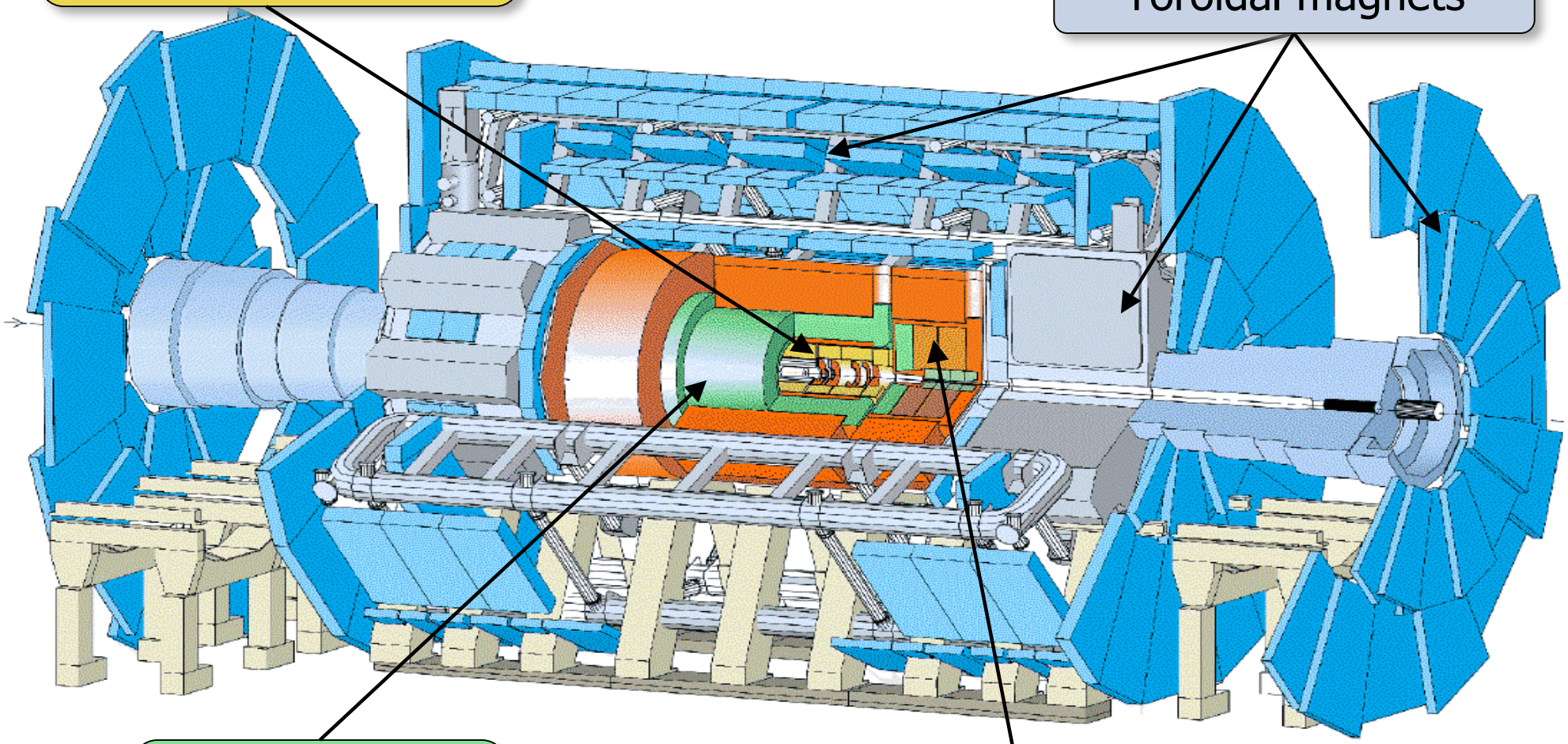
Track and Vertex Reconstruction in ATLAS

With special thanks to:
T. Cornelissen,
V. Kartvelishvili, G. Piacquadio,
K. Prokofiev, A. Salzburger,
L. Vacavant, A. Wildauer

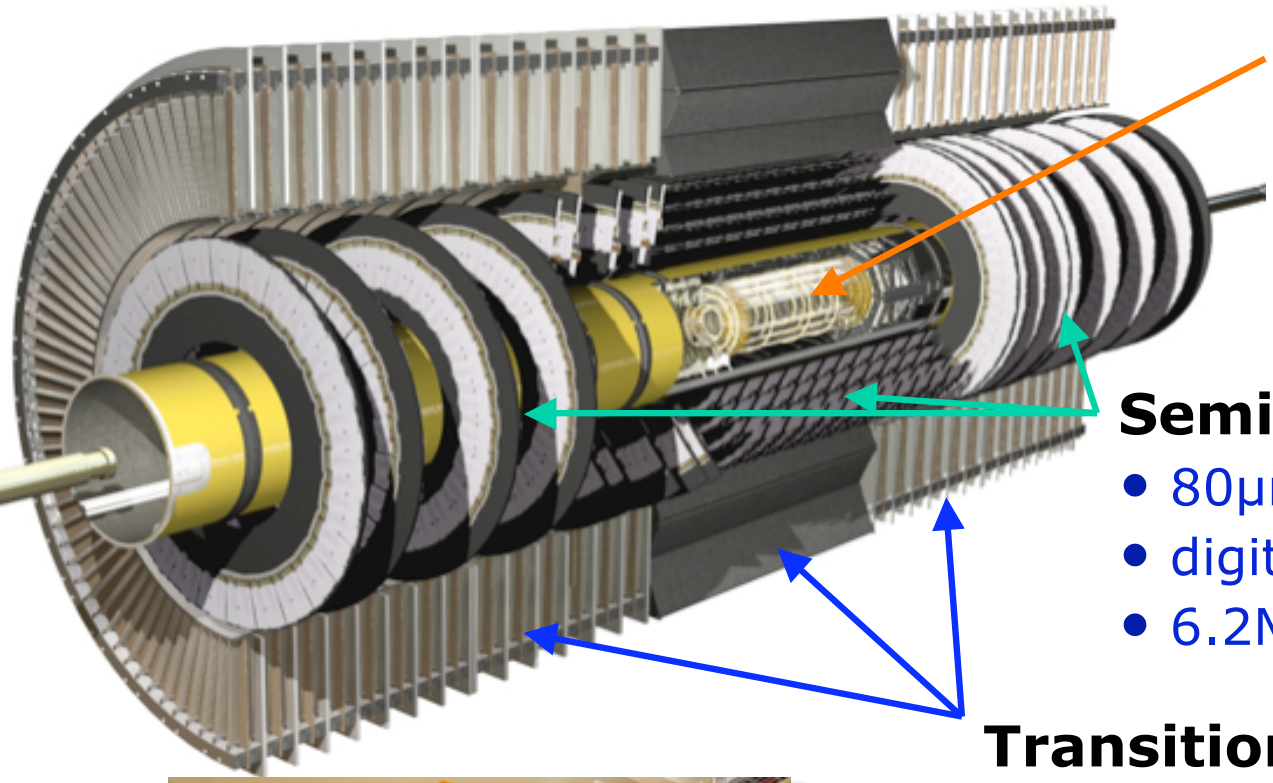
Wolfgang Liebig (NIKHEF)
on behalf of the
ATLAS Collaboration

The ATLAS Experiment



46x22 meter
~7000 tons

ATLAS Inner Detector



Pixel Detector

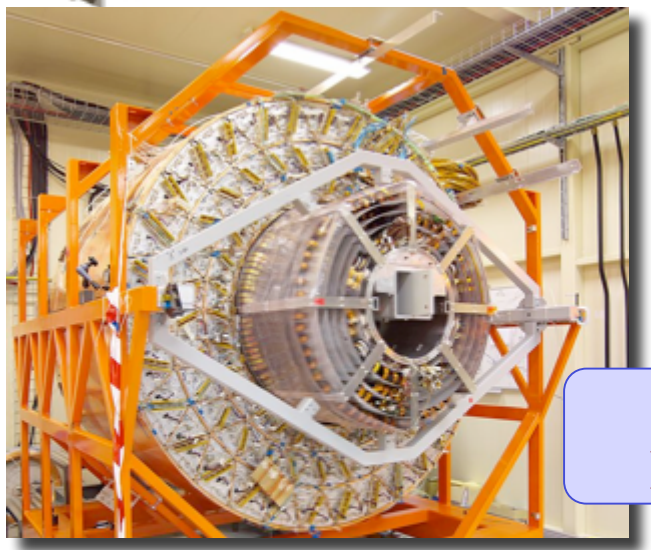
- 50 x 400 μm pixels
- time-over-threshold signal
- 80M channels

Semi-Conductor Tracker (SCT)

- 80μm pitched strips
- digital signal
- 6.2M channels

Transition Radiation Tracker (TRT)

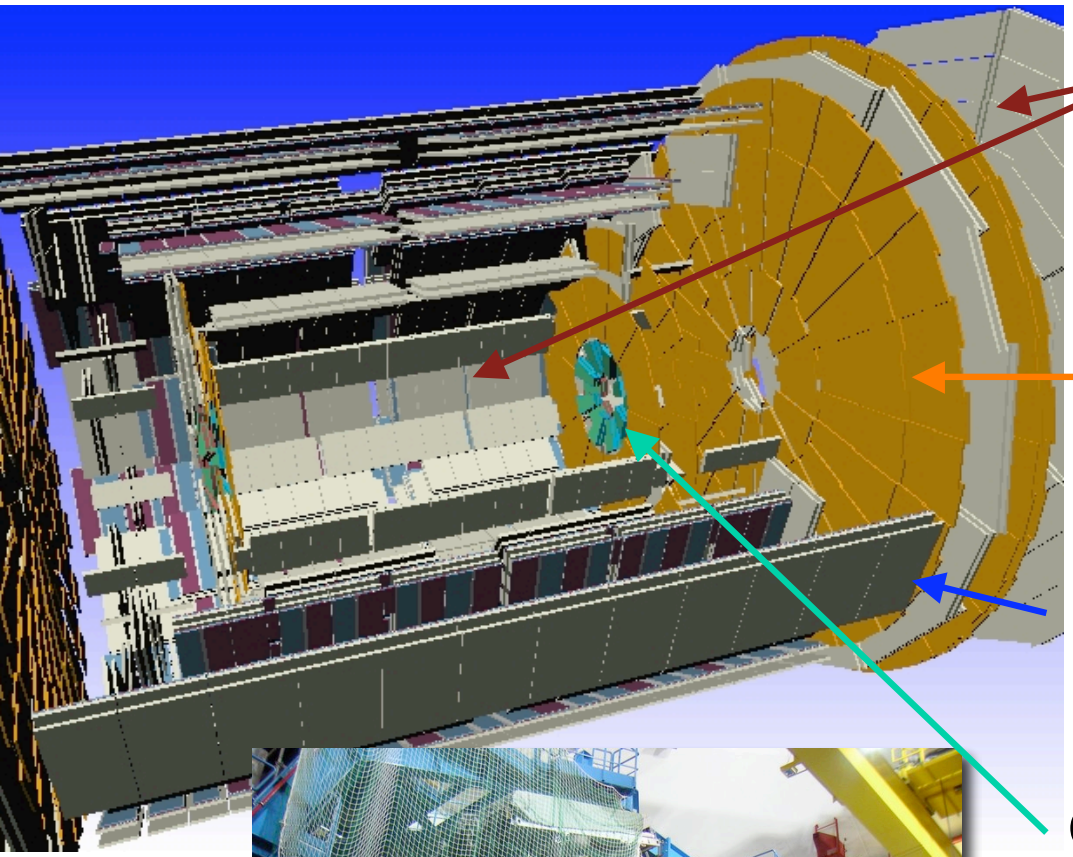
- 4mm Ø straws, up to 1.5m long
- drift time and high-threshold signals
- 298K channels



See talk by D. Robinson

ATLAS Muon Spectrometer

tracking info is also provided by the Muon Spectrometer:



Monitored Drift Tubes (MDT)

- 30mm Ø tubes
- time-over-threshold signal
- 370k channels (barrel+endcaps)

Thin-Gap Chambers (TGC)

- ~30mm pitched strips
- trigger signal, endcaps

Resistive Plate Chambers (RPC)

