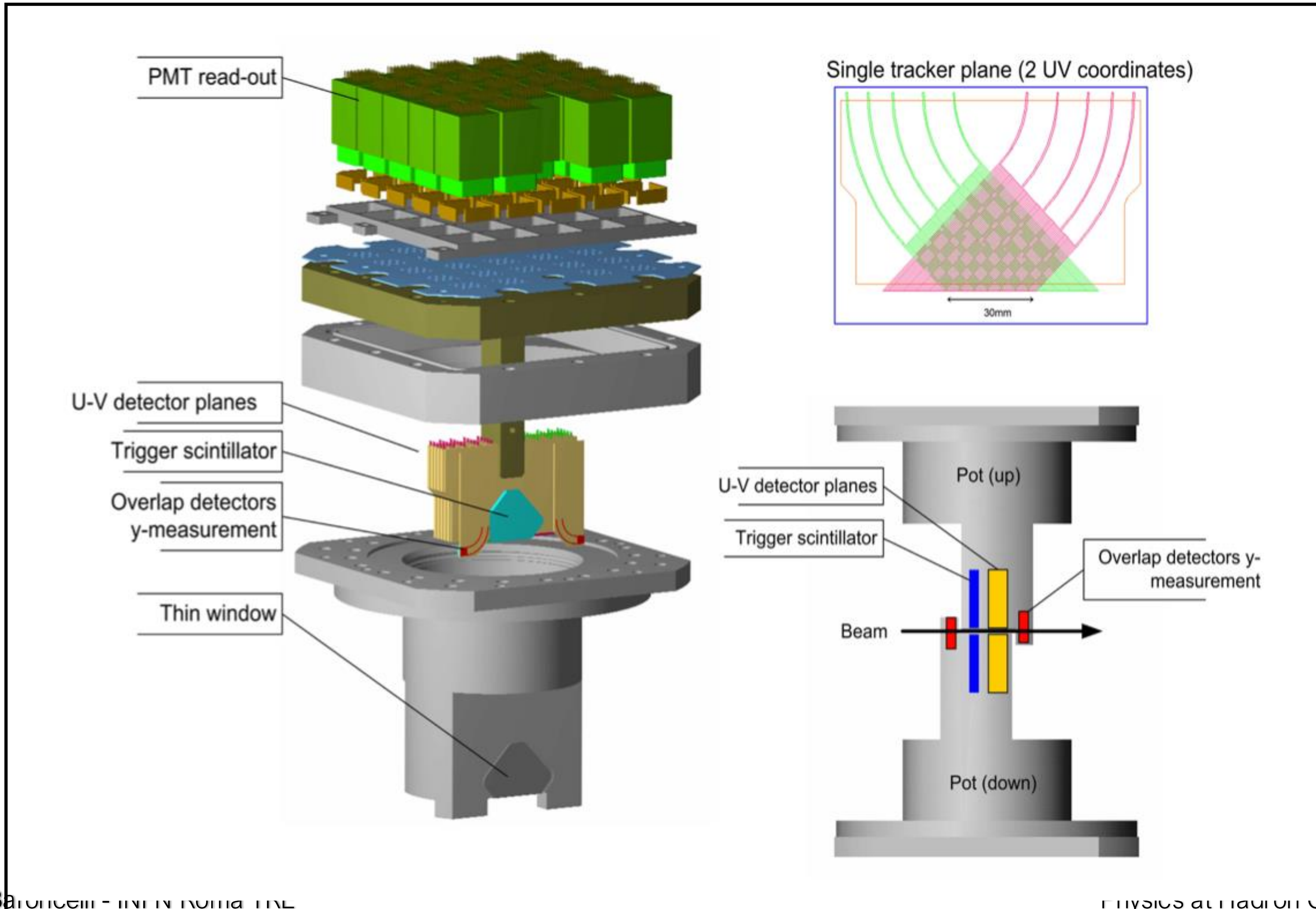
Detectors in vertical plane only.

Calibration:

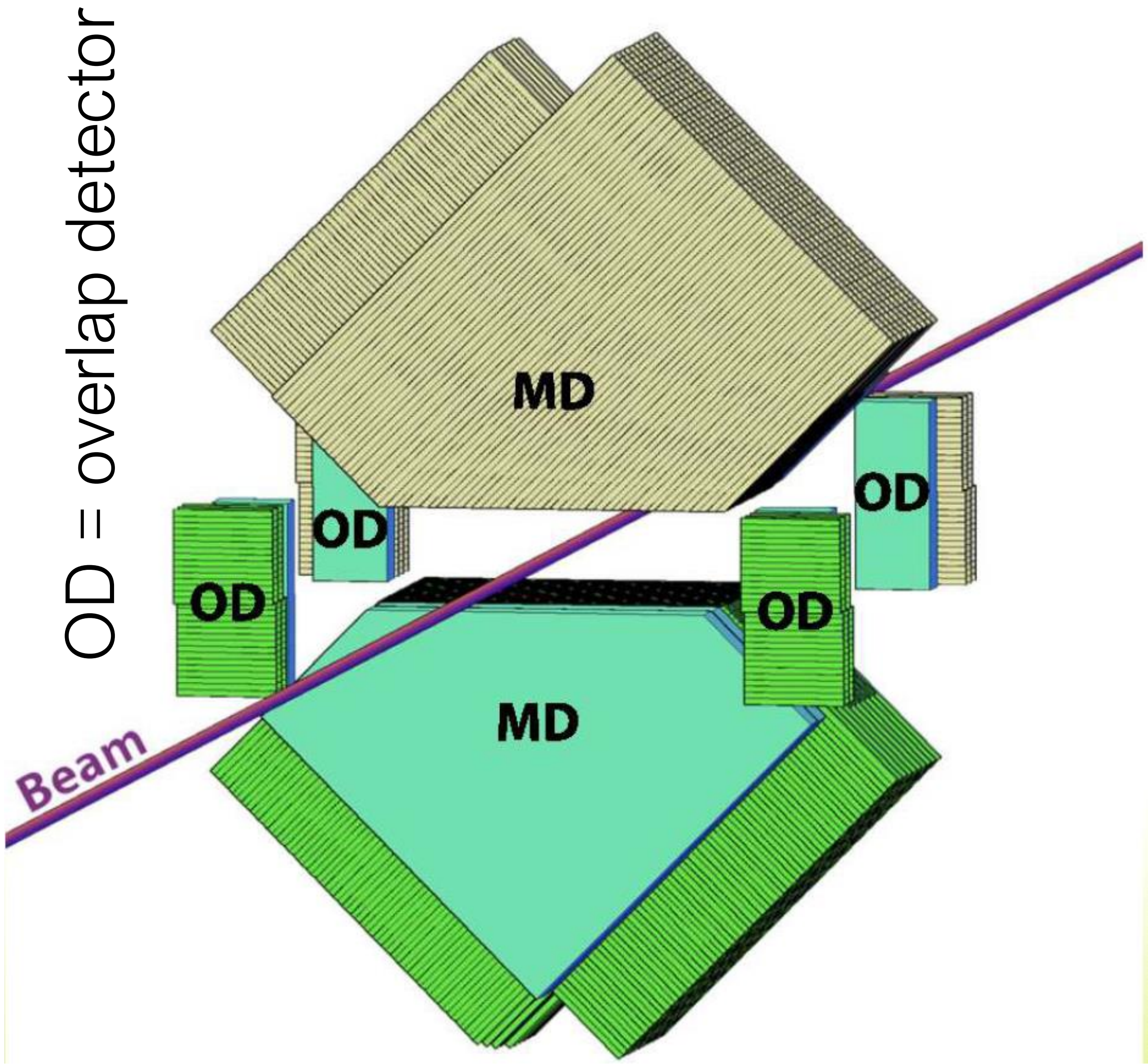
- Beam positioning monitors (BPMs) and hit multiplicities used to calibrate detector positions with respect to beam
- Overlap extrusions used to calibrate distance between upper and lower detectors

