# ATLAS: Data/MC comparisons for the Inner Detector tracking and vertexing

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On behalf of the ATLAS collaboration

LPCC Simulation Workshop
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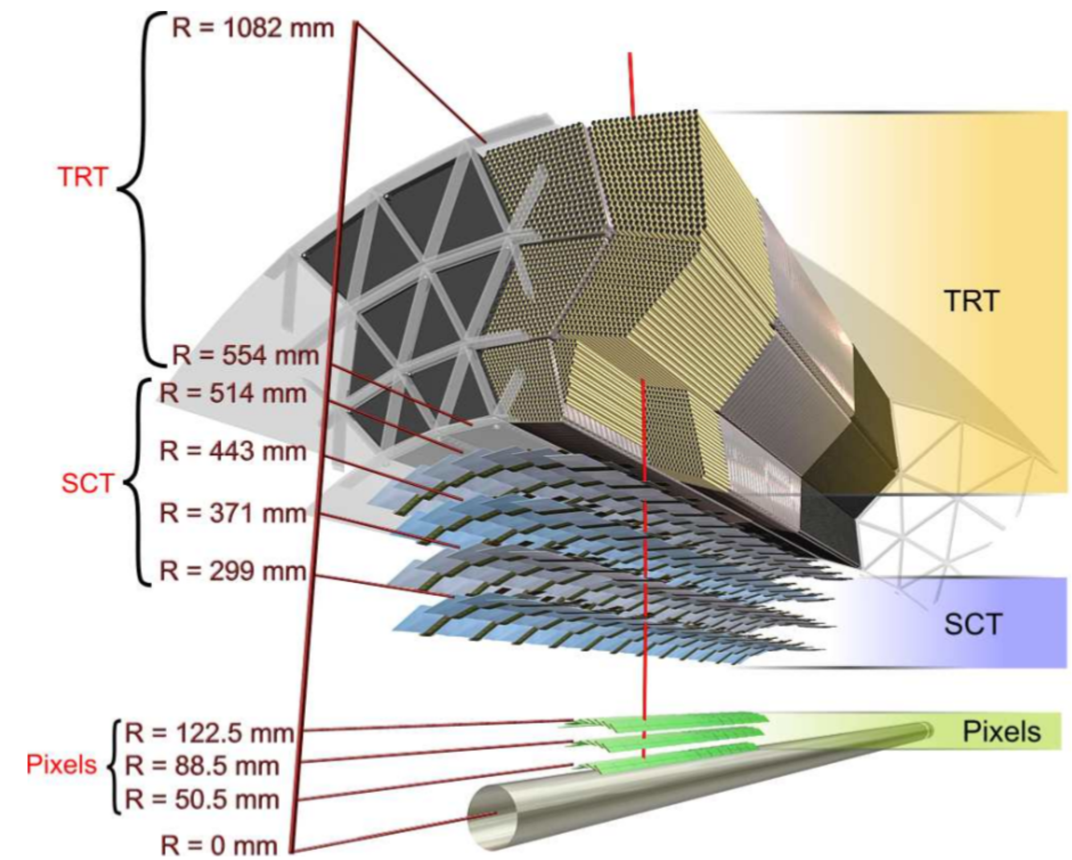
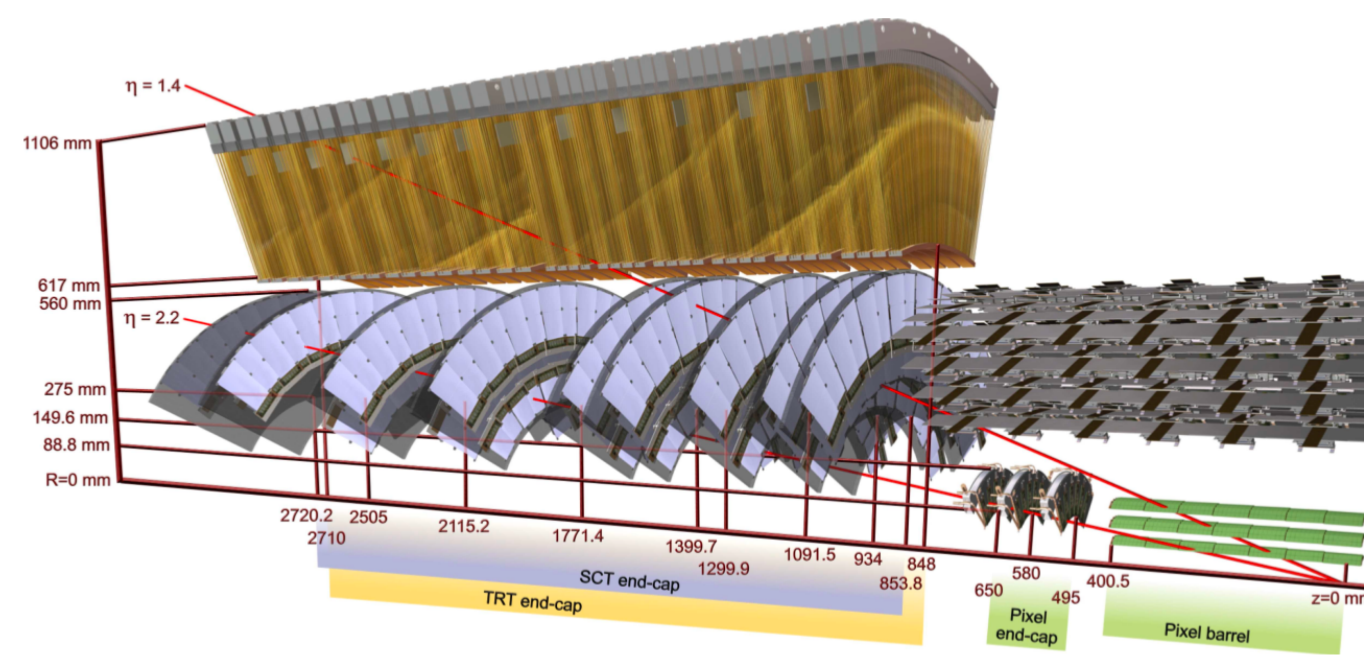
# Inner Detector Tracking System

- The ID is a combined tracking system within the ATLAS detector
- It consists of three types of sub-detectors:
  - Pixel (silicon pads)
  - SCT (silicon micro-strips)
  - TRT (gaseous proportional tube with transition radiation detection)
- Each subsystem divided into:
  - Barrel (B)
  - 2 Endcap regions (A, C)



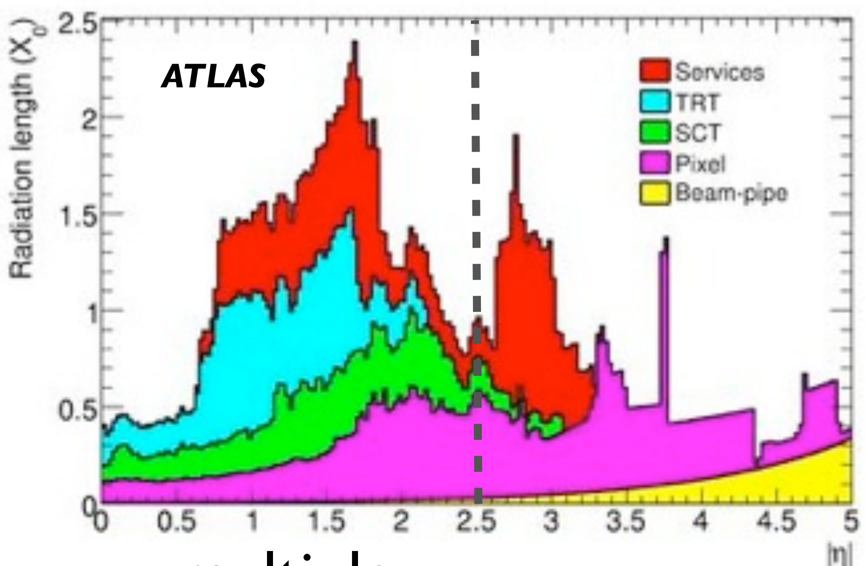

| | Channels | Resolution X× Y(μm) | <Hits>/ track |
|---|---|---|---|
| Pixel | $80\times10^6$ | 10×115 | ~3 |
| SCT | $6.3\times10^6$ | 17×580 | ~8 |
| TRT | $3.5\times10^5$ | 130 | ~36 |



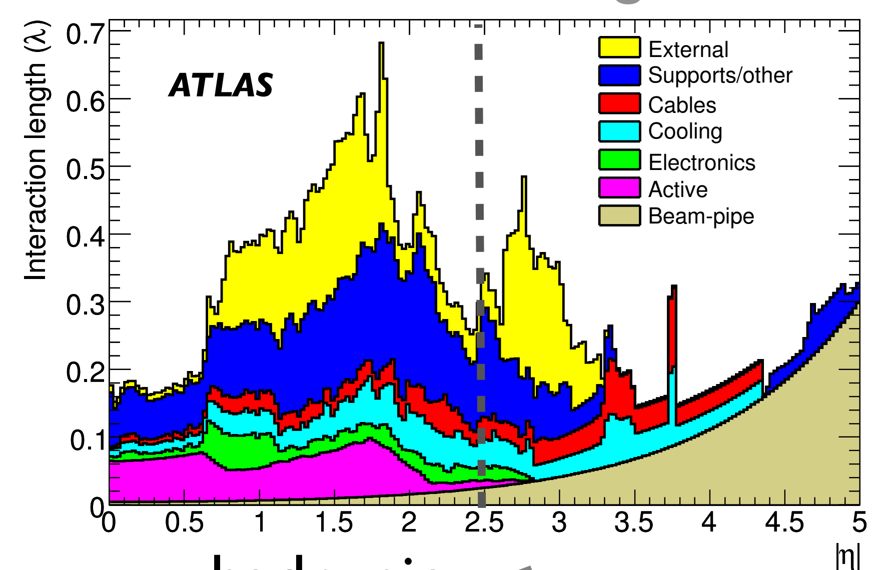
# Material

- ATLAS tracking resolution and efficiency mostly driven by interactions in detector material
  - beyond |η|>0.5 resolution increases and efficiency drops

Radiation Length



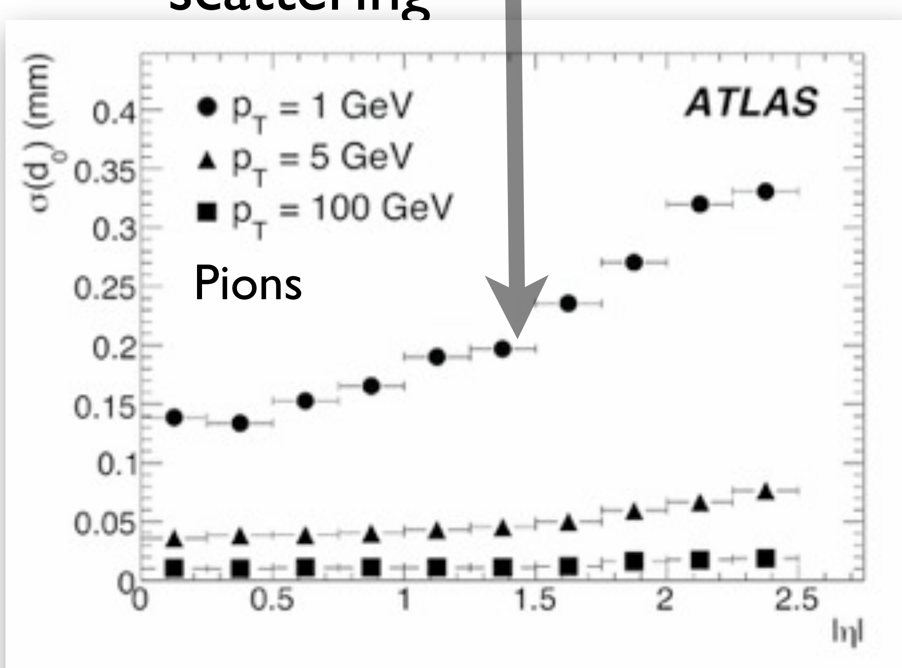

Interaction Length

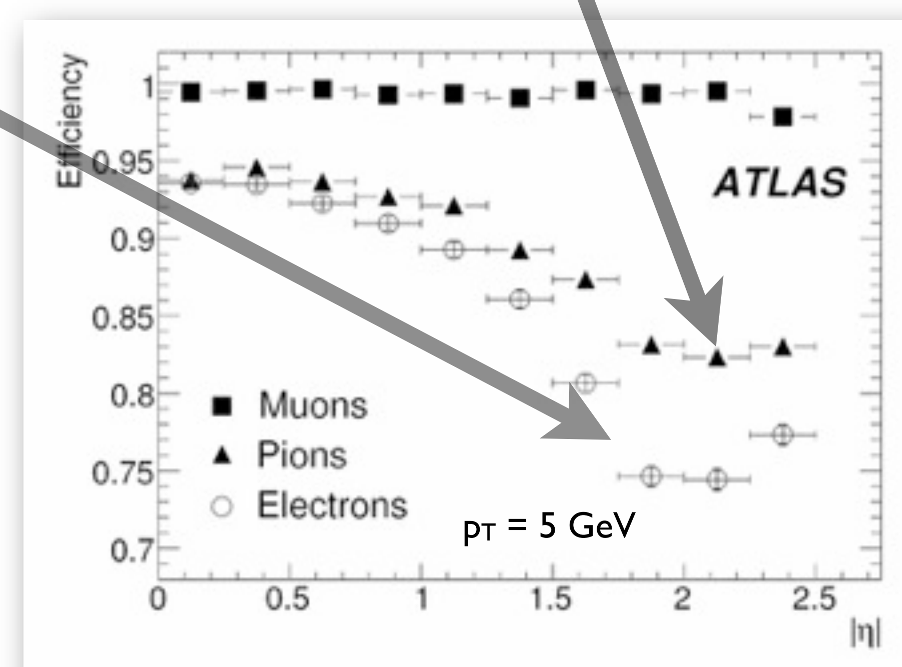



multiple scattering

Brems-strahlung

hadronic interactions

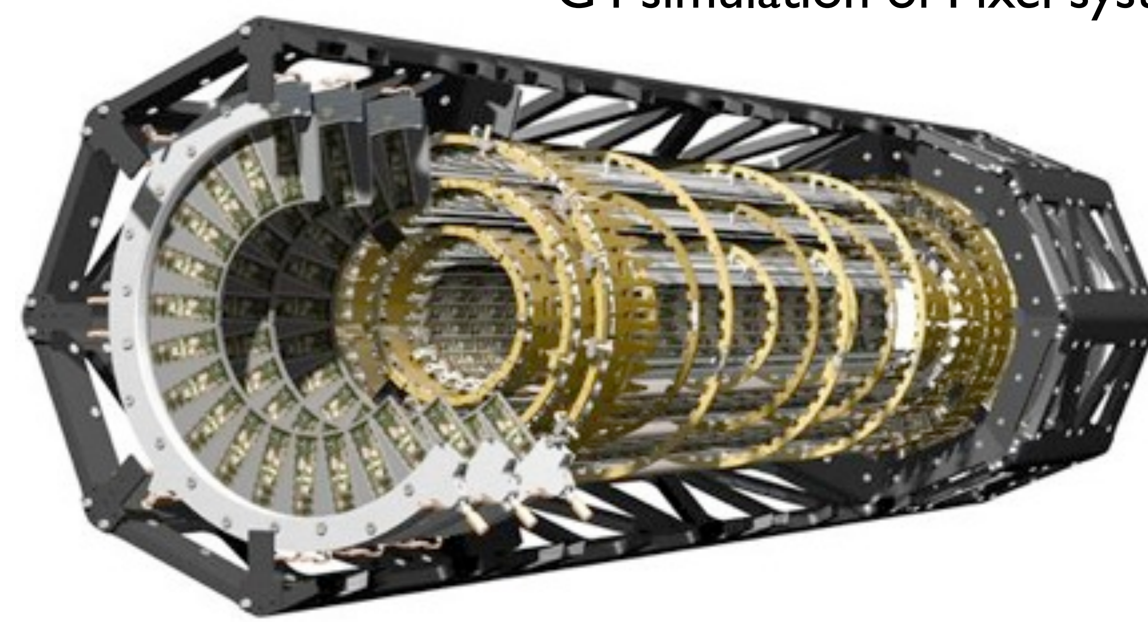


# Detector Geometry

- Large detector material within the inner detector
  - resolution and efficiency affected by multiple scattering
  - tracking performance depends highly on knowledge and simulation of material
- Geometry model translated into G4 used to implement detector with high granularity (1.8M volumes)
- Extrapolation algorithms provide ability to propagate particles through geometry model, including material corrections
- Set of physics processes used to describe interactions with matter

