

Geant4 for medical applications

V.Ivanchenko, CERN, Geneva, Switzerland

14 October 2009

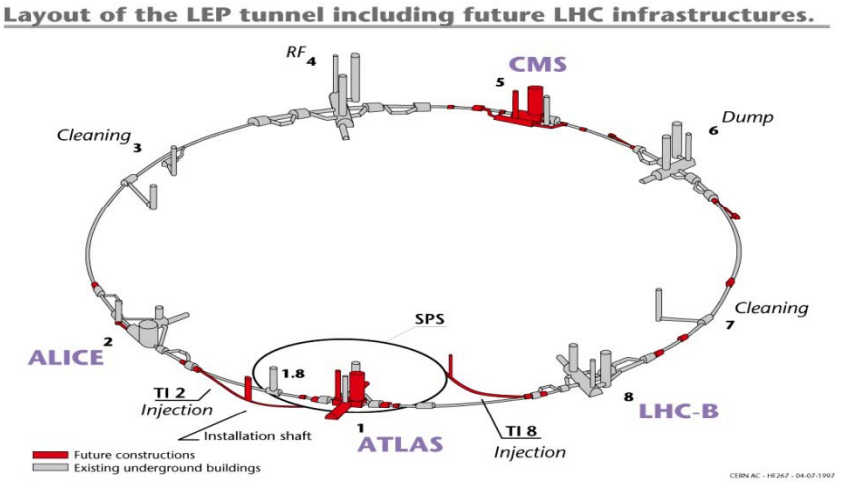
Thanks to G.Folger, S.Inserti, M.Maire, D.Wright and other Geant4 members for slides used in this talk

Outline

- Introduction
  - Geant4 History
- Geant4 electromagnetic (EM) physics
  - Geant4 EM working groups
  - Geant4 EM sub-packages
  - Validation of EM physics
  - Selected processes and validation results
- Geant4 hadronic physics for medical applications
- Physics Lists options
- Geant4 user support

