# Luminosity @ LHC

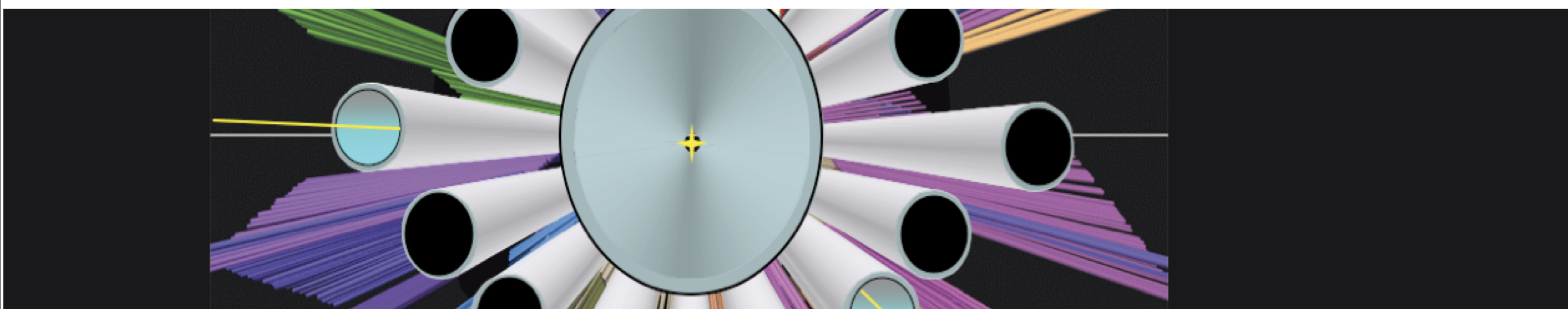
## How to measure cross sections ...

event rate

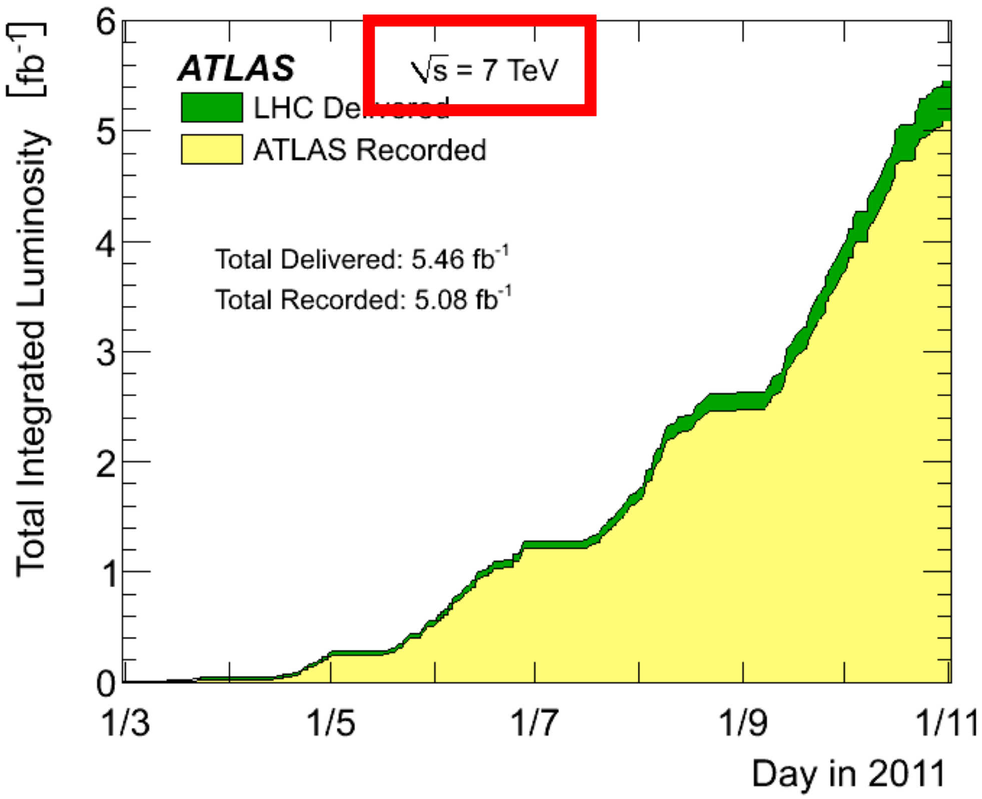
Cross section

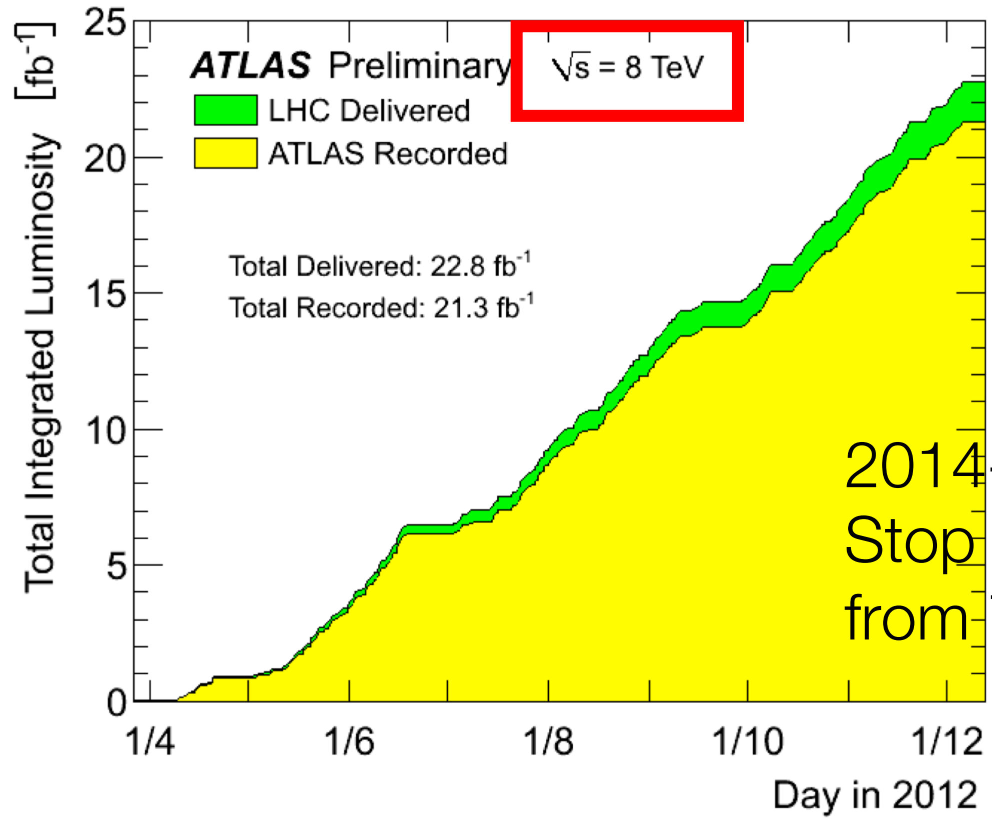
$$N = L \times \sigma$$

Luminosity
(Machine parameter)

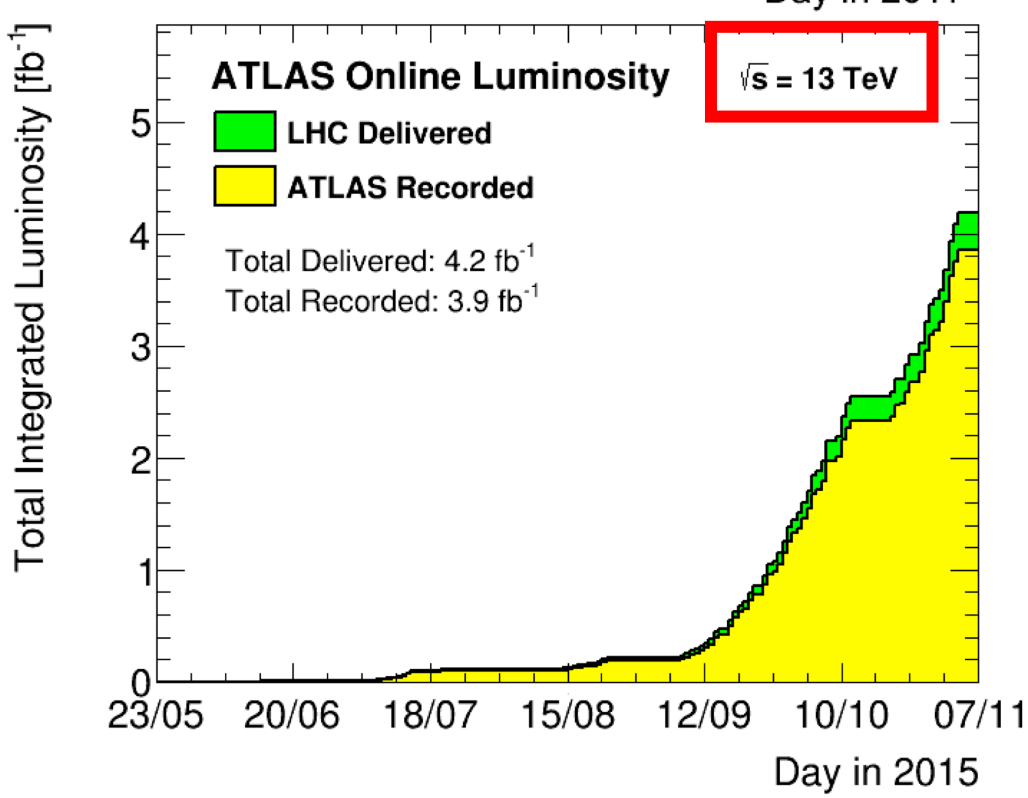


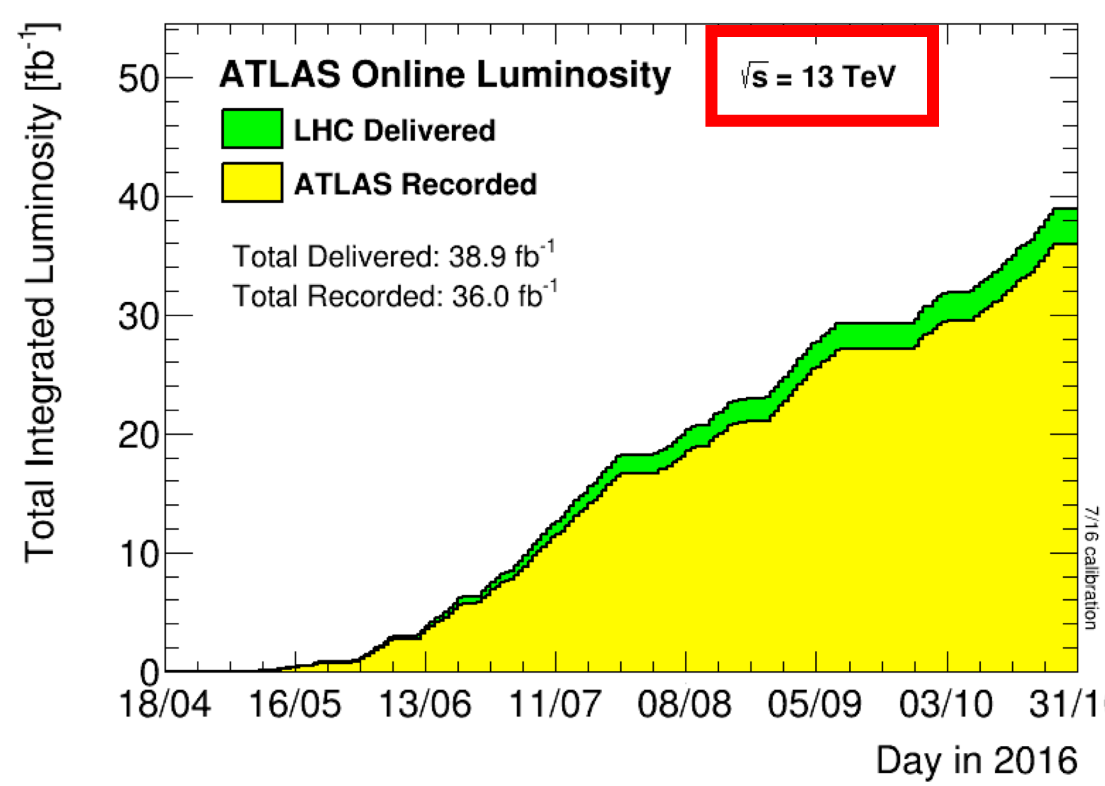
# Luminosities at LHCin run-I/II



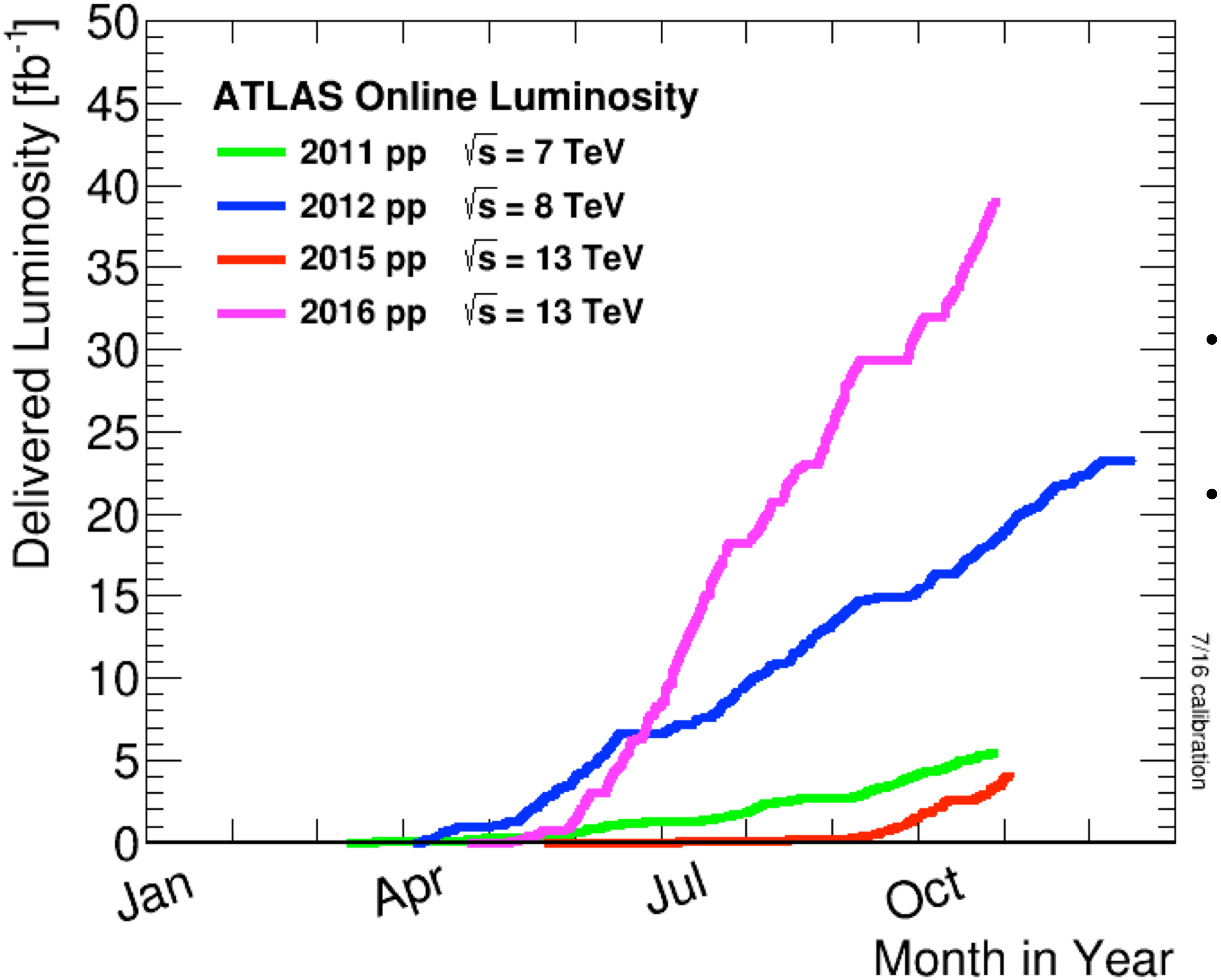




2014-2015 LHC Stop ➔ √s goes from 7,8 to 13 TeV



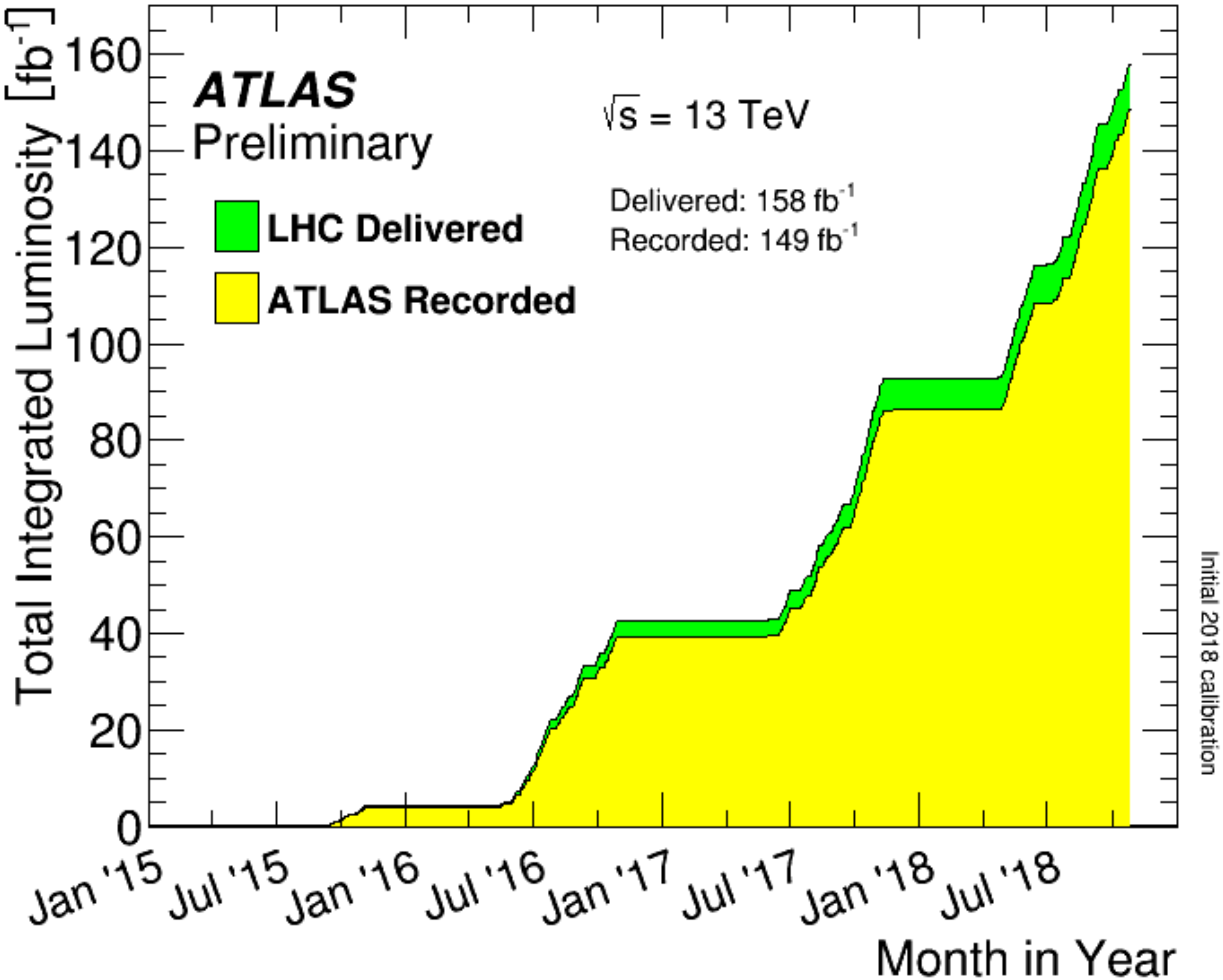



# Multiple-Years Luminosity in ATLAS




- Slope changes significantly and increases with year
- Summer run / winter stop

# Luminosity in Run2



# Cross Section & Luminosity

**Number of observed events**

just count …

**Background**

measured from data or calculated from theory

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

**Luminosity**

determined by accelerator, triggers, …

**Efficiency**

many factors, optimized by experimentalist

# How to measure luminosity

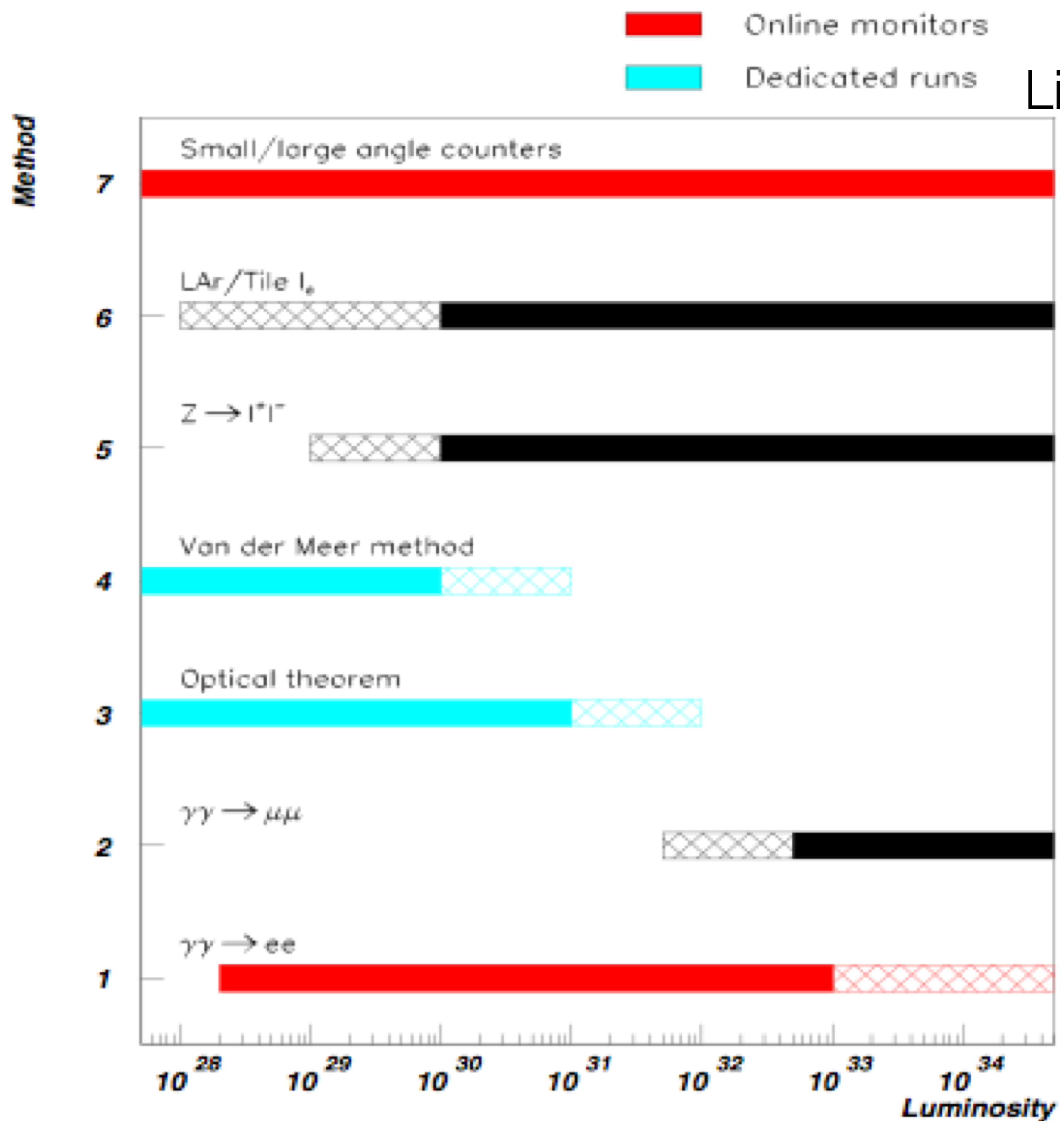
1. Direct bunch profile and intensity measurements
   - Van der Meer scan (VdM) — ALICE, ATLAS, CMS, LHCb
   - Beam-Gas-Imaging (BGI) — LHCb
2. Based on optical theorem
   - Forward scattering at very low angles
   - Cross-calibration of luminosity detectors
   - Challenging, program ongoing

ATLAS with ALFA,
CMS with TOTEM

… and to monitor it with time

use of tracking detectors & calorimeters

# Luminosity Determination @ LHC




Red → Monitors
Light blue → Measurements

Methods as
summarized in ATLAS TDR

[ATLAS Technical Design Report, Vol. I]

# External material

ALICE ATLAS CMS LHCb

## Measurement of the luminosity at LHC

Gabriel Anders
CERN

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

August 11$^{th}$, 2014
Physics at LHC and beyond (Quy Nhon, Vietnam)

# Luminosity Determination @ LHC (old slide)



Accuracy: from 10%-
To today ~3%

## Absolute Methods:

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]
Rate of pp ➛ γγ ➛ μμ, ee [needs: QED & photon flux]
Optical theorem: $\sigma_{tot}$ ~ Im f(0) [needs: forward elastic and total inel. x-sec]
Elastic scattering in Coulomb region ...

