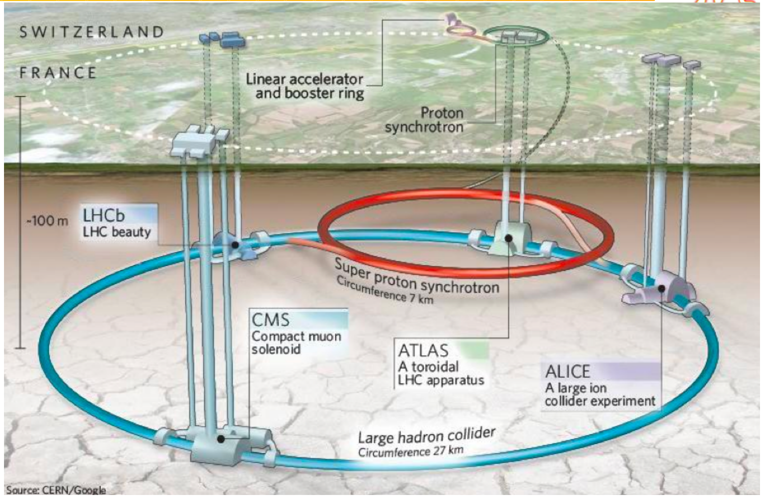
Tracking and vertexing performance of the ATLAS Inner Detector at the LHC

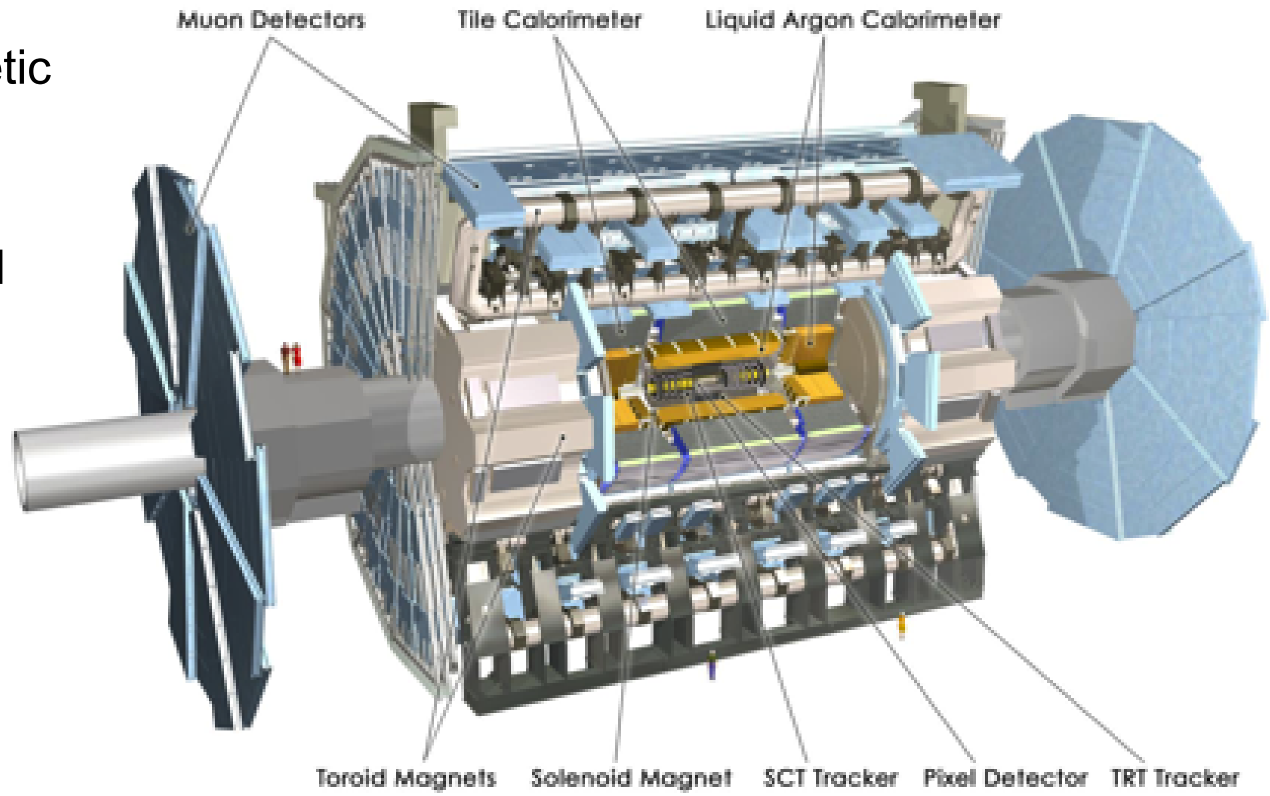
S. Martí
IFIC-València
On behalf of ATLAS coll.
RD 11, Florence
6/July/2011

The ATLAS experiment at the LHC

- LHC: Large Hadron Collider
  - Proton-proton collisions at 900 GeV (2009)
  - Proton-proton collisions at 7 TeV (2010-11)
  - Lead-lead ion collisions (2010)

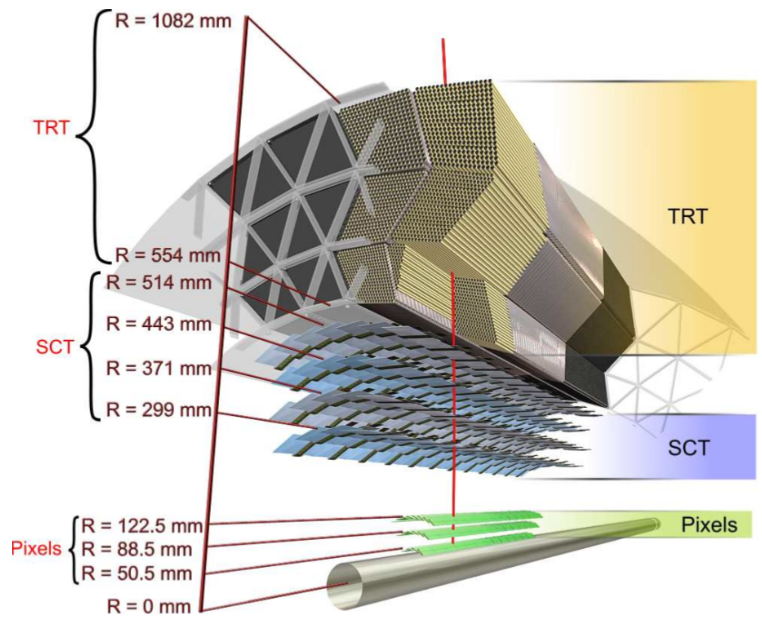


- ATLAS: general purpouse experiment
  - Tracking system (Inner Detector)
    - Efficient and accurate charged particle reconstruction
  - Calorimeter system
    - Electromagnetic
    - Hadronic
  - Muon system
    - Air core toroid

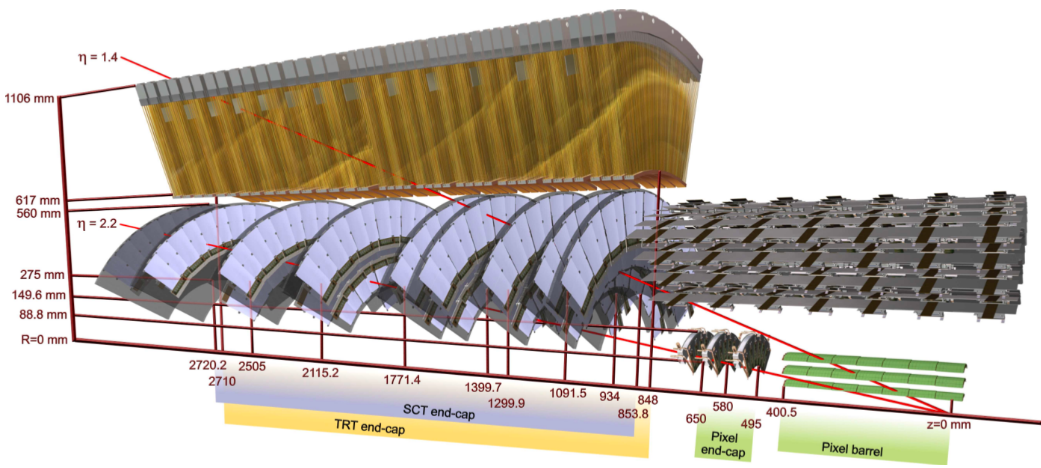


Inner Detector: tracking system

- The Inner Detector (ID) is the main tracking system of ATLAS. The ID comprises 3 different subsystems embedded in a 2T axial field.
  - Pixel (3 measurements/track)*
  - SCT (8 measurements/track)*
  - TRT (30 measurements/track)
- Each subsystem is composed of:
  - Barrel (B)
  - 2 end caps (A,C)
- Sensor dimensions and resolutions
  - # channels



Subdetector	r (cm)	Elements size	Resolution (X * Y)	hits/track (average)	channels
Pixel (silicon pads)	5 – 12.5	50 µm * 400 µm	10 µm * 115 µm	3	80×10^6
SCT (silicon microstrips)	30 – 52	80 µm * 12 cm (stereo)	17 µm * 580 µm	8	6.3×10^6
TRT (Transition Radiation)	56 – 107	4 mm (diameter)	130 µm	30	3.5×10^5



* There are some regions with module overlaps

Detector status

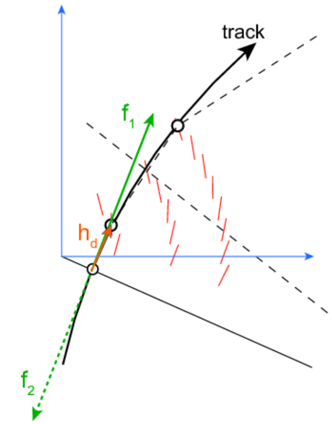
- Overall active detector

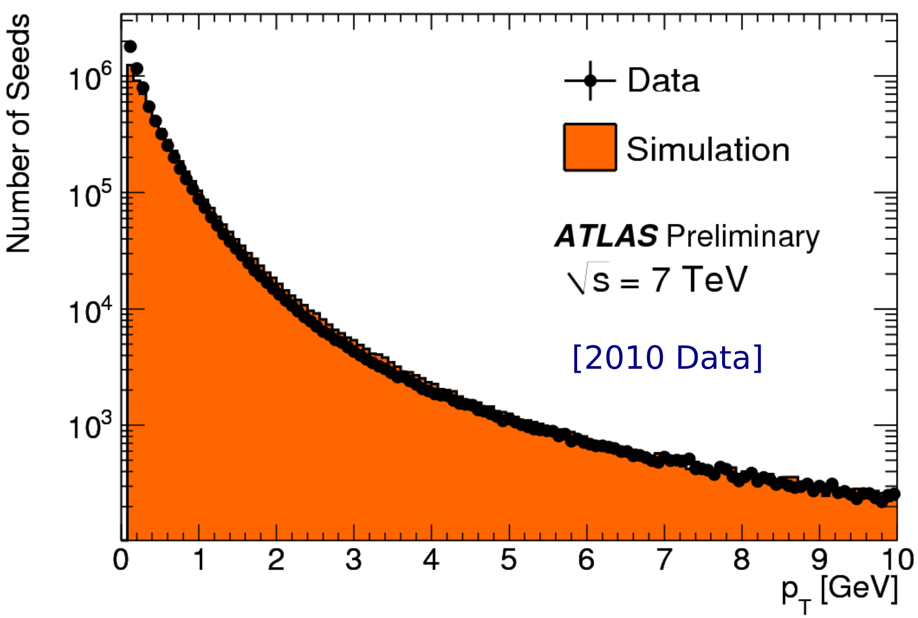
subdetector	# channels	Approx. Operational
Pixel	80 M	97.3 %
SCT (microstrips)	6.3 M	99.2 %
TRT (Transition Radiation Tracker)	350 k	97.1 %

