Geant4 Physics Evaluation in ATLAS

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1 – ATLAS Inner Detector/Pixels
2 – ATLAS Liquid Argon Calorimeters
3 – ATLAS Muon System
4 – ATLAS Tile Calorimeter

This Talk:

- GEANT4: brief history and introduction
- Strategies for GEANT4 physics validation in ATLAS
- Muon energy loss and secondaries production in the ATLAS calorimeters and muon detectors
- Electromagnetic shower simulations in calorimeters
- Hadronic interactions in tracking devices and calorimeters
- Conclusions

GEANT4: A Brief Introduction

Some GEANT4 history: (see also http://wwwasd.web.cern.ch/wwwasd/geant4/geant4.html)

- started as RD44 (1994-1998) at CERN with aim to provide a toolkit based on object-oriented software technology as a replacement for the GEANT3 framework;
- since the first production version in 1999 the world-wide GEANT4 collaboration provides development, maintenance and user support;

GEANT4 in ATLAS:

- ATLAS/GEANT4 Comparison Project initiated in 2000 to validate available physics models and establish lines of communication with GEANT4 developers;
- mostly "private" codes used by various (sub)detectors in GEANT4 physics evaluation phase (2000-now) -> avoid delays by software integration and design issues -> quick response highly appreciated by GEANT4 team!
- now software consolidation and integration phase, preparation for full physics simulation in Data Challenge 2 (spring 2004): GEANT4 -> ATHENA integration nearly complete for Liquid Argon calorimeters (Leltchouk, Seligman);

What are the GEANT4 Features?

Similarities to GEANT3:

- provides all tools to describe complex detector geometries based on a pre-defined list of volume shapes;
- has pre-defined list with principal particle properties;
- has default particle tracking and stepping functionality;
- has default hit definition;
- has similar physics models for various particle types for direct comparisons;
- allows graphical presentations of detector geometries and shower development;

Differences to GEANT3:

- allows implementation of complex user-defined volume shapes (G4Accordion for the ATLAS Electromagnetic Barrel absorber folds, for example);
- no pre-defined materials or tracking medium properties, but straight forward client interfaces to implement those (also for mixtures);

More GEANT4 Features

Other differences to GEANT3:

- interaction physics ("physics lists") completely user controlled, but some important examples and support from experts are provided, especially for hadronic interactions – also attempt by GEANT4 to collect and publish user experience;
- no overall tracking (kinetic) energy threshold;
- explicit production of secondaries controlled by minimum range cut, rather than energy threshold;
- no default I/O or persistency package;
- very configurable: user can control interaction physics, tracking, stepping (mandatory in case of user defined volume shapes), graphical viewer (DAWN, VRML…);
- toolkit, rather than framework, allows integration into other frameworks like ATHENA;

Strategies for G4 Physics Validation in ATLAS

GEANT4 physics benchmarking:

- compare features of interaction models with similar features in the old GEANT3.21 baseline (includes variables not accessible in the experiment);
- try to understand differences in applied models, like the effect of cuts on simulation parameters in the different variable space (range cut vs energy threshold in secondaries production…);

Validation:

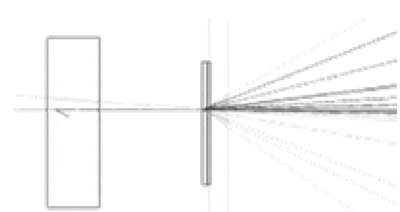
- use available experimental reference data from testbeams for various sub-detectors and particle types to determine prediction power of models in GEANT4 (and GEANT3);
- use different sensitivities of sub-detectors (energy loss, track multiplici-ties, shower shapes…) to estimate GEANT4 performance;
- tune GEANT4 models ("physics lists") and parameters (range cut) for optimal representation of the experimental detector signal with ALL relevant aspects;

G4 Validation Strategies: Some Requirements…

- Geometry description:
  - has to be as close as possible to the testbeam setup (active detectors and relevant parts of the environment, like inactive materials in beams);
  - identical in GEANT3 and GEANT4;
  - often common (simple) database used (muon detectors, calorimeters) to describe (testbeam) detectors in GEANT3 and GEANT4:

    example: forward calorimeter uses actual machining and cabling database in simulations to describe electrode dimensions, locations and readout channel mapping;
- Environment in the experiment:
  - particles in simulations are generated following beam profiles (muon detectors, calorimeters) and momentum spectra in testbeam (muon system);
  - features of electronic readout which can not be unfolded from experimental signal are modeled to best knowledge in simulation (incoherent and coherent electronic noise, digitization effect on signal…);

