Luminosity Measurement and Monitoring in ATLAS

LHC Machine-Experiments Workshop

On behalf of ATLAS Collaboration

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OUTLINE

- Motivations for Luminosity measurements
- ATLAS' forward detectors
- Techniques for Luminosity measurements
- Open Problems/ Conclusion

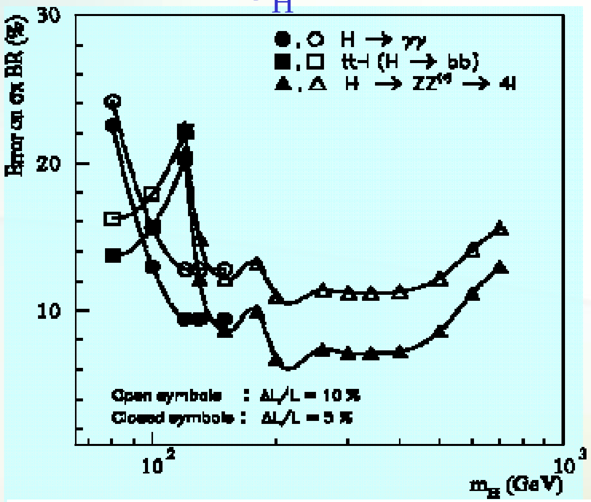
Motivation I

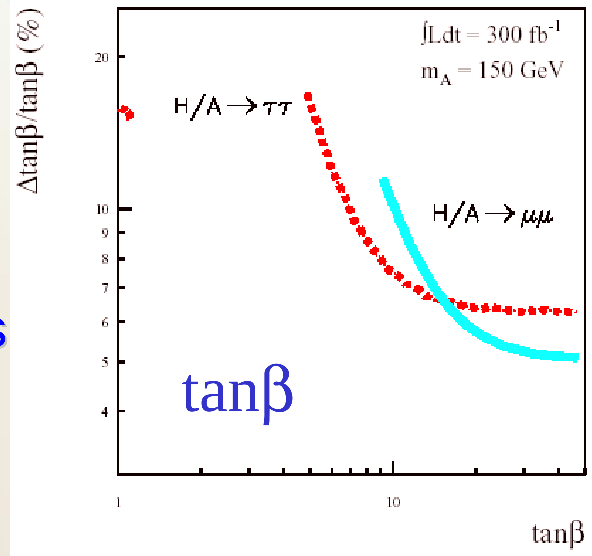
- **Analysis of all the data samples and acquisition time frame**
  - **Cross section measure of "well known" processes**
    - **ttbar**
    - **W/Z**
    - **…**
  - **New Physic evidence**
    - **Deviation from SM prediction**
  - **Higgs production study**
    - **Cross section**
    - **tanβ in MSSM Higgs, …**

Luminosity dominating errors for many studies

Goal ~ 2-3% accuracy

$\sigma_H \times BR$





tanβ

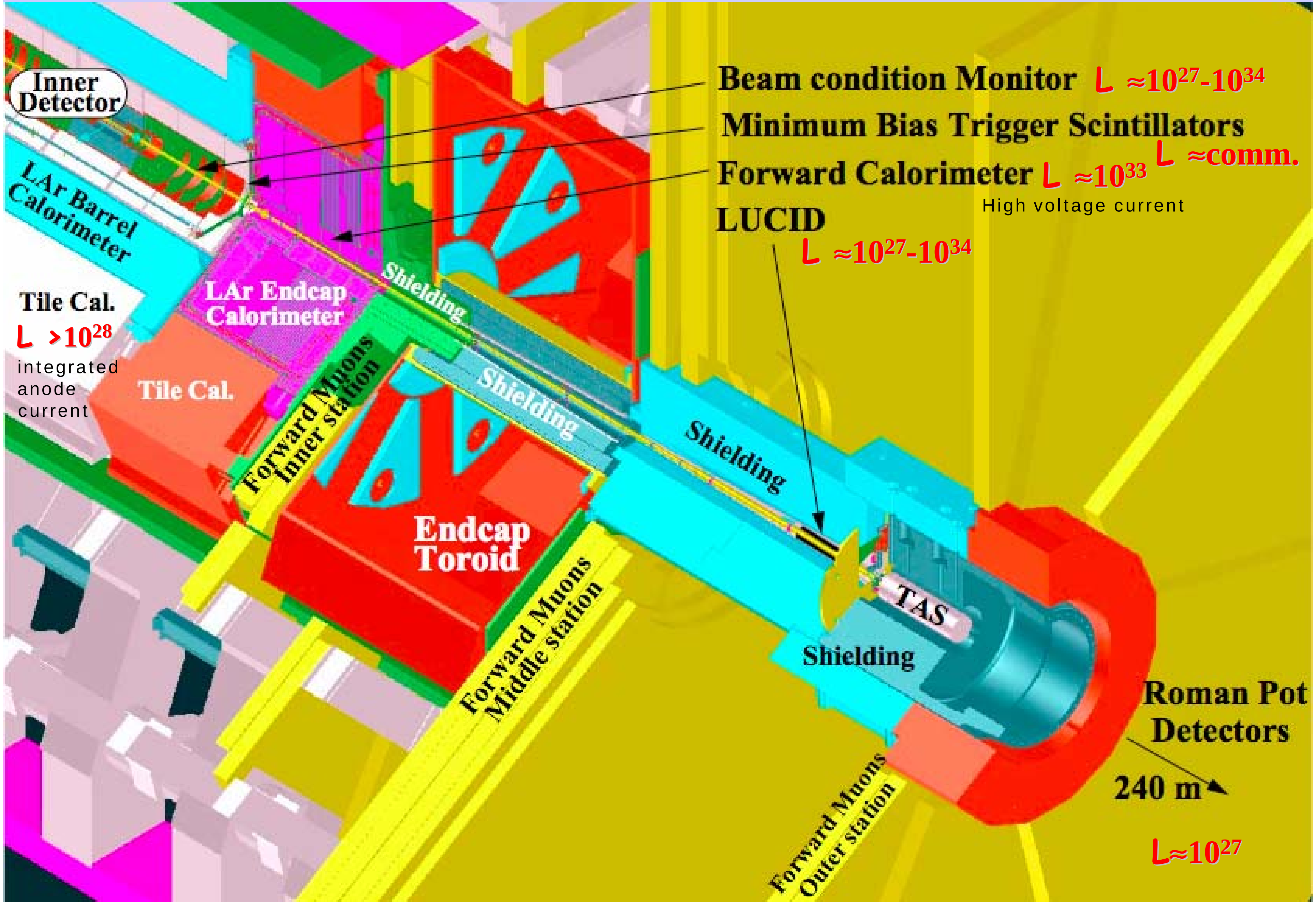
[ATLAS-TDR-15, May 1999]

