Geant4 status and applications

John Apostolakis, CERN
for Geant4 collaboration

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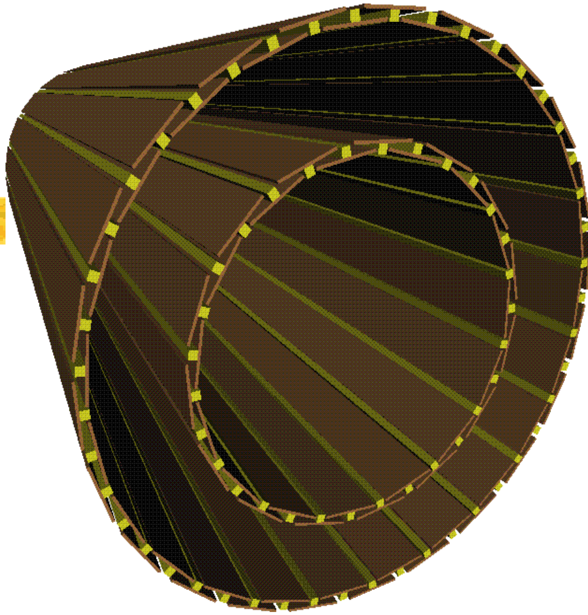


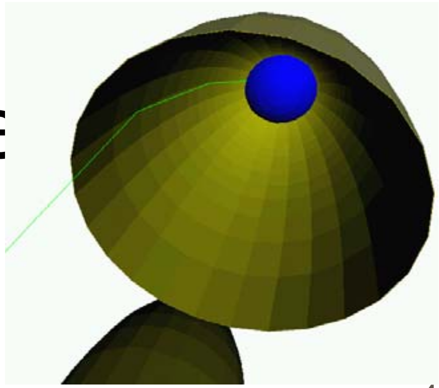
- Geant4's kernel
- EM Physics processes
  - Comparisons with data
- Hadronic framework, models
- Utilization of Geant4
- Status and plans

GEANT 4

- Detector simulation tool-kit for HEP
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology
  - provide the method for building, maintaining it.
- Requirements from:
  - LHC
  - heavy ions, CP violation, cosmic rays
  - medical and space science applications
- World-wide collaboration

Geant4 Capabilities

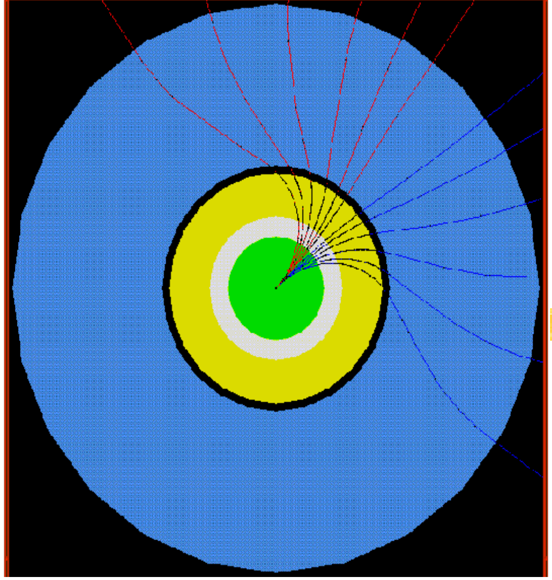
- Powerful structure and kernel
  - tracking, stacks, geometry, hits, …
- Extensive & transparent physics models
  - electromagnetic, hadronic, …
- Framework for fast simulation
- Additional capabilities/interface
  - persistency, visualization, ...



Geant4 kernel

- Creates & manages runs, events, tracks
  - a run is configuration of geometry, physics & event generator.
- Allows particles to be prioritized easily at no cost
  - 3 default stacks, postponement.
- Tracking is general (unique)
  - physics lists can be tailored for different use cases
- Enables the creation of user defined hits
  - able to handle pile-up.
- Versatile volumes and navigator for Geometry

Propagating in a field



Charged particles follow paths that approximate their curved trajectories in an electromagnetic field.

- It is possible to tailor
  - the accuracy of the splitting of the curve into linear segments,
  - the accuracy in intersecting each volume boundaries.
- These can be set now to different values for a single volume or for a hierarchy.

Electromagnetic processes

Initial goal (RD44) was to create EM physics at least at equivalent to Geant-3

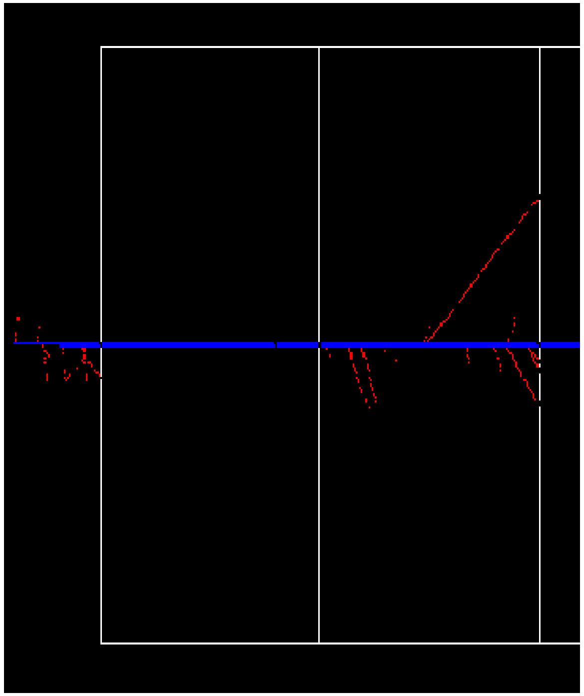
New concepts emerged and were implemented:

- Distinction between production threshold and tracking cut
- Expressing production cuts in terms of range instead of energy
- Creating an effective range from the distance to the nearest boundary

Electromagnetic processes

Processes new to Geant4

- Multiple Scattering: new model
  - includes lateral displacement (new)
  - no path length restriction
- New process: Transition radiation
  - from physics models
- Photo-Absorption Ionisation model
  - Alternative energy loss



Electromagnetic physics

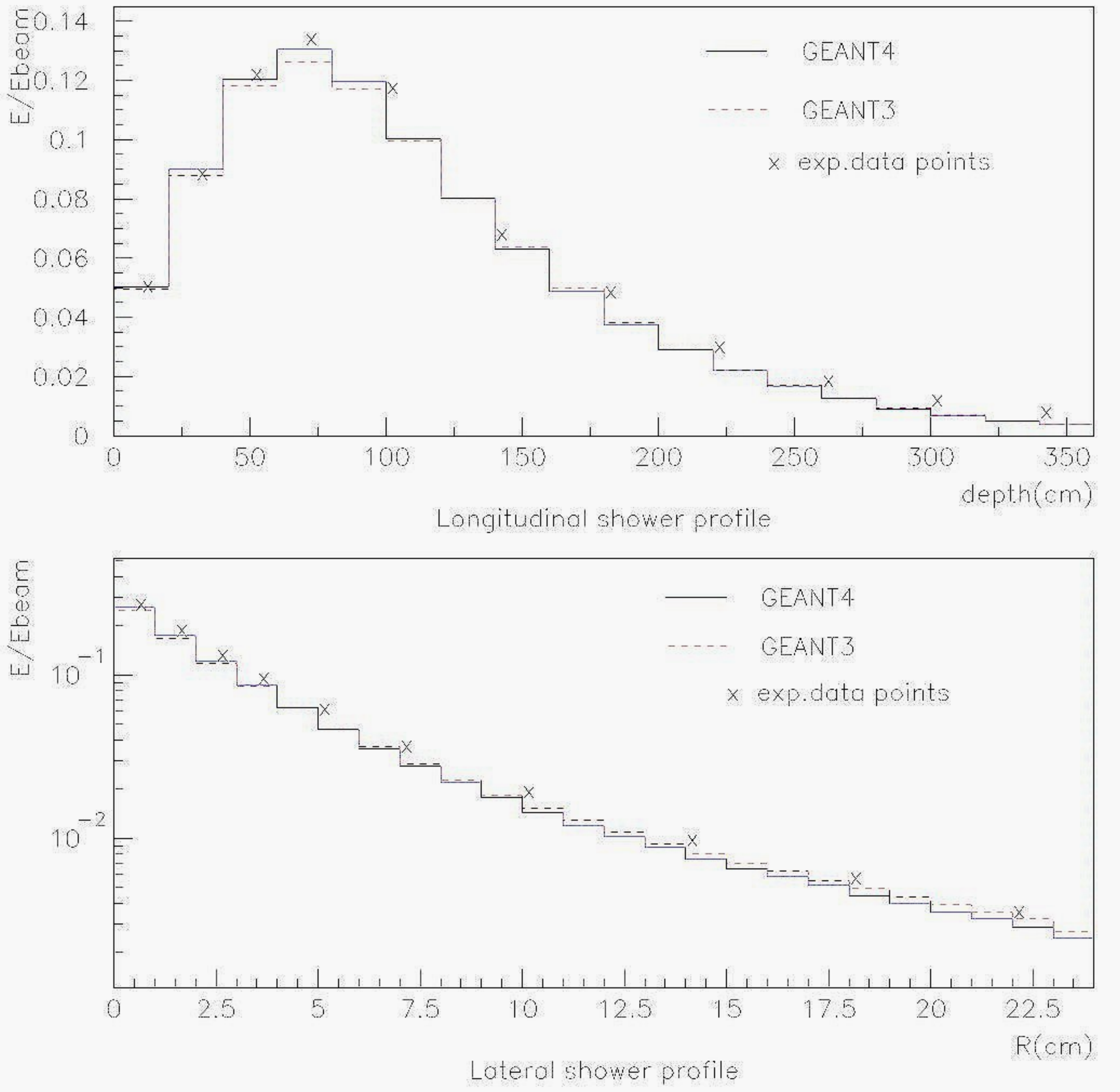
- Gammas:
  - Gamma-conversion, Compton scattering, Photo-electric effect
- Leptons(e, μ), charged hadrons, ions
  - Energy loss (Ionisation, Bremstrahlung) or PAI model energy loss, Multiple scattering, Transition radiation, Synchrotron radiation,
- Photons:
  - Cerenkov, Rayleigh, Reflection, Refraction, Absorption, Scintillation
- High energy muons and lepton-hadron interactions
- Alternative implementation ("low energy")
  - for applications that need to 1 KeV
  - details in parallel talk (Tuesday, Track 5)

Shower profile

1 GeV electron in H_2O

G4, Data G3

- Good agreement seen with the data

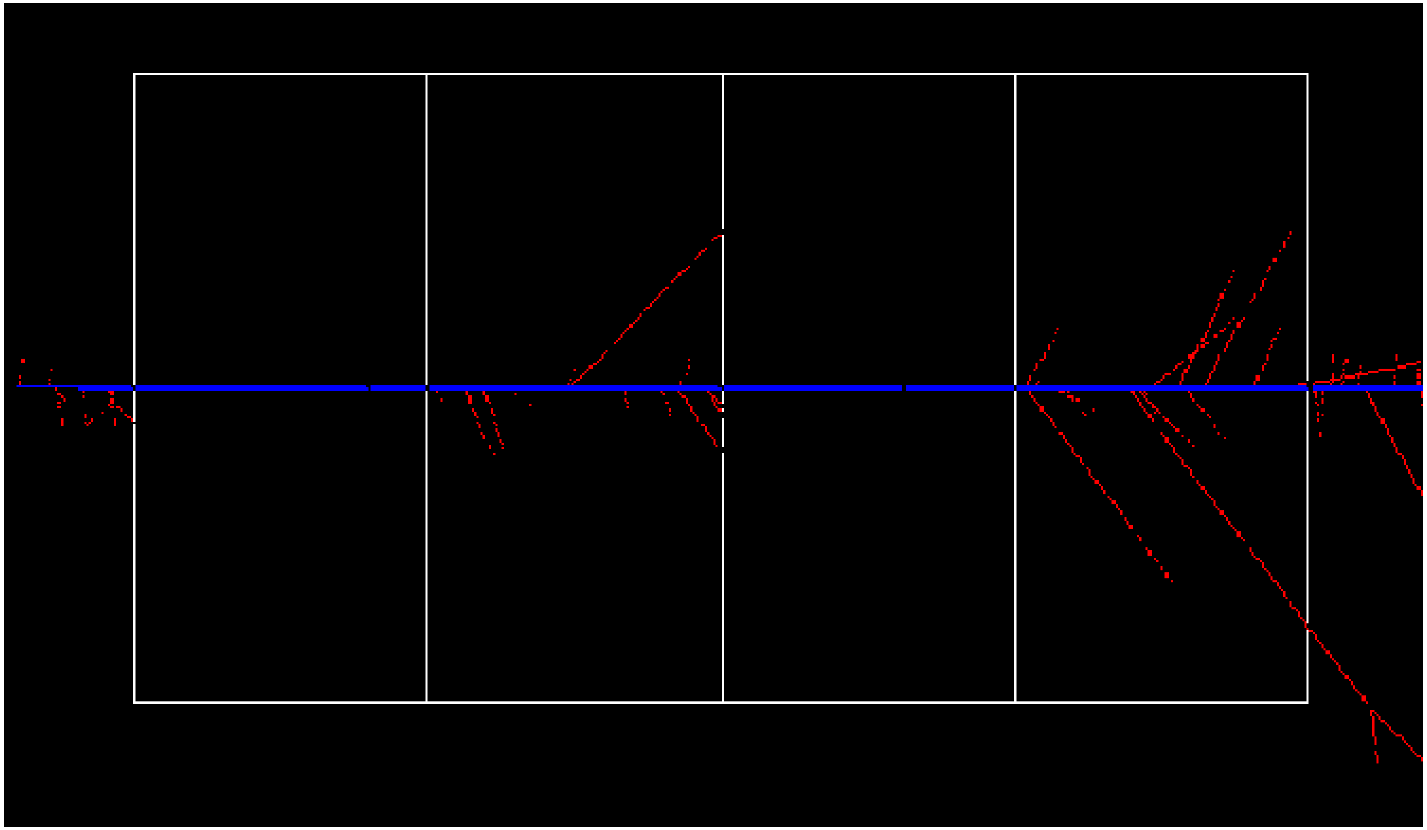


Cuts: production & user

- Coherent "production cuts"
  - validity range of models fully exploited
  - kernel can enforce consistent production cuts
    - yet processes can ask to override when they need to.
  - treatment of boundary effects (Figures)
- Cuts in range rather than Energy
    - Geant3 used cuts in Energy - inefficient
    - significant gain in results quality vs CPU usage
- User can cut in Energy, track length, TOF ..