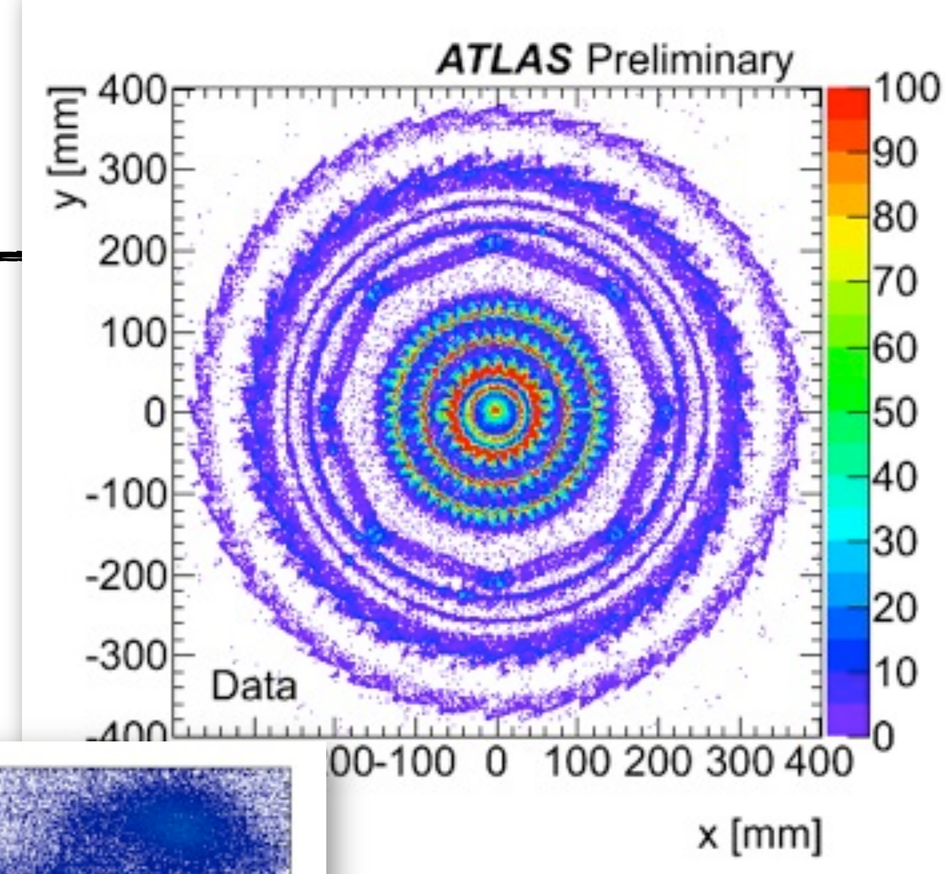
G4 simulation of Pixel system

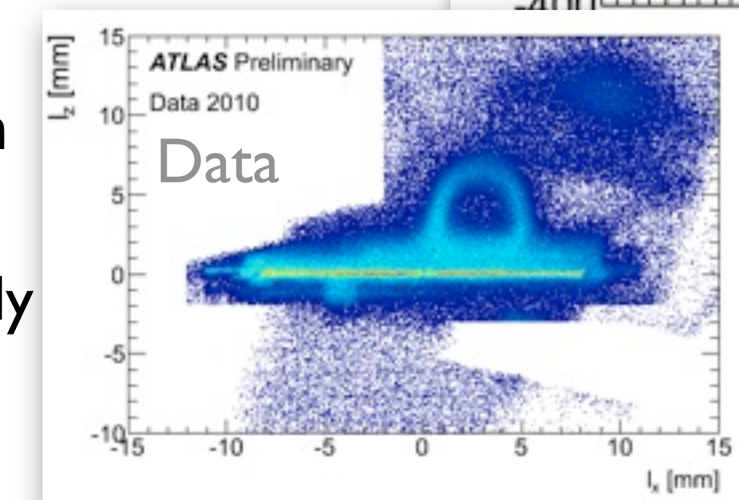


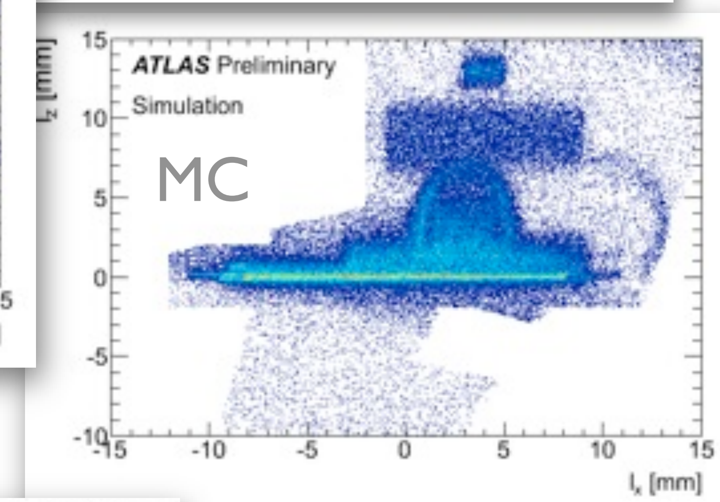
| | estimated | simulation |
|---|---|---|
| Pixel | 201 kg | 197 kg |
| SCT | 672 ±15 kg | 672 kg |
| TRT | 2961 ±14 kg | 2962 kg |

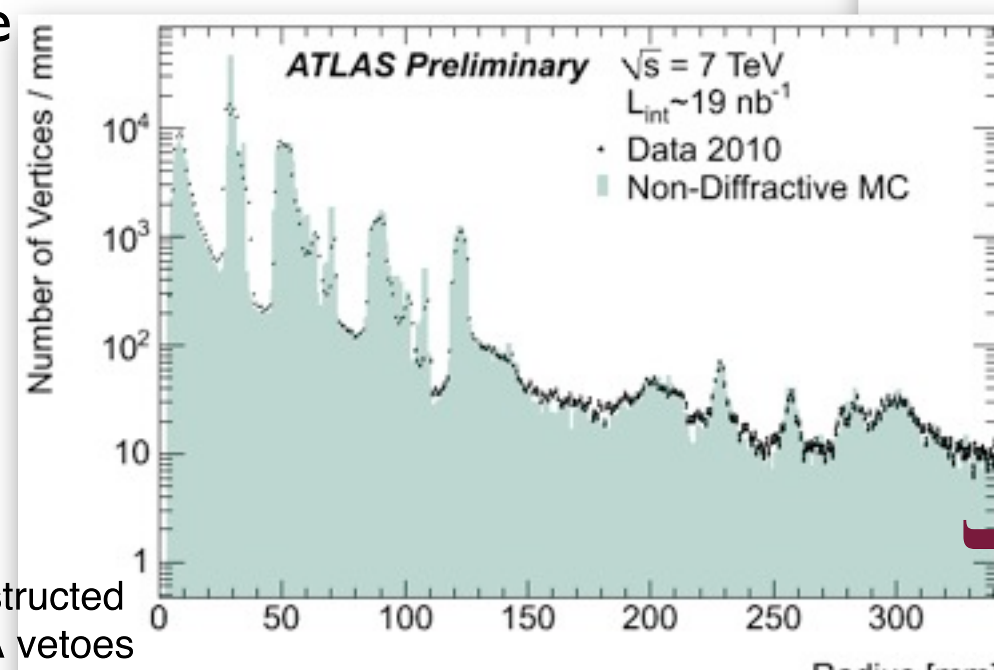
# Material Studies

- Simulated geometry has to be checked and compared with data
- Precise knowledge of material within detector volume necessary
  - tomography with electrons from Photonconversions
- Reconstruction of hadron interaction vertices as additional method
  - good vertex resolution allows the study of fine details
- Material uncertainty in simulation
  - better than ~5% in central region
  - at the level of ~10% in most of the Endcaps



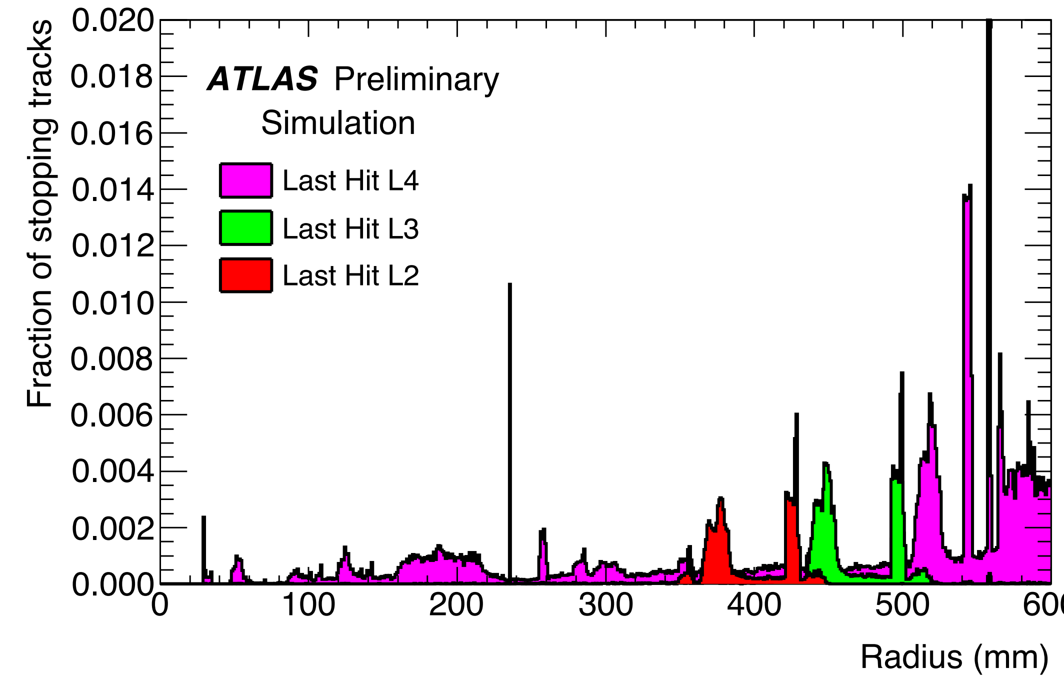




Radial positions of reconstructed vertices after $K_S^0$, γ and Λ vetoes

➡for details see Talk of Olivier Arnaez

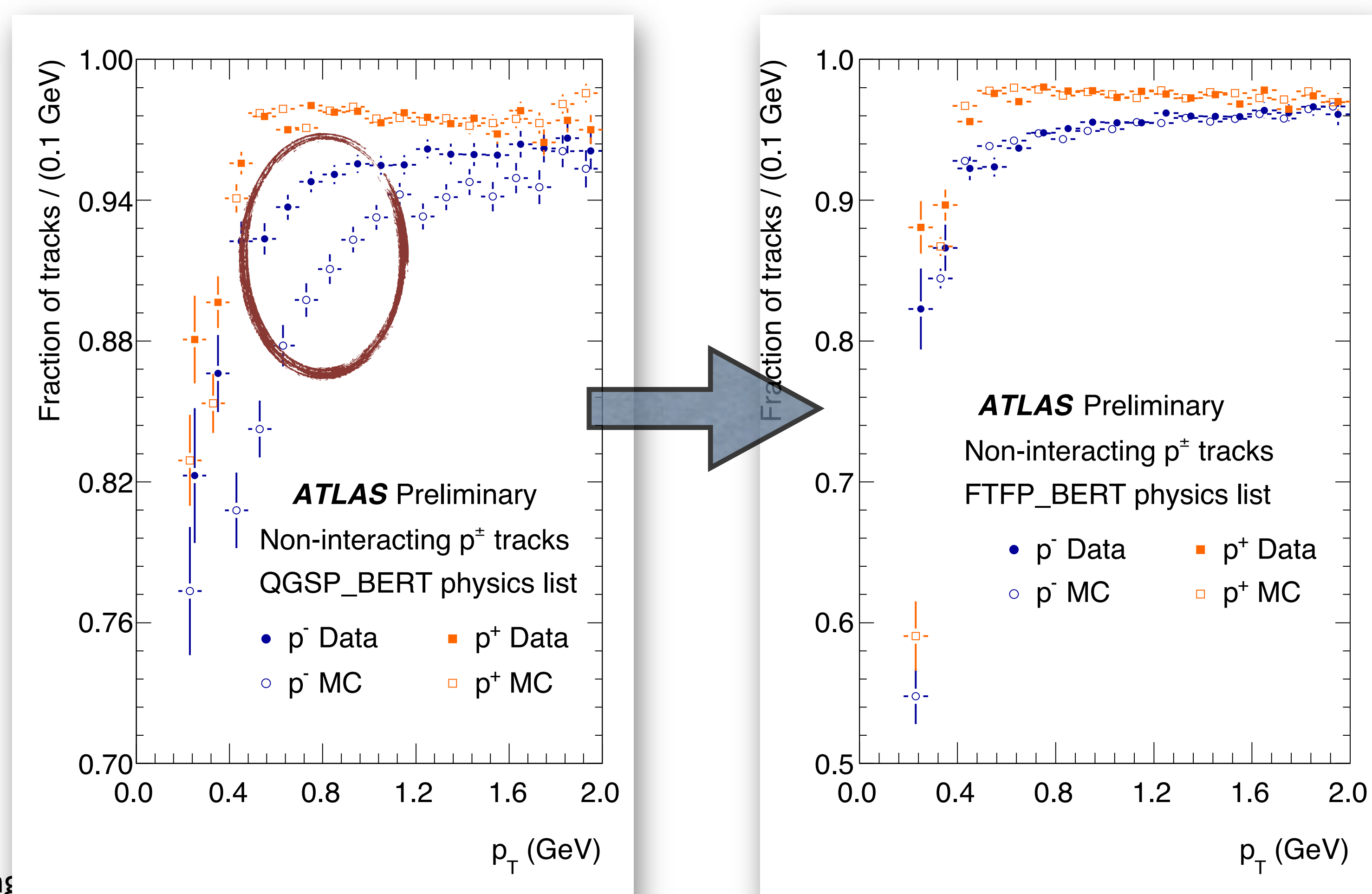
# Stopping Tracks in SCT

- Study of stopping tracks with last hit in layer 2, last hit in layer 3 and non-interacting tracks
- Low momentum tracks are sensitive to the material in the inner detector
- Different clean samples using protons from Λ decays and pions from $K_s^0$ decays
- Differences between charges due to module tilt and different interaction cross-sections