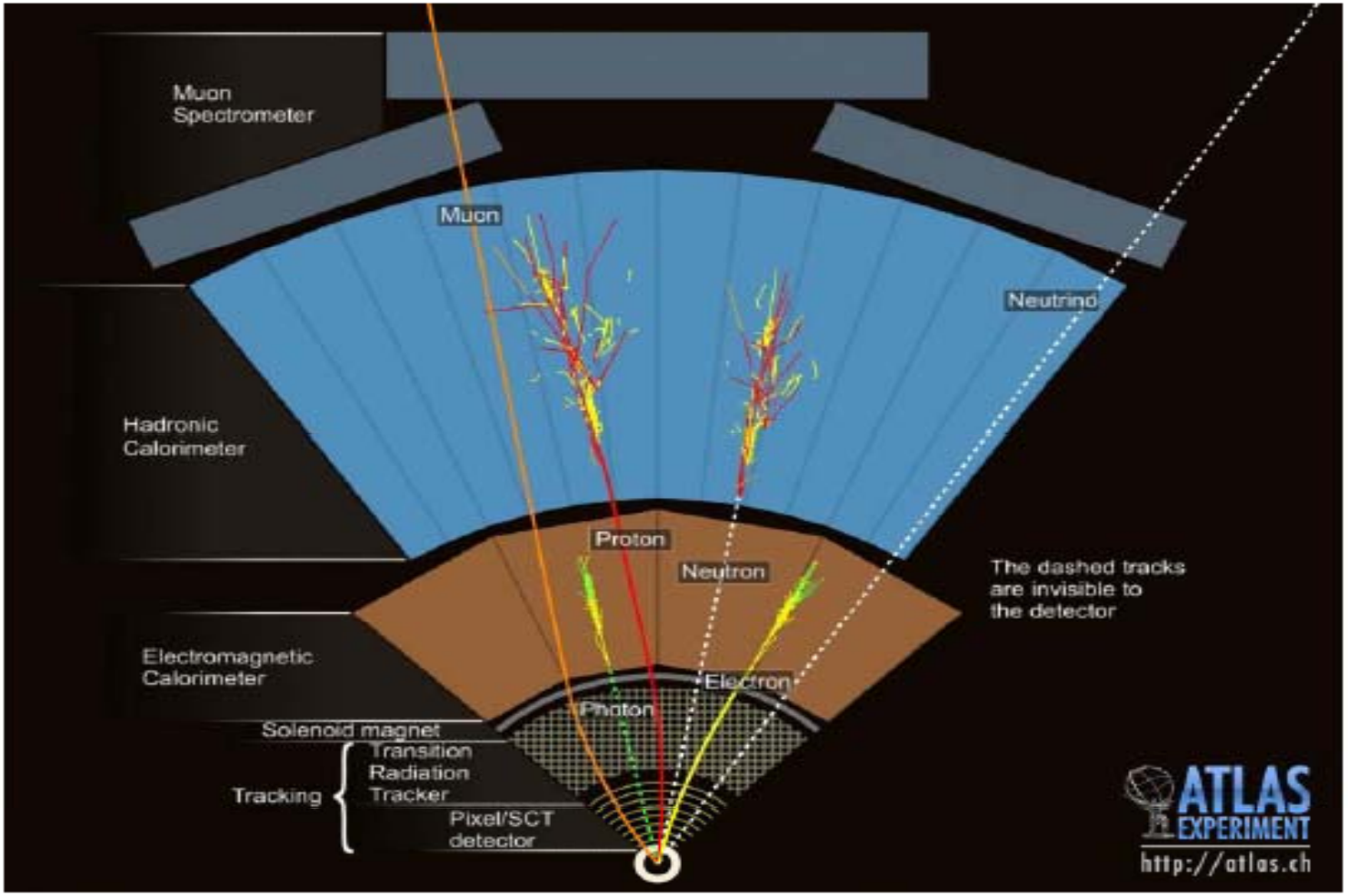
Introduction

Geant4 history



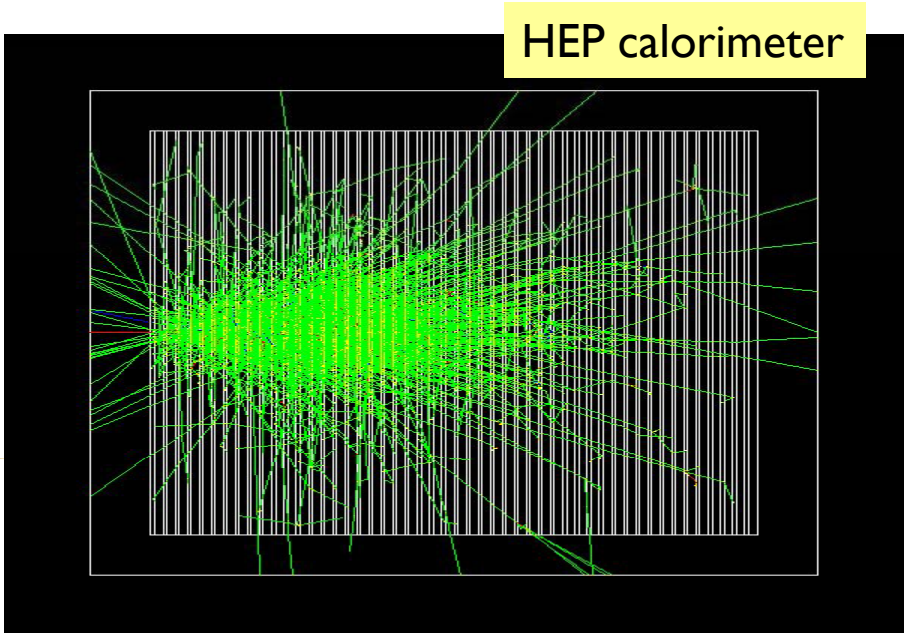
- The project have been started 1994
  - In a framework of R&D on LHC software
  - C++ and OO was chosen
  - CERN, SLAC, KEK and other HEP institutions
- The 1st version was delivered in 1998
  - Geant4 Collaboration was formed
  - In production for BaBar experiment SLAC since 2001
  - In productions for ATLAS, CMS, LHCb since 2004
- Current production version G4 9.2p01 (p02)
  - Used for LHC mass production
    - Version 9.3beta is available since June, 2009
    - 9.3 is planed for December, 2009

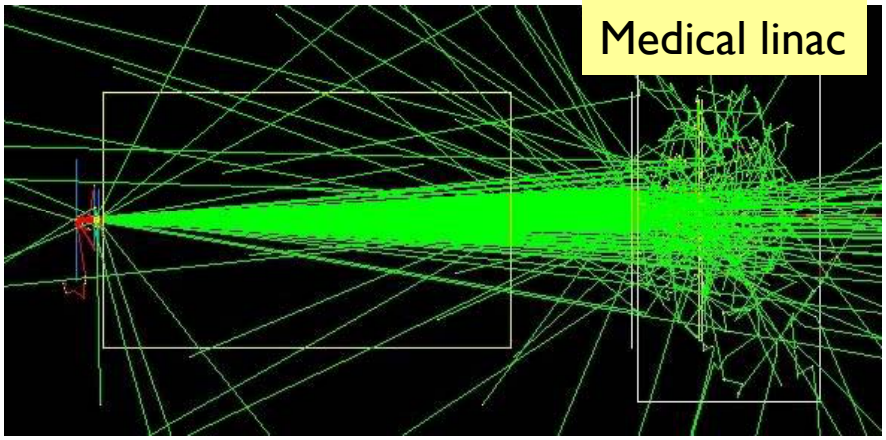
Geant4 simulation of ATLAS experiment at LHC, CERN



Gamma and Electron Transport

- **Photon processes:**
  - **γ conversion into e^+e^- pair**
  - **Compton scattering**
  - **Photoelectric effect**
  - **Rayleigh scattering in low-energy package**
  - **Gamma-nuclear interaction in hadronic sub-package CHIPS**
- **Electron and positron processes:**
  - **Ionization**
  - **Coulomb scattering**
  - **Bremsstrahlung**
  - **Nuclear interaction in hadronic sub-package CHIPS**
- **Positron annihilation**
- **Many Geant4 applications with electron and gamma beams**





Geant4 EM physics

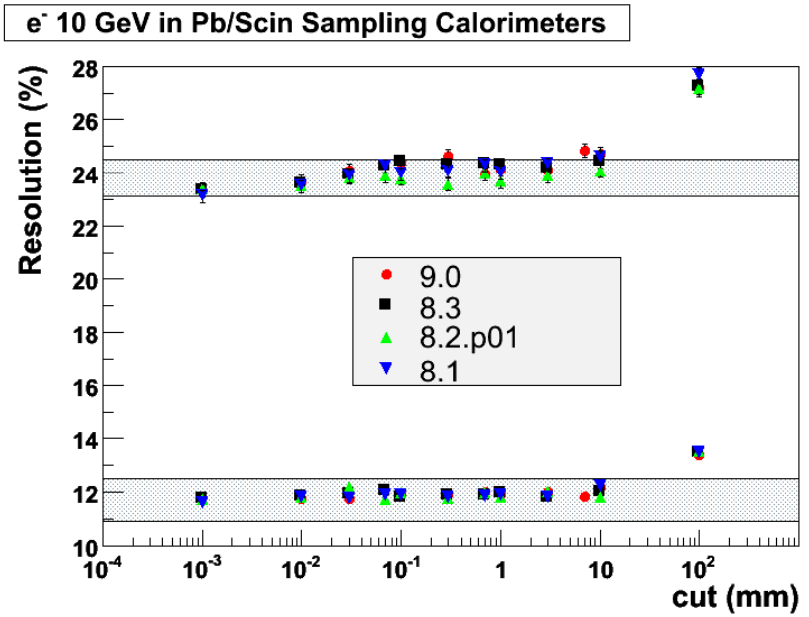
EM Standard Physics working group

- Many years is used in production for BaBar, ATLAS, CMS and other HEP experiments
- Main focus today is LHC and other HEP experiments including ILC
- Many common requirements for HEP, space, medical and other applications
- Working group page:

http://cern.ch/geant4/collaboration/working_groups/electromagnetic/index.shtml

Standard EM sub-packages

- ***Standard***
  - γ, e up to 100 TeV
  - hadrons up to 100 TeV
  - ions up to 100 TeV
- ***Muons***
  - up to 1 PeV
  - Energy loss propagator
- ***Xrays***
  - X-ray and optical photon production processes
- ***Optical***
  - Optical photon interactions
- ***High-energy***
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- ***Polarisation***
  - New package for simulation of polarized beams