GEANT4

5cm Pb, CO_2, Pb, CO_2



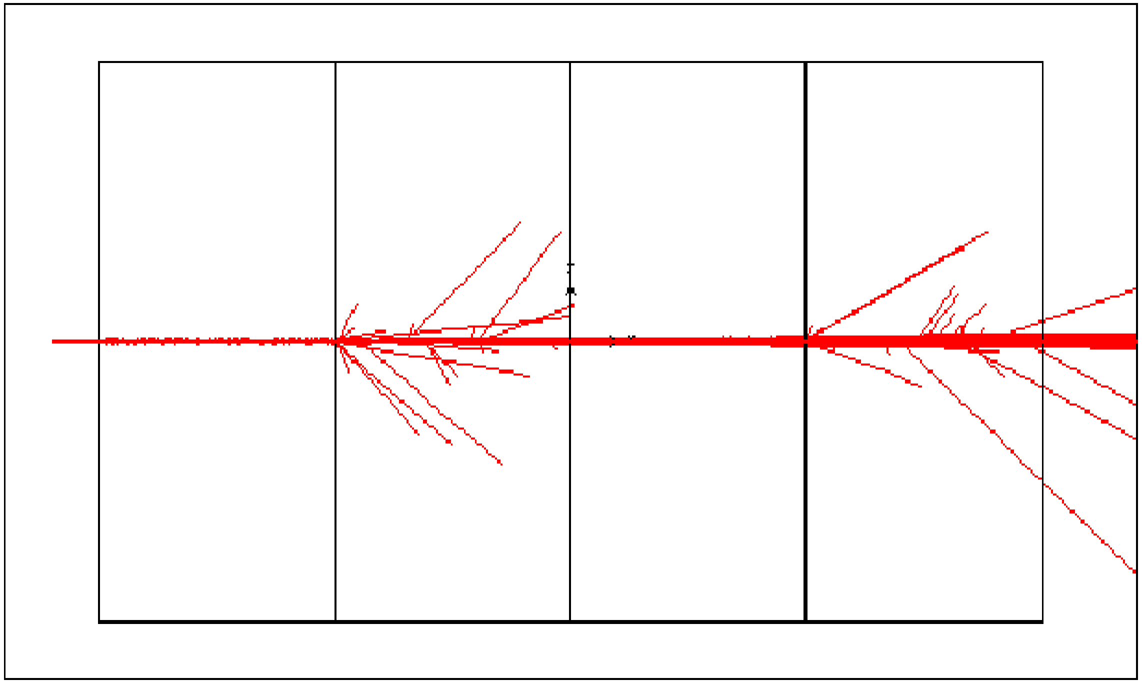
Cut: 2mm

Pb 2.5 MeV

CO_2 55keV

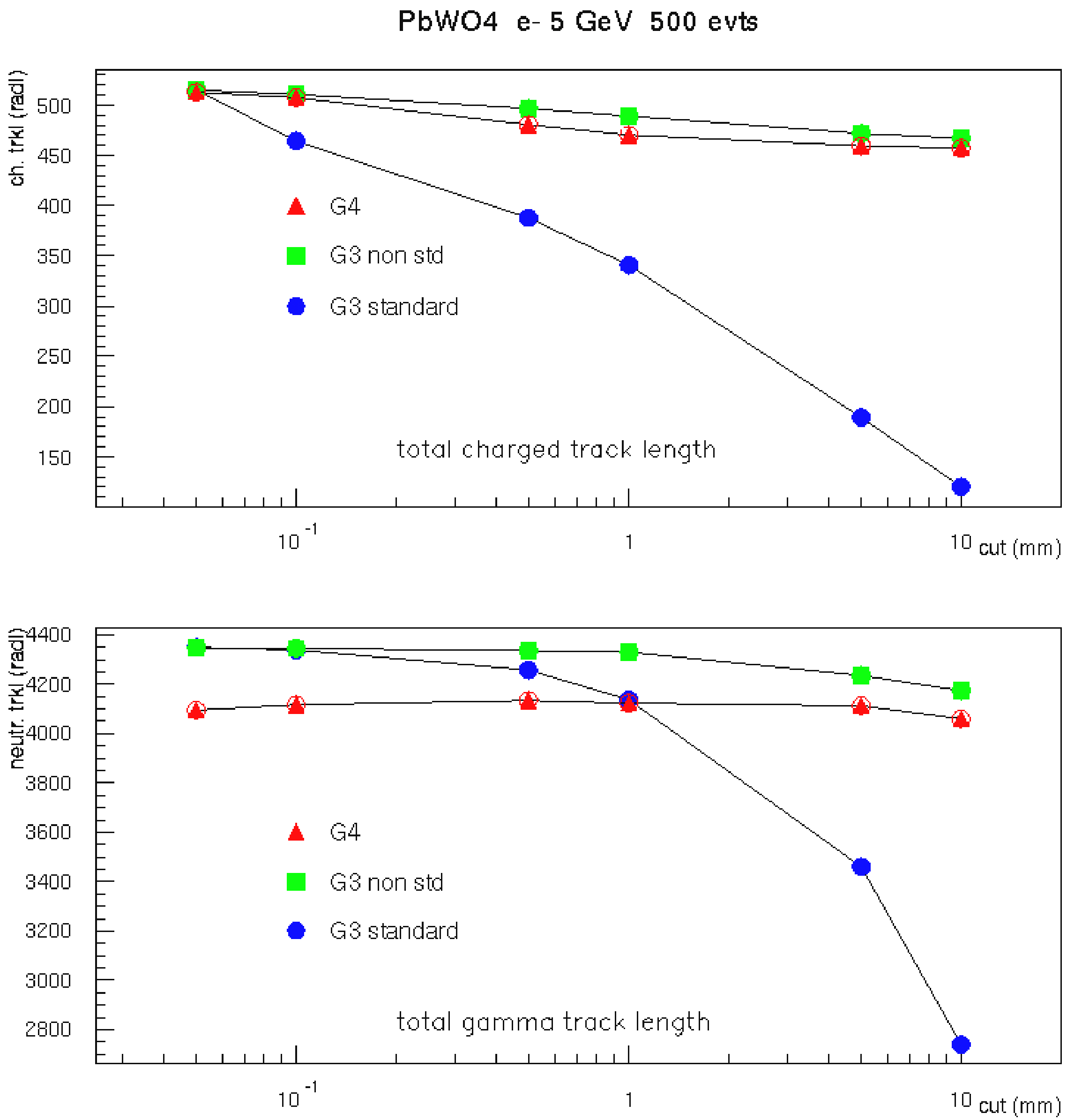
GEANT3 run

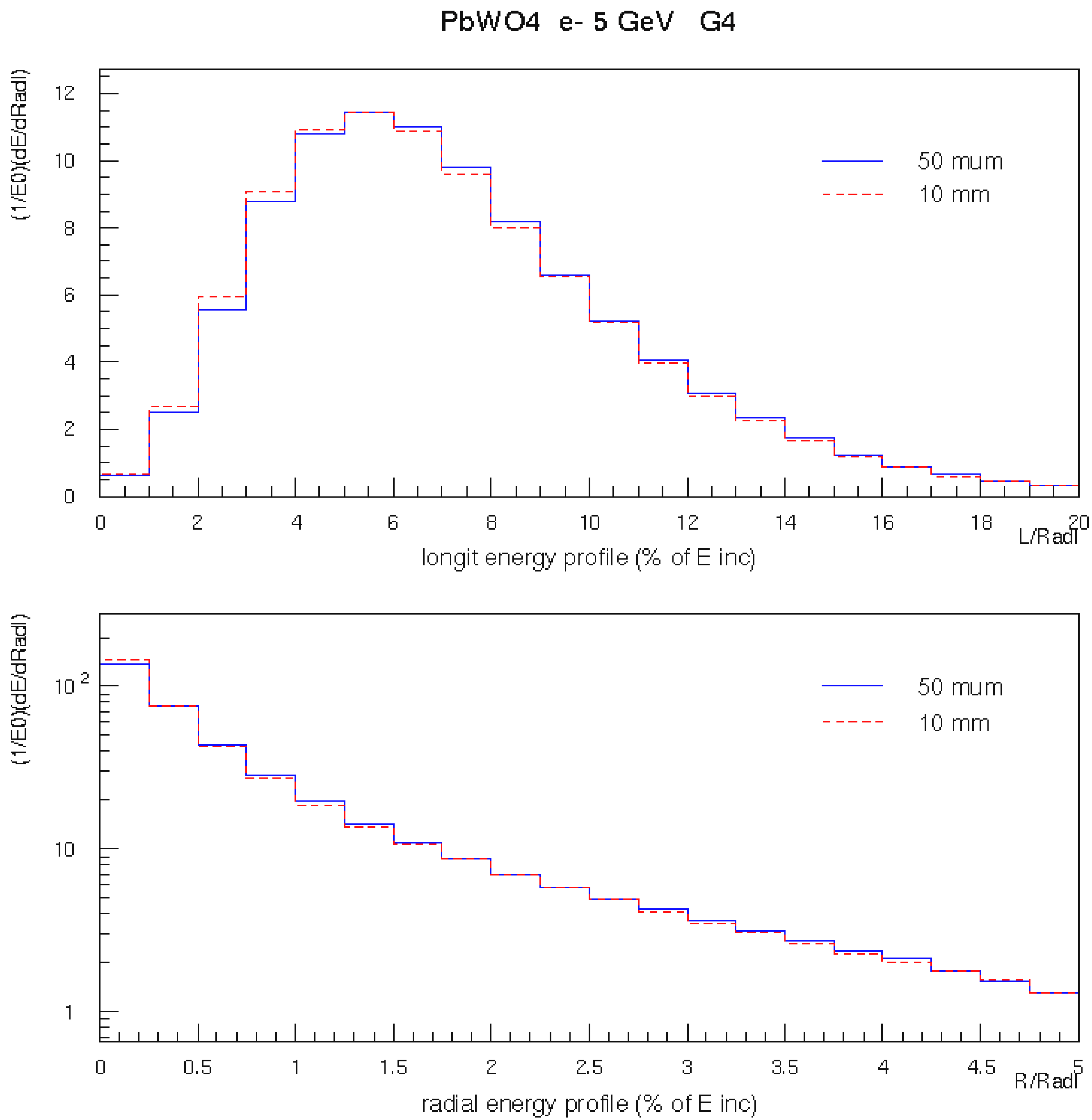
5cm Pb, CO_2, Pb, CO_2



Changing cuts

- Results very stable with variation of cuts
  - even track length
- Also see shower profiles for different cuts (next slide)
  - between 10mm and 50 microns

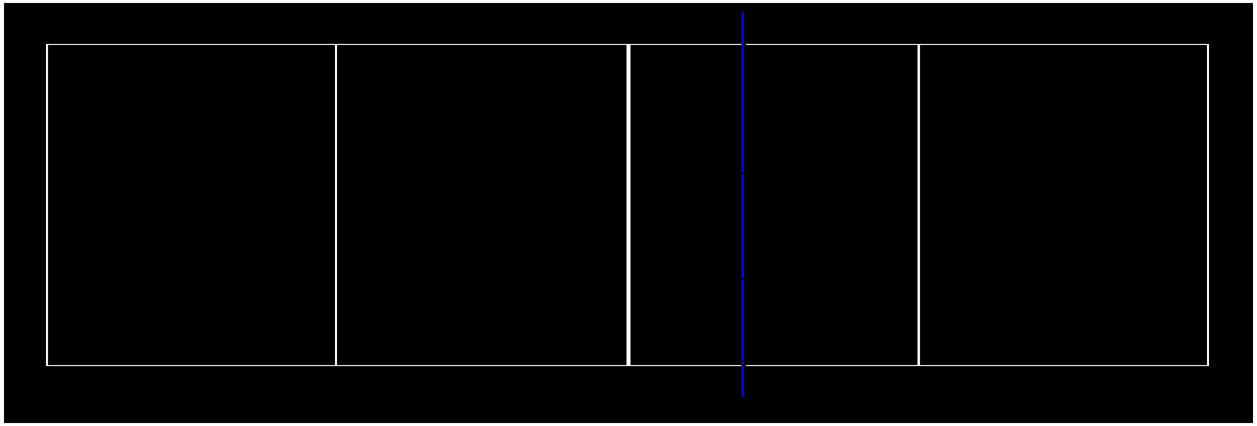




PbWO4 e- 5 GeV G4
(1/E0)(dE/dRadl)
50 mum
10 mm
L/Radl
longit energy profile (% of E inc)
(1/E0)(dE/dRadl)
50 mum
10 mm
R/Radl
radial energy profile (% of E inc)

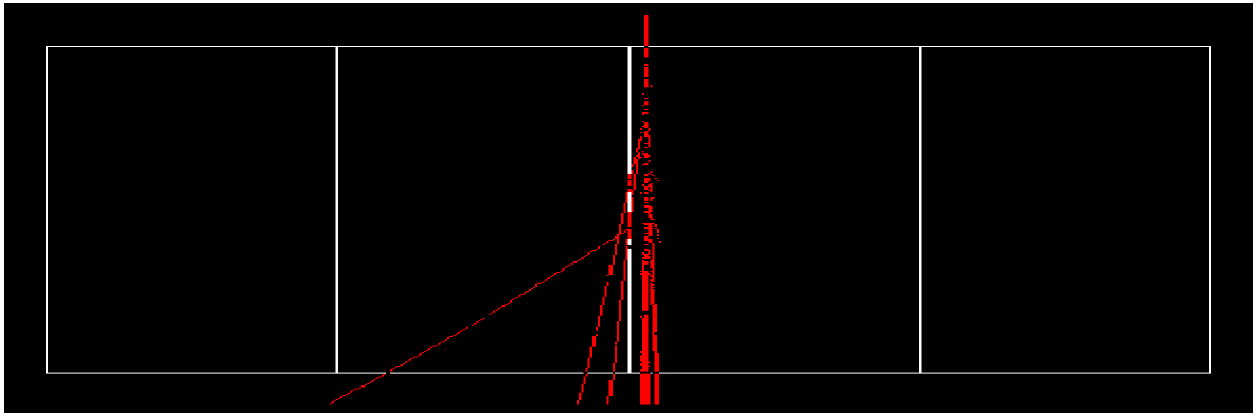
Secondaries produced only if they could escape

