The LUCID-2 luminometer

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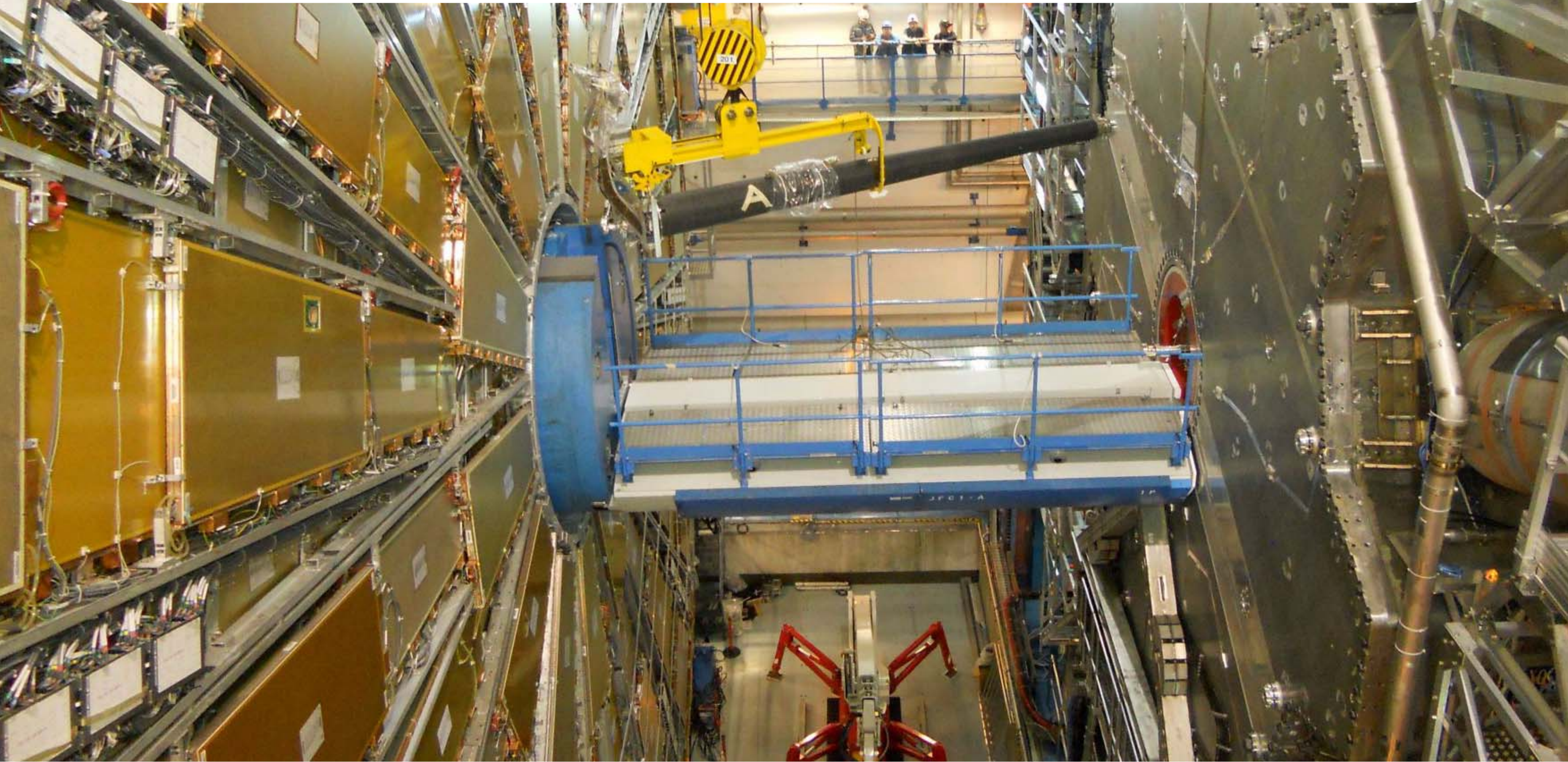
for the ATLAS-LUCID group



Introduction

Challenges in measuring luminosity at the LHC:

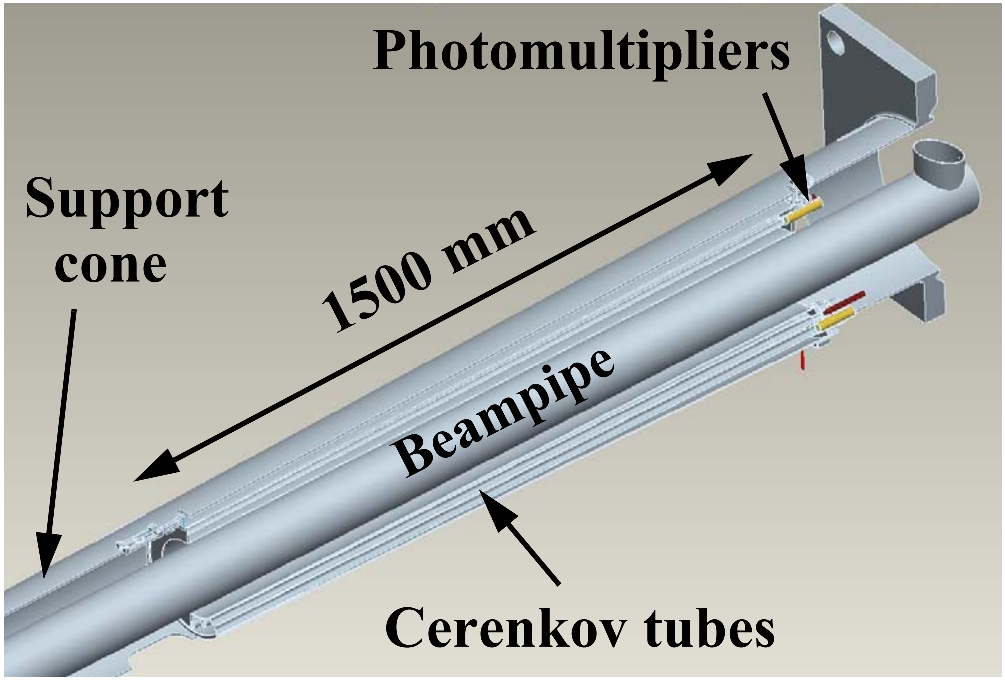
- The number of pp-interactions (μ) can exceed 70 while a μ as low as 10^{-3} has to be accurately measured in calibration fills.
- The time between the 2544 colliding bunch pairs is only 25 ns.
- Only one calibration fill per year requires a stable detector and a system to monitor the detector response.
- Pile-up of particles from different pp-interactions can affect luminosity calculations.
- The measurement has to be reliable and able to operate also with unstable LHC beams and produce both online and offline luminosity.
- High levels of radiation requires radiation-hard detectors.

LUCID History

The LUCID-1 detector (2009-2013)

Gas Cherenkov detector

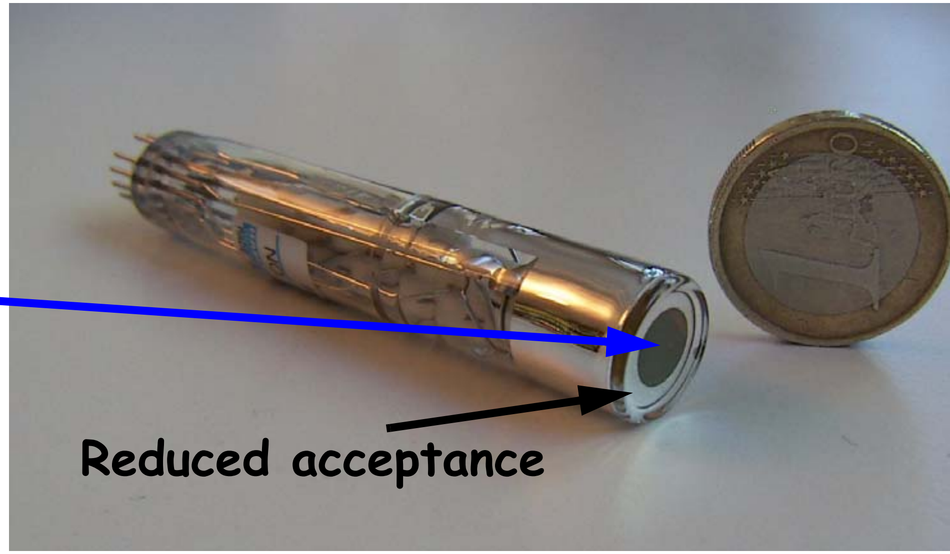
Medium: C_4F_{10} in 1.5m long aluminium tubes
(& quartz window on photomultipliers)



The LUCID-2 detector (2015-2025)

