Status of tracking and vertexing on ATLAS

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ANL Analysis Jamboree

Outline

- Inner Detector requirements and design
- Brief description of Tracking algorithms
- Performance
  - MC samples (detector paper)
  - Cosmic ray data (Fall 2008)
- Vertexing algorithms and performance
- Summary

Requirements for the Inner Detector (ID)

- ATLAS is a multi-purpose detector that will operate at various LHC luminosities, ranging from 10^{30} to $10^{34}/cm^2/s$
  - Broad physics program will need precise measurements of jets (including b-jets), electrons, muons, taus, exclusive B decay channels, photons, missing Energy
  - Lot of background radiation; detectors need to be rad hard
- Need to find tracks with high efficiency and low fake rates, in a busy environment (with as many as 24 minbias events/bunch x-ing), provide good momentum measurement, find primary and secondary vertices, measure impact params, while maximizing η acceptance
  - Match muons in Muon spectrometer to tracks in ID and improve their momentum determination
  - Match calorimeter deposit to a track and discriminate between electrons and photons
  - Find vertices due to taus, exclusive B hadron decays, and within jets to identify b-jets, charm jets…
  - Need to budget material carefully to minimize interactions, conversions

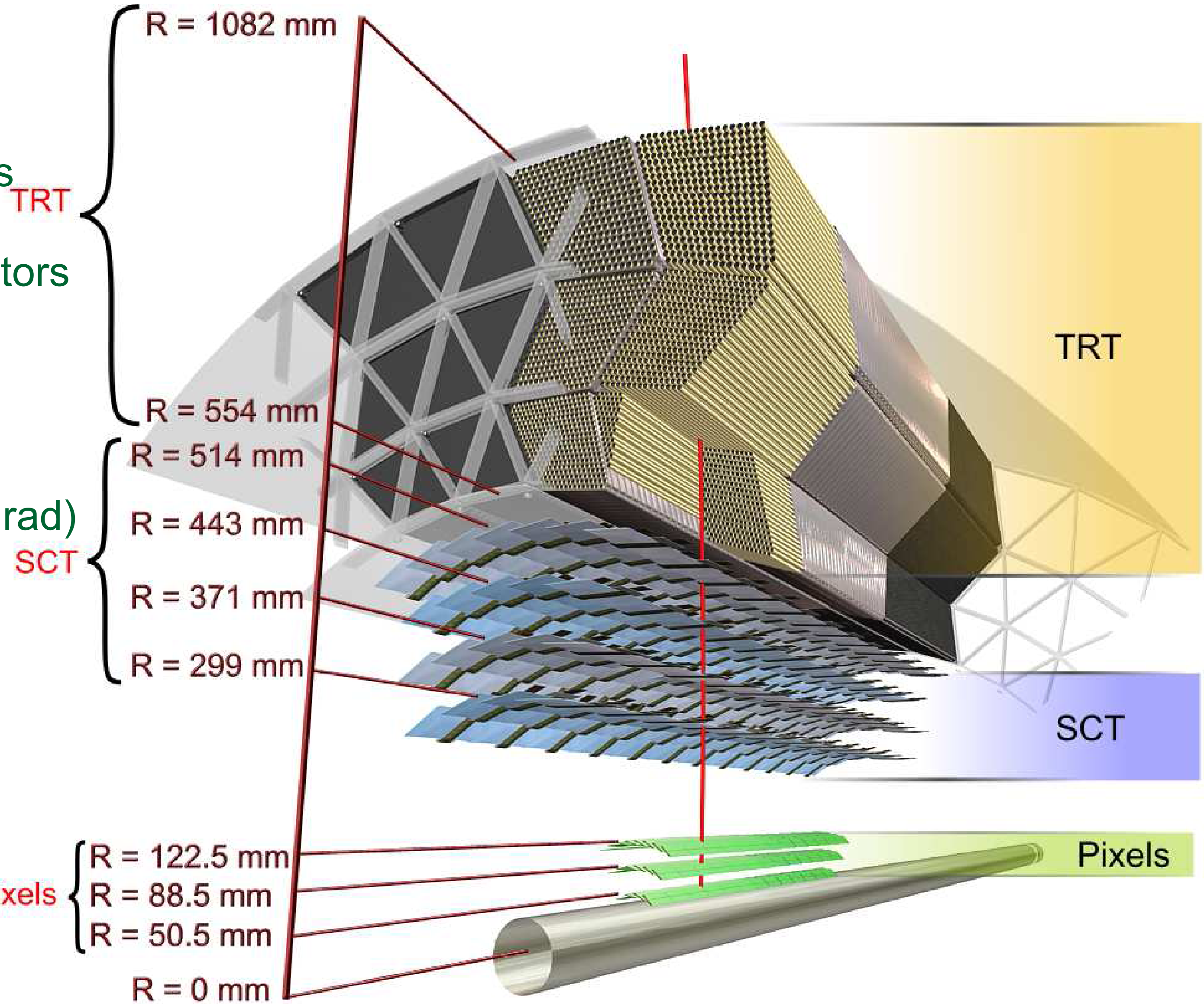
Chosen Design

- Innermost layers are Silicon Pixels, surrounded by a Silicon strip detector, followed by straw tubes filled with gas, all within a 2T field
  - Pixels provide very high granularity, high precision measurements very close to the interaction point – vertex finding, measure impact parameters
  - Strip detector contributes to momentum measurements, vertex finding and IP meas., pattern recognition
  - Transition Radiation Tracker provides measurements out to large radius, aiding in pattern recognition and momentum
    - Also aids in electron identification from Transition Radiation
  - No one system dominates momentum measurement leading to a robust design

Only R measurement
4 mm diameter straws
Filled with $XeCO_2O_2$
Interleaved with radiators

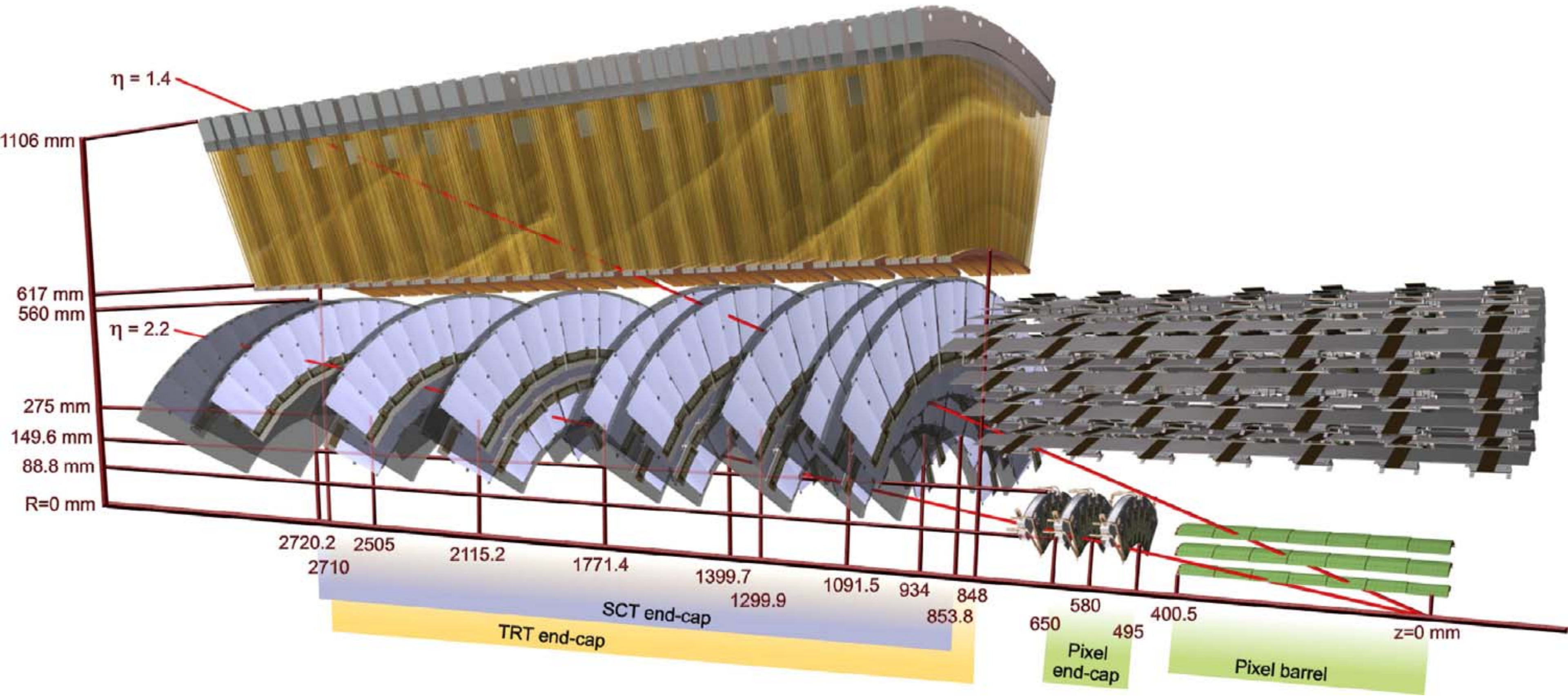
Z is measured via
Stereo layers (± 40 mrad)
80 μ pitch

Measure R & Z
Size: 50μ x 400μ



TRT: 351K channels

Accuracy ~ 130μ (R-φ) – in reality, it will be close to 170-180 μ

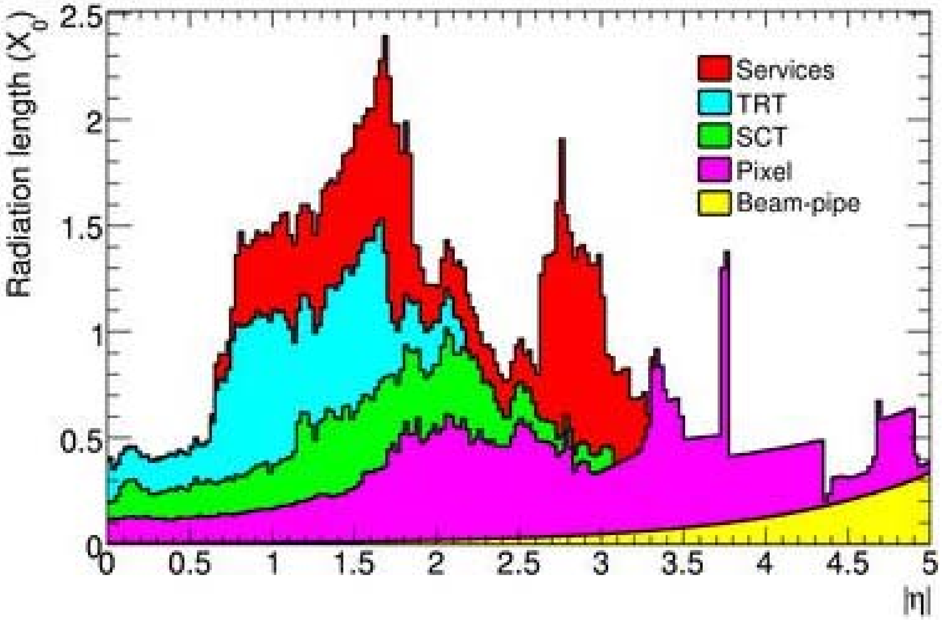


Pixels: 1.7 m^2 of Si ($80*10^6$ channels)

Accuracy ~ 10μ (R-φ) & 115μ (Z)

SCT: 60 m^2 of Si ($6.3*10^6$ channels)

Accuracy ~ 17μ (R-φ) & 580μ (Z)



Lot of material!!

