New trends in detector and background simulation: Geant4.

J.P. Wellisch

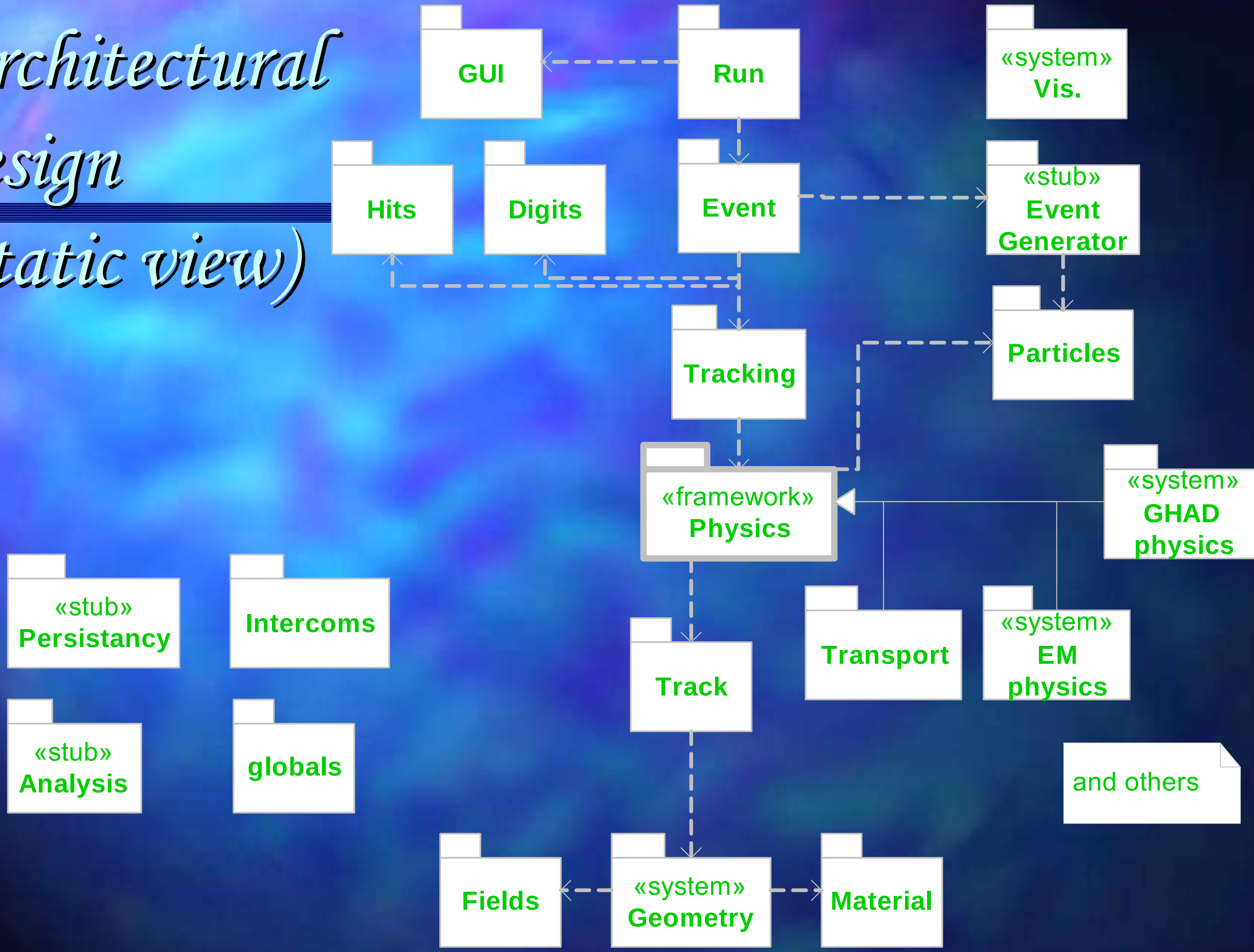
What is Geant4?

- Geant4 is the successor of GEANT 3.21.
- Geant4 is the first successful attempt to re-design a major package of CERN software for the next generation of HEP experiments using an Object-Oriented environment.
- A variety of requirements also come from heavy ion physics, CP violation physics, cosmic ray physics, medical applications and space science applications.
- In order to meet such requirements, a large degree of functionality and flexibility have been provided.

Principal software considerations:

- Use an open and extendible architecture.
- Use implementation frameworks to achieve maximum extendibility and flexibility in the physics modeling
- We invite collaboration with all experts, to render the physics base of geant4 as rich as possible
- Use abstract interfaces to de-couple and enable independent development by experts
- Ensure that the physics implementations are both accessible to and transparent for the user, so results can more easily be verified, and if deviations or surprising agreement were found, they can be traced back, and the modeling can be adapted to the usage.

Architectural design (static view)



What I will say: Key capabilities in selected areas

- Geometry.
- Electromagnetic physics.
- Hadronic physics.

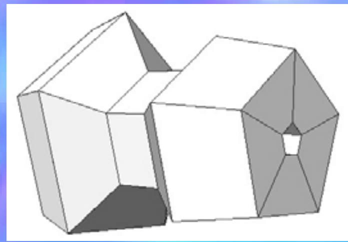
- Application highlights from accelerator and astro-particle physics, and space engineering.

What I will not say

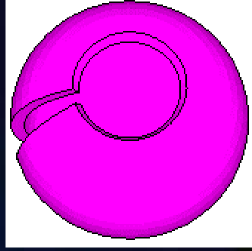
- Visualization.
- GUIs.
- Intercoms.
- Hits, digits, tallying.
- Variance reduction.
- Run and event frameworks.
- Tracking, stacking, transportation.

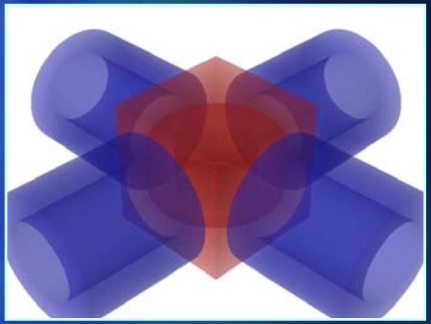
Key geometry capabilities

- Describing a setup as volume hierarchy or ‘flat’ structure
  - Allows to describe highly complex setups (millions of volumes)
  - Tools for creating & checking complex structures
- Fast navigation in complex geometry models
  - Automatic optimization
- Geometry models can be ‘dynamic’
  - Changing the setup at run-time
- Multiple geometries
  - For tracking, hits/readout, biasing/scoring, fast simulation
- Defining geometrical ‘regions’
  - Choice of production threshold
  - Triggering of fast simulation



Rich set of solid types:



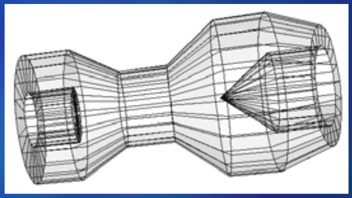


CSG *(Constructed Solid Geometries)*

- simple solids

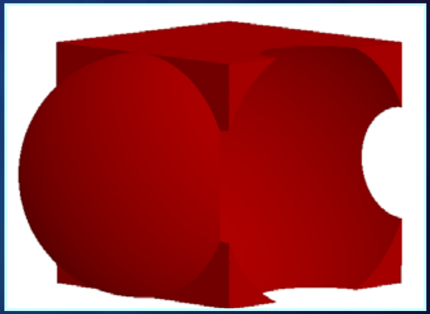
Boolean solids

- union, subtraction…



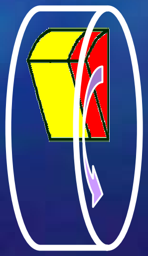
BREPS *(Boundary REPresented Solids)*

- volumes defined by boundary surfaces
- cylinders, cones, toroid, polyhedron, etc.



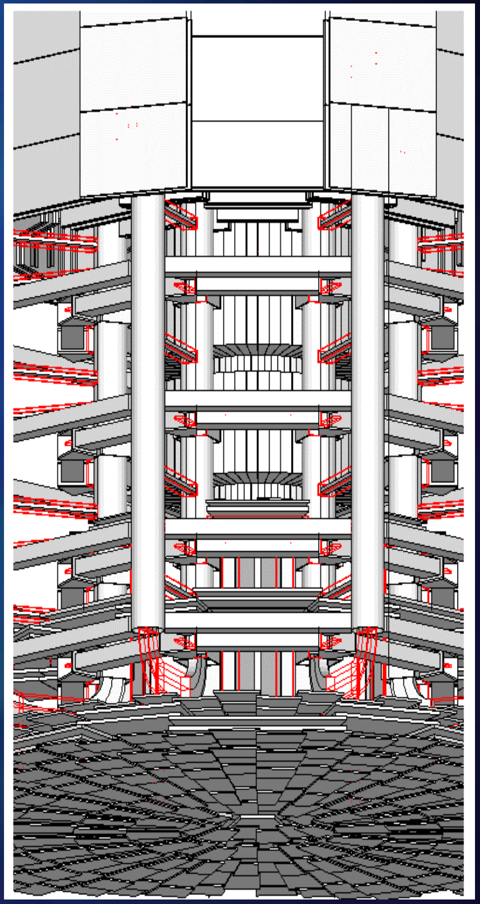
Fields: any variable, non-uniform field (ideally differentiable)

Magnetic, electric, combined…

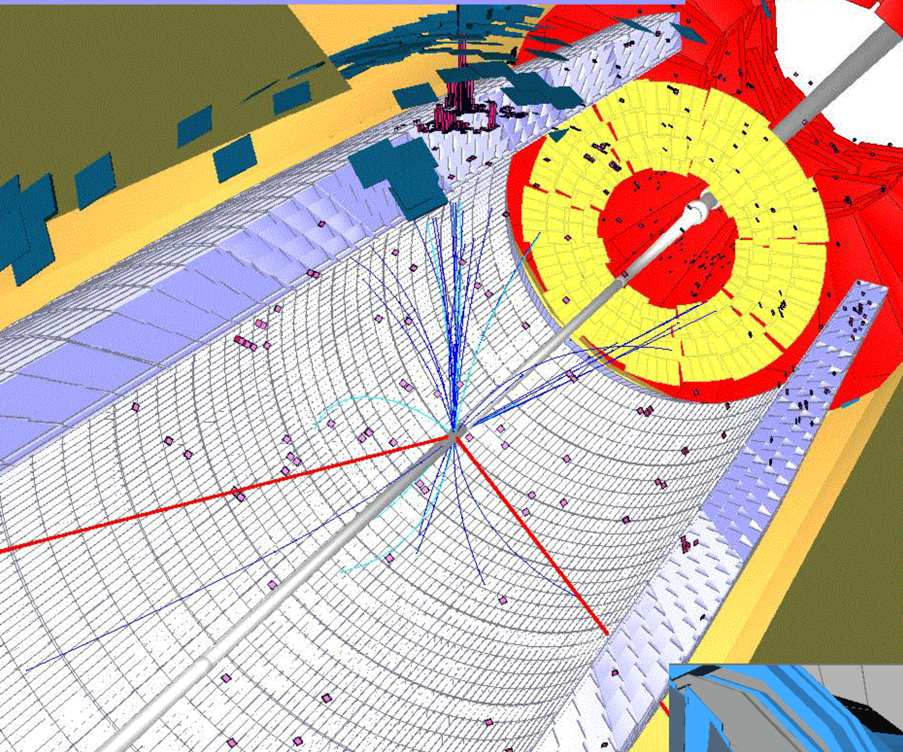


Facilities for debugging setups

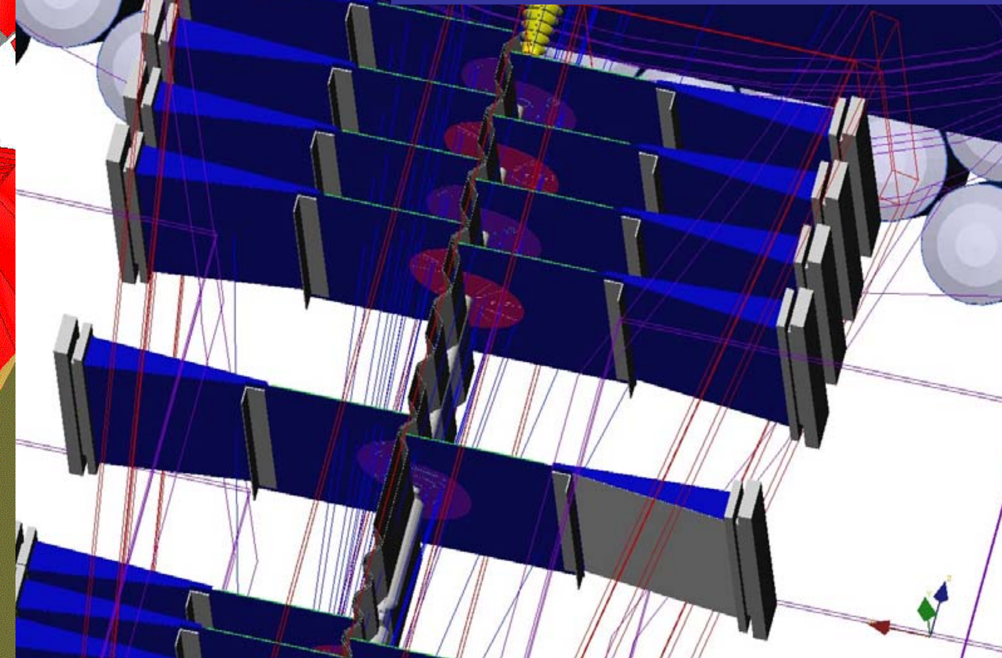
- Special facilities allow a user to
  - Group volumes to create regular geometry patterns
    - an ‘assembly’ of volumes can be imprinted several times
  - Reflect part of a structure (as above)
  - Debug the geometry setup (see picture at right)
    - Using contributed tools & embedded commands
  - Characterizing parts with common attributes (regions)
  - Calculate the volume of a solid & the mass of a setup
- A geometry setup can be described either in C++ code or:
  - Using a simple tool (Geant4 Geometry Editor)
  - Importing / exporting from external XML format
    - e.g. GDML (Geometry Description Markup Language)
    - http://cern.ch/GDML
  - Through other specialized applications
    - e.g. interactively in GATE (http://lphe.epfl.ch/~PET/research/gate)



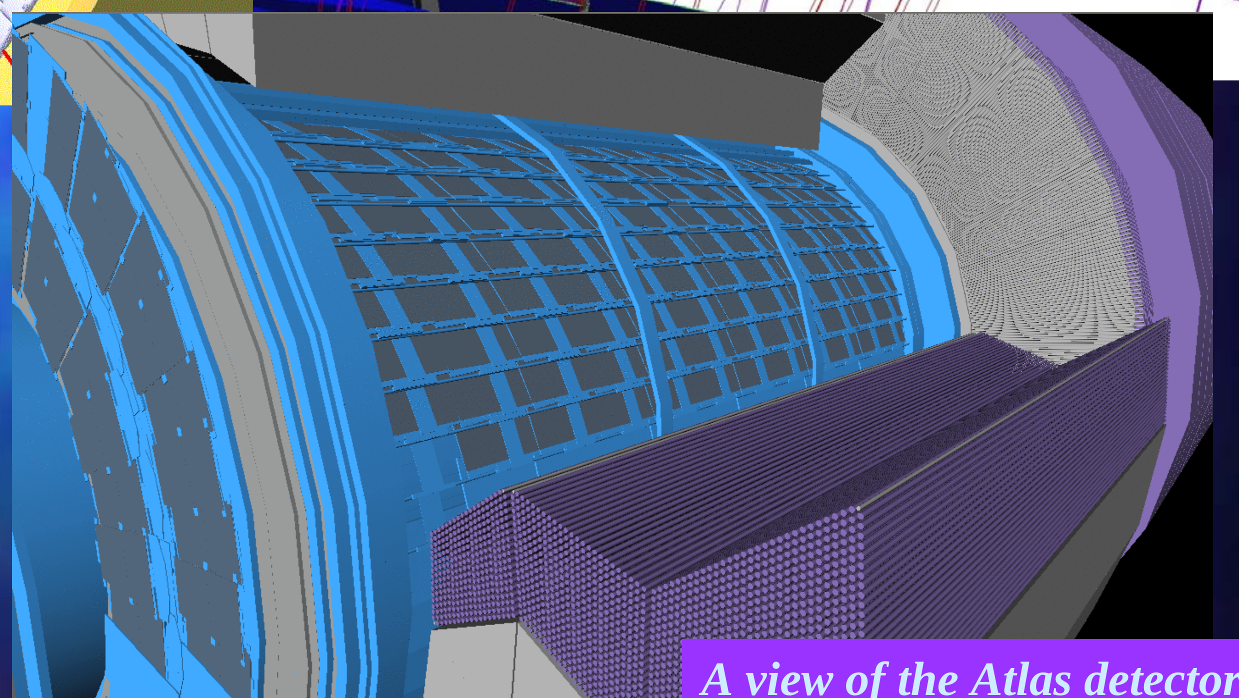
An event in the CMS detector



An event in the LHCb detector



A few example setups
from LHC experiments …



A view of the Atlas detector

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Electromagnetic Physics in Geant4

- Processes of gamma, electron, and positron interactions with media are traditionally called “Electromagnetic Processes” (EM)
- Hadron interactions with atomic electrons are provided by G4 EM
- Optical photon generation and interaction are also under responsibility of EM physics group

- Two sets of codes: standard electromagnetic physics, and low energy physics.

