10th **International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors**

Offline calibration and performance of the ATLAS Pixel Detector

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for the ATLAS Collaboration

- The ATLAS Pixel Detector
- Efficiency
- Resolution
- Detector properties
  - Lorentz angle
  - Energy loss measurement

…and what you do with all that

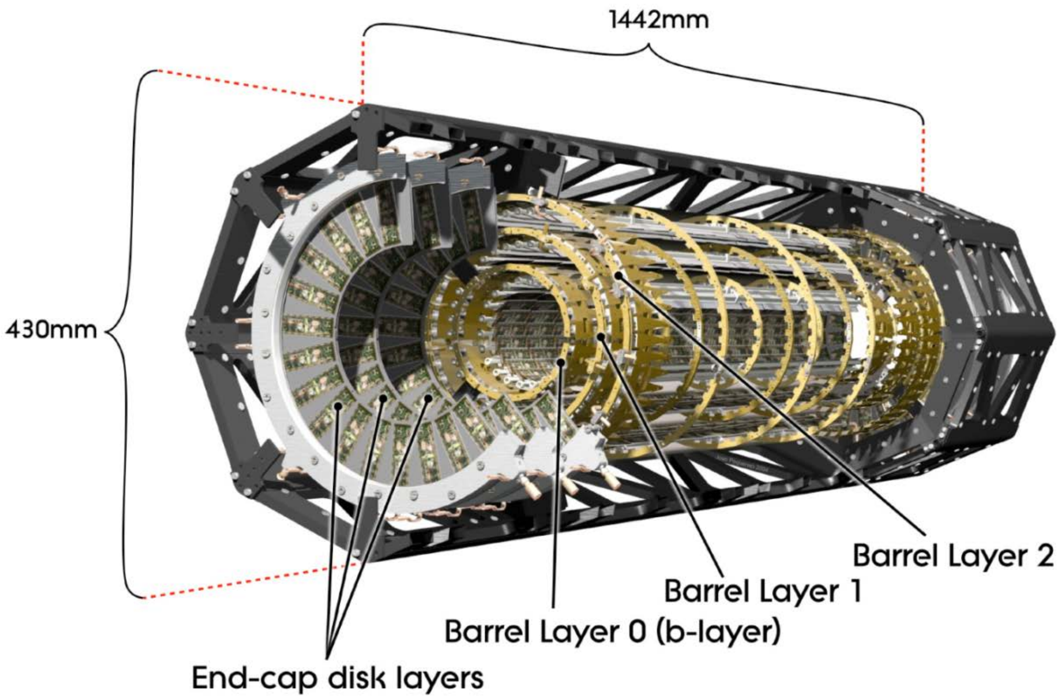
No alignment and tracking performance
S. Marti's talk later today
No radiation damage issue
S. Gibson's talk on Friday

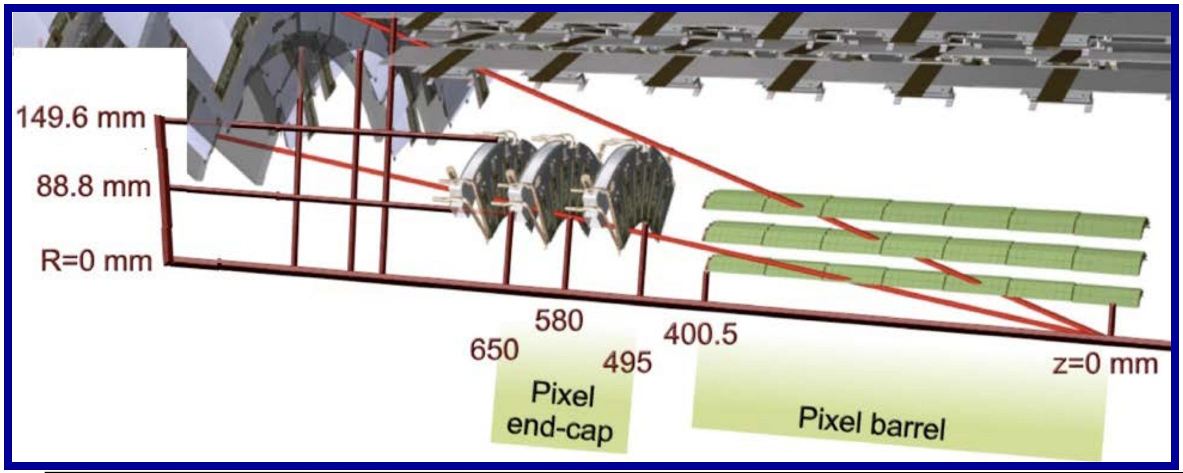
Introduction:

- Pixel Detector layout
- Module concept

THE ATLAS PIXEL DETECTOR

The ATLAS Pixel Detector

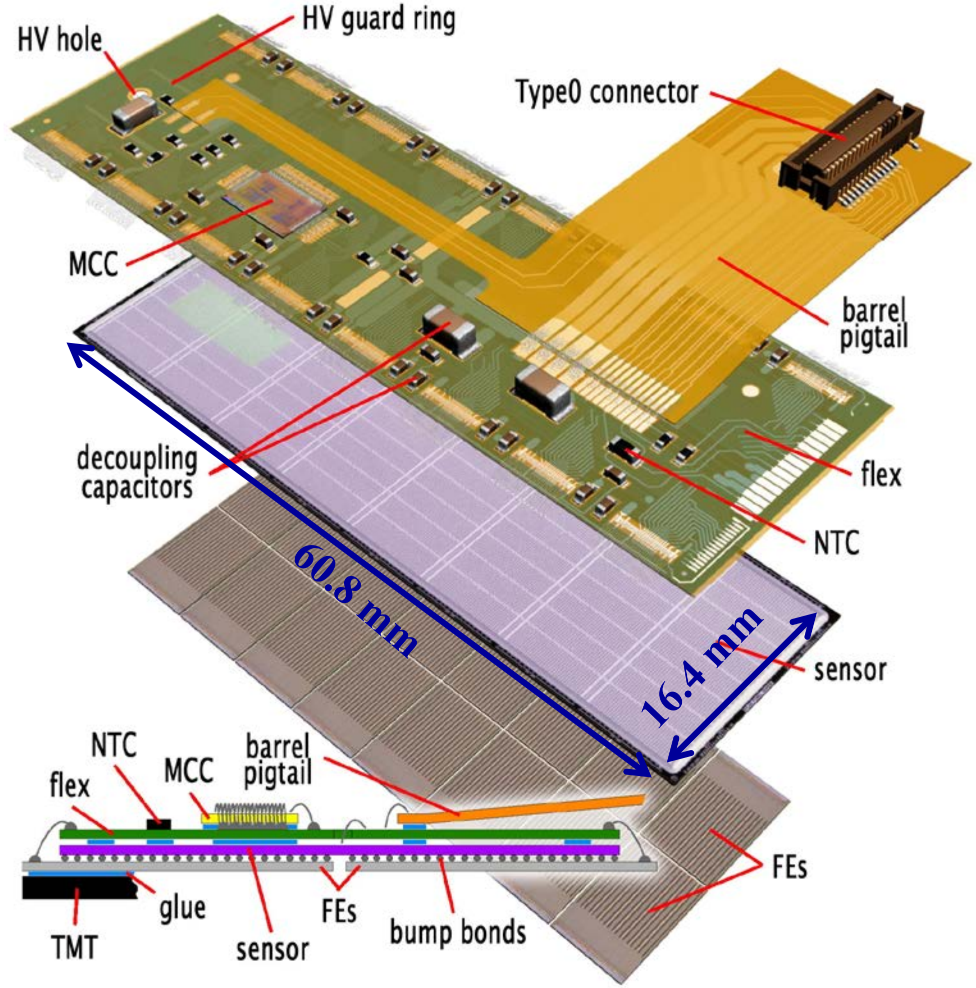




- **Three barrel layers:**
  - R= 5 cm (Layer-0), 9 cm (Layer-1), 12 cm (Layer-2)
  - modules tilted by 20º in the Rϕ plane to overcompensate the Lorentz angle.
- **Two endcaps:**
  - three disks each
  - 48 modules/disk
- **Three precise measurement points up to |η|<2.5:**
  - RΦ resolution:10 µm
  - η (R or z) resolution: 115 µm
- 1456 barrel modules and 288 forward modules, for a total of 80 million channels and a sensitive area of 1.7 m^2.
  - Environmental temperature about -13 ºC
  - 2 T solenoidal magnetic field.

Module overview

- **Sensor**
  - 47232 n-on-n pixels with moderated p-spray insulation
  - 250 μm thickness
  - 50 μm (RΦ) × 400 μm (η)
  - 328 rows (x_{local}) × 144 columns (y_{local})
- **16 FE chips**
  - bump bonded to sensor
- **Flex Hybrid**
  - passive components
  - Module Controller Chip to perform distribution of commands and event building.
- **Radiation-hard design:**
  - Dose 500 Gy
  - NIEL 10^{15} n_{eq}/cm^2 fluence



5 years at 10^{34} $cm^{-2}s^{-1}$

Mapping the detector

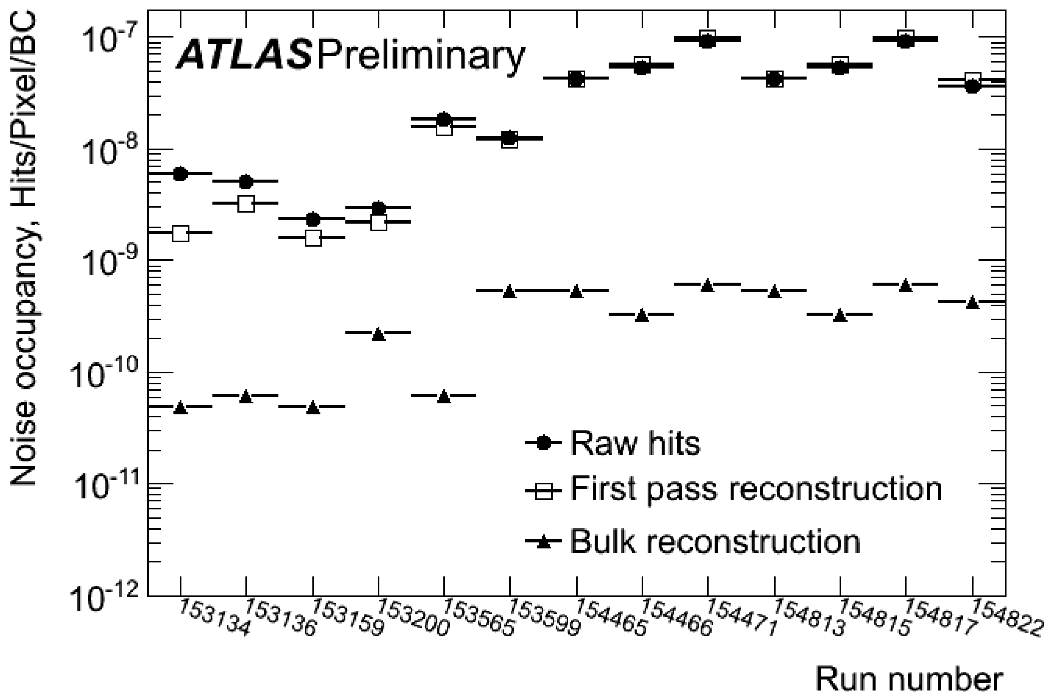
- Noise maps
- Inefficiency maps

Putting all in MC and use it reconstruction (*p*-*p* and Pb-Pb)