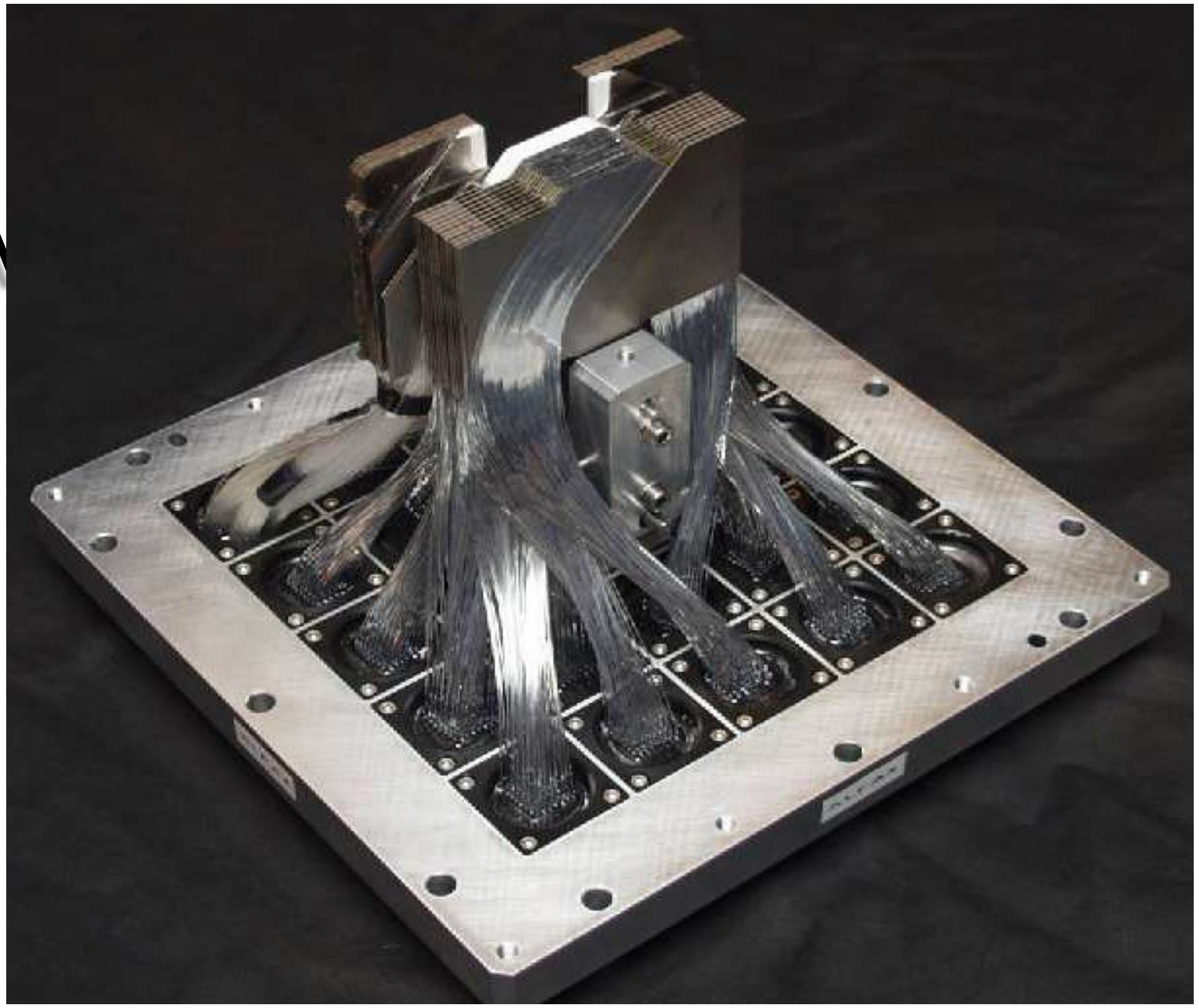


ALFA – Absolute Luminosity for ATLAS



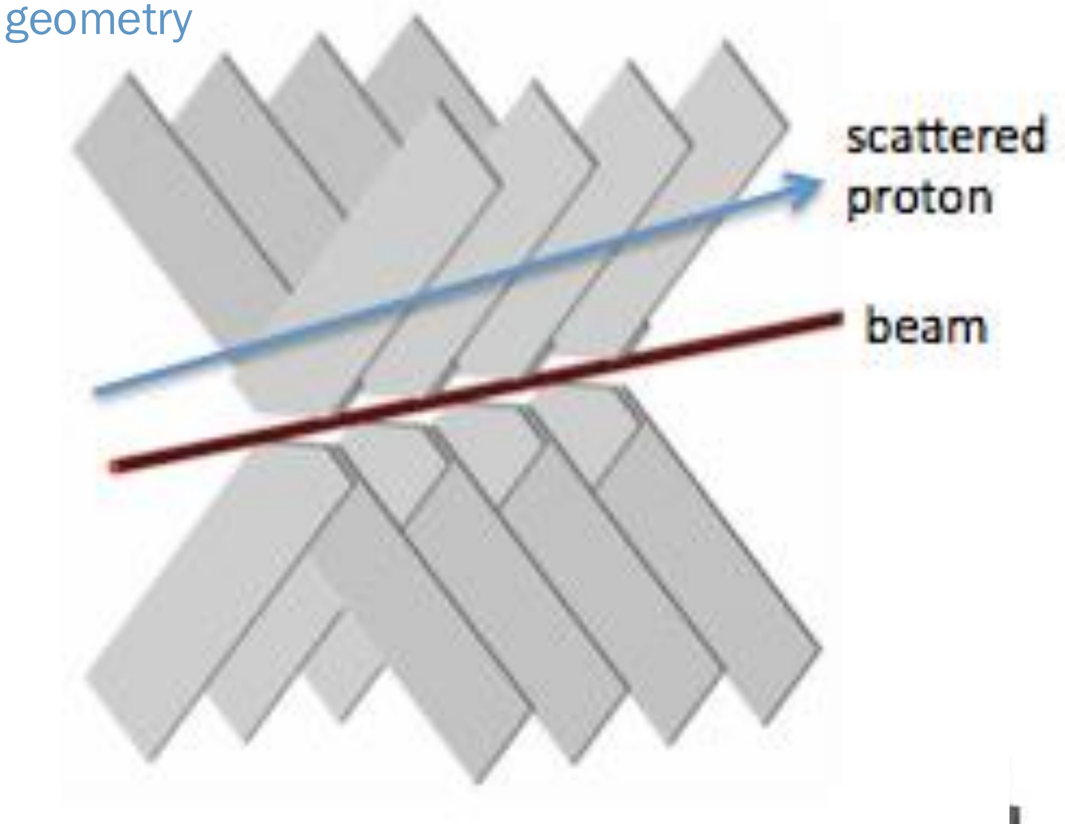
ALFA – Absolute Luminosity for ATLAS





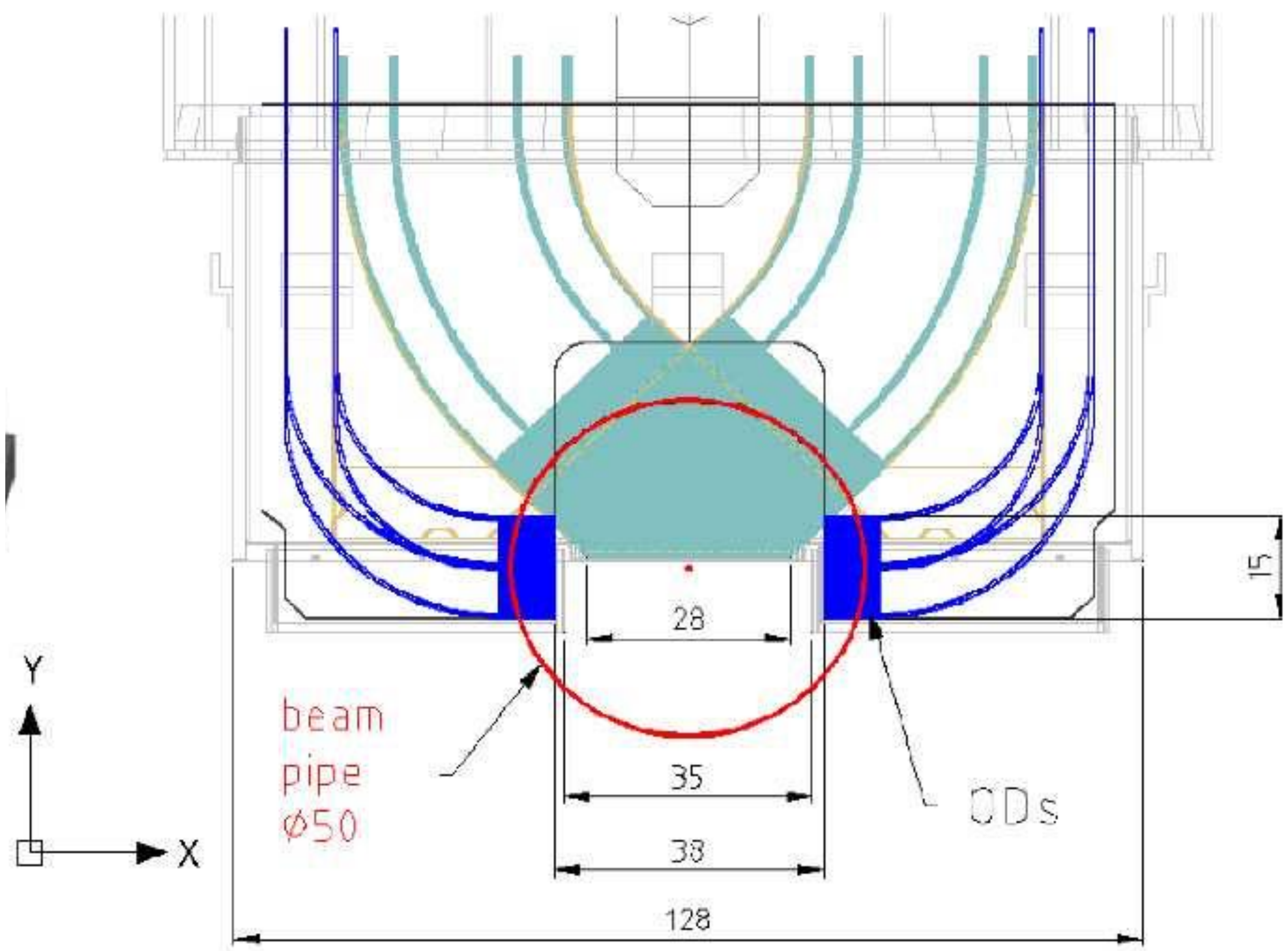
ALFA – Absolute Luminosity for ATLAS

Scintillating fibers
in U-V geometry



Schematic view of tracker module ...