Accuracy: 5-10%
[PDF knowledge, ...]

Accuracy: 1-5% ?
[TDR; needs forw. tagging]

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

TOTEM

Combination of the above ...

Accuracy: 2-3%

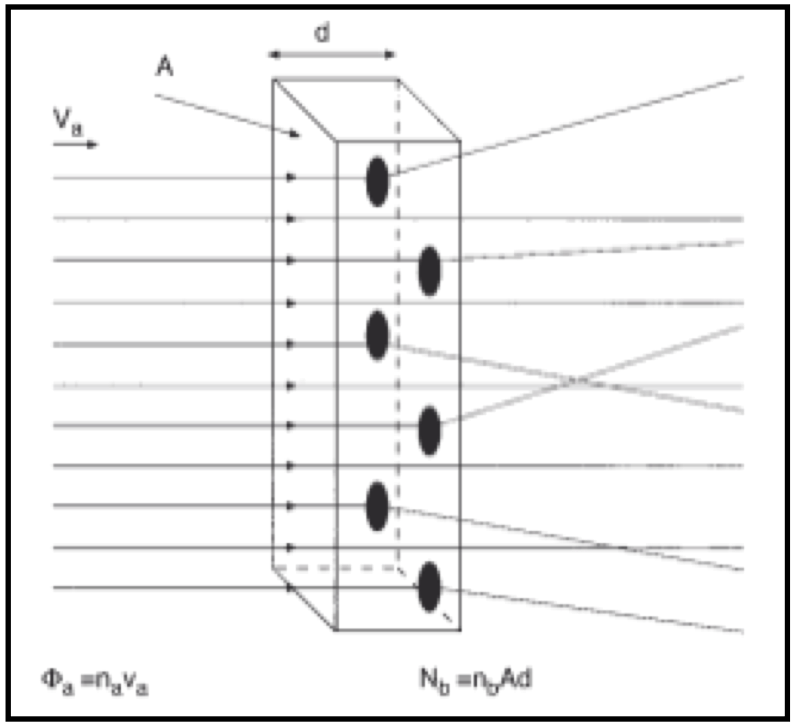
## Relative Methods:

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

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

# Cross Section & Luminosity

## Colliders




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

$\Phi_a$ : 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
$\sigma_a$ : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

Instantaneous Luminosity

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

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

Collider experiment:

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

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

LHC:

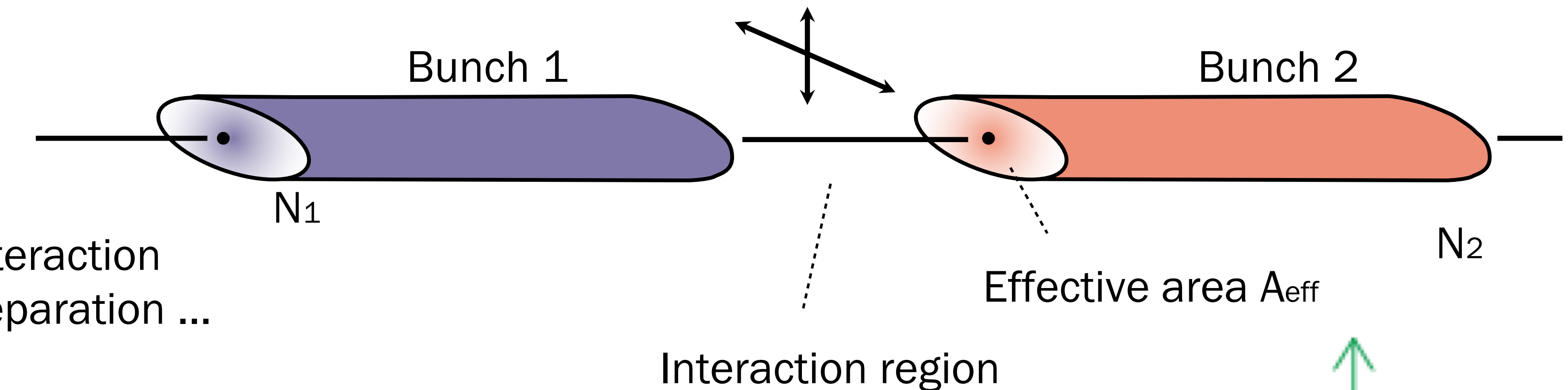
| | | |
|---|---|---|
| $N_x$ | ~ | $10^{11}$ |
| A | ~ | .0005 $mm^2$ |
| n | ~ | 2800 |
| *f* | ~ | 11 kHz |
| L | ~ | $10^{34}$ $cm^{-2}$ $s^{-1}$ |

$N_a$ : 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
$\sigma_x$ : standard deviation of beam profile in x
$\sigma_y$ : standard deviation of beam profile in y

# Van-der-Meer Separation Scan

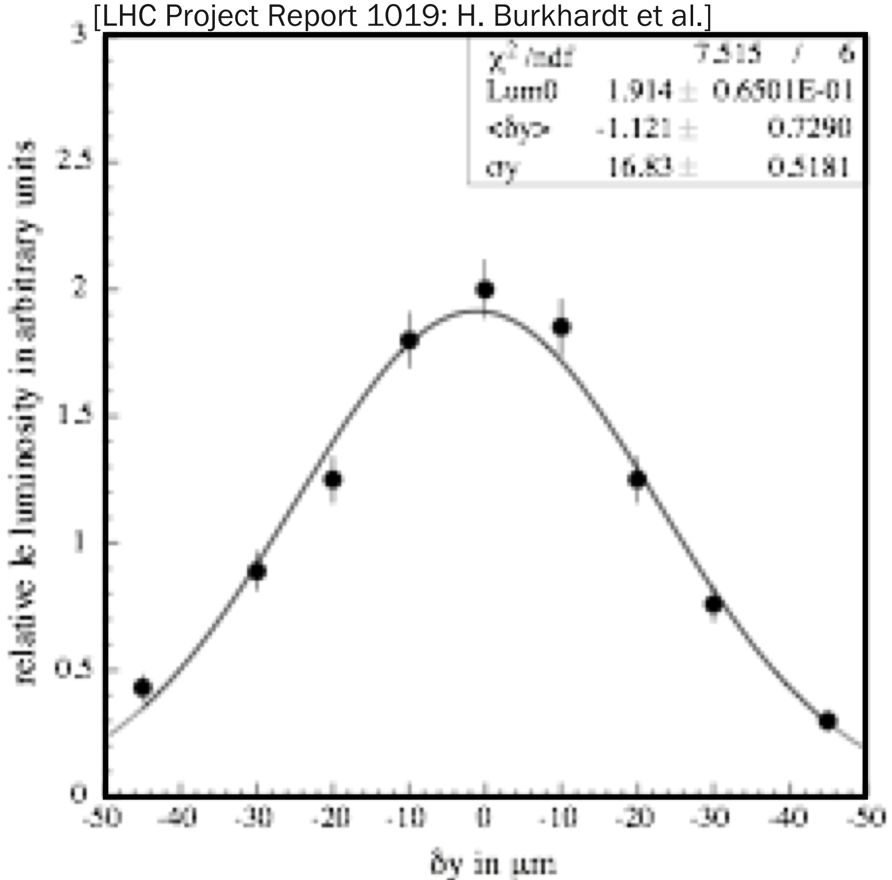
teraction regions ATLAS (IP1), ALICE (IP2), CMS (IP5) and LHCb (IP8). All interaction regions are equipped with

## Determine beam size …




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

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




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

Rate

[IPAC 2010, S. White et al.]

[November 2009].

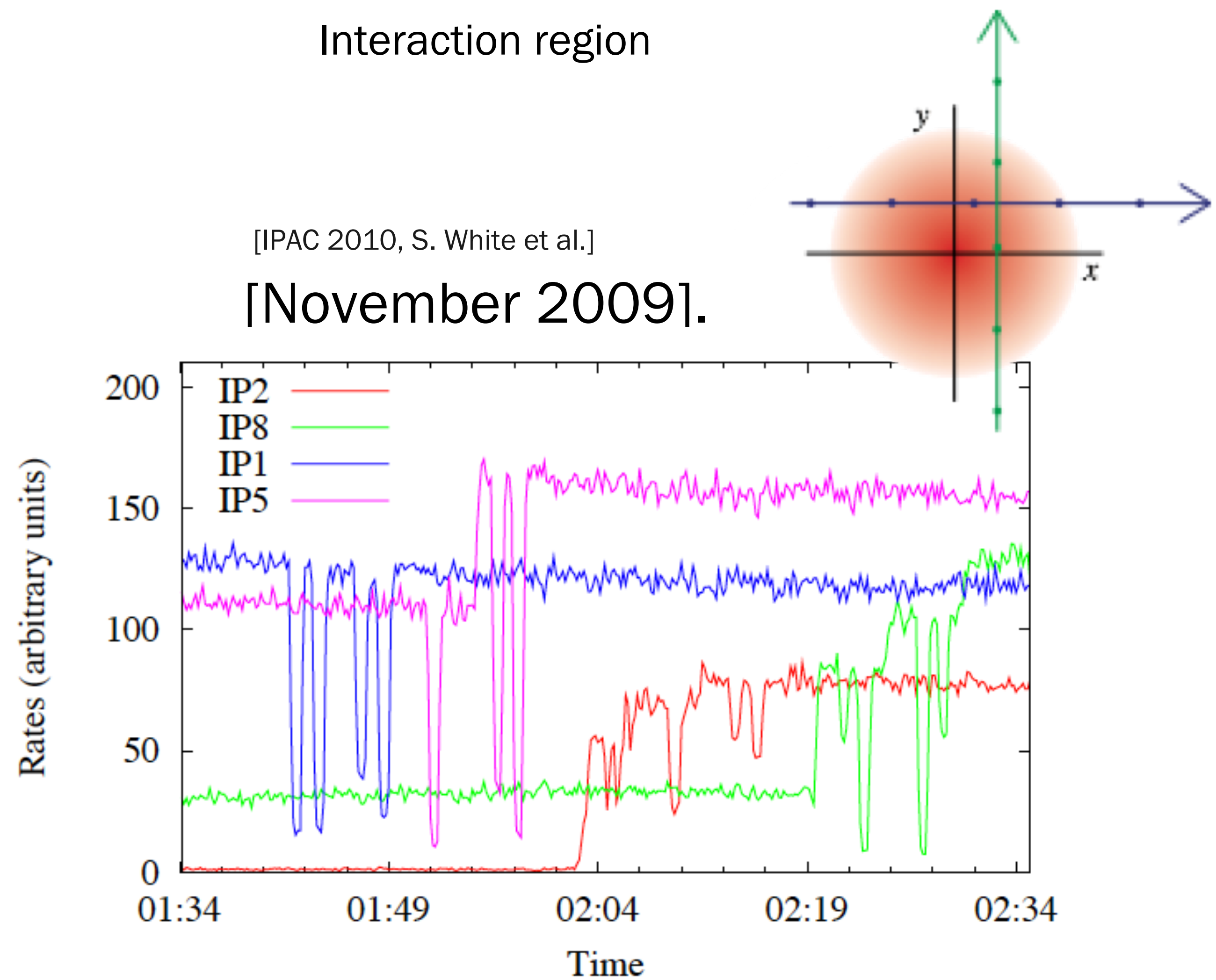


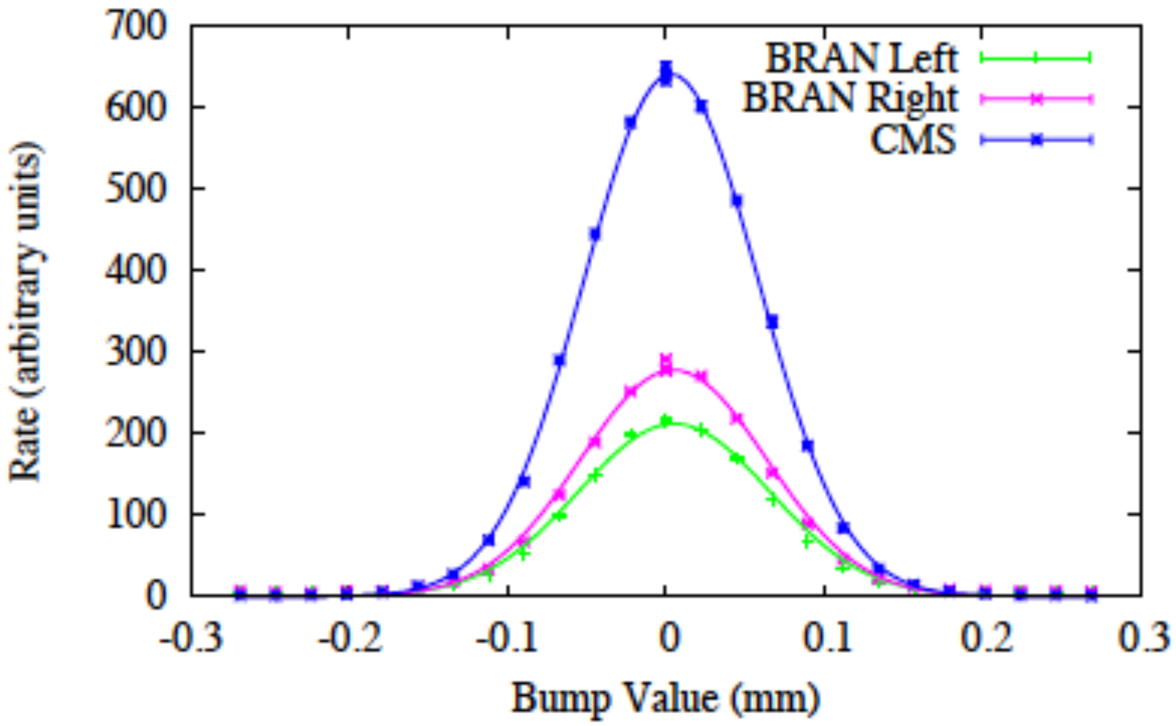

Figure 2: Optimization scans performed for squeezed optics in all IPs.

# Shape of the beam : 1 g or 2 g?

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

Factorizability

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



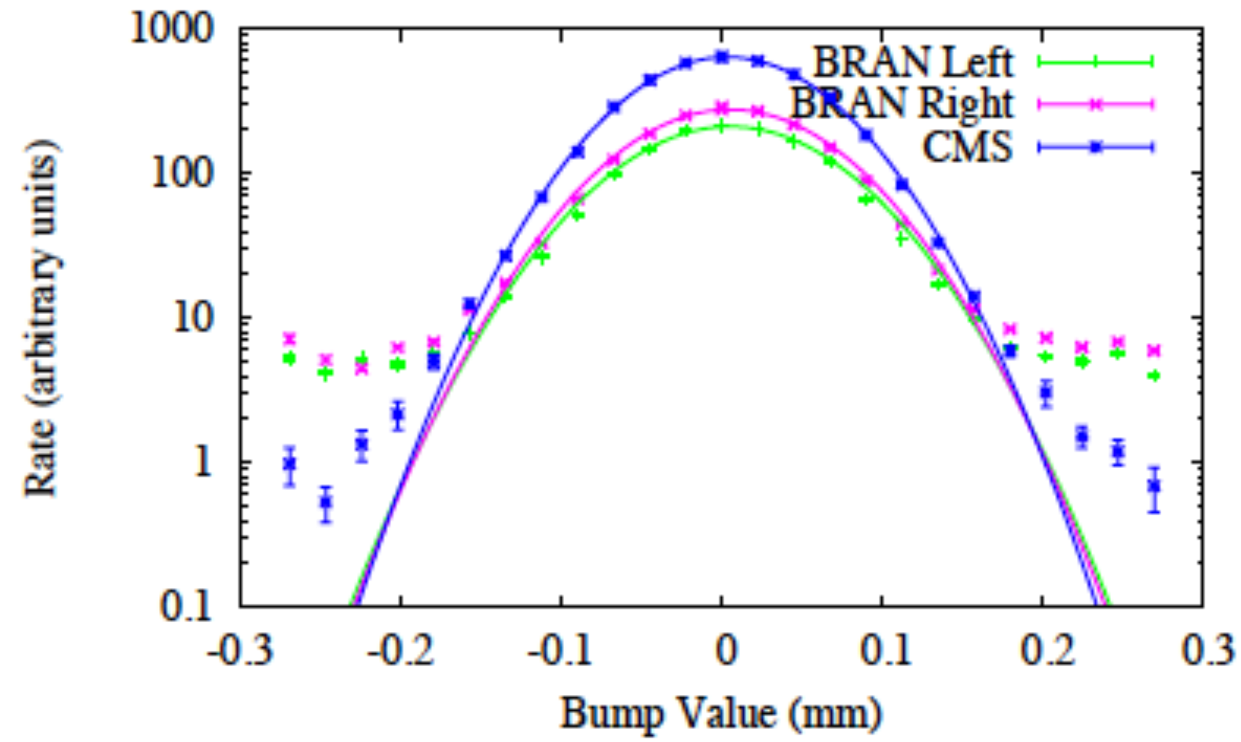
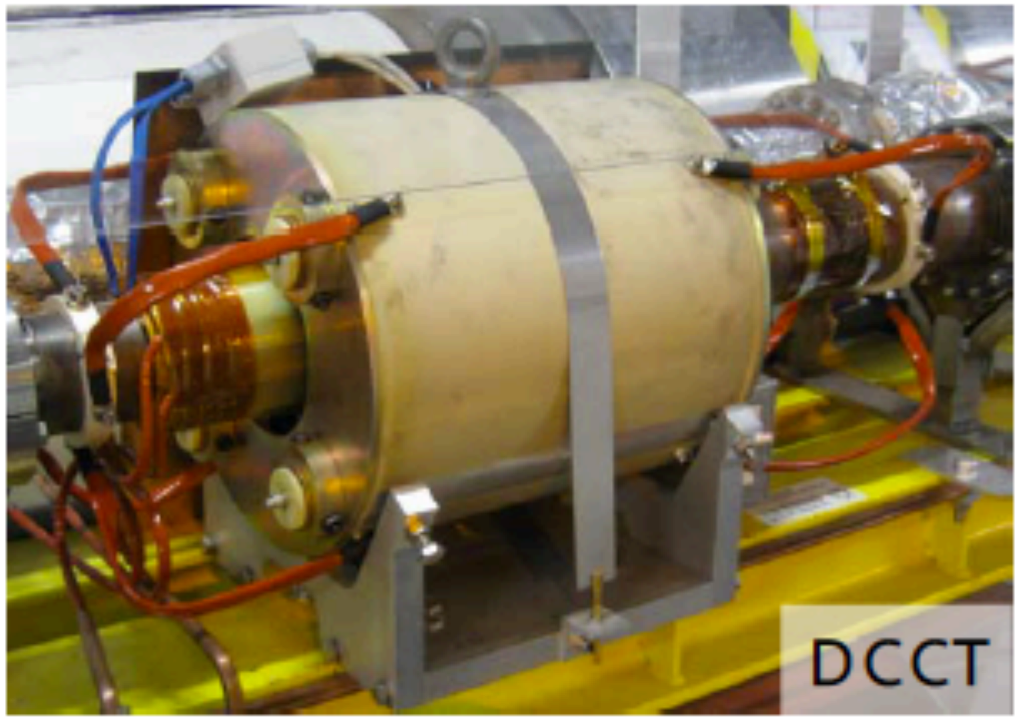




Figure 4: Same horizontal scan in IP5 shown in logarithmic scale with pure Gaussian fits.