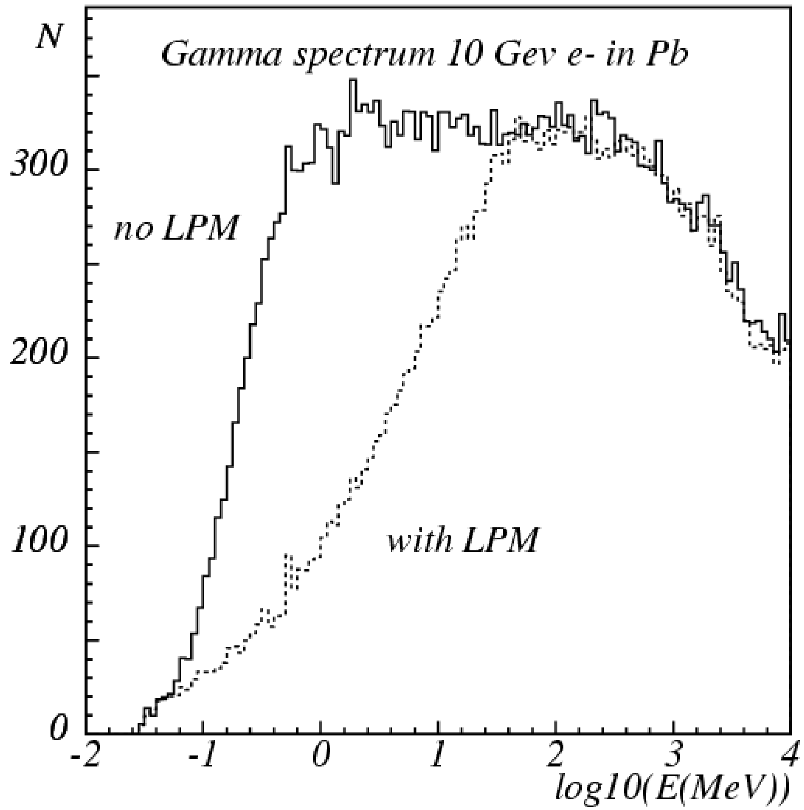
Standard EM packages

- Largely a natural evolution of the GEANT 3 EM physics
- Includes a complete set of models for simulation of EM processes in the energy range from 1 keV to 10 PeV
  - Sub-packages: utils, standard, muons, highenergy, xrays
- Includes optical photons production and transport
- Universal approach for energy loss processes:
  - Continuous energy loss for transfers below cut
  - Sampling of secondary with energy above the cut
- Cuts expressed in term of particle range
- Focus on particle physics, but well applicable for instrumentation, space, and medicine studies

Standard EM Physics

- Review of G3 models have been done
- More precise theories are used if possible
- Main processes:
  - ionization
  - bremsstrahlung
  - multiple scattering
  - photoelectric effect
  - Compton scattering
  - gamma conversion
  - e^+ annihilation
  - Cherenkov radiation
  - scintillation
  - synchrotron radiation

Landau-Pomeranchuk-Migdal Effect for bremsstrahlung



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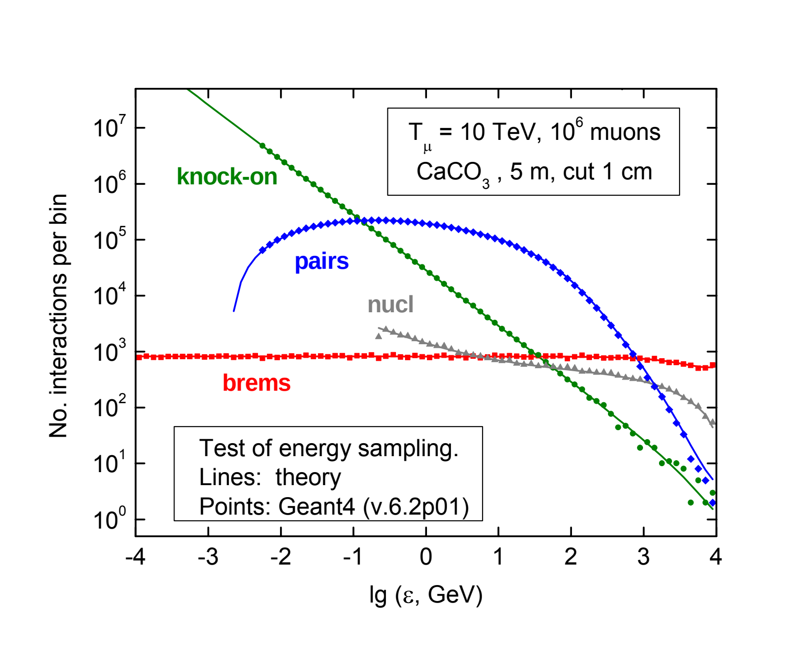
Geant4 muon interactions

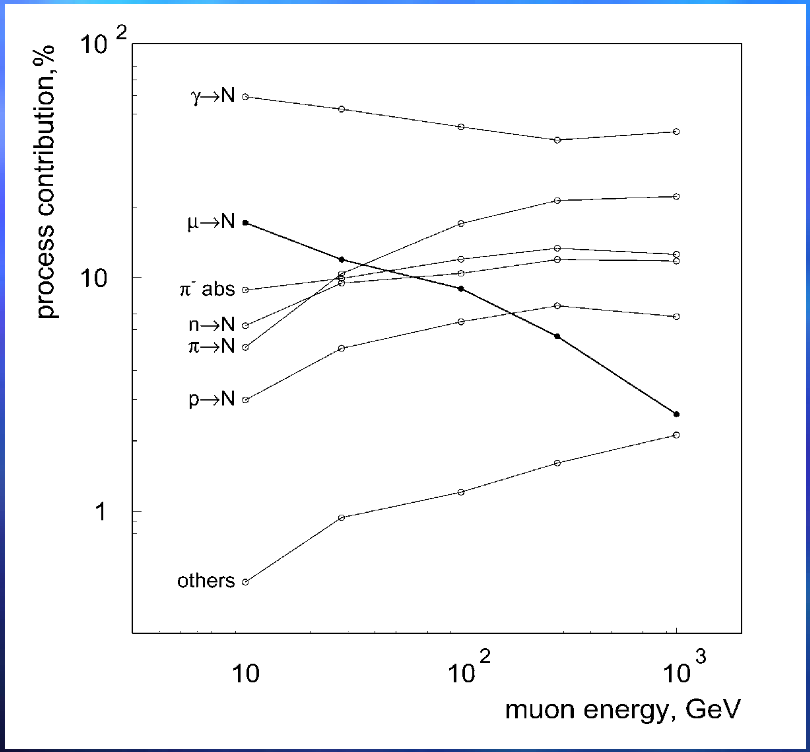
- Basic processes:
  - Ionisation
  - Bremsstrahlung
  - Production of e^+e^-
  - Muon-nuclear interactions
- Muon production and transport in Geant4 is available up to 10 PeV

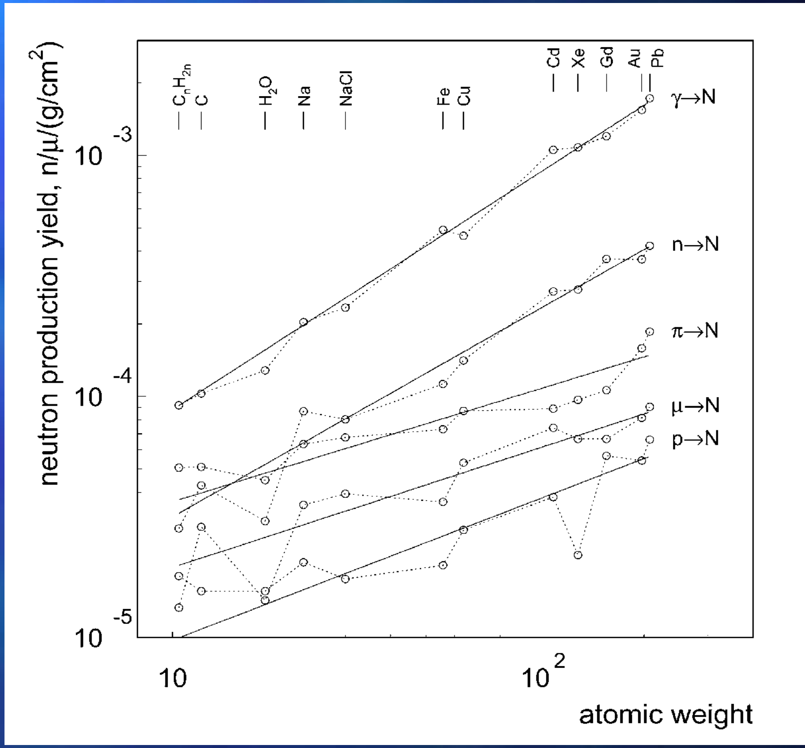
Verification of muon processes At high energy



Muon induced neutron yield by process

(hep-ex/0411026v4)





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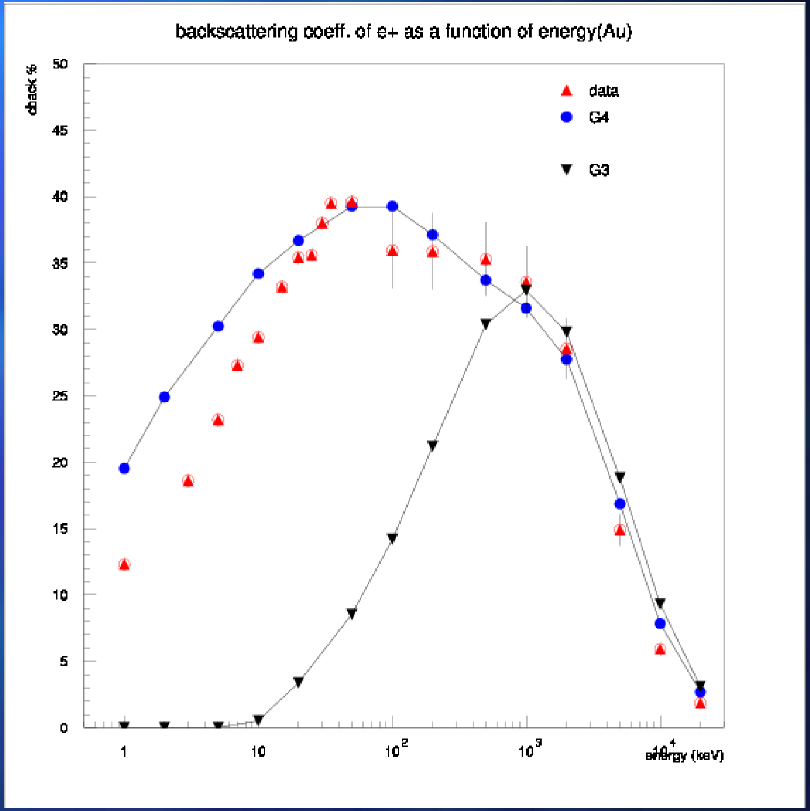
New Multiple Scattering Model

- Based on Lewis theory PR 78 (1950) 526
- Does not constraint the step size
- Provides simulation of physical length of a track
- Provides simulation of transverse displacement



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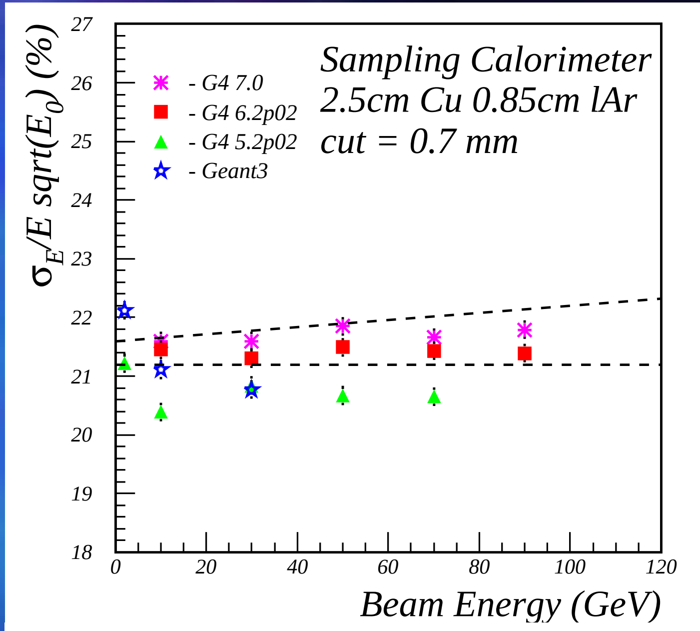
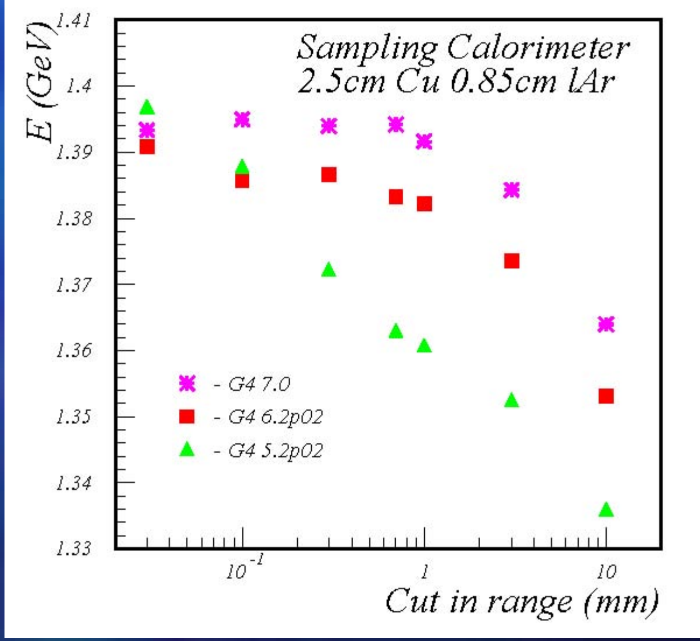
Integral approach

- EM cross sections strongly depend on energy
- Integral approach: interaction probability is sampled using integral method
- Integral method for tracking and updated model of multiple scattering provide less cut dependent results
- Is available from G4 6.0





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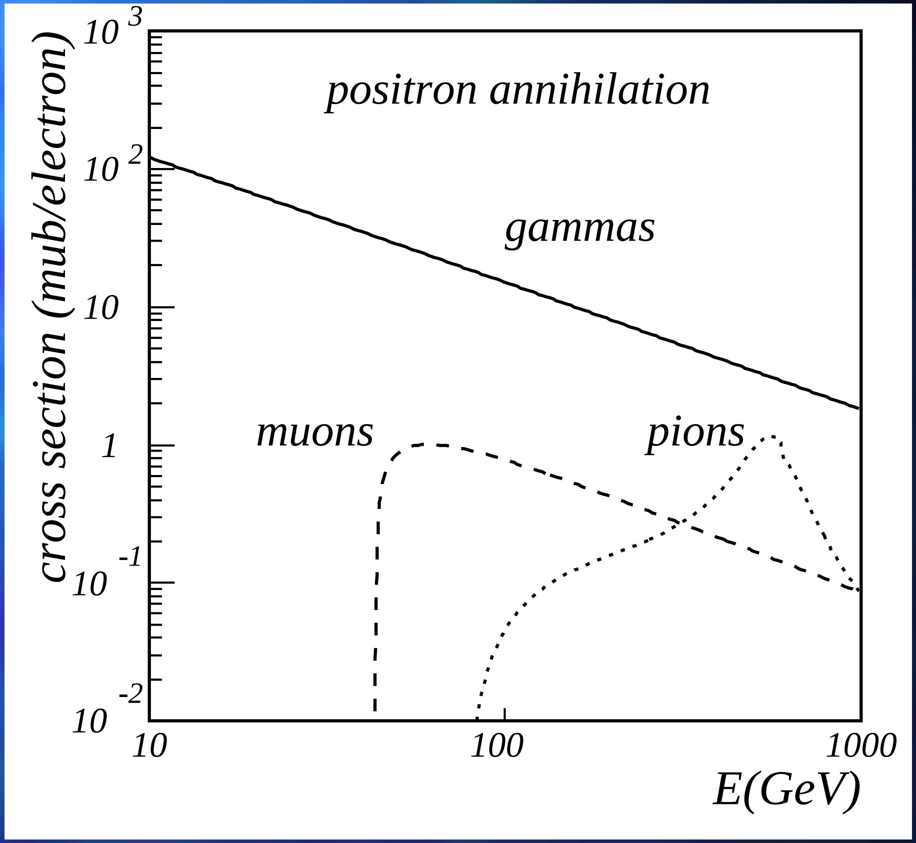
New High energy EM processes

- EM background due to high energy EM interaction with media:
  - $\gamma \rightarrow \mu^+\mu^-$ ($\sigma \sim Z^2$)
  - e^+ (e^-) $\rightarrow \mu^+\mu^-$ ($\sigma \sim Z$)
  - e^+ (e^-) $\rightarrow \pi^+\pi^-$ ($\sigma \sim Z$)
- Visible at LEP and High at SLC
- Of particular concern for linear colliders



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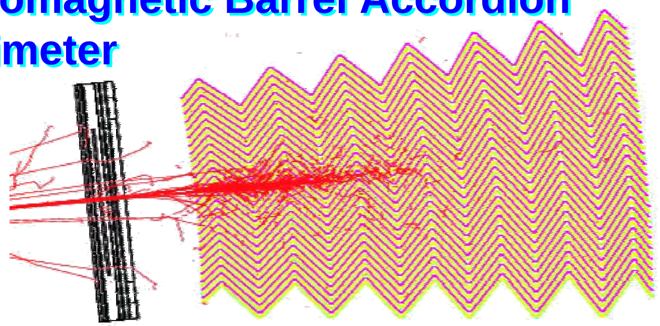
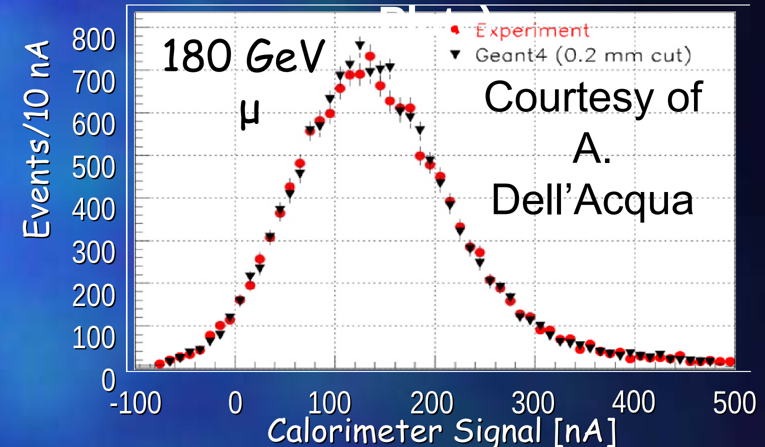
Geant4 electron response in ATLAS calorimetry

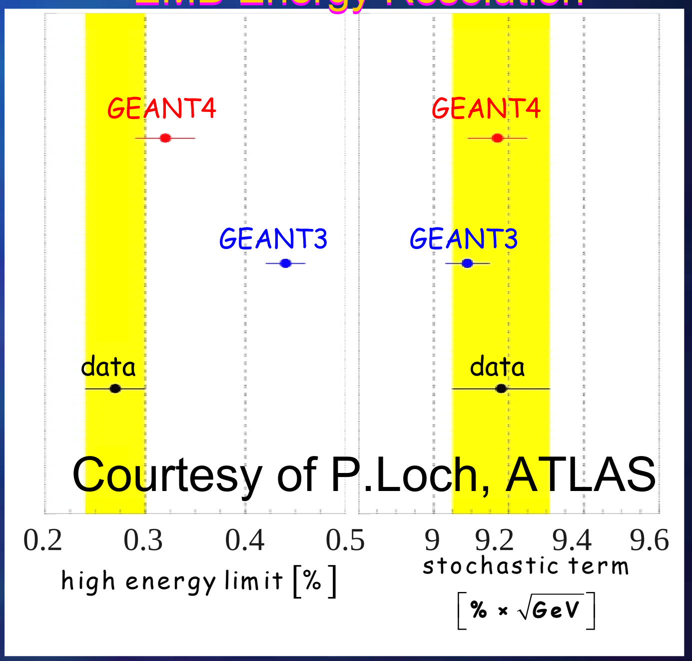
10 GeV electron in the ATLAS Electromagnetic Barrel Accordion Calorimeter