Sensitive area with U-V geometry (light blue) ...
Overlap detectors and fibers (dark blue) ...
LHC Beam pipe (red) ...



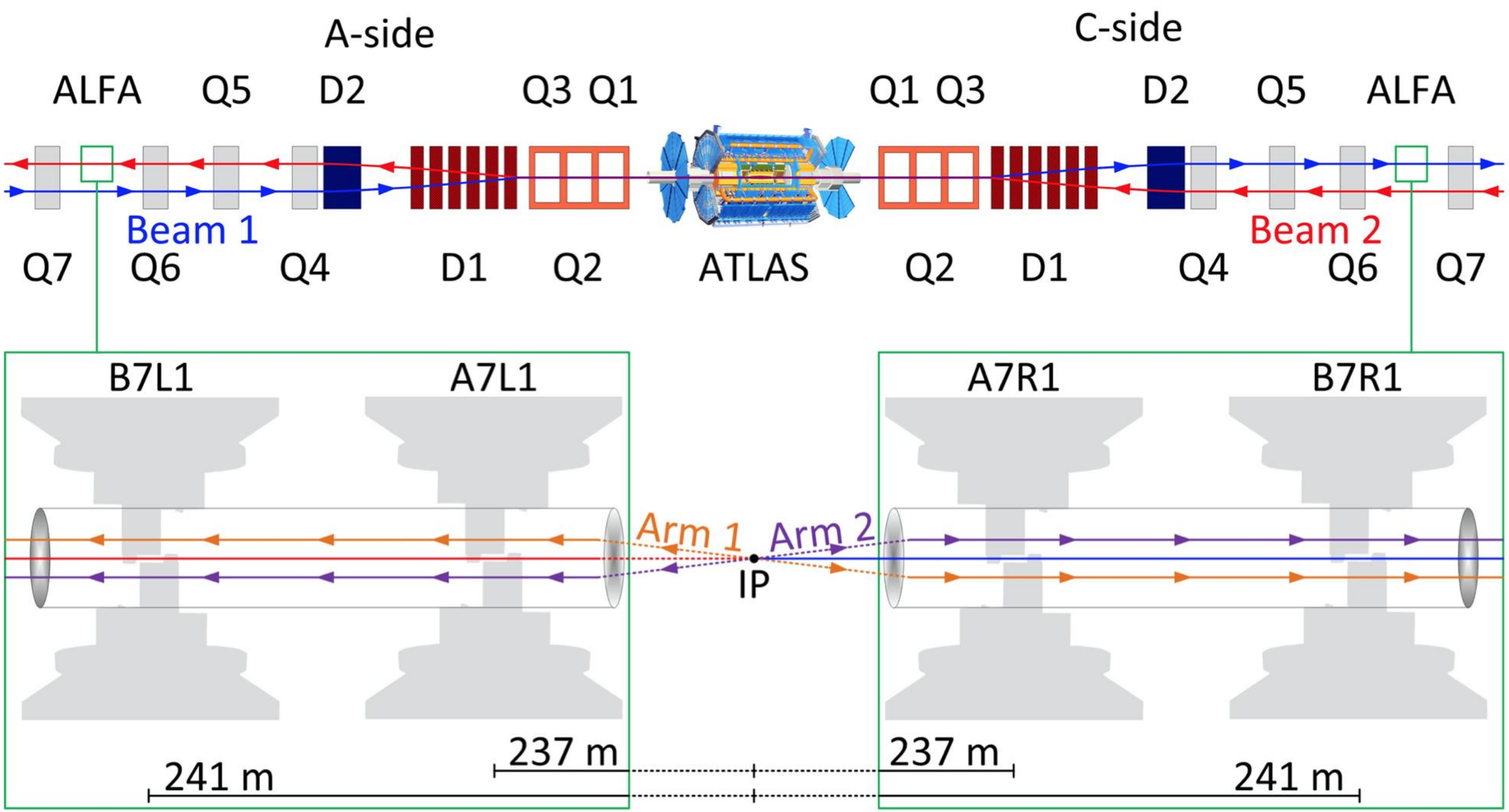
Single-cladded 0.5 mm square fibers used to track scattered protons ...

20 detector planes with 64 fibers each ...
[expected position resolution: 30 μm]

Dead region less than 100 μm ...

Efficiency > 90% per plane ...

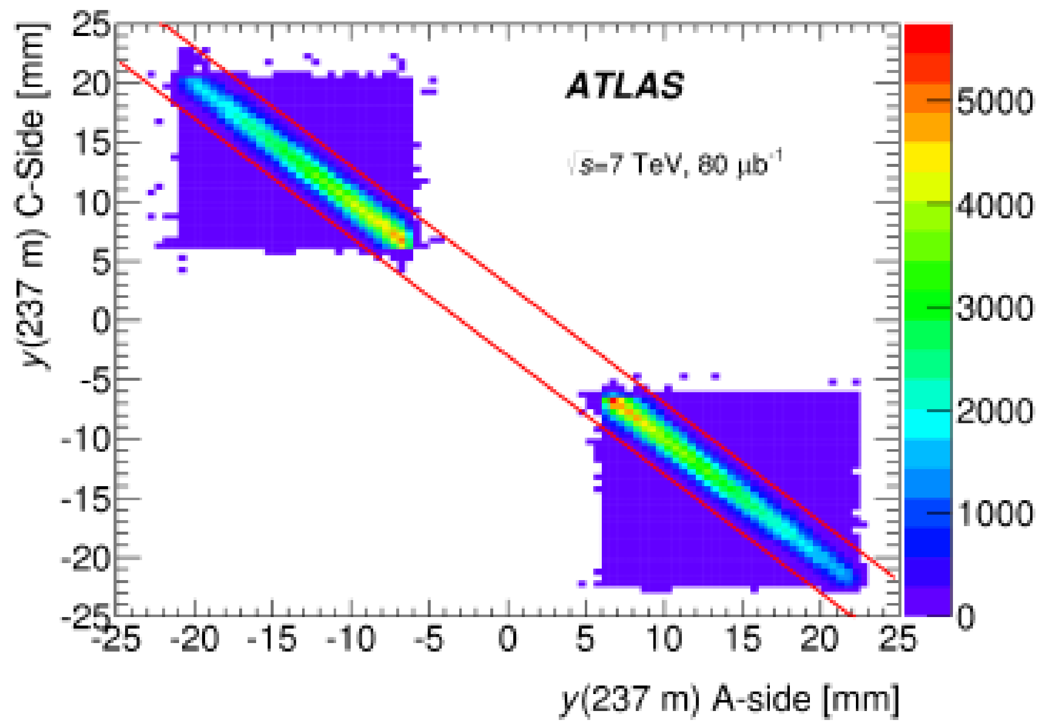
ALFA detector

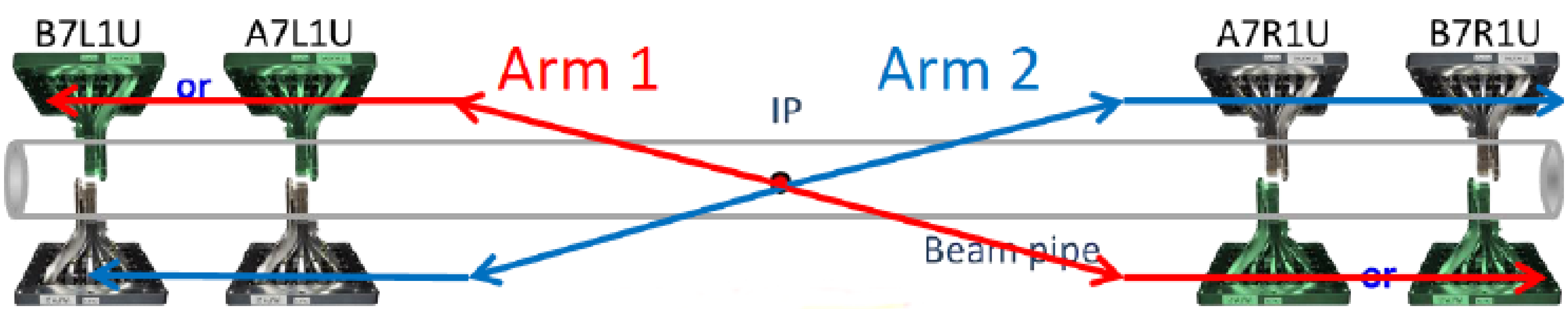


ALFA detector : signal events

Elastic event selection

- Elastic events are selected with tracks in all four stations in an arm.
- The tracks are also required to fulfill certain correlations between inner-outer stations and between A-side and C-side.