- Electrons lose ~20-50% of their energy by the time they leave the SCT
- 10-50% of photons convert before leaving the SCT

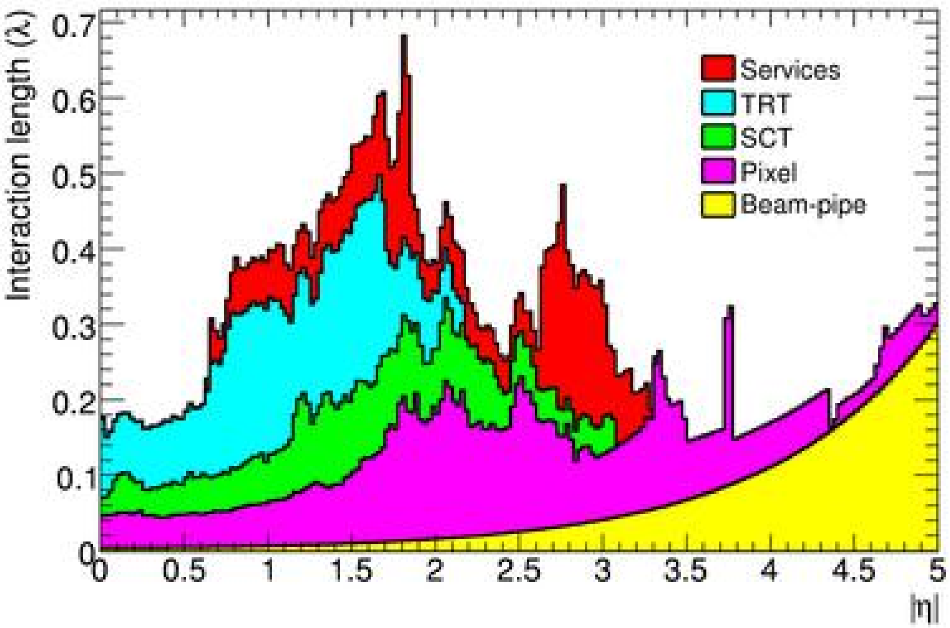
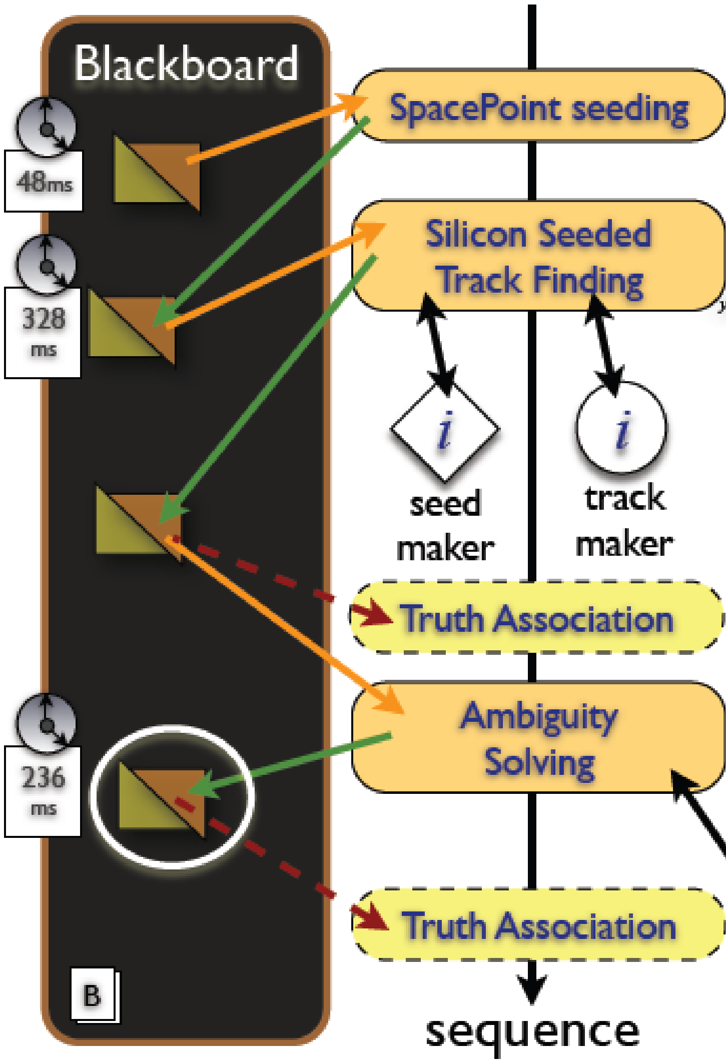


Figure 3: Material distribution (X_0, λ) at the exit of the ID envelope, including the services and thermal enclosures. The distribution is shown as a function of $|\eta|$ and averaged over ϕ. The breakdown indicates the contributions of external services and of individual sub-detectors, including services in their active volume.

Tracking Algorithms

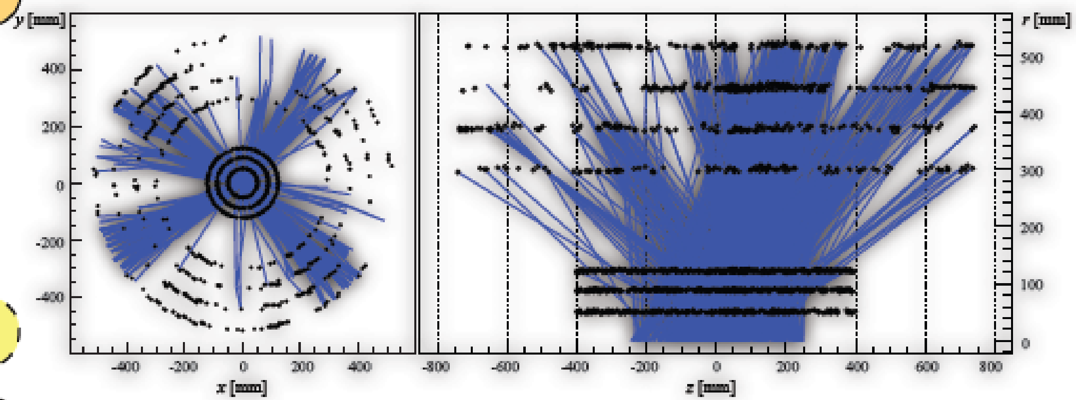
- Till about 6 years ago, tracking algorithms were monolithic packages (mainly ported from Fortran)
  - Each package dealt with geometry, data model, algorithms individually
- New design (aka New Tracking or NewT) is much more modular:
  - Applicable to both ID and Muon spectrometer – common data model, detector description model…
  - Standardized interfaces for common tools – track extrapolation, material description, calibration,…
  - Different track fitting techniques (global-χ^2 ,Kalman-filters, Gaussian-sum filters & DNA (for brem recovery…), can be studied

ID track reconstruction - inside out (I)



transforms local hit information on detection devices (2-dim) to 3-dim objects (with surface constraint)

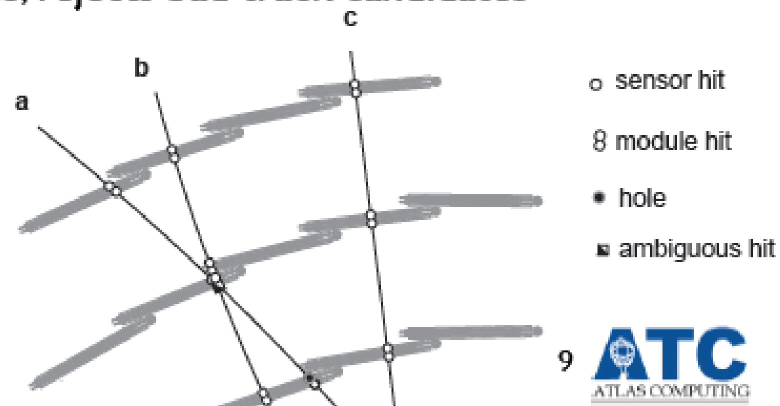
finds space point seeds (flexible 3,4,5 ... space points) to build first track candidates



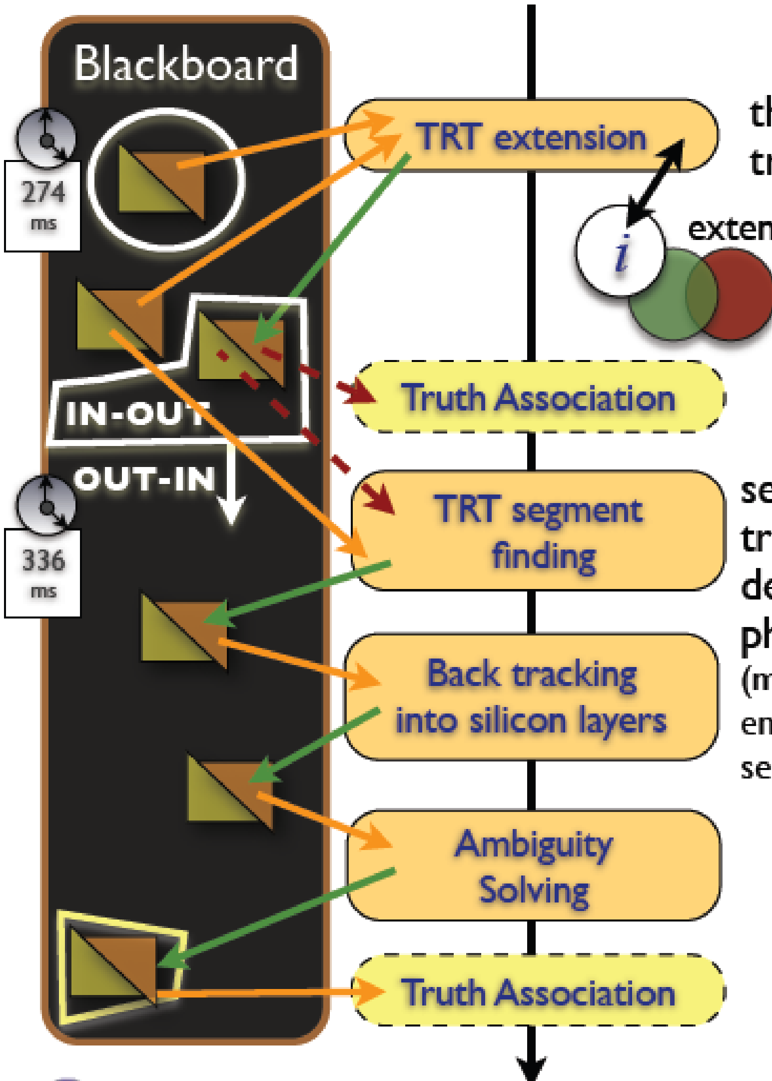
scores tracks in respect to another, resolves or flags hit ambiguities, rejects bad track candidates

e.g. scoring for SCT

scoring tool



ID track reconstruction - inside out (II) + outside in

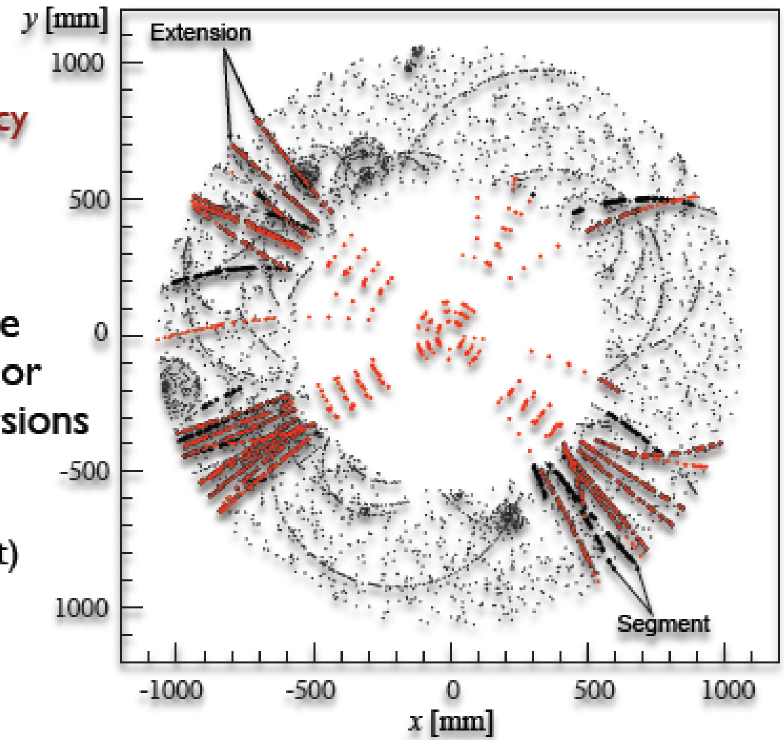


the resolved *silicon* tracks are extended into the transition radiation tracker (TRT)