# Measuring beam populations

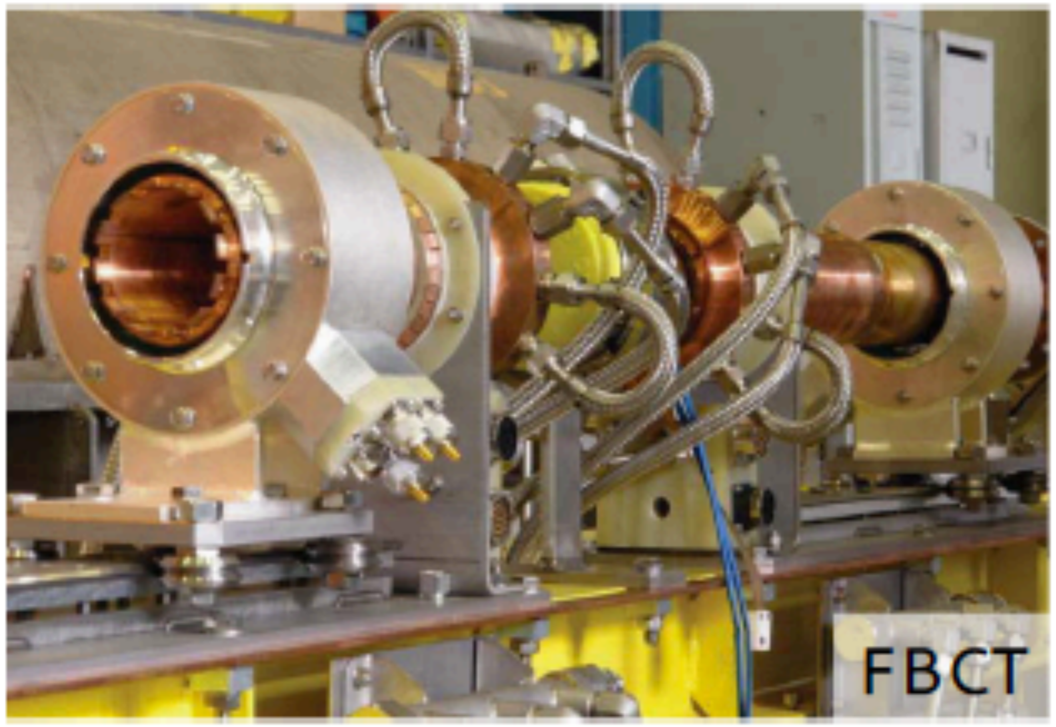


## DC Current Transformer




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

## Fast Beam Current Transformer




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

- 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

# … of the bunch structure…1

The LHC is operated at the radio frequency (RF) of about 400 MHz, which corresponds to exactly 35640 RF bins of about 2.5 ns length and equidistantly distributed over the ring circumference. These RF bins are conventionally numbered from 1 to 35640. ***Nominally, only one out of ten bins is filled with a bunch.*** By convention, these bins are numbered 1, 11, 21, 31, ... 35631, and they are each associated with a bunch slot **spanning 25 ns** and numbered from 1 to 3564. The slot, also called Bunch Crossing ID (BCID), is just a convenient index to discuss the LHC measurements in customary “40 MHz” parlance. For luminosity calibration measurements, it is important to remember that the base RF of the LHC is 400 MHz. The captured particles of an LHC bunch are contained within an RF bucket 1–1.5 ns long (4 sigma length). 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%for LHC p  beams and about 5%for LHC Pb beams (except when problems with, for example, the RF cavities occur). To obtain a precision better than this on the bunch populations of the nominally filled RF bins, it is necessary to consider the full longitudinal distribution of the two rings. Conventionally, the small bunches in those RF bins which are within the 12. 5 ns range around the center of a nominally filled RF bin are called satellite bunches, while those which are outside this range are lumped altogether in the so-called ghost charge.

# Some details on the bunch structure…2

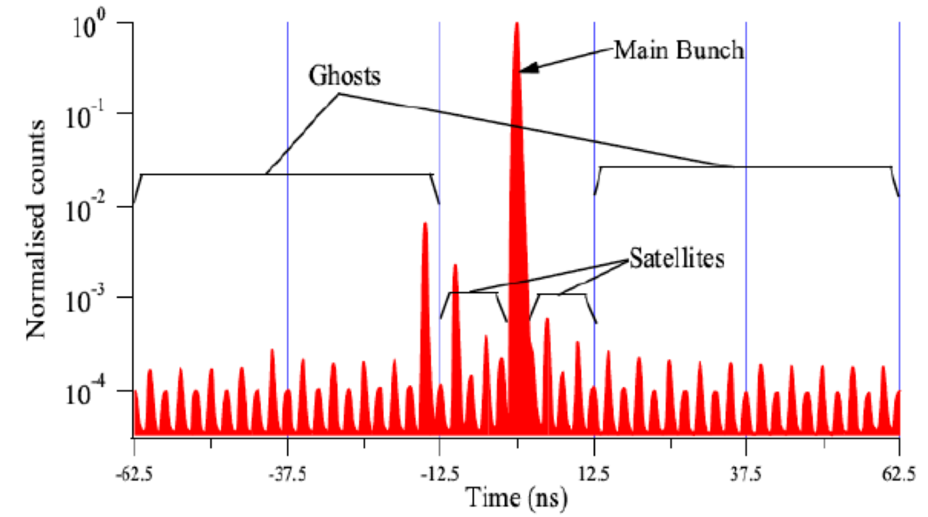
The total beam population of beam j = 1 or 2 (measured with the DCCTs [3]) is assumed to be the sum of the following components

$$N_{to}t,\, j = N_{main},\, j + N_{ghost},\, j + N_{pilots},\, j\,. \quad (1)$$

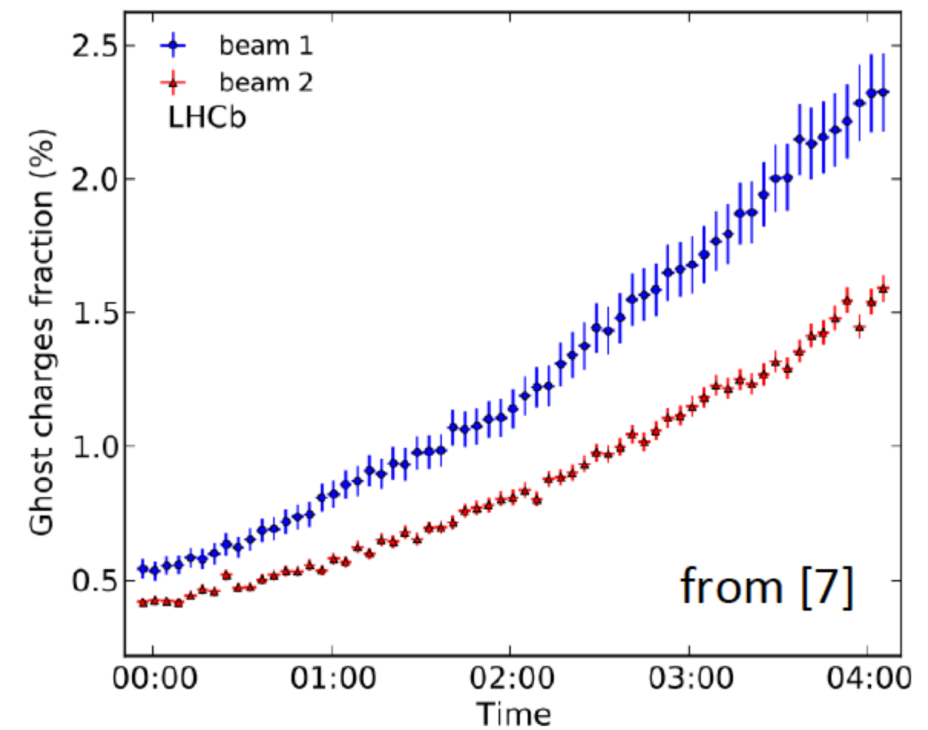
where $N_{main}, j$ is the charge of all slots nominally filled with a high intensity bunch (a ‘main’ bunch), $N_{ghost}, j$ is the ghost charge and $N_{pilots}, j$ the charge of all slots containing a ‘pilot’ bunch (not used in all fills, see below). In our definition, **the term $N_{main}, j$ is what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

# Bunch 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]



# VdM scans in ATLAS

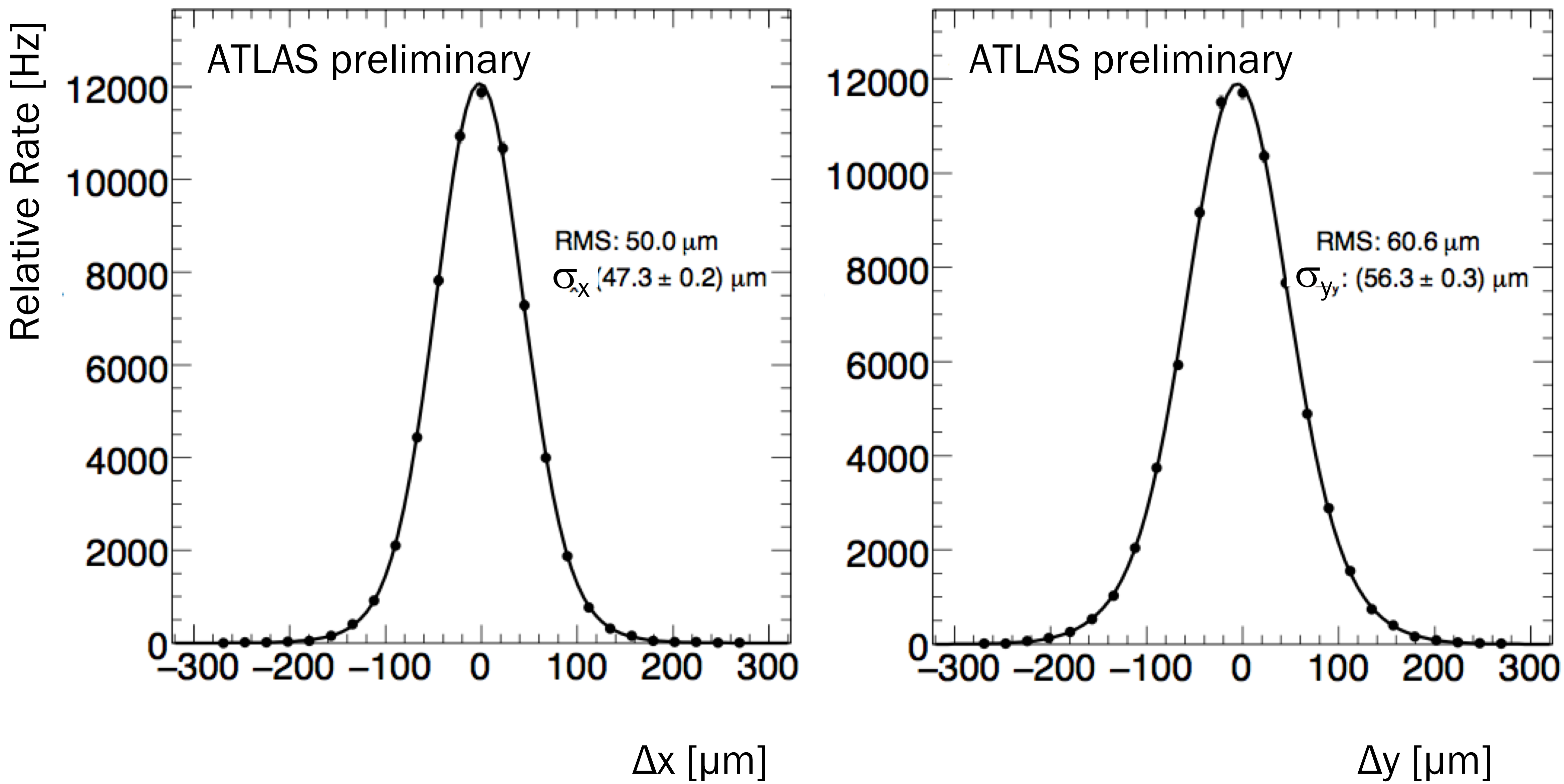
**Table 2** Summary of the main characteristics of the 2010 and 2011 *vdM* scans performed at the ATLAS interaction point. Scan directions are indicated by "H" for horizontal and "V" for vertical. The values of luminosity/bunch and $\mu$ are given for zero beam separation.

| 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 $\beta$-function at IP [$\beta^*$] (m) | 2 | 2 | 3.5 | 1.5 |
| Approx. transverse single beam size $\sigma_b$ ($\mu$m) | 45 | 45 | 57 | 40 |
| Nominal half crossing angle ($\mu$rad) | 0 | 0 | $\pm 100$ | $\pm 120$ |
| Typical luminosity/bunch ($\mu b^{-1}/s$) | $4.5 \cdot 10^{-3}$ | $1.8 \cdot 10^{-2}$ | 0.22 | 0.38 |
| $\mu$ (interactions/crossing) | 0.03 | 0.11 | 1.3 | 2.3 |

Low luminosity runs, clean measurement

# ATLAS Beam Profiles






[Scans from May 2010]

# Profile of VdM scan

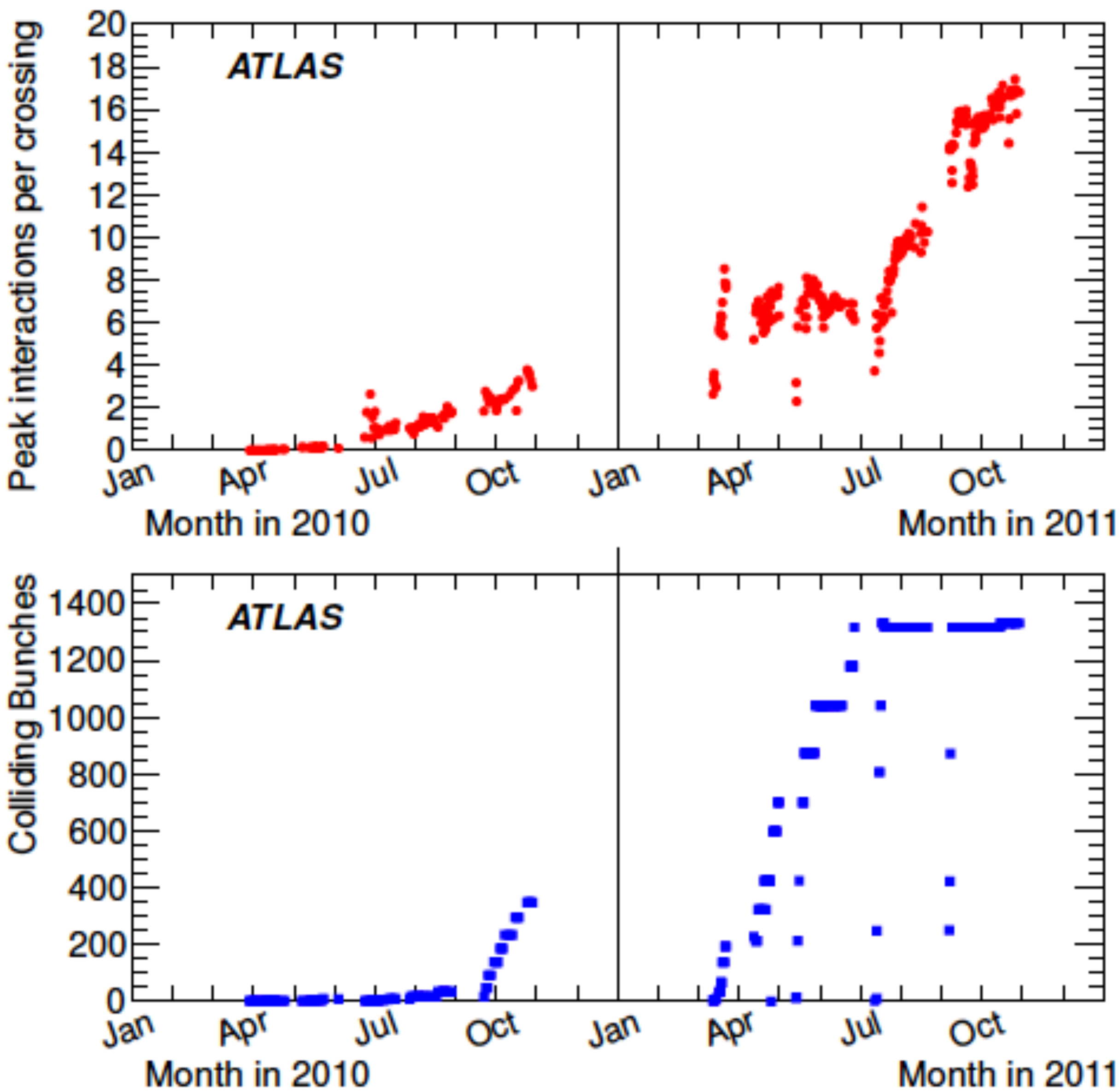
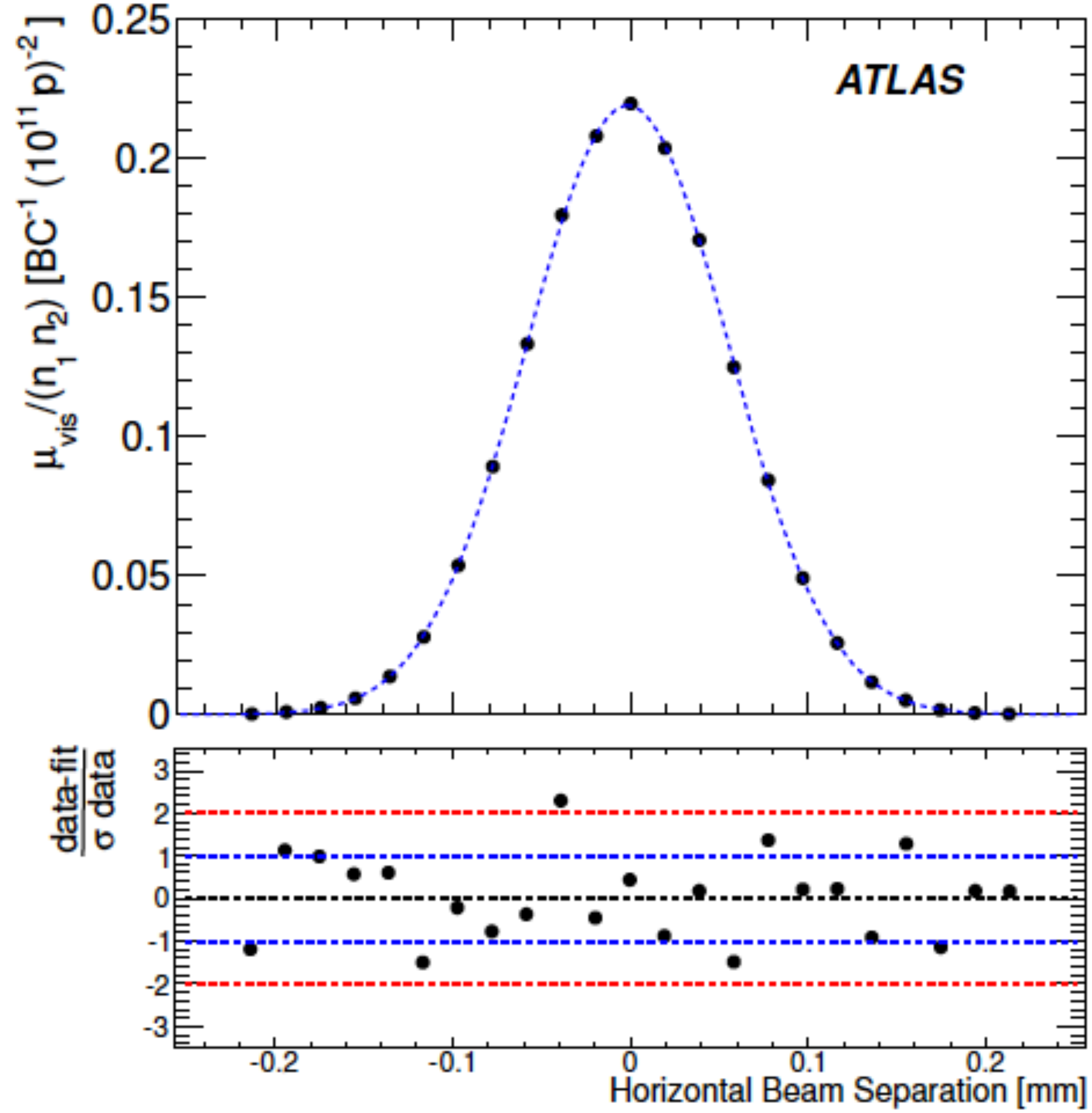



**Fig. 1** Average number of inelastic *pp* interactions per bunch crossin at the start of each LHC fill (above) and number of colliding bunche per LHC fill (below) are shown as a function of time in 2010 and 2011 The product of these two quantities is proportional to the peak lumi nosity at the start of each fill.