Lead CO_2 Lead CO_2



Range < safety

Secondaries CANNOT leave Pb: NOT produced



Range > safety

Secondaries could leave Pb: produced

Confrontation with data

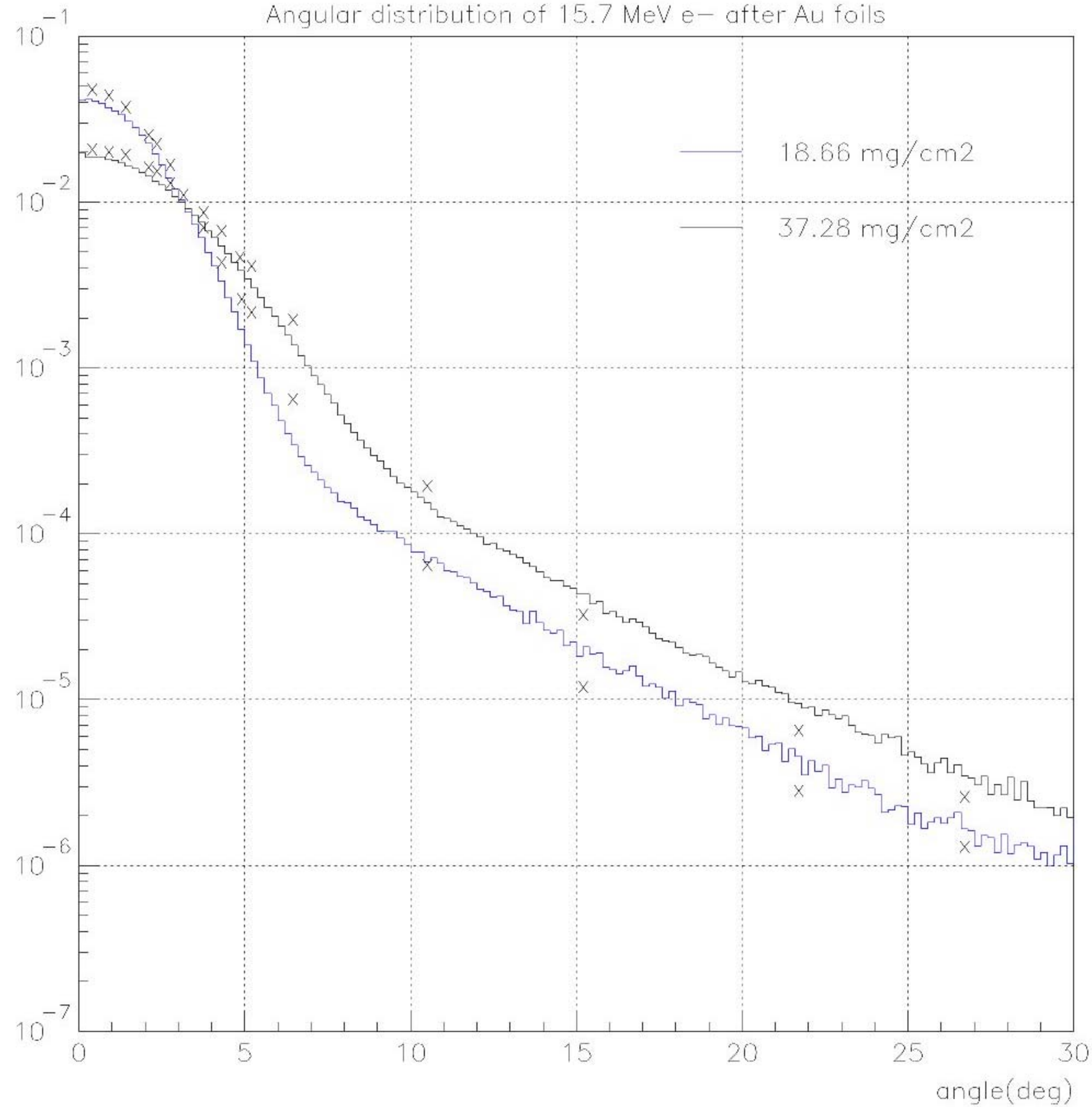
- Many comparisons made by WG, and results presented
  - and put in Web gallery
- A lot of comparisons are ongoing, starting
  - within the collaboration (eg in experiment groups)
  - in other experiments, groups in other fields
    - diverse uses (eg outer-space, medical, ..)
    - often small groups

Alternatives for Energy Loss

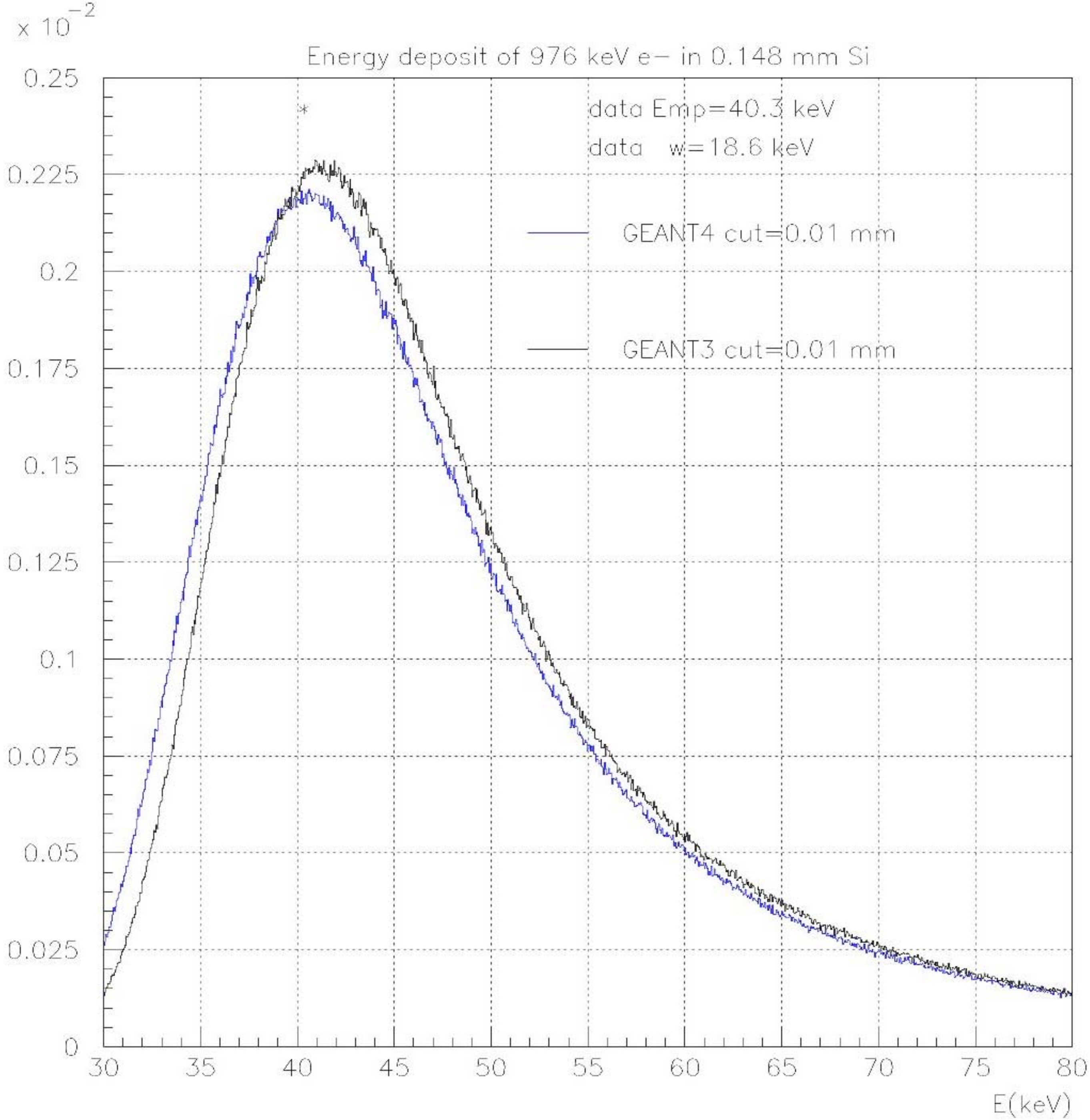
- 'Standard' differential
    - Extended down to 1 KeV
    - Creates more secondaries near volume borders
- PAI model for gases/thin absorbers
- Integral Energy Loss processes
  - Integration of cross section over Energy
    - DE/E not constrained for e+/e-
    - hadronic resonances can be seen (future)

Multiple scattering model

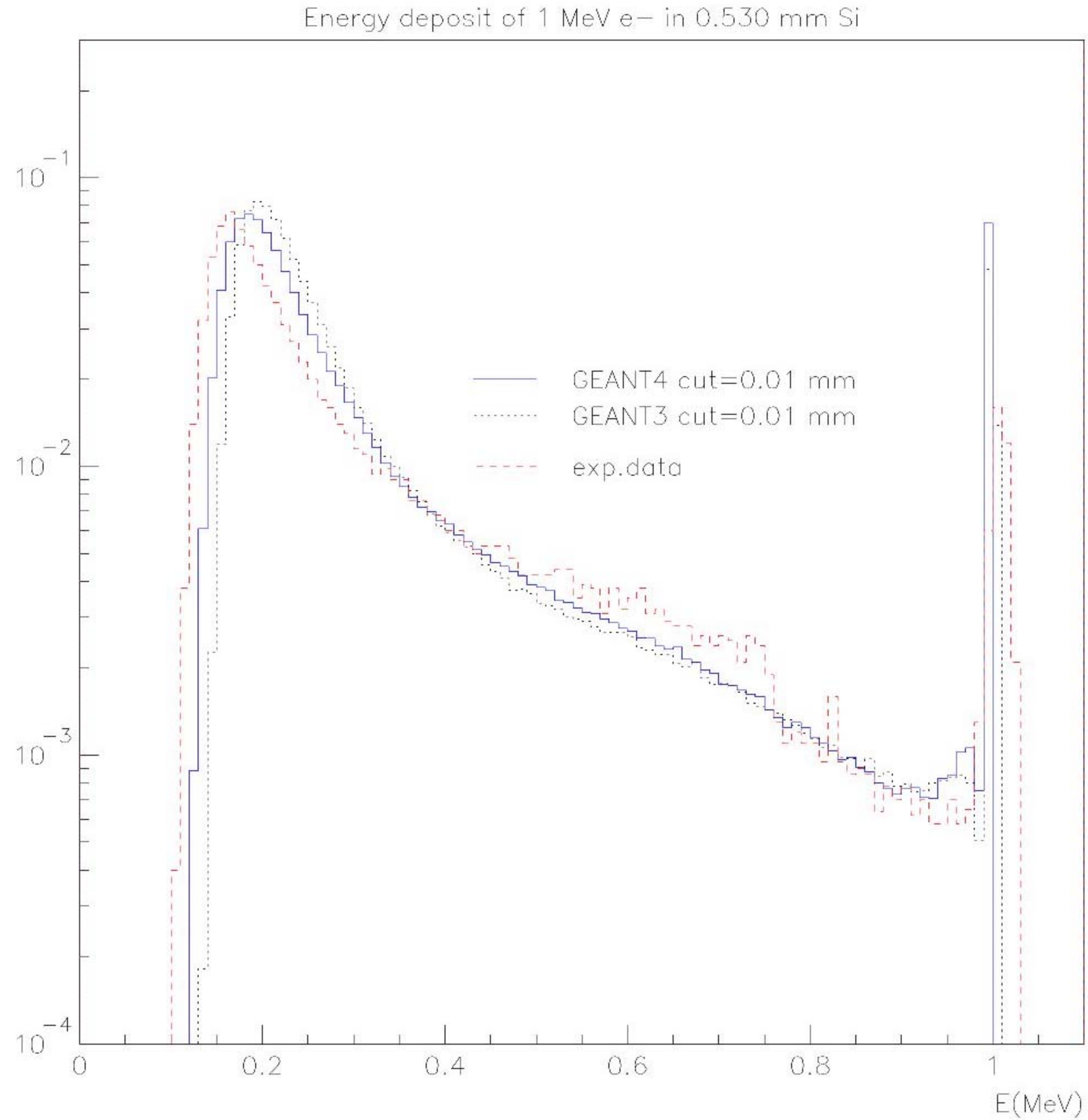
- A new model for multiple scattering based on the Lewis theory is implemented
  - since public β release in 1998.
- It randomizes momentum direction and displacement of a track.
  - Step length, time of flight, and energy loss along the step are affected, and
  - It does not constrain the step length.



Angular distribution of 15.7 MeV e− after Au foils
18.66 mg/cm2
37.28 mg/cm2
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
5
10
15
20
25
30
angle(deg)