EFFICIENCY

Offline calibration

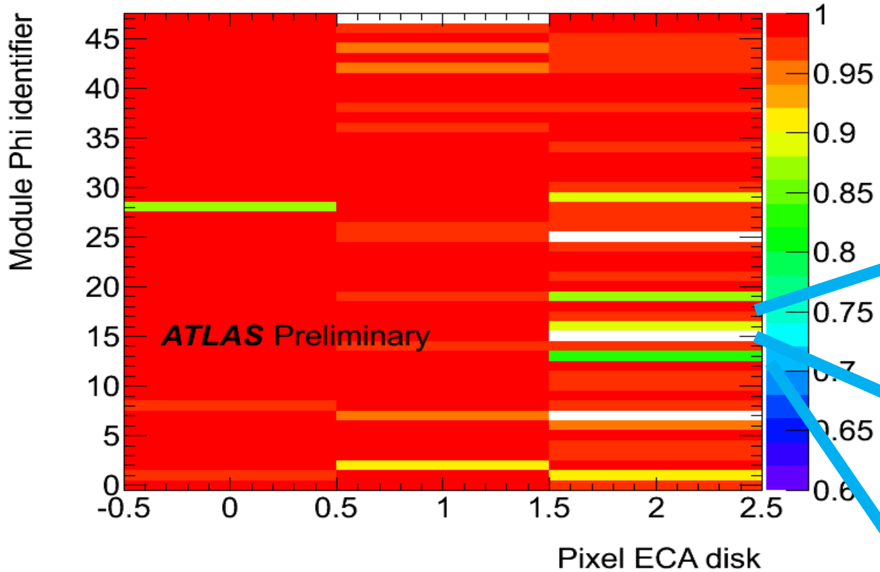
- **"Calibration loop"**
  - first pass reconstruction of a subset of physics and calibration data
  - calibration
    - noise maps (per fill)
    - dead channels (~monthly)
    - charge sharing
  - reconstruction of bulk of data

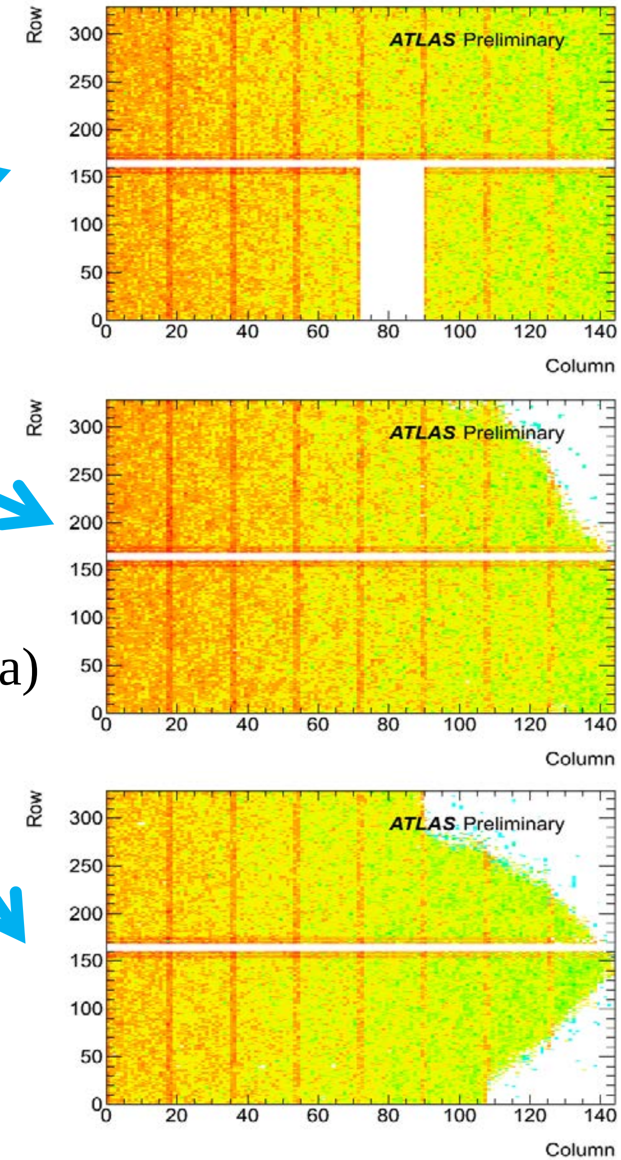


- **Dedicated calibration stream:**
  - random trigger on empty LHC bunches
  - 10 Hz rate
  - 29 kB/event
- **Express stream:**
  - ~10 Hz of physics trigger

- Mask noisy channels from reconstruction:
  - occupancy >1-5×10^{-5} hit/BC
  - typically 300-1500 channels masked offline
- **Noise rate in bulk reconstruction**
  - <0.2 hits/event
    (compared to few hundreds in collisions)

Sources of inefficiency

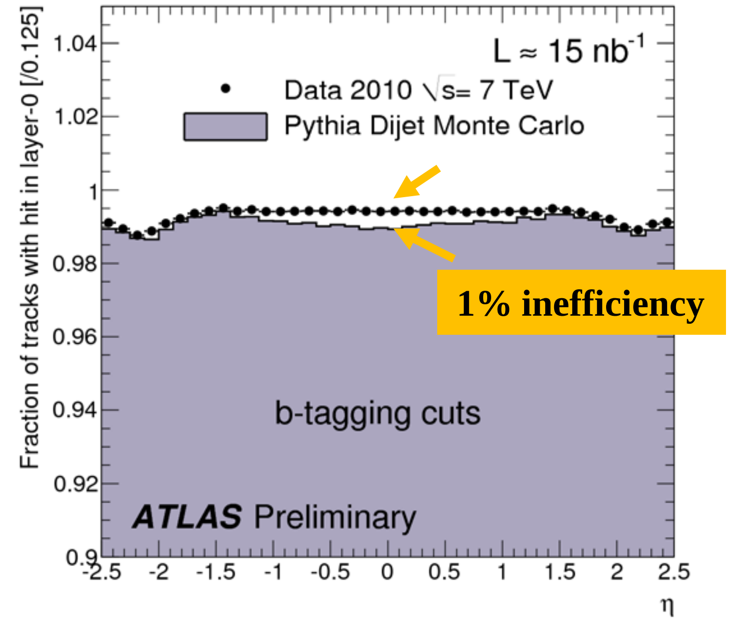


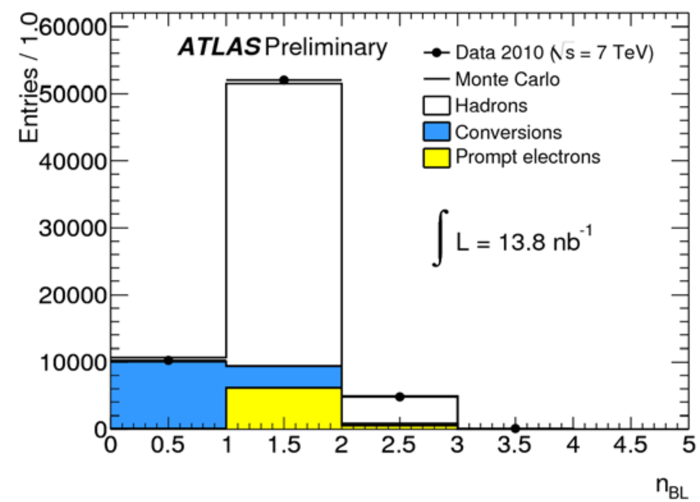


- **Permanent non-operational modules (55/1744)**
- **Temporary non-operational modules** (monitored on data)
- **Maps of inefficient channels:**
  - Dead FE chips (47/27904)
  - Defective bump bonds
  - Bad channels (failing calibrations/disabled online)
  - **Very stable with time:**
    - ~260k channel (0.3%)
    - About 50% due to FE failures

Where efficiency matter most!

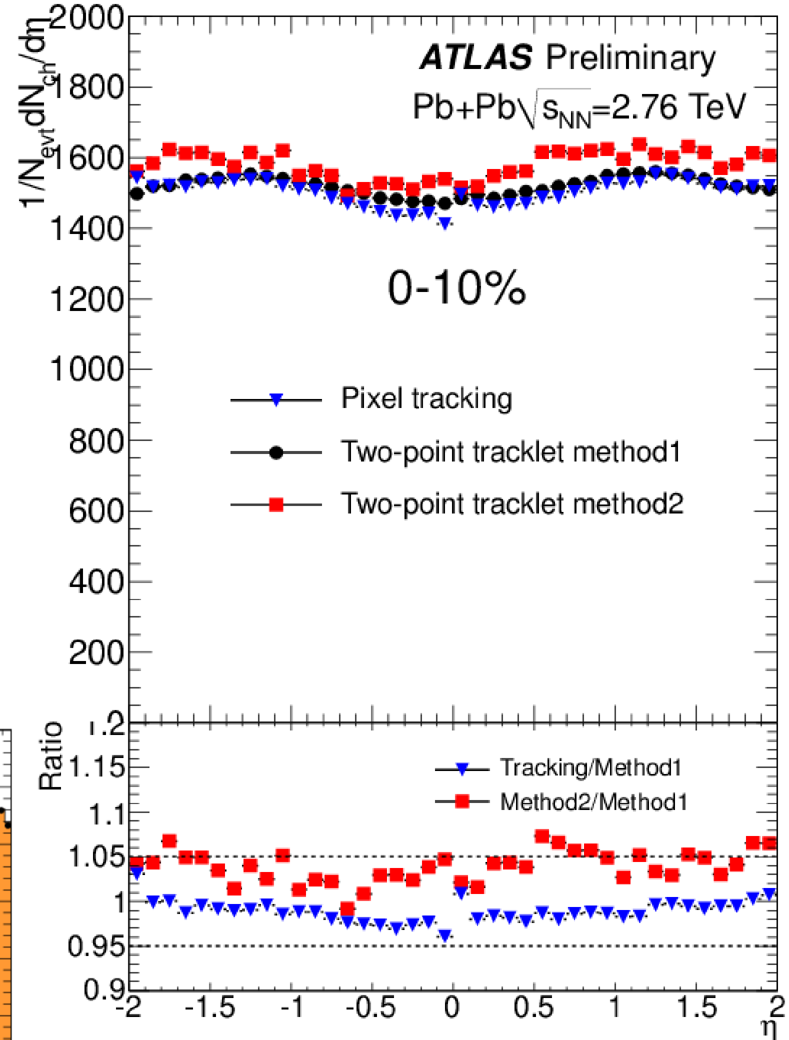
- Intrinsic efficiency measured with cosmic rays and in test beams **almost 100%**.
- This is also confirmed in operation.
- Innermost layer is most critical:
  - Impact parameter resolution is significantly worse is lowest R measurement is missing.
  - It is effectively use to discriminate primary and secondary particles:
    - e/γ separation
    - Soft-QCD studies
    - Heavy-ion reconstruction