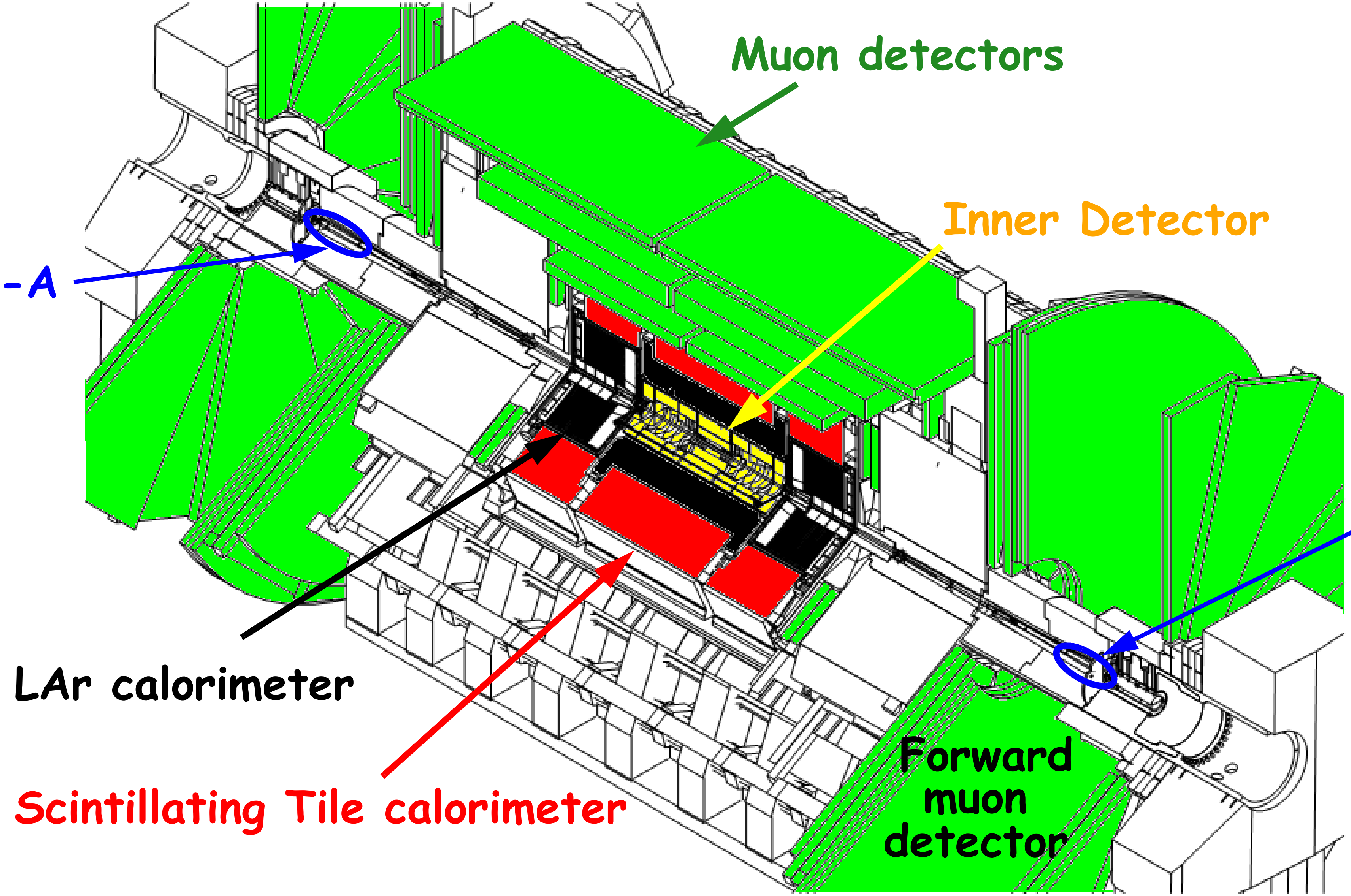
Quartz Cherenkov detector

Medium: Photomultiplier quartz windows
(some with reduced acceptance)
&
Bundles of quartz fibers.

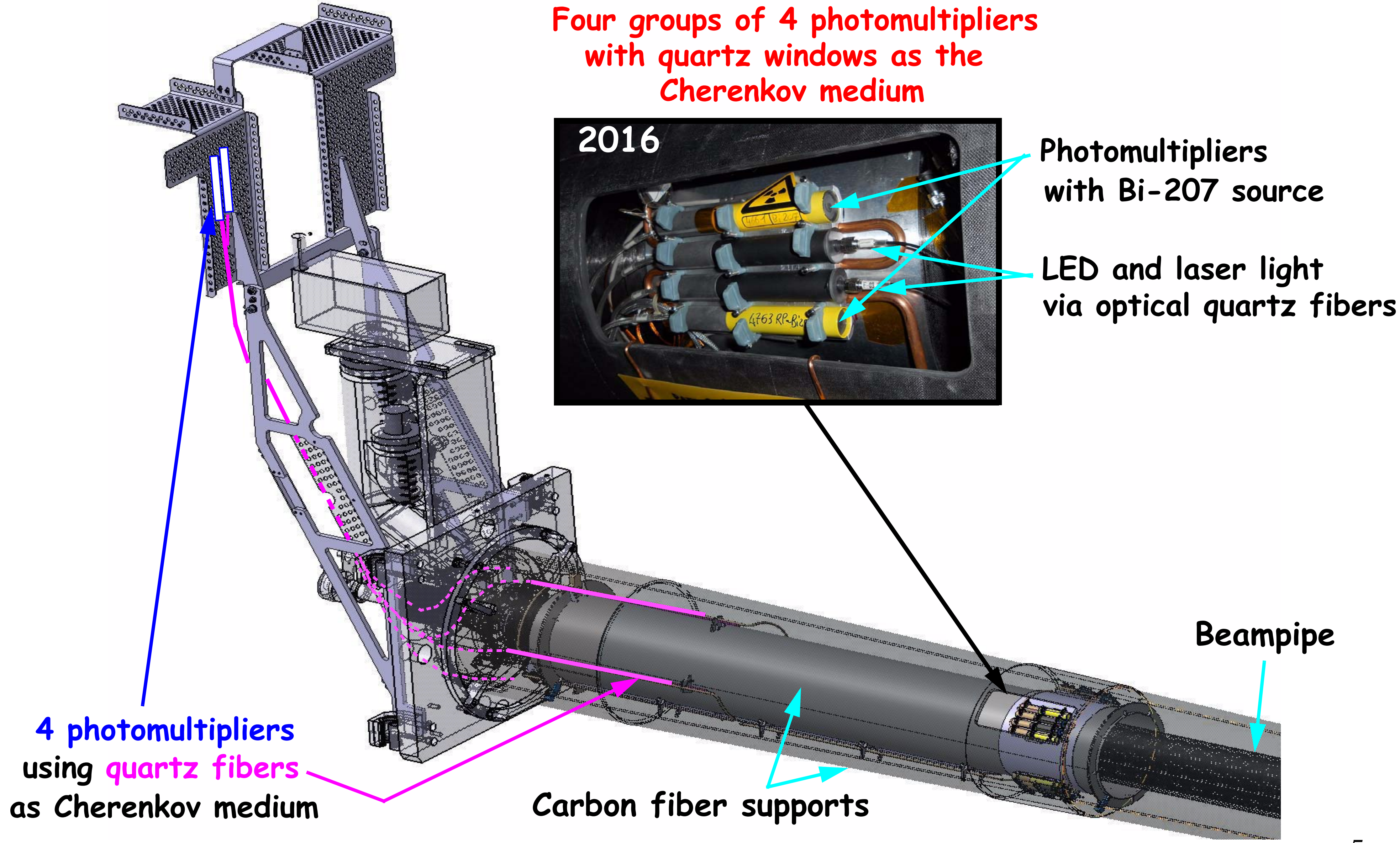


Location in ATLAS

Two detectors 17-18 m from the interaction point and 12-13 cm from the beamline (η = 5.6).



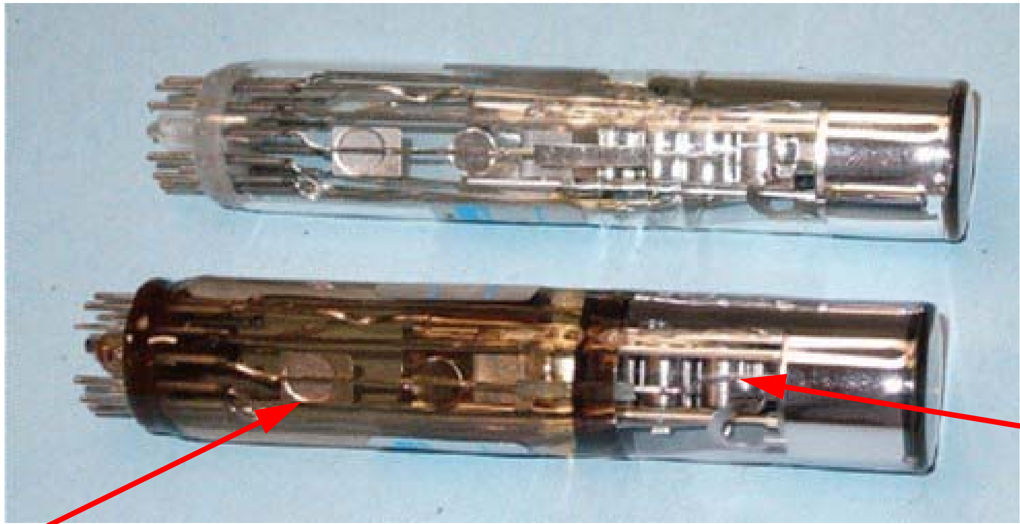
The LUCID-2 detector



Radiation hardness

Before radiation exposure

After exposure to 200 kGray



Fused silica glass ("quartz"): 100% SiO_2

Borosilicate glass: 80% SiO_2 + 4% Na_2O + 13% B_2O_3 + 3% Al_2O_3

Photomultipliers with fused silica (quartz) windows are radiation hard.