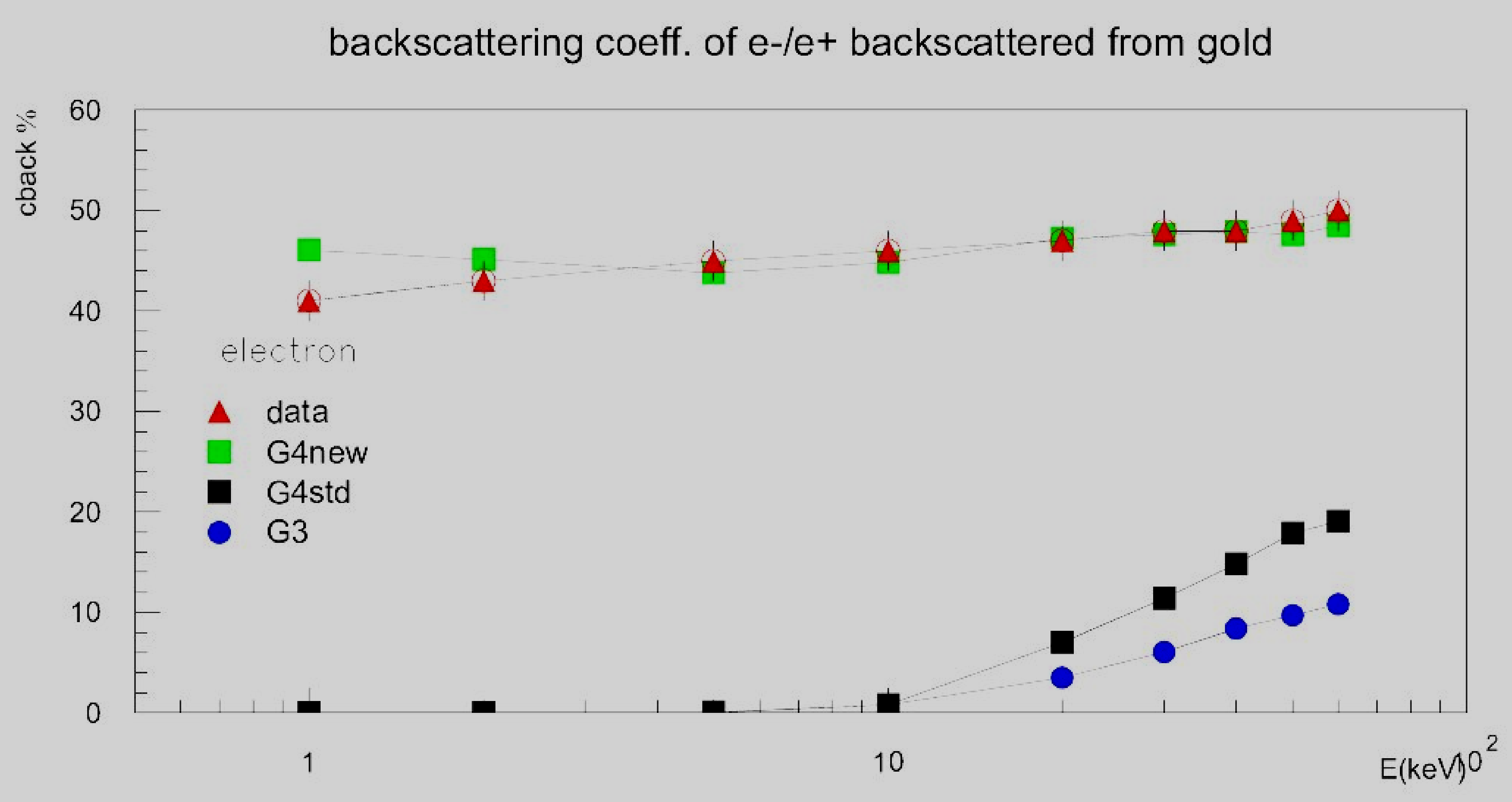


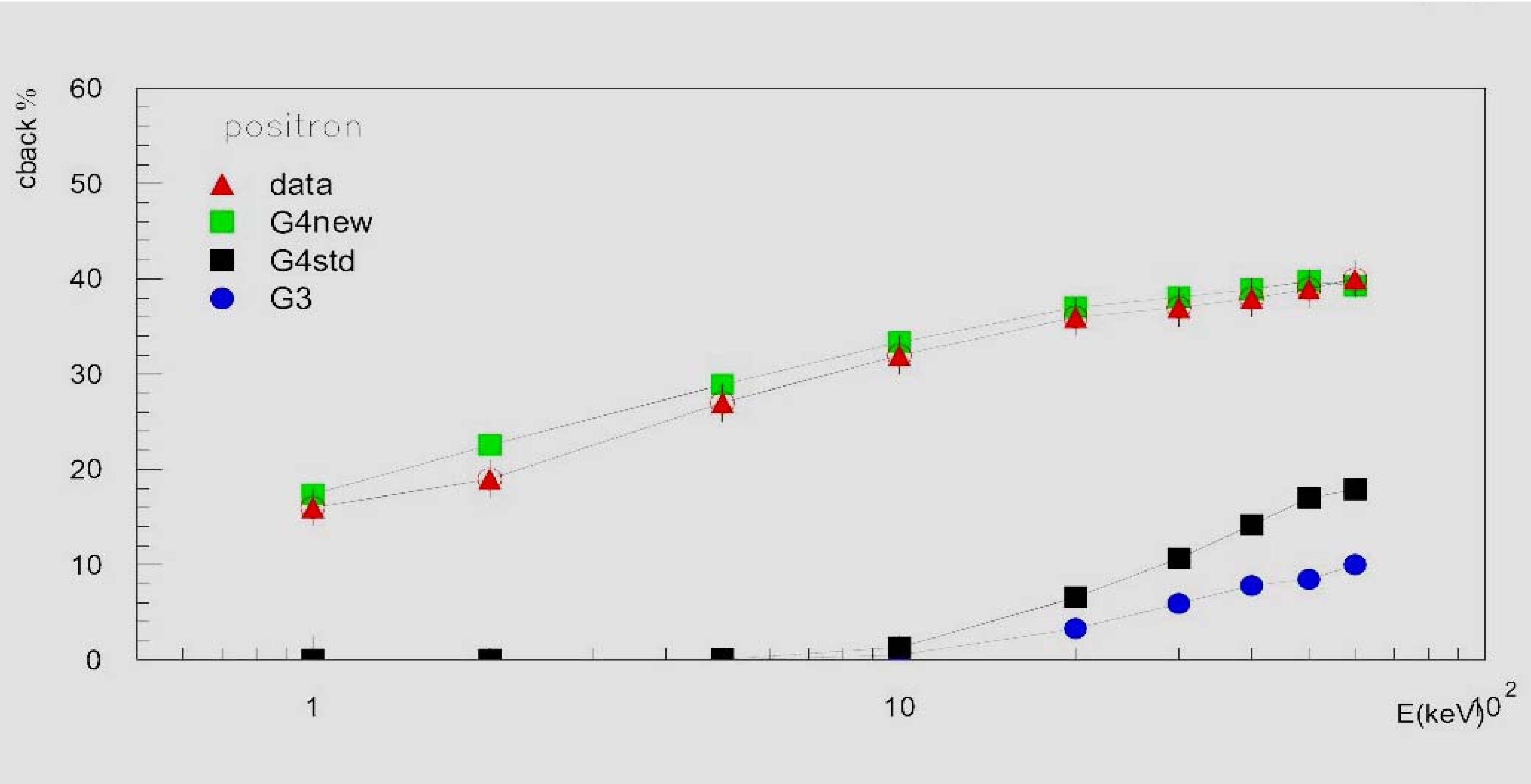
x 10^-2
Energy deposit of 976 keV e- in 0.148 mm Si
data Emp=40.3 keV
data w=18.6 keV
GEANT4 cut=0.01 mm
GEANT3 cut=0.01 mm
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
30
35
40
45
50
55
60
65
70
75
80
E(keV)



Energy deposit of 1 MeV e− in 0.530 mm Si
GEANT4 cut=0.01 mm
GEANT3 cut=0.01 mm
exp.data
E(MeV)

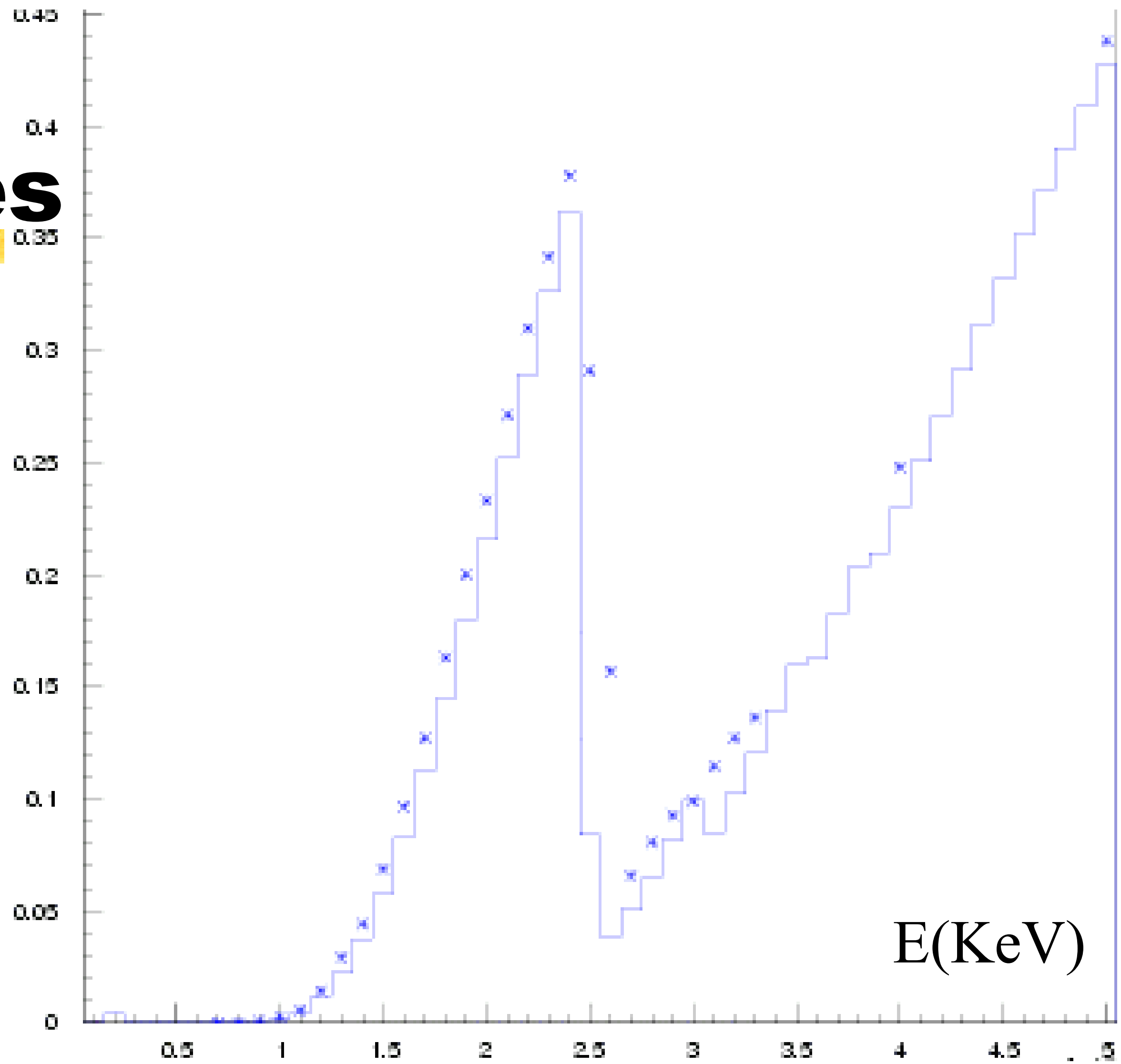
Under development




cback %
positron
data
G4new
G4std
G3
60
50
40
30
20
10
0
1
10
E(keV)
10^2

Low energy EM processes

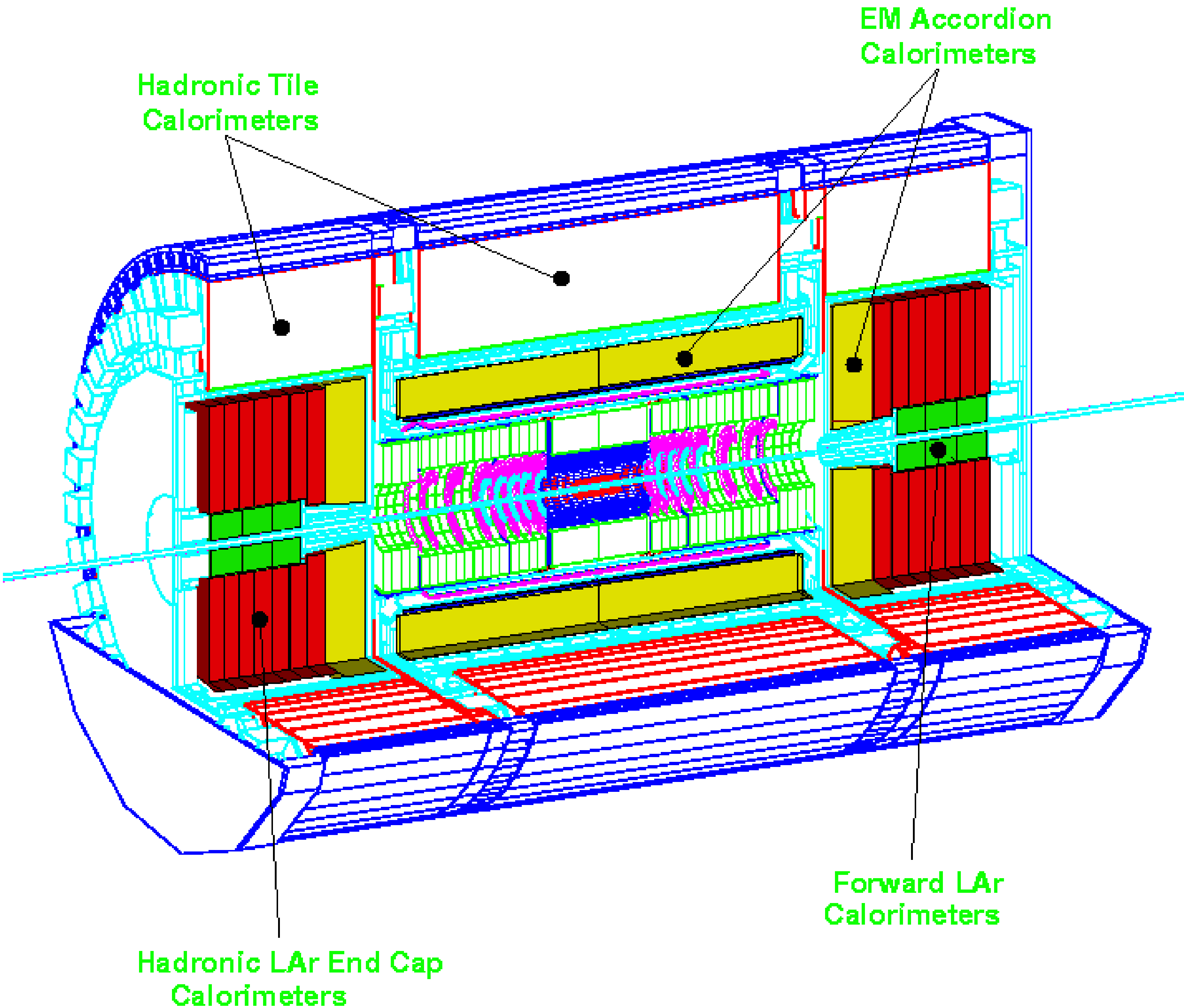
- Photons, electrons down to 250 eV
  - Xsec from EADL libr.
  - Thanks to
    M.G. Pia,
    P. Nieminen, ..
- Hadron EM interactions
- See 5-001 for an overview of Geant4 Low Energy EM Physics