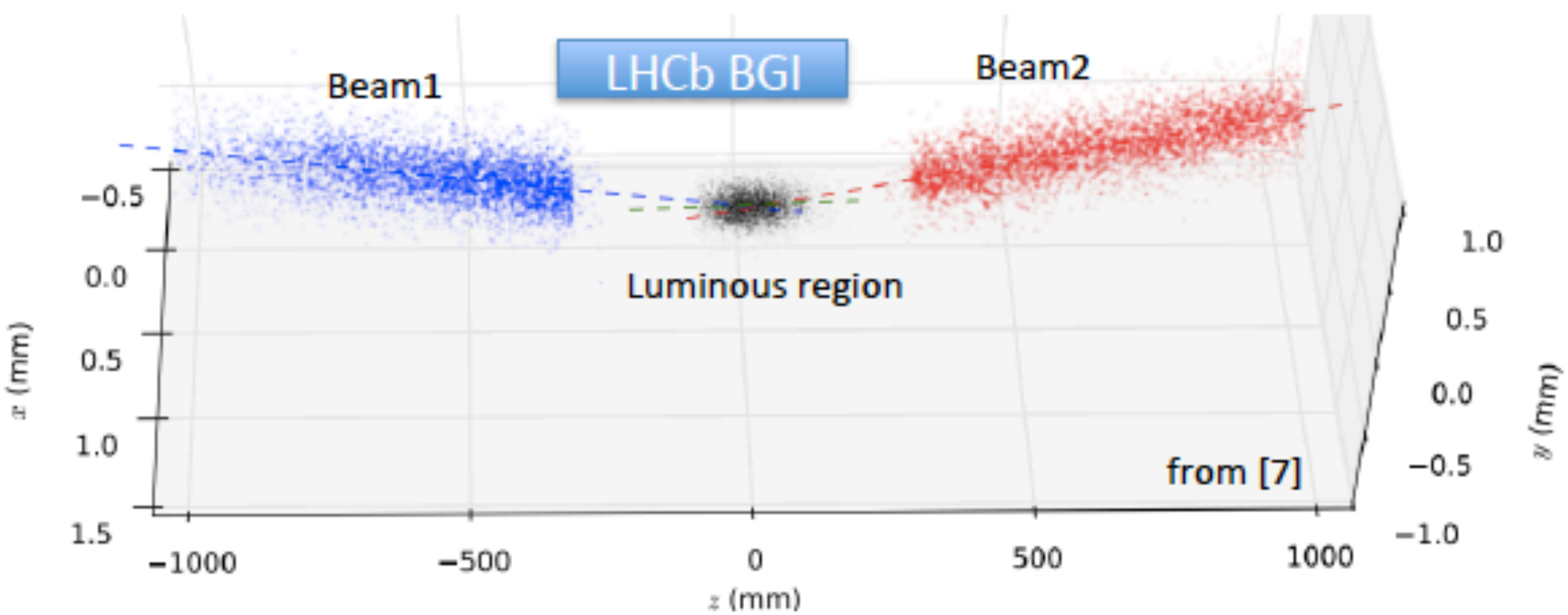
# Syst. errors in luminosity measurement

**Table 6** Relative systematic uncertainties on the determination of the visible cross-section $\sigma_{vis}$ from *vdM* scans in 2010. The assumed correlations of these parameters between scans is also indicated.

| Scan Number | I | II–III | IV–V | |
|---|---|---|---|---|
| Fill Number | 1059 | 1089 | 1386 | |
| Beam centring | 2% | 2% | 0.04% | Uncorrelated |
| Beam-position jitter | – | – | 0.3% | Uncorrelated |
| Emittance growth and other non-reproducibility | 3% | 3% | 0.5% | Uncorrelated |
| Fit model | 1% | 1% | 0.2% | Partially Correlated |
| Length scale calibration | 2% | 2% | 0.3% | Partially Correlated |
| Absolute length scale | 0.3% | 0.3% | 0.3% | Correlated |
| Beam–beam effects | – | – | 0.7% | Uncorrelated |
| Transverse correlations | 3% | 2% | 0.9% | Partially Correlated |
| $\mu$ dependence | 2% | 2% | 0.5% | Correlated |
| Scan subtotal | 5.6% | 5.1% | 1.5% | |
| Bunch population product | 5.6% | 4.4% | 3.1% | Partially Correlated |
| Total | 7.8% | 6.8% | 3.4% | |

# 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



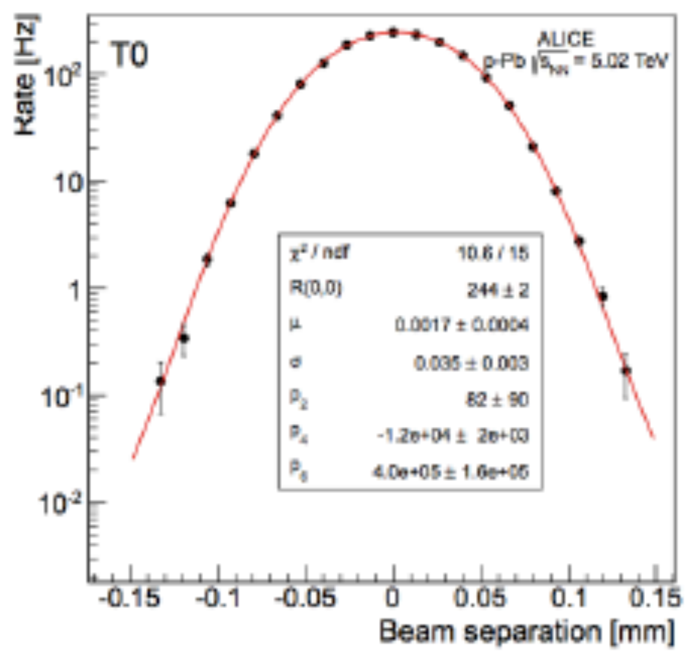
# Uncertainties - 1

- Only a selection of the most important systematic uncertainties is listed in the following

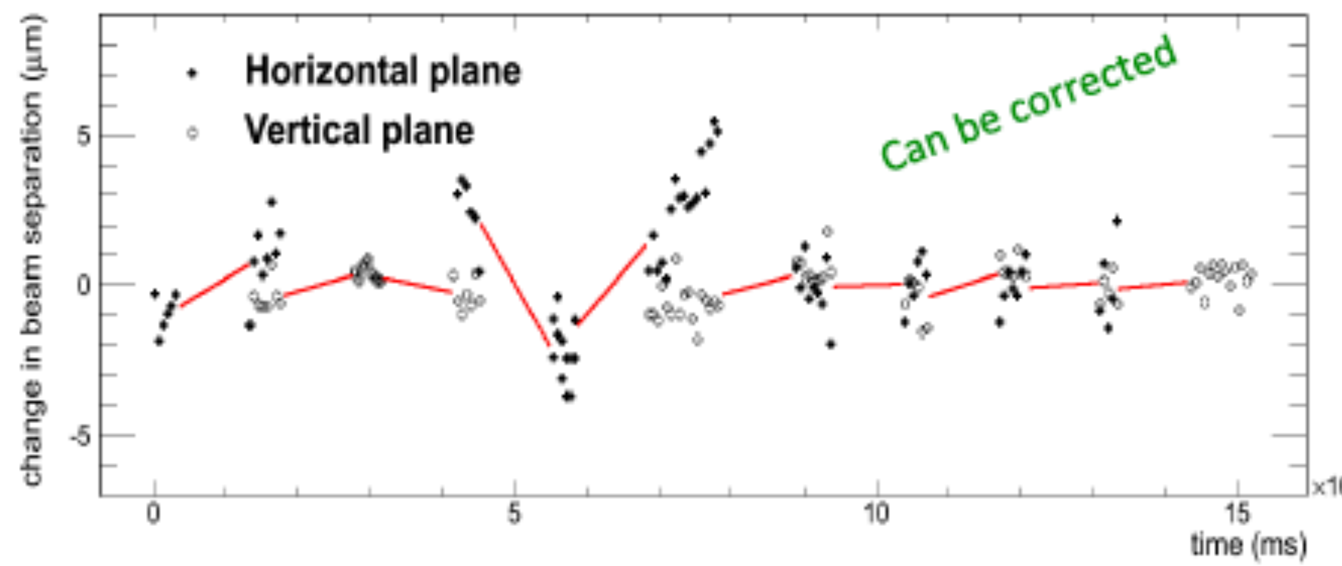
| Calibration uncertainties | VdM scan | BGI |
|---|---|---|
| | Scan curve model | Bunch shape model (accounts for factorizability) |
| | Factorizability | |
| | Beam-Beam effects | Vertexing resolution |
| | Orbit drifts | Detector alignment & crossing angle |
| | Reproducibility | |
| **Calibration transfer uncertainties from low $\mathcal{L}$ calibration to high $\mathcal{L}$ physics** | $\mu$-dependence | |
| | Radiation effects | |
| **Monitoring uncertainty** | Long-term stability | |

# Uncertainties - 2

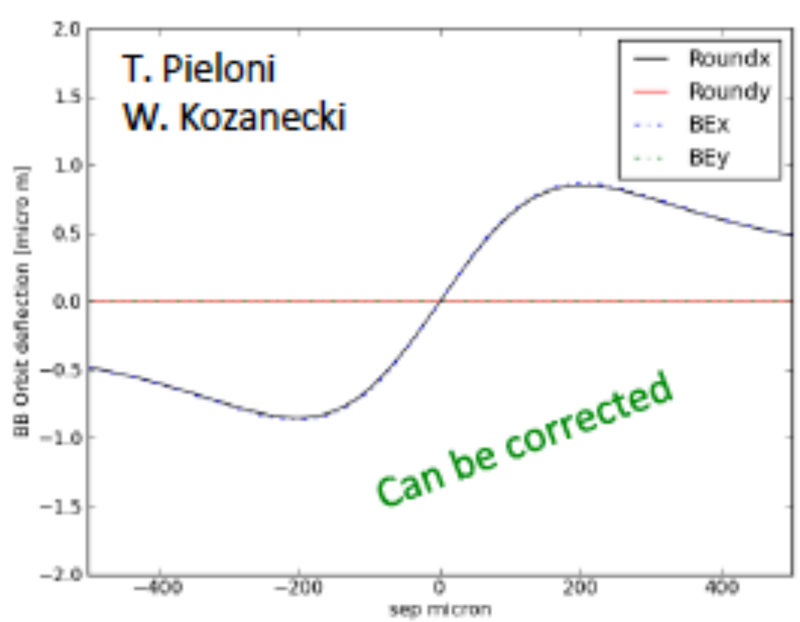
## Choice of scan curve model




## Orbit drifts




## Beam-beam effects




**Beam-beam deflection**
- Orbit shift dependent on beam separation

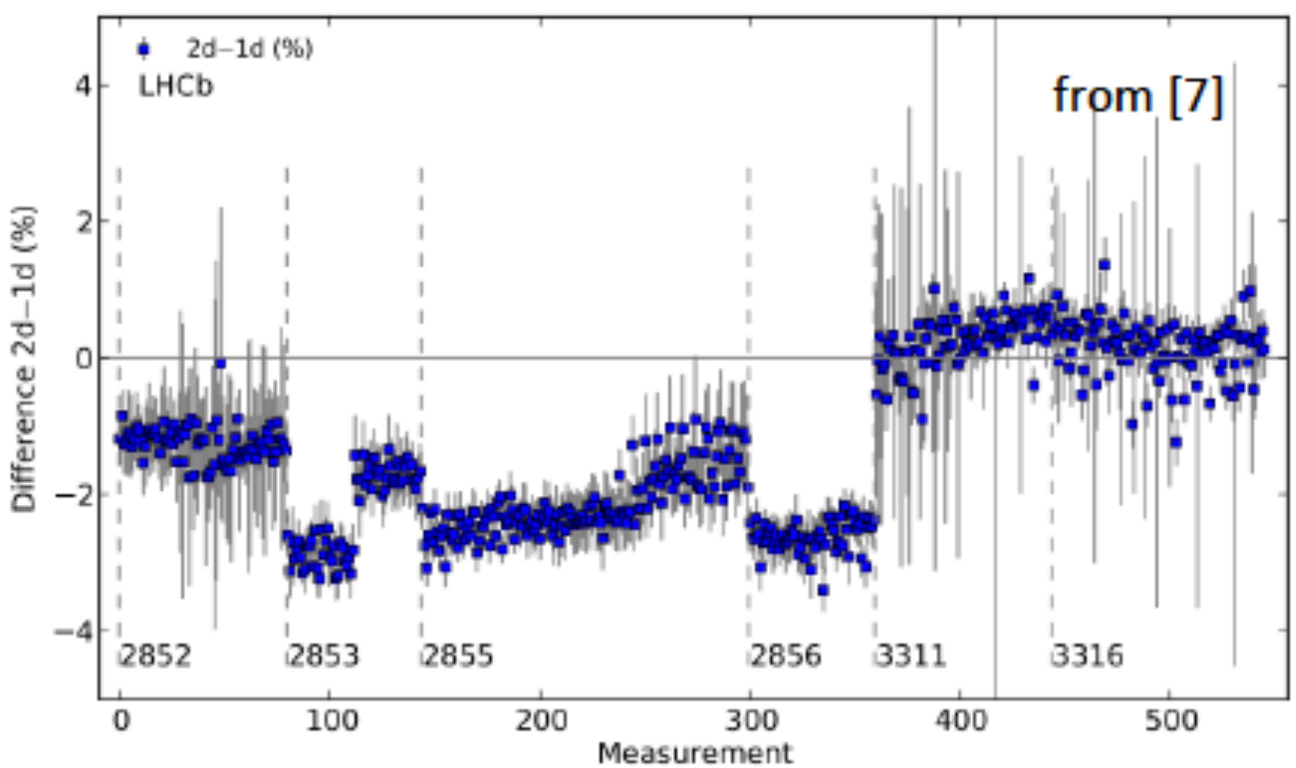
**Dynamic β**
- Beam sizes vary during VdM scan since beams exert focussing/ defocussing force on each other

lers

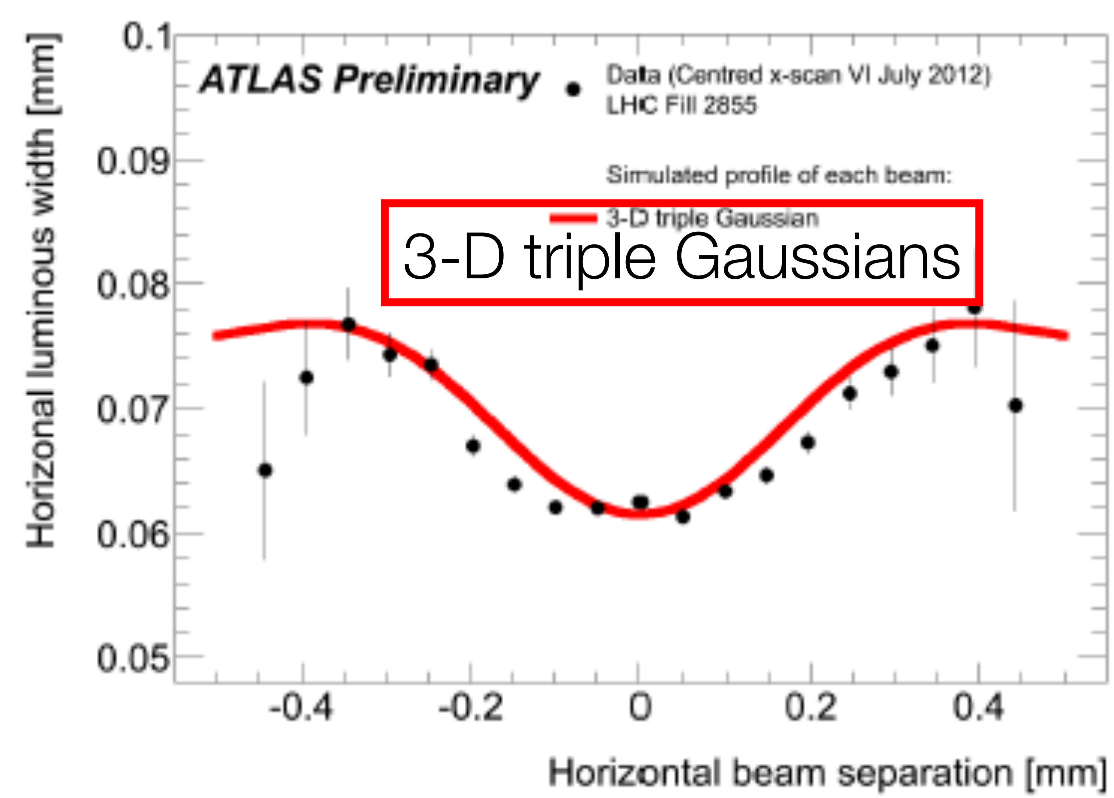
# Uncertainties - 3

- Non-factorizability of beam densities could be tracked down as the source for significant inconsistencies in some VdM scans
  - Its effect on VdM scans is new territory and was first studied at LHC
- Two approaches to deal with the factorizability problem
  - Accelerator experts prepare good beams which have approx. factorizable densities
  - Experiments measure the non-factorizability and develop new methods to correct for it (based on BGI, luminous-region evolution during scan)

**Difference between factorizable and non-factorizable model**




**Monitoring the luminous region during VdM scans**



# Snapshot of Luminosities uncertainties

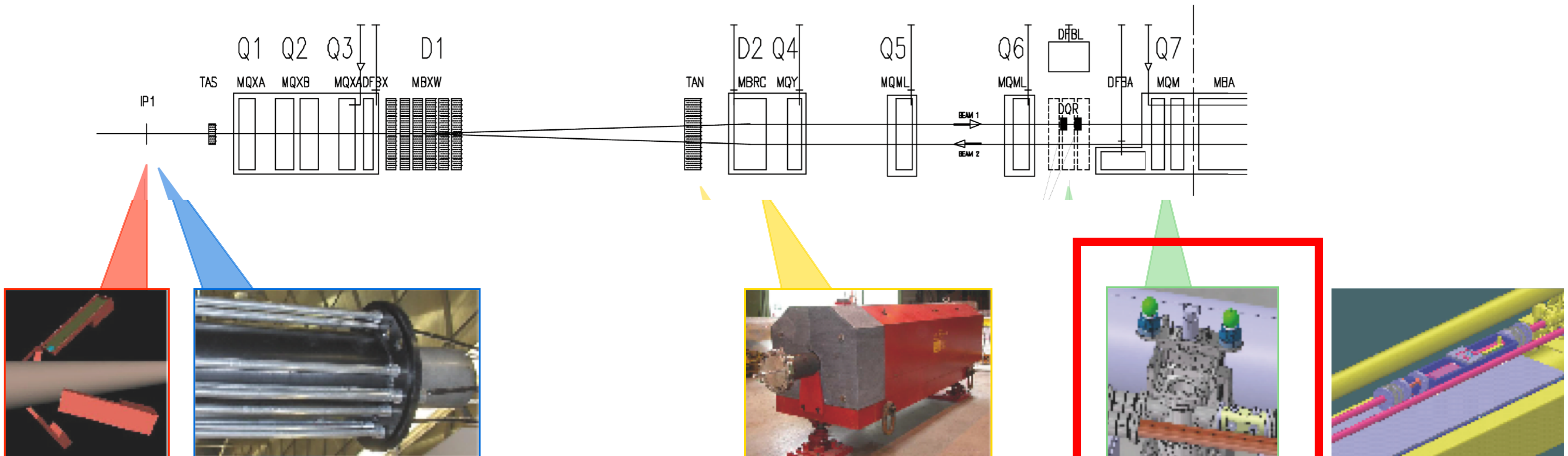
Parts of table reproduced from [11]

| | 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** |
| **$\mu$-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 via Forward Scattering



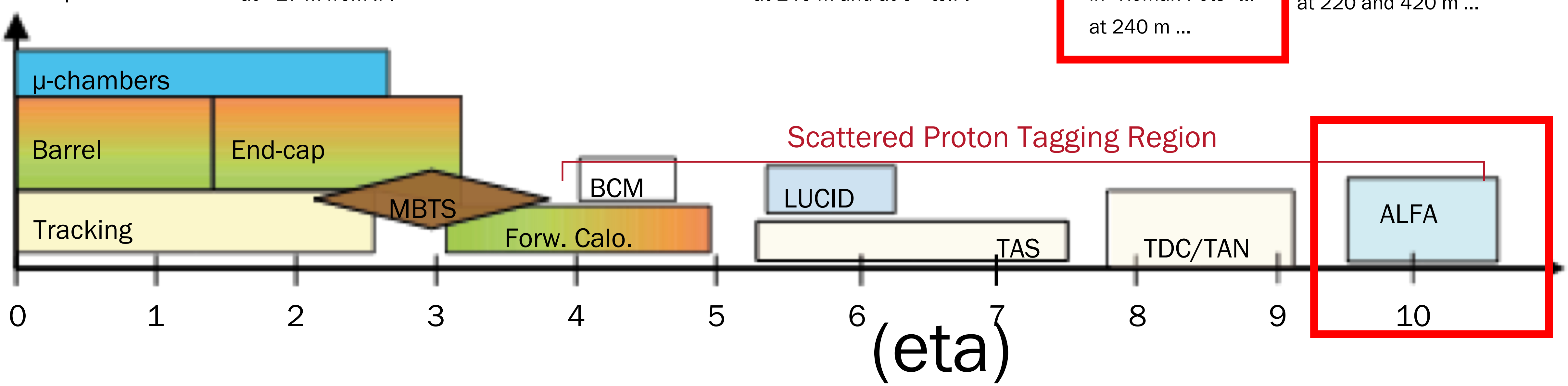

BCM
[Beam Condition Monitor]
Diamond sensors
at z = ±184 cm
4 modules per side

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 ...

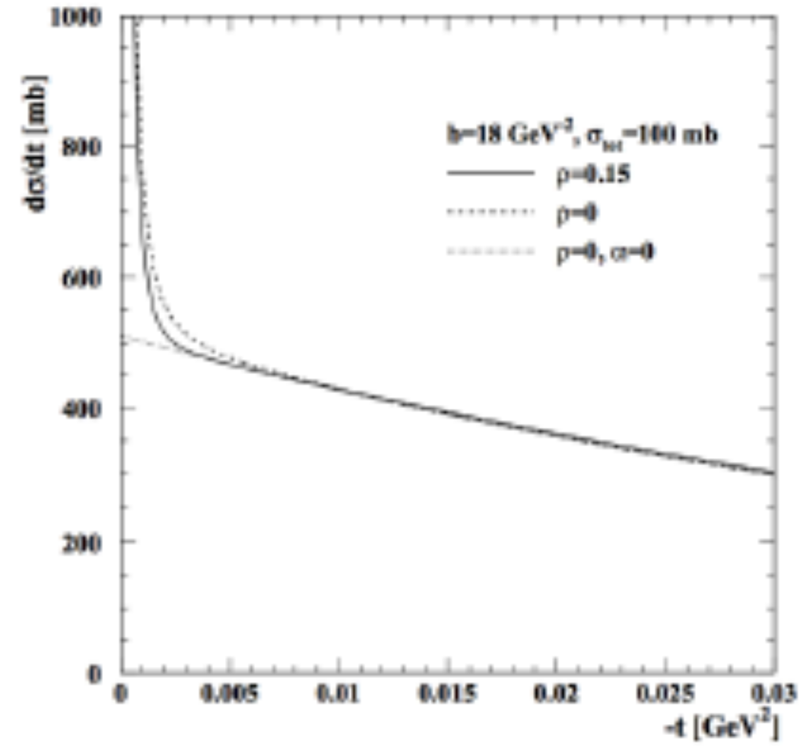
AFP
[Track & ToF System]
LHC Upgrade ...
at 220 and 420 m ...