The photomultipliers have been exposed to gamma radiation from the CALLIOPE Co-60 source (200 kGray) and neutrons from the TAPIRO facility ($2.6 \times 10^{14} n/cm^2$).

An increase of the dark current was observed but no change of signal size or gain.

The dose to the photomultipliers in 2015 was measured to be 9.4 kGray.

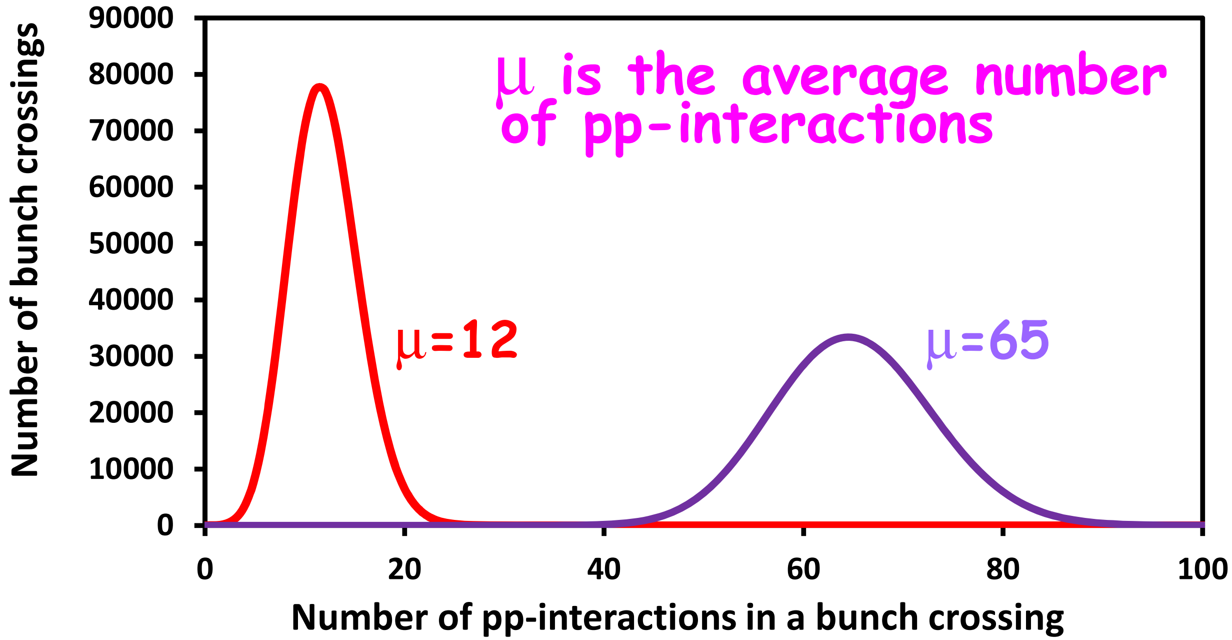
Measuring luminosity with LUCID

LUCID measures the average instantaneous luminosity for each individual pair of colliding LHC bunches during time periods that are about 60s long.

11245.5 Hz (LHC revolution frequency)

$$\mathcal{L}_{Inst} = f_{LHC} \frac{\mu}{\sigma_{inel}} = f_{LHC} \frac{\mu_{vis}}{\sigma_{vis}}$$

Inelastic cross section



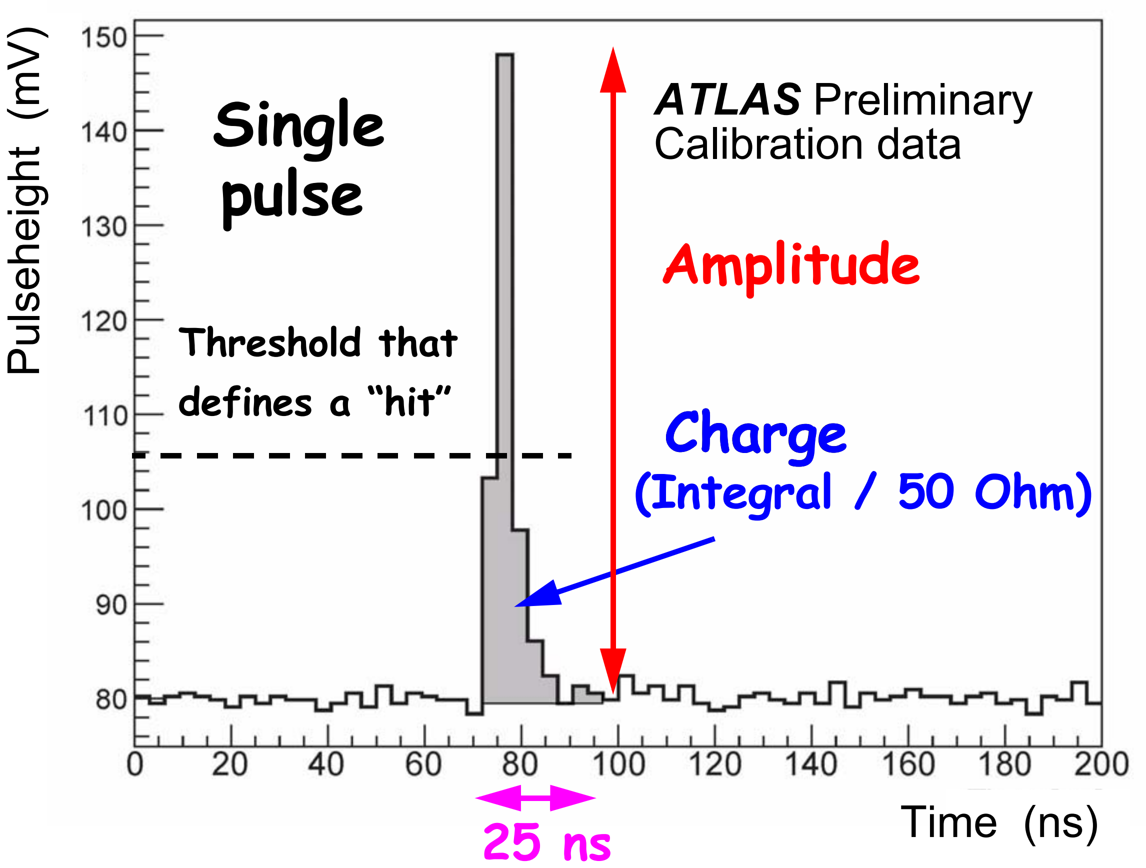
$\mu_{vis} = \varepsilon\mu$ "Visible" μ. Measured from detector rates.

$\sigma_{vis} = \varepsilon\sigma_{inel}$ "Visible" cross section. Measured in beam separation scans.

efficiency & acceptance (ε)

Measuring luminosity with LUCID

Flash ADCs measure the pulseheight from LUCID photomultipliers every 3.125 ns



FPGAs calculate amplitude and charge in every 25 ns bunch crossing period and count hits.

HIT COUNTING:

Count the number of pulses above a threshold (hits) or the fraction (f) of bunch crossings with atleast one hit:

$$\mu_{vis} = \varepsilon\mu = -\ln(1 - f)$$

CHARGE COUNTING:

Integrate the pulses and measure the charge (C) of all pulses in a time period:

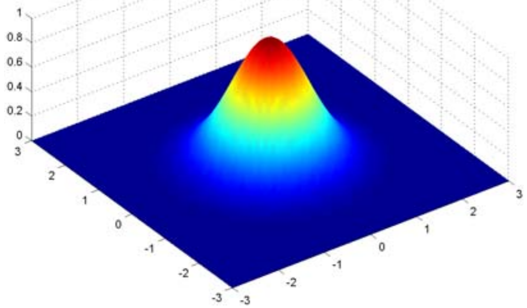
$$\mu_{vis} = C / C_n$$

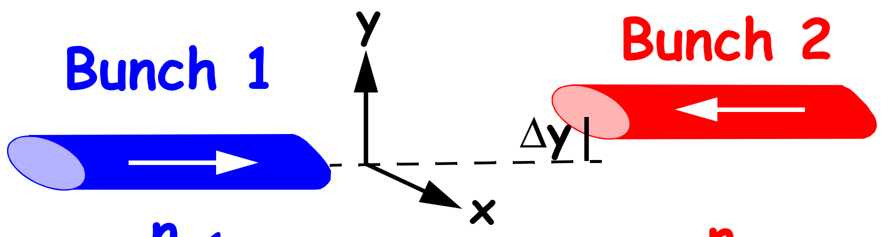
where C_n is a normalization constant.