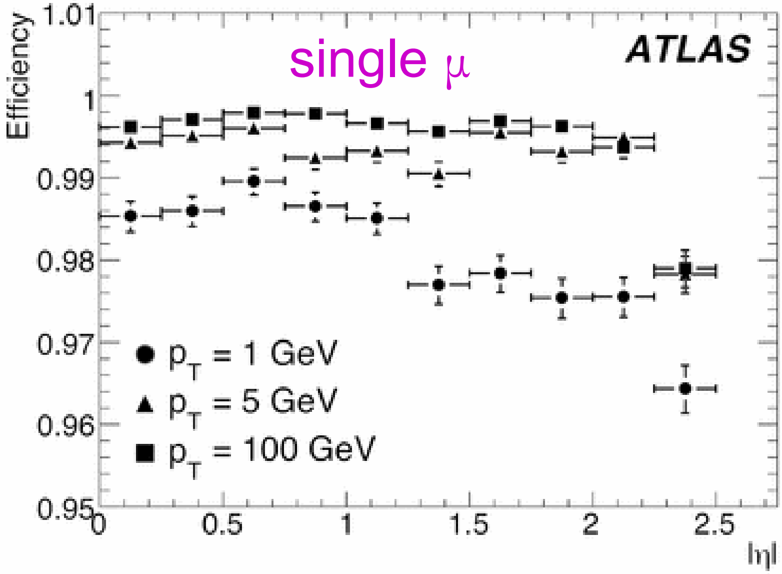
extension finder

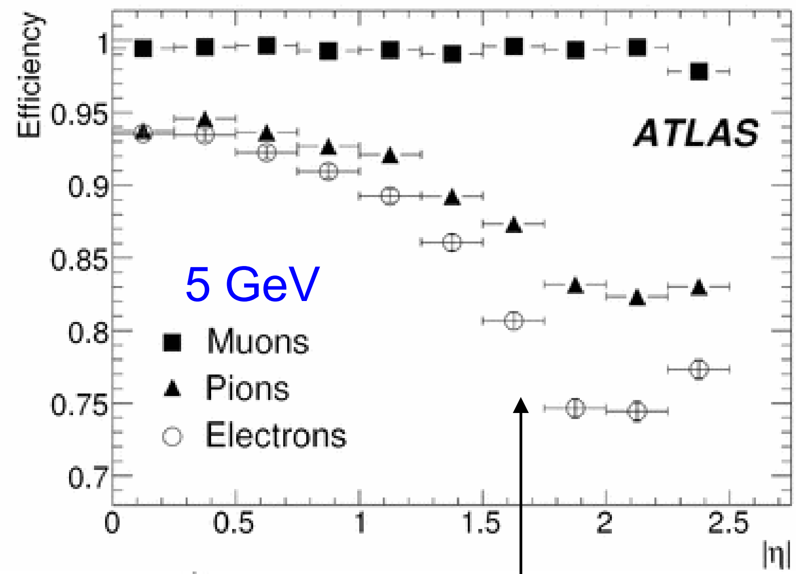
standard,
high occupancy version

searches for tracks from late decay vertices or photon conversions
(may not have enough Si hits for seeding inside-out)



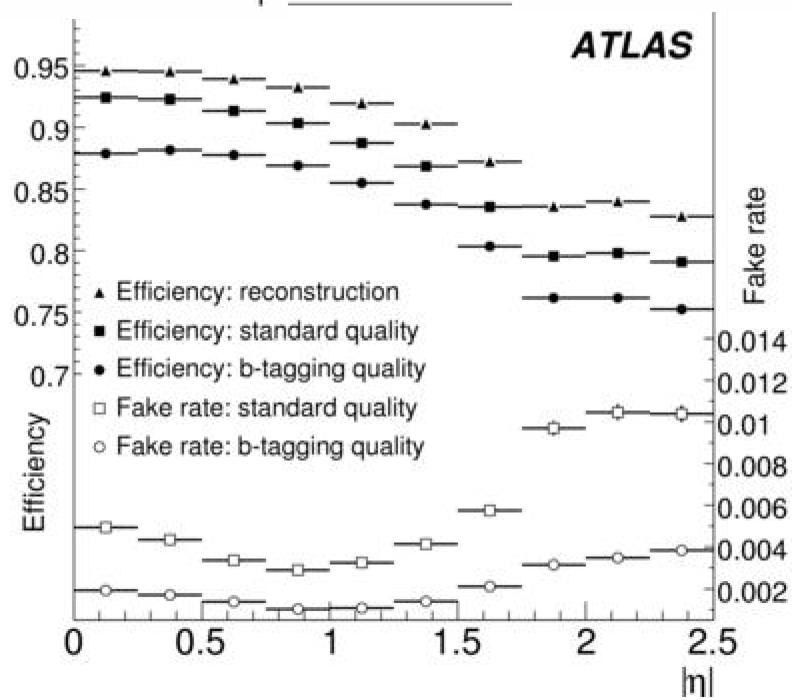
Performance – misalignment, mis-calibration, pile-up are neglected





Drop-off in ε for e/π reflects conversions, interactions

Efficiency and fakes for π's in ttbar events



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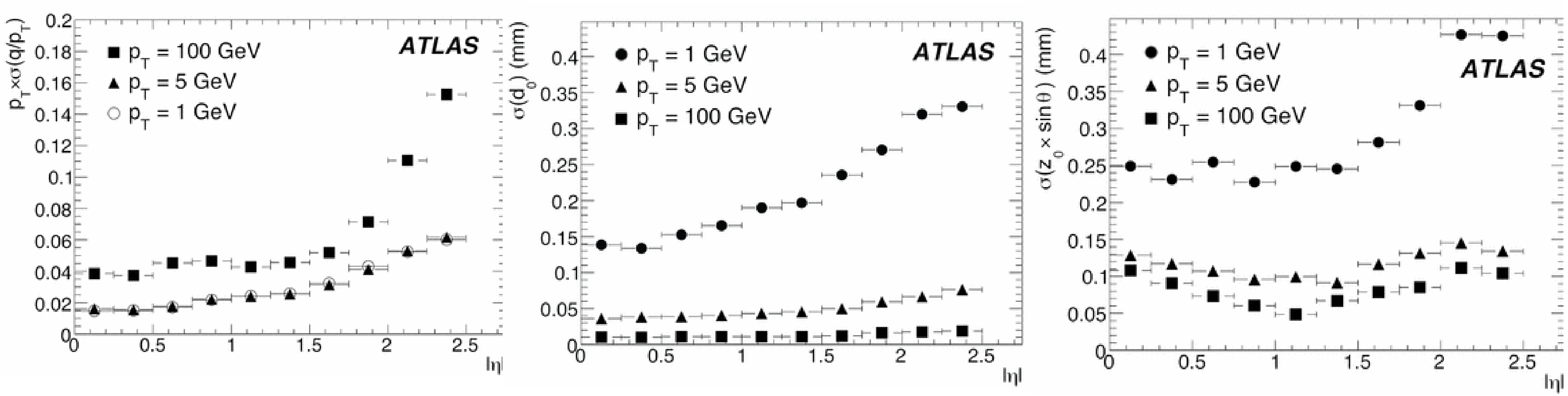
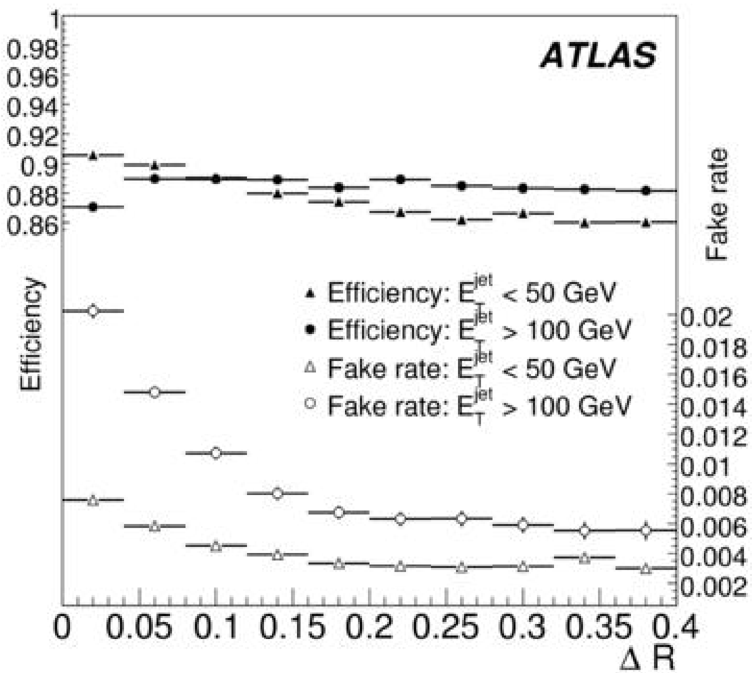
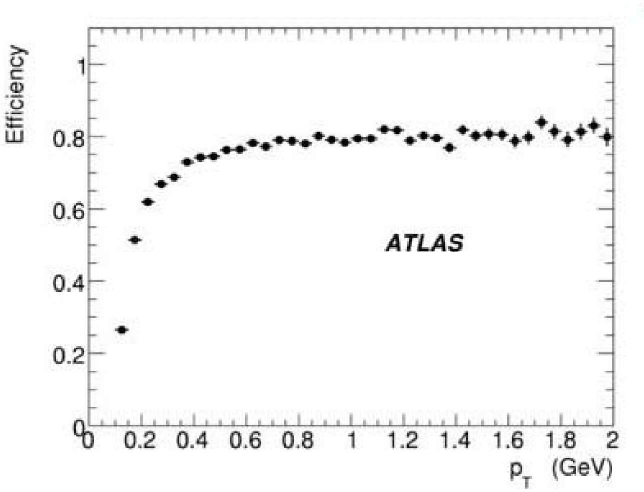


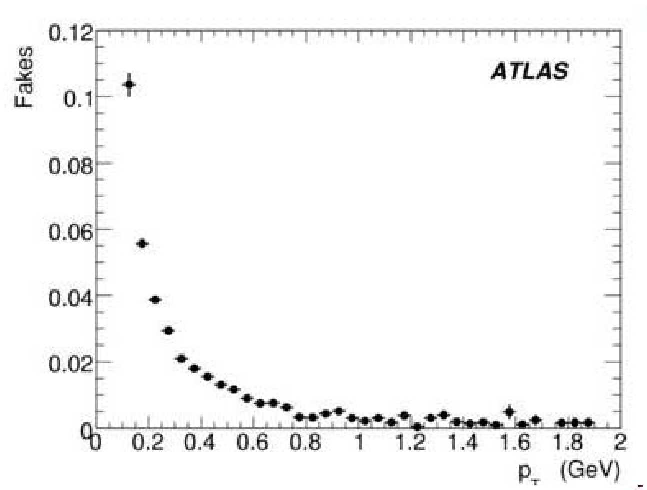
Resolutions for $\delta(p_T)/p_T$, 2d and Z impact parameters – single μ's



ε/fake rates for π's within jets in ttbar events
ΔR is distance between track & jet axis

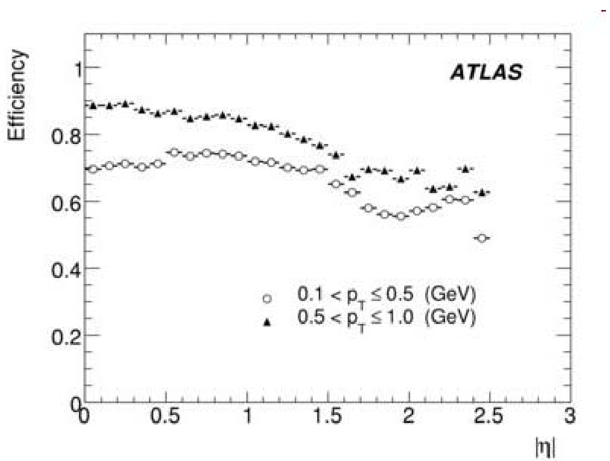
Low pt Tracking for minbias physics

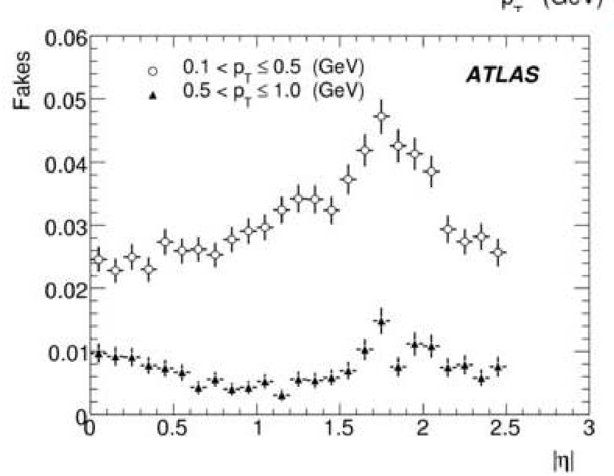




Efficiency & fakes

f(pt)



