ATLAS inner detector and flavour tagging

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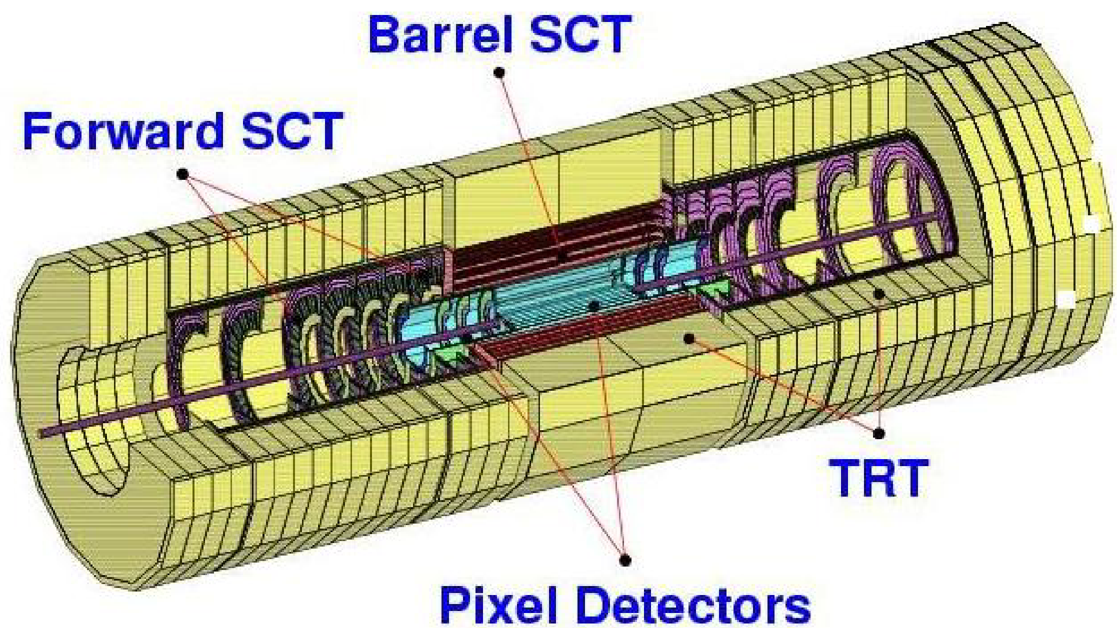
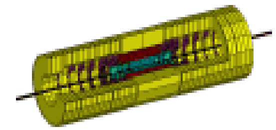
LHC physics and detectors symposium, 1/5/03

- Overview of ATLAS inner detector
  - Challenges for tracking at LHC
  - ATLAS ID design, recent changes
  - Initial layout without staged items
- Status of detector construction
  - Subdetectors and integration
- Performance of the detector
  - Alignment and calibration
  - Software evolution
  - Flavour tagging: b, τ
- Conclusion



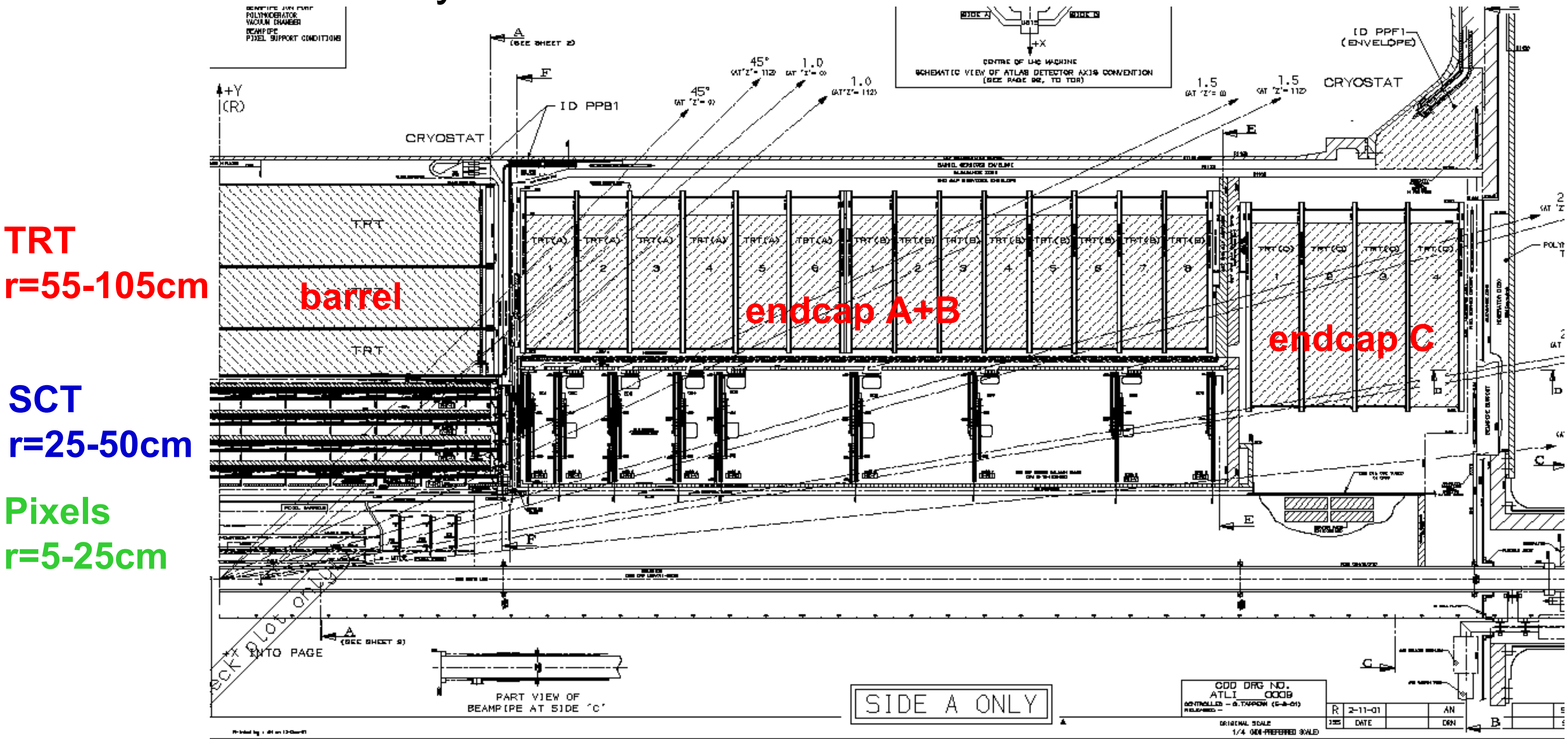
Tracking at LHC



- Challenges for LHC tracking detectors
  - Occupancy: around 700 tracks within acceptance ($|\eta|<2.5$) per high lumi event
  - Time between bunch crossing: 25 ns – need very fast response/electronics
  - Radiation damage: fluence from 10^{13}-10^{14} equiv. 1 MeV neutrons/cm^2/year
  - Material: minimise to avoid compromising calorimeter performance for e.g. $H\rightarrow\gamma\gamma$
    - Limited space (r < 1.1 m) – keep costs of solenoid and calorimeter under control
- ATLAS solution based on three technologies
  - Mixture of space point and continuous tracking – for resolution and pat.rec.
  - Pixel detector
    - 3 barrel layers, 3 endcap disks: 12 μm r-ϕ and 60 μm r-z resolution
  - Semiconductor Tracker (SCT)
    - Large area (60 m^2) silicon detector: 4 barrels and 9 disks in each endcap
    - Four points per track, 16 μm r-ϕ and 580 μm r-z resolution (40 mrad stereo)
  - Transition radiation tracker (TRT)
    - Straw tube detector (axial barrel/radial endcap); 4mm diameter straws; r~50-105 cm
    - Electron ID through detection of transition radiation photons