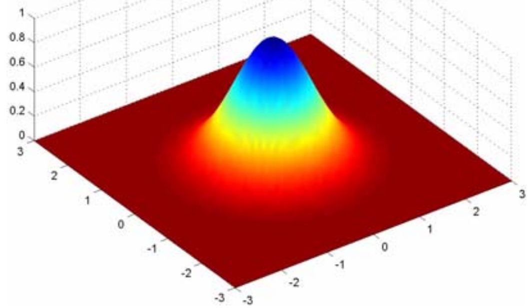
Every photomultiplier can be used as an independent luminosity detector

Absolute calibration of LUCID

$\rho_1(x,y)$ ← Transverse proton density functions → $\rho_2(x,y)$







n_{p1} Number of protons

n_{p2} Number of protons

$$\mathcal{L}^{peak}_{Inst} = f_{LHC}\, n_{p1} n_{p2} \int \rho_1(x,y)\rho_2(x,y)\,dx\,dy$$

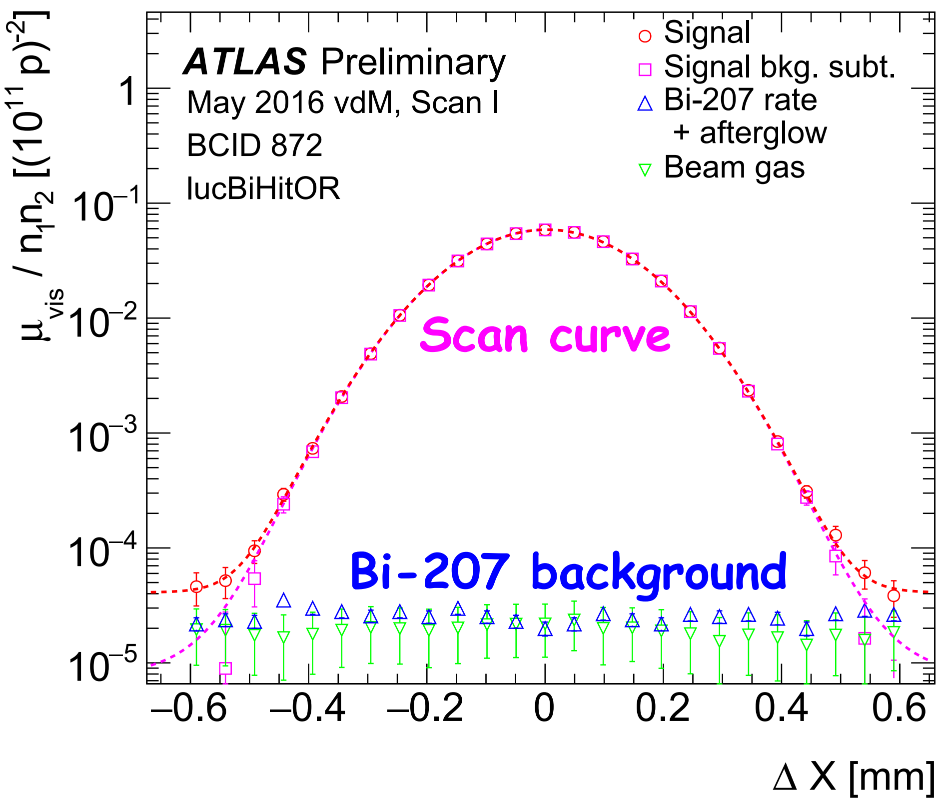
One can show that $\sigma_{vis} = 2\pi \dfrac{\mu^{peak}_{vis} \Sigma_x \Sigma_y}{n_{p1} n_{p2}}$

where

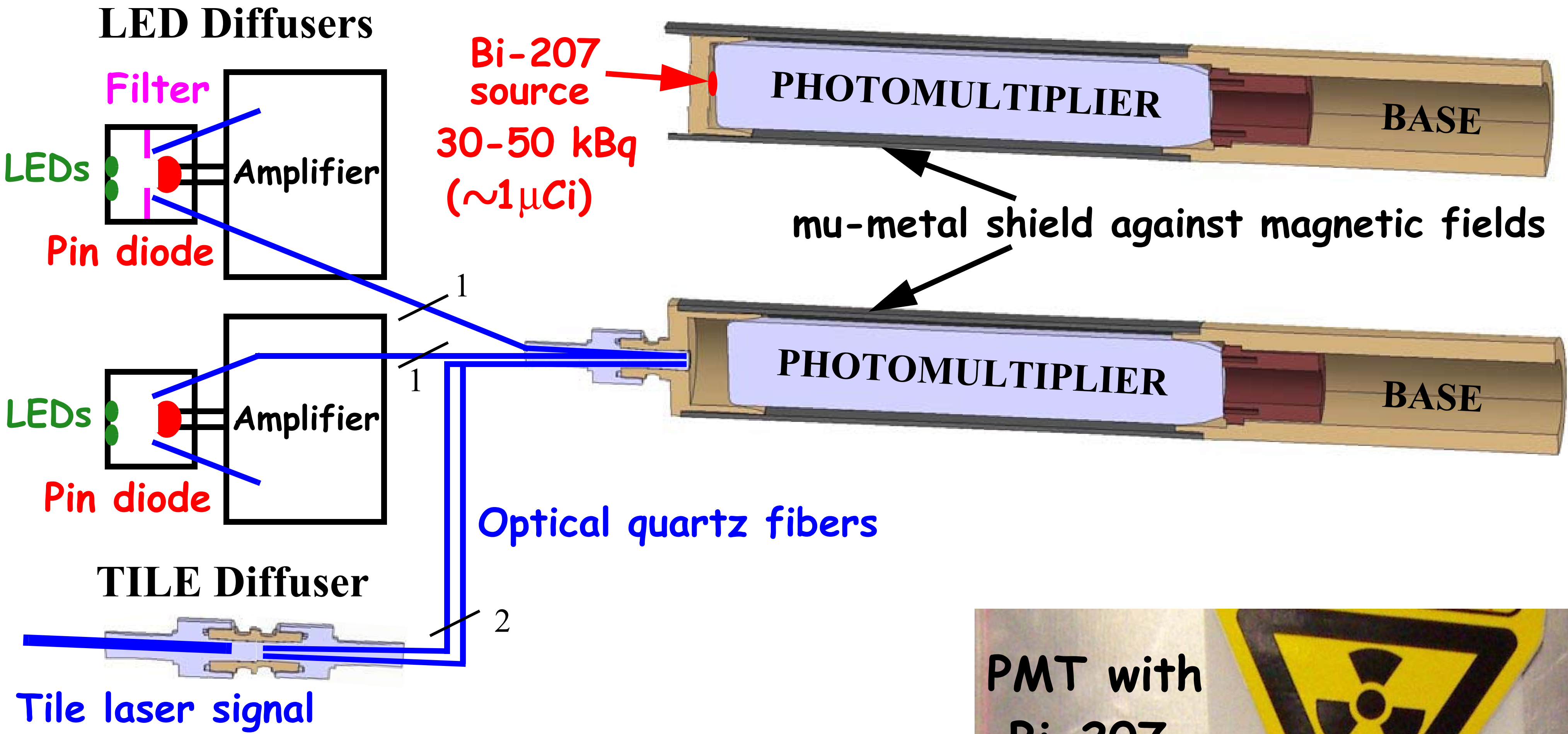
μ^{peak}_{vis} peak value of the scan curves

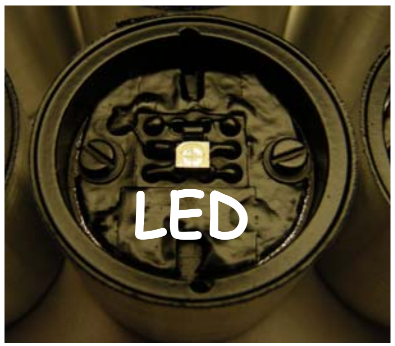
$\Sigma_x \Sigma_y$ widths of the scan curves

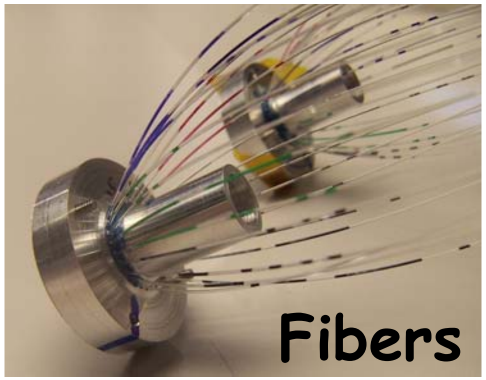
$n_{p1} n_{p2}$ number of protons per bunch



