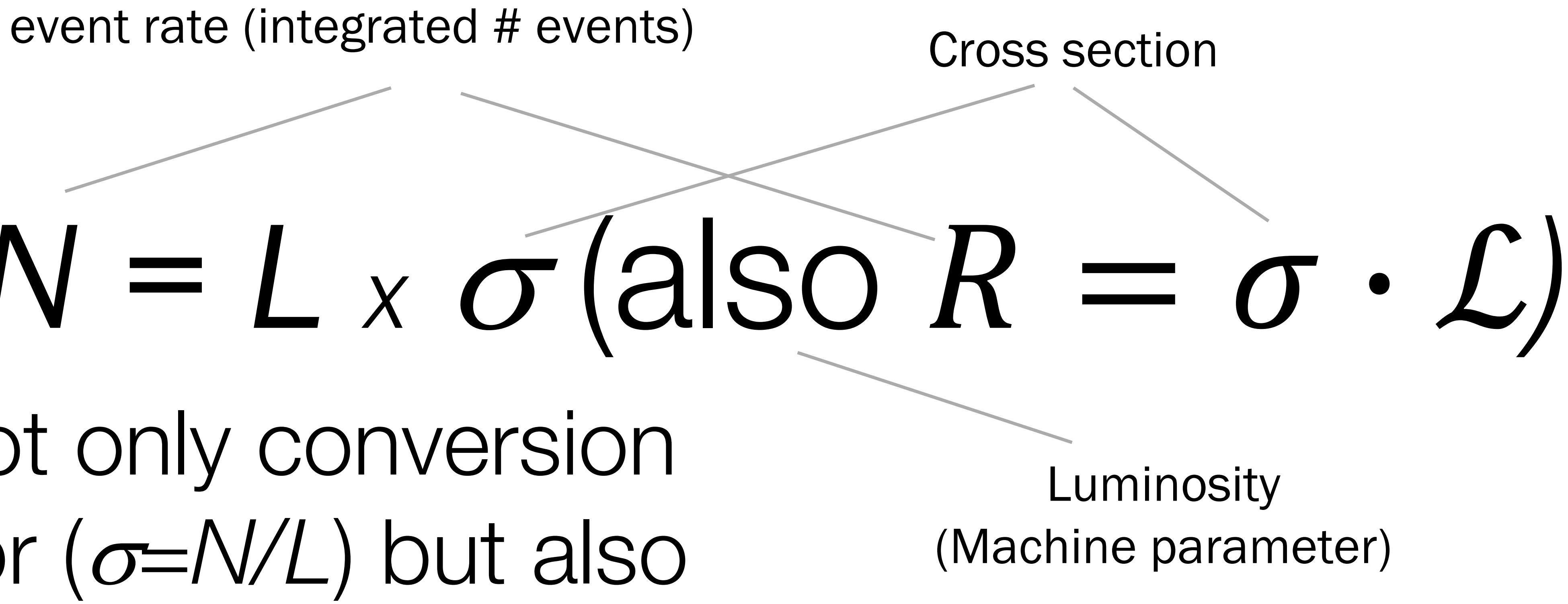
Luminosity measurements

Collider Physics
Toni Baroncelli

Year 2023

Luminosity @ LHC

How to measure cross sections …



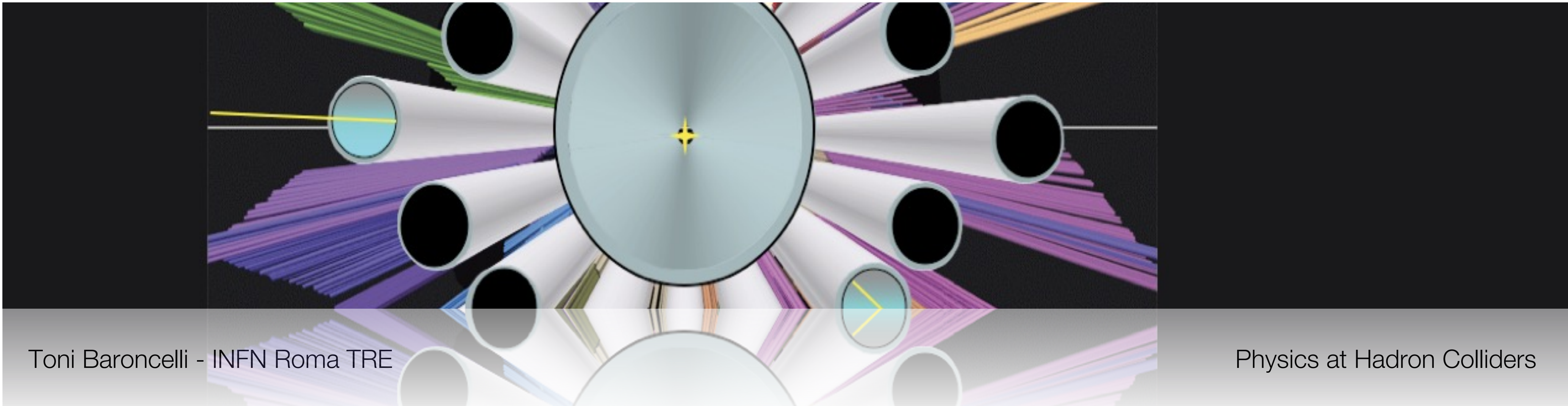
event rate (integrated # events)

Cross section

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

Luminosity
(Machine parameter)

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



$\mathcal{L}$: Measurements and Monitoring

We have to distinguish between

- Absolute measurements of Luminosity

  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?)

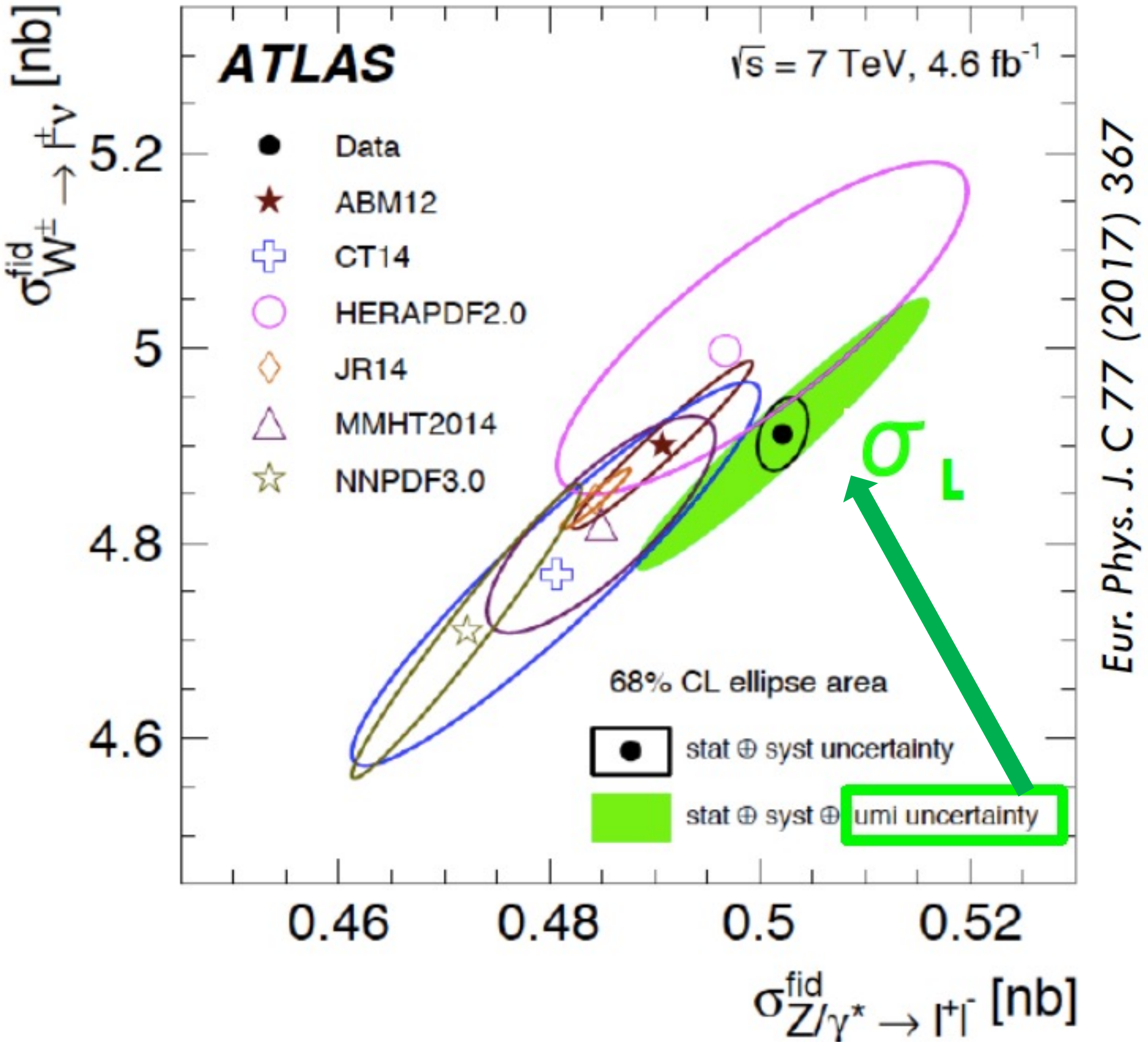
- Monitoring of Luminosity
  Any detector sensitive to intensity of beams (tracking, calorimeters, continuous measurements during time)

The second indicator 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%



Eur. Phys. J. C 77 (2017) 367

Toni Baroncelli Experimental High Energy Physics at Colliders Winter 2023

Luminosity Measurements: basic

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

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

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

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

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

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

$$\sigma = \mathrm{N}/L$$

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

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)

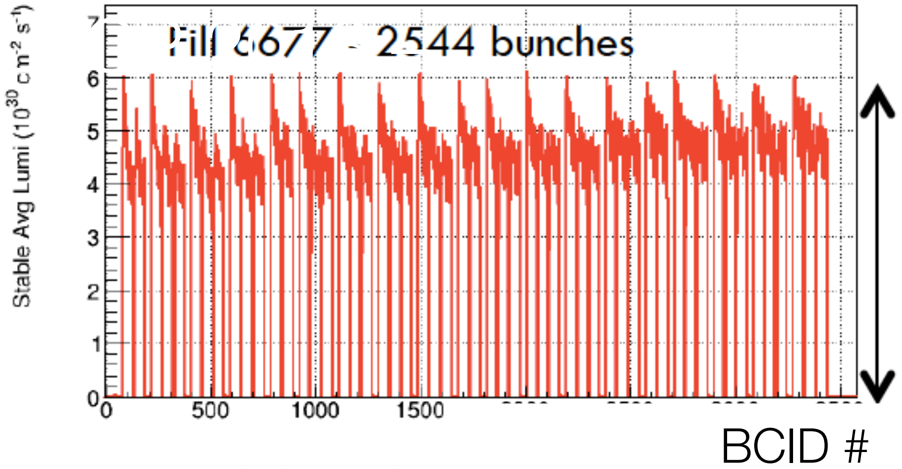
ε = acceptance and efficiency of luminosity detector

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

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

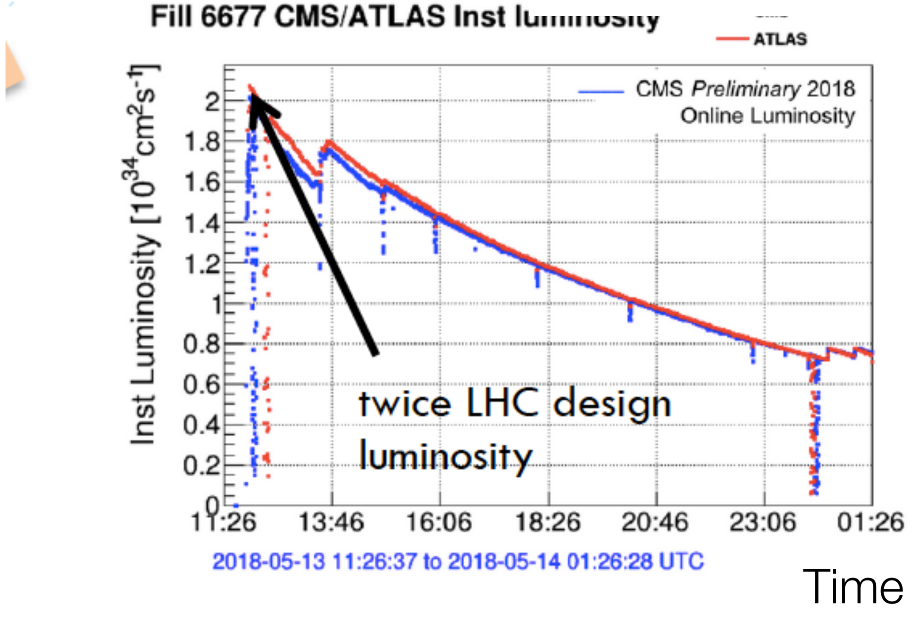
The Devil is in the Details

- 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



$\mu \approx 40$

Bunch-by-bunch luminosity



Bunch-integrated luminosity over fill (about 12 hours)

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

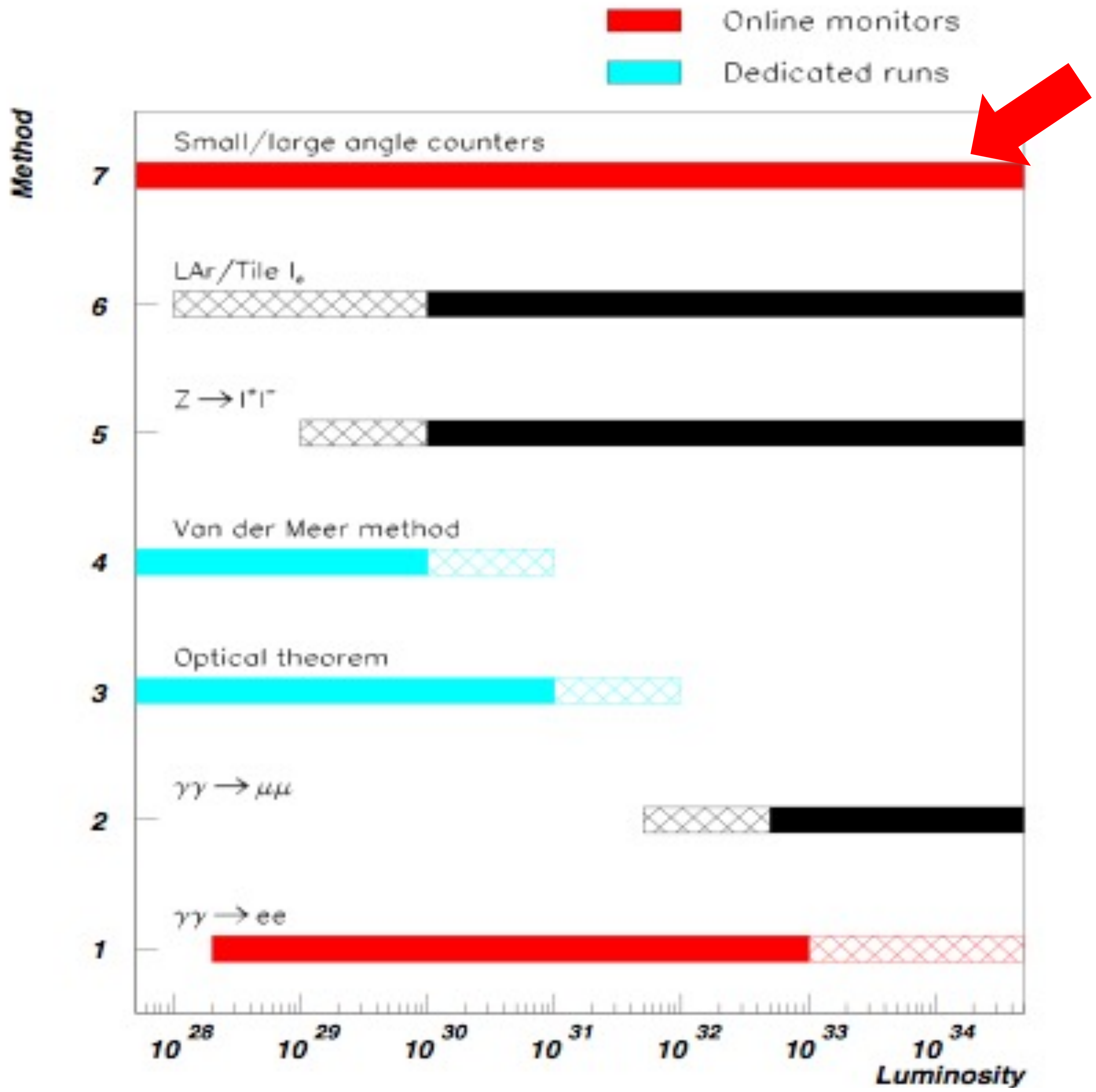
Near future

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

… and to monitor it with time

use of tracking detectors & calorimeters

Luminosity Determination at the LHC (history)



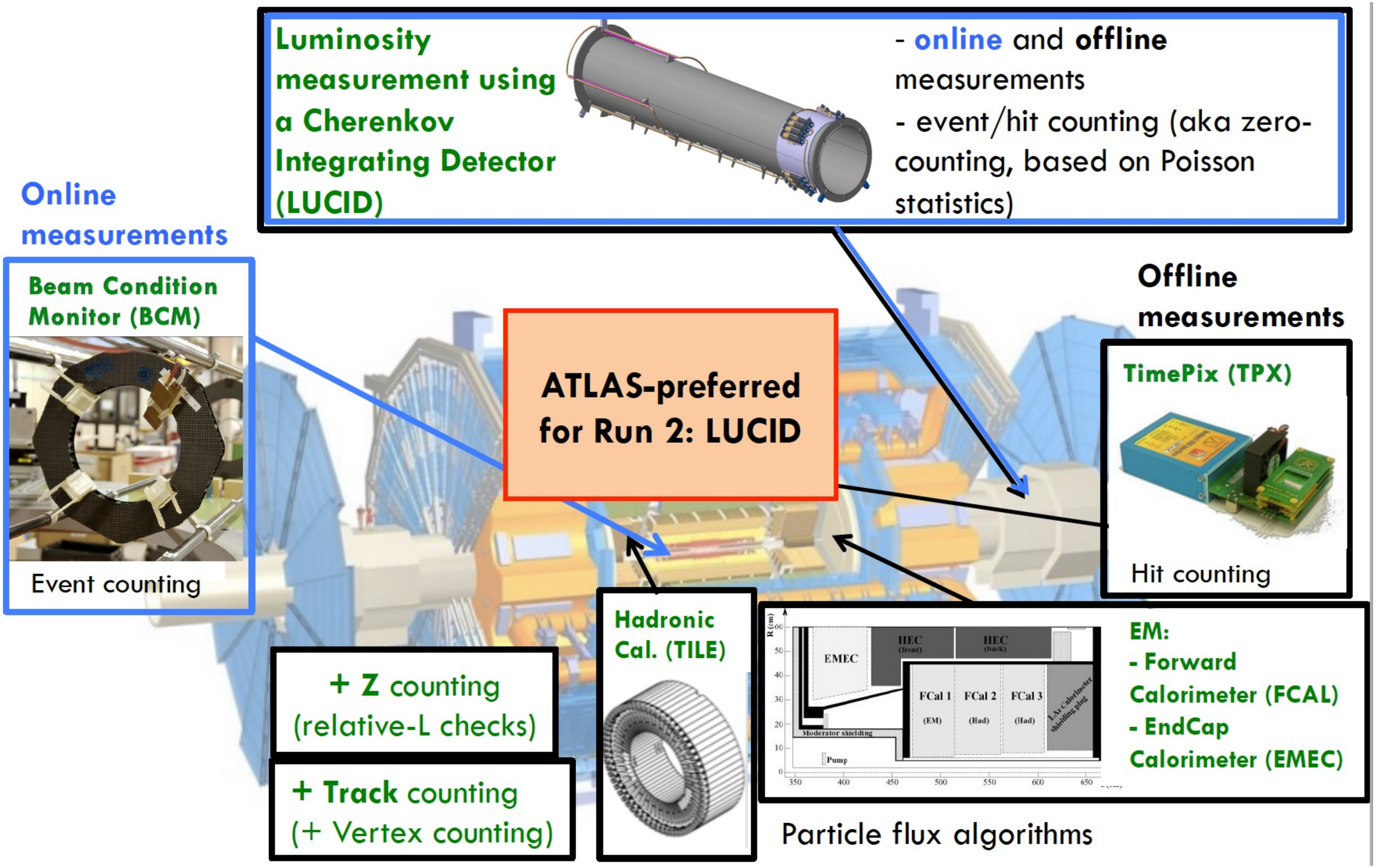
ATLAS with ALFA,
CMS with TOTEM

Methods as
summarized in ATLAS TDR

[ATLAS Technical Design Report, Vol. I]

Red → Monitors
Light blue → Measurements

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)