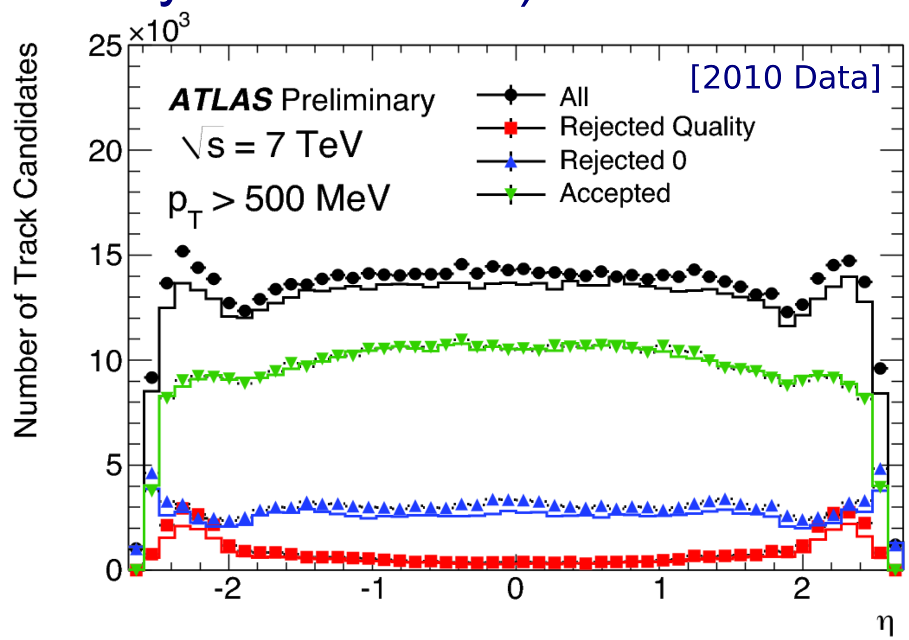
- Pixels:
  - 48 disabled modules (out of 1744)
    - 6 of them in the innermost layer (B-layer)
  - Permanent failures: mixture of HV, LV and optical connection problems
  - Temporary failures: optical transmitters, busy read out, etc.
- SCT:
  - 24 disabled modules (out of 4880)
    - 14 of them in the same cooling loop in outermost end-cap disk
  - Some failures also due to optical transmitters
- TRT:
  - Most failures due to HV
  - Barrel 1.5%, end-cap C 0.2%, end-cap A 1.1%

Pattern recognition

- Two-stage pattern recognition
  - Inside-out → pixel seeding + outward extension
  - Outside-in → TRT track segment seed + inward extension
- Performance at the different levels of the track reconstruction
  - Seeding, track candidate fitting, solving ambiguities
- A robust pattern recognition is a key ingredient for good tracking
  - Changing conditions of noisy/dead modules
  - Varying detector calibrations and alignment
- Excellent performance (already with the early ATLAS data)

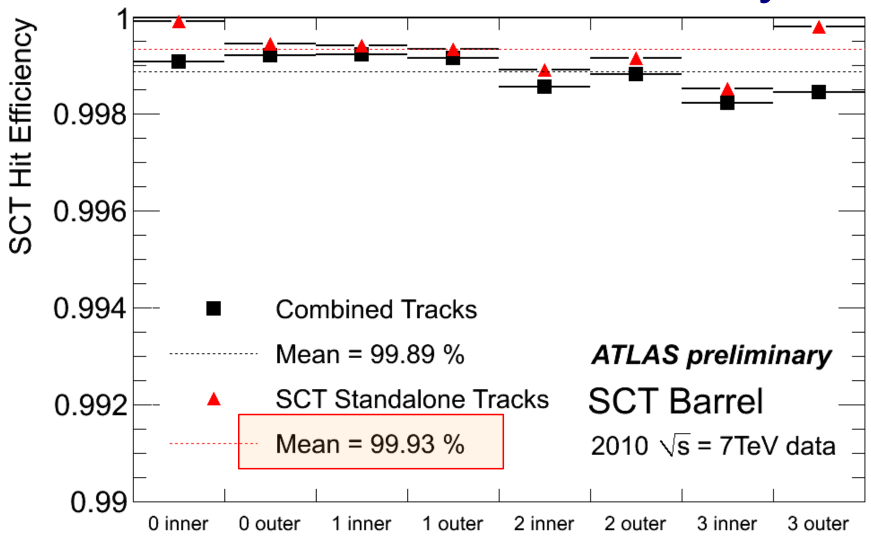


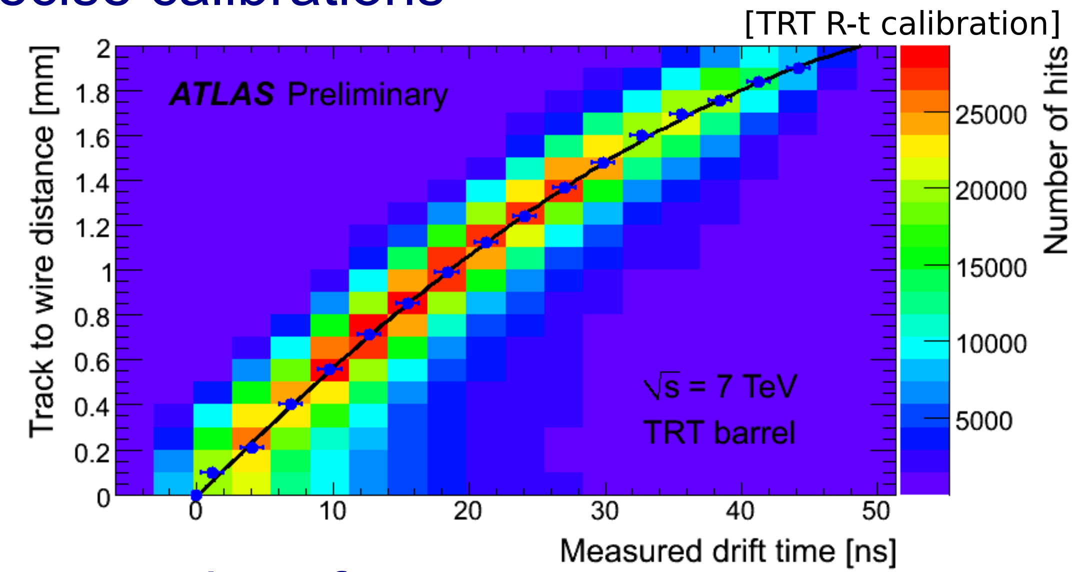




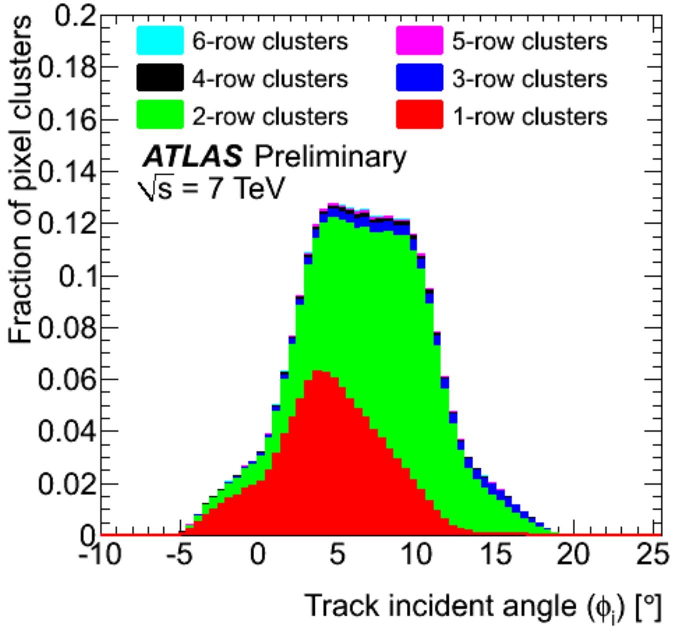
Precision positioning of space points

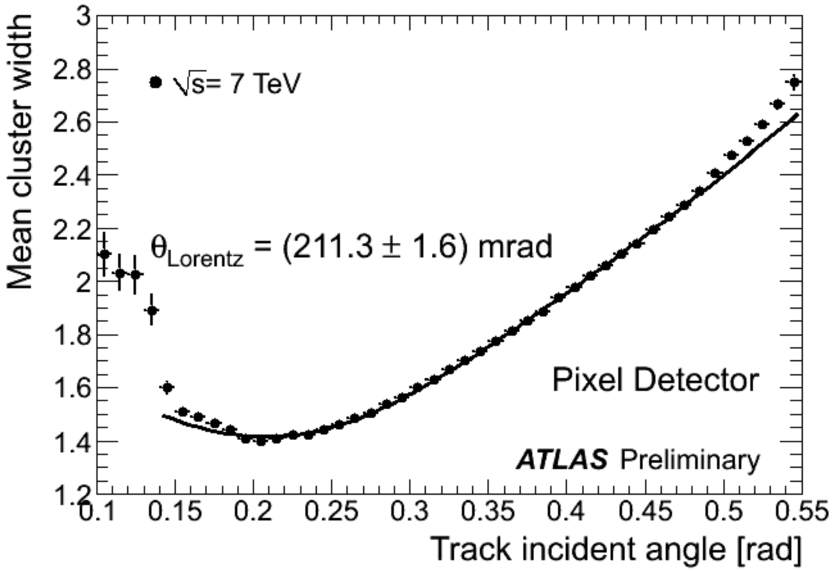
- Excellent detector efficiency and precise calibrations





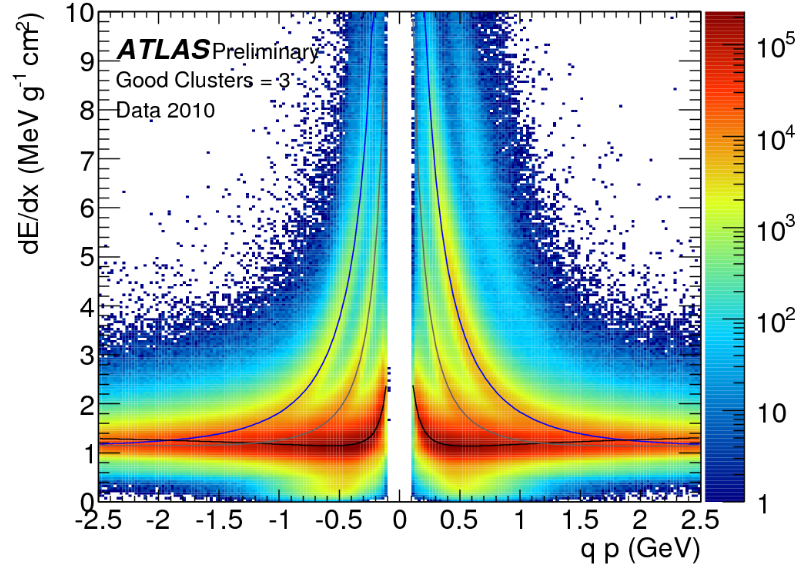
- Precise pixel clusterization includes corrections for:
  - Incident angle, Lorentz angle, charge sharing, time-over-threshold, etc.