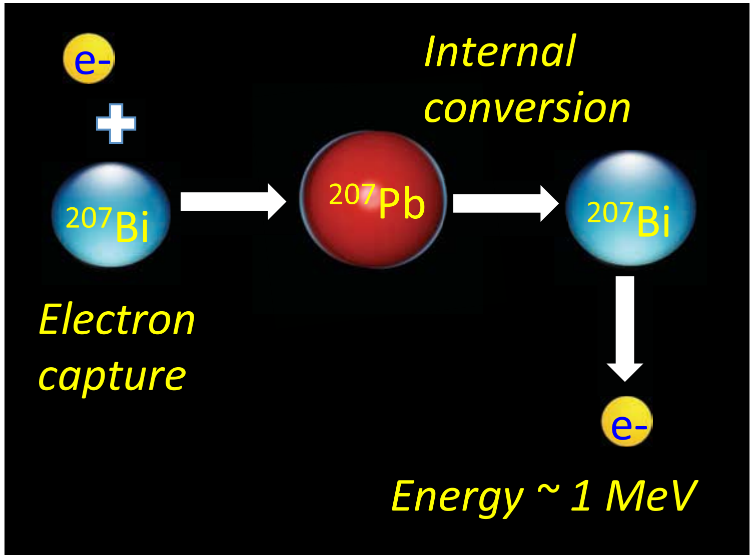
Three different monitoring systems







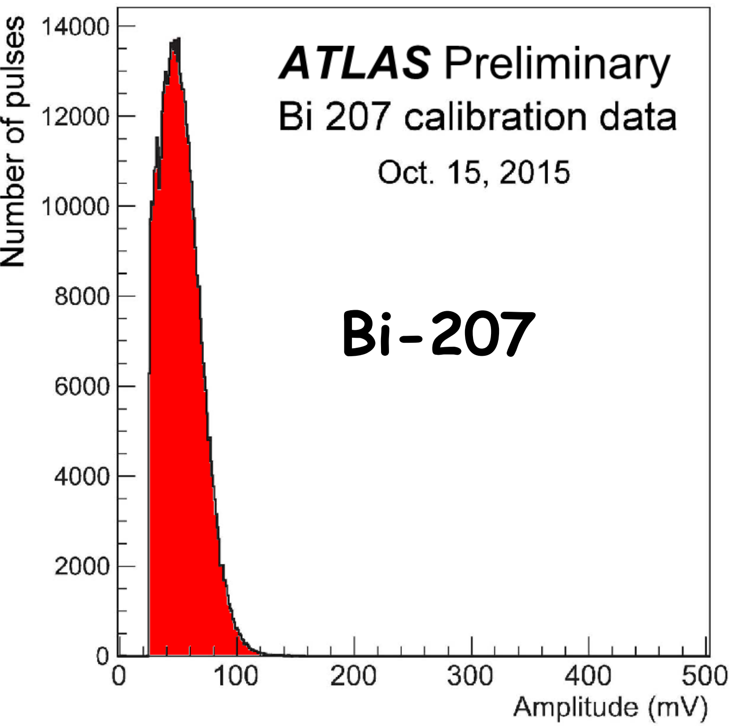
The Bi-207 monitoring system

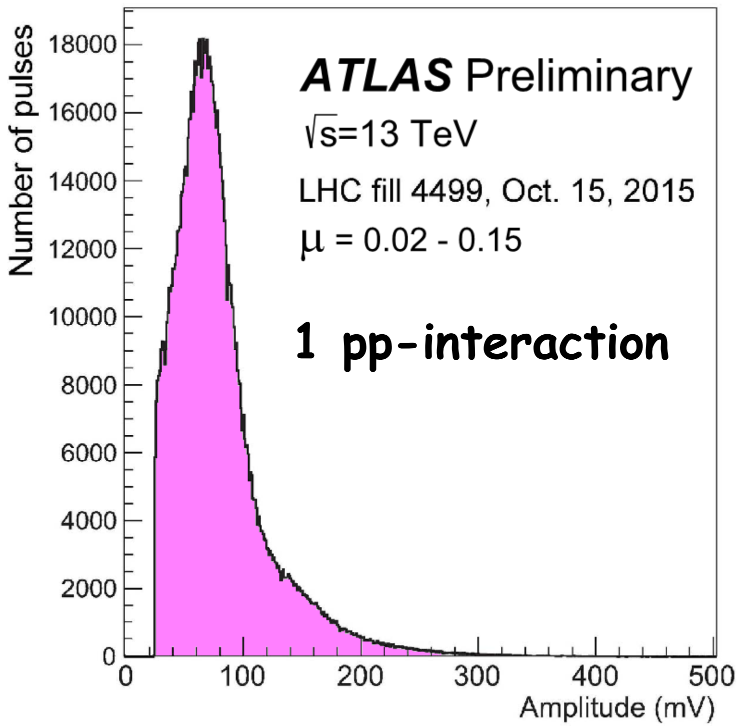


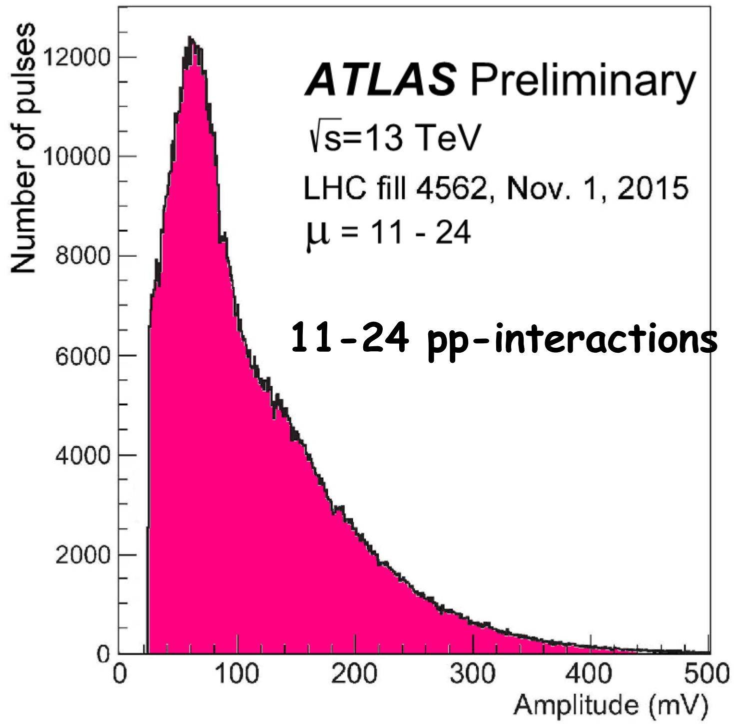
The gain monitoring system that uses radioactive Bi-207 has performed better than the system based on LED light.

Bi-207 produces electrons with energies above the Cherenkov threshold in quartz.

The amplitude distributions for Bi-207 electrons and particles from LHC interactions are similar.