- ***Results for the Default Physics Lists***
- ***Two configurations:***
  - 5 mm Pb/5 mm Scintillator
  - 10 mm Pb/ 2.5 mm Scintillator
- ***Data* from NIM A262 (1987) 229; NIM A274 (1989) 134**

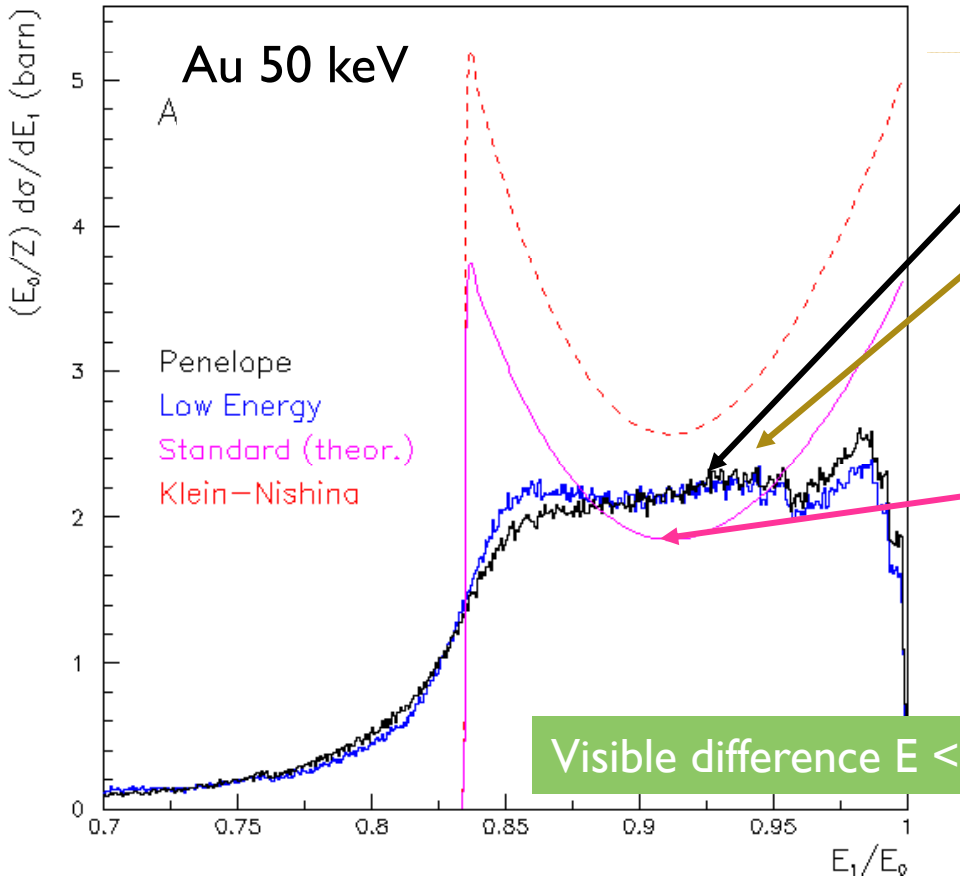
Geant4 EM Low-energy group

- Was created in 2000 and was leaded by M.G.Pia
- S.Incerti was elected as a working group coordinator in spring 2008
- Low-energy working group have been reorganized with main goals:
  - To increase manpower and efficiency of the group
    - Sub-group structure have been implemented
  - To enable more active participation of experts in low-energy EM projects
    - Including medical physicists
  - To extend capability of the sub-package
    - Migration to model design common with the standard package have been done and the prototype is already available with 9.3beta

Doppler broadening in Compton scattering g4 9.2

On behalf of L. Pandola

Compton scattering: electrons bound and not at rest (as assumed for Klein-Nishina)
→ change of angular distribution, reduction of XS



Visible difference E < 0.5 MeV

G4**PenelopeCompton** includes it (**analytical** approach)

G4LowEnergyCompton recently updated (by M.G.Pia) to deal with Doppler broadening (**EGS database** approach)

Good agreement Penelope-LowE

Standard Compton **includes cross section** suppression, but samples final state according to Klein-Nishina

Looking for suitable **validation data**

Important comment

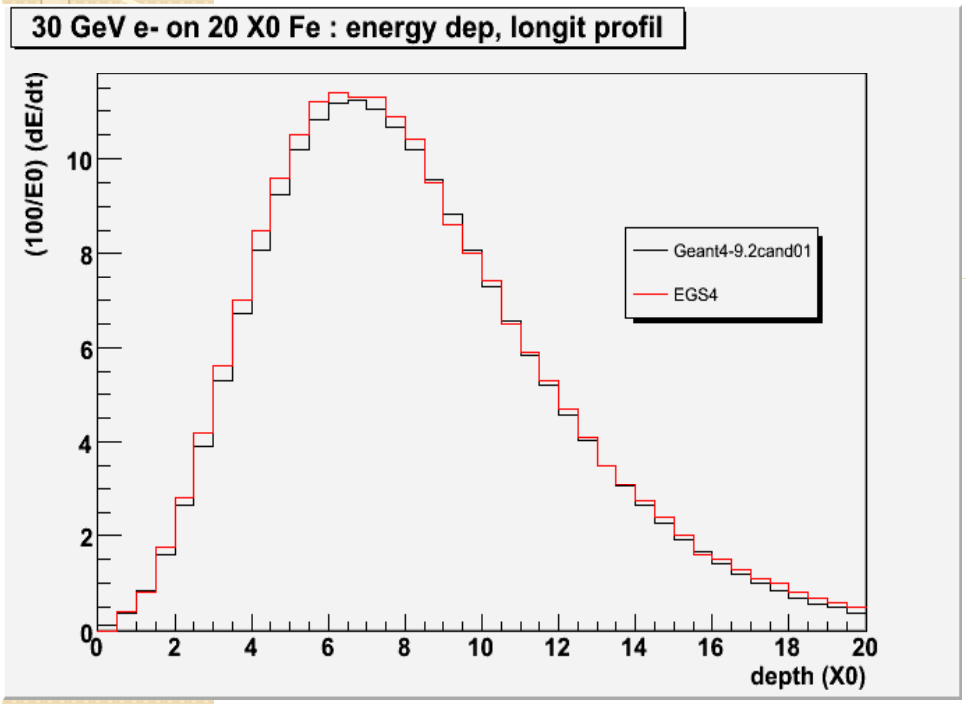
- Geant4 tracking by default does not apply tracking cut, so any particles is tracked until absorption or zero kinetic energy
- Low-energy limit of EM models not well defined
  - Standard EM package can provide tracking until zero energy
  - Precision of simulation is defined via cut in range, which defines accuracy of simulation in space
- The choice of model (standard/low-energy) requires extra validation corresponding to the concrete application