no interaction

Relative Fraction




→Antiprotons are not modeled by QGSP_BERT physics list

→Change to FTPP_BERT

➥for details see Talk of John Chapman

# Stopping Tracks in SCT

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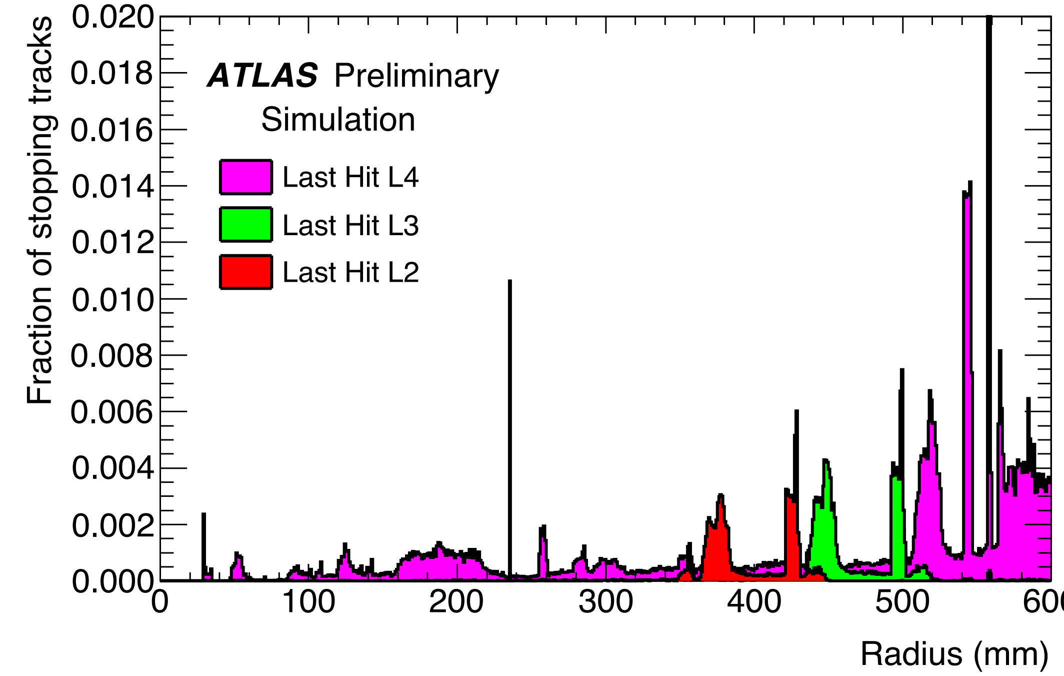
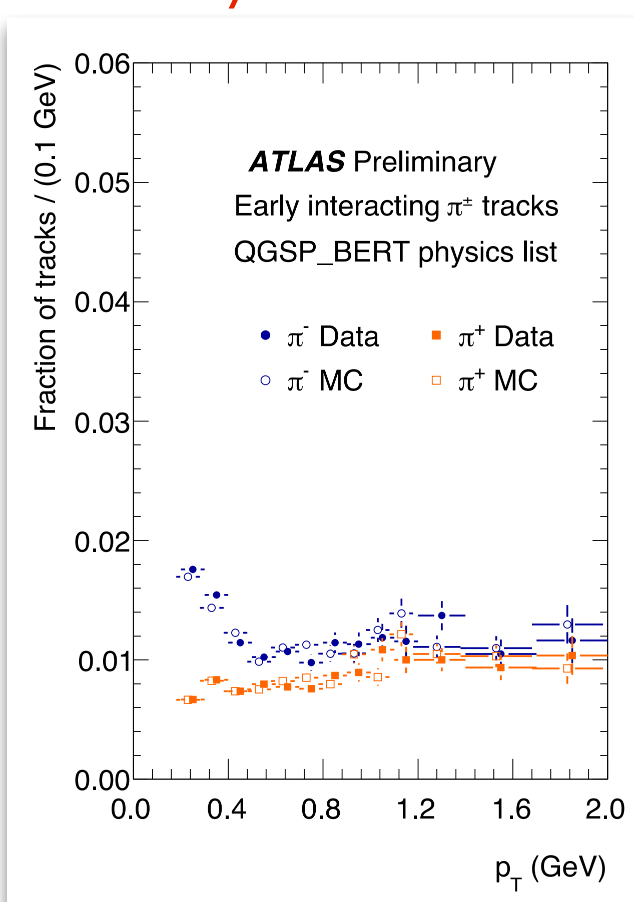
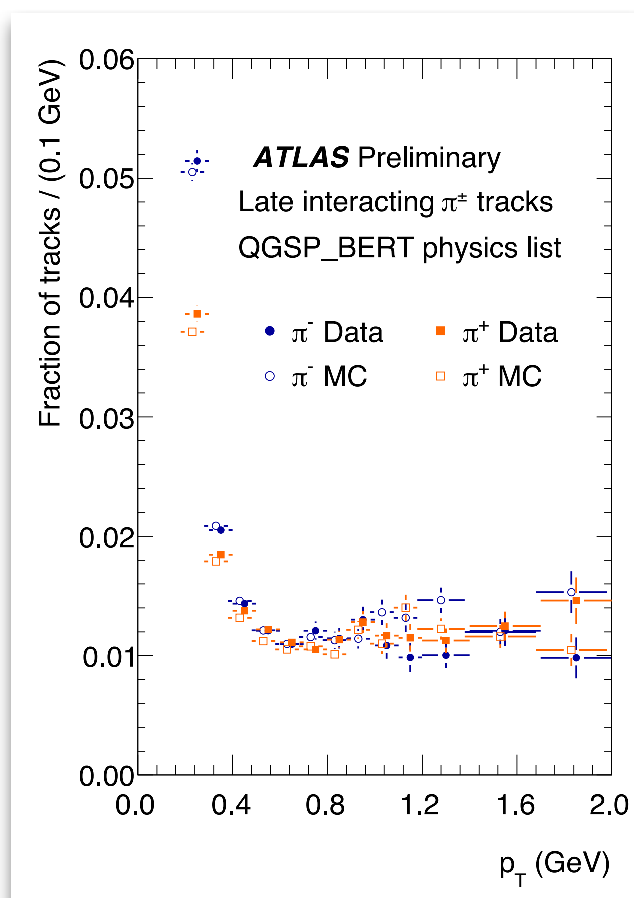


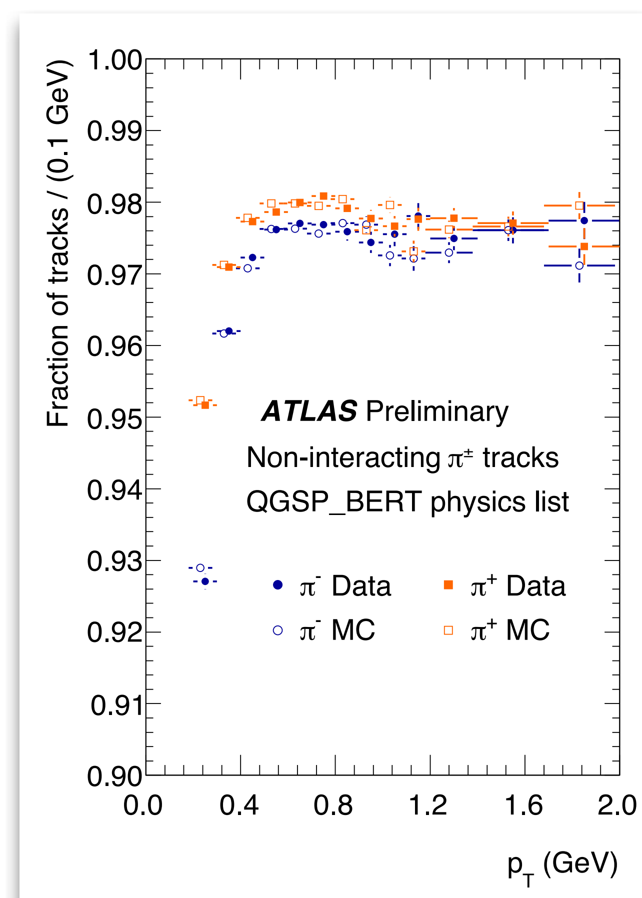

early interaction




late interaction

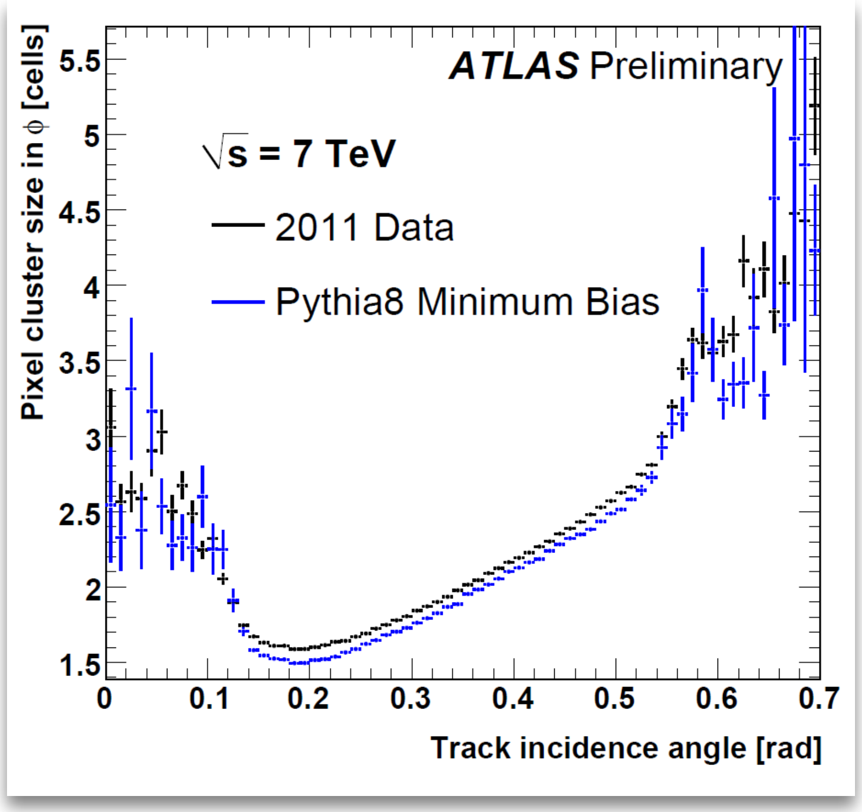


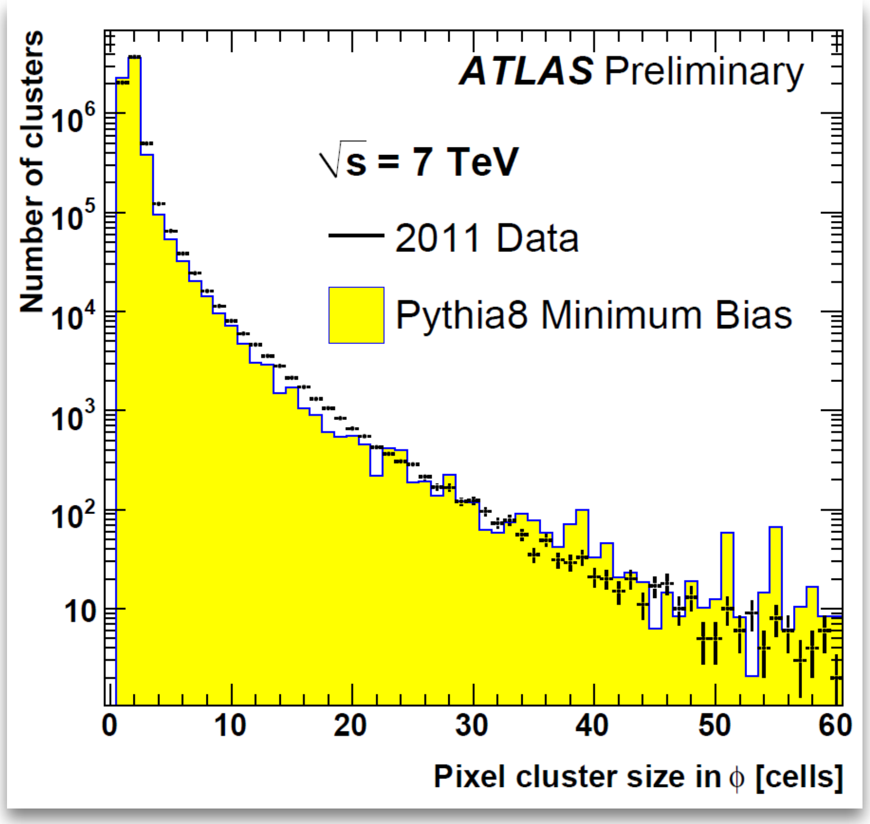

no interaction



# Pixel - Simulation

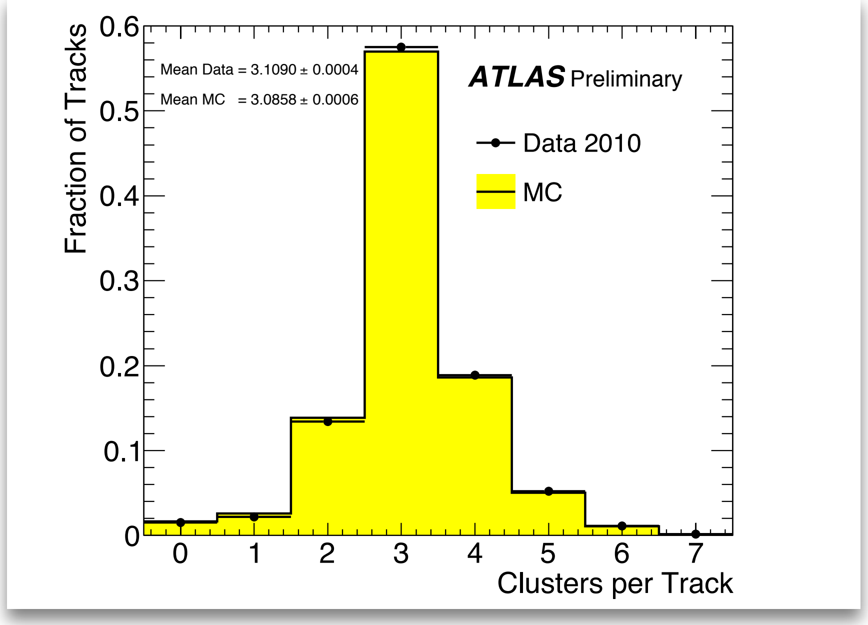
- G4 simulates energy loss of particles passing modules
- In digitization charge response calculated
  - based on a simple drift model (including Lorentz-angle and thermal diffusion)
  - instrumental effects added afterwards (thermal noise and cross-talk)
- Clusterisation algorithm builds cluster and computes position and attached error
- Use database to mask detector in reconstruction for dead modules ...
- Distribution of number of pixel as a function of incident angle shows similar behavior in data and MC
  - simulation of pixel size works fairly well but still not perfect
  - disagreement could not be reduced by more realistic (and more CPU consuming) model

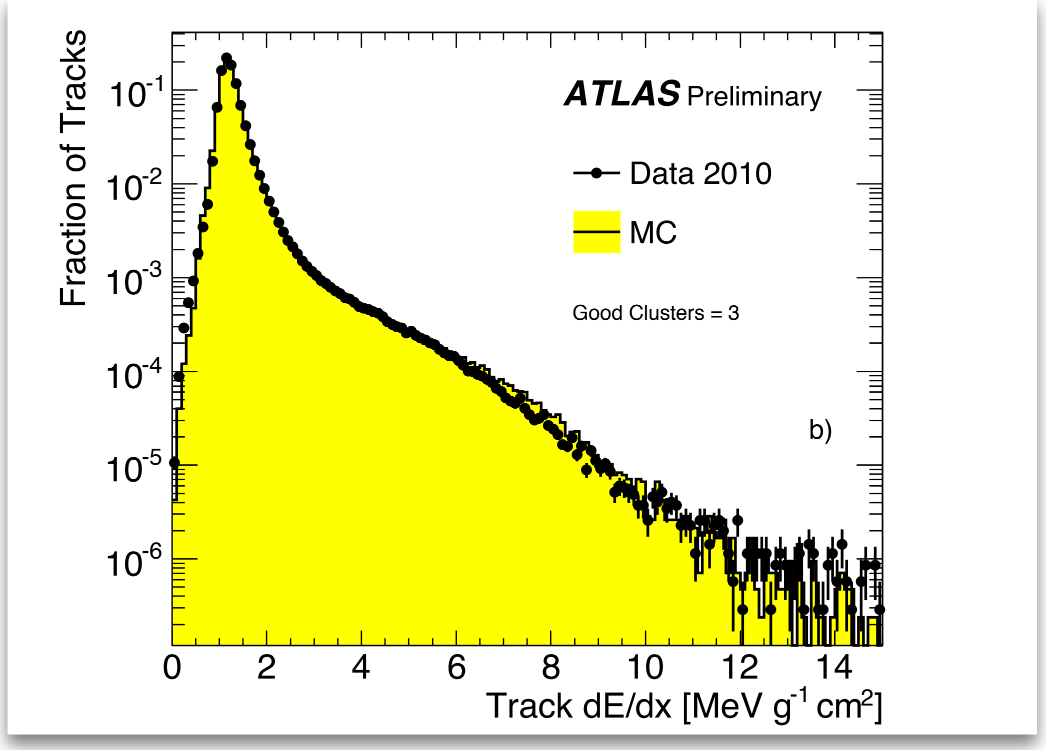


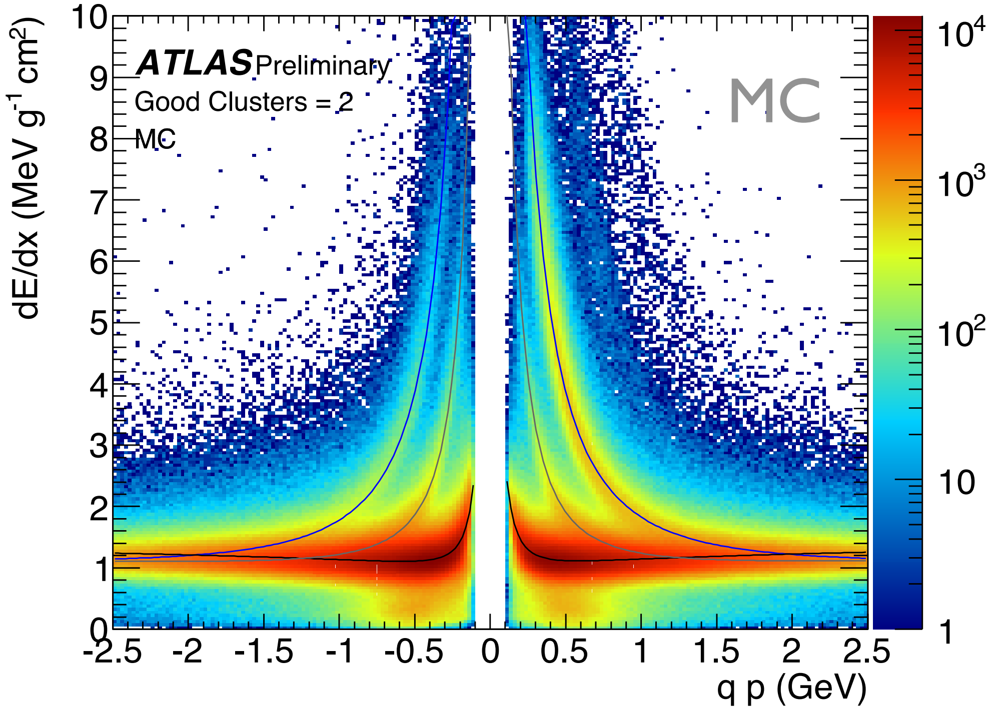



# Pixel dE/dx

- Better model help to improve ToT (and hence dE/dx) simulation
- After reconstruction based on simulation and measured knowledge of detector there is now a good description of reconstructed energy loss
- Due to the same behavior in data and MC this can be used as a powerful tool for particle identification in the low momentum region