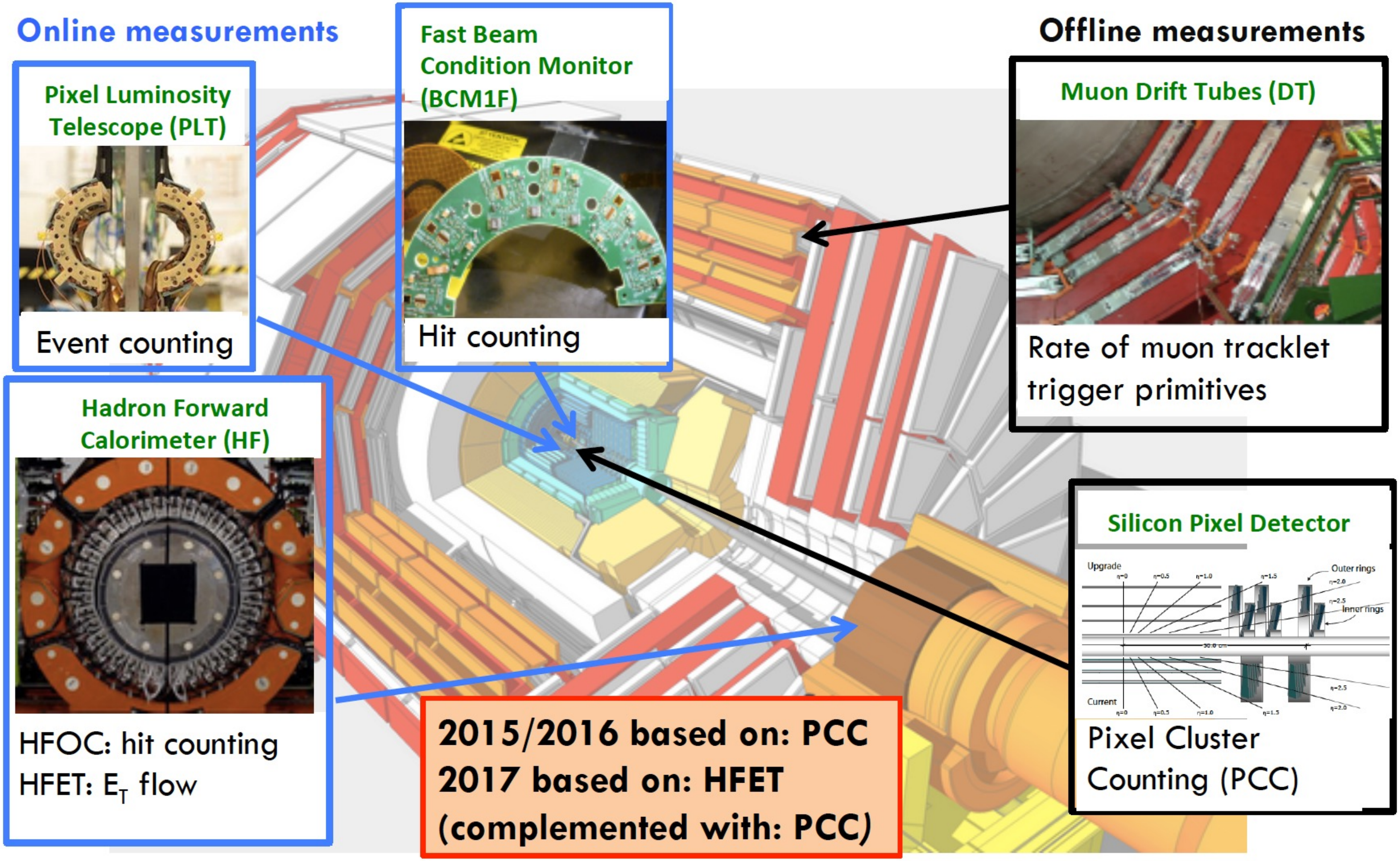
+ Track counting (+ Vertex counting)

Hadronic Cal. (TILE)

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

Particle flux algorithms

CMS Luminosity Detectors



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)

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

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

Efficiency

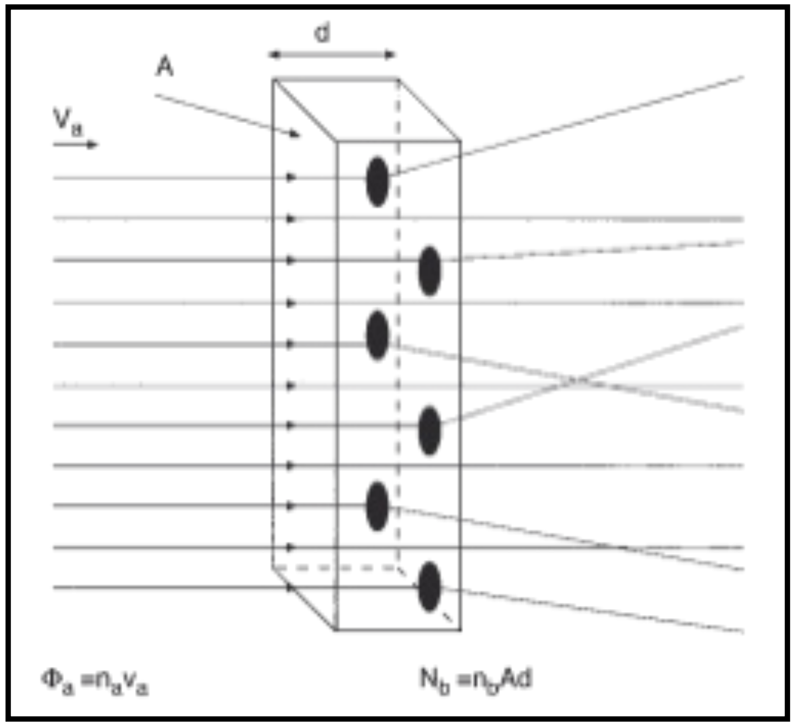
many factors, optimized by experimentalist

Luminosity

determined by accelerator, triggers, …

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

Cross Section & Luminosity



$$\Phi_a = \frac{\dot N_a}{A} = n_a v_a$$

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

Colliders

Instantaneous Luminosity

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

$$N = \sigma \cdot \underbrace{\int L\,dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

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

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

σ_x, σ_y : not well known

LHC:

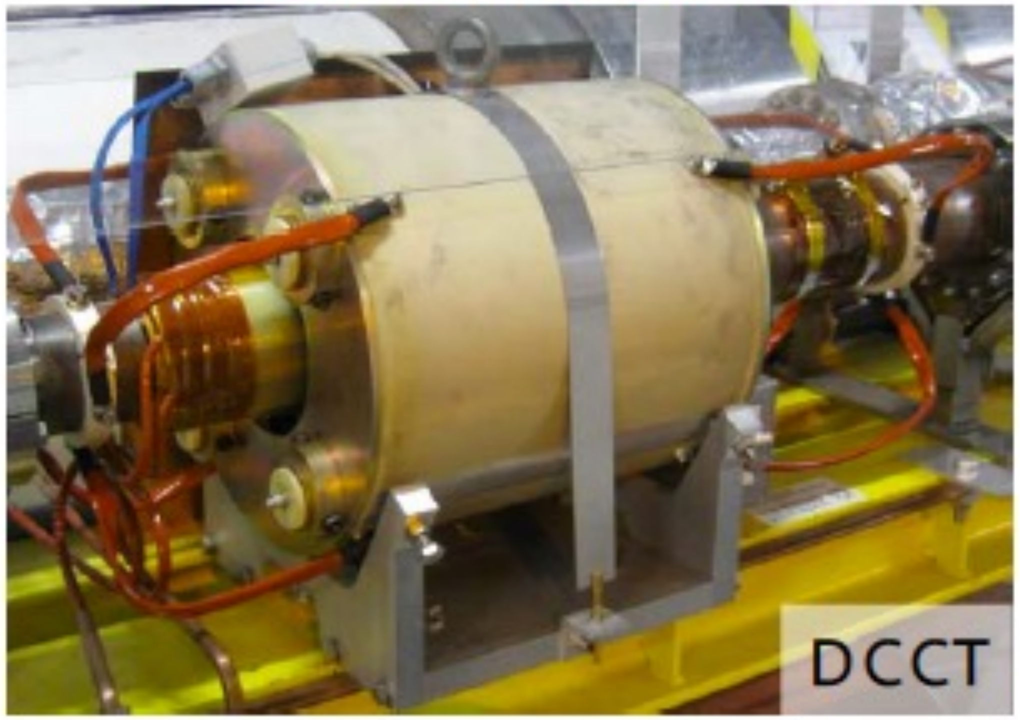
N_x ~ 10^{11}
A ~ .0005 mm^2
n ~ 2800
f ~ 11 kHz

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

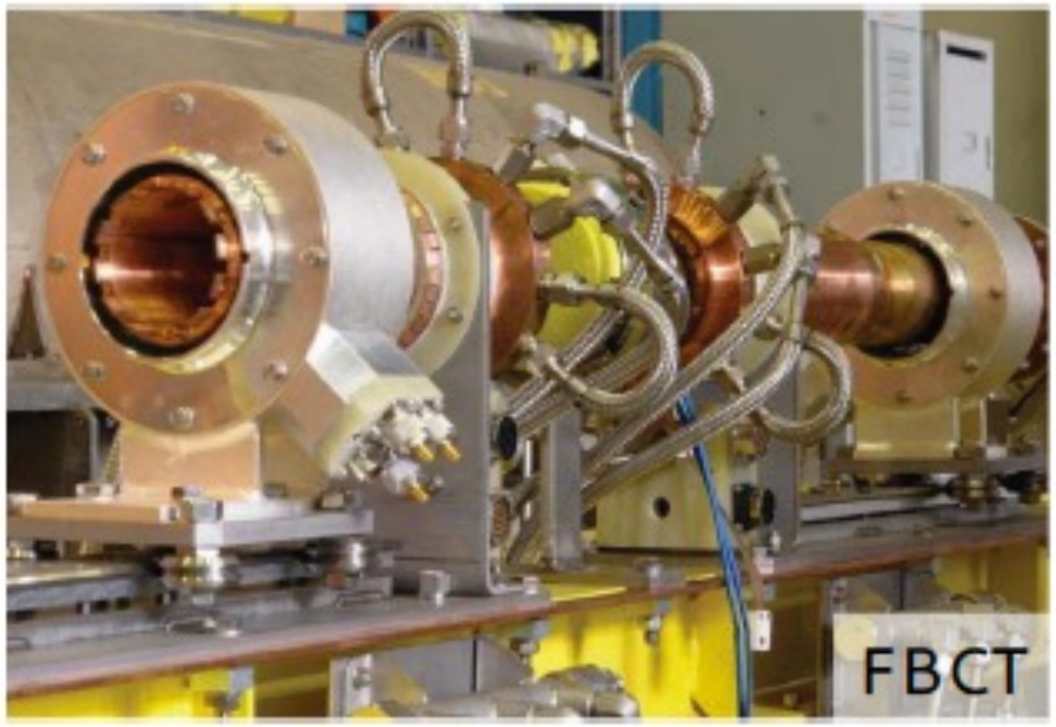
Measuring beam populations → N_1 N_2

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

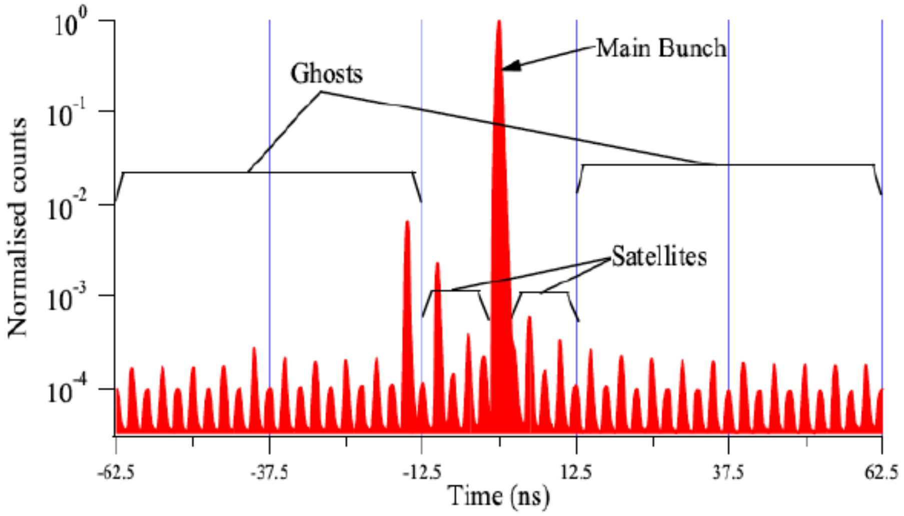
- Relative fraction of total current in each BCID from FBCT
- Normalization to overall current scale provided by DCCT

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

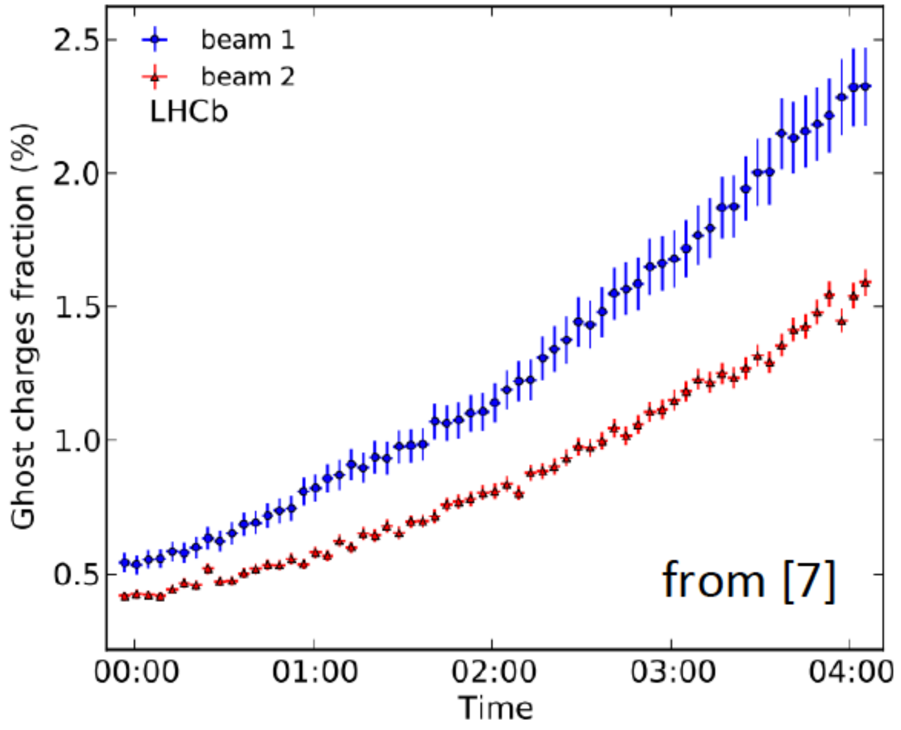
Kristof Kreutzfeldt, U. Gießen

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]

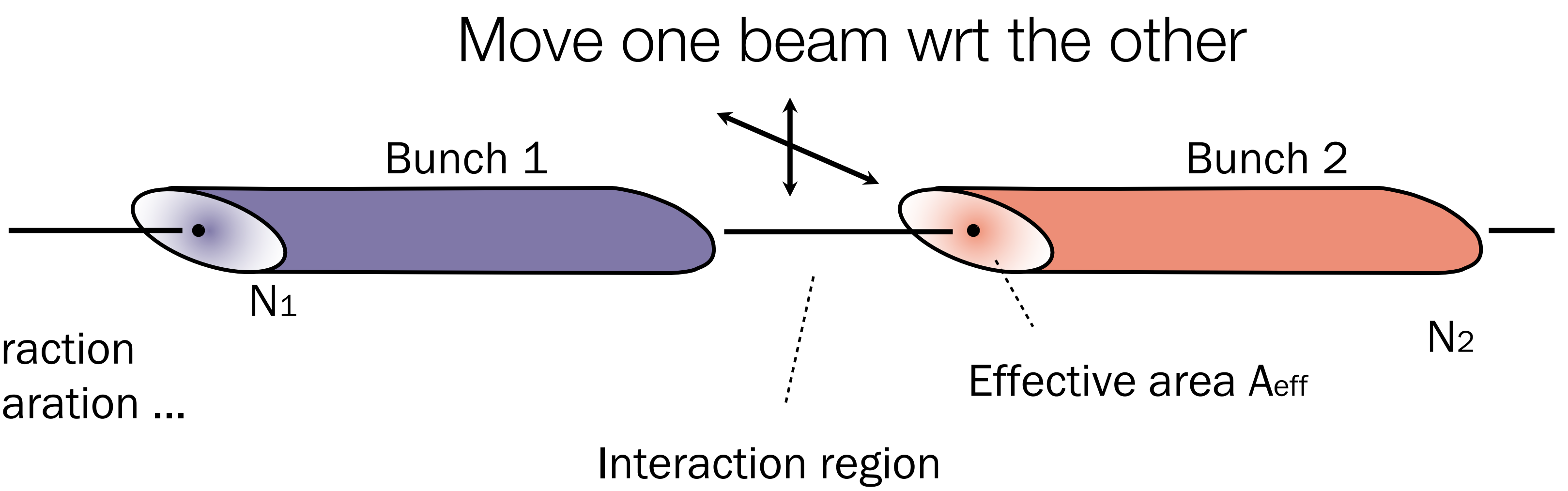


from [7]

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 …

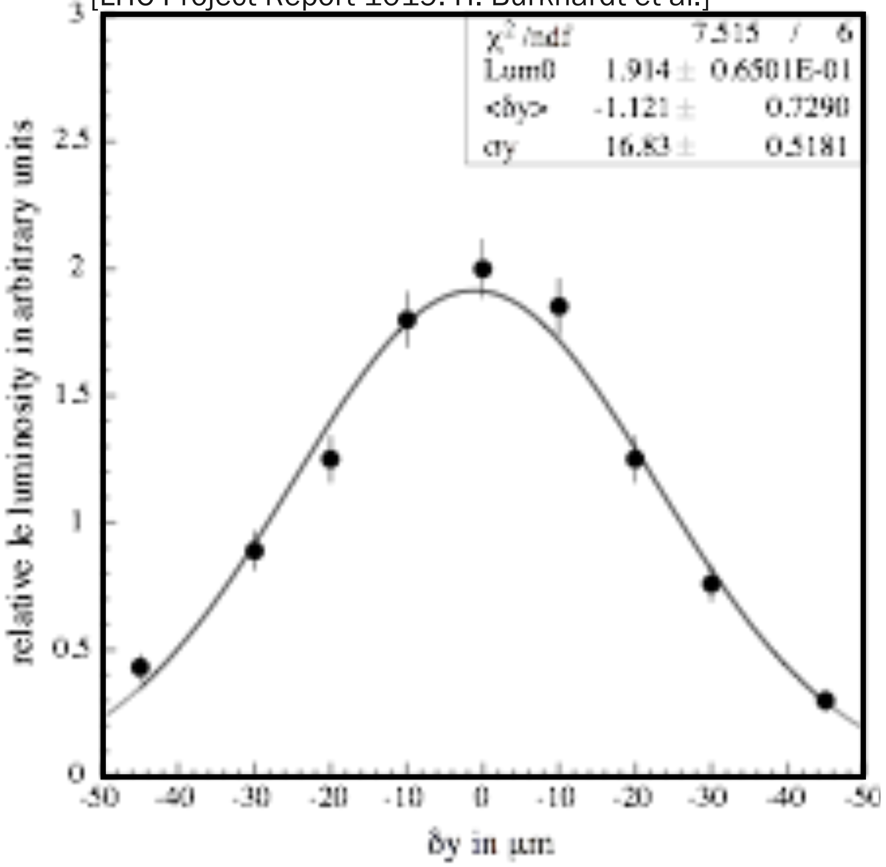


Move one beam wrt the other

Effective area A_{eff}

Interaction region

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

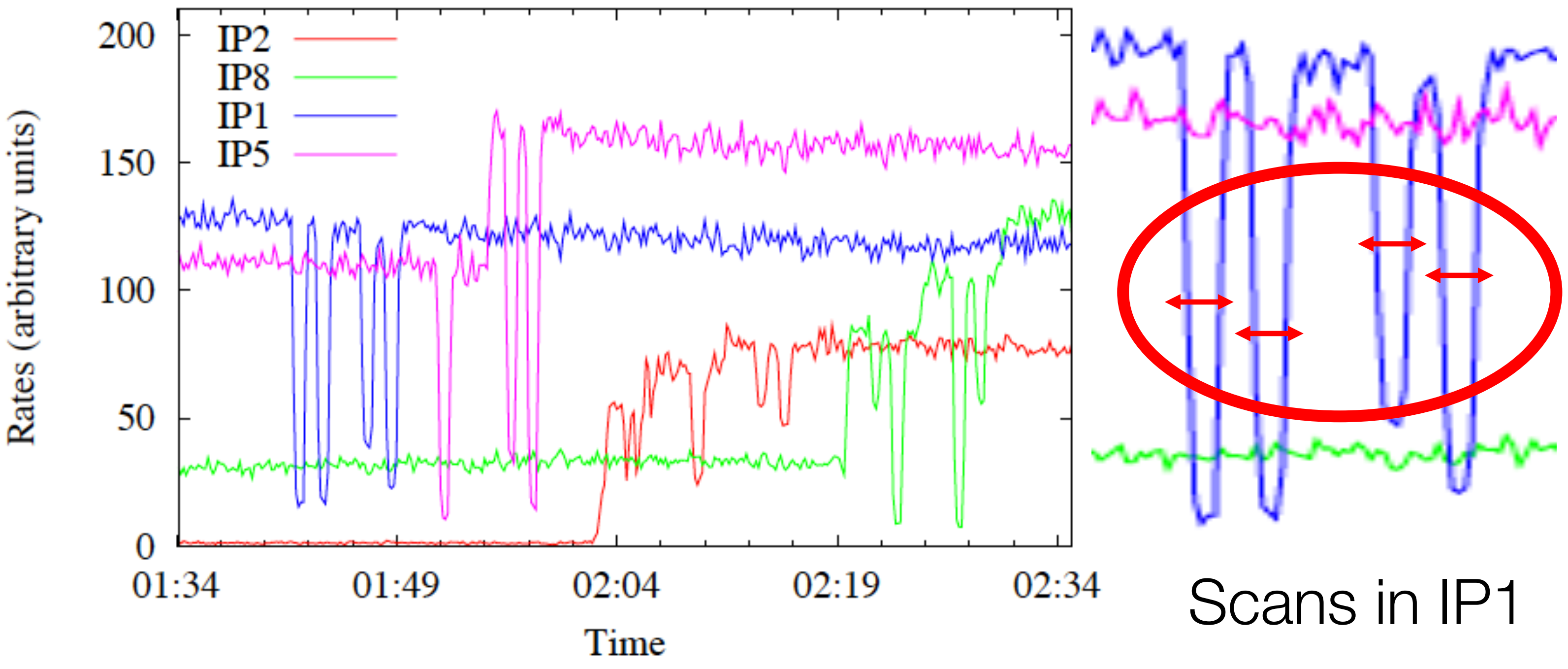


$$\frac{L}{L_0} = \exp\left[-\left(\frac{\delta_x}{2\sigma_x}\right)^2 - \left(\frac{\delta_y}{2\sigma_y}\right)^2\right]$$

Assumption: the two beams have the same profile!

[IPAC 2010, S. White et al.]

[November 2009].