- ~30mm pitched strips
- trigger signal, barrel

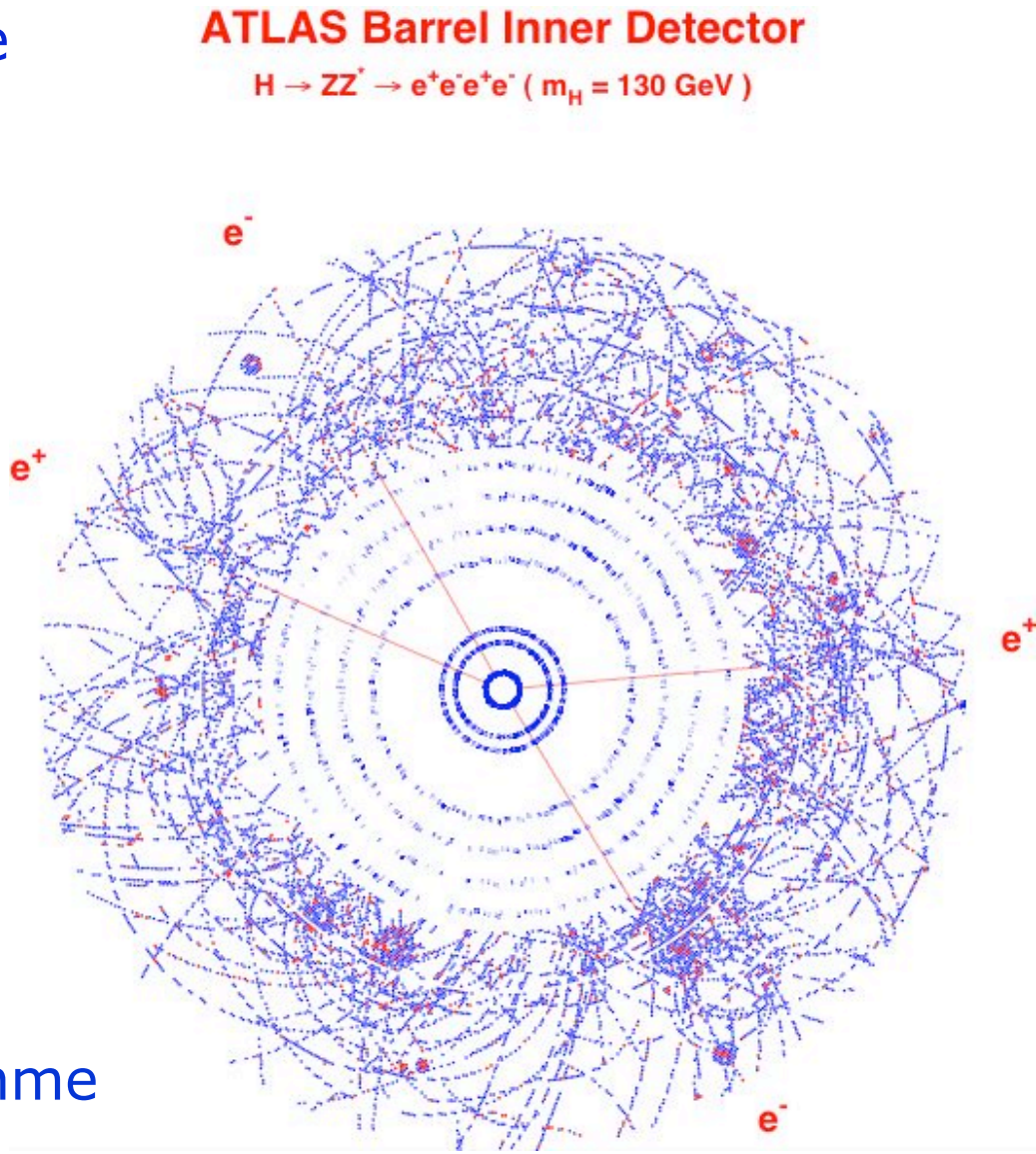
Cathode Strip Chambers (CSC)

- 5mm cathode pitch
- far-forward endcaps only

Inner Detector tracking software has been developed together with Muon Spectrometer (where relevant)

Track and Vertex Reconstruction at LHC

- Detectors for LHC are a challenge
- Good event reconstruction is part of a functioning detector !
- Needs to cope with (for example)
  - large detectors but high resolution
    - ➠ sensitive to deformations
  - ~24 simultaneous p-p collisions at $10^{34}cm^{-2}s$ design luminosity
    - ➠ complicated event topology
  - huge amount of data, triggering
    - ➠ very fast and stable algorithms
  - delicate physics questions
    - ➠ avoid systematic errors
- ATLAS meets challenge with careful software preparation and intensive commissioning programme



Track/Vertex Reconstruction Software

- ATLAS before 2004: competing monolithic packages
  - good (complementary) performance
  - closed algorithms with incompatible data models
  - similar situation in Inner Det., Muon Spec. and Vertexing
- 2003: strong recommendation by internal software review
  - common data objects
  - modularised logical structure: algorithms using common services and common tools
  - exploit synergies between Inner and Muon trackers, basis for combined reconstruction, calibration, alignment
- Today's ATLAS Software (eg. Inner Detector)

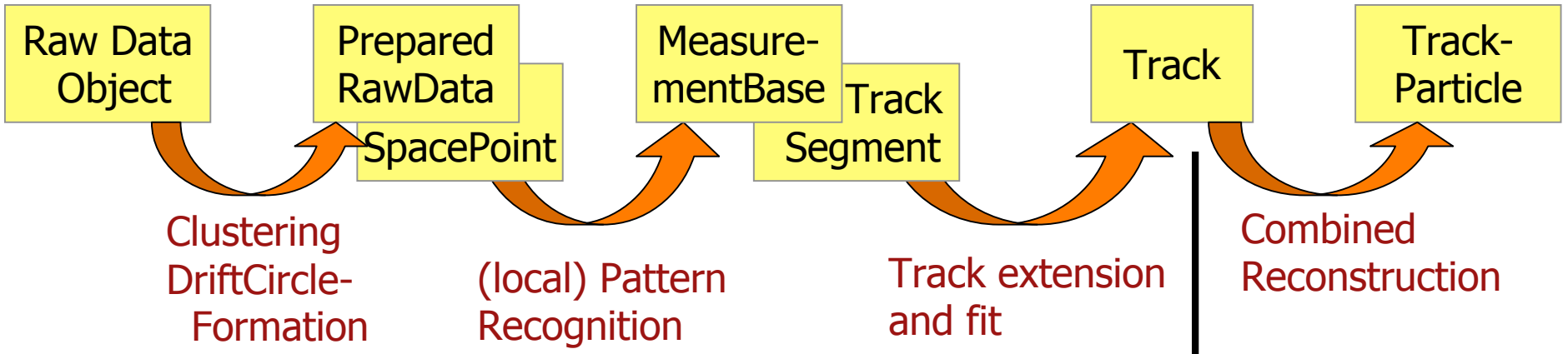
  migration of old algorithms, add new tracking techniques

  ⇒ collaboration within tracking/vertexing and across projects

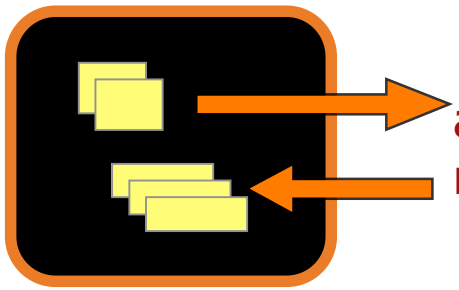
  ⇒ thorough preparation for effects expected with real data

Main motivation and challenge: if realistic effects are not properly corrected, advanced detector capabilities may easily be lost

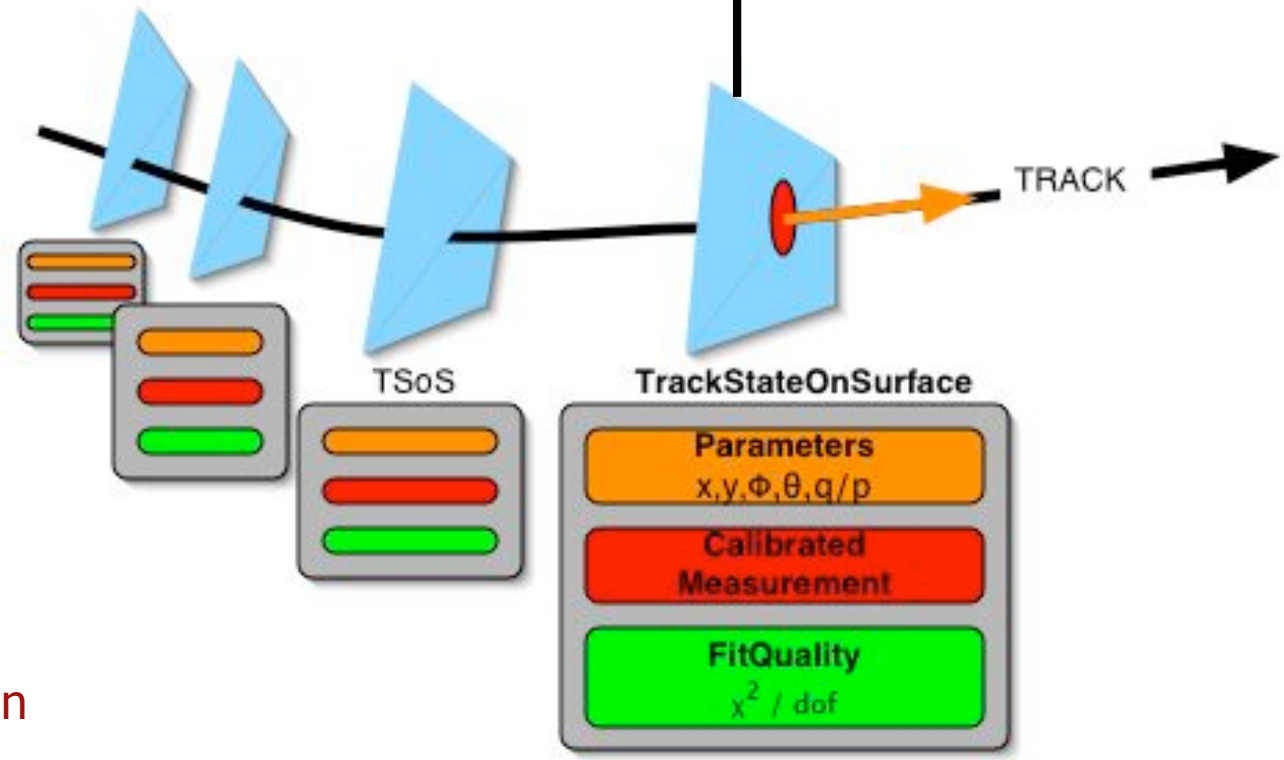
Tracking Event Data Model



- stages of reconstruction
- common (base-) classes for all tracking detectors
- data strictly separated from algorithms
- data containers written and read from event store ("blackboard design")



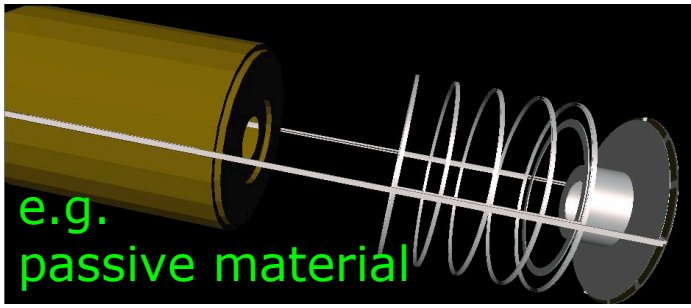
any stage of reconstruction



Common Services

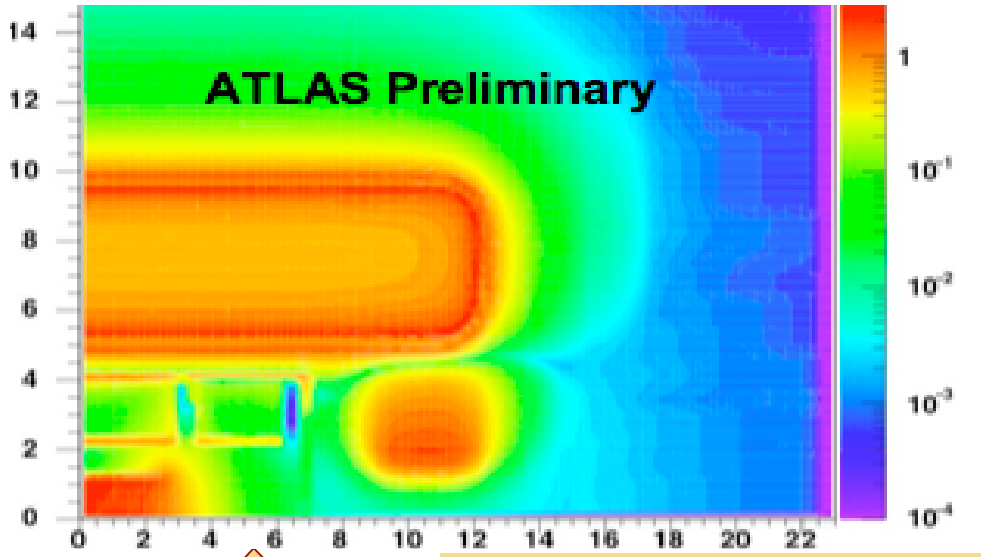
GeoModel: detector description

- common for simulation and reconstruction
- aligned geometry & material constants