Motivation II

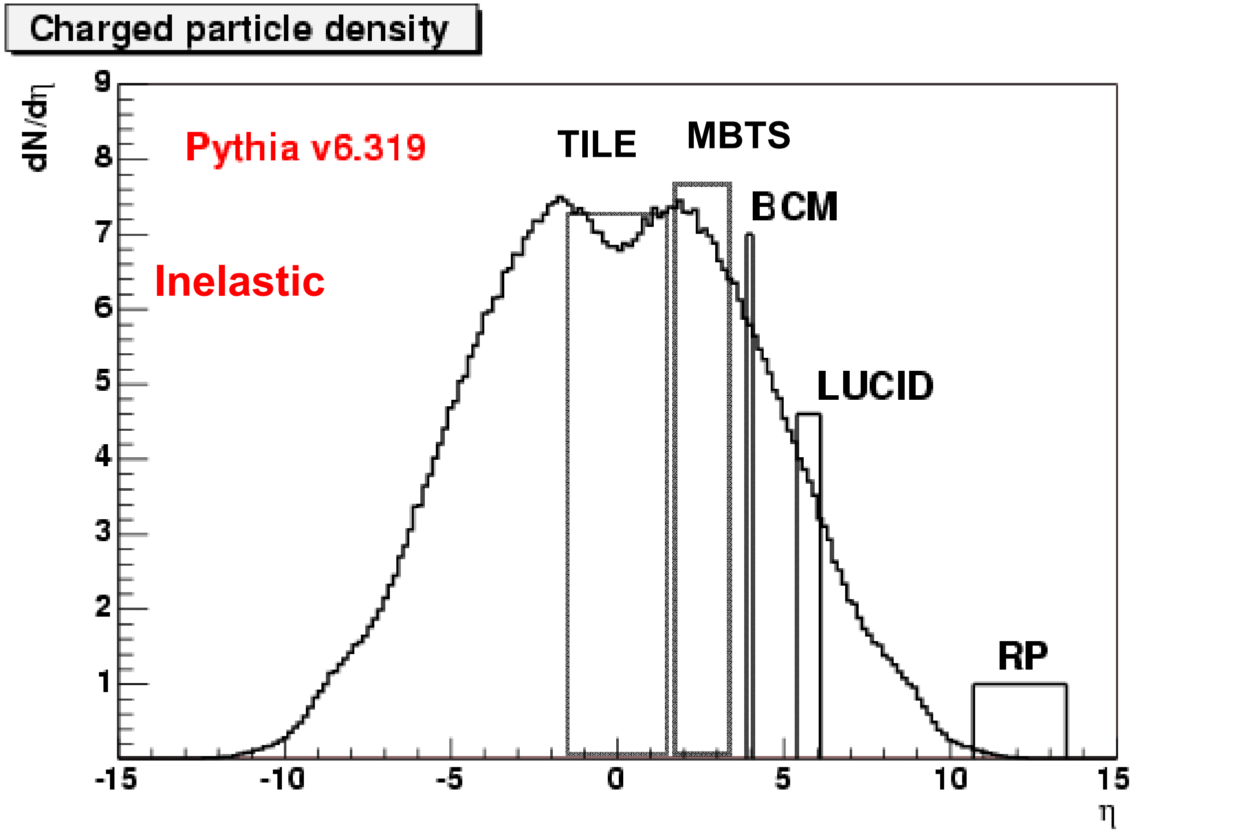
- Fast control of running conditions
  - Determine beam background
  - Prevent beam loss
- Efficiently use of beam and optimize yield
  - Trigger optimization (pre-scaler)
- Provide online luminosity measurement for LHC

- Study beam deterioration
- Monitor luminosity bunch-by-bunch

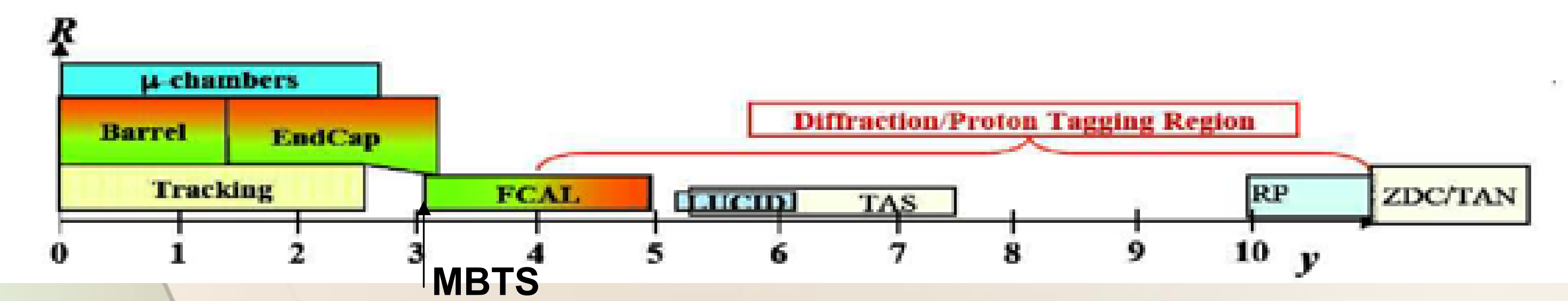
Forward Detectors @ ATLAS



η coverage

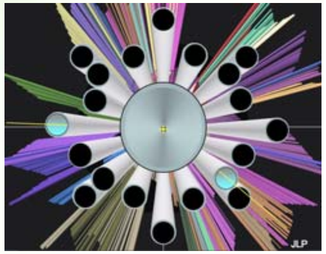


Charged particle density
dN/dη
Pythia v6.319
Inelastic
TILE
MBTS
BCM
LUCID
RP
-15
-10
-5
0
5
10
15
η

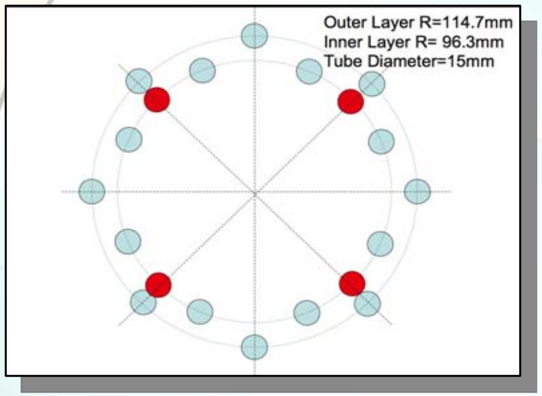


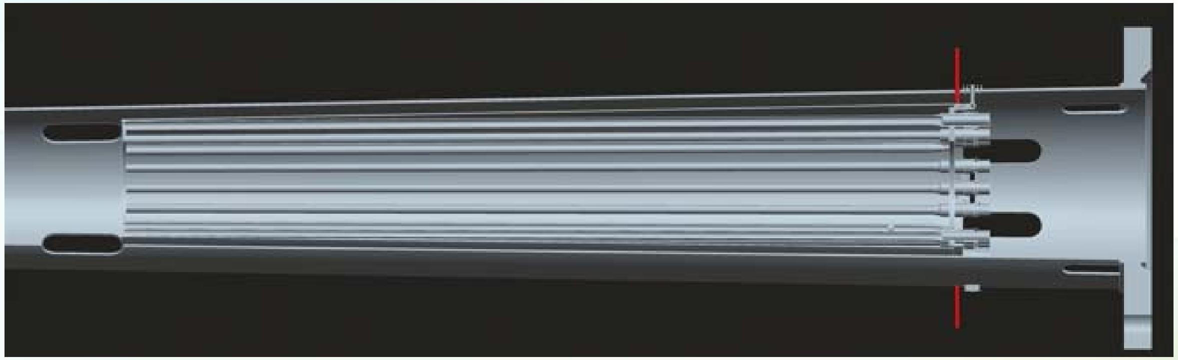
R
μ-chambers
Barrel
EndCap
Tracking
FCAL
LUCID
TAS
Diffraction/Proton Tagging Region
RP
ZDC/TAN
0 1 2 3 4 5 6 7 8 9 10 y
MBTS

LUCID: luminosity monitor



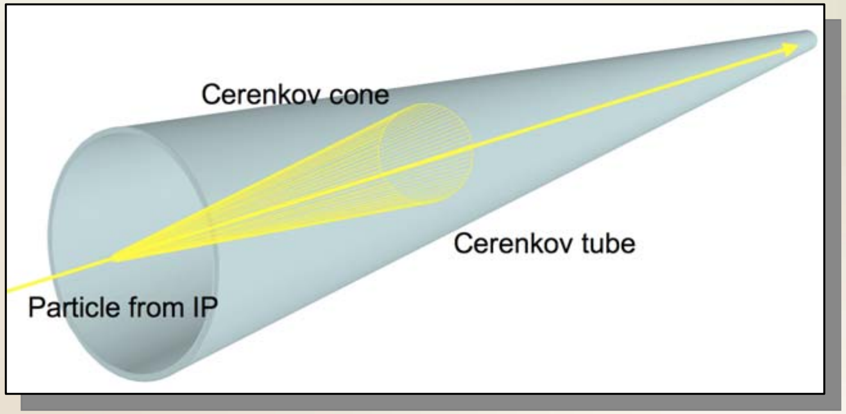
LUCID : “LUminosity measurement using Cerenkov Integrating Detector



