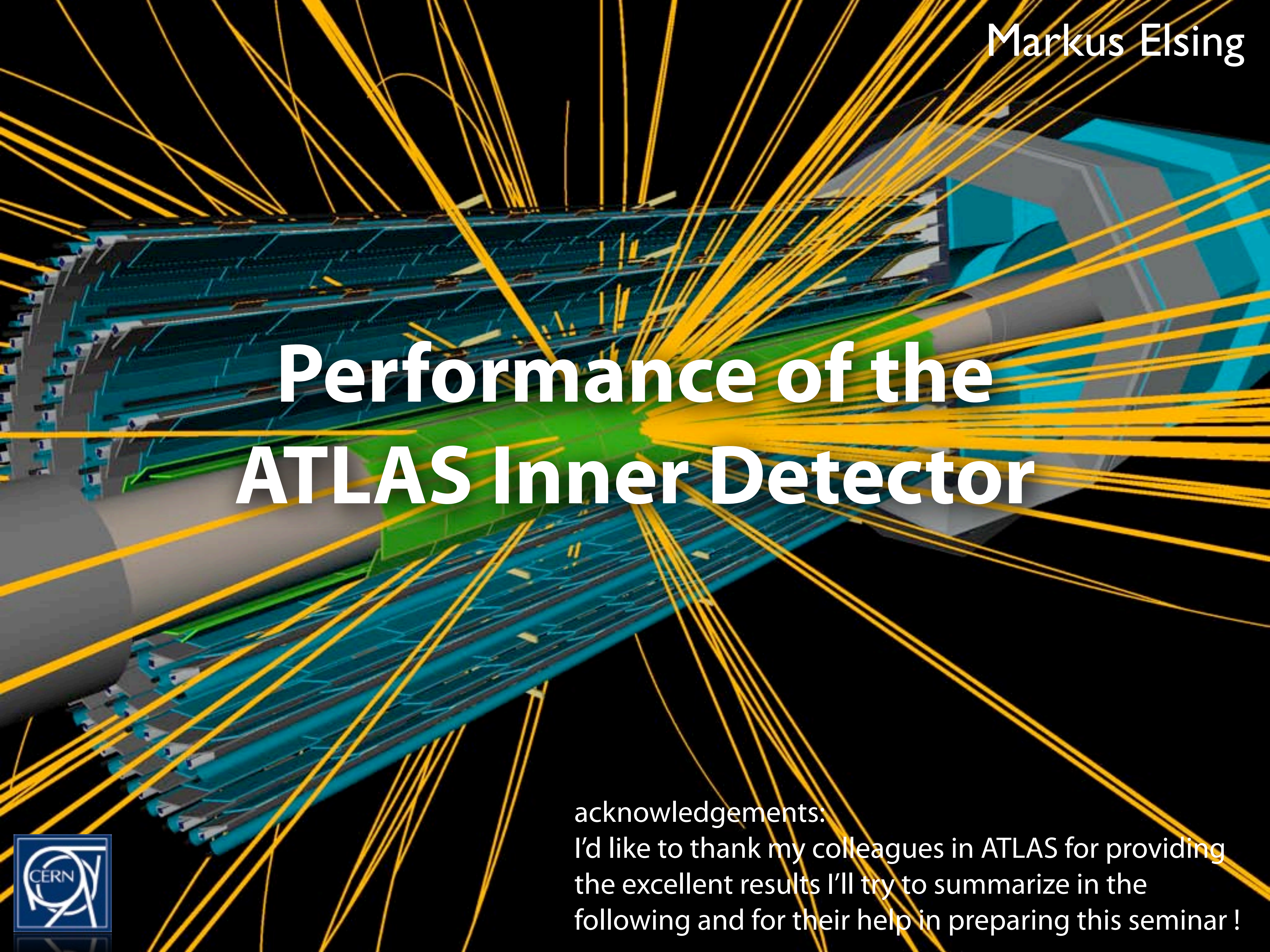
Markus Elsing

Performance of the ATLAS Inner Detector



acknowledgements:
I'd like to thank my colleagues in ATLAS for providing the excellent results I'll try to summarize in the following and for their help in preparing this seminar !

Outline of this Seminar

- short introduction
- expected tracking performance
- commissioning of Inner Detector reconstruction
  - ➡ calibration, tracking, alignment, material, ...
- tracking performance
  - ➡ especially in jets and with pileup
  - ➡ vertexing and b-tagging
- upgrade: expected performance improvements with the Insertable B-Layer (IBL)

Introduction

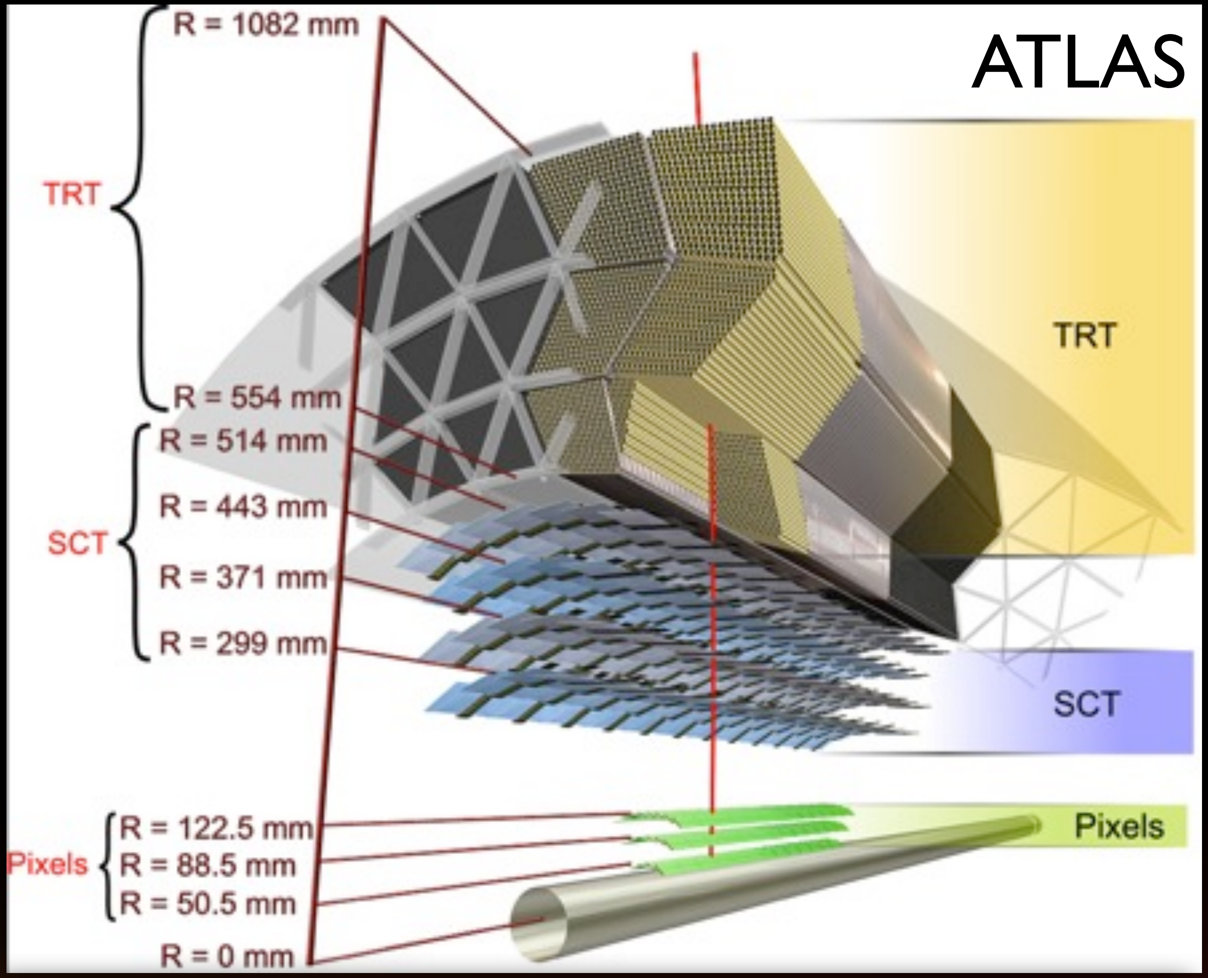
- broad **physics program** covered by **ATLAS**
  - ➡ general purpose pp experiment to cover:
    - SM QCD/W/Z/top, Higgs, SUSY, Exotics, ...
    - some aspects in b-physics
    - ability to do heavy ion physics
- **detector** designed to optimize physics performance
  - ➡ at design luminosities (10^{34} $cm^{-2}s^{-1}$) and pileup (~23 min.bias events)
  - ➡ possibly sustain heavy ion “central” event multiplicities
- task of **event reconstruction** is to identify objects
  - ➡ e/μ/τ leptons, photons, (b) jets, missing E_T, exclusive hadronic states...
  - ➡ requires **combining information** from tracking detector with calorimetric and muon spectrometer measurements
  - ➡ **tracking** is a central aspect of the event reconstruction

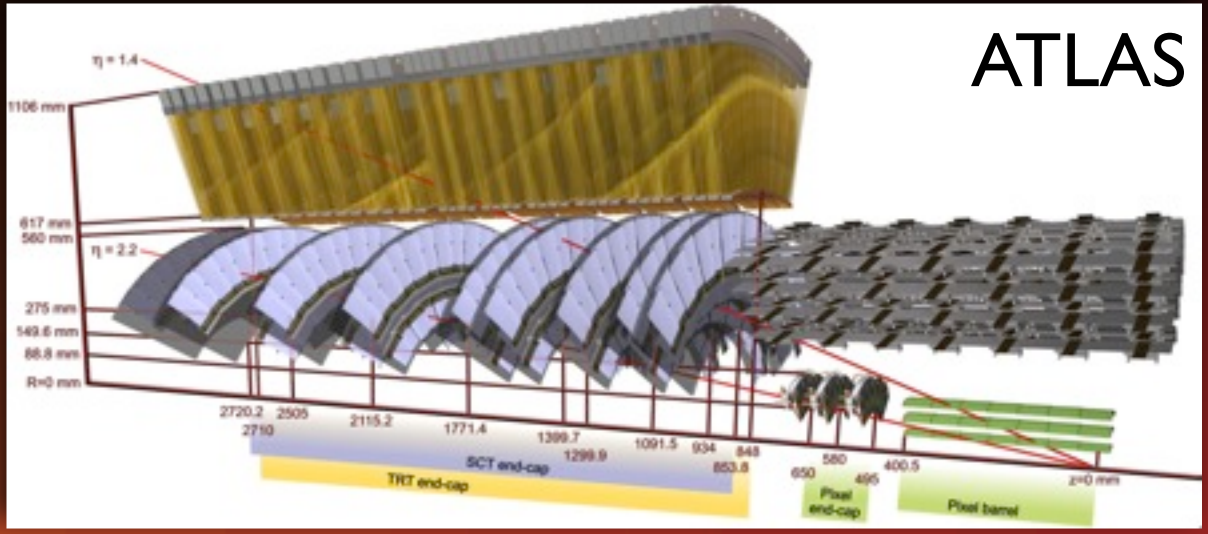
Introduction

- requirements on ATLAS Inner Detector
  - ➡ **precision tracking** at LHC luminosities (central heavy ion event multiplicities) with a hermitic detector covering 5 units in η
  - ➡ precise **primary/secondary vertex** reconstruction and to provide excellent **b-tagging in jets**
  - ➡ reconstruction of **electrons** (and converted photons)
  - ➡ tracking of **muons** combined with muon spectrometer, good resolution over the full accessible momentum range
  - ➡ enable (hadronic) **tau**, exclusive **b-** and **c-hadron** reconstruction
  - ➡ provide **particle identification**
    - transition radiation in ATLAS TRT for **electron identification**
    - as well dE/dx in Pixels or TRT
  - ➡ not to forget: enable fast tracking for **(high level) trigger**
- constraints on detector design
  - ➡ **minimize material** for best precision and to minimize interactions before the calorimeter
  - ➡ increasing **sensor granularity** to reduce occupancy
    - increase number of electronics channels and heat load
    - leading to more material

ATLAS Inner Detector Layout

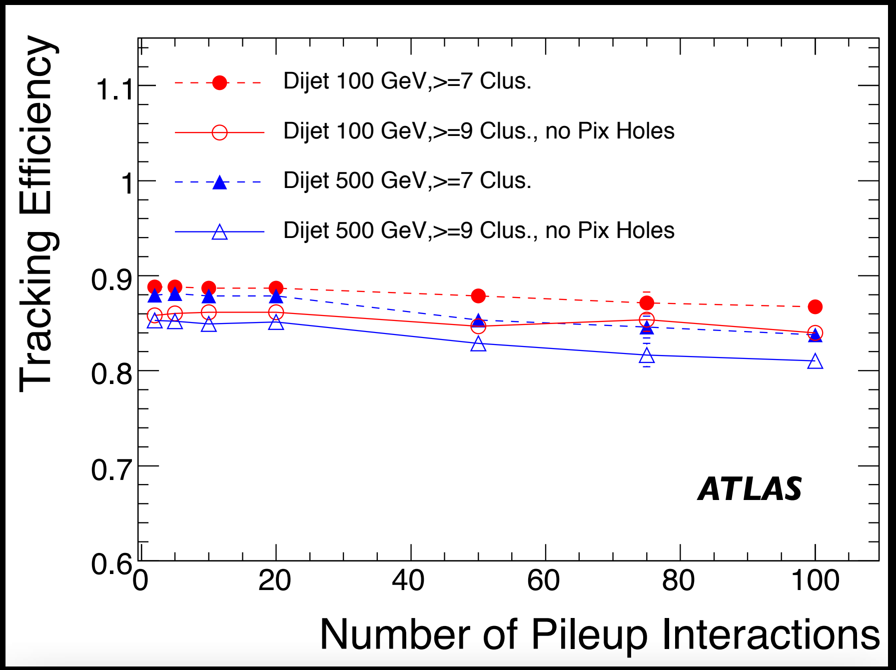
- 3 subsystems:
  - ➡ 3 layer **Pixel** system, 3 endcap disks
    - 1744 Pixel modules
    - 80.4 million channels
    - pitch 50 μm × 400 μm
    - total of 1.8 m^2
  - ➡ 4 layers of small angle stereo strips, 9 endcap disks each side (**SCT**)
    - 4088 double sided modules
    - 6.3 million channels
    - pitch 80 μm, 40 mrad stereo angle
    - total of 60 m^2
  - ➡ Transition Radiation Tracker (**TRT**)
    - typically 36 hits per track
    - transition radiation to identify electrons
    - total of 350K channels

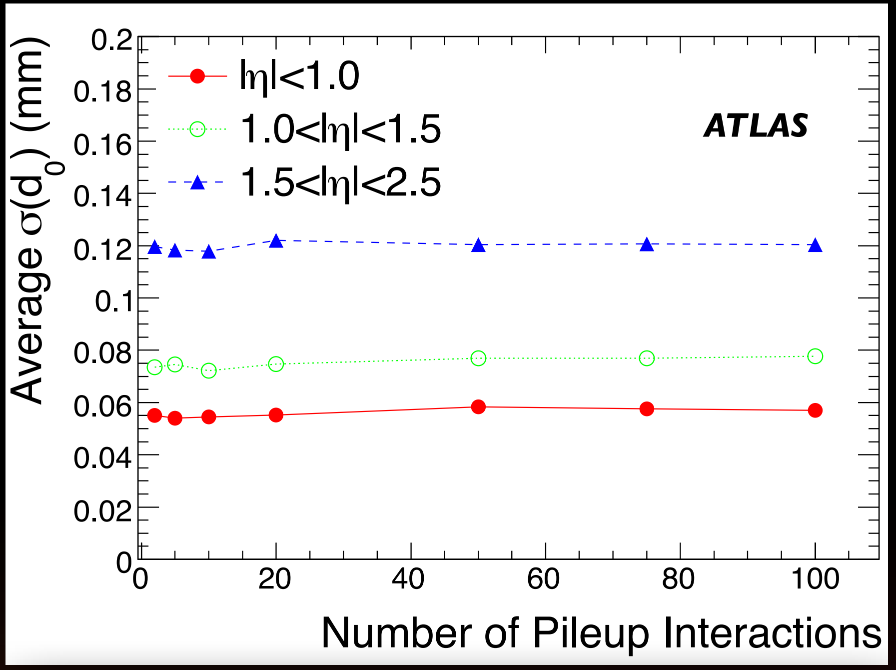


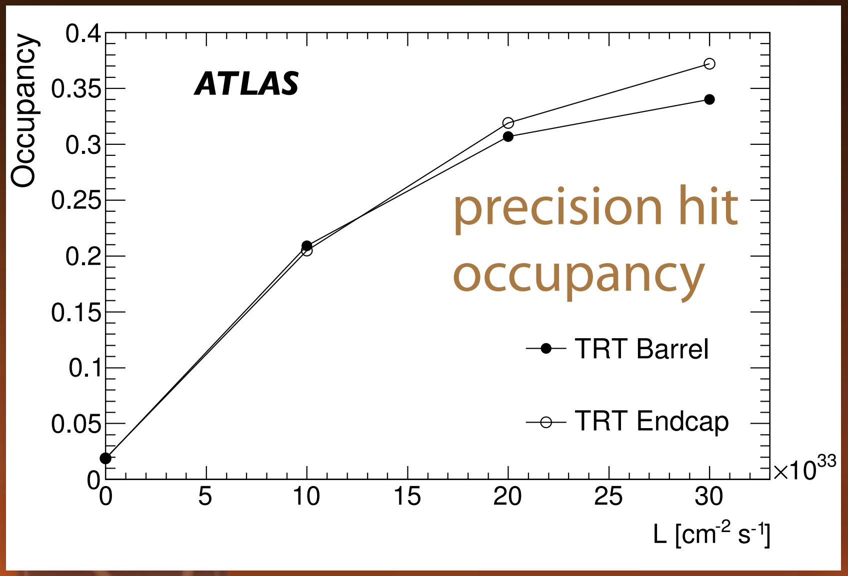


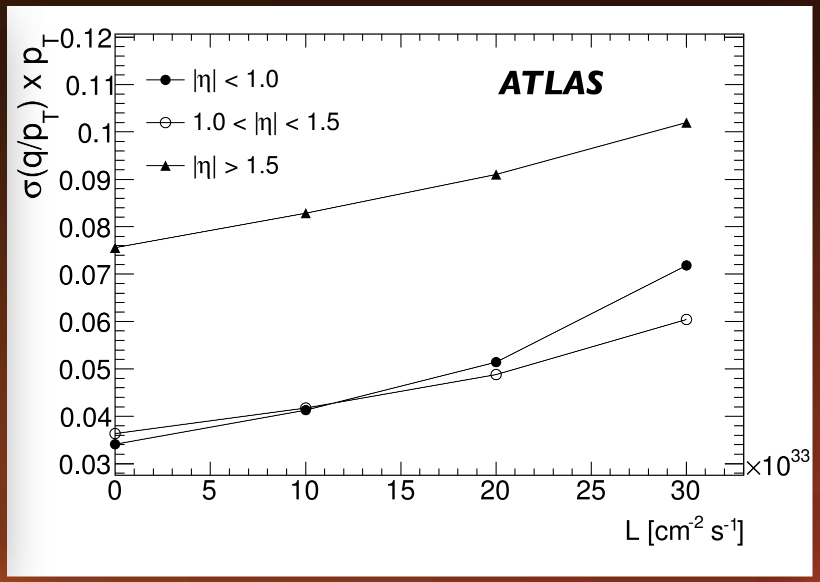
Expected Performance

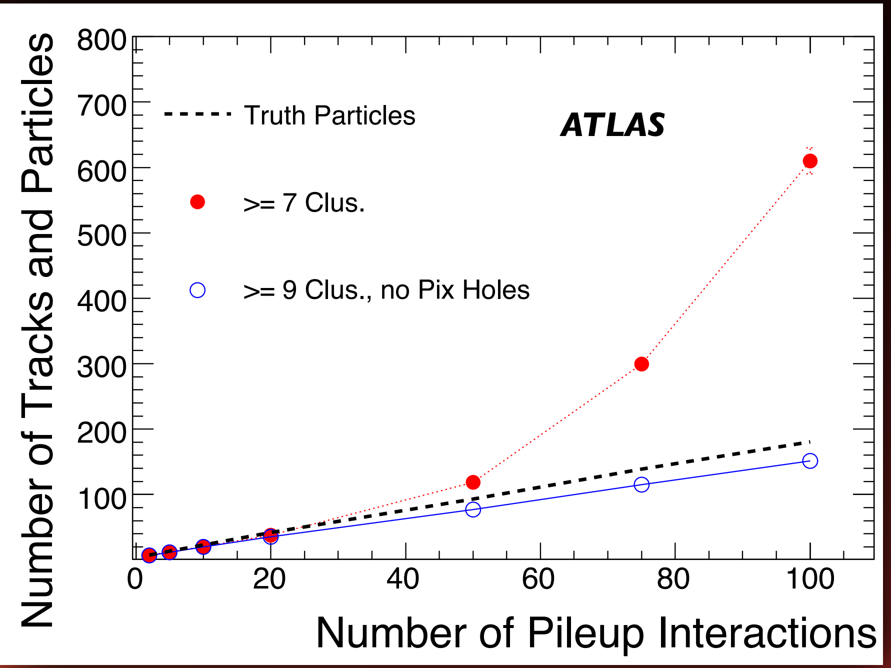
- excellent preparation before startup
  - ➡ more than 10 years of simulation and test beam
  - ➡ cosmics data taking in 2008 and 2009
  - ➡ payed off last year !
- detailed simulation studies
  - ➡ document expected performance in TDRs
  - ➡ few of the known critical items:
    - material effects limit efficiency and resolution at low p_t
    - good (local) alignment for b-tagging
    - momentum scale and alignment "weak modes"
  - ➡ focus for commissioning of tracking and vertexing





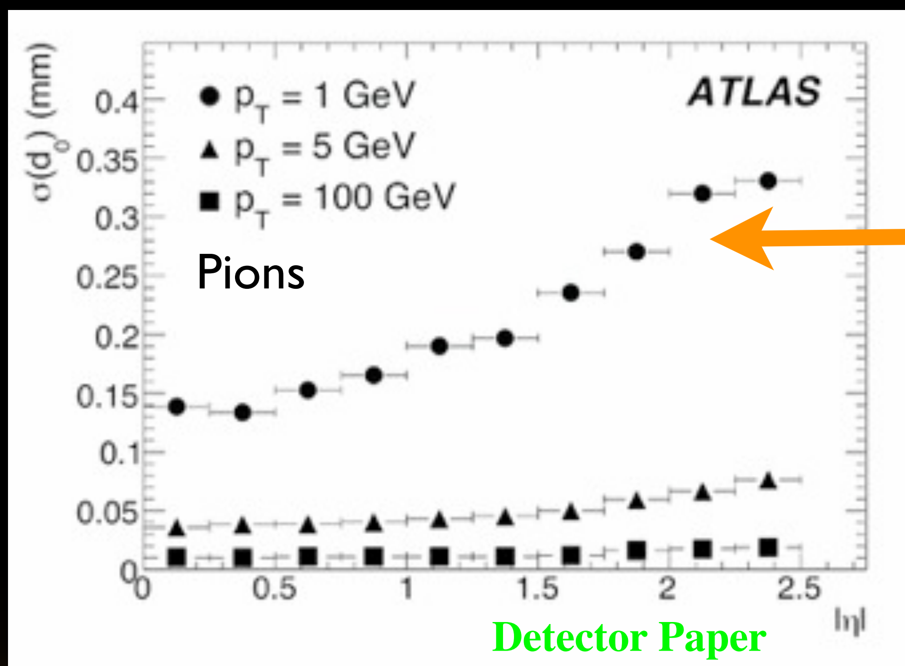


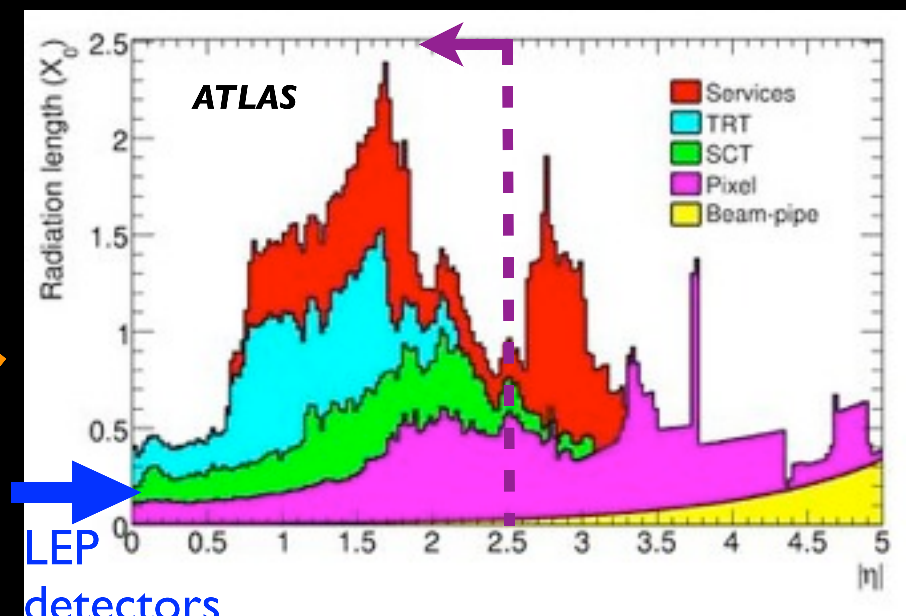




Material Budget limits Performance !

- tracking resolution and efficiency mostly driven by interactions in detector material



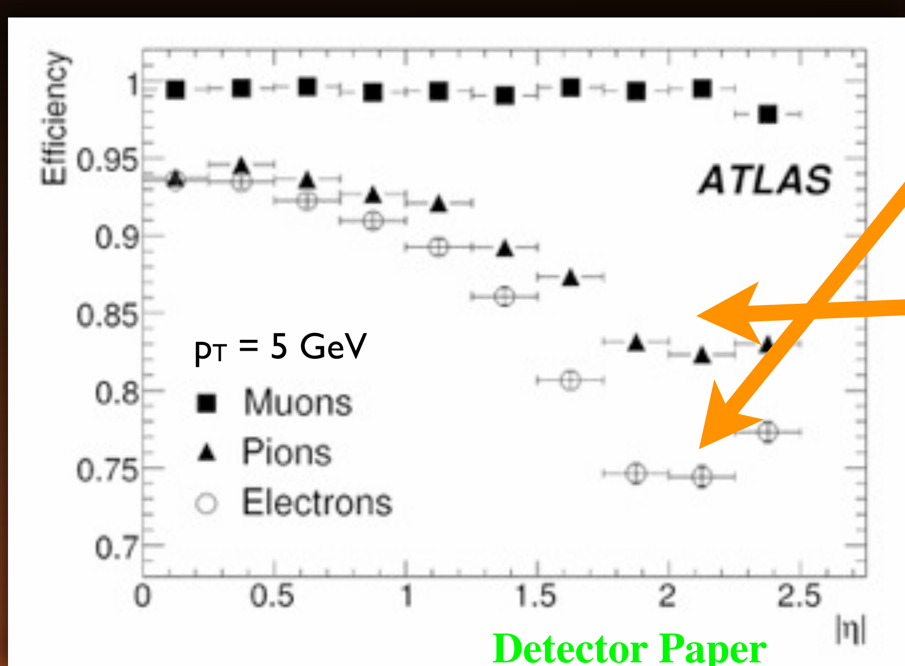


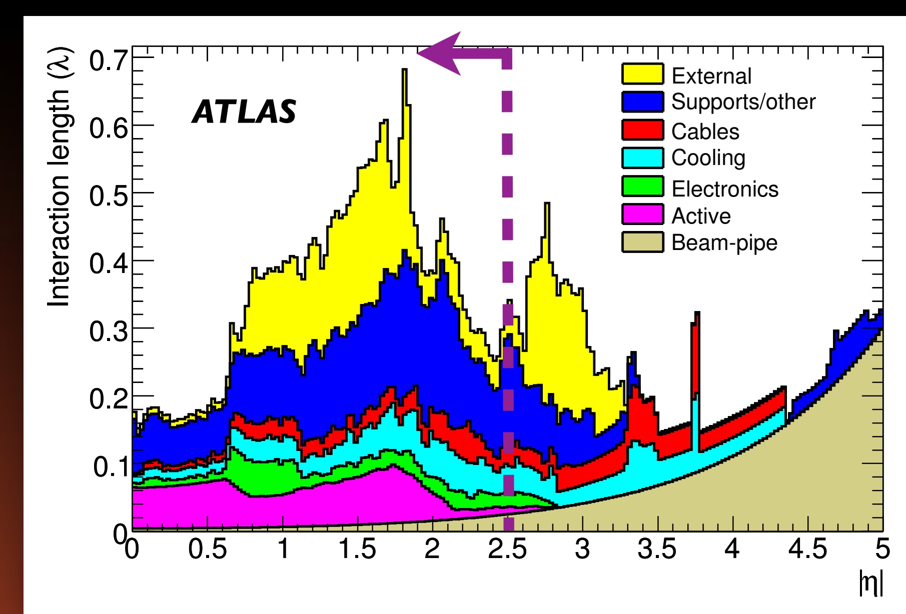
LEP detectors

multiple scattering

Brems-strahlung

hadronic interactions





➡ total weight of Inner Detector: 4.5 tons

Weighing Detectors during Construction

- huge effort in experiments
  - ➡ put each individual detector part on balance and compare with model
  - ➡ measured weight of their tracker and its components
  - ➡ correct the geometry implementation in simulation and reconstruction

ATLAS	estimated from measurements	simulation
Pixel package	201 kg	197 kg
SCT detector	672 ±15 kg	672 kg
TRT detector	2961 ±14 kg	2962 kg

example: ATLAS TRT measured before and after insertion of the SCT

- notice:
  - ➡ significant increase in material budget since Technical Proposal
    (we see a similar trend with IBL now)

Date	ATLAS $\eta \approx 0$	ATLAS $\eta \approx 1.7$	CMS $\eta \approx 0$	CMS $\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

Required new Software Technologies

- complex G4 geometries not optimal for reconstruction
  - ➡ simplified **tracking geometries**
- reduced number of volumes
  - ➡ blending details of material