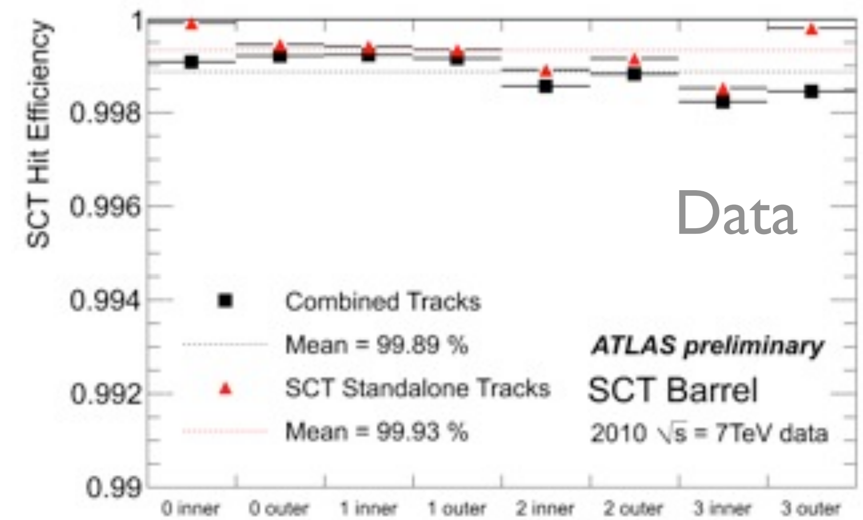


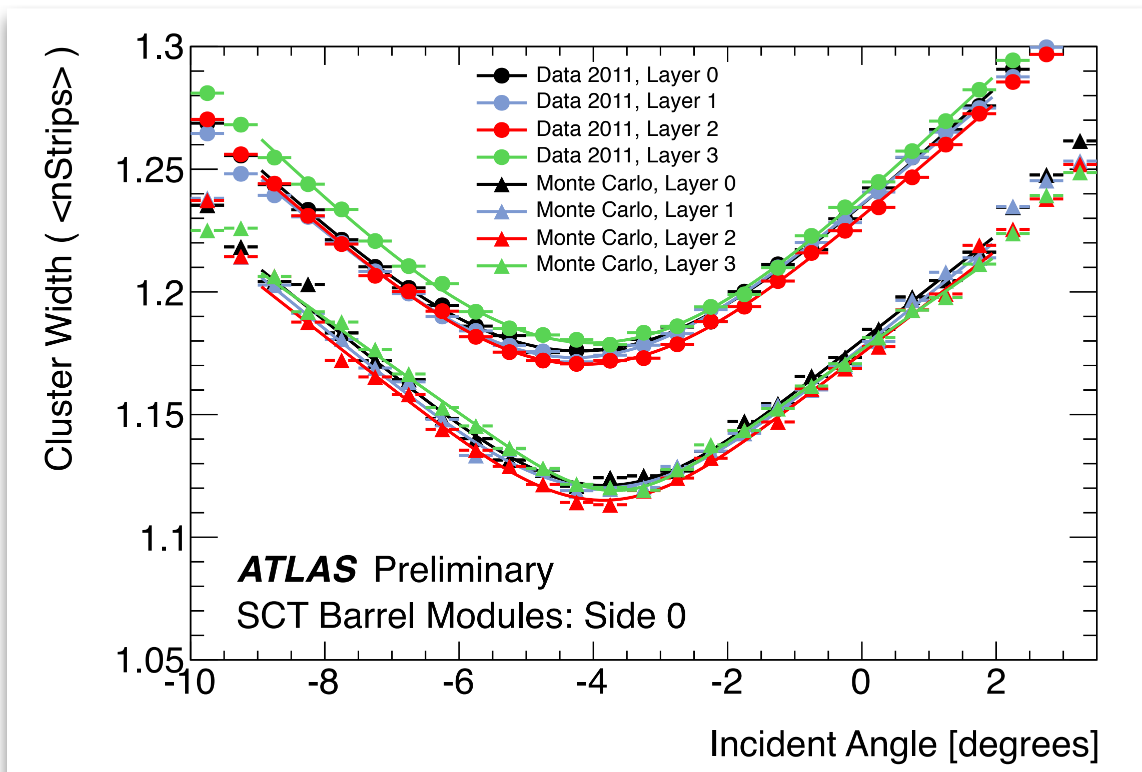



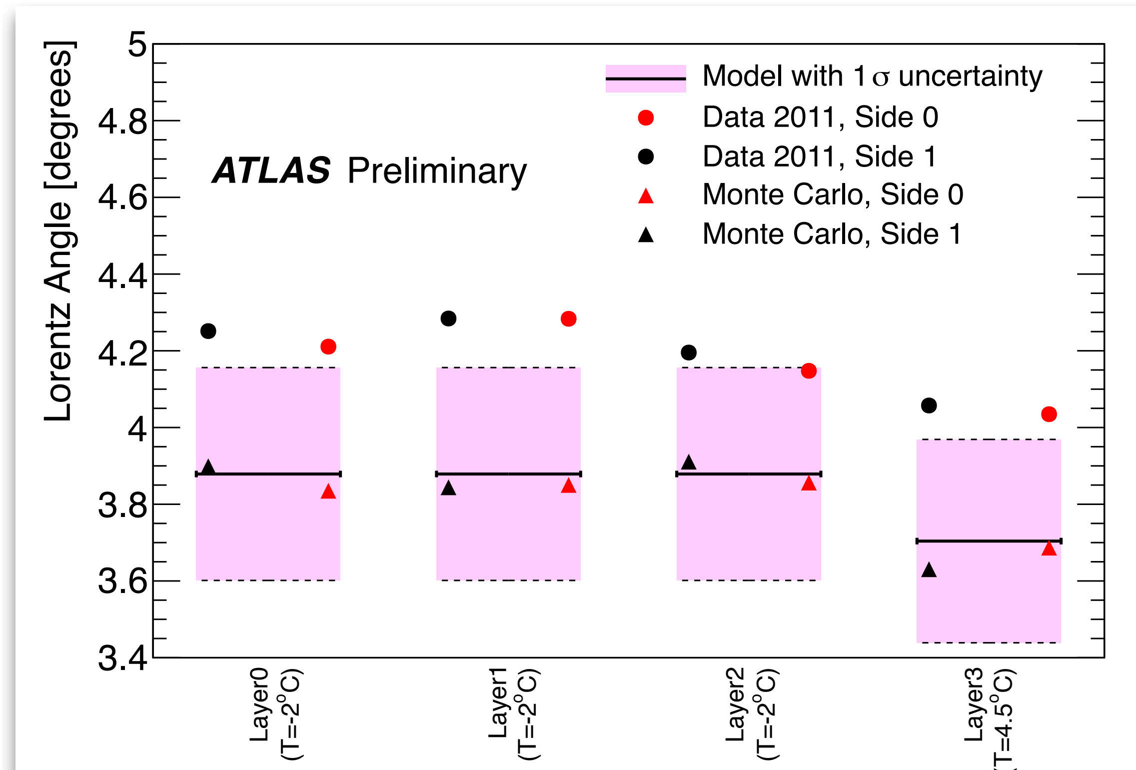



# SCT

- Energy loss simulated in G5 (range cut of 50 µm)
- During digitization charges drifted to wafer using Lorentz-angle taking fluctuations into account
- Simulation improved using measured efficiencies, electronic noise and cluster properties



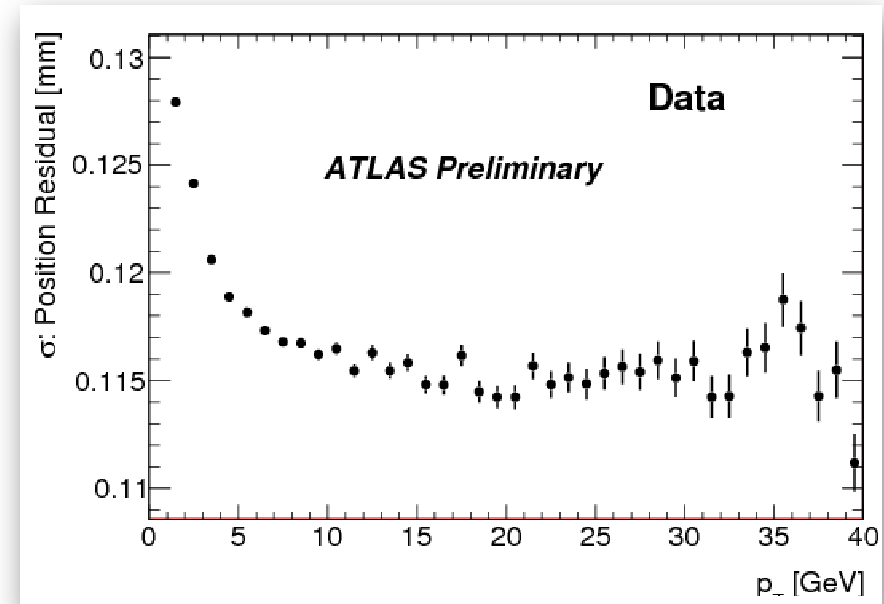



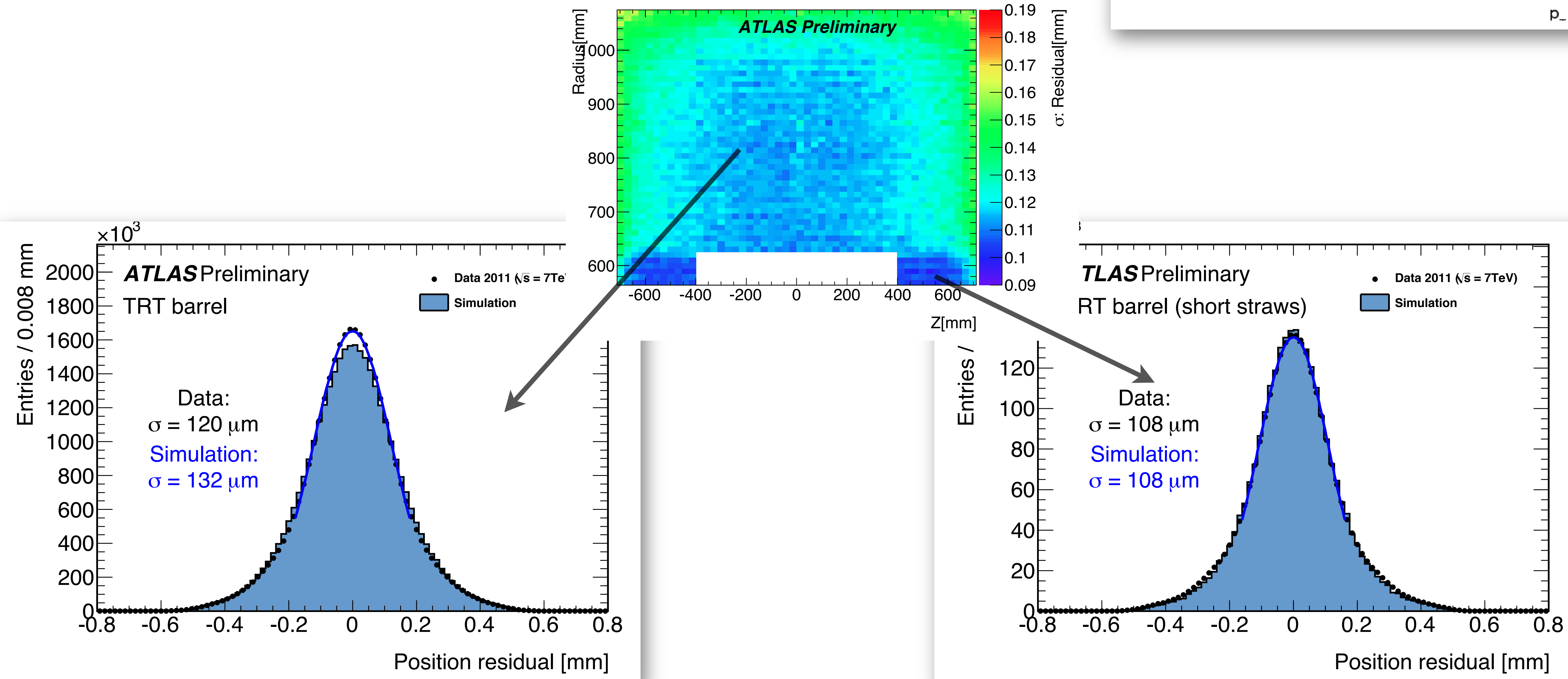




- Potential reduction of difference using improved charge transport model and pulse modeling plus a reduction in G4 range (minimal range cut is 1 µm)
  - both the transport model and the higher G4 granularity would cause dramatic increase in CPU time

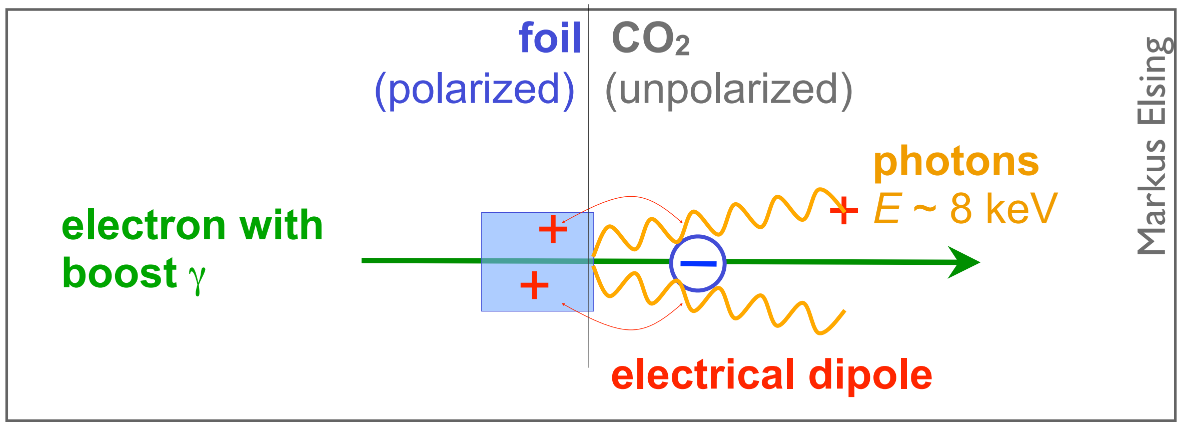
# TRT

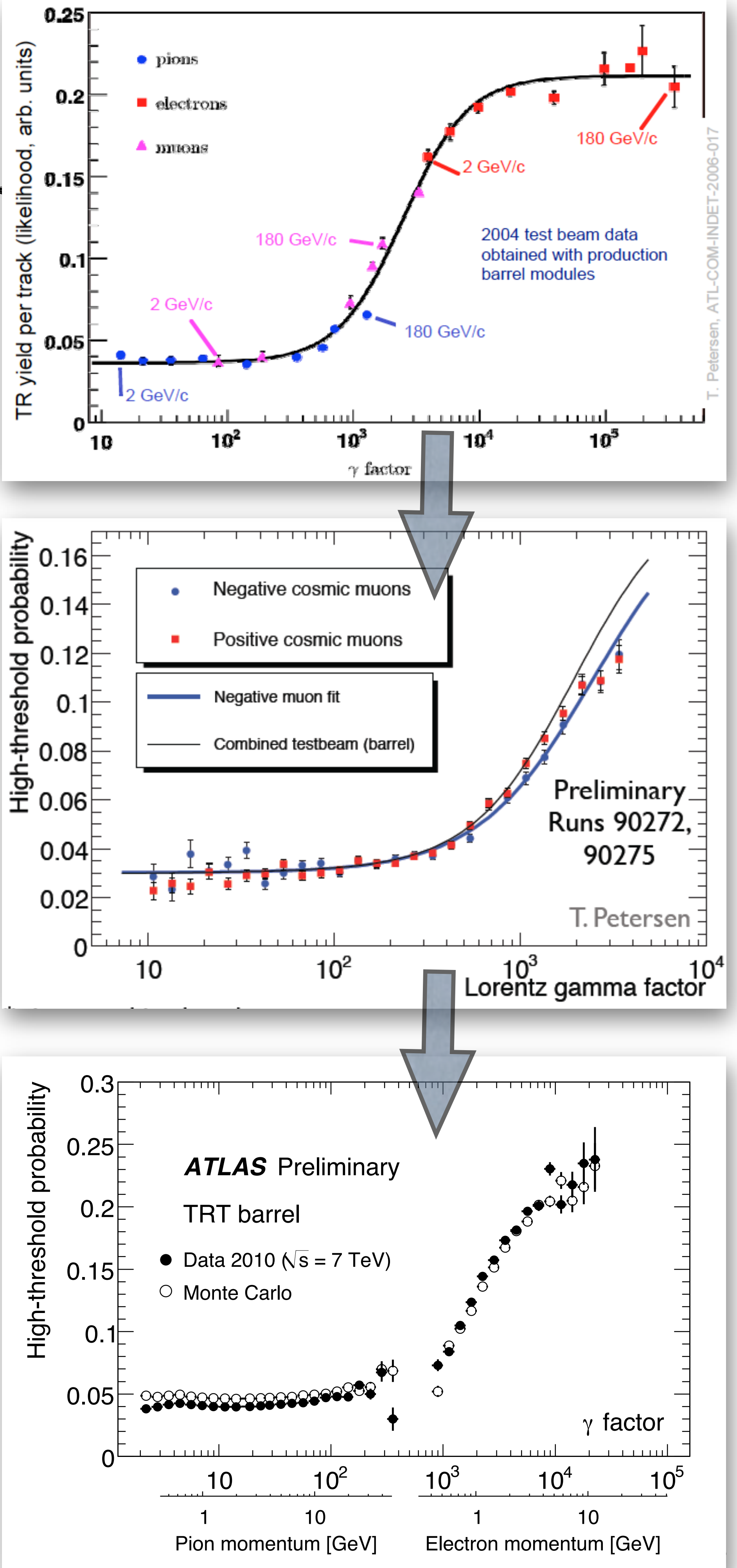
- TRT can improve track resolution significantly especially at high momentum tracks
- Hit resolution depends on detector position (here shown for $p_T$ > 2 GeV tracks)
  - for Barrel region resolution in MC overestimated
  - best resolution for hits in innermost region (short straws)