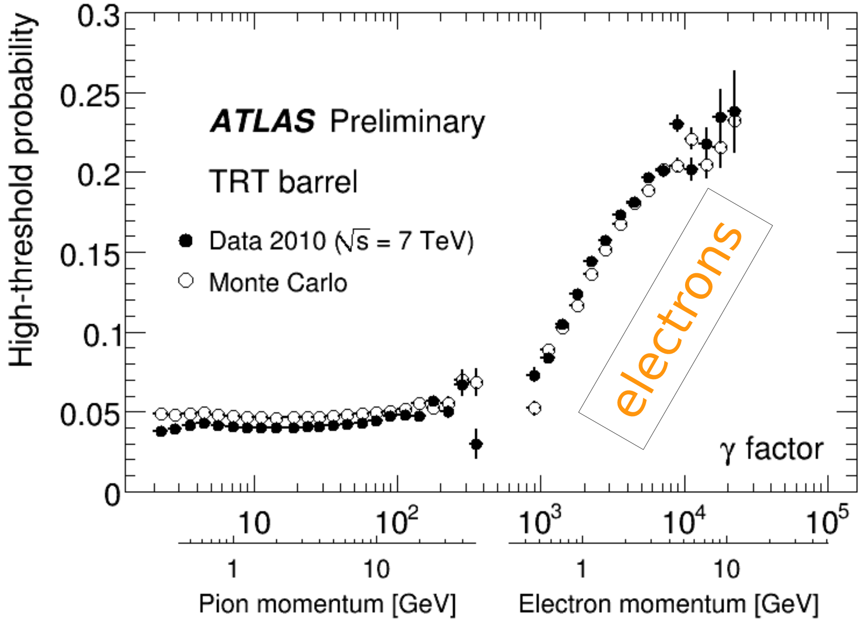
Particle ID

- Particle ID in the Pixel detector thanks to dE/dx
  - Using cluster charge info.
  - Bands visibles for:
    - π^+,π^-
    - k^+,k^-
    - p, $\bar{p}$
    - Deuterons

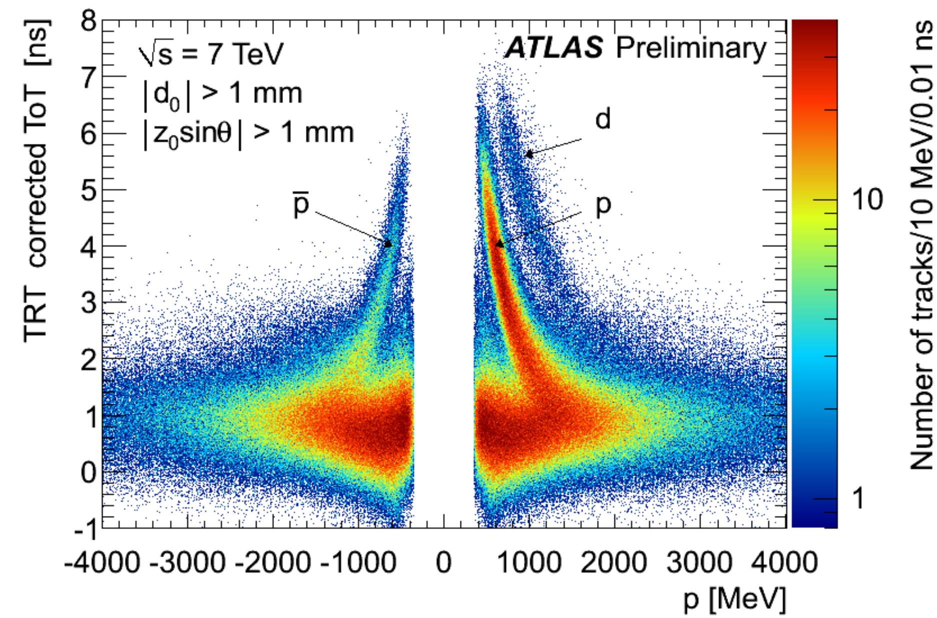


- Particle identification in TRT
  - High threshold hits: Transition radiation onset (for electron ID) & dE/dx

[Tansition radiation onset]

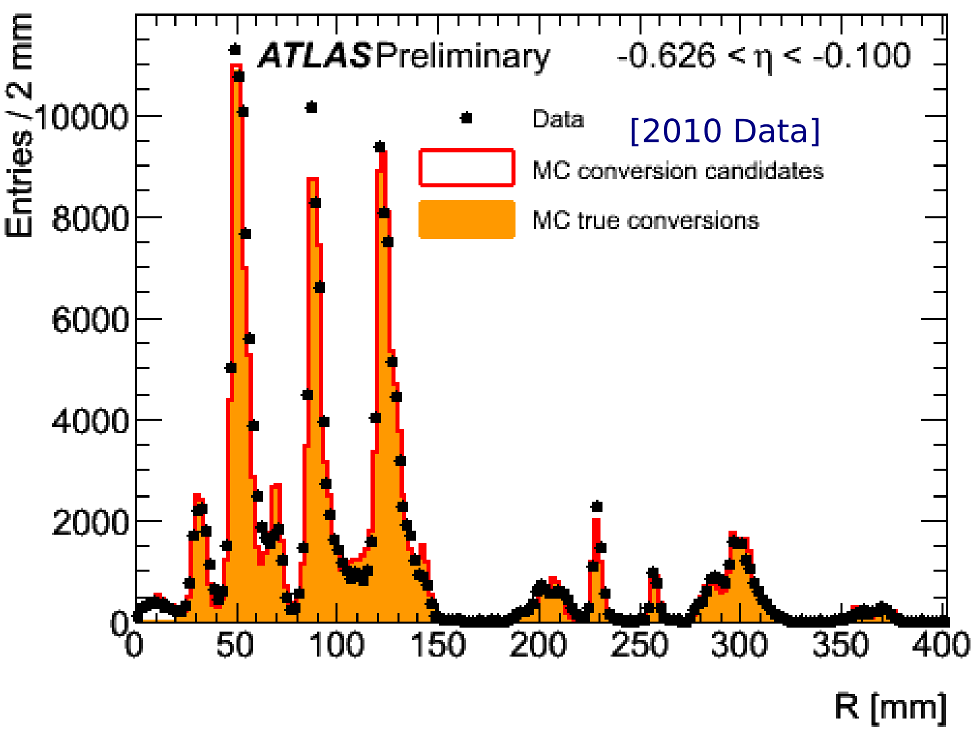


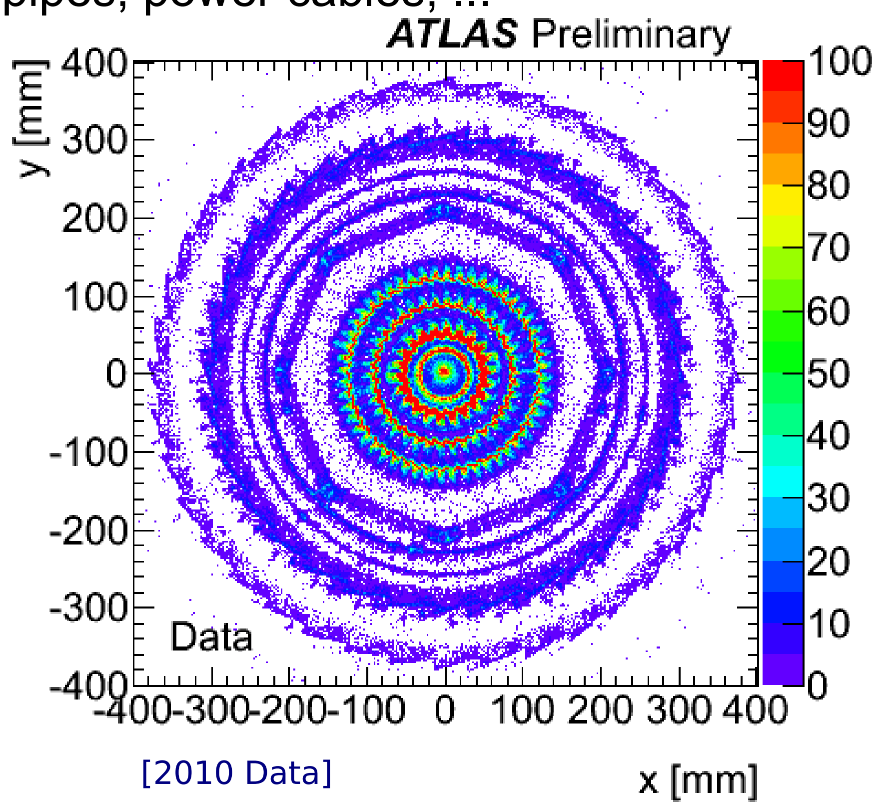
[dE/dx for secondary particles]



Material studies

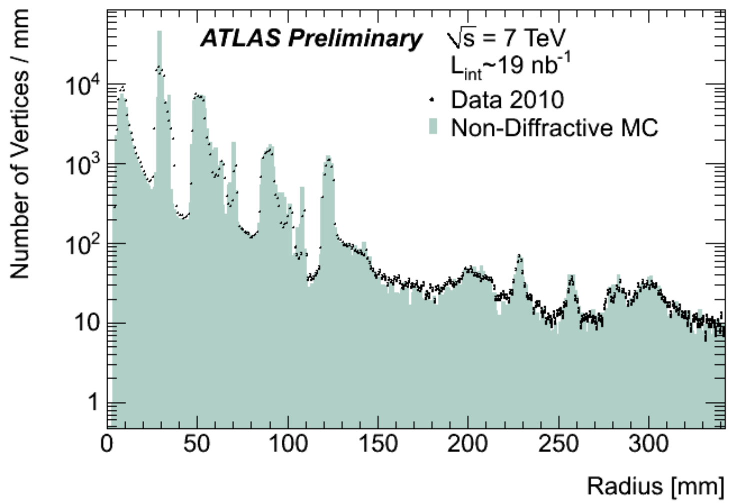
- The precise knowledge of the material budget within the tracking volume is mandatory for an accurate track reconstruction
  - Photon conversions & hadronic interactions allow to study the material
- Photon conversions allow for:
  - Very precise estimate of the material
    - "calibrate" w.r.t. well known reference object as beam pipe.
  - Understand geometrical data/MC differences
    - supporting structures, cooling pipes, power cables, ...