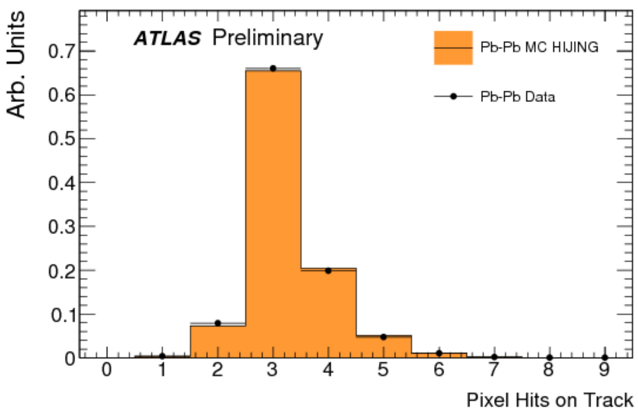


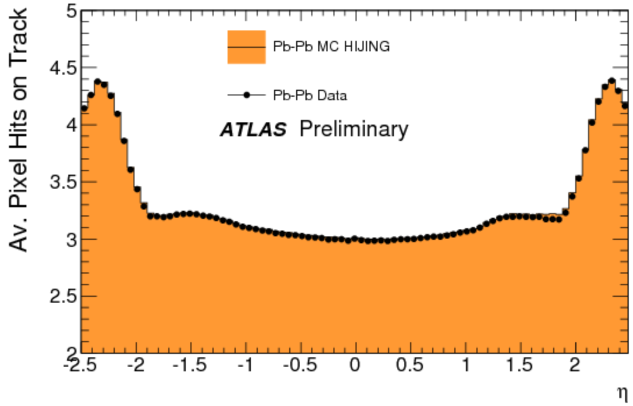


Heavy-Ion performance

- To reduce fake tracks in busy HI environments (~10000 tracks) no "holes" allowed in Pixel Detector
  - Correct mapping of inefficiency is critical
- Pixel-only tracking powerful for counting very low momentum tracks:
  - **3-points** tracks
  - **Vertex+2-points** tracks
  - Very different efficiency correction.
- **Excellent modeling in simulation.**







Calibration of charge interpolation

Width of track-hit residuals

…and how to make an *hadro*graphy of the detector

RESOLUTION

Charge sharing

- **Point resolution can be improved using the pulse height measurements.**
- **Charge sharing variables:**

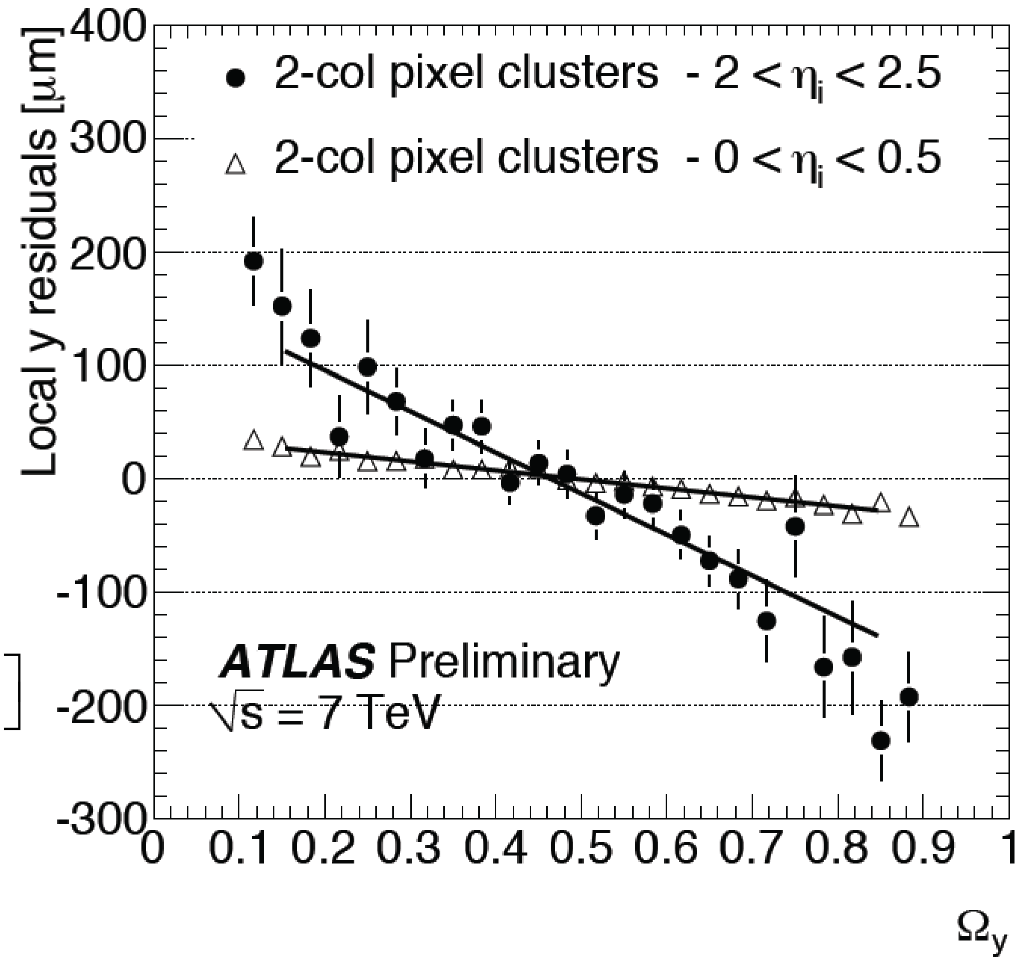
$$\Omega_x = \frac{Q_{\text{last row}}}{Q_{\text{first row}} + Q_{\text{last row}}}$$

$$\Omega_y = \frac{Q_{\text{last column}}}{Q_{\text{first column}} + Q_{\text{last column}}}$$

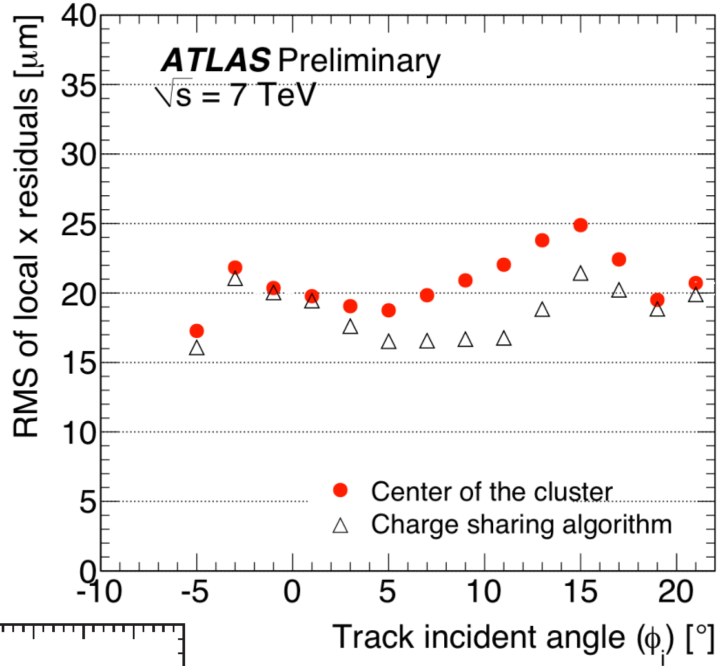
- **Cluster position correction:**

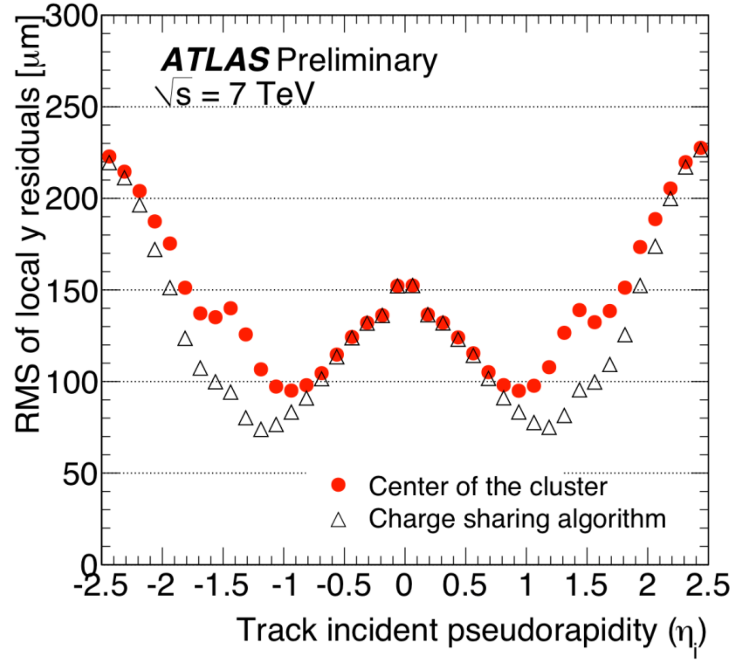
$$(x_c, y_c) \rightarrow$$
$$\left[x_c + \Delta_x\left(\Omega_x - 1/2\right), y_c + \Delta_y\left(\Omega_y - 1/2\right)\right]$$

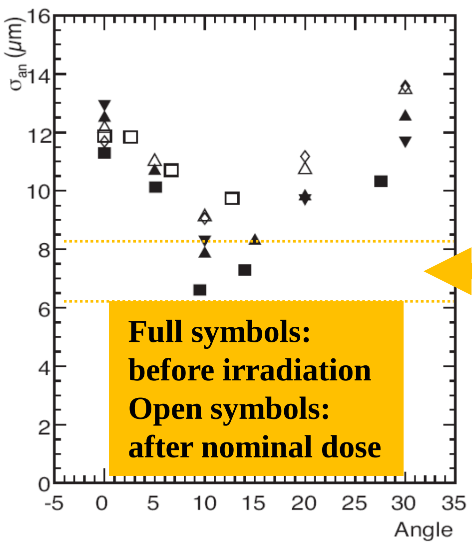
- The parameters Δ_x, Δ_y:
  - depend on cluster size and incident angle
  - **determined from dependence of uncorrected residuals on Ω_x, Ω_y**



Charge sharing: resolution





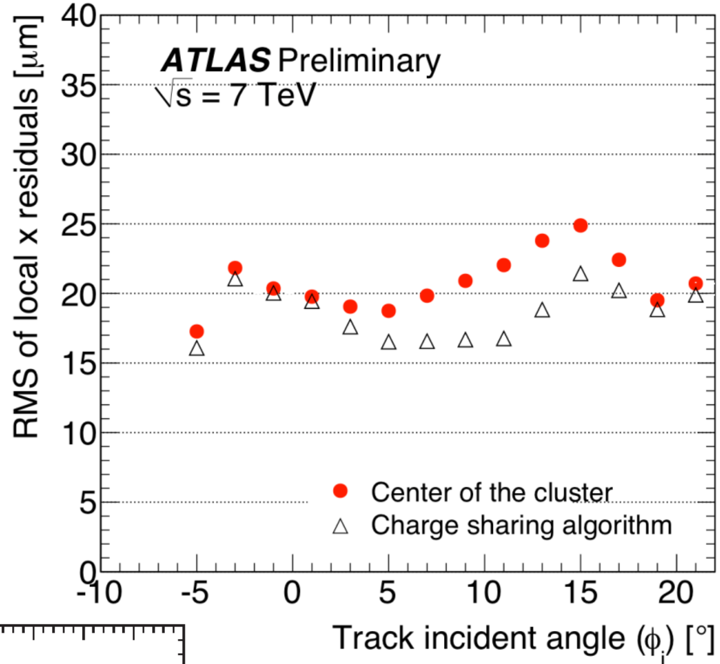


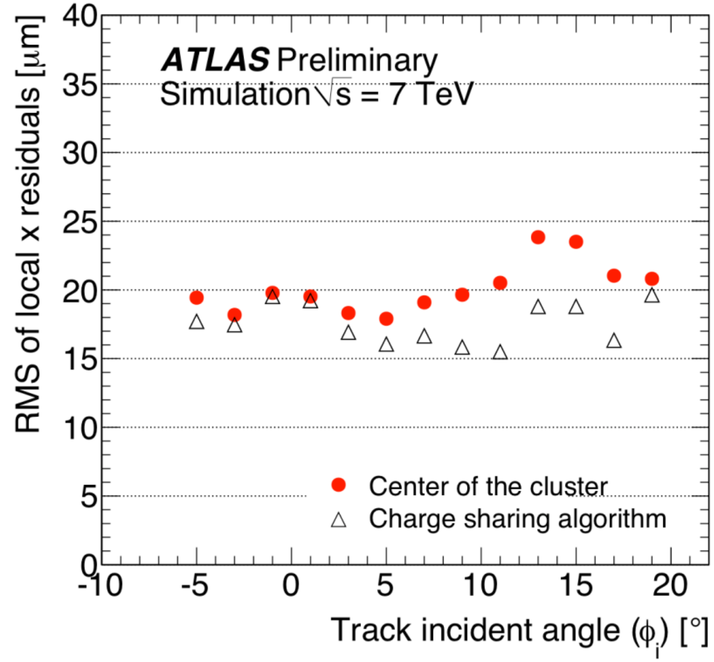
Clear improvement in the angular region populated by 2-pixel clusters.