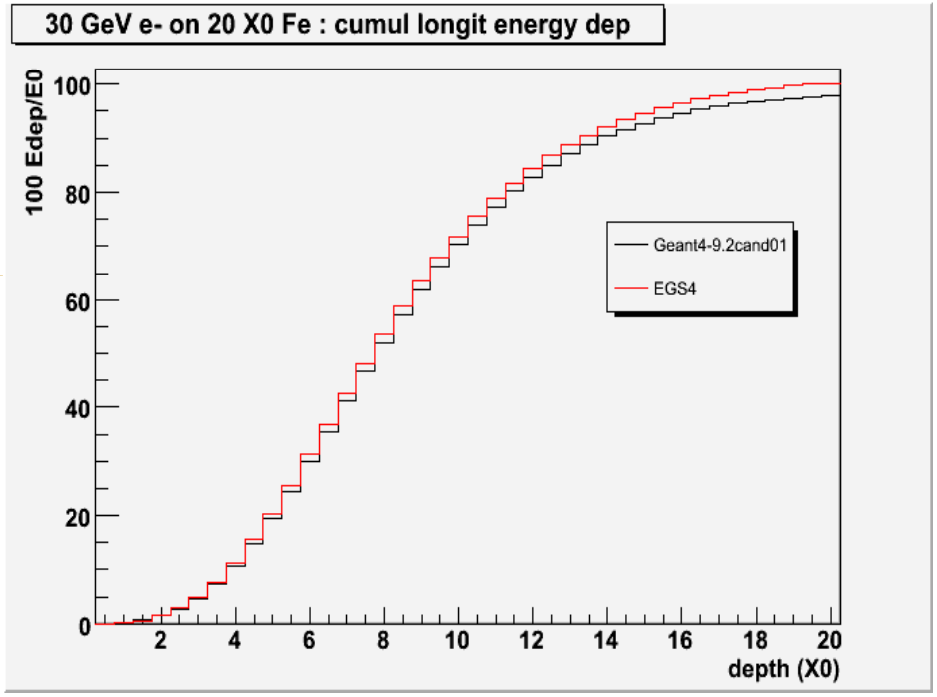
Validation of EM physics

- All processes and models are exercised by integration tests http://spreadsheets.google.com/ccc?key=pVWTkls9xs0juh3Wqm-B3LQ
  - 30 tests specialized for EM processes, in other tests EM processes also are used
    - Regression control of physics output
    - Acceptance tests of important output variables
    - Used by Geant4 system testing team
- Testing suite for EM Standard for high statistic tests http://spreadsheets.google.com/pub?key=pw2-SY7kU6F6T0bLY9OIiNw
  - Regular runs in batch mode (CERN, LAPP, KEK)
  - Scripts for running and analysis
  - Results are available in the web
  - Regression tests to compare Geant4 releases
  - The most number of tests versus data
- Long process required manpower
  - Always welcome user validation efforts and independent user publications

Selected EM processes and validation results

Testing suite result for shower profile Geant4 versus EGS4





- Small difference in normalizations: EGS4 normalized to total energy deposition, so shower leak is excluded

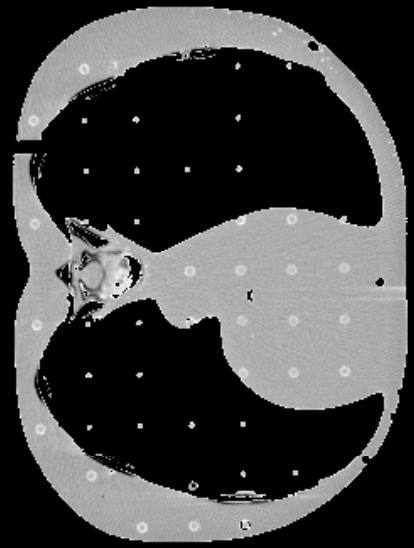
Comparison with commercial treatment planning systems

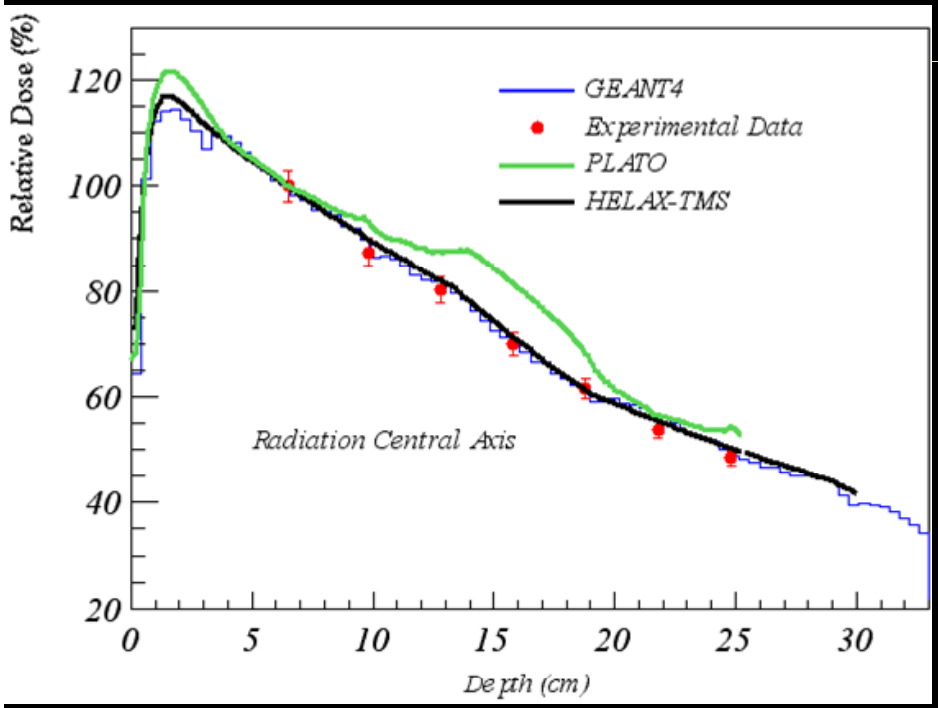
M. C. Lopes [1], L. Peralta [2], P. Rodrigues [2], A. Trindade [2]
[1] IPOFG-CROC Coimbra Oncological Regional Center - [2] LIP - Lisbon