ATLAS inner detector

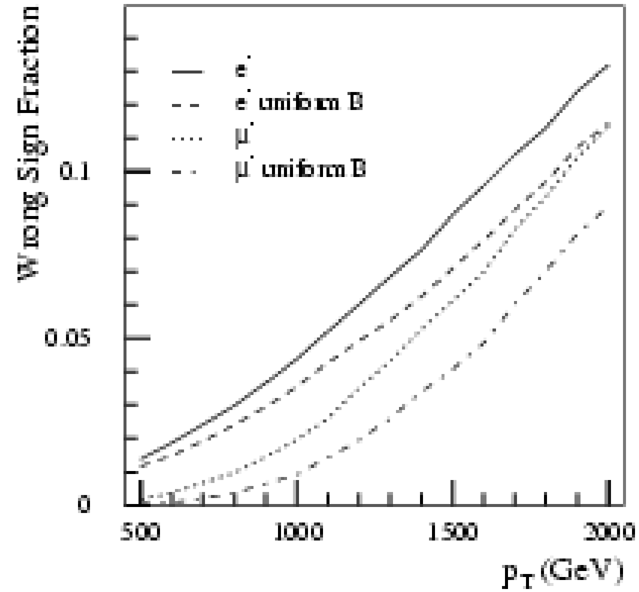
- Inner detector layout:

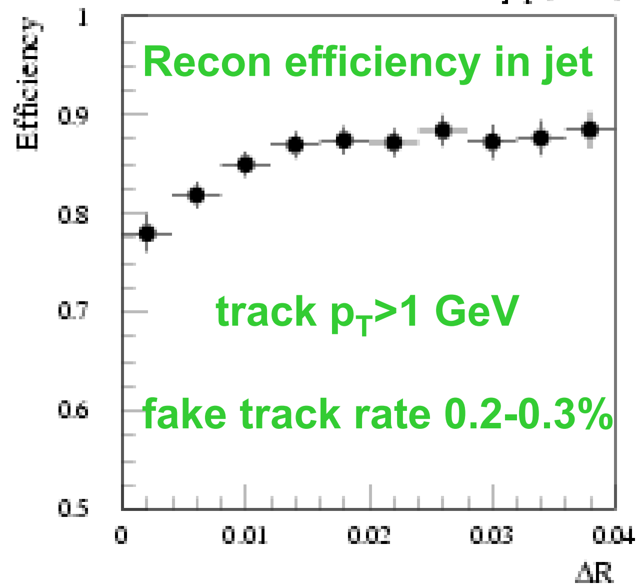


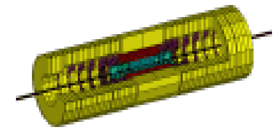
- Initial detector without staged items:
  - No middle pixel barrel layer and endcap disk (keep b layer), no TRT C wheels

Key design parameters

- ID inside barrel cryostat including solenoid and LAr calorimeter
  - 2T solenoid field, non uniform at high z
    - Reduces to 1.0T at z=2.7m
  - p_T resolution: charge det. at ~500 GeV
  - Full coverage to $|\eta|$=2.5 for all detectors
- Pattern recognition inside jets / with pileup
  - Challenging: high track density
  - 7 precision points/track (3 pixel+4 SCT)
    - Each r-ϕ and z (40 mrad stereo in SCT)
  - Up to 36 TRT straw hits
    - Continuous tracking… optimised for tracking performance not TR e-ID
    - π rejection up to 100 for 80% e-ID efi.
  - cotθ resl. <10^{-3}, V^0 finding, b-tagging
  - Results from Physics TDR (1999)
    - Reference for ID performance