	G4	tracking
ATLAS	4.8 M	10.2K *

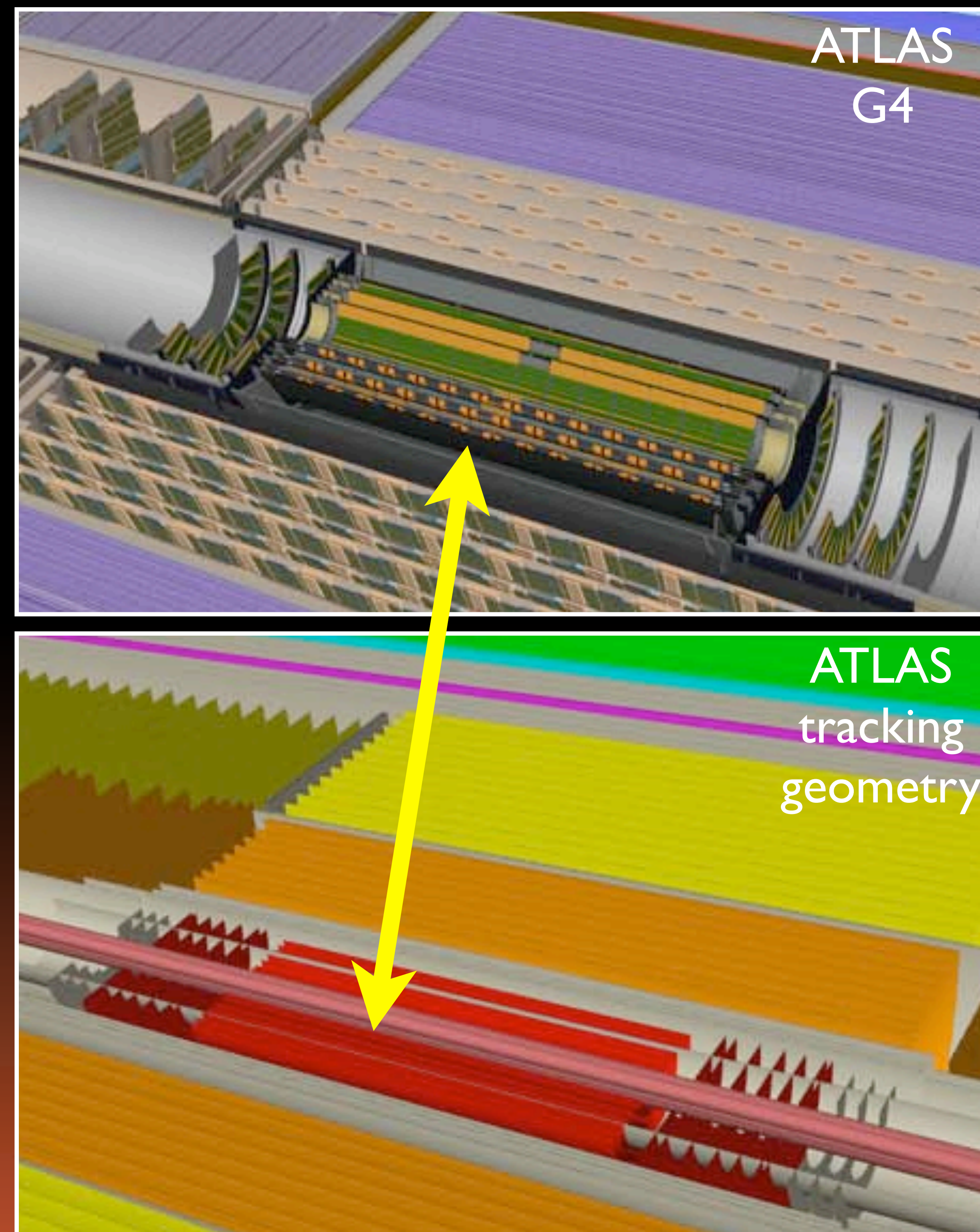
*2 plus a surface per Si sensor

- ➡ use embedded navigation scheme to optimize CPU performance

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

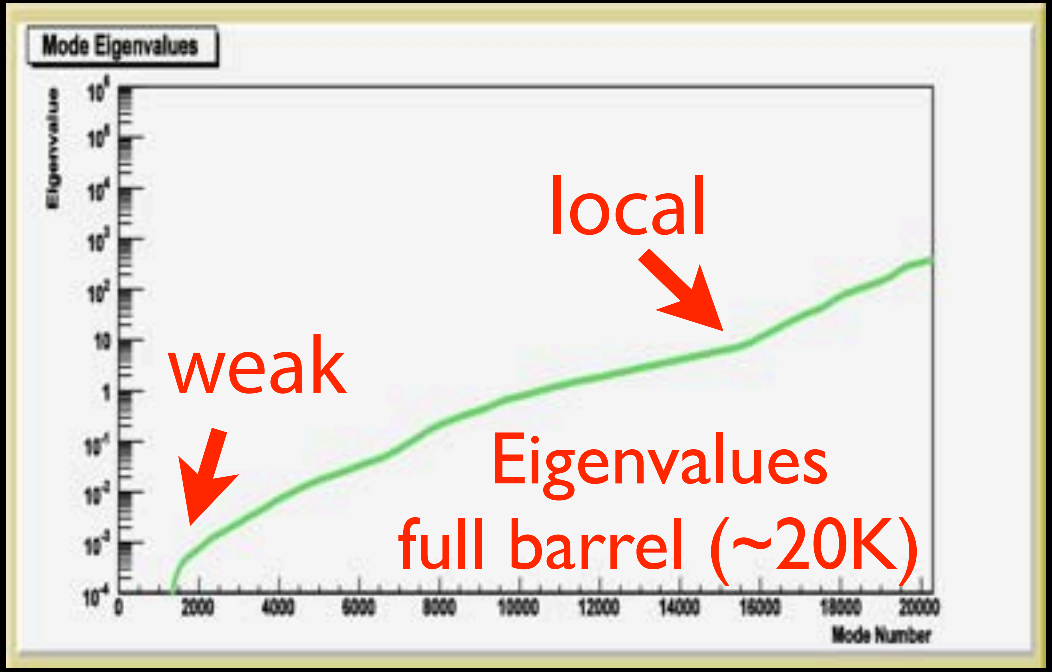
(neutral geantinos, no field lookups)

- ➡ as well basis of fast simulation engine

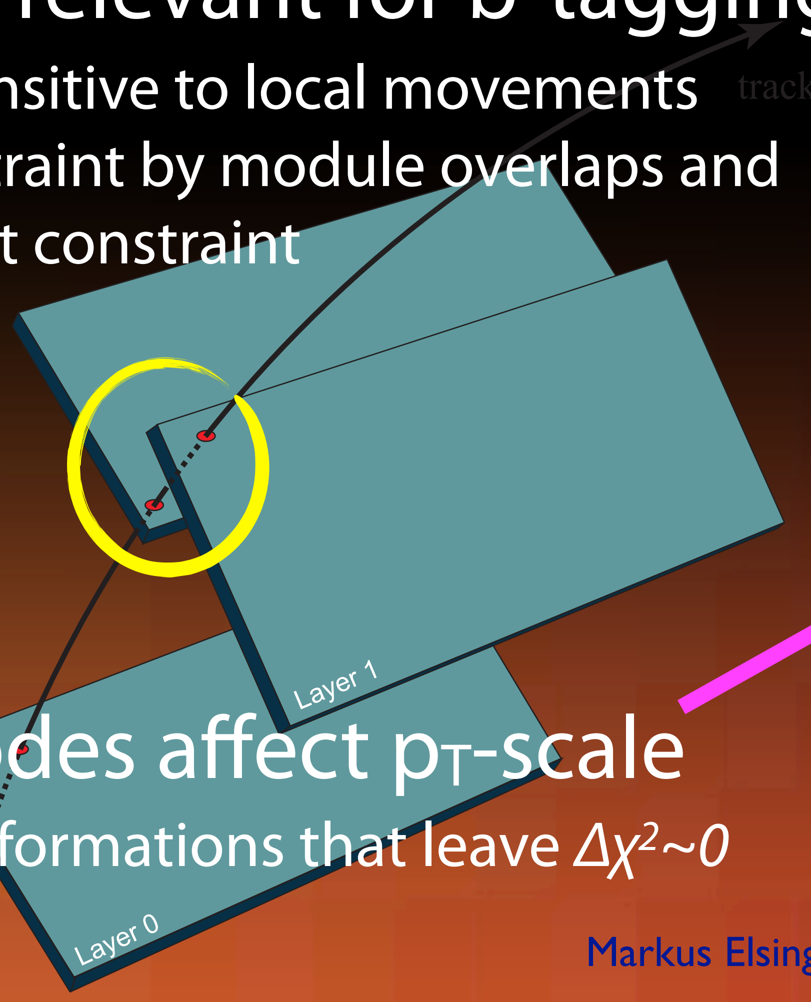


Alignment and Weak Modes

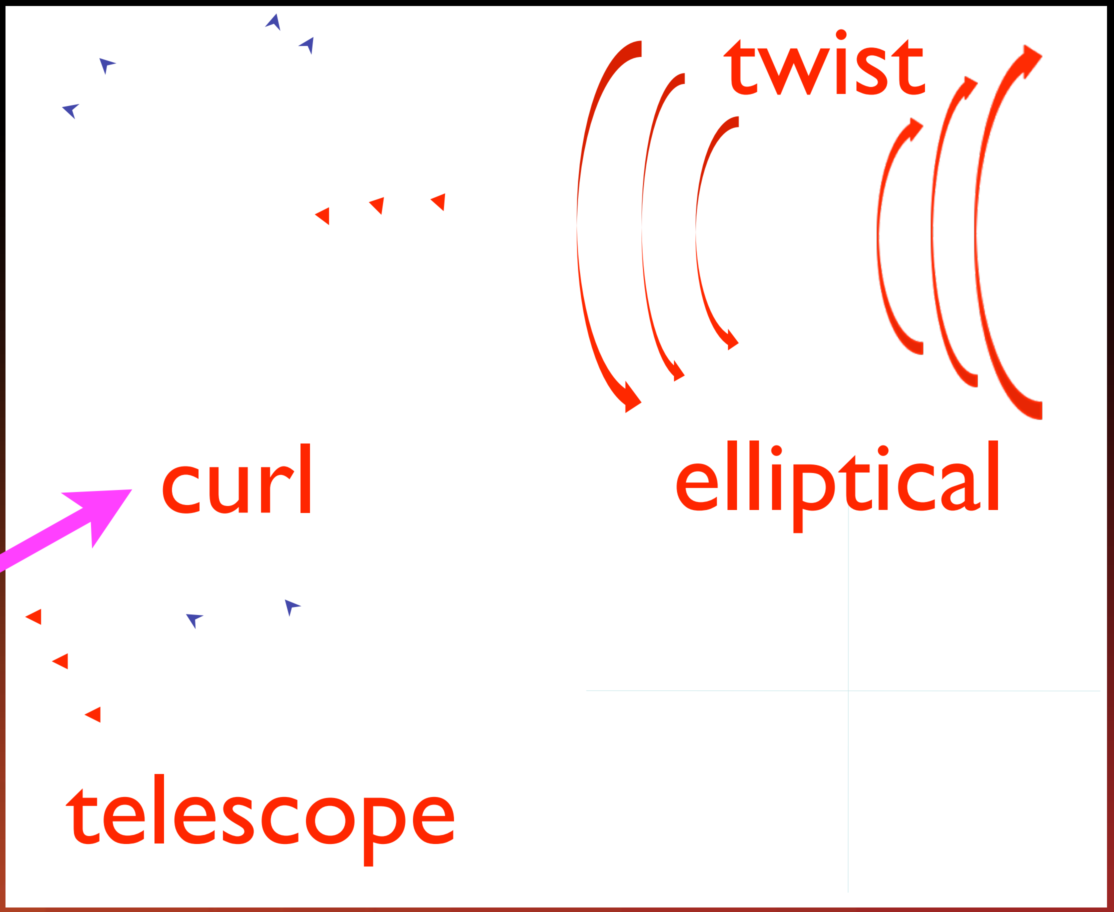
- global-χ^2 alignment
  - ➡ diagonalize alignment matrix (6 x 6k)^2
  - ➡ enables studies of Eigenvalue spectrum
    - well constraint : local movements
    - less well constraint : overall deformations
    - not constraint : global transform



- residuals relevant for b-tagging
  - ➡ mostly sensitive to local movements
  - ➡ well constraint by module overlaps and beam spot constraint

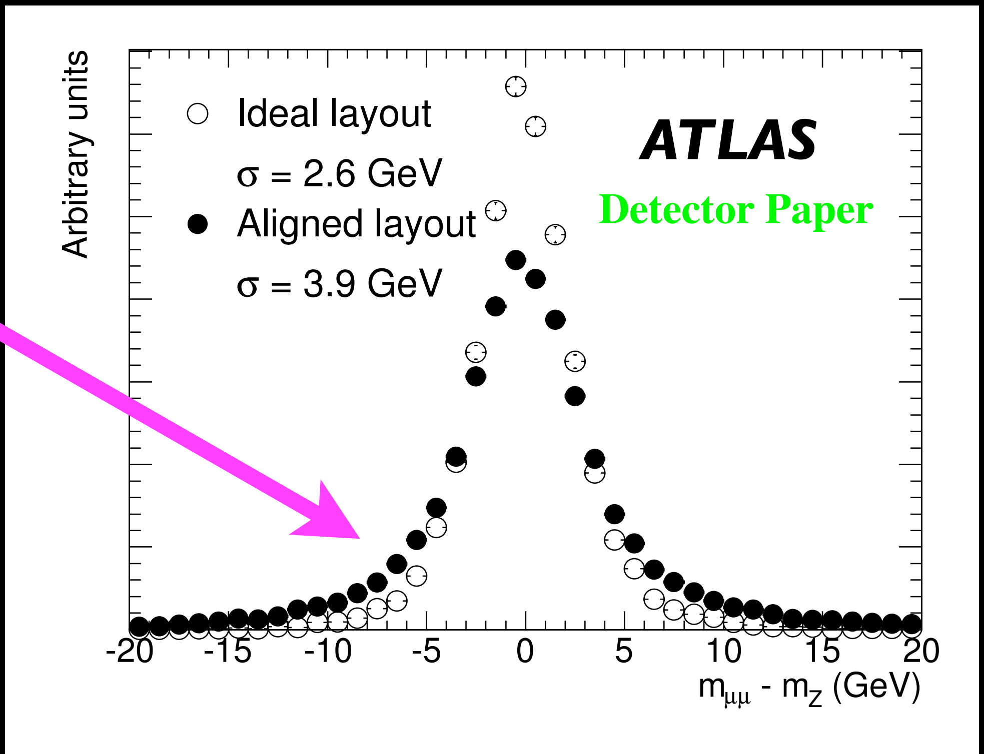


- weak modes affect p_T-scale
  - ➡ overall deformations that leave $\Delta\chi^2$~0

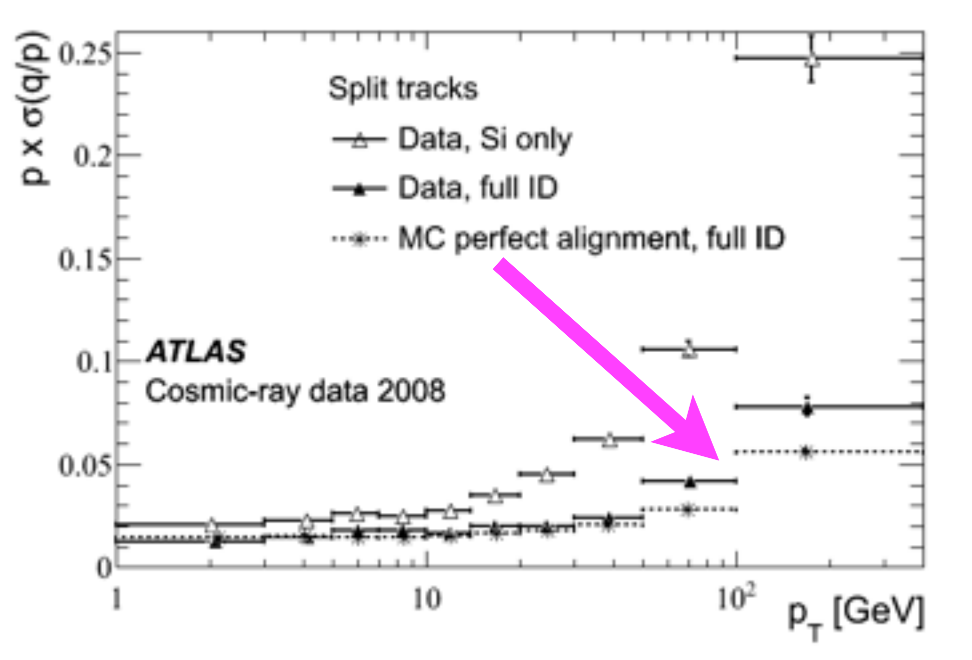


Did we expect Weak Mode Effects ?

- "Detector Paper" MC study:
  - ➡ ideal Z mass resolution 2.6 GeV
  - ➡ misalign MC by 100 µm, re-align using:
    - high-p_T muons and cosmics
  - ➡ Z mass resolution degraded to 3.9 GeV (!)
    - not corrected by alignment procedure



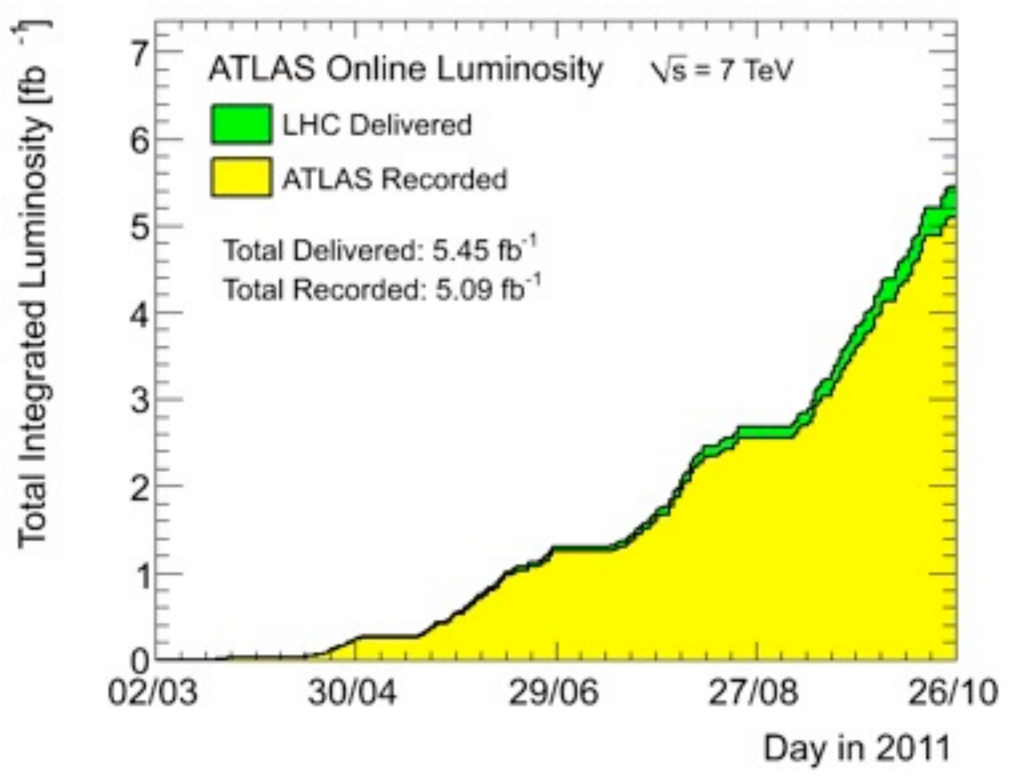
- cosmics study using split tracks
  - ➡ good performance overall
    - cosmics are mostly in the barrel (!)
    - done with the alignment at the time...
  - ➡ but: at higher p_T the data starts to diverge from MC
    - reflects limited calibration at the time
    - possible hint for weak mode effect in alignment

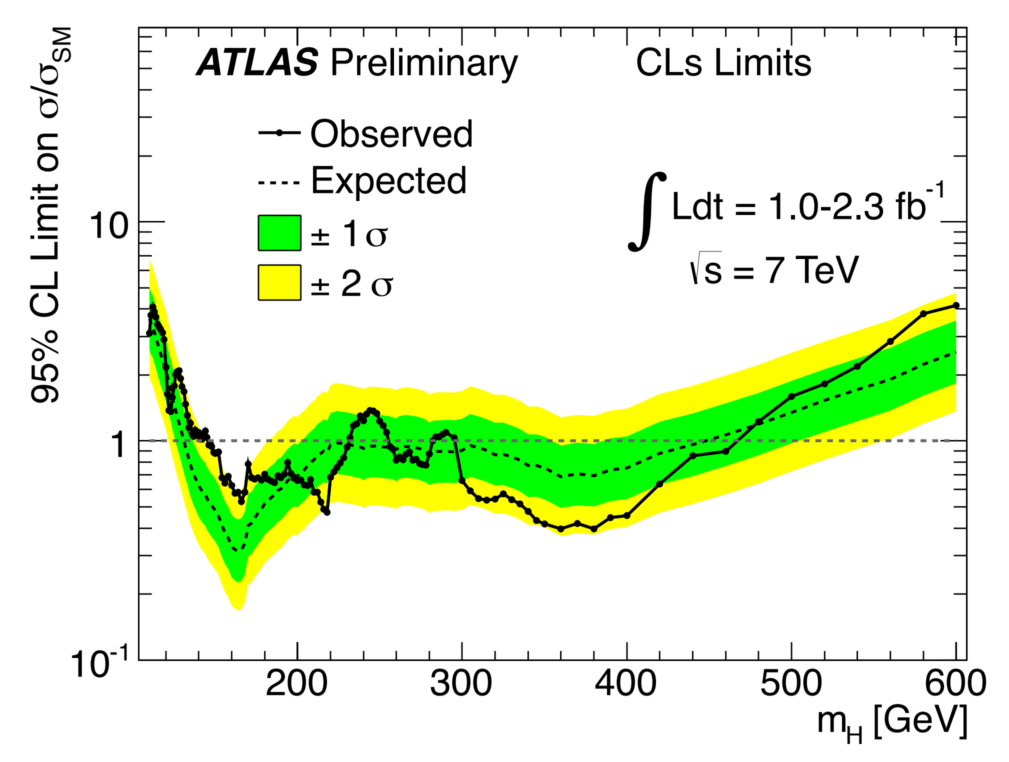


Excitement with first beams...

Commissioning with Collision Data

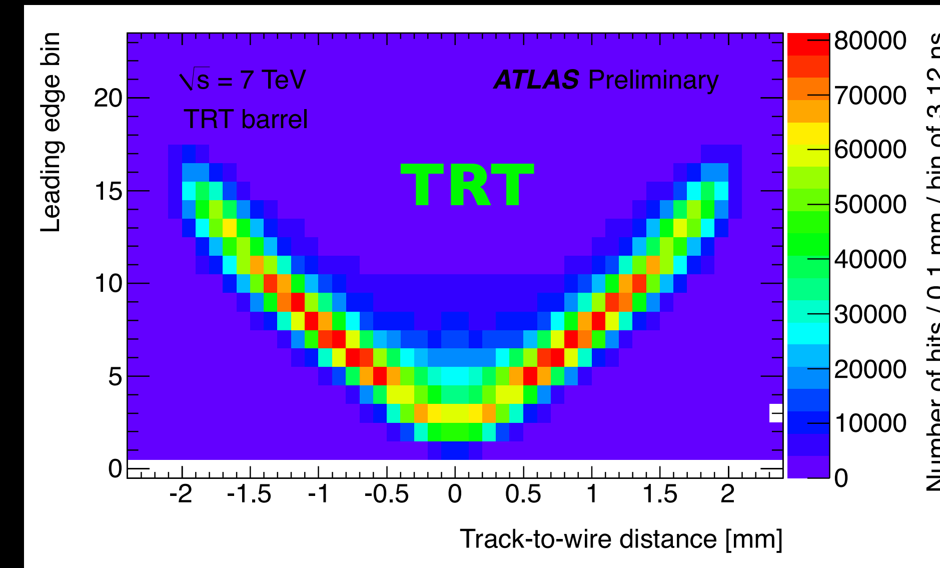
- LHC has done fantastic since !
- a long way from first collisions to physics
  - ➡ commission full readout chain (detector, trigger, DAQ)
  - ➡ calibrate and align the detector
  - ➡ optimize the tracking performance, allow for changing levels of pileup
  - ➡ ...
- basis of commissioning the tracking is work done on the detector !
  - ➡ not be able here to do justice to all aspects of detector calibration...

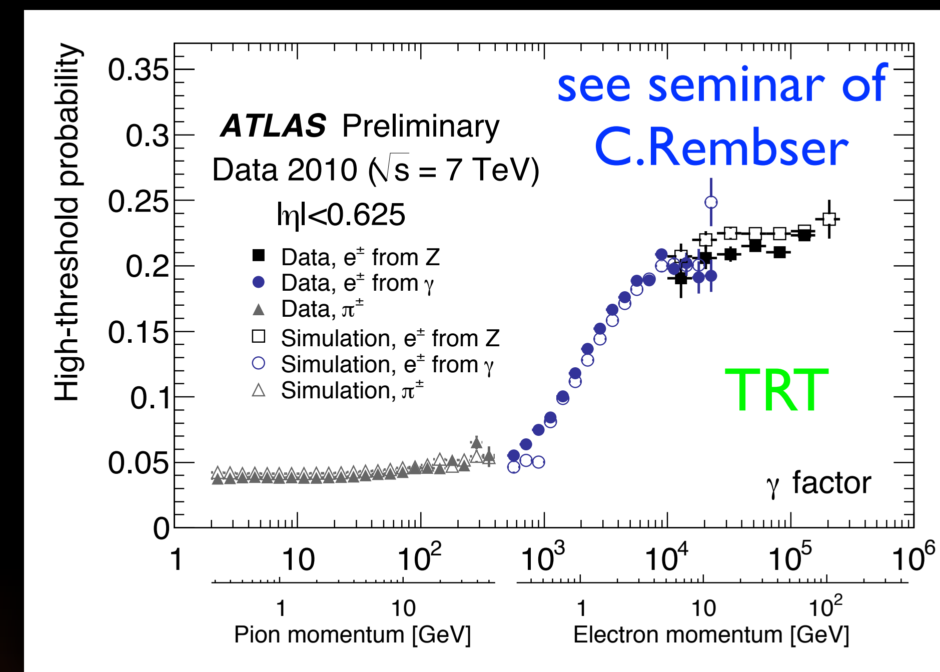


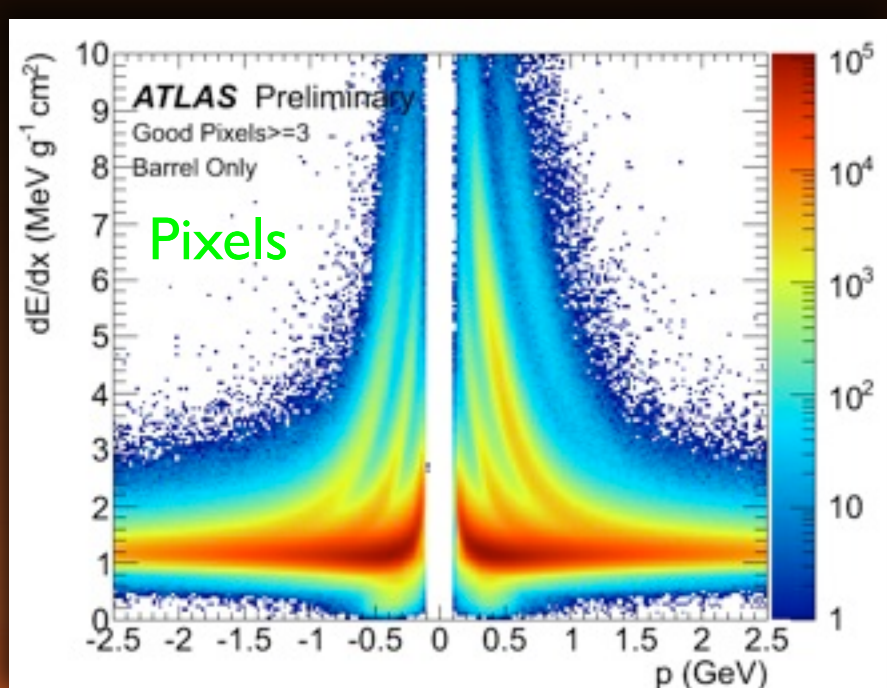


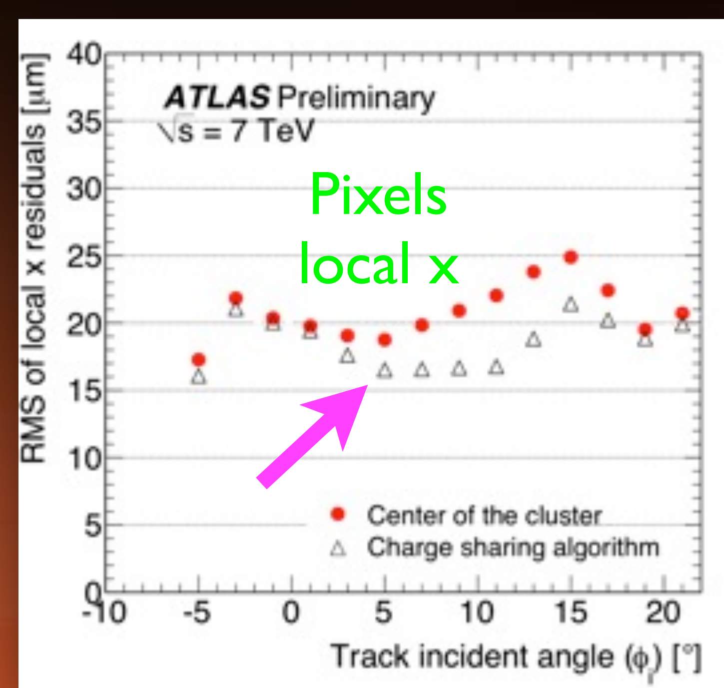
Detector Calibration

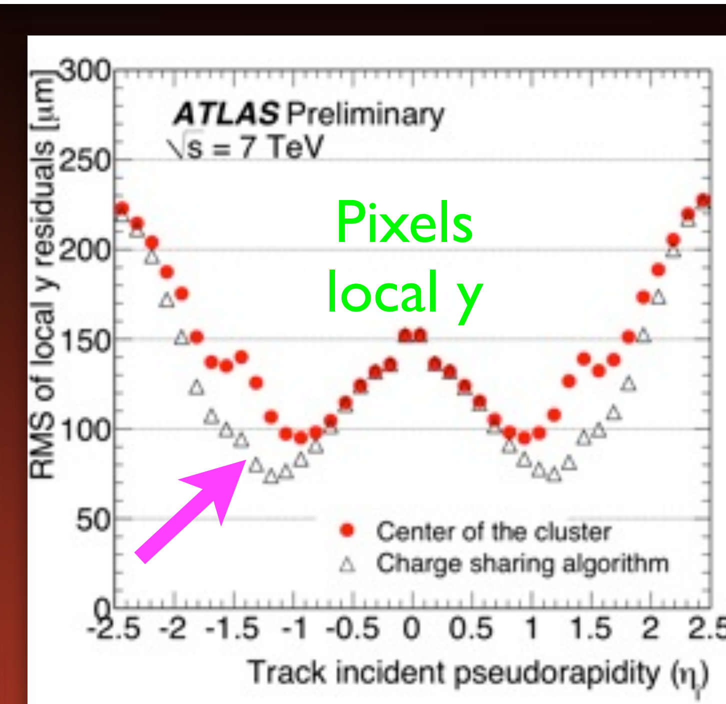
- careful calibration of detectors
  - ➡ required to reach design performance
  - ➡ online (thresholds,...) and offline
  - ➡ monitoring of variations with time
- examples:
  - ➡ TRT: R–t relation and high threshold probability
  - ➡ calibration of time over threshold in Pixels
    - required to explore power of analog clustering
    - provide dE/dx for low p_T particles as well