TAS: Target Absorber Secondaries
TAN: Target Absorber Neutrals

# Optical theorem basics

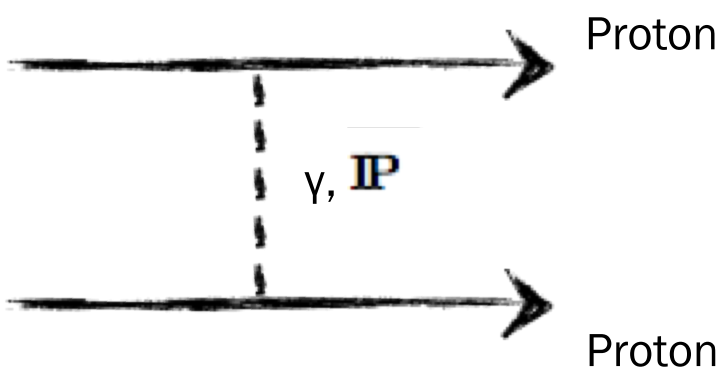
- TOTEM for CMS and ALFA for ATLAS are able to perform absolute luminosity measurements
- Based on Optical theorem
  - Measurements of the total rate in combination with the *t*-dependence of the elastic cross section (TOTEM)
  - Measurements of elastic scattering rates in the Coulomb interference region(ALFA)




- 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

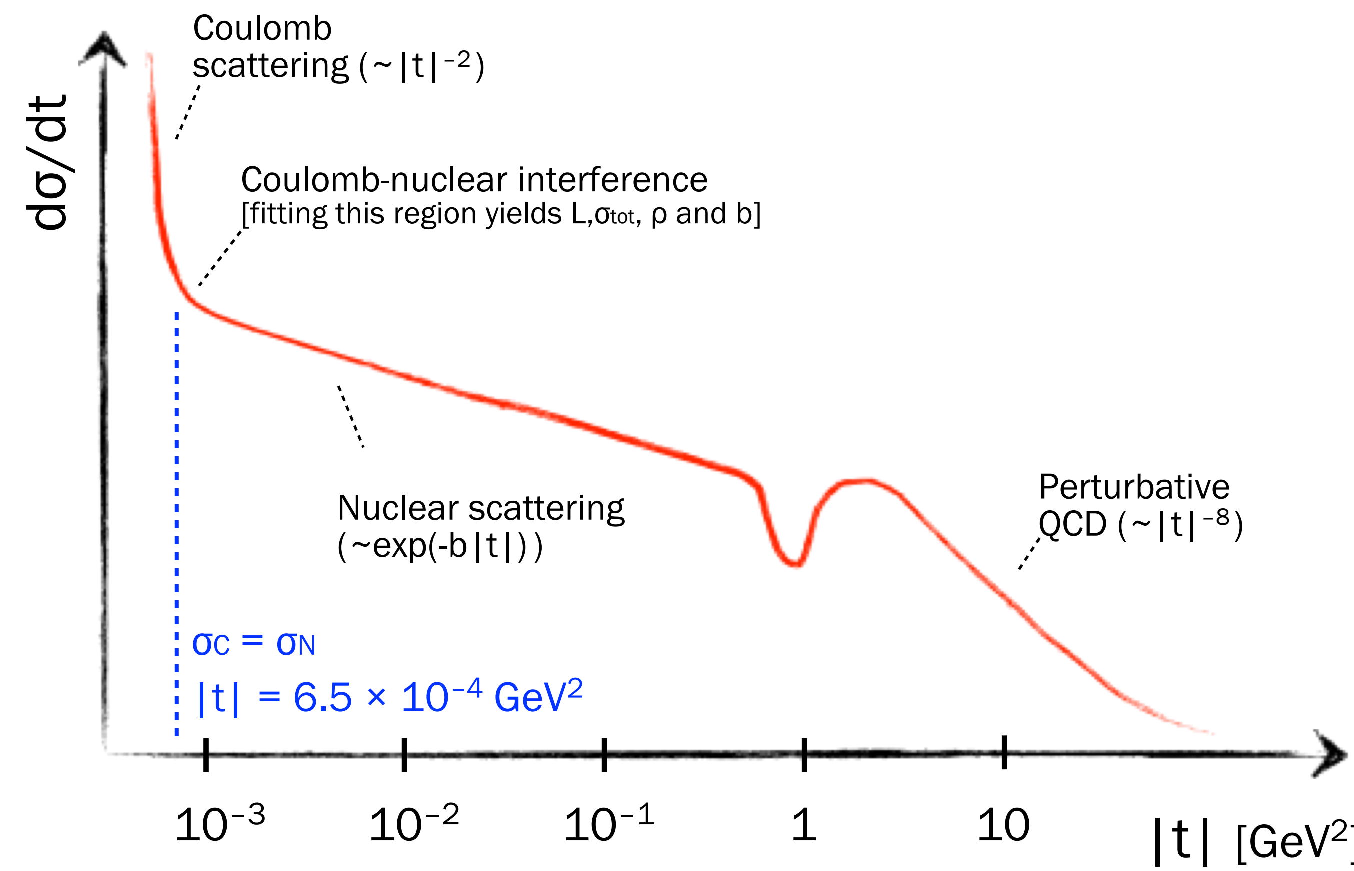
# ALFA – Absolute Luminosity for ATLAS

## 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, $\sigma_{tot}$, and the parameters ρ and b …

Perform fit to:

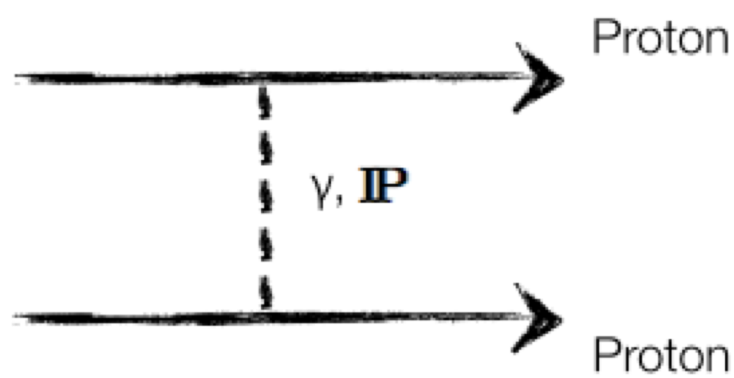
$$\frac{dN}{dt} = L\left(\underbrace{\frac{4\pi\alpha^2}{|t|^2}}_{\text{Coulomb Scattering}} - \underbrace{\frac{\alpha\rho\sigma_{\text{tot}}e^{\frac{-b|t|}{2}}}{|t|}}_{\text{Coulomb/nuclear Interference}} + \underbrace{\frac{\sigma_{\text{tot}}^2(1+\rho^2)e^{-b|t|}}{16\pi}}_{\text{Nuclear Scattering}}\right)$$

with:

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

# ALFA – Absolute Luminosity for ATLAS

Elastic Scattering:

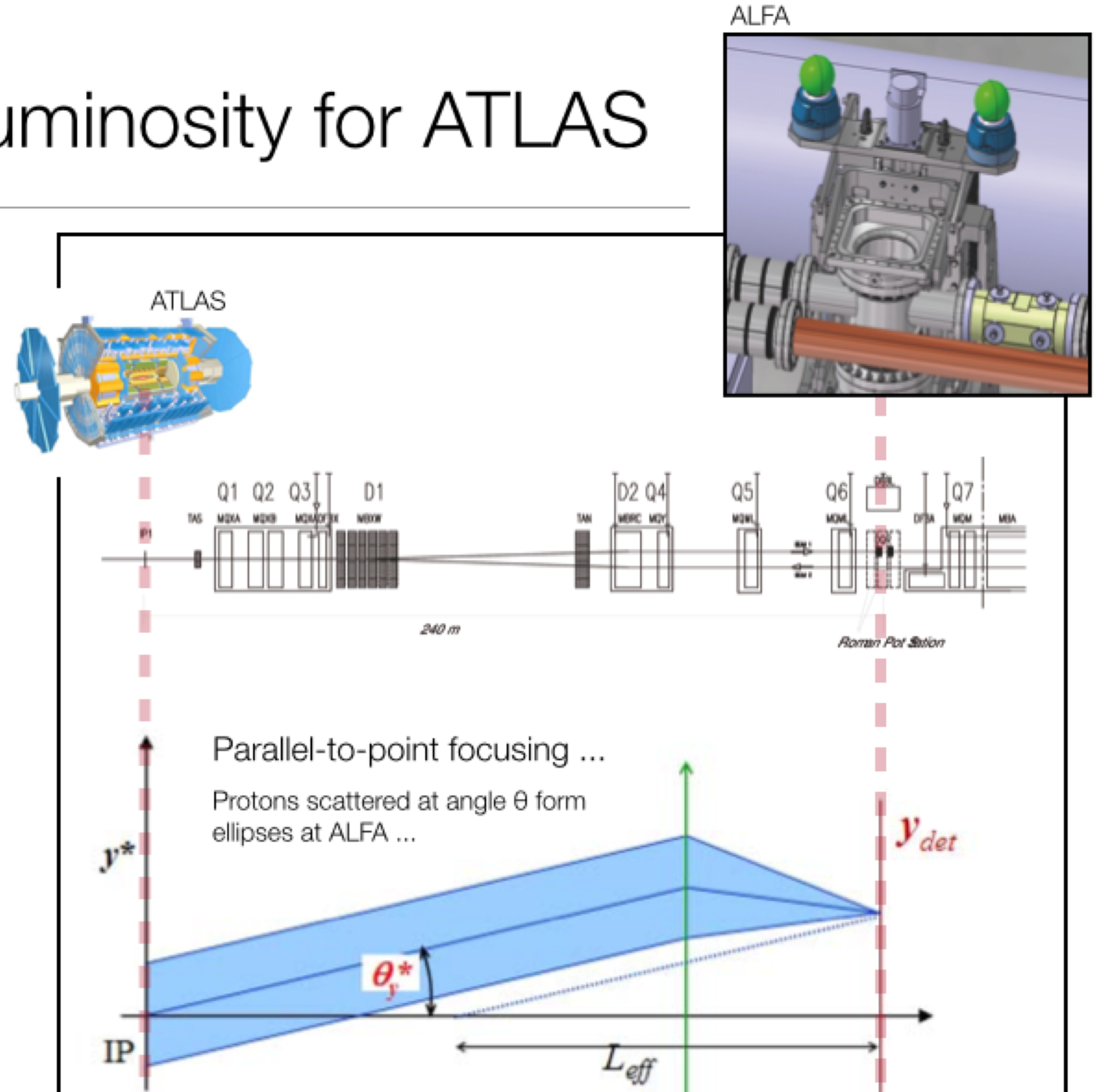



$$t = (p_i - p_i') \sim p^2\theta^2$$

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

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



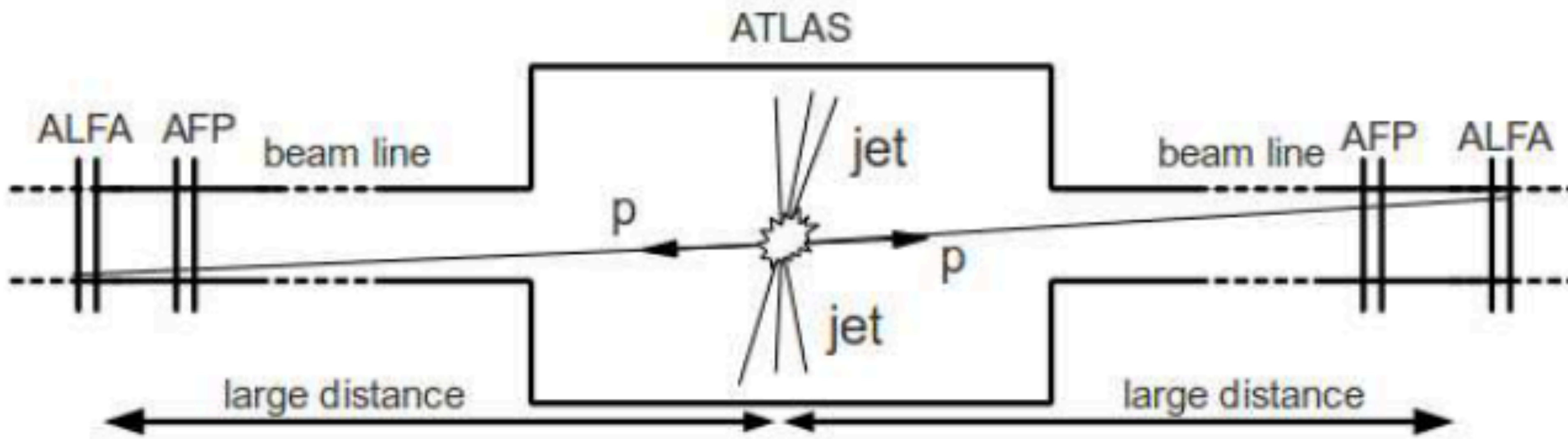

$$y_{\mathrm{det}} = \theta_y \cdot L_{\mathrm{eff}}$$

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

# AFP & ALFA : geometry

## Forward Detectors @ IP1

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




**ALFA**

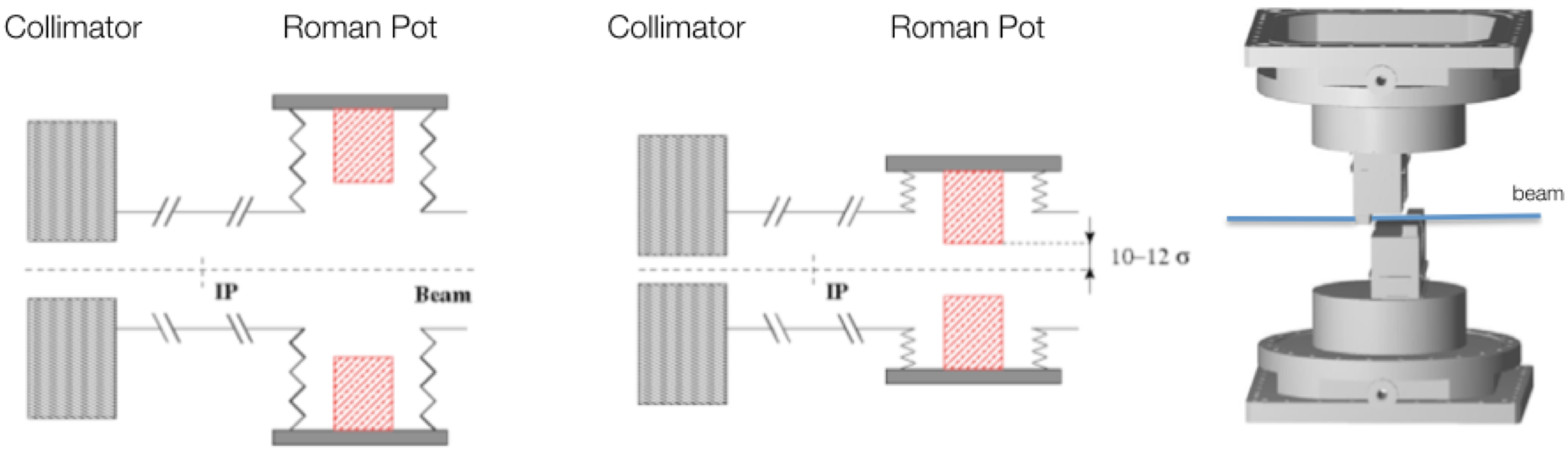
- **A**bsolute **L**uminosity **F**or **A**TLAS
- exist, 240 m from ATLAS IP
- soft diffraction (elastic scattering)
- special runs (high $\beta^*$ optics)
- vertically inserted Roman Pots
- tracking detectors, resolution: $\sigma_x = \sigma_y = 30\ \mu$m

**AFP**

- **A**TLAS **F**orward **P**roton
- planned, 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

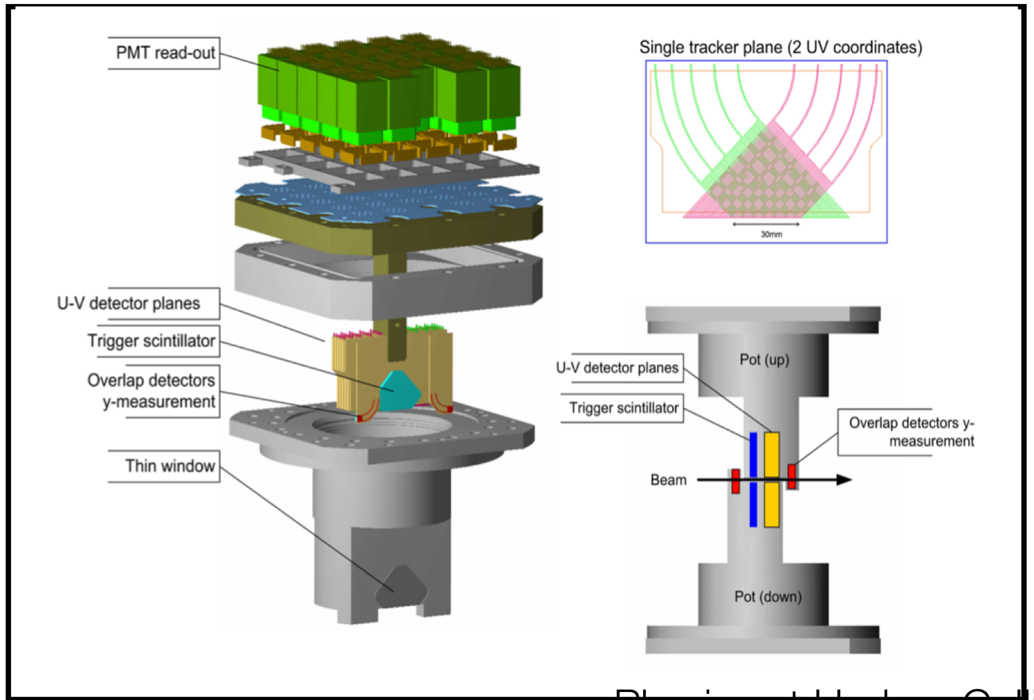



Roman Pots, based on modified Totem design, used to move detectors near to stable beam.

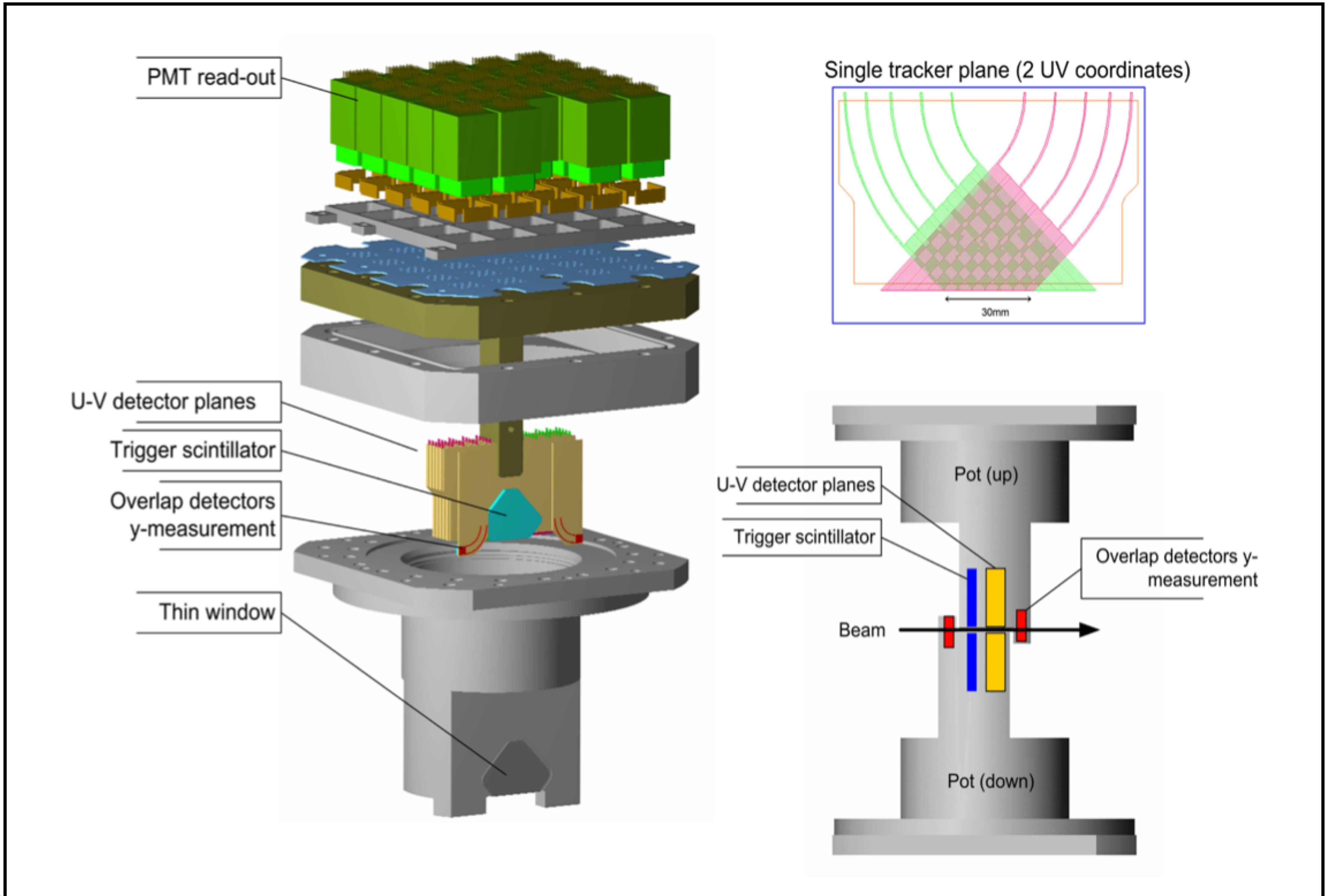
Detectors in vertical plane only.