From test beam studies intrinsic resolution 6-8 μm, before radiation damage

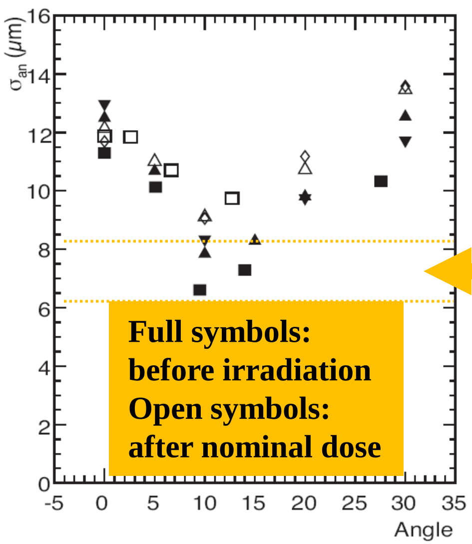
N.B.: residuals include also extrapolation resolution

Charge sharing: resolution





Good agreement with simulation



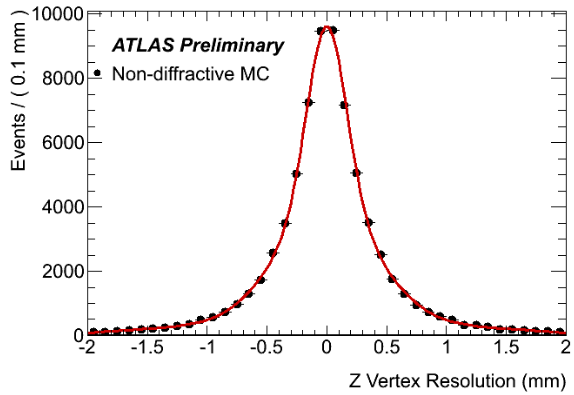
Clear improvement in the angular region populated by 2-pixel clusters.

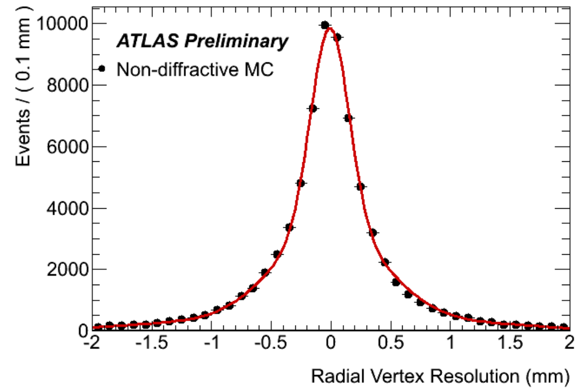
From test beam studies intrinsic resolution 6-8 μm, before radiation damage

N.B.: residuals include also extrapolation resolution

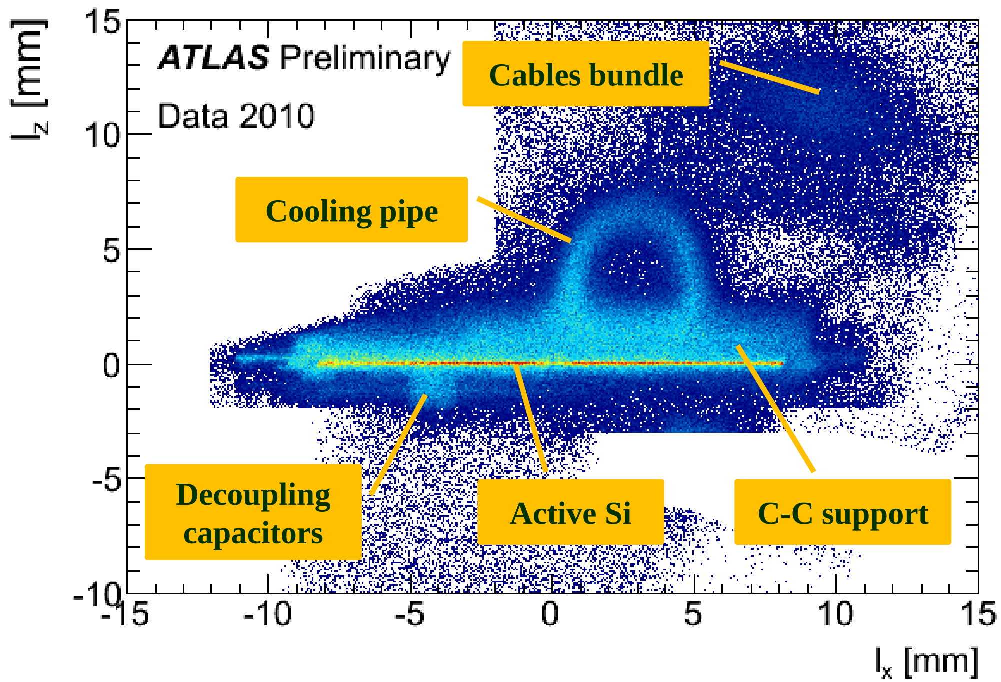
Hadro-graphy

- Material mapping usually performed by photon conversions





- Hadronic interactions can reach a better position resolution:
  - larger opening angle
  - σ=160 μm at Layer-0
- Very accurate detector mapping!



- Applications:
  - Average λ_I measurement
  - Positioning of non-sensitive material (beam pipe, support structures)

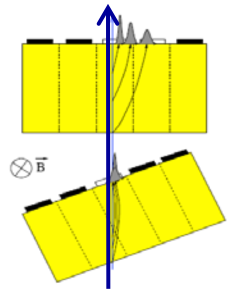
- Lorentz angle
- Energy loss measurement

DETECTOR PROPERTIES

Lorentz angle

- Drift in silicon is affected by E×B effect
- Charge is (de)focused along the Lorentz angle direction:

$$\tan \alpha_L = \mu_H B$$

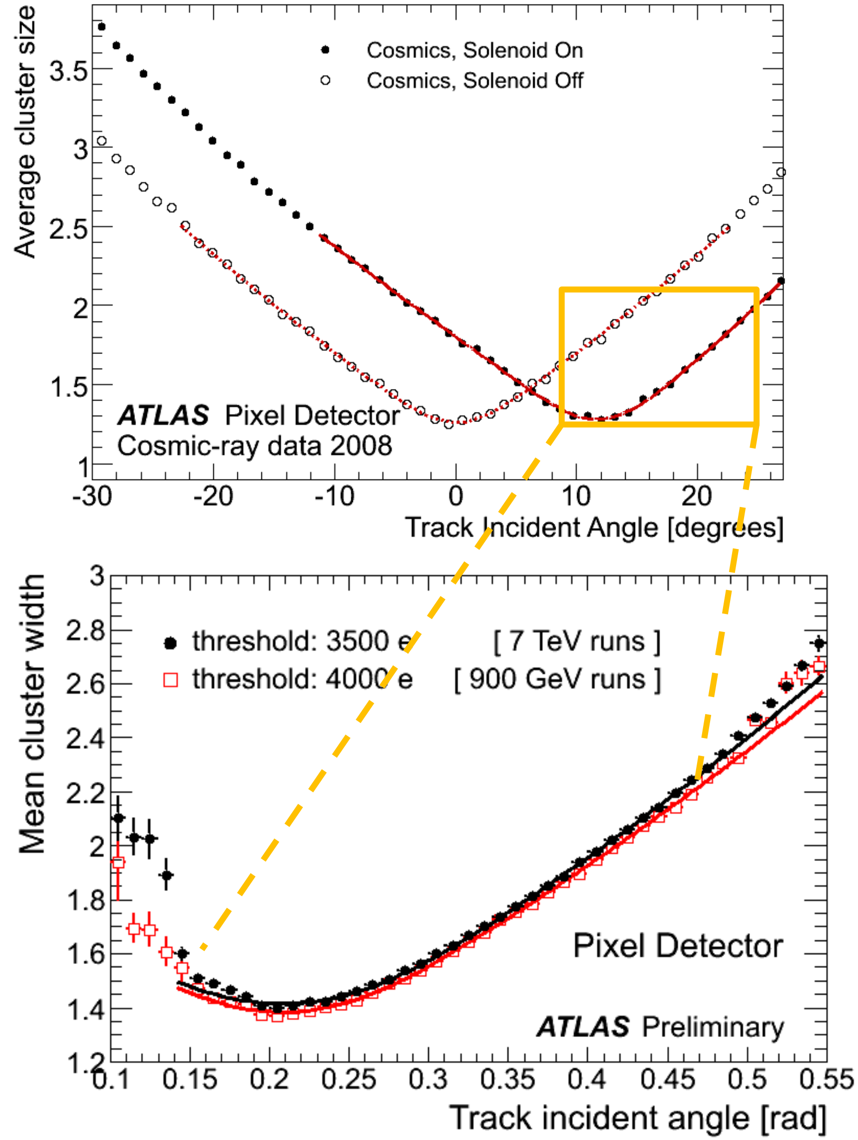


- Point displacement ≈ 30 μm for pixels
- **Measurement using cluster size vs. incidence angle α:**

$$\text{cluster size} = a\left(\tan \alpha - \tan \alpha_L\right) + b / \sqrt{\cos \alpha}$$

Data sample	α_L [°]
Cosmic rays	$11.77 \pm 0.03^{+0.13}_{-0.23}$
√s = 900 GeV	12.12±0.15
√s = 7 TeV	12.11±0.09