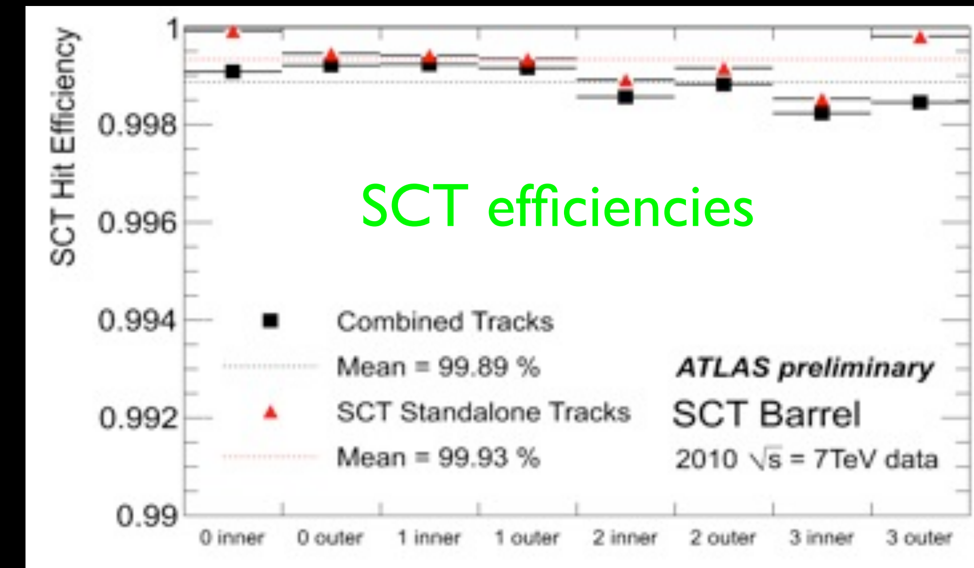


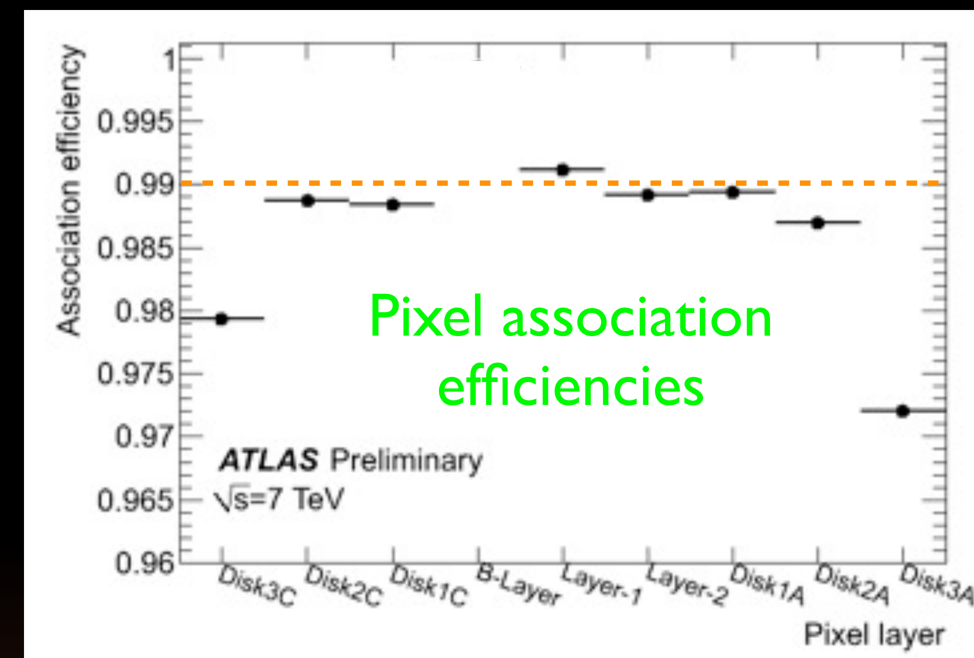


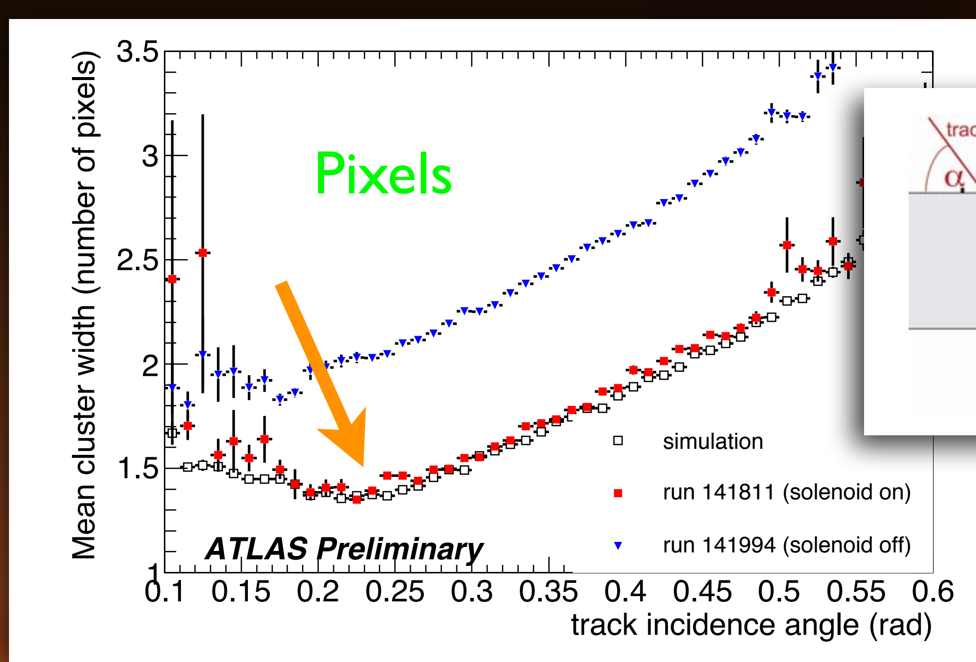


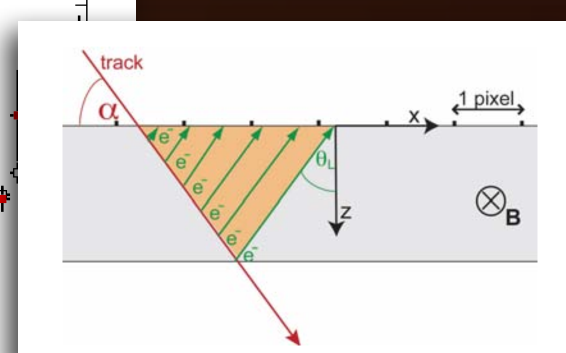
Detector Calibration

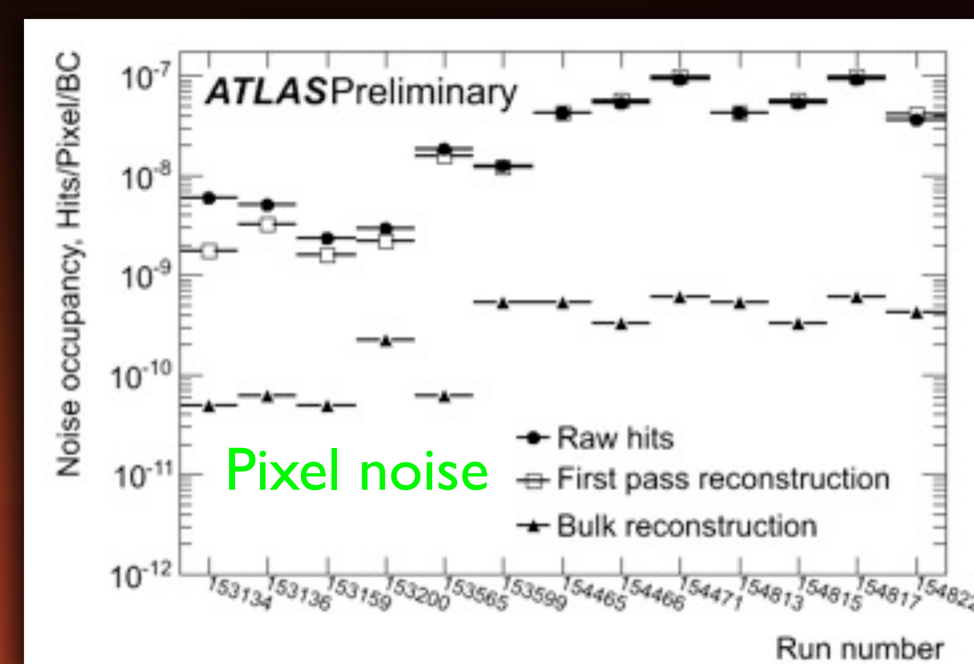
- study detector efficiencies
  - ➡ identify dead channels, chips, modules
    - typically **≥97%** of detectors are operational
    - after correction for known defects typical sensor efficiencies are **>99%** (!)
  - ➡ very low noise levels observed in Pixels/SCT
- measure Lorentz angle
  - ➡ as usual study cluster sizes vs track incident angle
  - ➡ input to tuning of cluster properties
    - adjusting digitization parameters to match data











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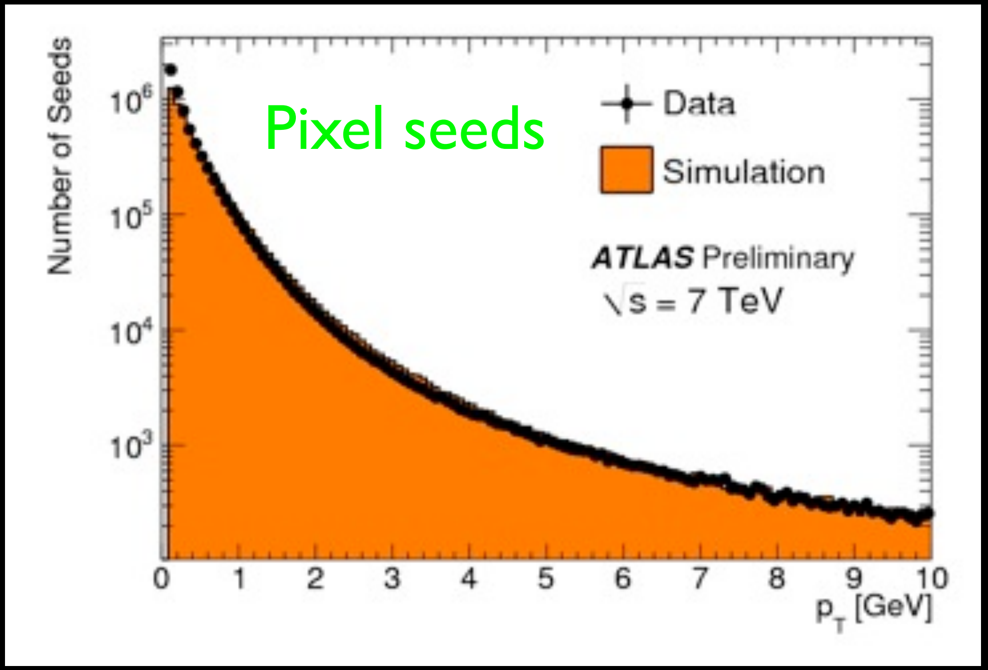
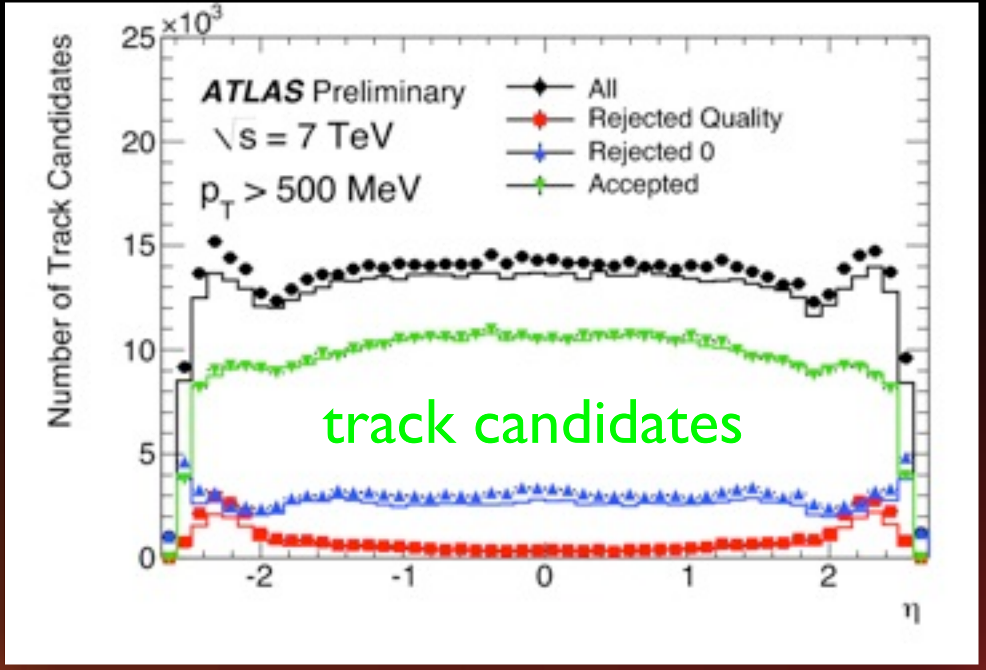
Pattern Recognition

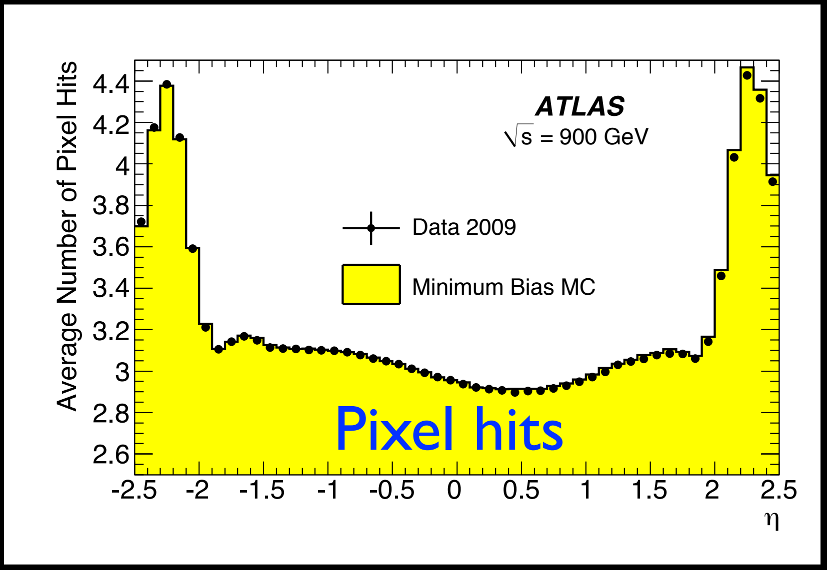
- 2 staged track reconstruction
  - ➡ inside-out: Pixel seeded + extending outwards
  - ➡ outside-in: seeded on TRT segments
- ensure “robustness”
  - ➡ allow for dead/noise modules
  - ➡ error scaling to reflect calibration + alignment
  - ➡ especially important at startup
    - very good performance even with early data
- study performance at different levels in reconstruction process
  - ➡ seeding / candidate fitting / ambiguity
  - ➡ basis for understanding tracking results

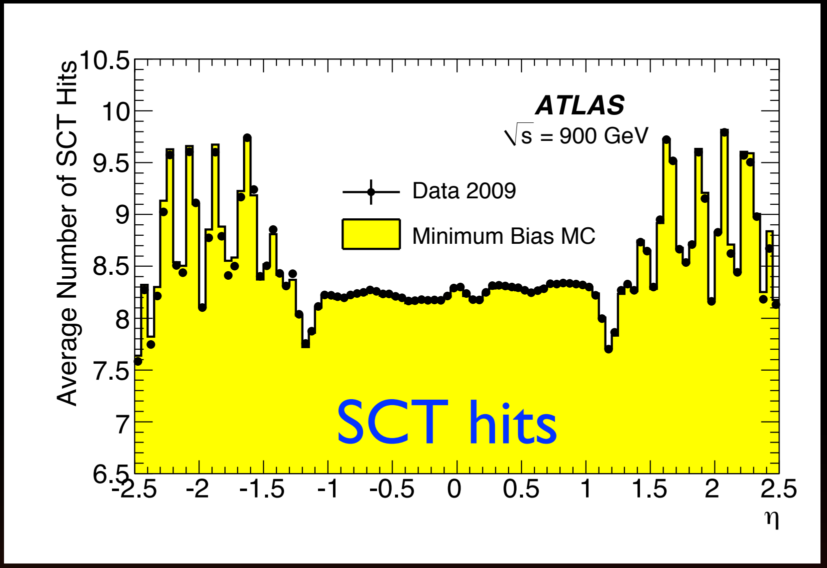




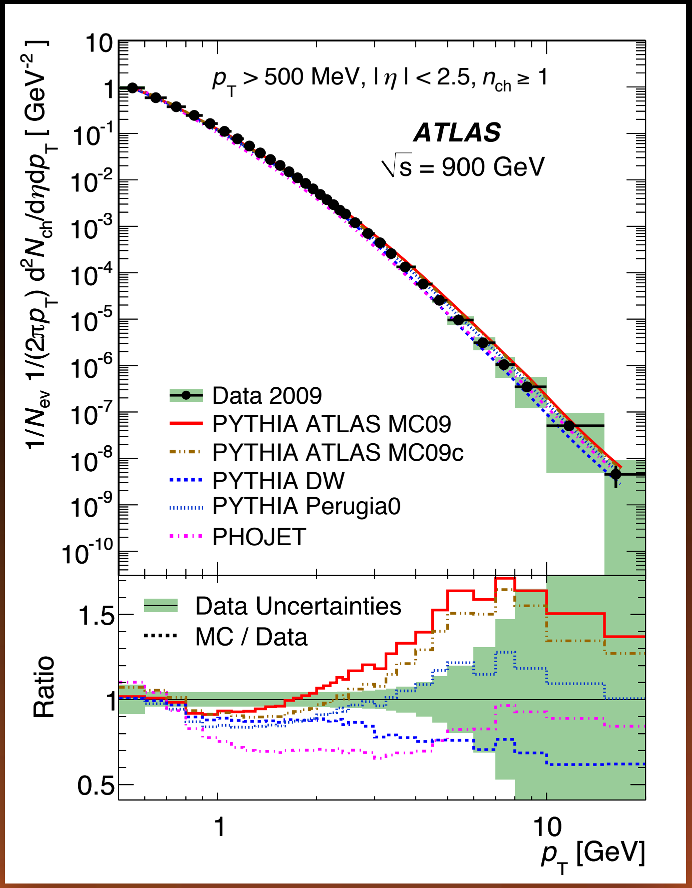
Tracking Commissioning

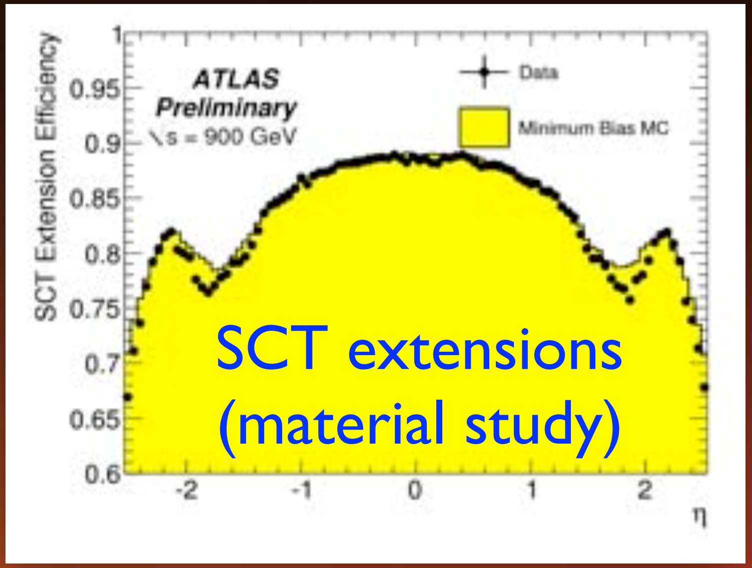
- detailed studies of properties of tracks in 900 GeV data
  - ➡ hit associations, fit quality, etc.
    - allow for known defects in simulation
  - ➡ leading towards first publications
    - as expected, tracking systematics driven by material uncertainties (!!)

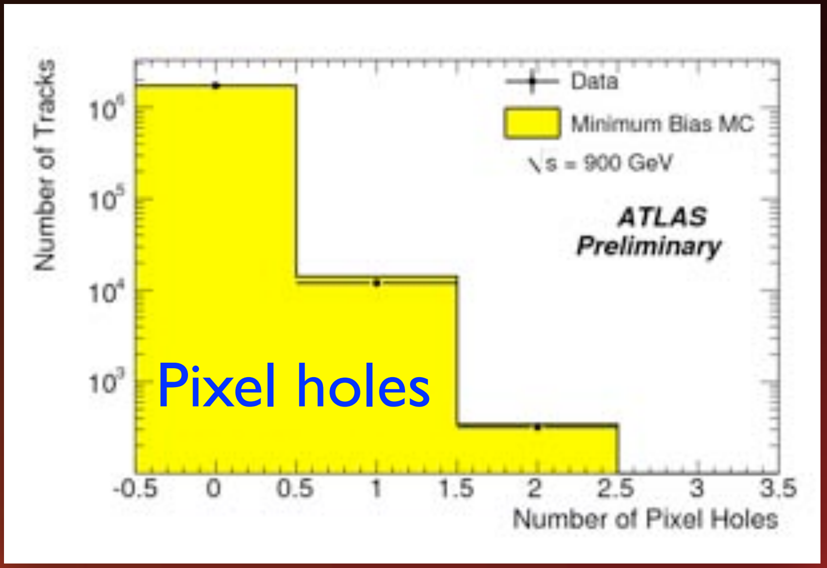




min.bias charged particle spectra

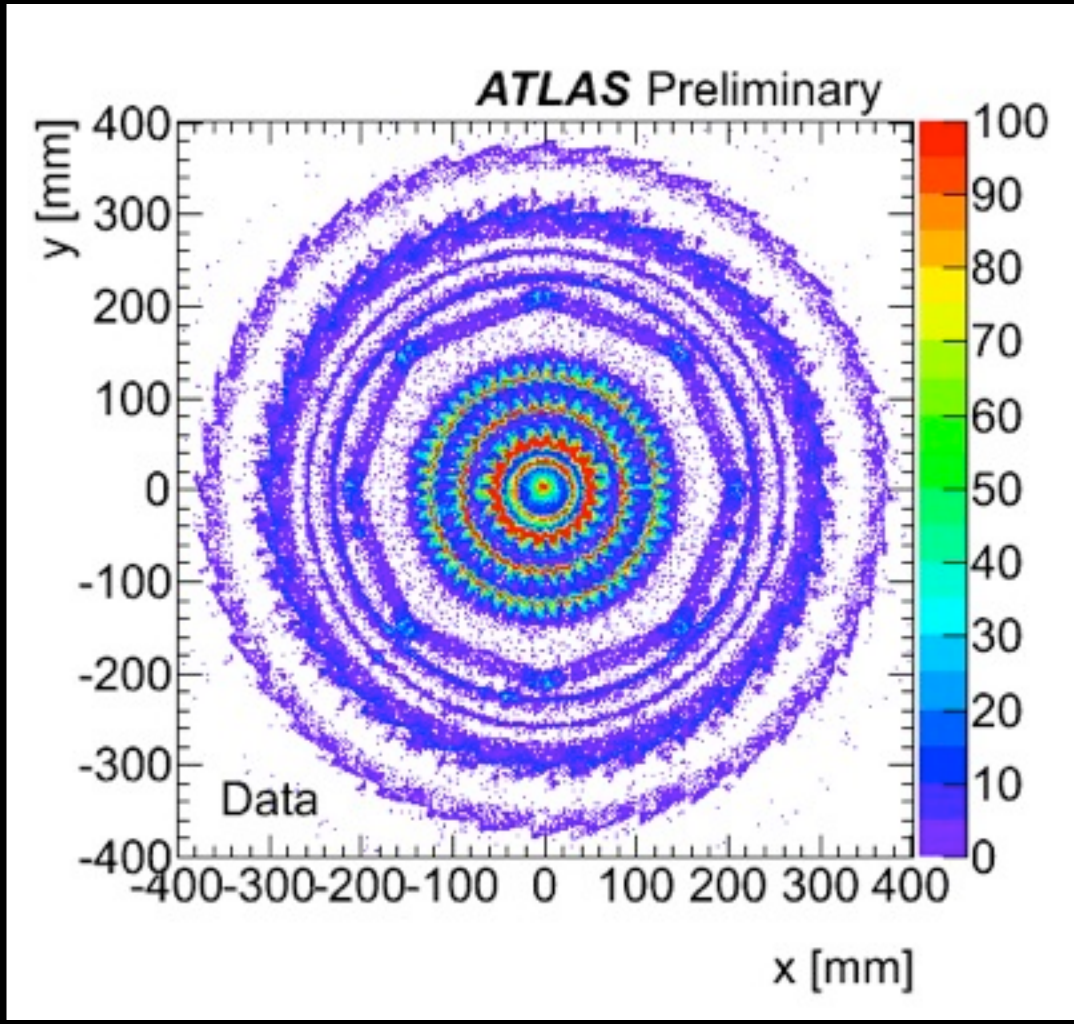


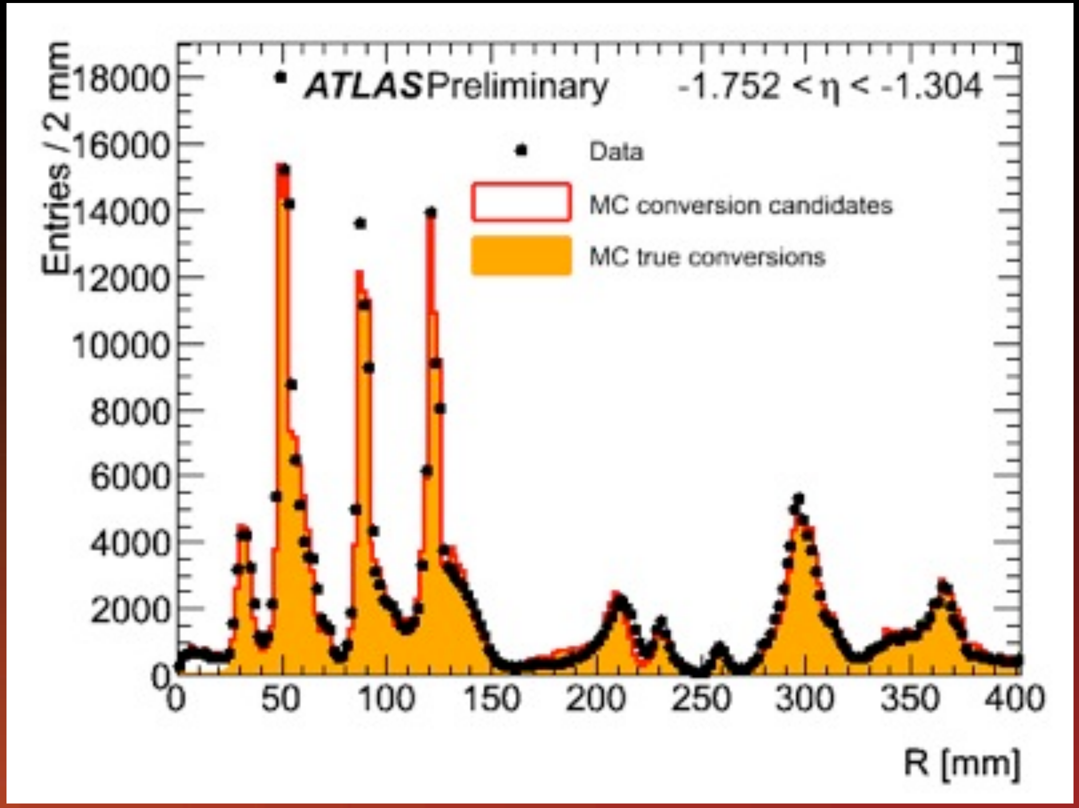




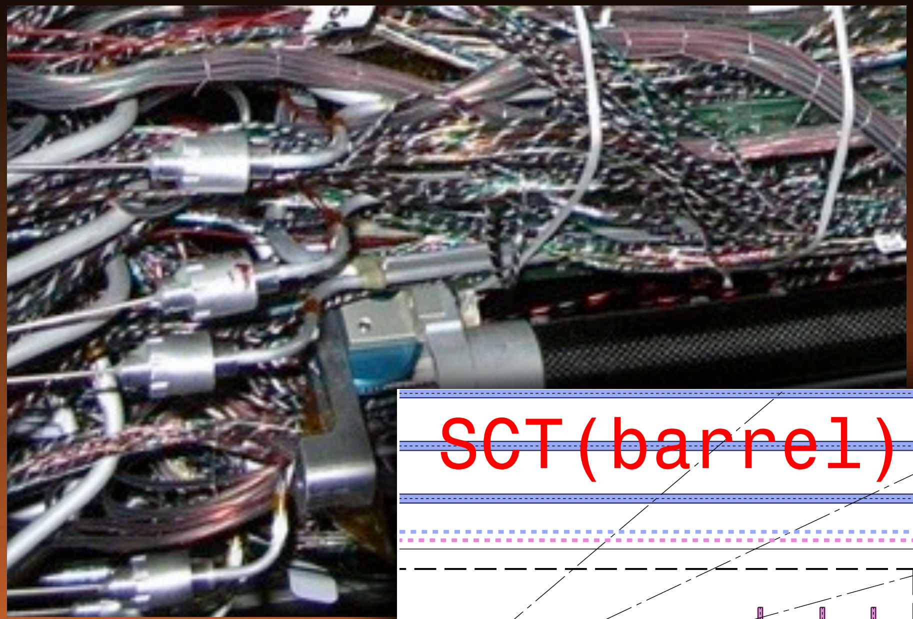
Conversions

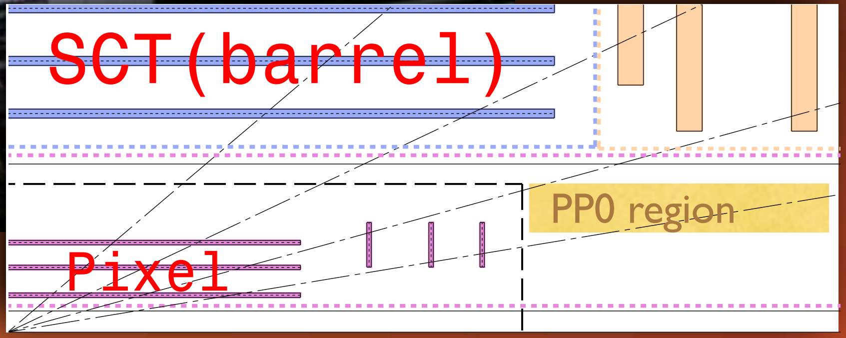
- detailed tomography of material with γ conversions
  - ➡ able to map details in material distribution
    - measure difference in data/MC, e.g. PP0
  - ➡ ultimately should result in a very precise estimate of material
    - need to control reconstruction efficiency
    - calibrate measurement, e.g. on “known” beam pipe
    - needs a large dataset to reach precision





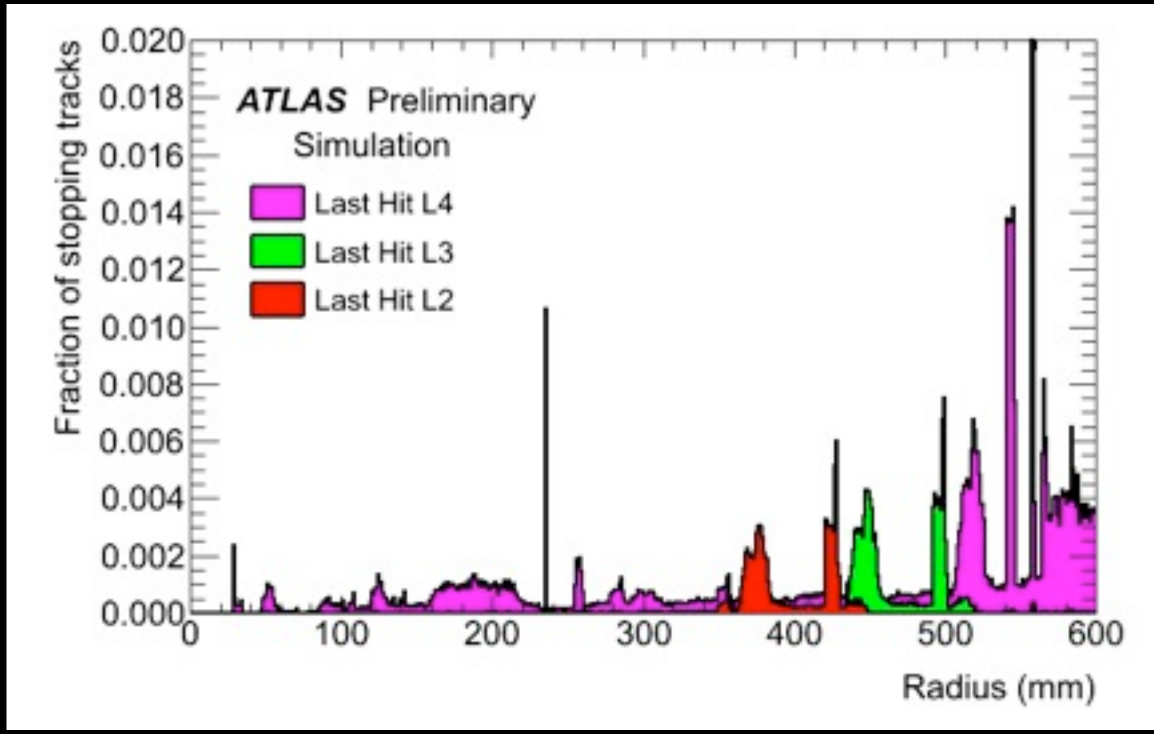
ATLAS Pixel PP0 region

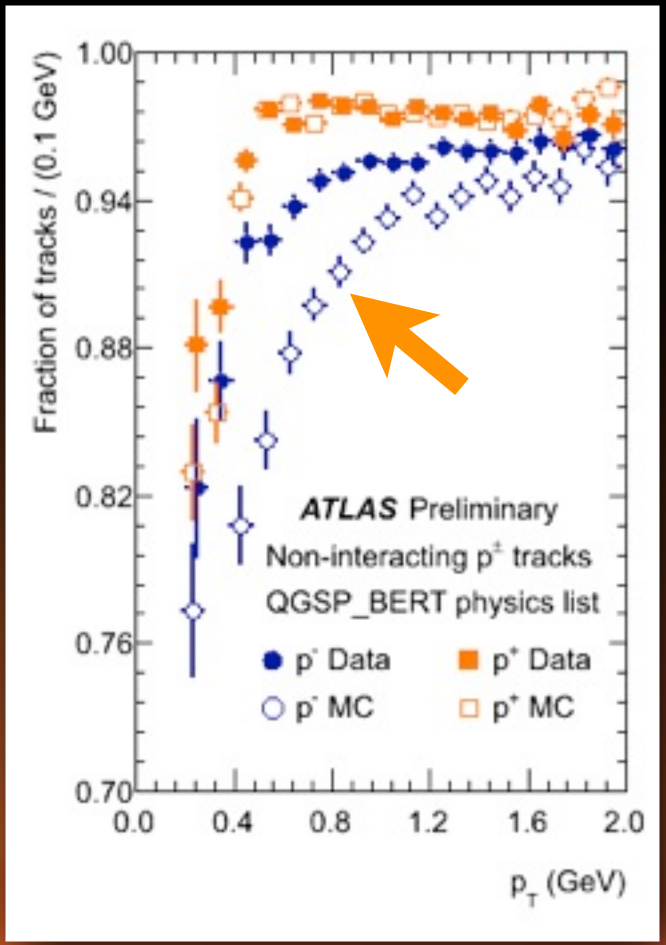


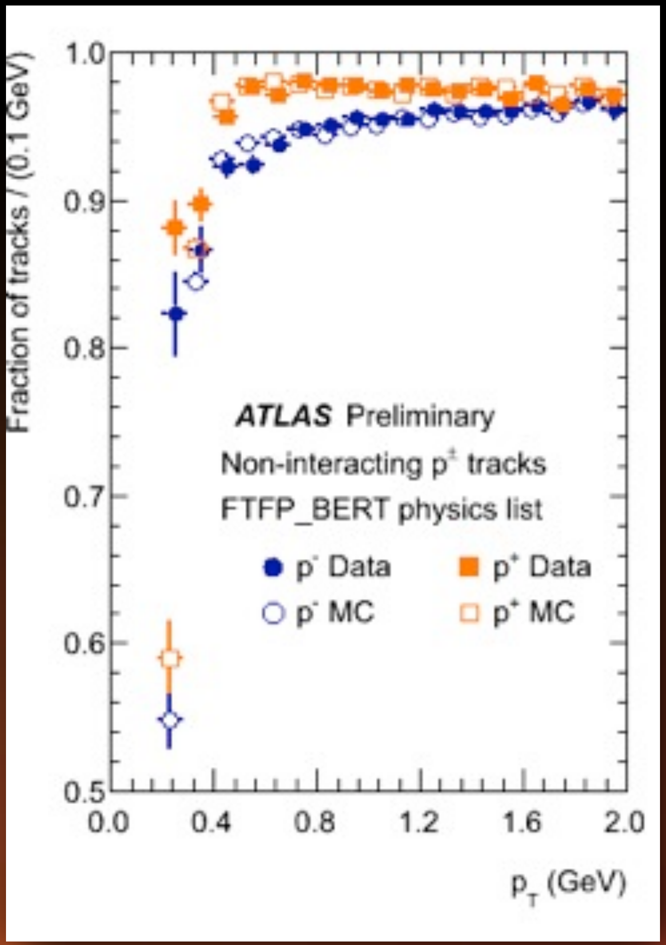


Stopping Tracks in SCT

- based of last hits on tracks
  - ➡ soft p and π from K^0_s and Λ decays
  - ➡ sensitive to material at larger radii
- charge dependences seen
  - ➡ geometry effect (module tilts)
  - ➡ differences in cross sections