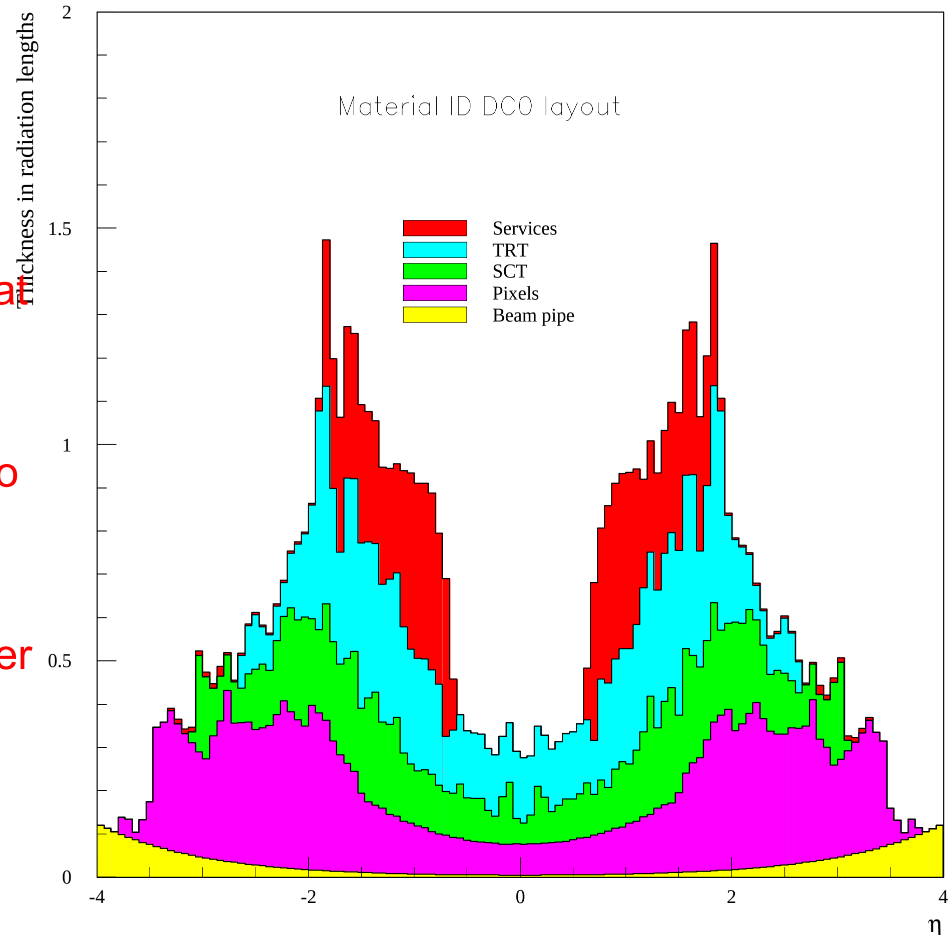






Recent design changes

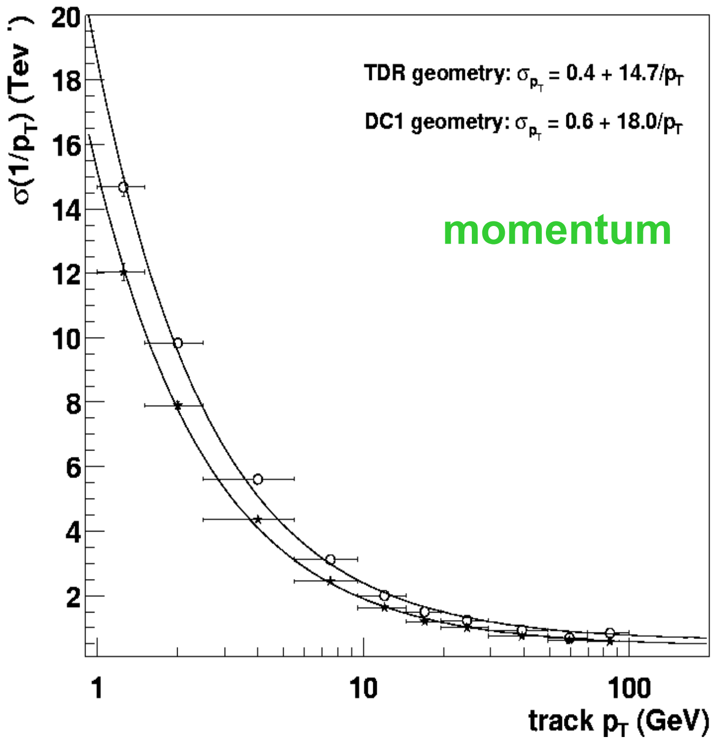
- Main changes are to pixel detector
  - Fully insertable layout
    - Pixels can be installed (and upgraded) without disturbing rest of ID
    - All pixel services run inside SCT endcap at low radius – mostly outside η acceptance
  - Change in detector radii
    - 1^{st} pixel layer ('B layer') moved from 4.3 to 5.0 cm to accommodate larger beampipe
  - Change in pixel material
    - Factor 1.5 increase per layer due to thicker sensors, full engineering module design
- Lots of detailed engineering changes to SCT and TRT
  - Realistic services, connectors, thermal enclosures, patch panels…
    - An ongoing process as detectors go into production – still some updates to do

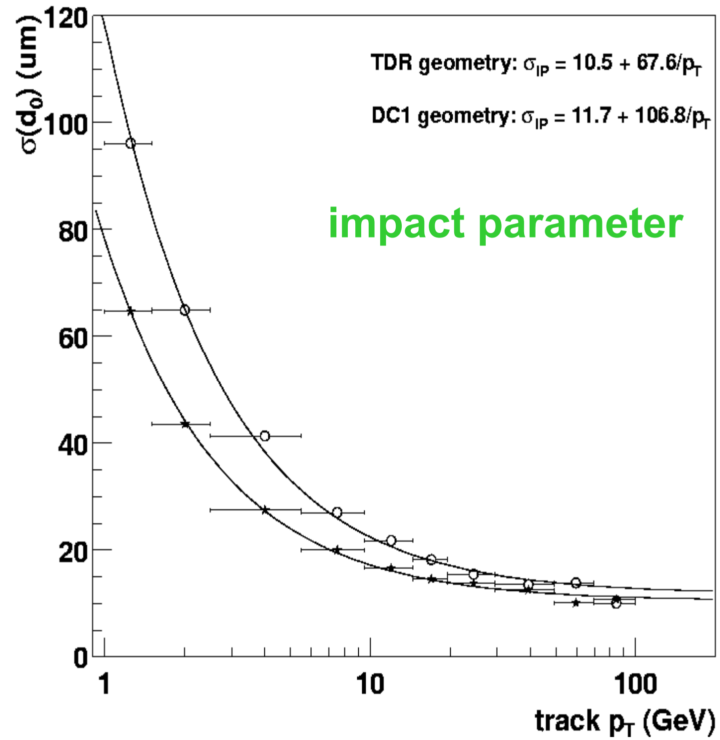


- At η=0, have 0.3 X_0, rising to around 1 X_0 in detectors at $|\eta|$=2
- Services all at high radius – little impact

Effect of design changes

- Most visible in the transverse momentum and impact parameter resolution



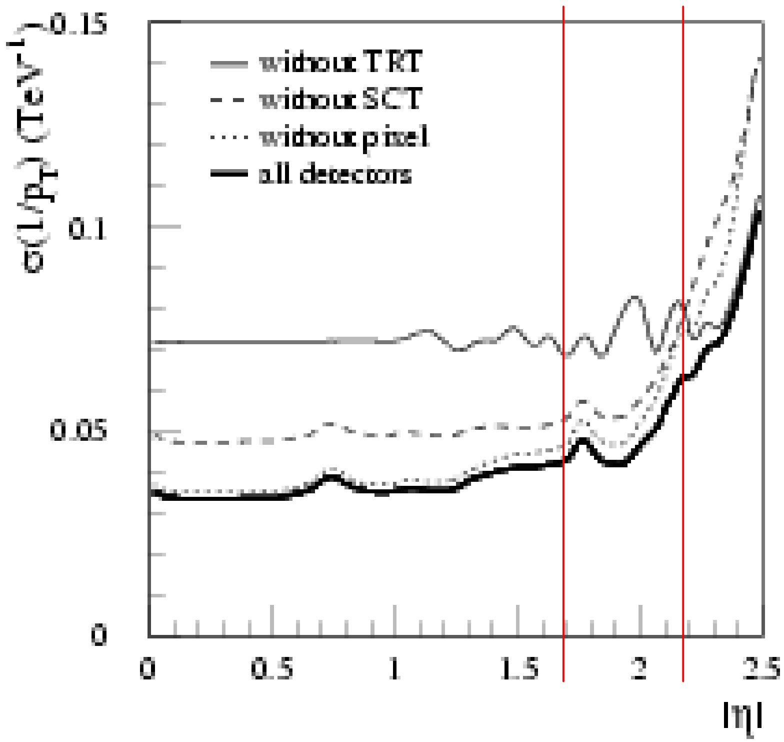


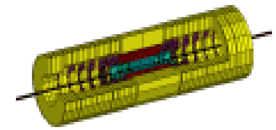
- Momentum and IP multiple scattering terms increase by 1.2 and 1.6 at η=0
  - Effect of increased material and larger radius of first layer
  - Some impact on physics performance – see later …