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



EMB Energy Resolution

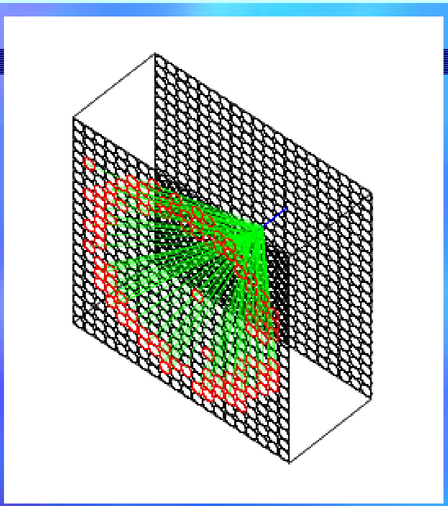


Geant4 reproduces the average electron signal as a function of incident energy in all ATLAS calorimeters very well

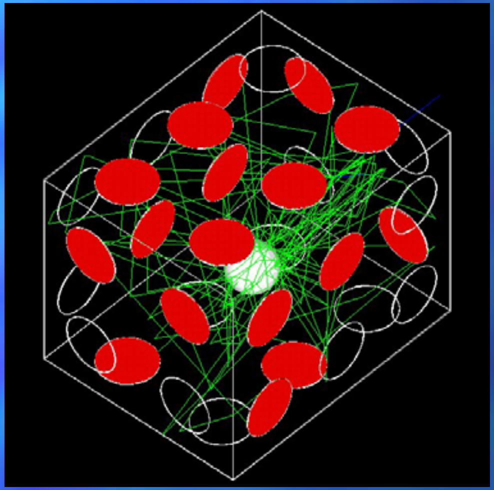
Signal fluctuations in EMB are very well simulated

Optical Processes

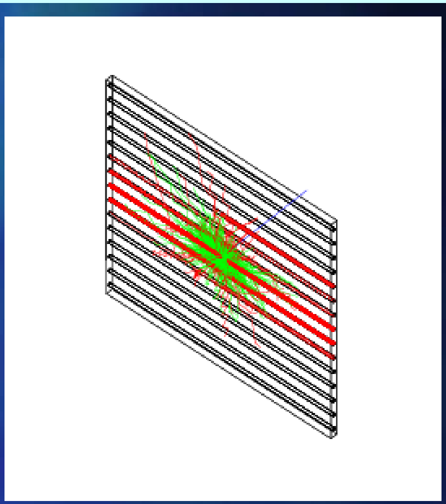
Cherenkov ring simulation



Light collection in liquid detector



Wave length shifter simulation



- The same geometry as for the main G4 tracking is used
- Surface properties can be defined in great detail for simulation of refraction and absorption
- The scintillation process allows to simulate slow and fast components
- Wave length shifter process is available

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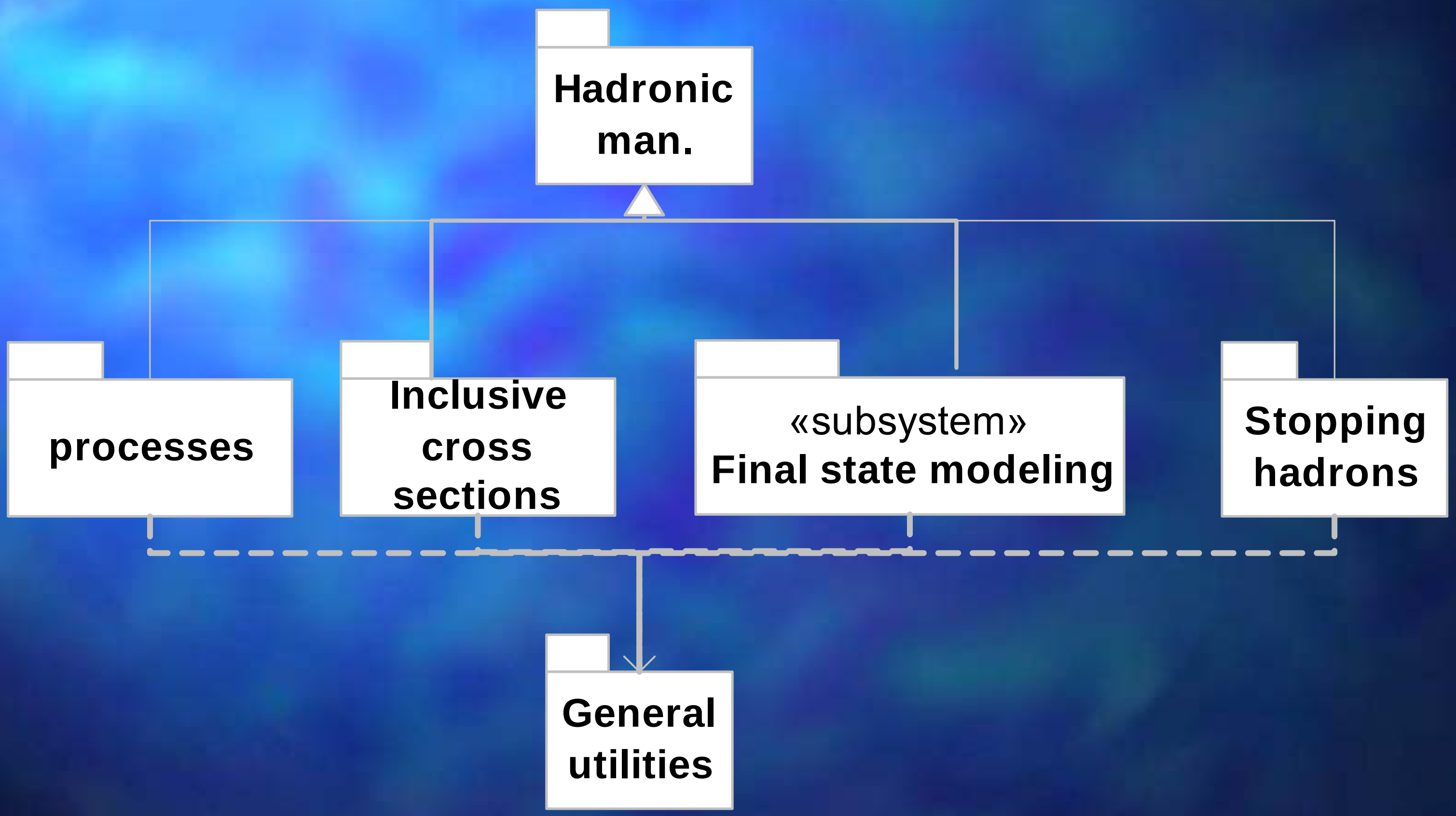
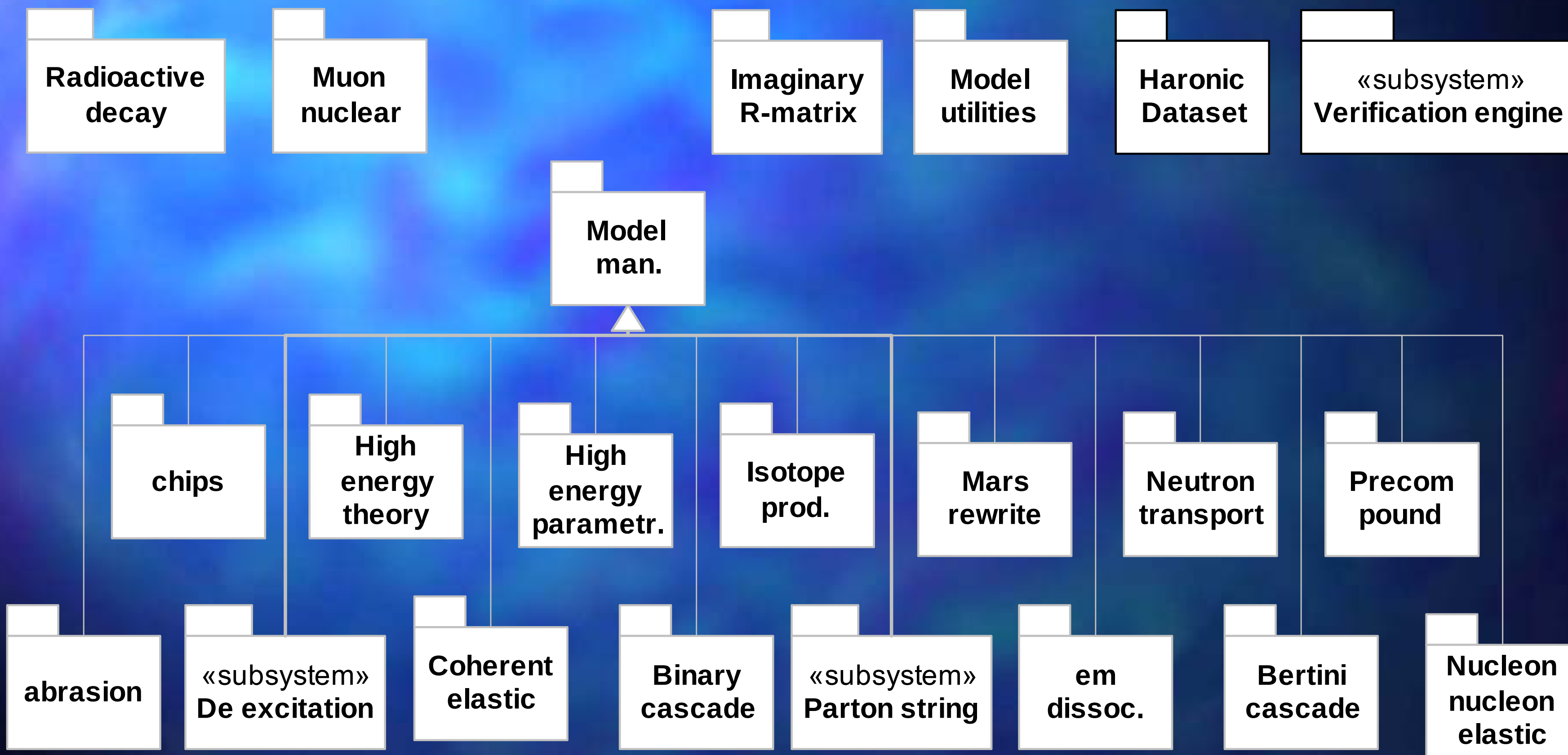
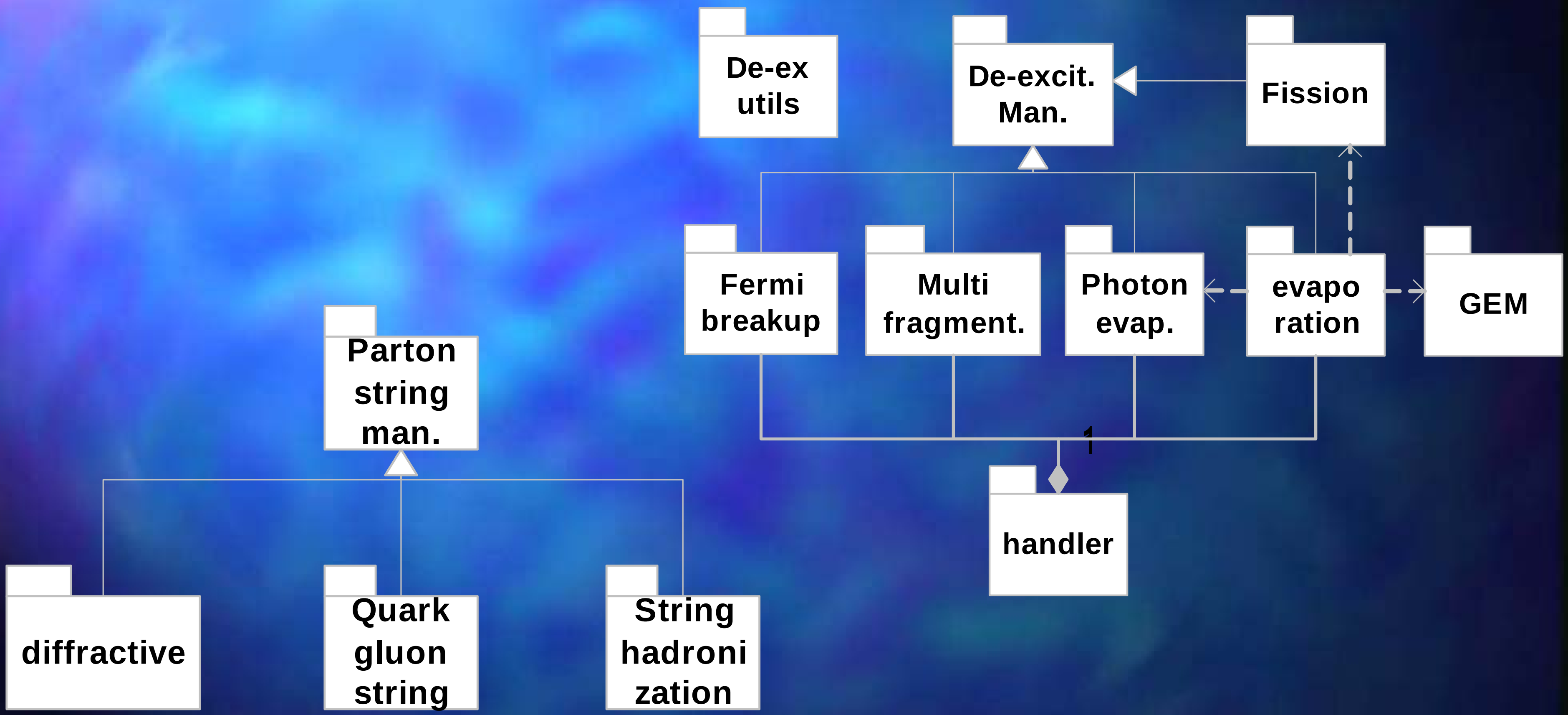
Packages of the HADRONIC GHAD system (top level)



Packages of the GHAD system (final state modeling subsystem)



Packages of the GHAD system (de-excitation and parton string subsystems)



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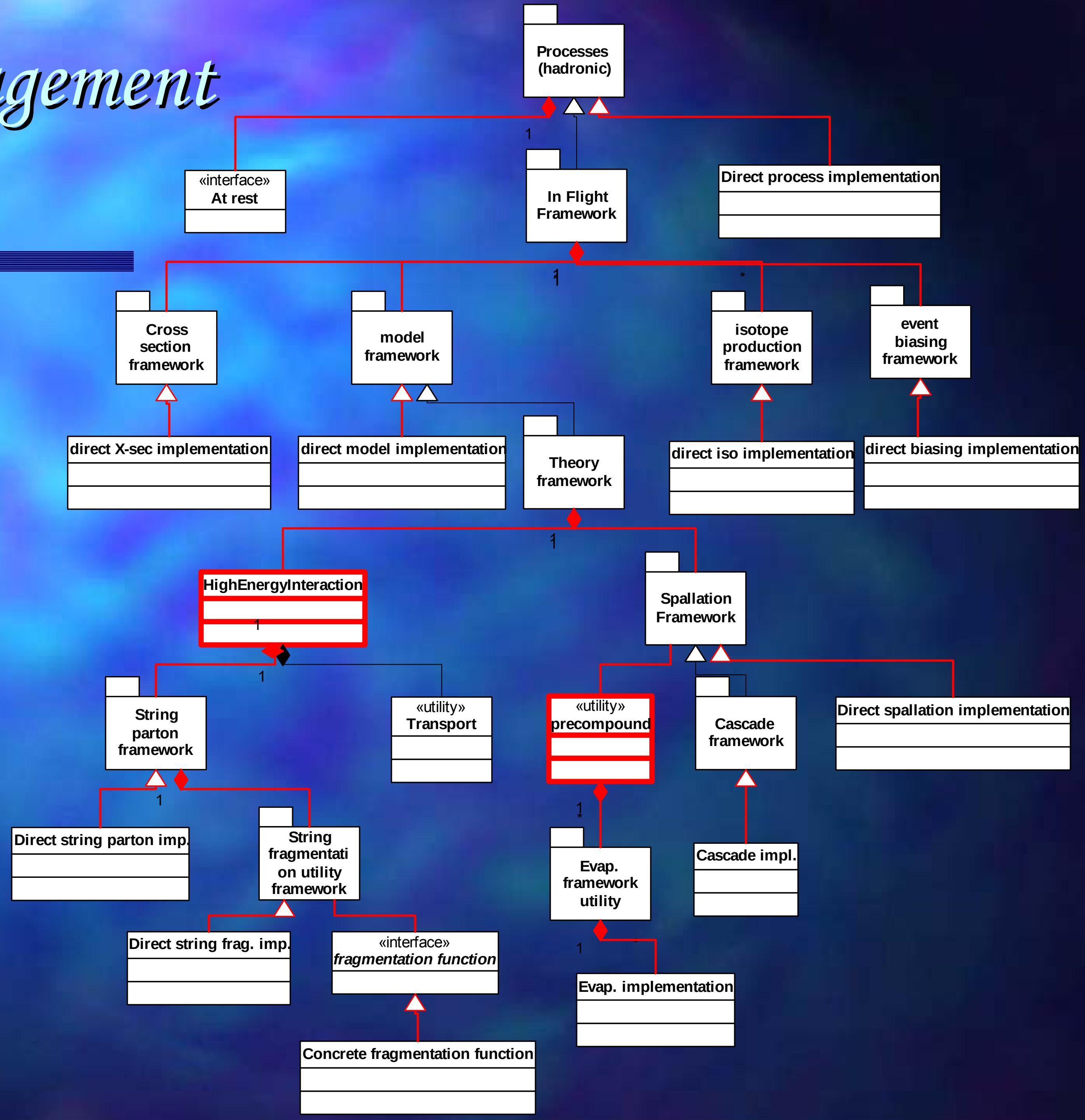
Model management in GHAD