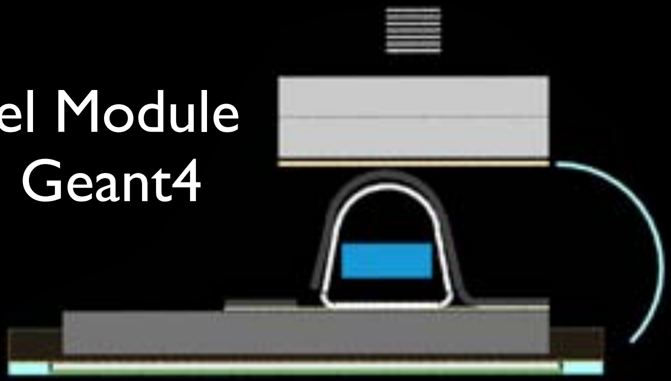
- allows to study modeling of hadronic interactions in G4
  - ➡ QGSP_BERT does not model anti-protons well
  - ➡ better described by FTFP_BERT

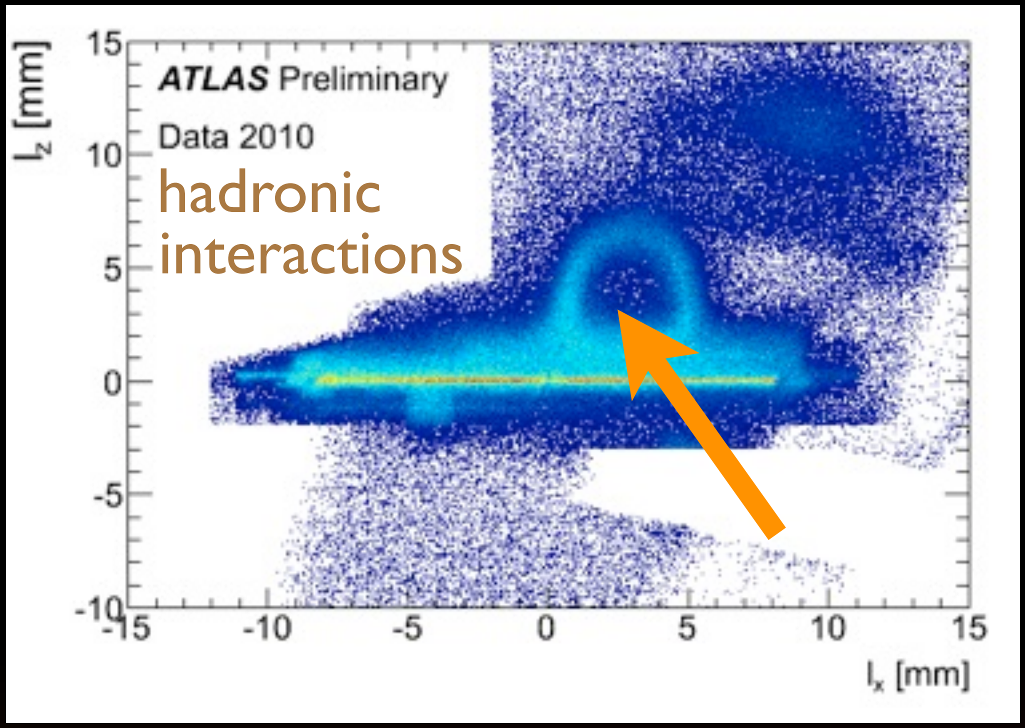
Further Material Studies

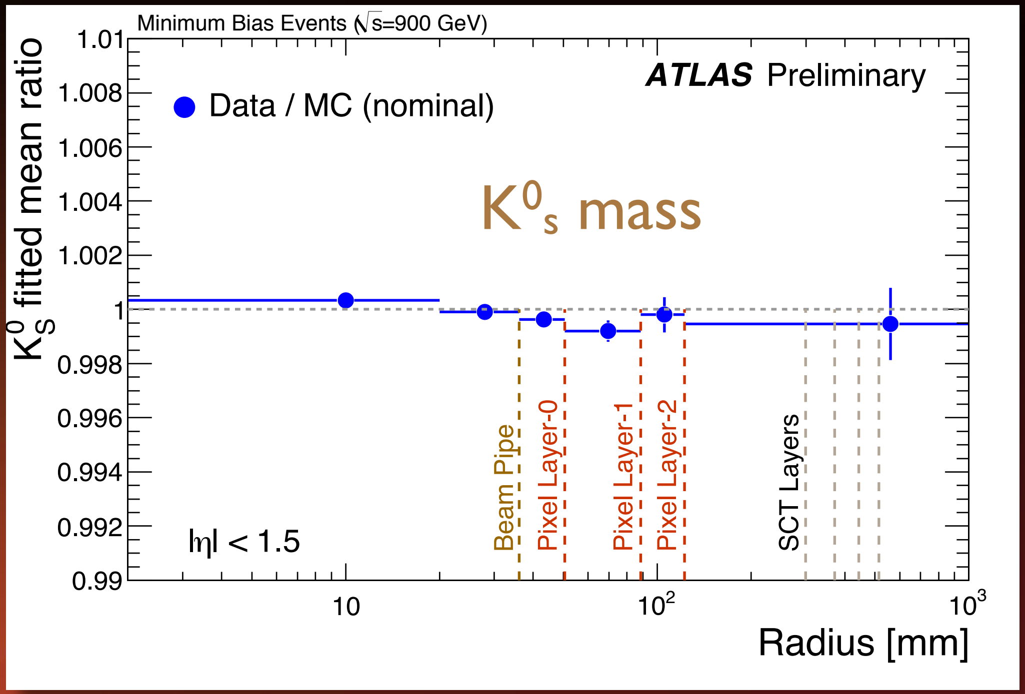
- hadronic interactions for precise tomography of detector material
  - ➡ good vtx resolution allows to study fine details
  - ➡ e.g., study levels of cooling liquid or shift in beam pipe position w.r.t. Pixel b-layer

- material uncertainty in simulation
  - ➡ constraint by sum of different techniques
    - conversions and hadronic interactions
    - study K^0_S and other mass signals
    - stopping tracks, SCT extension efficiency
    - study of multiple scattering resolution term
  - ➡ estimated uncertainty
    - better than **~5%** in central region
    - at the level of **~10%** in most of the endcaps

Pixel Module in Geant4



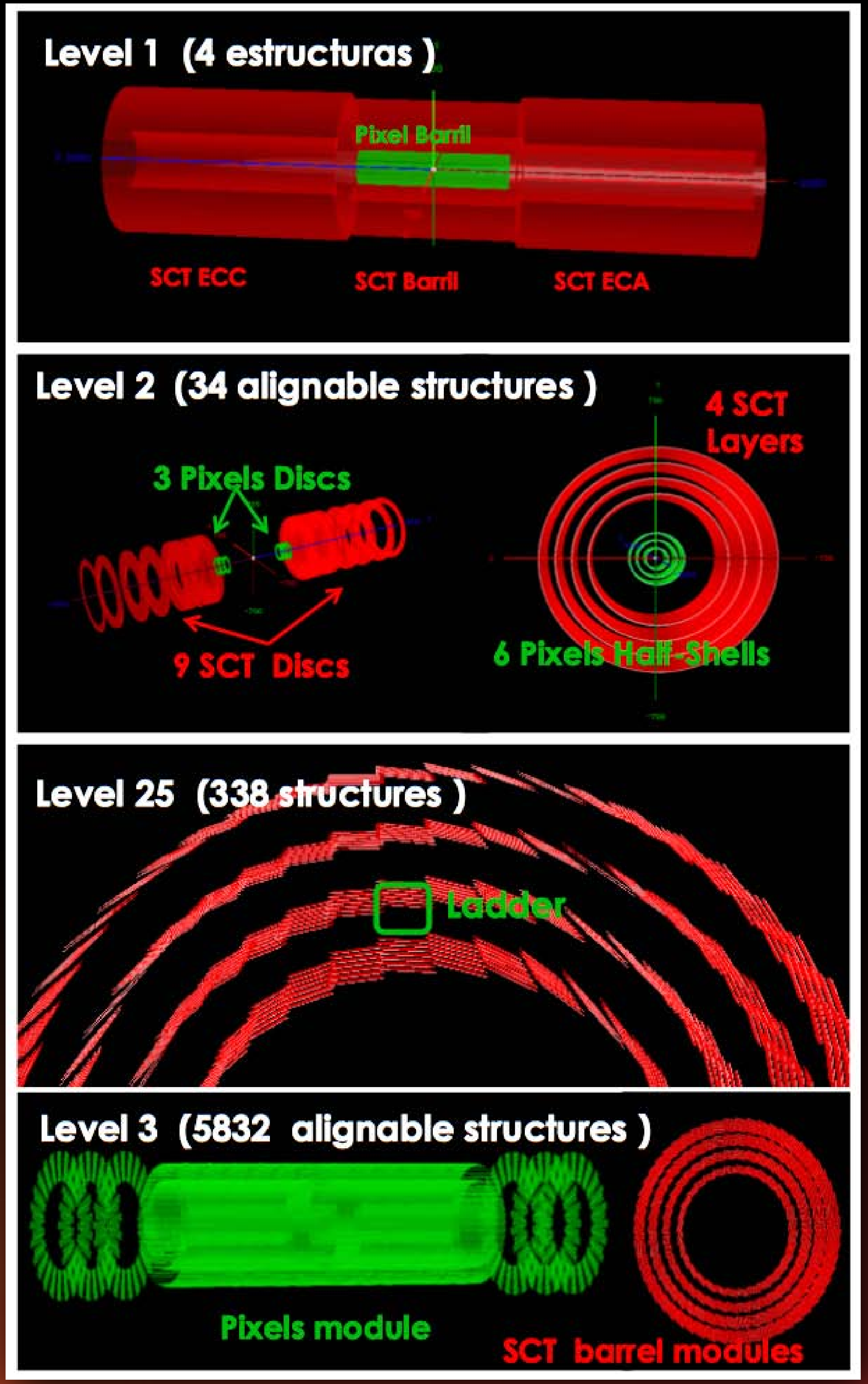




Detector Alignment

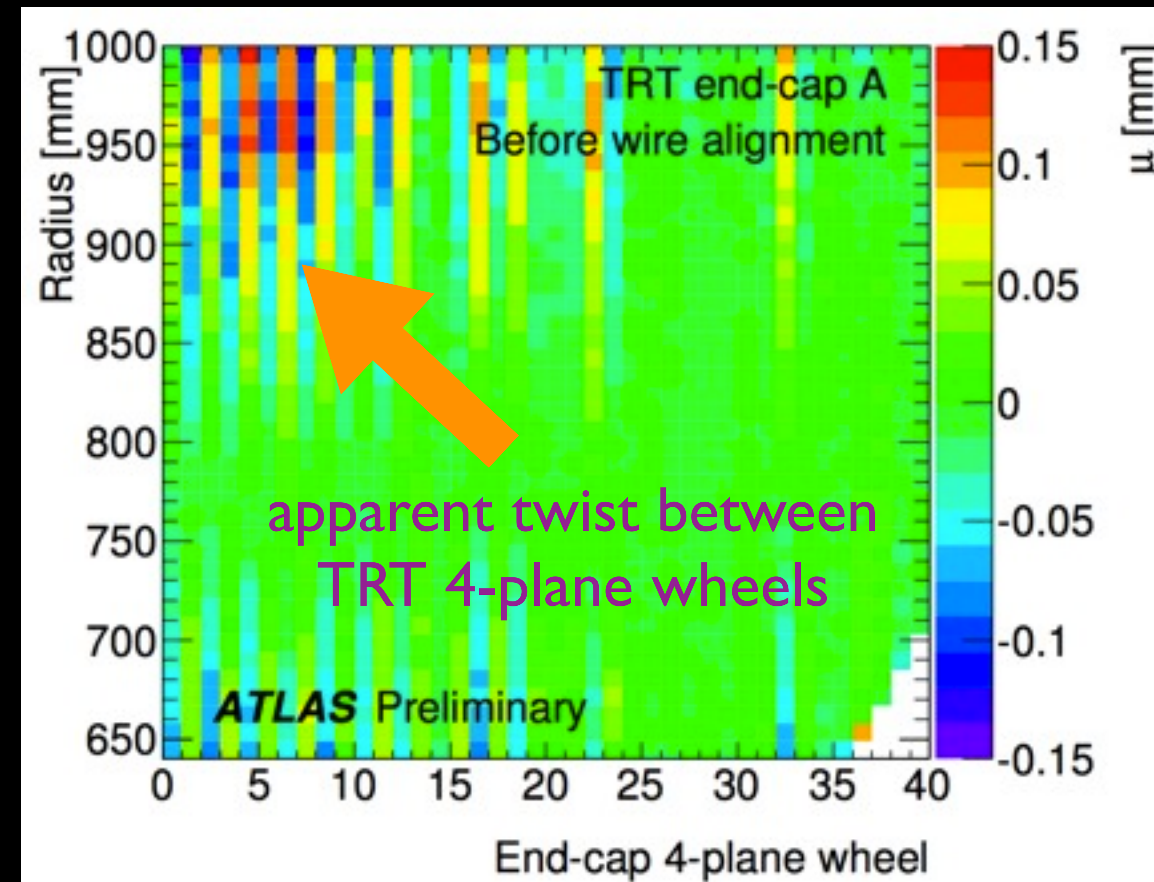
- alignment strategy
  - ➡ starting point is detailed survey
  - ➡ alignment stream with high-p_t tracks
    - mix pp and cosmic data
  - ➡ define different levels of granularity
    - level 1 (e.g.SCT barrel)
    - level 3 (module)
  - ➡ global-χ^2 and local alignment

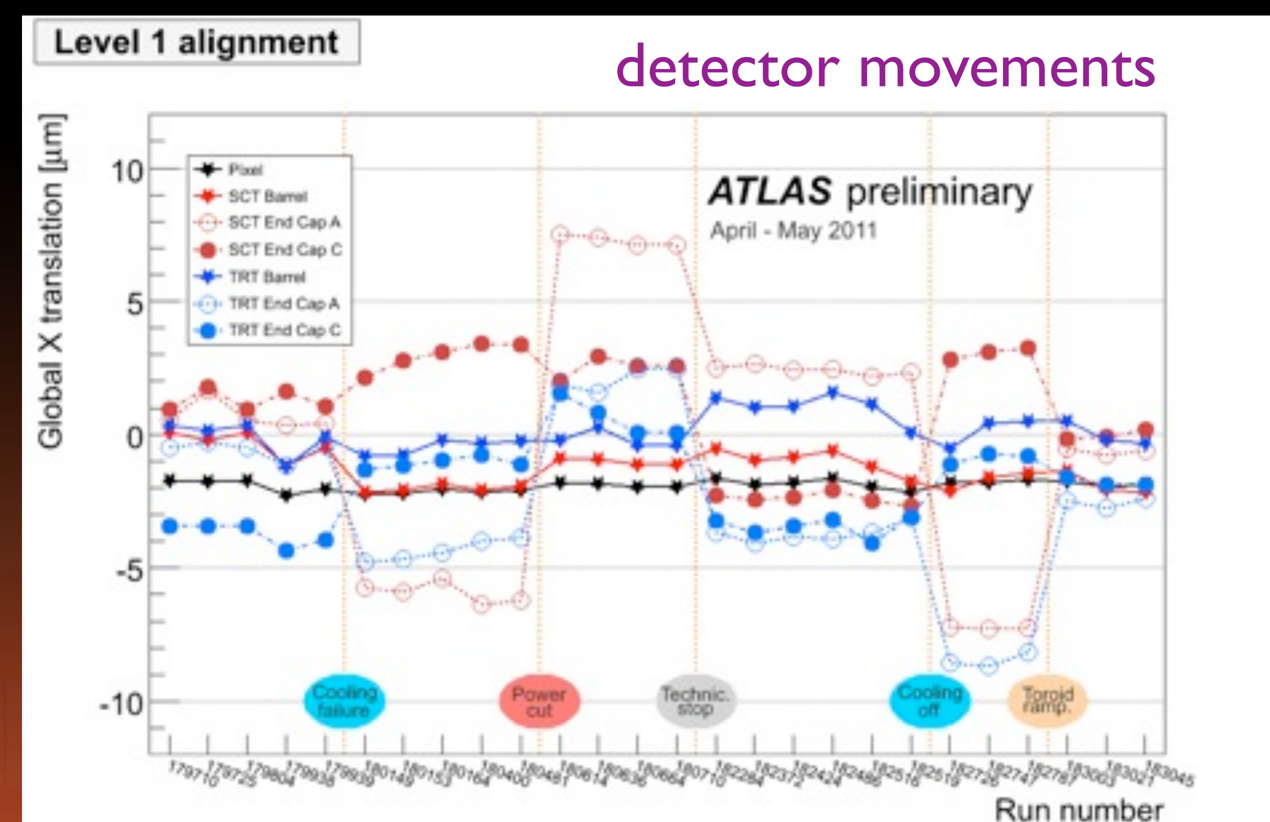
Structures	Pixel	SCT	TRT
Level1	1	3	3
Level 2	12	22	96
Level 3	1744	4088	350848



Detector Alignment

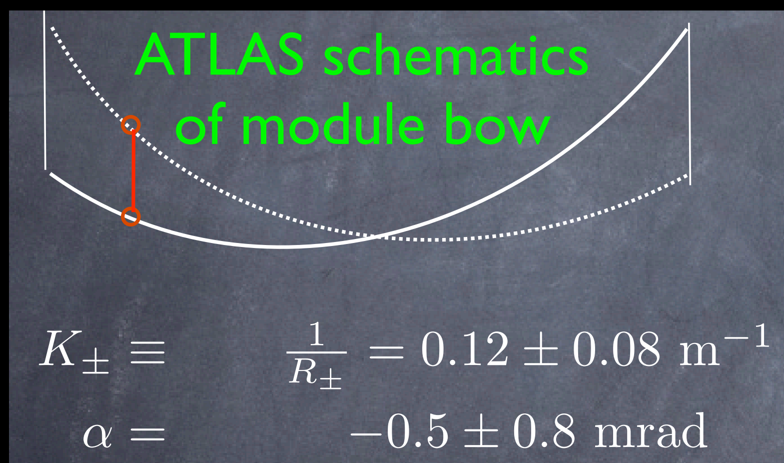
- is an art...
  - ➡ plenty of subtle effects to allow for
- Pixel stave bowing
  - ➡ probably mechanical stress from mounting
- TRT wire alignment
  - ➡ twist between 4 plane wheels
  - ➡ traced back to the wheel production
  - ➡ fix with alignment of each wire (!!)
- detector movements
  - ➡ traced back to
    - cooling failures
    - power cuts
    - magnet ramps
  - ➡ level-1 movements of ~5μm *(mostly)*



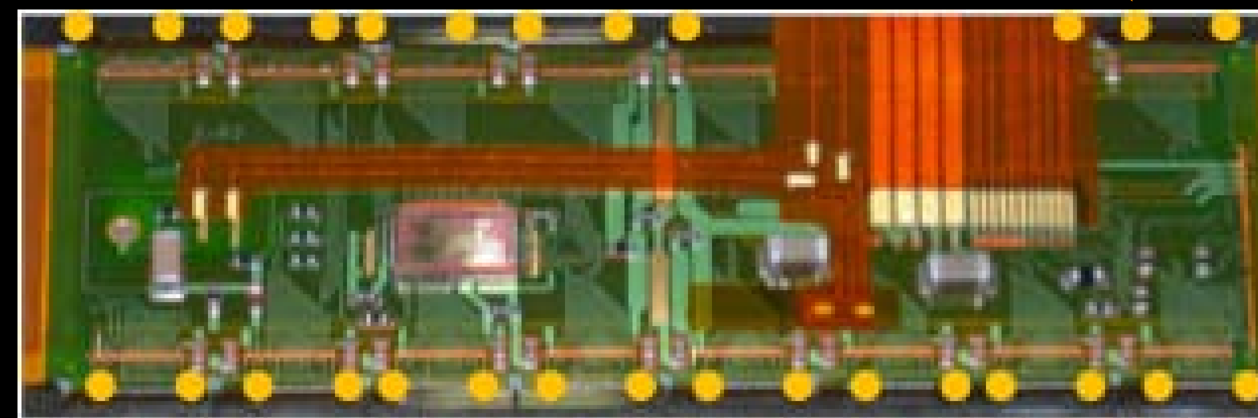


Pixel Module Distortions

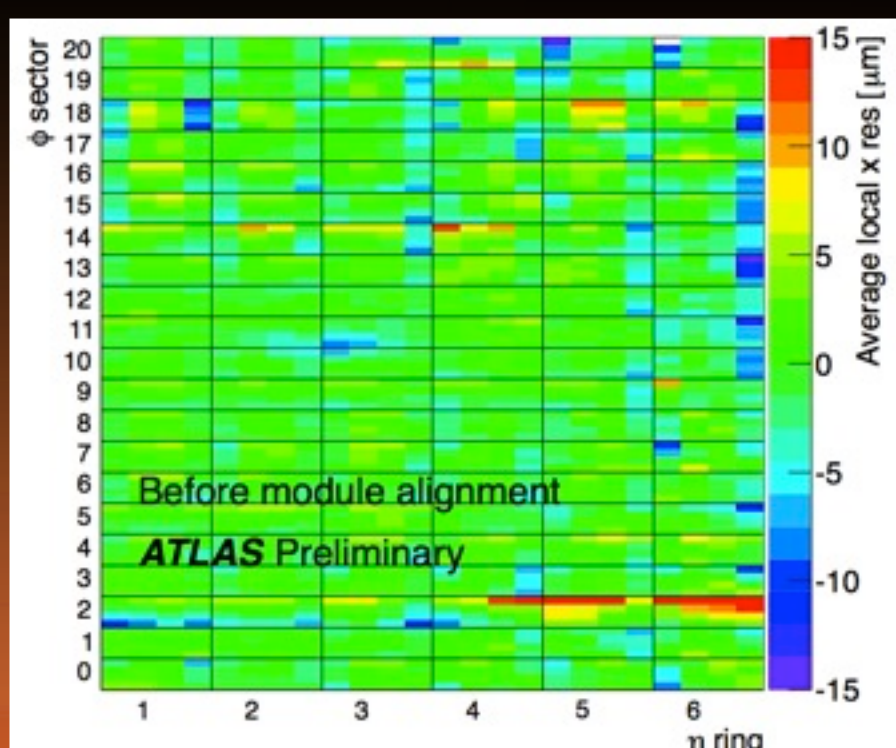
- survey told us Pixel modules are not flat

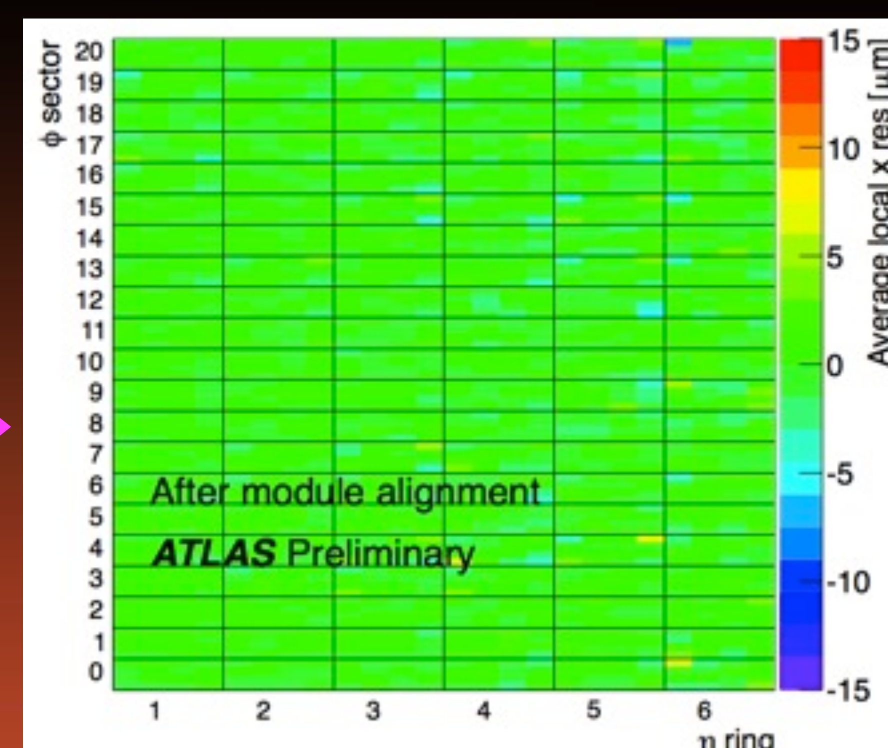


survey points



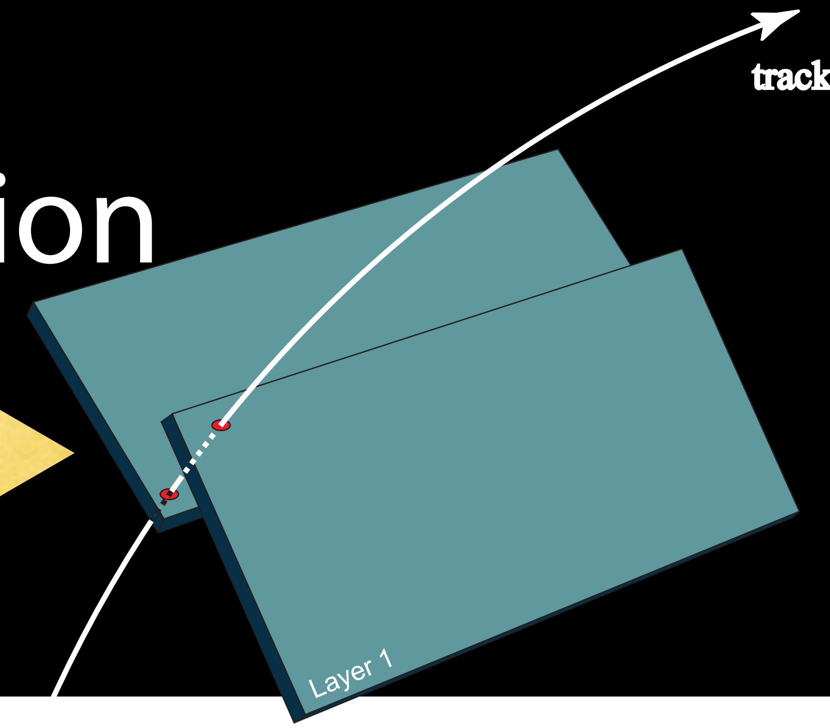
- correct cluster positions for module shape
  - ➡ significant improvement in resolution (SCT bow is small, current not corrected)

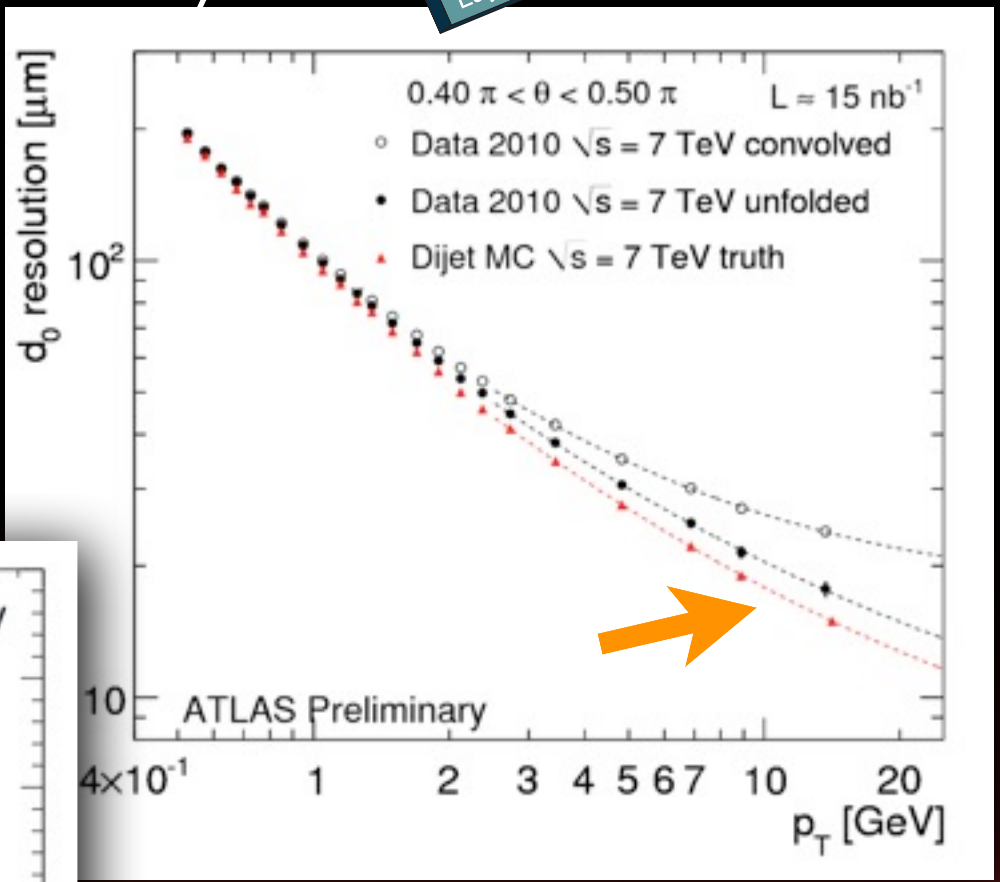


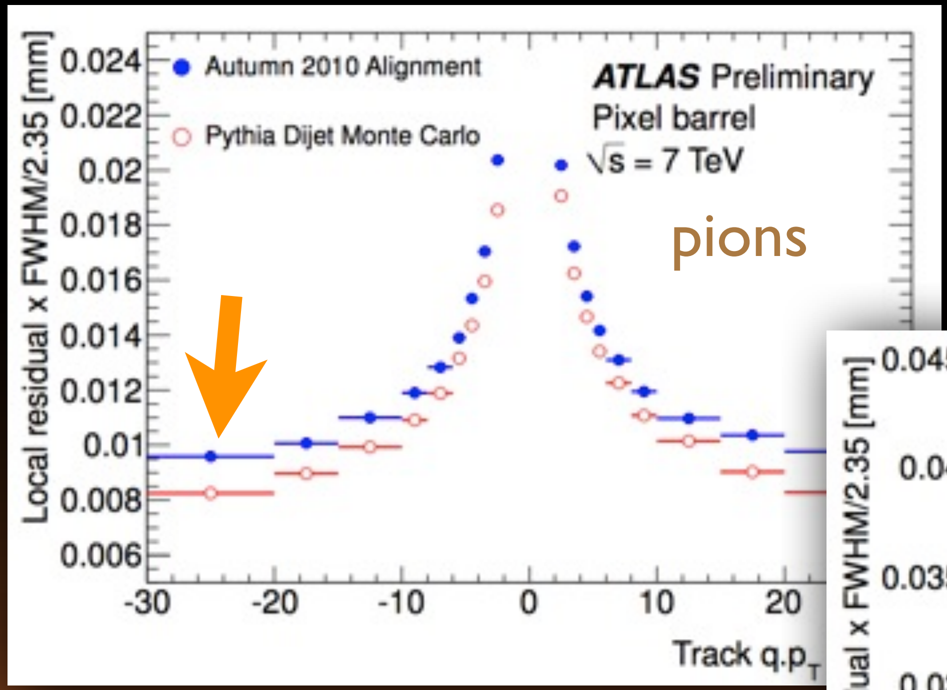


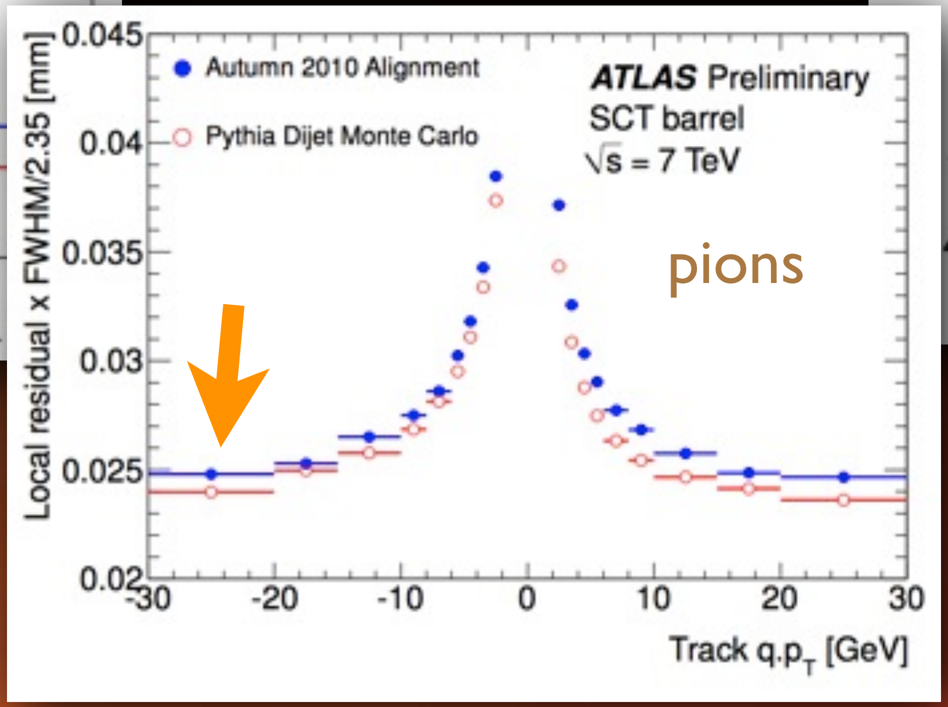
Residuals and Impact Resolution

- driven by local misalignments
  - ➡ quickly approaching design resolutions
  - ➡ some small problems still visible
    - hence apply some error scaling in fit
  - ➡ material dominates at low p_T