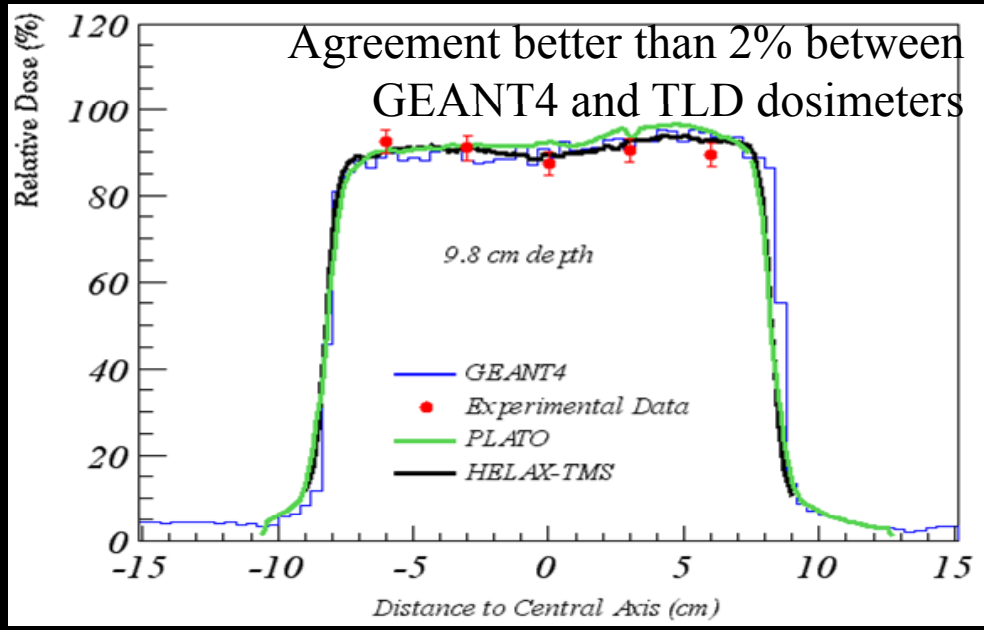
CT-simulation with a Rando phantom
Experimental data obtained with TLD LiF dosimeter

CT images used to define the geometry:

a thorax slice from a Rando anthropomorphic phantom







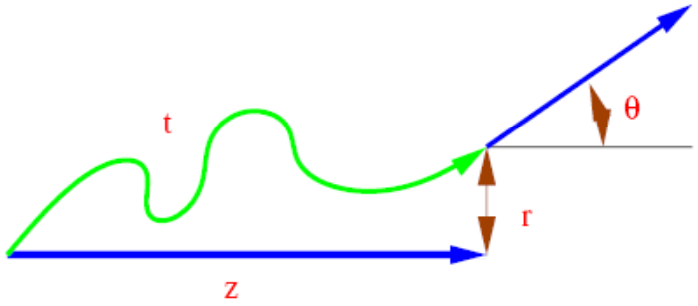
Agreement better than 2% between GEANT4 and TLD dosimeters

LIP

Elastic (Rutherford) scattering of changed particles

Multiple Coulomb scattering (MSC)

Charged particles traversing a finite thickness of matter suffer repeated elastic Coulomb scattering. The cumulative effect of these small angle scatterings is a net deflection from the original particle direction.



- longitudinal displacement z (or geometrical path length)
- lateral displacement r, Φ
- true (or corrected) path length t
- angular deflection θ, ϕ

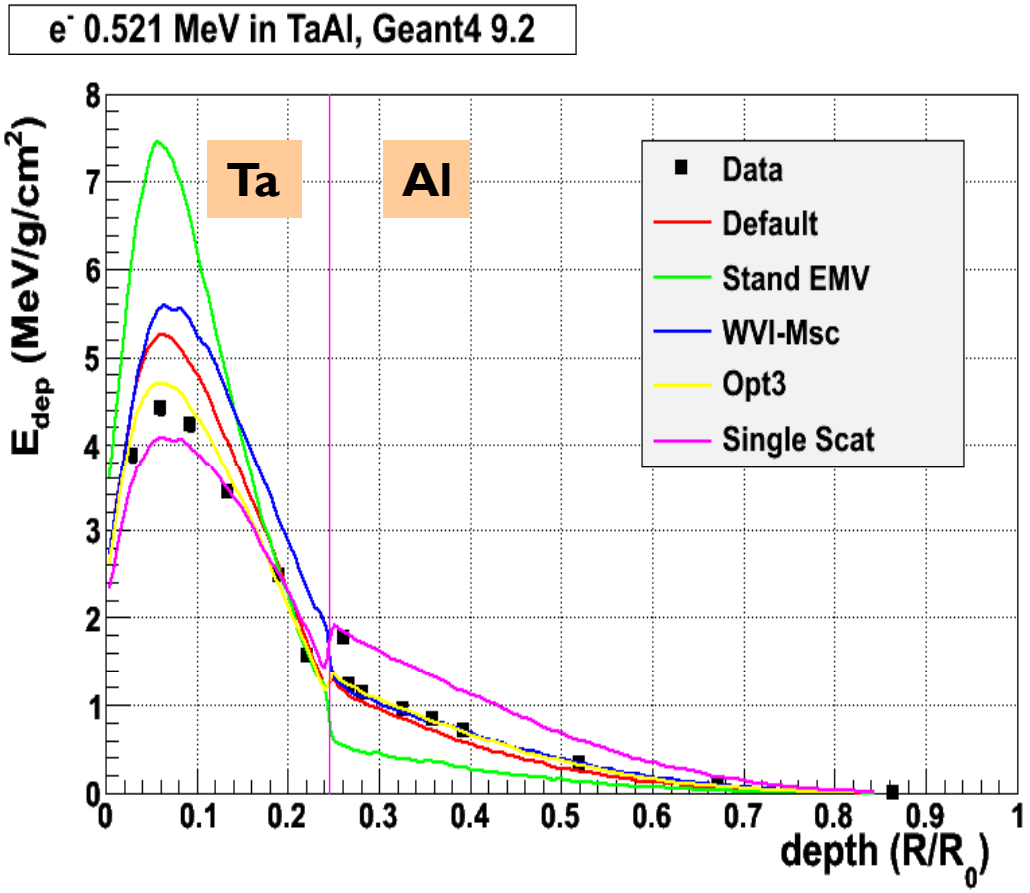
Current state of art for msc/single scattering models