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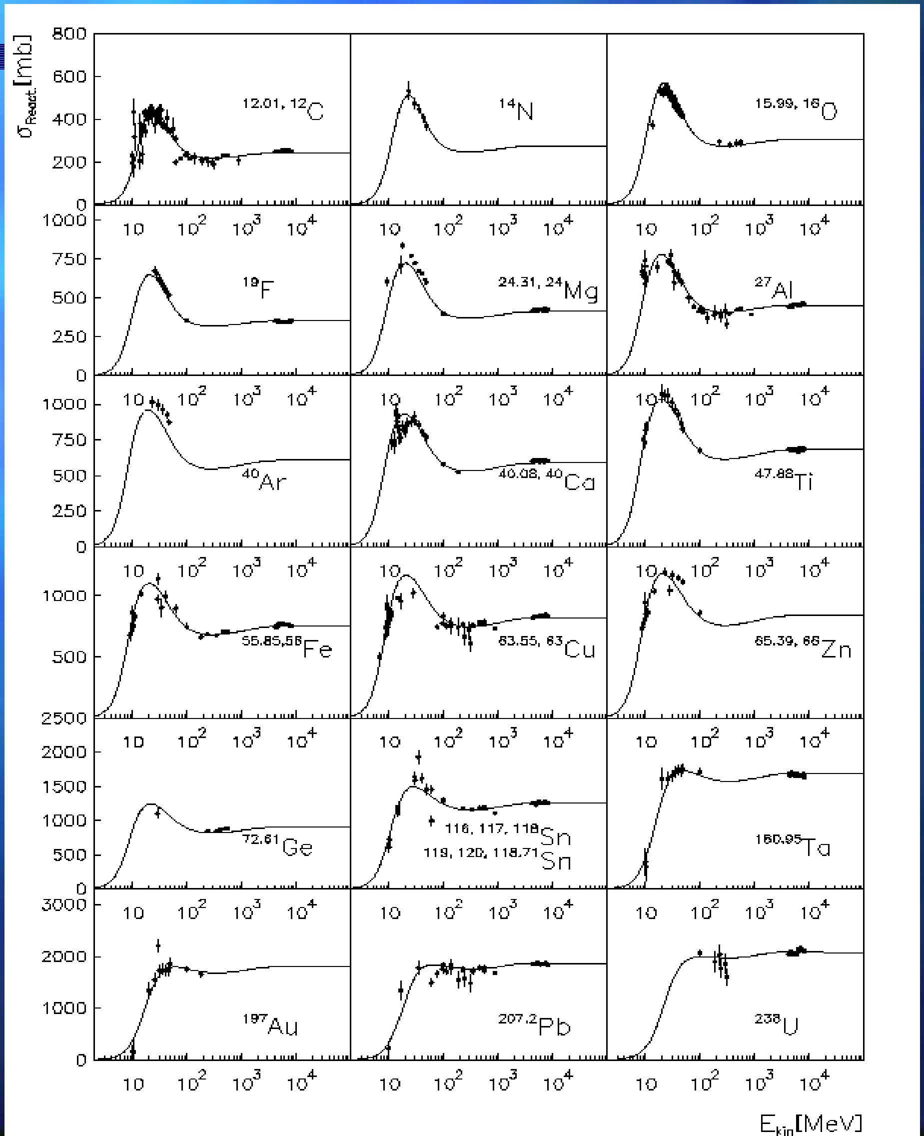
Hadronic physics descriptive power

- The physics performance verification of GHAD is grouped into several sections:
  - Inclusive cross-sections
  - Thin target comparisons
  - Verification of model components
  - Code comparisons (least effective)
  - Complete application tests
  - Robustness.

Proton reaction cross-section:



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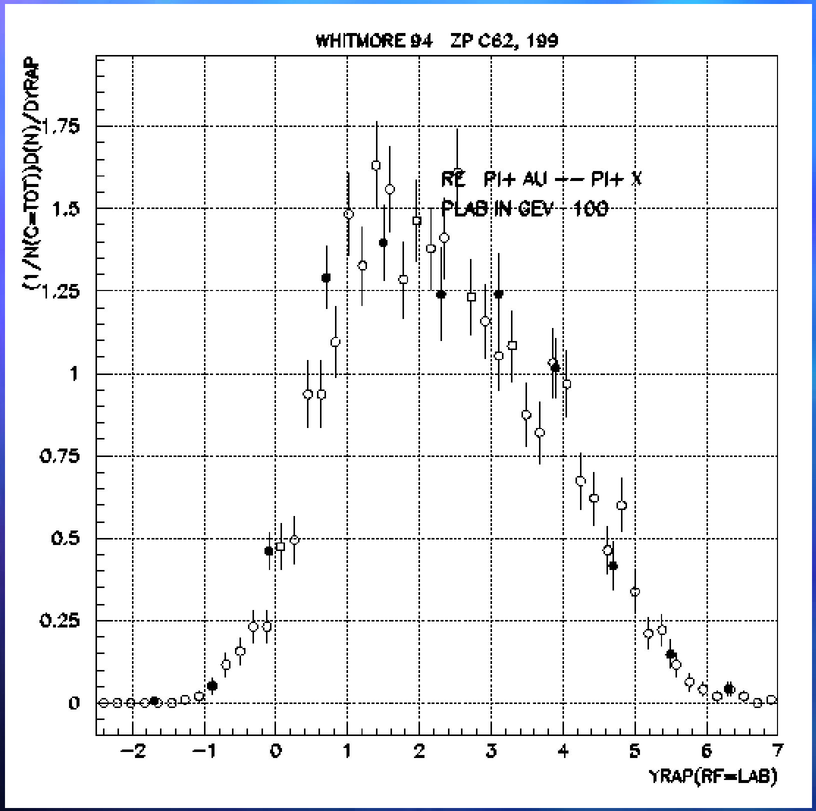
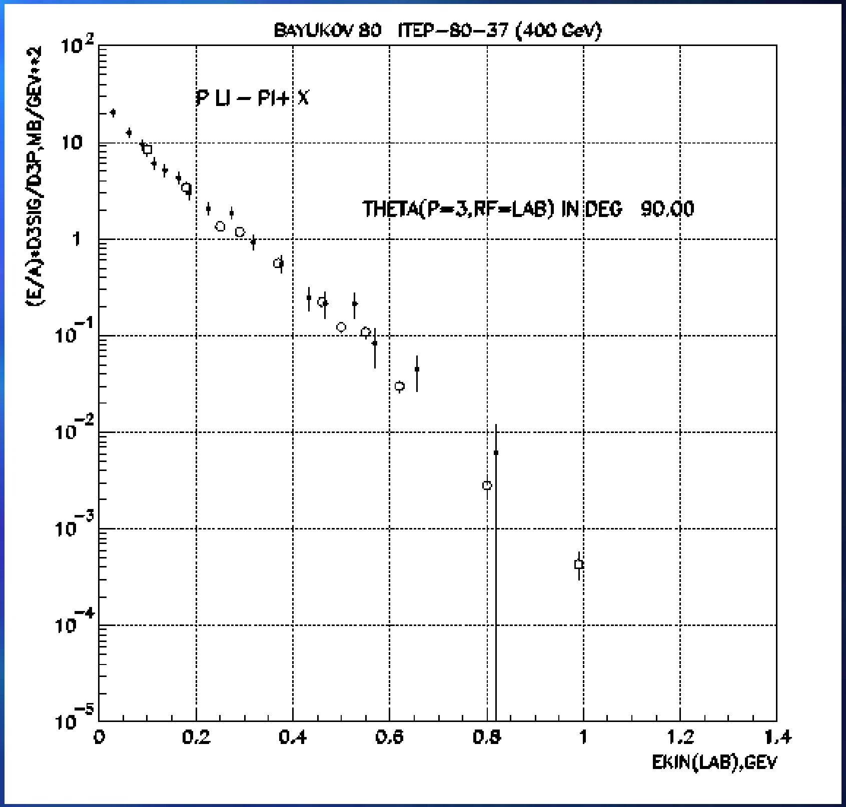
Pion production examples, QGS:

Rapidity distributions and invariant cross-section predictions in quark gluon string model





100 GeV pi+ on Gold

400GeV protons on Lithium

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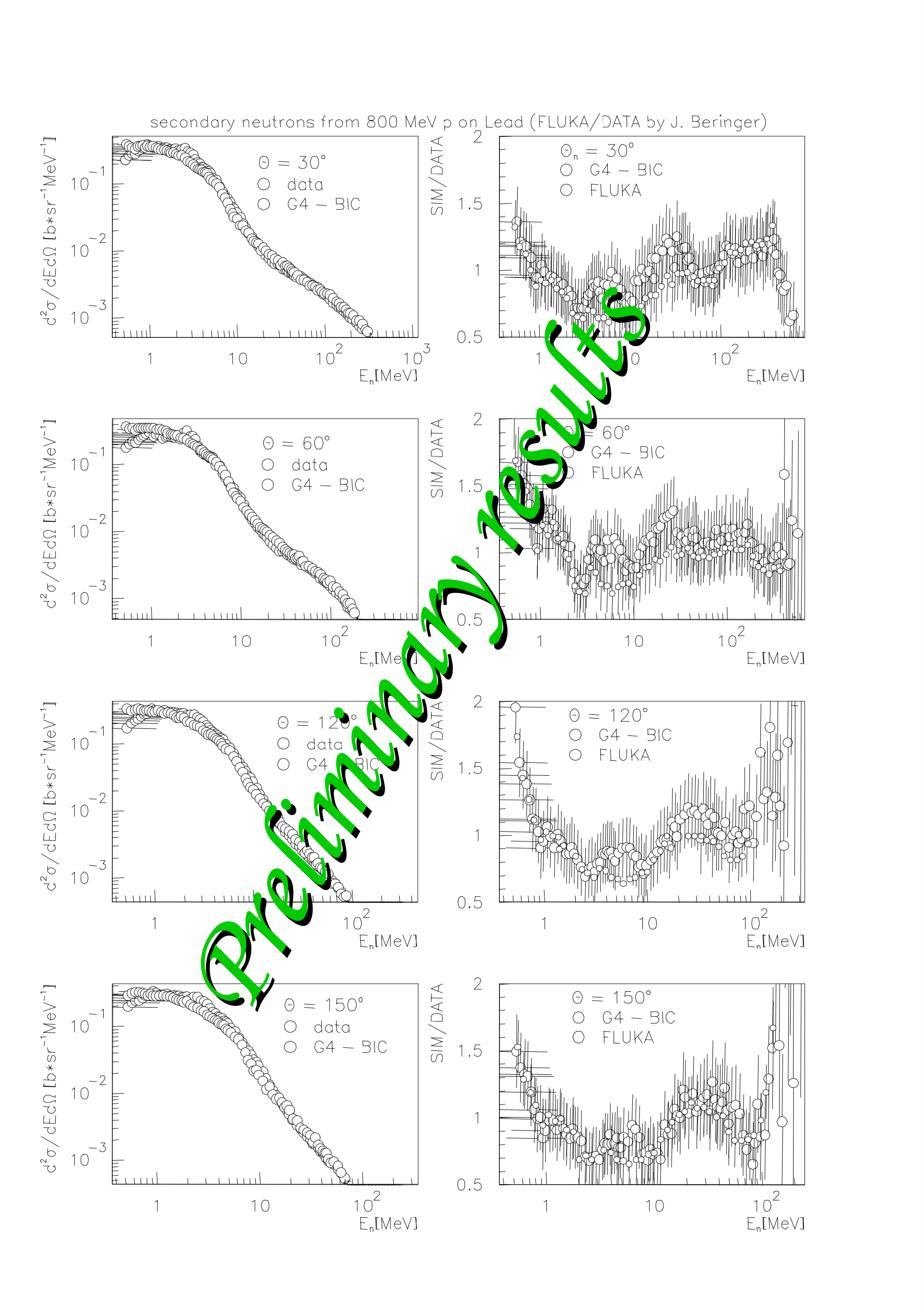
The latest, greatest in Binary Cascades



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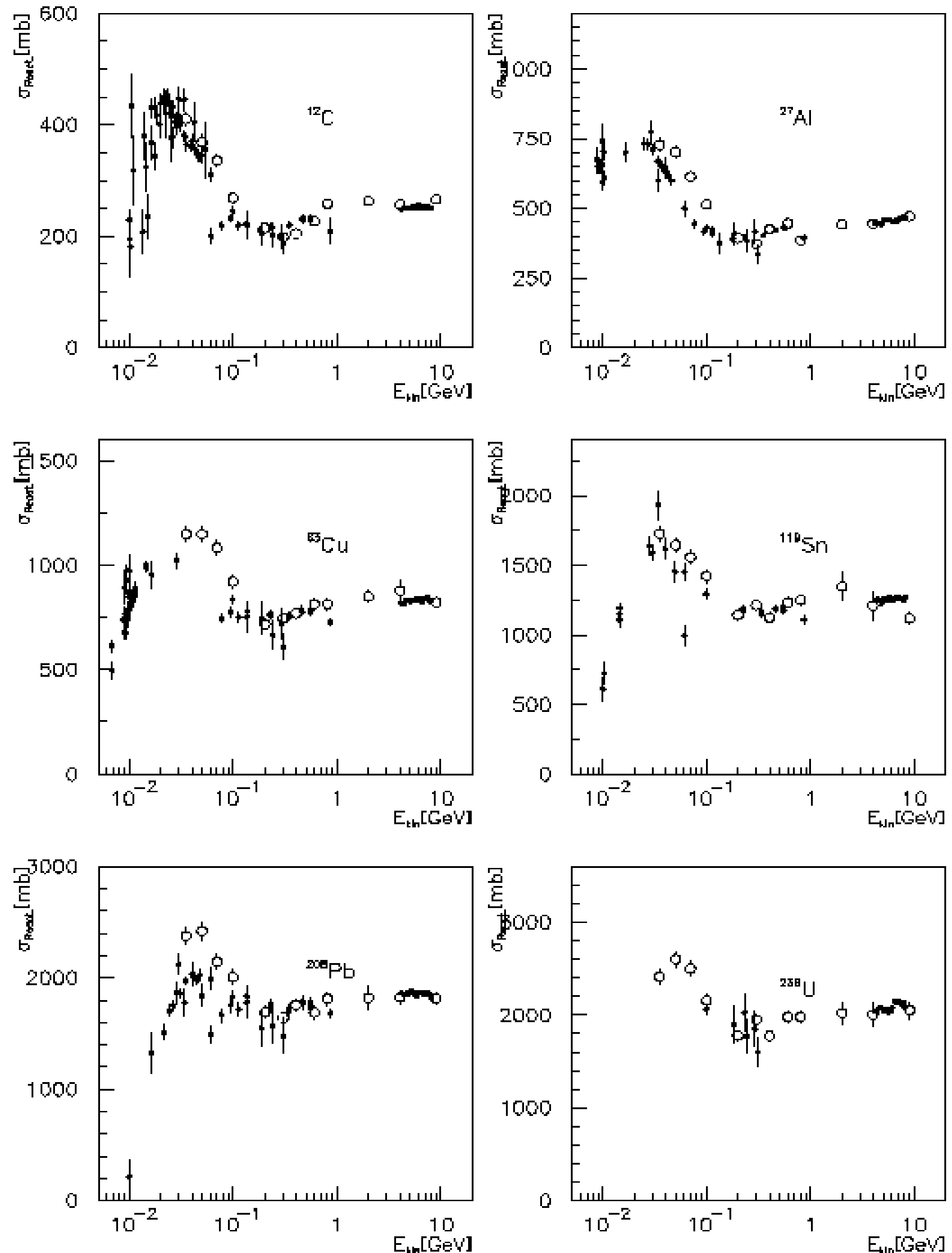
Binary cascade prediction of proton reaction cross section

Sample the impact parameter over a very large area.

Make the ratio of 'hits' to number of sampling attempts.

Multiply with the area sampled.



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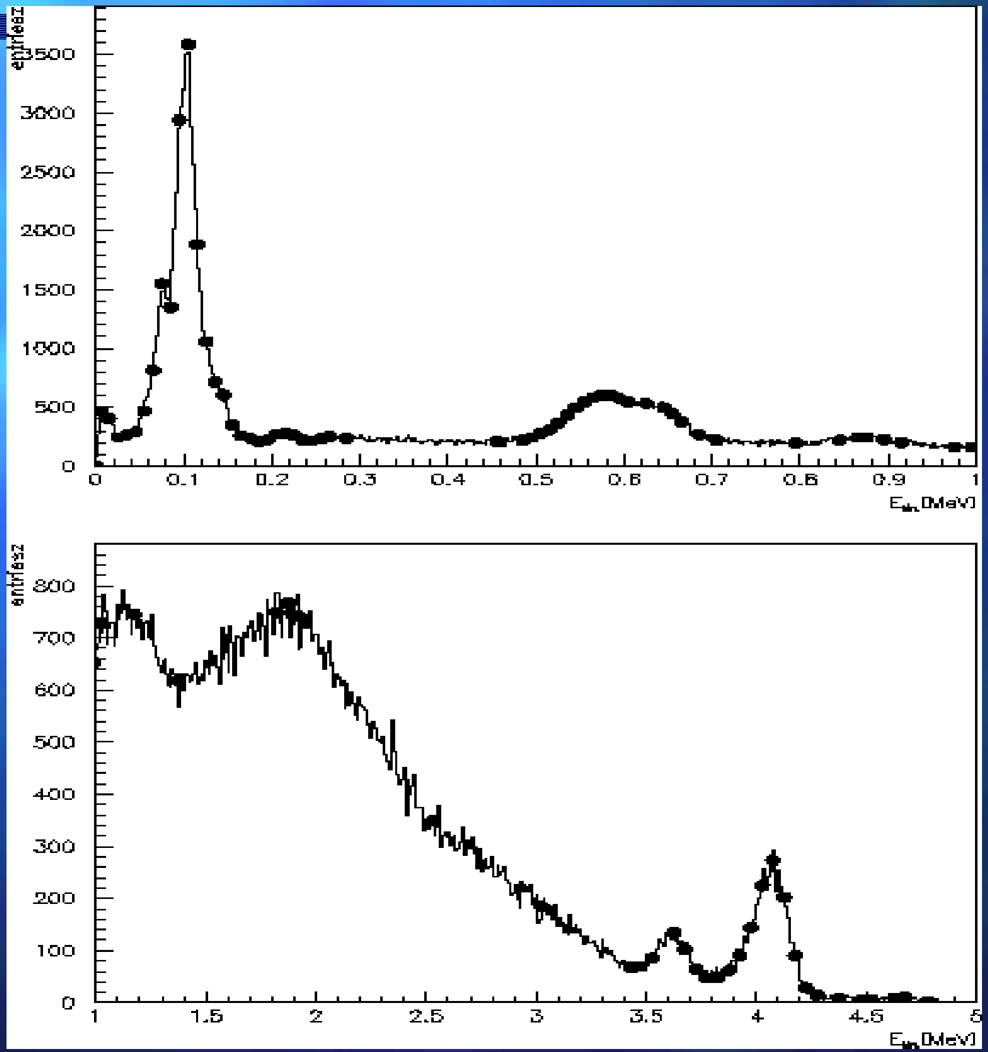
Low energy neutron transport: gammas from 14 MeV capture on Uranium