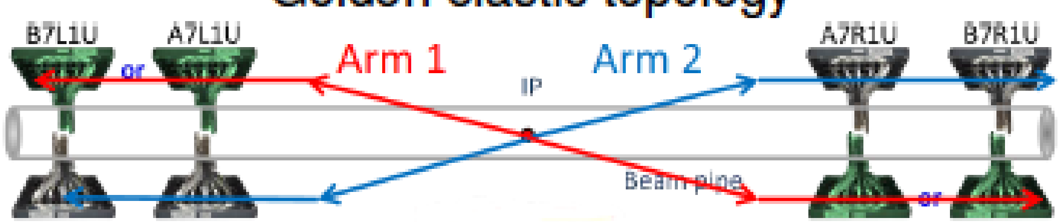


ALFA detector : background events

Background

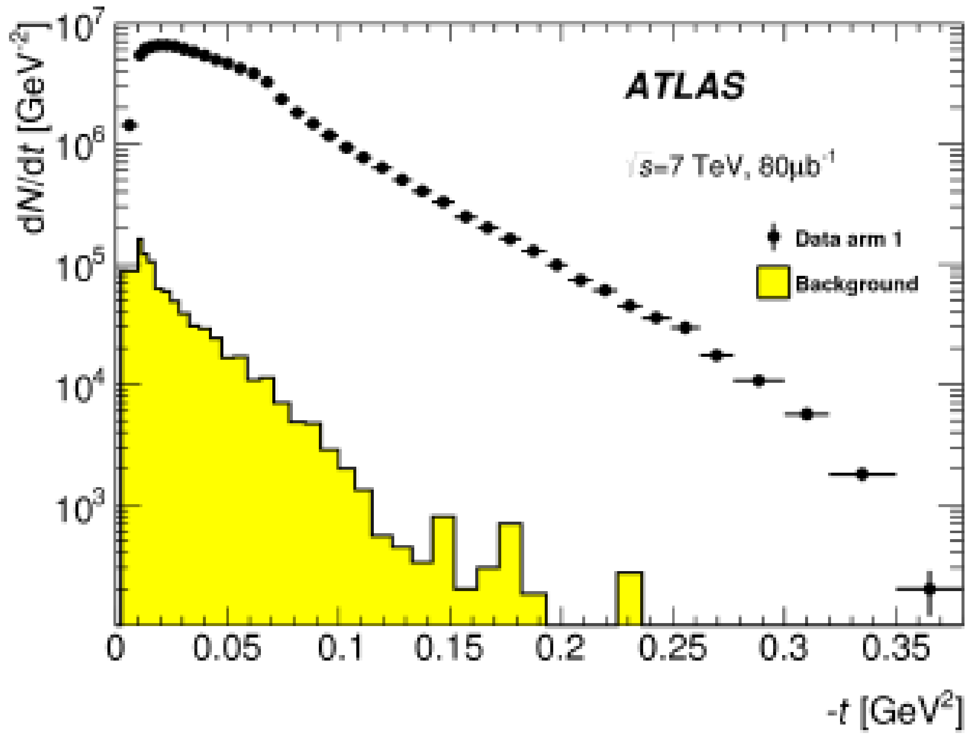
- Sources of irreducible background is:
  1) two incident halo particle,
  2) a single diffractive proton and a halo particle,
  3) double pomeron exchange with two protons in ALFA.
- A t-spectrum for background is determined from anti-golden events by flipping the coordinates of one of the tracks.
- Background fraction is $\sim 0.5\%$ and halo+halo is the dominant source.

Golden elastic topology



Anti-golden topology

Reconstructed t-spectrum



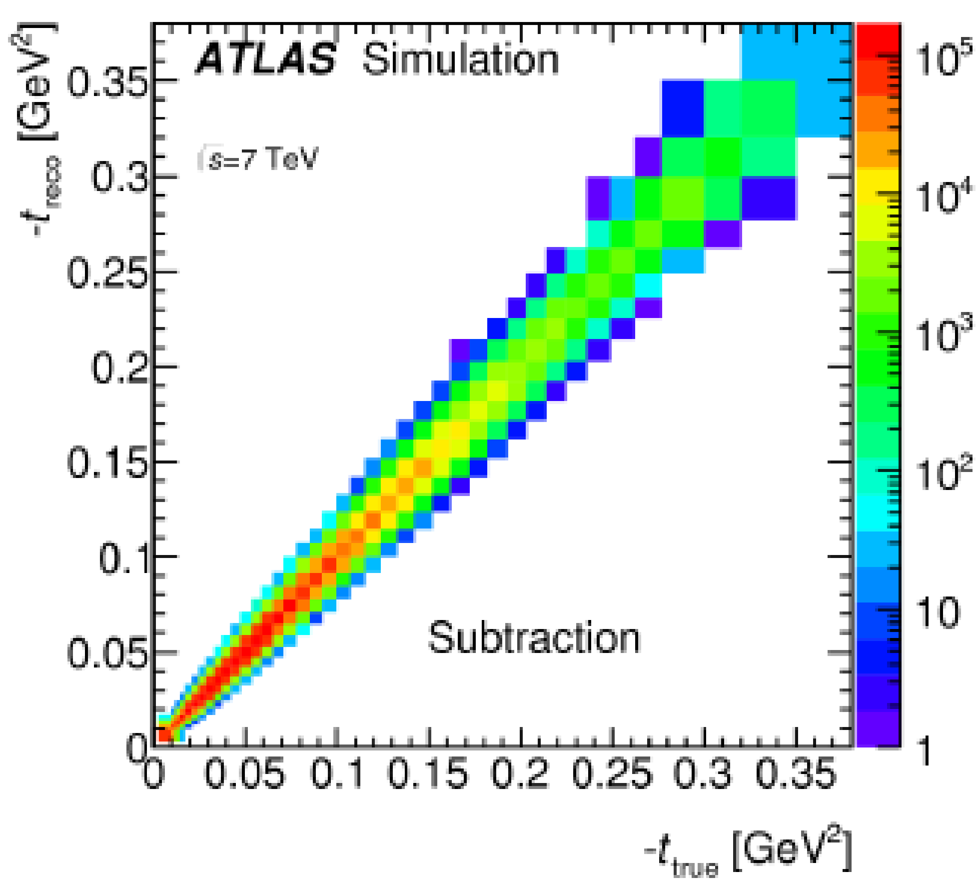
ALFA : acceptance & unfolding

Simulation: Acceptance & unfolding

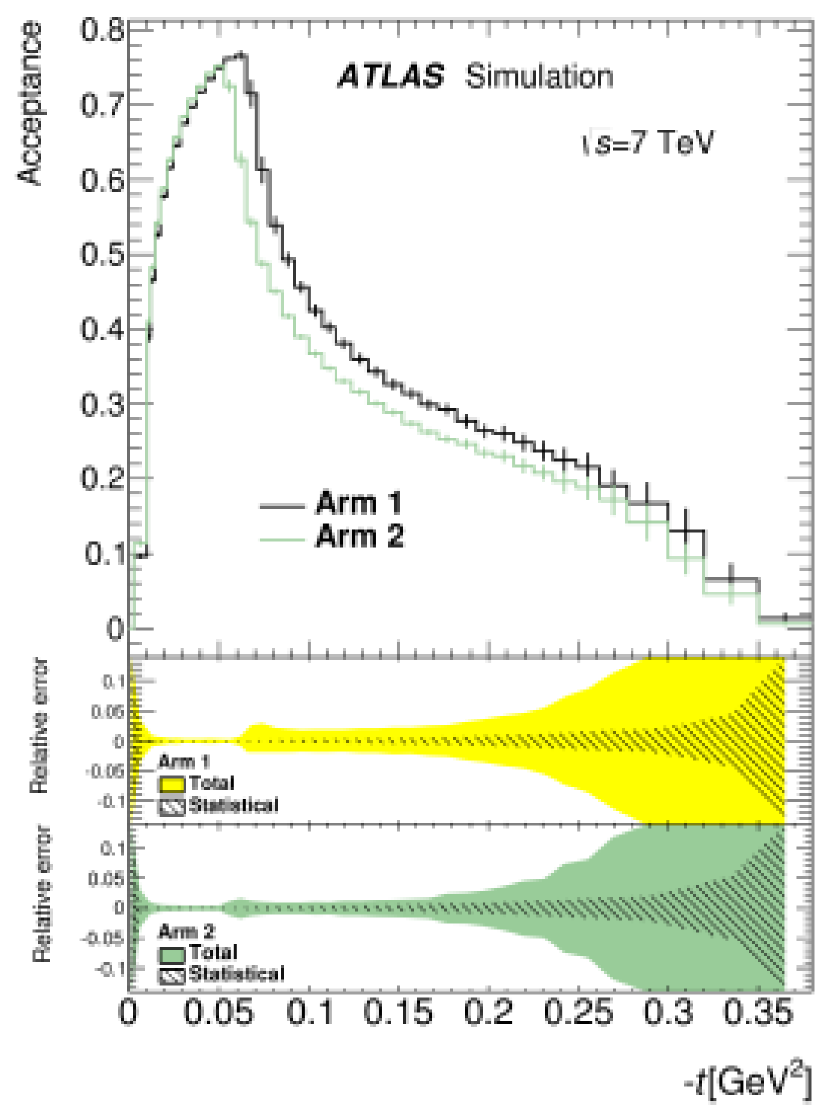
- The measured t-spectrum is affected by detector resolution and acceptance and must be corrected for these effects.
- PYTHIA8 used as elastic scattering generator.
- Beam transport from IP to ALFA done using MadX.
- Simulated tracks are used to find a reconstructed t.
- Transition matrix used to unfold the raw t-spectrum.