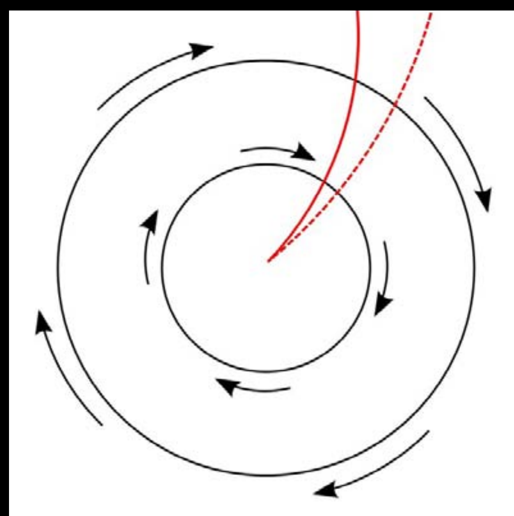




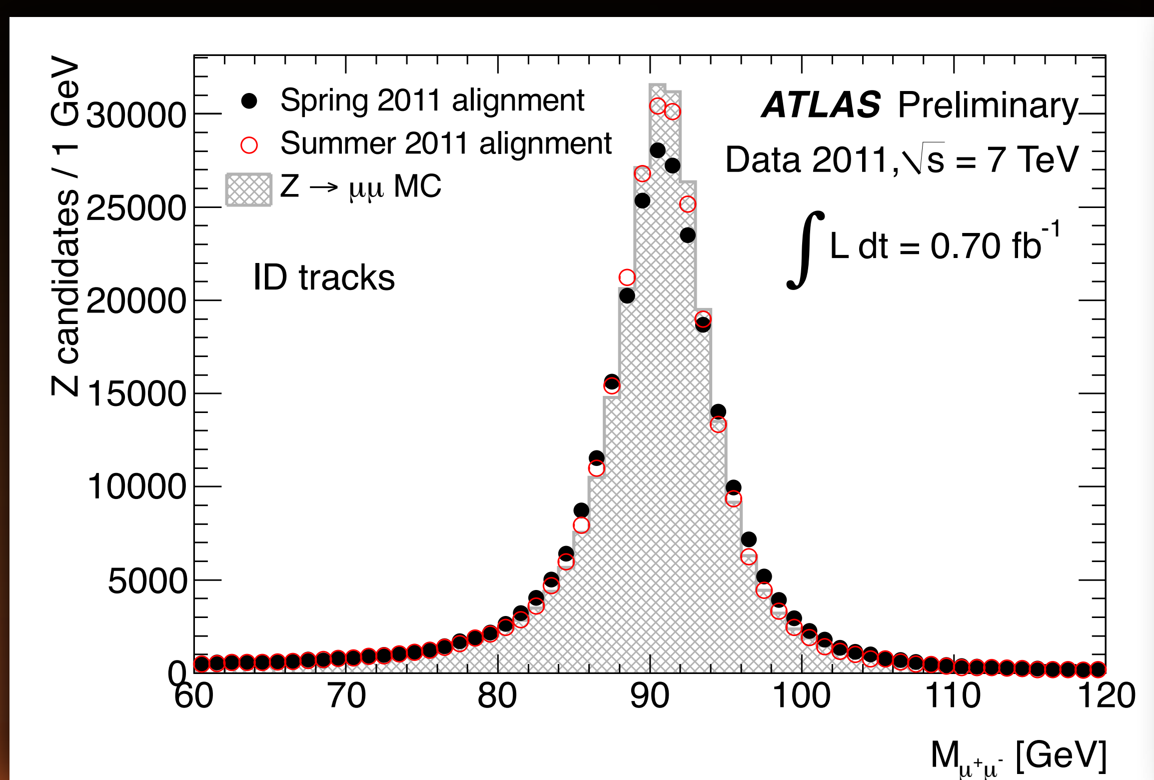


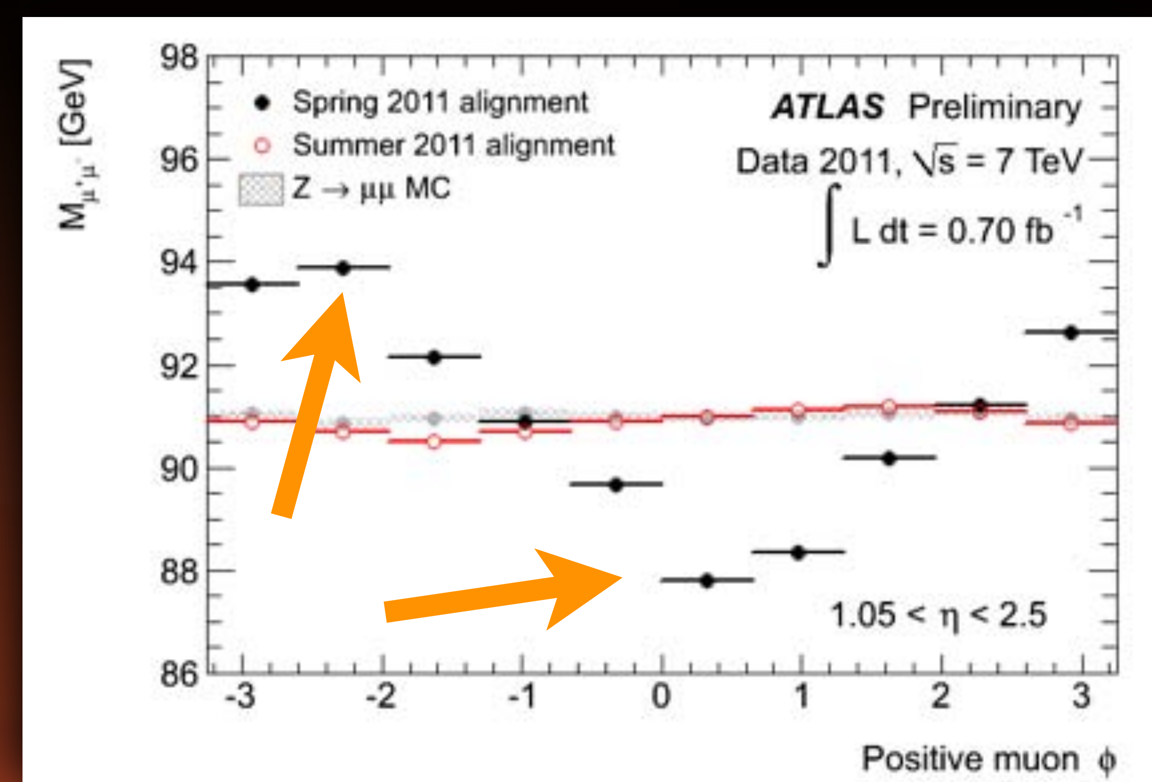
Evidence for Weak Modes ?

example:
curl weak mode



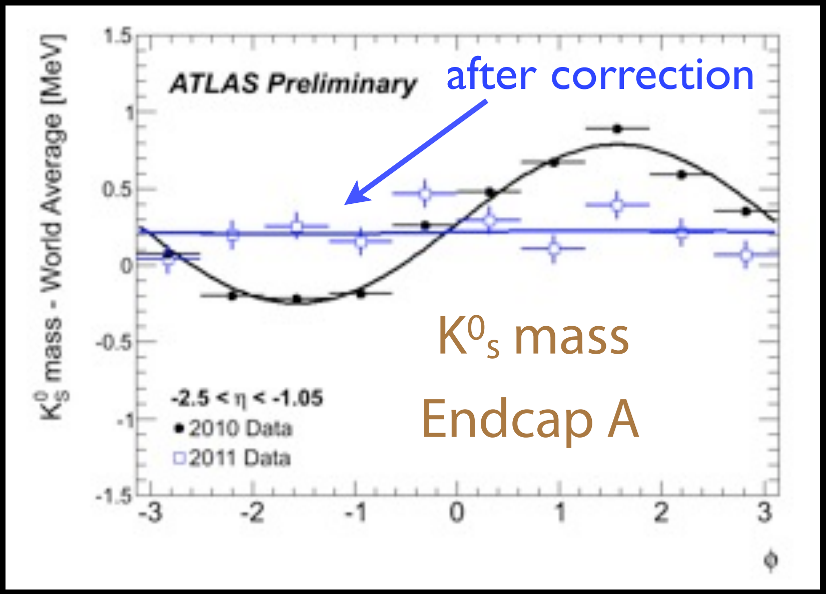
- "weak modes" are global deformations
  - ➡ leave fit-χ^2 nearly unchanged
  - ➡ affect momentum scale, e.g. Z-mass resolution
- limiting performance in data
  - ➡ saw modulation in Z mass vs $\phi(\mu^+)$ in endcaps
- external constraints to control weak modes
  - ➡ TRT to constrain Silicon alignment
  - ➡ currently: electron E/p using calorimeter
  - ➡ check: muon momentum in tracker vs muon spectrometer

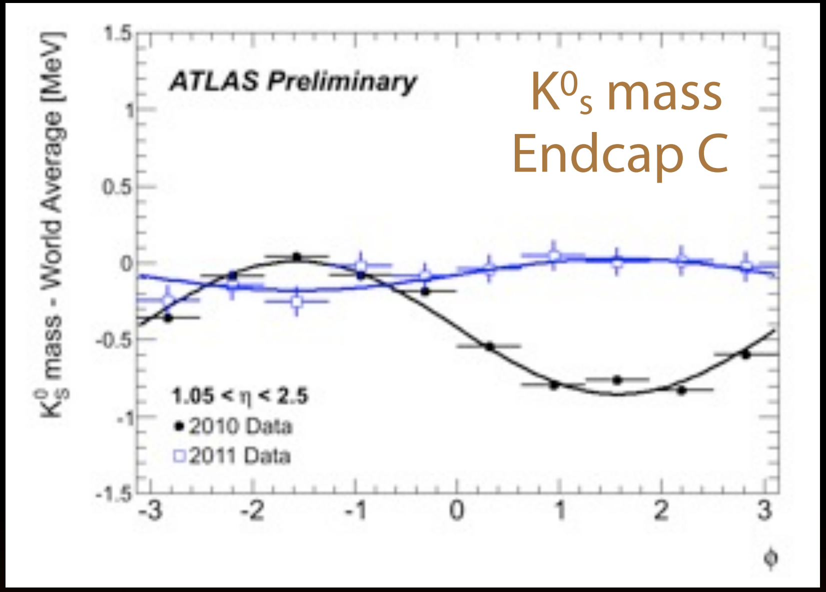


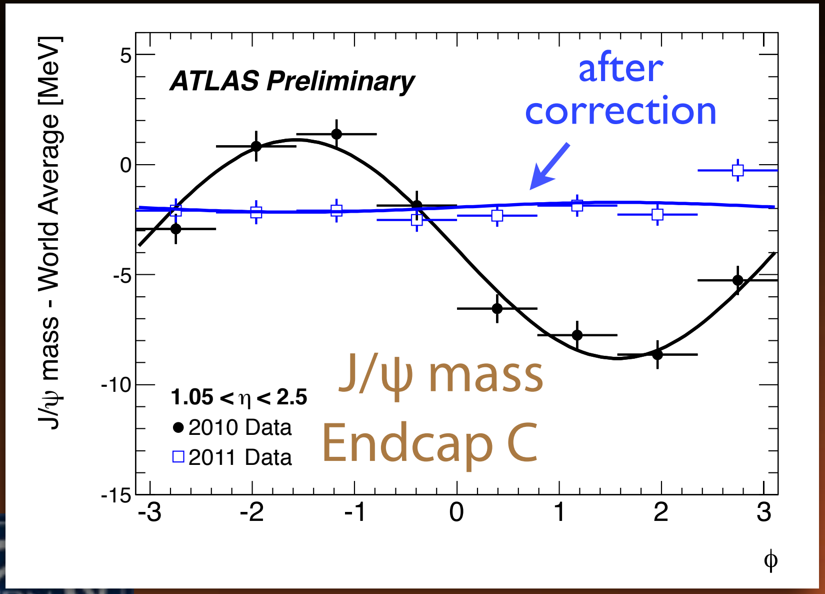


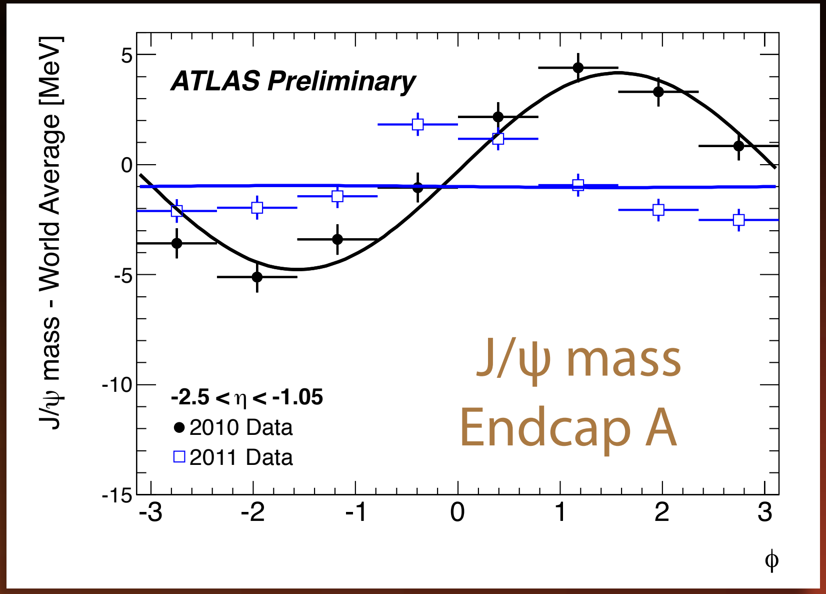
Detector tilt vs B-Field

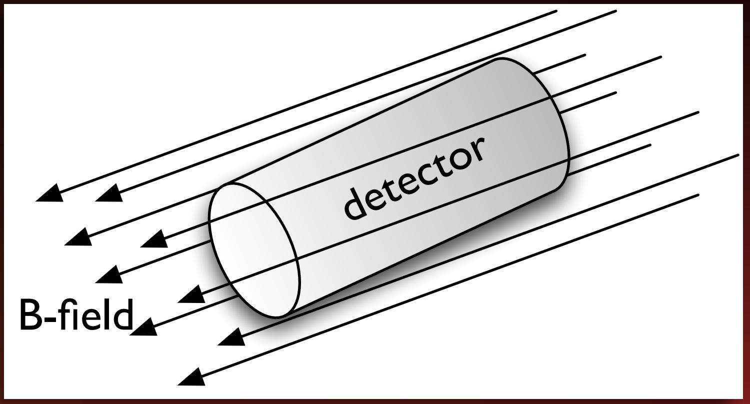
- tilt in visible in K^0_s and J/ψ mass bias as a function of φ
  - ➡ results in a sine modulation in mass in opposite directions in both endcaps
  - ➡ corrected by **0.55 *mrad*** field rotation around y
    - roughly consistent with survey constraints





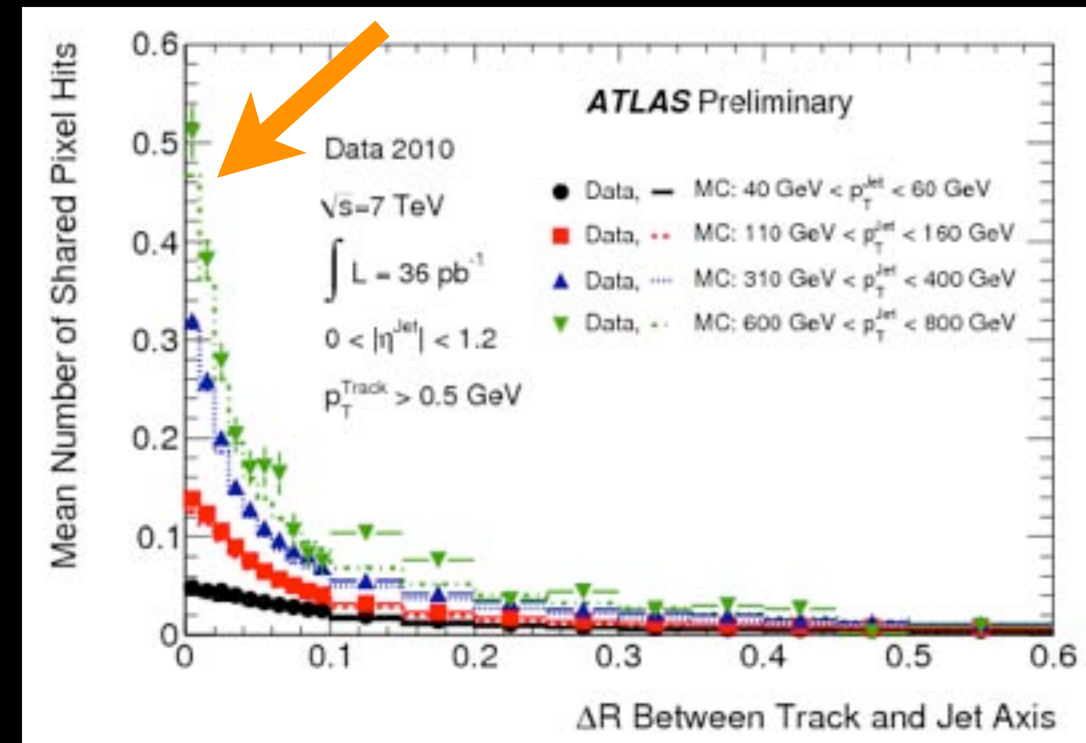


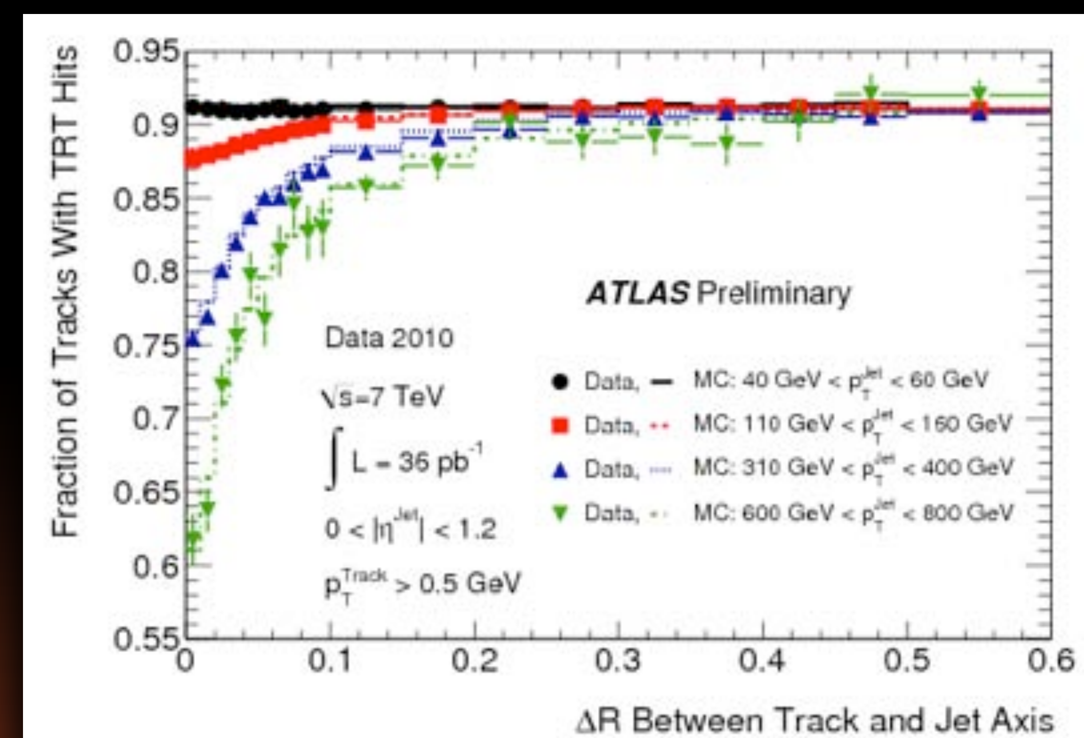


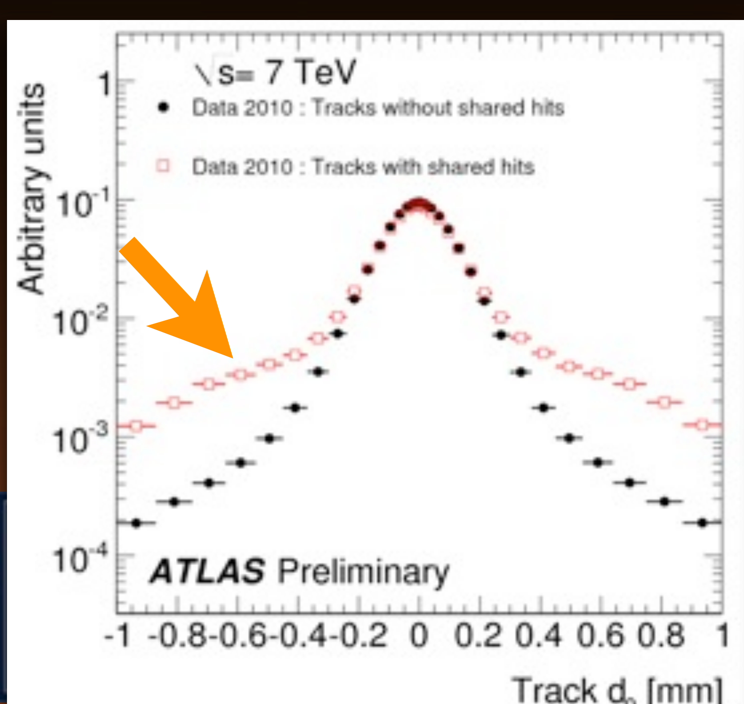


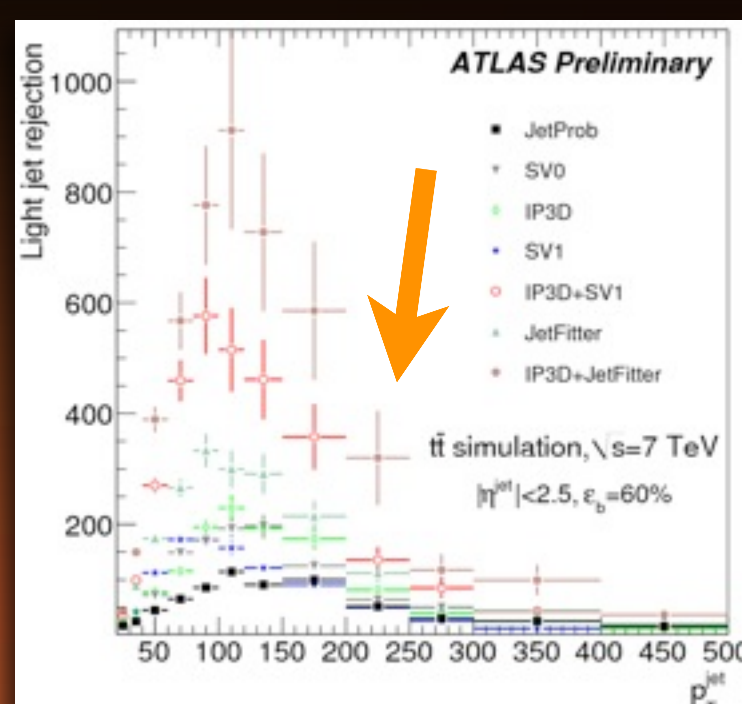
Tracking in Jets

- double track resolution effects ?
  - ➡ study tracks vs p_T of anti-k_T (0.6) jets
- several effects visible in jet core
  - ➡ shared hits in Pixels
  - ➡ TRT association efficiency (quality cuts)
- limits tracking performance
  - ➡ especially for b-tagging !
  - ➡ loss in rejection at high-p_T





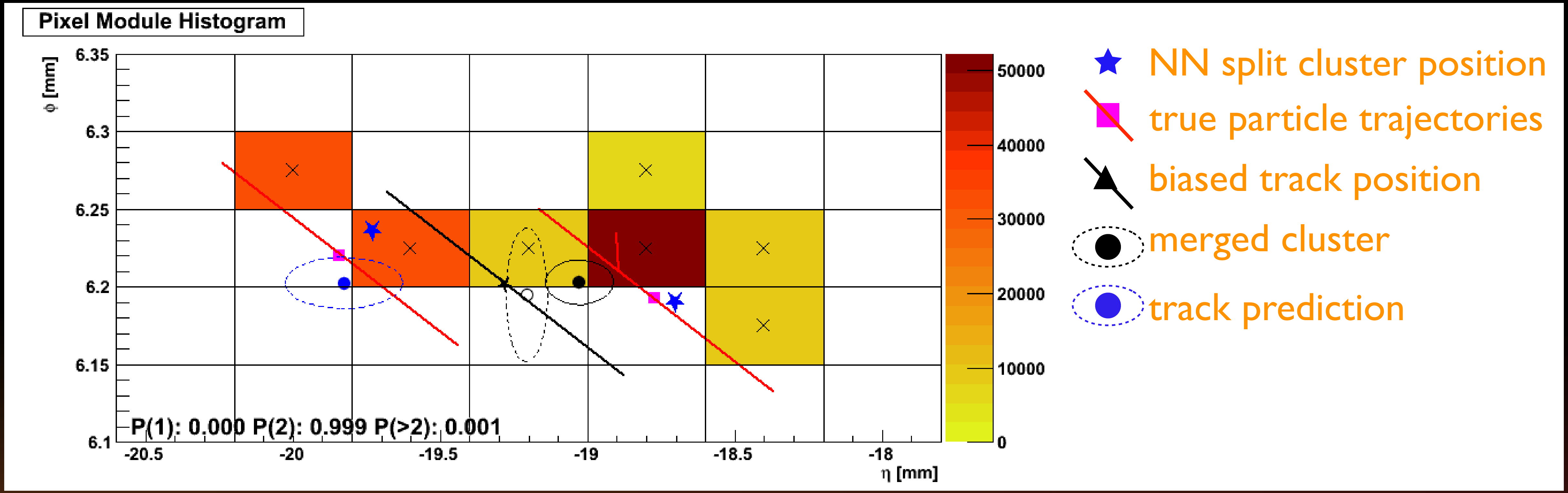




- new clustering to improve
  - ➡ explore full analog information in Pixels

Merged Pixel Clusters

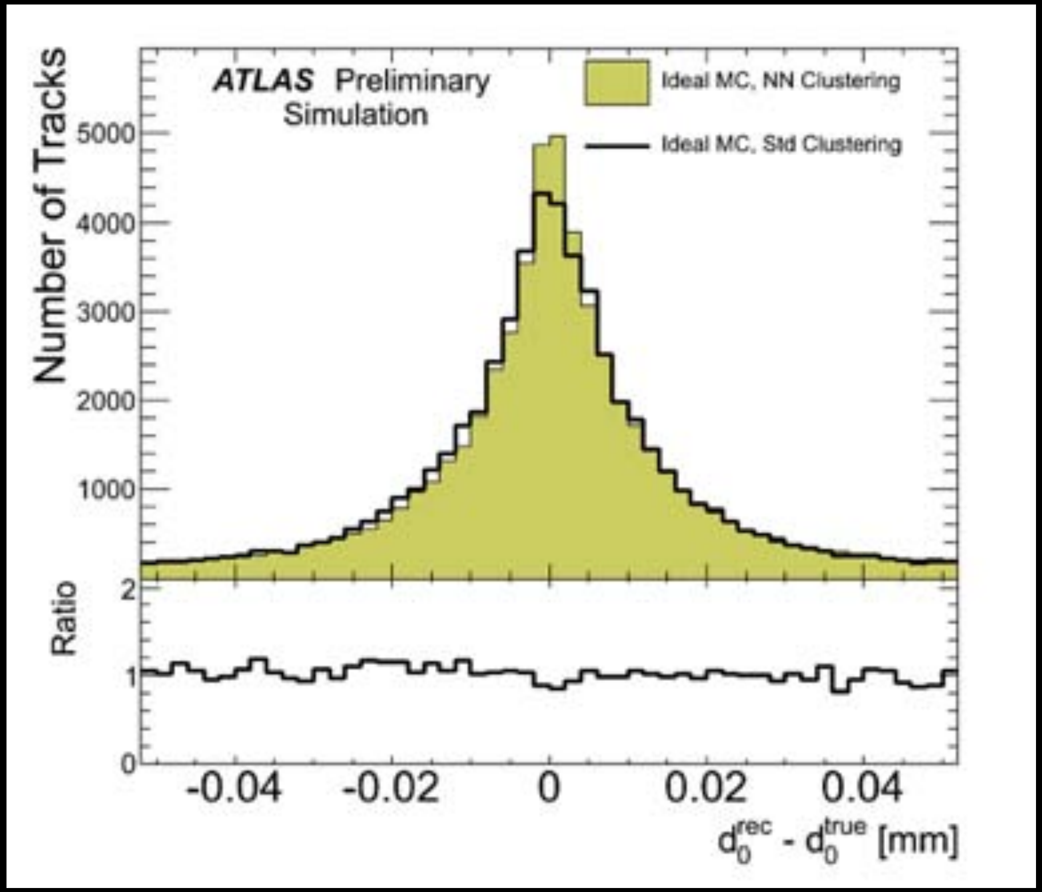
- typical merged cluster with naive clustering algorithm
  - ➡ old clustering was searching for all neighboring pixels that fired
  - ➡ analog information just used to estimate barycenter of cluster

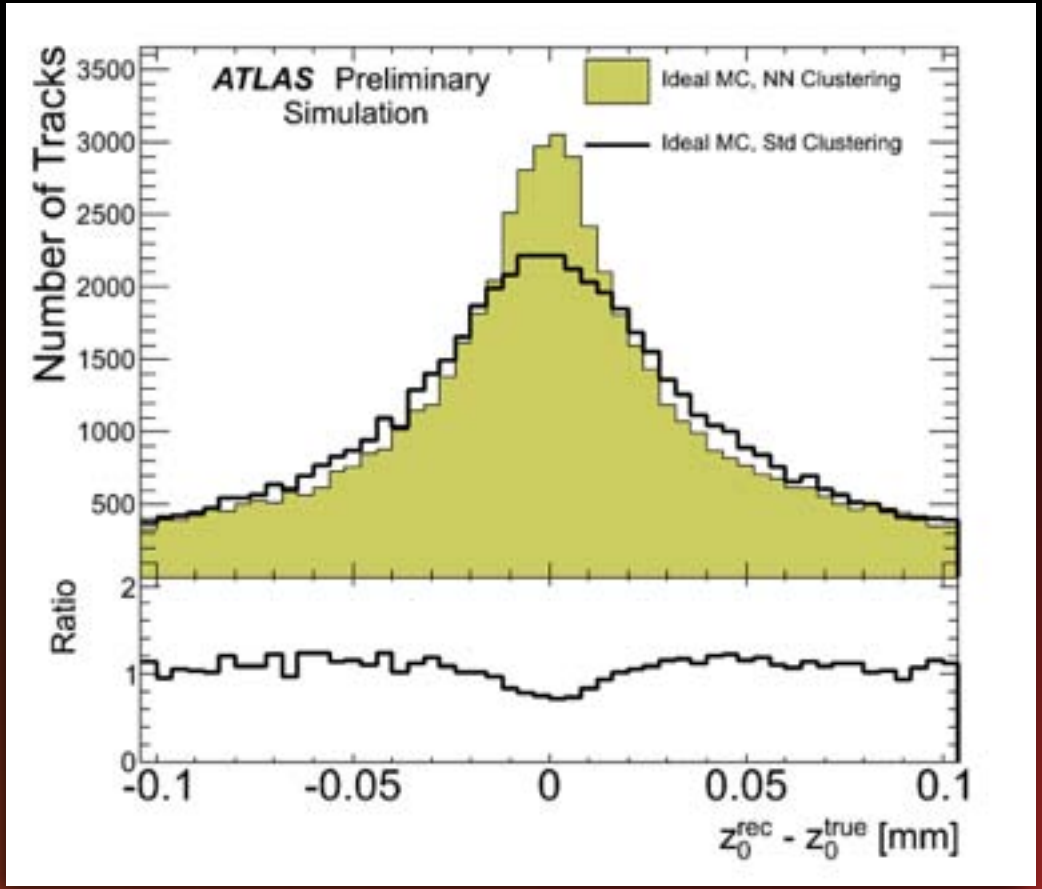


- many merged clusters can be resolved using full analog information
  - ➡ process pre-clusters Pixel information to split them if possible