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

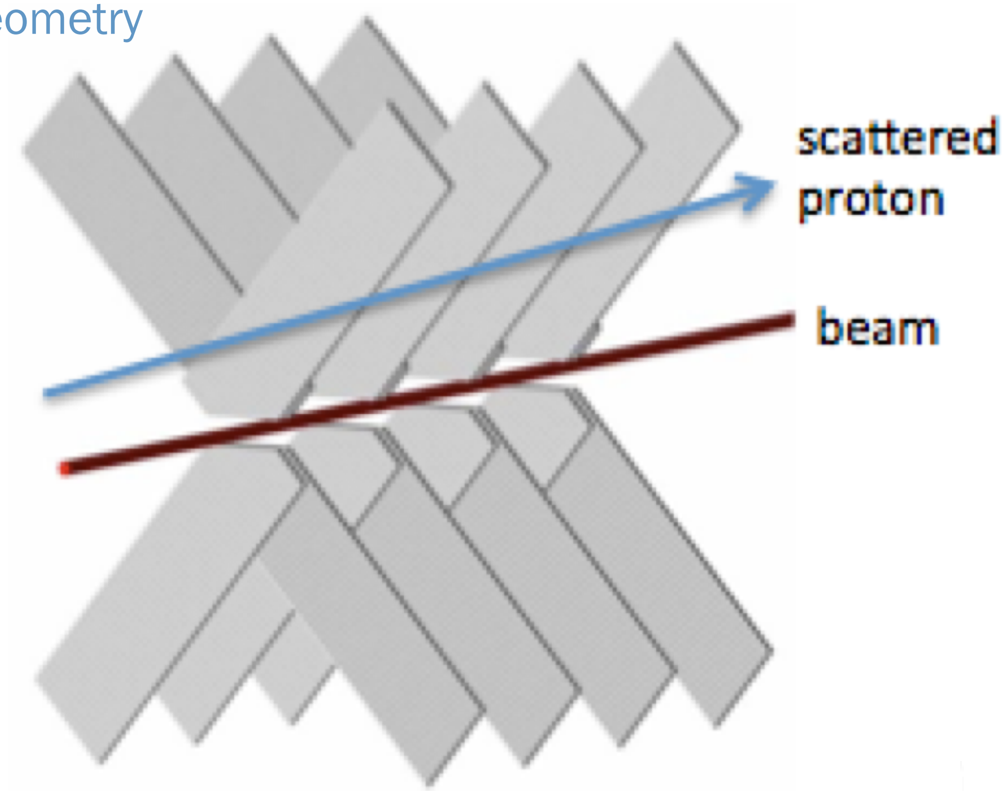


# ALFA – Absolute Luminosity for ATLAS



# ALFA – Absolute Luminosity for ATLAS

Scintillating fibers
in U-V geometry




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

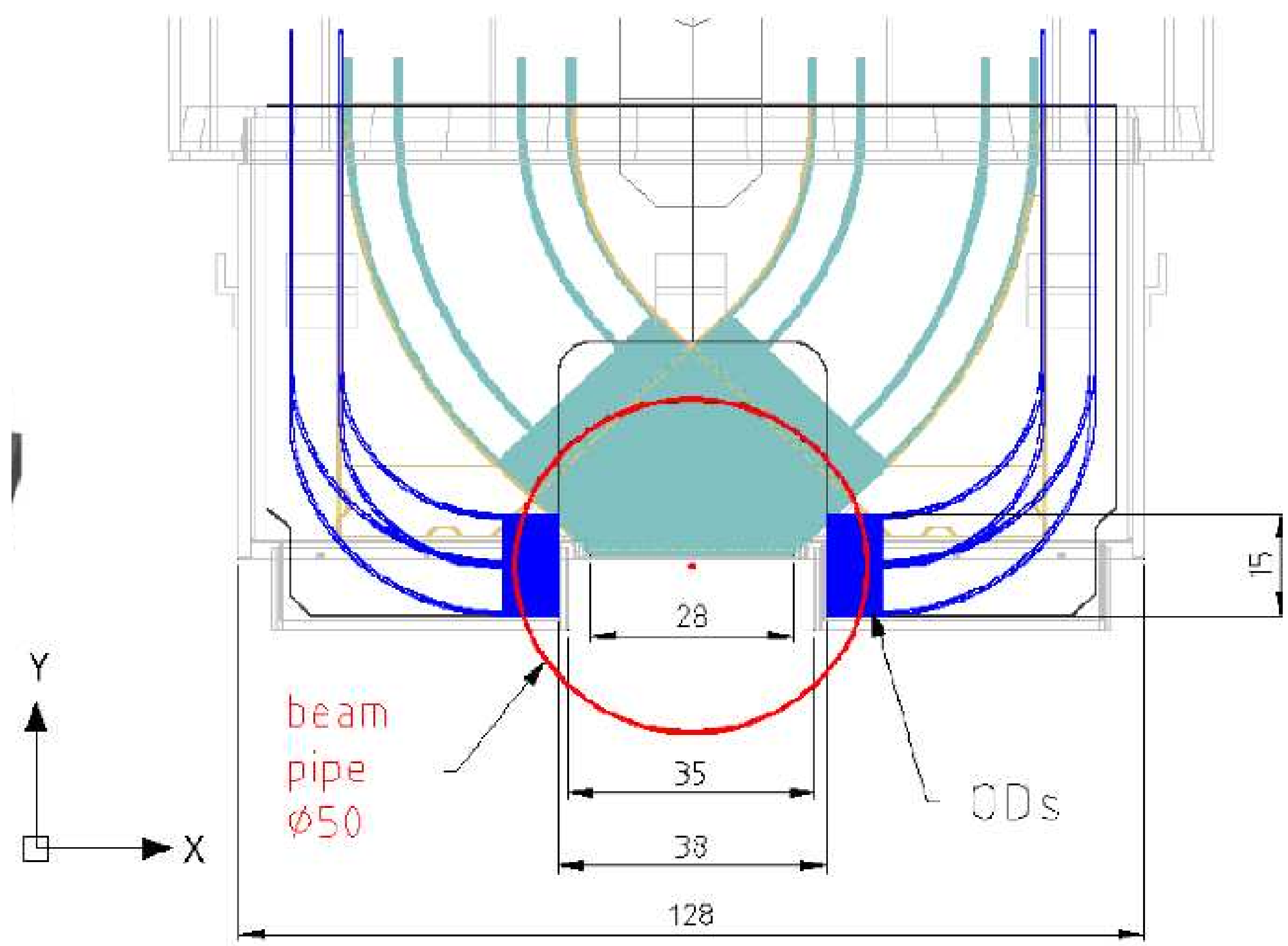
20 detector planes with 64 fibers each …
[expected position resolution: 30 μm]

Dead region less than 100 μm …

Efficiency > 90% per plane …

Schematic view of tracker module …

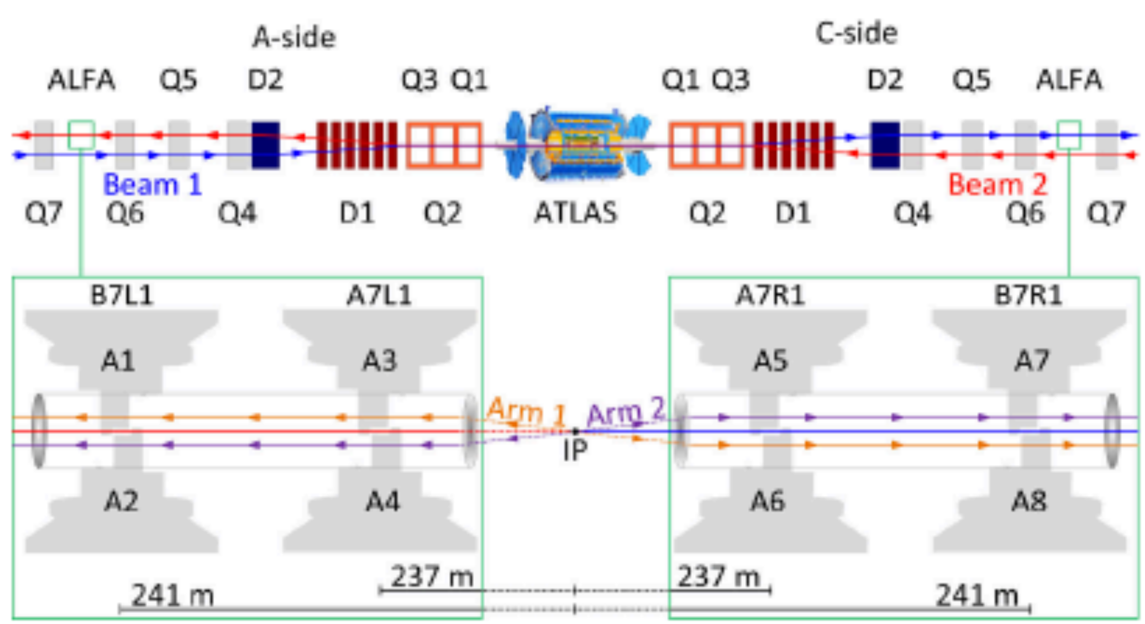
Sensitive area with U-V geometry (light blue) …
Overlap detectors and fibers (dark blue) …
LHC Beam pipe (red) …

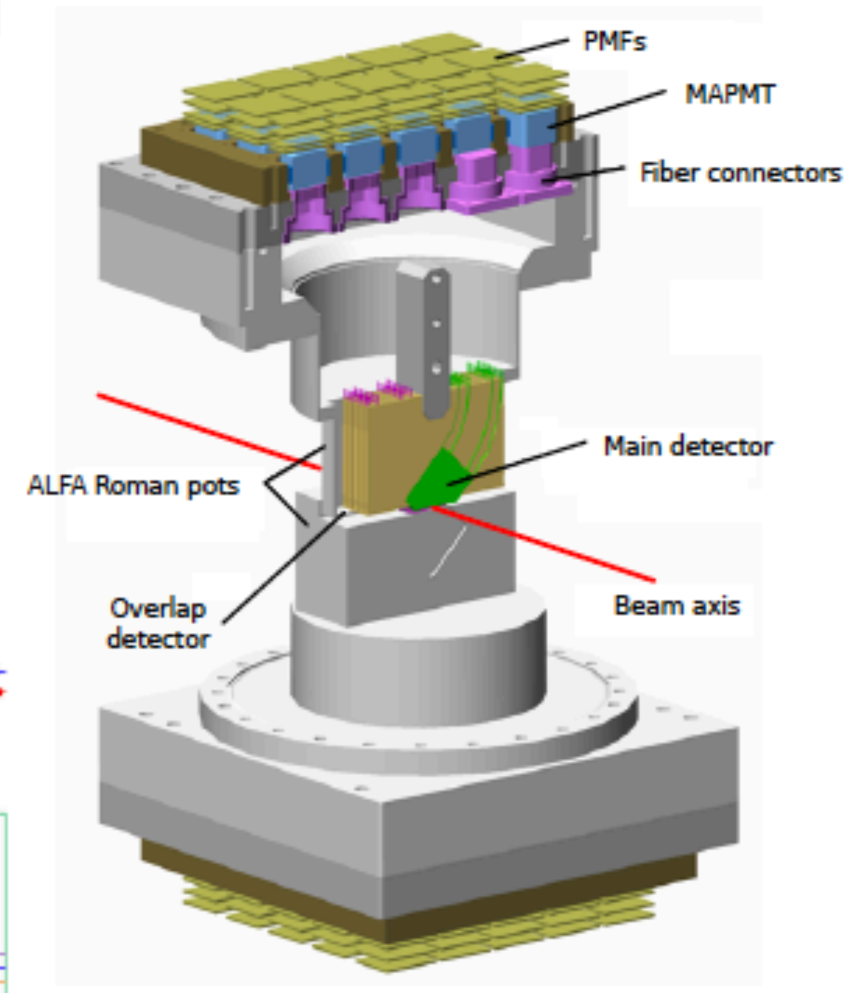


# ALFA detector

## The Absolute Luminosity For ATLAS (ALFA) detector

- Build to measure elastically scattered protons at $\mu$rad angles.
- Located 240 m from the ATLAS interaction point (IP) inside Roman Pots.
- Approaches outgoing beams in vertical direction.
- The main detector (MD) is build of $10 \times 2$ orthogonal layers of scintillating fibers.
  - The fiber width of 500 $\mu$m and layer staggering gives $\approx$ 30 $\mu$m tracking resolution.
- The overlap detectors (OD) also use scintillating fibers and are used for detector alignment.
- Trigger tiles of scintillating plastic cover MDs and ODs.



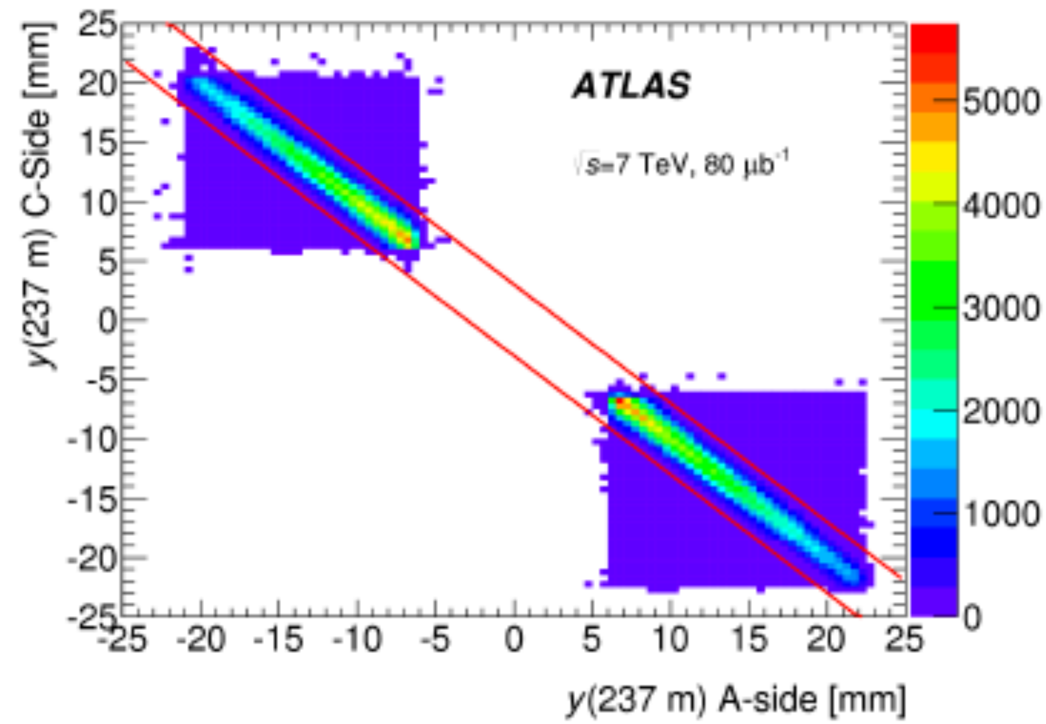



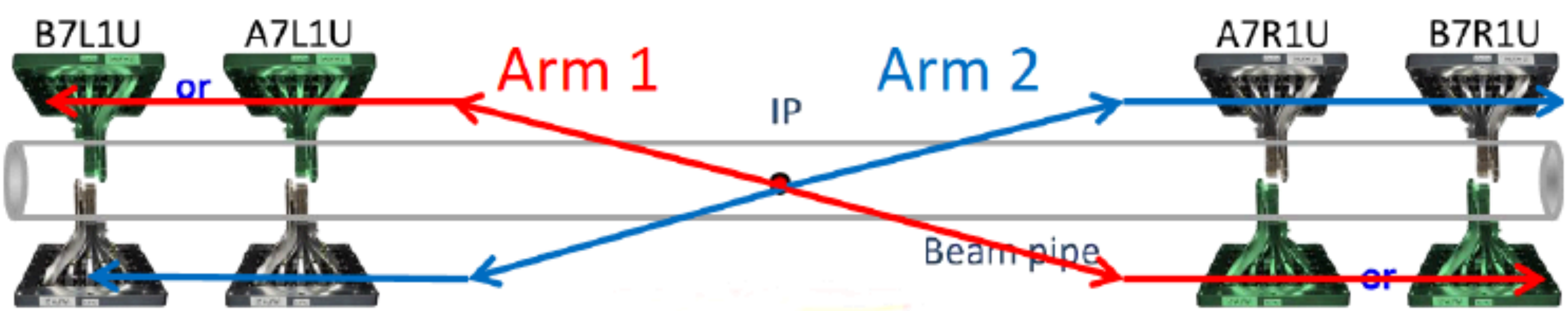

[ATL-LUM-2010-001]

# 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

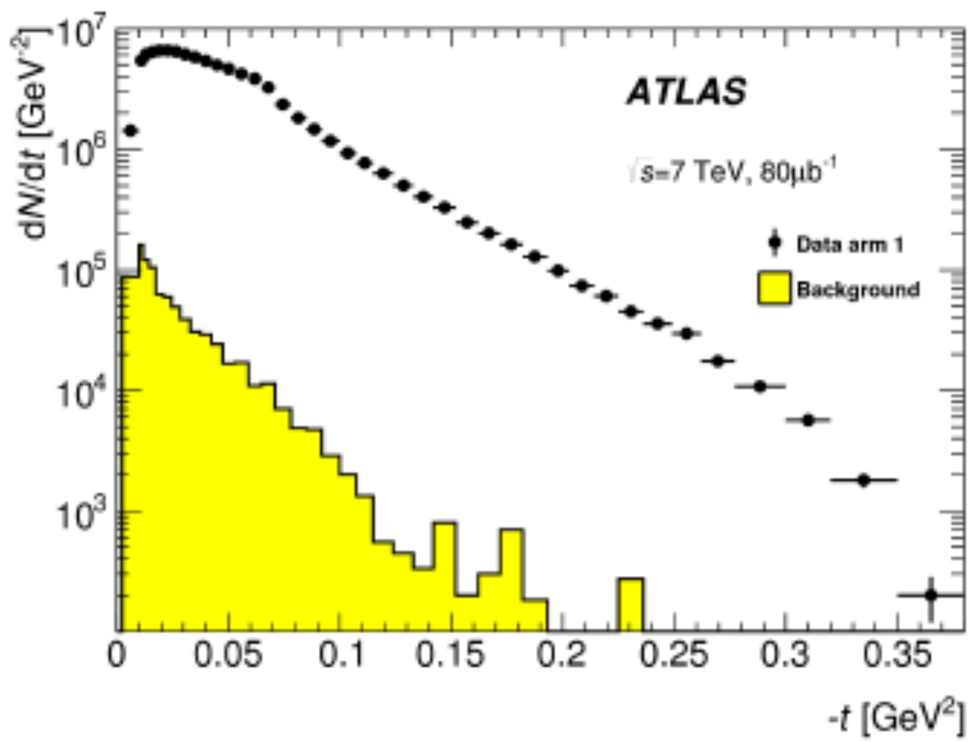
## Background

- 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

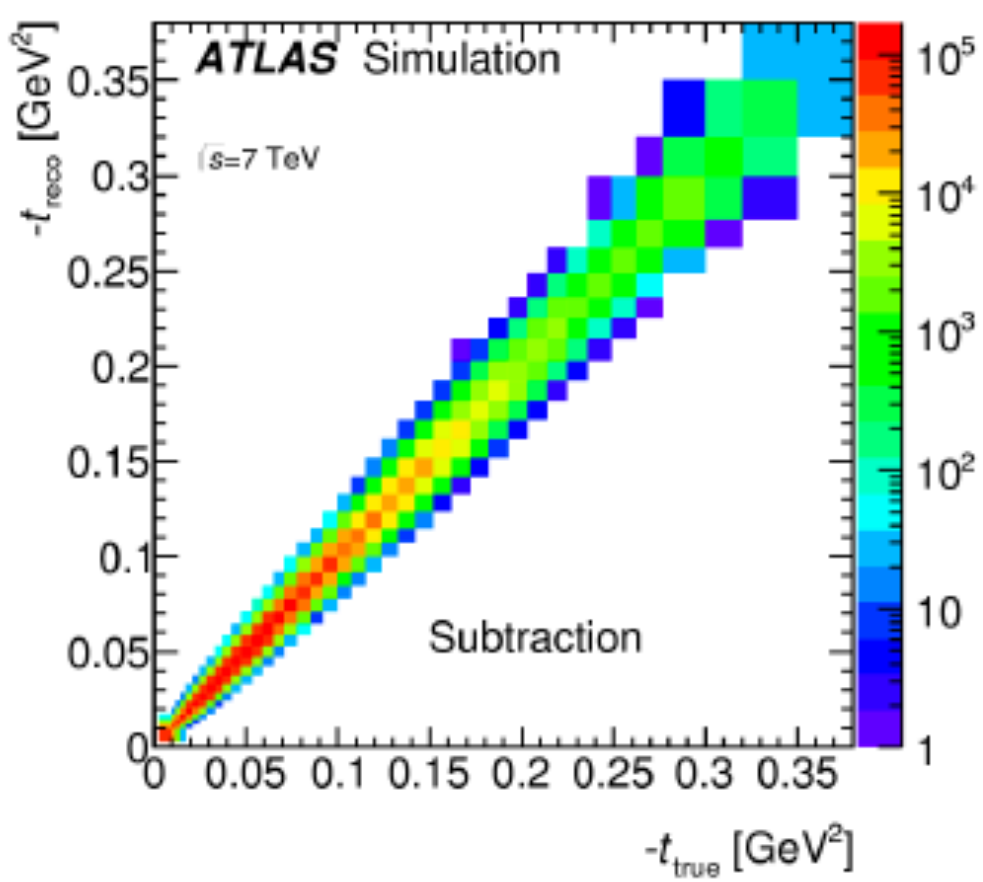


# ALFA : acceptance & unfolding

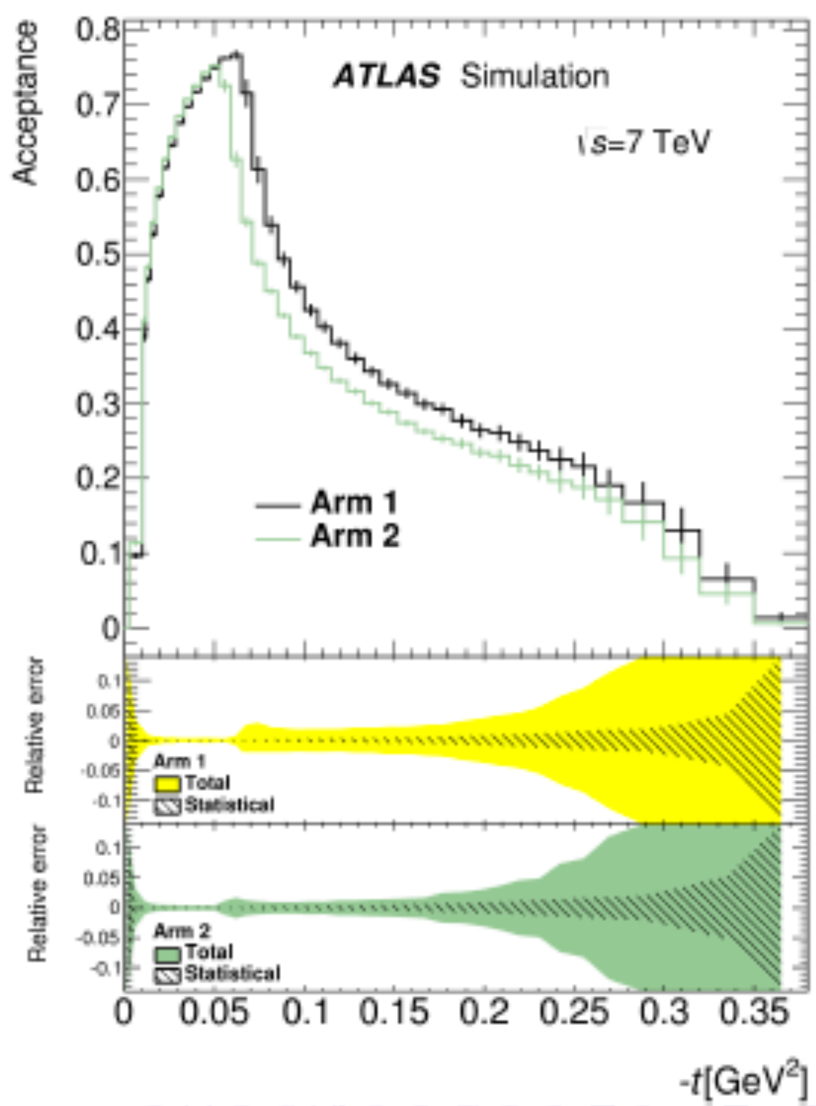
## Simulation: Acceptance & unfolding

- 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.