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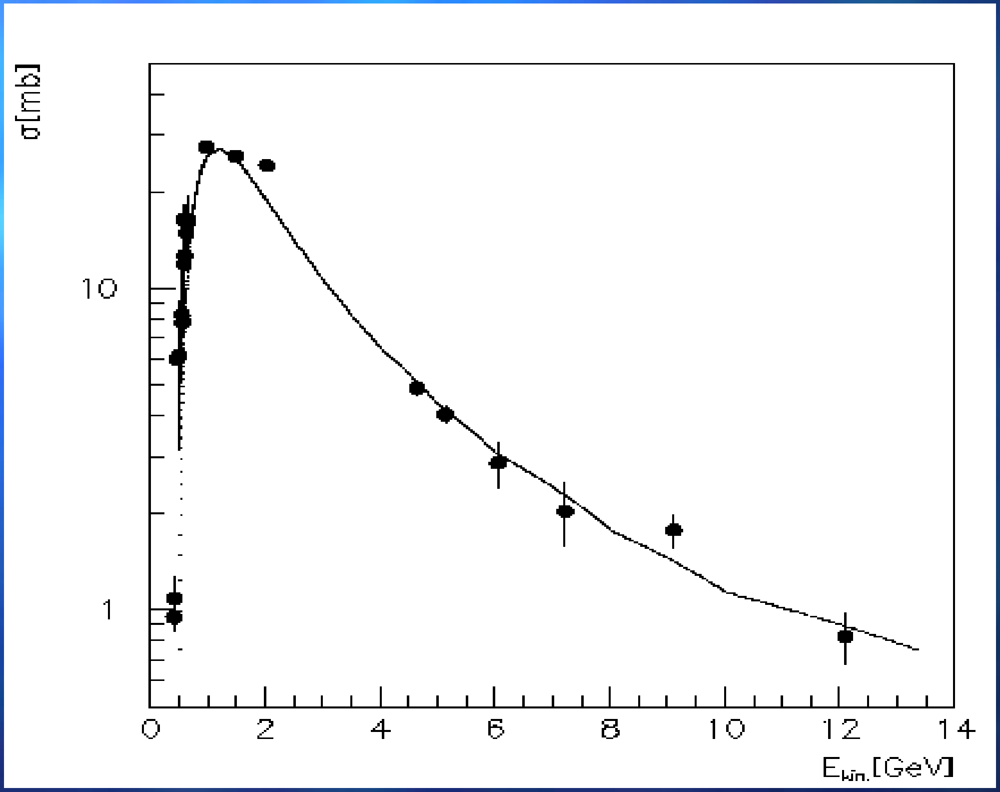
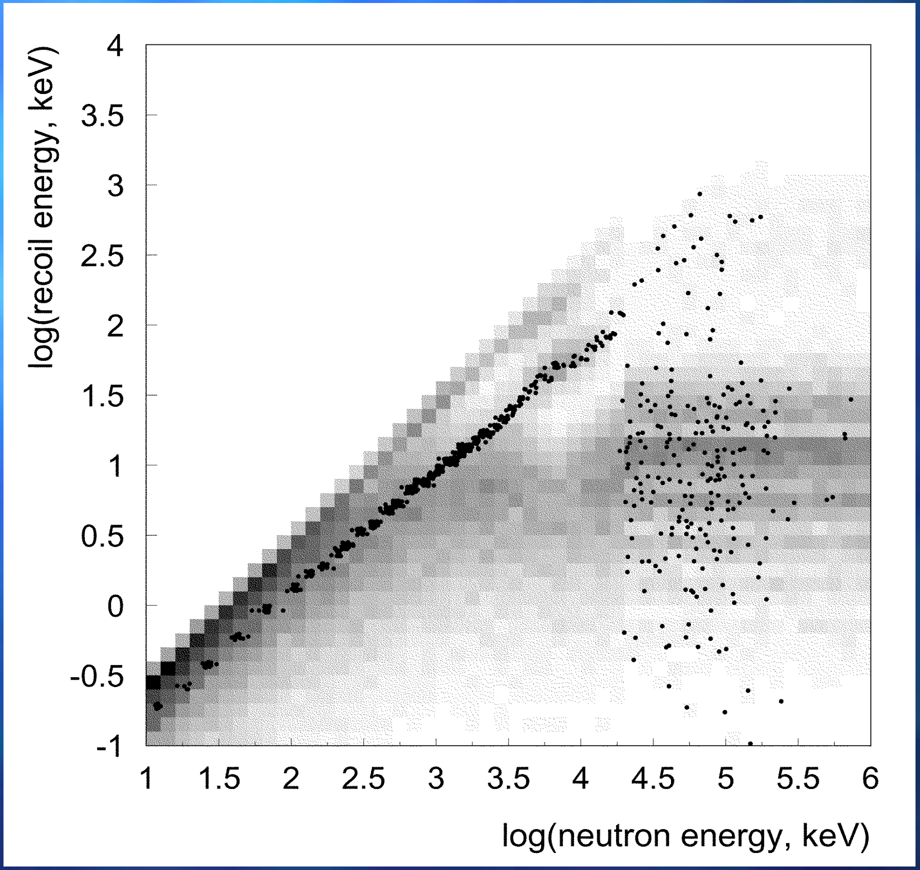
Predicting the Delta production cross-section in pp scattering by binary casacde



Gammas and conversion electrons in ^{57}Co: geant4 vs. RADLIST

	RADLIST (BNL)		Geant4	
Radiation	Energy (keV)	Intensity (100dks)	Energy (keV)	Intensity (100dks)
CE K	7.301	71.00 (6.0)	7.301	70.55 (1.88)
CE			12.899	10.00 (0.70)
CE L	13.567	7.40 (0.6)	13.562	5.95 (0.54)
CE			13.687	0.35 (0.13)
CE			14.315	0.85 (0.21)
CE			14.405	0.45 (0.19)
CE K	114.949	1.83 (0.14)	114.949	1.95 (0.31)
CE			120.497	5.70 (0.53)
CE L	121.215	0.19 (0.020)		
CE M+	121.968	0.03 (0.005)		
CE K	129.361	1.30 (0.16)	129.362	1.25 (0.25)
CE			134.910	0.25 (0.11)
γ	14.413	9.16 (0.15)	14.413	10.05 (0.71)
γ	122.061	85.60 (0.17)	122.061	86.05 (2.07)
γ	136.474	10.68 (0.08)	136.474	10.05 (0.71)
γ	692.410	0.15 (0.01)	692.030	0.15 (0.09)

Recoil spectra *(FLUKA =dots, ghad=shades)*



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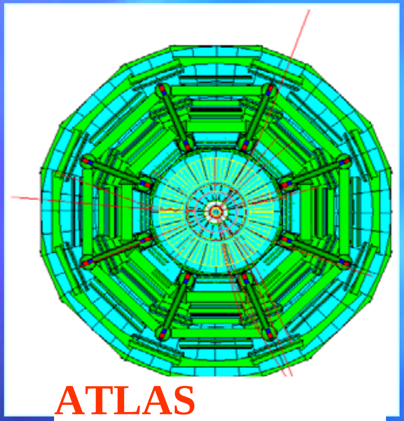
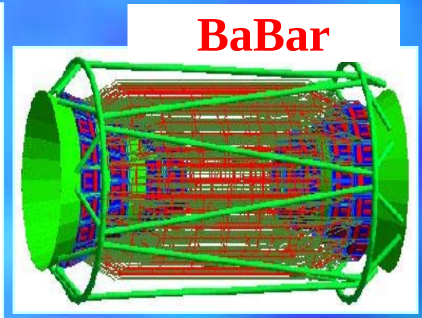
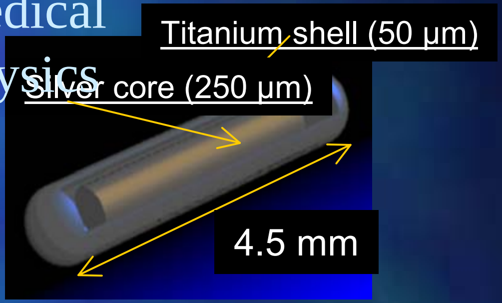
Who uses Geant4?

HEP and accelerator physics

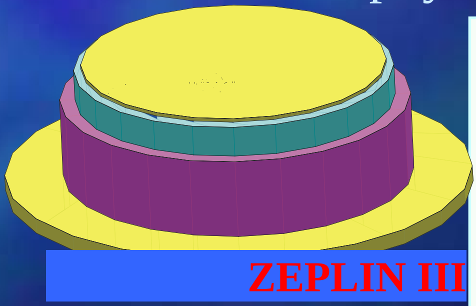




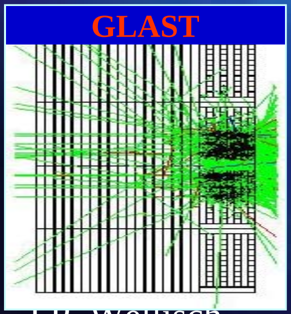
Medical physics

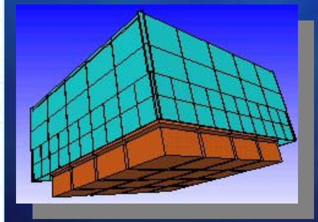


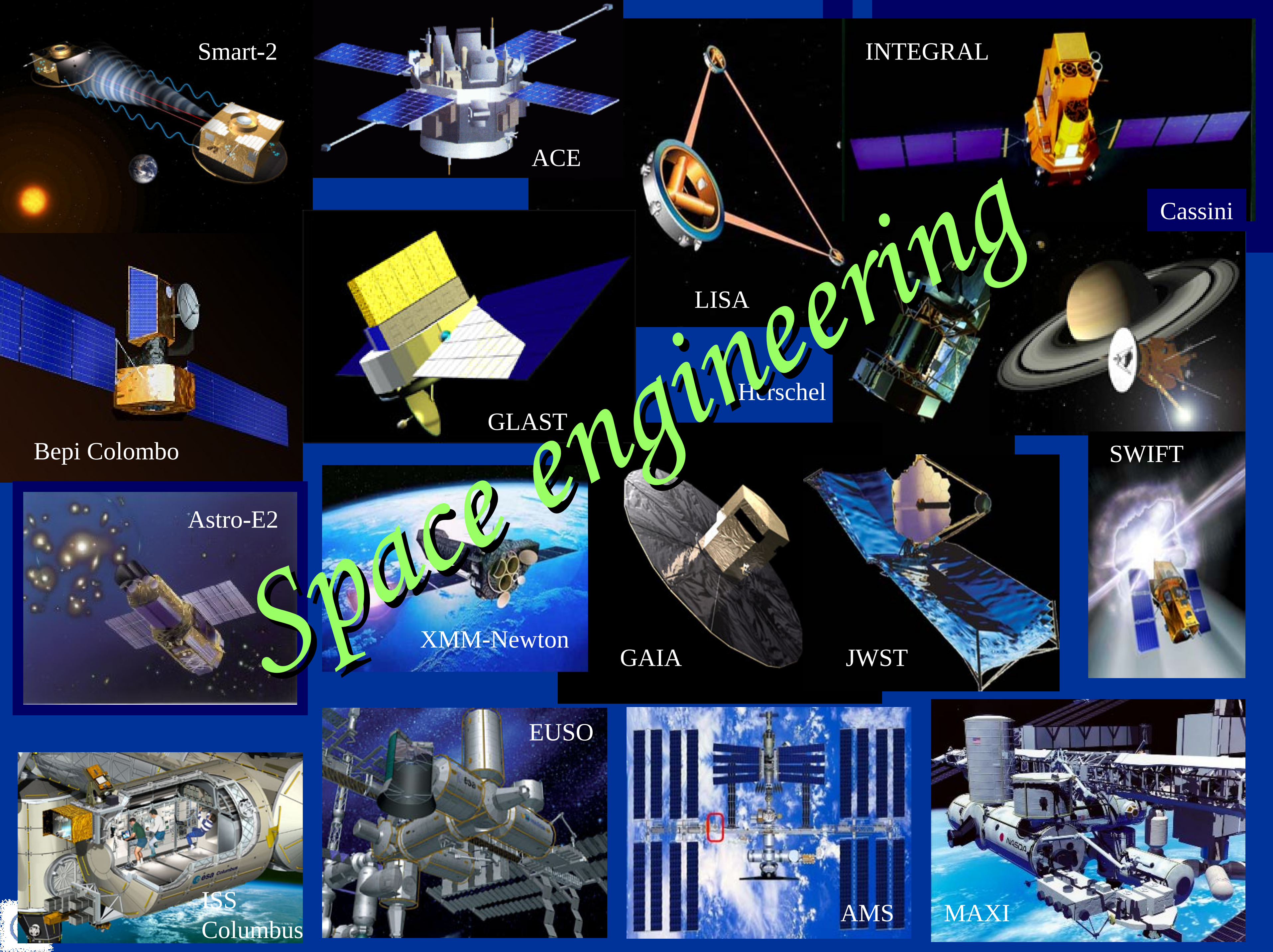
Astroparticle and underground physics



Astrophysics and γ ray astronomy






Space engineering
Smart-2
ACE
LISA
INTEGRAL
Cassini
Bepi Colombo
GLAST
Herschel
SWIFT
Astro-E2
XMM-Newton
GAIA
JWST
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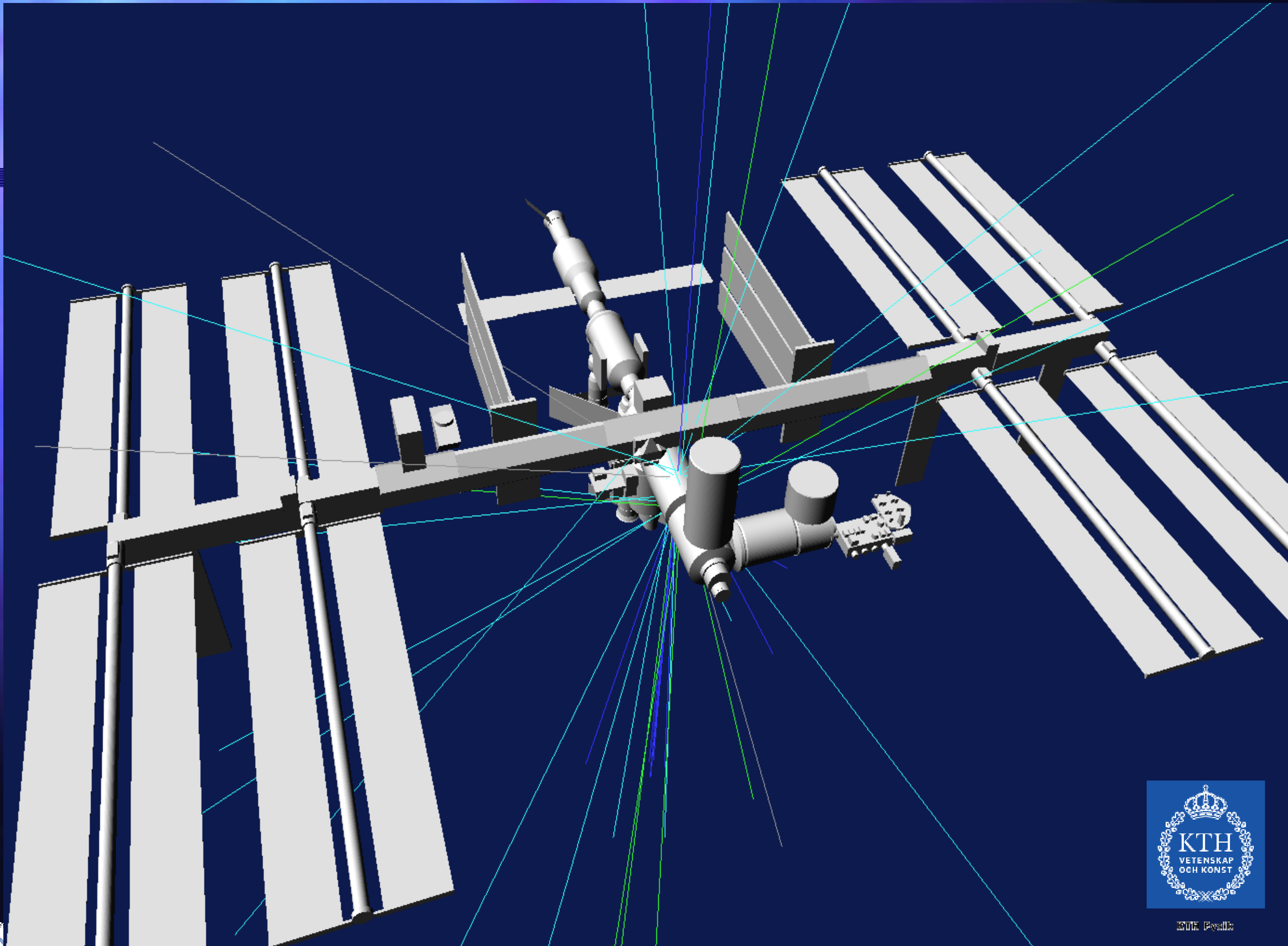
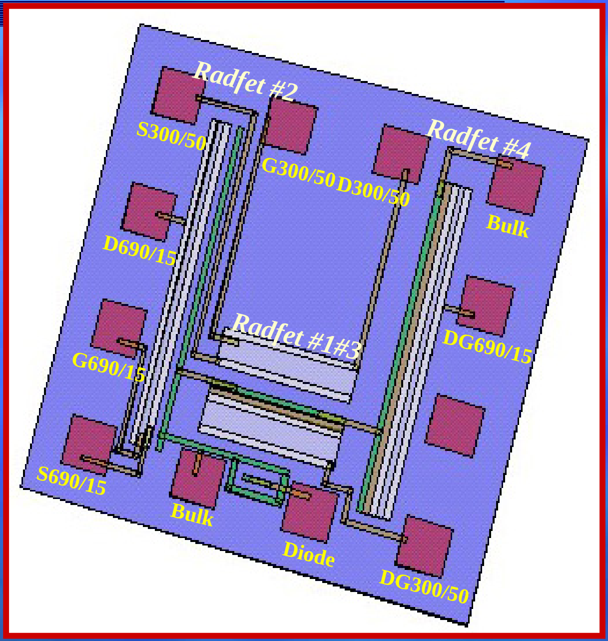
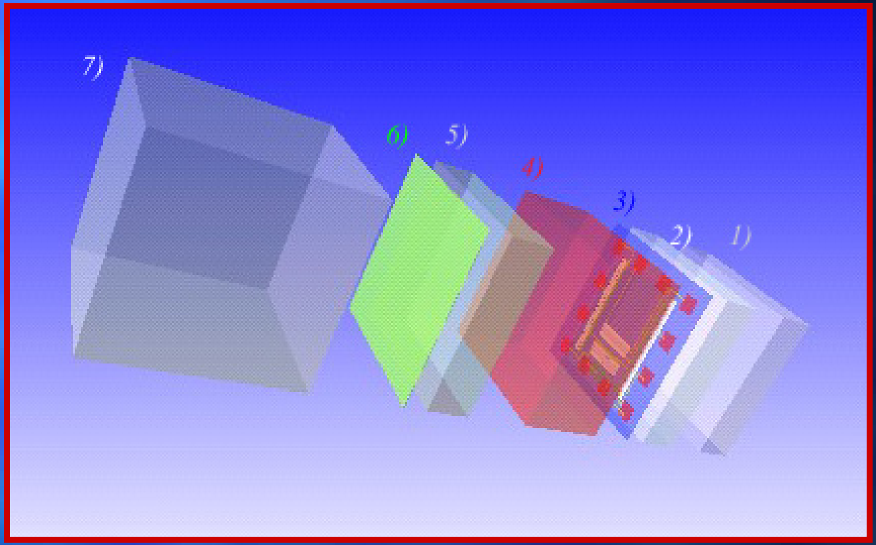
ISS
Columbus
AMS
MAXI