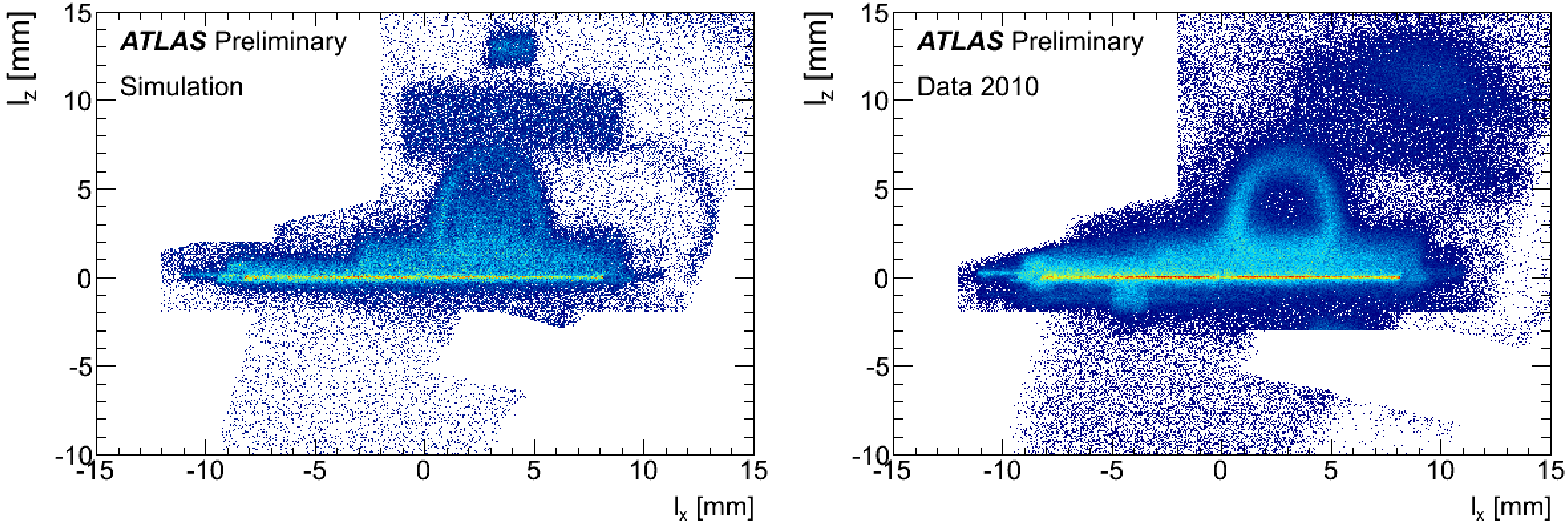
Hadronic interactions

- Reconstruction of hadron interaction vertices is a precise method for a detector tomography
  - Reveal the true material
  - Excellent vertex resolution is mandatory



- Material uncertainty in simulation
  - Better than 5% in barrel region
  - At the 10% level in the end-caps
  - Study of systematics: ongoing

[Hadronic interactions in the vicinity of a pixel module]



- The limited knowledge of the alignment constants should not lead to a significant degradation of the track parameters beyond the intrinsic tracker resolution, nor introduce biases
  - Initial physics goal: maximum 20% degradation
  - Mechanical assembly precision

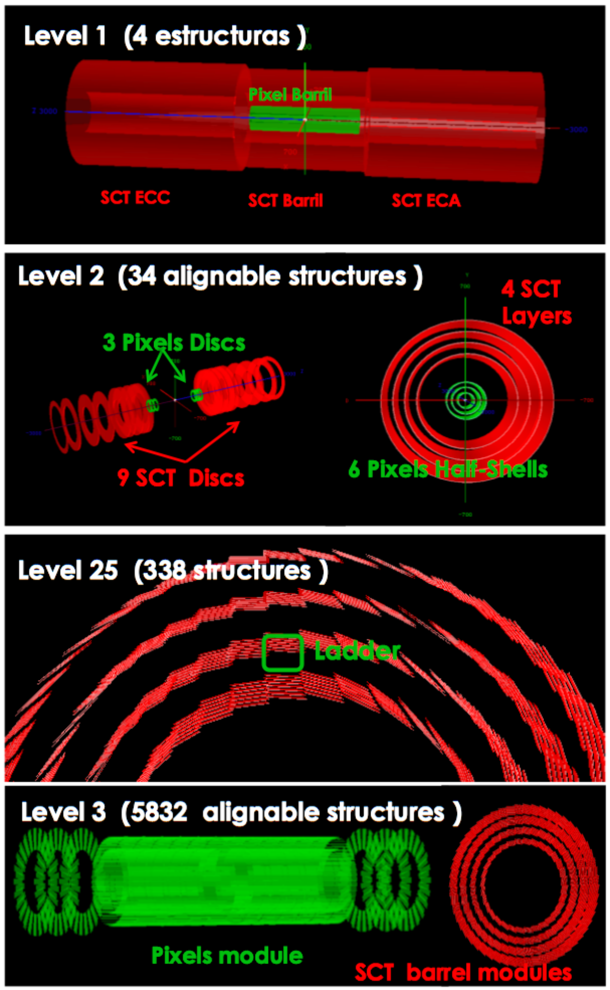
	pixels		SCT	
	barrel	endcap	barrel	endcap
rΦ(μm)	7	7	12	12
z (μm)	20	100	50	200

[maximum allowed random misalignment of the silicon modules]

- Higher accuracy is required for precision physics measurements
  - A 15-20 MeV precision in the W mass requires 1μm alignment precision.
  - Higgs search, if $180 < m_h < 400$ GeV ($H \rightarrow ZZ \rightarrow 4\ell$)
  - B-tagging: impact parameter & mass
- Alignment using 7 TeV data: hard momentum (minimize scattering)
  - Calibration stream: filtered online by the High Level Trigger
    - Select isolated collision tracks with p_T cut > 9 GeV
  - Cosmic rays:
    - Triggered during empty LHC proton bunches (same detector conditions)
- Beam spot constraint
  - As well as survey assembly data, MS momentum and E/p constraints.

ID structures and alignment levels

- The alignment proceeds from large structures to module level with increasing granularity of structures and number of degrees of freedom
  - Barrel and/or end-caps
  - Barrel layers and end cap disks/wheels
  - Silicon modules and TRT wires



	structures			Corr. Size
	pixel	SCT	TRT	μm
Level 1	1	3	3	**1000**
Level 2	12	22	96	**100**
Level 3	1744	4088	350848	**10**

	strucures		DoFs
	pixel	SCT	#
Level 1	1	3	24
Level 2	12	22	204
Level 3	1744	4088	34992

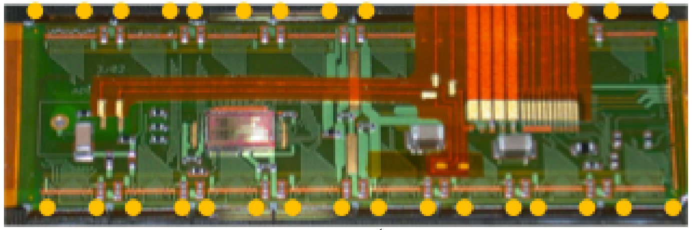
	TRT		DoFs
	Barrel	End cap	#
Level 1	1	2	18
Level 2	96	80	1056
straw	105088	245760	701696

Aligned DoFs		
pixel	SCT	TRT
10464	24528	701696

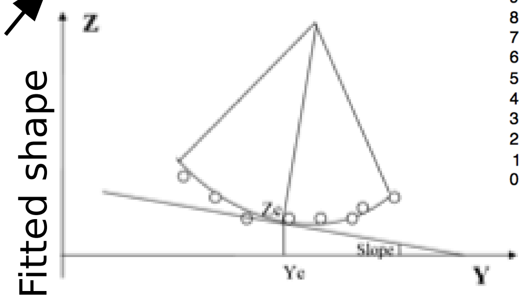
Alignment at module (wire) level

- Alignment of pixel modules including module deformations
  - Surveyed module shape and parameters stored in DB

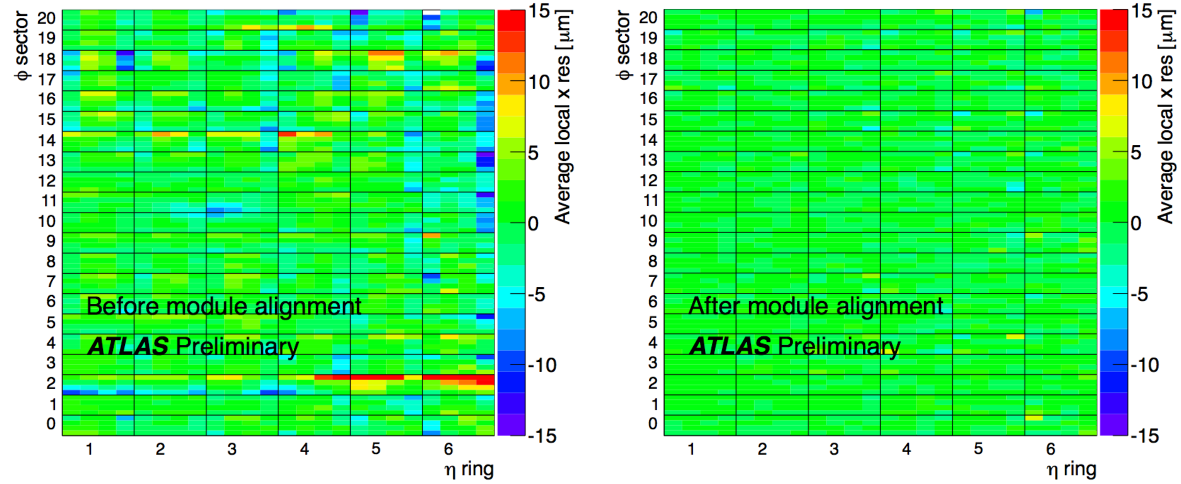
[Example of Pixel module]