Geant4 Setups (1)

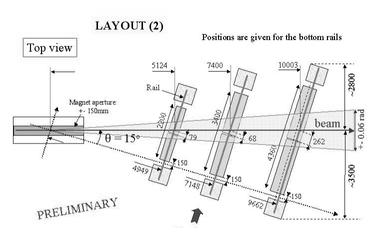


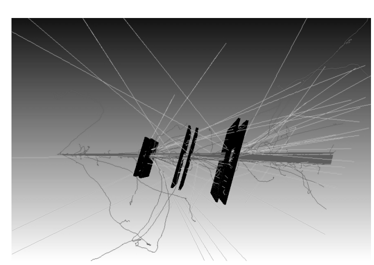
Detector plastic Cover (3mm thick)

Silicon sensor (280 µm thick)
FE chip (150 µm thick)
PCB (1 mm thick)

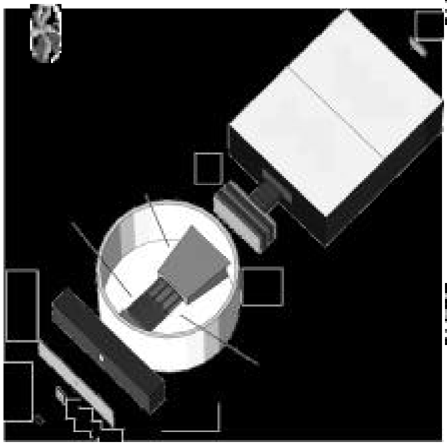
- Hadronic Interaction in Silicon Pixel Detector

- Muon Detector Testbeam

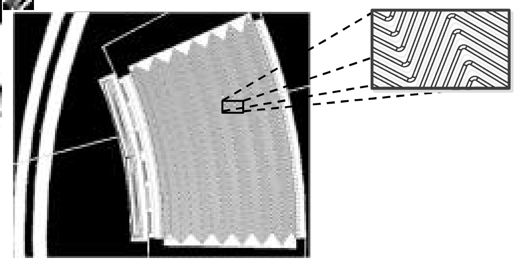




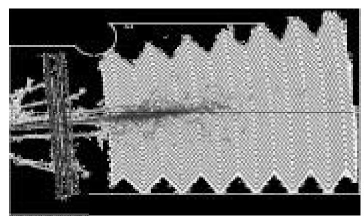
Geant4 Setups (2)



- Electromagnetic Barrel Accordion Calorimeter



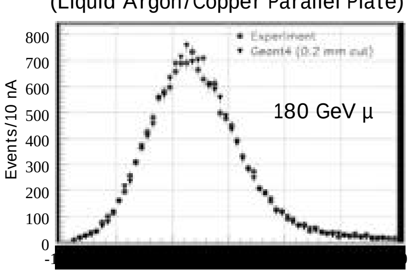
- 10 GeV Electron Shower



Muon Energy Loss

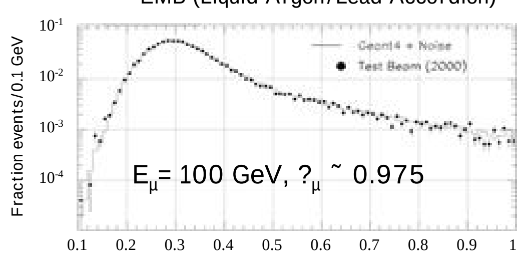
(Sept. 2002)

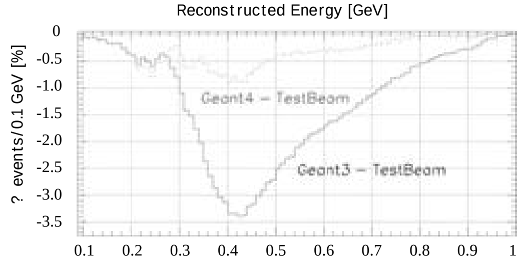
- Hadronic EndCap Calorimeter (HEC) (Liquid Argon/Copper Parallel Plate)



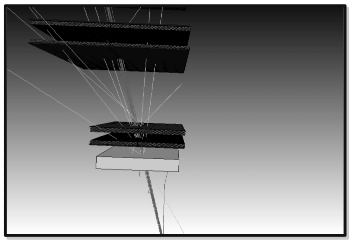
- G4 simulations (+ electronic noise) describe testbeam signals well, also in Tile Calorimeter (iron/scintillator technology, TileCal);
- some range cut dependence of G4 signal due to contribution from electromagnetic halo (d-electrons);