Tracking Geometry:

- fast geometry & material densities



B (Tesla) vs **R** and **z** (m)

Detector Calibration

- dead and noisy channels
- drift time

Magnetic field

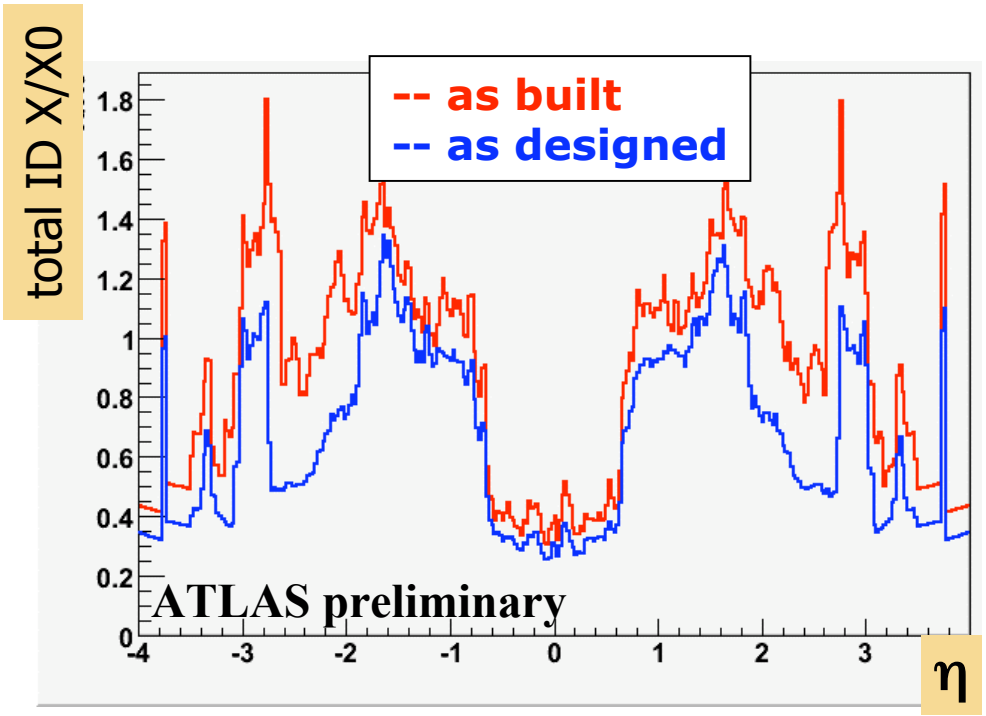
Beam spot

alignment corrections | *material densities* | *calibration* | *beam spot* | *magnetic field config.*

Conditions: meta-data *about* the detectors
Database organised by run intervals

Detector Description

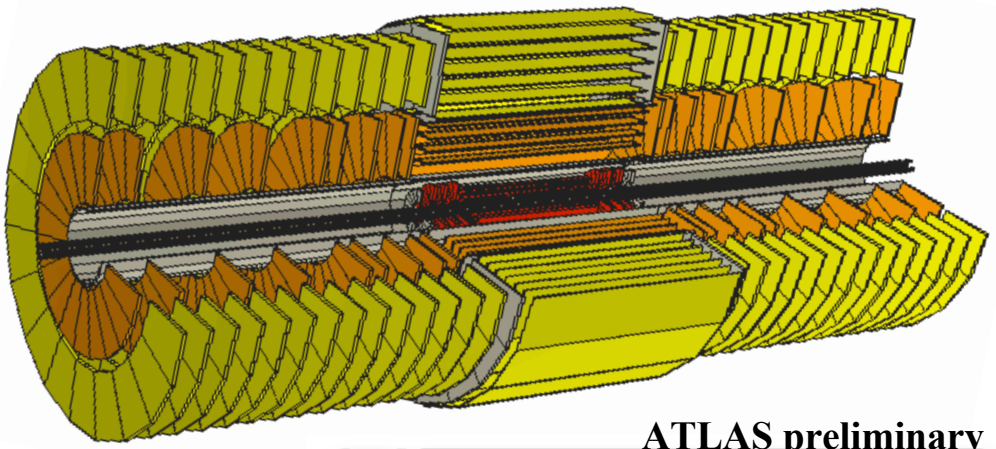
- ongoing effort towards correct and detailed as-built geometry
- items are measured and weighed as they are installed



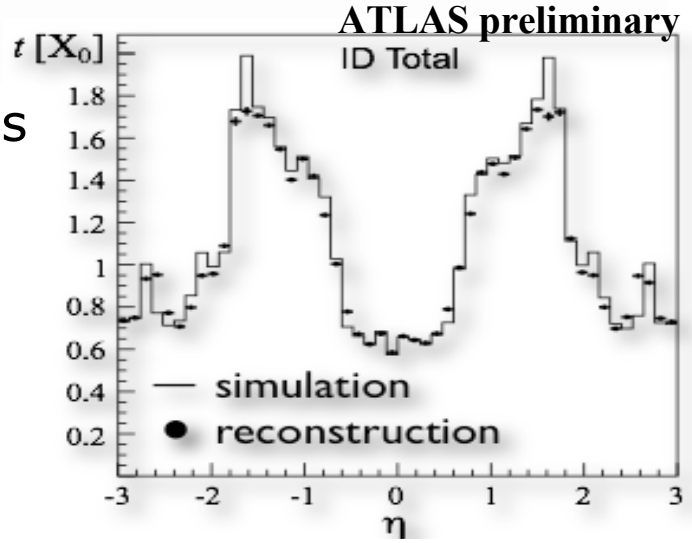
- **Calibration Data-Challenge:** test reconstruction+performance using distorted simulation

Tracking Geometry:

- fast and simplified detector descr.
- navigation and material effects
- Inner Detector: 125 layers/volumes (full detector descr. ~1M objects)

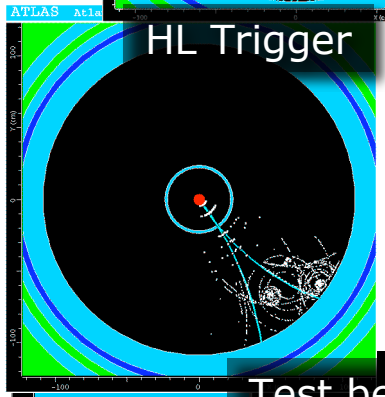


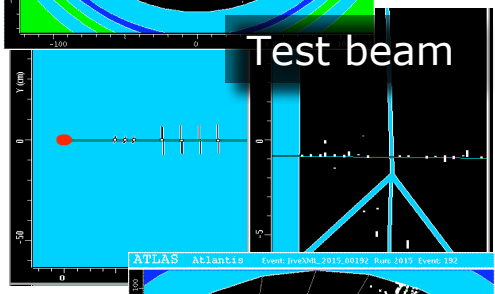
- reproduces Geant4 material

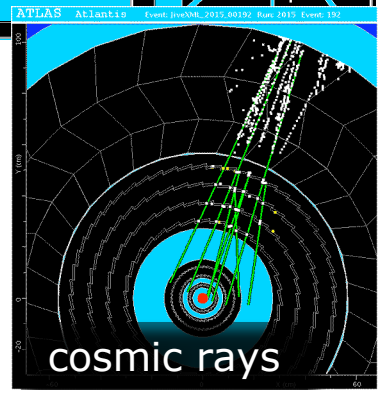


Inner Detector: New Modular Tracking

- Tracks from interaction region: Si-seeded track search
  - track candidate finding from Pixel+SCT
  - ambiguity solving including track fit
  - Extension to TRT and full re-fit
- Complementary strategies: under development
  - TRT-seeded search for recovering secondary tracks
  - V0s, conversions
- High-Level trigger tracking ("Event Filter")
  - apply same code to region of interest
- Cosmics+TestBeam Tracking: Two Strategies
  - additional small package for low track multiplicities



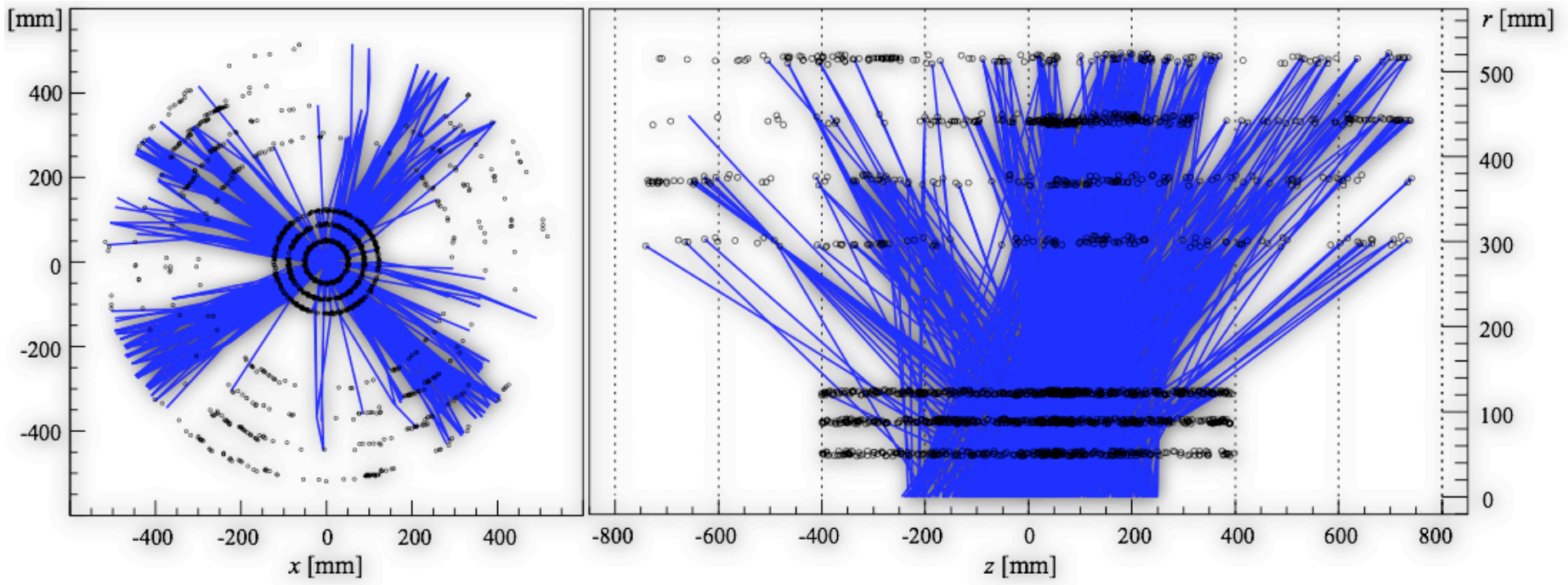




Fully modular structure
- each task/operation defined by abstract interface
- implemented by one or several (specialised) tools
- configurable at run time
- common tracking tools: designed for tasks in Inner Detector, Muon Spec. and combined (e.g. track fit)