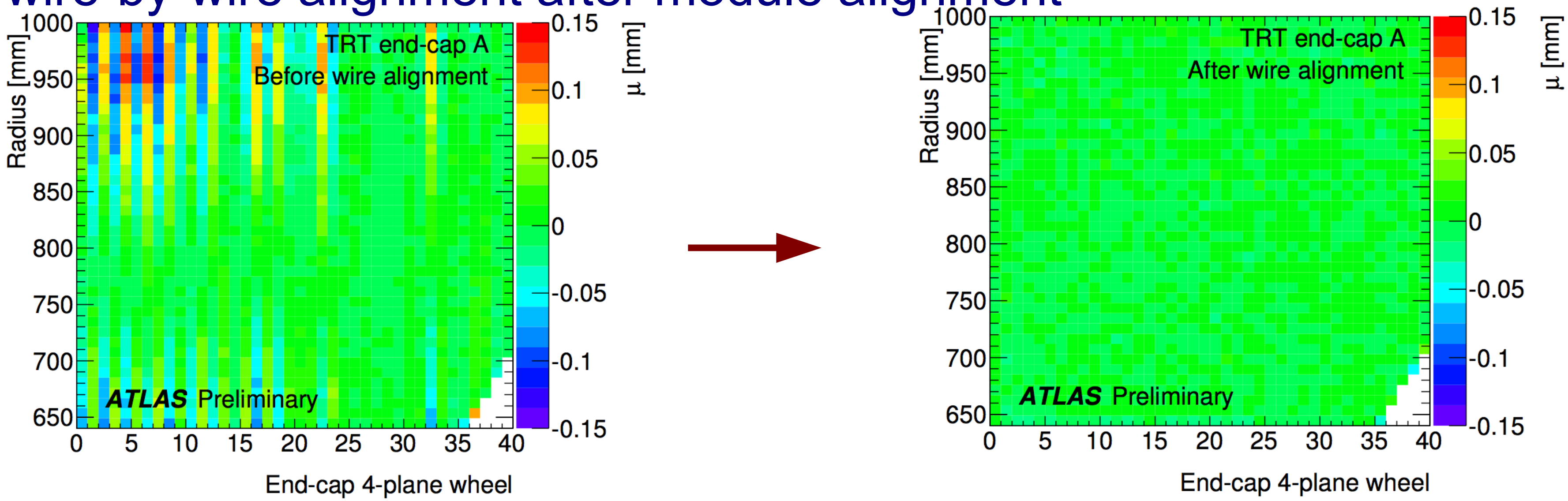
Survey points



Pixel residual maps: modules split in 4x4 grid

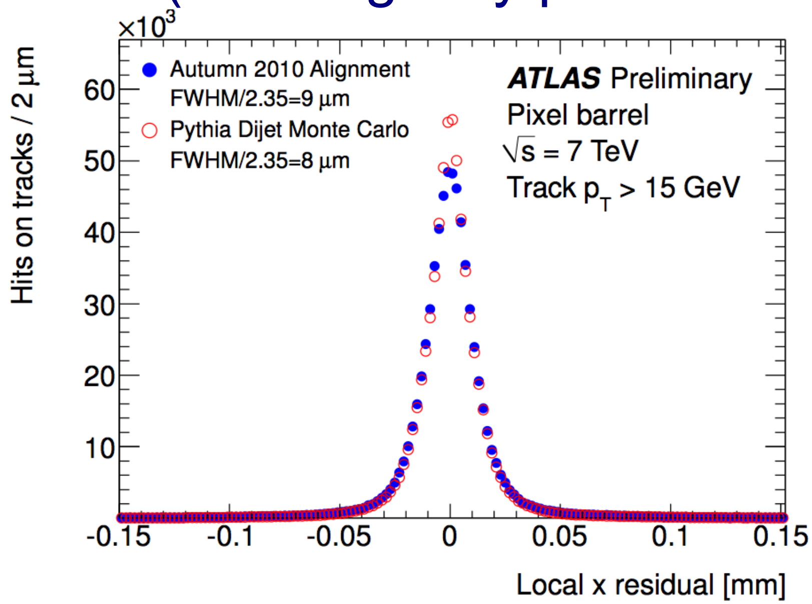


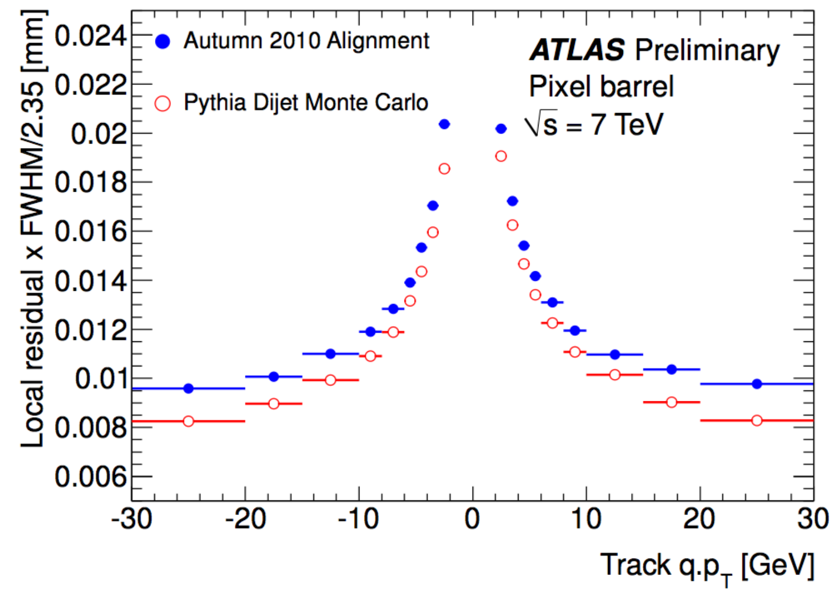
- TRT wire-by-wire alignment after module alignment



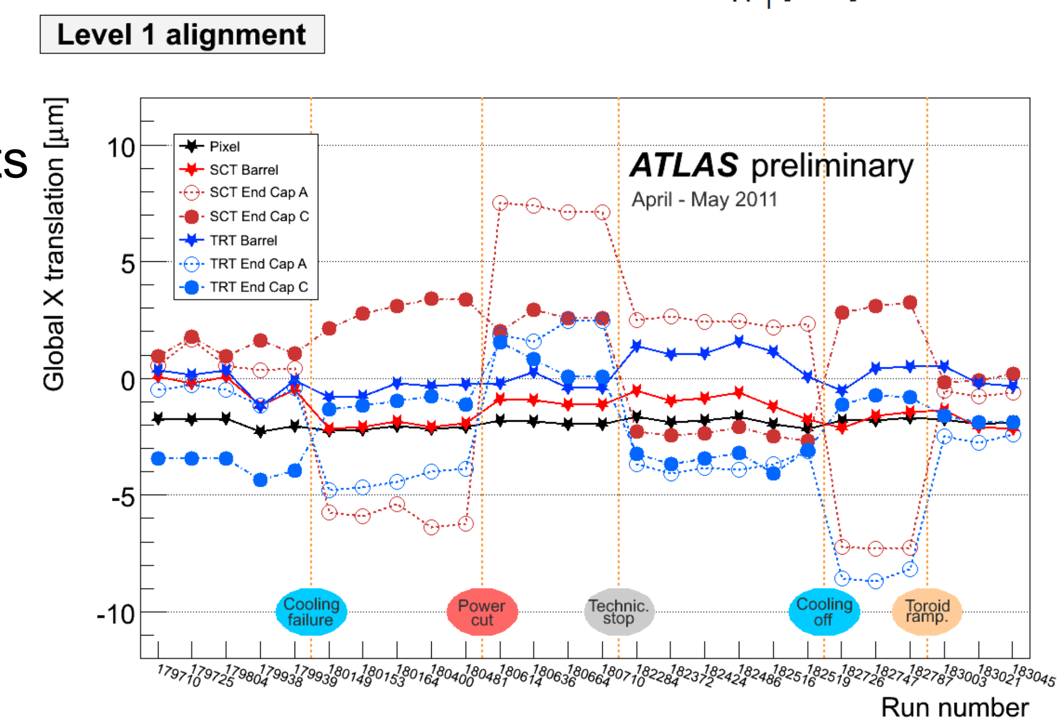
Alignment results

- Residuals (showing only pixel module residuals)



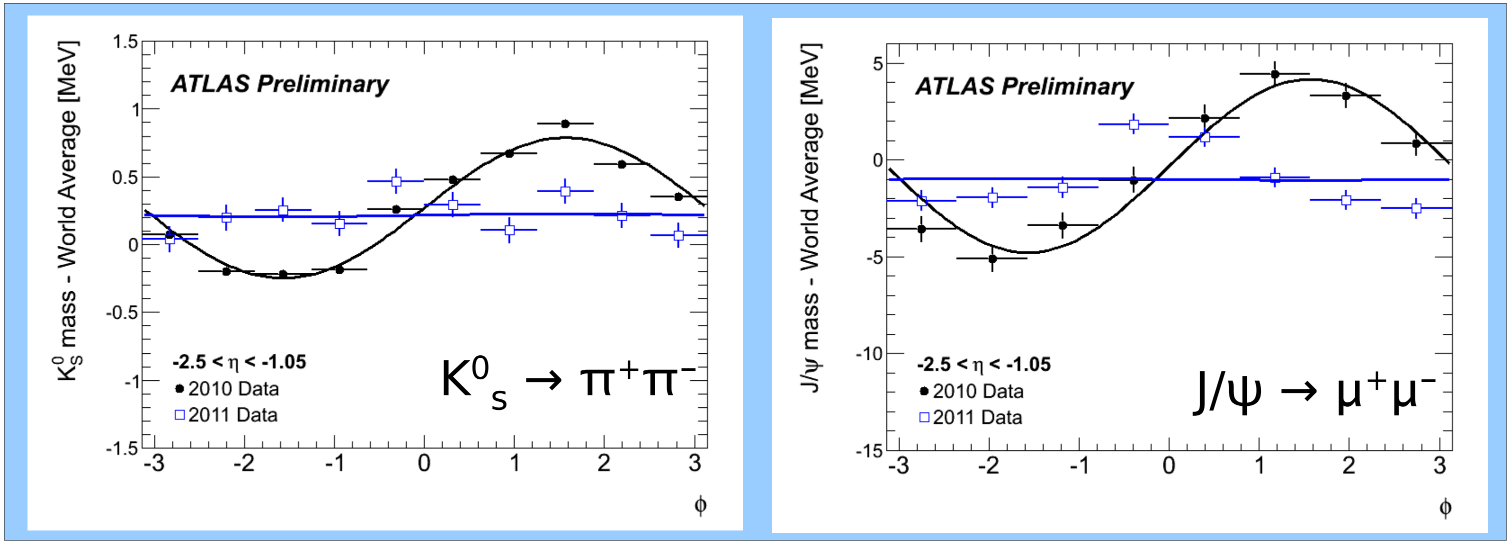


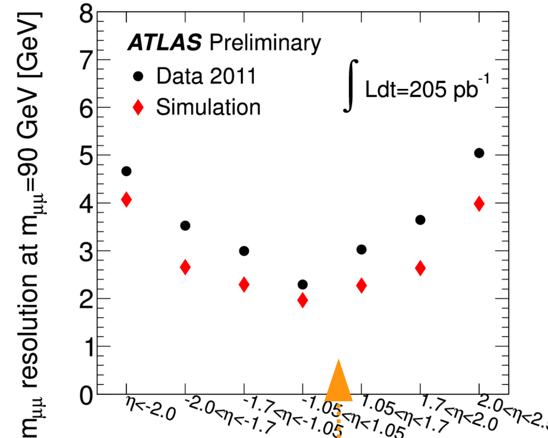
- Detector stability:
  - Movements due to hw incidents
    - Typical size <10 µm
  - Otherwise detector is stable
    - Movements < 1 µm



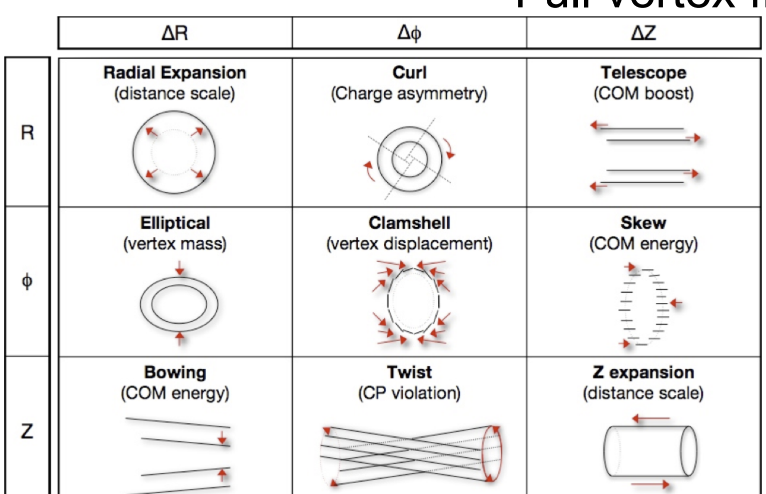
ID alignment validation using physics observables