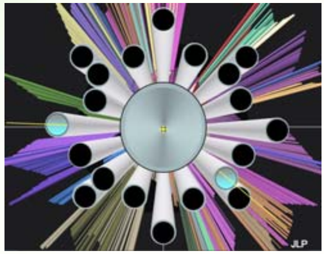


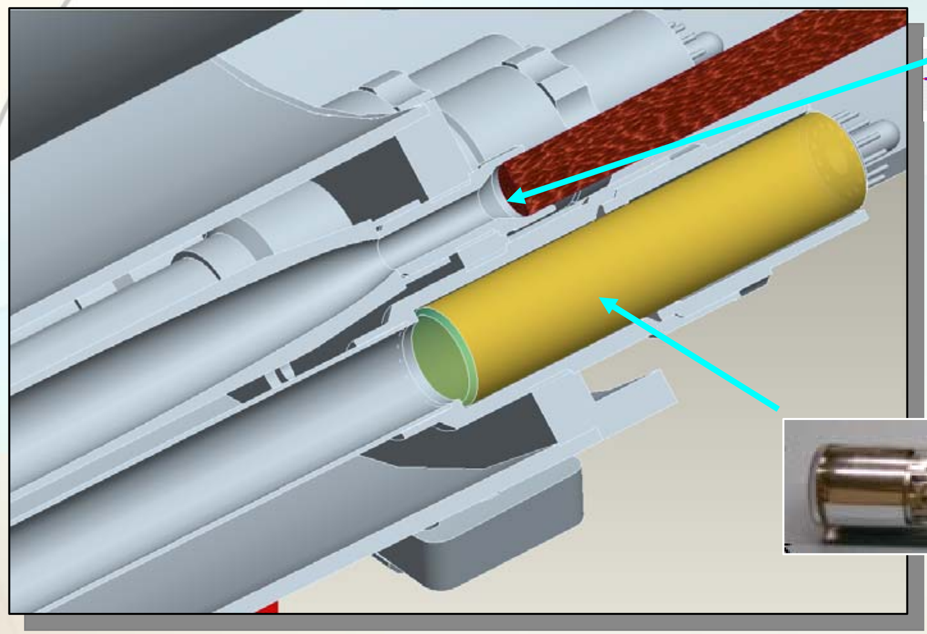
- 2 symmetric arrays of 20 x 1.5 m polished Aluminum tubes (Ø=1.5cm), filled with C_4F_{10}, surrounding the beam pipe and pointing the IP (Z~17 m)
- It can fit in available space & has low mass (< 25 kg/end)

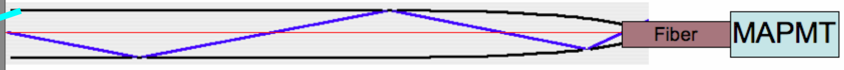
- Charged particles emit Cherenkov light at ~3 degrees (P=1 bar)
- Photons propagate along the tube with multiple reflections (~2.6) and read out by a PMT (Radiation hard)



LUCID: Light Detection





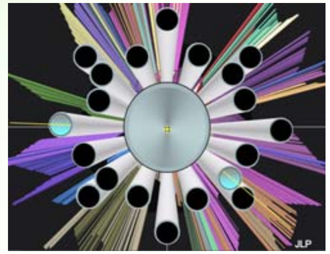


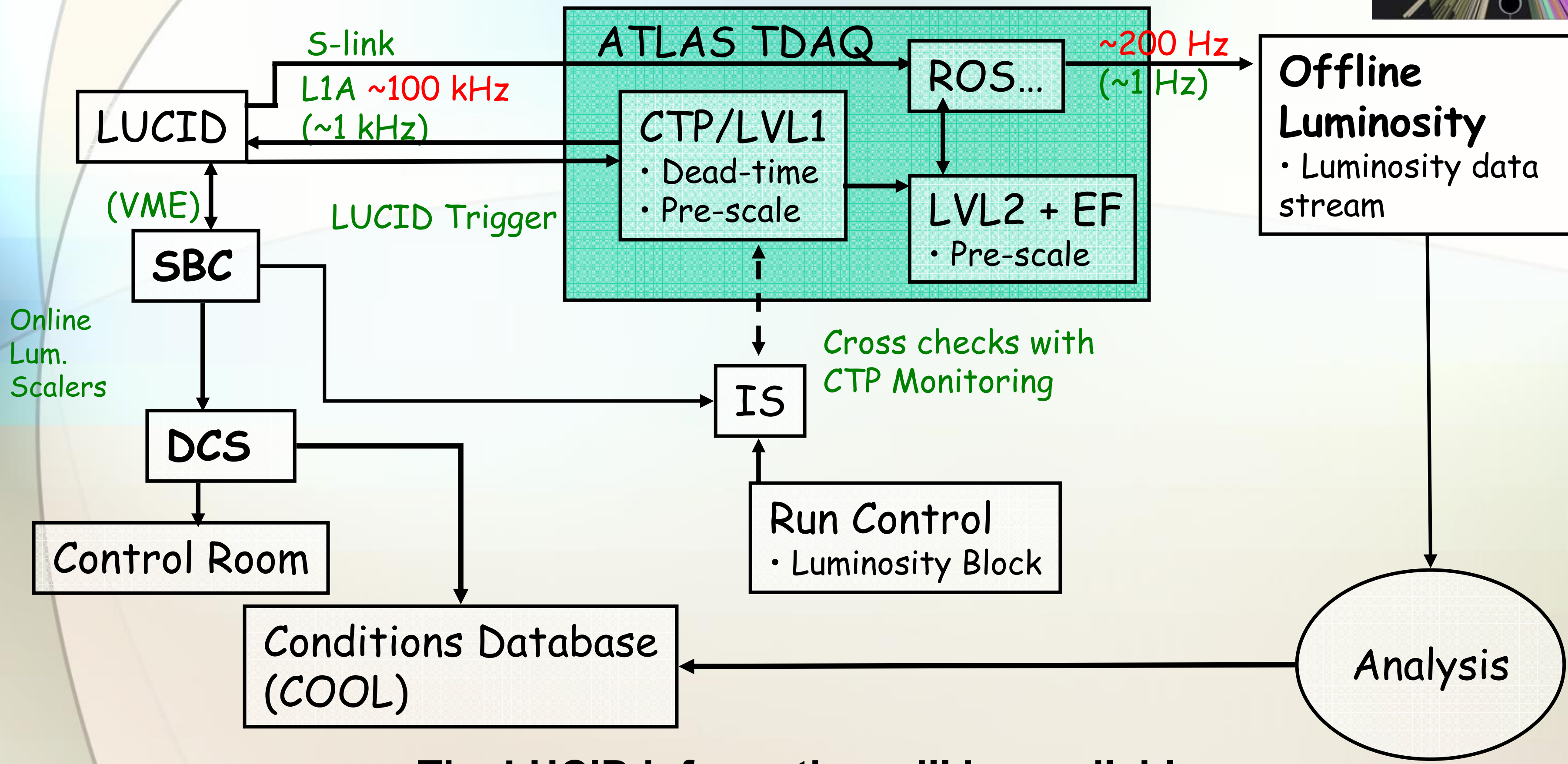
4 out of 20 tubes are readout by MaPMTs via fiber bundles (Test new detector design for high luminosity)

PMT readout - Baseline

- **The signal amplitude are used to measure the event track multiplicity (∝ μ ∝ L)**
- **The PMT time resolution of few ns could be used to measure bunch-by-bunch luminosity**