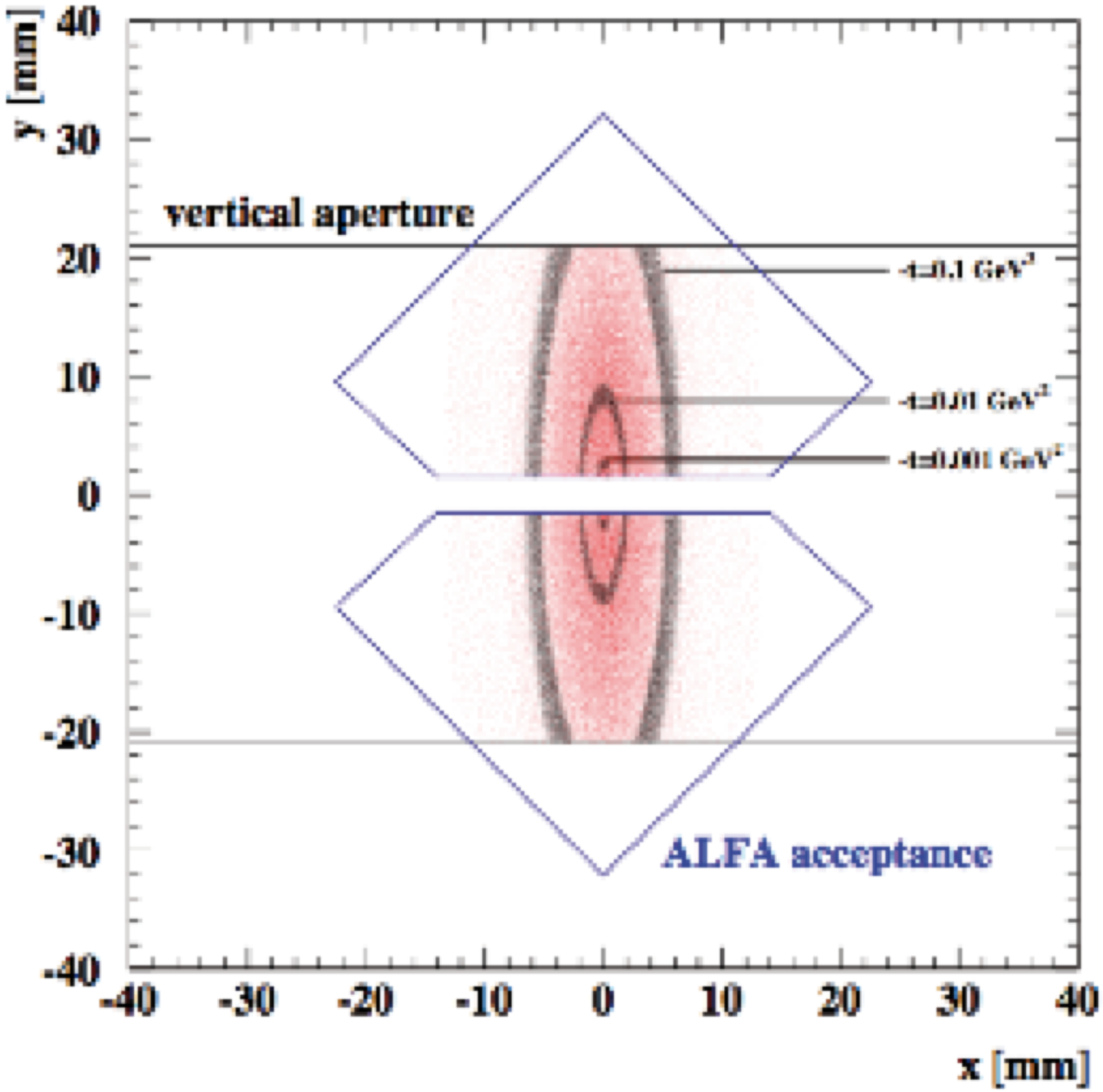
Transition matrix




Acceptance

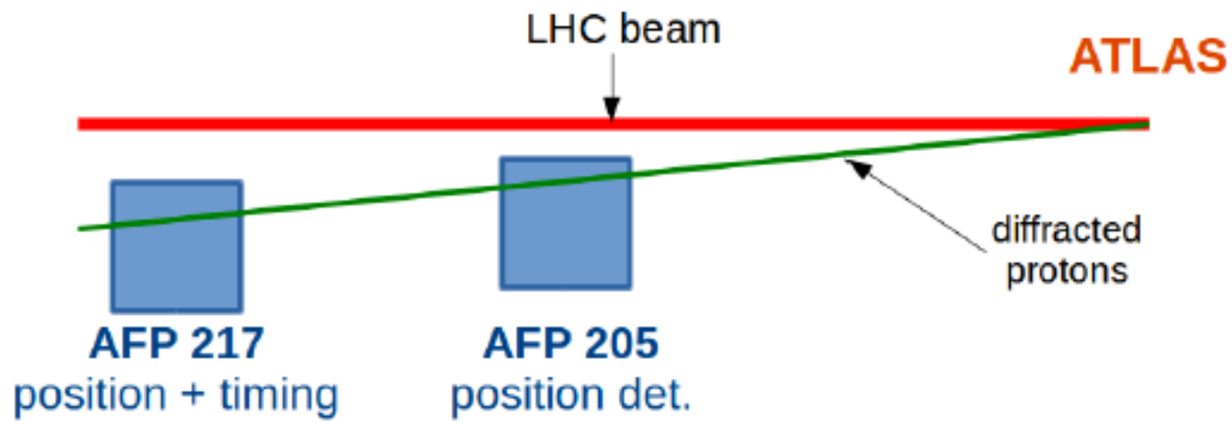


# ALFA – Absolute Luminosity for ATLAS




ALFA
Simulated hit distribution

# AFP detector

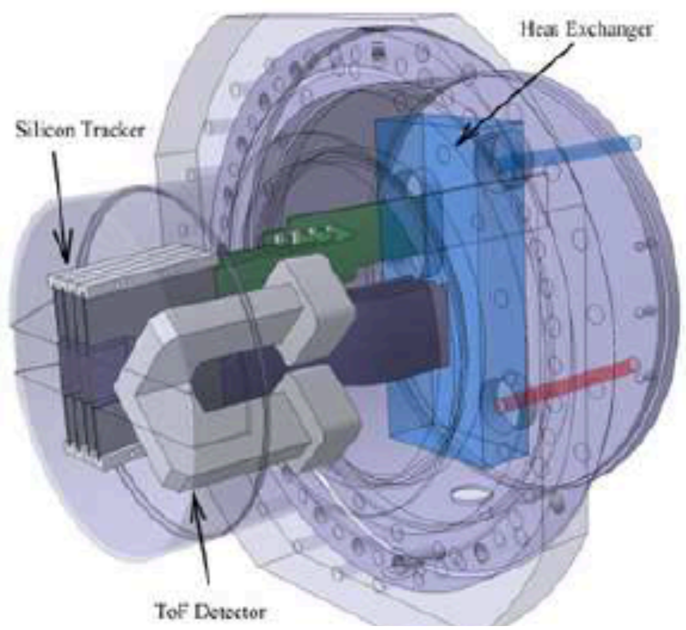



Near station (205 m from ATLAS IP):

- position detectors: 4 layers, staggered.

Far station (217 m from ATLAS IP):

- position detectors,
- ToF detectors: 4 x 4 bars.




**Goals:**

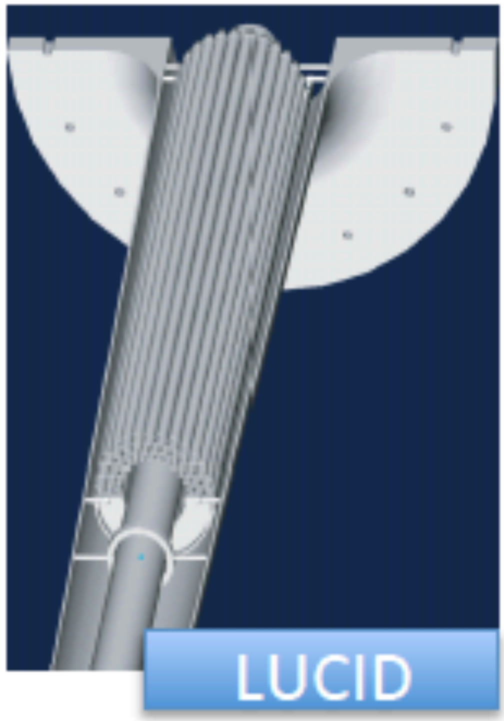
- debug the detector; explore the environment close to the LHC beam,
- special runs at low-$\mu$, focusing on high-rate diffractive physics processes,
- staged installation:
  - Winter 2015-2016 shutdown – installation of a single AFP arm with two Roman pot stations, the 0+2 AFP configuration (AFP0+2),
  - Winter 2016-2017 shutdown – installation of the second detector arm.

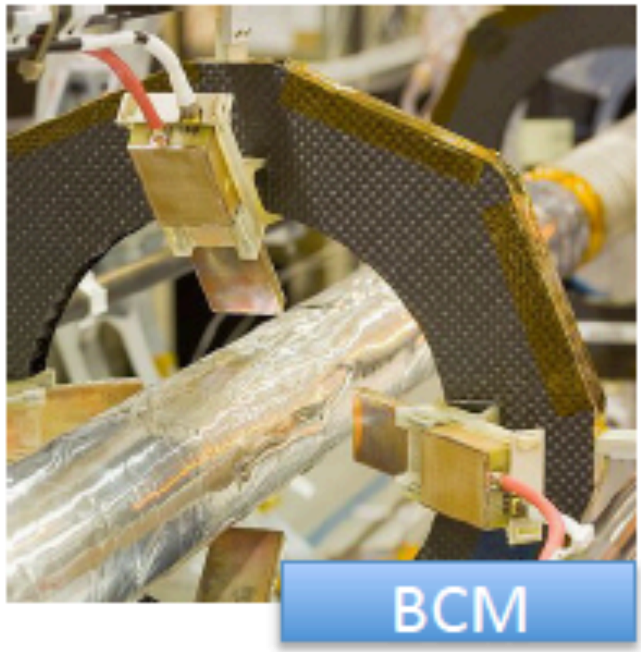
# ATLAS Luminosity detectors



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)
  - 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



# Summary of Luminosity Monitors

| Device | Algorithms | Technology | BCID-aware | ACR Desk |
|---|---|---|---|---|
| BCM | Event counting | Diamond semi-conductors | • | ID |
| LUCID | Event (Hit) counting<br>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<br>Cluster counting<br>Track counting | Diamond pixels | • | ID |

# Early LHC Luminosity Measurement

Particle counting:

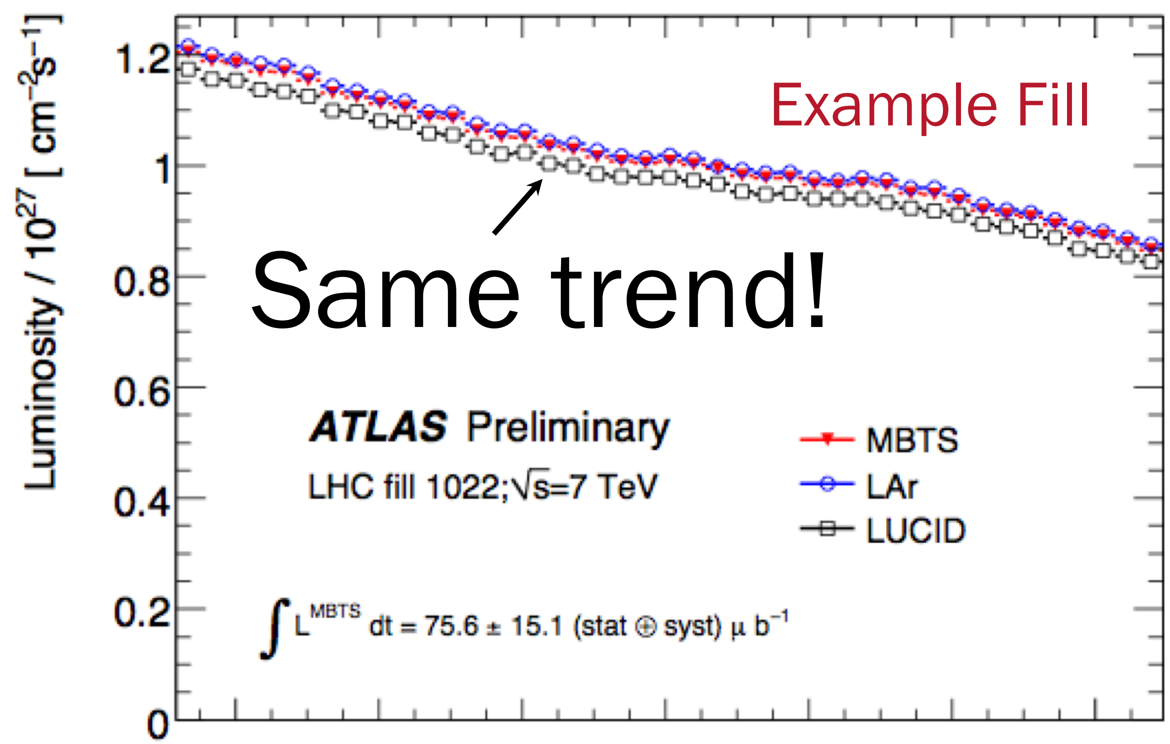
Charged Tracks (MBTS)

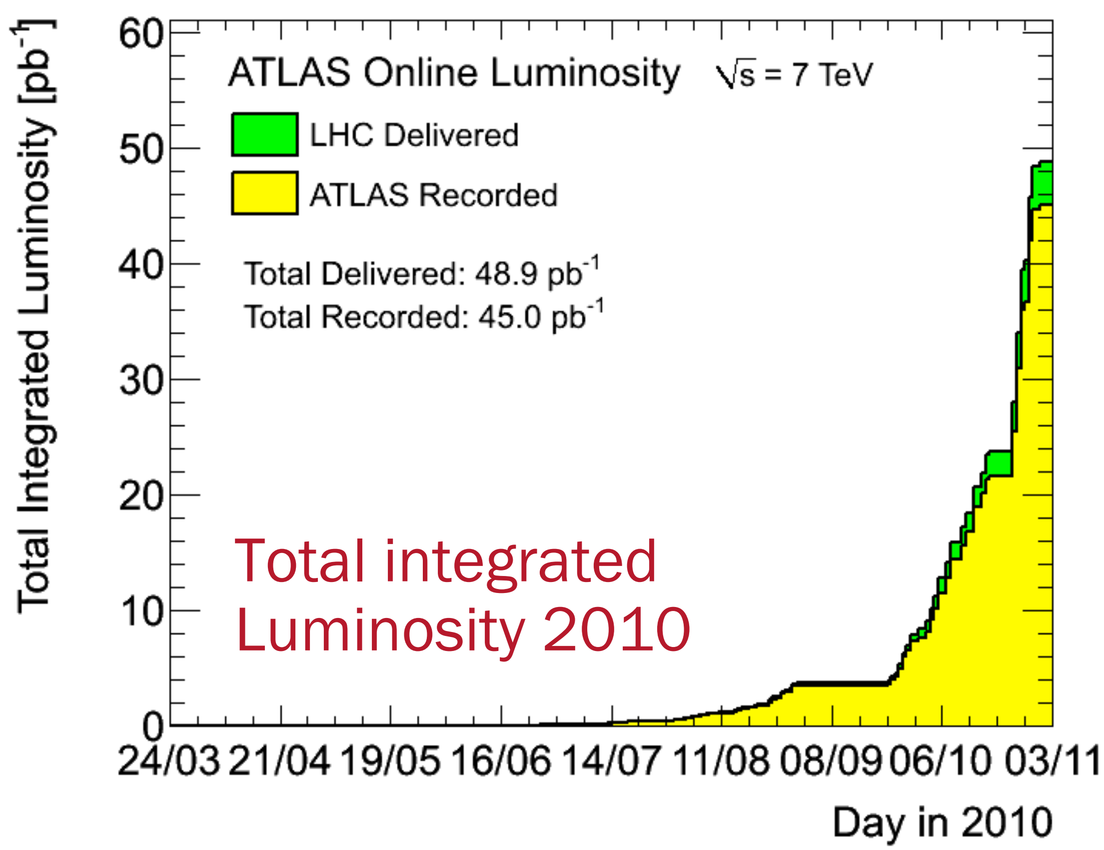
Calorimeter deposits (LAR)

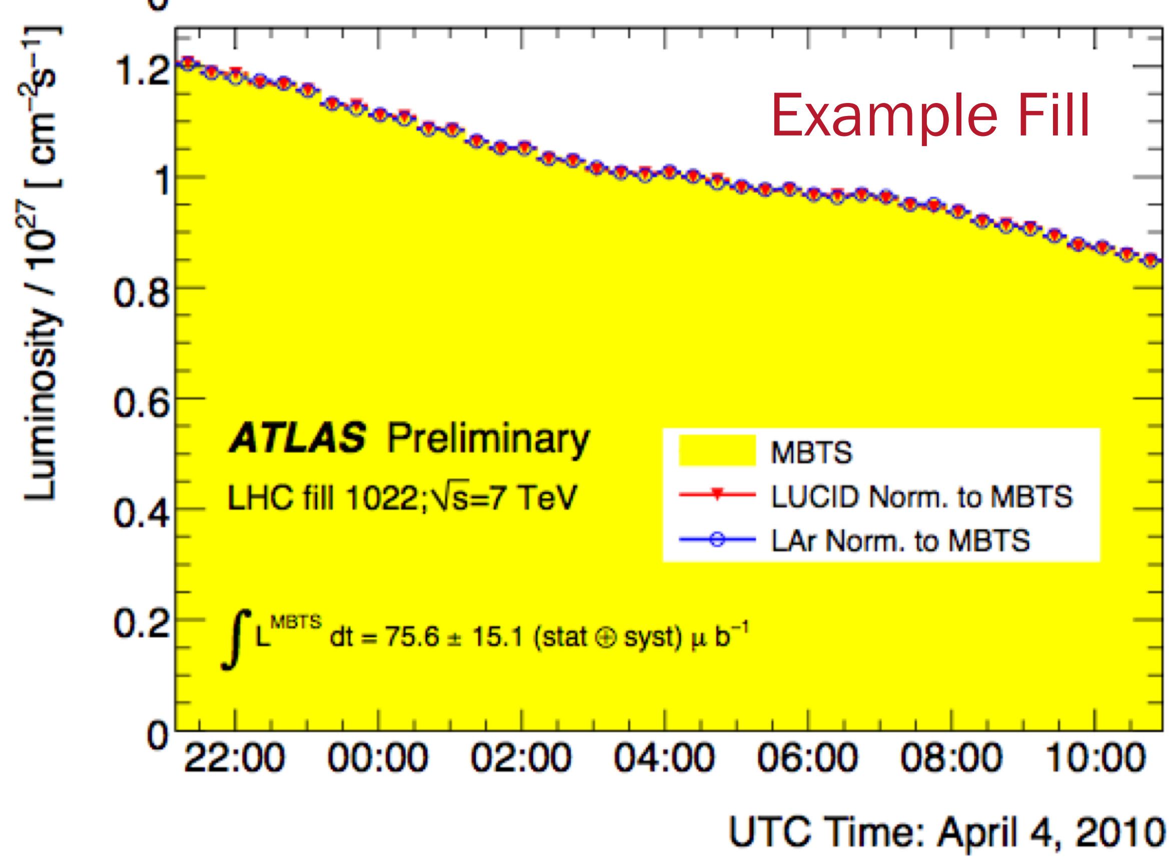
[Normalization via Monte Carlo]

Forward Particles (LUCID)