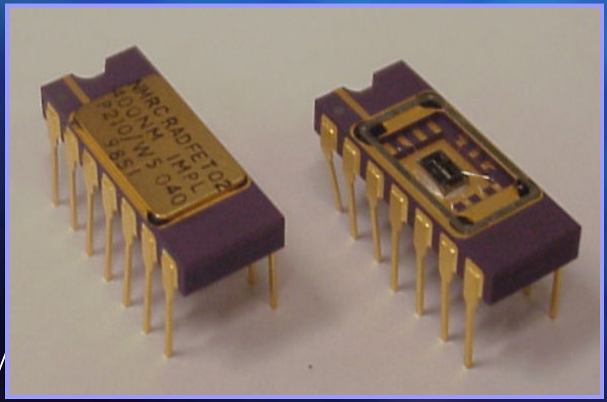


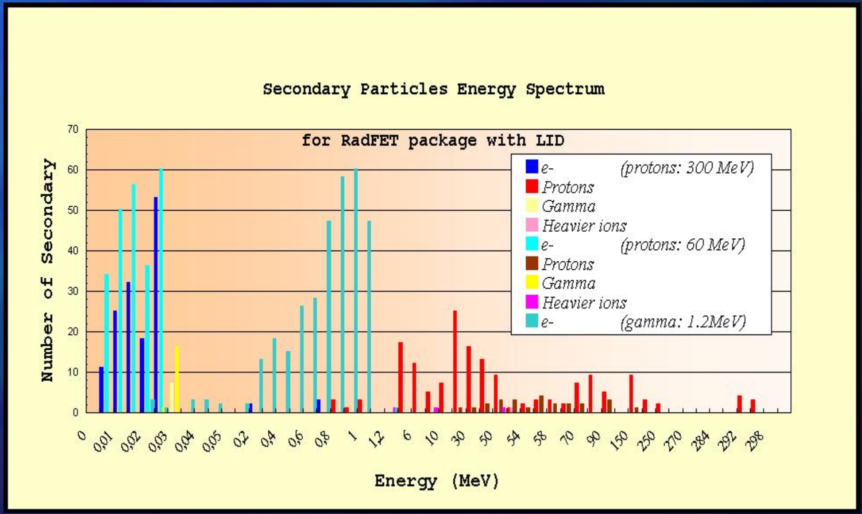
Courtesy T. Ersmark, KTH Stockholm

Geant4 interface to microelectronic component radiation models

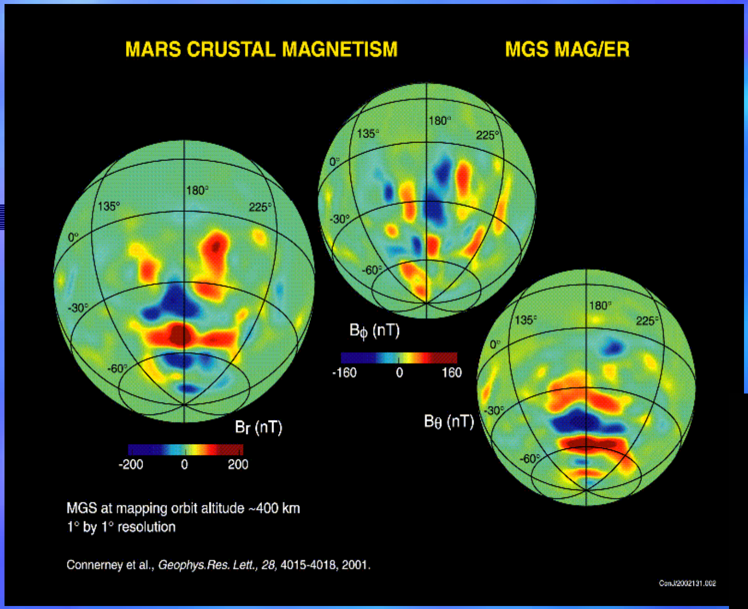


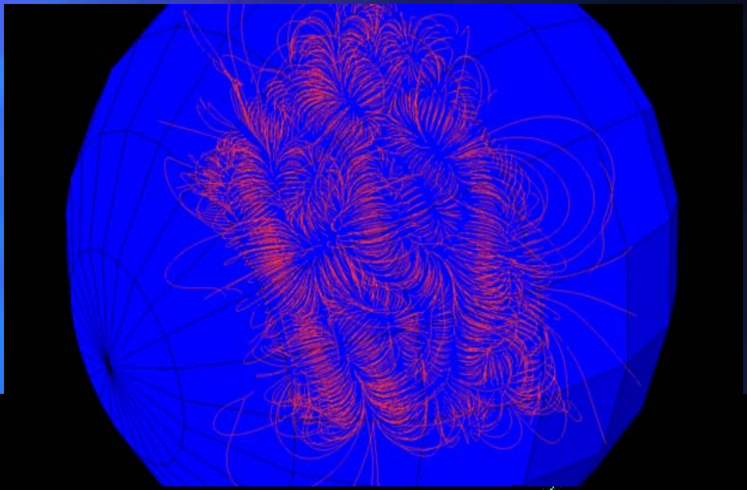


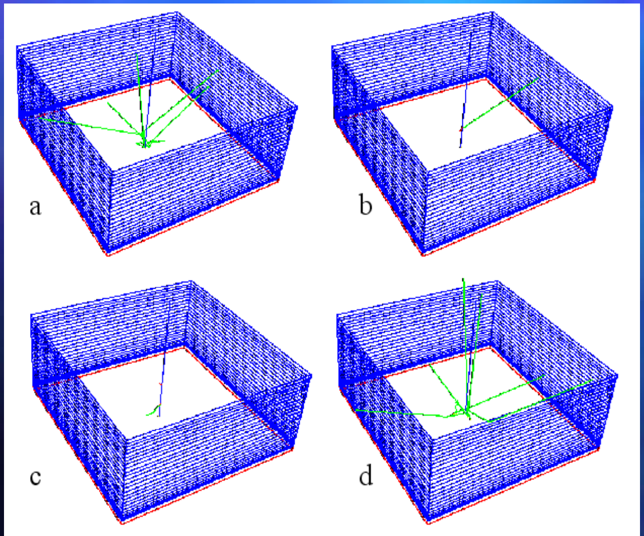


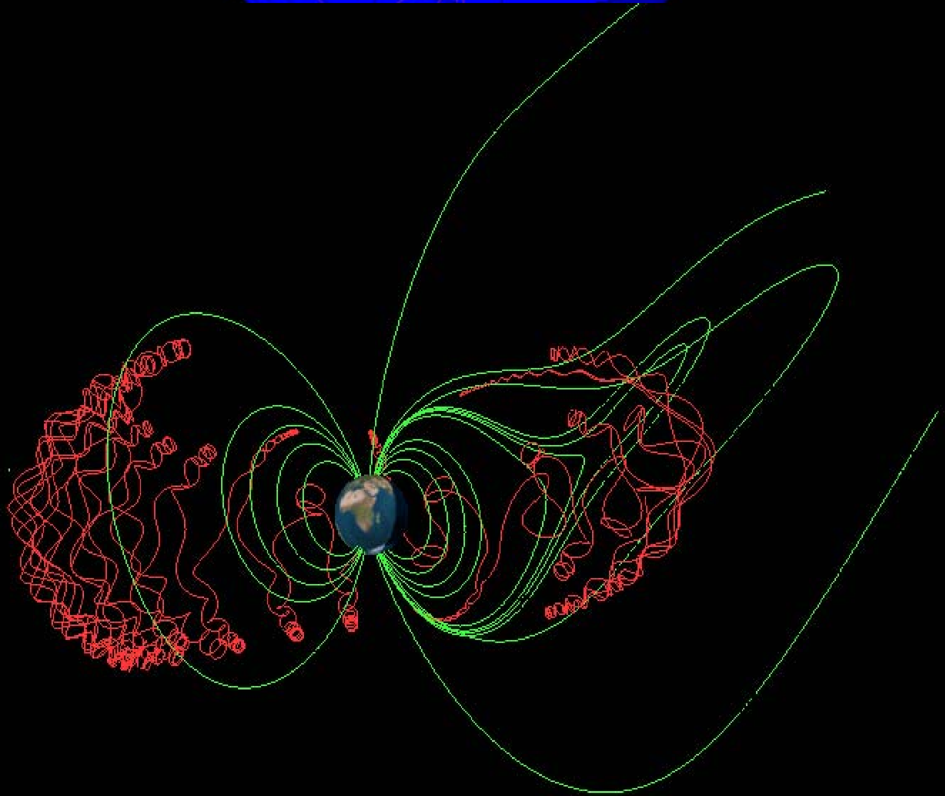


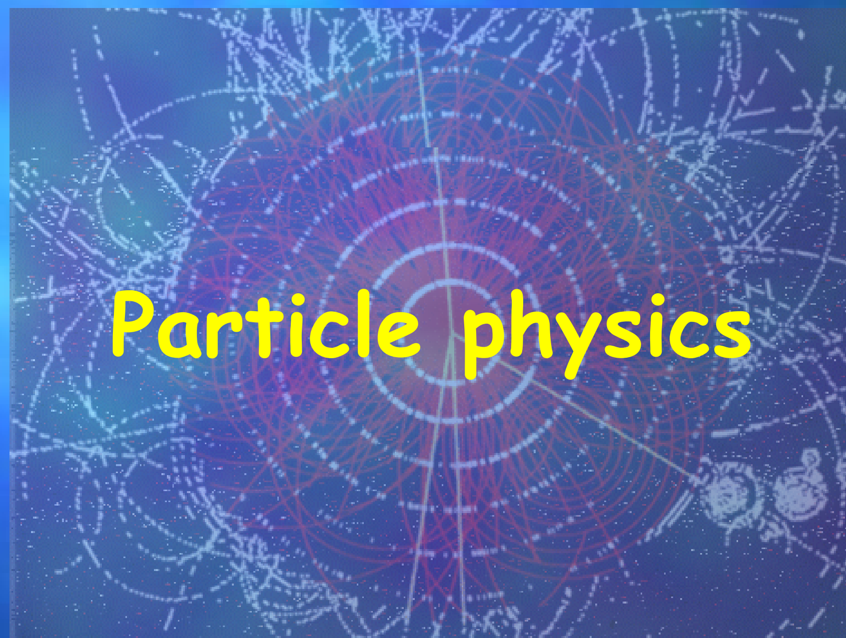
Ana Keating (ESA-ESTEC)


MARS CRUSTAL MAGNETISM
MGS MAG/ER
180°
135°
225°
0°
-30°
-60°
B_r (nT)
-200
0
200
B_ϕ (nT)
-160
0
160
B_θ (nT)
MGS at mapping orbit altitude ~400 km
1° by 1° resolution
Connerney et al., *Geophys.Res. Lett., 28,* 4015-4018, 2001.