The LUCID Data Flow

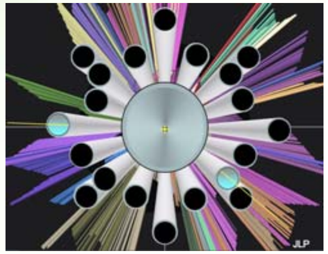




The LUCID information will be available:

1. **in the global ATLAS triggered event**
2. **in the online monitor**
3. **to possibly trigger interaction events or reject high multiplicity events**

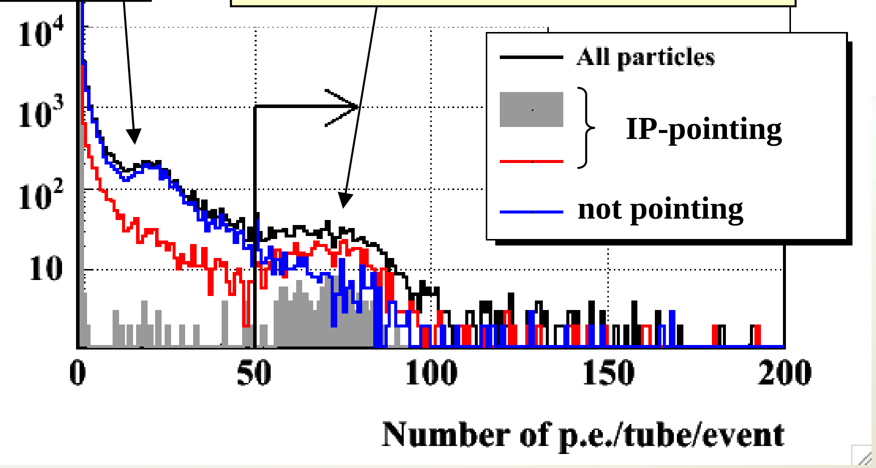
LUCID Performances



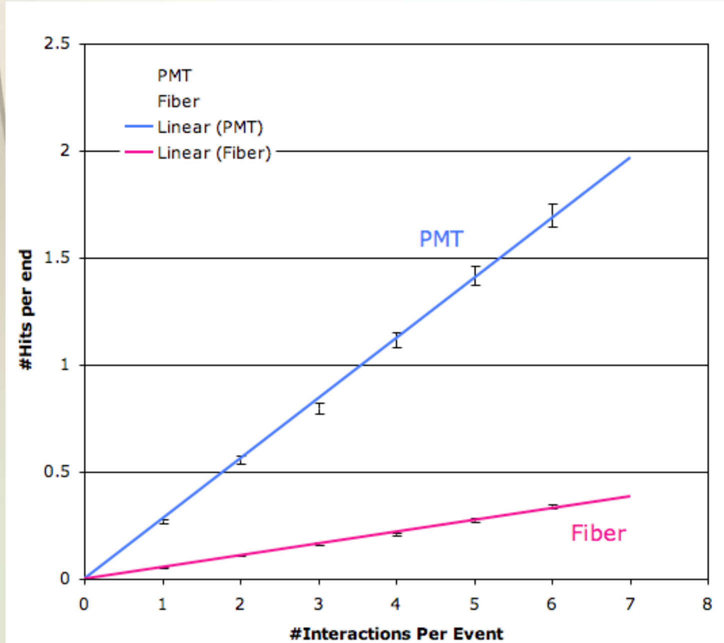
1 interaction per event

Cherenkov photons from PMT quartz window

Cherenkov photons from gas + PMT



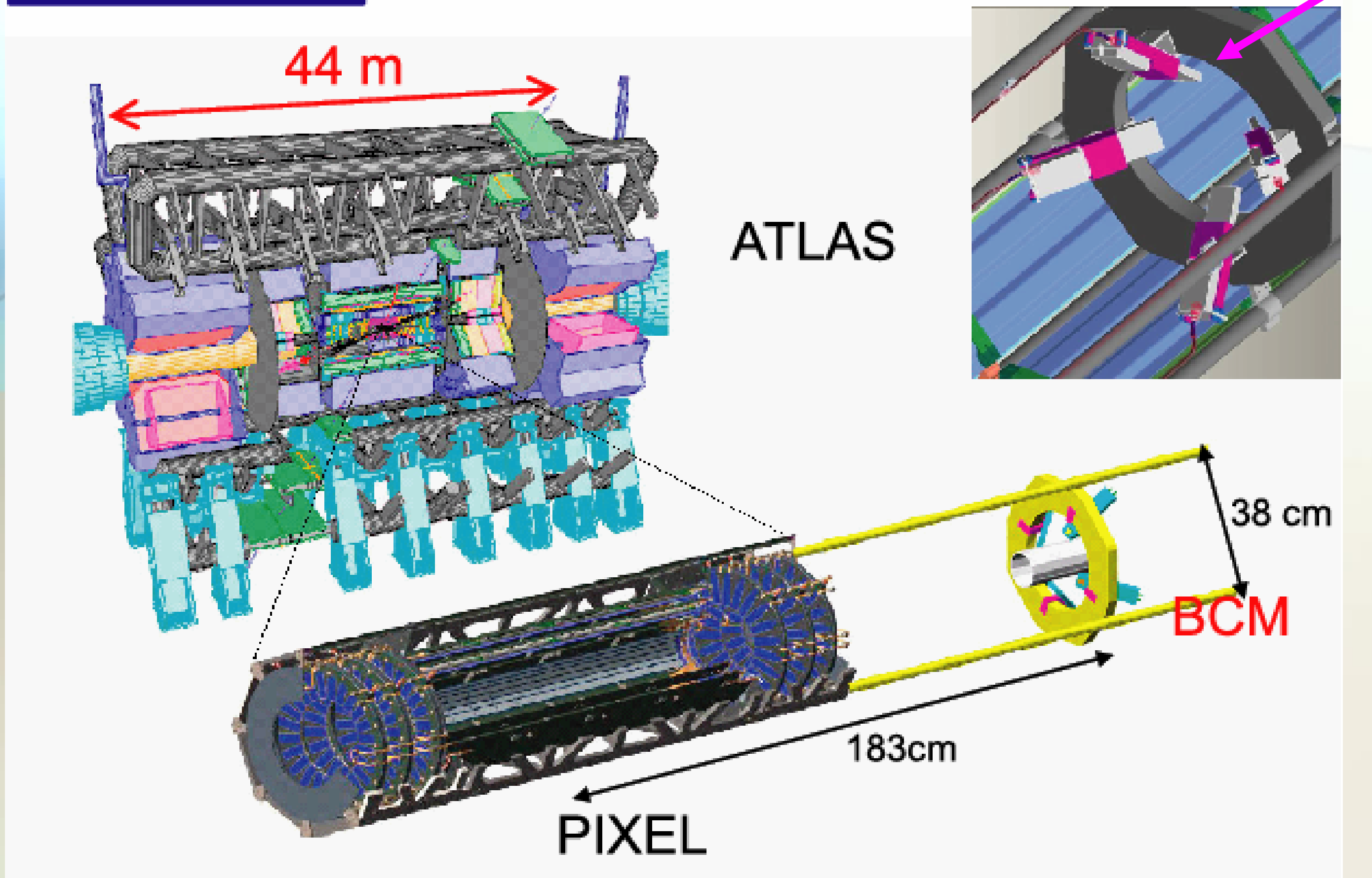
- **Sensitive to IP-pointing tracks above threshold**
- **Much shorter paths for non pointing secondaries**



- **The response of the detector is linear with both PMT and fiber read-out**
- **Detector occupancy with fiber read-out is lower → more suitable at high luminosity**

Beam Condition Monitor

Realisation



4 diamond sensors:
1x1 cm^2
500 µm thick

Radiation hard (50 Mrad, 10^{15} π /cm^2)