t_{true} at production vs t_{reco} at detection

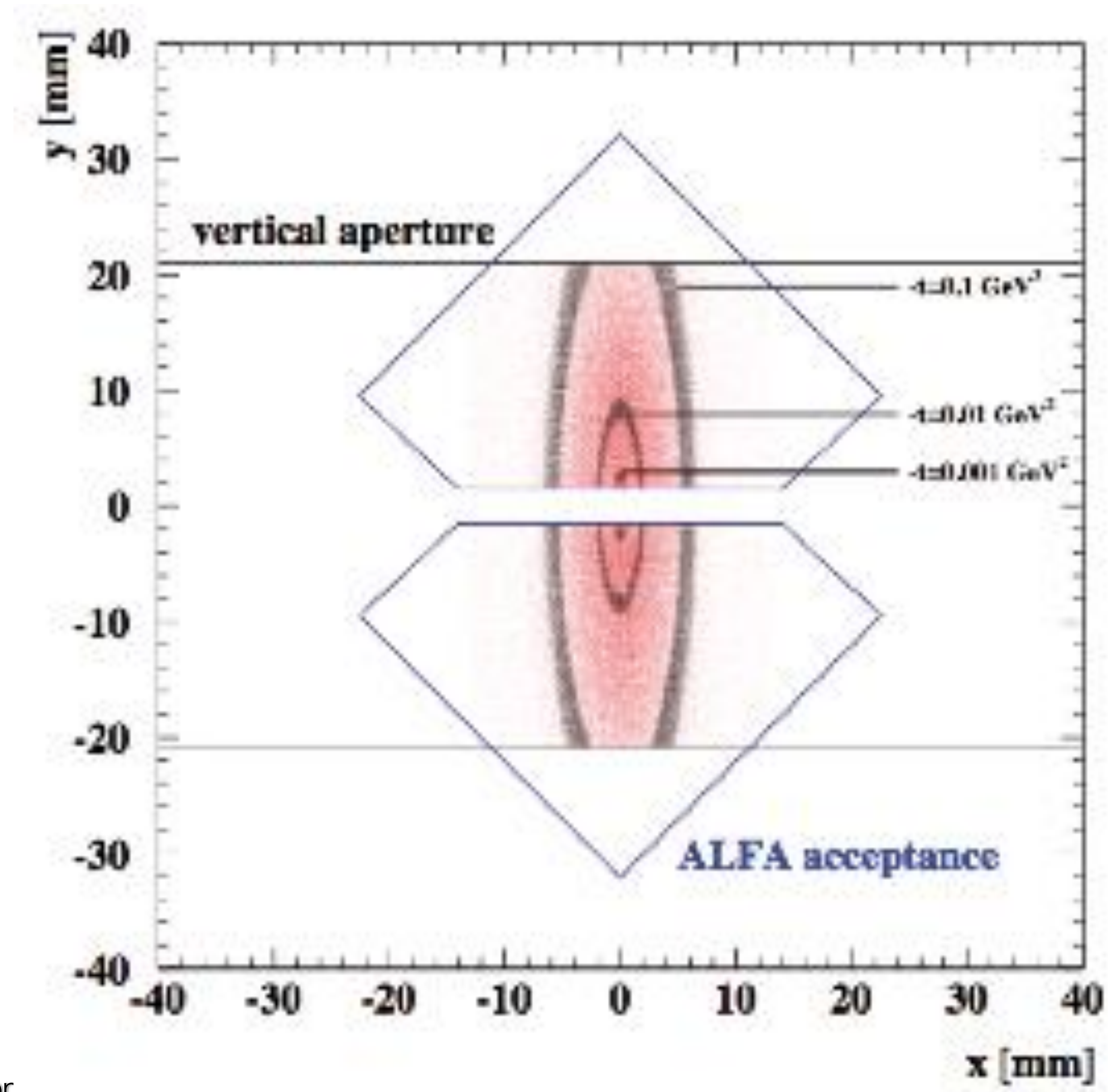
Transition matrix



Acceptance



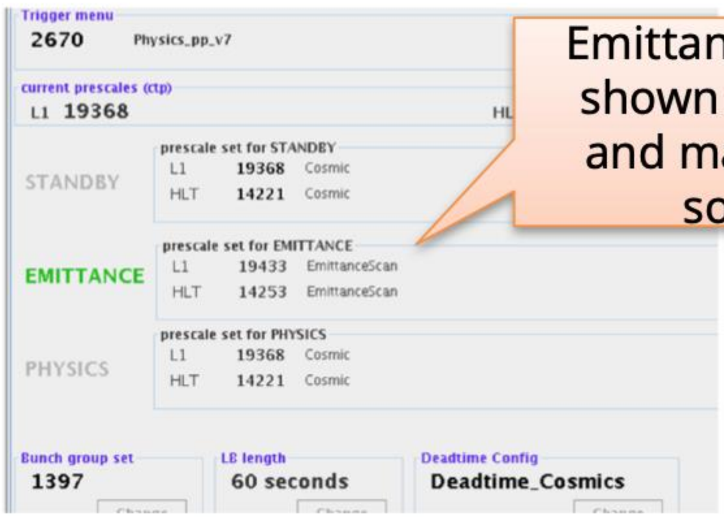
ALFA – Absolute Luminosity for ATLAS



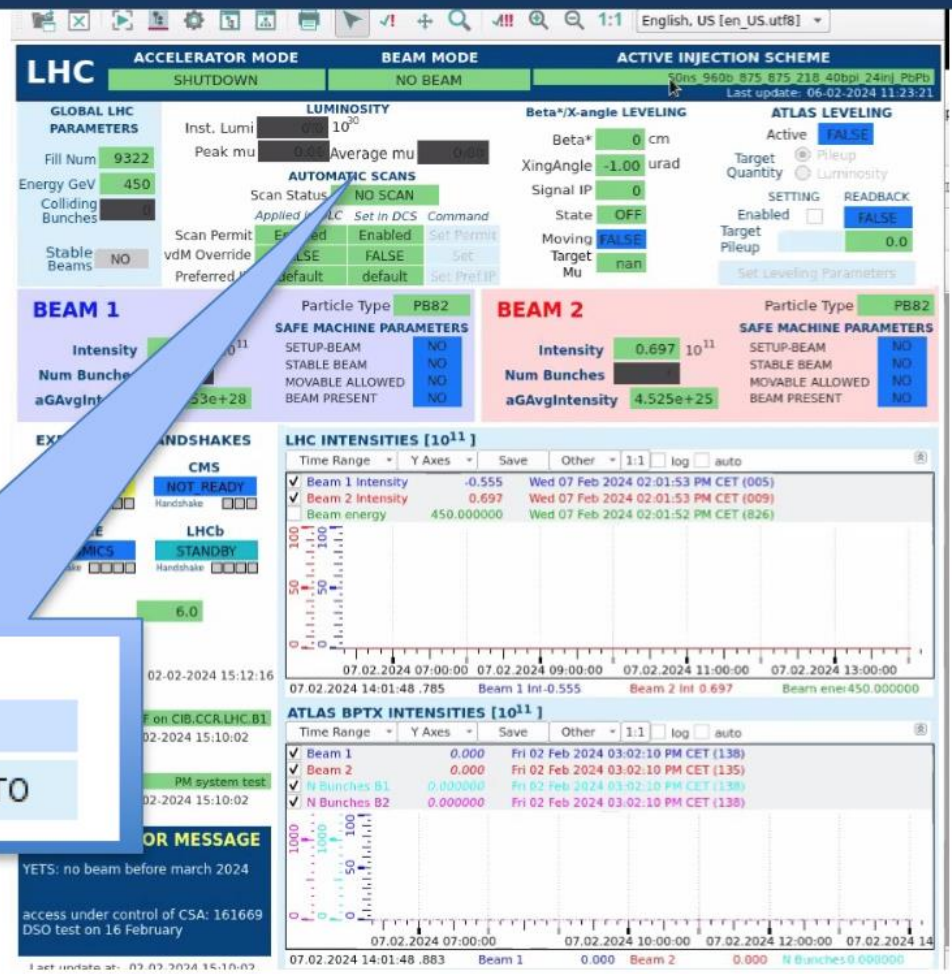
ALFA
Simulated hit distribution

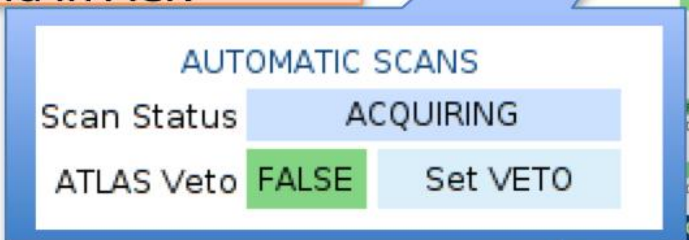
Emittance Scans in LHC

- **Emittance Scan**: a quick vdM scan performed during stable beams, separating the beams in x and y