# Transition Radiation



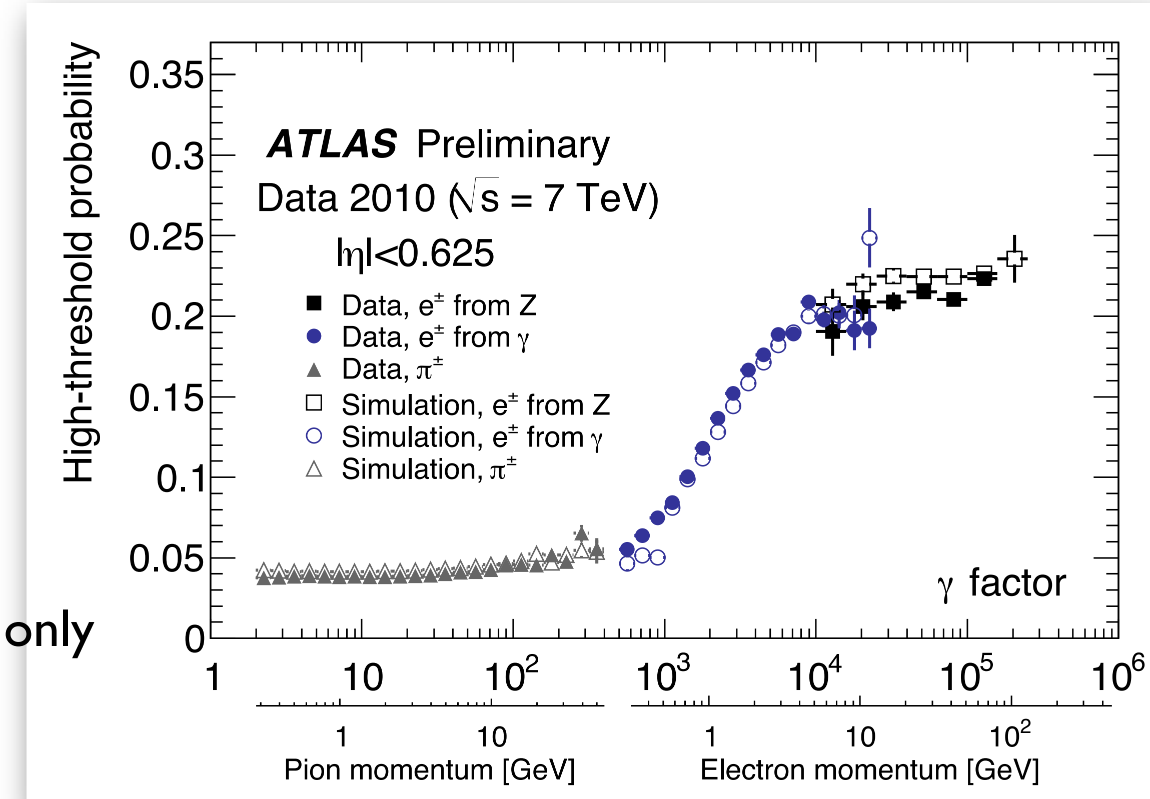



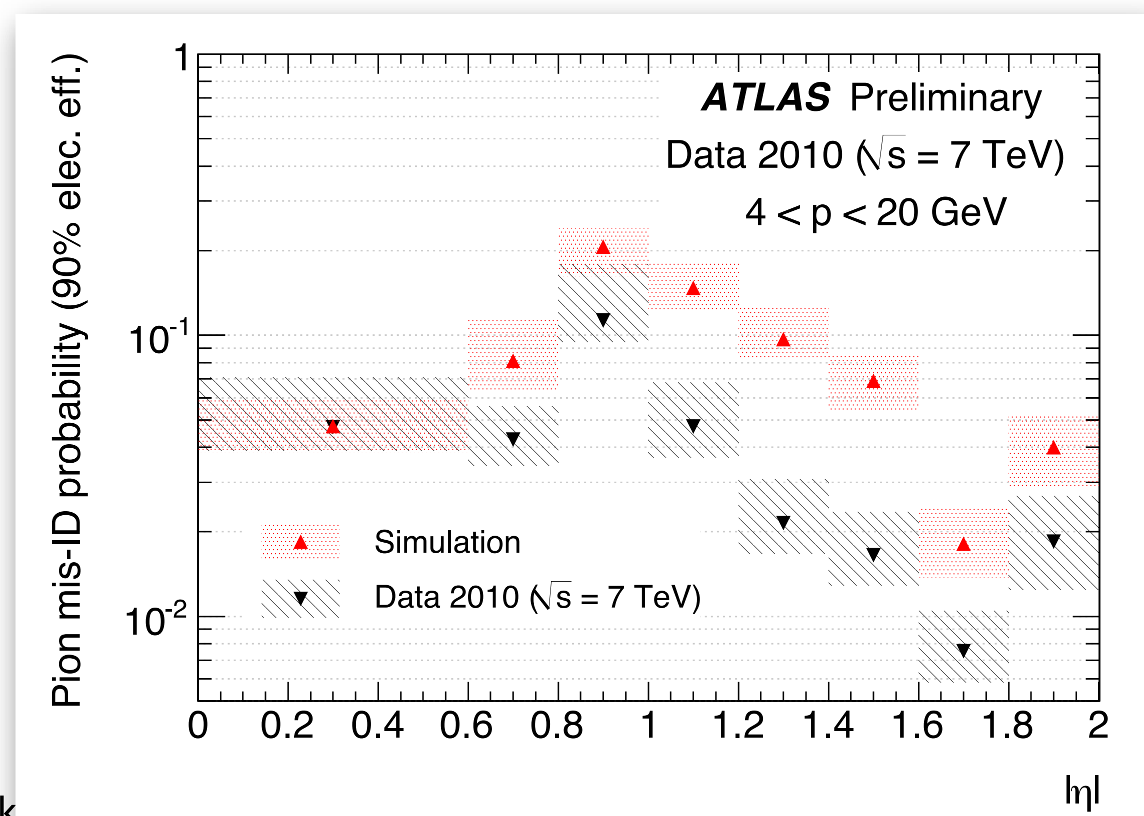

- Transition-Radiation model to simulate energy loss of charged particles passing from vacuum to a foil
  - based on P.Nevski (NIMA, 522,116 (2004))
  - predicts energy loss as a function of $\gamma$
- Spectrum has to be tuned with measurements
  - first measurement using test-beam data with different energies
  - improvements after comparison with cosmics
  - next step is to tune with collision data
- List of discrete photons handed to G4
- For high energy deposit (~6 keV) hit treated as high threshold hit

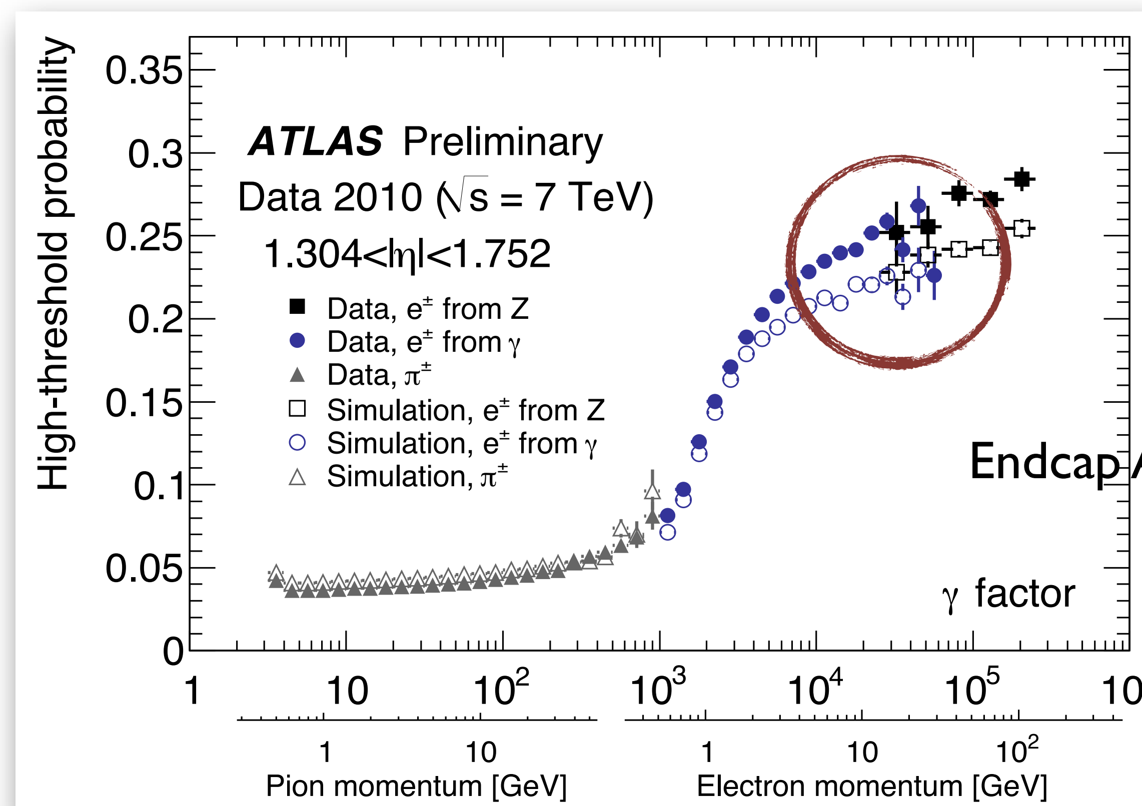
# TRT Particle Identification

- Turn-on behavior seen as a function of γ
- Deviations in Endcap region
  - B-type wheels have extra radiator filled compared to A-type (hence more TR)
  - pre-tuned simulation underestimates the TR in A-type wheels (fixed now)
- Barrel module prototype used to tune simulation using test-beam data
- HT probability and dE/dx can be used for particle identification

Barrel only



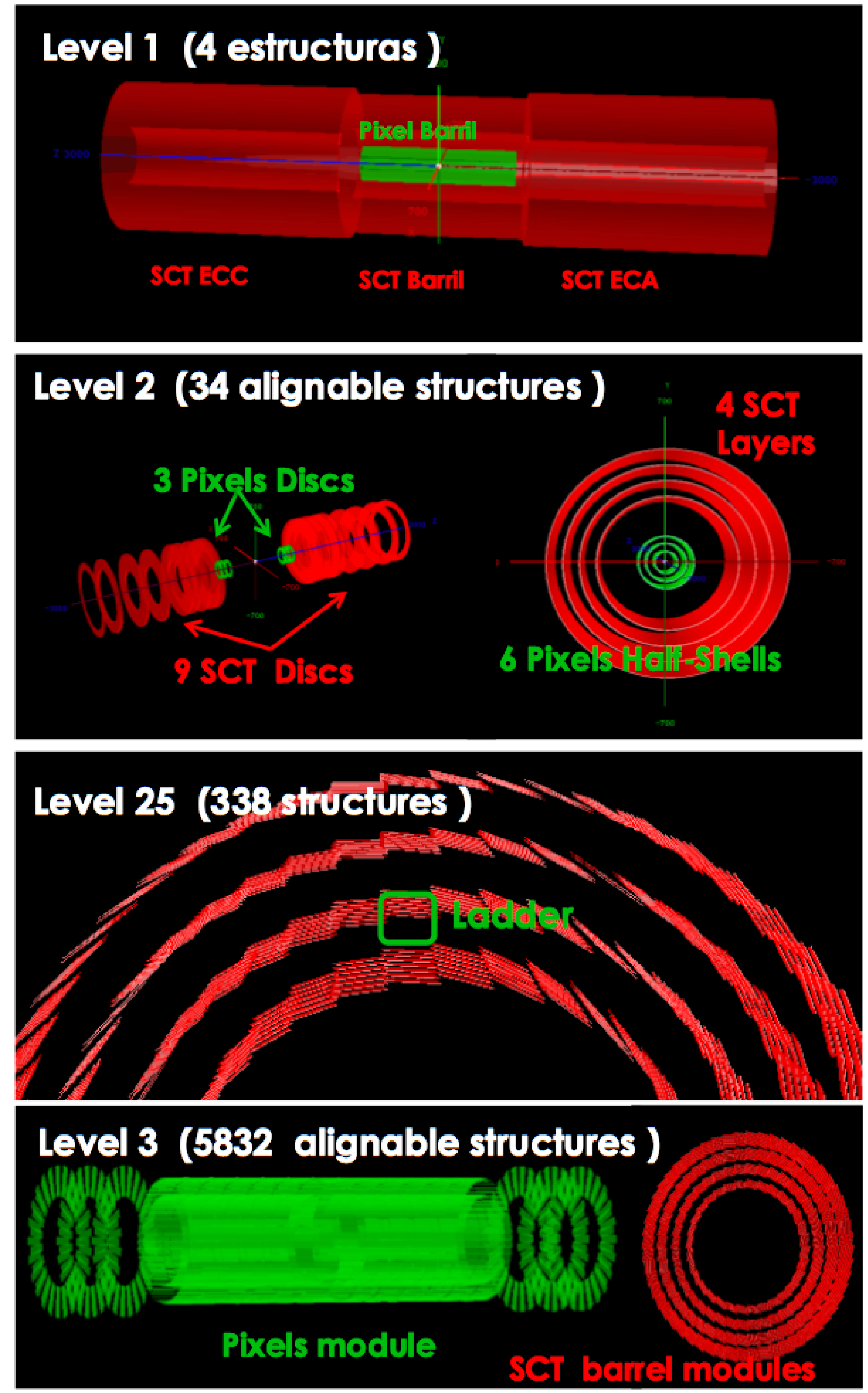




Endcap A wheels

# Inner Detector Alignment

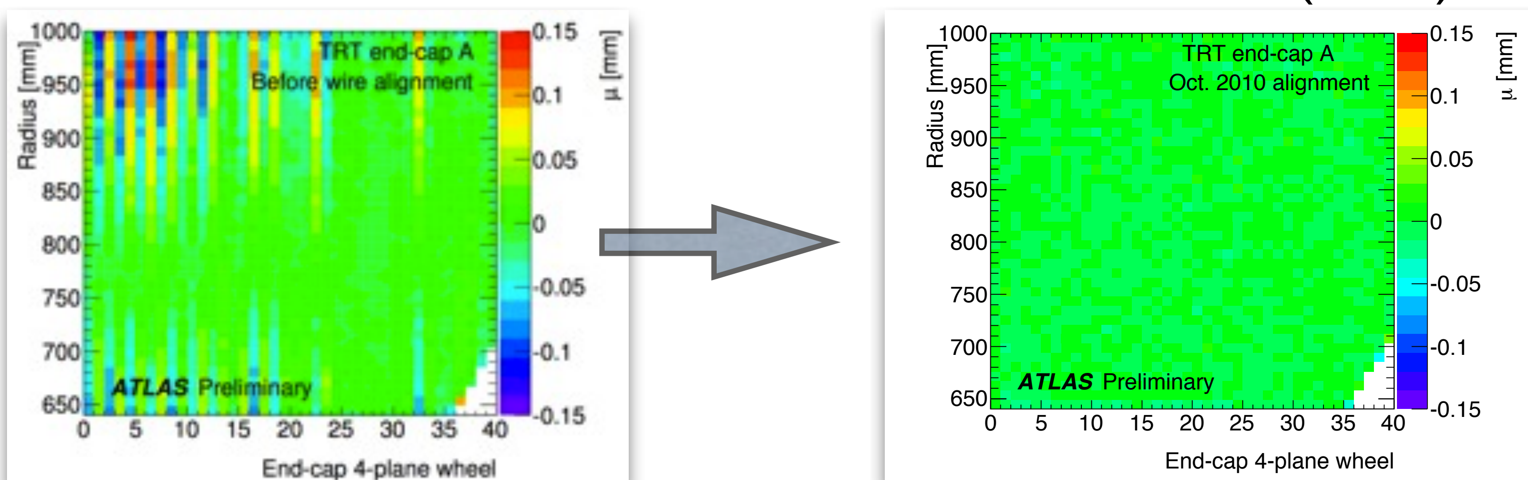
- Mis-measured relative position between detector pieces should not reduce intrinsic tracking resolution
- High accuracy needed for precision physics measurement
  - e.g. a 10-15 MeV precision in W mass requires a ~1 μm alignment
- Using calibration stream (isolated track with $p_T$>9 GeV) and cosmic events during empty proton bunches
- Alignment parameters are determined iteratively in three steps with increasing number of aligned substructures
  - including different number of degrees of freedoms for each structure in total 10464, 24528 and 701696 D.o.F for Pixel, SCT and TRT are needed