Initial layout without staged items

- Initial detector layout will not have:
  - Middle pixel barrel layer (r=9 cm)
    - But B-layer is still there
  - Middle pixel disk (z=58 cm)
  - TRT C wheels (acceptance 1.7<η<2.5)
- Effect on:
  - b-tagging performance
    - ~25% reduction in light quark rejection
  - Momentum resolution
    - Around 50% worse in high η region
  - Pattern recognition capability
    - Difficult to quantify, but occurs for initial low luminosity running where patrec is easiest
- Physics impact:
  - 15-20% more luminosity for 'initial discoveries'
  - Full detector needed for high-lumi running

momentum resolution

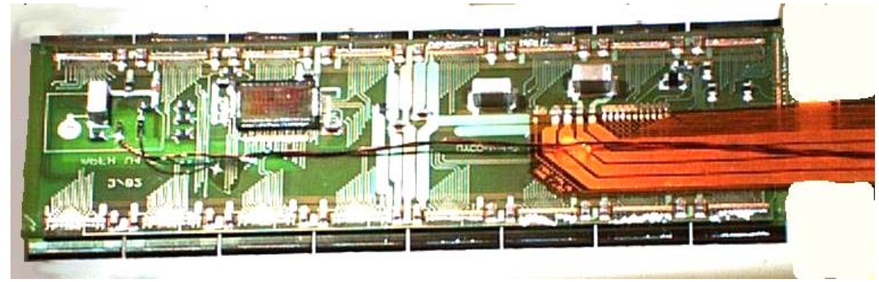




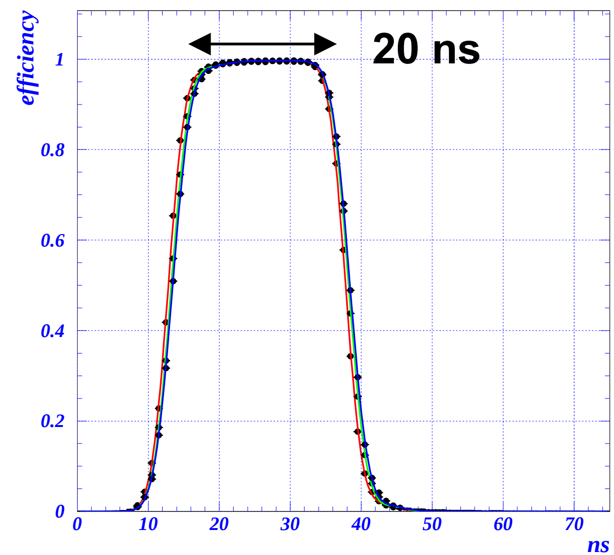
Detector status - pixels

- Last subdetector to be installed
  - Pixel sensors and mechanics in production
  - Electronics (DSM) in last design iterations
    - Pilot production runs – use for first ‘final’ modules to gain time and experience
    - Integration of several chips + flex circuit onto one module shows good performance
- Tests with irradiated modules (10^{15} n/cm^2)
  - Uniform behaviour – efficiency > 99%
    - Low timing dispersion between pixels
  - Low noise - < 10^{-7} noise hit / pixel after irradiation – 10 hits in whole ATLAS pixels
- Next steps
  - Big effort on irradiation, system test and beam test of modules this year
    - Produce 2-300 modules this year (10-15%)
    - Production debugging, QA, tests ⇒ disks

Pixel module

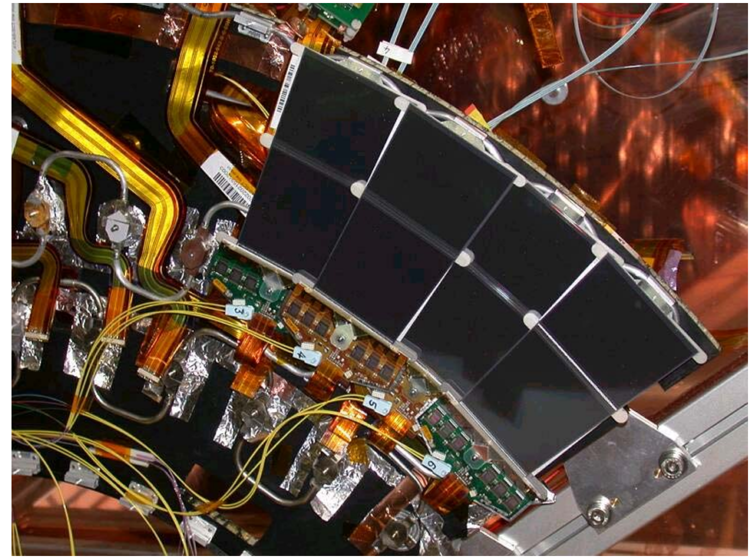


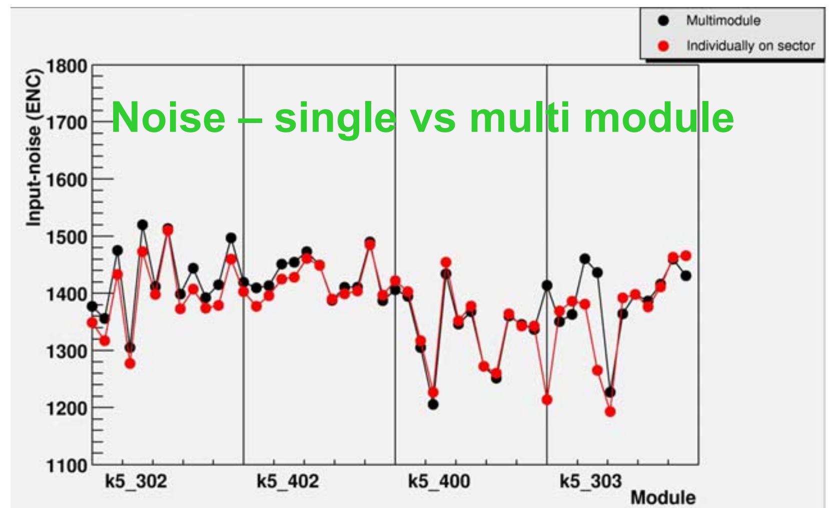
Efficiency vs t_0 in testbeam



Detector status - SCT

- Production of basic components ~ done
  - Delivery and acceptance of all sensors
  - Front end ASICs almost completed
- Major effort now on module assembly
  - Barrel module production in several sites
  - Initial endcap modules had noise problems
    - Redesigned 'hybrid' (module circuit board) during summer, produced and tested
    - Performance within requirements, before and after irradiation, test beam OK
  - Now producing all other components, prepare for module assembly
- Assembly of first SCT barrel starting
  - Finalise cooling and structural components
    - Assembly of ~400 modules, integration,cooling, testing, DAQ, DCS
  - First barrel delivery to CERN end 2003