- Typical scan duration 5 min, usually at beginning of end of a fill
- The LHC uses it for on-the-fly diagnostics, ATLAS can use it to cross-check calibrations

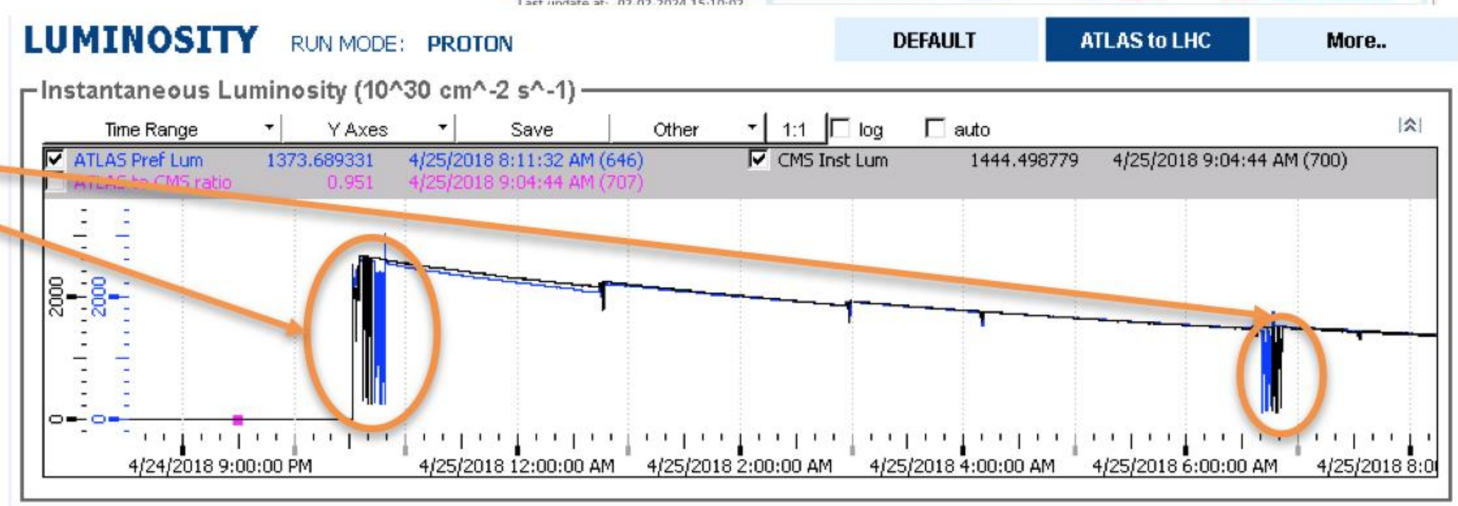


Emittance Scan ongoing shown in Trigger Panel and marked by special sound in ACR





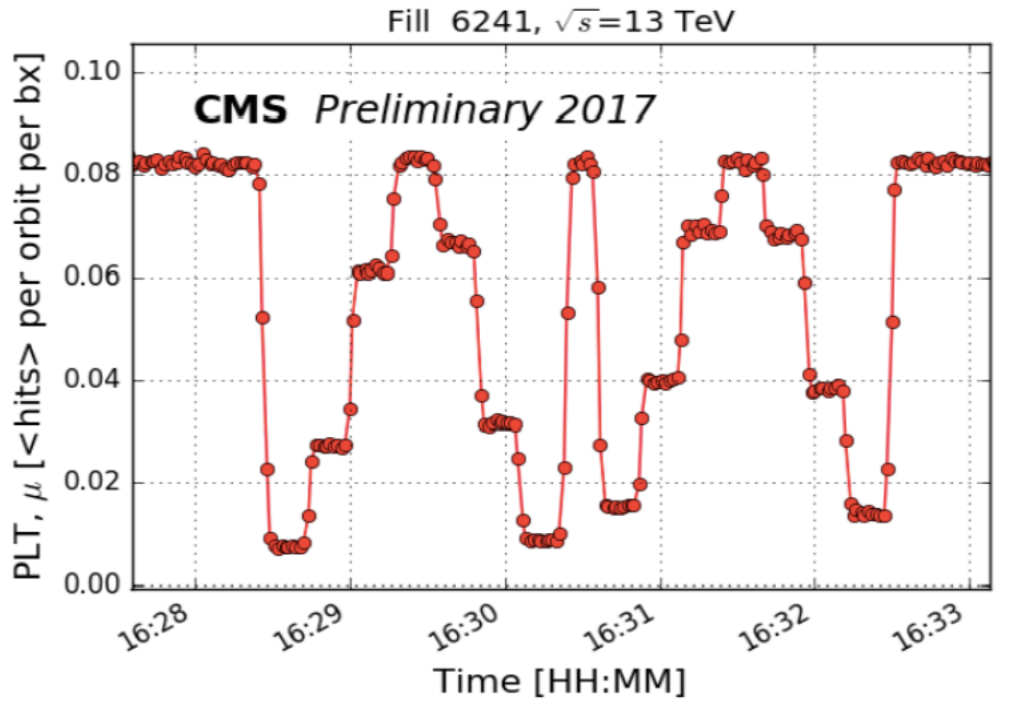
- Emittance scan visible in DCS and LHC page 1!