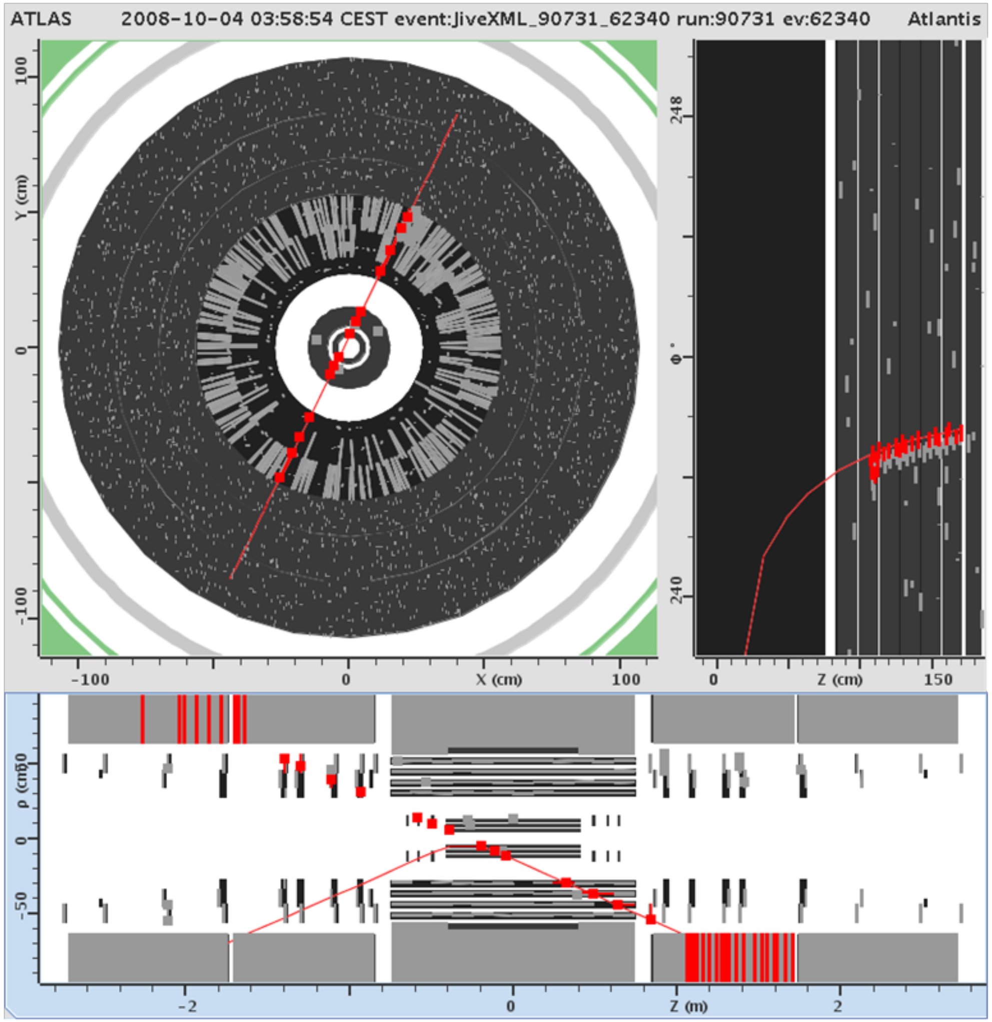


f(η)

Cosmic Ray data

- In Fall’08, ~7M cosmic ray events were collected with the Inner Detector. Used to study:
  - Calibration & Alignment of sub-detectors
  - Tracking Performance
    - Modified version of New Tracking was used
      - Data preparation was different to a/c for timing differences
      - Pattern recognition module was different
      - Used conditions services for (the first time) for cluster creation and drift circles
  - Also used to commission the Inner Detector trigger

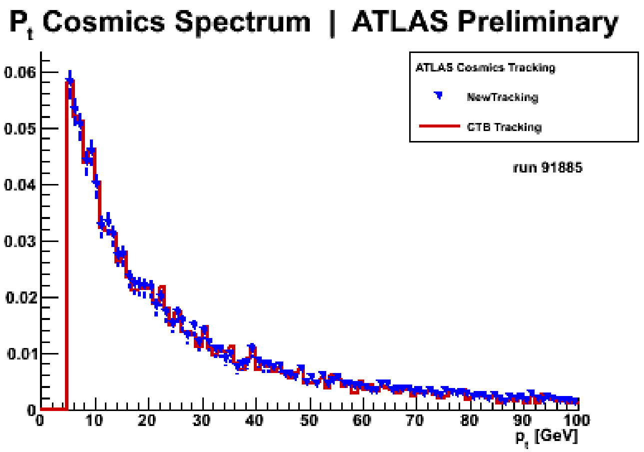
Combined barrel + EC track

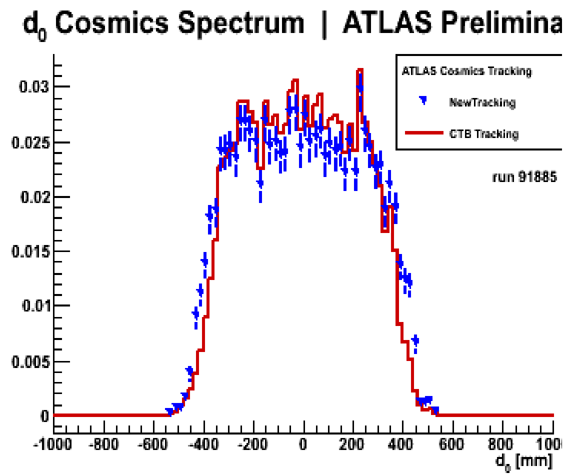


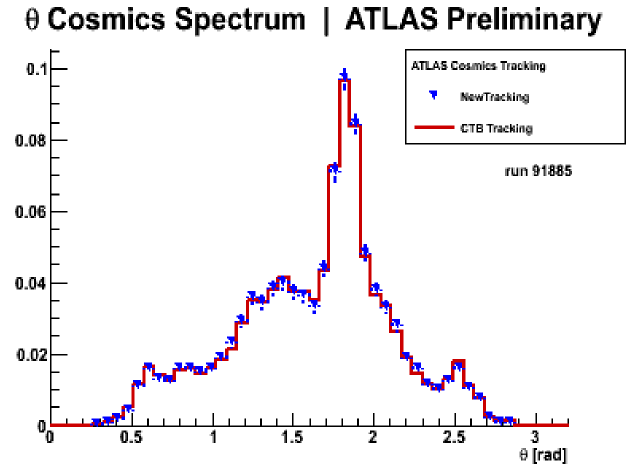
- Cosmic track hitting
  - TRT endcap,
  - SCT barrel + endcap,
  - pixel barrel + endcap
- Very useful for alignment

Probably not a typical event!

New Tracking vs. CTB (Cosmic and Test Beam) Tracking

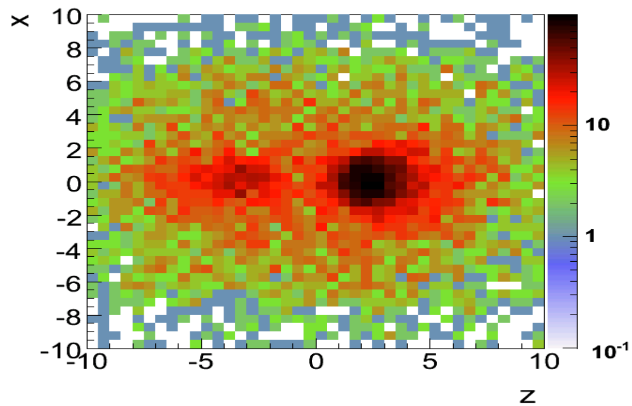




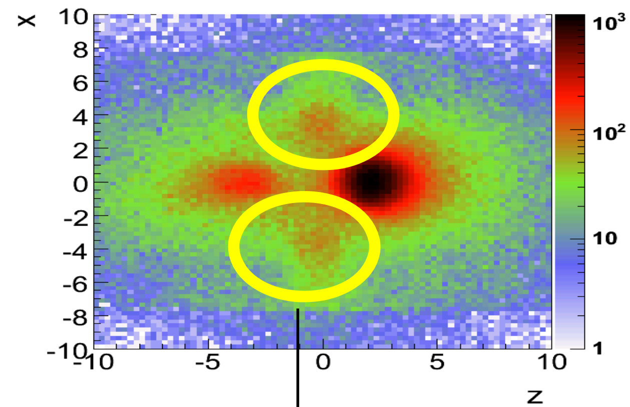


- Very loose cuts
- Characteristic cosmic spectra observed
  -> different from collisions events

Intersection of tracks extrapolated to a plane 10.5 m above ATLAS center



MC

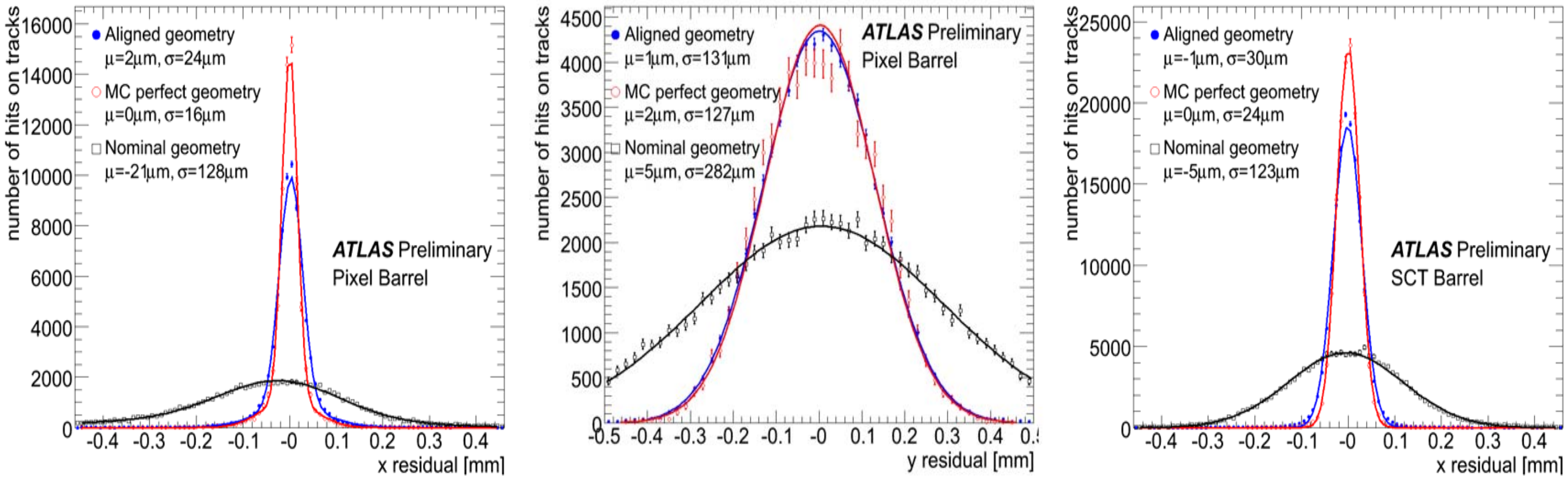


Data

Elevator shafts not in MC

From Manuel Kayl

Hit residual distributions



- Residuals in Pixel and SCT show large improvement with respect to nominal geometry after (L3) alignment (for 2 of 6 dof)
- Mean and width of distributions is approaching the MC simulation
- Residual resolutions indicate remaining misalignment of O(20 um)

From Manuel Kayl

Estimation of tracking performance

- Tracking performance variables like impact parameter resolution can be studied using cosmic tracks split up in upper and lower half tracks

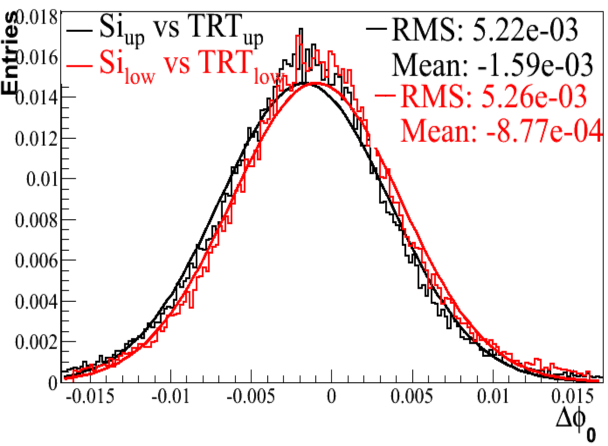
- Sort hits in upper and lower hits and refit tracks
  - > two separate "collision-like" tracks
- Constrain tracks close to interaction region
- Possible to estimate track parameter resolutions from distributions of difference in track parameters (e.g. $d_{0,\text{ upper track}} - d_{0,\text{ lower track}} = \Delta d_0$)
- Or, compare Si only w/ TRT for upper and lower separately