Scans in IP1

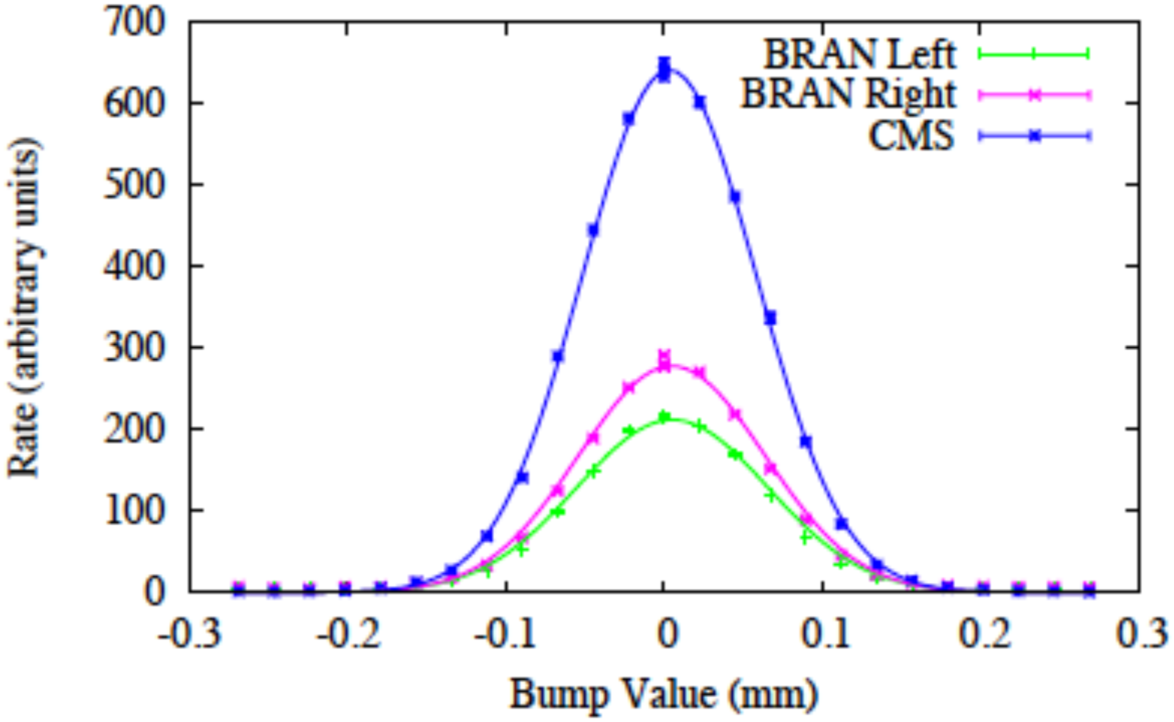
Figure 2: Optimization scans performed for squeezed optics in all IPs.

σ_x σ_y of the beam : factorability!

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

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

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



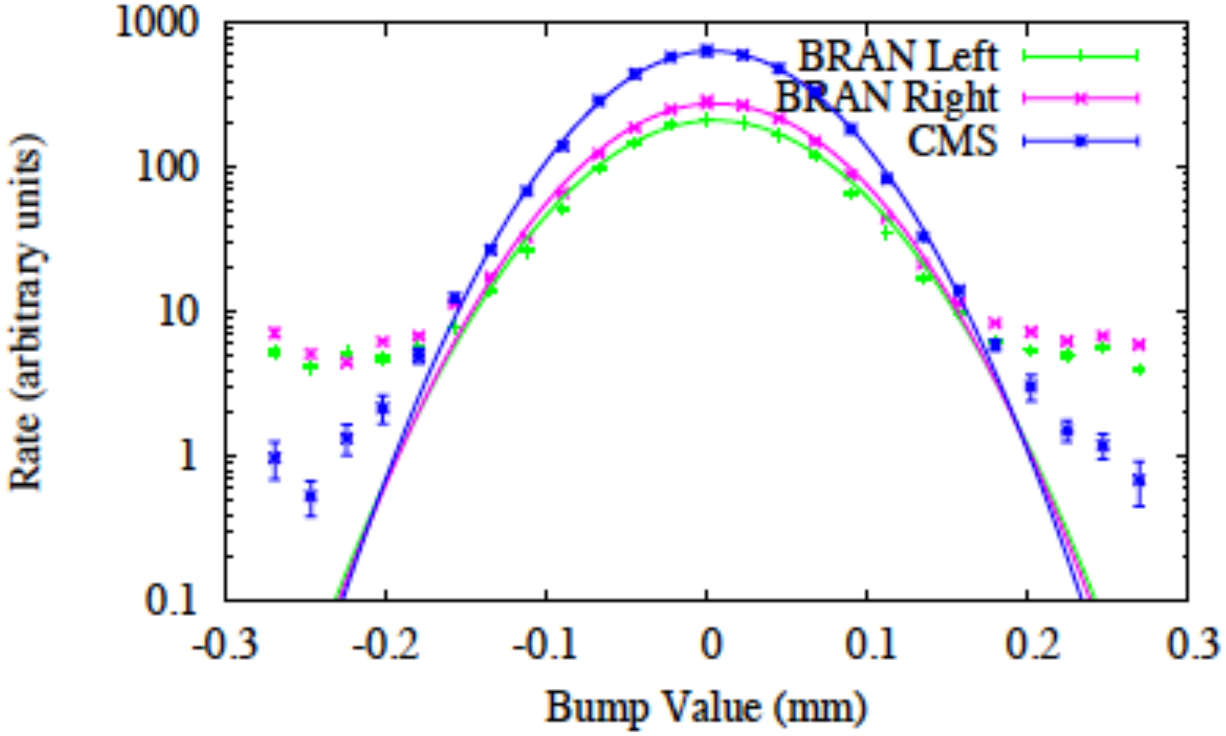
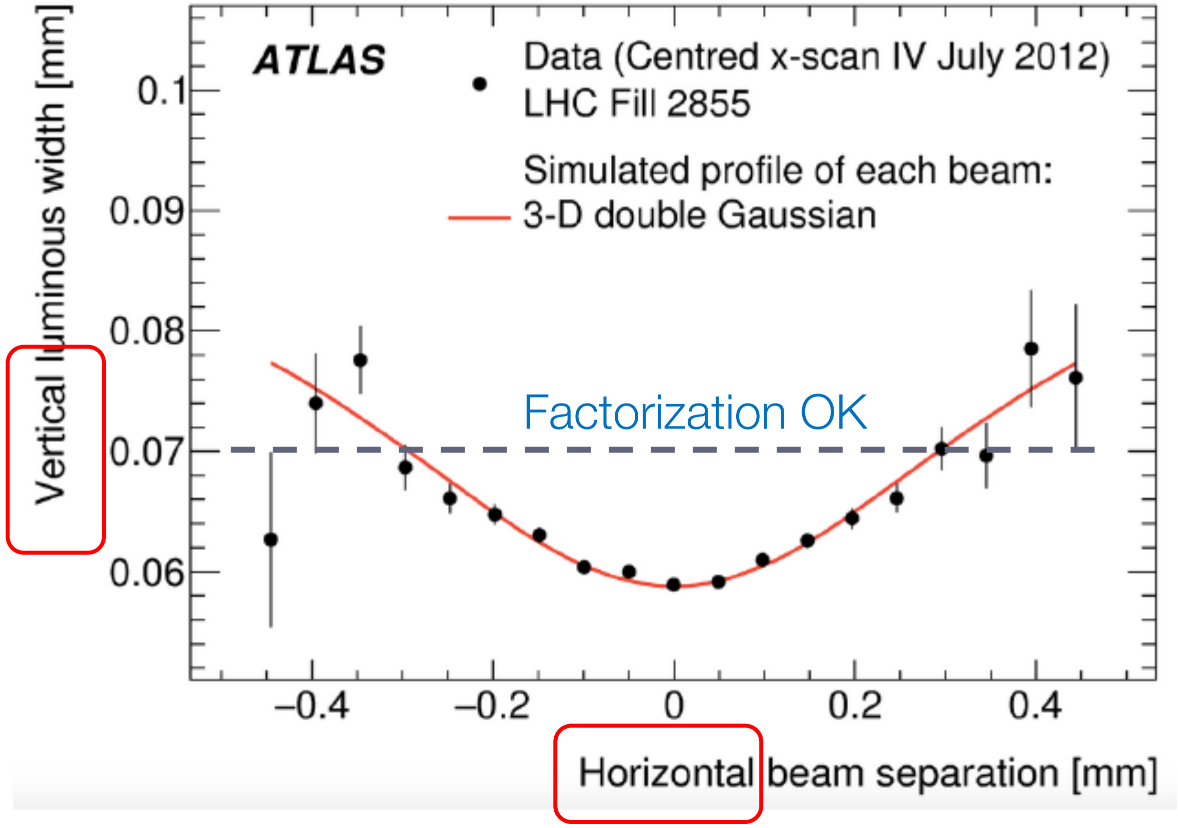


Figure 4: Same horizontal scan in IP5 shown in logarithmic scale with pure Gaussian fits.

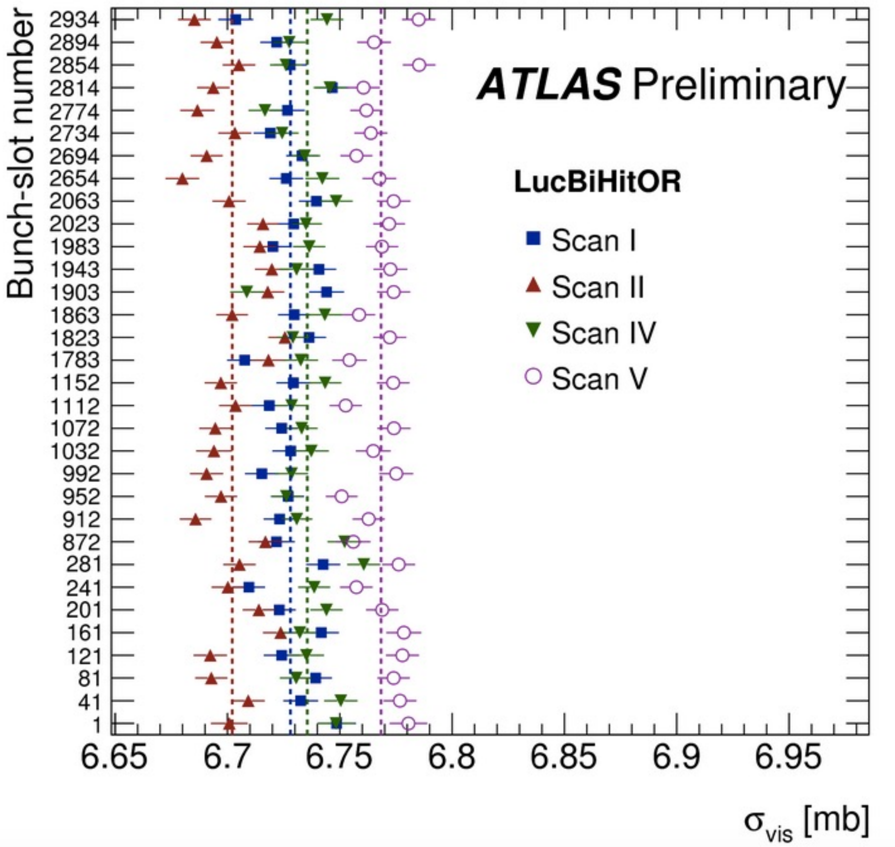
Systematic effects



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 %

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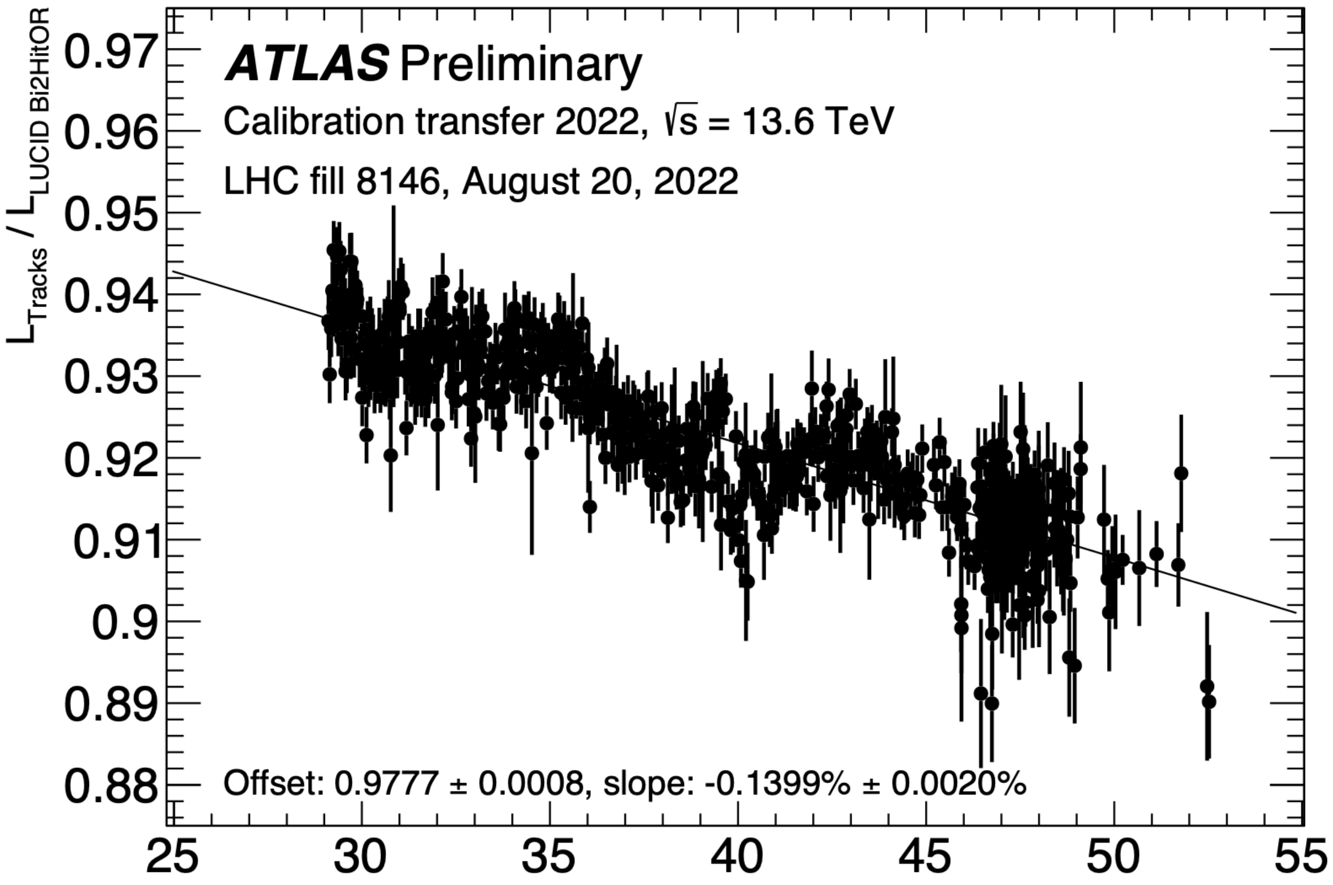
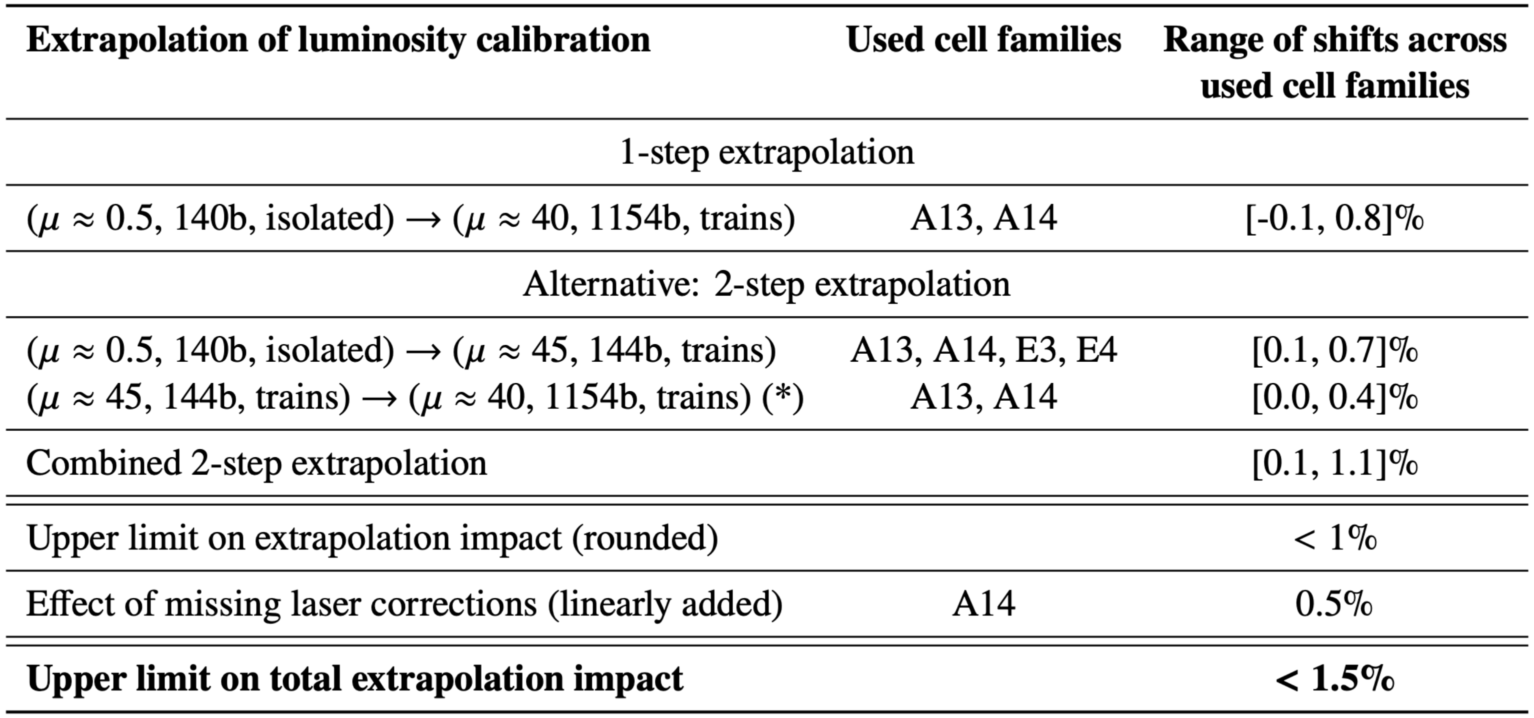
Extrapolating the VdM Luminosity



Extrapolation depends on

- Number of bunches
- Number of superimposed interactions



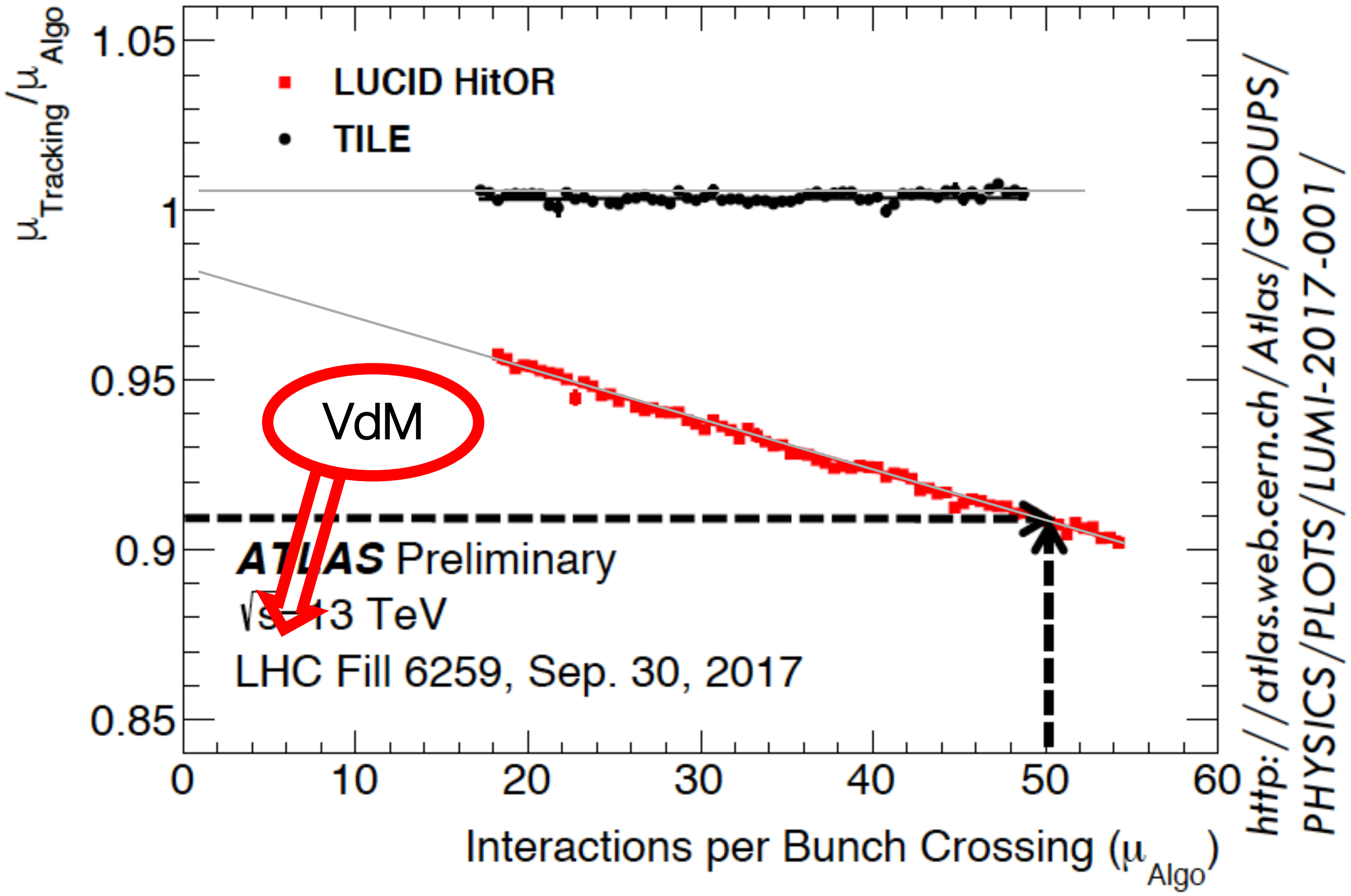
Extrapolation of luminosity calibration	Used cell families	Range of shifts across used cell families
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 40$, 1154b, trains)	A13, A14	[-0.1, 0.8]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 45$, 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 ?