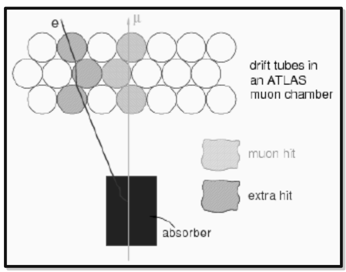
- Electromagnetic Barrel Calorimeter EMB (Liquid Argon/Lead Accordion)





Secondaries Production by Muons (Sept. 2002)





Muon Detector:

- extra hits produced in dedicated testbeam setup with Al and Fe targets (10, 20 and 30 cm deep), about ~37 cm from first chamber;
- probability for extra hits measured in data at various muon energies (20-300 GeV);
- GEANT4 can reproduce the distance of the extra hit to the muon track quite well;
- extra hit probability can be reproduced between 3 – 10% for Fe, some larger discrepancies (35%) remain for Al (preliminary analysis);
- subject is still under study (more news expected in mid-October);

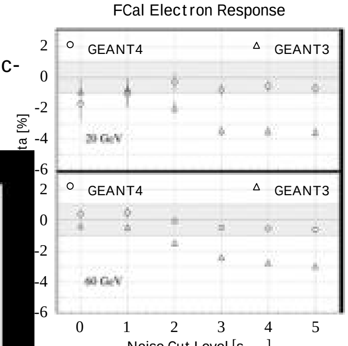
Geant4 Electron Response in ATLAS Calorimetry

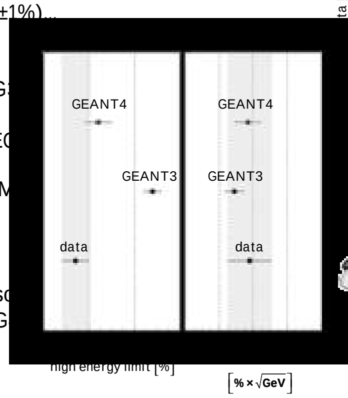
(Sept. 2002)

Overall signal characteristics:

- GEANT4 reproduces the average electron signal as function of the incident energy in all ATLAS calorimeters very well (testbeam setup or analysis induced non-linearities typically within ±1%)...
- ...but average signal can be smaller than in G… and data (1-3% for 20-700 µm range cut in HE…
- signal fluctuations in EM… very well simulated;
- electromagnetic FCal: high energy limit of reso… lution function ~5% in G… ~ 4% in data and G3;

FCal Electron Response





- TileCal: stochastic term 22%GeV$^{1/2}$ G4/G3, 26%GeV$^{1/2}$ data; high energy limit very comparable;

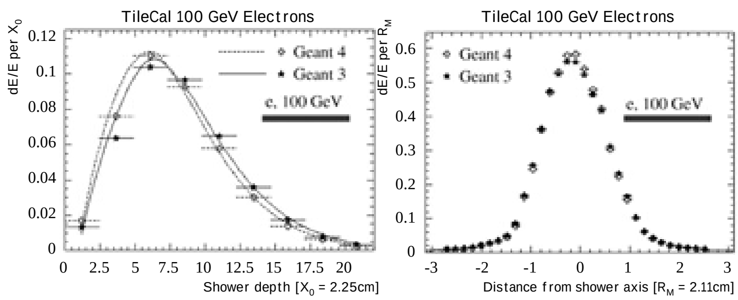
Electron Shower Shapes & Composition (1)

(Sept. 2002)

Shower shape analysis:

- GEANT4 electromagnetic showers in the EMB are more compact longitudinally than in G3: about 3-13% less signal in the first $4.3X_0$, but 1.5-2.5% more signal in the following $16X_0$, and 5-15% less signal (large fluctuations) in the final $2X_0$ for 20-245 GeV electrons;

- GEANT4 electron shower in TileCal starts earlier and is slightly narrower than in G3:



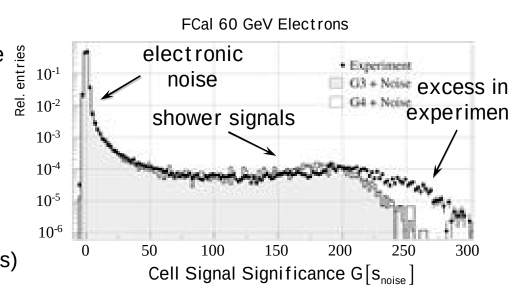
Electron Shower Shapes & Composition (2)

(Sept. 2002)

Shower composition:

- cell signal significance spectrum is the distribution of the signal-to-noise ratio in all individual channels for all electrons of a given impact energy;