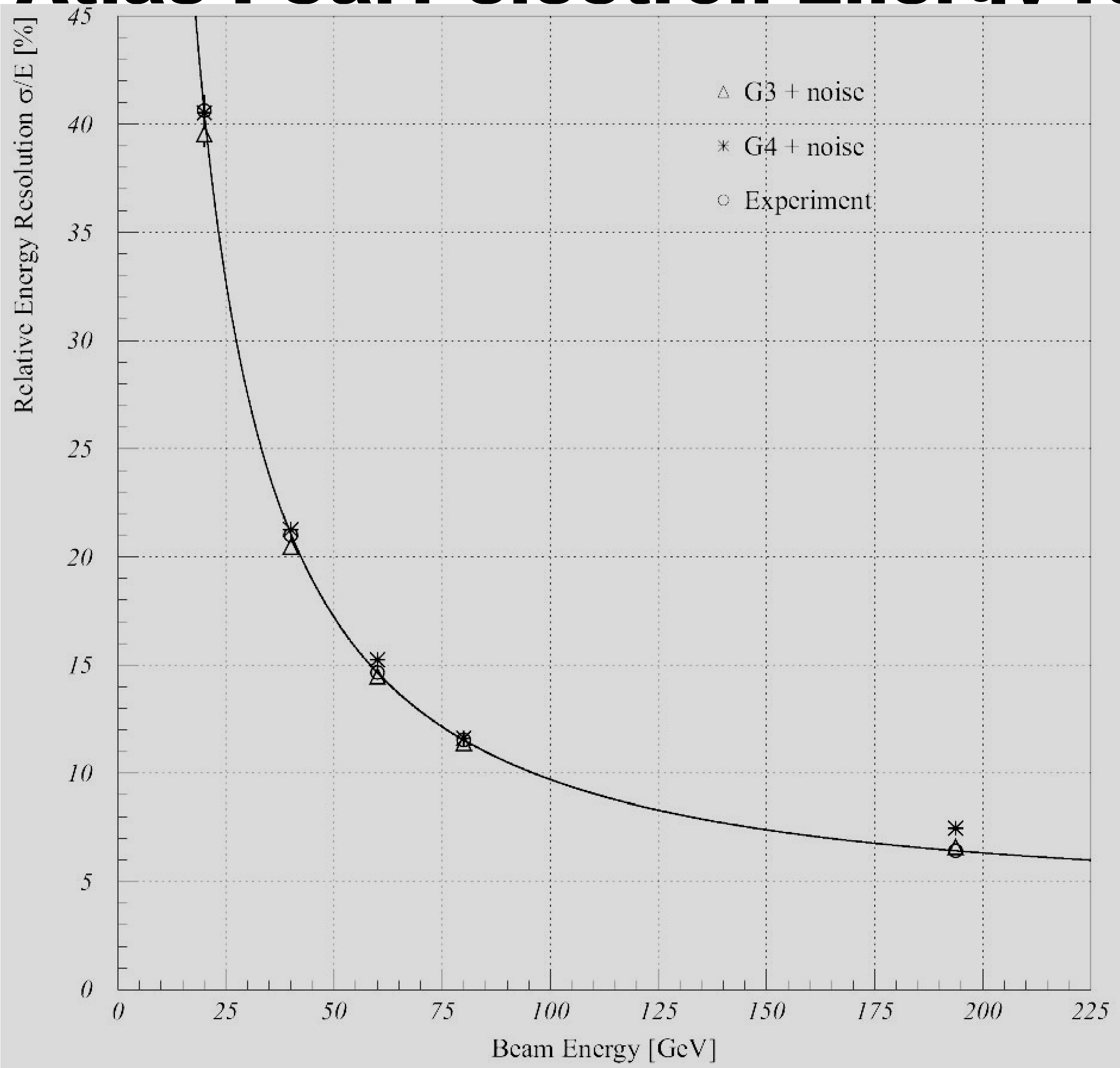
Photon transmission through 1 mm Pb, showing shell effects

Comparison projects

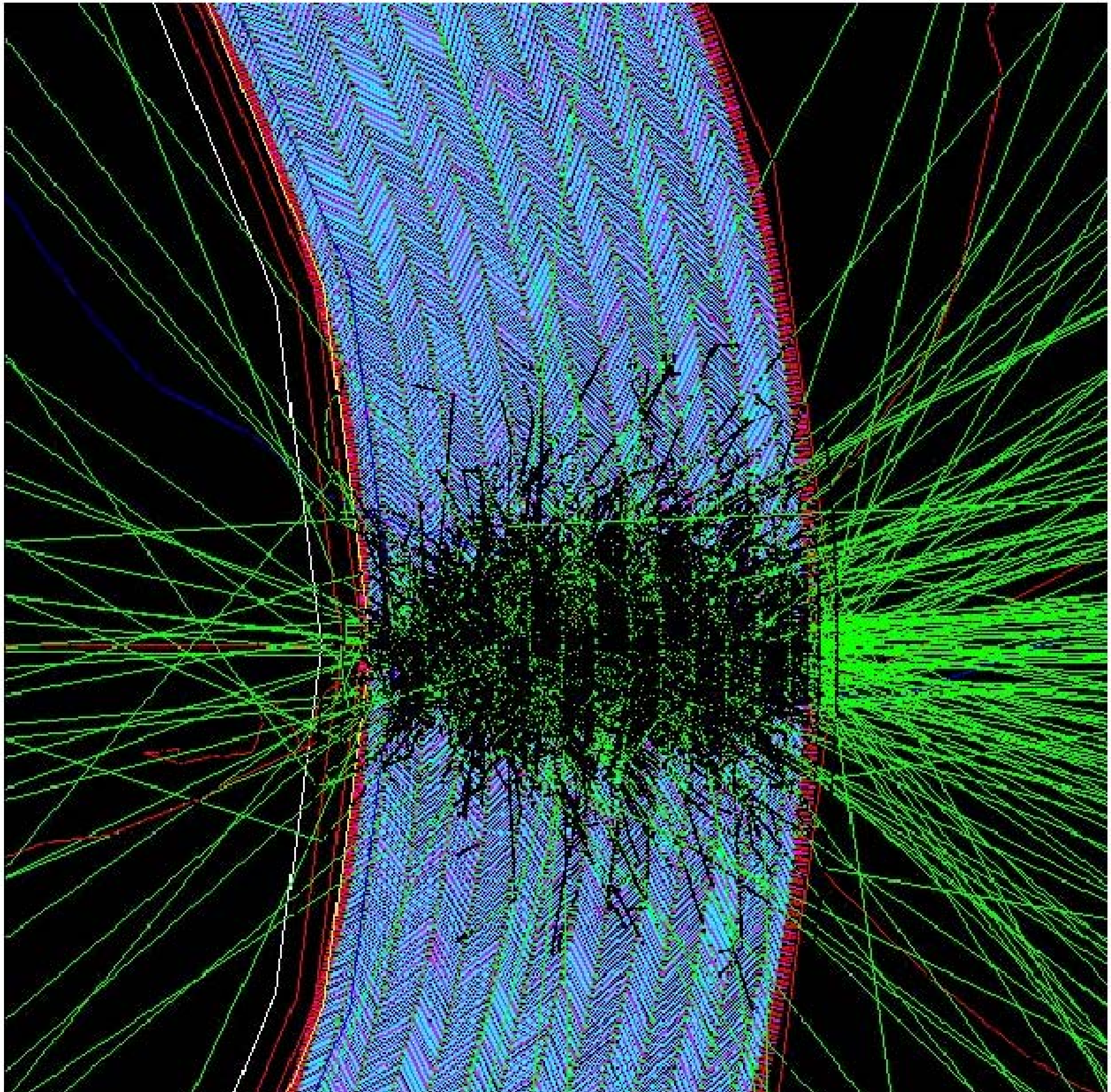
- Established join projects for comparing Geant4 results with experimental/test-beam data.
- First results in 2000, publications expected end 2001.
- Collaboration with experiments
  - ATLAS (projects with data of test beams of 4 calorimeters)
  - BaBar (with experiment data for tracker, drift chamber)
- Following slides are taken from presentations at conferences & workshops
  - For details: see presentation of D. Salihagic (Tuesday in Track5)


EM Accordion Calorimeters
Hadronic Tile Calorimeters
Forward LAr Calorimeters
Hadronic LAr End Cap Calorimeters

Atlas FCal1 electron Energy resolution



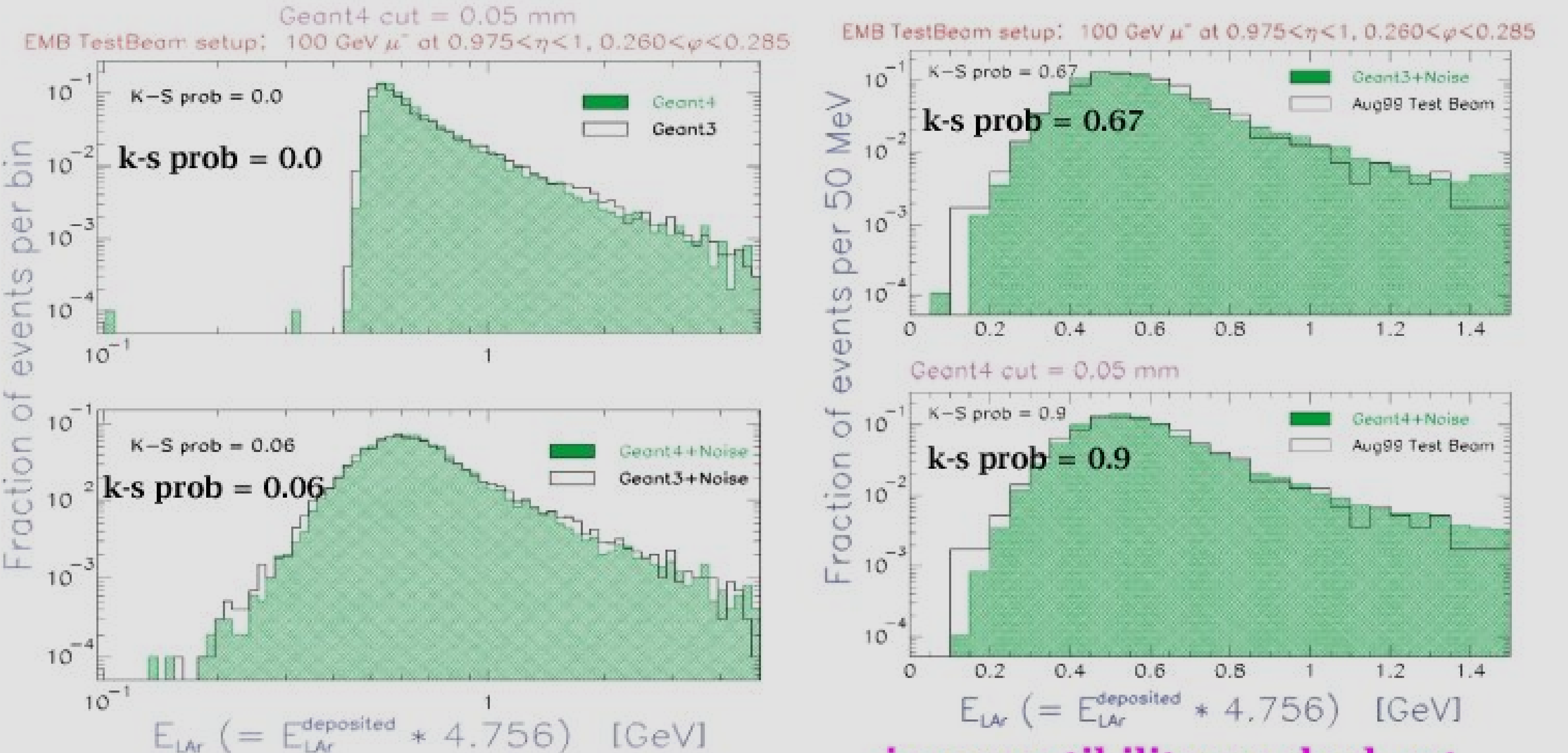
Thanks to
Rachid Manzini
& Peter Loch
& Atlas FCAL



Thanks to Gaston Parrour, Kostas Kordas and Atlas LAr

Muons in EMB

G4.3.0R1



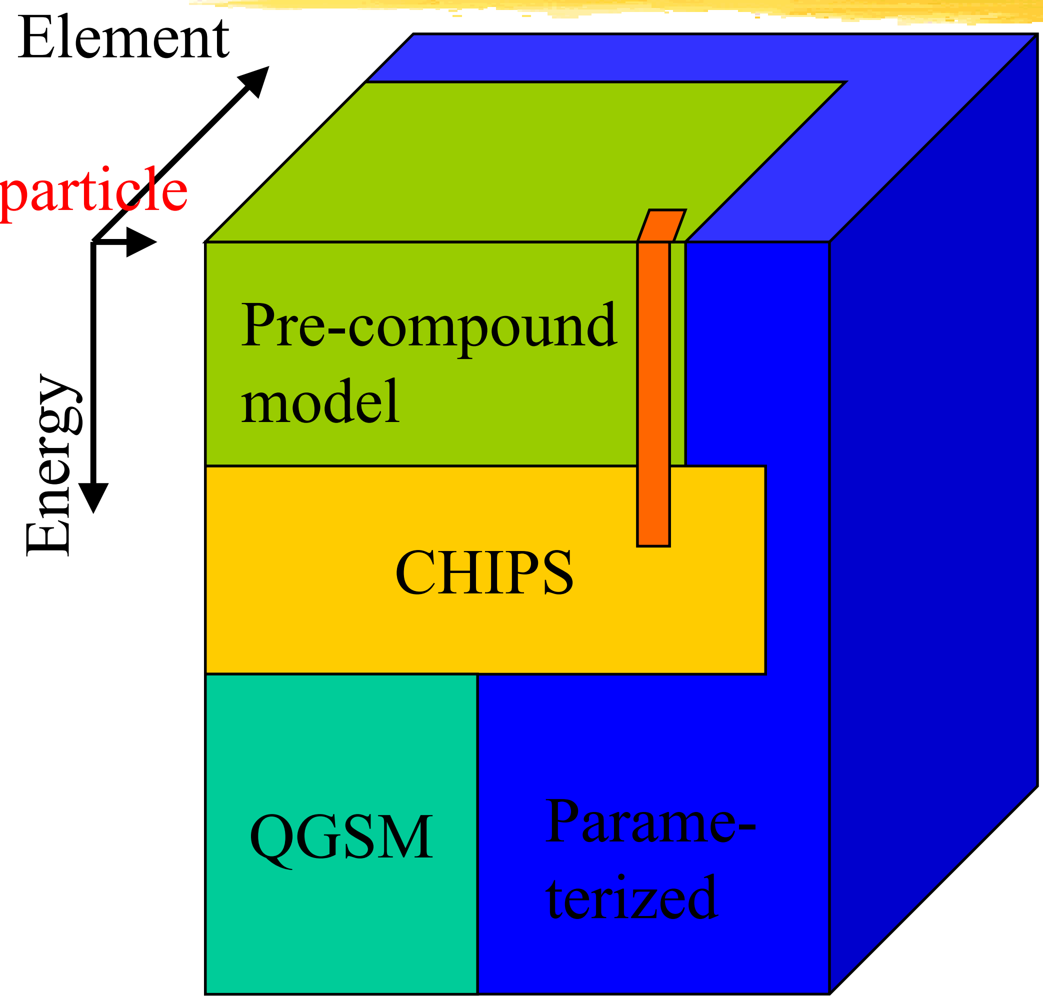
G3/G4 distributions statistically incompatible - K-S tests fail

incompatibility washed out because of the limited size of the test beam sample - More muons in the analysis pipe line .

Hadronic processes

- Five level implementation framework
  - allows models to be used in combination at different levels
    - Solving the mix and match problem in the framework
- Variety of models and cross-sections
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource requirements
- Components can be assembled in an optimized way for each use case.
  - A simple example is illustrated in figure (next page)

Assembling processes



- Illustrative example of assembling models into an inelastic process for set of particles
  - Uses levels 1 & 2 of framework

Hadronic processes

- Each hadronic process may have one or more
  - cross section data sets and
  - final state production models

  associated with it. Each one has its own applicability.
- We define “data set” and “model” broadly
  - A “data set” is an object that encapsulates methods and data for calculating total cross sections.
  - A “model” is an object that encapsulates methods and data for calculating final states.