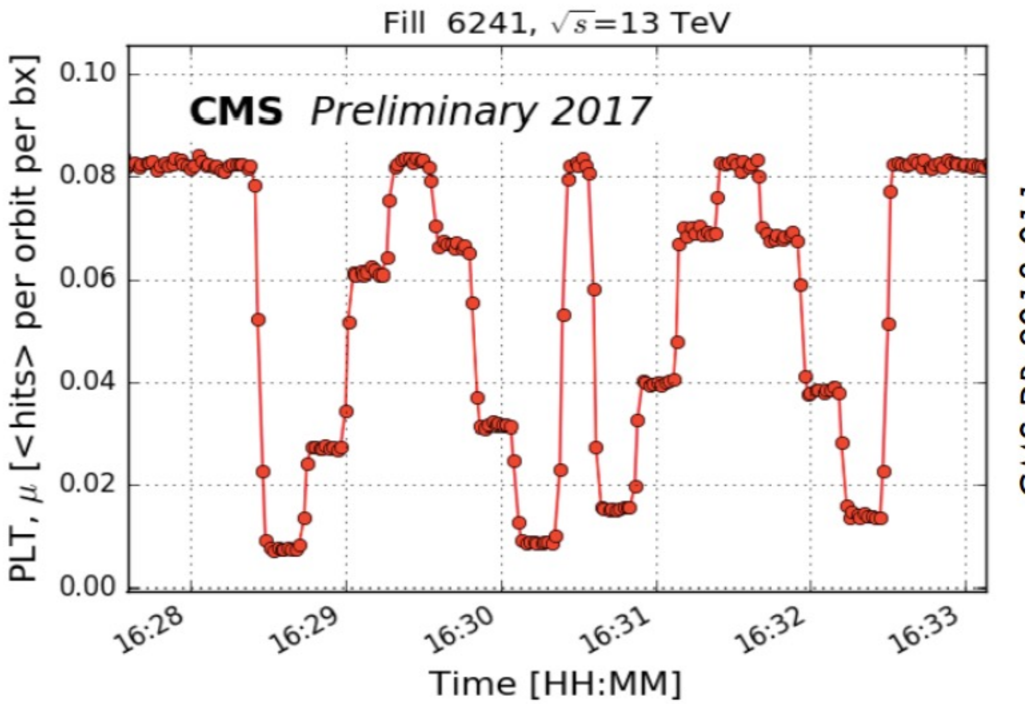
A: tracking luminosity (~#tracks) is not (or very little) sensitive to bunches and pile-up.

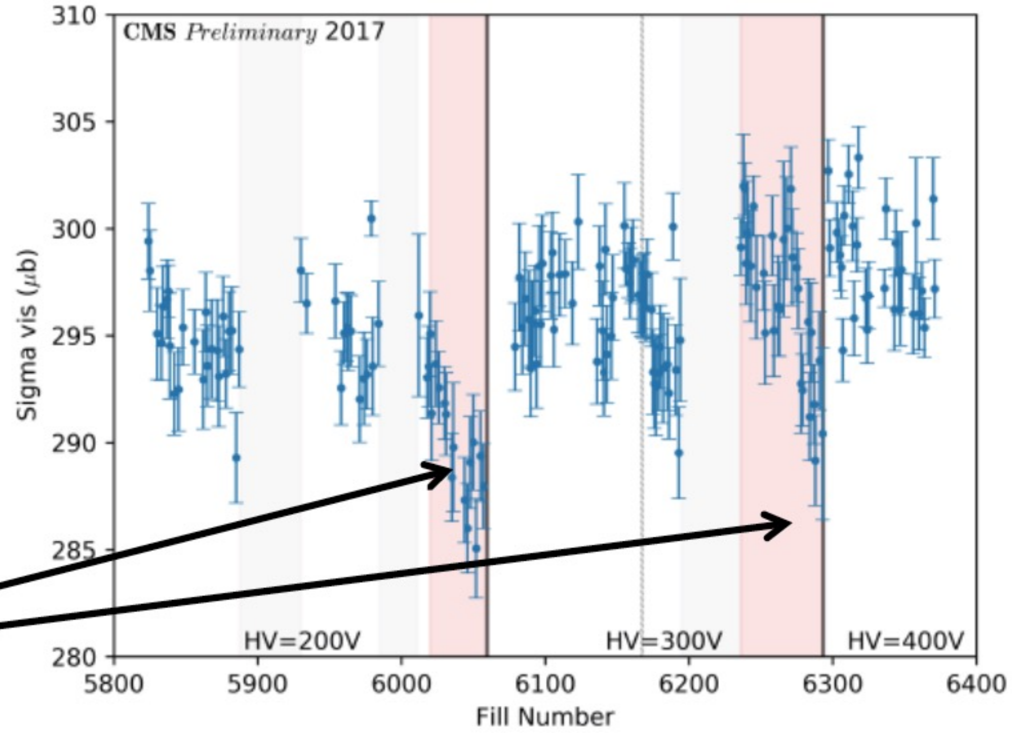
Non-linearity correction from Tracking
ATLAS: typical correction @ μ = 50 for LUCID hit counting in 2017: - 9%
Systematic uncertainty evaluated by comparing with calorimeter-based correction in 2017: ±1.3%
CMS: Non-linearity correction from emittance-scan analysis (i.e. "absolute")
typical correction @ μ = 50 for HFET in 2017: 1.5 %
Systematic uncertainty evaluated by comparing residual relative non-linearity of luminometers on 2017: ±1.5%

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





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Detector effects

Some details on the bunch structure…2

- 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:

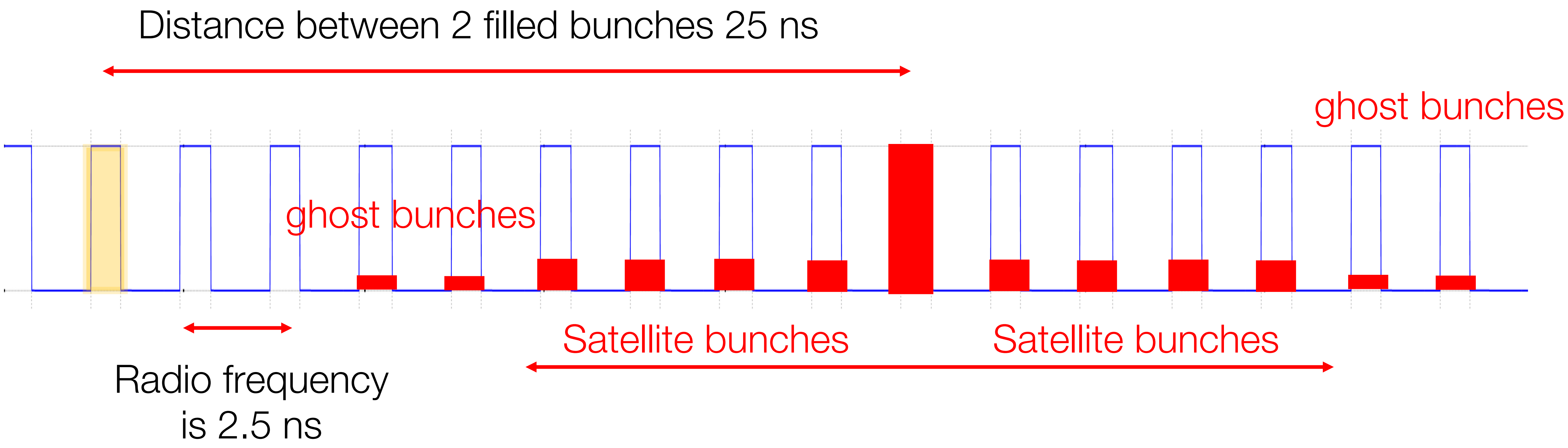
- Nominal bunches (main)
- satellite bunches
- ghost charge.

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

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

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.

Bunch structure of LHC



Distance between 2 filled bunches 25 ns

ghost bunches

ghost bunches

Satellite bunches

Satellite bunches

Radio frequency
is 2.5 ns

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

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

VdM scans in ATLAS

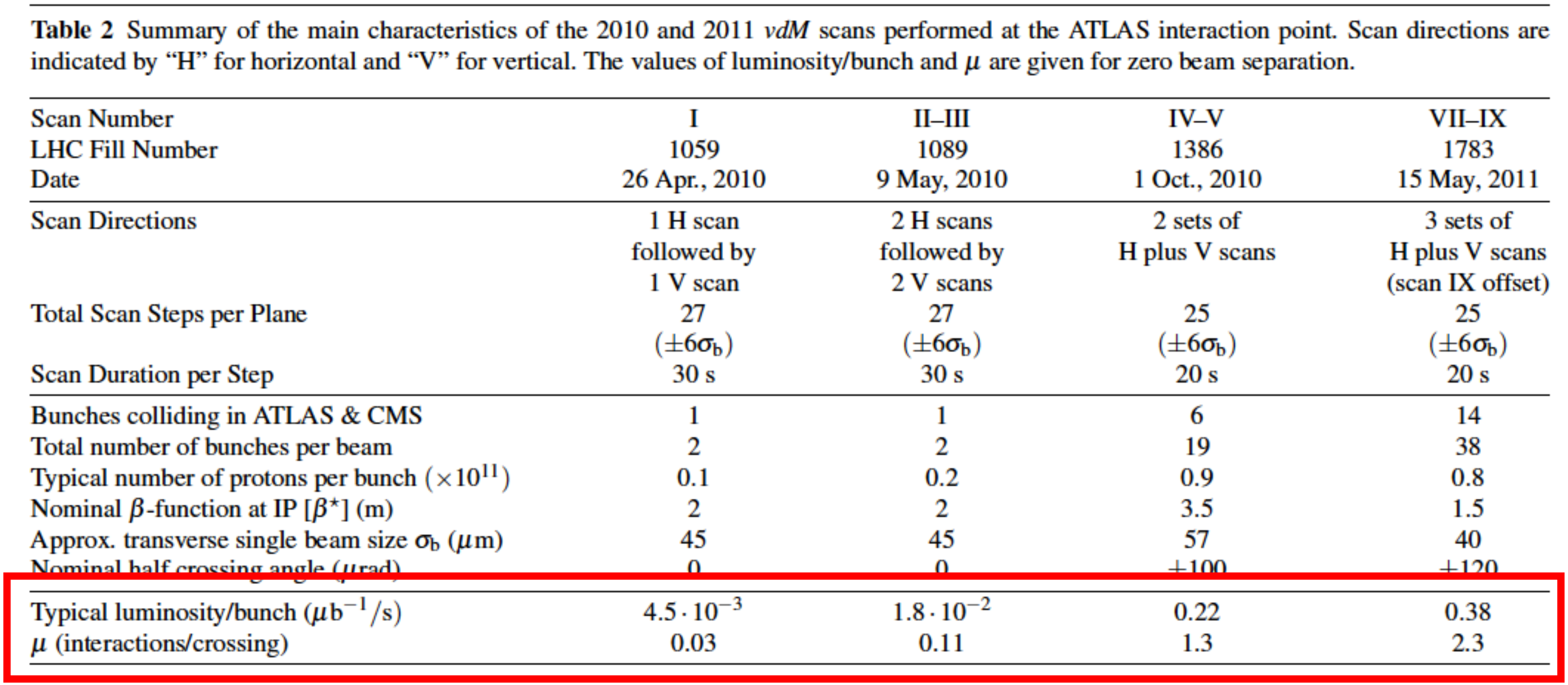


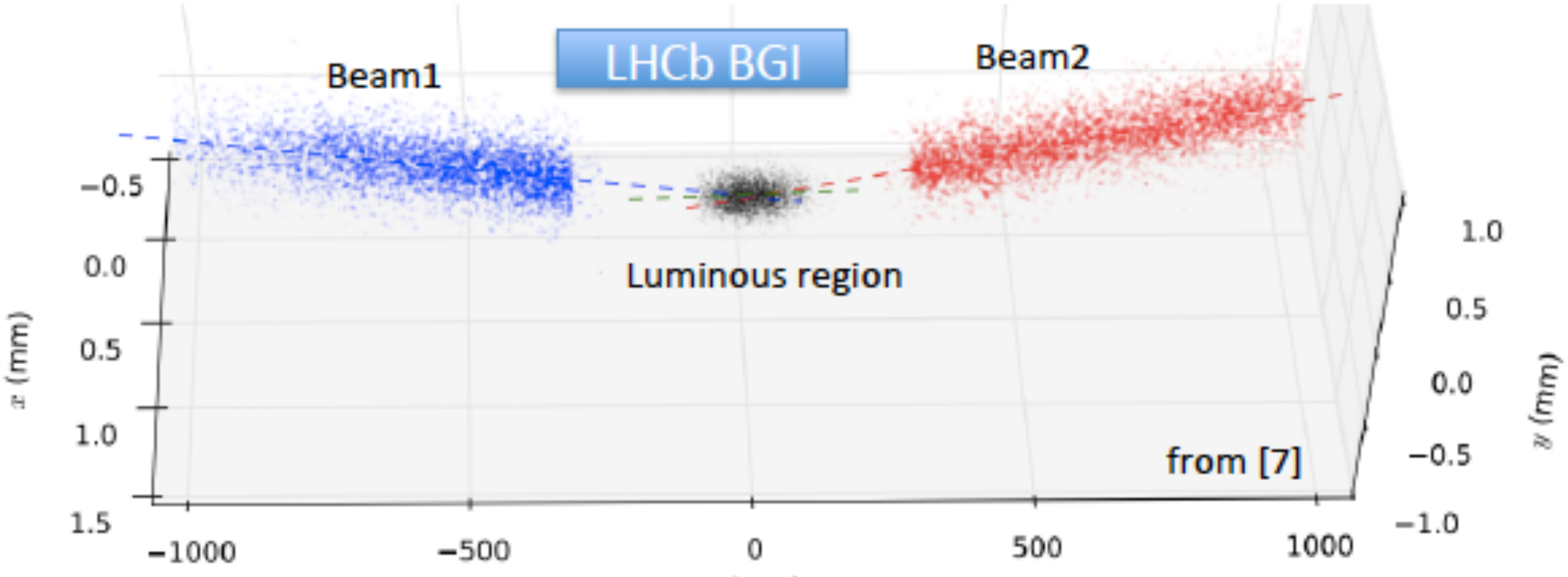
Table 2 Summary of the main characteristics of the 2010 and 2011 *vdM* scans performed at the ATLAS interaction point. Scan directions are indicated by "H" for horizontal and "V" for vertical. The values of luminosity/bunch and μ are given for zero beam separation.

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

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

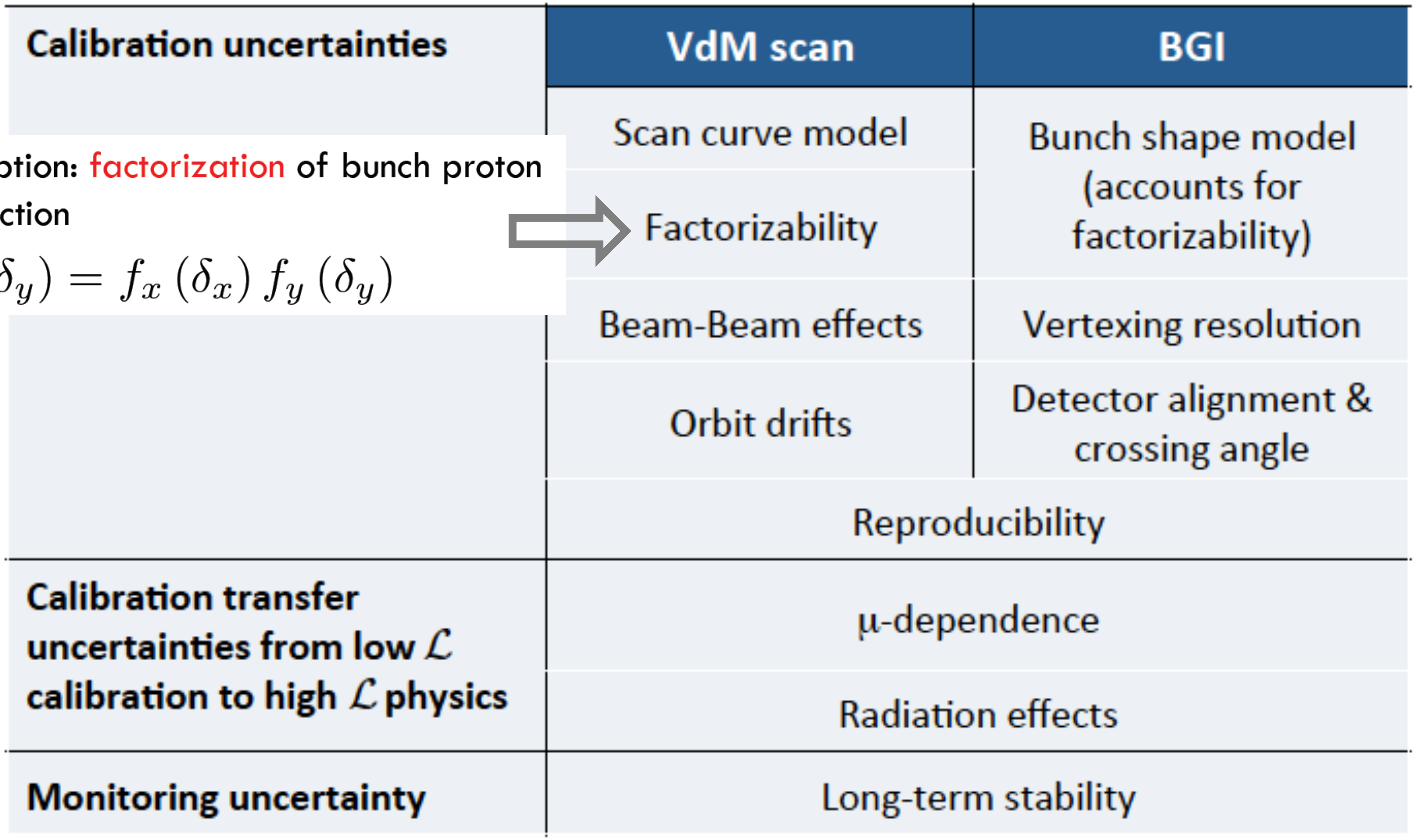


from [7]

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



Key assumption: factorization of bunch proton density function

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

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	

Snapshot of Luminosities uncertainties

Parts of table reproduced from [11]

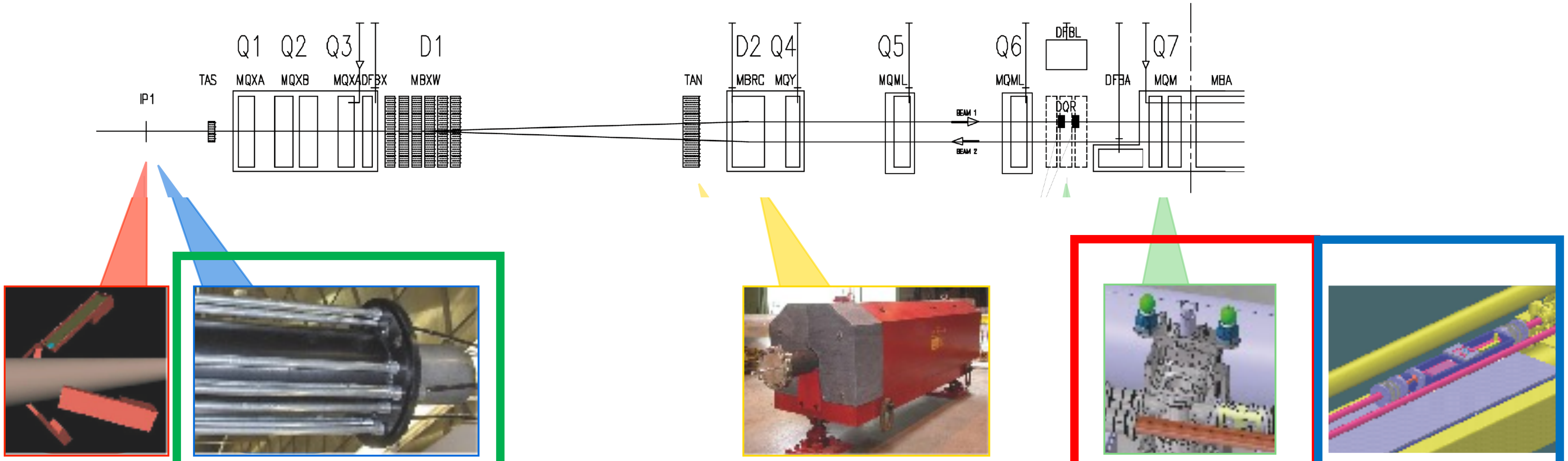
	ALICE	ATLAS	CMS	LHCb
Running period	2013	2011	2012	2012
Sqrt(s) [TeV]	5.02	7	8	8
Running mode	**Pb-p**	**p-p**	**p-p**	**p-p**
Reference	[8]	[9]	[10]	In the process of being made publicly available
Absolute calibration method	VdM	VdM	VdM	VdM + BGI *
$\Delta\sigma_{vis}/\sigma_{vis}$ [%]	**2.8**	**1.53**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

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.

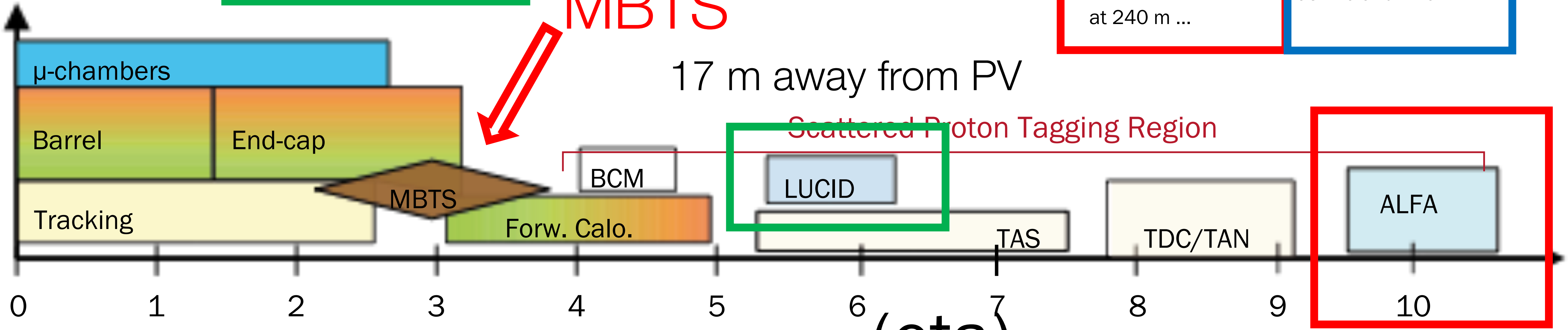
ZDC
[Forward Neutrals]
W^{74} /Quartz calo
at 140 m and at 0° toIP.