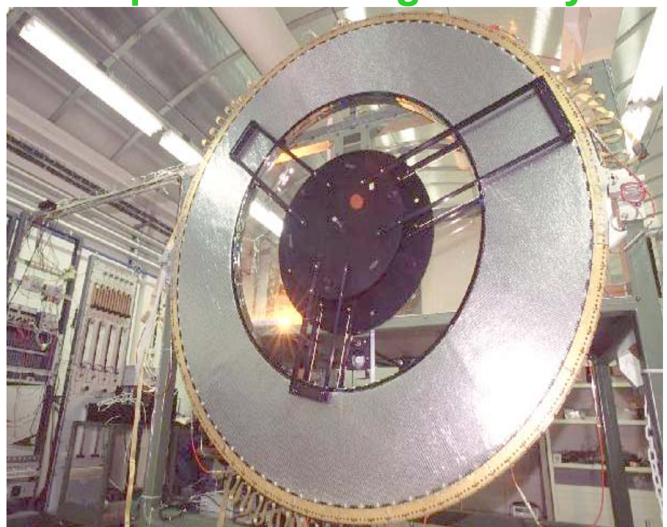


Detector status - TRT

- Progress with components:
  - Straw production finished
  - Electronics – digital chip switched to DSM technology – in production
    - Some delays on analogue FE chips
- Module production and gas studies
  - Problem with barrel wire joint: delay stringing
    - Reassess active gas:⇒ 70% Xe+27%CO_2+3%O_2
    - Many tests of new gas – TRT performance is not significantly changed
    - New concept of 'cleaning runs' (with collisions) – ~1 day with ~10% CF_4 to remove Si deposits on wires. Tracking but no TR.
    - Wire stringing now continuing
  - Endcap wheels – first delivered to CERN
    - Now starting up series production in Russia
  - Start to assemble barrel modules and stack endcap wheels at CERN in next year …

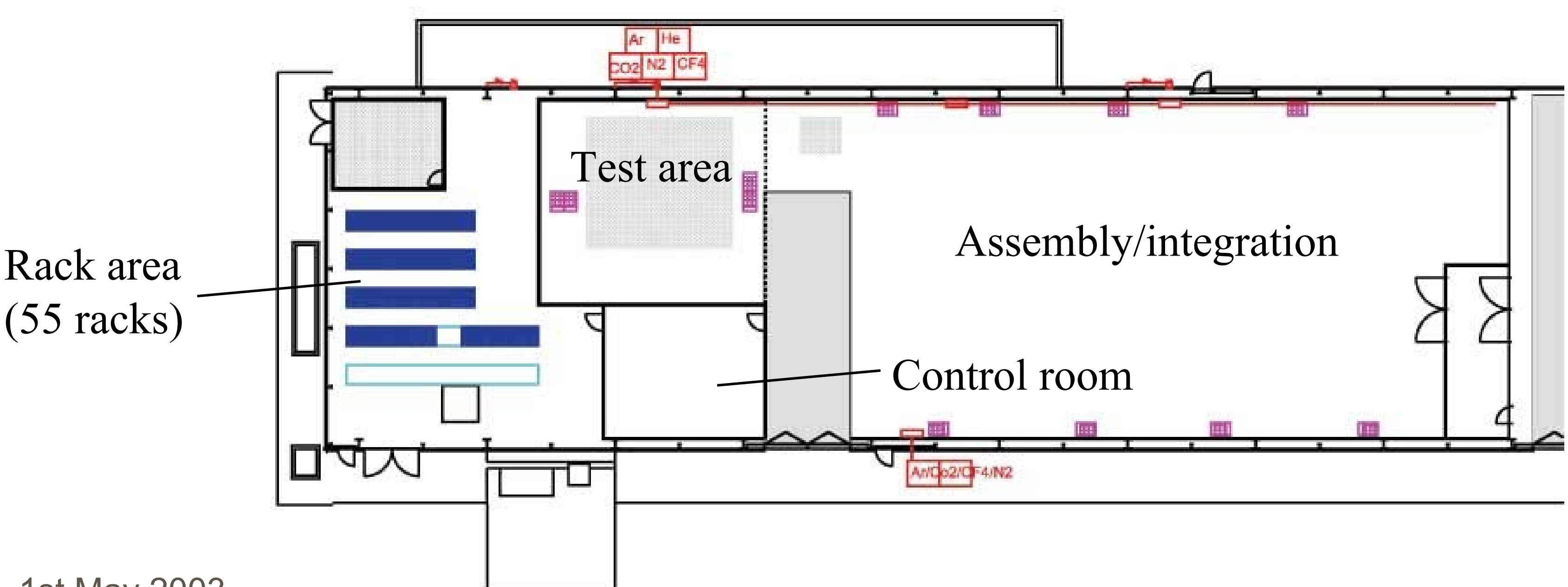
Barrel module production

Endcap wheel wire geometry test



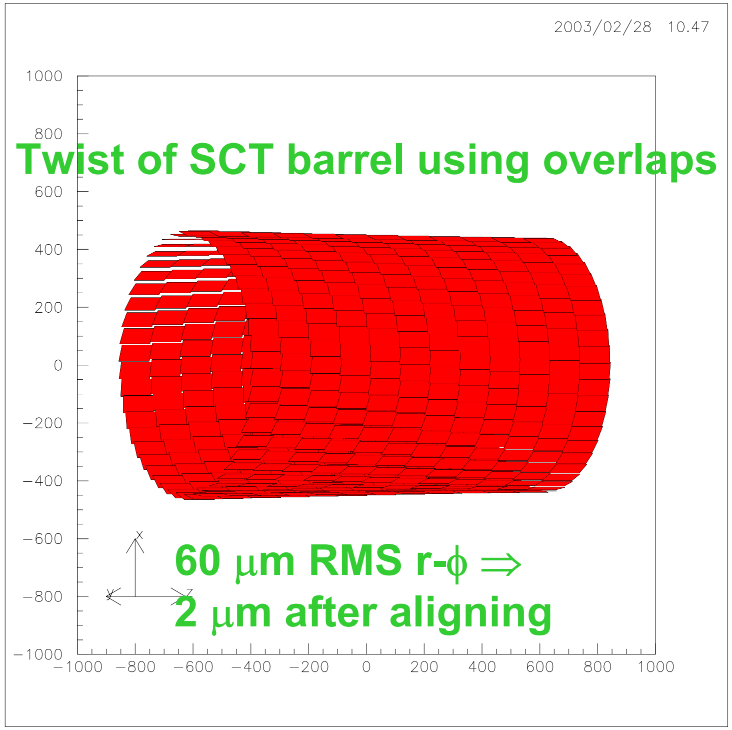
Putting it together

- ID components beginning to come together at CERN
  - Setting up dedicated facility at ATLAS pit for integration and assembly
    - SCT 4-barrel integration, TRT barrel assembly and endcap 'stacking'
    - SCT-TRT integration and testing (separate and combined)
    - Pixel detector assembly (together with beampipe)
  - Significant infrastructure (moderate cleanroom, cooling, DAQ, DCS…)
    - Preparation of building/infrastructure being finalised – first detector pieces 2nd half 2003