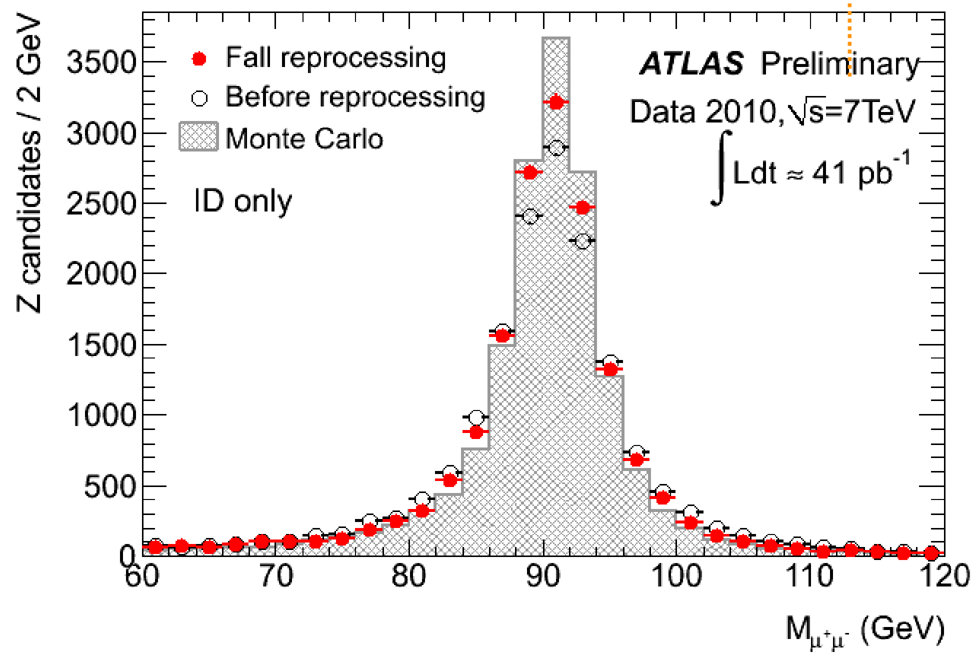
- Detected a relative rotation of the solenoid and ID axis: 53 μrad !





- Weak modes. Systematic studies with K^0_s, J/ψ and $Z \rightarrow \mu^+\mu^-$
  - MS constraint,
  - E/p for electrons
  - Full vertex fit





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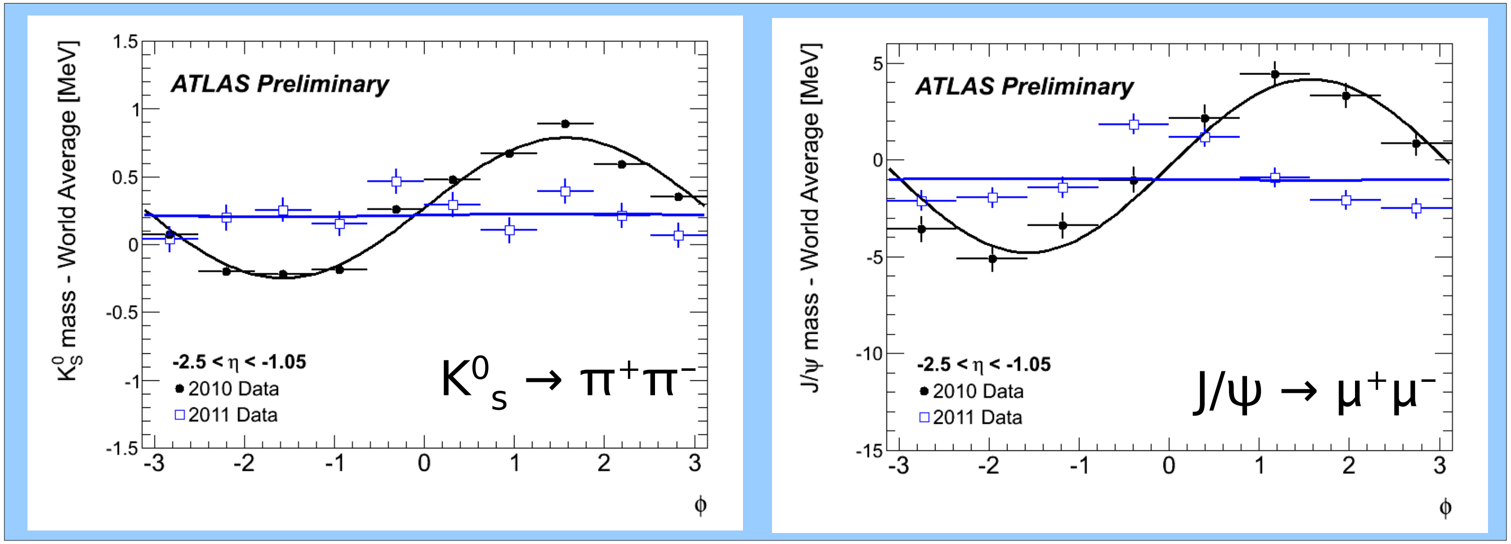

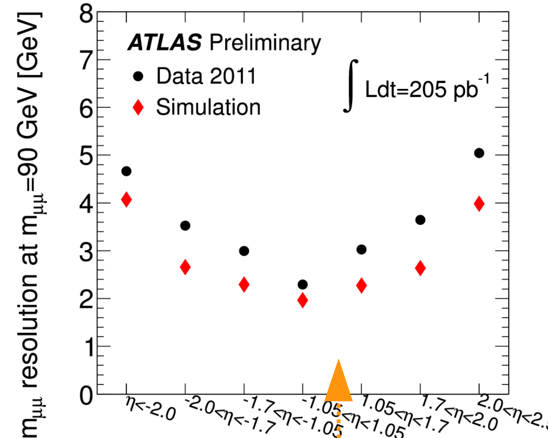

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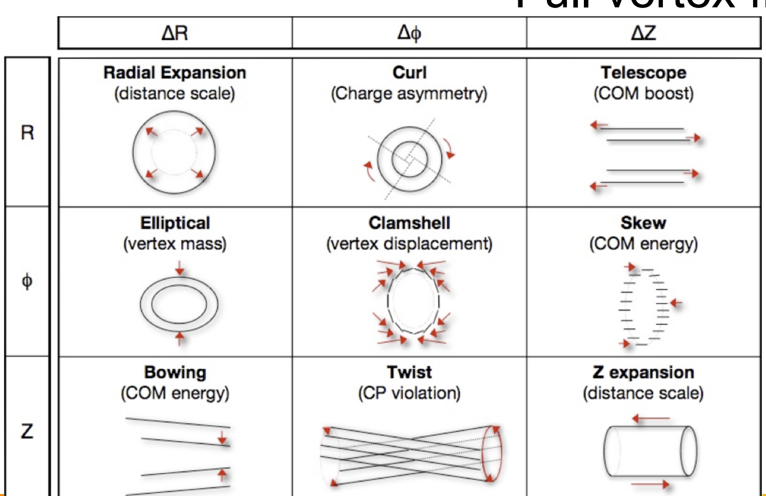
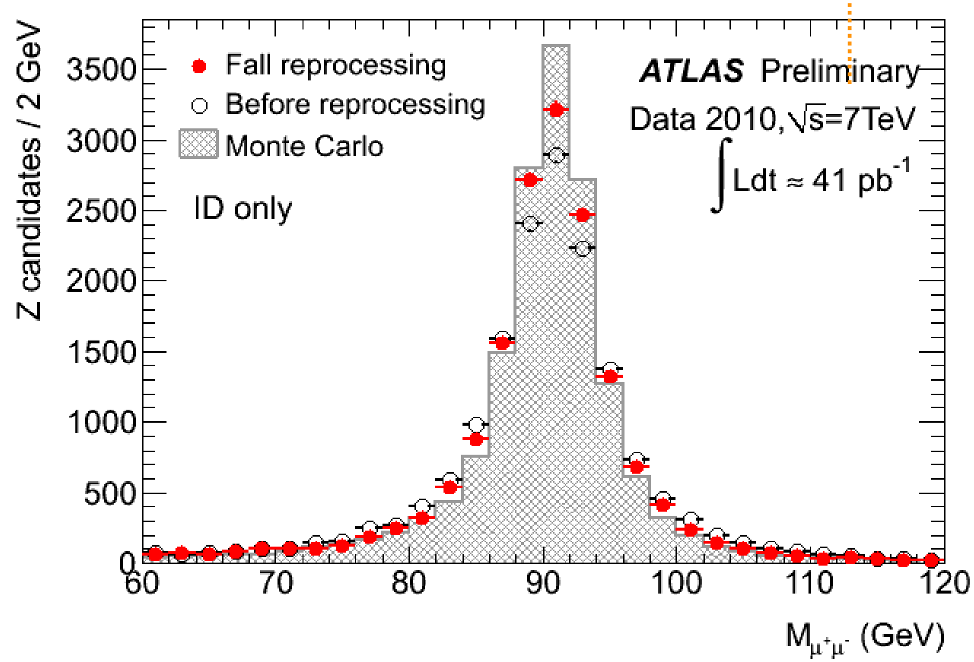
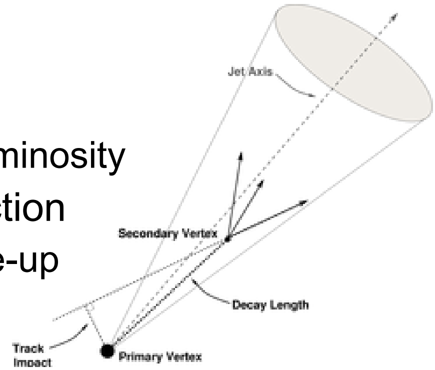
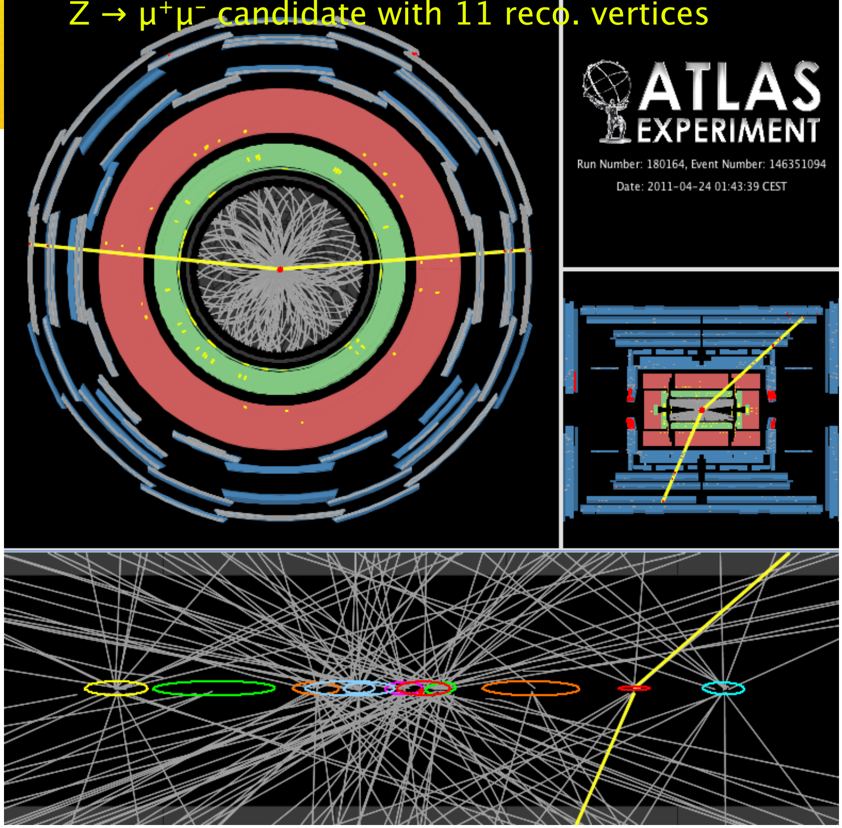