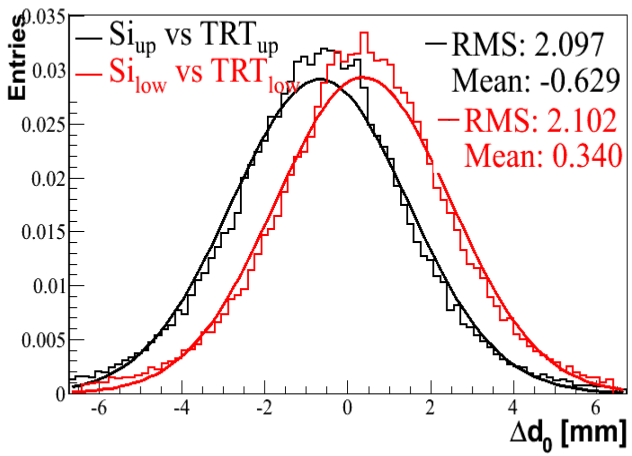
From Manuel Kayl

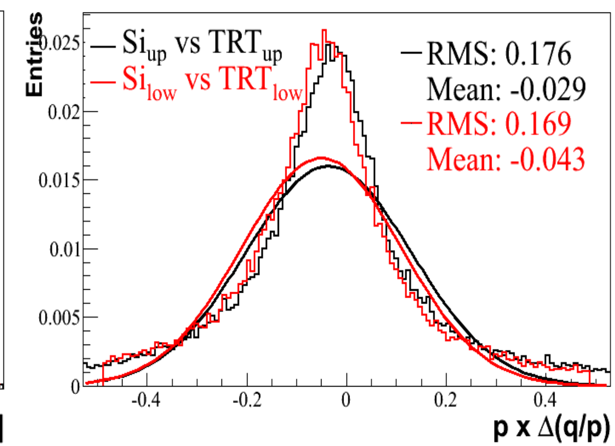
Comparison of half tracks reconstructed separately in TRT and Si segments:

- 2 upper half tracks and 2 lower half tracks produced
- Compare upper and lower track segments ($TRT_{up} - Si_{up}$, $TRT_{low} - Si_{low}$)

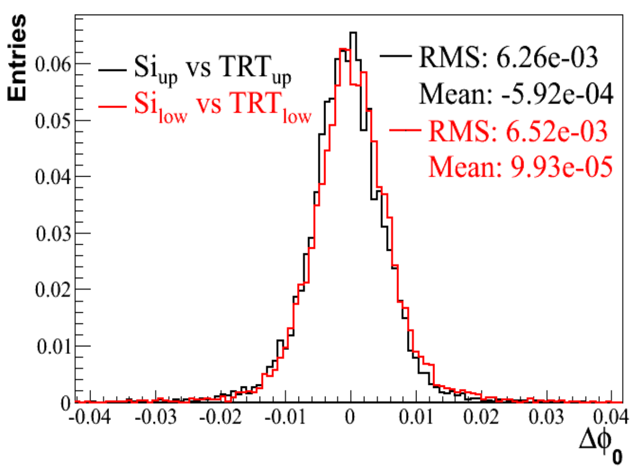
From Manuel Kayl

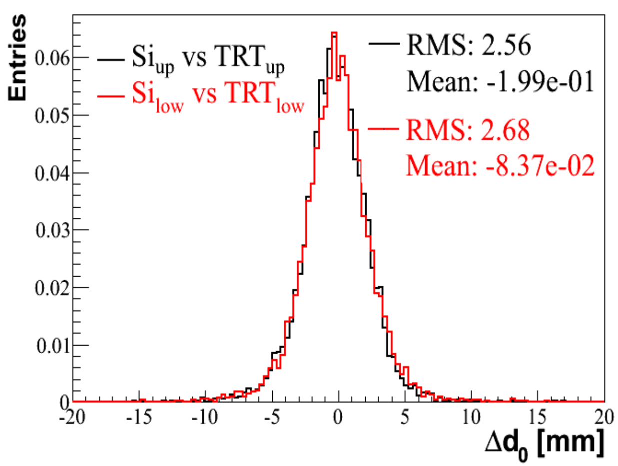


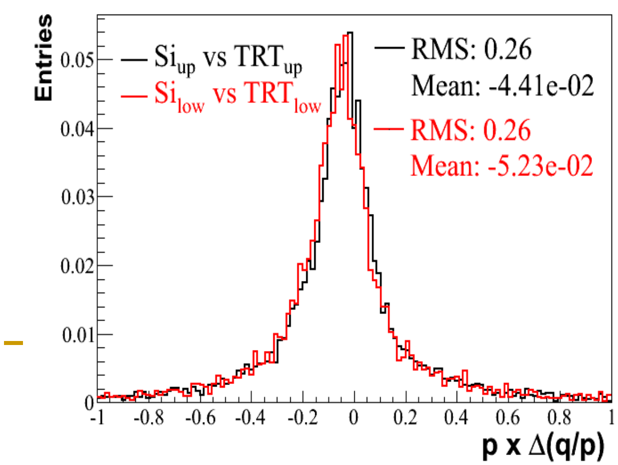




After new alignment (L2 TRT, i.e., at module level) - Ongoing

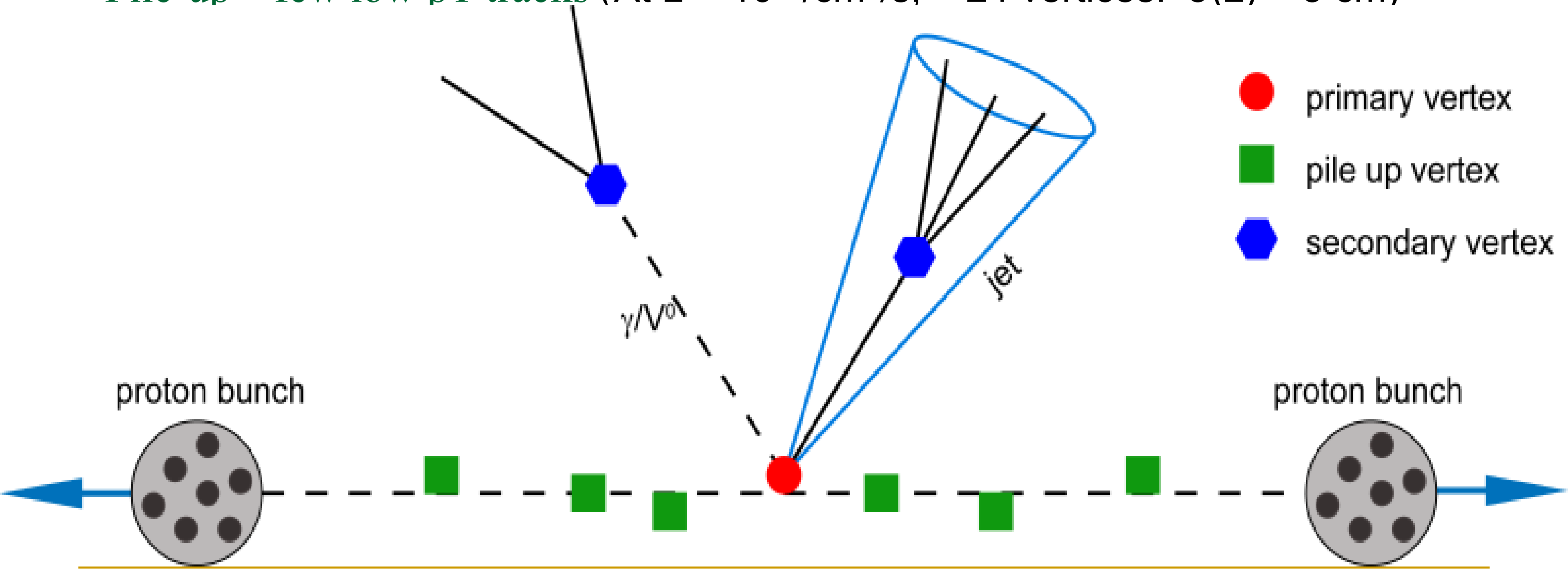




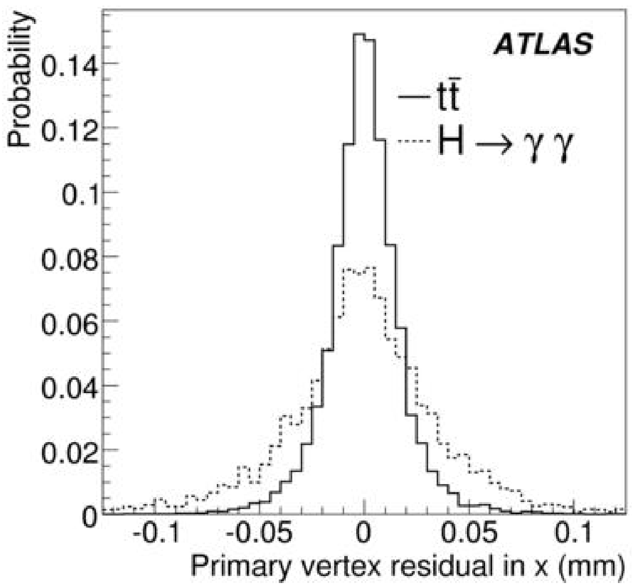


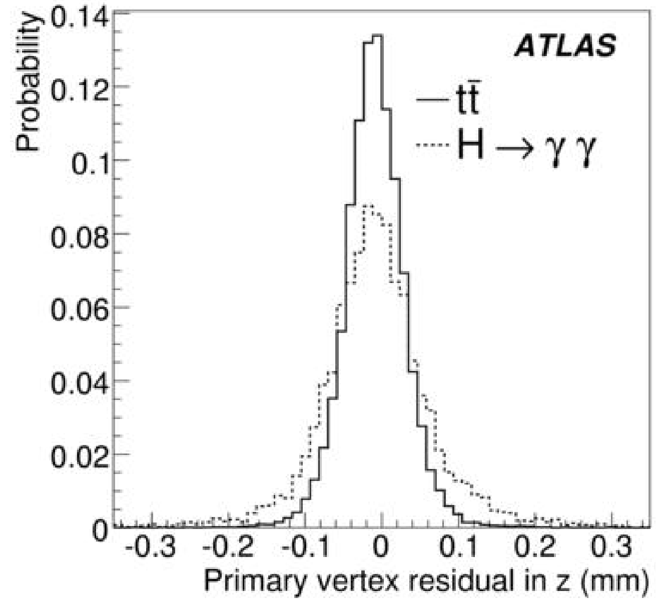
Vertexing algorithms have a variety of needs, modular in design:

- Primary – usually many high pT tracks (H → γγ has fewer tracks)
- Secondary:
  - τ decays
  - B/D vertices are close to PV, and in a jetty environment
  - Ks/γ are further out in radius
- Pile-up – few low pT tracks (At L = $10^{34}/cm^2/s$, ~ 24 vertices: σ(z) ~ 5 cm)



Primary Vertex





PV residual along x & z, for events w/ top-quarks & Hγγ w/ mH=120GeV. The results are shown w/o pile-up and w/o any beam constraint.

Event	x-y res (μ)	Z res (μ)	Reco ε (%)	Selection ε
tt (no BC)	18	41	100	99%
tt (BC)	11	40	100	99
Hγγ (no BC)	36	72	96	79
Hγγ (BC)	14	66	96	79