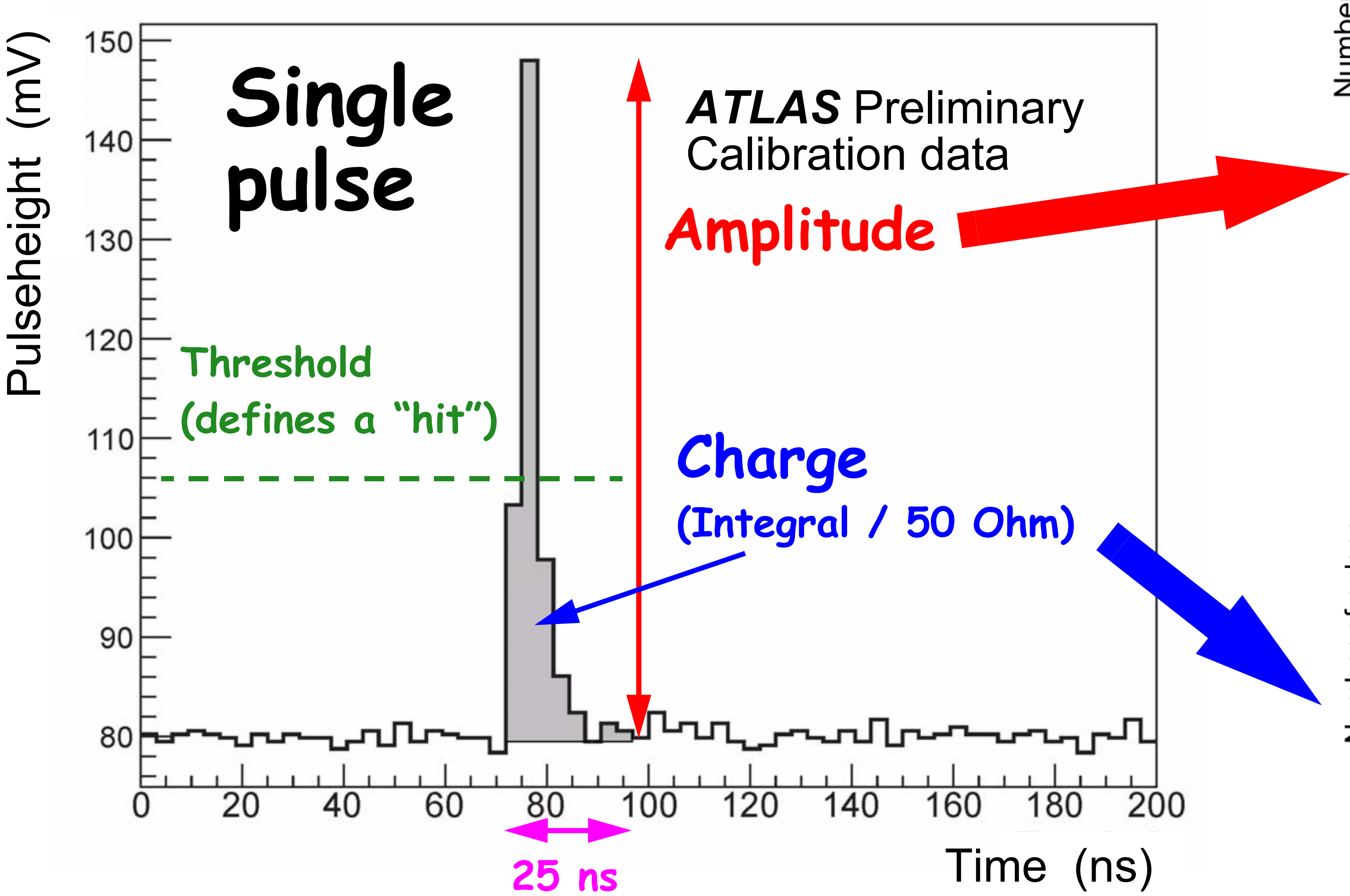


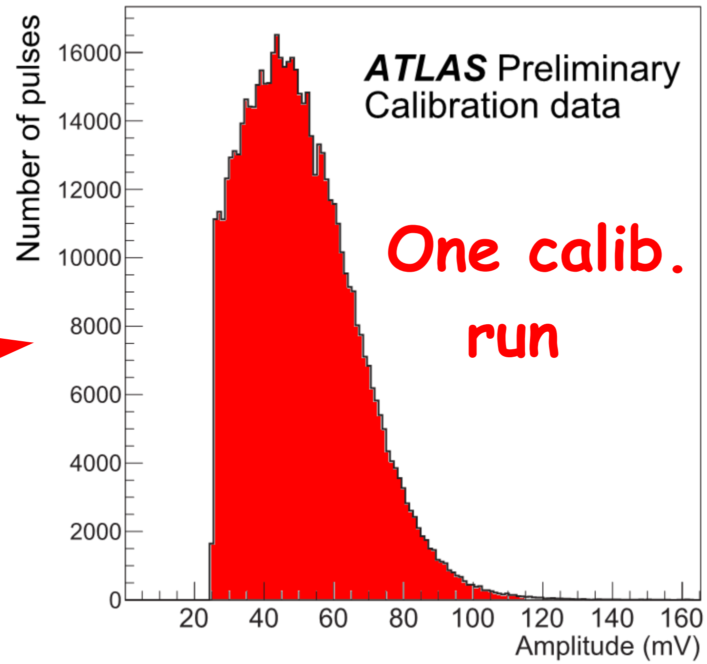


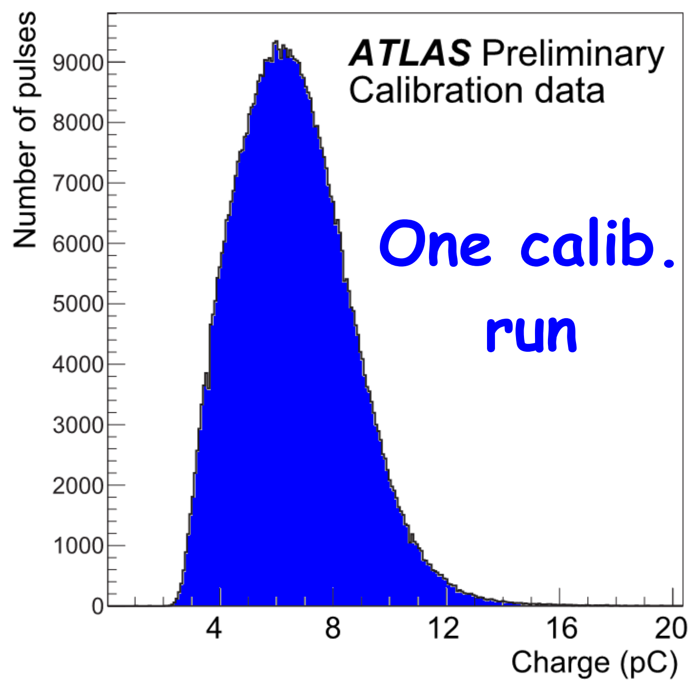
The Bi-207 monitoring system

ATLAS LUCID

Monitoring runs are made between almost all LHC fills.



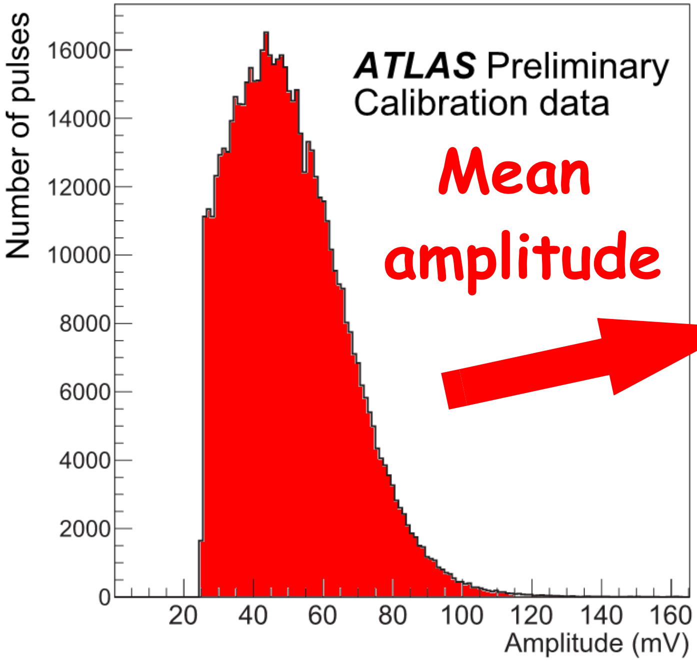


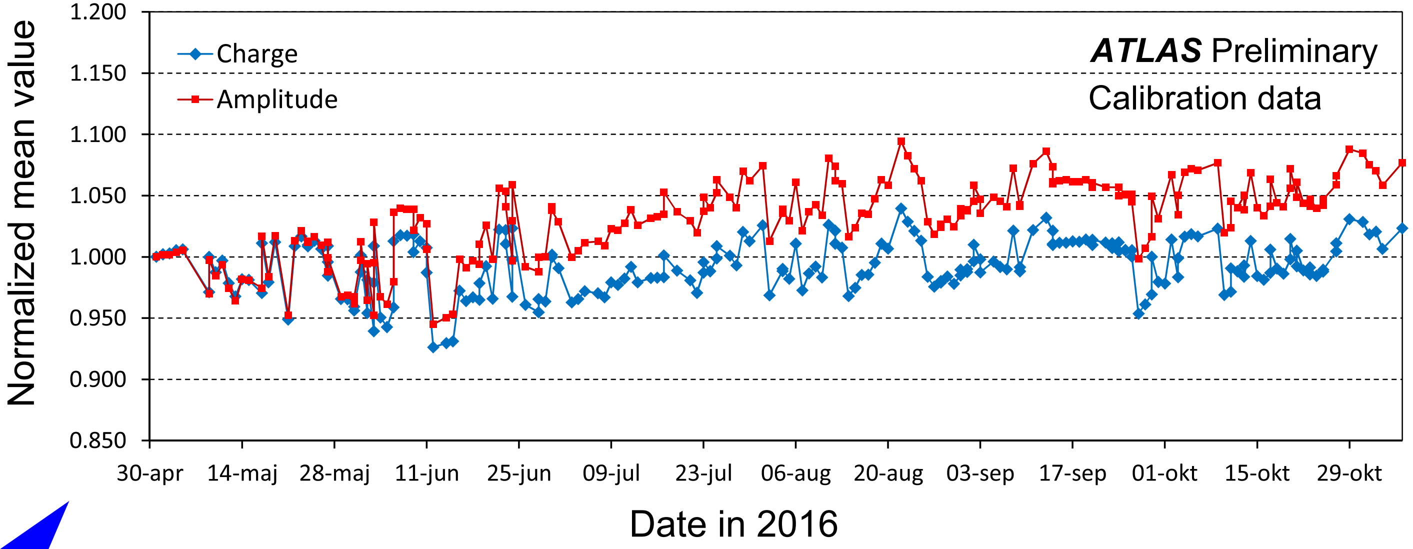


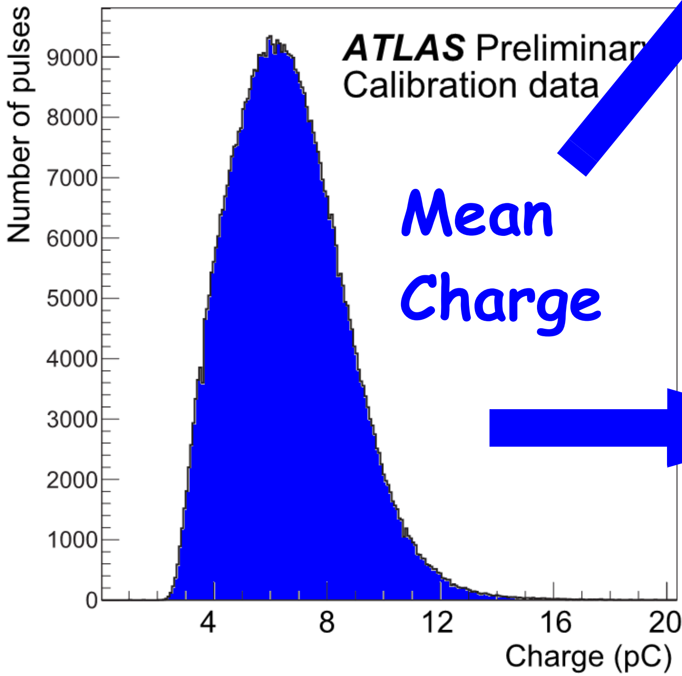
The mean values of amplitude and charge in the monitoring runs are used to correct the LUCID measurements (online & offline).