Alignment and calibration

- Unprecedented requirements for alignment and calibration of ATLAS ID:
  - For most physics, 7μm (pixel), 12 μm (SCT), ~30 μm (TRT) r-φ alignment required
    - On scales over O(1m), with 10s of kW of heat load… challenging
  - For precision physics (e.g. 15 MeV W mass measurement), need r-φ at 1 μm level
  - B-field needs to be understood to 0.05% – combination of field mapping and fitting
- Strategies for alignment:
  - Precision mechanics and optical surveys
    - At many stages in construction and assembly
  - Pre-installation X-ray survey of SCT (and TRT?)
    - Locate modules to 10 μm r-φ, 50 μm z precision
  - Alignment with tracks during running
    - Exploit overlaps and 'normal' tracks (e.g. W,b→μ)
    - Potential to solve for whole SCT+pixels (6 d.o.f./module) and all TRT straws (alignment plus R-t calibration) in few hours data taking + processing
  - FSI – in-situ laser-based interferometry for SCT
    - Monitor distortions of SCT structures in real time



Software and performance

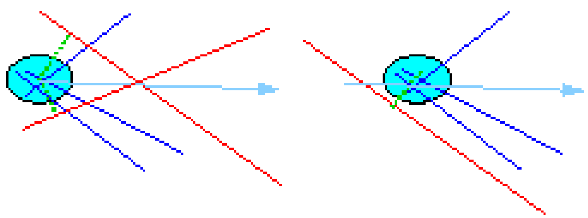
- Two major pattern recognition and trackfitting programs:
  - xKalman – Kalman filter based approach, seeded from TRT or SCT/pixels
  - iPatRec – combinatoric space point search in SCT/pixels, extrapolate to TRT
    - Similar results on simulated data – best final approach will depend on real-life detector performance.
    - Mixed Fortran/C^{++} versions used for PhysicsTDR, now major effort in migrating to OO analysis framework (Athena) and common elements where possible.
  - Major effort on 'event data model' for inner detector
    - Flow of information: digitisation $\Rightarrow$ 'byte stream' data $\Rightarrow$ clusters $\Rightarrow$ space points$\Rightarrow$tracks
    - Work starting on including proper alignment and calibration information in chain.
- Data challenges:
  - Simulating and reconstructing ATLAS events is a major operation
    - Data challenges DC0/DC1 – 1000s CPUs used for weeks,worldwide – starting to use GRID-type tools.
    - DC1 data used for following performance studies – compare with old PhysTDR results
    - So far, results without pileup (additional minimum bias events) – later phase of DC1

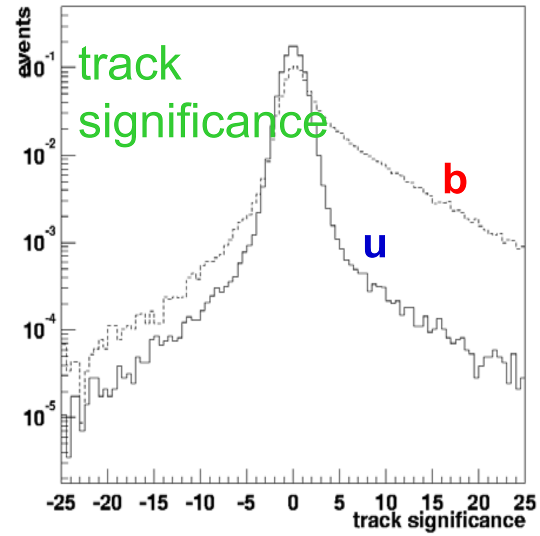
Flavour tagging - introduction

- Flavour tagging studies concentrated on b-jets:
  - Top quark decays: $t \rightarrow bW$ – essential tool for study of top physics
  - Objects coupling preferentially to heavy particles, e.g. Higgs bosons
    - Important for many discovery channels at both low and high luminosity
- Main focus on b-tagging using long lifetime and high mass of b hadrons
  - Tracks with large impact parameters w.r.t. primary vertex, secondary vertices
    - Also some tagging power from $b \rightarrow l$ decays – soft electrons, or muons in TileCal
  - Simple and fast b-tagging algorithms in level 2 trigger and event filter
- Properties of b-jets of interest:
  - Wide momentum range, from 15 GeV to 400 GeV (range of Higgs masses)
    - Multiple scattering dominates at low jet energies, pattern recognition at high energies
  - Typically define jets with a cone size of $\Delta R=0.4$
    - Catches nearly all b decay products, charged track multiplicity 5-10 for $p_T>1$ GeV, around half from b decay, others from fragmentation.
    - Particles from minimum bias relatively unimportant (in pp), especially at low luminosity
- Recent work: performance with latest layouts, algorithmic improvements

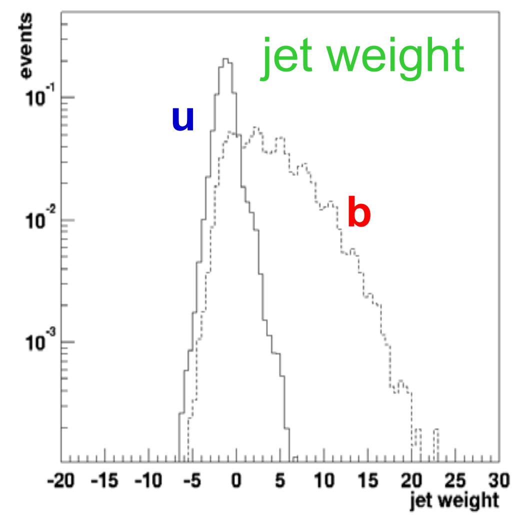
b-tagging – basic method

- Main b-tagging algorithms based on **impact parameter significance S**
  - Look at transverse IP relative to beamspot position, divided by error
  - Sign according to direction of nearest jet





- Transform into a ratios of probabilities for tracks of significance S from light and b jets
- Combine the probabilities for all tracks into a jet weight.
  - Simple in transverse plane, as beamspot is small (15 μm) and stable.
  - If primary vertex of interaction can be reconstructed (resolution around 30 μm), can also use z coordinate info (‘2D+z’ / ‘3D’)