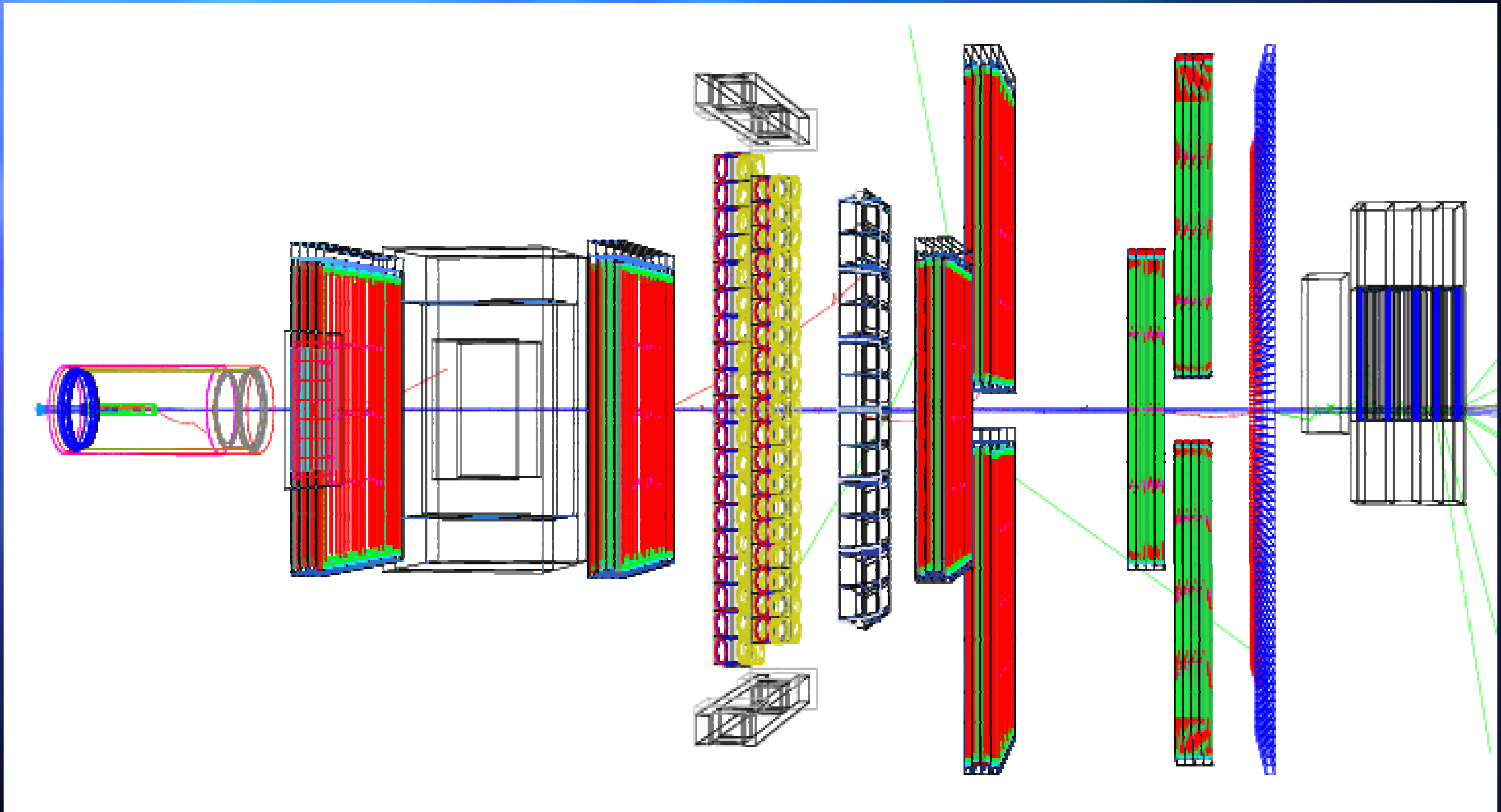



a
b
c
d



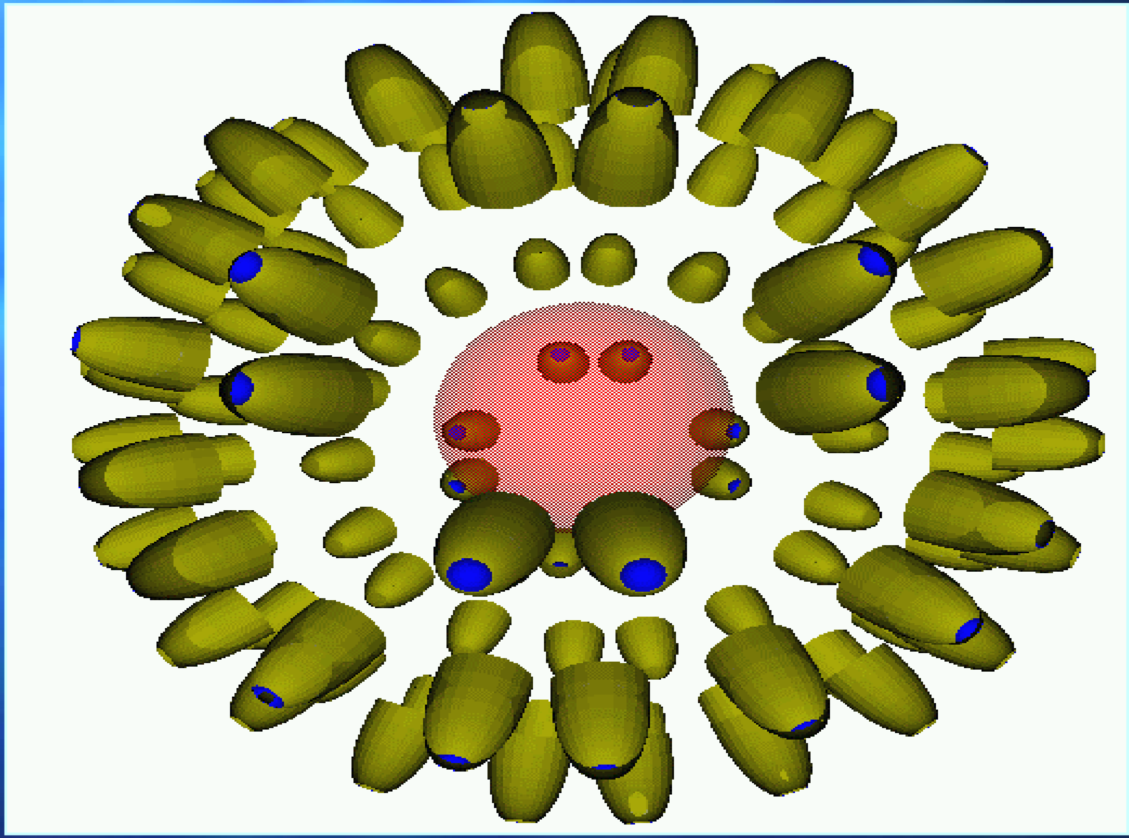

Particle physics

HARP

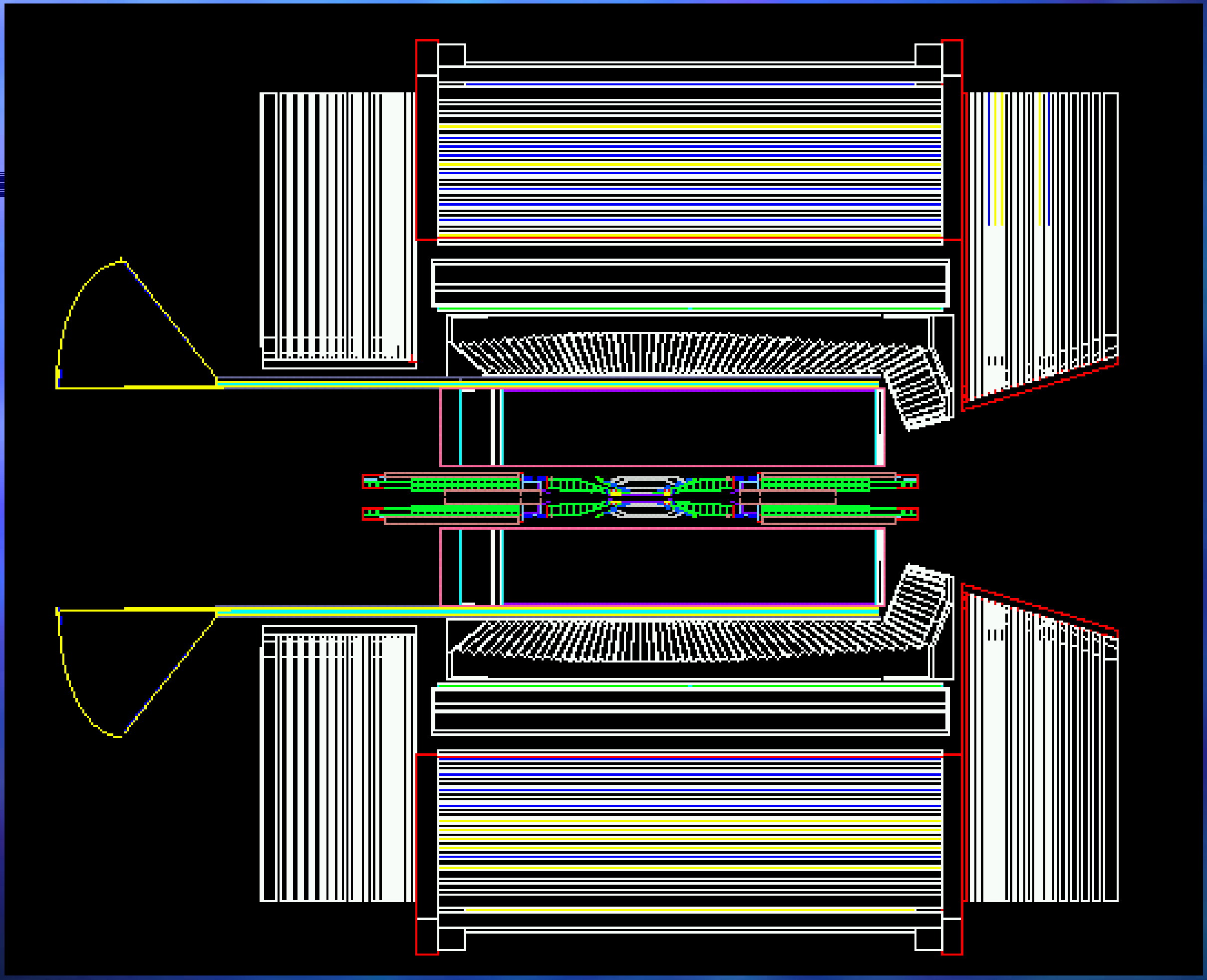


Courtesy of Pedro Arce for the HARP Collaboration

Borexino



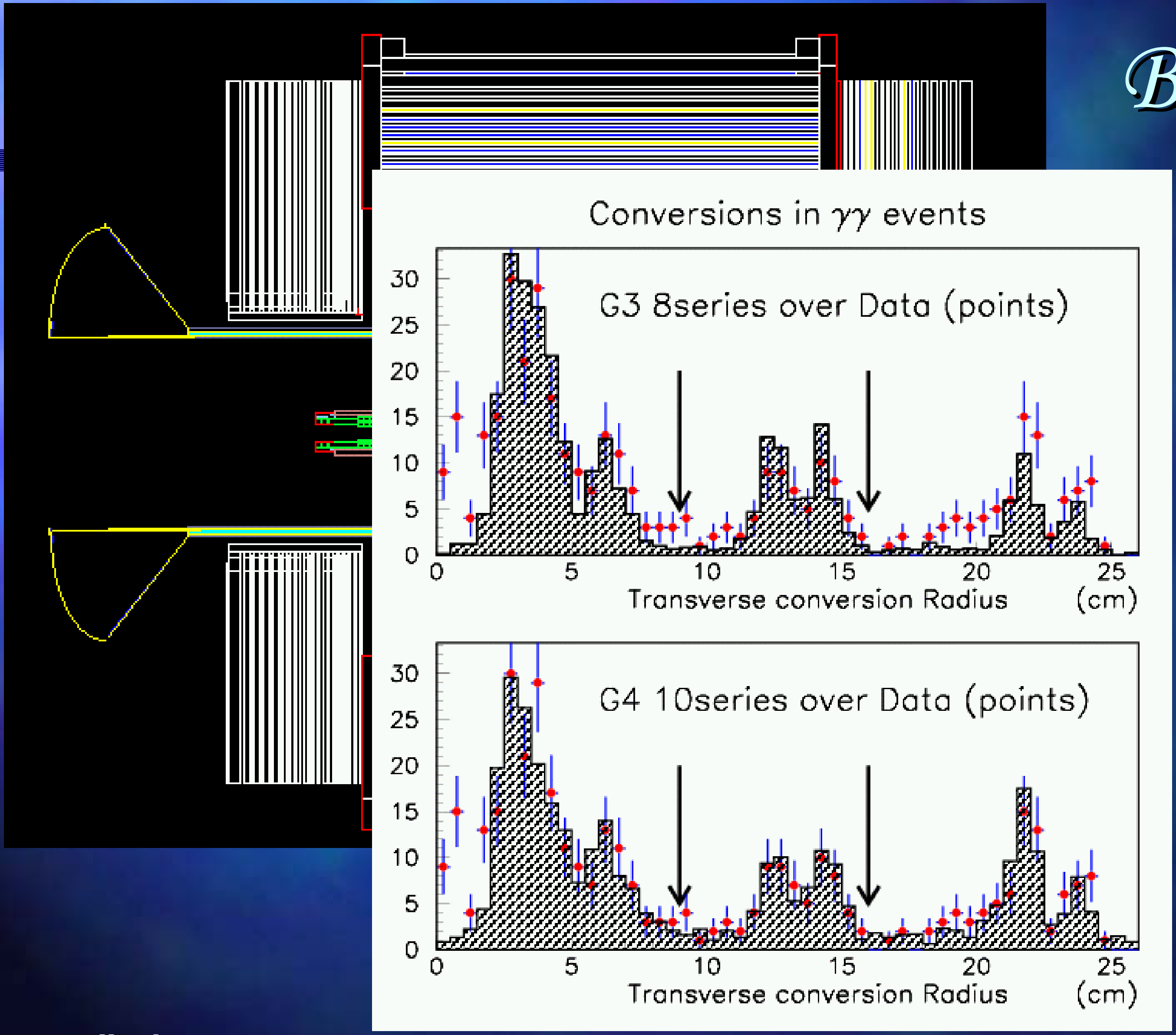
J.P. Wellisch.



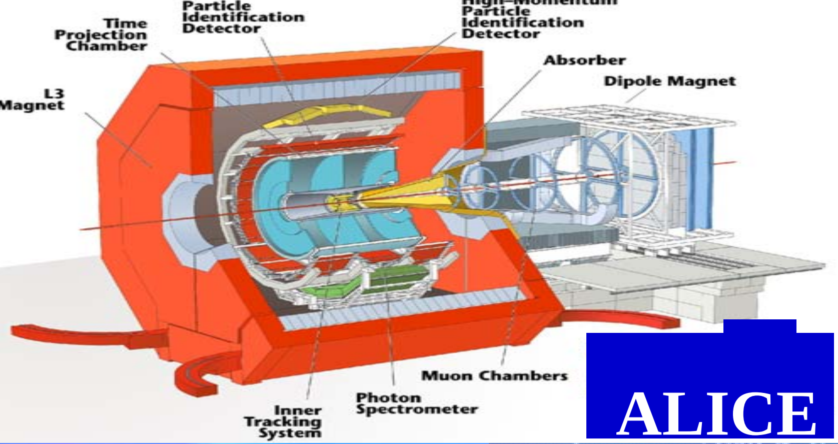
BaBar

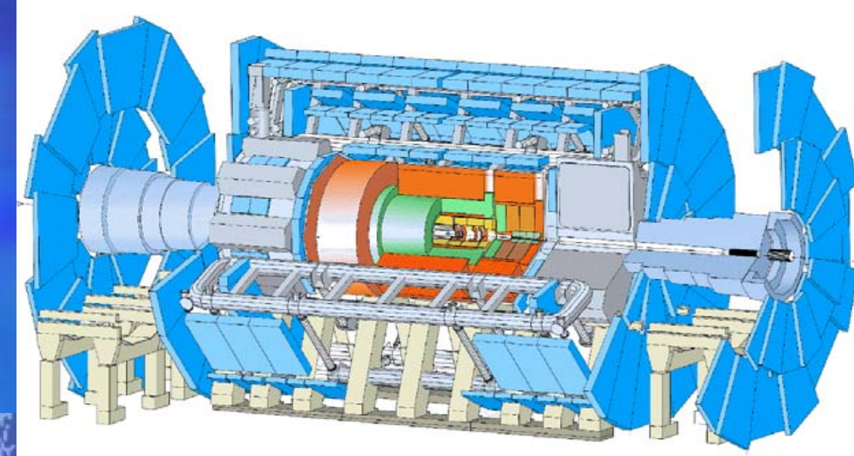
- Geant4 based simulation since 2001 production
- More than 10^{10} events

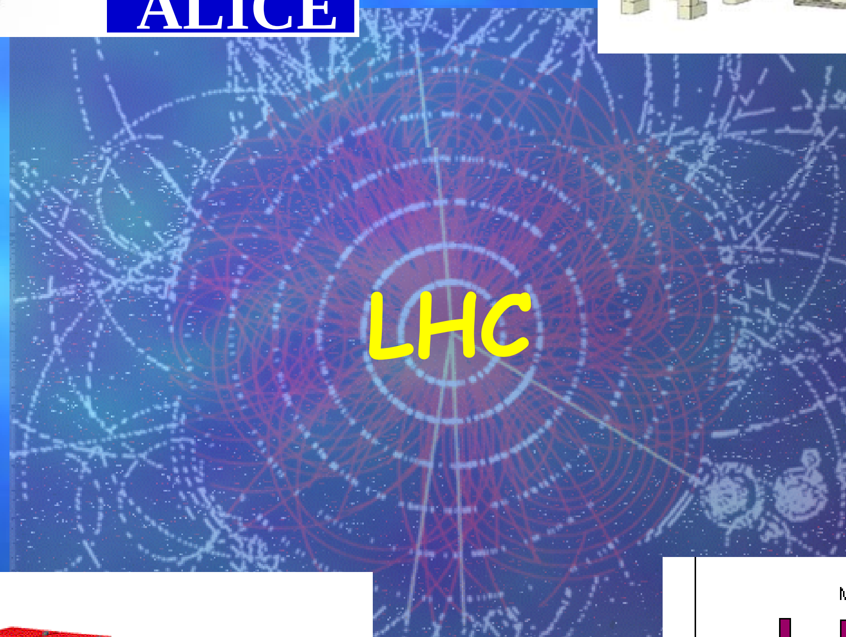
BaBar

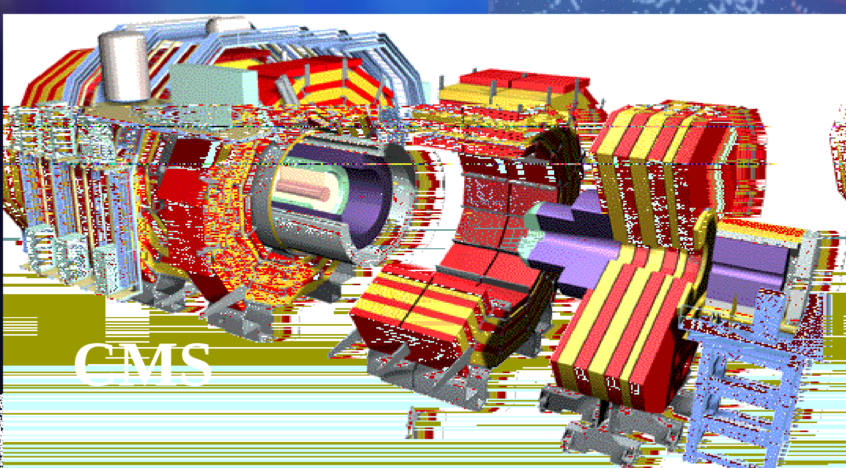


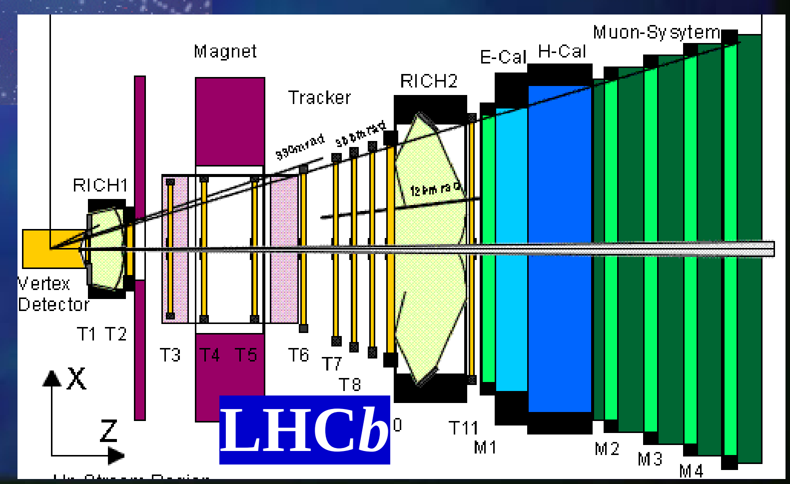
- **Geant4 based simulation since 2001 production**
- **More than 10^{10} events**


Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
ALICE

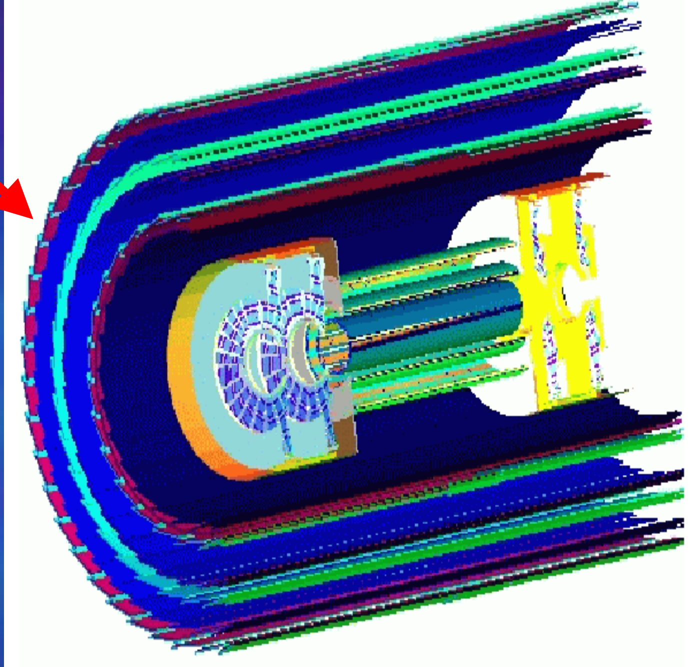



LHC


CMS

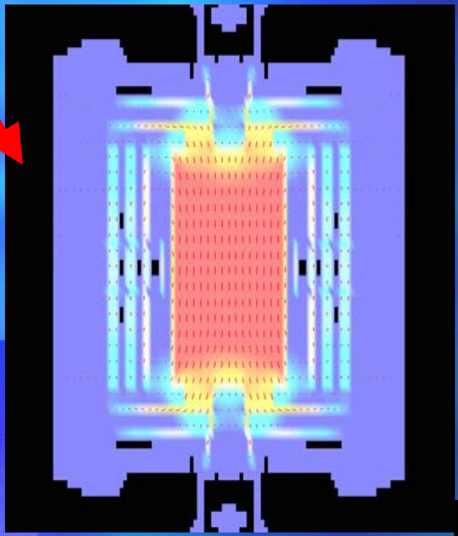

Magnet
Muon-Sy sytem
E-Cal
H-Cal
Tracker
RICH2
RICH1
Vertex Detector
T1 T2
T3
T4
T5
T6
T7
T8
T11
M1
M2
M3
M4
X
Z
LHCb