Track Finding in the Si Detectors

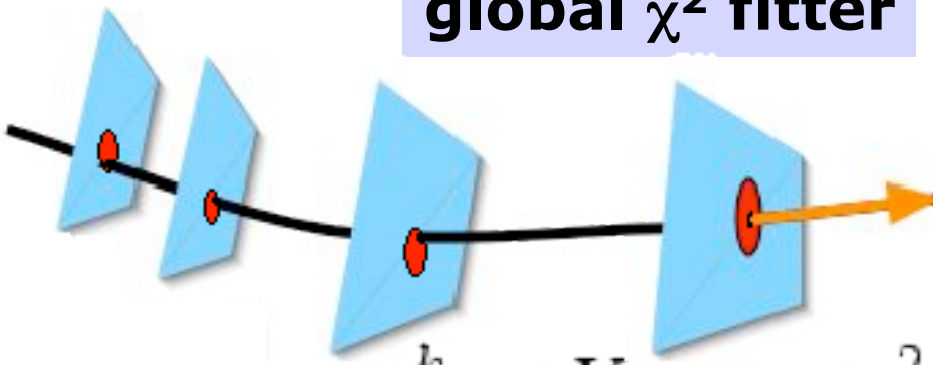
- Provide 3D space-points: 2D hit (pixel or stereo strips) on surface
- Find track seeds with at least 3 space points (curvature)



- extend to full ATLAS Pixel + SCT track candidate
- score candidates according to hits, holes, $\chi 2$ scattering…
- detect shared hits and resolve ambiguities by doing full track fit
- fitted parameters seed local pattern recognition in TRT

ATLAS Track Fit Algorithms

global χ^2 fitter

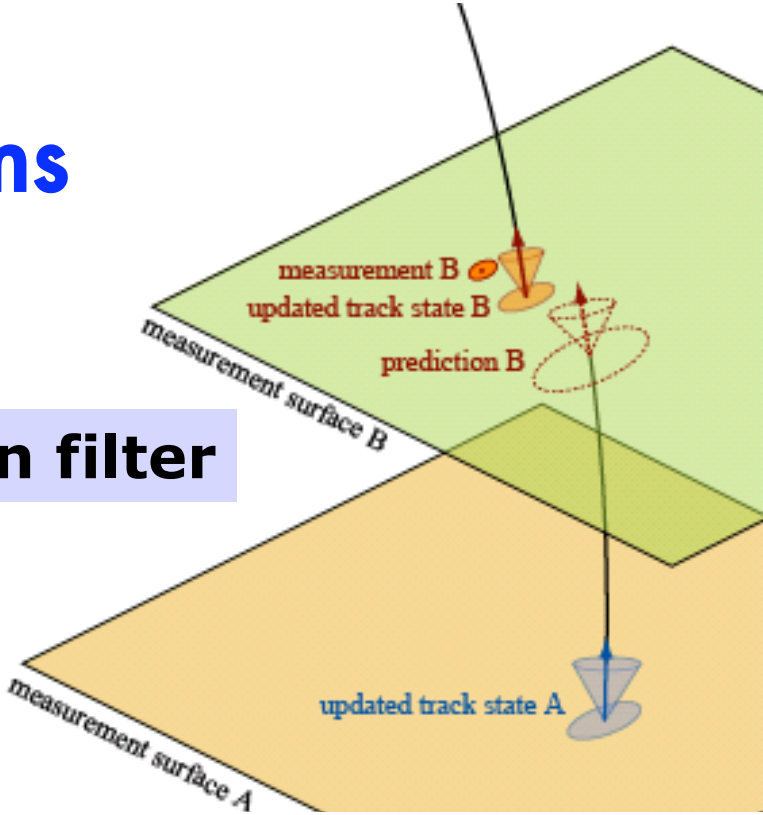


$$\chi^2 = \sum_{i=1}^{k} \left(\frac{X_i - \mu_i}{\sigma_i} \right)^2$$

- Legacy code and new tool
- Chi2 extended for multiple scattering and energy loss
- in use in MuonSpectrometer and muon combined track fit
- same material constants as Kalman fit

G.Lutz, NIM A 273 (1988) 349
T.Cornelissen et al, Proc of CHEP2007 #144

Kalman filter



- flexible MS/Eloss model
- Default in Inner Detector
- Several powerful extensions
  - Dynamic Noise Adjustment, Gaussian Sum Filter (electron bremsstrahlung)
  - Deterministic Annealing Filter (high occupancy tracking)

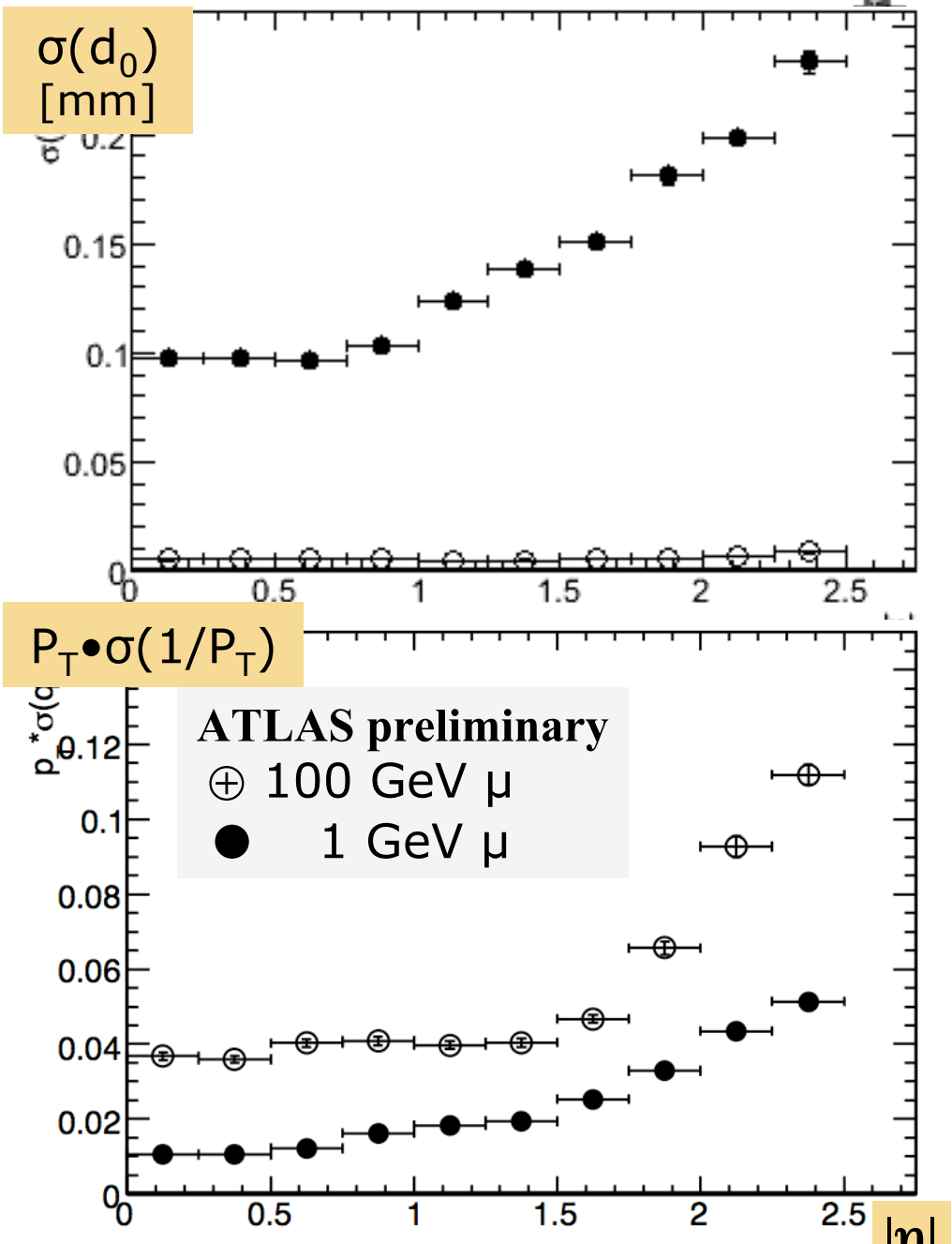
R.Frühwirth et al, NIM A 262 (1987) 444
V.Kartvelishvili, IPRD06, Nucl.Phys B (proc)
R.Fühwirth, Comp.Phys.Comm 154 (2003) 131.
A. Strandlie et al, Comp.Phys.Comm 133 (2000) 34

Inner Detector Tracking Performance

- validate good performance as part of reconstruction
- efficiencies and resolutions

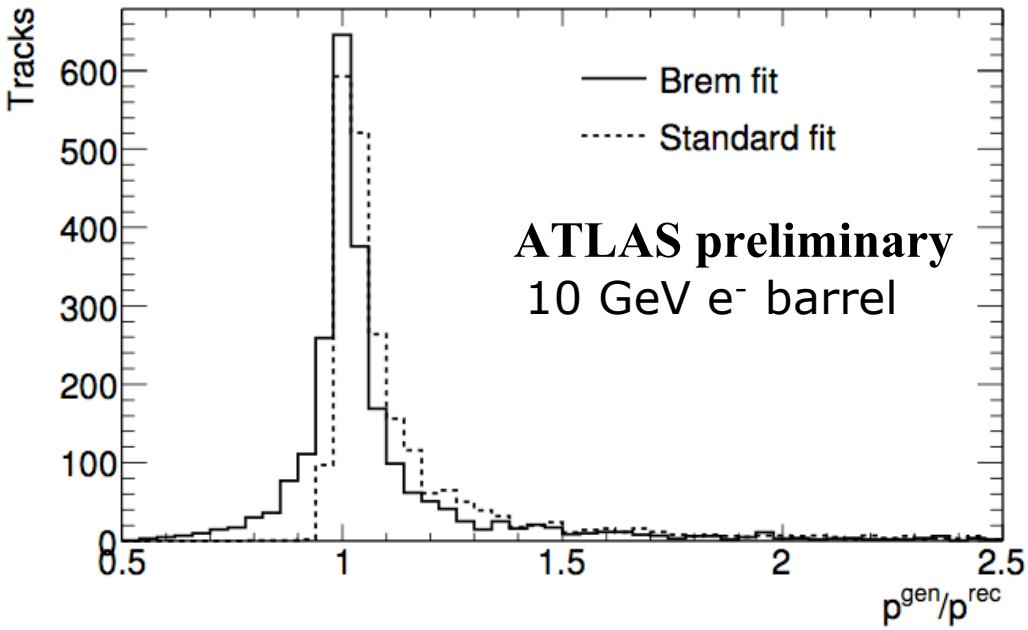
efficiency/fake [%]	Z->μμ	ttbar
barrel	99/0.4	98/--
transition	99/0.6	97/0.14
end-cap	96/1.2	96/0.34

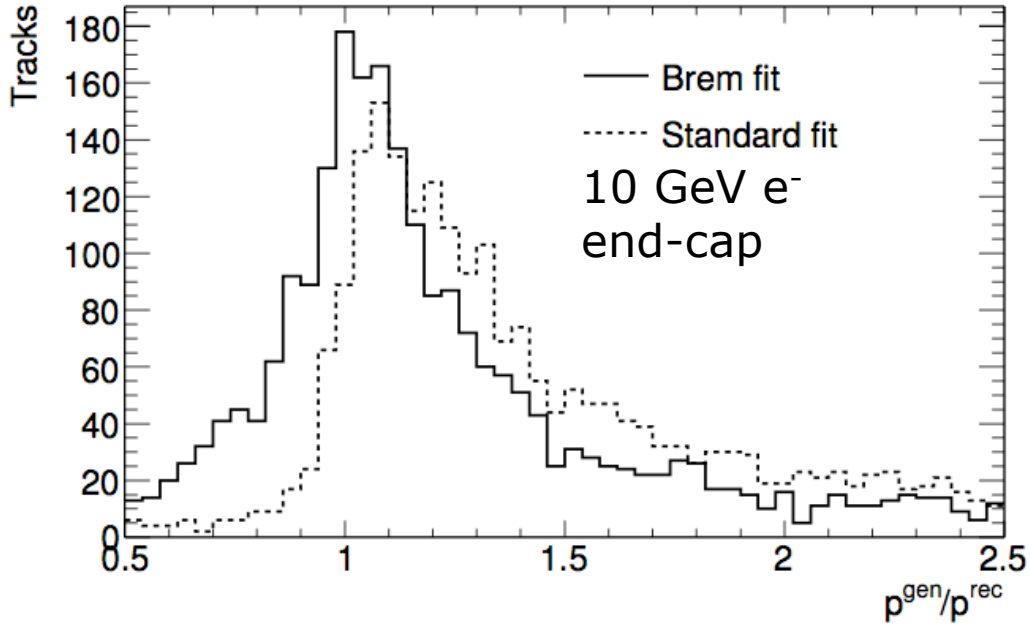
- pull quantities to test calibration and material effects
- code & performance monitored by daily automatic framework