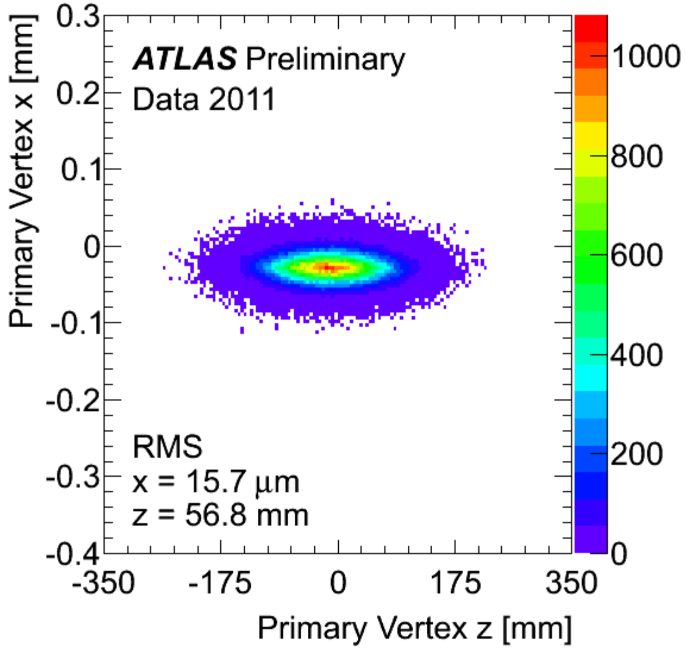


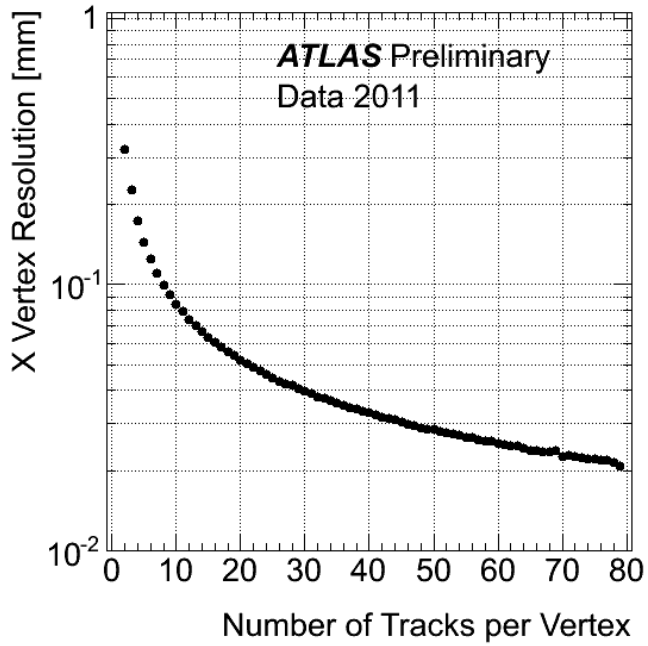
Vertex reconstruction

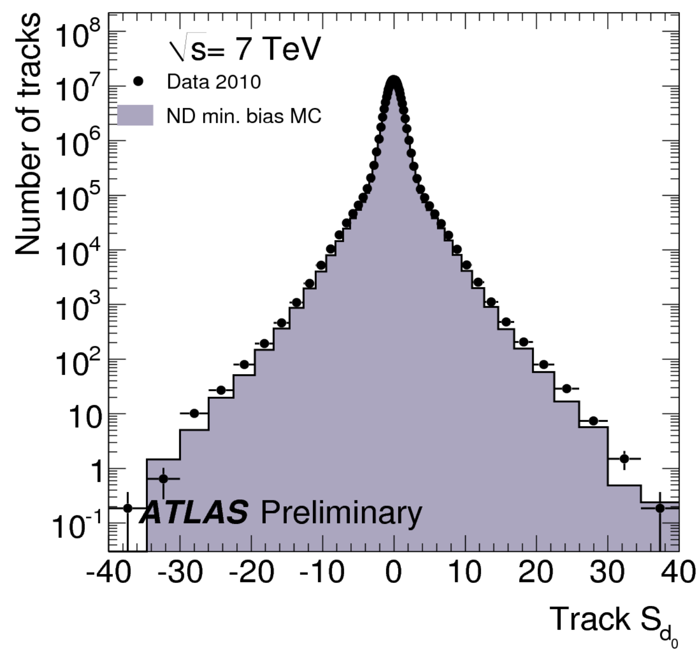
- Precise vertex reconstruction is necessary to achieve the physics goals: specially with event pile-up
- Beam spot is routinely computed: online and offline
- Iterative vertex finder & adaptive fitter
- Vertex resolution extracted with real data: split vertex
- Applications
  - PV counting
    - Luminosity
  - Jet vertex fraction
    - pile-up
  - B-tagging





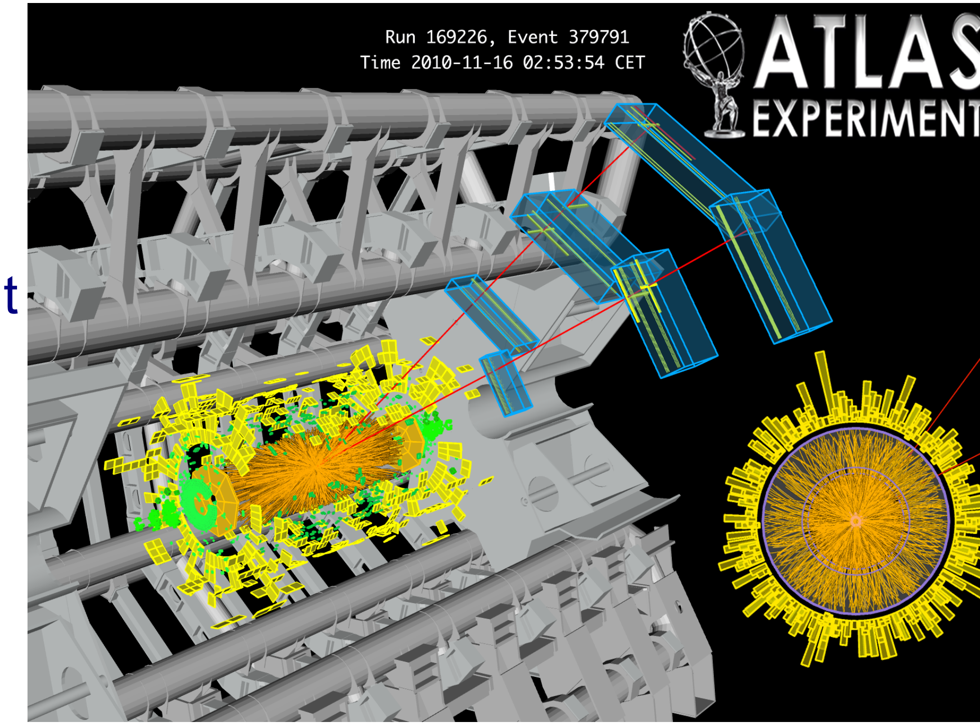




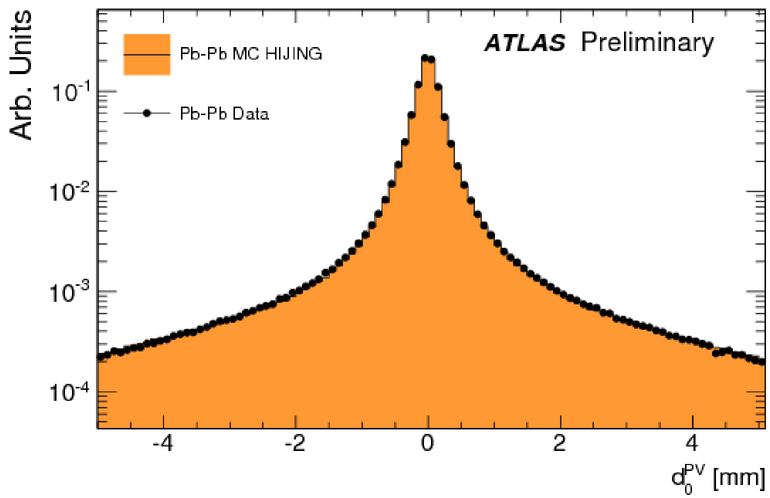


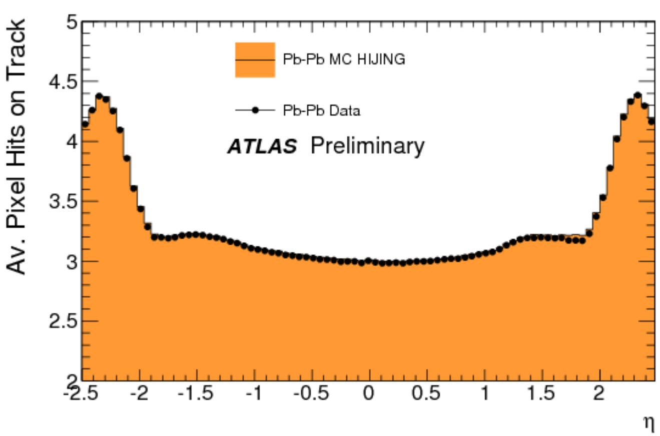
Heavy ion data

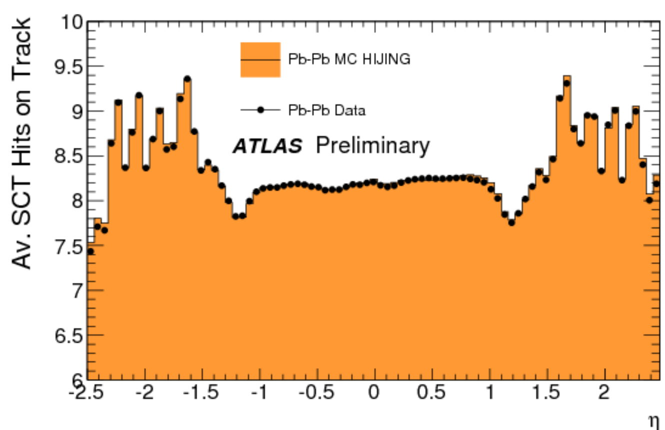
- Tracking in the Heavy Ion collision data was quite challenging
  - Very high track multiplicity
  - Anticipation of the pile-up events
  - Tighten hit requirements
    - Keep fake rate low