5 cm radius from the beam

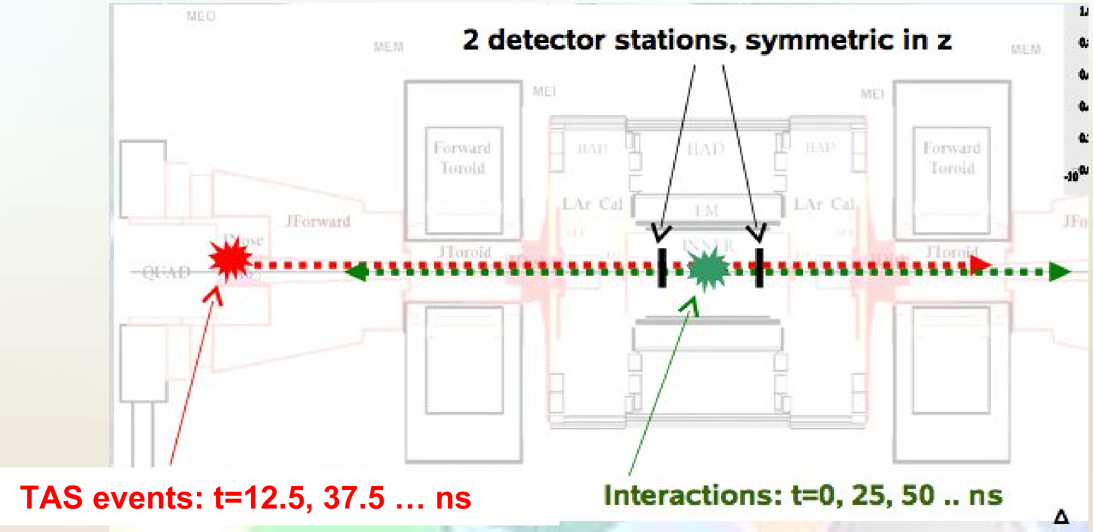
1.8 m from the IP on each side

Pseudo-rapidity coverage $3.9 < |\eta| < 4.1$

BCM

- The BCM is foreseen to provide monitor information about anomalous beam conditions (beam-gas and beam-collimator interaction events, beam loss)
- Designed to work for the full luminosity range of LHC
- Designed with a sufficient time resolution to identify individual bunch crossings (Rise-time ~ 1 ns, Width ~ 3 ns, Restoration ~ 10 ns)

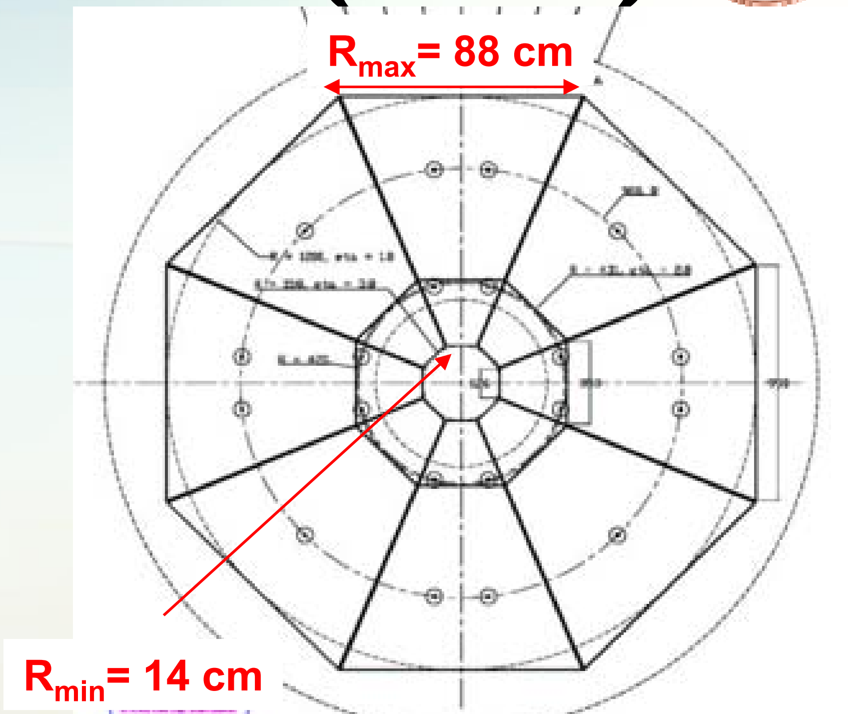
- Distinguish interactions from background via time of flight (interactions in time, background out of time on one side)

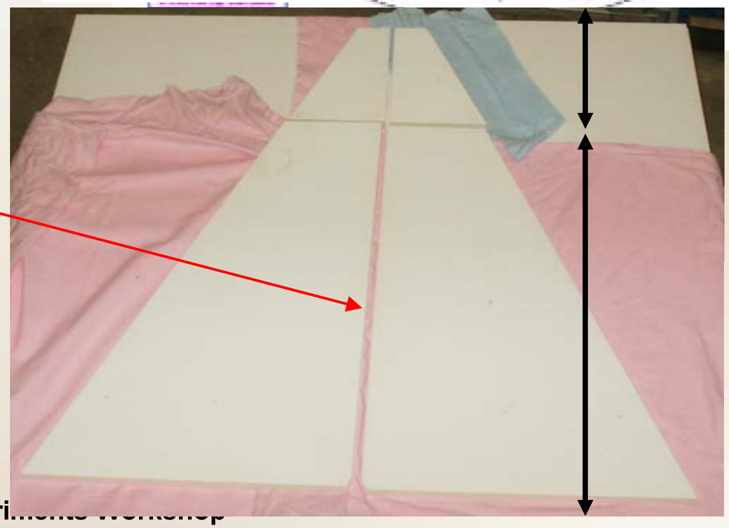


- The amplitude of the signal can be used to determine the number of particles transverse the detector
- Possibility for luminosity measurement is under study

Minimum Bias Trigger Scintillator Counters (MBTS)

- Wedge-shape plastic scintillators installed on the front face of LAr end-cap cryostat (Z=±3.6 m)
- Each scintillator cover $\Delta\phi = 2\pi/8$ and consist of two separated sections ($2.1 < \eta_{inn} < 2.8$, $2.8 < \eta_{out} < 3.8$)
- Material: Polystyrene doped with fluorescing agent
- Light emitted is collected by wavelength-shifter optical fibers embedded in grooves in the scintillator
- These fibers are connected to the PMTs and readout electronics designed for the calorimeter





MBTS

- MBTS goal is trigger on physics and veto halo events during the commissioning phase (L< 5 x 10^{32} $cm^{-2}s^{-1}$)
- It will work from the first beam till 3-4 months and will be dismounted during the first shut down
- It is able to detect 1 minimum ionizing particle
- It provides LVL1 trigger information and data to the ROS for triggered events

- Can be used to determine luminosity by counting the minimum bias trigger rate
- The precision of the measurement is limited by expected significant radiation damage

Calorimeters

TileCal

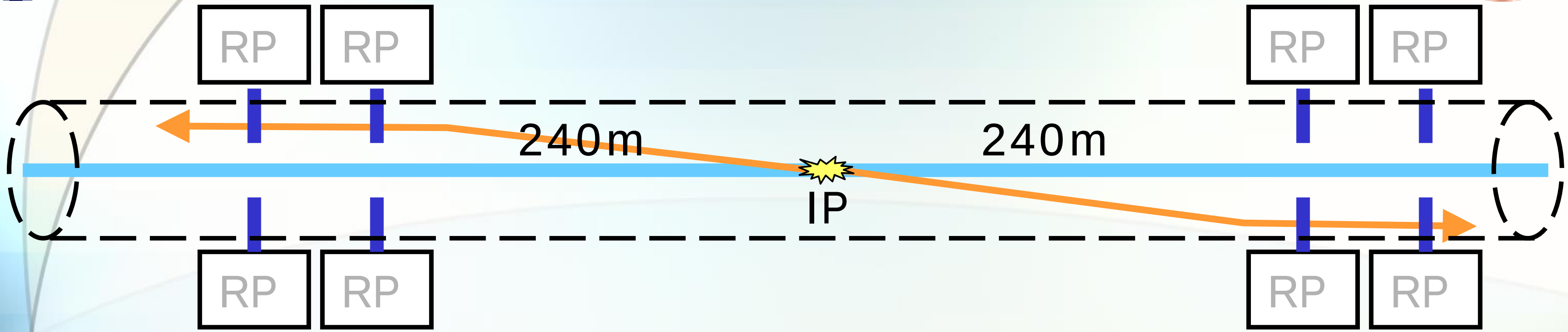
Minimum bias monitor via integrated anode current of the PMTs (high luminosity)