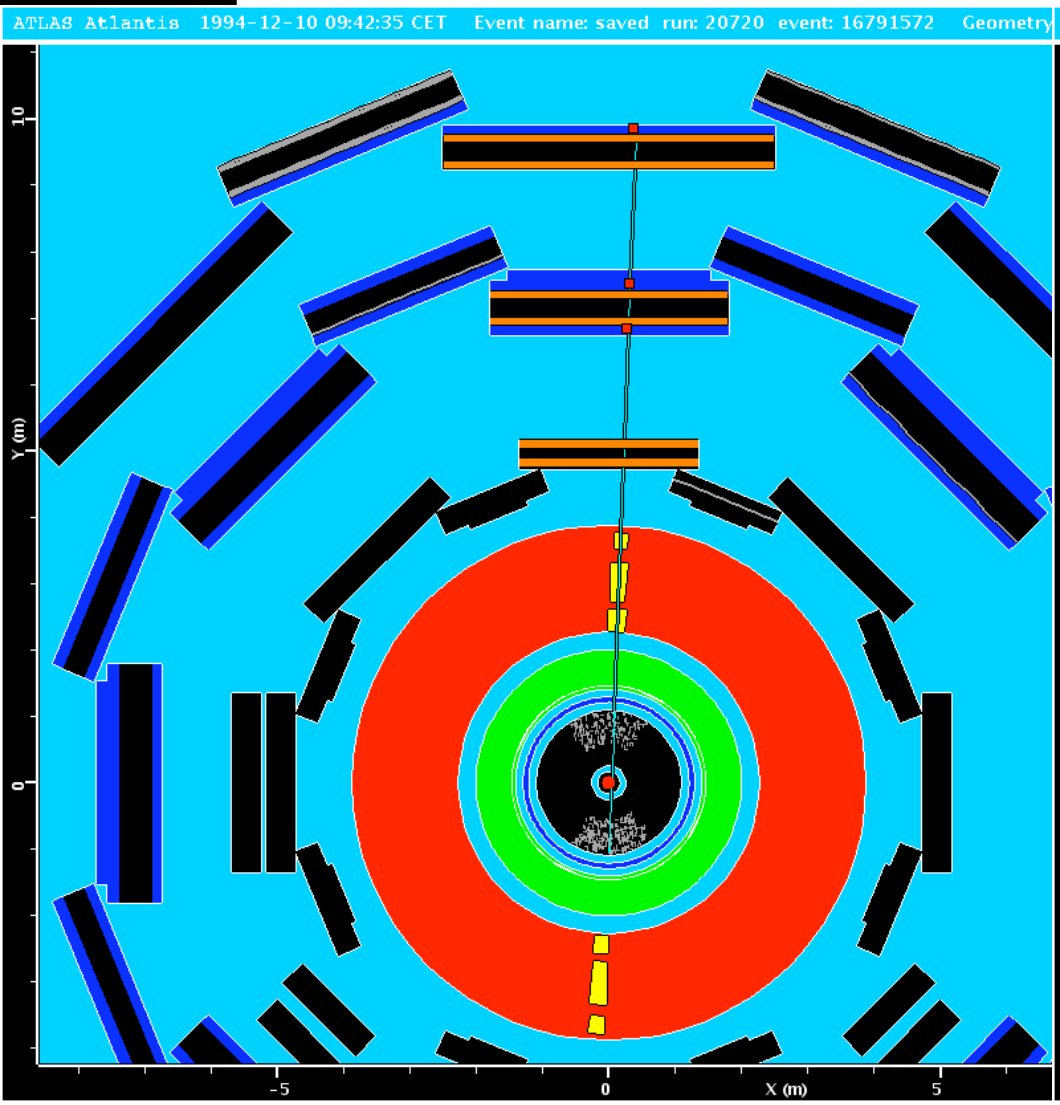
Electron Tracking in Si Detectors

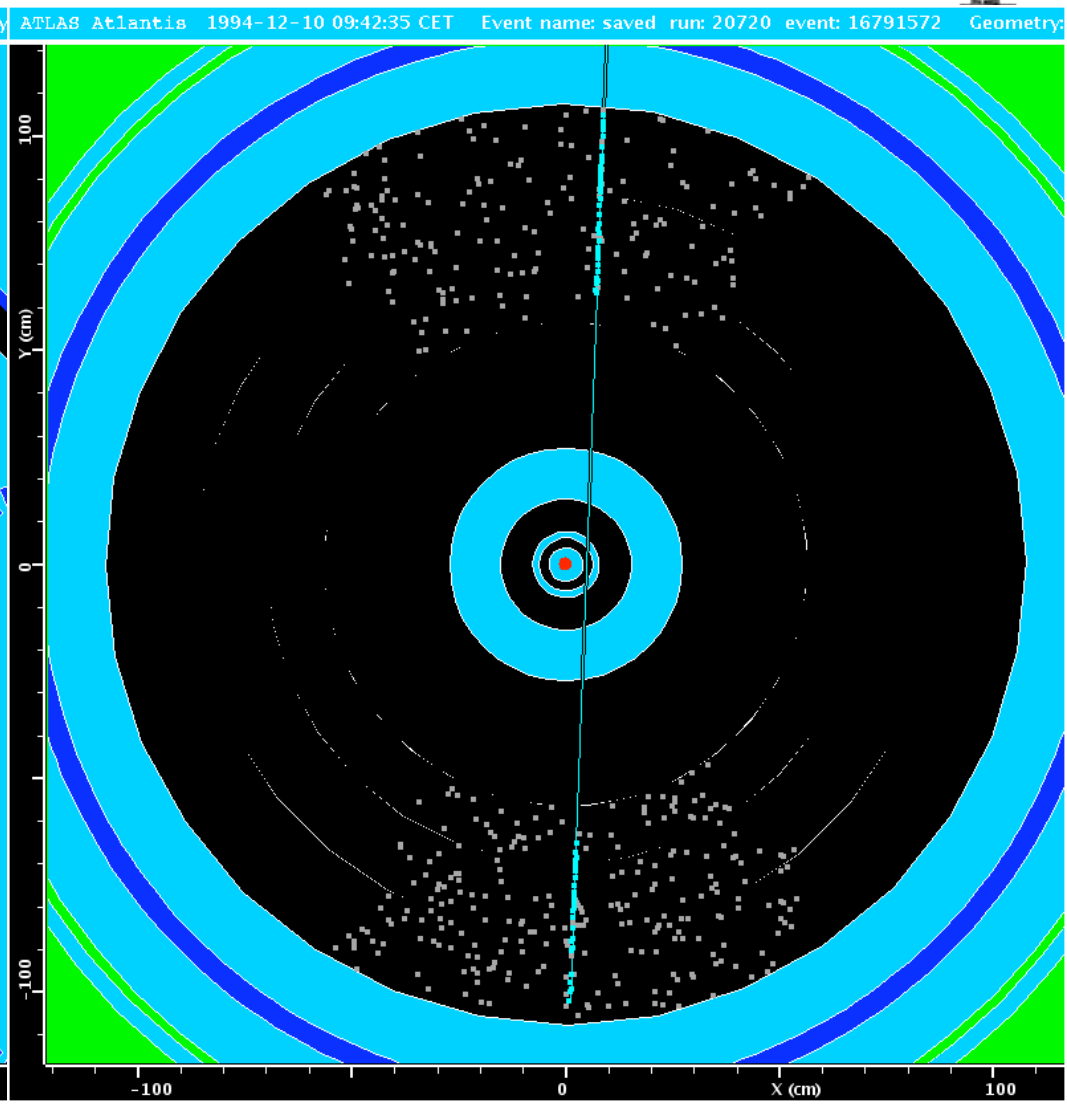
- electron bremsstrahlung can not be described by Gaussian process noise
- standard track fit biased
- several electron-specific track fits
- novel approach in ATLAS:
  Dynamic Noise Adjustment
  extension of standard Kalman filter
  - detect if position of next hit indicates (strong) brem'
  - if not continue KF. If yes, estimate z (energy fraction retained by electron)
  - calculate probability of z using material
  - calculate extra noise for covariance term s(q/p) and continue KF
- barrel layers: 2-6% radiation length probability for significant brem
- effects of brem much higher in end-cap (dead material)





Commissioning with Cosmic Rays





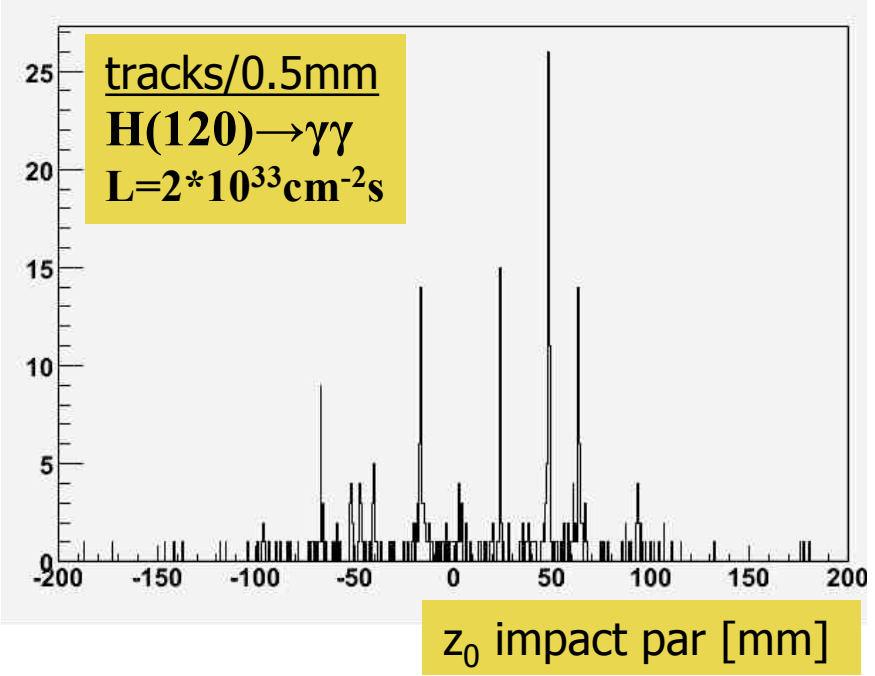
Combined reconstruction of a cosmic μ in ATLAS

See also talks by
D. Dobos, T. Golling

Vertex Reconstruction

Primary Vertex

- LHC beam spot $\sigma_x=\sigma_y=15\mu m$, $\sigma_z=5.6cm$
- however, better knowledge required for combined reconstruction (b- and tau tagging) and physics analyses (Higgs search, B-physics)
- separate signal from pile-up vertices
- different finding and fitting techniques available



Secondary Vertex

- identify decay vertex of B, D hadrons
- essential for inclusive b-tagging
- same fitting techniques as for primary vertex (secondary vertex finding is specific to the task)

Vertices of exclusive decays or photon conversions

- reconstruct specific topology, e.g. $J/\psi \rightarrow \mu\mu$, V_0 decay, $\gamma \rightarrow e^+e^-$
- kinematic fitting: mass constraint, pointing to primary vertex etc.