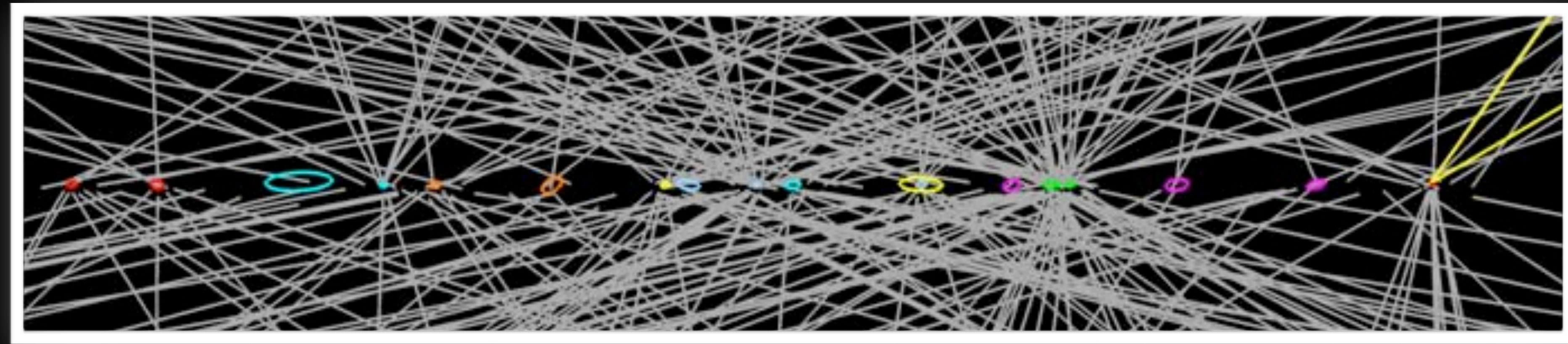
New Pixel Clustering

- novel algorithm to split merge clusters
  - ➡ neural network (NN) based technique
  - ➡ run 5 networks:
    - NN1: probability a cluster is 1/2/>2 tracks
    - NN2: best position for each (sub)cluster
    - NN3: error estimate for cluster
    - NN4+5: redo NN2+3 using track prediction
  - ➡ adapt pattern recognition
- new clustering been deployed in recent 2011 reprocessing
  - ➡ improved cluster resolution, especially in z
  - ➡ dramatic reduction in rate of shared b-layer hits due to unresolved merged clusters



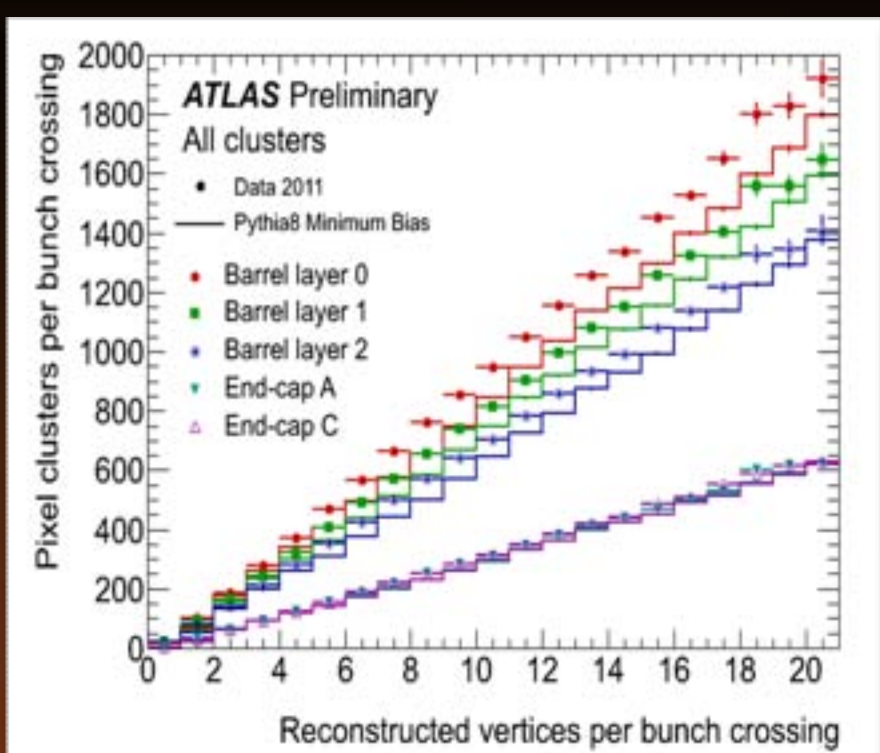


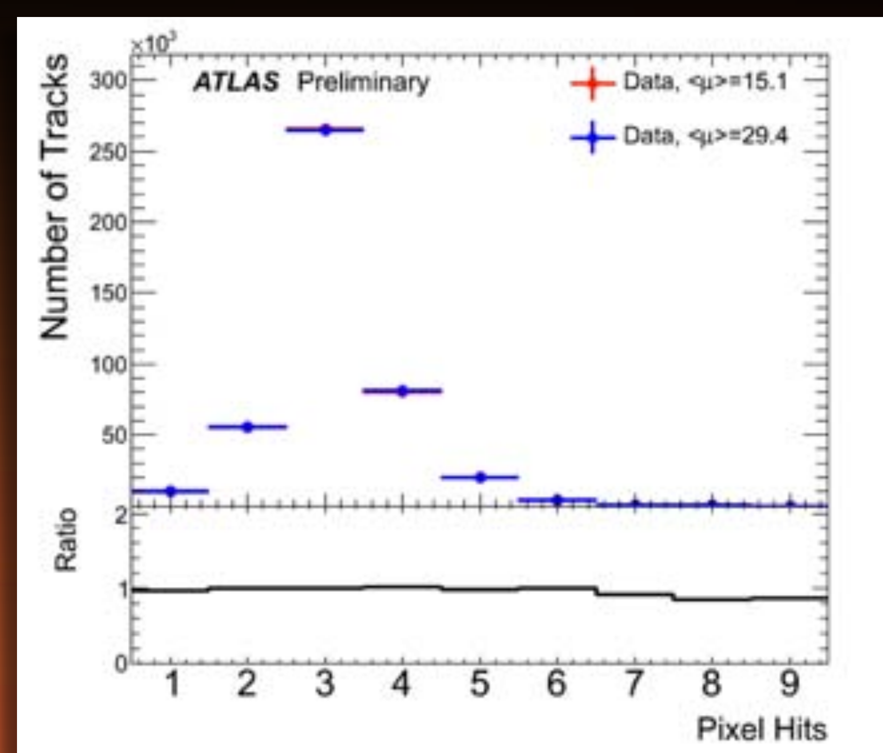
Pileup

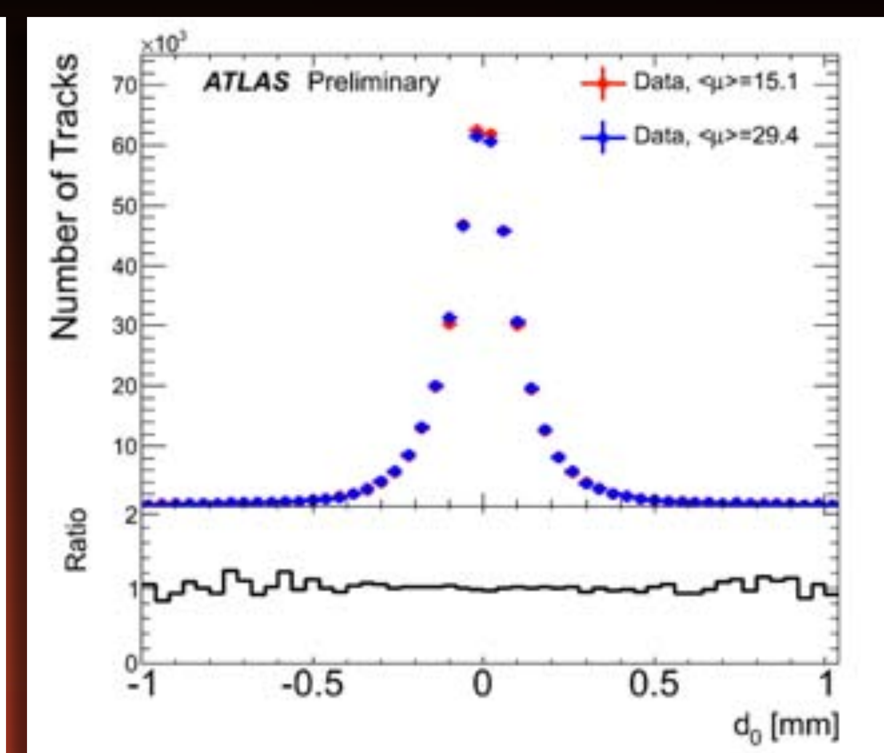


event with 20 reconstructed vertices

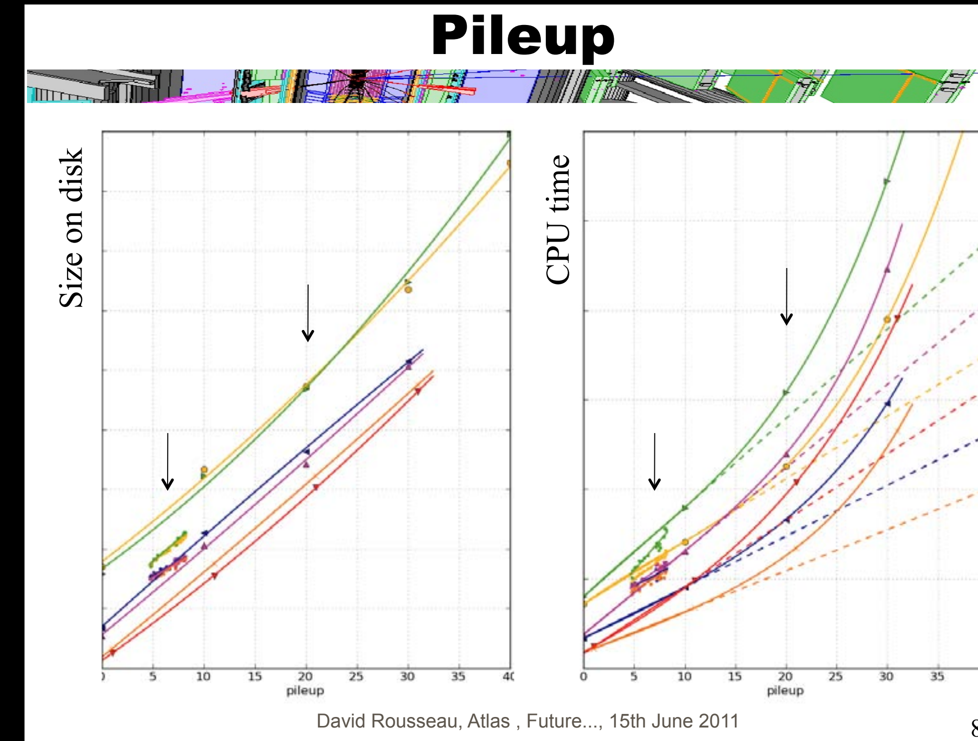
- event pileup is a reality
  - ➡ in 2011 we reached **50%** of design levels, but at ***50 nsec*** bunch spacing
  - ➡ may expect 2-3 times increase in 2012
- occupancies and tracking performance as expected
  - ➡ recent high pileup LHC runs very useful to study high pileup regime
  - ➡ resolutions and reconstruction efficiencies are not affected
  - ➡ fake rate is naturally increasing with loose tracking cuts







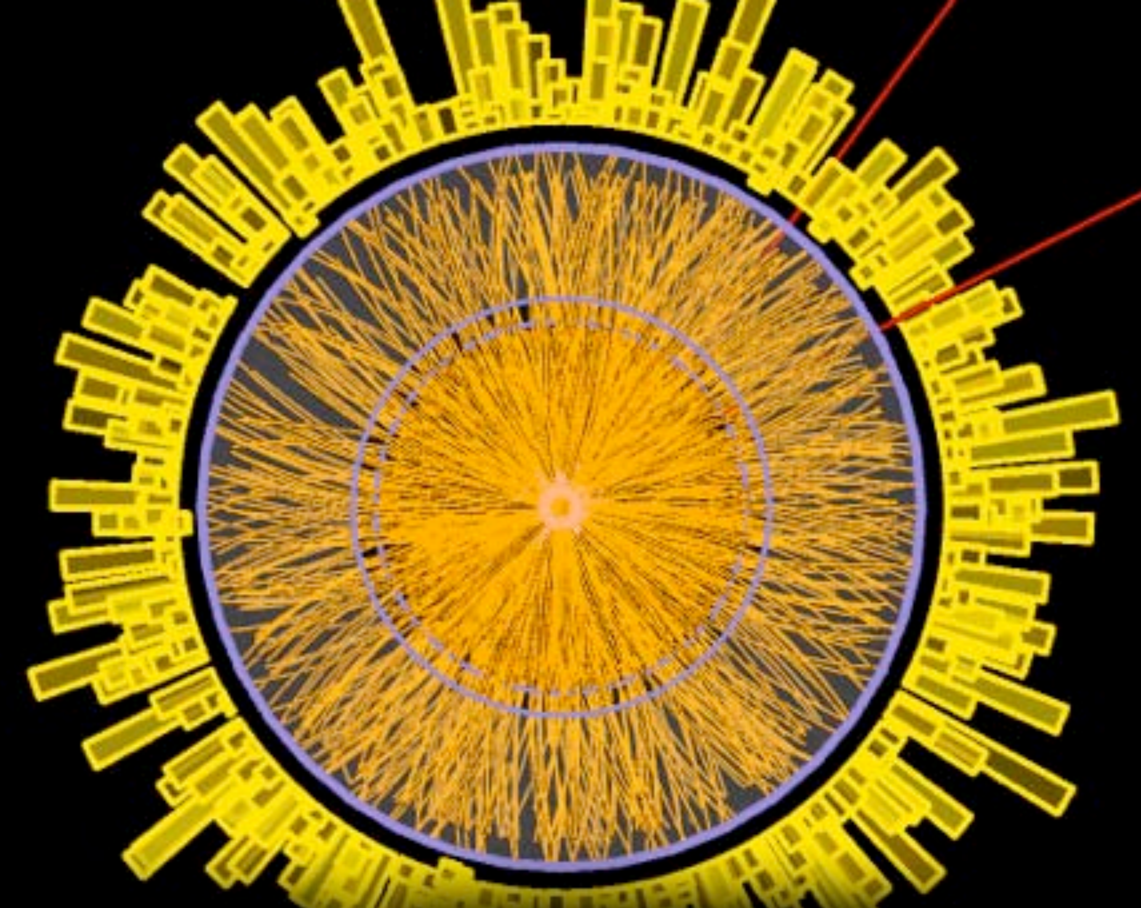
Pileup and Resources



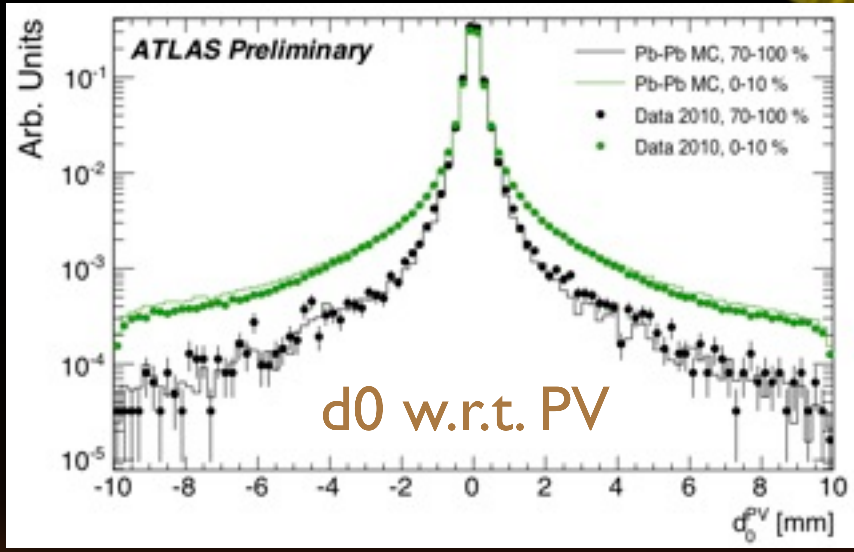
- resource needs scale fast
  - ➡ tracking is a resource driver
- global optimization
  - ➡ requirements on tracking evolves with physics program
  - ➡ different luminosity regimes lead to different **working points**

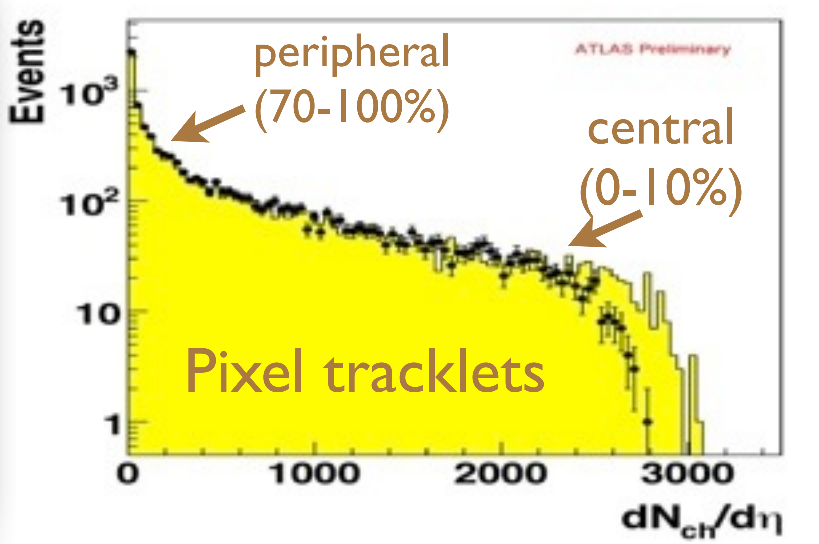
2009 / early 2010	commissioning Min.Bias	pt > 50 MeV open cuts, robust settings min. 5 clusters
2010 stable running < ~4 events pileup	low lumi physics program (soft QCD, b-physics, ...), b-tagging...	pt > 100 MeV min. 7 clusters
2011 pp running ~11 events pileup	focus more on high-pt physics (top, W/Z, Higgs), b-tagging...	pt > 400 MeV, harder cuts in seeding min. 7 clusters
Phase I upgrade including IBL 24-50 events pileup	high-pt physics, study new physics (I hope), b-tagging....	pt > 900 MeV, harder tracking cuts, min. 9 clusters
SLHC up to 100-200 events pileup	replace Inner Detector to cover very high luminosity physics program	further evolve strategy... R-o-I or z-vertex seeding, reco. per trigger type, GPUs

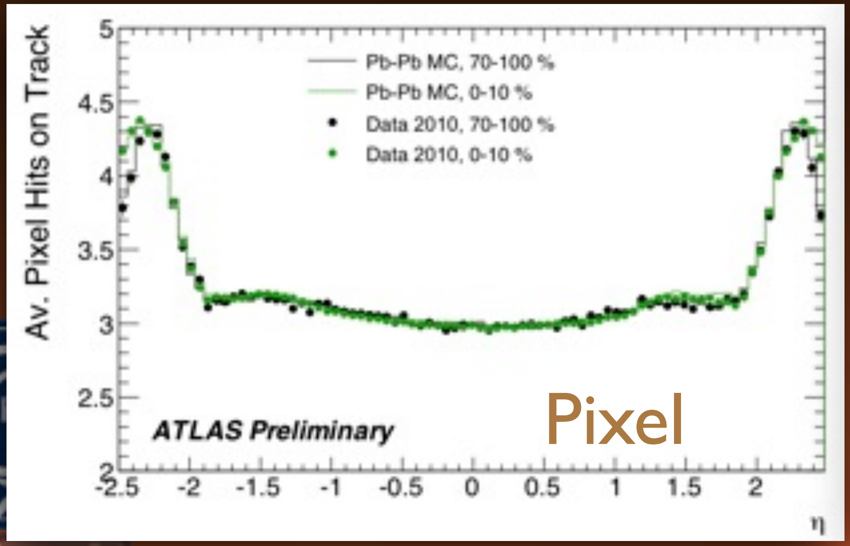
Heavy Ion Tracking

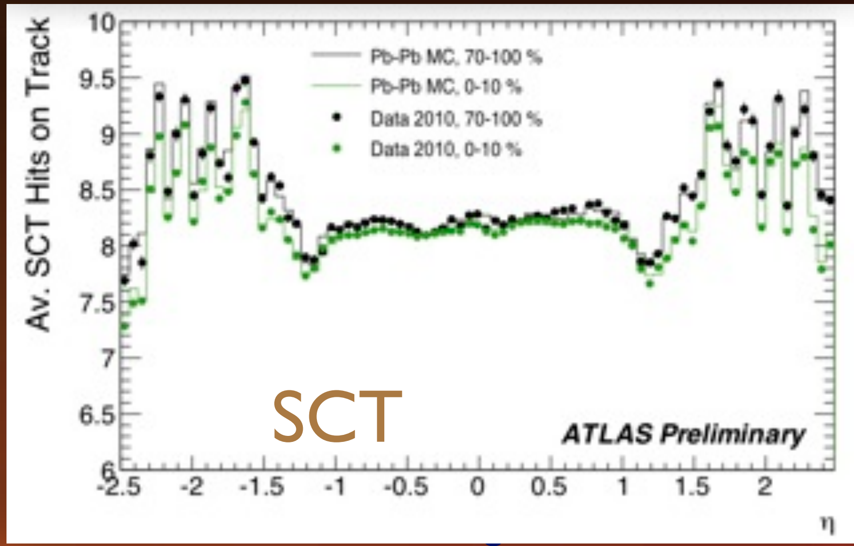


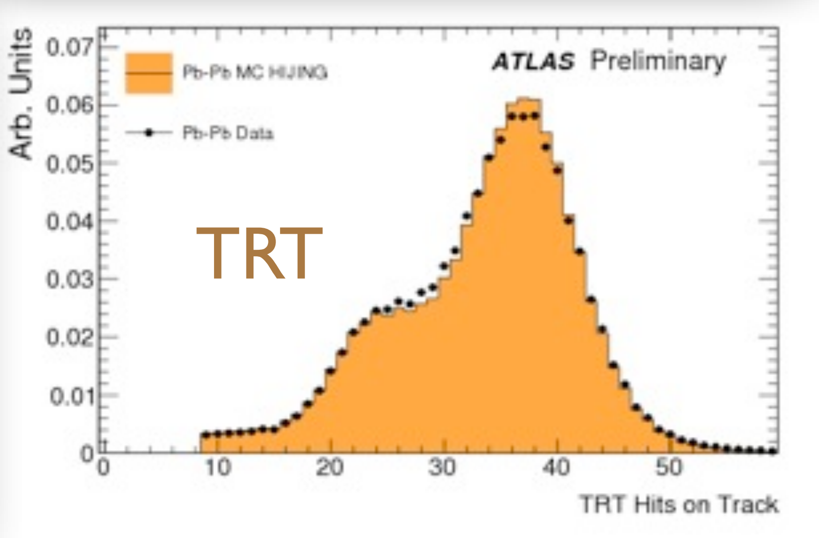
- high multiplicity tracking
  - ➡ adapt seed finding (z vertex constraint to save CPU)
  - ➡ tighten hit requirement to control fakes in central events (similar to sLHC setup)
- excellent tracking performance
  - ➡ even in central events
  - ➡ performance well described by MC
  - ➡ good testing ground for high in-time pileup with data





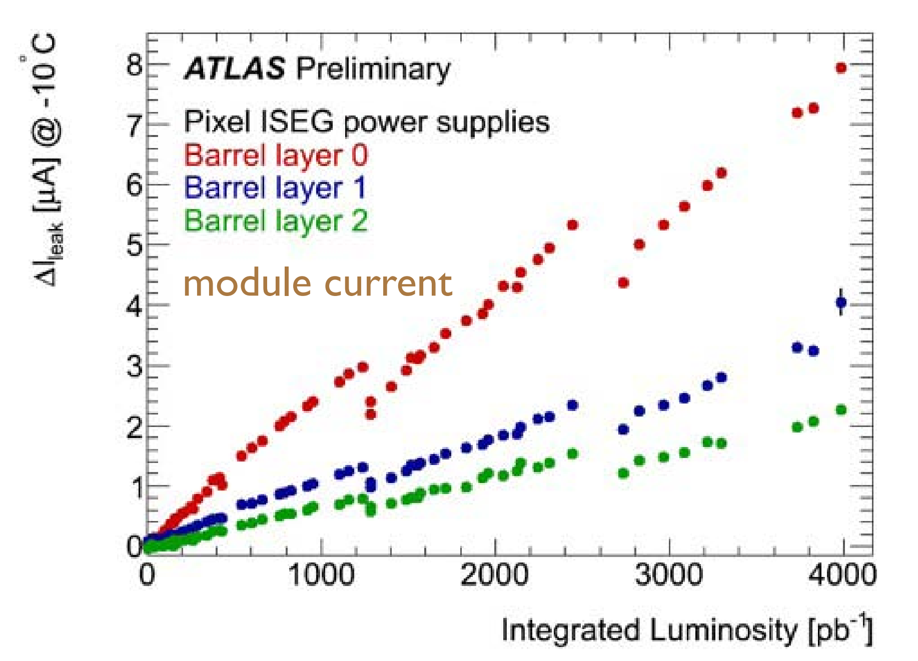


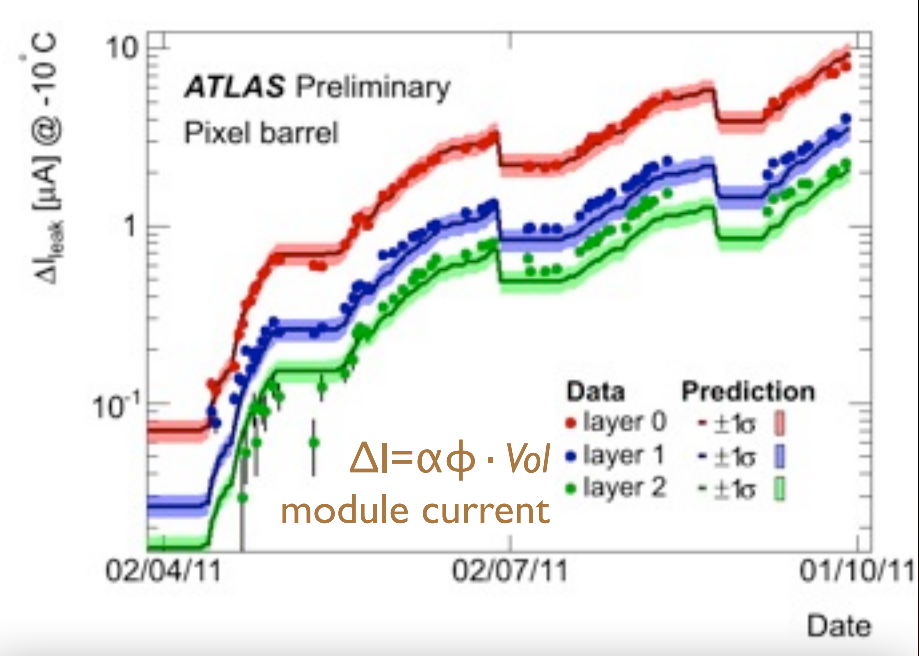


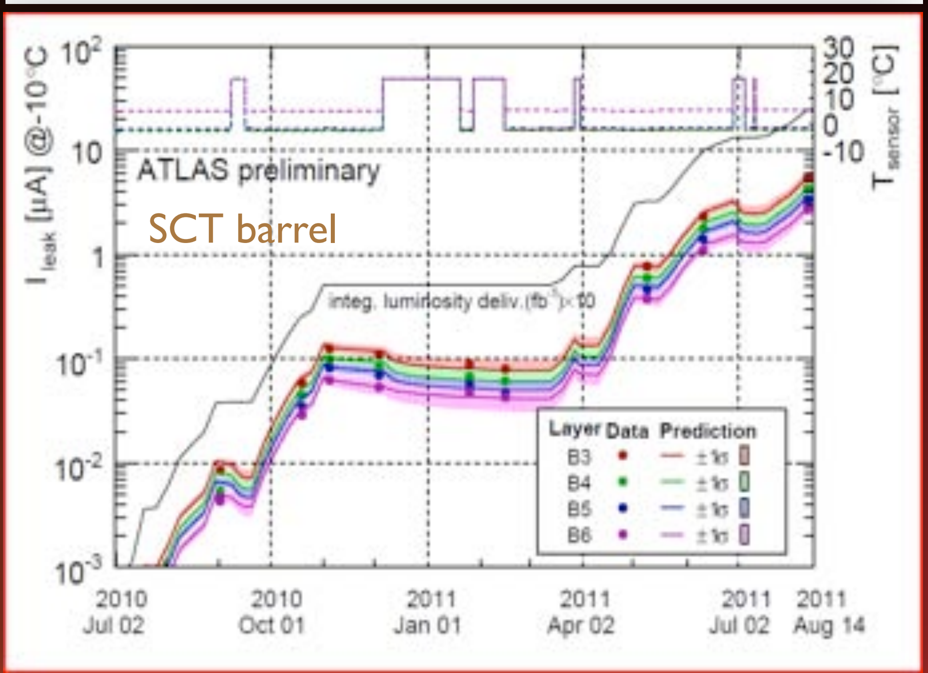


Radiation Damage

- effects became visible in recent months with increasing luminosity
  - ➡ b-layer:
    - $\phi = 2.43 \cdot 10^{12} \cdot (1\text{ MeV neq})/\text{fb}^{-1}$
    - type inversion at ~10 fb^{-1}
- monitor radiation effects on silicon
  - ➡ leakage current and cross talk measurements
- currents from HV power supplies
  - ➡ compare measured leakage currents with:
    - lumi profile
    - expected fluence ϕ from Phojet/Fluka
    - silicon volume
    - damage constant α from test beam
  - ➡ good agreement for Pixels and SCT after correction for annealing periods
    - cooling off, e.g. during technical stops

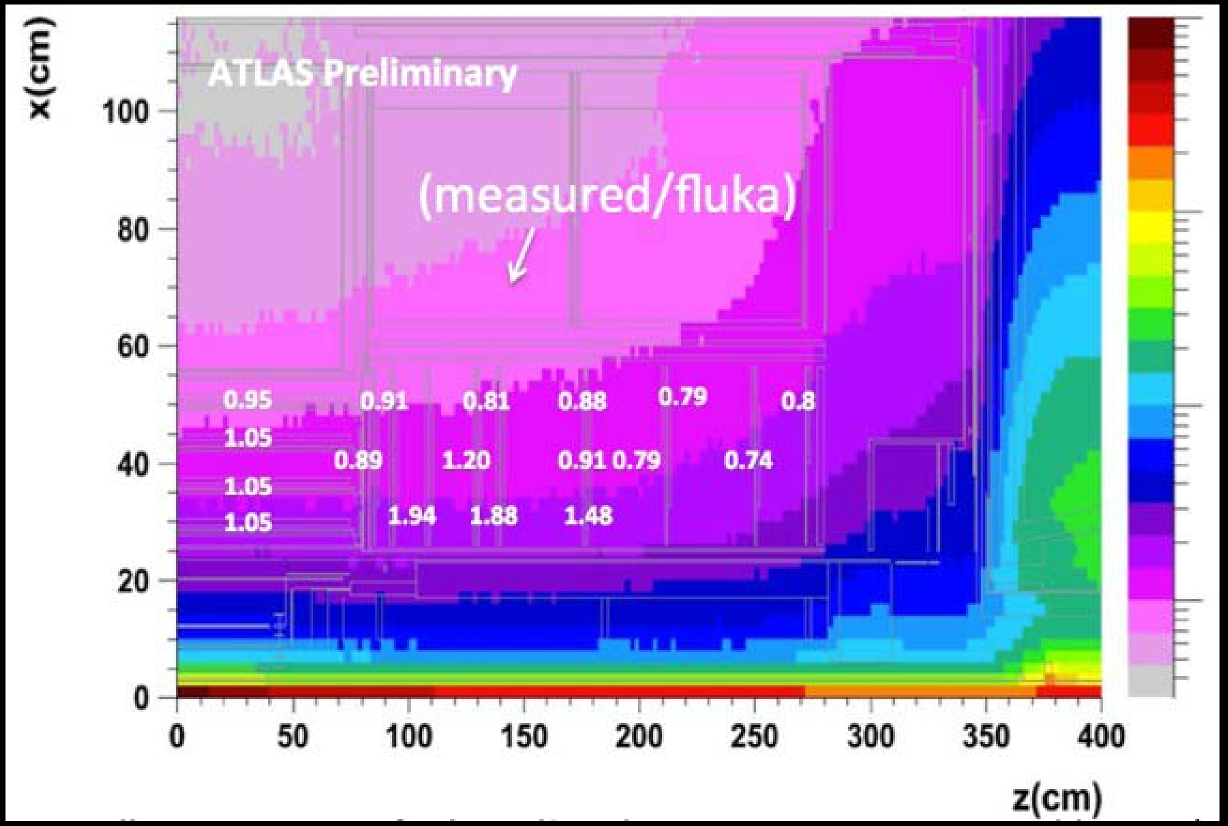




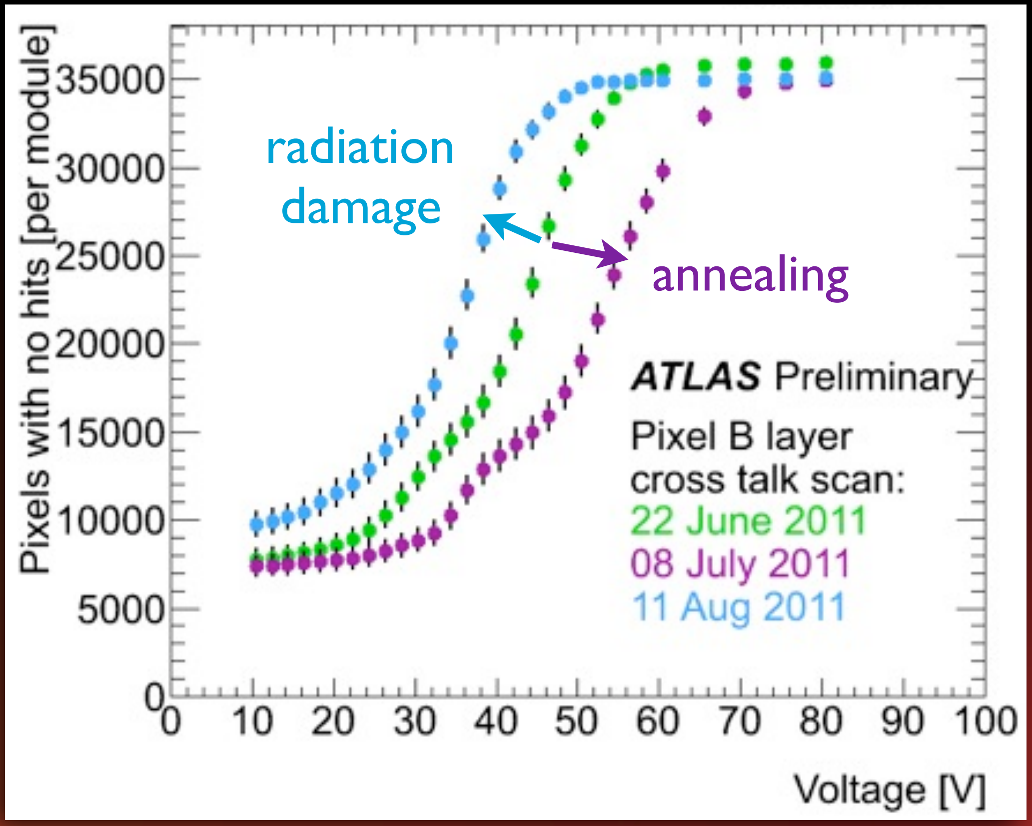


Radiation Damage

- comparison of measured fluences with Fluka
  - ➡ SCT leakage currents
  - ➡ good agreement in barrel, endcaps show some differences
  - ➡ consistently higher at inner rings (due to different sensors ?)