Model	Particle type	Energy limit	Specifics and applicability
Urban (Urban 2006)	any	-	Default model, (Lewis1950) approach, tuned to data, LHC production
Screened Nuclear Recoil (Mendenhall and Weller 2005)	p, ions	< 100 MeV/A	Theory based, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space applications
Goudsmit-Saunderson (new, O.Kadri 2009)	e^+, e^-	< 1 GeV	Theory based cross sections (Goudsmit and Saunderson 1950), EPSEPA code developed by Penelope group , final state using EGSnrc method (Kawrakov et al. 1998), precise electron transport
Coulomb Scattering (new, 2008)	any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (new, 2008)	any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons

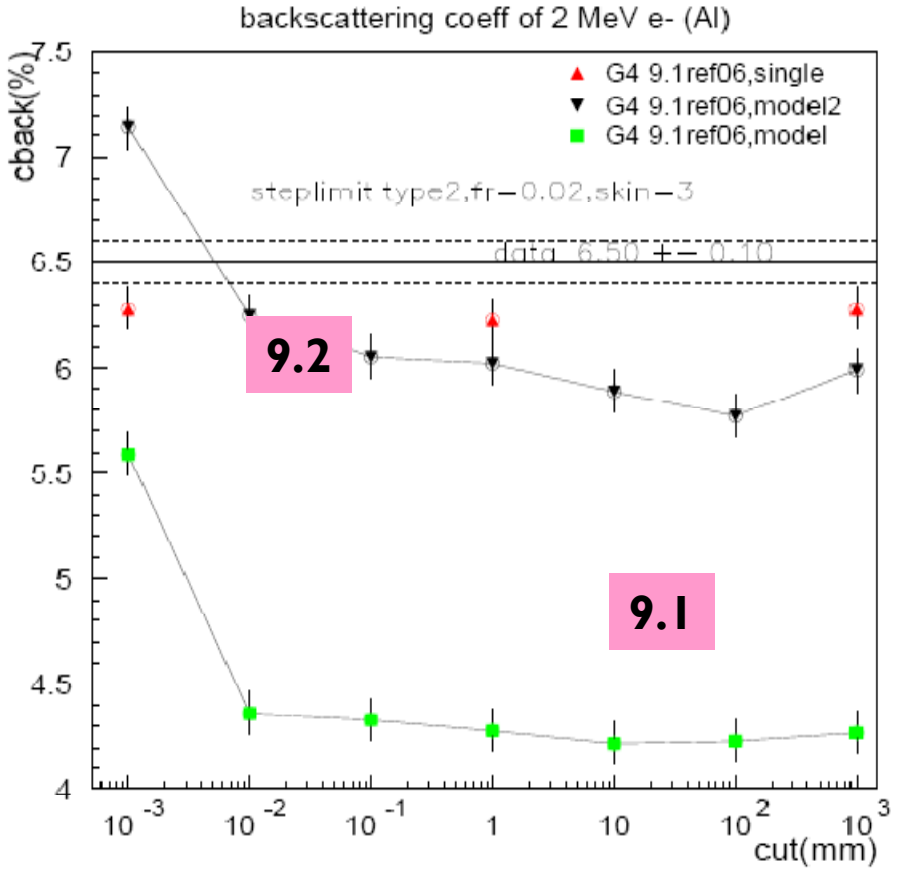
Test of e^- transport versus Sandia data