Preliminary, only stat. uncertainty



- **Difference due to temperature!**

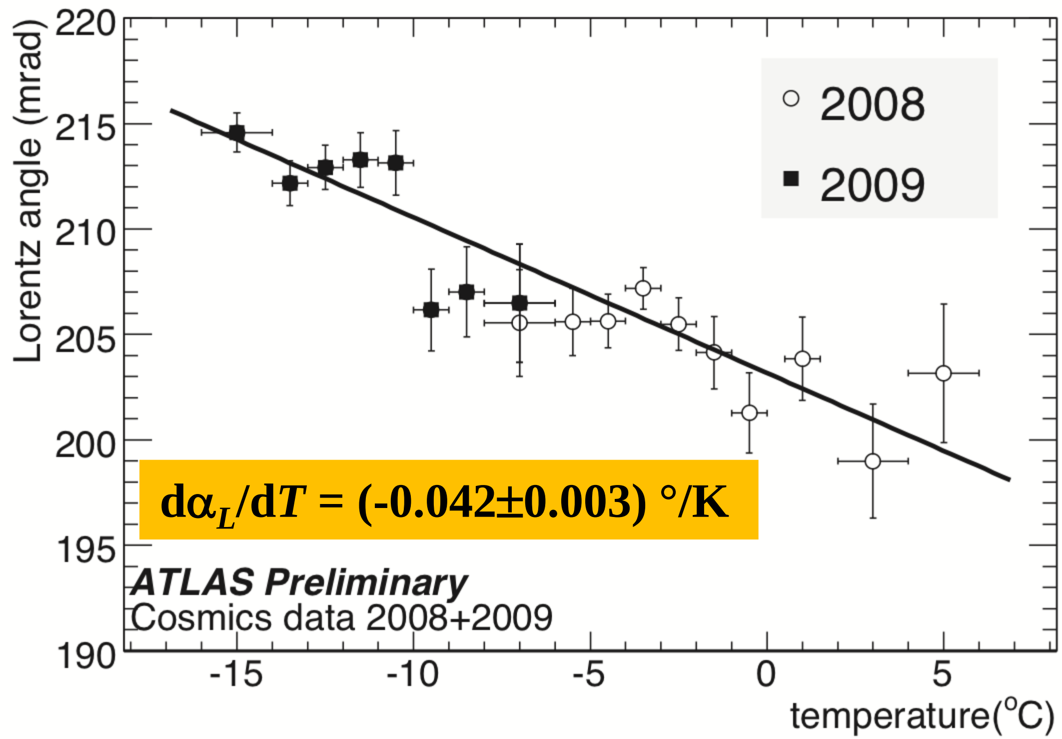
Lorentz angle: T dependence

- **The cooling system was commissioned in 2008.**
- Since 2009 operation at nominal settings.
- **The different operational point allows to measure *T* dependence of Lorentz angle**

$$\tan\theta_L = \mu_H B$$

$$\mu_H = \frac{r v_s / E_c}{\left(1 + \left(E / E_c\right)^{\beta}\right)^{1/\beta}}$$

	Electrons
$v_s(\mathrm{cm\ s^{-1}})$	$1.53 \cdot 10^9 \cdot T^{-0.87}$
$E_c(\mathrm{V\ cm^{-1}})$	$1.01 \cdot T^{1.55}$
β	$2.57 \cdot 10^{-2} \cdot T^{0.66}$
r	$1.13 + 0.0008 \cdot (T - 273)$



Expected from parameterization: -0.042 °/K
Point correction is small: ~0.1 μm/K
...but nice it can be observed

Parameterization: C. Jacoboni *et al.*, Solid-State Electronics 20 (1977) 77-89.
T. Lari, ATL-INDET-2001-004

Specific energy loss measurement

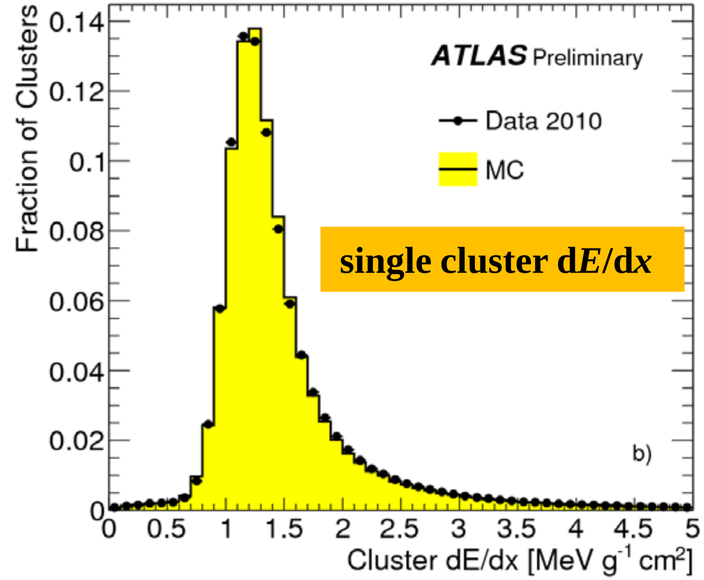
- **ToT charge measurement well modeled by MC simulation:**
  - from cosmic ray data:

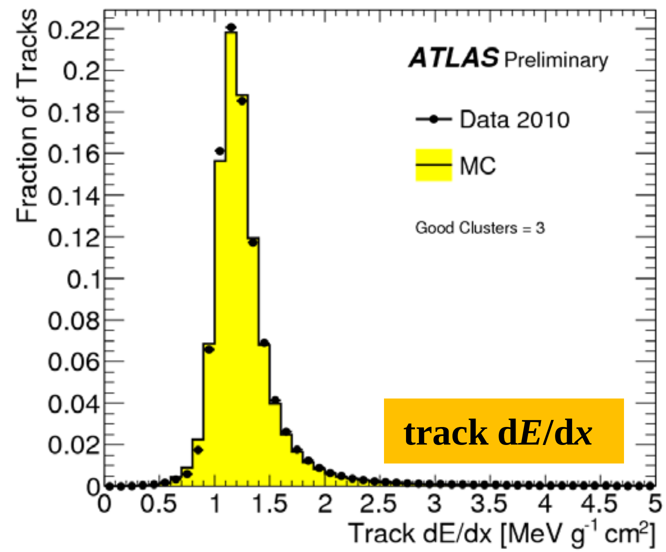
$$\frac{Q_{\mathrm{data}}}{Q_{\mathrm{MC}}} = 0.986 \pm 0.002\ \text{(stat.)} \pm 0.030\ \text{(syst.)}$$

- Since typically **a track has three pixel hits**, they can be combined to provide a **dE/dx measurement**:
  - remove clusters near module edges or in the ganged region;
  - use truncated mean, discarding the cluster with highest energy deposit.

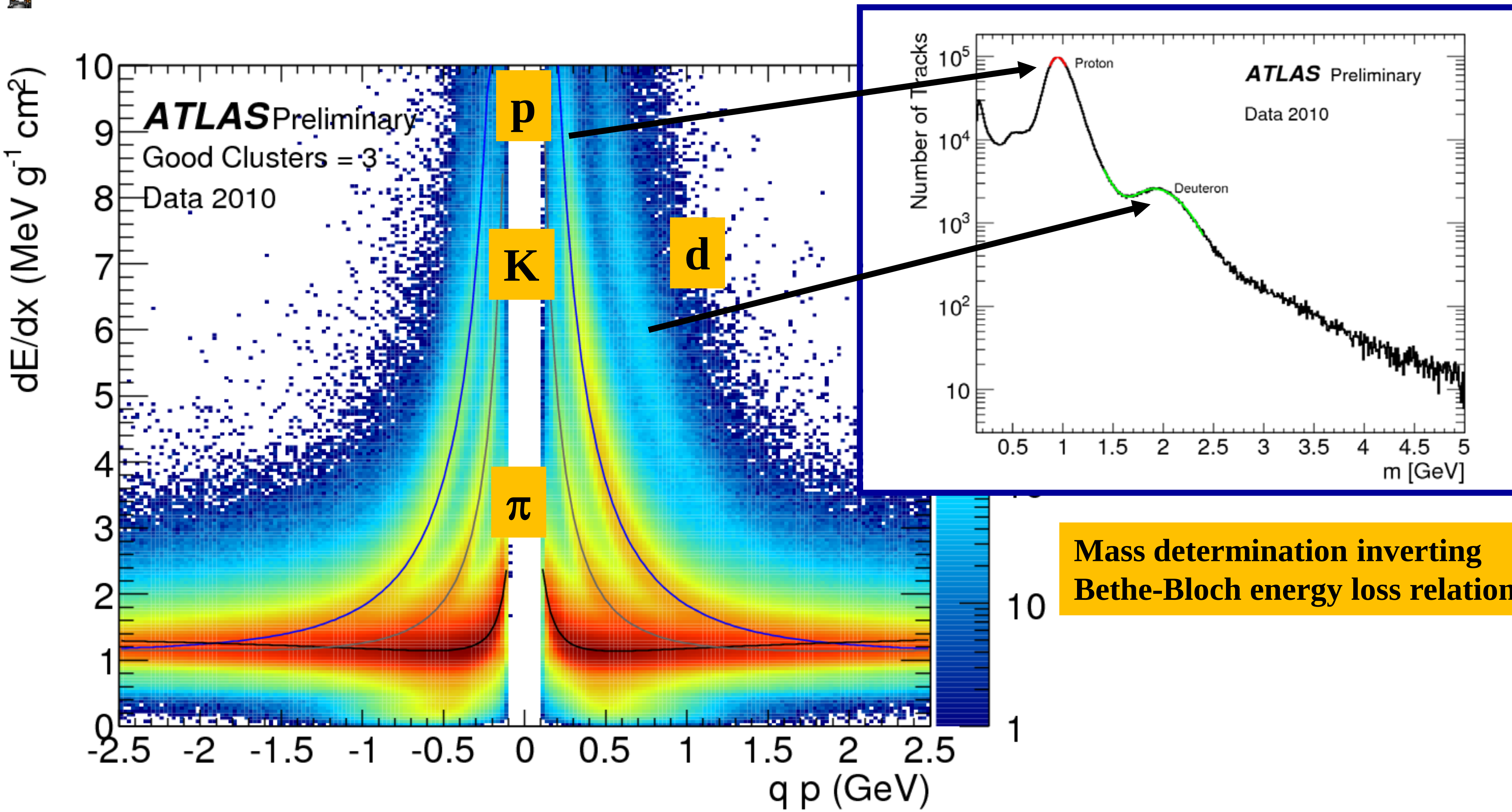
  Suppress most Landau tails.

- **Resolution of 11% measured on the relativistic plateau**





dE/dx at work

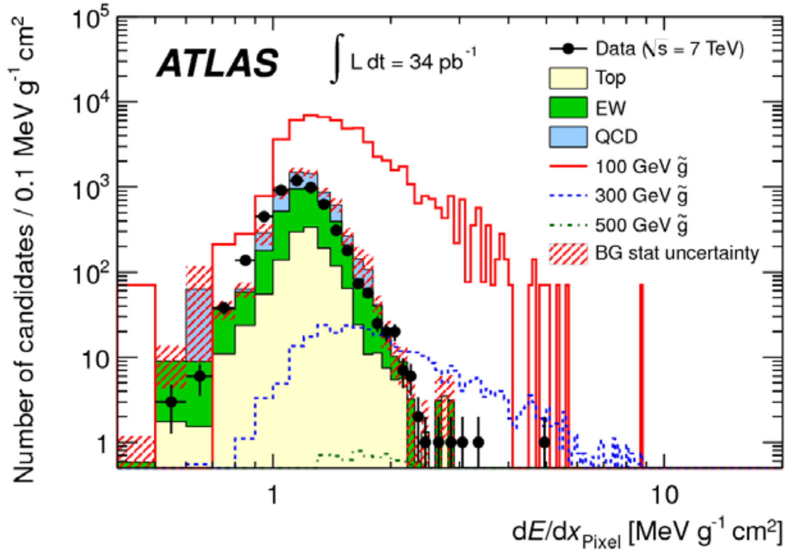


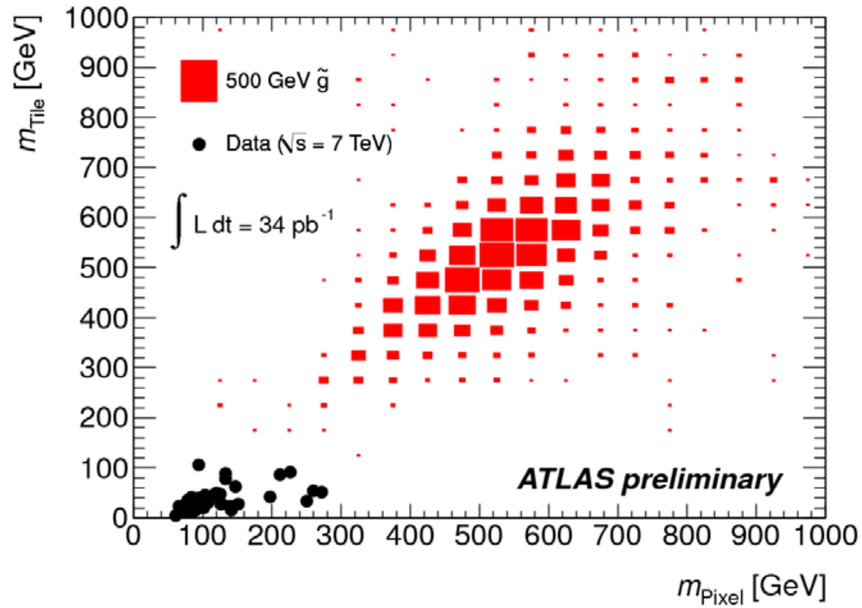
Mass determination inverting Bethe-Bloch energy loss relation