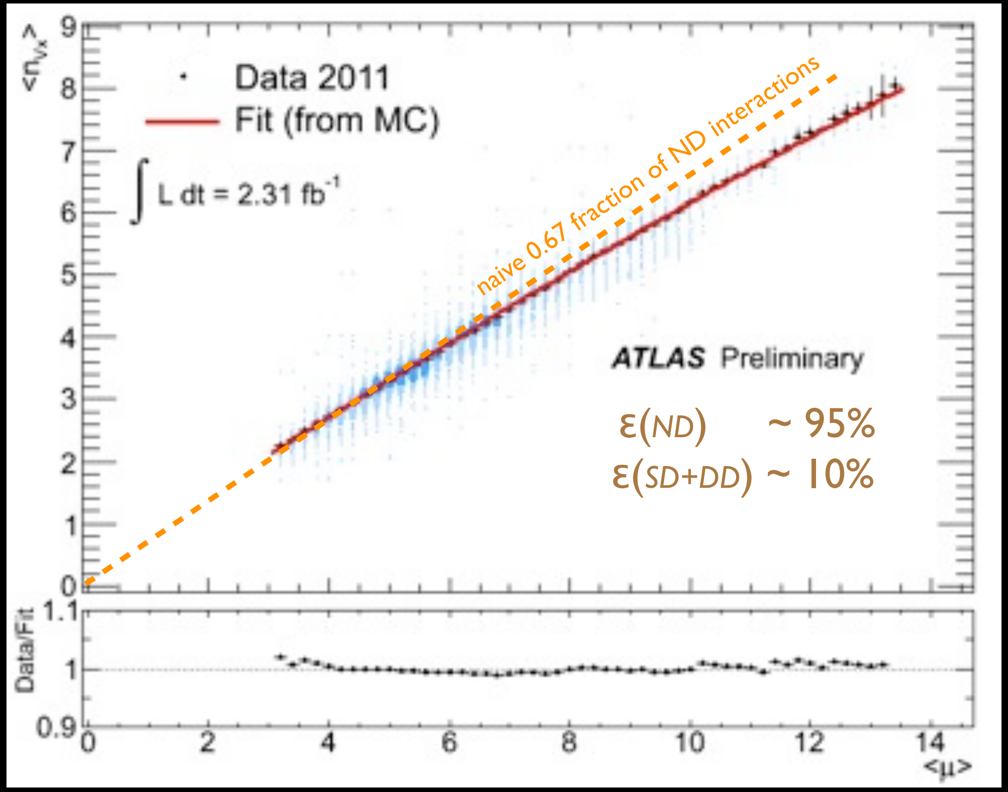


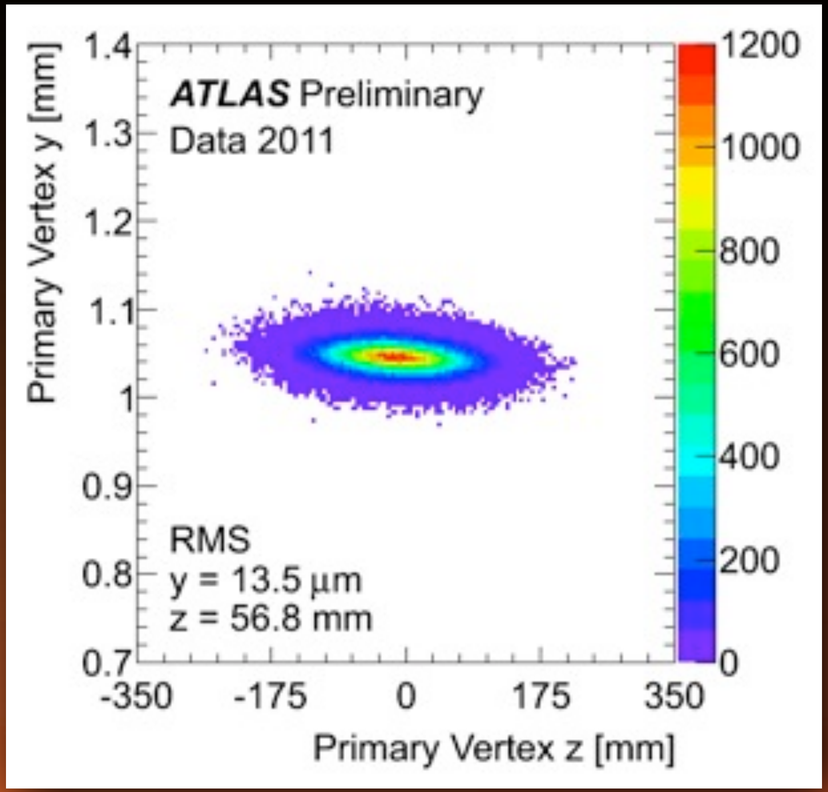
- cross-talk measurements (before type inversion)
  - ➡ inject charge into one pixel, read neighbor:
    - ‣ not fully depleted: high-ohmic short
    - ‣ fully depleted: pixels are isolated
  - ➡ annealing effects induced an increase in Vdep from June to July

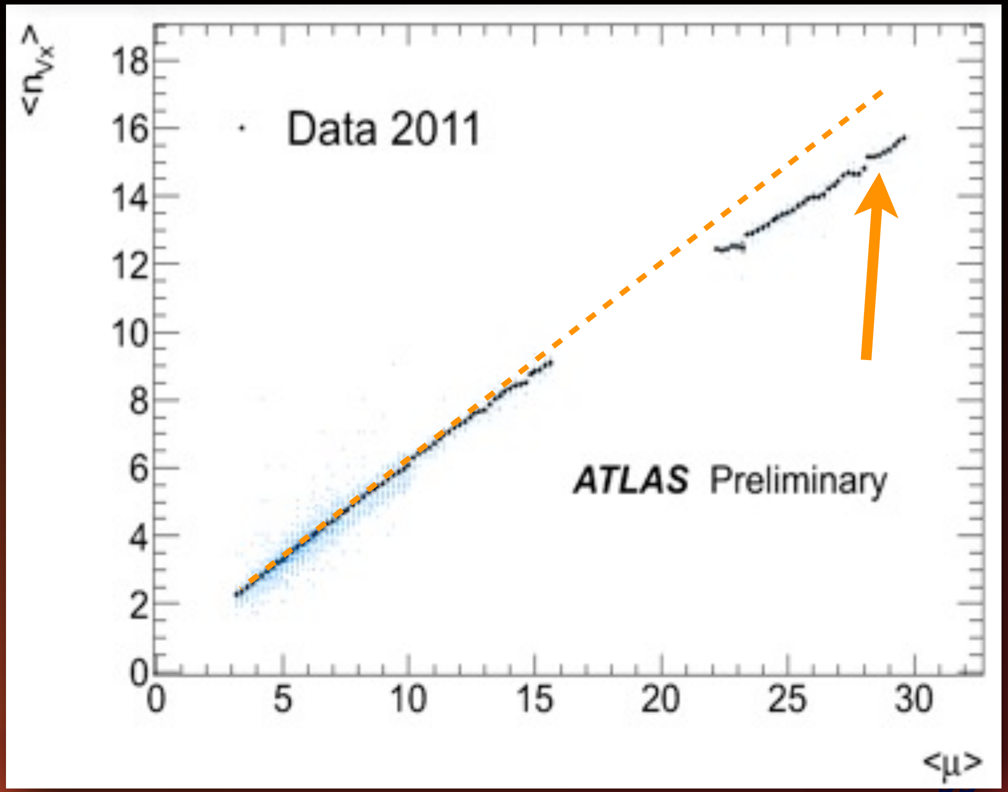


Primary Vertex Reconstruction

- beam spot routinely determined
  - ➡ averaged over short periods of time (LB)
  - ➡ input to primary vertex reconstruction as a constraint
- primary vertex finding
  - ➡ ATLAS (and CMS) use an iterative vertex finder and an adaptive fitter
  - ➡ some reduced efficiency for min.bias pileup vertices vs <μ>

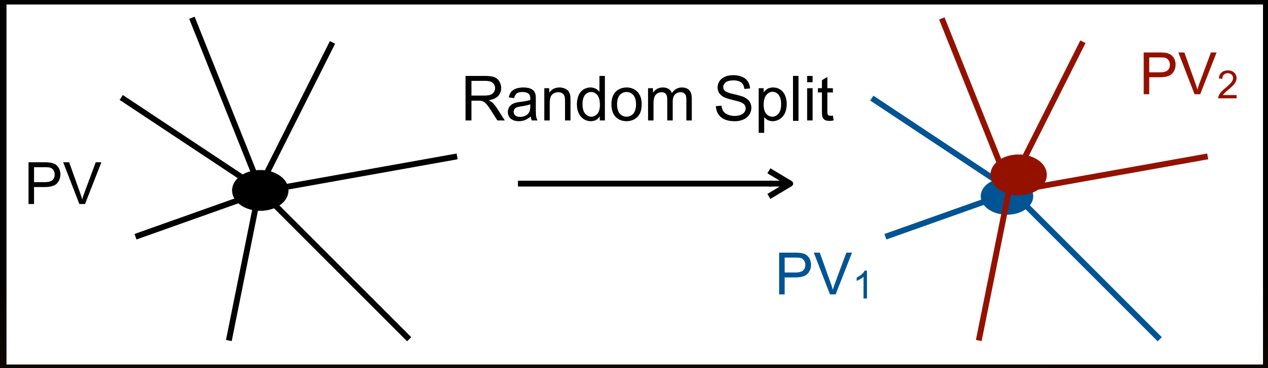




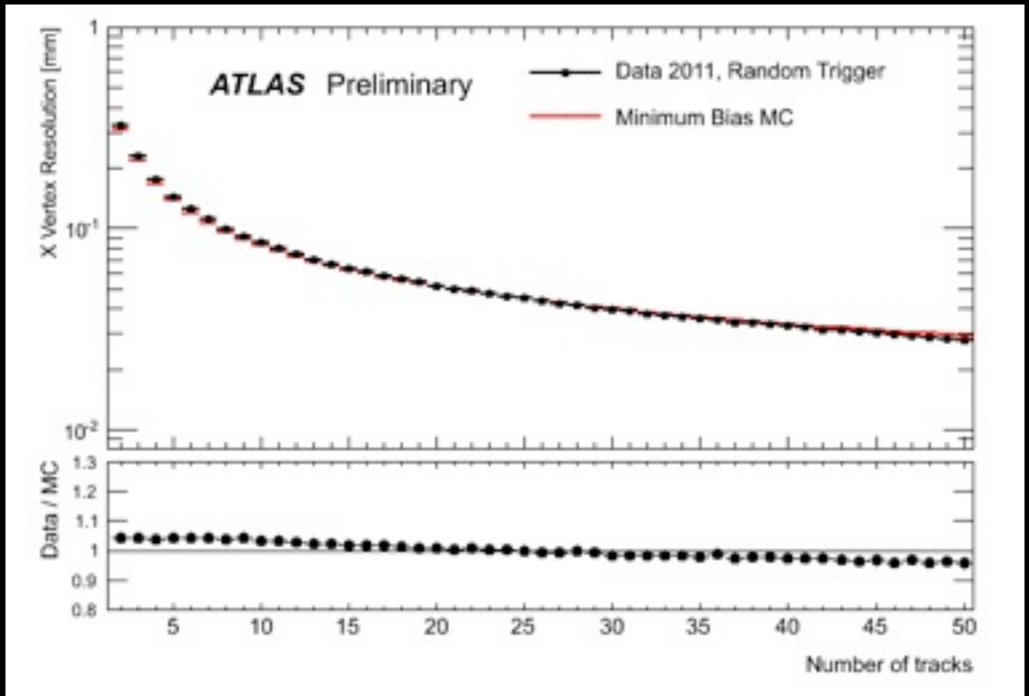


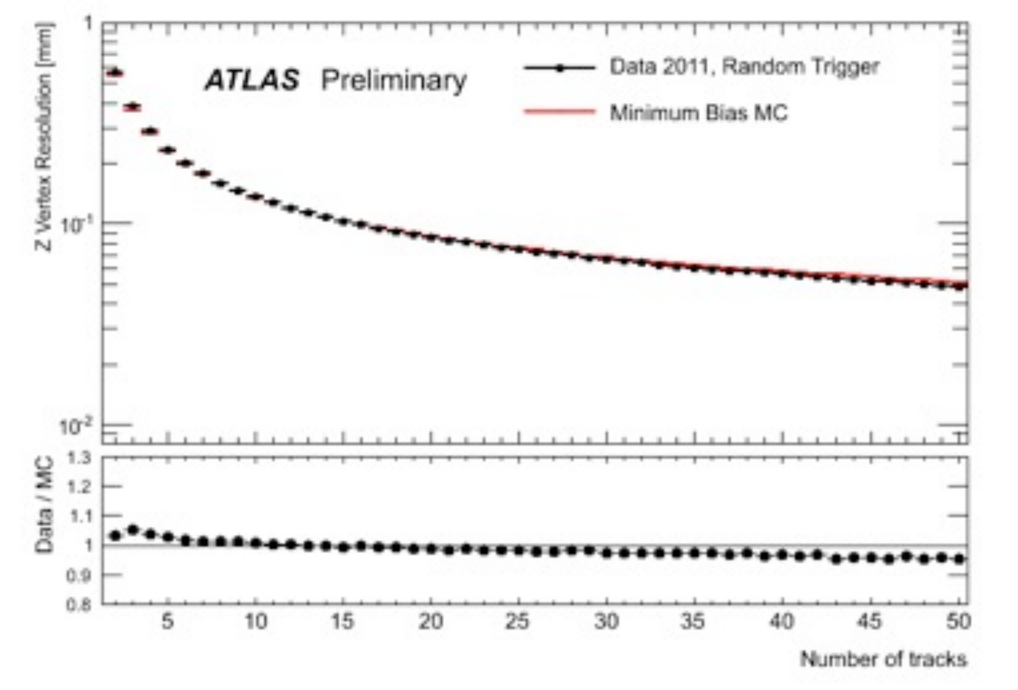
Primary Vertex Resolution from Data

- primary vertex is input to b-tagging, etc.
  - ➡ need to understand precisely the resolution in data



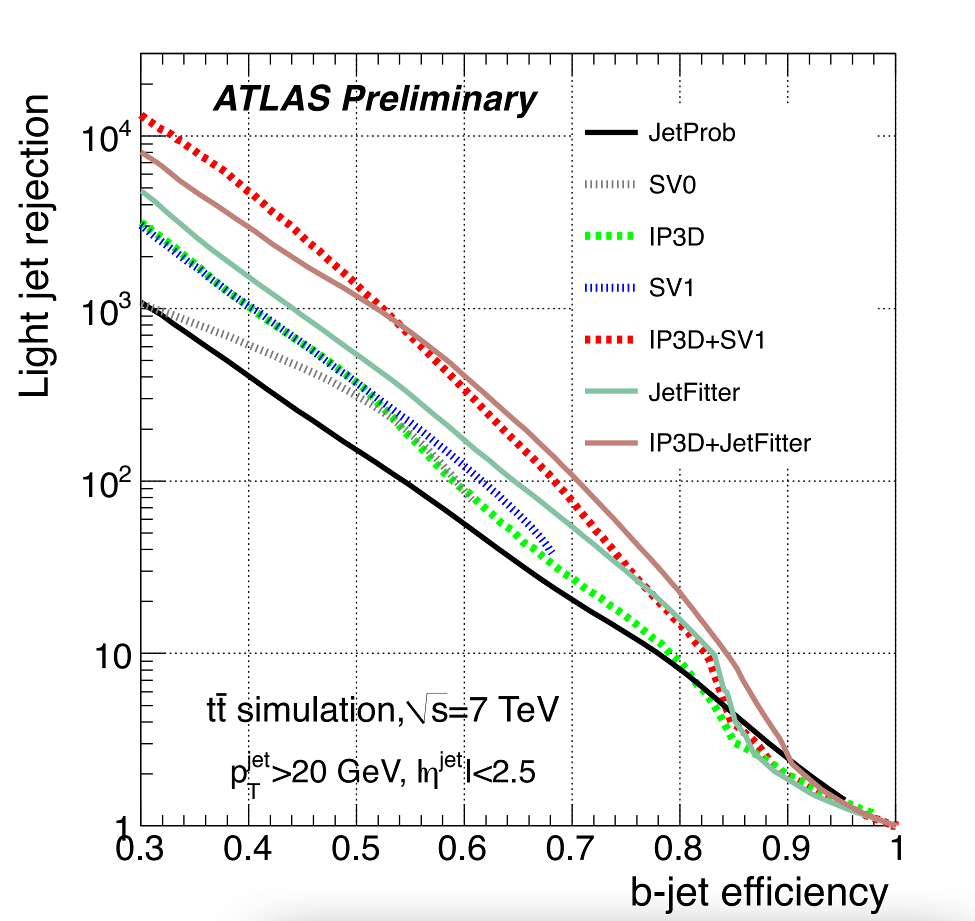
- split vertex technique
  - ➡ data driven method
  - ➡ split vertex in 2 and study difference in the 2 fitted positions as function of n tracks
  - ➡ very good description in MC

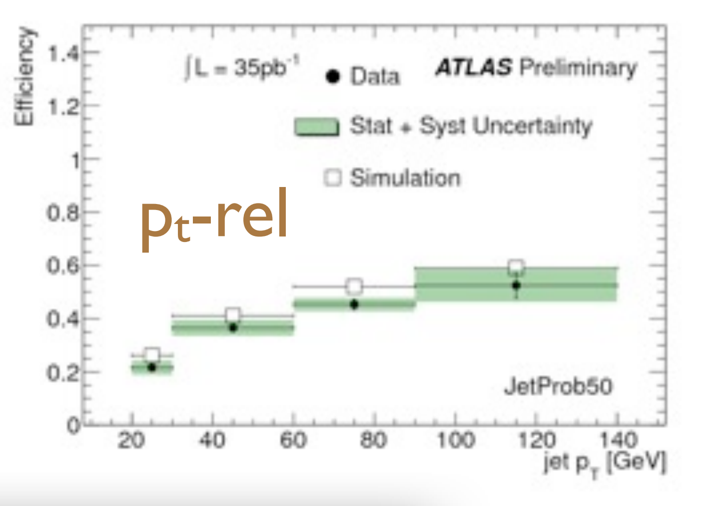


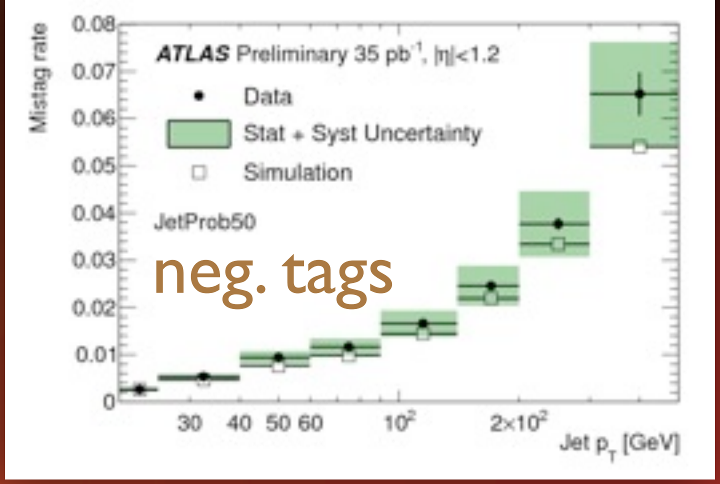


b-Jet Tagging

- “early tagging” techniques
  - ➡ **soft lepton** tagger
  - ➡ **track counting** of significant IP offsets
  - ➡ **jet probability**
    - construct probability that IP significance of all tracks in jet is compatible with PV
  - ➡ **secondary vertex** (SV) tagger
    - decay length significance
- more elaborate taggers
  - ➡ use multi-variant techniques to classify jets
  - ➡ construct IP based likelihood using b/c/light templates (**IP2D** and **IP3D**)
  - ➡ combined likelihood taggers using IP and secondary vertex information (**IP3D+SV0**)
  - ➡ vertex decay chain tagger (**JetFitter**)
  - ➡ in regular use since this summer
- data driven performance studies !

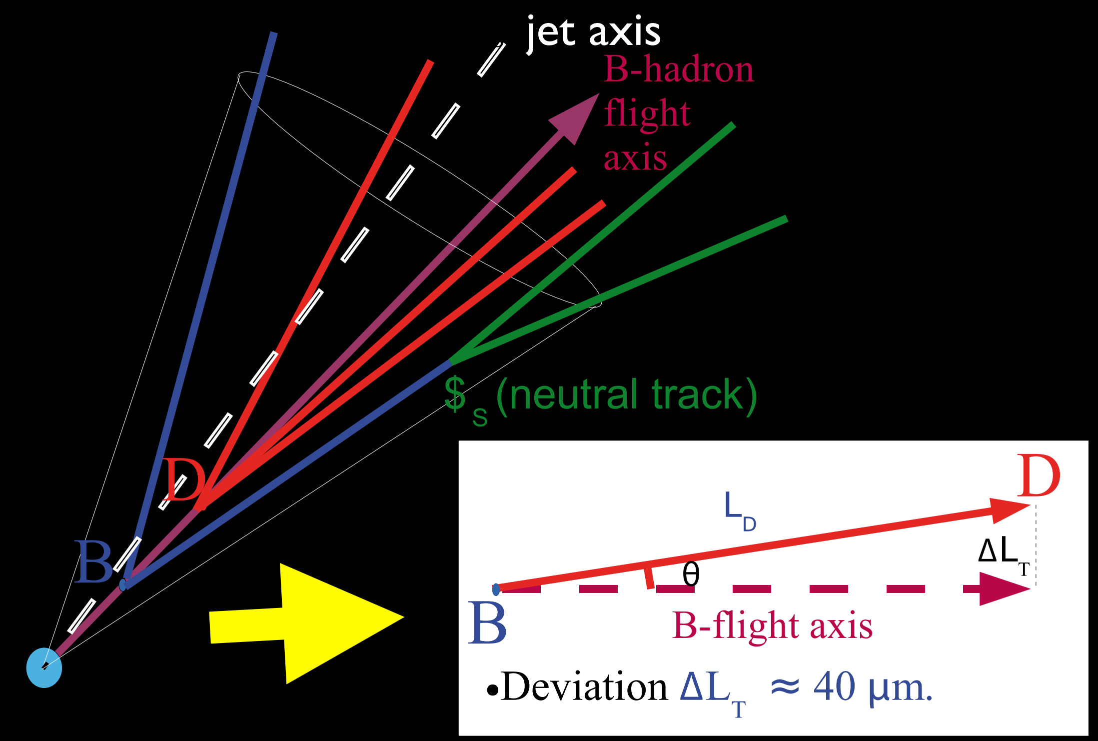


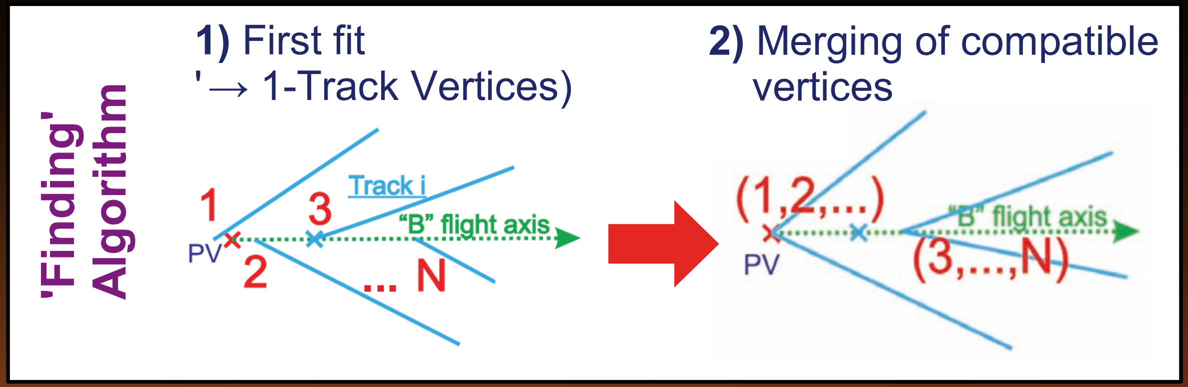


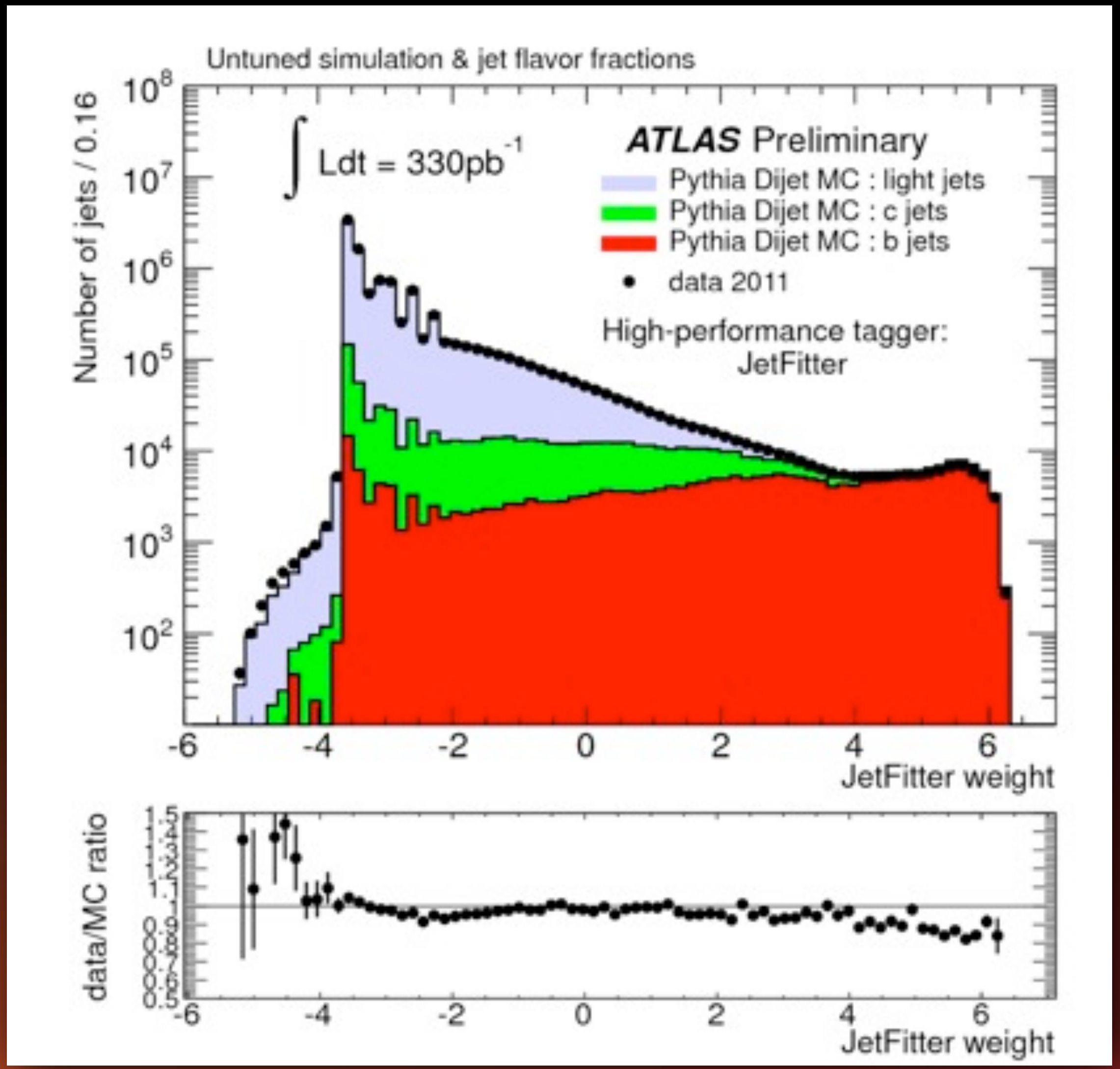


JetFitter as a b-Jet Tagger

- conventional vertex tagger
  - ➡ fits all displaced tracks into a common geometrical vertex
- JetFitter
  - ➡ **b**-/**c**-hadron vertices and primary vertex approximately on the same line
  - ➡ fit of **1..N** vertices along jet axis
  - ➡ mathematical extension of conventional Kalman filter vertex fitter