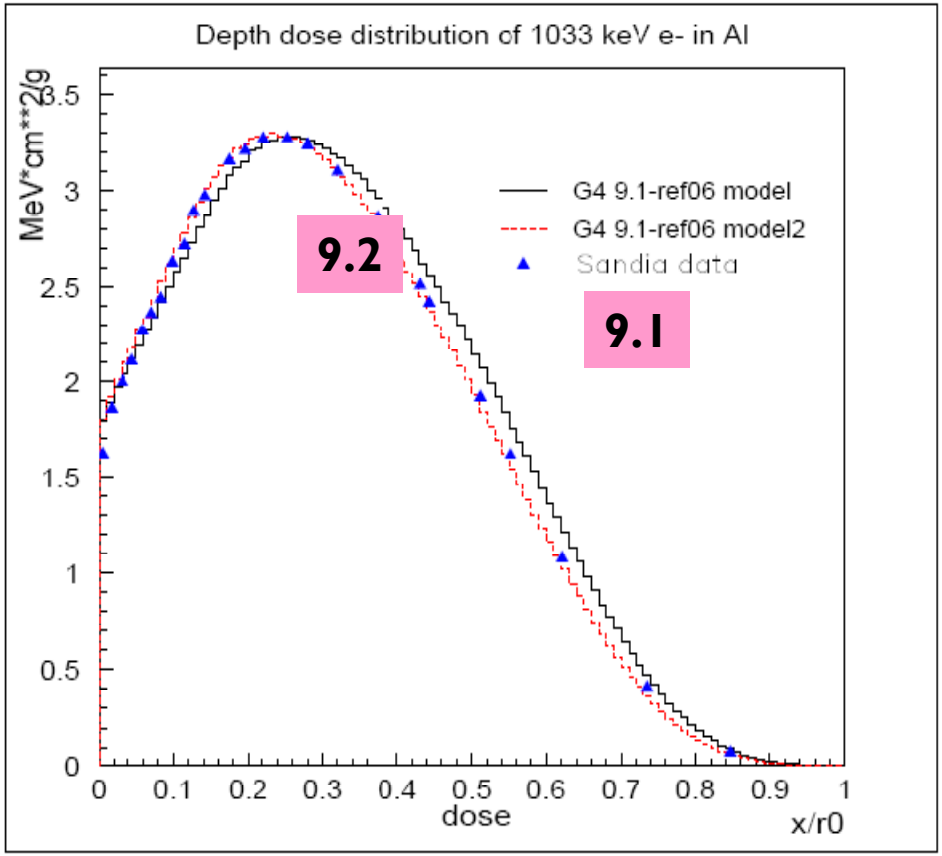
(details in O.Kadri et al, NIM B258 (2007) 358)

- Sensitive to multiple scattering
- Directly connected with LHC calorimeters results
- Tuned Urban's msc model#2
  - Opt3 is best in describing data



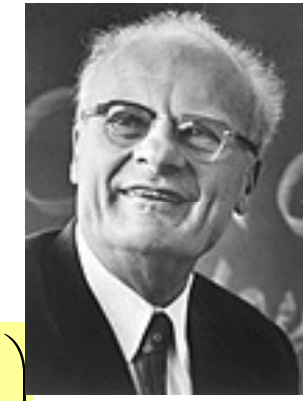
Upgrade of multiple scattering model





Old msc default version will be kept for backward compatibility

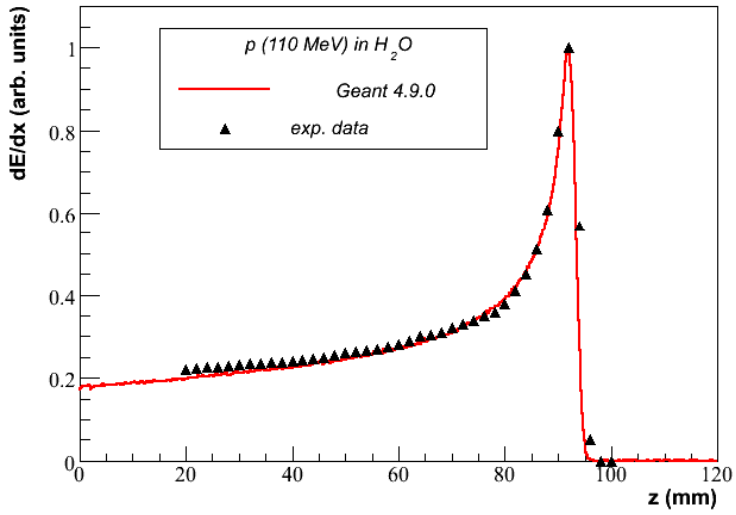
Hadron and ion EM physics



- Coulomb scattering
- Ionization
- Bethe-Bloch formula with corrections used for E>2 MeV

$$-\frac{dE}{dx} = 4\pi N_e r_0^2 \frac{z^2}{\beta^2}\left(\ln\frac{2m_e c^2\beta^2\gamma^2}{I} - \frac{\beta^2}{2}\left(1-\frac{T_c}{T_{\max}}\right) - \frac{C}{Z} + \frac{G-\delta-F}{2} + zL_1 + z^2 L_2\right)$$

  - C – shell correction
  - G – Mott correction
  - δ – density correction
  - F – finite size correction
  - L_1- Barkas correction
  - L_2- Bloch correction
  - Nuclear stopping
  - Ion effective charge
- Bragg peak parameterizations for E
  - ICRU'49 and NIST databases



Sampling of δ-electrons for hadrons and ions

Energetic δ rays

The differential cross-section per atom for producing an electron of kinetic energy T, with $I \ll T_{cut} \leq T \leq T_{max}$, can be written :

$$\frac{d\sigma}{dT} = 2\pi r_e^2 mc^2 Z \frac{z_p^2}{\beta^2} \frac{1}{T^2} \left[1 - \beta^2 \frac{T}{T_{max}} + \frac{T^2}{2E^2} \right]$$

(the last term for spin 1/2 only).

The integration (3) gives :