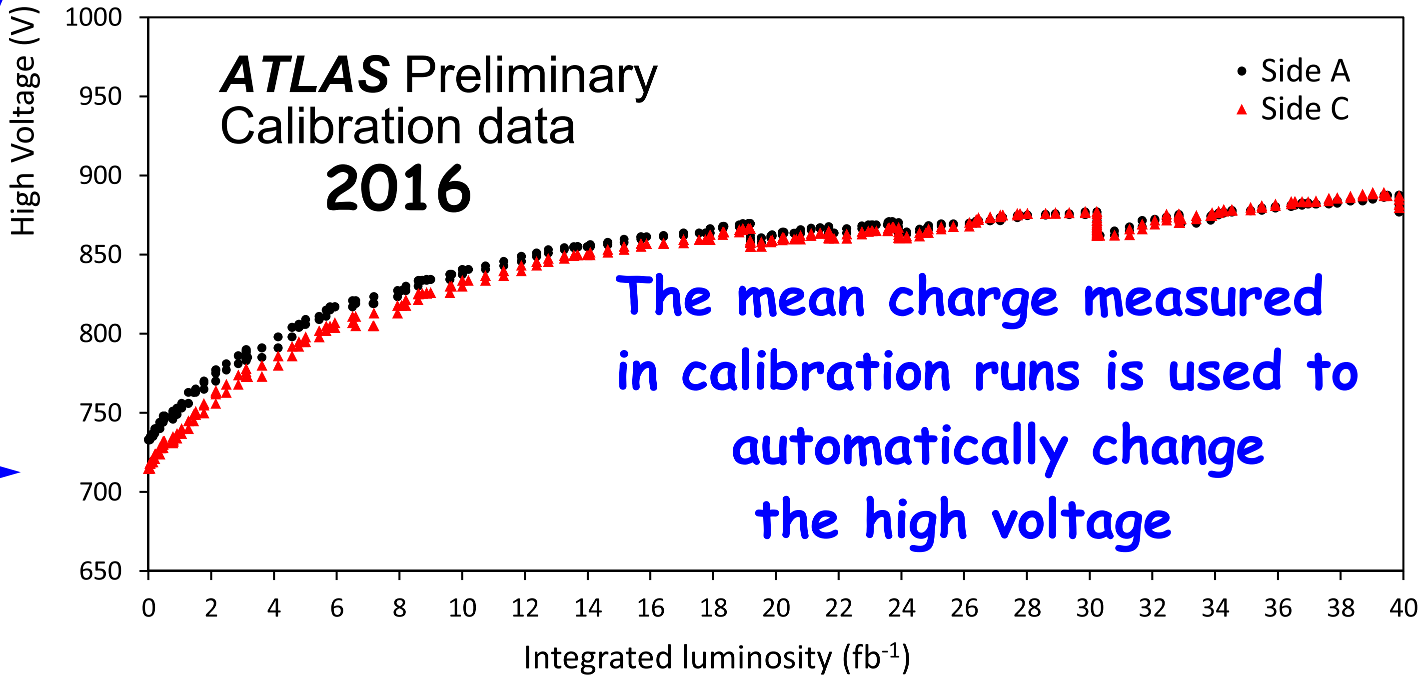
ATLAS LUCID

The Bi-207 monitoring system







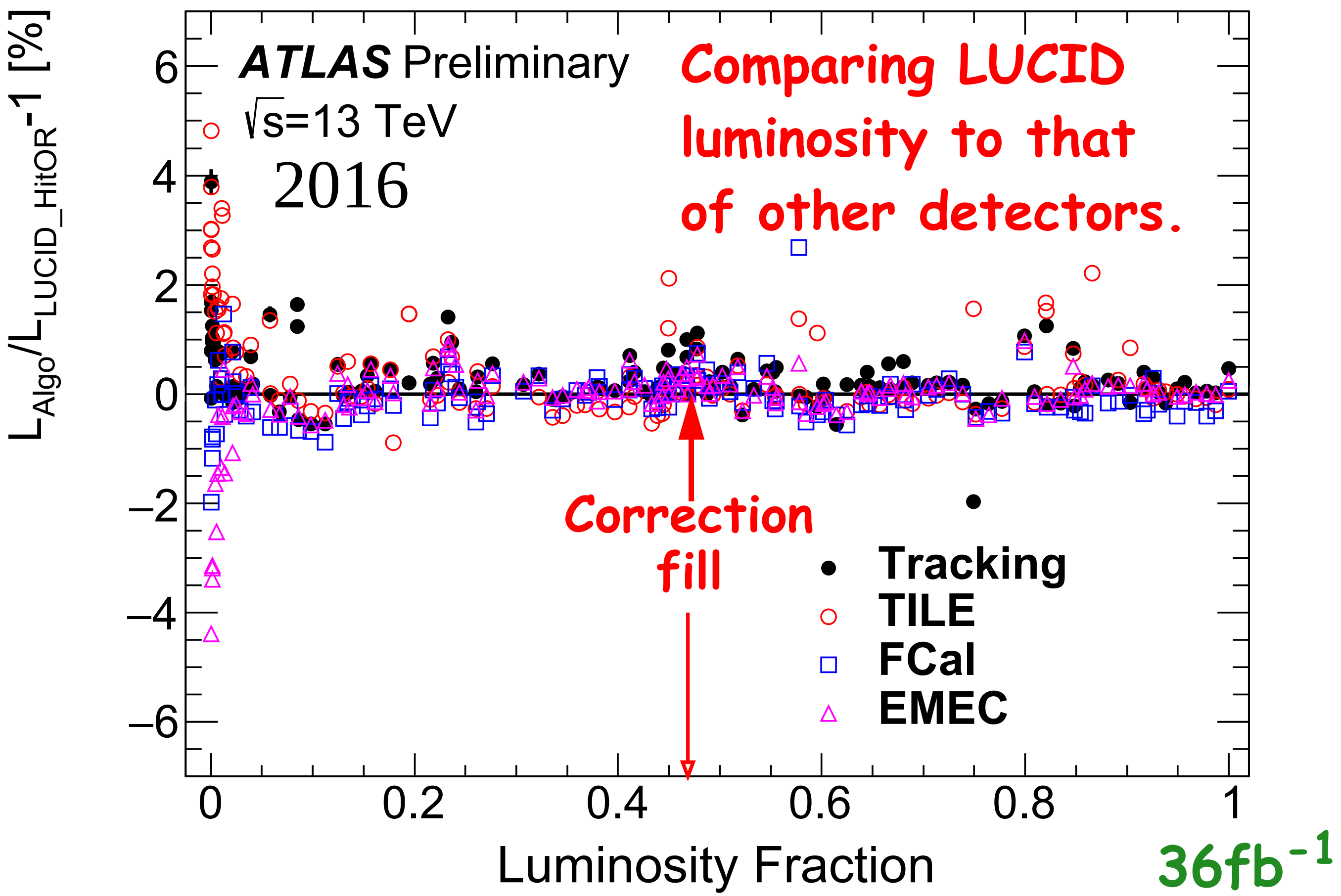


The mean charge measured in calibration runs is used to automatically change the high voltage

Accuracy of the luminosity measurement

Corrections are made in order to improve the accuracy of the luminosity measurement:

1. The LUCID luminosity is corrected for gain changes using the Bi-207 system.
2. A μ-dependent correction from track counting in one fill is applied to all data.
3. A 0.7% correction for LUCID gain drift observed by other detectors is made.



The statistical error on the luminosity measurement is insignificant.

The total systematic errors in the luminosity analysis is estimated to be:

2015: 2.1%

2016: 2.2%

Summary

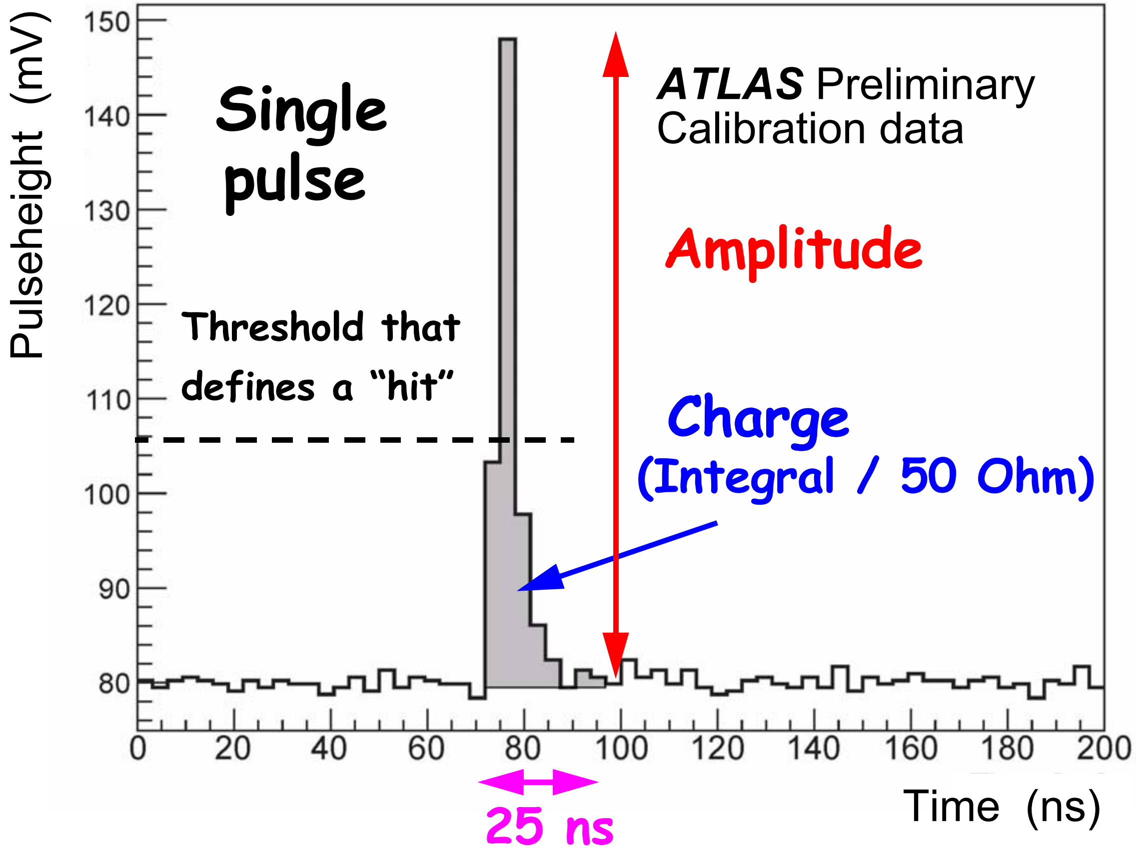
- The LUCID-2 detector is the main luminometer of the ATLAS experiment.
- It is a Cherenkov detector that uses radiation-hard quartz as a Cherenkov medium.
- The success of the detector is due to a novel system of monitoring the photomultiplier gain with small amounts of radioactive Bi-207.
- The detector is fast and can measure the luminosity for 2544 individual colliding bunch pairs that are only 25 ns apart.
- The systematic error in the ATLAS luminosity measurement, where LUCID-2 is the main detector, is only slightly above 2%.