Hadronic processes at rest

- At Rest processes
  - pion absorption
  - kaon absorption
  - neutron capture
  - antiproton annihilation
  - antineutron annihilation
  - mu capture
- At Rest processes may generate secondaries after some time interval.

Hadronic processes in flight

- Four types of processes
  - Elastic scattering
  - Inelastic scattering
  - Fission
  - Capture
- Examples
  - Parameterization driven models originally based on GHEISHA with many improvements
  - Data driven models based on ENDF/B-VI
  - Theory driven models for inelastic scattering

Modeling approaches

1. Data driven approach

- Neutrons
  - from numerous evaluated data libraries
  - down to thermal energies, up to 20 MeV
  - Isotope production (see next slide)
  - Induced Fission & Capture (H.Fesefeldt)
    - used above 20 MeV
- Photon-evaporation, radioactive decay, etc.

2. Parameterized models

  - Gheisha + fixes + new parameterizations (H.F, TRIUMF)

Modeling approaches (cont.)

3. Theoretical models, from low E to high E

- Pre-Compound Model + Evaporation Phase
- Cascades, CHIPS and QMD models
- String models
  - Excitation, fragmentation, hadronisation models
- Interface to event generator(s)
  - In future

Pre-Compound Model & Evaporation Phase

- Traditional pre-equilibrium model
  - as good as existing ones
- Evaporation:
  - Weisskopf-Ewing model
  - Fermi breakup model
  - Model for fission
  - Multi-fragmentation model (Bondorf)
  - Photon Evaporation
  - only missing Internal Conversion
    - (suppressed by more than 10^4, funding expected)
- Future: 2nd Pre-Compound, from HETC re-eng. (in 2002)

Cascade energy range

- Parameterized
- Bertini cascade (from HETC)
  - collaboration milestone for 2001 (Helsinki)
- Chiral Invariant Phase Space decay,"CHIPS"
  - 1st implementation now (Jefferson Lab.)
  - collaboration milestone 2001
- Kinetic model (INFN, Frankfurt)
- Further future: Relativistic QMD (Frankfurt), rewrite of INUCL code (Helsinki)

String models

- FTF string model, derived from Fritiof
  - but no Rutherford scattering
- Quark Gluon String model (~ Dual Parton)
  - for proton, neutron, π, K^+/K^- induced reaction
    - string decay as in JETSET
    - following Kaidalov's formulation
    - using FTF algorithm for energy transfer in case of single diffraction (~6% cases)

future: K_0, γ, anti-nucleon induced reactions

Future additions

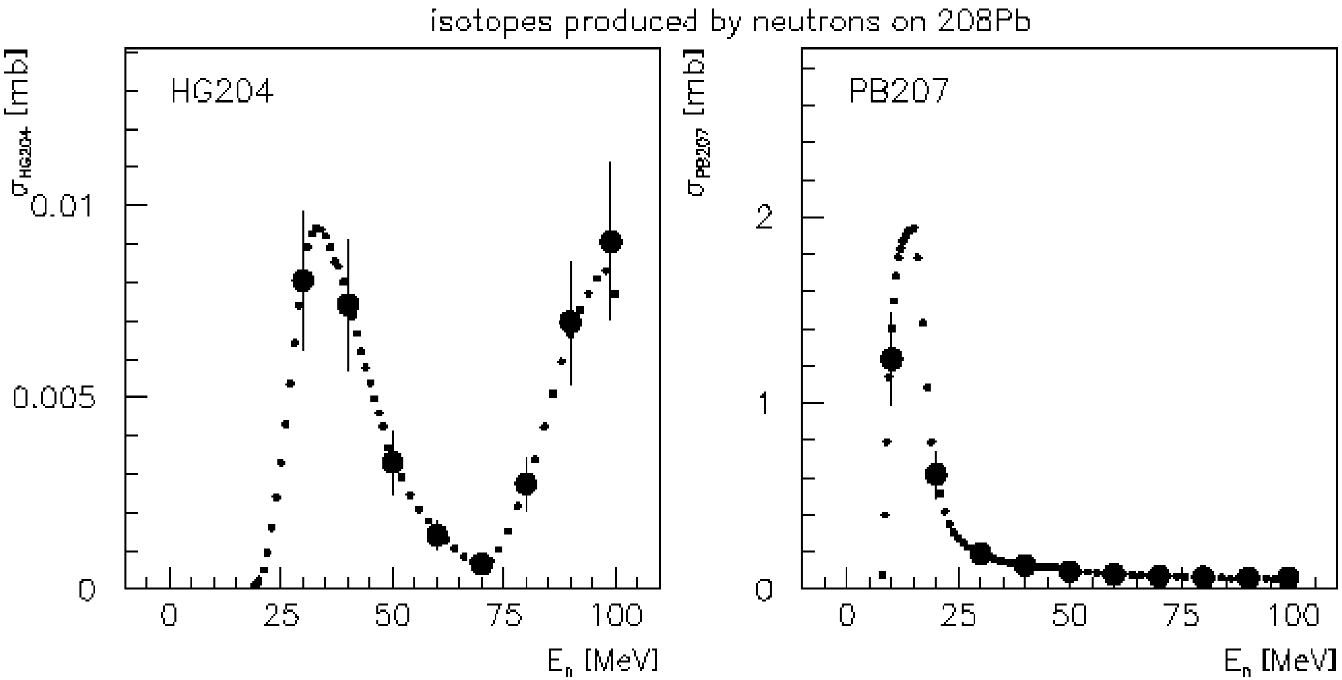
- Quark molecular dynamics model (Frankfurt)
- Nucleus-Nucleus
  - via QMD (Frankfurt)
  - for light nuclei using pre-compound and cascades
  - ablation/abration model
- Parton cascade (ansatz of K. Geiger)
- ‘Re-use’ of Pythia7
  - for hadron-nuclear & hadron-hadron interactions

Some of the Improved Hadronic Physics 1999-2001

- Neutron & proton induced isotope production models
  - up to 100 MeV (J.P. Wellisch)
- Multi-fragmentation and pre-compound
  - redesign & refinement (V. Lara)
- Additional string model (J.P.Wellisch)
  - for proton, neutron, π, K+/K- induced reactions
- Special cross-section classes for neutron, proton, and ion induced reactions (D. Axen, M. Laidlaw, J.P.W.)
- Retuning of High Energy Models (H. Fesefeldt) || (JPW)
- Doppler broadening of neutron X-section on the fly

Isotope Production

- Isotopes produced by neutrons on Lead 208



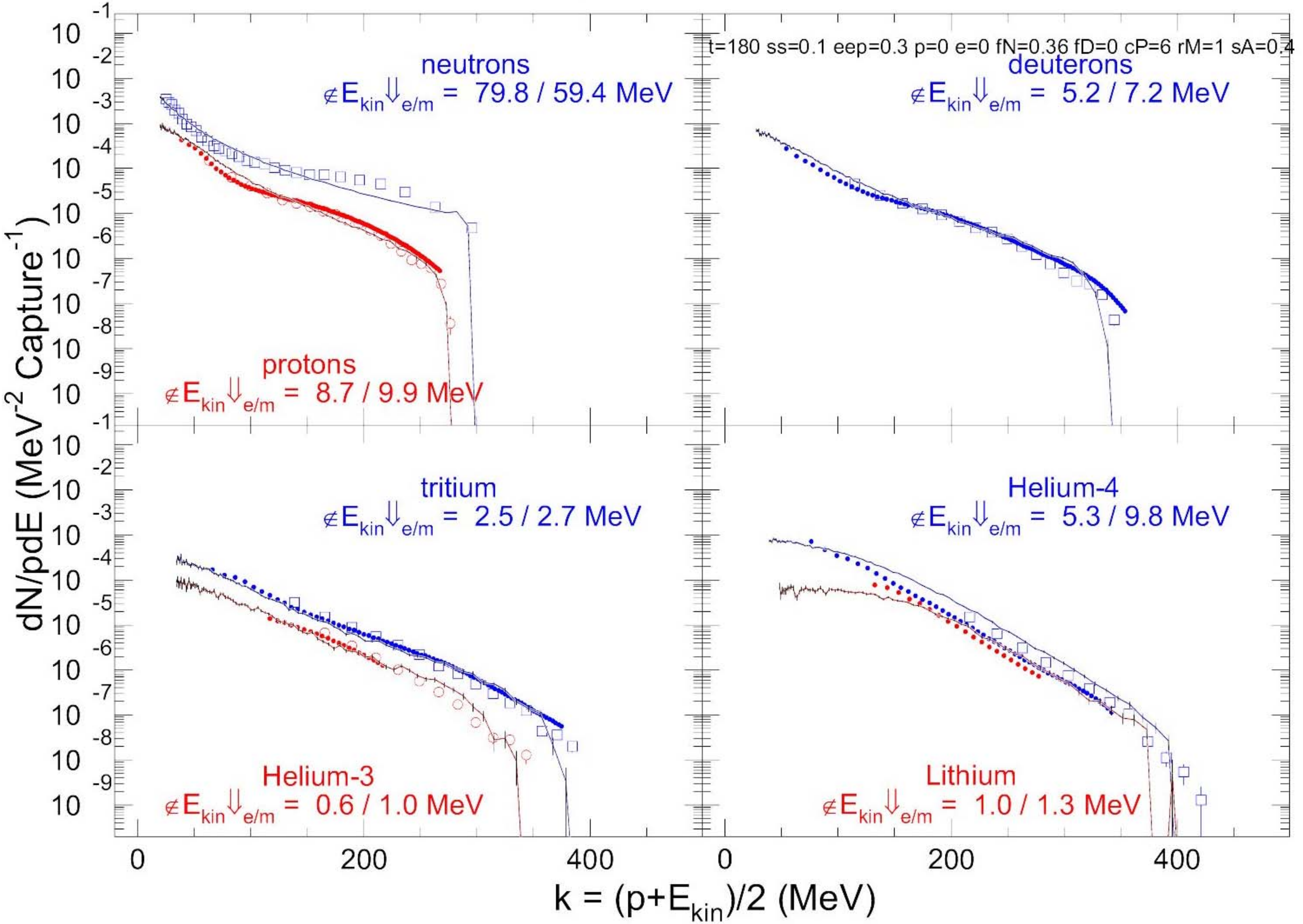
- Small dots: evaluated data
- Circles with error bars: Geant4
  - latest model
  - included since Geant4 1.0

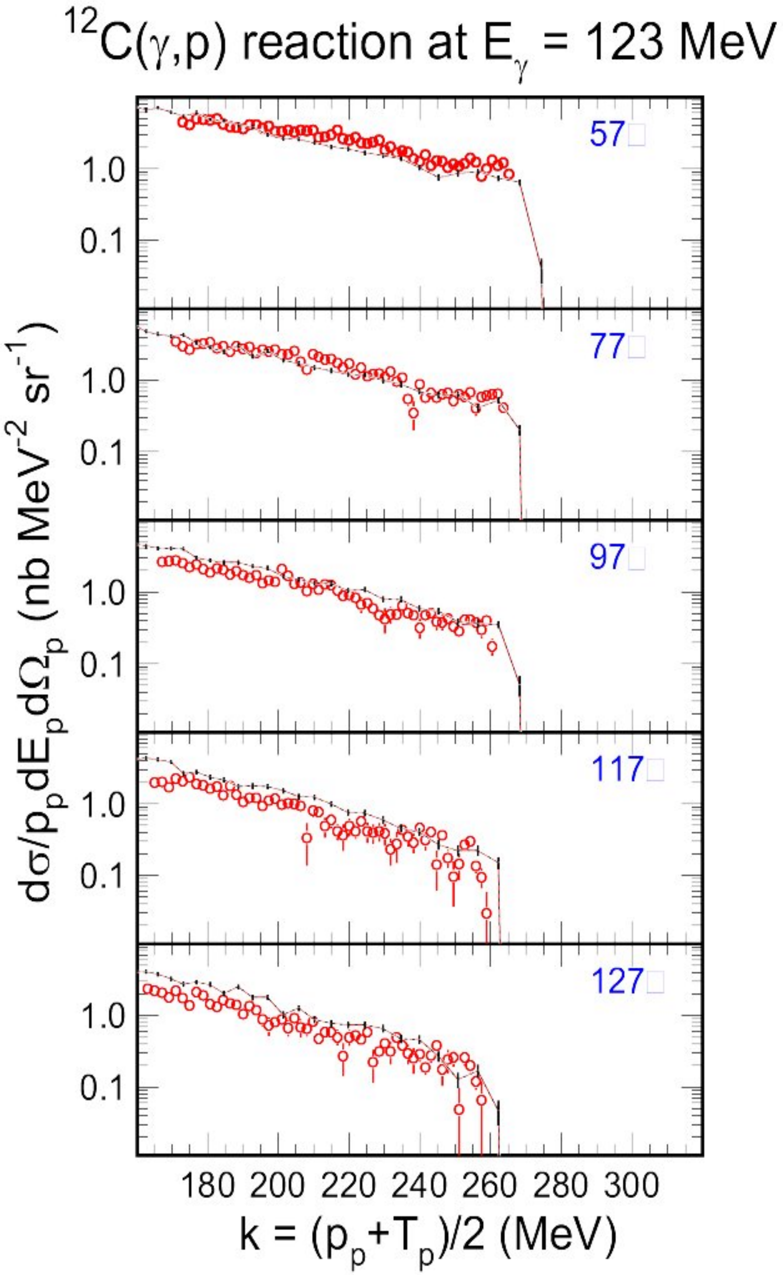
J.P.Wellisch

CHIPS

- New physics model/event generator
- From ~100 MeV to ~10 GeV
- Applications to date:
  - Pbar annihilation at rest
  - Pi capture
  - Gamma-nucleus interactions
  - Intranuclear transport
    - after high energy interaction
- Schedule for release end 2001

Pion capture on ^{12}C nucleus





Thanks to M. Kossov,
J.P. Wellisch,
P.V. Degtaryenko

For more on Hadronic Physics in Geant4, see the presentation in Track 5 by J.P. Wellisch, 5-004

"Hadronic Shower Models in Geant4: Validation strategy and Results"

Other processes

- Decay
- Optical processes
  - Reflection, refraction, absorption
- Photolepton-hadron
- Transportation
  - interrogates geometry, field motion