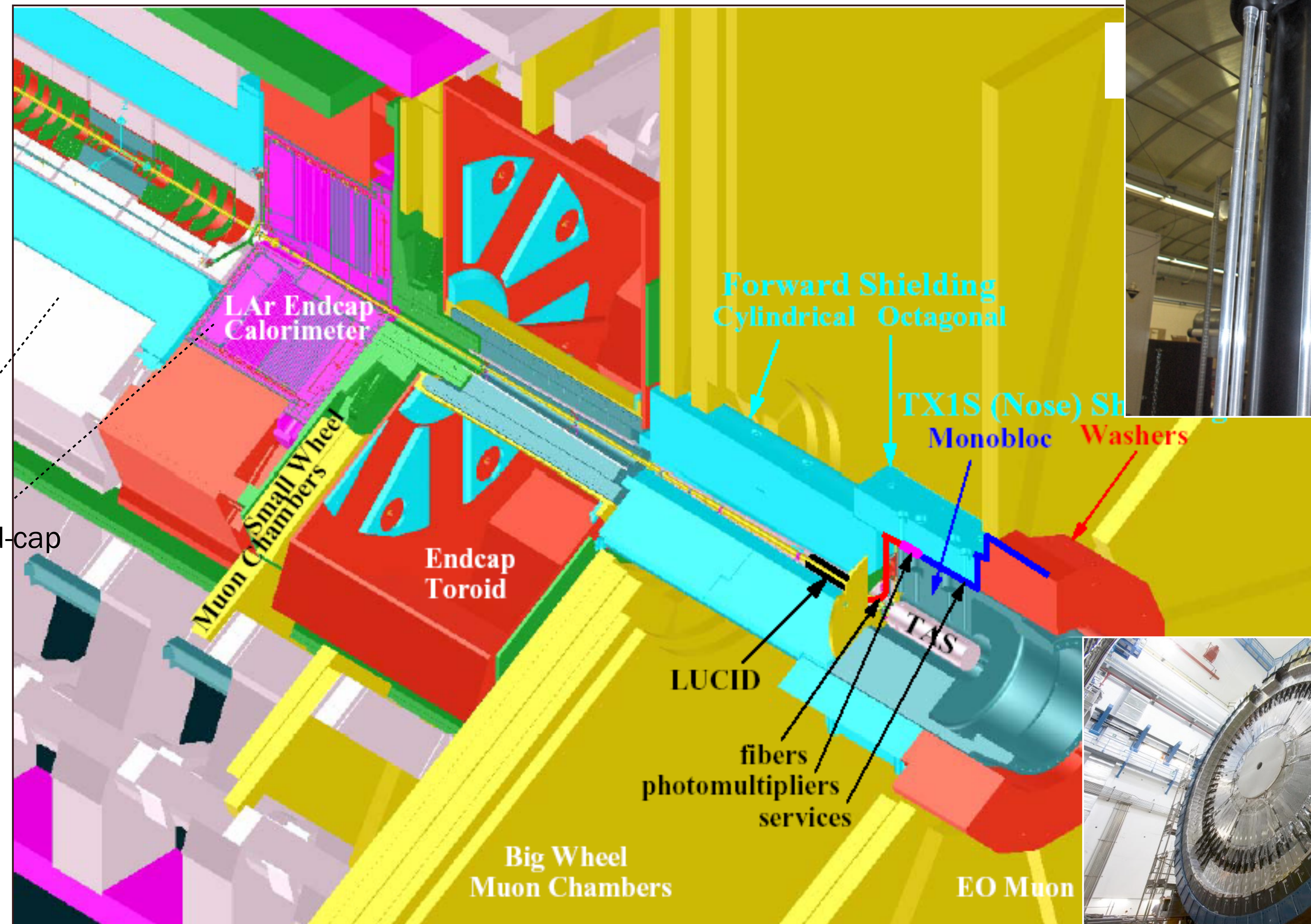
[Relative Method; normalization to MBTS/LAr]



# ATLAS Forward Region

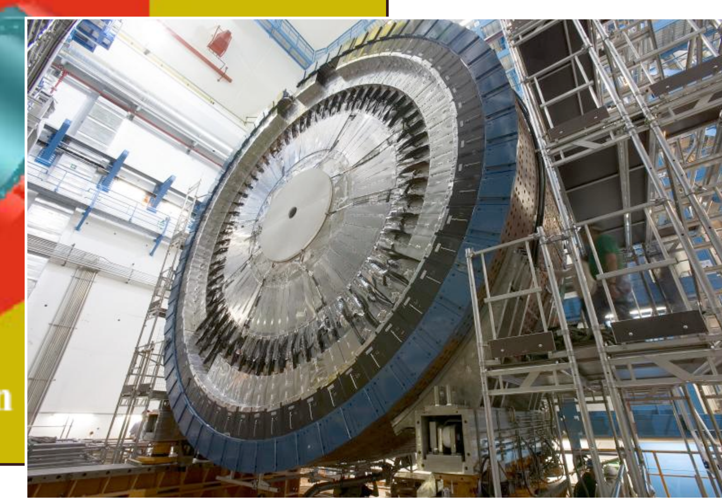



MBTS

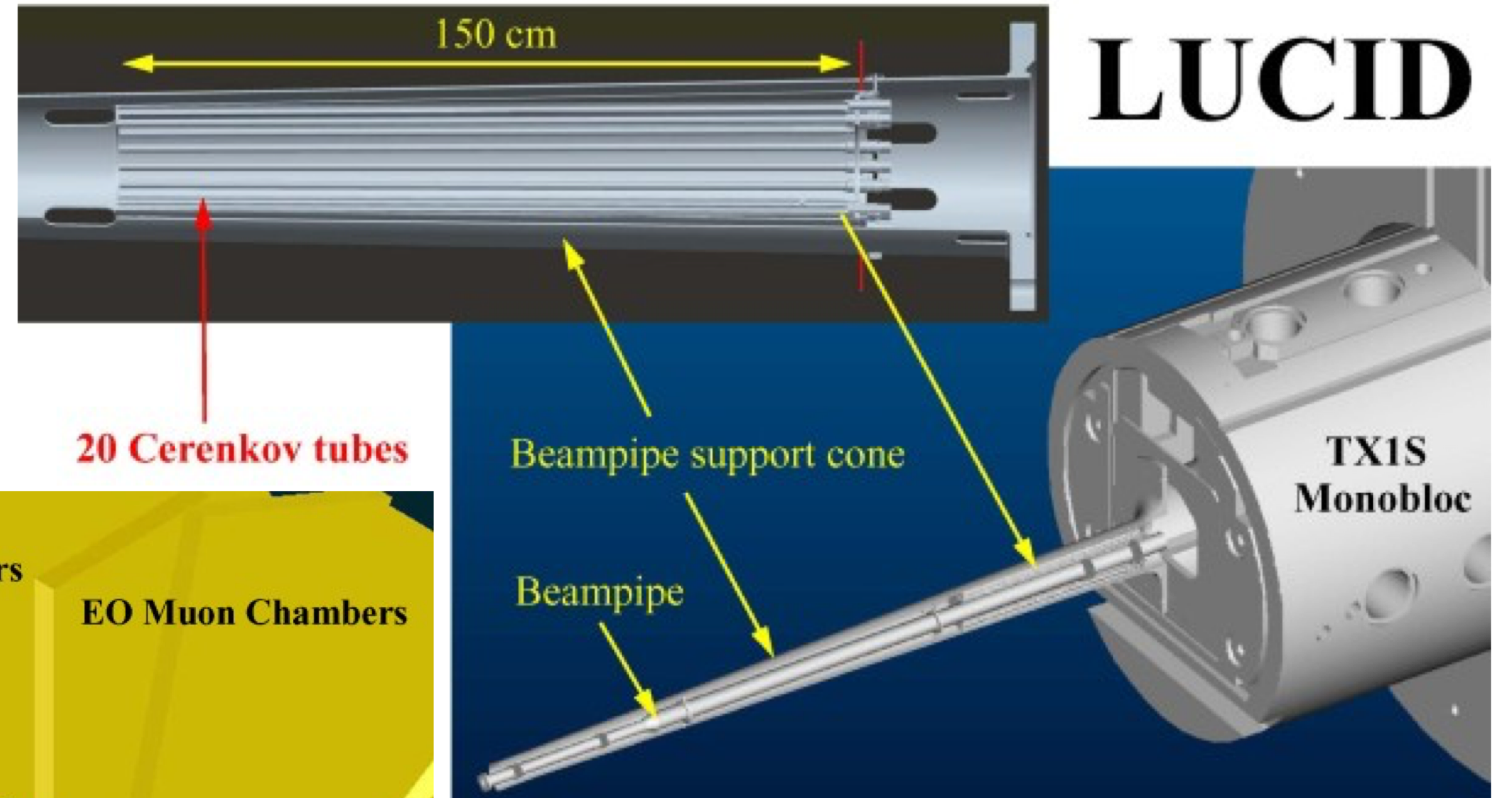
LAr End-cap

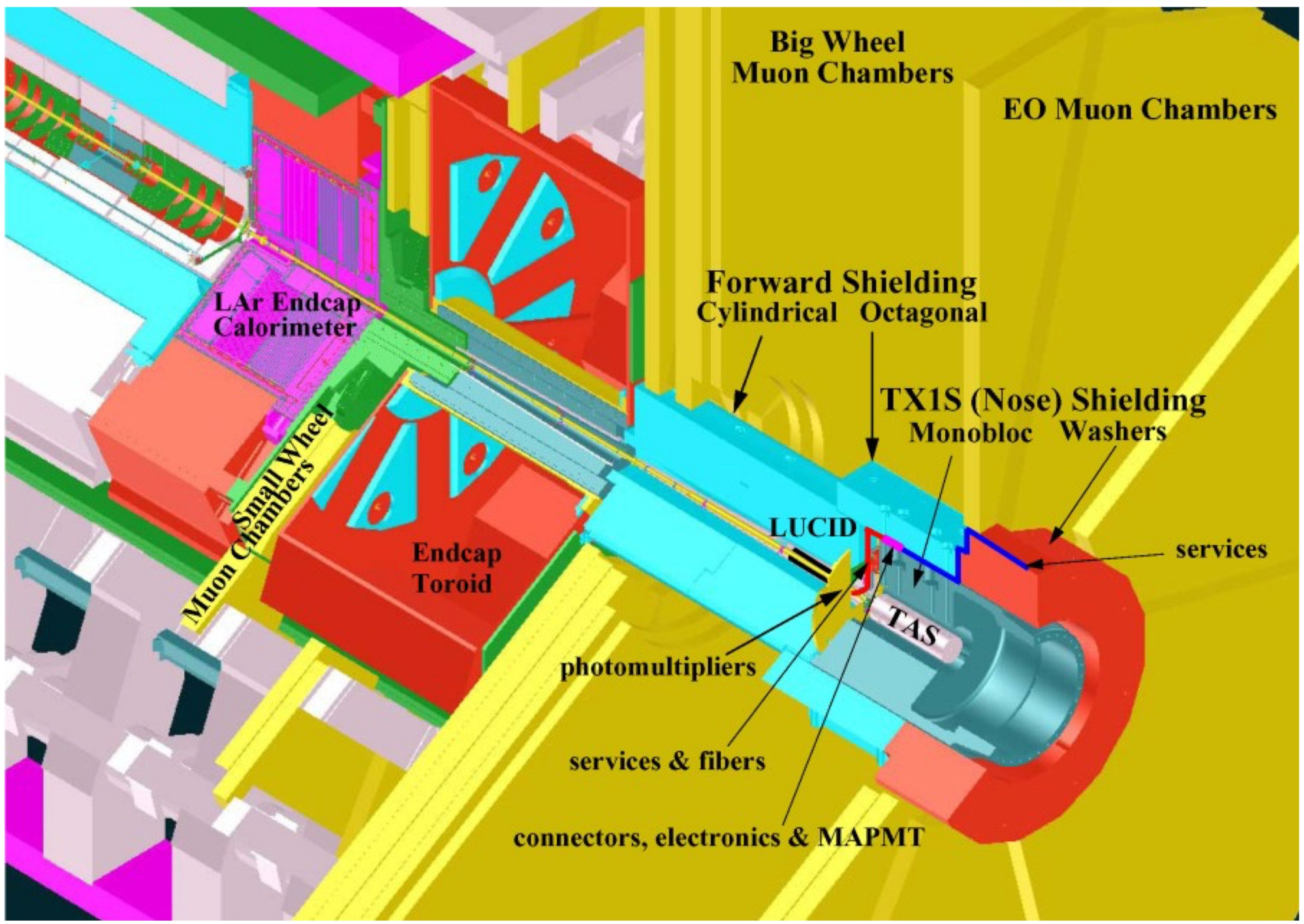
courtesy J.Pinhold

LUCID vessel

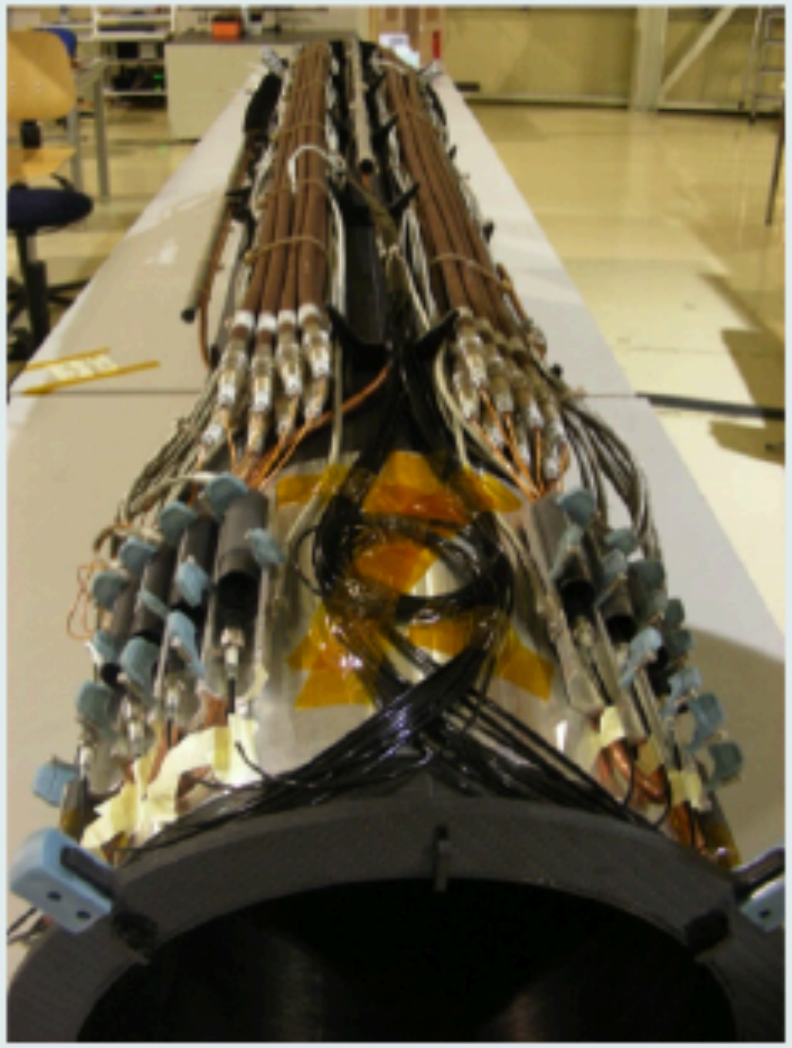


# LUCID


150 cm
LUCID
20 Cerenkov tubes
Beampipe support cone
Beampipe
TX1S
Monobloc

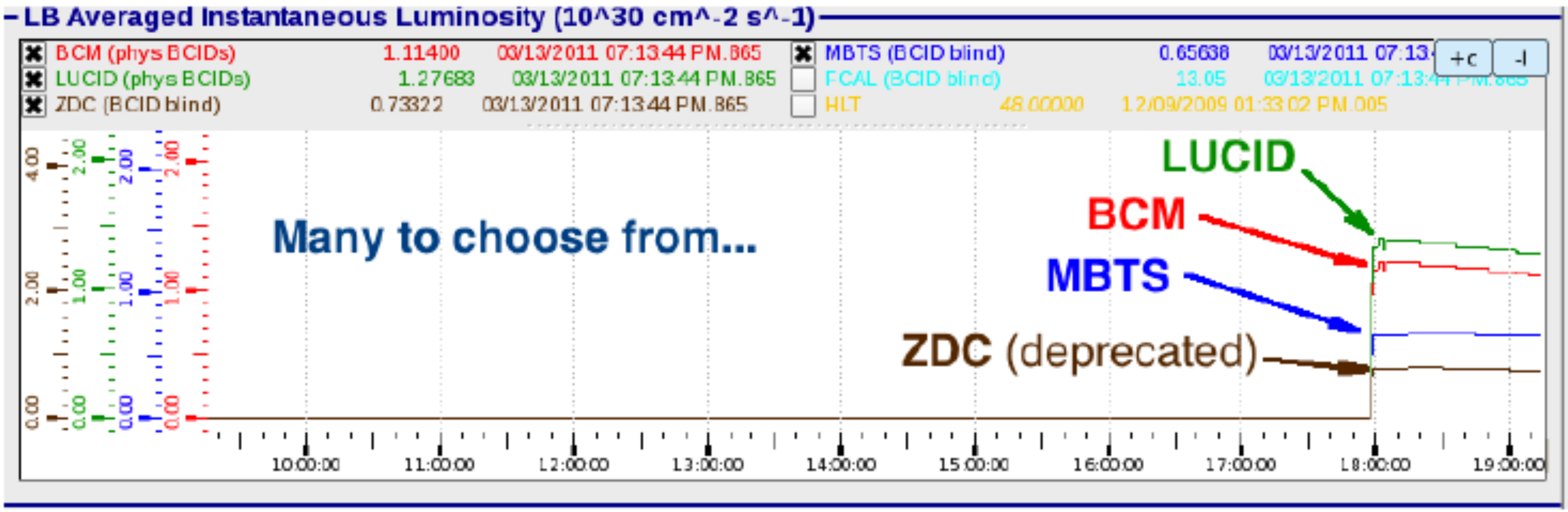

Big Wheel
Muon Chambers
EO Muon Chambers
LAr Endcap
Calorimeter
Small Wheel
Muon Chambers
Forward Shielding
Cylindrical Octagonal
TX1S (Nose) Shielding
Monobloc Washers
LUCID
services
Endcap
Toroid
TAS
photomultipliers
services & fibers
connectors, electronics & MAPMT

# 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.

# Comparison among different monitors



# Backup slides

# Methods for Luminosity Measurement - 1

The luminosity L of a pp collider can be expressed as

$$\mathcal{L} = \frac{R_{\mathrm{inel}}}{\sigma_{\mathrm{inel}}}$$

$\mathcal{L}$ instantaneous luminosity
$\mathcal{L}_{int}$ integrated luminosity

where $R_{inel}$ is the rate of inelastic collisions and $\boldsymbol{\sigma}_{inel}$ is the pp inelastic cross-section. For a storage ring, operating at a revolution frequency $f_r$ and with $n_b$ bunch pairs colliding per revolution, this expression can be rewritten as

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

where $\boldsymbol{\mu}$ is the average number of inelastic interactions per bunch crossing.

ATLAS monitors the delivered luminosity by measuring the observed interaction rate per crossing, $\boldsymbol{\mu}_{vis}$, independently with a variety of detectors and using several different algorithms. The luminosity can then be written as

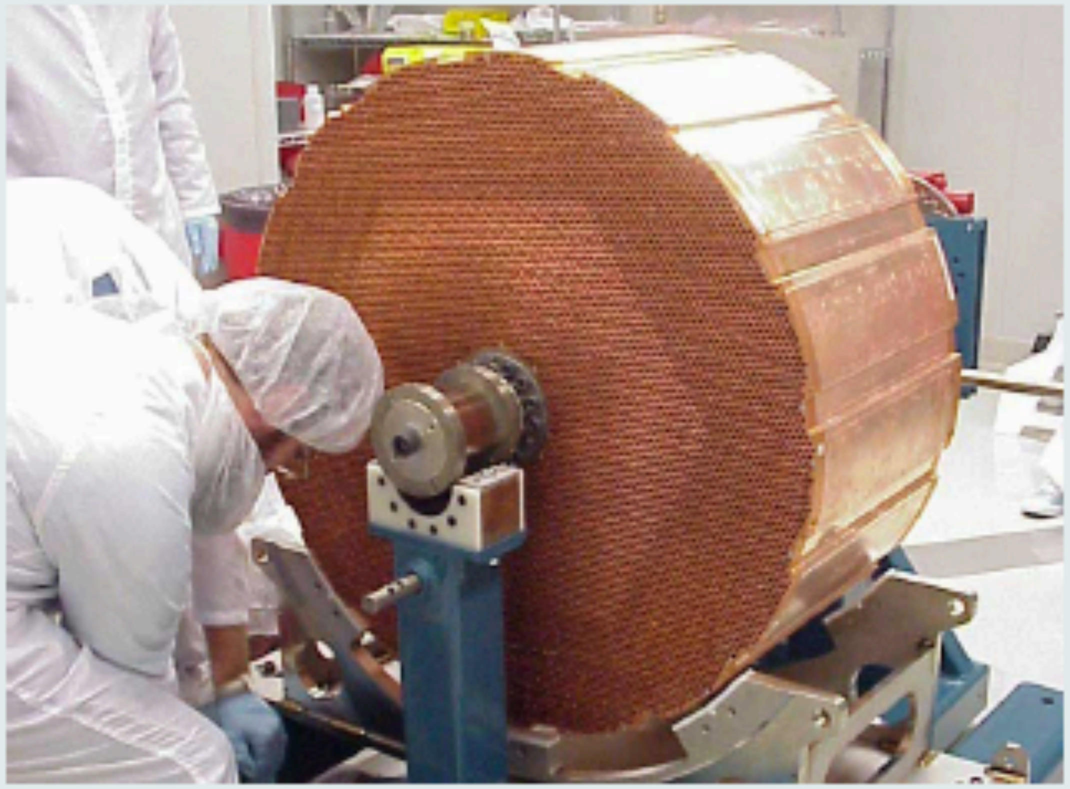
$$\mathcal{L} = \frac{\mu_{\mathrm{vis}} n_{\mathrm{b}} f_{\mathrm{r}}}{\sigma_{\mathrm{vis}}}$$

# 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.

# Methods for Luminosity Measurement - 2



Where $\sigma_{vis} = \varepsilon\sigma_{inel}$ is the total inelastic cross-section multiplied by the efficiency $\varepsilon$ of the detector and efficiency and similarly $\mu_{vis}$. Since $\mu_{vis}$ is an observable quantity the calibration of the luminosity scale is equivalent to determining the visible cross-section.

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

Methods:

- Event counting algorithms, count events satisfying selection criteria. In the limit $\mu_{vis} << 1$ then $\mu_{vis} \approx N/N_{BC}$ where N selected events, $N_{BC}$ number bunch crossings. In the limit case in which all bunch crossings contain one event passing criteria, then event counting algorithms contain no information about the interaction rate
- Hit counting algorithm, rather than counting events count hits above some threshold. This approach is much more robust and saturates much more slowly wrt previous method

# Methods for Luminosity Measurement - 3



The calibration of $\sigma_{vis}$ is performed using a dedicated method based on beam-separation sca ns, called  van der Meer (vdM) method. The dilivered luminosity can be written in terms of acc elerator parameters as

$$\mathcal{L} = \frac{n_{\mathrm{b}} f_{\mathrm{r}} n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

Where $n_1$ and $n_2$ are the bunch populations (protons per bunch) and $\Sigma_x$ $\Sigma_y$ are the beam width s in the x,y direction. More in the following.

# Van der Meer scan basics

- The key idea of the VdM scan is to relate the overlap integral to the rate integral [12]:

$$\Omega_x = \frac{R_x(0)}{\int R_x(\delta)\, d\delta}$$

Rate measured by detector

Beam separation

- Defining the convolved beam size $\Sigma_x$ as

$$\Sigma_x = \frac{1}{\sqrt{2\pi}}\frac{1}{\Omega_x}$$

the luminosity becomes

$$\mathcal{L} = \frac{n_b\, f_r\, n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

Convolved beam sizes

Measured in vdM scan

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

Detector independent

Detector dependent

Measured by beam instrumentation