Applications: R-hadron searches

- Direct application of dE/dx measurement is the search for new particles:
  - **high mass**
  - **long-lived**
  - **charged** .
- Example: **R-hadrons**
  - **colourless** states predicted in some SUSY models, composed by stable **squarks** and **gluinos** and ordinary particles
- **Signature:**
  - High-p_T tracks with high energy loss
  - Combination with time-of-flight measurement by calorimeters.
- **Exclusion limits at 95% CL:**

$$m_{\tilde{b}} > 294 \text{ GeV}$$
$$m_{\tilde{t}} > 309 \text{ GeV}$$
$$m_{\tilde{g}} > 562 \text{ GeV}$$



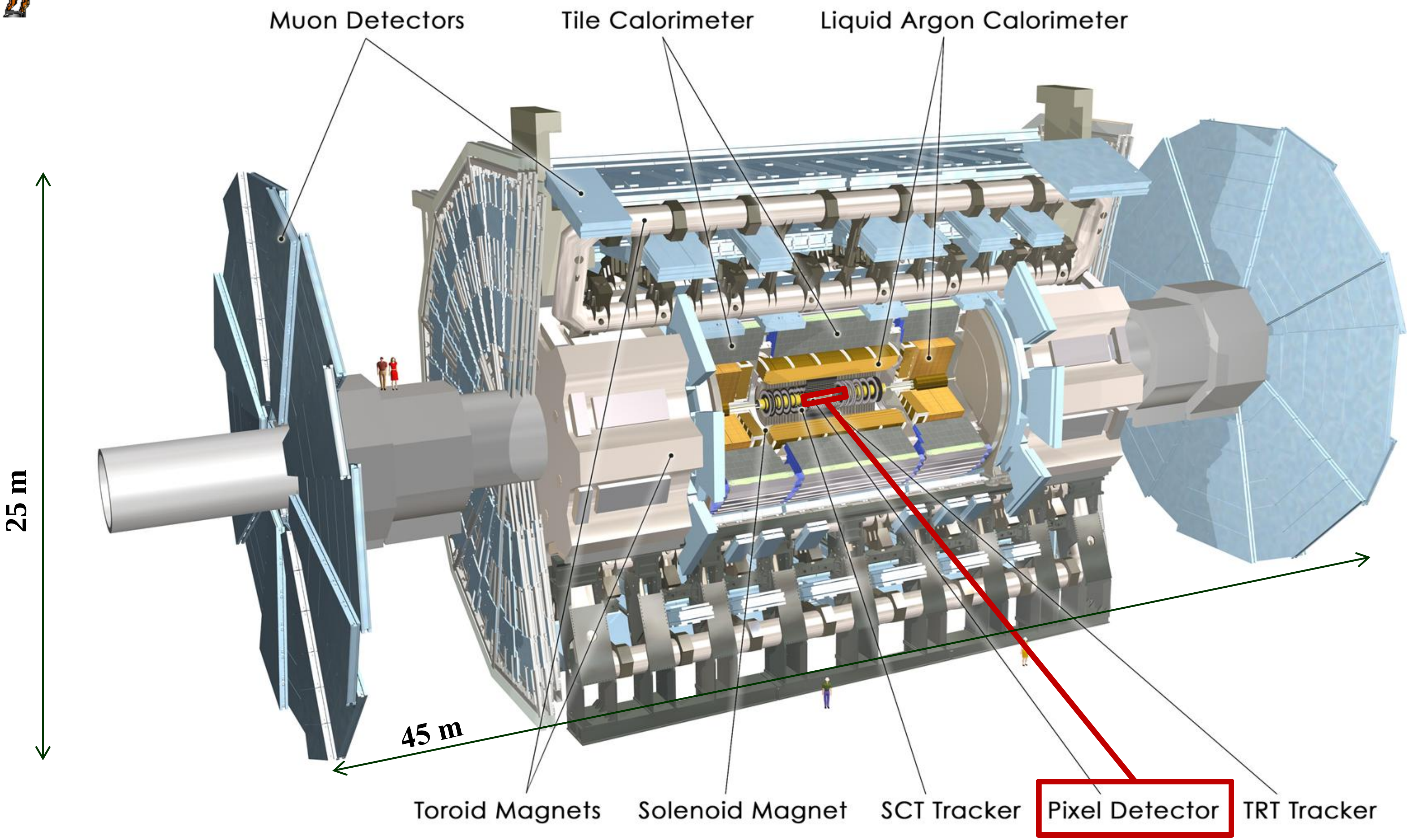


Conclusions

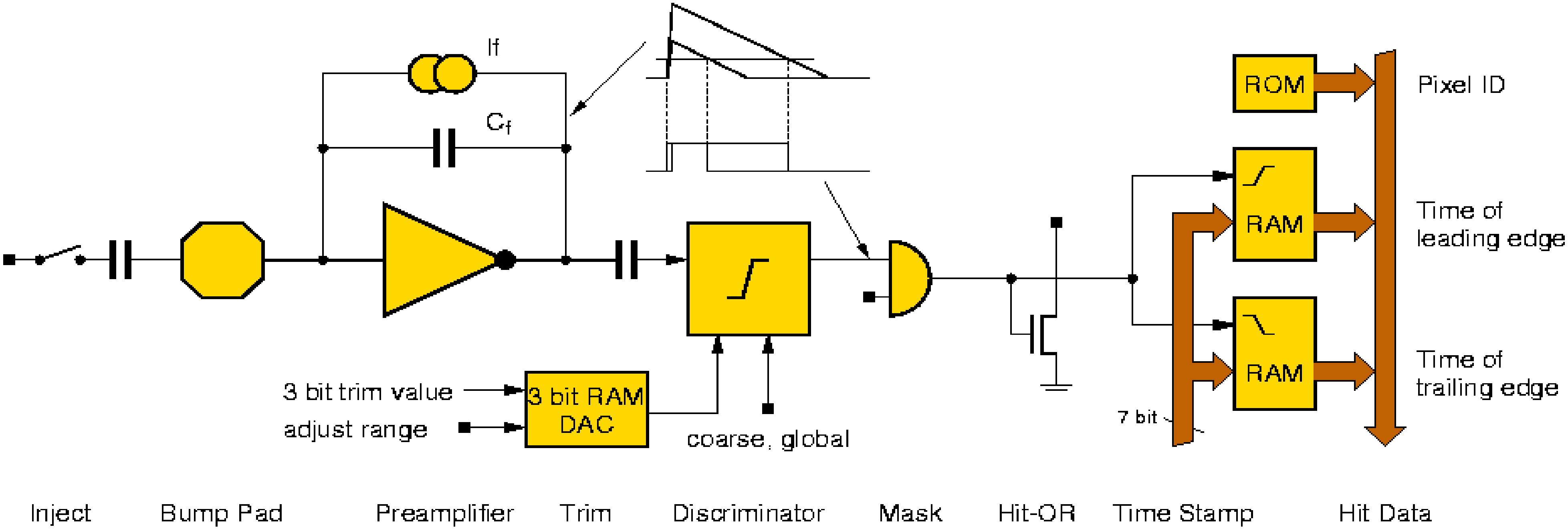
- **Full detector characterization performed:**
  - Mapping of inefficiencies
  - Calibration of charge sharing
  - Lorentz angle measurement and its temperature dependence
  - d*E*/d*x* measurement with 11% resolution
  - Material estimation
- **Excellent performance:**
  - noise occupancy rate O(10^{-10})
  - track association efficiency at 99% level
  - Resolution near to nominal
- **Pixels in ATLAS physics publications:**
  - Electron and photons
  - Heavy long-lived charged particles
  - Particle multiplicity in heavy ion collisions

BACKUP

A Toroidal LHC Apparatus

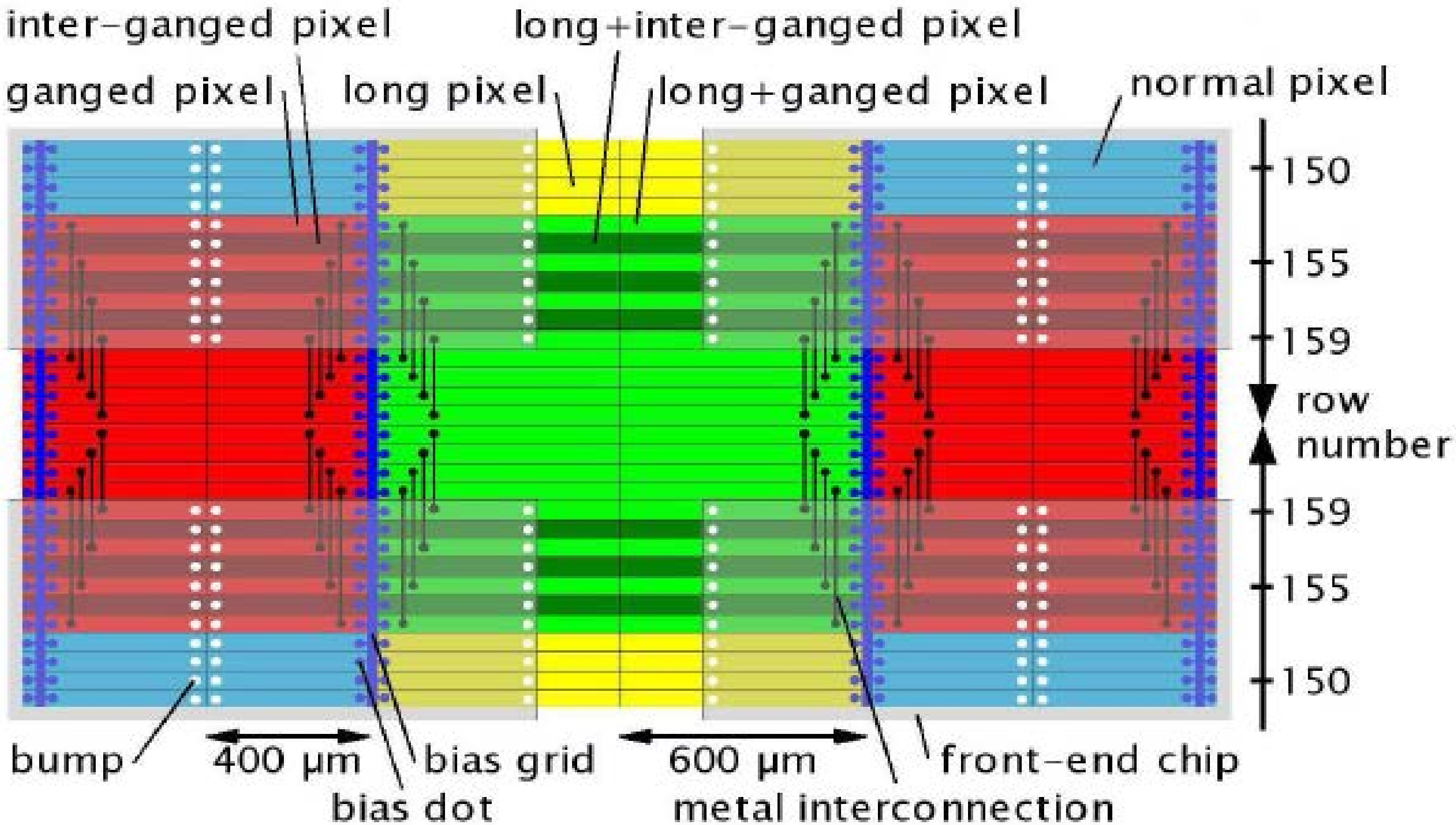


Front-end electronics concept



- Fast charge amplifier with constant current feedback.
- Fast discriminator with tunable threshold (7-bit DAC)
- Storage of hits during the trigger latency time in 64 “End of Column” memory buffers for each column pair of 2×160 pixels