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



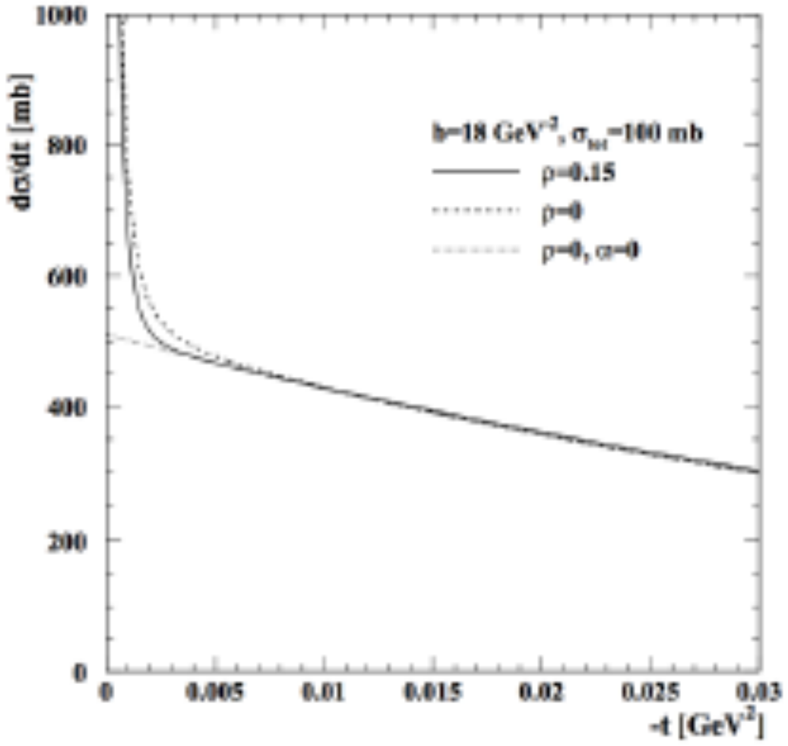
(eta)

240 m away from PV

TAS: Target Absorber Secondaries
TAN: Target Absorber Neutrals

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)

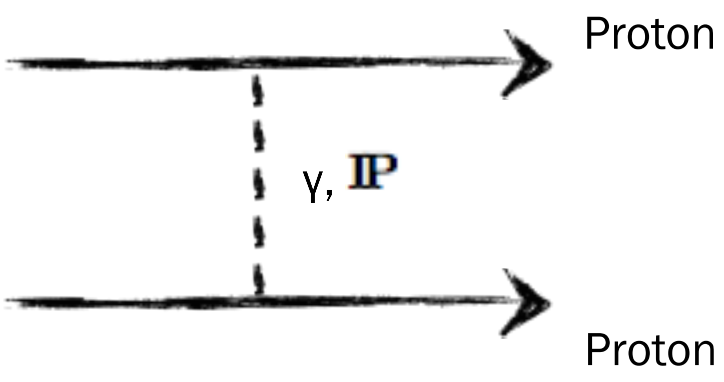


$$\boxed{N = L\,\sigma \rightarrow L = N / \sigma}$$

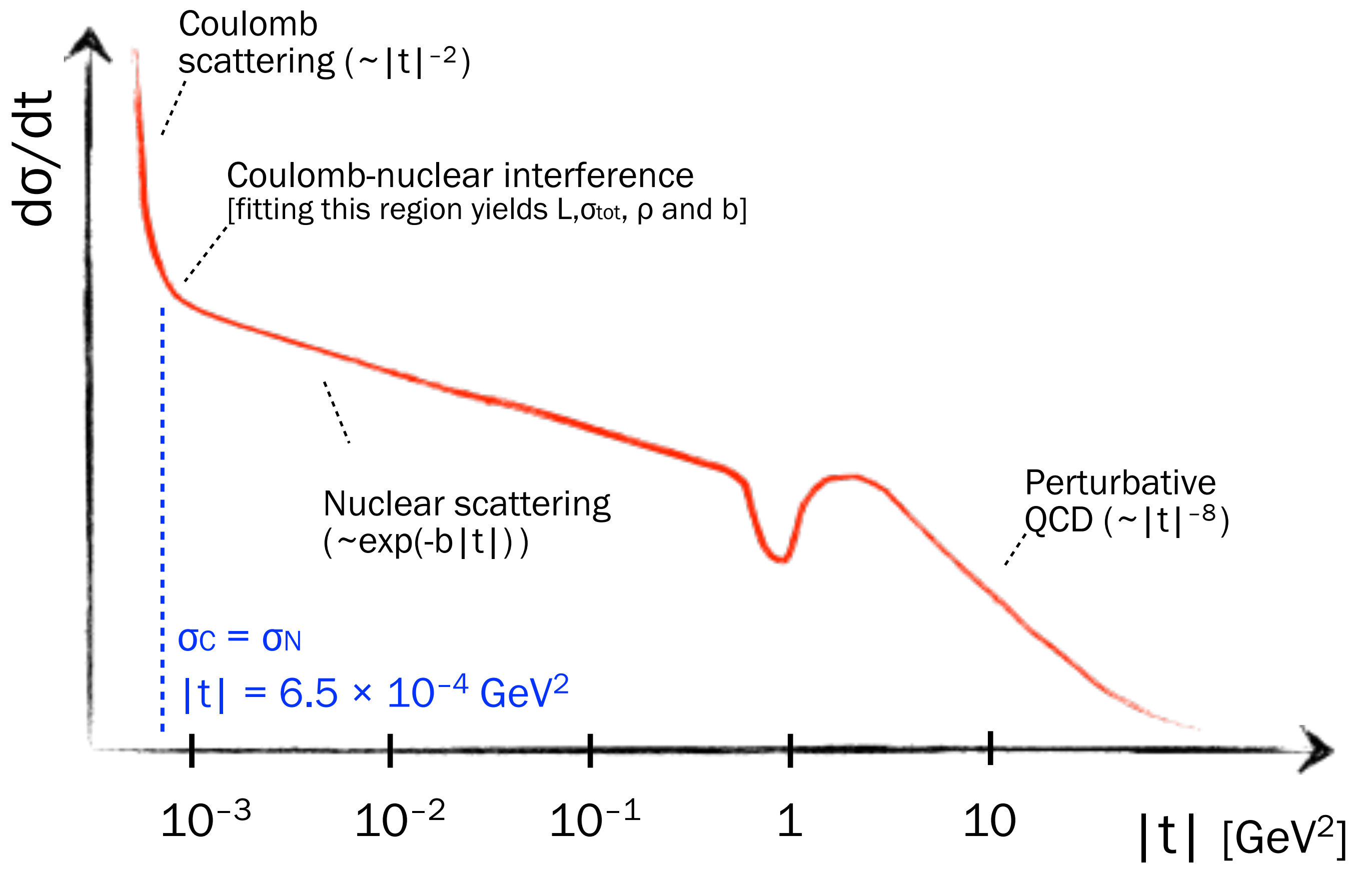
- Requires dedicated LHC fills with special magnet settings
- Roman pots far from the interaction points (about 200 m)
- Measurements at very low interaction rates
  - Cross-calibration of dedicated luminosity detectors
  - Extrapolation of calibration to typical physics conditions introduces big uncertainties
- 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

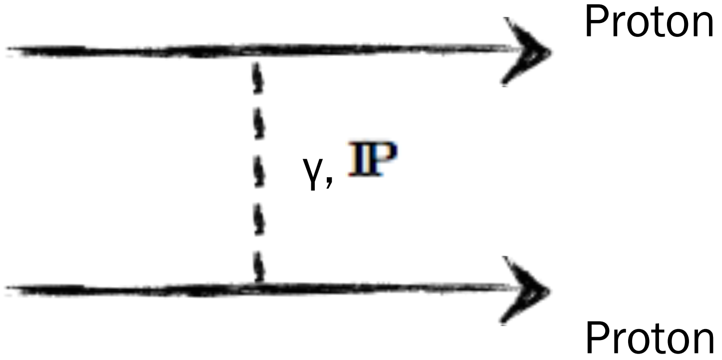
b : nuclear slope

σ_{tot} : total pp ➛X cross section

ALFA – Absolute Luminosity for ATLAS

ALFA

Elastic Scattering:

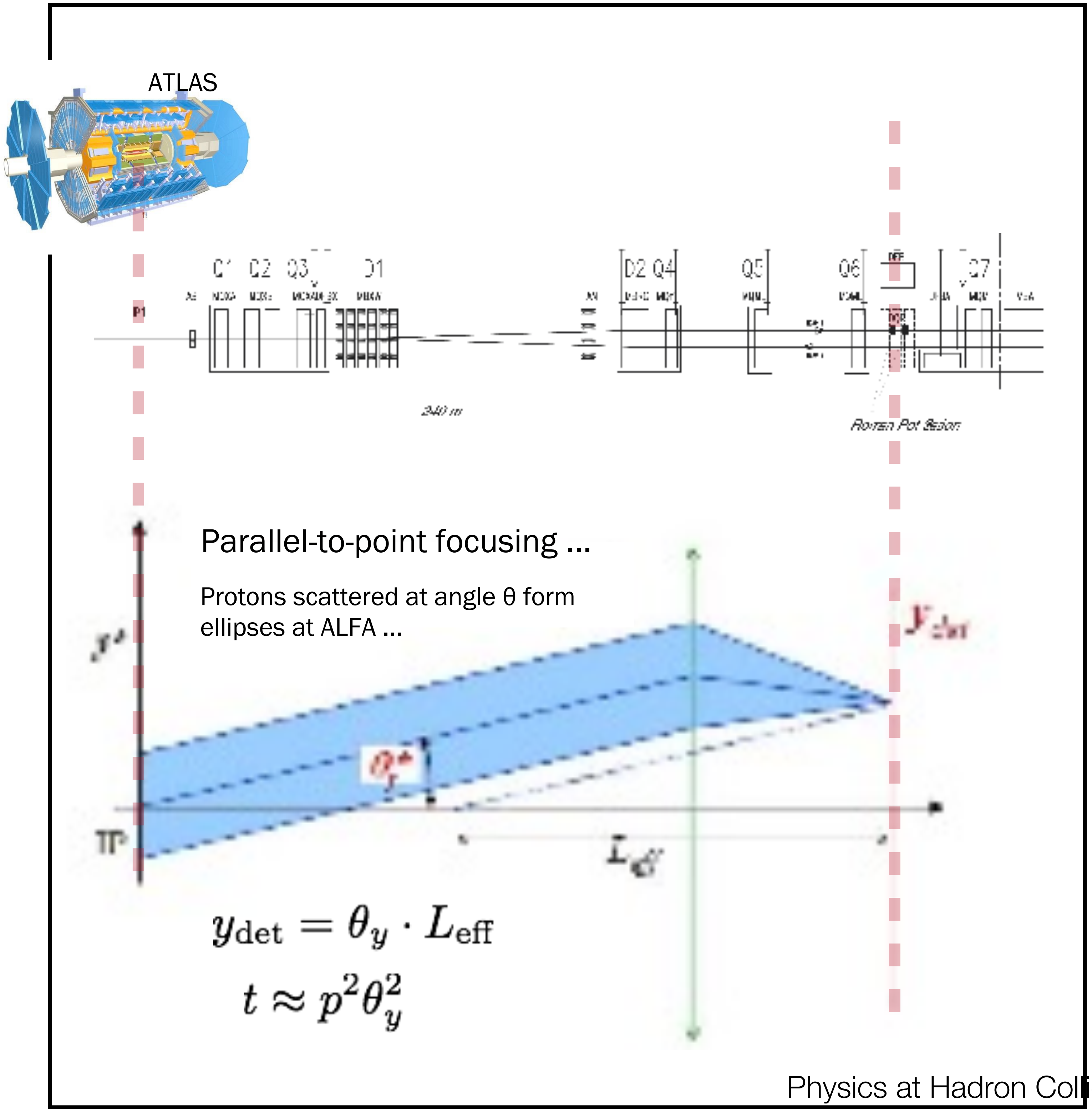


$$t = (p_i - p_i') \sim p^2\theta^2$$

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

- $\theta \approx 5 \cdot 10^{-6} = 5\ \mu\mathrm{rad}$
  $L_{\mathrm{eff}} \approx 240\ \mathrm{m}$
  [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 ..



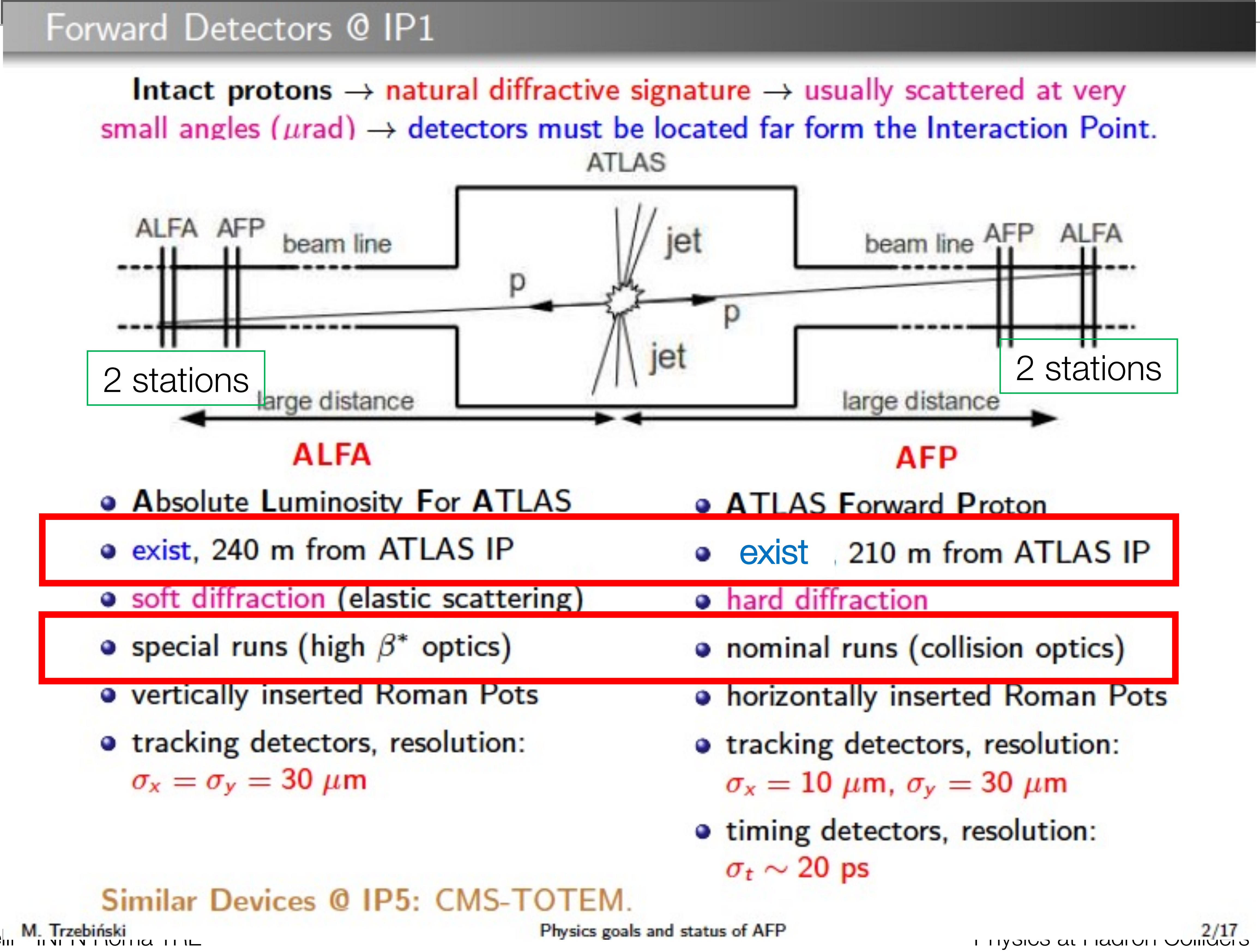
Parallel-to-point focusing ...

Protons scattered at angle θ form ellipses at ALFA ...

$$y_{\mathrm{det}} = \theta_y \cdot L_{\mathrm{eff}}$$

$$t \approx p^2\theta_y^2$$

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

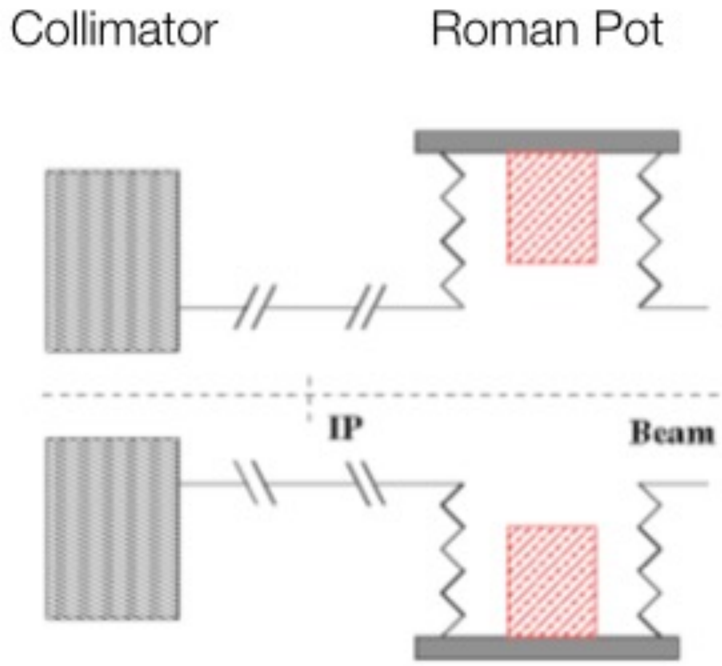
- **A**bsolute **L**uminosity **F**or **A**TLAS
- exist, 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high β^* optics)
- vertically inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = \sigma_y = 30\ \mu$m

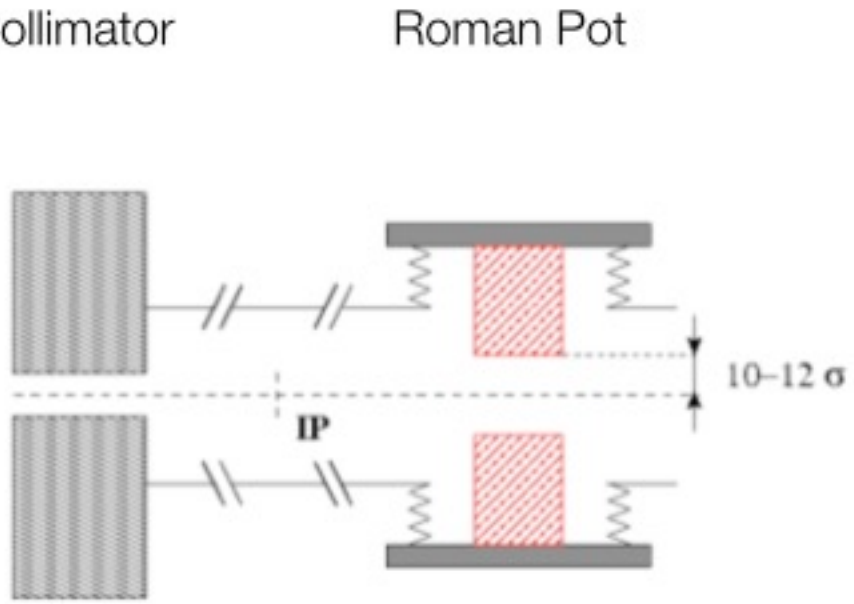
AFP

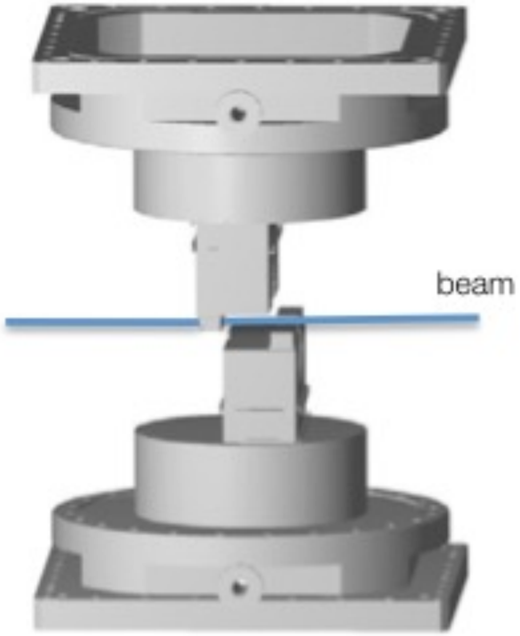
- **A**TLAS **F**orward **P**roton
- exist , 210 m from ATLAS IP
- hard diffraction
- nominal runs (collision optics)
- horizontally inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = 10\ \mu$m, $\sigma_y = 30\ \mu$m
- timing detectors, resolution: $\sigma_t \sim 20$ ps

Similar Devices @ IP5: CMS-TOTEM.

ALFA – Absolute Luminosity for ATLAS





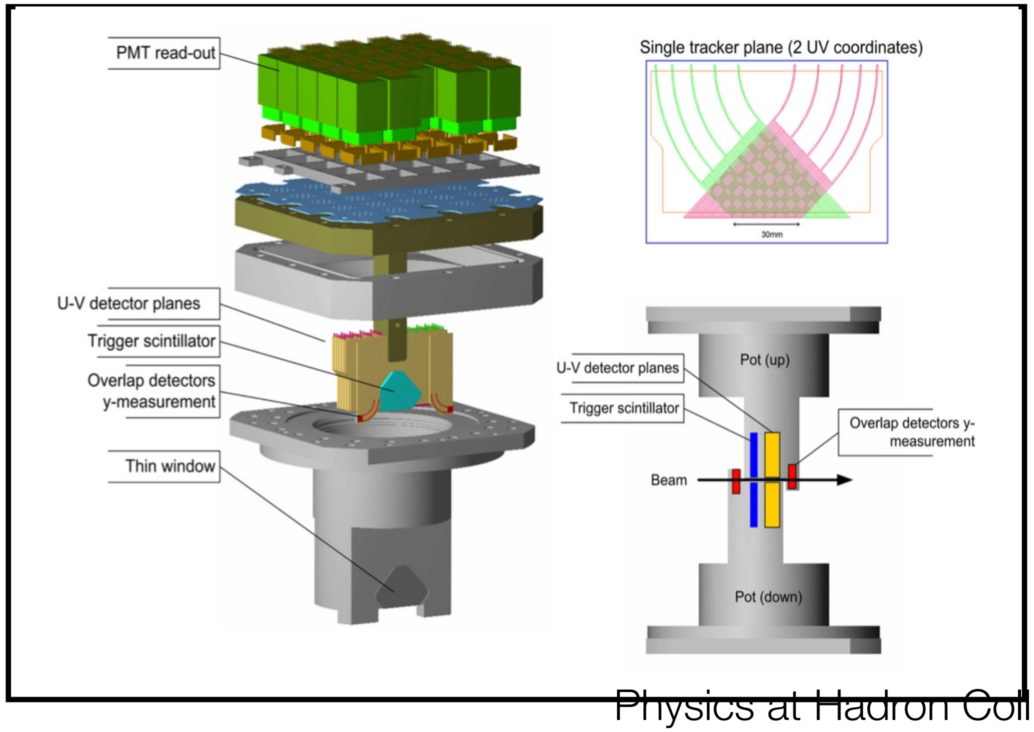


Roman Pots, based on modified Totem design, used to move detectors near to stable beam.