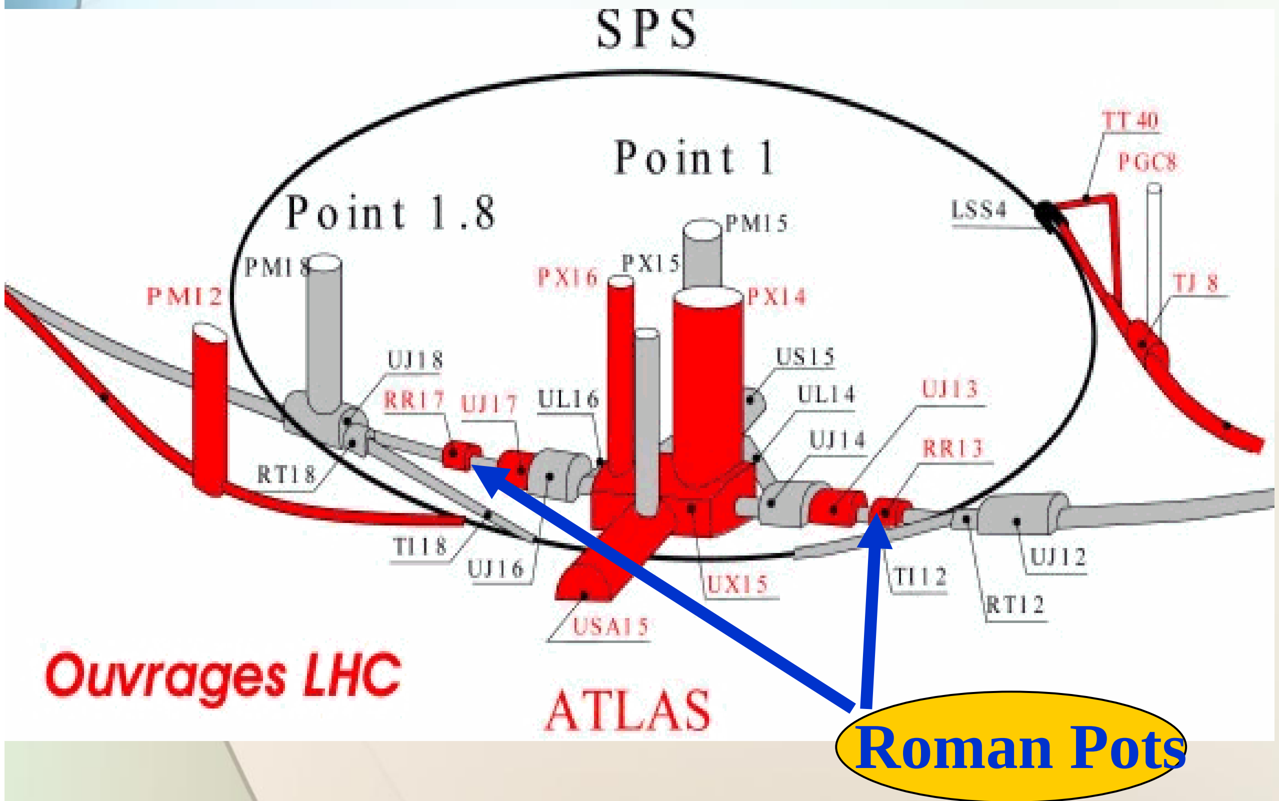
LAr

Minimum bias monitor via integrated high voltage current

Relative luminosity information will be provided from the local monitor systems outside the event stream

Roman Pots for ATLAS



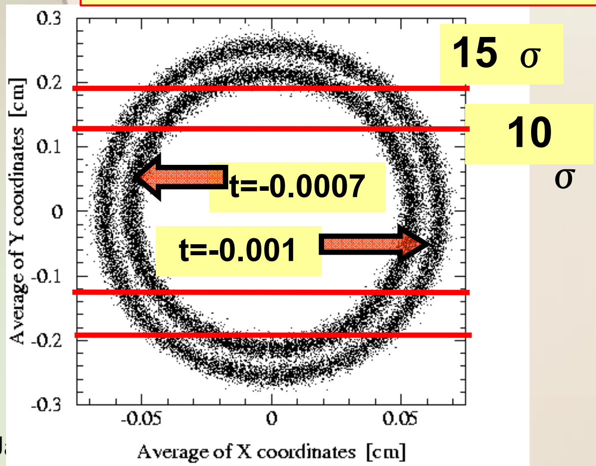


Two RP stations with top and bottom vertical pots, separated by 4 m, at each side 240 m from IP1

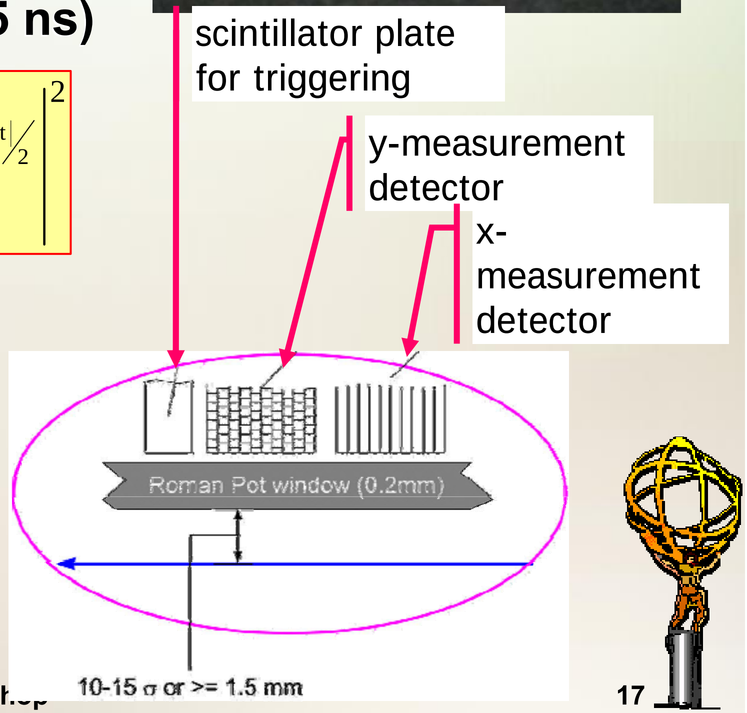
ATLAS' Roman Pots

- Measure elastic pp-scattering down to very small angles (~3 μ rad) $\Rightarrow$ Coulomb region $f_C \approx f_N$
- operate tracking detectors very close to the beam, 10 σ = 1.2 mm (position accuracy ~ 10 μm)
- detector resolution σ_d = 30 μm (t-resolution dominated by beam divergence)
- radiation tolerance 100 Gy/yr (dominated by beam halo)
- rate capability O(1 MHz) and time resolution O(5 ns)

$$\left.\frac{dN}{dt}\right|_{t=0} = L\pi |f_C + f_N|^2 \approx L\pi \left| -\frac{2\alpha_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2} \right|^2$$



$$-t = (p\theta^*)^2 = p^2(\theta_x^2 + \theta_x^2) = p^2\left(\left(\frac{x}{L_{eff,x}}\right)^2 + \left(\frac{y}{L_{eff,y}}\right)^2\right)$$