Beam constraint

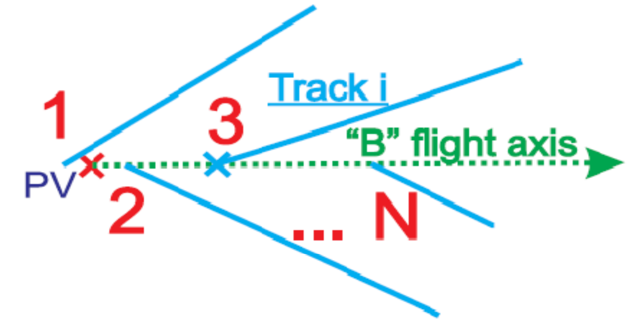
No pile-up vertices

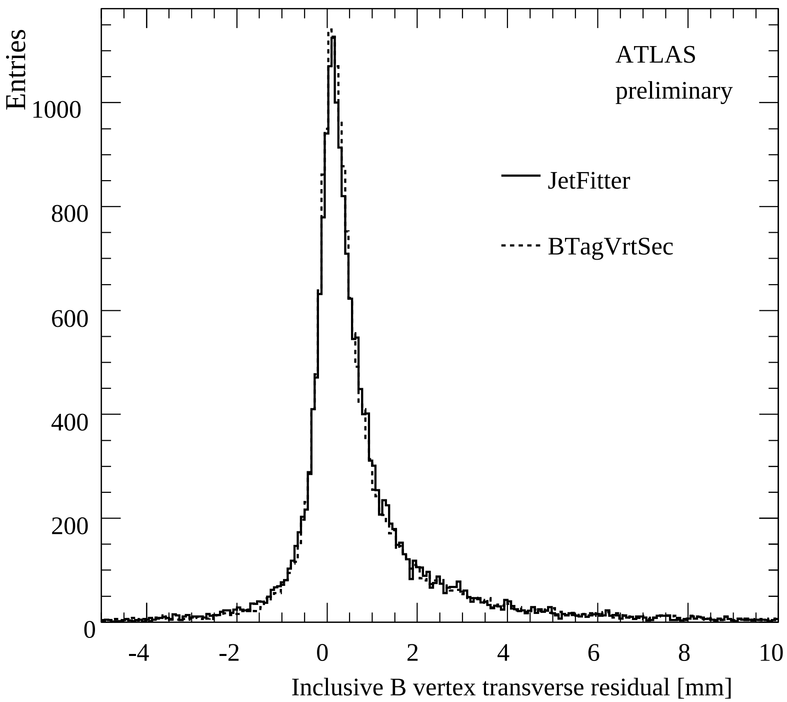
<2.4> pile up vertices

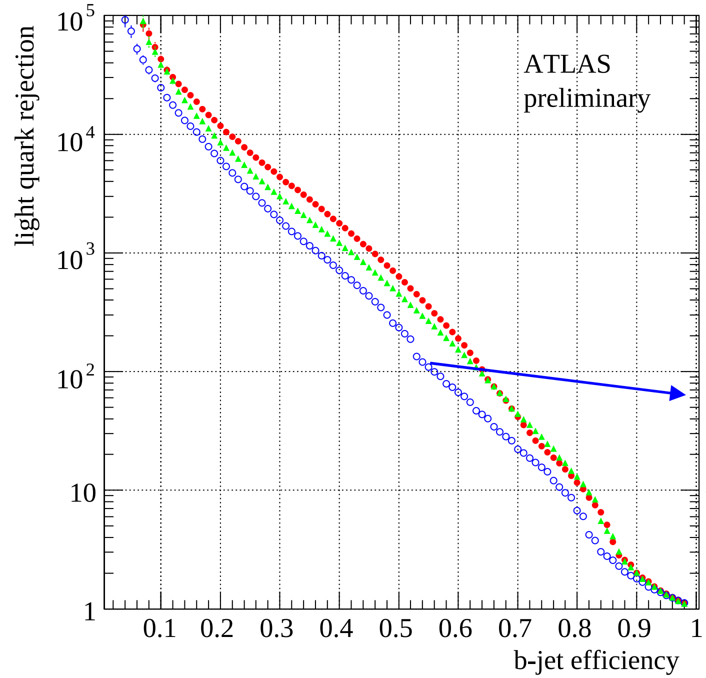
Secondary Vertex: b-jet tagging

SV finding is a critical component of tagging b-jets.
Different approaches:

- Inclusive vertex – fit to one common vertex
- Topological fit to B, D vertices along jet axis
- ε for former (~70%), latter (74-85%)
- Purity for former (~92%), latter (85-91%)



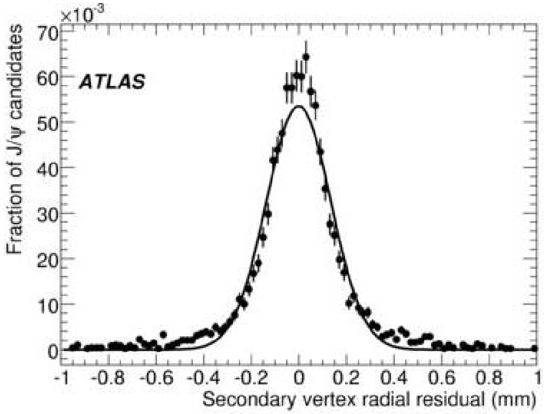


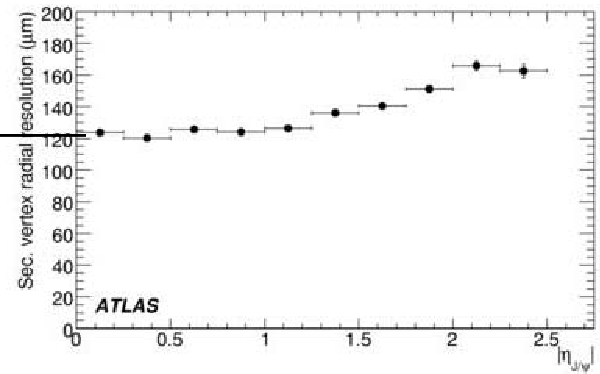


Only IP of tracks

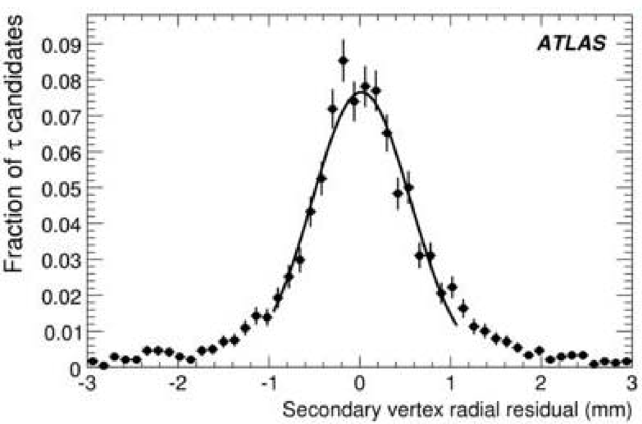
We use both IP & vertexing

Secondary vertex: B hadrons, τ

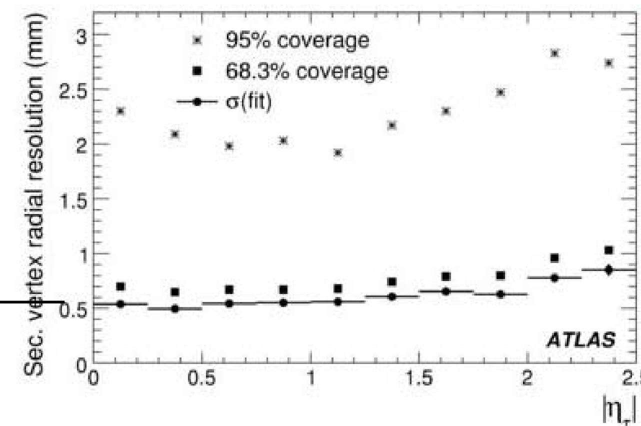




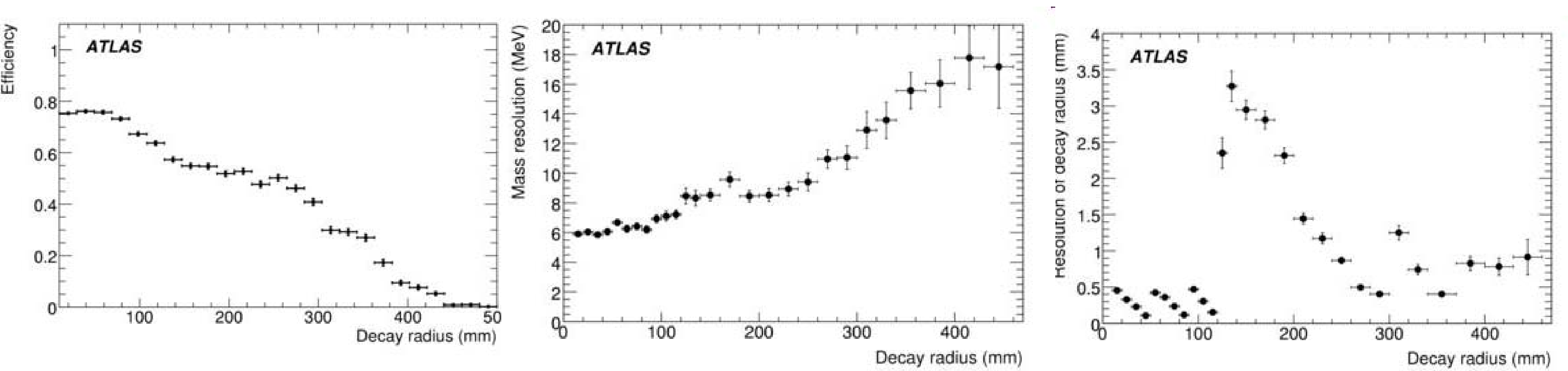
Resolution of the radial position of the secondary vertex for J/ψ→μμ decays in events w/ B decays for tracks with |η| around 0 (left) and as a function of |η| of the J/ψ (right)). The J/ψ have an average transverse momentum of 15GeV.



Z → ττ decays



Secondary vertex: K_s



Efficiency (left) for reconstruction of $K_s \rightarrow \pi^+\pi^-$ decays in events w/ B-hadron decays.

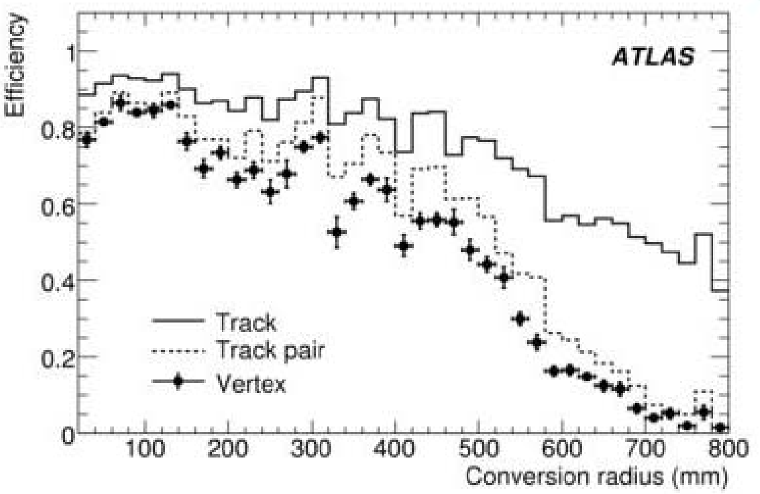
- Need 3D information – not available beyond SCT, hence $\varepsilon \rightarrow 0$

Resolution for the reconstructed radial position (center) and mass (right).

- The resolutions are best for decays just in front of the detector layers.
  - Barrel pixel layers are at: 51, 89 and 123 mm;
  - First two SCT layers are at 299 and 371 mm

Secondary Vertex: Photon conversions

- γ present a challenge because of the small opening angle between outgoing tracks

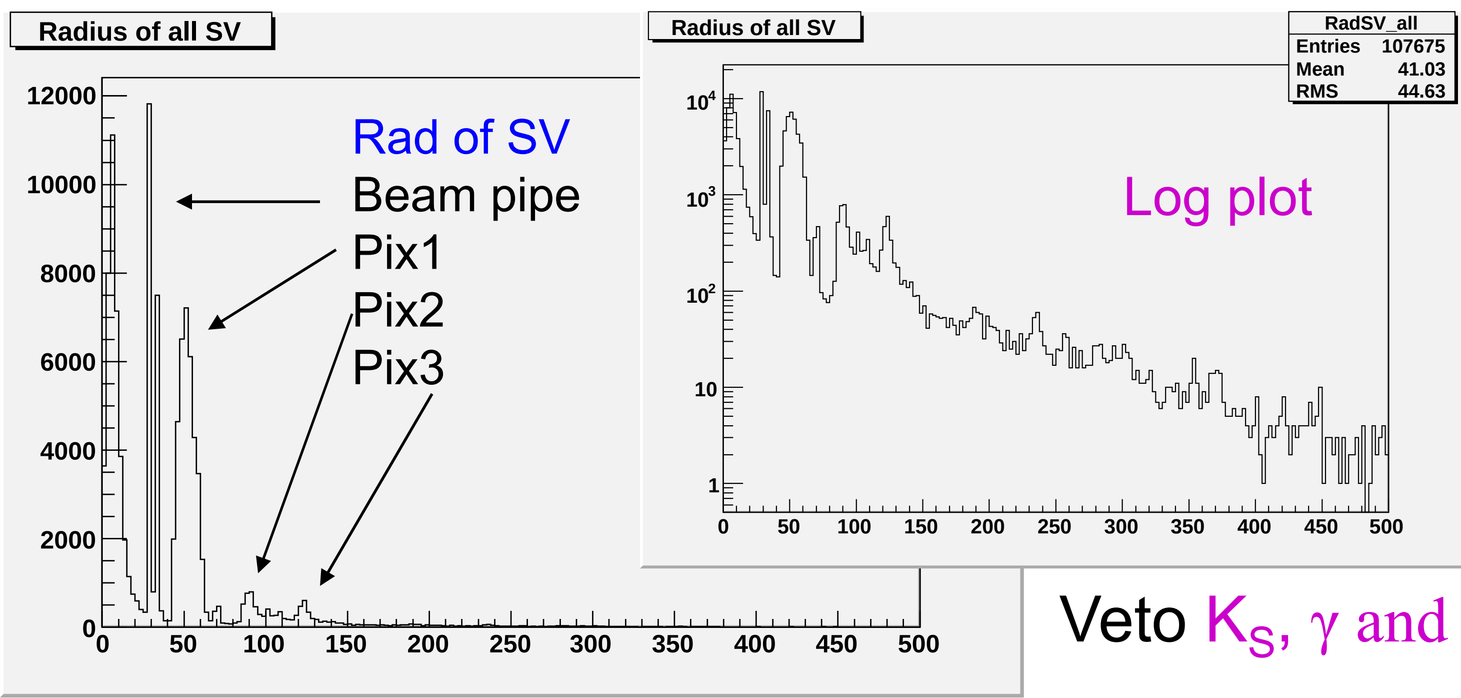


Efficiency to reconstruct conversions of photons w/ p_T=20GeV and $|\eta|<2.1$, as a function of radius

Shown are the efficiencies to reconstruct single tracks from conversions, the pair of tracks from the conversion and the conversion vertex.