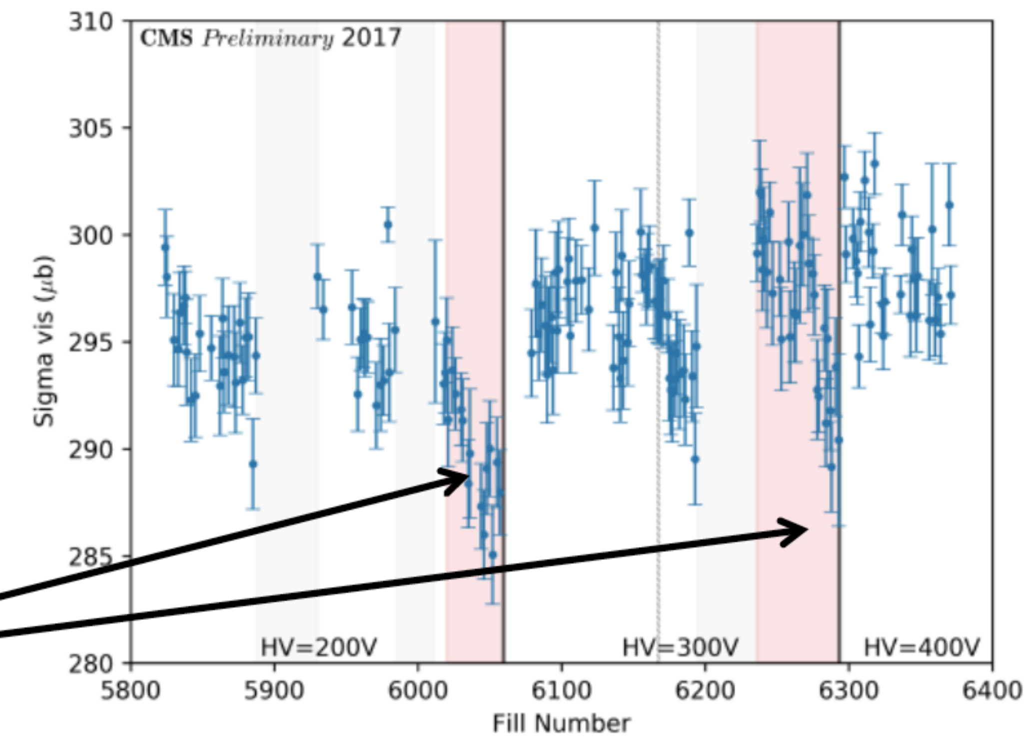


ATLAS & CMS: VdM-like scans

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



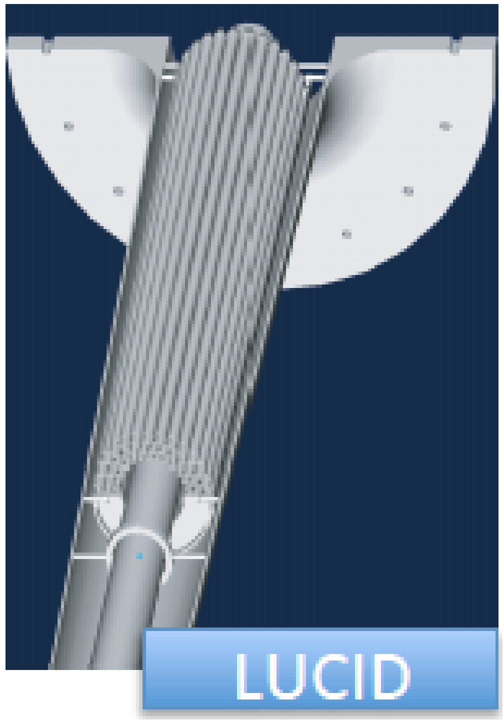


Detector effects

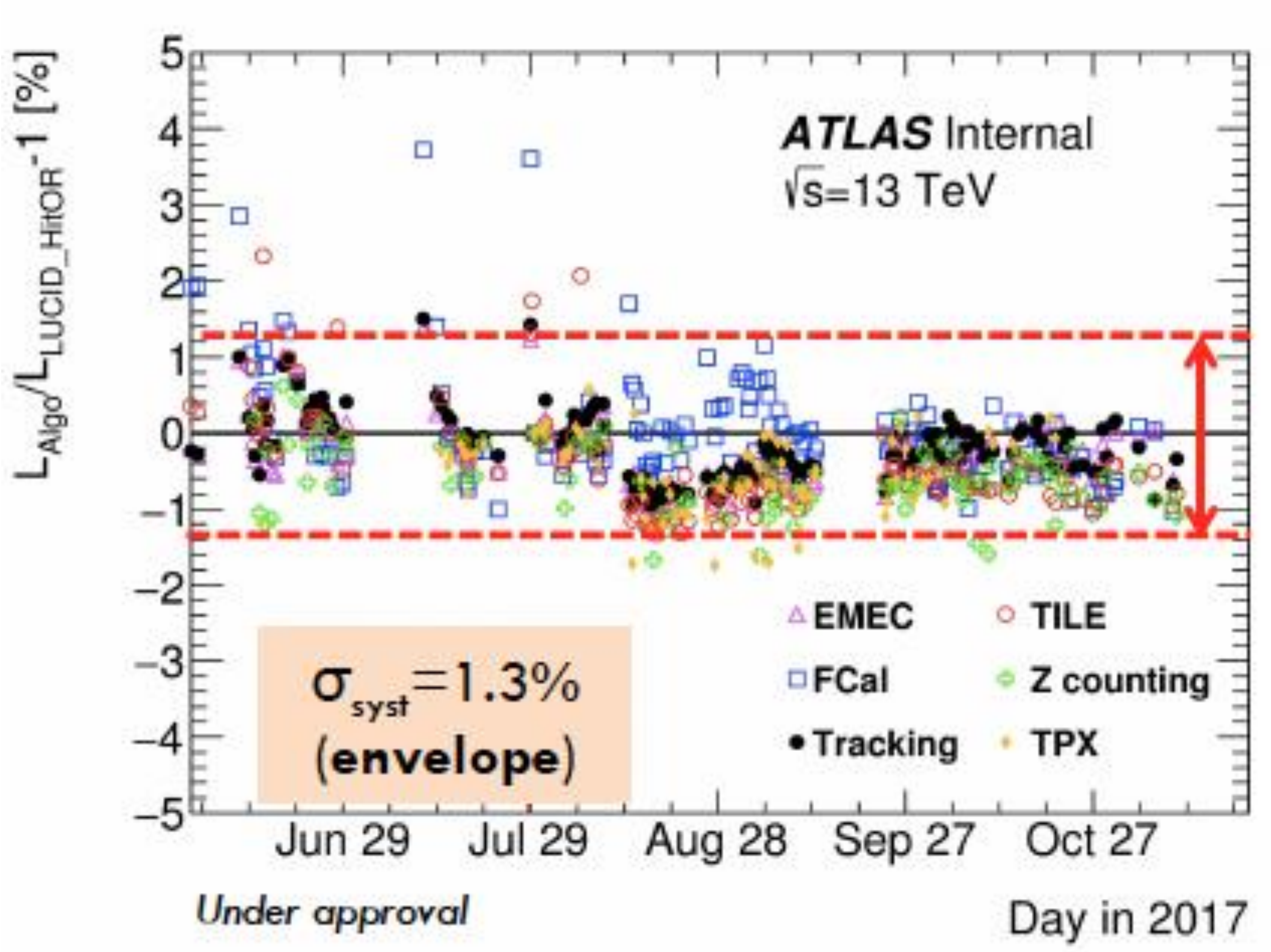
ATLAS Luminosity monitors

What between VdM scans?

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



On-line comparison different luminosity monitors



Calorimeters

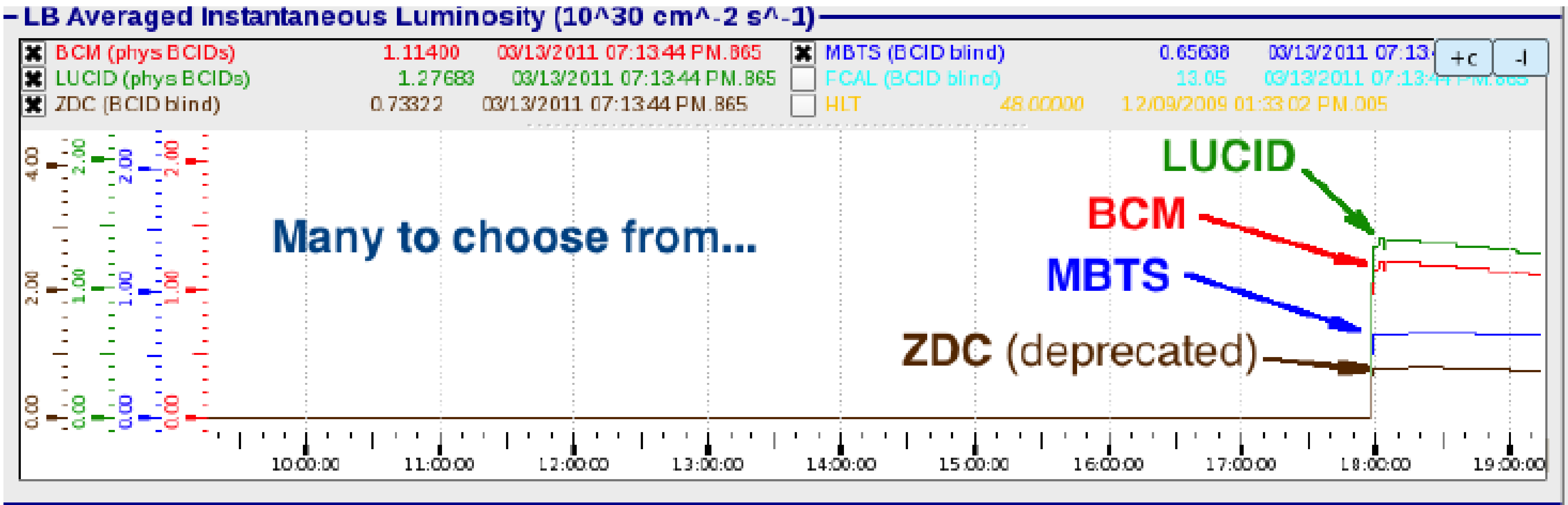
Tile Calorimeter

- **Technology:** Scintillator tiles connected to PMTs.
- **Highlights:** Particle flux measurement, far from beamline.
- **Sampling/Time resolution:** bunch-integrated response every few seconds.