BACK-UP

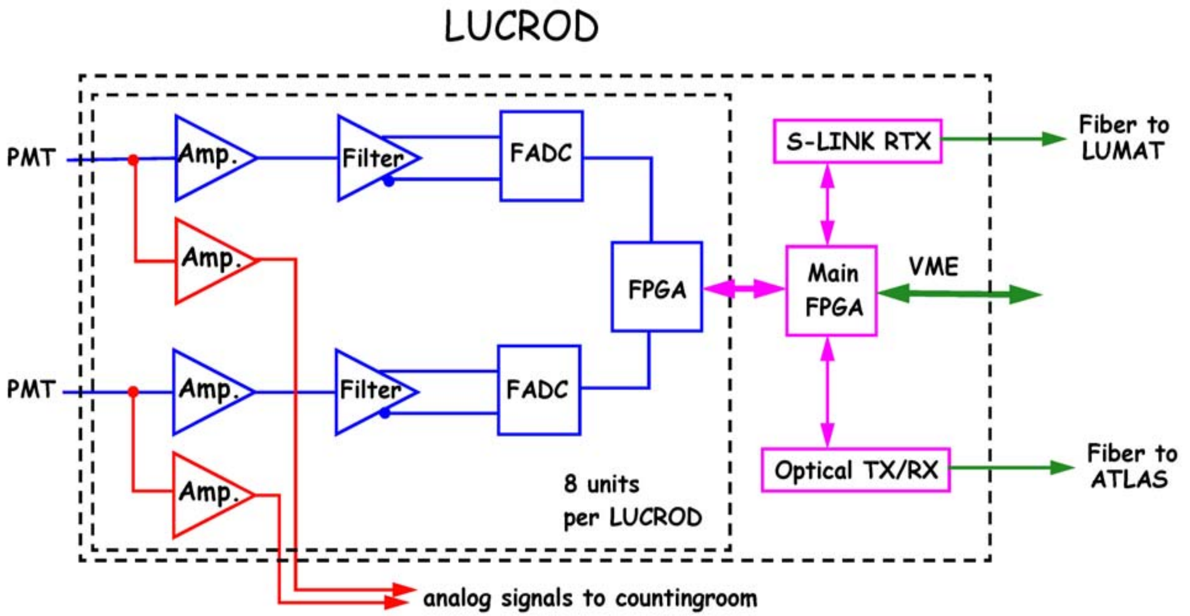
LUCID-2 electronics

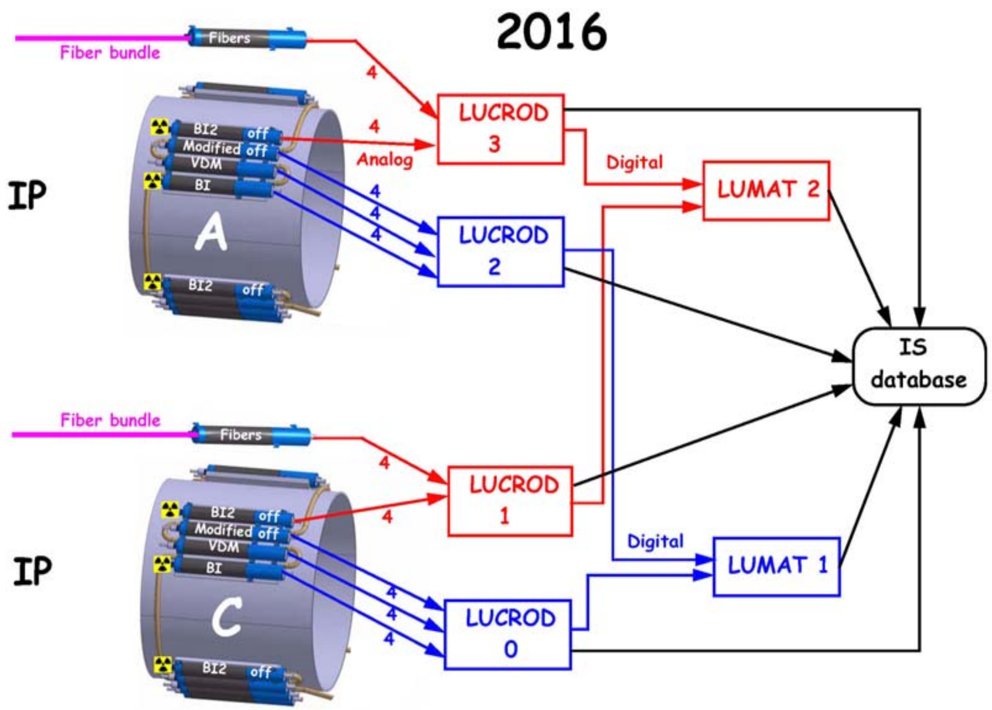
Four custom VME boards ("LUCROD") with FADCs perform 12 bit digital sampling of the photomultiplier signals and store them in FIFOs.

- FADC sampling rate: 320 MS/s (one every 3.125 ns)
- Number of samplings: 64
- Range of input signals: 1.5 V
- Optical data transfer: 1.3 Gb/s
- Max transfer rate: 100 k events/s



LUCID-2 electronics

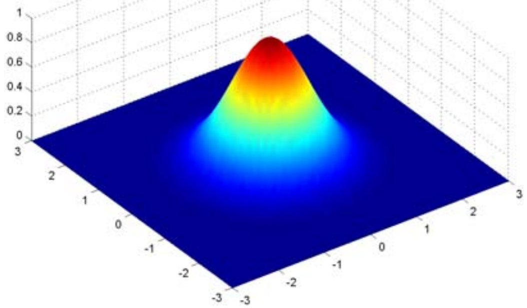


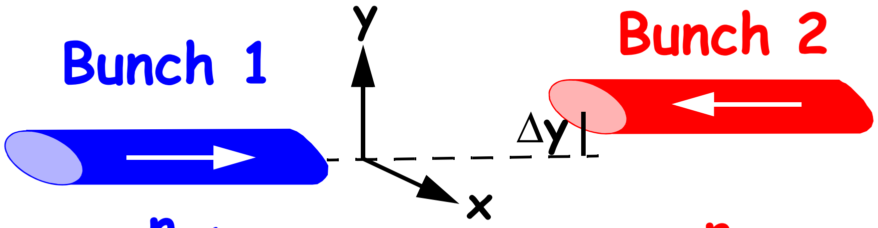


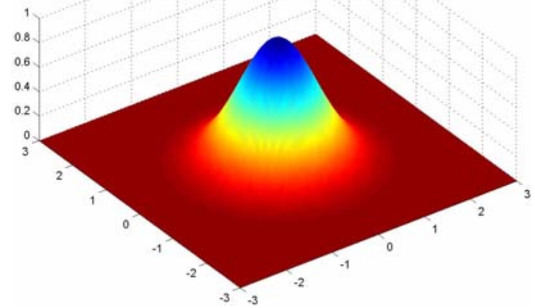
- FPGAs on the LUCRODs calculate signal amplitudes, integrate the signals to measure the charge in every 25 ns bunch crossing period and count hits.
- Two custom VME boards called "LUMAT" recieve hit patterns from the LUCRODs via optical transmission.
- The LUMATs correlate hits from the LUCRODs of the two detectors and produce online and offline luminosity measurements using different algorithms.

Van der Meer calibration: Principle

$\rho_1(x,y)$ ← Transverse proton density functions → $\rho_2(x,y)$







n_{p1} Number of protons

n_{p2} Number of protons

$$\mathcal{L}_{BC}^{peak} = f_{LHC}\, n_{p1} n_{p2} \int \rho_1(x,y)\rho_2(x,y)\,dxdy = f_{LHC} n_{p1} n_{p2} \frac{1}{2\pi\Sigma_x\Sigma_y}$$

Assumption of factorization: $\rho(x,y) = \rho(x)\rho(y)$

The width of scan curves

Lumi. from scan:

$$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{n_{p1} n_{p2}}{2\pi\Sigma_x\Sigma_y}$$

\+

Lumi. from counting events:

$$\mathcal{L}_{BC}^{peak} = f_{LHC} \frac{\mu_{vis}^{peak}}{\sigma_{vis}}$$

→

Calibration constant:

$$\sigma_{vis} = 2\pi \frac{\mu_{vis}^{peak}\Sigma_x\Sigma_y}{n_{p1} n_{p2}}$$

Scan curves

Current measurements