Secondary Vertex: Hadronic interactions

- Identify hadronic interactions at material surfaces, and get an estimate of interaction lengths directly
  - Use inclusive vertexing on minbias sample



Ongoing. Understand efficiency & fake rates

Veto K_S, γ and $Z<200$

Summary

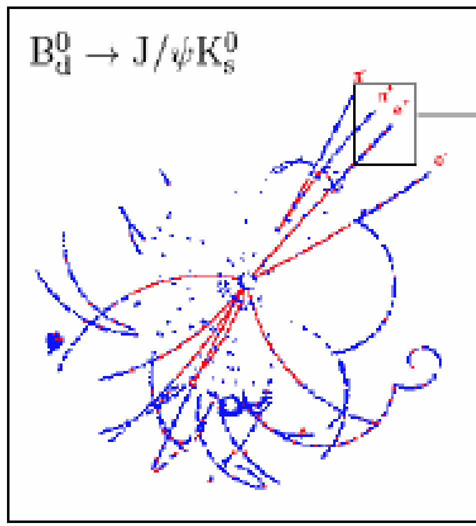
- A lot of effort has gone into providing robust, efficient tracking for a variety of needs
- Much work is still ongoing to understand calibrations, alignment
- Vertexing algorithms are in good shape
- Did not mention trigger based on ID
  - Tracking at L2 and Event Filter
- Ready for data!

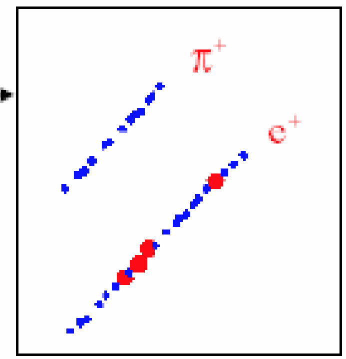
Backup slides

Detector: transition radiation

- Transition radiation: radiation produced by highly relativistic charged particles when they cross the boundary between two mediums of different dielectric constants ($C0_2$ and polypropylene foil/fibers in TRT)
- Total energy loss of particle depends on Lorentz factor – for two particles of a given energy, lighter particles have a higher γ and therefore radiate more than heavier particles
  - Provides stand-alone discrimination between pions (139 MeV^2/C^2) and electrons (.5 MeV^2/C^2)

- Photon emission spectrum peaks between 10-30 keV, X-ray range
- Energy deposited in TRT, average event:
  - Sum of ionization losses of charged particles: ~2.5 keV
  - Deposition due to transition radiation photon absorption: >5 keV



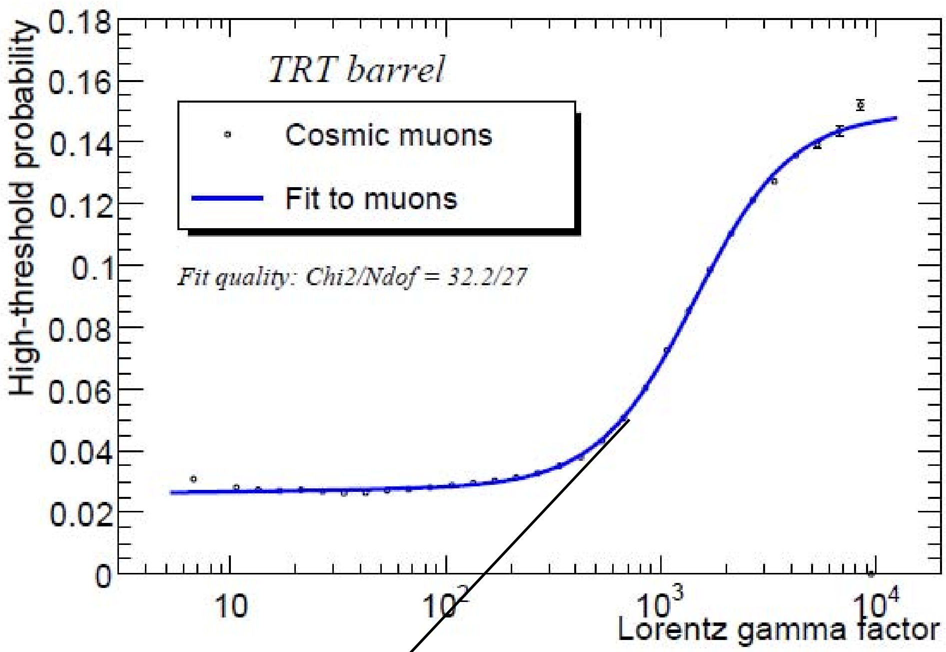


Simulated event, illustration of clusters from eletron/positron and pion hits – small blue dots are ionizing hits, large red dots are TR hits 7

ID week Cosmic Results for TRT 10th of February 2009

HT onset

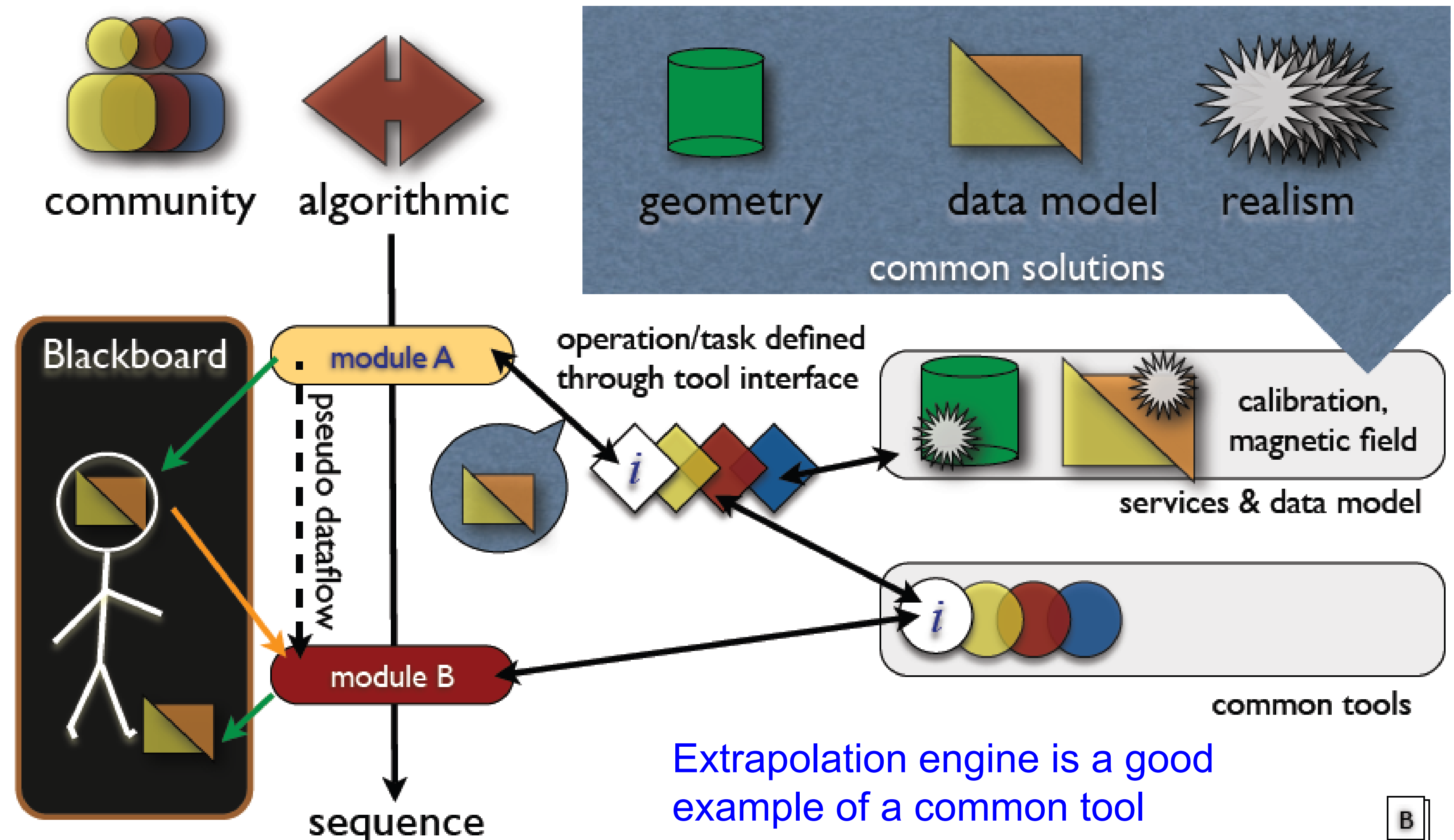
Averaging over charge and theta, the barrel HT onset curve fitted to logistic sigmoid:



Troels C. Petersen (CERN) 9/23

Electrons will start TR with P >~ 300-400 MeV. For pions, that is ~ 80 GeV

NEWT: commonality and individuality



Extrapolation engine is a good example of a common tool

- Mathematical Propagation
- Navigation
- Material effects

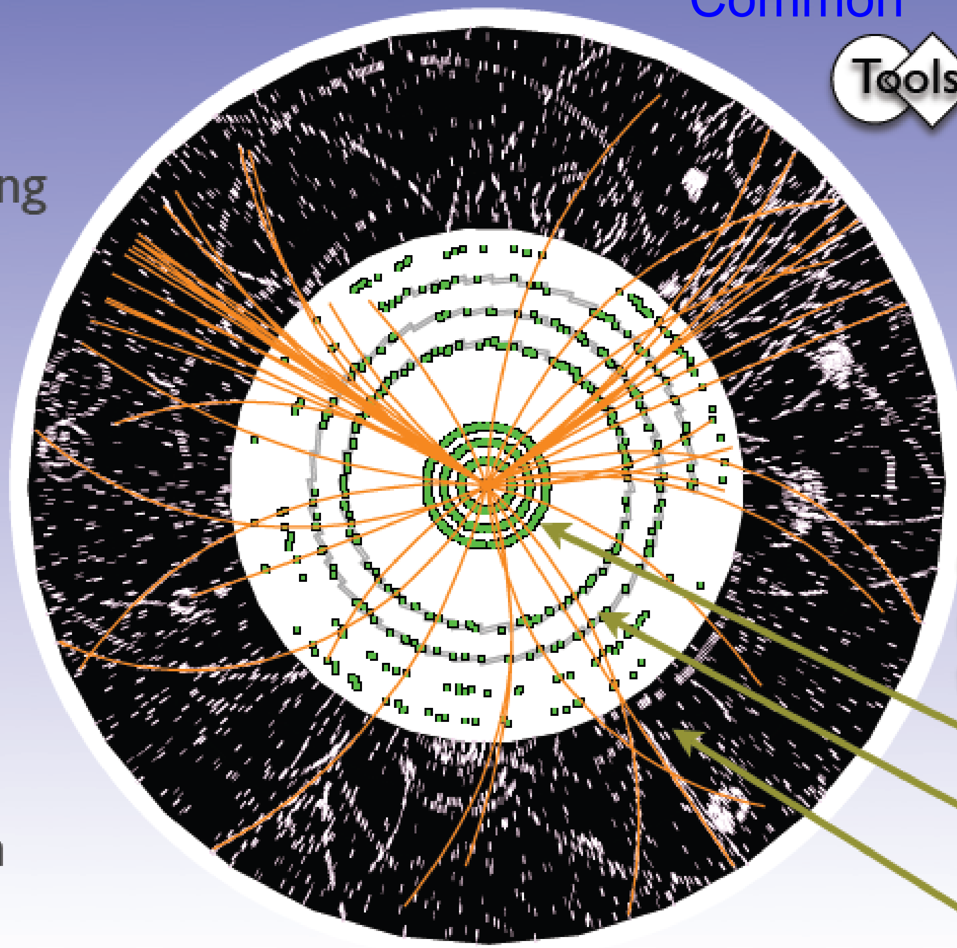
A. Salzburger - CHEP, Sep. 2007 - Victoria

4

Overview: ID reconstruction (nutshell view)

Modules

- pattern finding
- track fitting
- vertexing
- conversion & V0 finding
- particle identification



Common **Tools**

- extrapolation
- material description
- magnetic field
- Hit calibration
- ambiguity Solving
- alignment
- back tracking
- brem recovery

Good performance relies on all of these components !