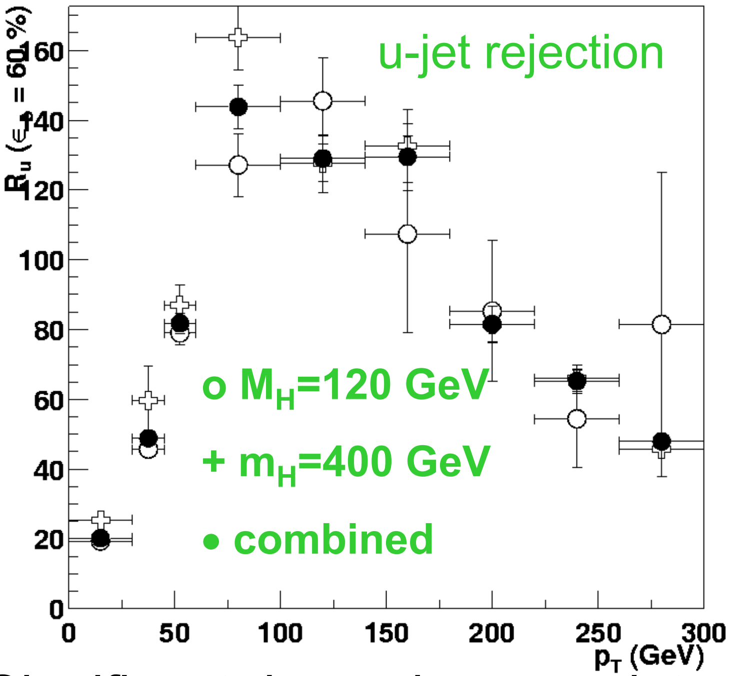
b-tagging performance I

- Study performance on WH events for m_H=120 and 400 GeV
  - Force H to decay to heavy ($b\bar{b}$) and light ($u\bar{u}$,$c\bar{c}$) jets to calculate rejection factors
  - Compare PhysTDR performance with DC1 layout using 2D and '3D' b-tagging:
    - For 50% b-jet tagging efficiency, look at rejection factors for u and c jets

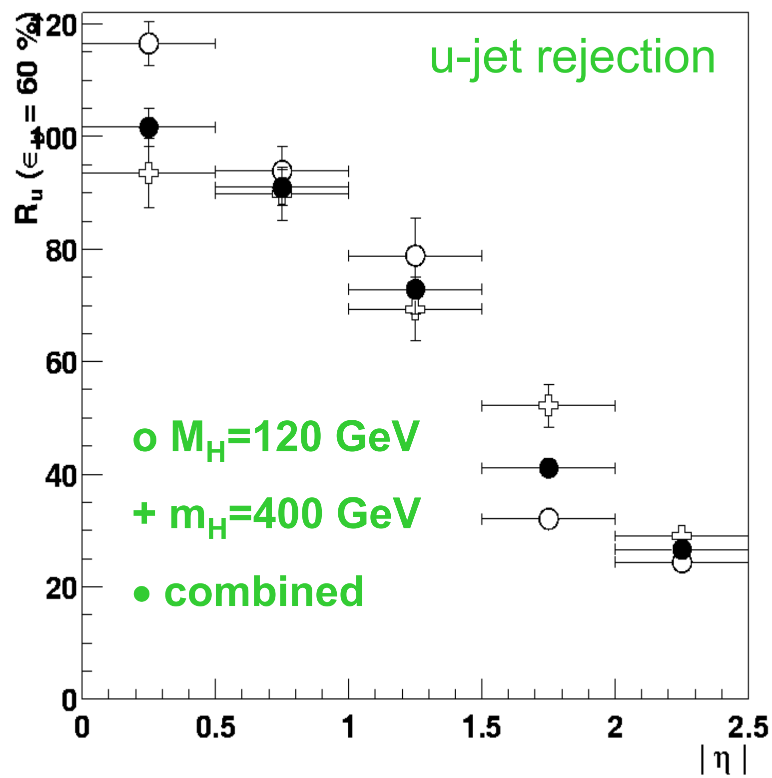
u/c rejection	PhysTDR	DC1 (2D)	DC1 (2D+z)
R_u(120 GeV)	359±23	189±8	321±14
R_u (400 GeV)	141±9	144±8	195±9
R_c (120 GeV)	11.5±0.4	9.8±0.1	12.3±0.2
R_c (400 GeV)	13.6±0.5	10.6±0.2	12.6±0.3

  - Significant deterioration in performance for low energy jets (m_H=120 GeV)
    - Low p_T tracks – multiple scattering and material important
    - Less significant for high energy u and for charm jets – improvements in pattern recognition – less tails in IP distributions
  - Including z information improves things, recovers at least PhysTDR performance

b tagging performance - II



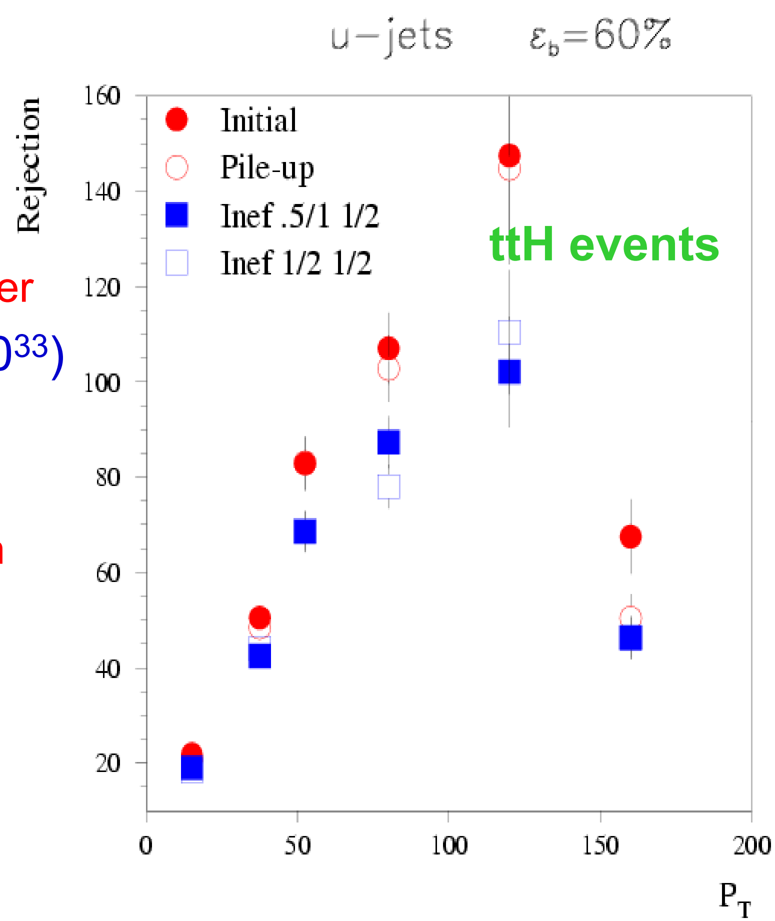
- Significant dependence on η:
  - Tracking performance degrades at high η, and jet energy rises for constant E_T