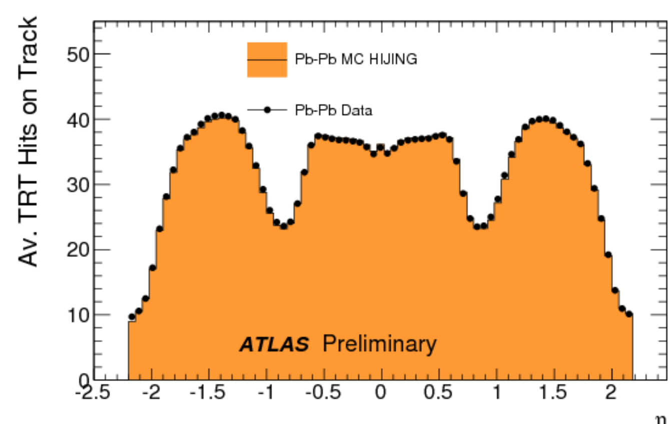


- Overall tracking performance was excellent



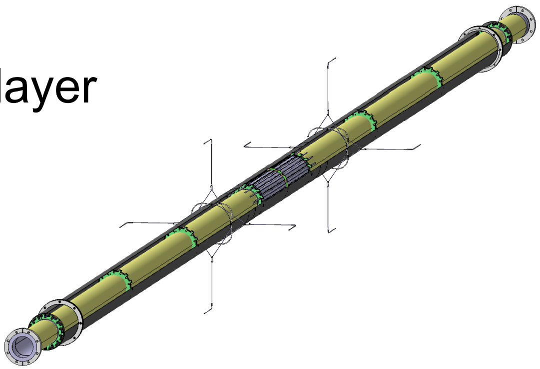


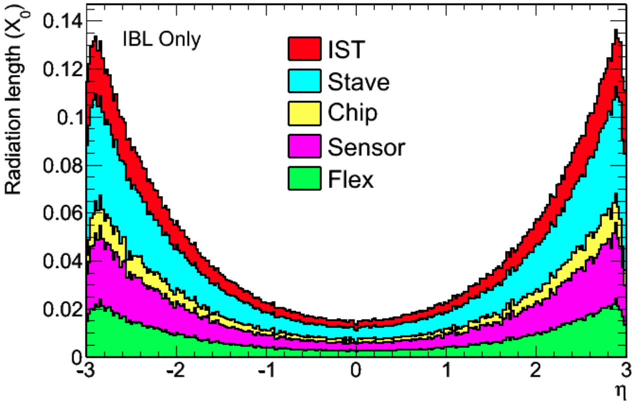


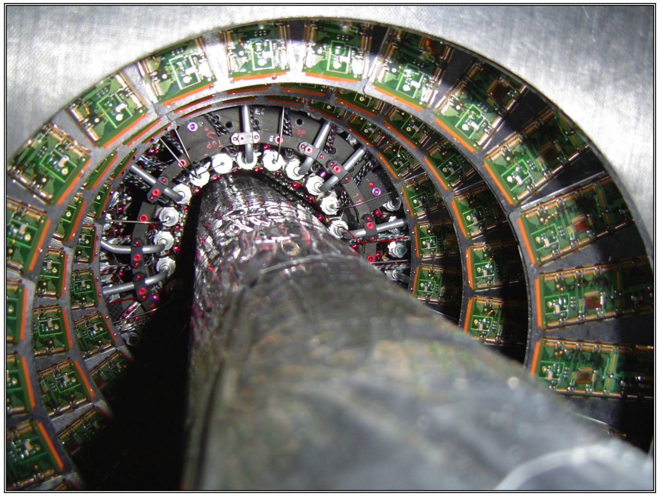


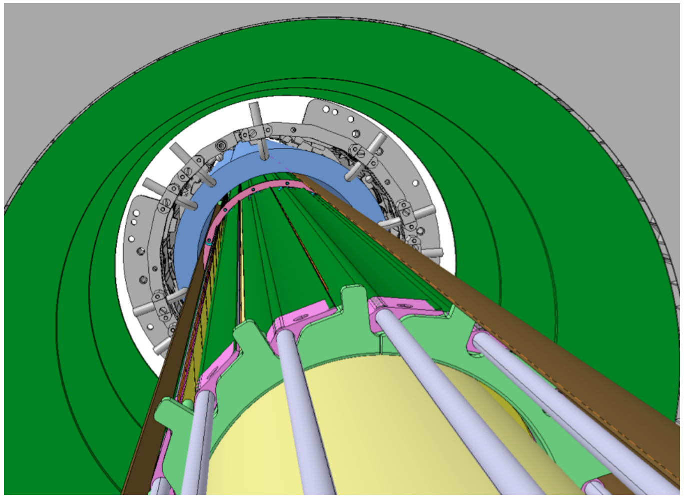
Future: IBL

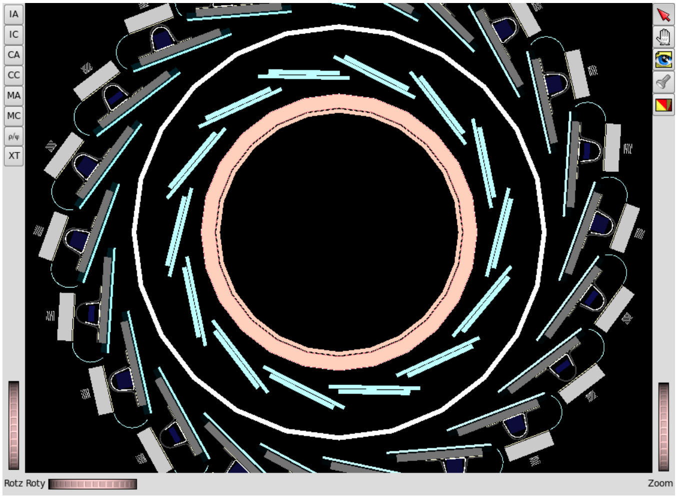
- Upgrade of the detector with the Insertable B Layer (IBL)
  - 4th layer of pixel detector:
  - To be inserted between a new beam pipe and the pixel B layer
- IBL Goals
  - Tracking robustness & B tagging (radius 2.5 cm)
  - Cope with luminosity increase ($2 \cdot 10^{34}$ cm^{-2} s^{-1})
  - Radiation dose (current B layer may become inefficient)
  - Add low material (adjusted to 1.5% of X_0)
- Installation: foreseen for next shutdown
  - Beam pipe replacement











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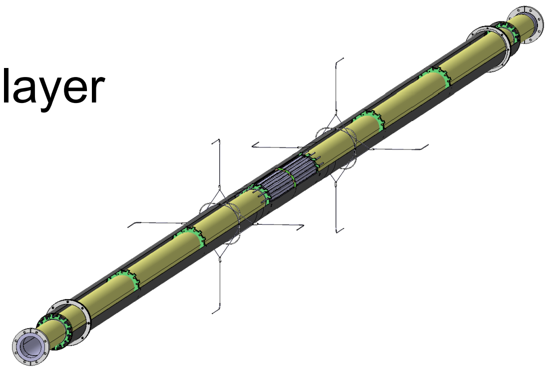

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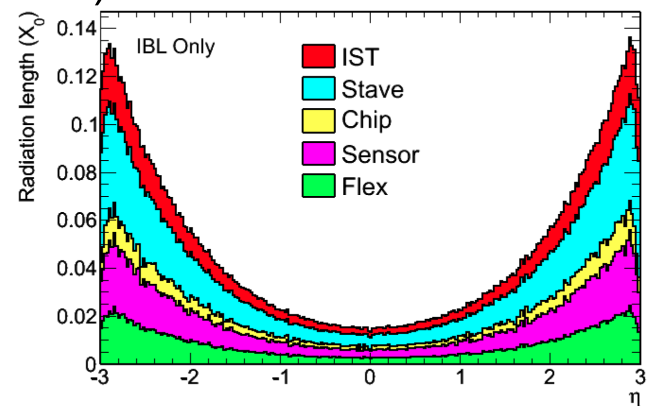

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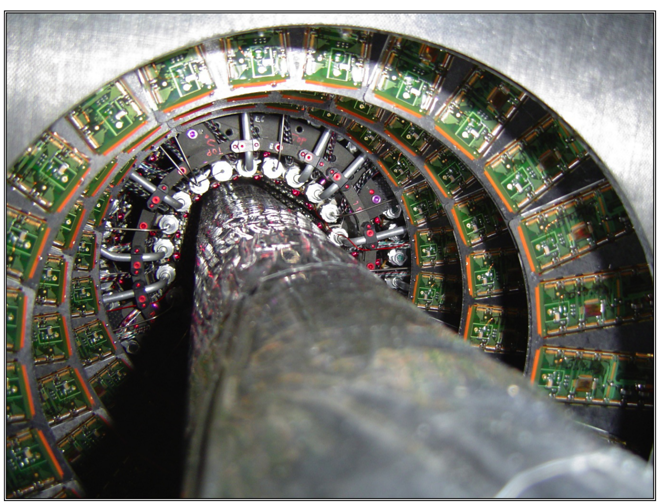

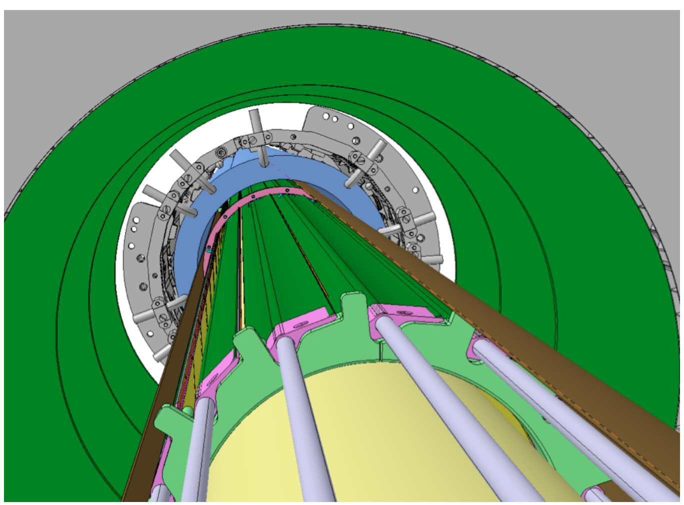

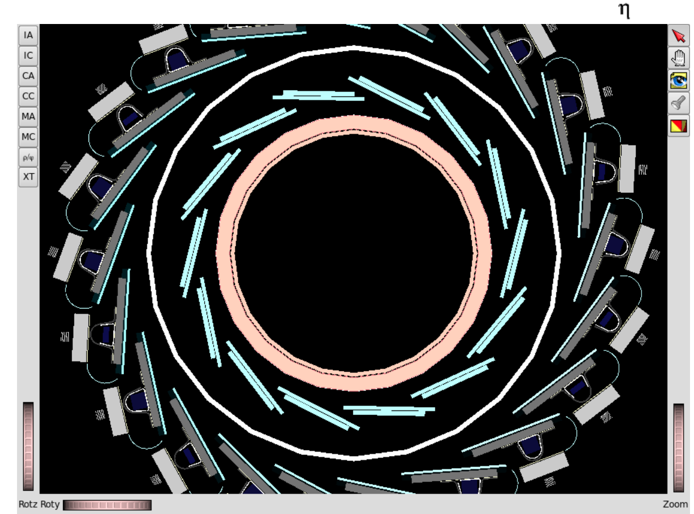

Summary

- The ATLAS Inner Detector is operating very efficiently
  - Pixel 97.3%; SCT 99.2%; TRT 97.1%
  - Up time (during collisions): Pixel 96.7%; SCT 97.5%; TRT 100%
- Very precise clustering thanks to:
  - Incident angle, Lorentz angle, time-over-threshold, charge sharing, etc.
  - Very good spatial resolution
- Particle ID: dE/dx in Pixel and TRT + TRT transition radiation
- Accurate tracking and vertexing
  - Improved understanding of the detector material within ID
- Alignment: > 700 k degrees of freedom !
  - Good understanding of the detector distortions
- Nice performance in physics observables
  - Z mass (and J/ψ, K_s,...)
- Looking forward to great physics results and discoveries!