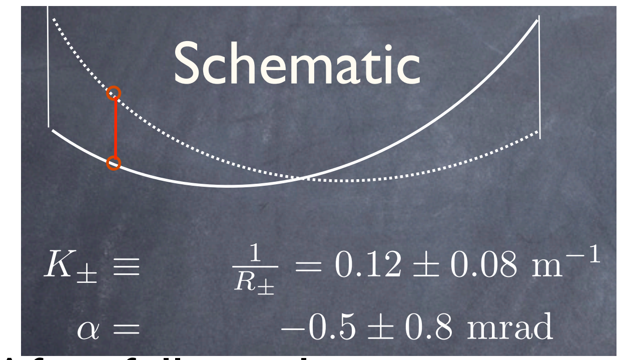
| Structures | Pixel | SCT | TRT |
|---|---|---|---|
| Level 1 | 1 | 3 | 3 |
| Level 2 | 12 | 22 | 96 |
| Level 3 | 1744 | 4088 | 350848 |



# Alignment Results

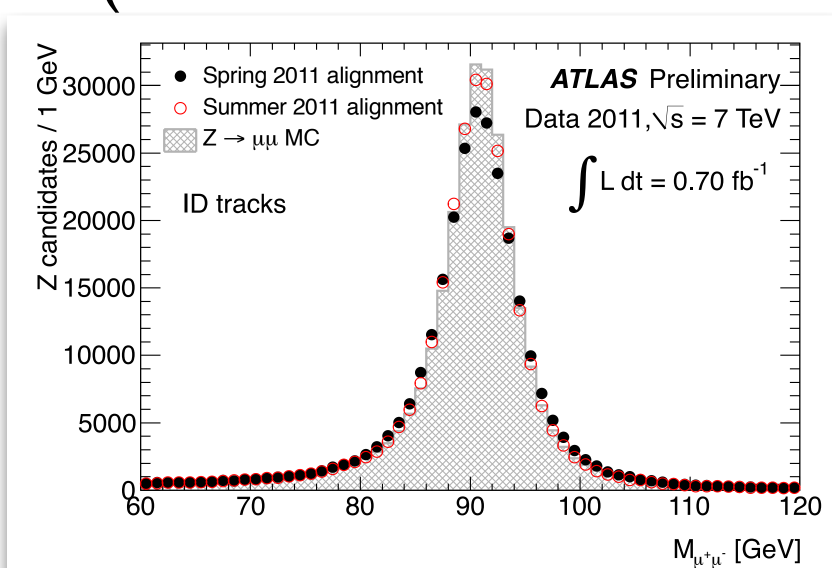
- Examples for local misalignment: Twist in TRT 4-plane wheel corrected with wire-by-wire correction or Pixel module deformation (bow)

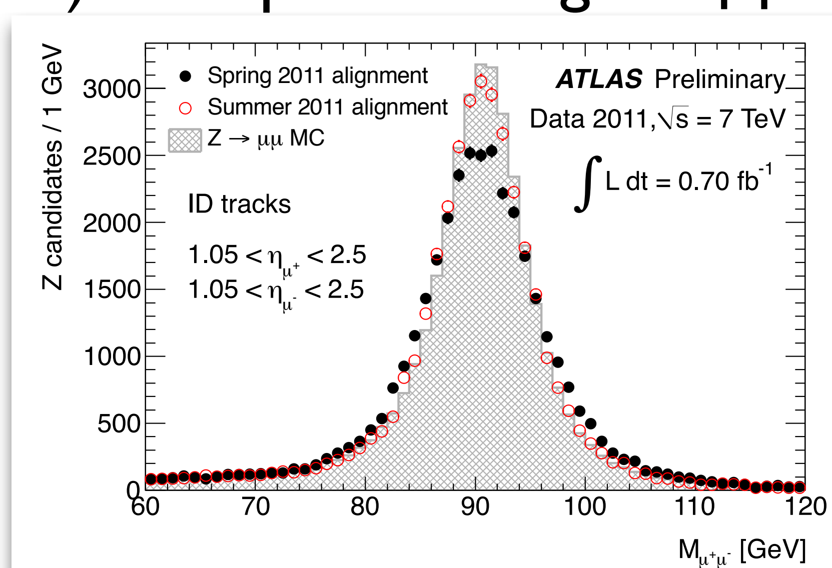



After full simulation corrected for during digitisation

- With more and more available data alignment is continuously improved (testbeam→cosmics→collisions) example showing Z→μμ for two sets of 2011

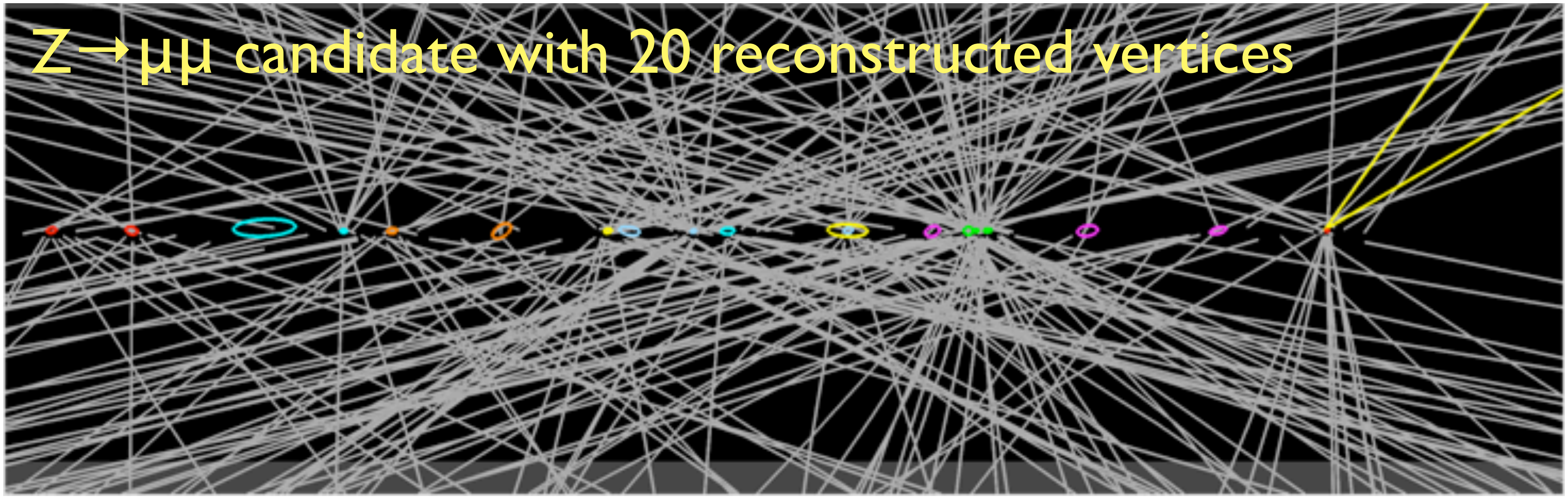



Use E/p constraint from e+ vs. e- and apply to muons

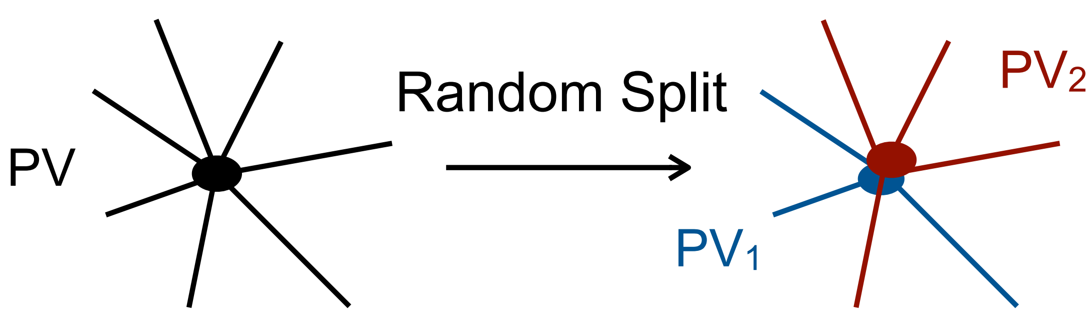
| Mass Res. (GeV) | Ideal | Additional res. | with E/p const |
|---|---|---|---|
| Barrel | 1.60 | 0.98±0.01 | 0.71±0.01 |
| Endcap | 3.42 | 3.03±0.03 | 1.16±0.01 |

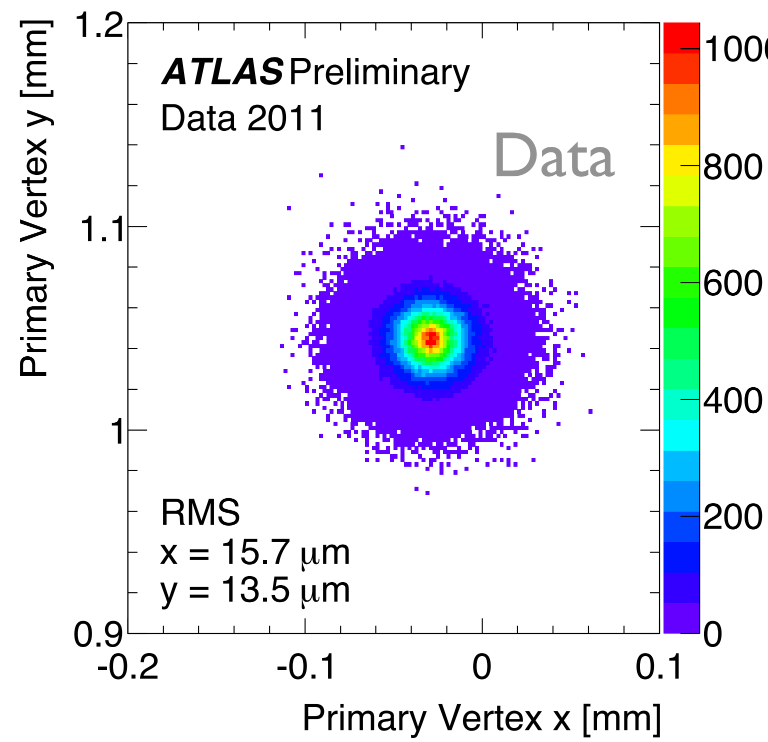
# Vertex Reconstruction

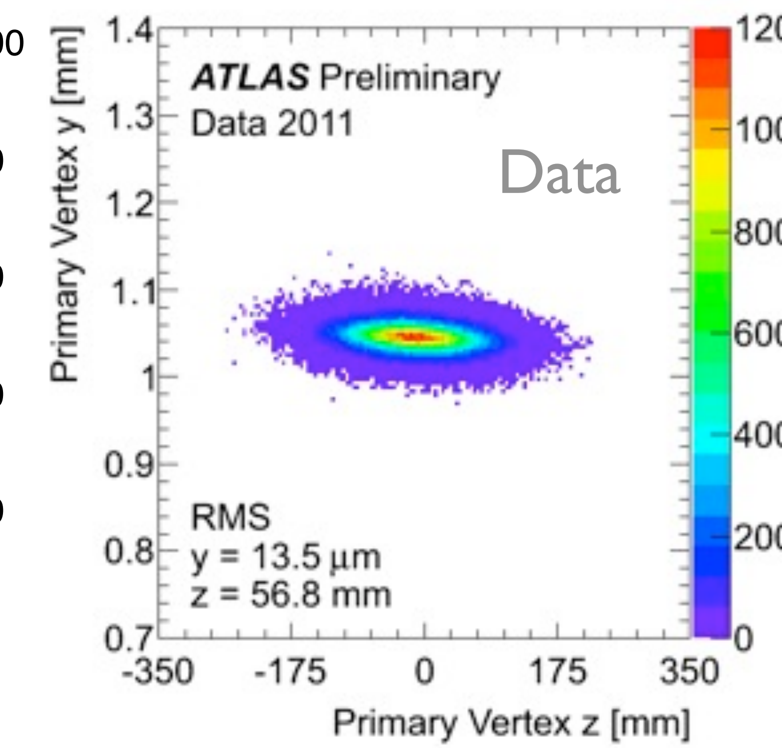



Two muons from Z associated to one of the vertices

- With iterative fitting procedures it is possible to fit primary and pile-up vertices
- Important to measure vertex resolution to understand influence of track and event reconstruction
- Vertex splitter to study effect
  - determines resolution in data

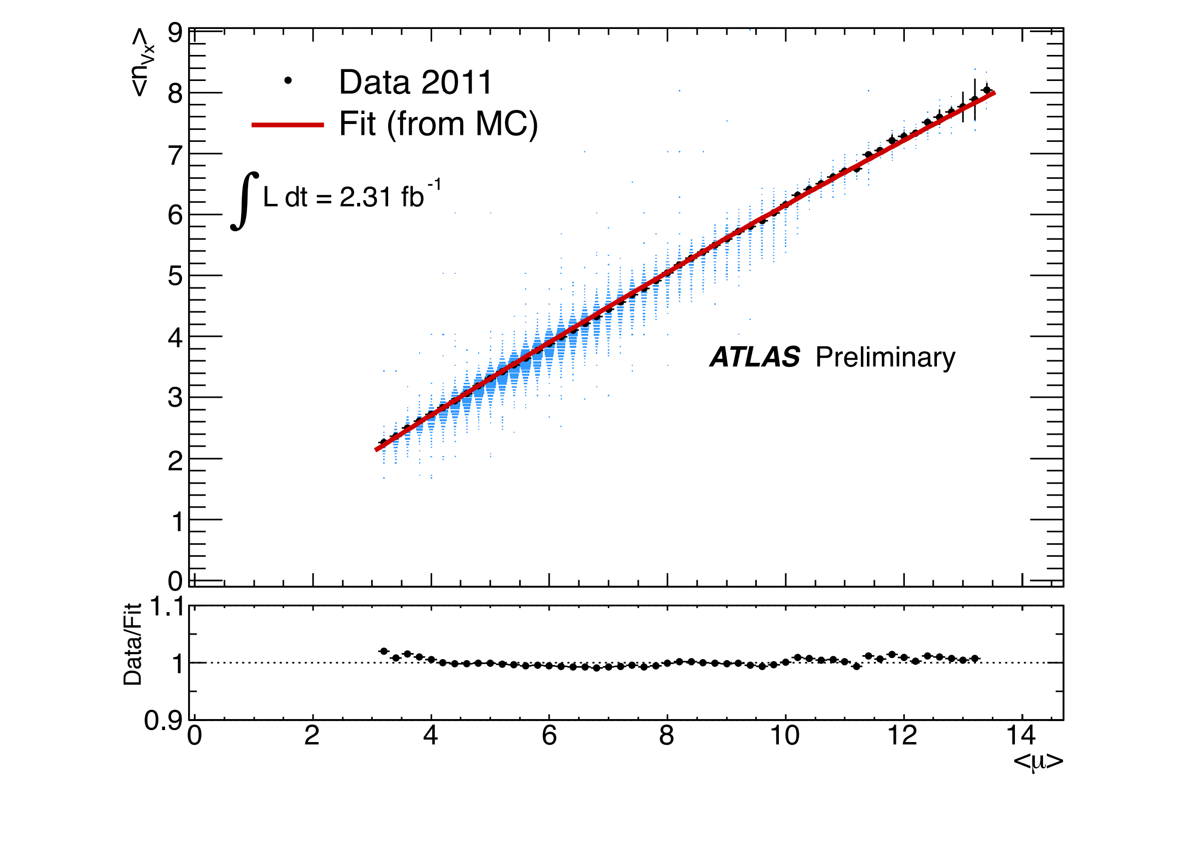


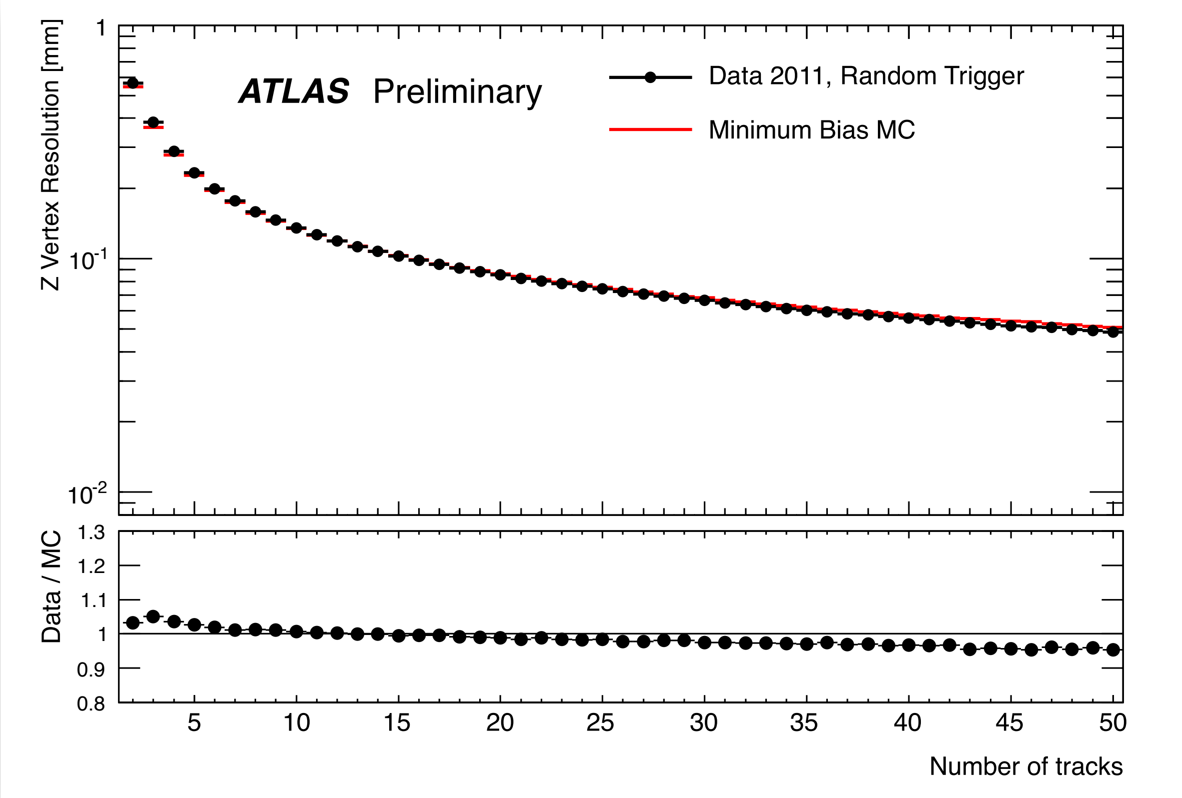



# Vertex Reconstruction

- Possible to determine average number of interactions from average number of vertices
  - also low multiplicity interactions included → does not reflect vertex reconstruction efficiency
  - Data distribution follows fit from MC
- Vertex resolution shown as a function of track multiplicity
  - general good agreement
  - small trend of underestimated resolution for low number and overestimated at high number