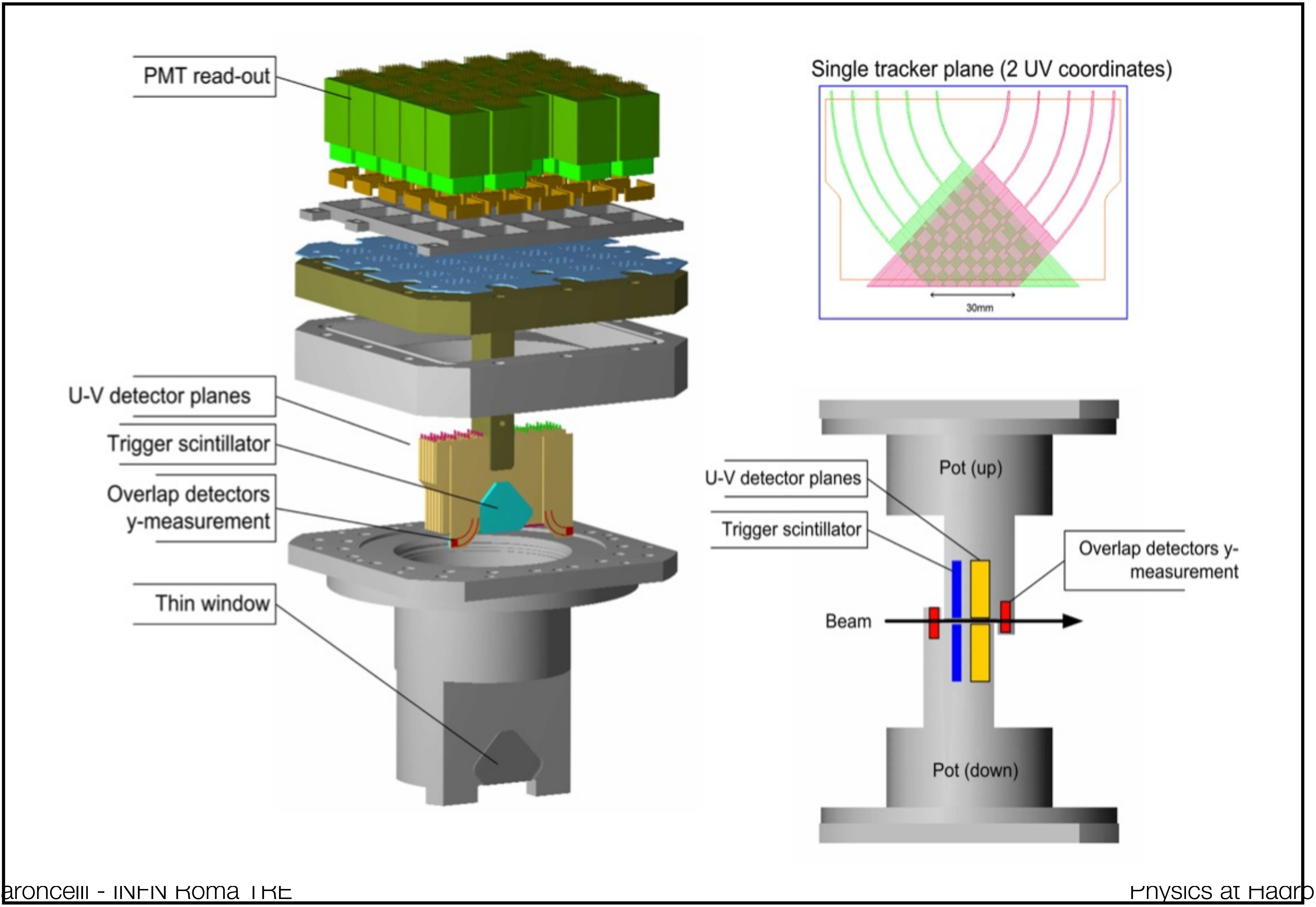
Detectors in vertical plane only.

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

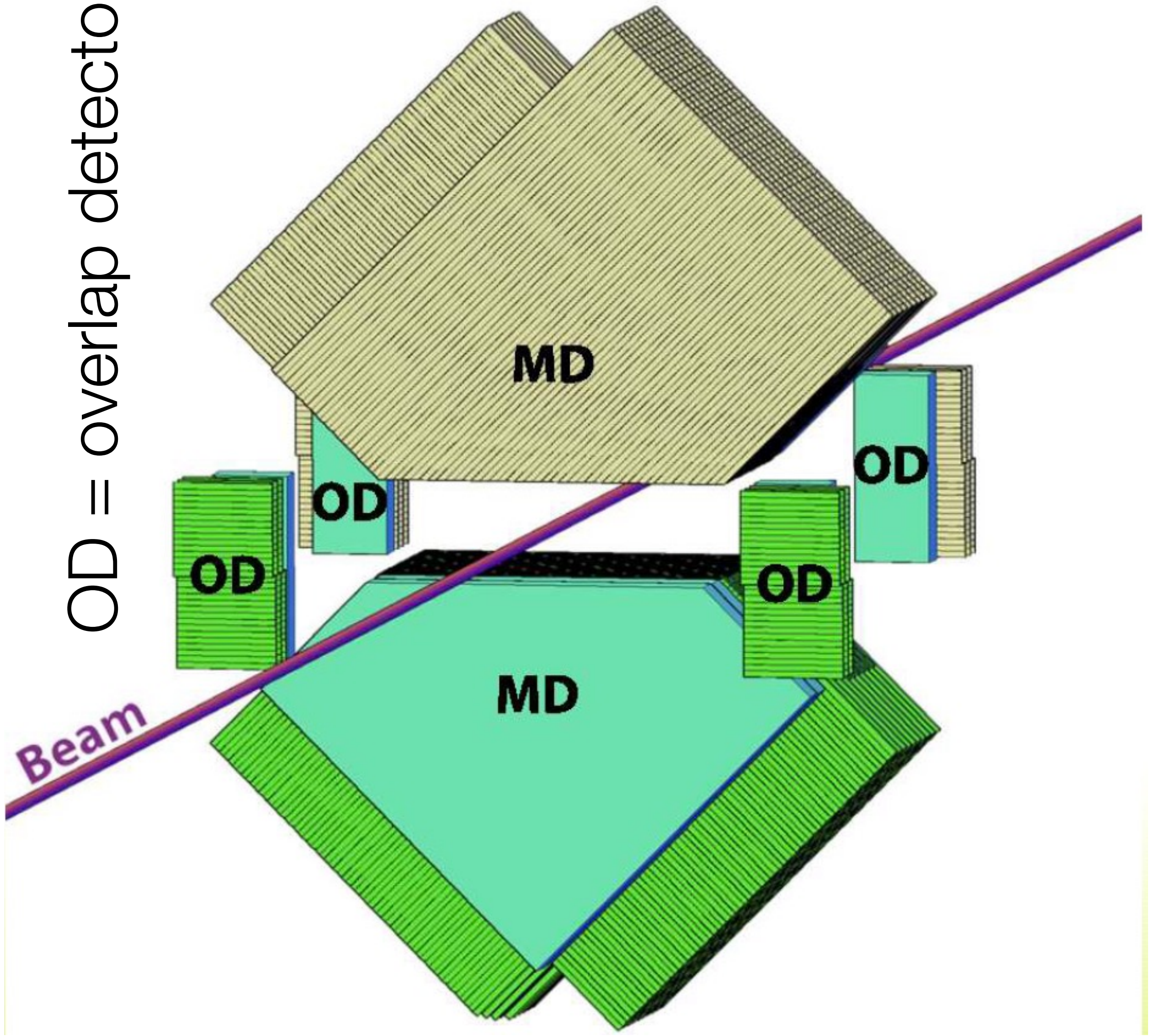


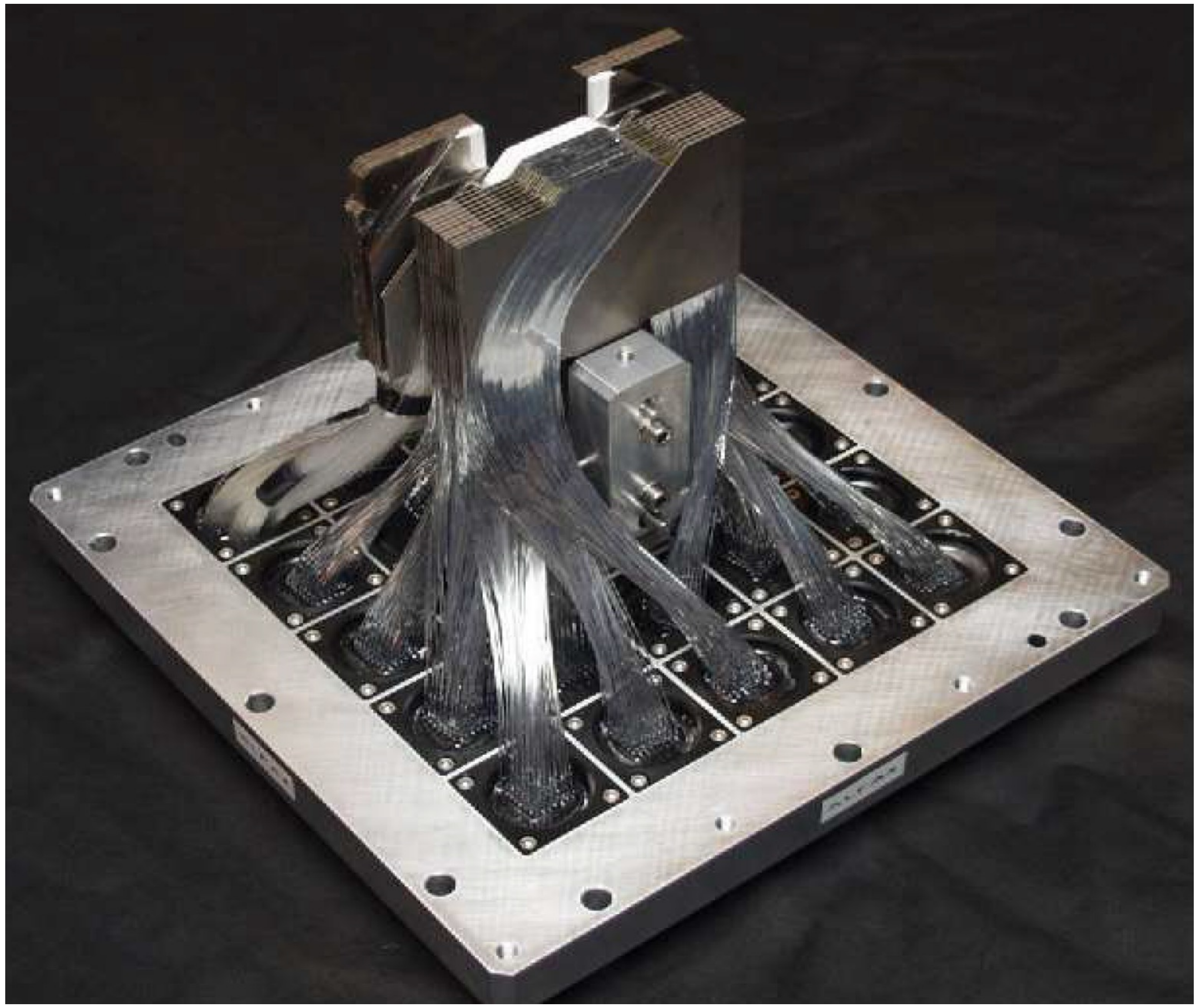
ALFA – Absolute Luminosity for ATLAS



ALFA detector

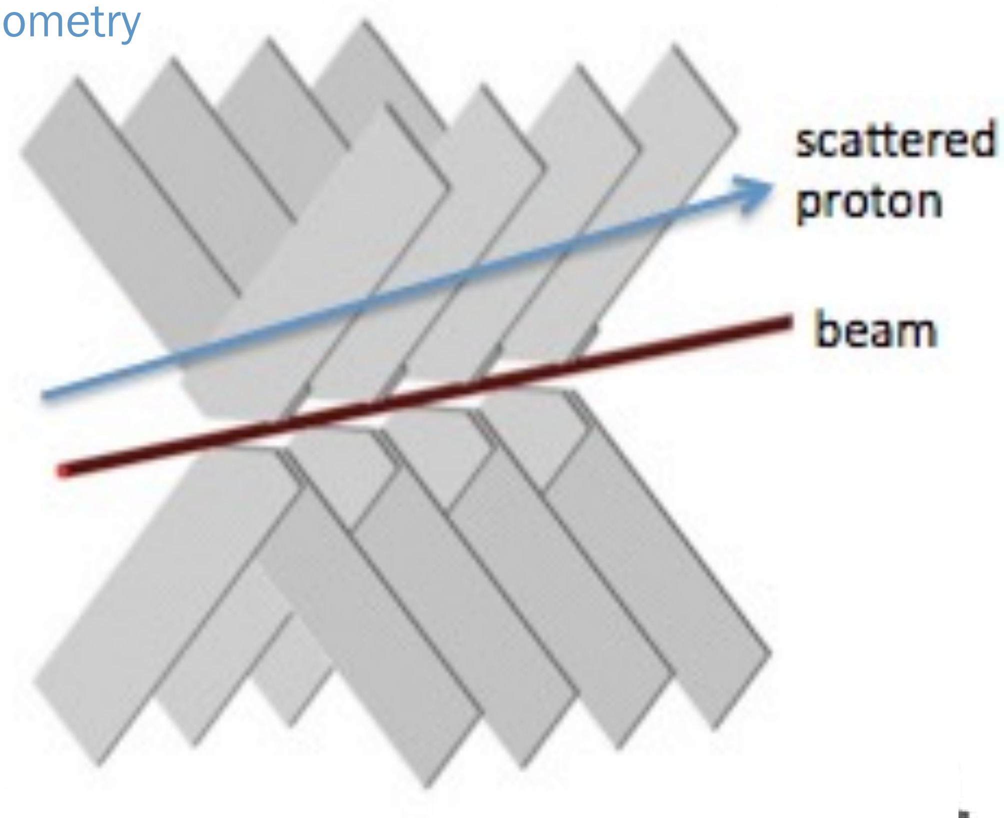
OD = overlap detector





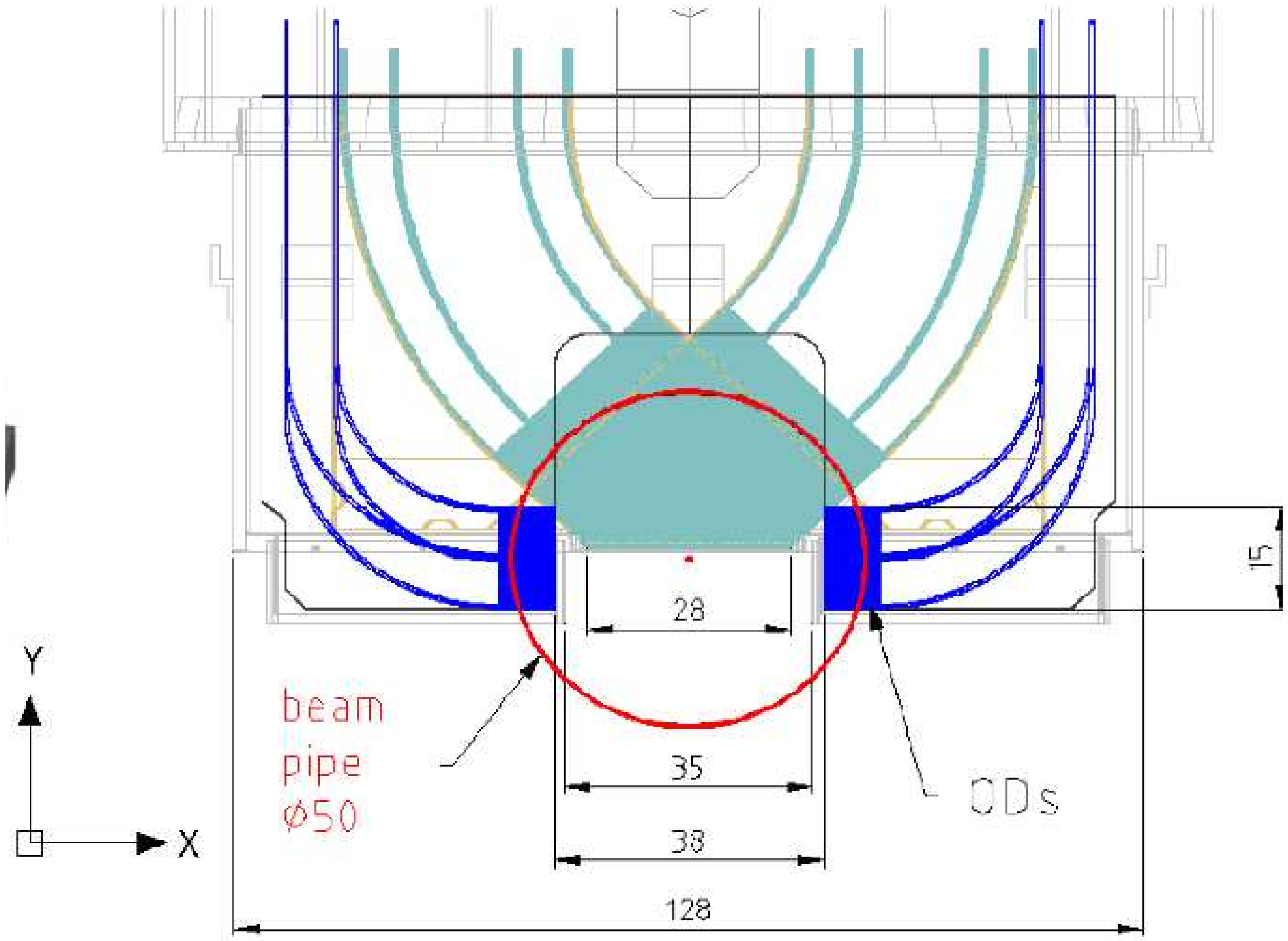
ALFA – Absolute Luminosity for ATLAS

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) …



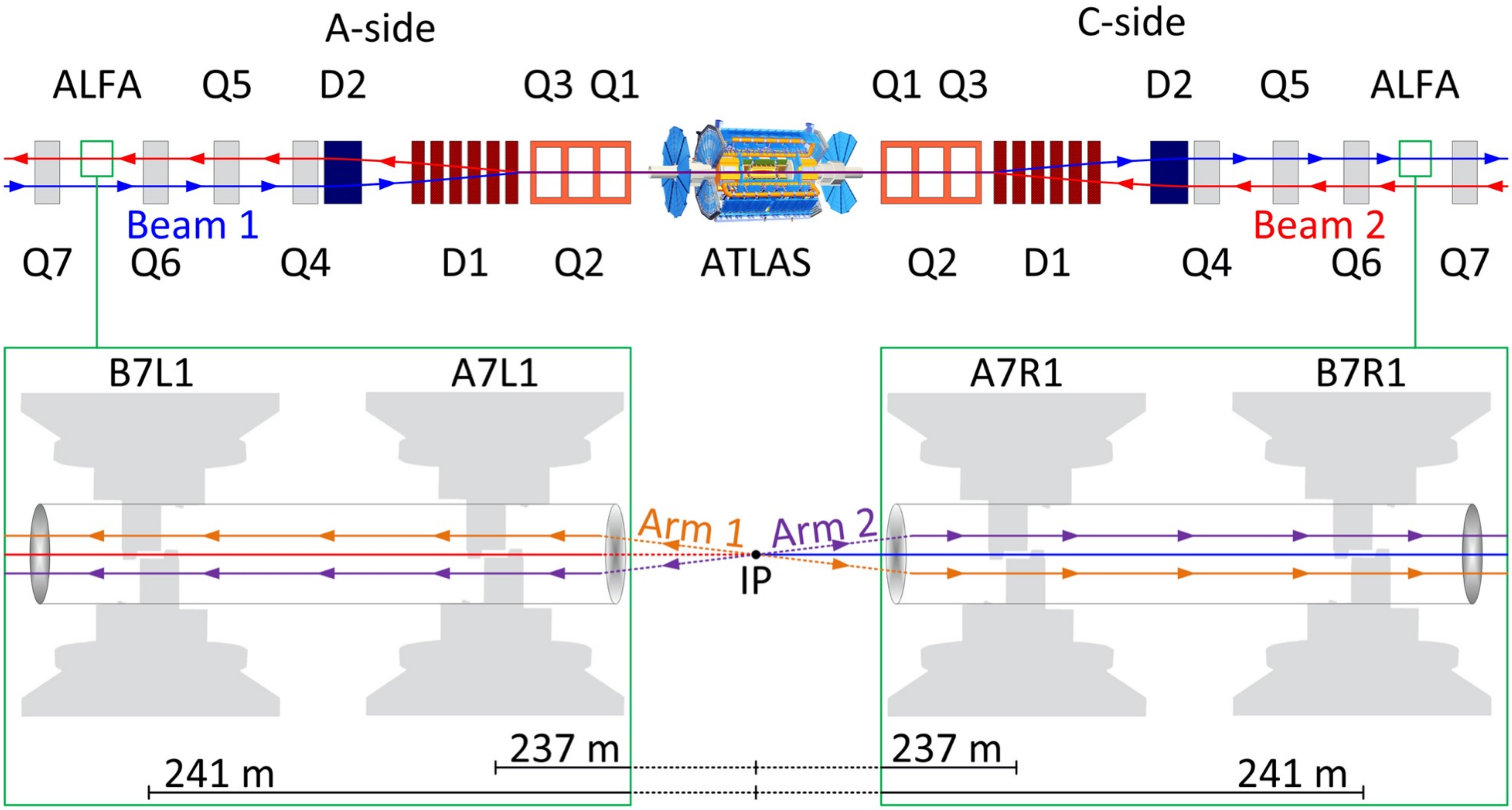
Single-cladded 0.5 mm square fibers used to track scattered protons …