3 layers Si pixel

4 layers Si strip (sandwich modules)

transition radiation tracker (~36 hits)

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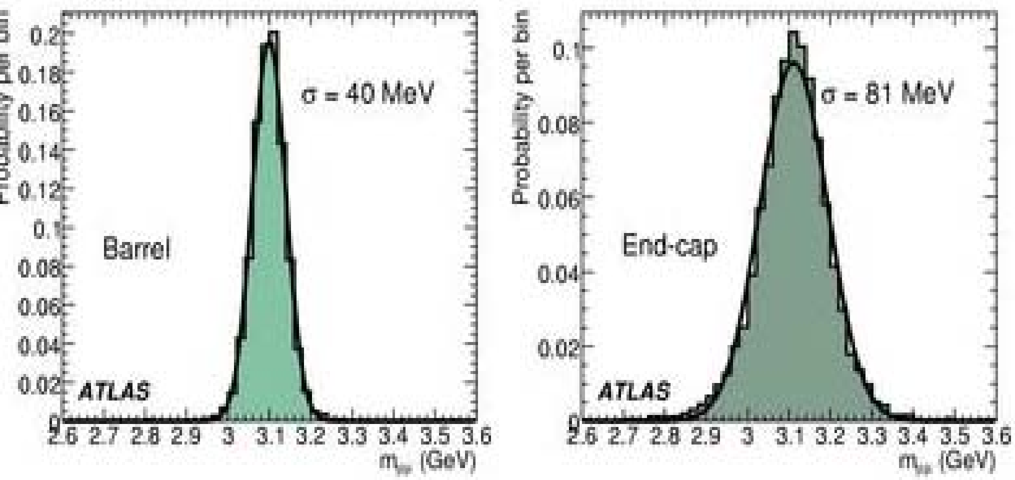
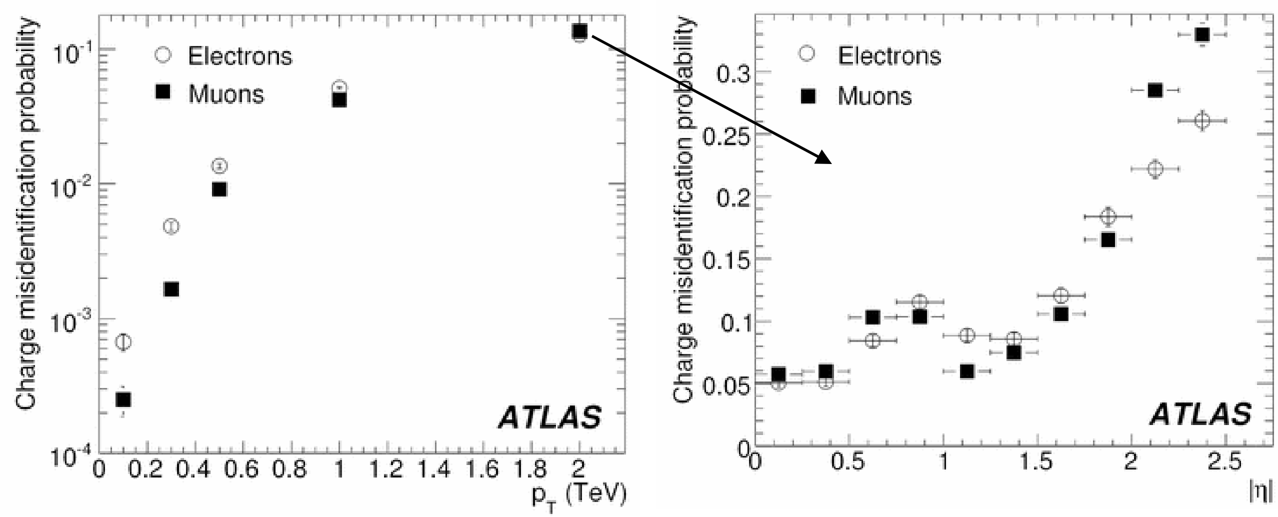
7 ATC ATLAS COMPUTING

Item		Radial extension (mm)	Length (mm)
Overall ID envelope		$36 < R < 1150$	$0 < \|z\| < 2727$
Pixel	Beam pipe	R=36	
	Overall envelope	$36 < R < 230$	$0 < \|z\| < 3300$
3 cylindrical layers	Sensitive barrel	$50.5 < R < 122.5$	$0 < \|z\| < 401$
2 x 3 disks	Sensitive End Cap	$89 < R < 150$	$495 < \|z\| < 650$
SCT	Overall envelope	$230 < R < 559$ (barrel)	$0 < \|z\| < 746$
		$230 < R < 635$ (EC)	$847.5 < \|z\| < 2727$
4 cylindrical layers	Sensitive barrel	$299 < R < 514$	$0 < \|z\| < 746$
2 x 9 disks	Sensitive End Cap	$270 < R < 560$	$847.5 < \|z\| < 2727$
TRT	Overall envelope	$550 < R < 1150$ (barrel)	$0 < \|z\| < 715$
		$559 < R < 1150$ (EC)	$847.5 < \|z\| < 2727$
36 traversed tubes per track	Sensitive barrel	$559 < R < 1080$	$0 < \|z\| < 715$
	Sensitive End Cap	$635 < R < 999$	$847.5 < \|z\| < 2727$

Performance – misalignment, mis-calibration, pile-up are neglected

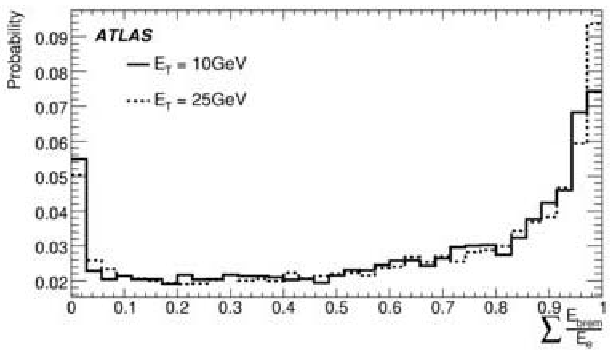


Mass for J/ψ (to muons)

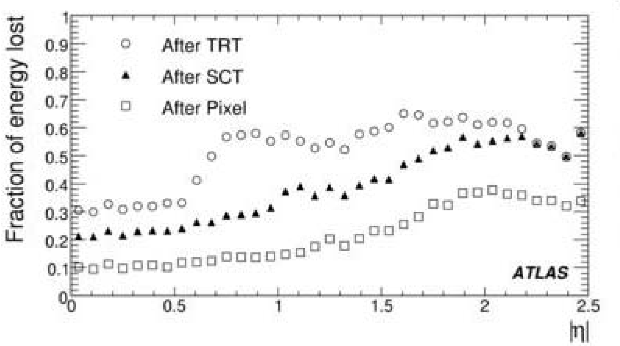


Probability of charge mis-identification as a function of pT and of η (for pT=2 TeV)

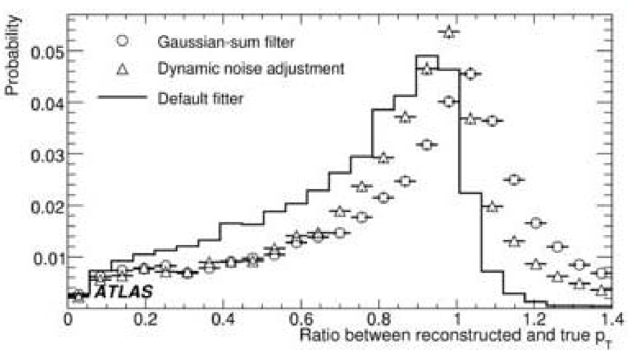
Electron reconstruction



Probability distribution as a function of the fraction of energy lost by electrons with pT=10GeV & 25GeV (integrated over a flat distribution in η with |η|<2.5) traversing the complete inner detector.

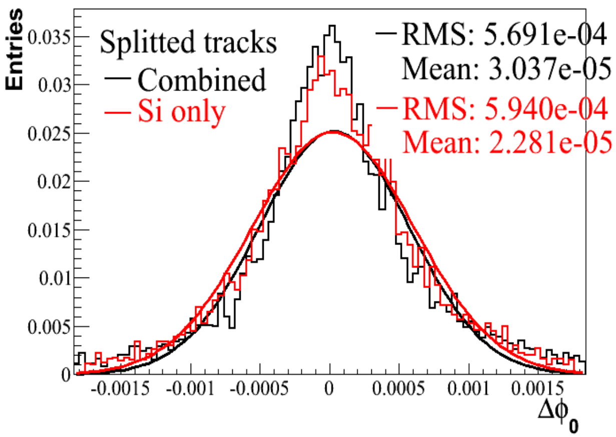


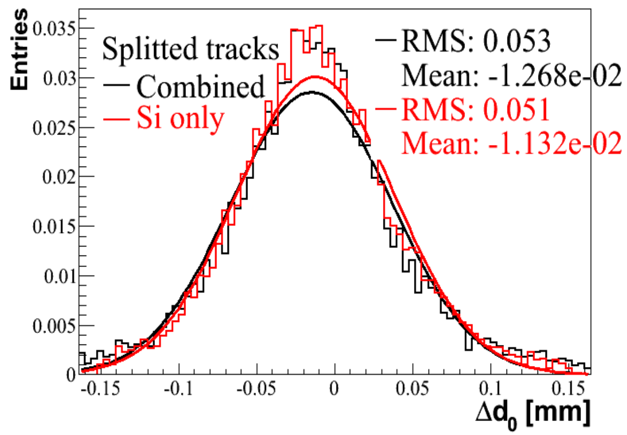
Fraction of energy lost on average by electrons with pT=25GeV as a function of |η|, when exiting the pixel, the SCT and the inner detector tracking volumes.
For |η|>2.2, there is no TRT material, hence the SCT and TRT lines merge.

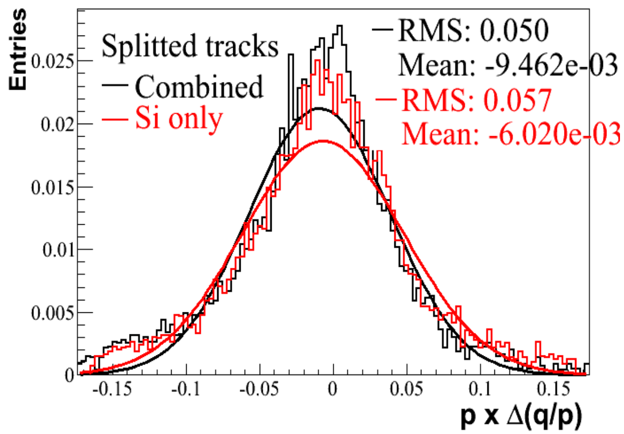


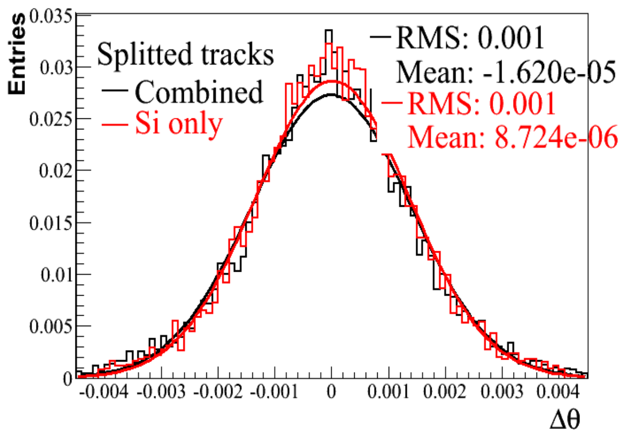
Probability distributions for the ratio of reconstructed to true momentum for electrons with pT=25GeV and |η|>1.5. Results are shown as probabilities per bin for the default Kalman fitter and for two brem recovery algorithms.

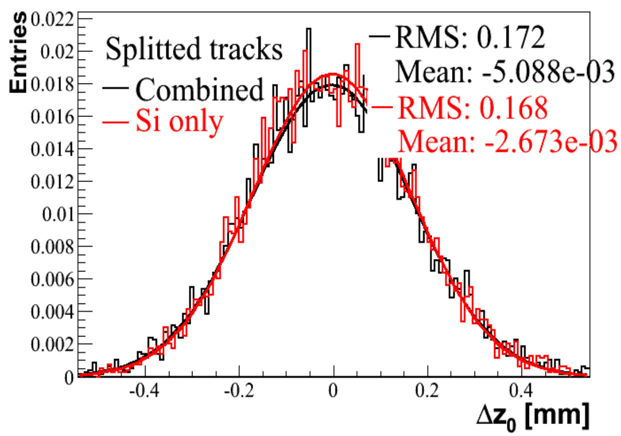
(Track Param) for Si-only vs Comb.











- Comparison of tracks with and without TRT extension
- Tight cuts, e.g $d_0 < 40$ mm

- Resolution (slightly) improves with TRT included as expected

Work continues to understand biases, and other effects

From Manuel Kayl