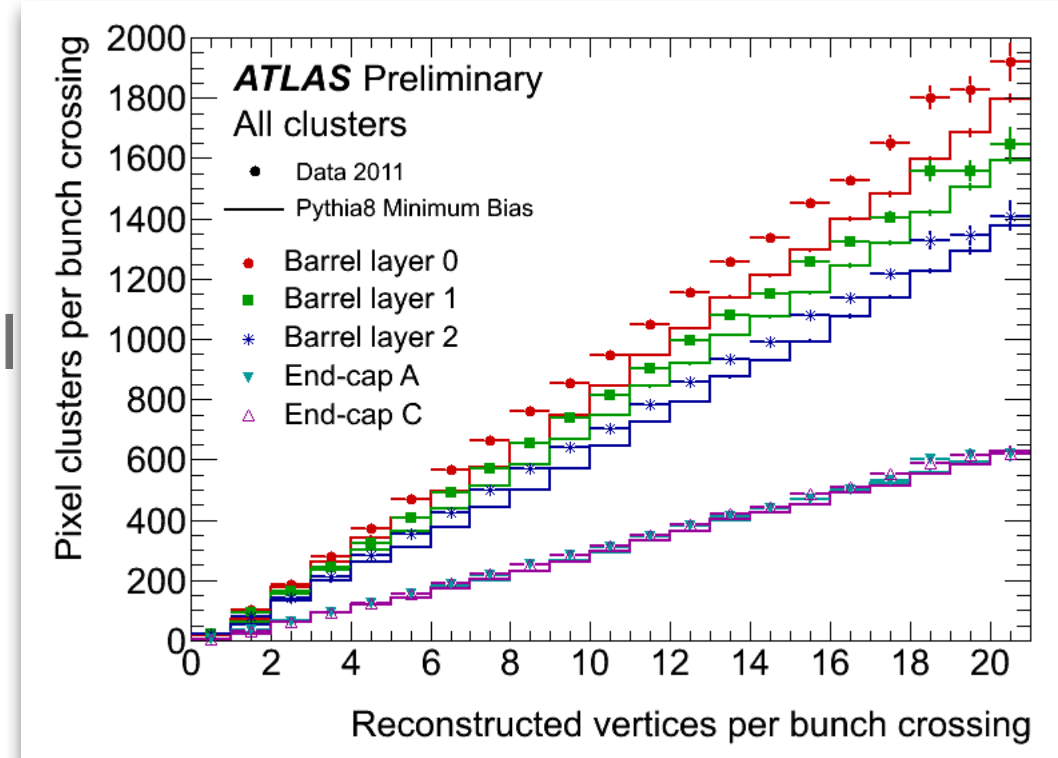



# Pile-Up Dependence

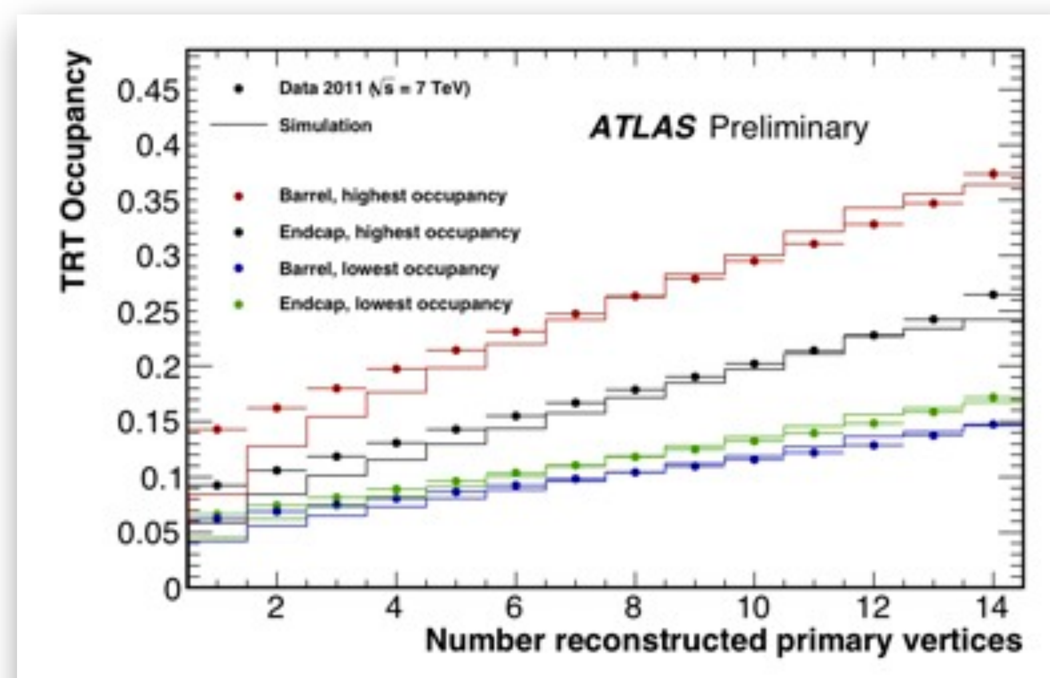
- Tracking performance depends on isolation of tracks/hits
- For higher occupancy not possible to have a unique association of hits
- Important to understand how number of hits is growing with number of vertices
- Pixel insensitive to out-of-time pileup →possible deviations from not simulated beam background
- For TRT significant out-of-time pileup and a higher occupancy of secondaries
- Offset also influenced by noise-hits and physics at hard scatter

based on 50 ns spacing

Pixel

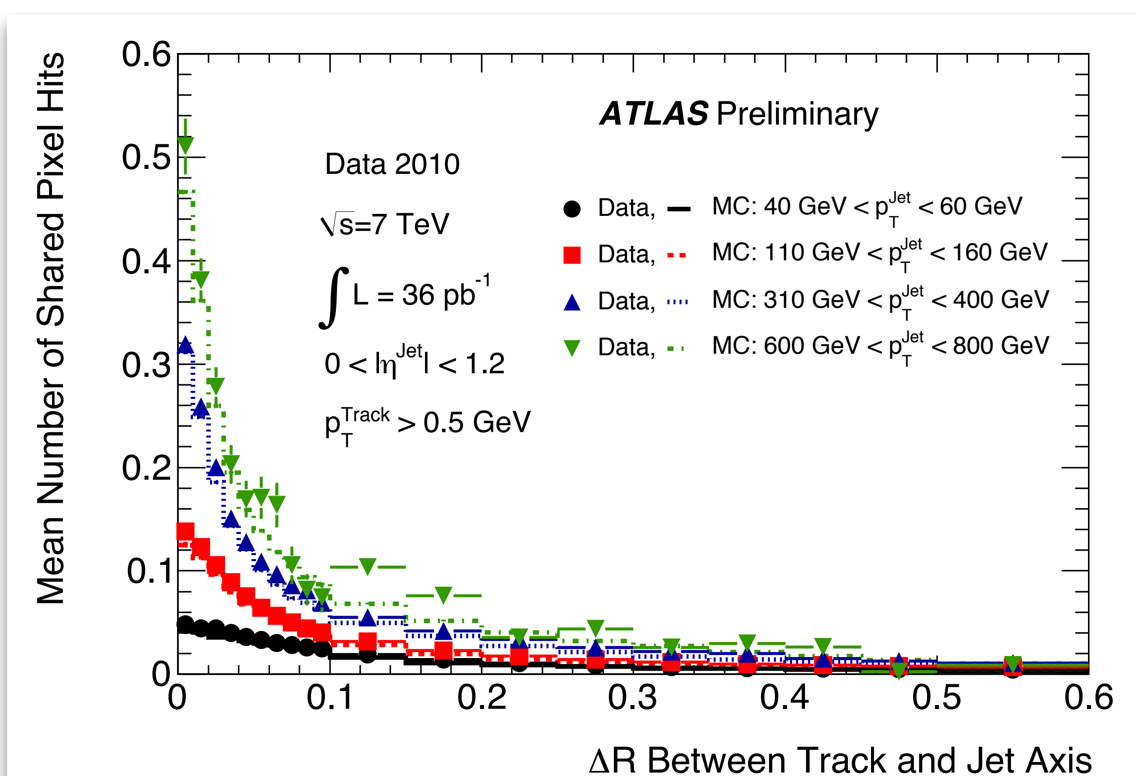


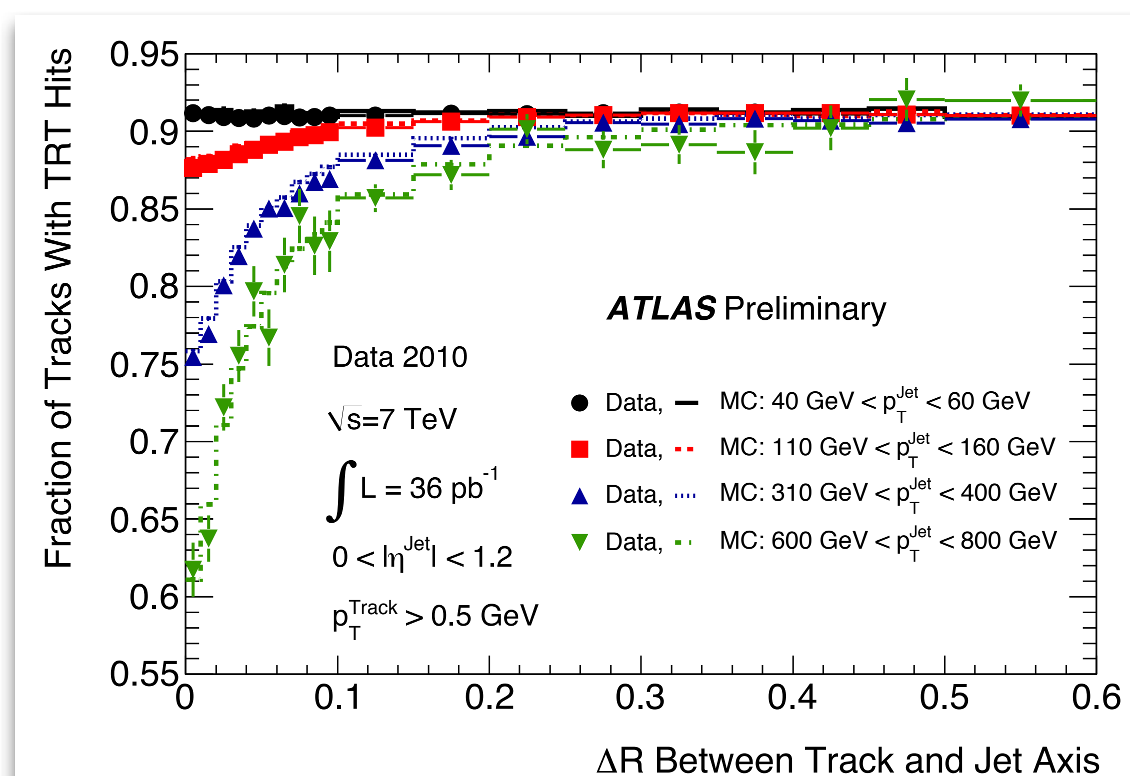

TRT



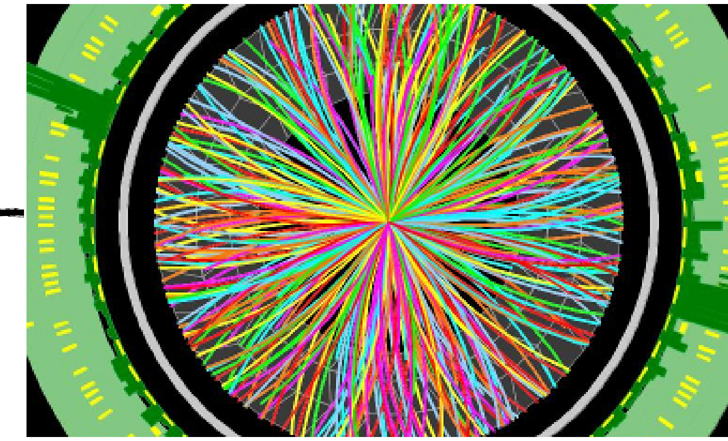
# Core of Jets

- Unique hit-to-track association is more complicated in dense region
- Can be studied as a function of isolation to jet axis
- In the region of higher density the probability for shared hits is higher
  - need improved cluster algorithms to reduce the fraction of shared hits
  - at the same time fraction of tracks with TRT association is reduced
- Effect is shown for four different jet momentum regions
- Monte Carlo is able to reproduce behavior
- In next improved clustering, the number of shared pixel hits can be improved by a factor of ~4 near the jet axis