Parameterization/Fast Simulation

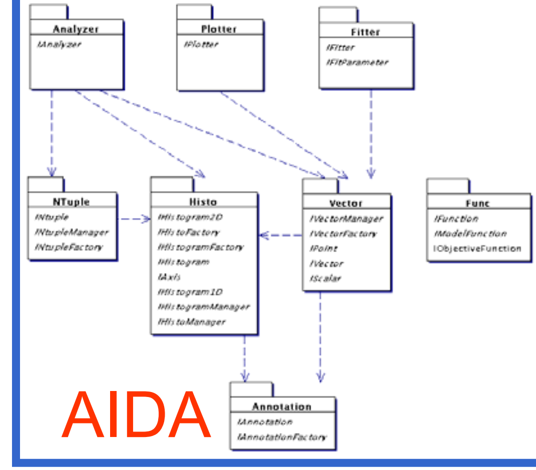
- Fast Simulation Manager
  - Framework for parameterization
  - Takes over from detailed simulation
  - can return to detailed simulation (eg cracks)
- Can trigger on particle, volume, ..
  - Parallel geometrical description
- User must create his/her own (for now)
- This parameterisation scheme utilised
  - For fast simulation of TR, PAI

Interface to external tools

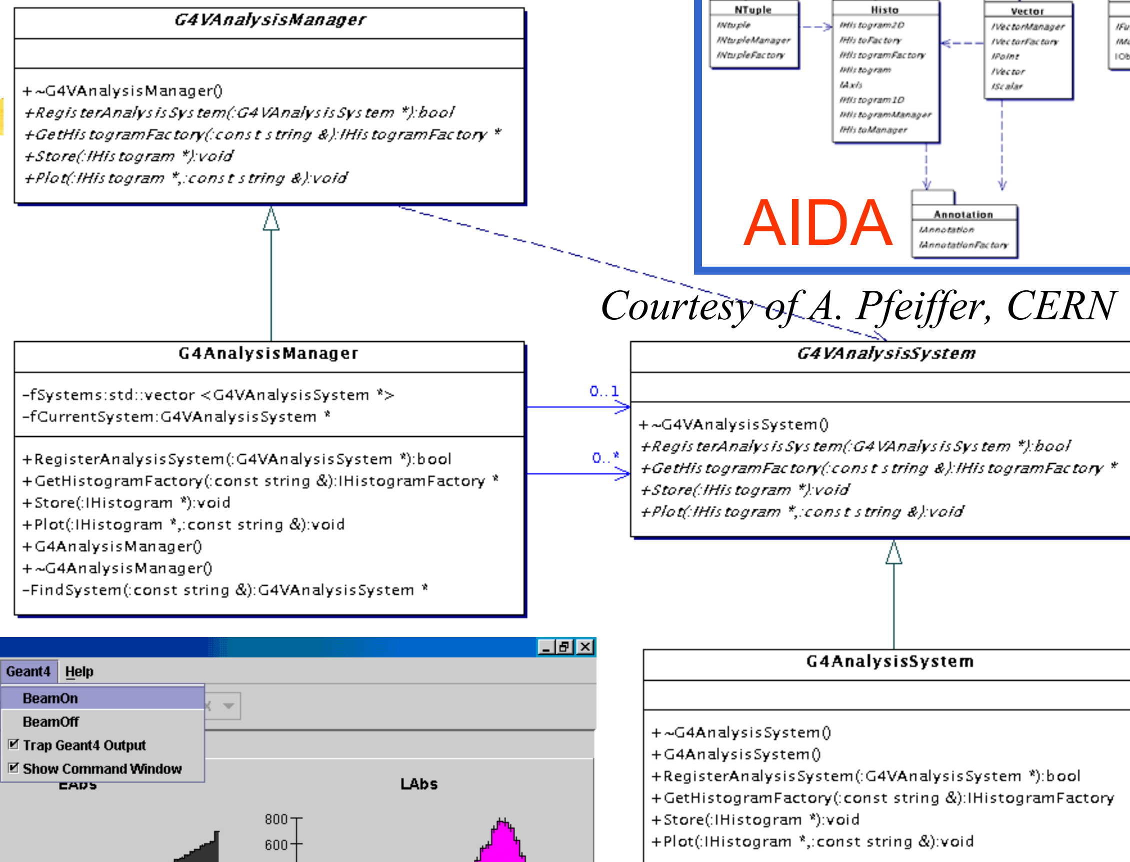
Through abstract interfaces

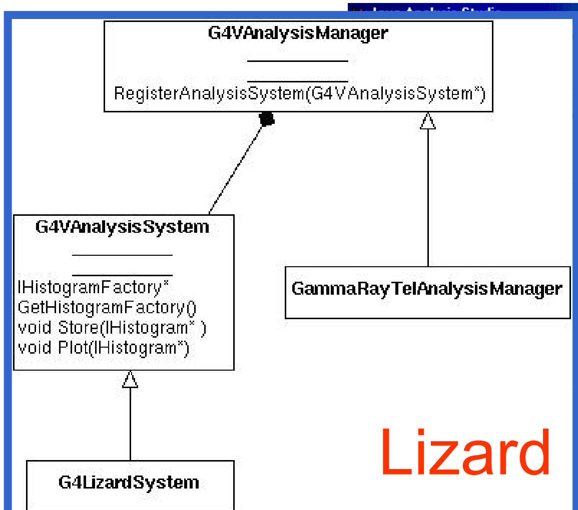
- *No dependence*
- *Minimize coupling of components*

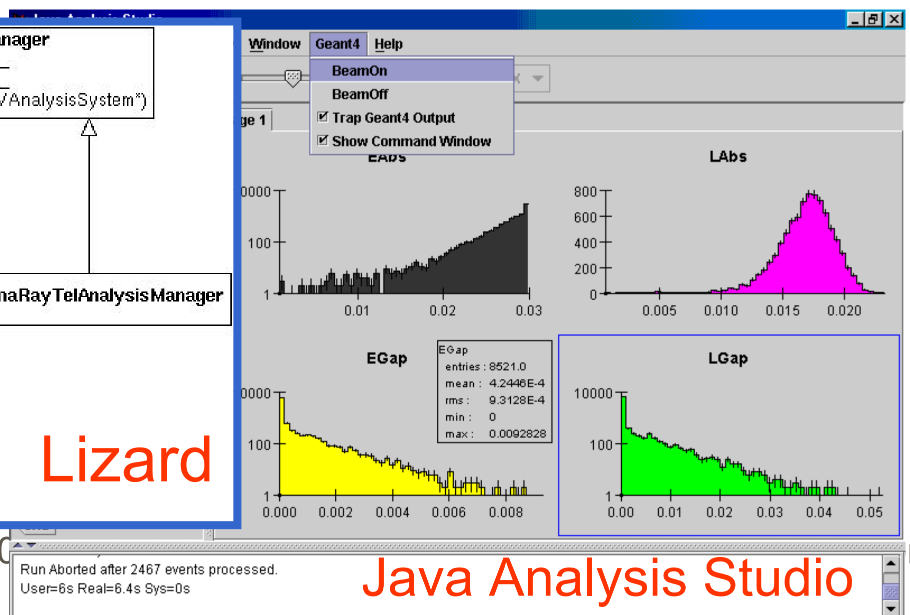
Example: AIDA & Analysis Tools



Courtesy of A. Pfeiffer, CERN





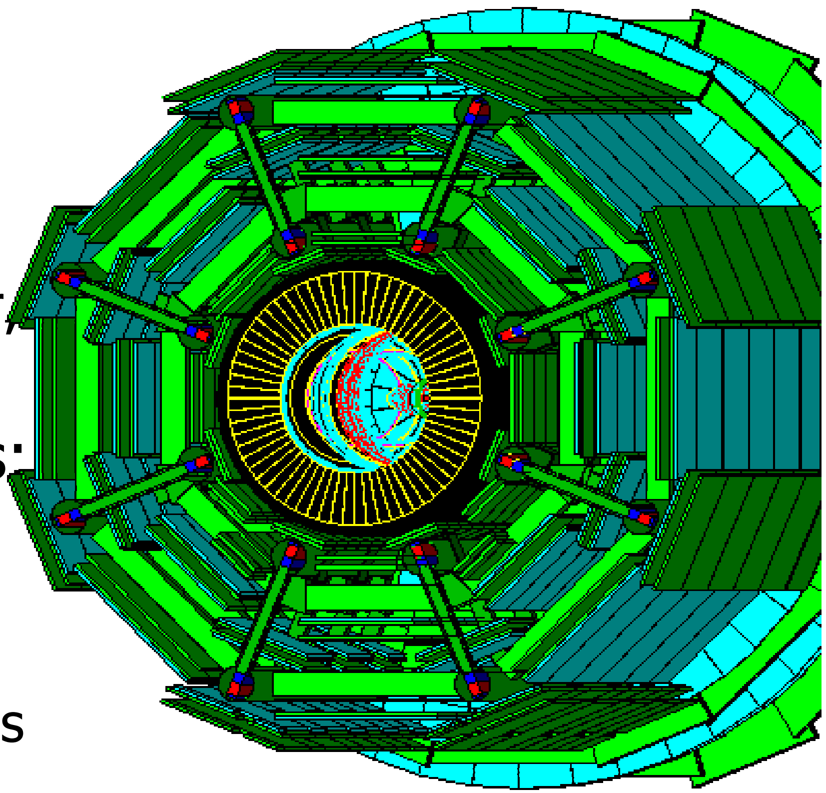


Similar approach:

- graphics
- (G)UI
- persistency
- etc.

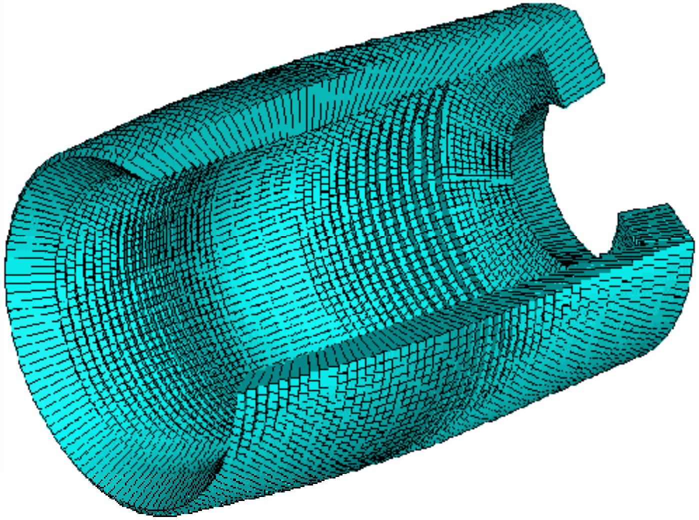
Visualization

- Much functionality is implemented
- Several drivers:
  - OpenGL, ***VRML,*** Open Inventor, Opacs, ***DAWN renderer (G4)***
- Also choice of User Interfaces:
  - Terminal (text) or
  - GUI: Momo (G4), OPACS
  - Editors for geometry, EM physics code generation



Object Persistency: Hits & other

- To store hits, use object persistency
- Abstract interface
  - ODBMS solution via RD45 (Objectivity)
  - Tracker-type and calorimeter-type hits
  - Saw minimal performance & storage overhead
- Minimal modifications
  - G4 kernel untouched
- *Also store:*
  - *Trajectories, Runs,*
  - *Events, Geometry*