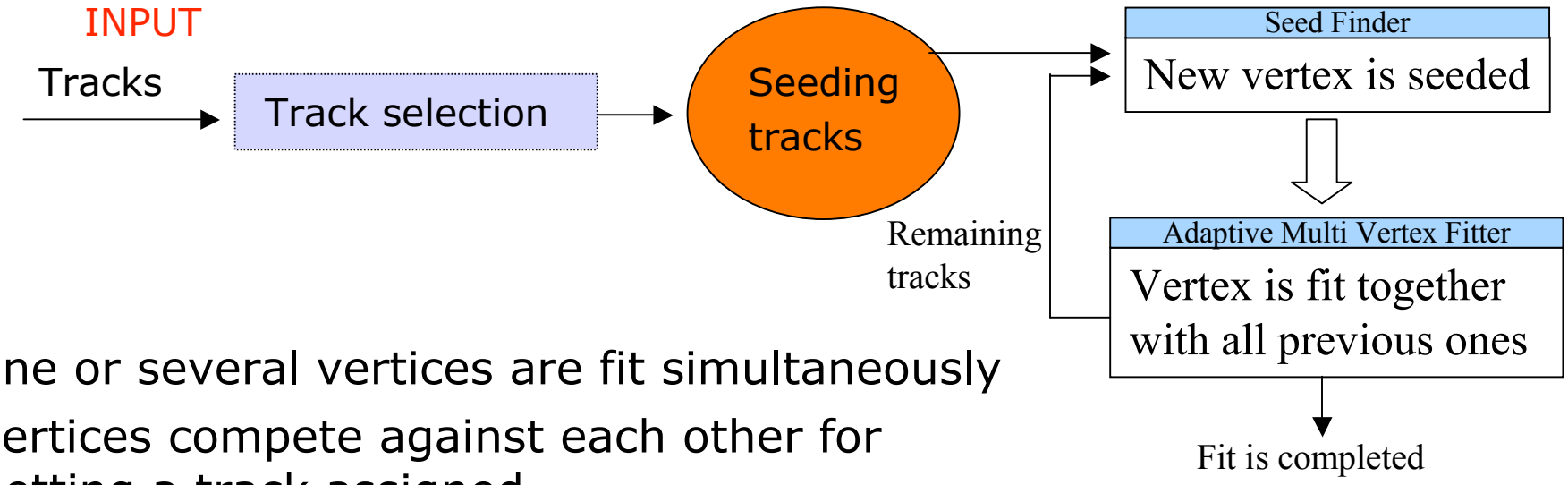
Vertex Reconstruction Software

Developed in parallel to Tracking Software:

- data structures are part of ATLAS event data model
- modularity and interfaces for tasks/operations
- migration of old code

VxCandidate
m_recVertex : Trk::RecVertex
m_vxTrackAtVertex : std::vector< Trk :: VxTrackAtVertex * >

Adaptive Multi-Vertex Fitter



- one or several vertices are fit simultaneously
- vertices compete against each other for getting a track assigned
- an iterative annealing procedure is used to approach a hard assignment

Vertex Fitters

Billoir tools package (*P.Billoir, S.Qian Nucl. Ins. and Meth. in Phys. Res. A311(1992) 139-150*)

- The equations of motion of a charged particle in the magnetic field are approximated with their Taylor expansion in the vicinity of the vertex.
- **FastVertexFitter:** the momentum vector is considered constant in the vicinity of the vertex. No refit of the incident tracks is performed.
- **FullVertexFitter:** The full parametrization of tracks is used, the refit of incident tracks is performed.

Sequential vertex fitter (*R.Frühwirth Nucl. Ins. and Meth. 225(1984) 352*)

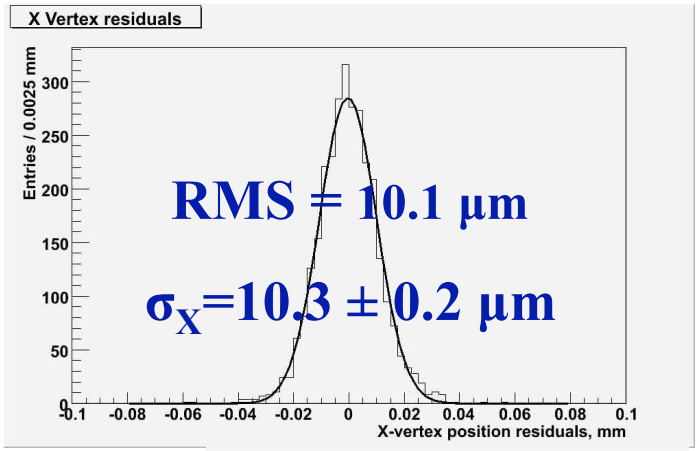
- Implements a conventional Kalman filter for the vertex fitting.
- A full analytical derivation of equation of motion is used.

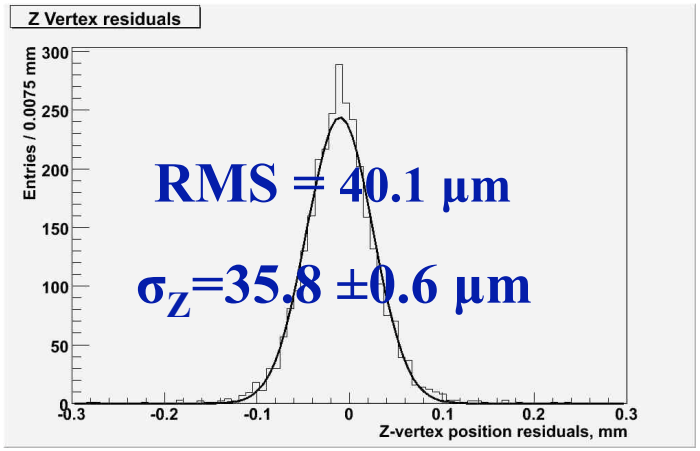
Adaptive vertex fitter (*R.Frühwirth et al. Nucl. Ins. and Meth. in Phys Res A 502 (2003) 699*)

- An iterative re-weighted least square algorithm.
- Down-weights tracks according to their compatibility to the vertex candidate.
- The outliers are thus efficiently discarded.

Primary Vertex Rec. Performance

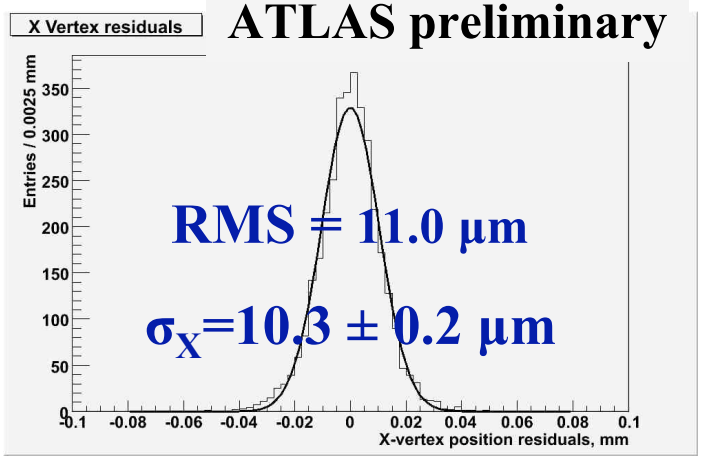
ATHENA rel. 12.0.6 Adaptive Multi Vertex Finder

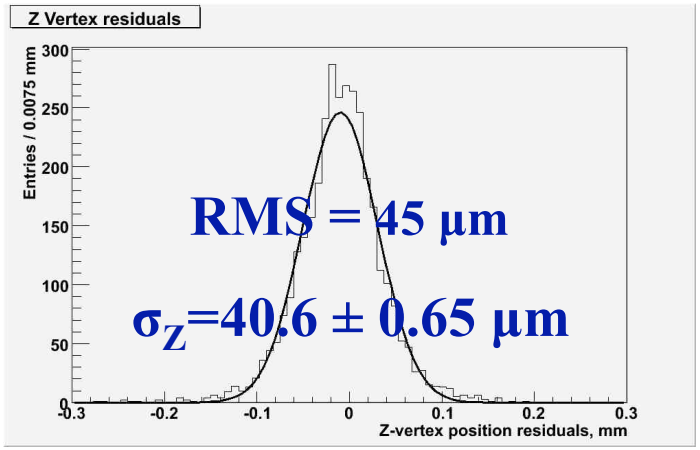




ttbar
Finding efficiency
(100 µm criterion)
ε= 96.9 ± 1.8 %

ATLAS preliminary





H(130)→4l
Finding efficiency
(100 µm criterion)
ε=94.1 ± 1.6 %

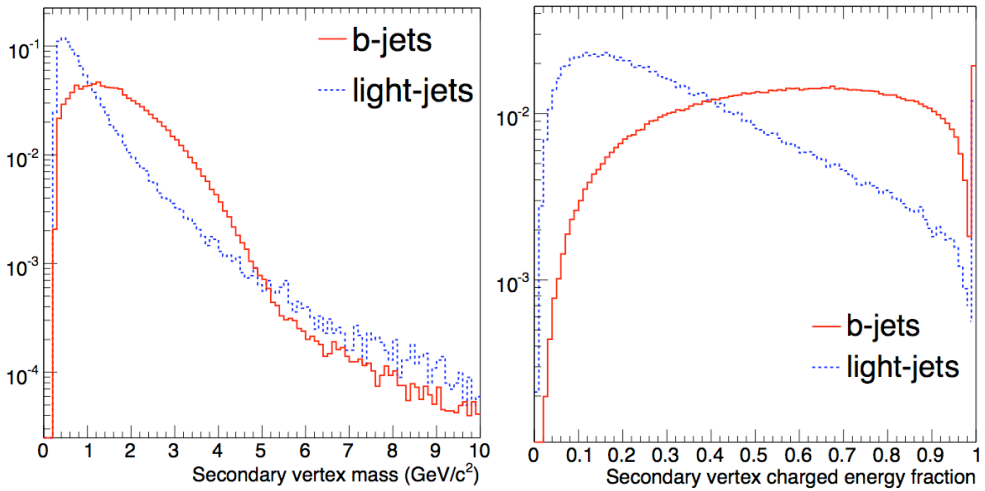
Realistic conditions: misaligned geometry with material distortion

Secondary vertex in flavour tagging

Improve tagging by adding information from B-decay vertex

- form inclusive vertex of b-hadron decay products
- purify seeds by kinematic cuts
- calculate discriminators, e.g.

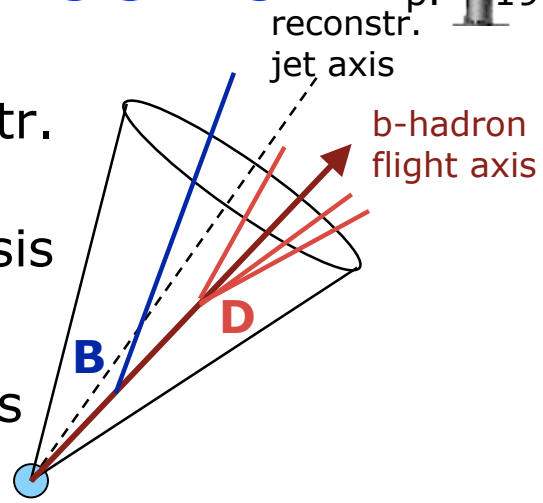
mass:, energy fraction:

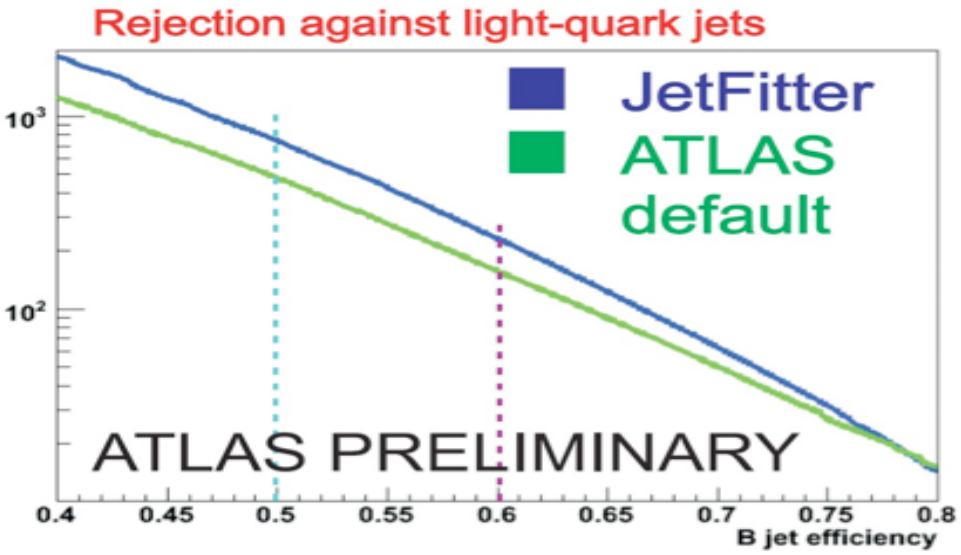


- sec. vertex efficiency ~60%
- increases light-quark rejection compared to impact-par. tag

New JetFitter:

- common geometr. vertex is not correct hypothesis
- fit B/D decay as separate vertices
- fit B/D decay as separate vertices by clustering them along b-hadron flight axis





- significantly better performance

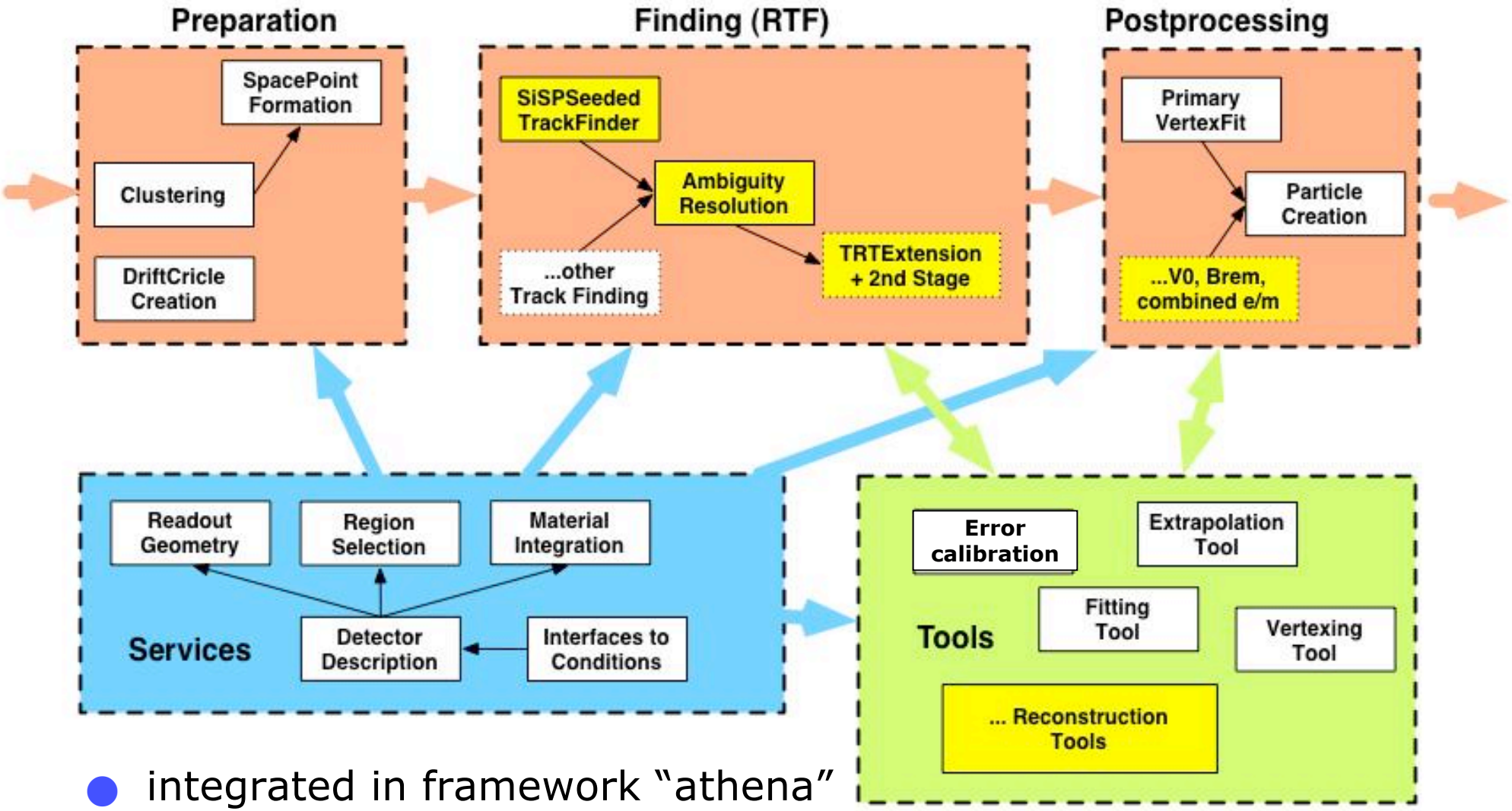
Summary and Outlook

- **ATLAS has redesigned its track & vertex reconstruction:**
  - modularity, common interfaces and data model
  - new code performs well (level of physics TDR or better)
  - several new developments integrated in new software
  - success with real data: combined test beam, cosmic μ
- **Software still being optimised and extended**
  - reconstruction of physics objects: $e^{\pm}$, $\mu^{\pm}$, tracks in jets…
  - vertex reconstruction in jets or with kinematic constraints
- **Thorough preparation for a realistic detector**
  - integrate alignment and calibration in reco framework
  - conditions support to cope with real detector
  - precise description of detector material
  - simulate realistic field, material and geometry
  - preparing for cosmic ray data with installed Si detectors
- **ATLAS Inner Detector tracking software will be well prepared for LHC turn-on**

Some BACKUP slides

BACK-UP

Framework for Reconstruction Design

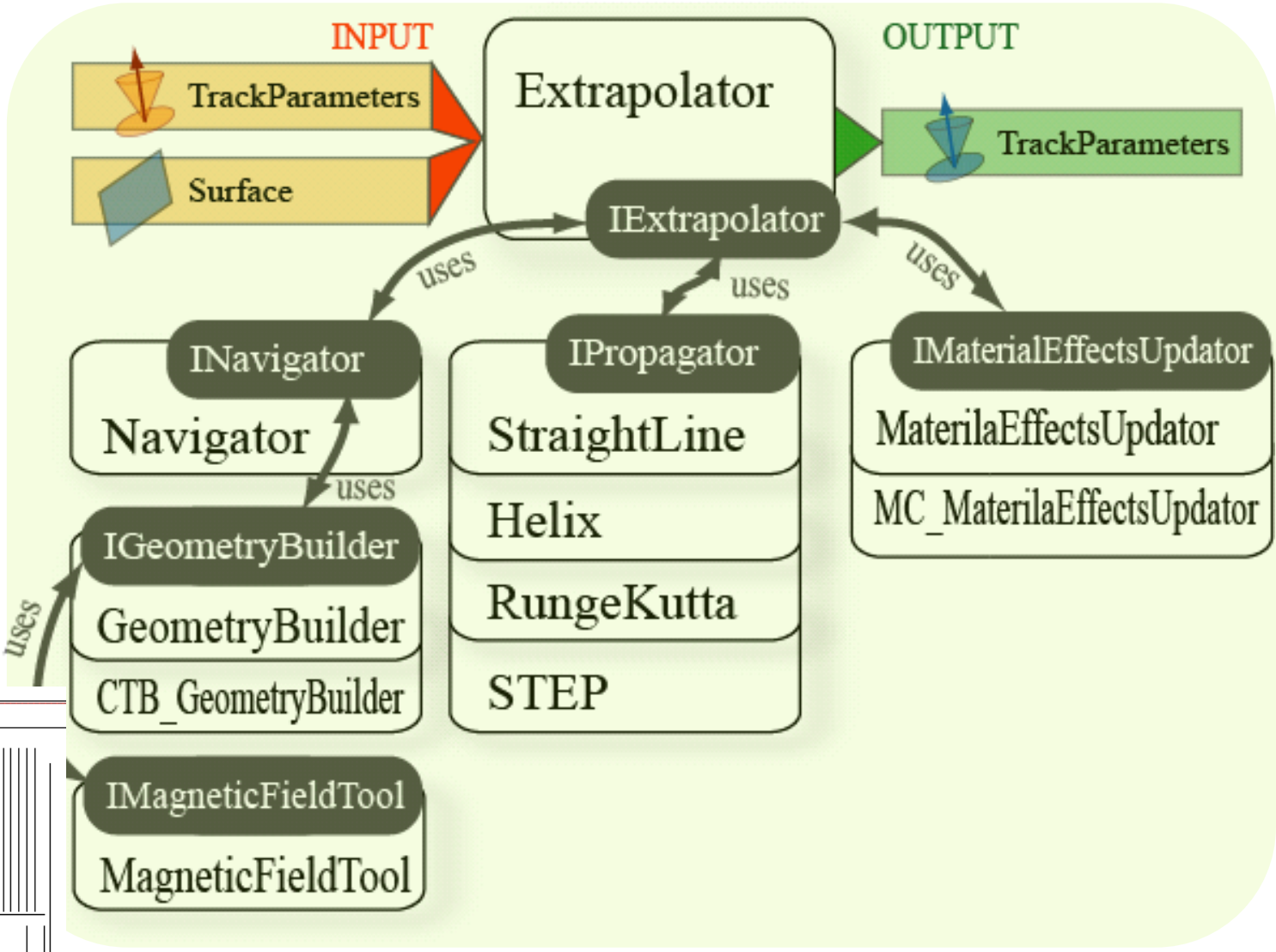


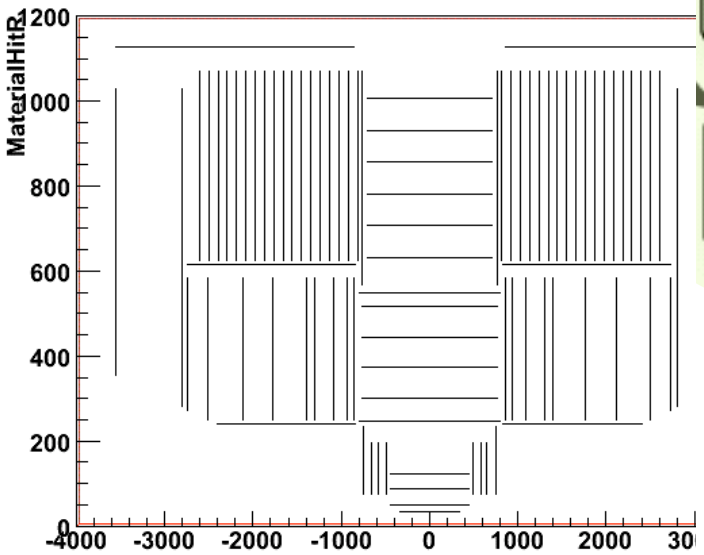
- integrated in framework "athena"
- data objects separated from algorithms
- for offline and event filter (3rd level trigger)

BACK-UP

Tracking Tools: Parameter Extrapolation

- available to entire ATLAS thanks to **det-independent tracking EDM**
- modular due to abstract interfaces
- uses TrackingGeo. to provide material effects to track fit