- to measure this spectrum for simulations requires modeling of noise in each channel in all simulated events (here: overlay experimental "empty" noise events on top of GEANT4 events)



- spectrum shows higher end point for data than for GEANT4 and GEANT3, indicating that larger (more significant) cell signals occur more often in the experiment -> denser showers on average;

Hadronic Shower Models in GEANT4

LHEP (similar to GHEISHA):

- uses parametrized models from LEP and others for inelastic scattering, no resonances;
- detailed secondary angular distributions for O(100 MeV) reactions may not be described very well;
- can often describe average quantities quite well (energy resolution, signal energy dependence…);

QGSP (GEANT4 only):

- features theory-driven modeling of high energetic pion, kaon and nucleon reactions – uses currently best known pion cross-sections;
- quark-gluon string model for “punch-through” interactions of projectile with nucleus, string excitation from quasi-eikonal approximation;
- pre-equilibrium decay model with evaporation phase for behaviour of nucleus after reaction (slow hadronic shower component);

(see also http://cmsdoc.cern.ch/~hpw/GHAD/HomePage/calorimetry/index.html

Hadronic Shower Models in GEANT4

QGSC (GEANT4 only):

- like QGSP for initial reaction, but fragmentation by chiral invariant phase-space decay (multi-quasmon fragmentation);

FTFP (GEANT4 only):

- similar to QGSP in the treatment of the fragmentation, but diffractive string excitation similar to FRITJOF, instead of quark-gluon strings;

QGSP, QGSC, and FTFP are very similar for all practical purposes, especially for the simulation of hadronic showers in calorimeters. LHEP shows larger differences to these packages. Results shown here concentrate on LHEP/QGSP comparisons with testbeam data and GEANT3.

Also, single interaction comparisons as shown here for GEANT4 hadronic shower models are not easy with GEANT3 hadronic shower models like GCALOR or GHEISHA, due to quantum number and energy/momentum non-conservation at this level in these models…

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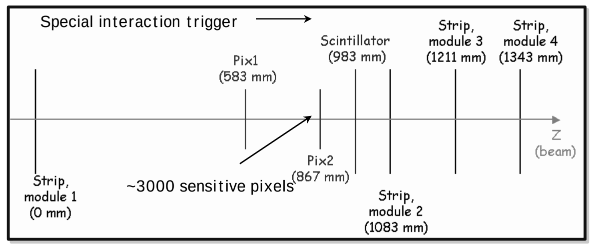
Individual Hadronic Interactions

(Sept. 2002)

Inelastic interaction properties:

- energy from nuclear break-up in the course of a hadronic inelastic interactions causes large signals in the silicon pixel detector in ATLAS, if a pixel (small, 50 µm x 400 µm), is directly hit;
- this gives access to tests of single hadronic interaction modeling, especially concerning the nuclear part;
- testbeam setup of pixel detectors supports the study of these interactions;



- two models in GEANT4 studied: the parametric “GHEISHA”-type model (LHEP) and the quark-gluon string model (QGSP, H.P. Wellisch);

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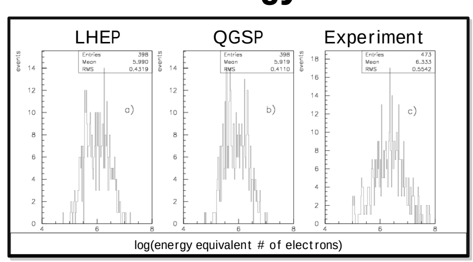
Individual Hadronic Interactions: Energy Release

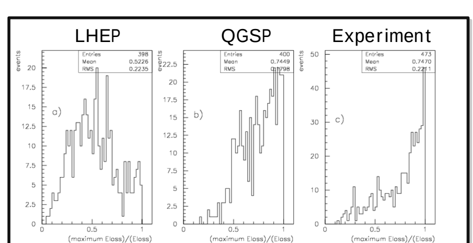
(Sept. 2002)

Interaction cluster:

- differences in shape and average (~5%-~7% too small for LHEP/QGSP) of released energy distribution for 180 GeV pions in interaction clusters;



- fraction of maximum single pixel release and total cluster energy release not very well reproduced by LHEP (shape, average ~26% too small);
- QGSP does better job on average (identical to data) for this variable, but still shape not completely reproduced yet (energy sharing between pixels in cluster);