Sliced view of CMS barrel detectors

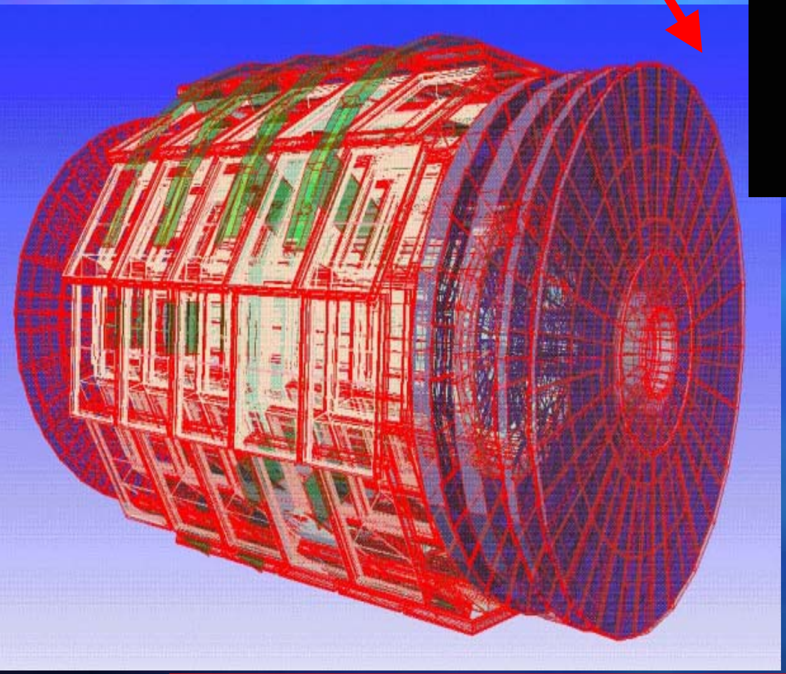


Courtesy of P.Arce, CMS

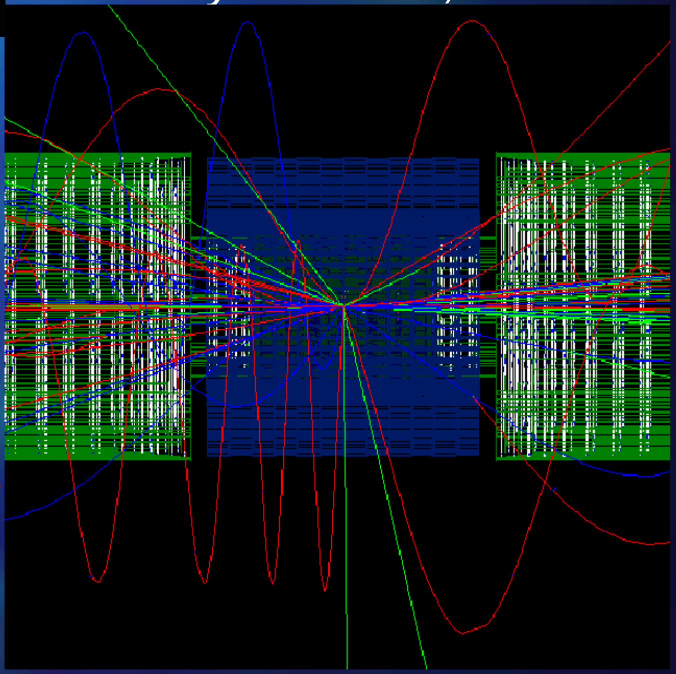
Magnetic field



View of CMS muon system

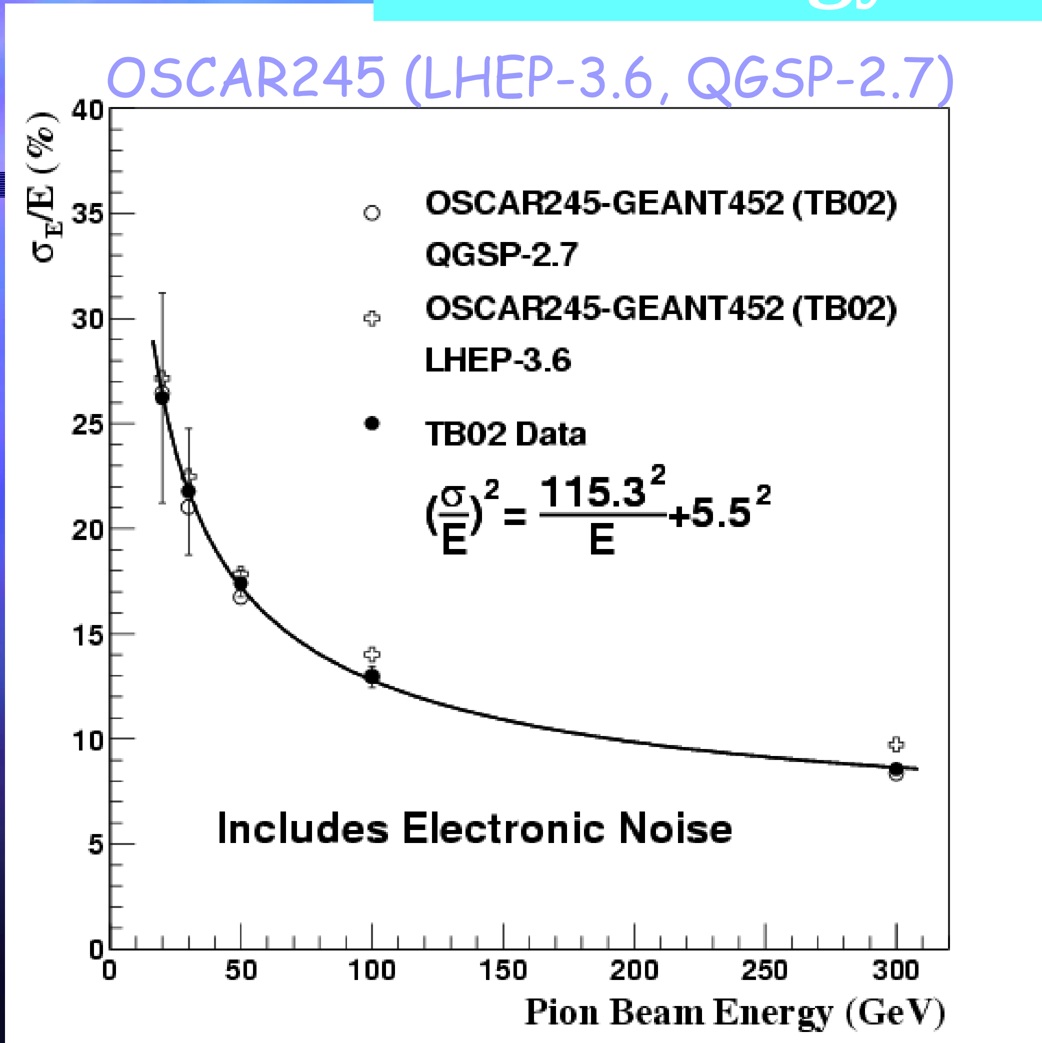


CMS



View of 180 Higgs event simulated in CMS Tracker detector

Pion Energy Resolution



	Data		Syst.	
E	$\sigma_E/E(\%)$	stat	bkgnd	calib
20.	26.22	0.15	5.00	0.1
30.	21.76	0.12	3.00	0.2
50.	17.40	0.10	0.60	0.2
100.	12.95	0.07	0.40	0.3
300.	8.55	0.05	0.00	0.3

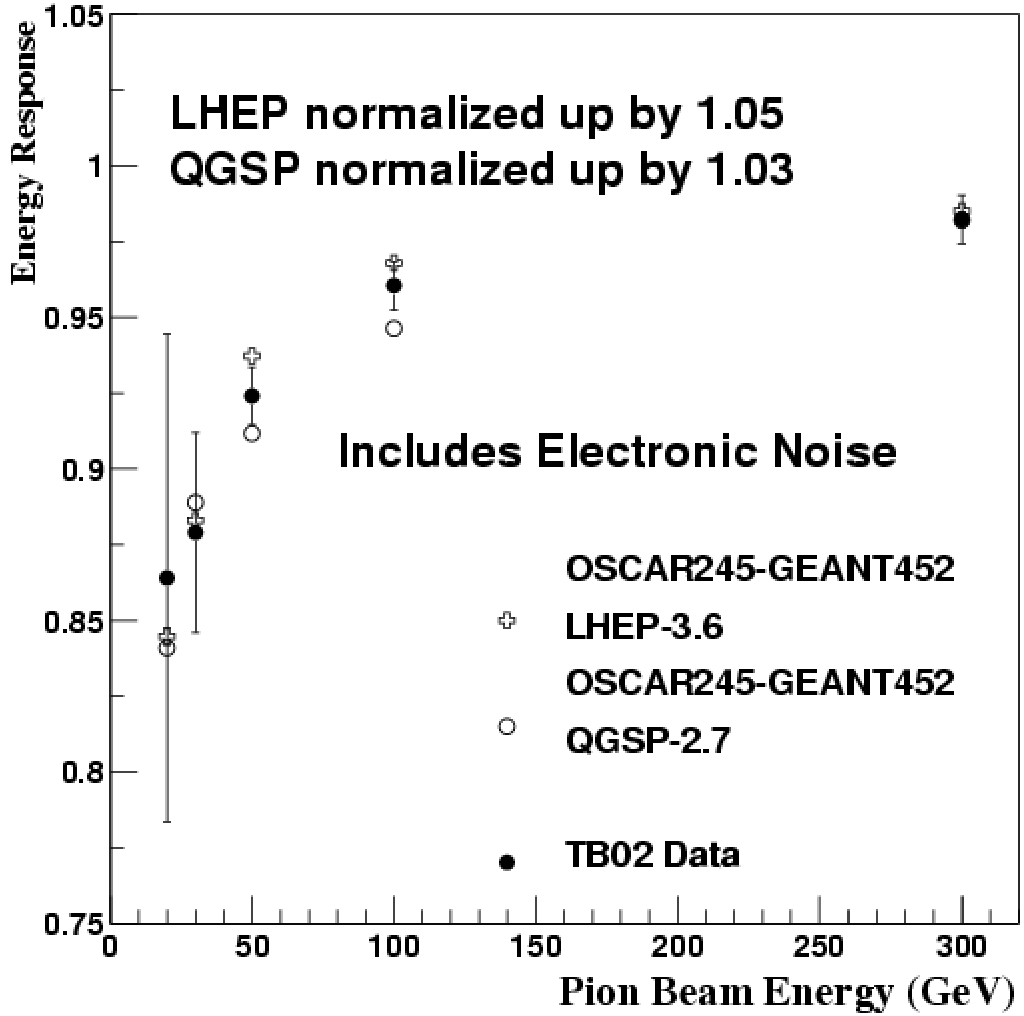
Syst. Errors 100% correlated in Energy, uncorrelated with each other (added in quadrature)

Excellent agreement in resolution

(LHEP a little higher than QGSP)

Pion Energy Linearity

OSCAR245 (LHEP-3.6, QGSP-2.7)



Data

Syst.

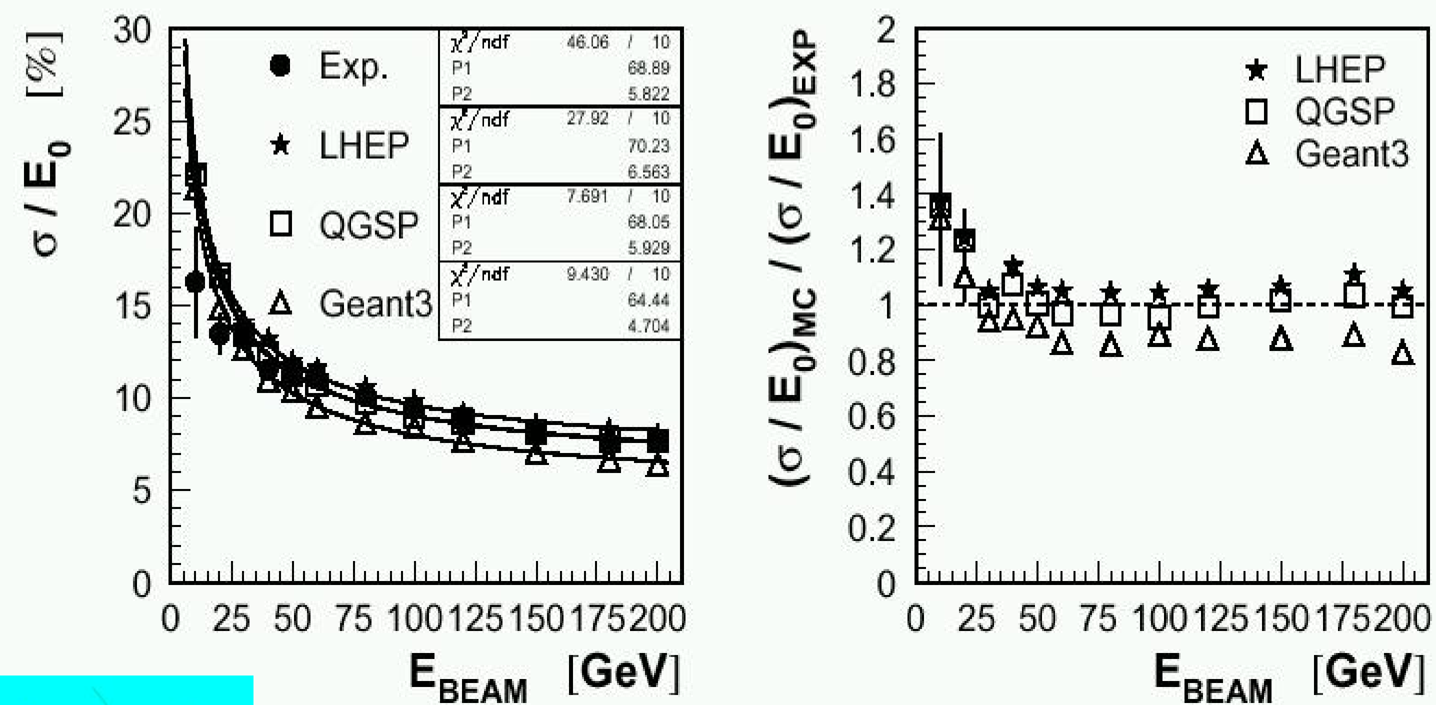
E	σ_E/E	stat	bkgnd	calib
20.	0.8640	0.0015	0.0800	0.008
30.	0.8790	0.0010	0.0320	0.008
50.	0.9240	0.0010	0.0050	0.008
100.	0.9604	0.0007	0.0003	0.008
300.	0.9823	0.0004	0.0003	0.008

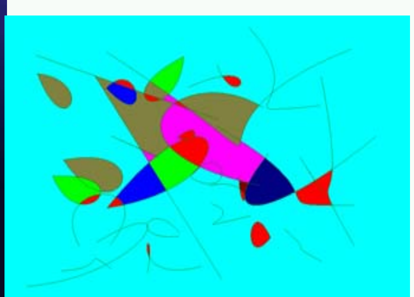
Syst. Errors 100% correlated in Energy, uncorrelated with each other (added in quadrature)

Excellent agreement in linearity

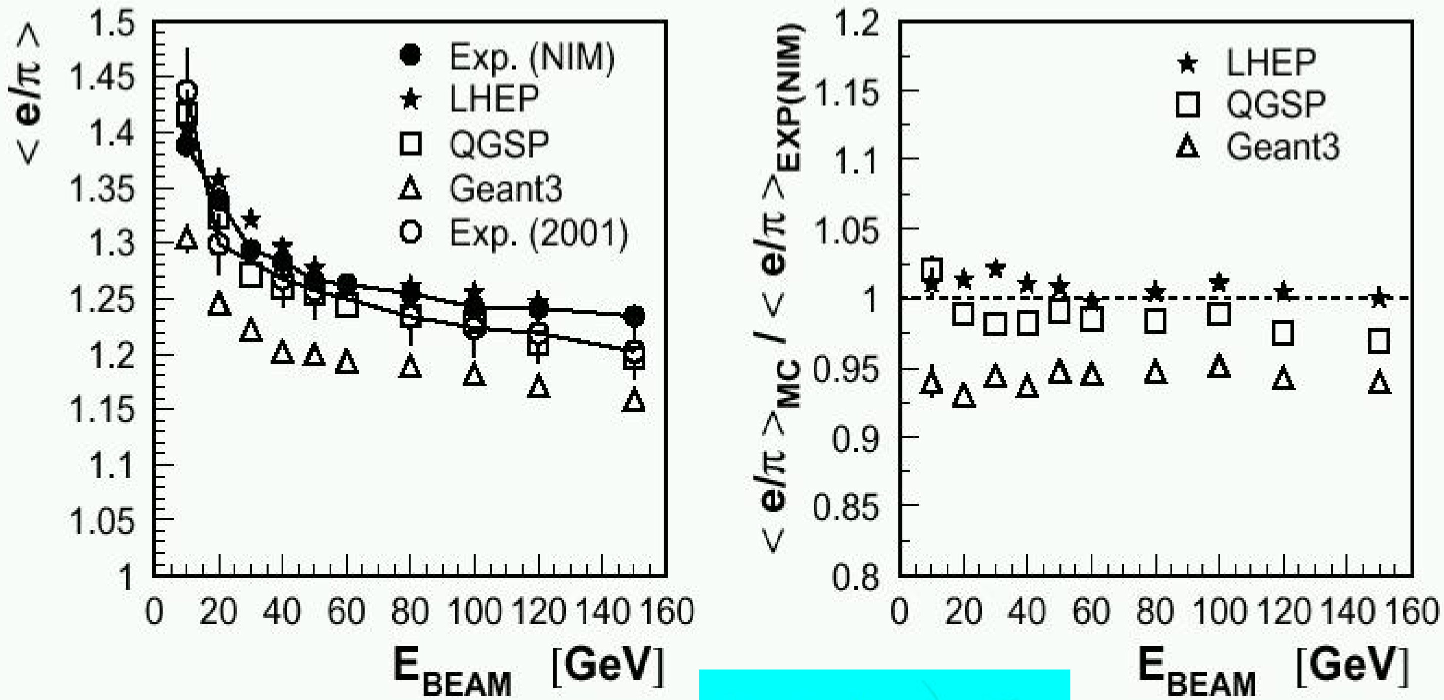
(LHEP/QGSP grows a little faster/slower than data)

Pion energy resolution

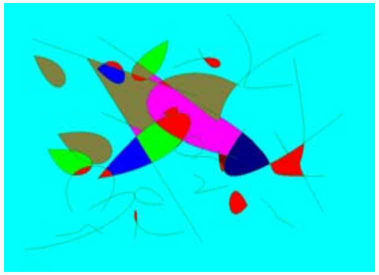




Ratio e/π



< e/π >
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0 20 40 60 80 100 120 140 160
E BEAM [GeV]
Exp. (NIM)
LHEP
QGSP
Geant3
Exp. (2001)
< e/π >MC / < e/π >EXP(NIM)
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0 20 40 60 80 100 120 140 160
E BEAM [GeV]
LHEP
QGSP
Geant3



We are currently providing simulation engines for these use-cases:

- LCG simulation project.
- HEP calorimetry.
- HEP trackers.
- 'Average' collider detector
- Low energy dosimetric applications
  with neutrons
- low energy nucleon penetration shielding
- linear collider neutron fluxes
- high energy penetration shielding
- medical and other life-saving neutron applications
- low energy dosimetric applications
- high energy production targets
  e.g. 400GeV protons on C or Be
- medium energy production targets
  e.g. 15-50 GeV p on light targets
- LHC neutron fluxes
- Air shower applications (still working on this)
- low background experiments

- http://www.geant4.com/hadronics/GHAD/HomePage