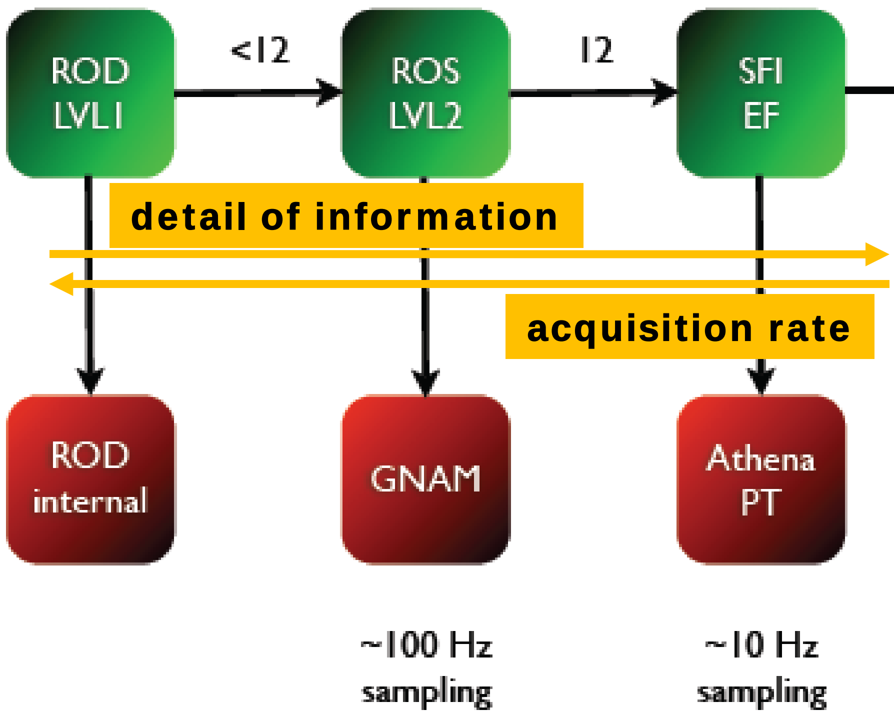
Pixel types



- For ganged pixels, the spacing in the inter-chip region and in the chip-edge regions are different:
  for multiple-pixel clusters it is possible to disentangle in which region it was generated.

Monitoring

ONLINE



- Occupancy
- Readout errors
- ToT distribution

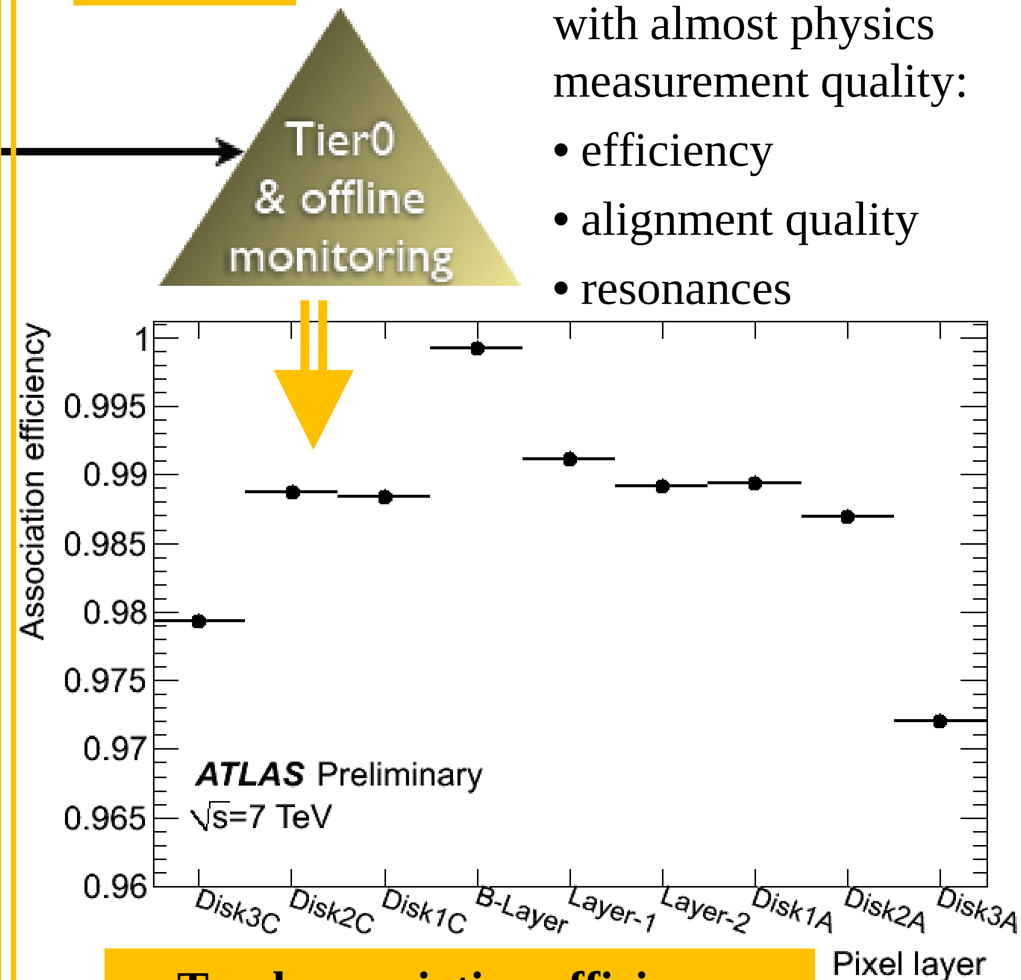
+ Disabled modules

+ Hit and cluster properties
+ Track reconstruction

OFFLINE

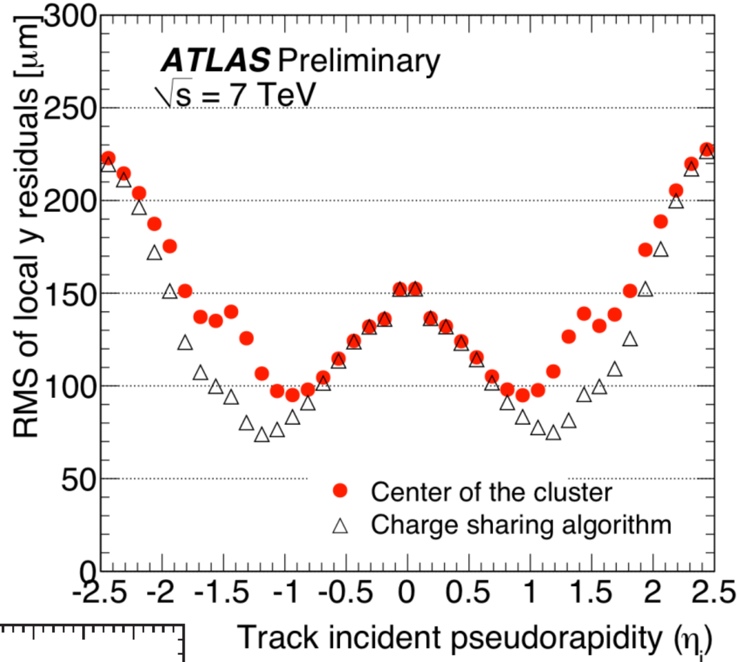
Information with almost physics measurement quality:

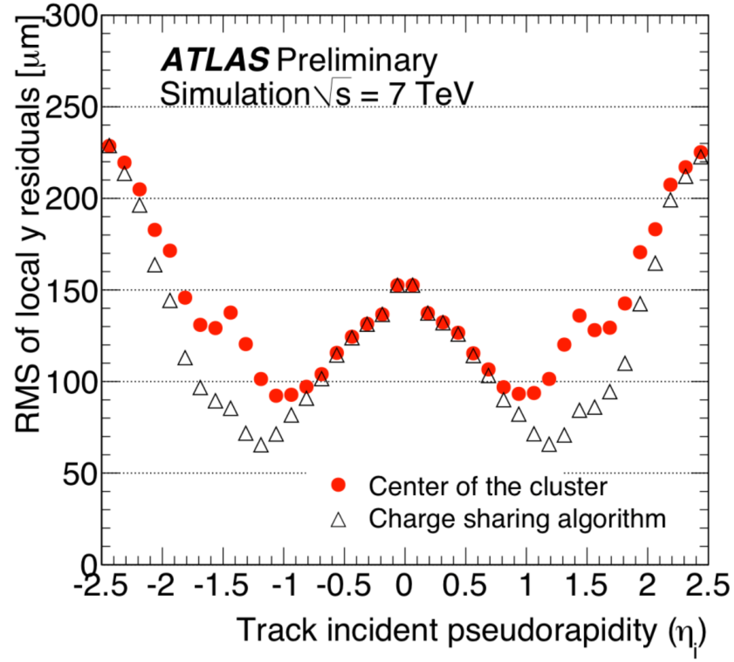
- efficiency
- alignment quality
- resonances



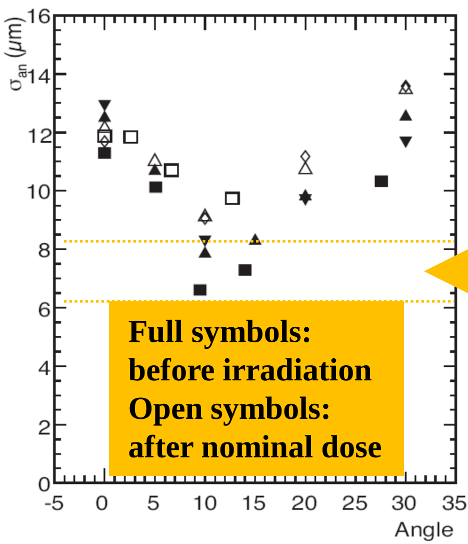
Track association efficiency
(corrected for dead modules)

Charge sharing: resolution





Good agreement with simulation



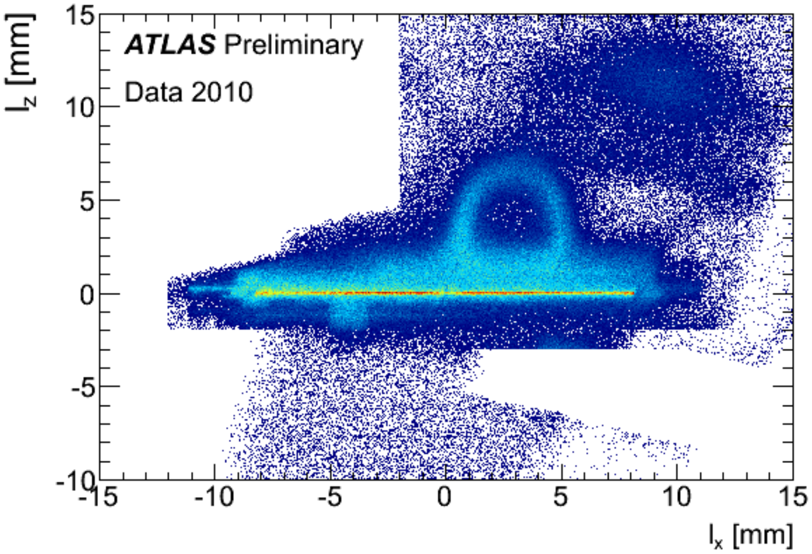
Clear improvement in the angular region populated by 2-pixel clusters.