Techniques for Luminosity measurements

- **Use a relatively well known, copious, process:**
  - Inclusive inelastic pp cross-section
    - large acceptance at small angles

$$\mu \cdot f_{BC} = \sigma_{in} \cdot L$$

- μ = avg. # of interactions/b.c.
- f = frequency of bunch crossings
- σ_{in} = tot inelastic cross-section
- L = inst. luminosity

- **Use dedicated detector:**

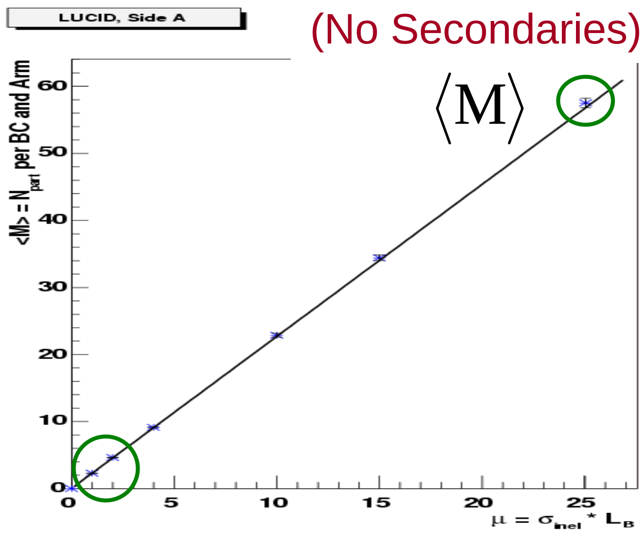
$$\tilde{\mu}_{\alpha} \cdot f_{BC} = \sigma_{in} \cdot \varepsilon_{\alpha}^{detector} \cdot L$$

- **Use a good estimator**
  - Measure the fraction of crossings with pp interactions
    - Use: $P_0(\mu) = e^{-\mu}$ prob. of no int.
  - Direct counting # of pp interactions
    - Counting particles
    - Counting hits
- **Cross-calibrate**
  - Machine information
  - Roman Pots
  - Rarer, clean, better understood physic processes

Monitor Calibration Strategy

Run LUCID in parallel with calibration measurement

LUCID with 200 tubes
(No Secondaries)



$$\langle M \rangle = \langle C \rangle \cdot A \cdot L$$

Measured by LUCID

Measured by LUCID
(at low luminosity μ<1)

Calibration Constant:
A = $\varepsilon_{pp} \times \sigma_{inel}$

Given by calibration method

Calculated ε and measured σ_{tot} used for consistency cross checks

Advantage of "Parallel" Calibration

$$A = \sigma_{tot} \cdot \varepsilon$$

Measured:
Not easy at high precision,
e.g. CDF vs E811 discrepancy

Calculated:
Acceptance shown at the Tevatron to be difficult to calculate in forward region

Whole Calibration Methods

- Initially,
  LHC Machine Parameters
  (Precision: ~10%)

- Medium term
  Physics processes, W/Z & μμ/ee
  (Precision: ~5-10%)

- Late 2009 – Early 2010 ← Including estimated latency for data-taking and analysis
  Roman Pot (ALFA) measurement
  (Precision: ~2-3%)

Conclusions

- A big effort is made by the ATLAS collaboration to provide as many methods as possible to monitor luminosity
- Different detectors based on different working techniques are studied and ready for installation
- Monitors' information are available both in the ATLAS TDAQ than outside the event stream
- Luminosity will be monitored bunch-by-bunch and synchronized with LBs
- Absolute calibration against Machine Luminosity and Roman Pots. Calculated ε and measured σ_{tot} only used for consistency cross checks

Backup

Luminosity with Collision (zero) counting method

Measure the average of the Poisson distribution by measuring the **0 bin**.

$$P_0(\mu) = e^{-\mu}$$

$$\mu = \sigma_{inel} \cdot \langle L_B \rangle = \text{Mean \# interactions per (any) BC}$$

$$\frac{n_{pp}}{n_{BC}} = \text{Collision Rate}$$

$$1 - \frac{n_{pp}}{n_{BC}} = \text{“Zero” Rate}$$

$$\frac{n_{pp}}{n_{BC}} = 1 - e^{-\varepsilon_{pp}\mu} \xrightarrow[\mu \ll 1]{} \varepsilon_{pp}\mu$$

Detection efficiency of one interaction

Linear relation between measured quantity and luminosity at low luminosity (μ<< 1)

- Advantages:
  - Less sensitive to ADC calibration
  - Formula is correct at every L
- Disadvantages
  - Not linear at higher luminosity (μ ≥ 1)
  - Statistically limited at very high L ($P_0(\mu=25) \cong 10^{-8}$)

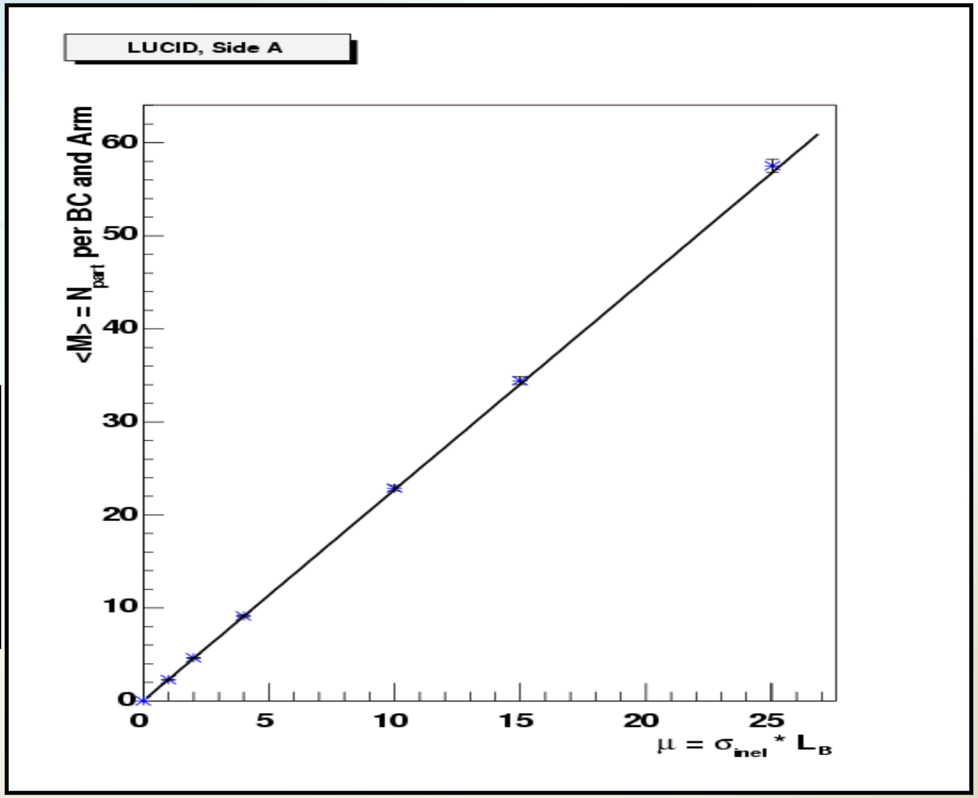
Particle Counting
(Baseline Method)