More on Individual Hadronic Interactions

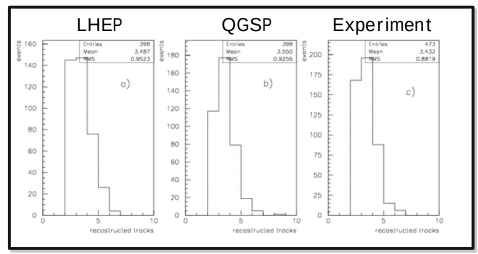
(Sept. 2002)

Spread of energy:

- other variables tested with pixel detector: cluster width, longest distance between hit pixel and cluster barycenter -> no clear preference for one of the chosen models at this time (mostly problems with shapes of distributions);

Charged track multiplicity:

- average charged track multiplicity in in-elastic hadronic interaction described well with both models (within 2-3%), with a slight preference for LHEP;

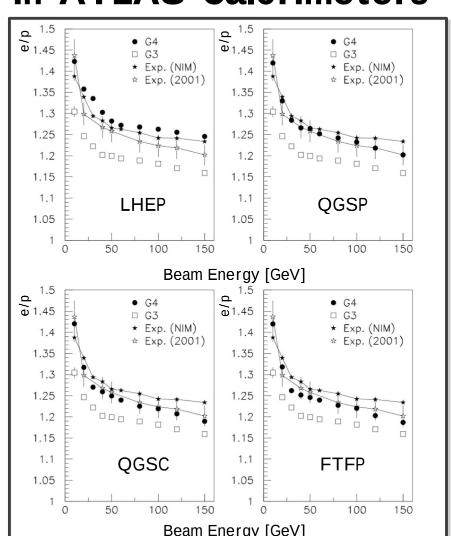


Geant4 Hadronic Signals in ATLAS Calorimeters

(July 2003)

Calorimeter pion response:

- e/p signal ratio for non-compensating calorimeter like the ATLAS Liquid Argon Hadronic Endcap Calorimeter (HEC) is important characteristic to be reproduced by shower models -> required for use of simulation to determine calibration functions;
- e/p signal ration in HEC (and hadronic TileCal) not well reproduced by GEANT4 LHEP – but already somewhat better than GCALOR in GEANT3.21;
- GEANT4 QGSP, QGSC and FTFP do a much better job for this important variable;

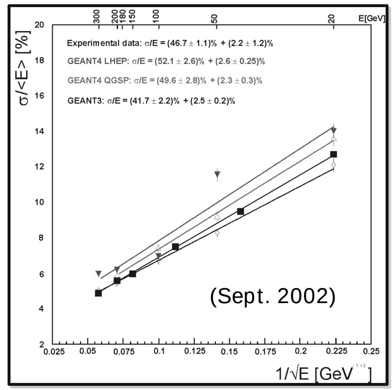


Geant4 Hadronic Signal Characteristics

Pion energy resolution:

- good description of experimental pion energy resolution by QGSP in TileCal; LHEP cannot describe stochastic term, but fits correct high energy limit;
- GEANT3/GCALOR predicts significantly less signal fluctuations than measured in testbeam for pions in HEC and TileCal;
- GEANT4 QGSP reproduces shower- and sampling fluctuations and constant term for pions in HEC within the errors; QGSC and FTFP close, but LHEP significantly off (July 2003);

TileCal Pion Energy Resolution



Pion longitudinal shower profiles:

- rather poor description of experimental energy sharing between longitudinal segments in HEC by all GEANT4 quark-string models; pion showers generally start too early; LHEP delivers an acceptable description of the longitudinal profiles, at about the same level as GCalor in Geant3.21 (July 2003);

Conclusions (1):

- GEANT4 can simulate relevant features of muon, electron and pion signals in various ATLAS detectors, now generally better than GEANT3;
- remaining discrepancies are addressed and reported to the GEANT4 team; communication with experts is well established, and most problems are addressed quickly;
- ATLAS has a significant amount of appropriate testbeam data for the calorimeters, inner detector modules, and the muon detectors to evaluate the GEANT4 physics models in detail – excellent use of the testbeam data!
- sometimes not easy to follow up with GEANT4 progress for ATLAS sub-detector systems, due to lack of manpower -> hard to follow and monitor GEANT4 evolution -> more automated benchmark tests needed;

Conclusions (2):

- Geant4 is definitively a mature and useful product for large scale detector response simulations, therefore: start using it for all simulations, specifically testbeams and physics – it is the only open source toolkit backed by a large number of interaction model teams and experts from all over the world -> guarantees future support and improvements!!
- still work needed to fully integrate GEANT4 into ATHENA to be ready for DC2 in spring 2004 – contact your sub-detector simulation software coordinator for actual status of implementation…;
- …and again, start using it in the ATHENA framework!