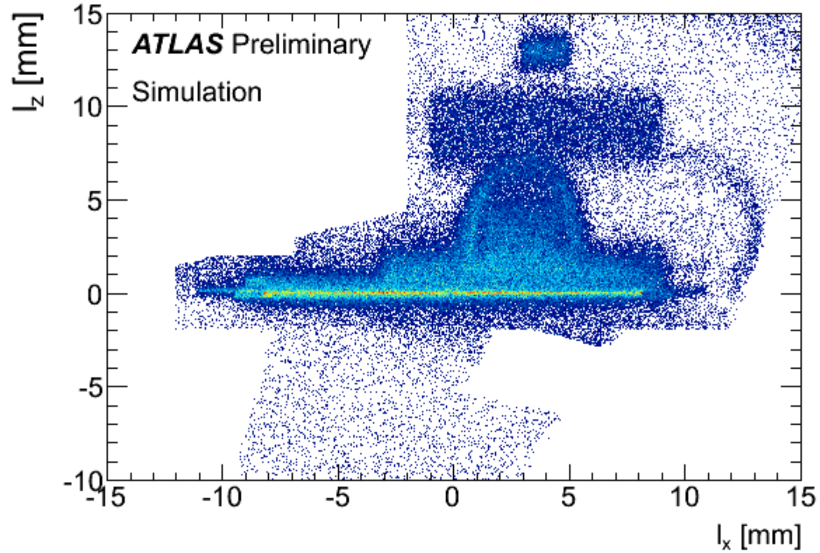
From test beam studies intrinsic resolution 6-8 μm, before radiation damage

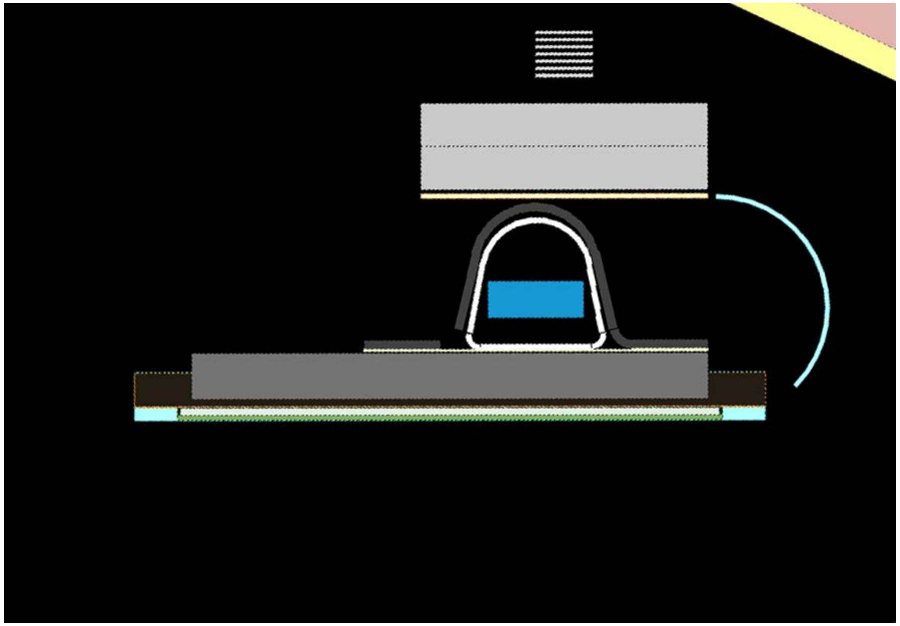
Unfortunately residuals include also extrapolation resolution:

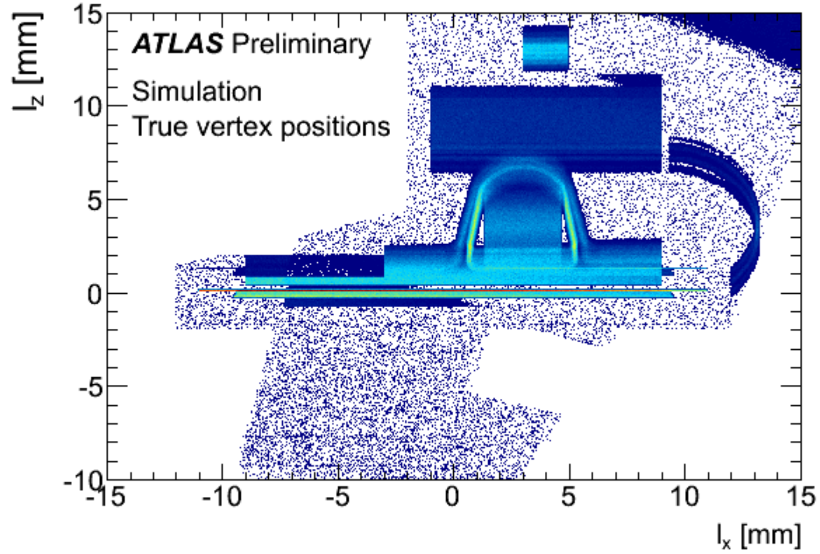
in minimum bias collisions dominated by multiple scattering term.

Hadronic interaction maps



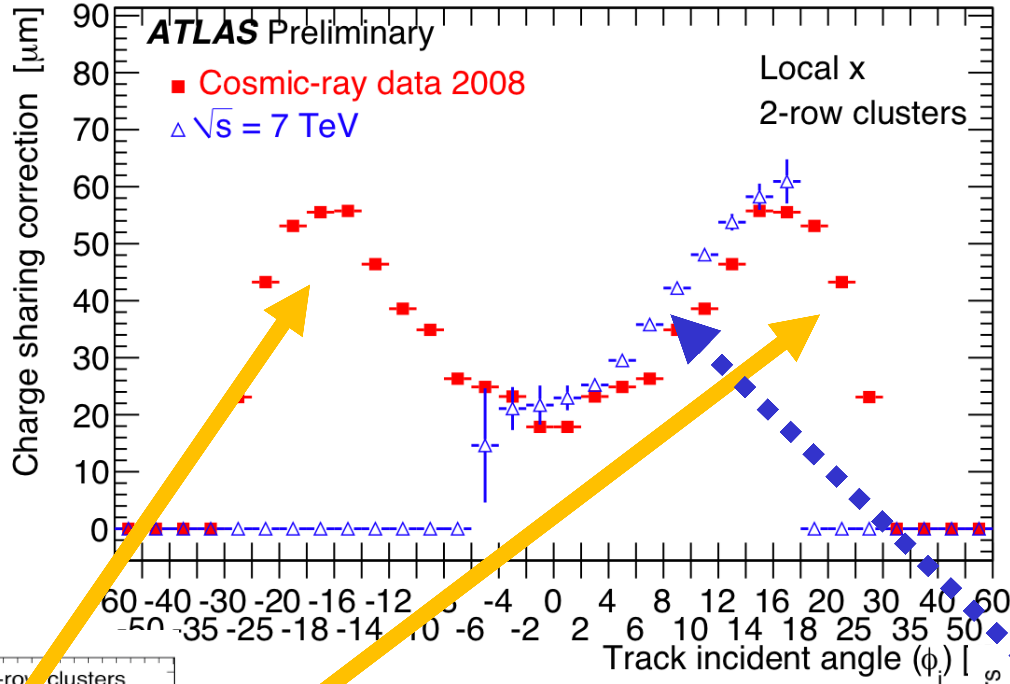


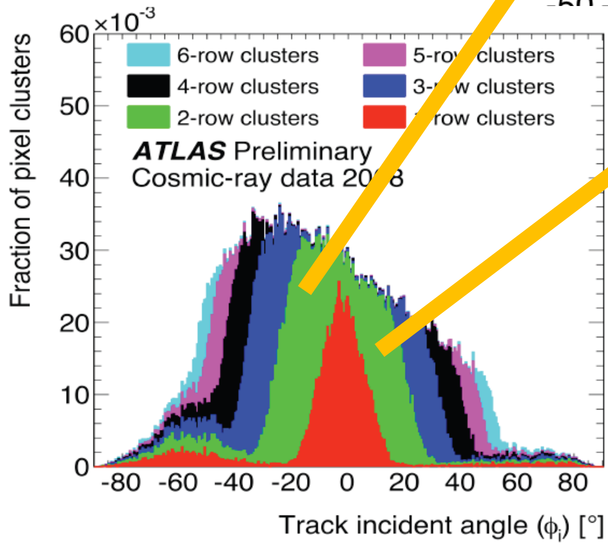




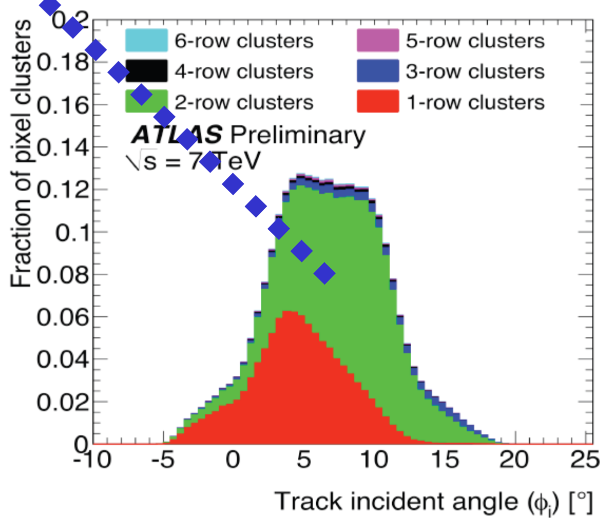
Charge sharing (2)

Δ_x for 2-hit clusters





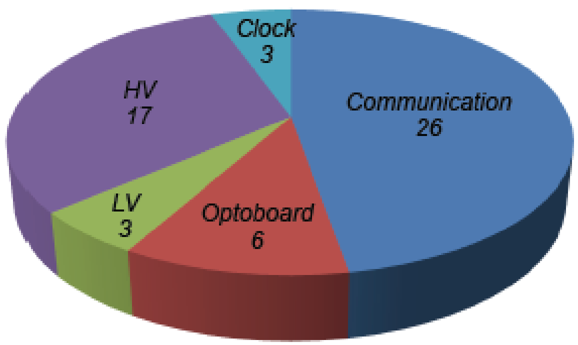
N.B.: different thresholds used for cosmic rays and collision data



Pixel Detector Status

- 96.8% of the detector active in data taking
  - 55 Modules disabled (3.2%)
    (6 modules due to a single opto-board failure)
  - 47 FE chips disabled (0.16%)
  - In particular failures are linked to thermal cycles
    → an attempt has been made to reduce the problem by smaller temperature variations with first modest results, more refinements will be tried
  - The percentage of disabled modules grew from 2.1% to 3.2% in 3 years of operations

Disabled modules by failure type:



Inactive fraction per layer:

B-layer	3.1 %
Layer 1	1.4 %
Layer 2	4.6 %
Endcap A	2.8 %
Endcap C	2.8 %