Constructed to be Linear even in Pile-Up Region

$$\langle M \rangle = \langle C \rangle \cdot \varepsilon_{pp} \cdot \mu$$

Mean # Particles per BC

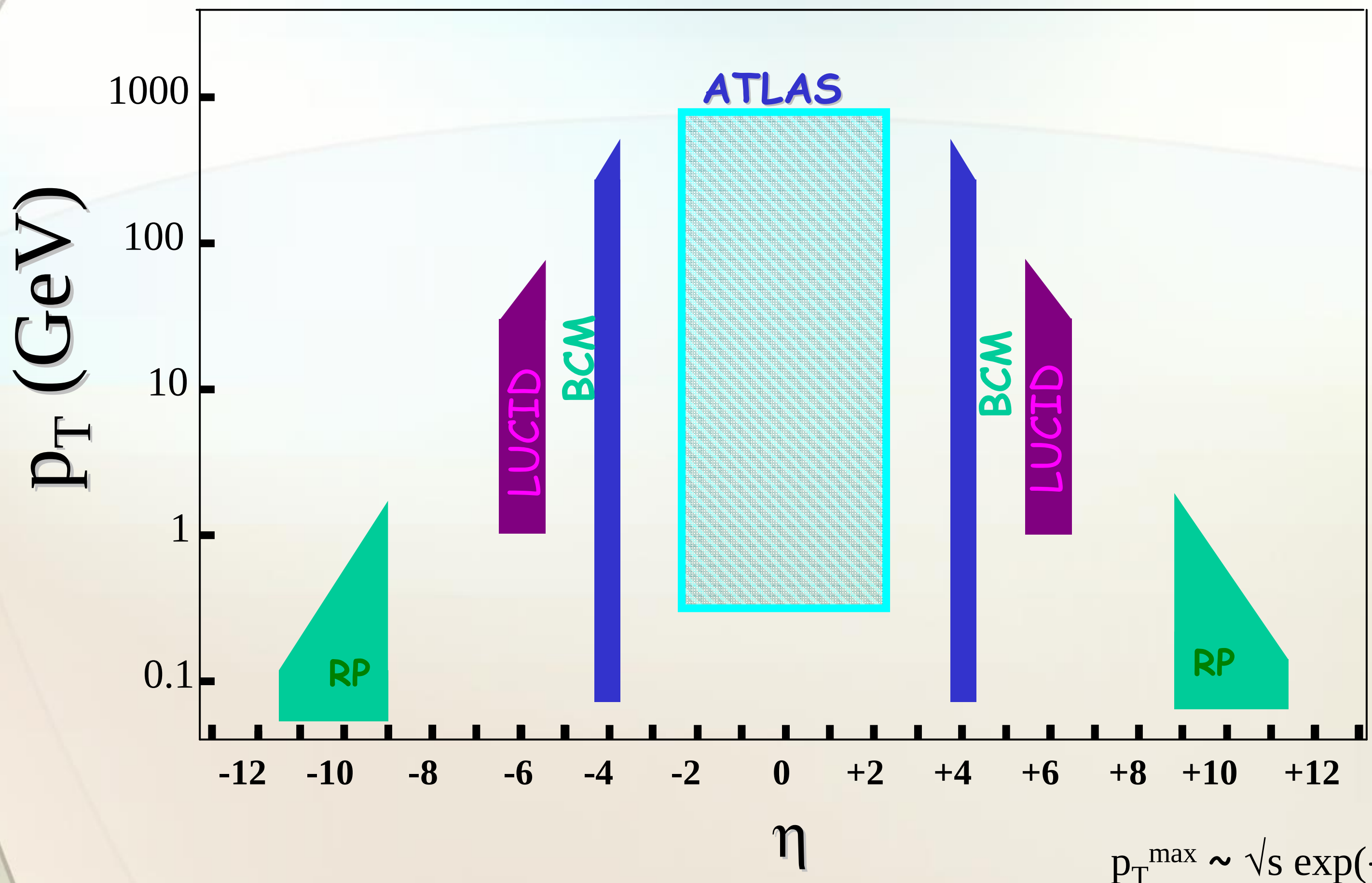
Mean # Particles per Detected Interaction (measured at low lum. where the prob. For >1 int./BC is very small)



Detector Requirements:

- Acceptance coverage sensitive to min. bias event rate
- Time resolution to make measurement for individual BCs
- Capable of counting particles
- Calibrated by efficiency (acceptance) and inelastic cross section from calibration measurement or calculations

p_T-η ATLAS' Coverage



$p_T^{max} \sim \sqrt{s}\ \exp(-\eta)$

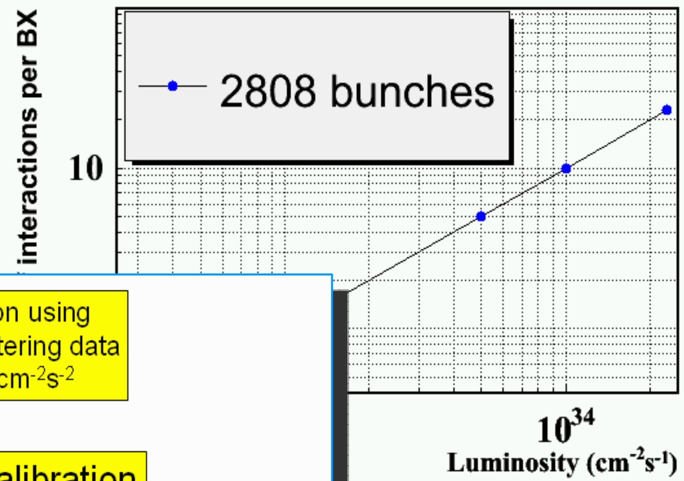
Commissioning and Start-up phases

LHC 40 MHz Beam:

→ 3564 possible bunch crossings (BC)

→ Only 2808 BC will be filled due to injection etc. (e.g. 89um long-gap)

Parameter	Comm	Nominal	Unit
Energy	0.9	7	TeV
# of Bunches	2808	2808	
# of particles per bunch			
Luminosity	10^{27} - 10^{32}		
β *			
<#> of interactions/ev			



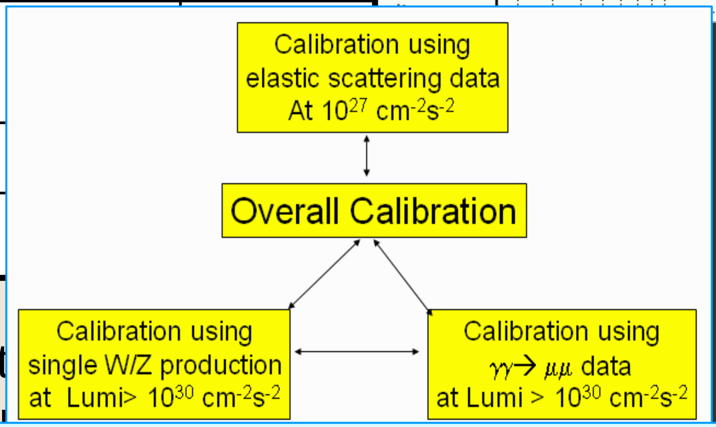
Observables:

→ Time structure of luminosit

→ Instantaneous lum. corres ... f BCs

→ The BC will in practice i

→ Bunch Luminosity = Inte



Calibration can be carried from elastic scattering data over the full dynamic range

Physic Processes

QED: small σ_{QED}

No Monitor Online

- $pp \rightarrow (p+\gamma^*)+(p+\gamma^*) \rightarrow p+(\mu^- \mu^+)+p$
  - Low rate (<< 1 Hz) still at $L=10^{34}$ cm^{-2} s^{-1}
  - Process calculated with ~1% accuracy

EW: W/Z → leptons

- Theoretically well understood processes (calculated till NNLO)
- High rate: ~6Hz for $Z \rightarrow \mu^+\mu^-$, ~60Hz for $W \rightarrow \mu\nu$ at $L=10^{34}$ cm^{-2} s^{-1}
  - Online monitor at high luminosity

    $(\Delta\mathcal{L}/\mathcal{L})_{syst}$ ~ 4-6% *; $(\Delta L/L)_{stat}$ ~ 1-5% *

QCD: σ_{tot} ~ 100 mb

- Roman Pots at dedicated luminosity ($L \approx 10^{27}$ cm^{-2} s^{-1}) and optic
  - Absolute Luminosity $\mathcal{L}$

Start up

- Counting of the number of bunch crossings with/without interaction
  - Online monitor ⇒ Relative Luminosity L

* Small statistical error (<1%) → homogeneous samples with at least 10K-100K ev