- Significant dependence on jet p_T:
  - Balance between multiple scattering (low p_T) and pattern recognition effects (high p_T)
    - Very dense jets at high energy
    - Best rejection around 100 GeV
    - Little intrinsic dependence on boson mass

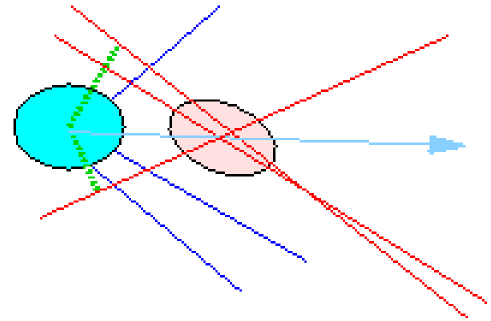
Study of $t\bar{t}H$ events

- More studies on $t\bar{t}H$ events:
  - Compared to WH, additional jets from t decays
    - ~20% rejection loss due to jet overlaps
    - Similar performance on b-jets from t and H
  - Effect of switching to 400 μm pixels in b layer
    - Around 10% degradation, but some may be recovered by choosing 'best' modules for b layer
  - Effect of low-lumi pileup (4.6 min-bias @ 2×10^{33})
    - Small – dominated track density from jet
  - Effect of initial 2-pixel layer layout
    - Worse IP resolution – around 30% degradation
  - Program of work to paramterise performance with new layout for fast simulations
- Calibration of b-tagging:
  - Use $t\bar{t}\rightarrow Wb\ W\bar{b}\rightarrow q\bar{q}b\ l\nu\bar{b}$ events
    - Select using b-tag + lepton ID from one top
    - Kinematic fit (m_{top}) on $q\bar{q}b$ system to ID b/u jets



Algorithm improvements

- Impact parameter method does not use all information:
  - Secondary vertex reconstruction
  - Vertex mass information
    - Important to get best performance at LEP and SLD, especially for c tagging
- First studies of secondary vertex recon.
  - Kalman filter-based fast vertex finding
  - Identify primary and all 2-track secondary vertices.
    - Merge secondaries to make b vertex
    - Vertex in 70% / 8% of b/u jets
  - Two discriminating variables:
    - Mass of b decay vertex
    - E_{vertex}/E_{jet} – fraction of jet energy in vertex
  - Combine variables with IP-based tag

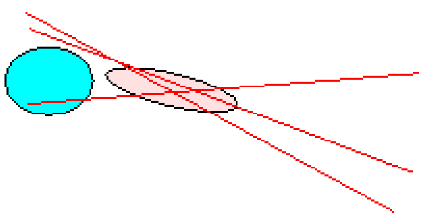


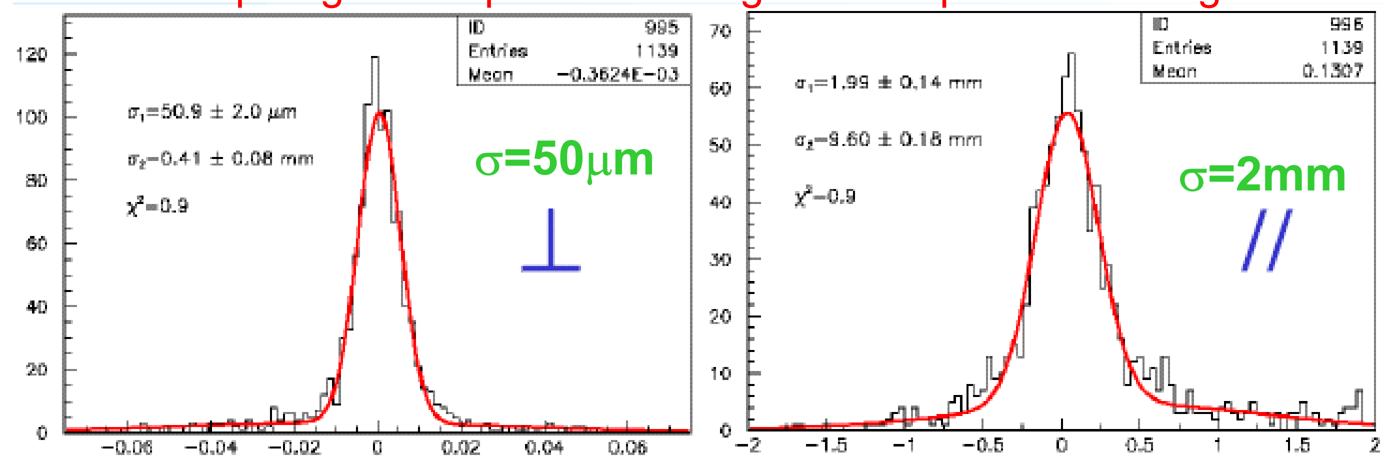
u rejection	2D+z	2D+z+vtx
3 pixel layers		
R_u(100 GeV)	430±53	751±125
R_u (400 GeV)	293±26	606±78
2 pixel layers		
R_u (100 GeV)	219±19	361±41
R_u (400 GeV)	198±15	351±34

- Factor 1.5-2 improvement in rejection, even for reduced 2-layer detector
  - Encouraging….

τ tagging

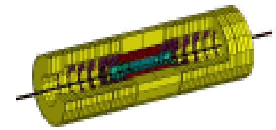
- τ tagging useful in e.g. $A/H \rightarrow \tau\tau$, usually in mixed leptonic/hadronic mode
  - Main selection tools are lepton ID and E^T_{miss}, rather than vertex selections
  - τ decays in very narrow cones, usually 1 or 3 charged particles – challenging
    - Small impact parameters, low multiplicity vertices with small opening angle
  - Some study of reconstructing secondary vertices in 3 prong hadronic τ decays
    - Look at resolution on 3 prong vertex position orthogonal and parallel to τ flight direction





  - Cuts include requirement for 3-prong vertex separated from primary by > 4mm
  - Gives efficiency of 44%, QCD-jet rejection of $>10^3$ for 3 prong decays
    - Provides a modest (10%) enrichment of $A \rightarrow \tau\tau$ sample

Conclusions - the road ahead



- ATLAS inner detector design is now mature
  - Last phases of detailed engineering design ongoing
    - Services, patch panels, off detector components, integration
  - Initial layout without staged items
    - Moderate loss in performance – but need full detector for high luminosity
  - Most components now in production, and assembly is beginning
    - Some problems found (inevitable in such a large complex system), solutions being worked on and production proceeding.
  - Major work ahead on integration of ID parts coming to CERN, installation and commissioning – preparations are beginning
- Work continues on software and performance
  - Follow changes in engineering design and software evolution
  - Studies of alignment and calibration, for ‘day 1’ and ultimate performance
  - Performance is being maintained to meet ATLAS physics goals
    - Performance of detector is robust
    - New ideas – e.g. b-tagging with secondary vertices, use of τ tagging, heavy ions
- Look forward to exploiting the ATLAS ID for physics beginning in 2007