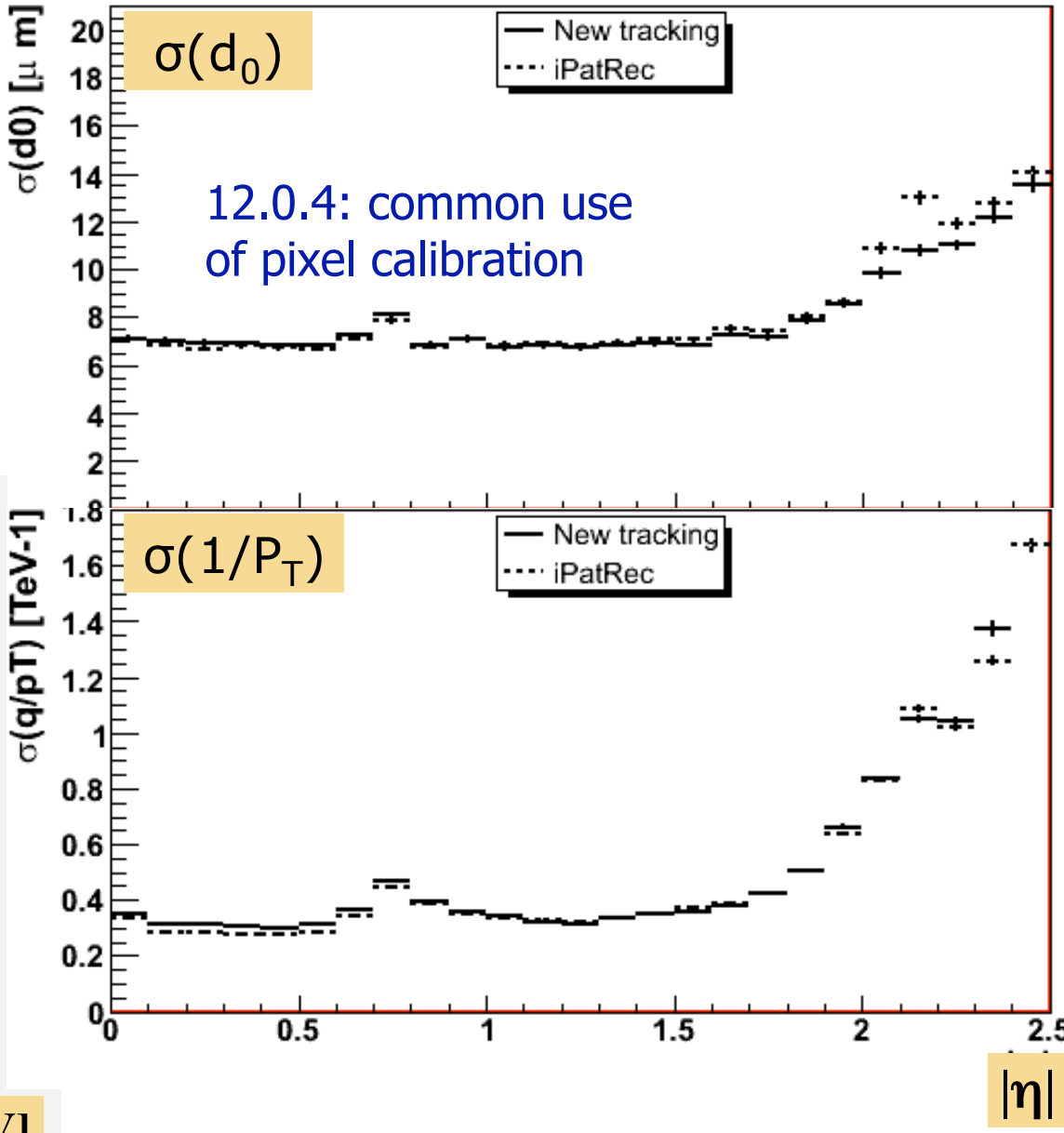
structured along functionality

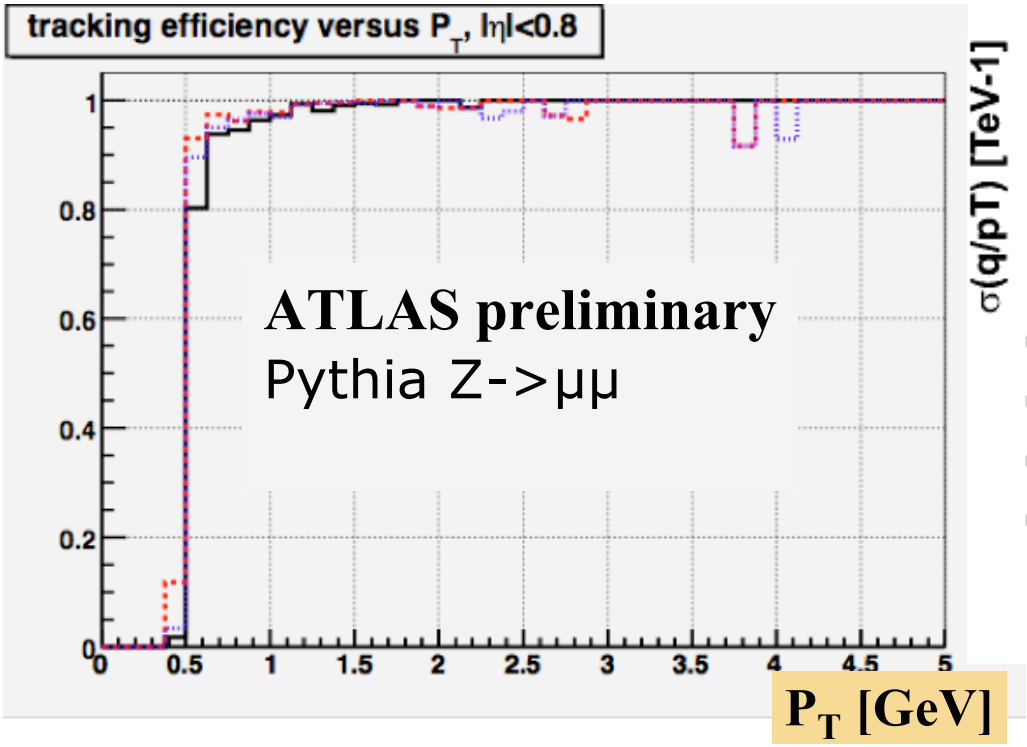
BACK-UP

Inner Detector Tracking Performance

- old algorithms still available as reference
- code development monitored by daily automatic framework
- good efficiencies and resolution achieved

single μ (200GeV)





BACK-UP

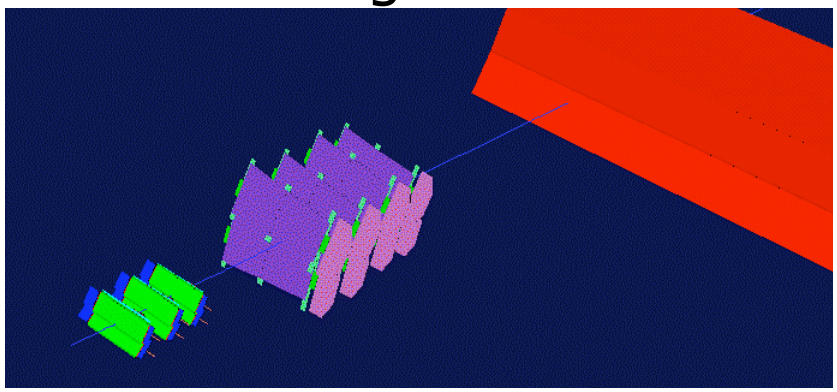
Expected Material Effects in Silicon

BACK-UP

Combined Test Beam 2004

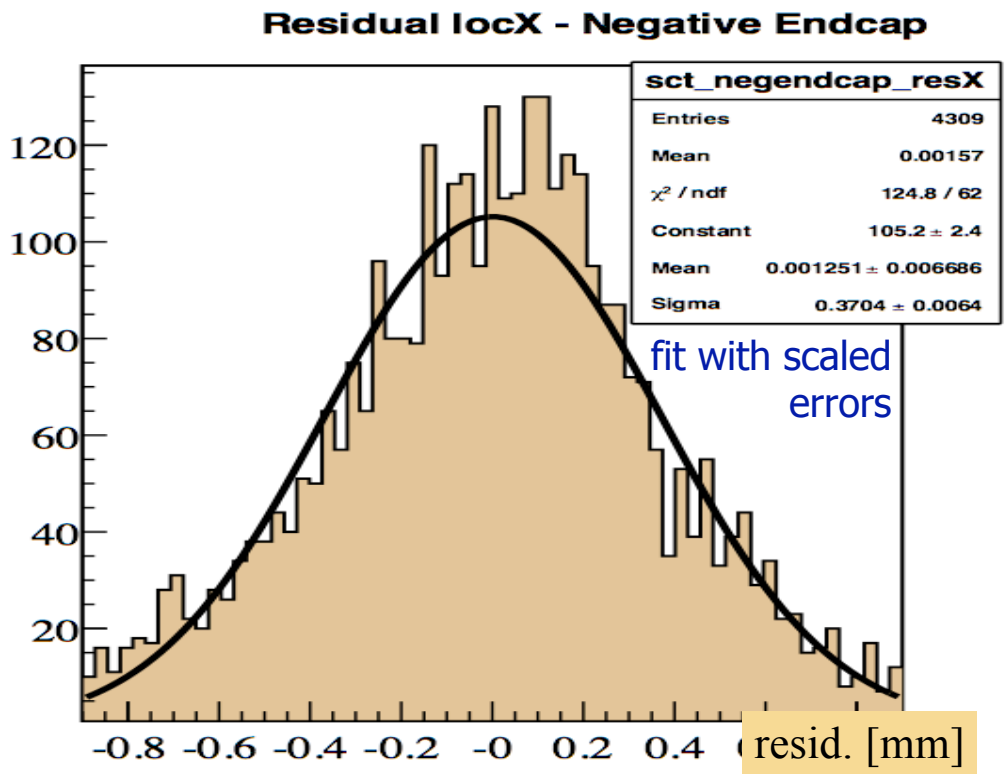
Combined test-beam 2004

- beams through slice of ATLAS

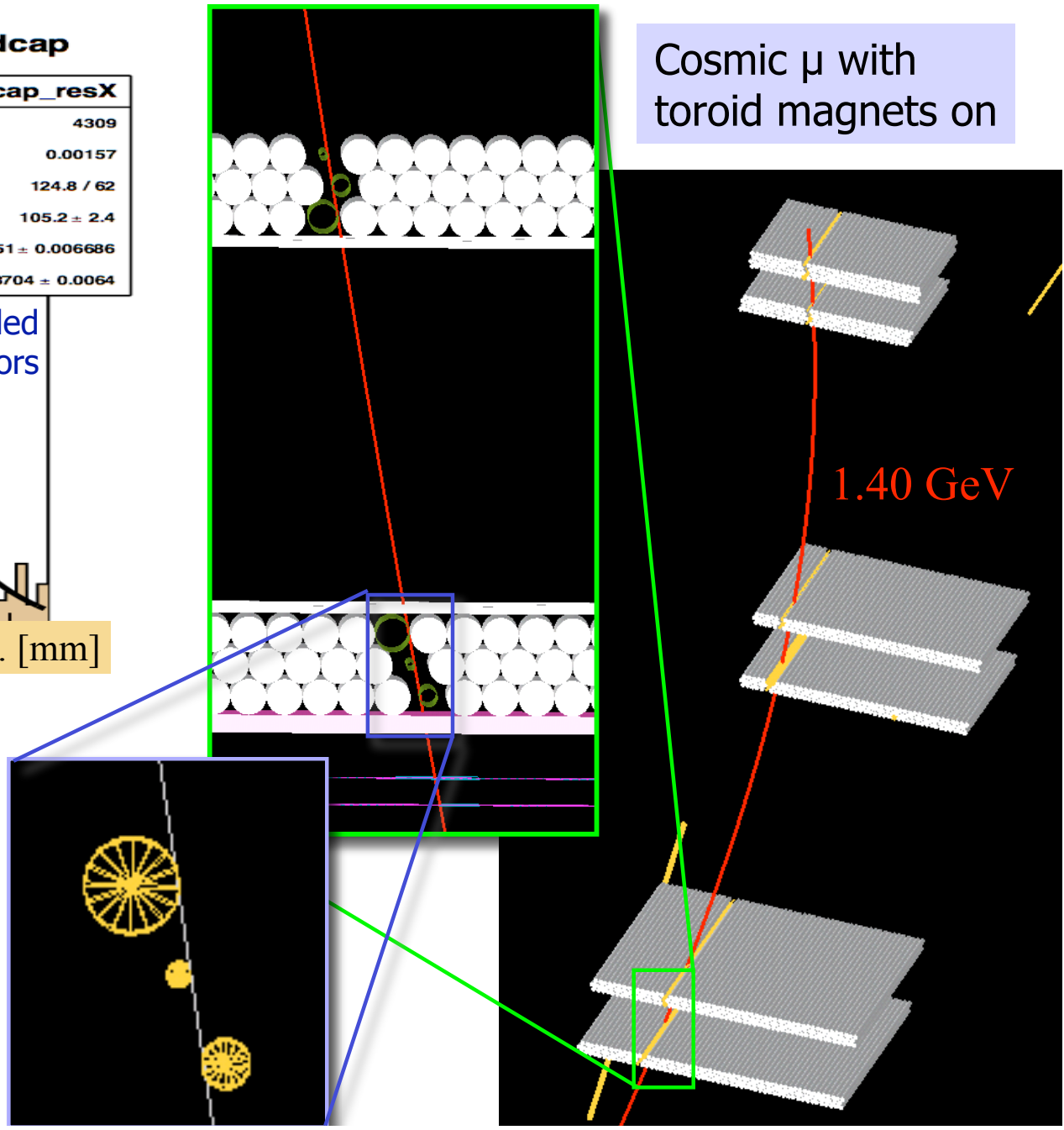


- Exercise tracking on real data
  - detector imperfections
  - data decoding
  - use conditions database
  - monitoring
- study performance and improve simulation for ATLAS

Commissioning with Cosmic Rays



Cosmic μ in SCT endcap before installation



Cosmic μ with toroid magnets on

See also talks by D.Dobos, D.Robinson