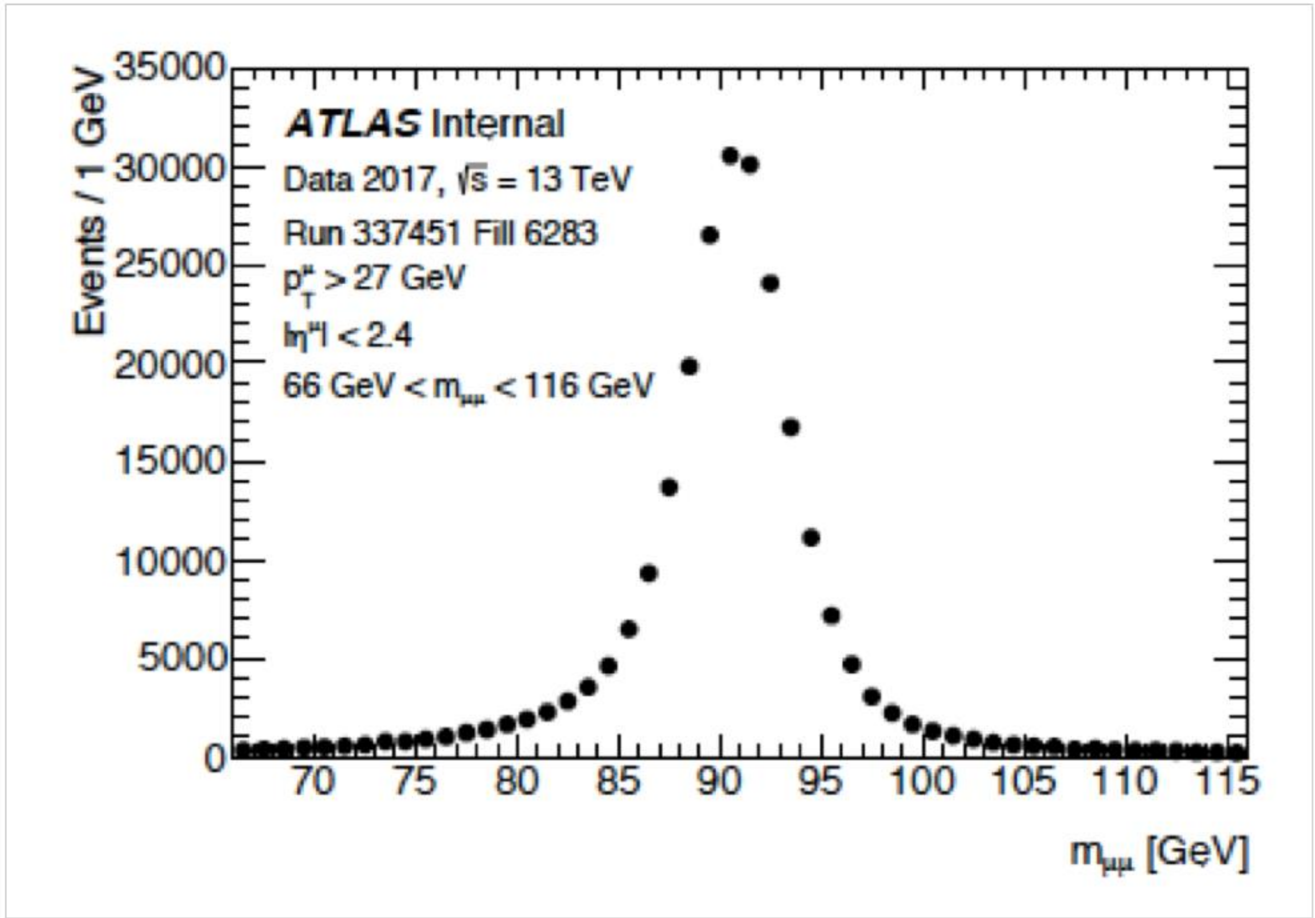
EMEC and FCal

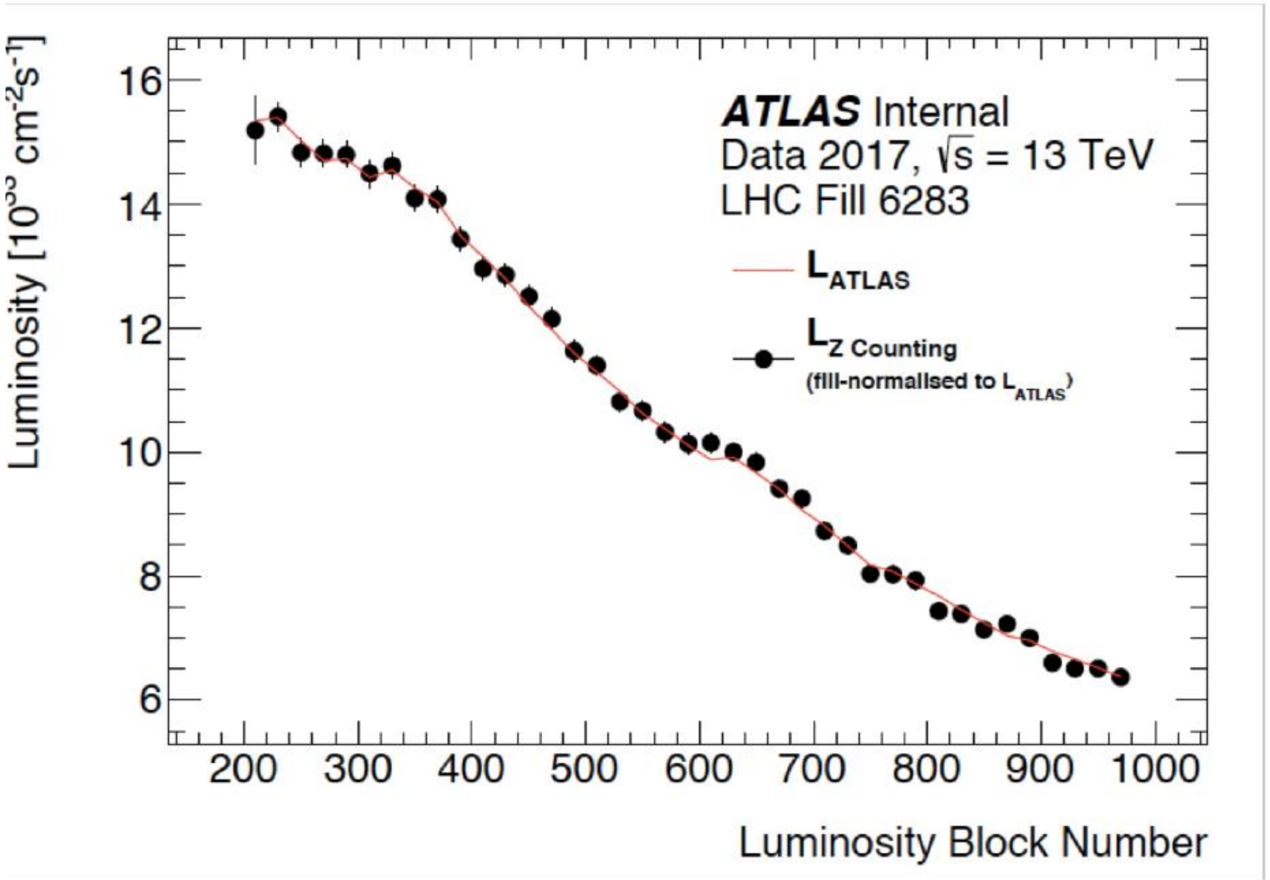
- **Technology:** Liquid argon gaps between electrodes under HV.
- **Highlights:** Particle flux measurement, closer to beamline.
- **Sampling/Time resolution:** bunch-integrated response every few seconds.

Comparison among different monitors



Z counting





The invariant mass distribution of the muon pairs of the 240,000 Z -> $\mu\mu$ boson events selecting

- two muons with p_T> 27 GeV,
- η < 2.4
- 66 < $m_{\mu\mu}$ < 116 GeV.

The statistical errors are smaller than the symbol size.

Comparison between Z counting and L_{Lucid}

Backup slides

Titolo Testo

Luminosity Determination @ LHC (old slide)

Absolute Methods:

Accuracy: from 10%-
To today ~3%

Determination from LHC parameters; van-der-Meer separation scans ...
Rate measurement for standard candle processes ...

LHC Examples:

Rate of pp ➛ Z/W ➛ $\ell\ell/\ell\nu$ [needs: electroweak cross sections]
Accuracy: 5-10%
[PDF knowledge, ...]

Rate of pp ➛ γγ ➛ μμ, ee [needs: QED & photon flux]
Accuracy: 1-5% ?
[TDR; needs forw. tagging]

Optical theorem: $\sigma_{tot} \sim \text{Im } f(0)$ [needs: forward elastic and total inel. x-sec]
Elastic scattering in Coulomb region ...
[needs σ_{tot}; needs forw. instrumentation]
Accuracy: 5-10%

Combination of the above ...

Accuracy: 2-3%

TOTEM

Relative Methods:

Particle counting; using Cherenkov monitors [e.g. LUCID @ ATLAS]
[needs to be calibrated for absolute luminosity]

Aim: Luminosity accuracy of 2-3% ...