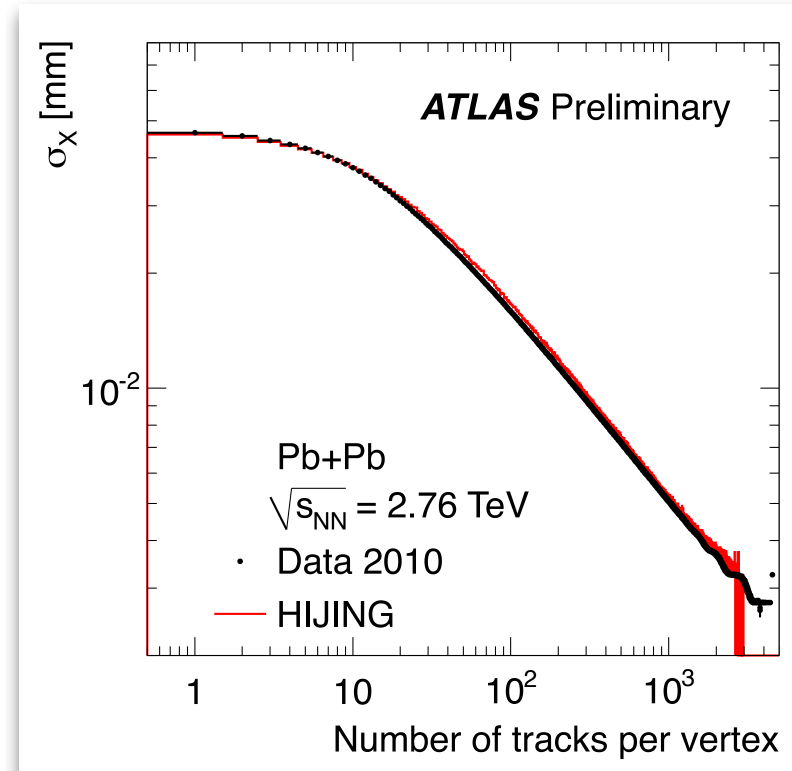


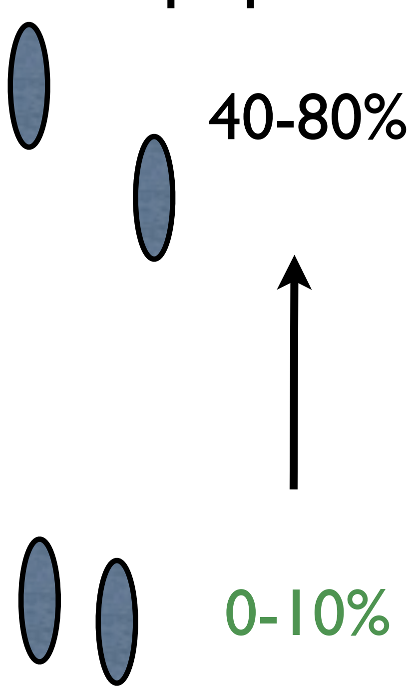
# Heavy Ion Tracking



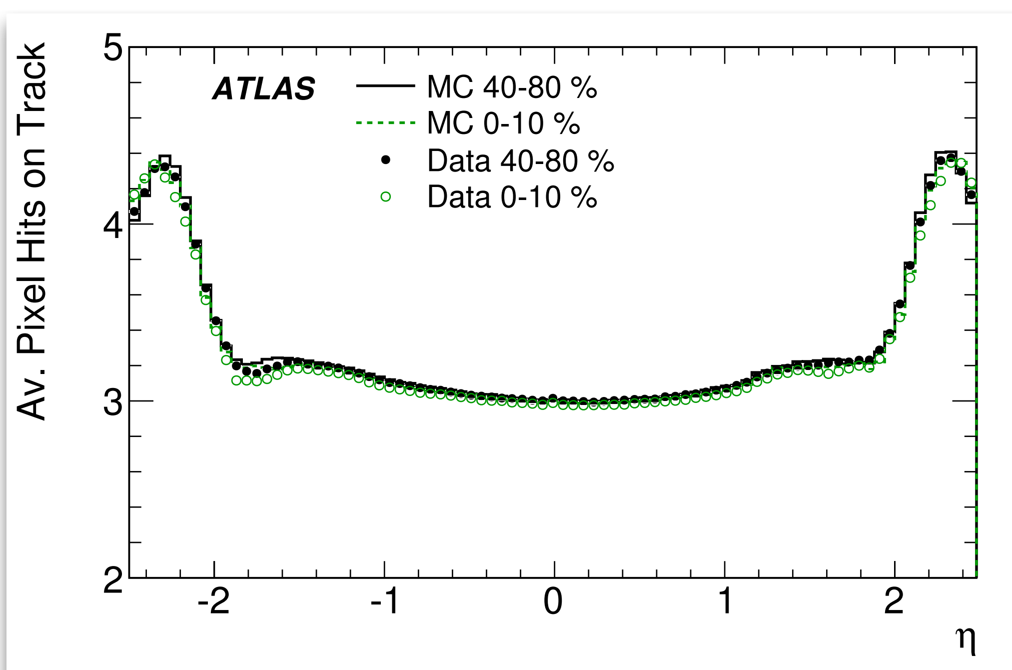
- Heavy Ion conditions give also opportunity to study tracking under high occupancy conditions
- Can study performance vs "centrality" to cover different conditions
  - average number of SCT/Pixel hits on tracks shown for extreme cases of centrality
  - also good vertexing under HI conditions
  - dependence of vertex resolution as a function of track multiplicity well modeled
- excellent tracking performance observed

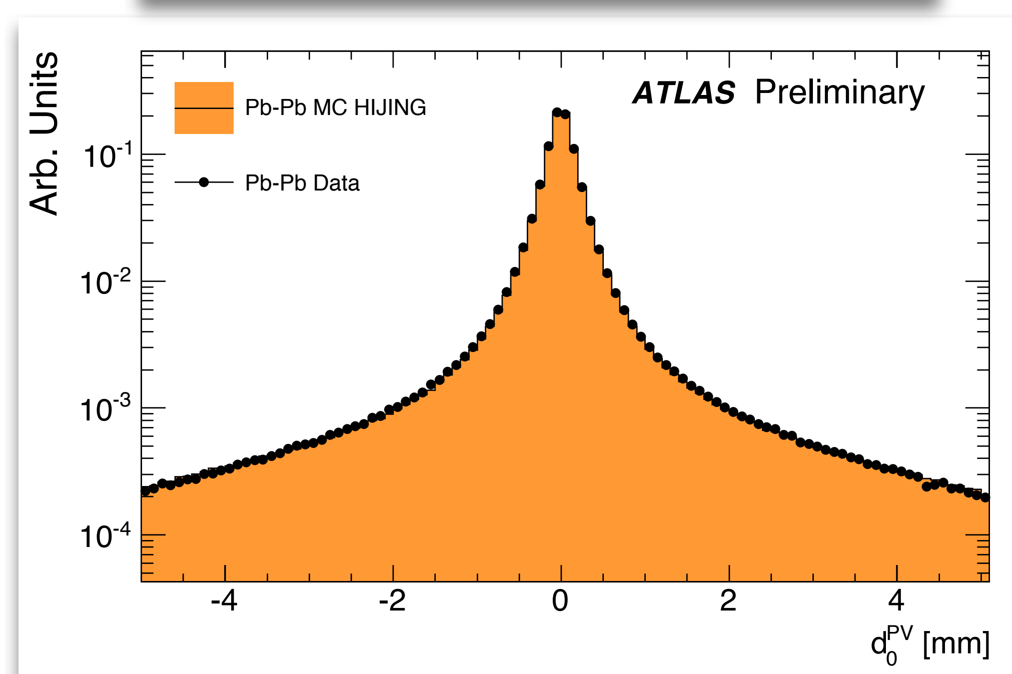



**most periphal**




**most central**



# Summary

- Geometry model in G4 to navigate simulated events through ATLAS detector and calculate detector response
- Material budget controlled with secondary interactions and stopping tracks
- Alignment continuously improved to optimize detector performance
- After Pixel calibration precise track measurement and particle identification possible
- Good SCT modeling, most of the potential improvements interconnected with large computing time
- Model of Transition Radiation step-by-step tuned; full G4 would require hugh CPU
- Due to fast and precise reconstruction of Pixel possible to reconstruct multiple vertices per event
- Even under HI conditions good tracking performance and reconstruction
- Not possible to cover all topics, sorry if I missed something important

# Thanks

**Thanks for help, material and patient explanations:**

M. Elsing, D. Froidevaux, J. Adelman, P. Ward, F. Djama, A. Andreazza, A. Salzburger, F. Luehring and many others ...

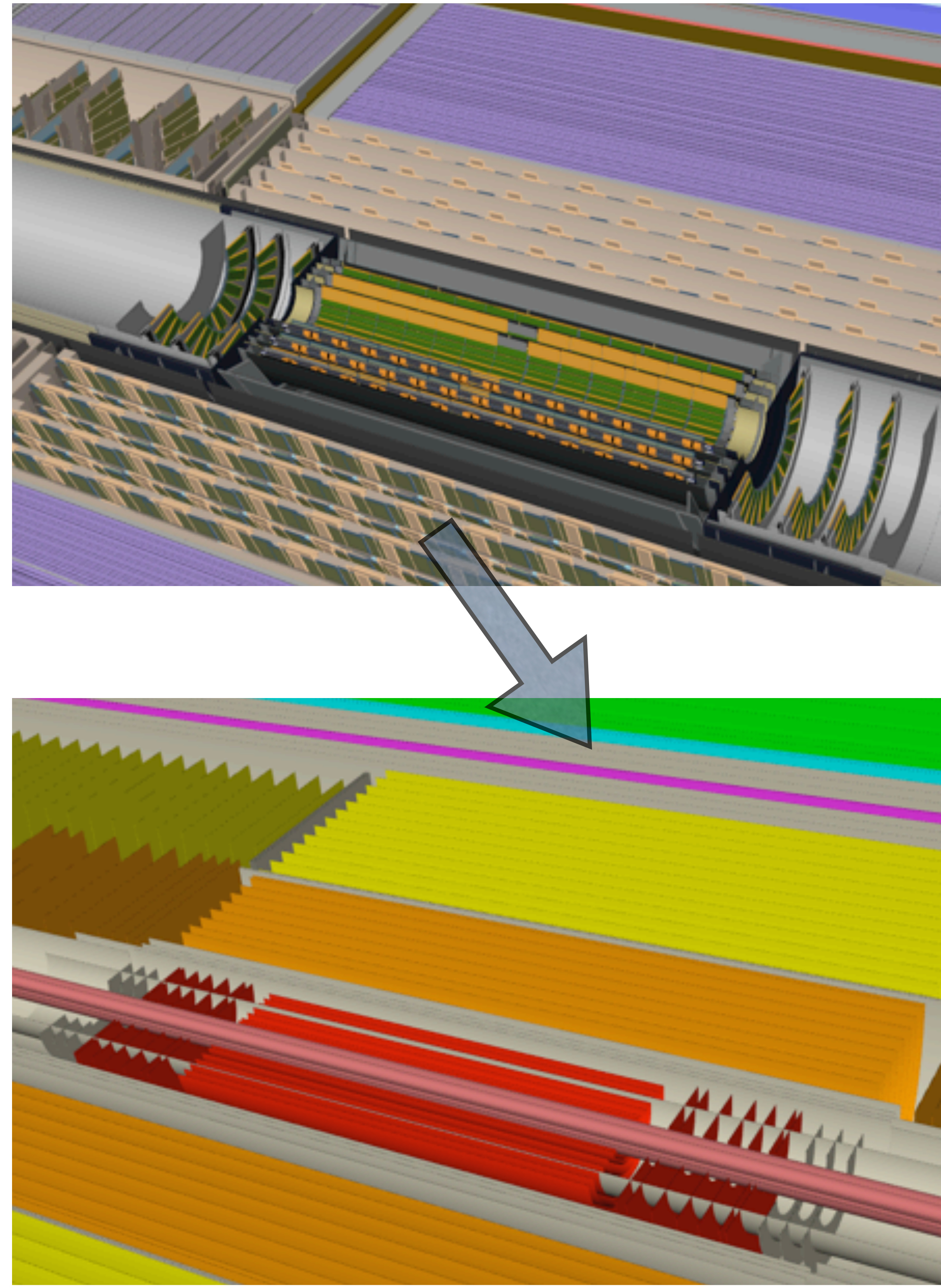
# Material

- The ATLAS simulation Infrastructure (slide 4,5)
- HION-2010-01 (slide 20)
- ATLAS-CONF-2011-012 (slide 2,16)
- ATLAS-CONF-2011-016 (slide 9)
- ATLAS-CONF-2011-128 (slide 13)
- Pixel public results TWiki (slide 8,18)
- SCT public results TWiki (slide 6,10)
- TRT public results TWiki (slide 11,12,18)
- Tracking public TWiki (slide 5,8,16,17,19,20)
- EventDisplay public TWiki (slide 16)

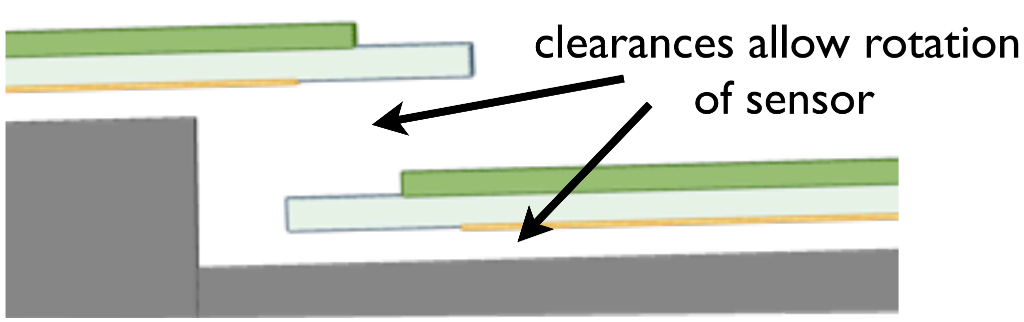
# Backup

# Geometries for Full and Fast Tracking

- Full Geometry too slow for tracking
  - use simplified model
- Combine volumes into larger volumes with same effective material
  - active surfaces for the interactions
  - interleaved with passive volumes with no interactions
  - reduces volumes to O(100)



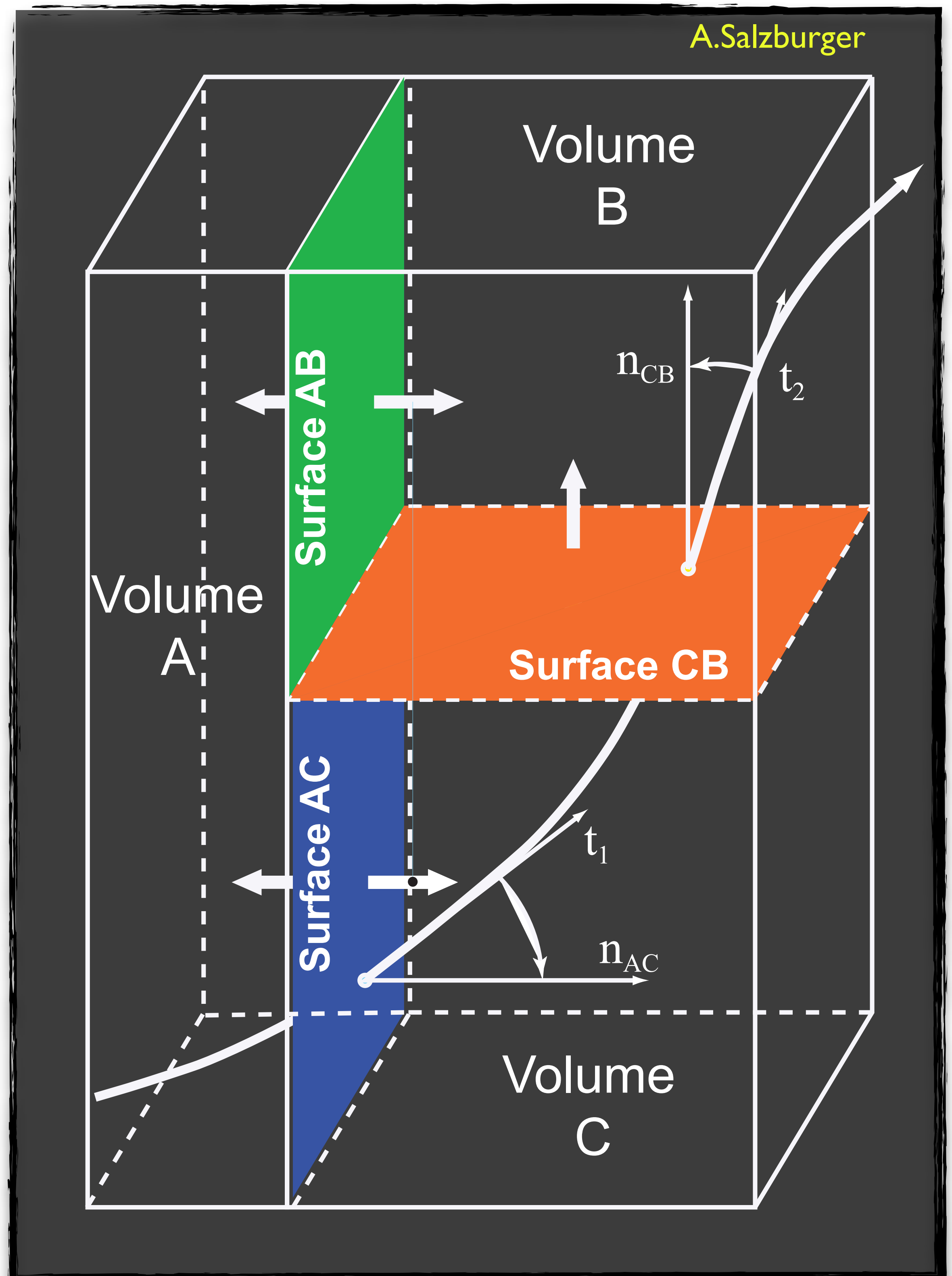
- Volumes for pixel separated from support structure
  - these empty spaces avoid volume clashes during MC studies



# Navigation Schemes

- Embedded navigation scheme in tracking geometries
  - G4 navigation uses voxelisation as generic navigation mechanism
  - embedded navigation for simplified models
  - used in pattern recognition, extrapolation, track fitting and fast simulation
- Connected volumes
  - developed geometry of connected volumes
  - new four-vector is calculated in each volume using information from boundary surfaces of connected volumes
  - Combination reduces CPU time significantly

| | G4 | tracking | ratio |
|---|---|---|---|
| crossed volumes in tracker | 474 | 95 | 5 |
| time in SI2K sec | 19.1 | 2.3 | 8.4 |



# b-Tagging

- Primary vertex is input to several physics applications (e.g. b-tagging)
- Robust taggers
  - inclusive secondary vertex tagger (SV0)
  - impact parameter significance (JetProb)
- Performance well studied
  - efficiency and miss-tag rate checked using e.g. lepton method or neg. tags