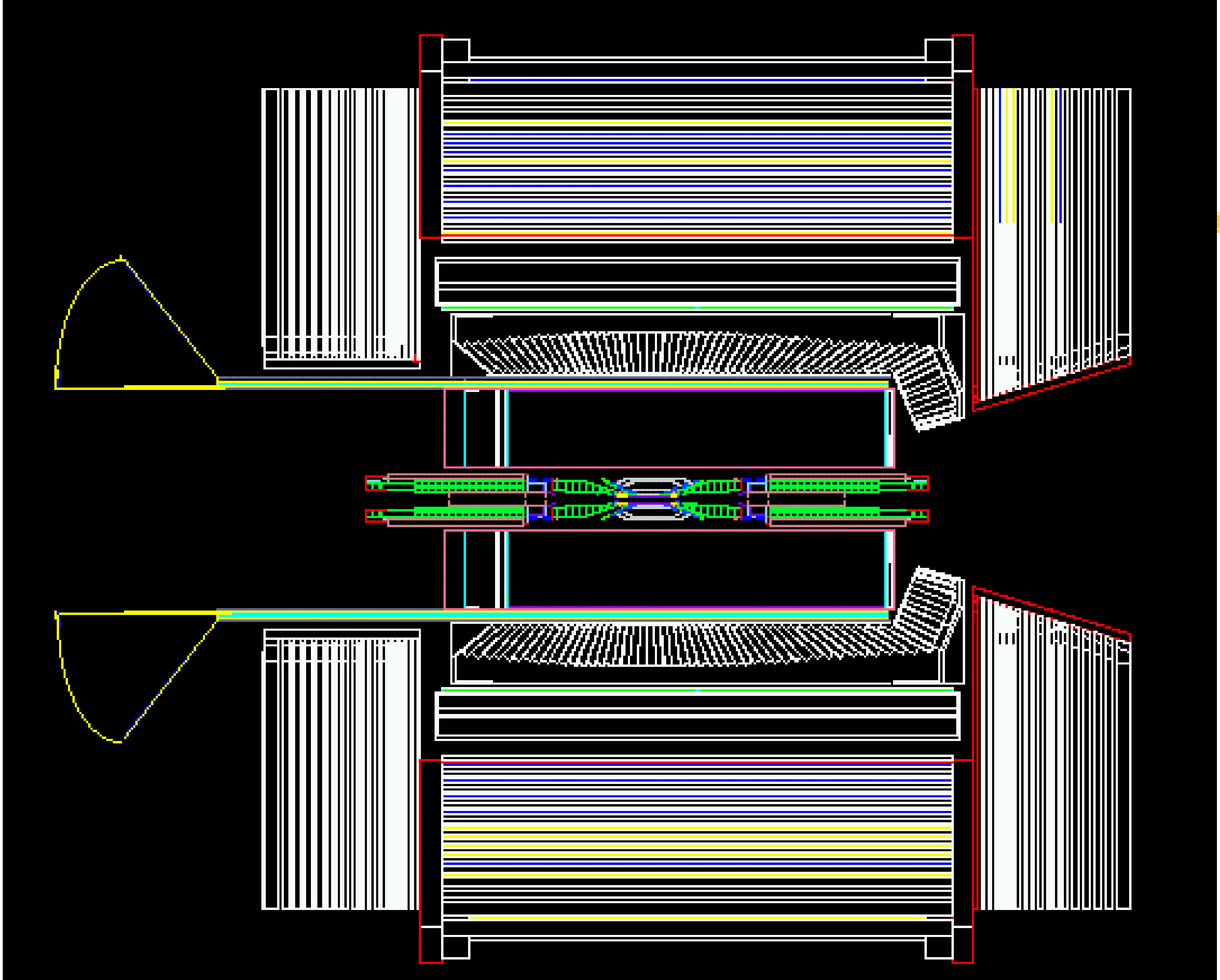
Use of Geant4

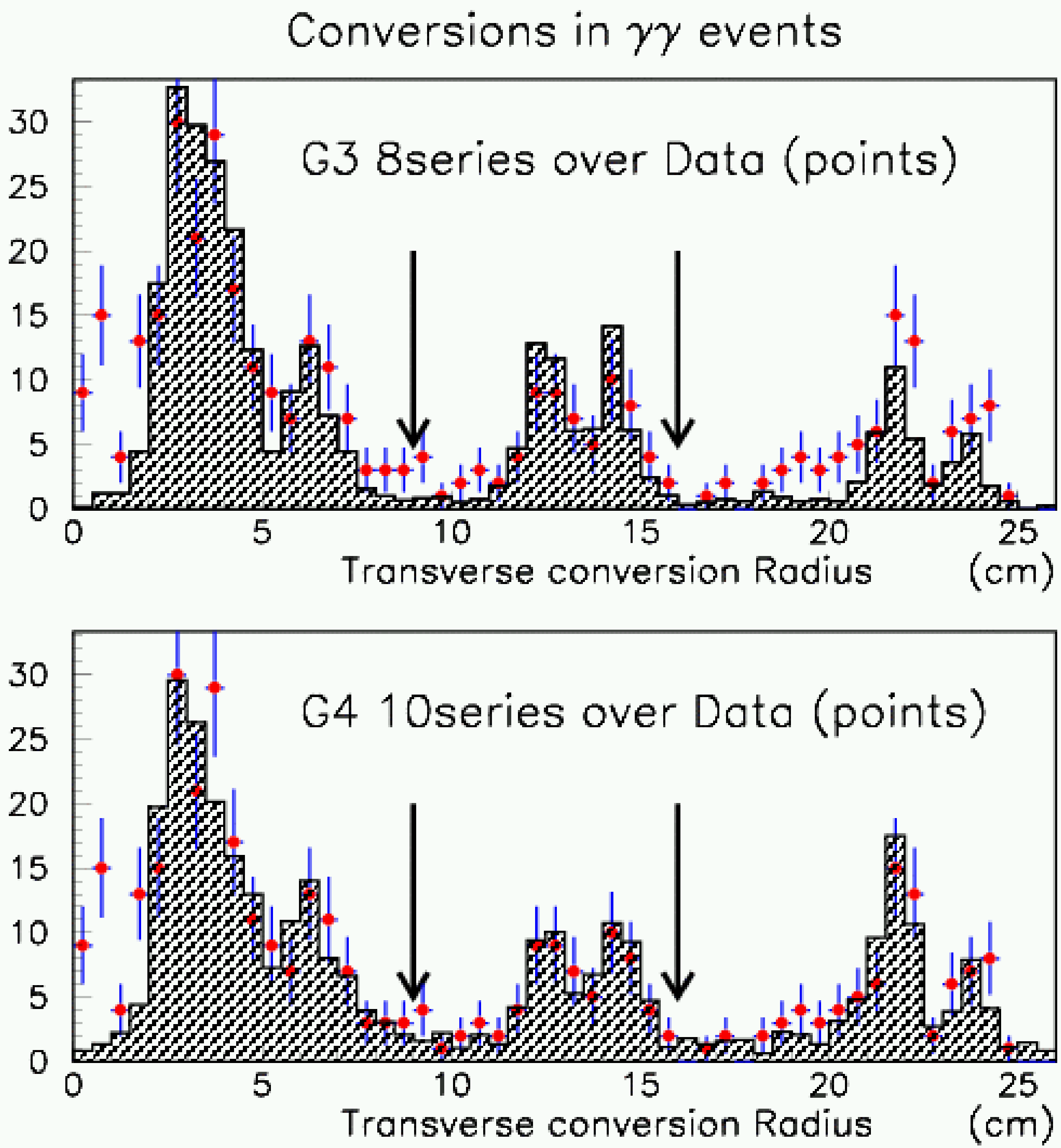
- Two and a half years from the first Geant4 public release, major experiments has already started to use Geant4 intensively:
  - BaBar: Full migration from G3 based simulator
  - HARP: Running today with G4 as only simulation
  - Atlas : G4 validation for all detector test beams 2000/1
  - CMS : Simulation of full detector based on G4 in 2001
- Usage of Geant4 has expanded to fields other than HEP.
  - Accelerator applications (T9 Harp, Muon fact.)
  - Space (see 5-002) and medical applications

BaBar full simulator 'BOGUS'

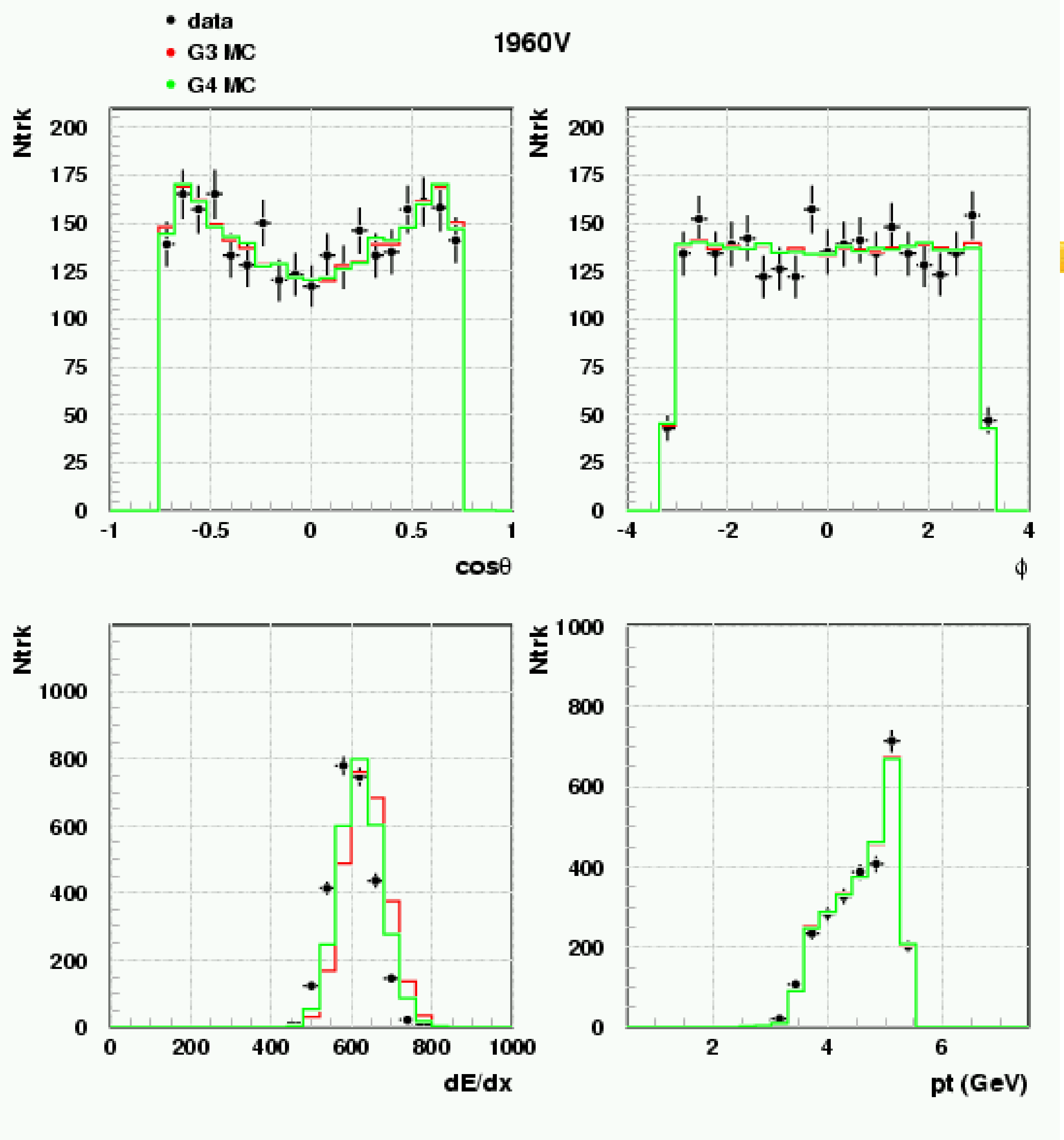
BaBar Object-oriented Geant4-based Unified Simulator

- 2.5 million events generated
  - Robust - Crash rate of 3 events / 1 million
  - No significant memory leaks
  - As good performance as BBSIM (Geant3)
- Comparisons with experimental data and BBSIM, were undertaken, using the full reconstruction chain.
- Decision to move to Geant4 and plan to utilize it exclusively for 2001 data.
  - Full production with BOGUS is starting soon: plans to simulate 200 million events by early 2002.





Conversions in $\gamma\gamma$ events
G3 8series over Data (points)
Transverse conversion Radius (cm)
G4 10series over Data (points)
Transverse conversion Radius (cm)


data
G3 MC
G4 MC
1960V
Ntrk
cosθ
ϕ
dE/dx
pt (GeV)

Atlas TRT tracker

Simulating energy deposition in thin straw tubes of gas.

- Precision requirements led to adoption of PAI model of energy loss for gas,
  - For remainder of detector the standard energy loss is applied (tailored physics list)
  - Good agreement in many comparisons.
  - Validated use of new concrete PAI parameterisations for fast simulation.
- Utilising transition radiation models.

Geant4 latest releases

- Geant4 3.0 released December 2000
  - with additional physics models
    - and refinements/improvements/corrections in existing ones
  - with new functionality, eg
    - first Analysis module, to use AIDA histograms+..
      - create manager of AIDA objects
    - new examples with visualisation, analysis
- Geant4 3.2 on June 29th, 2001

Performance?

- Geometry navigation
  - Geant4 automatically optimizes the user's geometrical description. And it provides faster navigation than optimized Geant3 descriptions.
- EM Physics computing performance goals
  - For the same physics performance, we seek speed at the level of Geant3 or better.
  - Keeping physics performance constant, optimise the speed that maintains the performance.
    - In two current speed benchmarks (thin silicon & simplified sampling calorimeter) these goals are achieved.

Performance?

- In experimental setups
  - Atlas EM Barrel: comparable performance
  - Atlas FCAL: Geant4 is 3x faster than Geant3
  - BaBar: comparable performance.
- Our goal is that Geant4 is at least as fast as Geant3 in almost every case
  - when its power and features are well exploited.
  - And, where required, ‘new’ techniques including shower parameterisation can be used to obtain large speedups (in acceptable trade-off with accuracy)

Future directions

The next major release, Geant4 4.0 in December, is scheduled to include

- New theoretical hadronic models
  - Re-engineered from HETC
  - CHIPS for gamma-Nucleus, π capture and intranuclear transport
- Ability to reduce initialisation time
  - By saving/retrieving physics processes' tables
- Ability to set different Cuts for different regions

Future directions

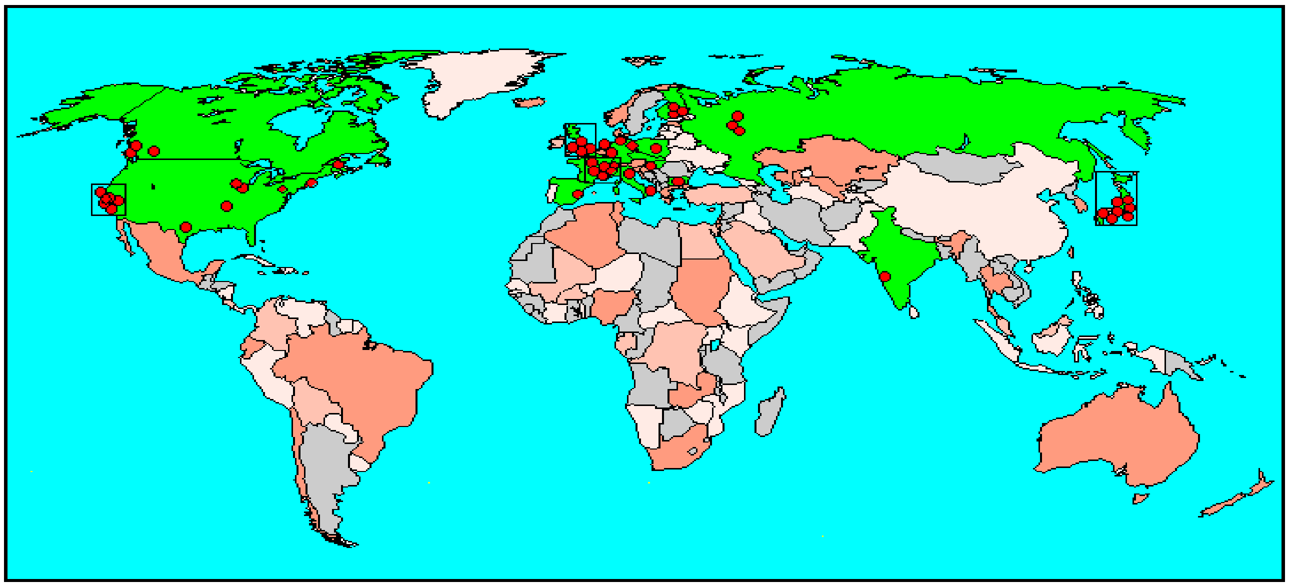
We plan

- To facilitate the specialization of those parts of hadronic physics lists that vary between use cases.
- To create and distribute “educated guess” physics lists corresponding to the major use cases of Geant4 involving hadronic physics,
  - As an aid and starting point for users.

Software process

- Geant4 has been the first software development in HEP to fully apply most recent software engineering methodologies.
- Current focus of Process Improvement in Geant4:
  - Q/A & Optimization activity
    - apply Q/A to the software product
  - Analysis & Design software cycle
    - identify the well established OOP procedure for development and maintenance
  - Testing
    - assure constant improvement and continuity to system testing
- For more on this see 8-008 (Wed.)

Geant4 Collaboration



Collaborators also from non-member institutions, including
Budker Inst. of Physics
IHEP Protvino
MEPHI Moscow
Pittsburg University

Summary

- Geant4 is in use today in running HEP experiments (BaBar, HARP)
- Results of comparing Geant4 versus data
  - are growing month by month,
  - have provided important 'yardsticks'.
- Geant4 has demonstrated important strenghts:
  - stability of results, flexibility, transparency.
- Refinements & development are ingoing.

Geant4 releases: timeline

- Dec '94 - Project start
- July 98 - First beta release
- Dec '98 - Geant4 0.0 release
- Jul '99 - Geant4 0.1 release
- ...
- Dec '00 - Geant4 3.0 release
- June 01 – Geant4 3.2 release
- Two public releases per year
  - Plus monthly development tags for collaboration users

CERN RD44

MoU-based collaboration

THE END

Note that it was not possible to give credit to all those who have contributed to Geant4 …