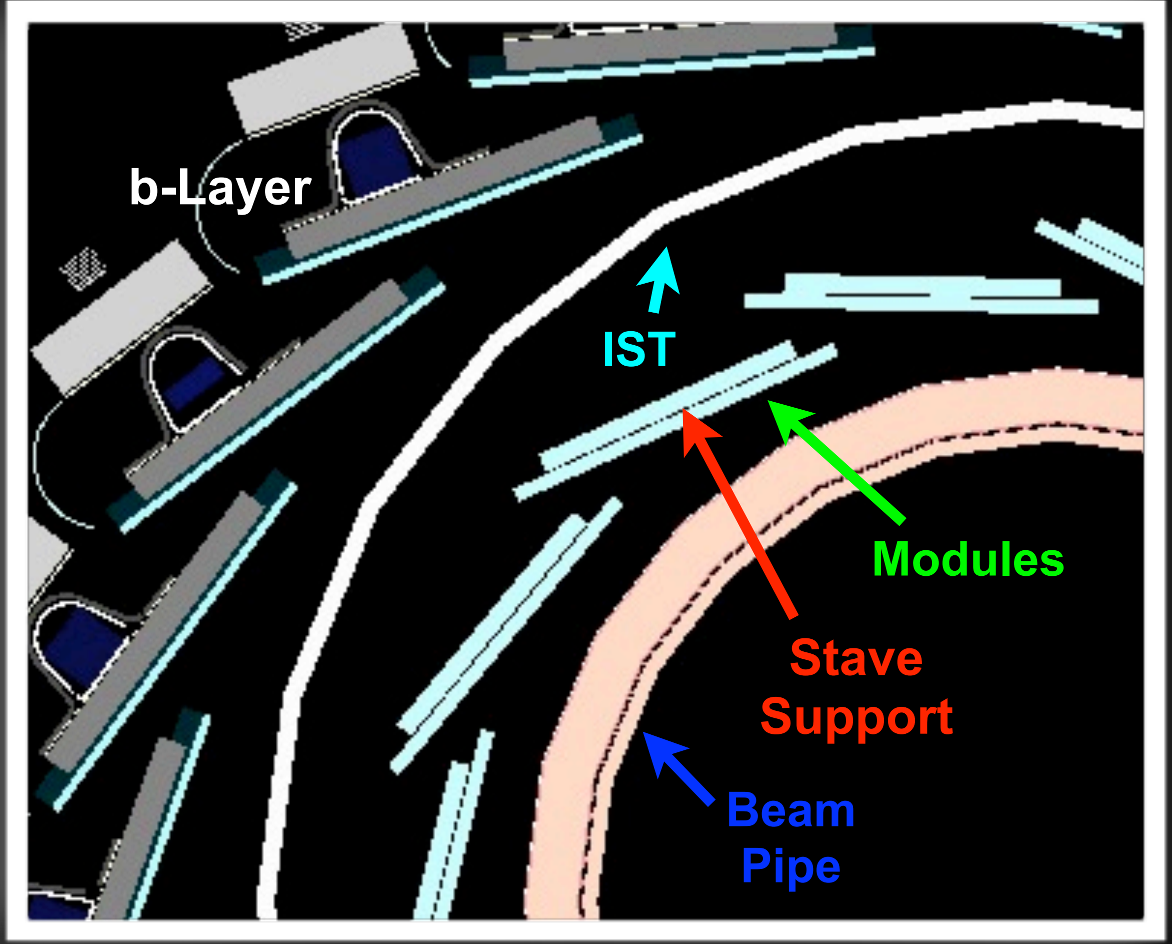


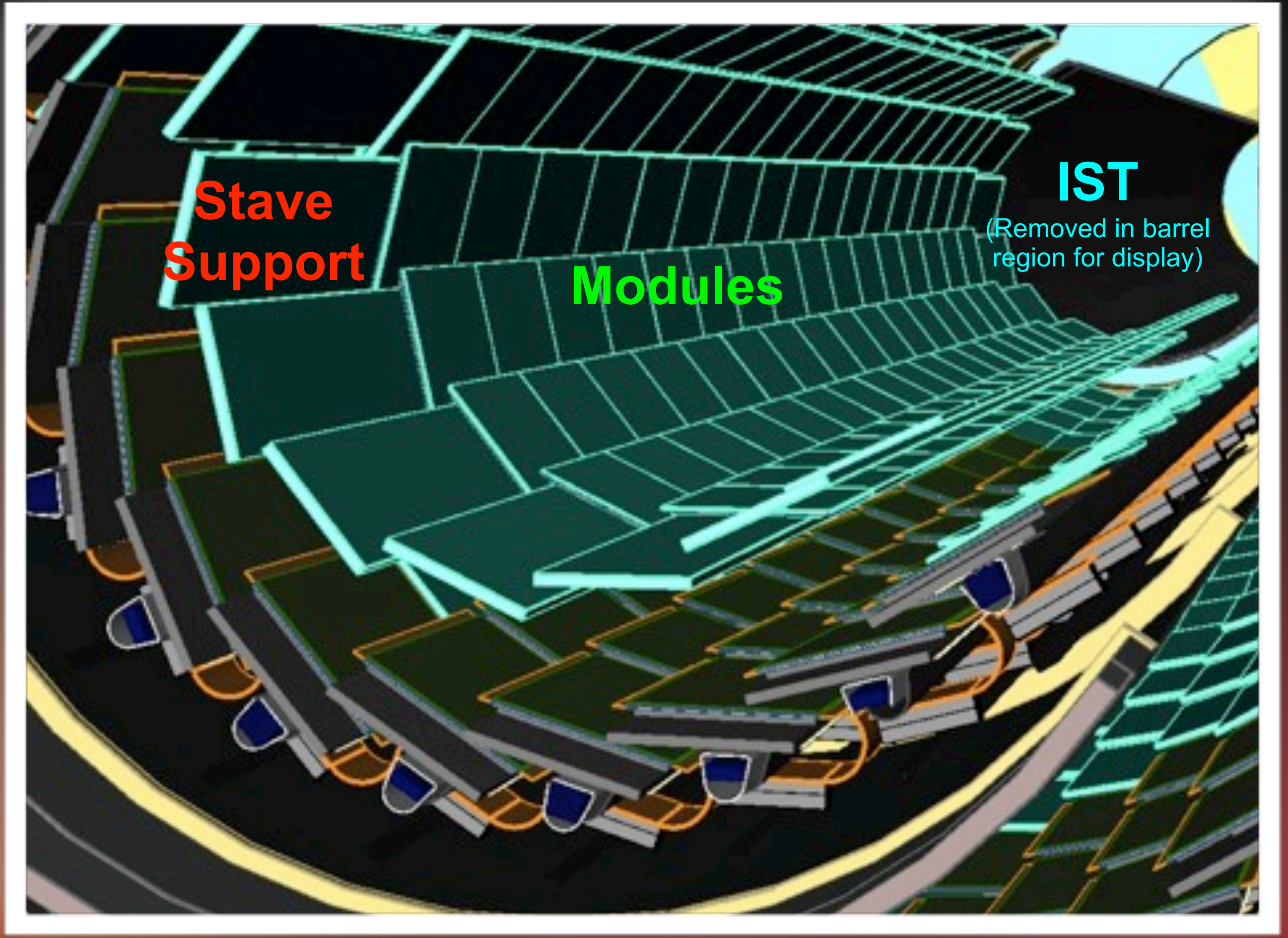


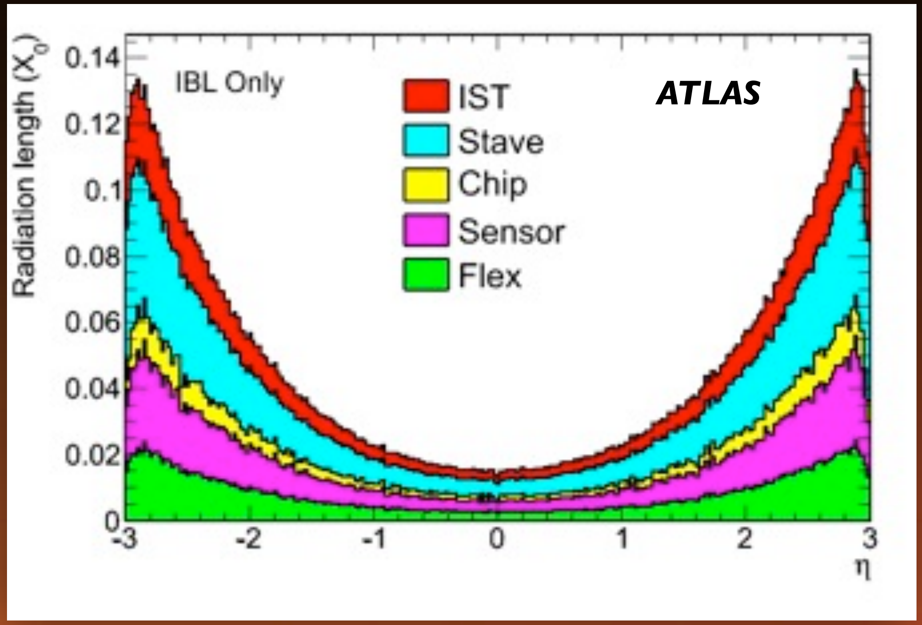
- up to **40%** better light rejection
  - ➡ IP3D+JetFitter is best b-jet tagger in use in ATLAS today

Outlook: IBL Tracking

- performance studies in G4
  - ➡ smaller beam pipe (R_{min} = 25 *mm*)
  - ➡ reconstruction: 4th Pixel layer
  - ➡ IBL material adjusted to 1.5% X_0
  - ➡ smaller z pitch (**250 *um***)
- installation next shutdown
  - ➡ ready for 14 TeV running
  - ➡ peak luminosities of $2{*}10^{34}\ cm^{-2}s^{-1}$
  - ➡ **25-50** pileup events

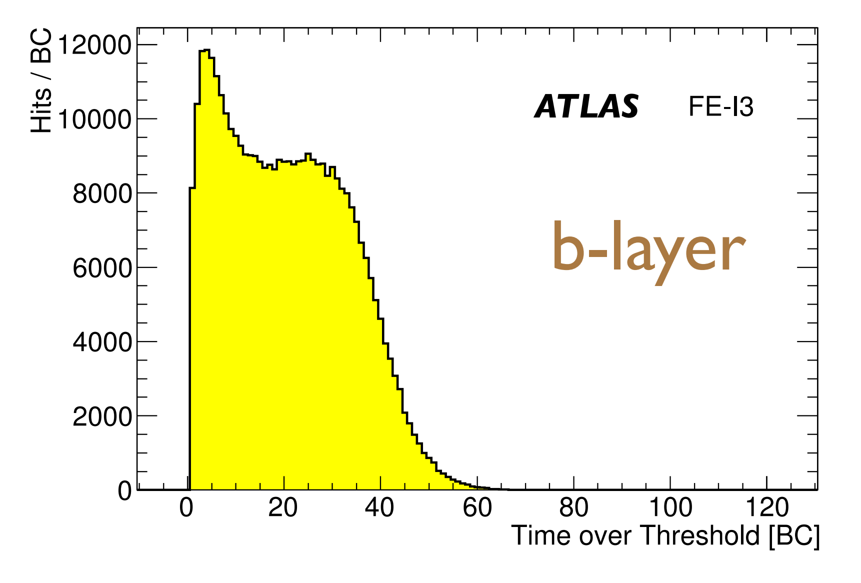


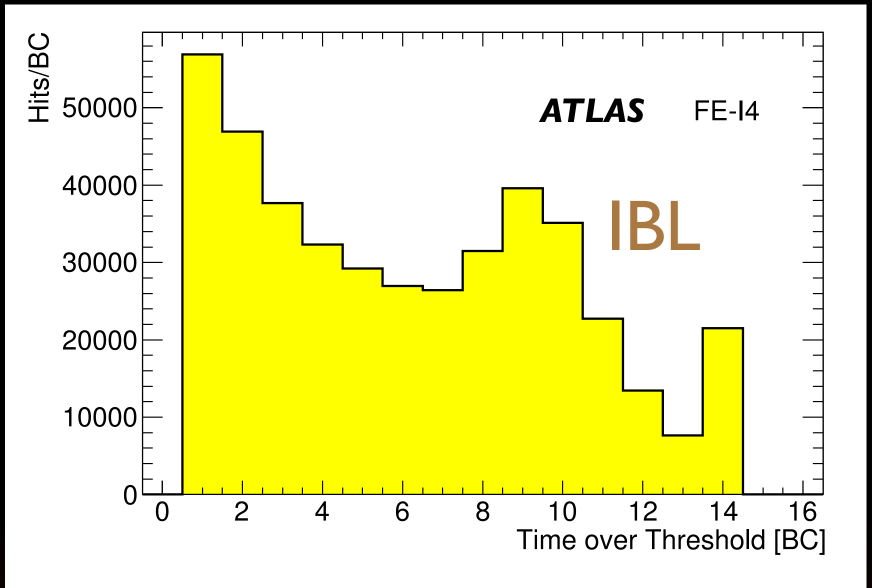


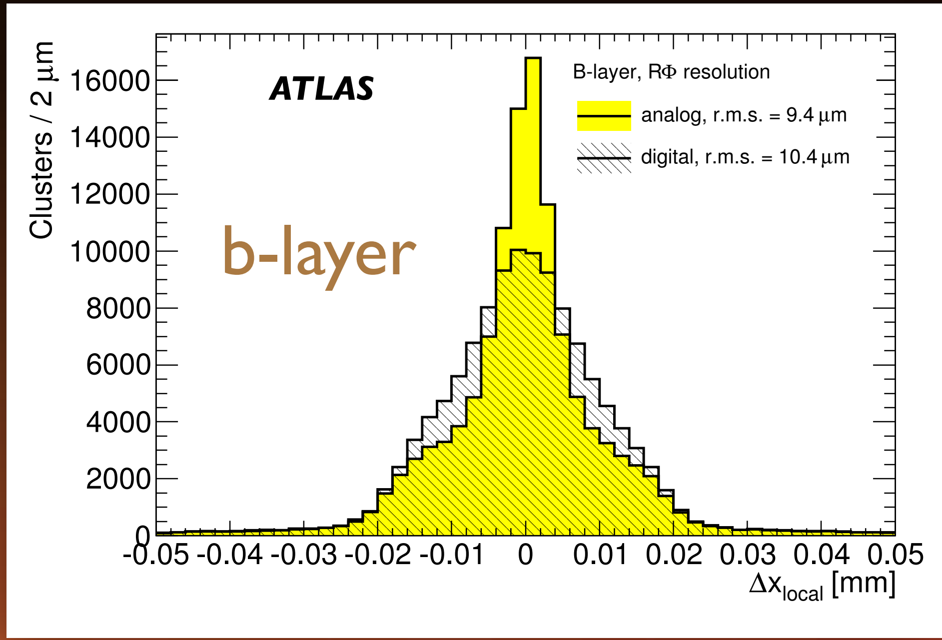


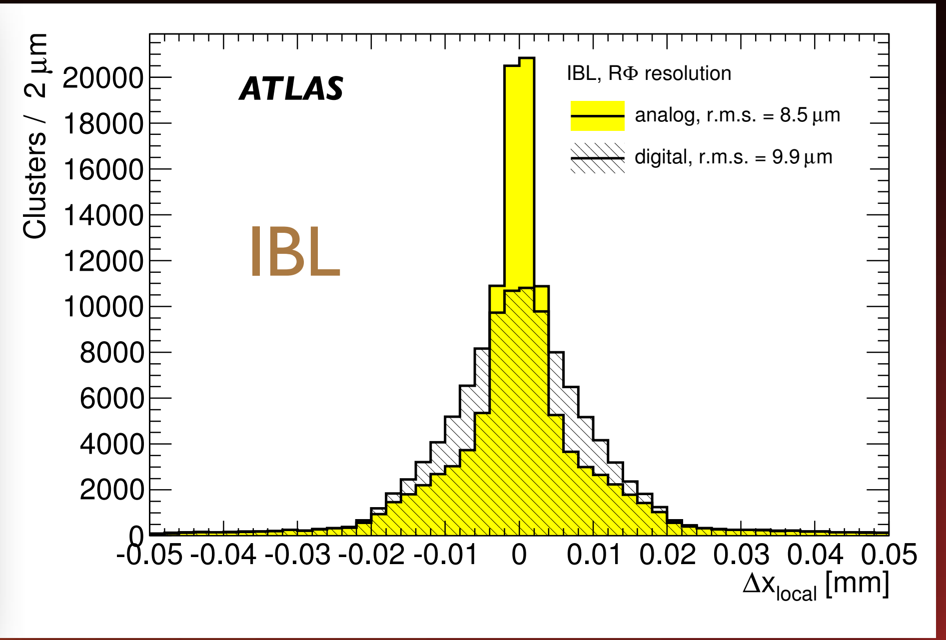
New FE-I4 Chip

- 4bit (FE-I4) calibration vs 8bit (FE-I3)
  - ➡ different dynamic range
    - and FE-I4 allows for overflows
  - ➡ average cluster size in IBL bigger than in b-layer
    - broader spectrum of incident angles
- compare cluster resolutions IBL (FE-I4) and b-layer (FE-I3)
  - ➡ similar in X_{local}, pitch drives improvement in Z_{local}



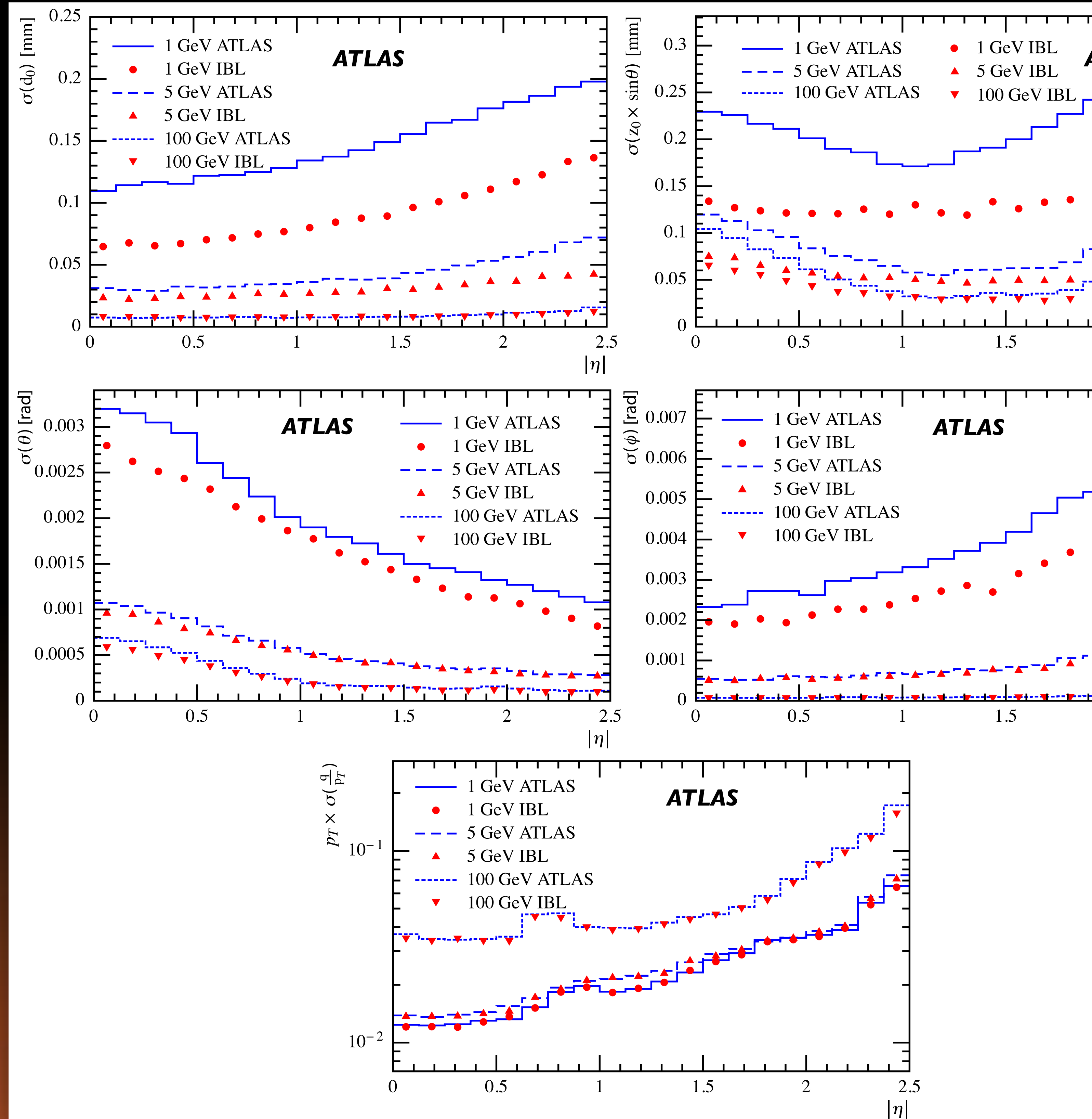






Tracking Performance (no Pileup)

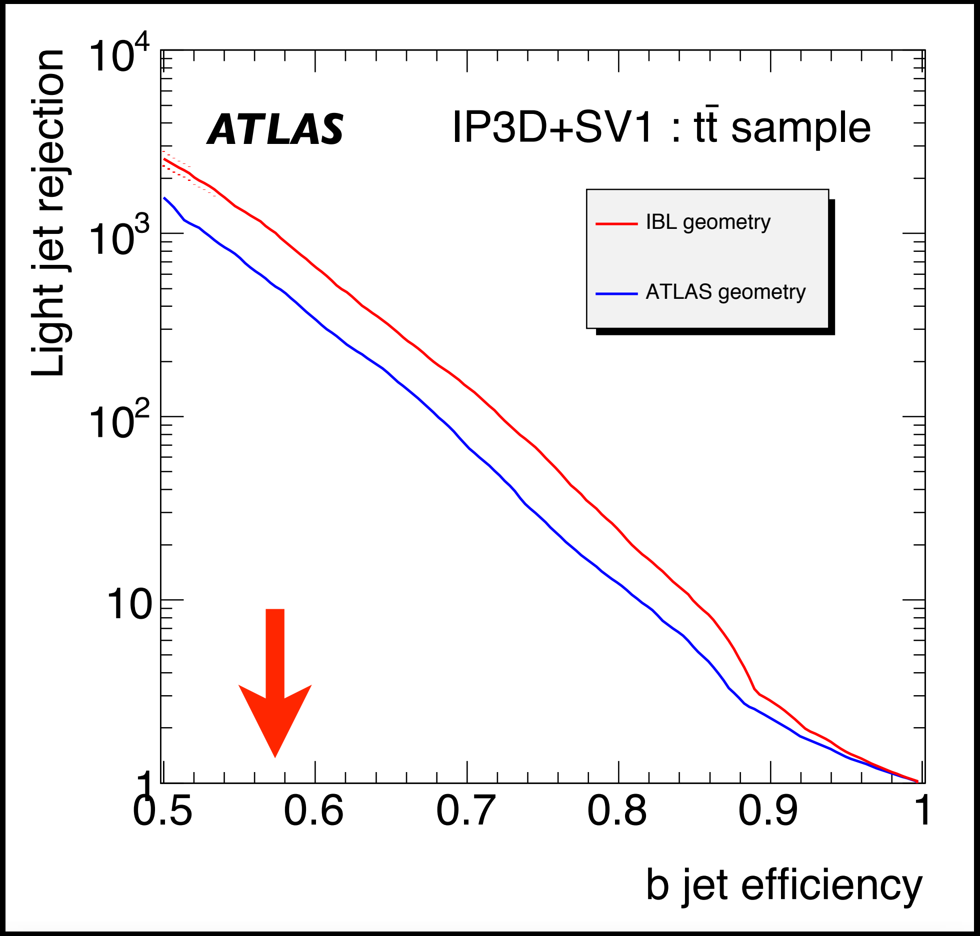
- expected results
  - ➡ smaller radius
  - ➡ small z pitch
  - ➡ less material between first and 2nd layer
  - ➡ track length ~ same
- improvements
  - ➡ better d_0 resolution
  - ➡ better z_0 resolution
  - ➡ θ and ϕ improved at low-pT
  - ➡ momentum resolution ~ unchanged
- as expected !

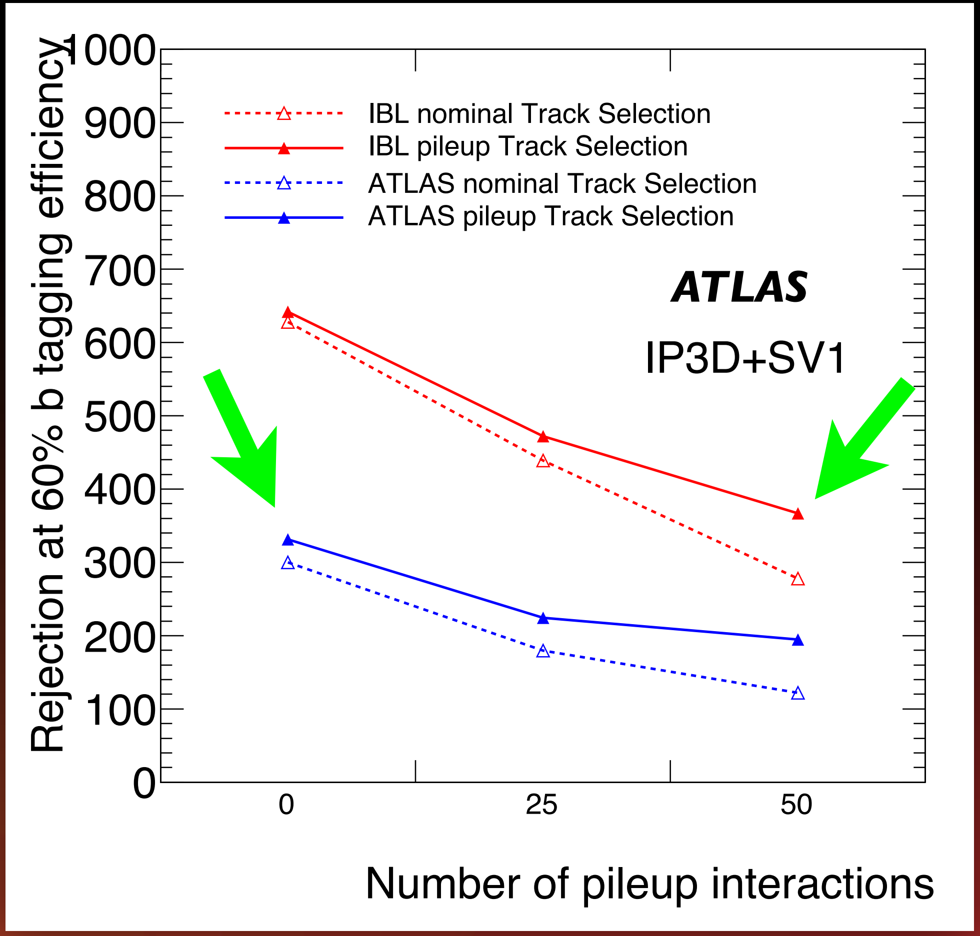


single muons

b-Tagging with IBL

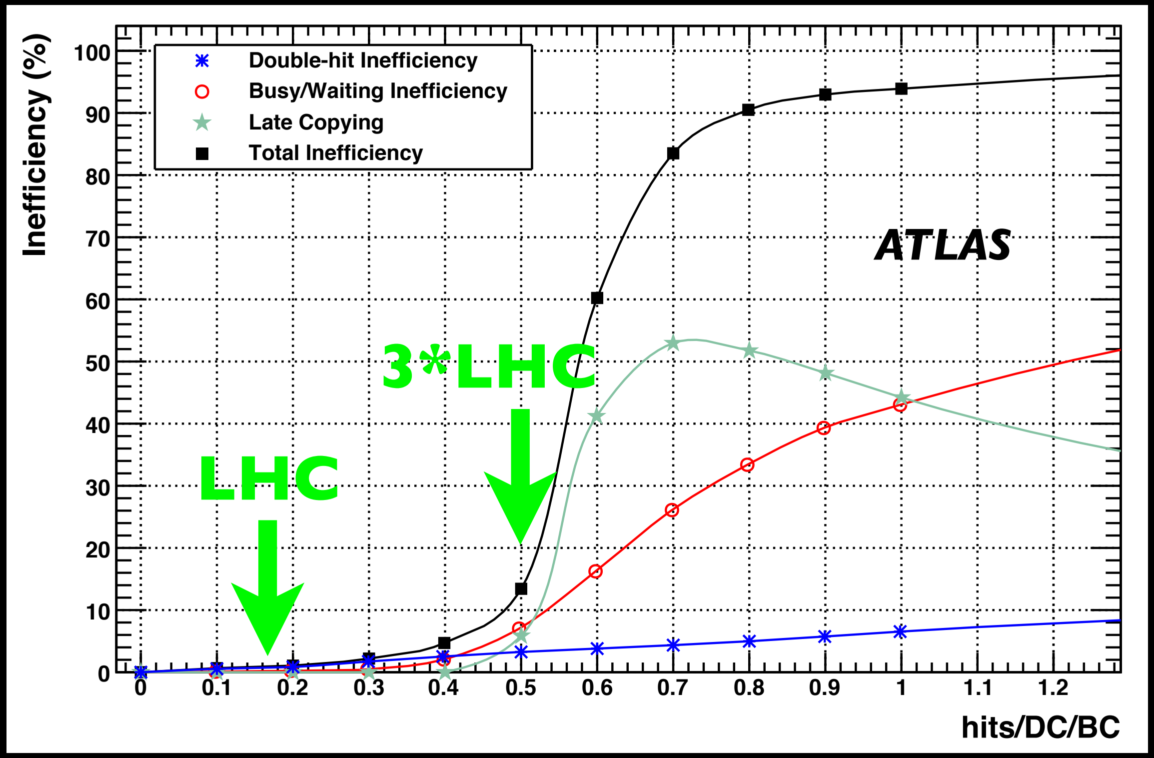
- pileup selection with IBL
  - ➡ ≥10 IBL+Pixel+SCT hits, ≤1 pixel hole
  - ➡ benefit from additional layer
  - ➡ leaves room for eventual inefficiencies in b-layer (tracking robustness)
- state of the art b-tagging
  - ➡ "IP3D" ~ $d_0 \oplus z_0$ impact significance likelihood
  - ➡ "IP3D+SV1" ~ adding secondary vertex information
- good performance with IBL and pileup
  - ➡ as good or better as for current ATLAS without pileup

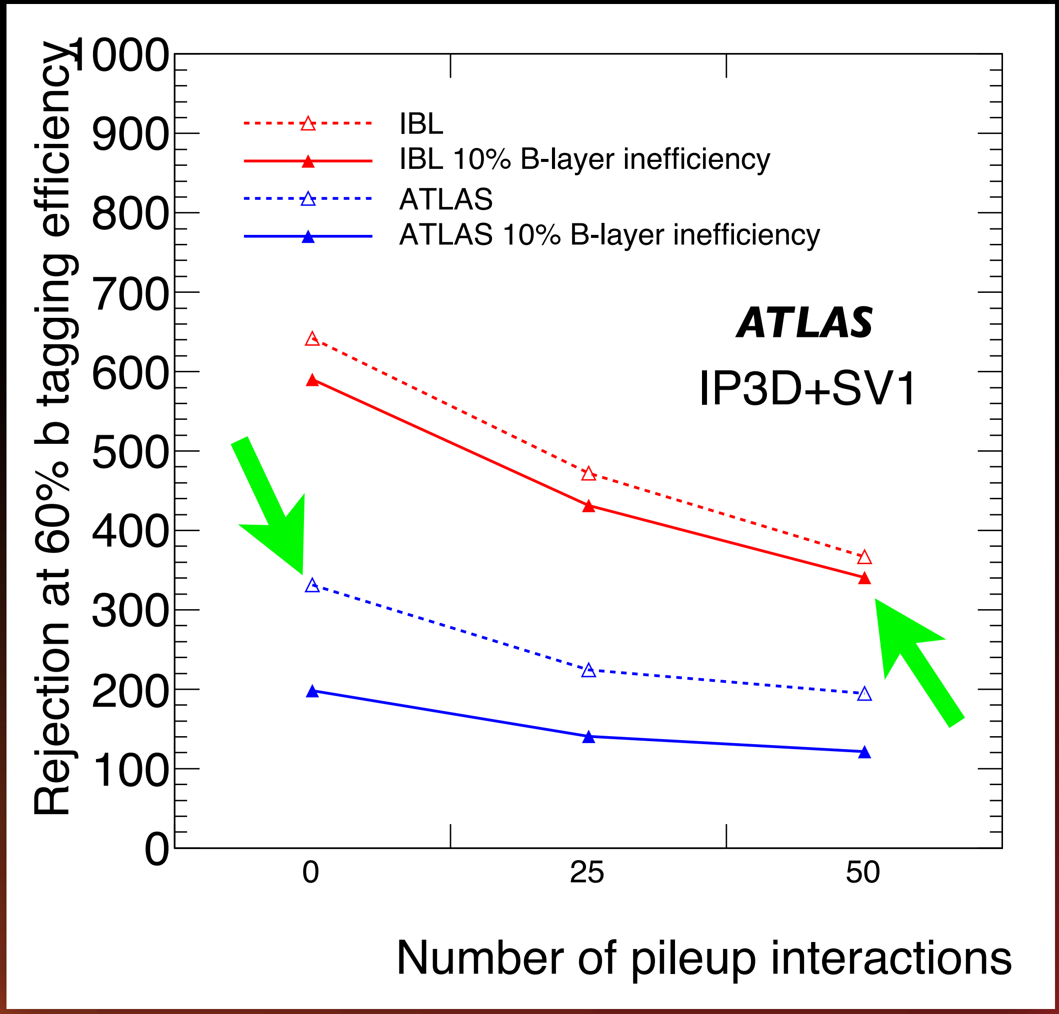




Detector Defects ?

- IBL helps to recover from detector defects
  - ➡ known bandwidth limitations of current FE-I3 chip leading to cluster inefficiencies
    - especially in b-layer (r=4*cm*)
  - ➡ eventual additional (known) dead modules
- study effect of 10% cluster inefficiency in b-layer with IBL
  - ➡ IBL fully recovers tracking efficiency and impact resolution
  - ➡ with IBL only small effects on b-tagging performance
  - ➡ similar results for other failure scenarios





Summary

- stringent requirements on Inner Detector to cover ATLAS physics program

- excellent performance reached !
  - ➡ years of preparation based on simulation and test beam
  - ➡ commissioning with cosmics and early beam
  - ➡ detailed studies of detector, tracking, material, alignment, pileup...
  - ➡ Heavy Ion running gave good insights into tracking at high occupancy

- tracking studies with IBL demonstrate performance of the detector with a 4 layer Pixel system at Phase 1 luminosities