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

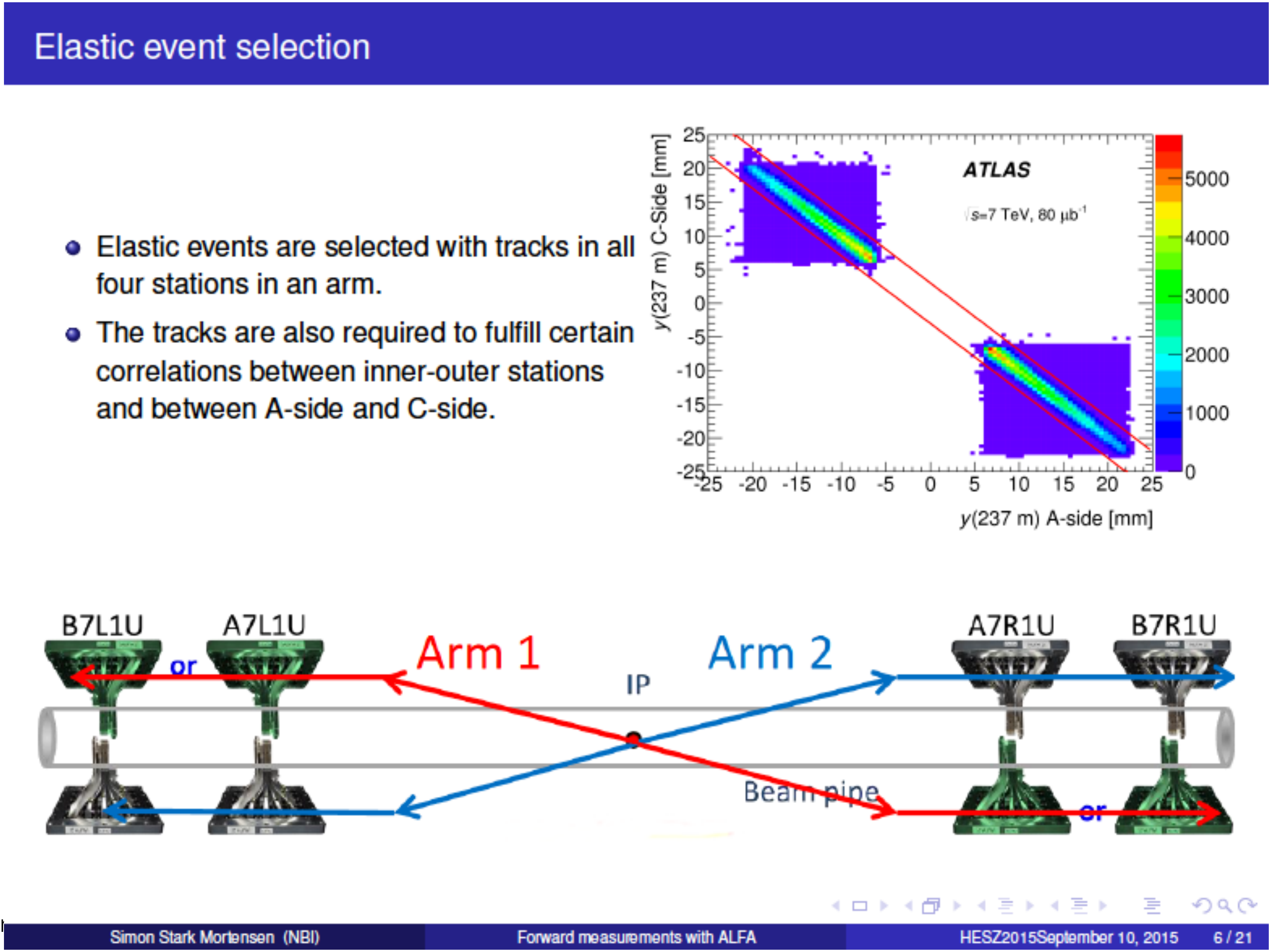
Dead region less than 100 µm …

Efficiency > 90% per plane …

ALFA detector



ALFA detector : signal events



Elastic event selection

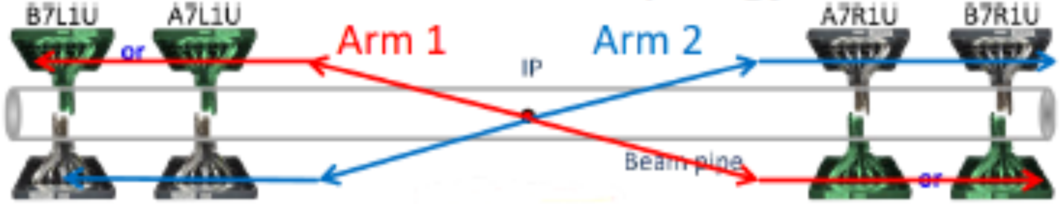
- Elastic events are selected with tracks in all four stations in an arm.
- The tracks are also required to fulfill certain correlations between inner-outer stations and between A-side and C-side.

ALFA detector : background events

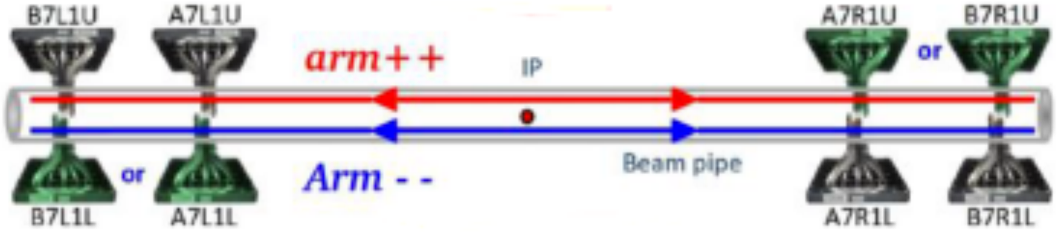
Background

- 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 ∼ 0.5% and halo+halo is the dominant source.

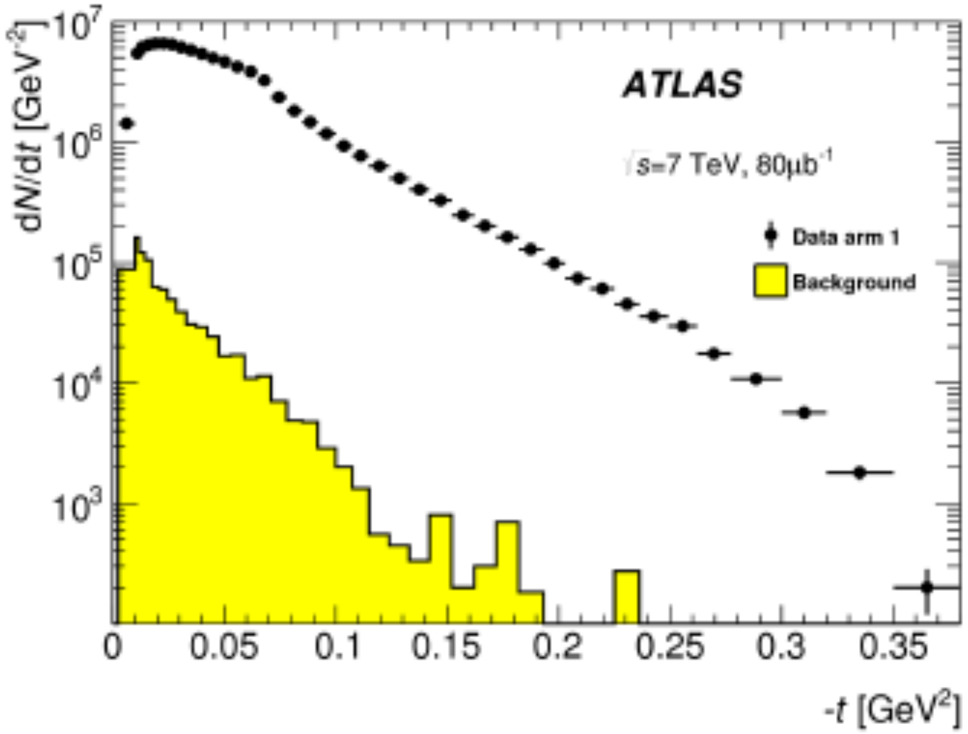
Golden elastic topology



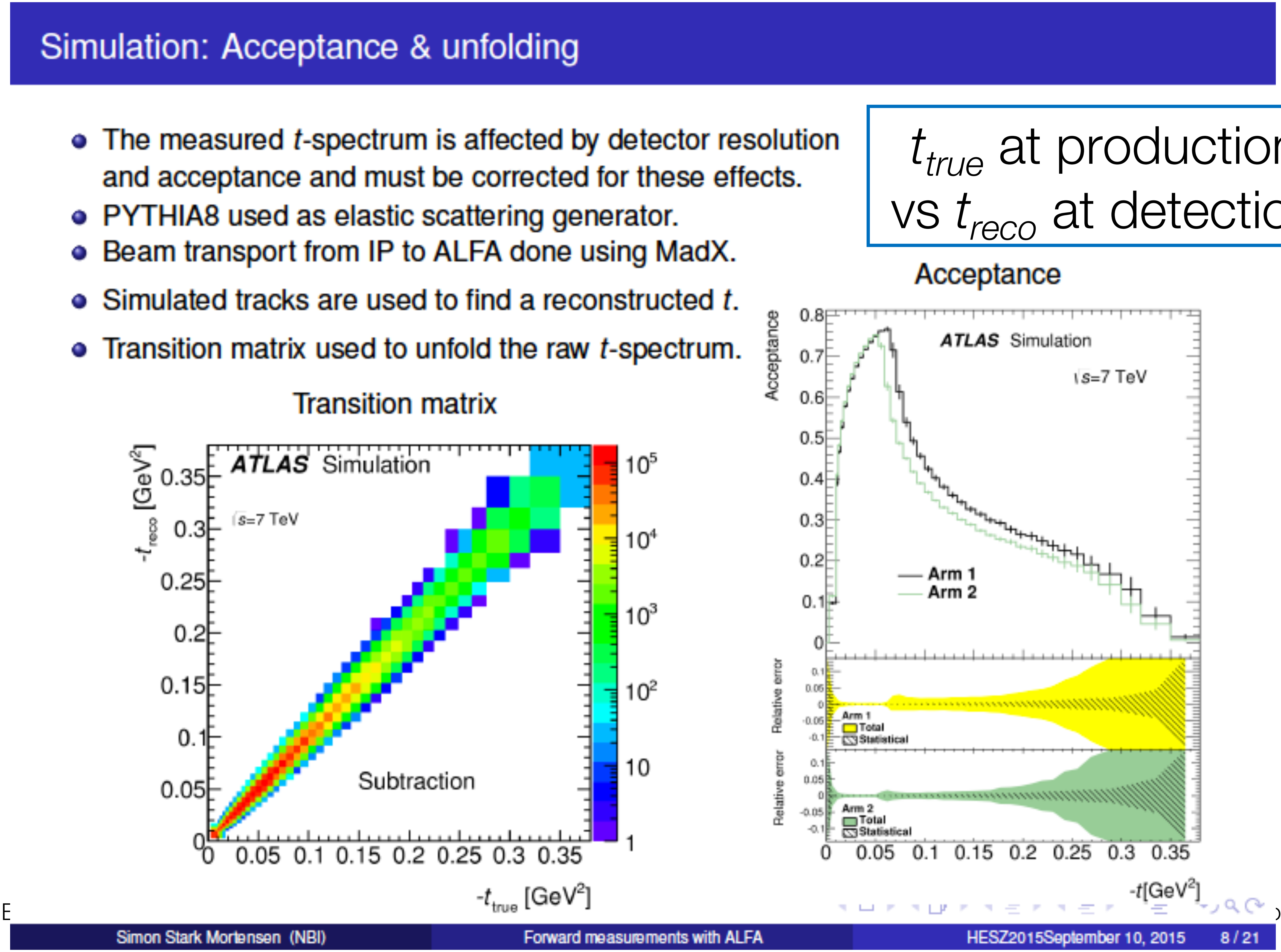
Anti-golden topology



Reconstructed *t*-spectrum



ALFA : acceptance & unfolding



Simulation: Acceptance & unfolding

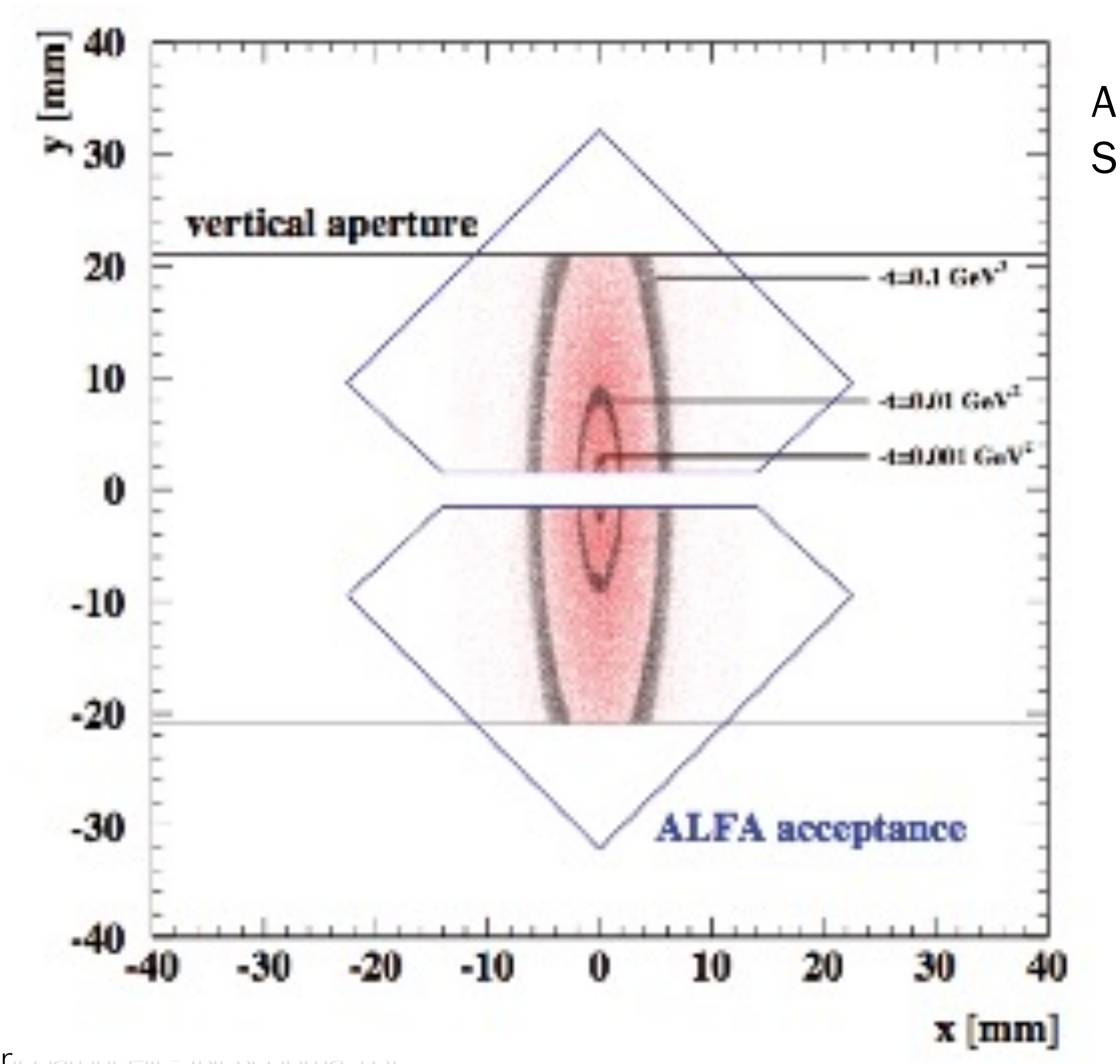
- The measured *t*-spectrum is affected by detector resolution and acceptance and must be corrected for these effects.
- PYTHIA8 used as elastic scattering generator.
- Beam transport from IP to ALFA done using MadX.
- Simulated tracks are used to find a reconstructed *t*.
- Transition matrix used to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

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

Transition matrix

Acceptance

ALFA – Absolute Luminosity for ATLAS

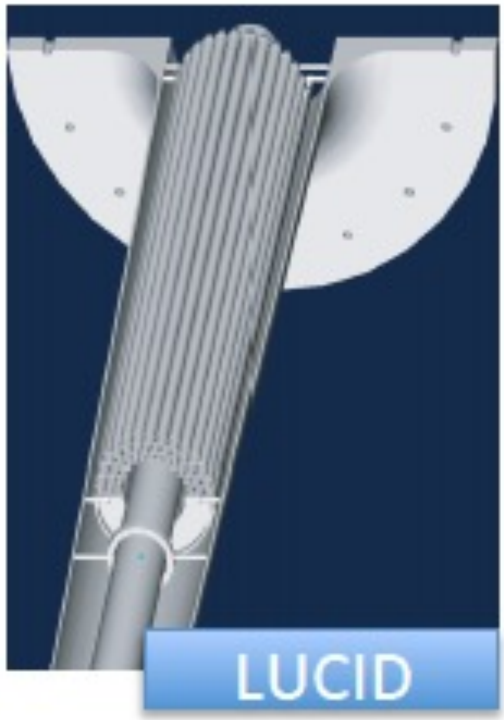


ALFA
Simulated hit distribution

ATLAS Luminosity monitors

What between VdM scans?

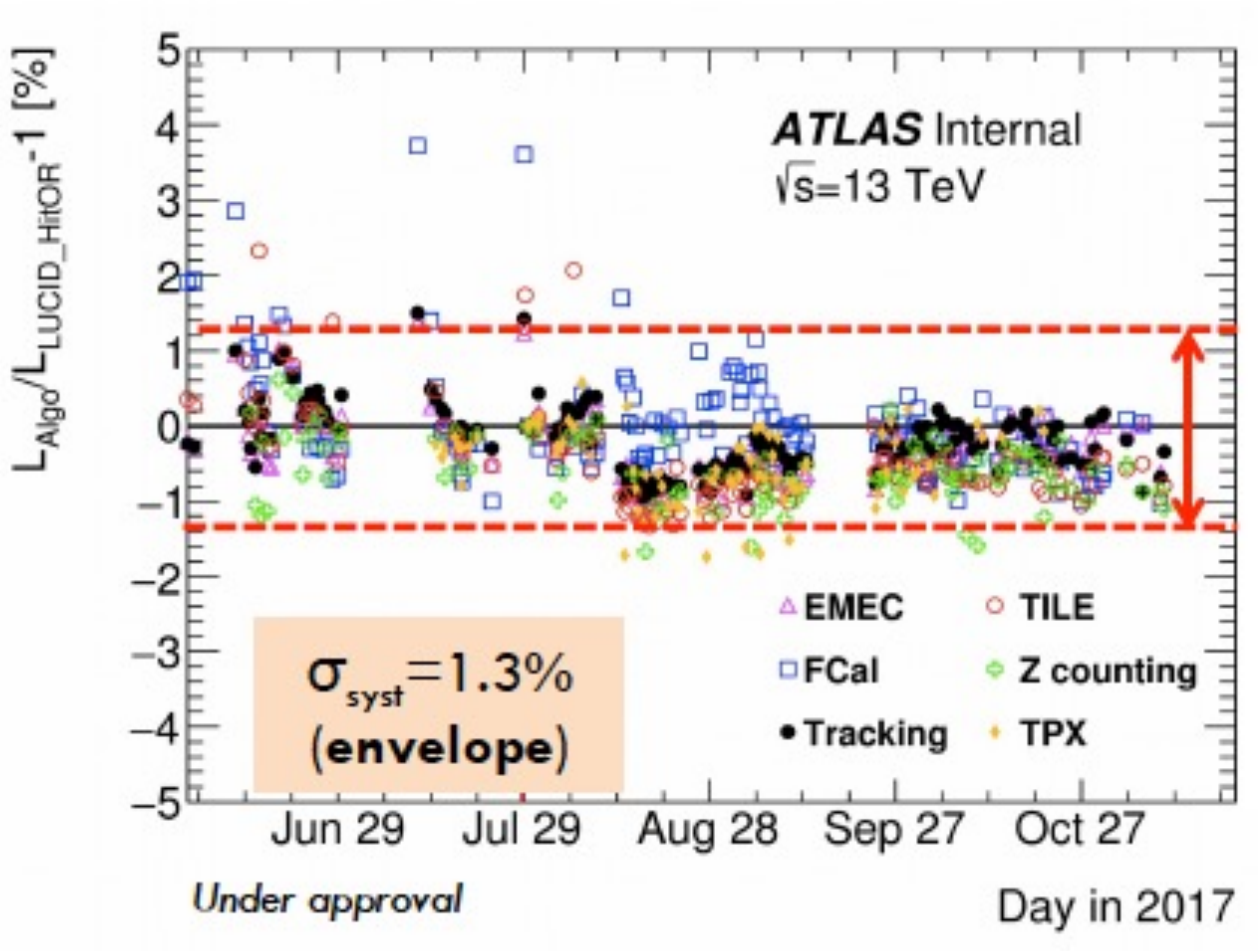
- LUCID
  - Dedicated luminosity monitor (5.6 < | η | < 6.0)
  - Cherenkov tubes
  - Zero-counting and hit-counting algorithms
- Beam Condition Monitor (BCM) ⇒ Beam dump!
  - Designed as beam protection system
  - Diamond-based sensor (| η | ~ 4.2)
  - Zero-counting algorithms
- Silicon detectors
  -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



Summary of Luminosity Monitors

Device	Algorithms	Technology	BCID-aware	ACR Desk
BCM	Event counting	Diamond semi-conductors	●	ID
LUCID	Event (Hit) counting Particle flux	Cerenkov quartz windows + PMTs	●	Calo
FCAL	Particle flux	LAr under HV		Calo
MBTS	Event counting	Scintillators + PMTs	●	Trigger
TILE	Particle flux	Scintillator tiles + PMTs		Calo
EMEC	Particle flux	LAr under HV		Calo
TPX	Cluster counting	Hybrid pixel		(TBD)
DBM	Event counting Cluster counting Track counting	Diamond pixels	●	ID

ATLAS Luminosity Monitoring in 2017



σ_{syst}=1.3%
(envelope)

Early LHC Luminosity Measurement

Particle counting:

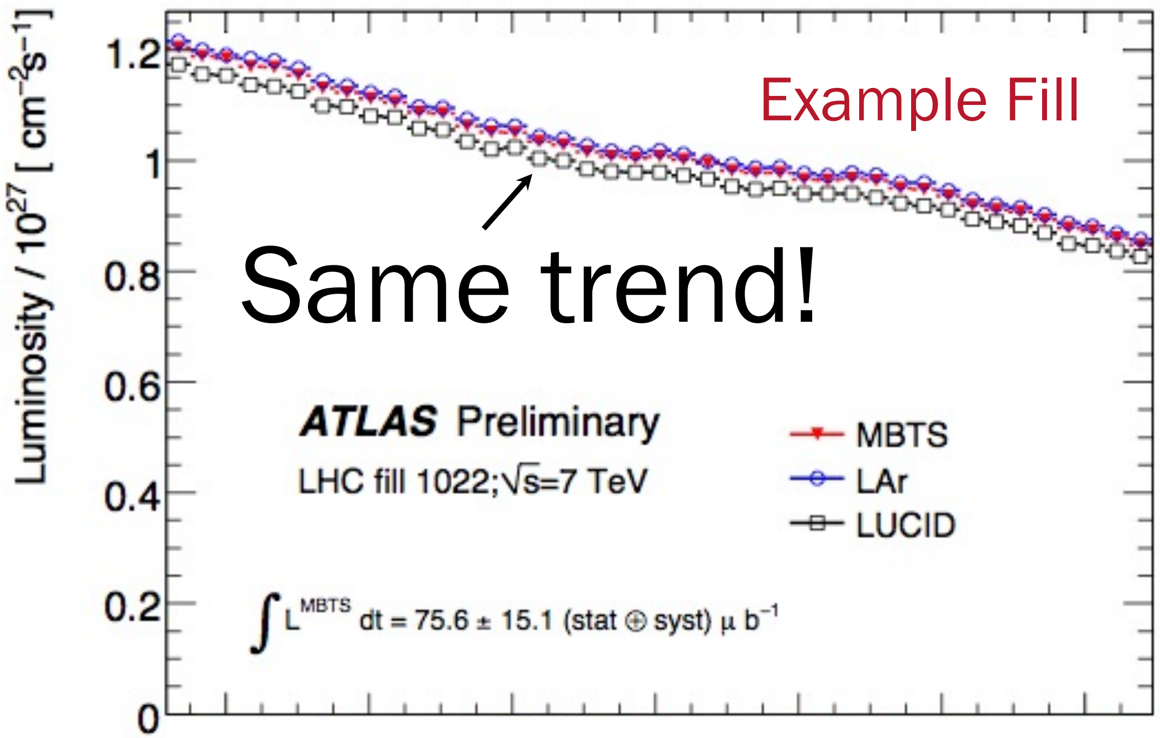
Charged Tracks (MBTS)

Calorimeter deposits (LAR)

[Normalization via Monte Carlo]

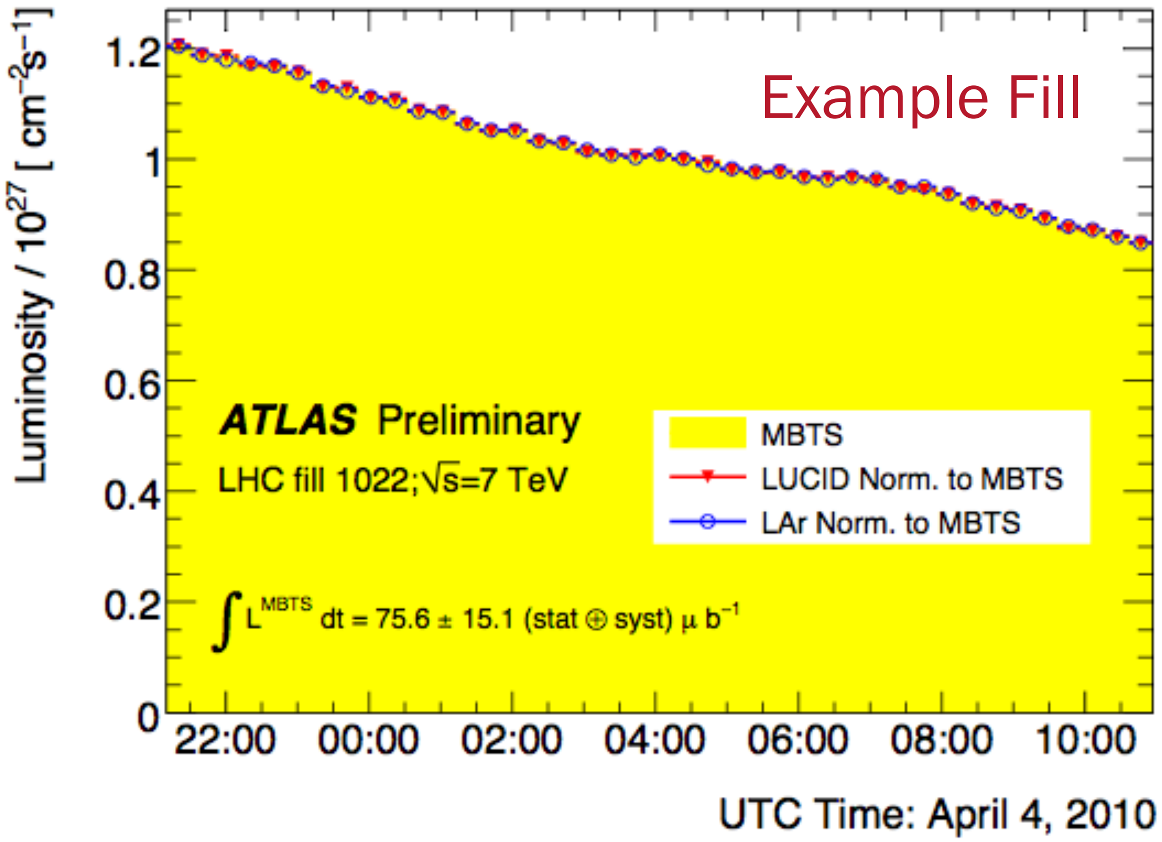
Forward Particles (LUCID)

[Relative Method; normalization to MBTS/LAr]

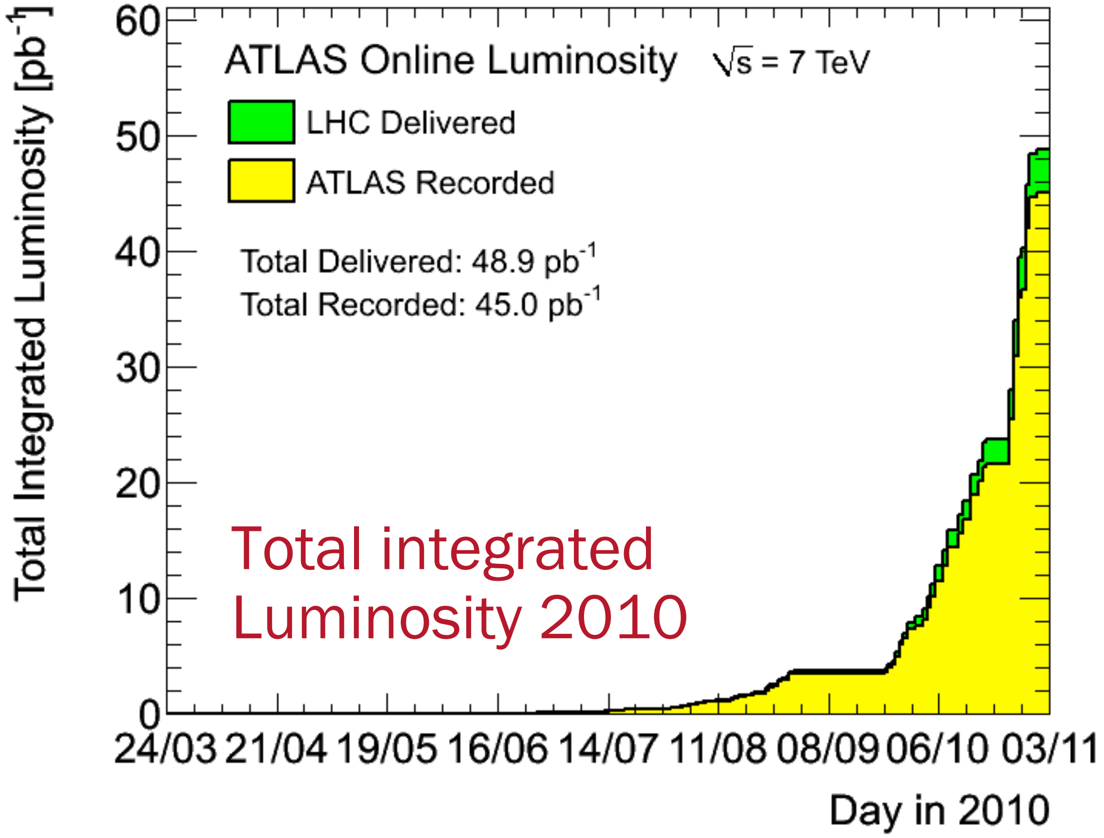


Example Fill

Same trend!

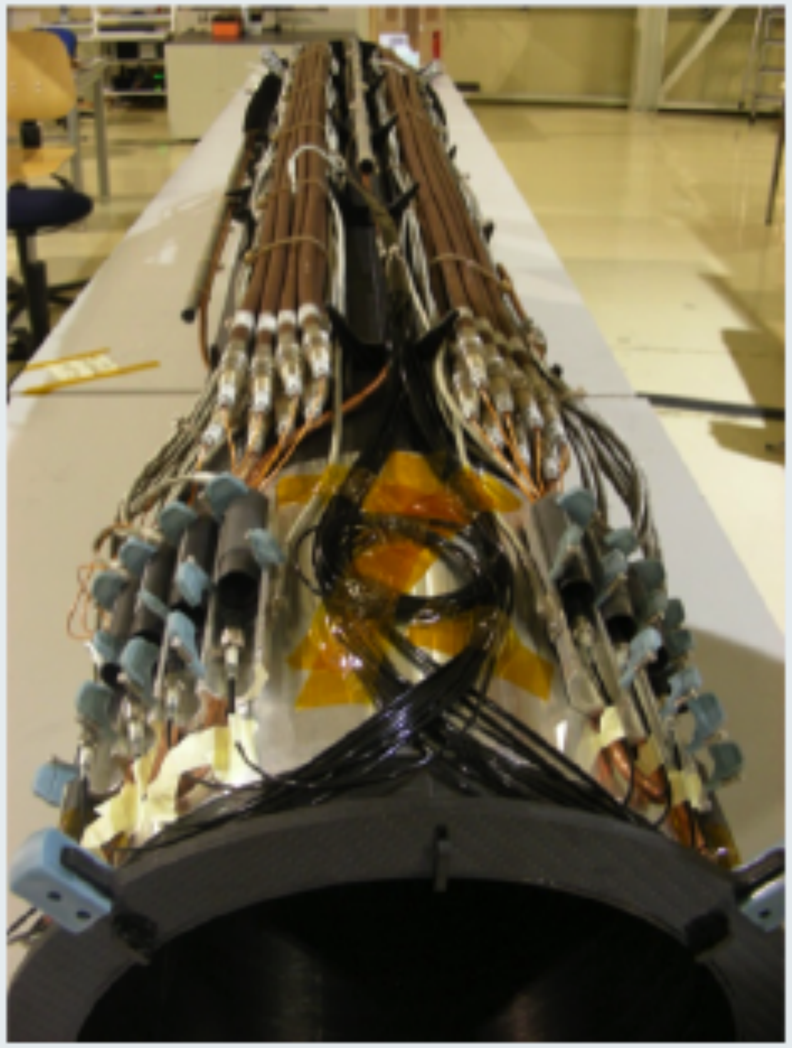


Example Fill



Total integrated Luminosity 2010

LUCID



- **Main role:** Luminosity Measurement.
- **Technology:** Cherenkov emitting quartz windows connect to PMTs.
- **Configuration:** 16 PMTs on each side of ATLAS, 17m from the IP.
- **Highlights:** Fast and high redundancy (each PMT read out individually). Capable of event and hit counting as well as and particle flux measurements.
- **Sampling/Time resolution:** Every BCID.
- Major upgrades for Run II: new calibration, more redundant measurements, reduced acceptance.

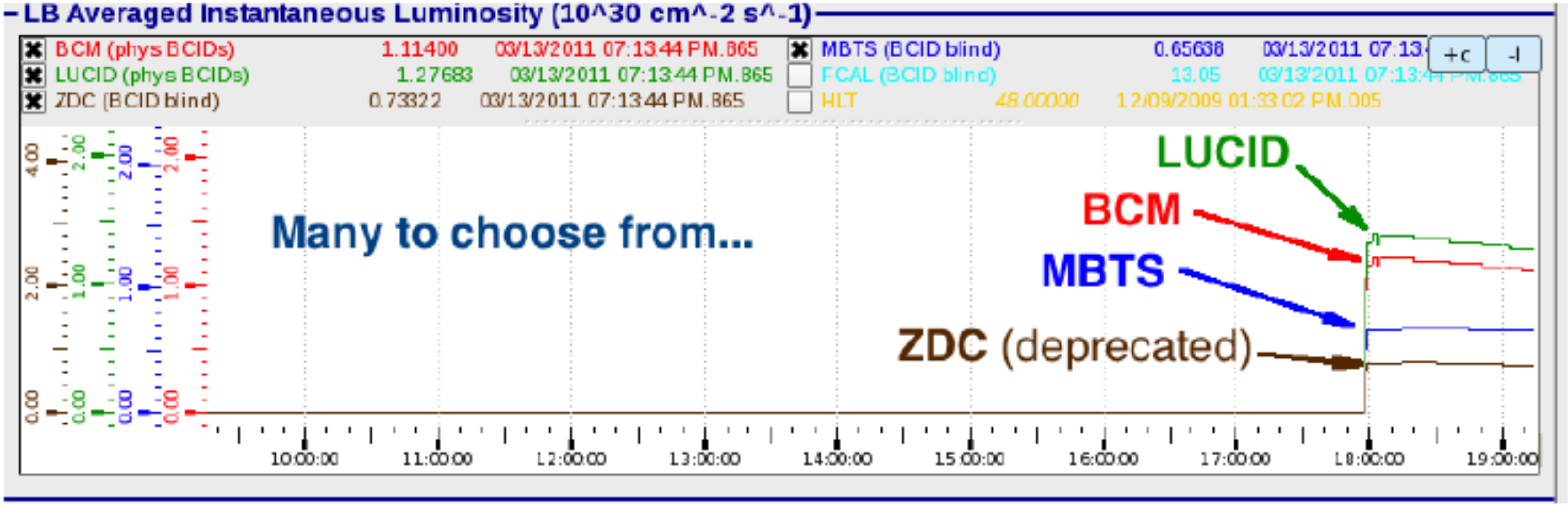
Tile Calorimeter

- **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



LB Averaged Instantaneous Luminosity (10^30 cm^-2 s^-1)

☒	BCM (phys BCIDs)	1.11400	03/13/2011 07:13:44 PM.865
☒	LUCID (phys BCIDs)	1.27683	03/13/2011 07:13:44 PM.865
☒	ZDC (BCID blind)	0.73322	03/13/2011 07:13:44 PM.865
☒	MBTS (BCID blind)	0.65638	03/13/2011 07:13
☐	FCAL (BCID blind)	13.05	03/13/2011 07:13:44 PM.865
☐	HLT	48.00000	12/09/2009 01:33:02 PM.005

Many to choose from...

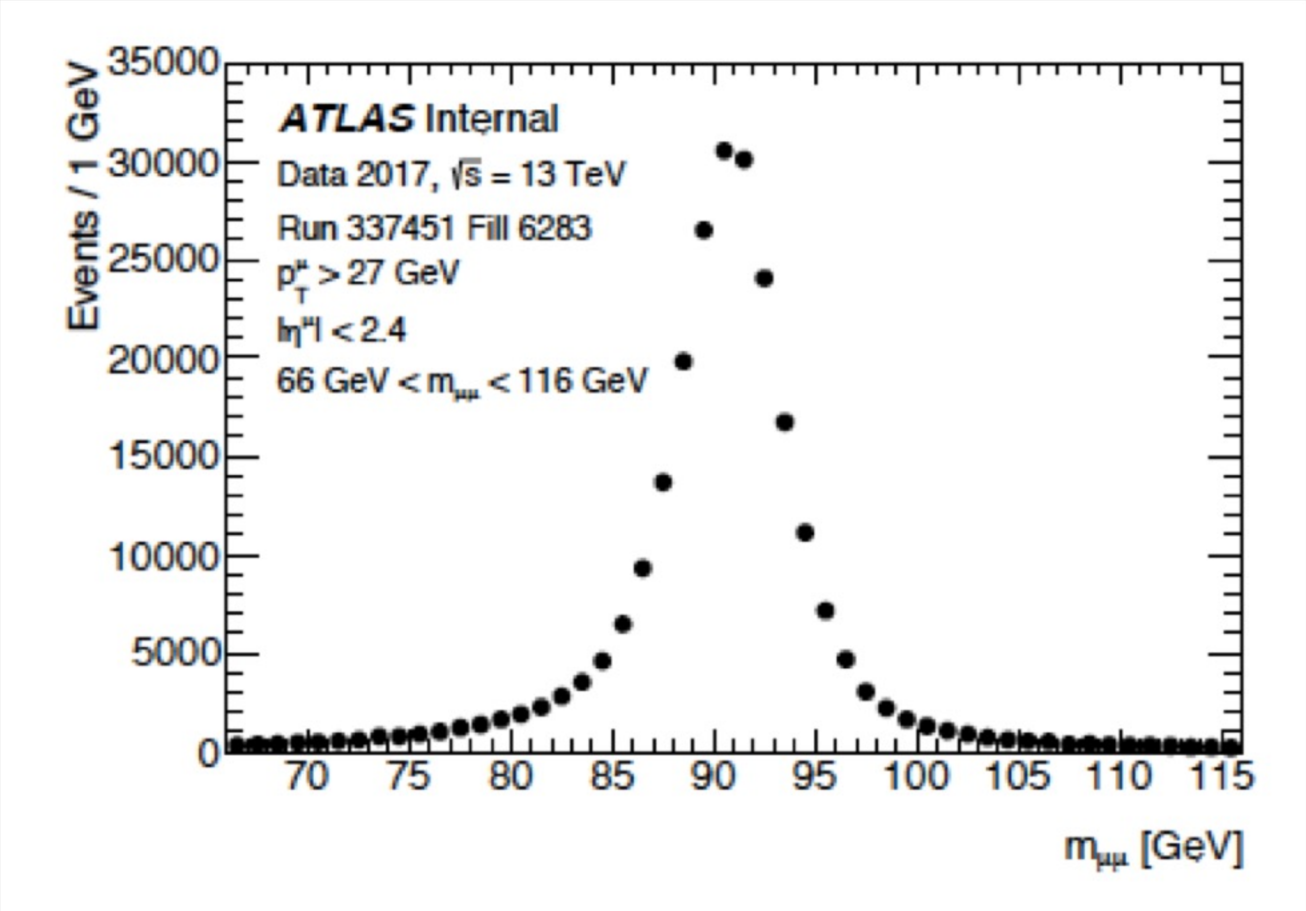
LUCID

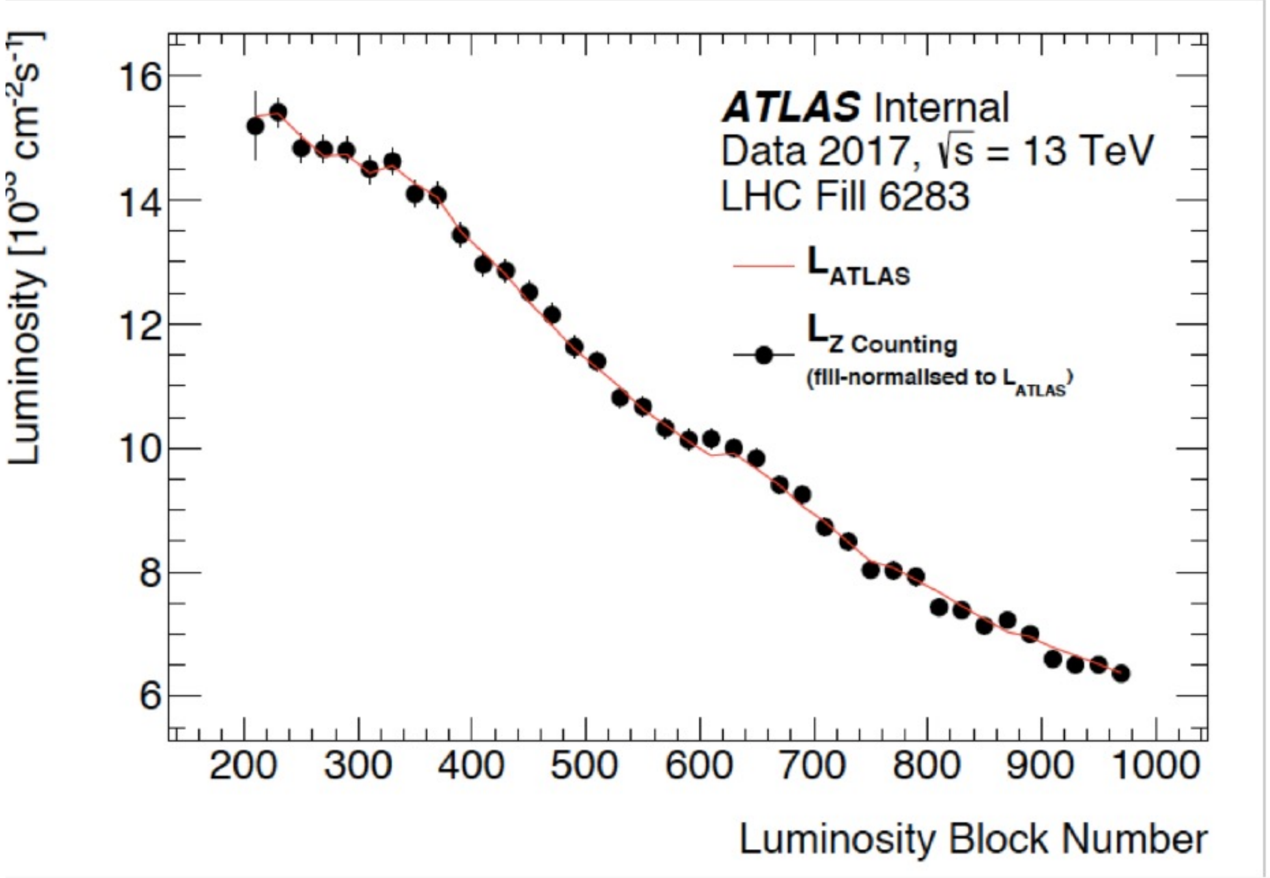
BCM

MBTS

ZDC (deprecated)

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,
- $\eta < 2.4$
- $66 < m_{\mu\mu} < 116$ GeV.

The statistical errors are smaller than the symbol size.

Comparison between Z counting and L_{Lucid}

Backup slides

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: $\sigma_{tot} \sim \mathrm{Im}\, f(0)$ [needs: forward elastic and total inel. x-sec]

Elastic scattering in Coulomb region ...

[needs σ_{tot}; needs forw. instrumentation]
Accuracy: 5-10%

TOTEM

Combination of the above ...

Accuracy: 2-3%

Relative Methods:

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

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