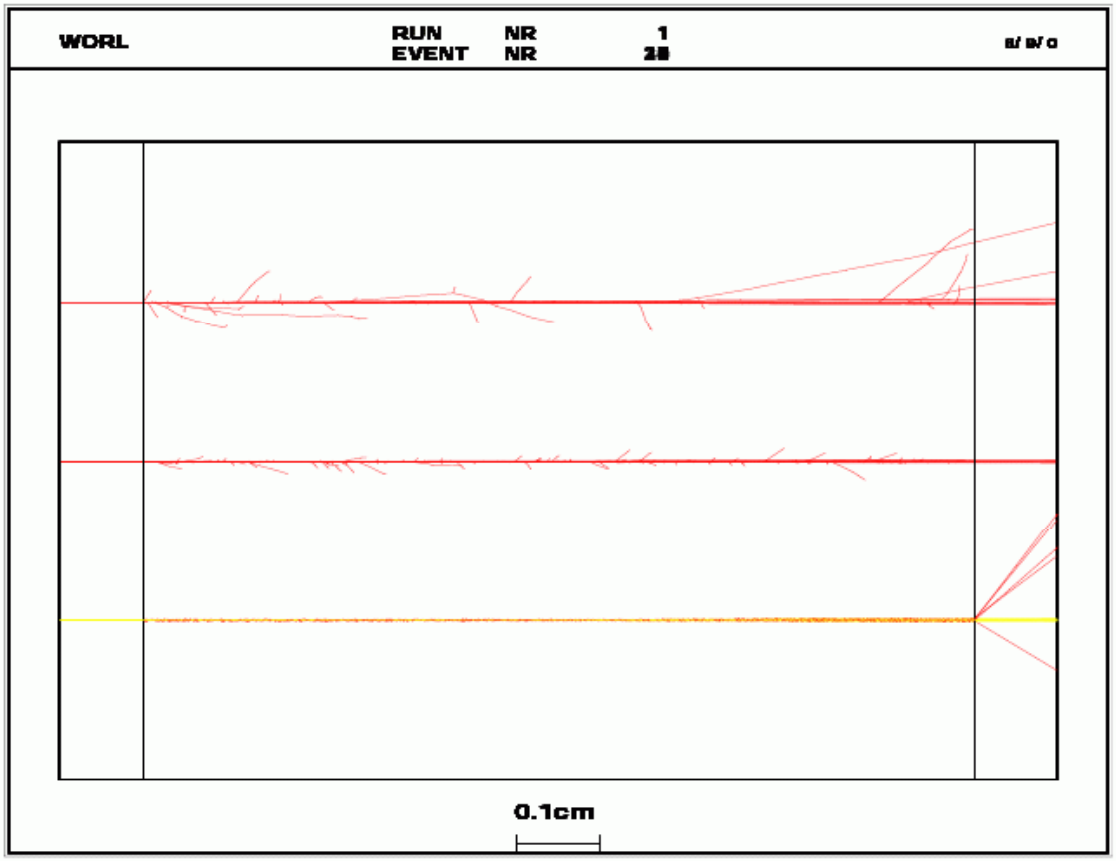
$$\sigma(Z, E, T_{cut}) = \frac{2\pi r_e^2 Z z_p^2}{\beta^2} \left[\left(\frac{1}{T_{cut}} - \frac{1}{T_{max}} \right) - \frac{\beta^2}{T_{max}} \ln \frac{T_{max}}{T_{cut}} + \frac{T_{max} - T_{cut}}{2E^2} \right]$$

(the last term for spin 1/2 only).

Examples of delta-ray production

Multiple scattering is not seen due the scale

200 MeV electrons, protons, alphas in 1 cm of Aluminium



e^-

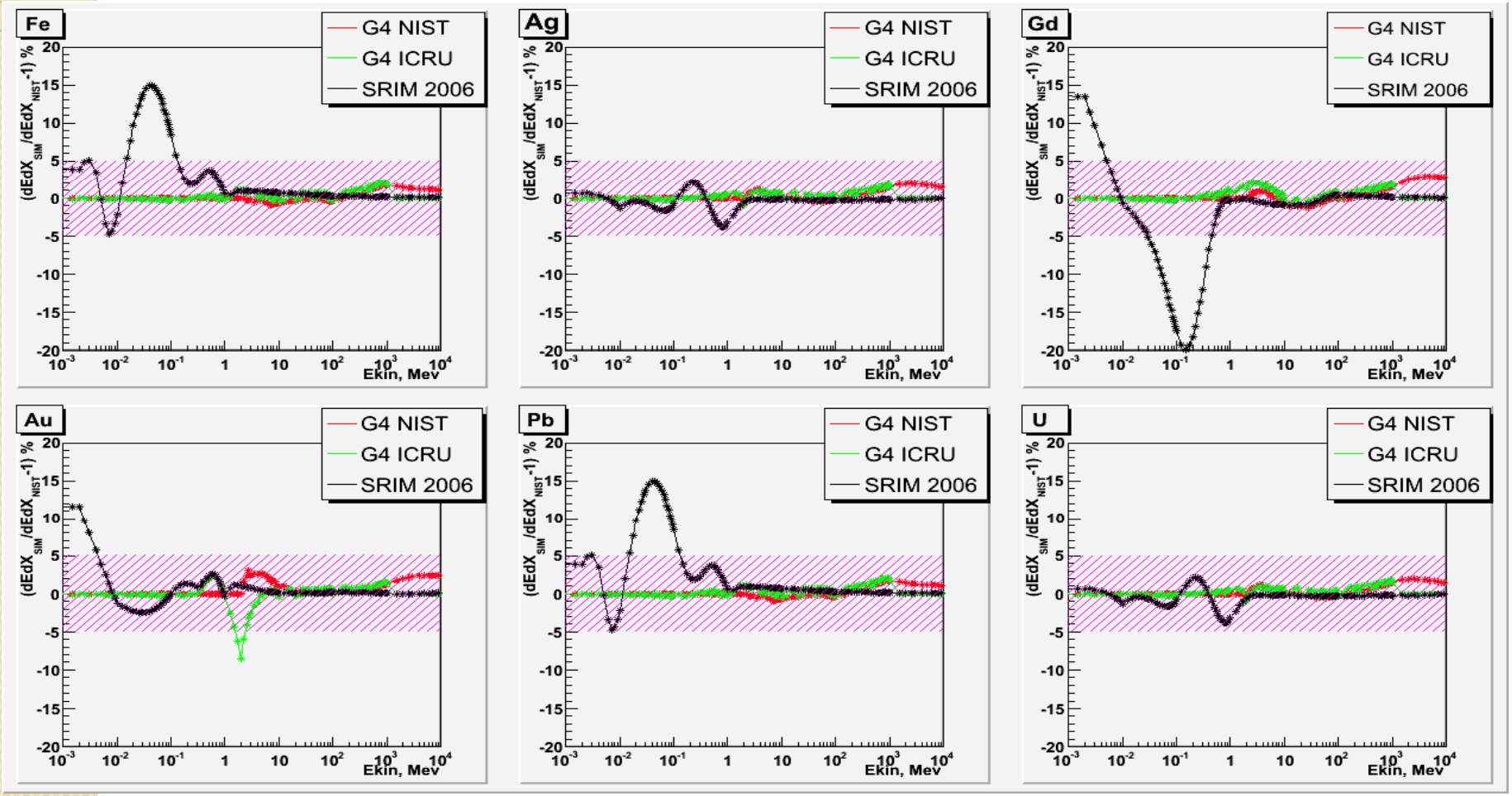
proton

alpha

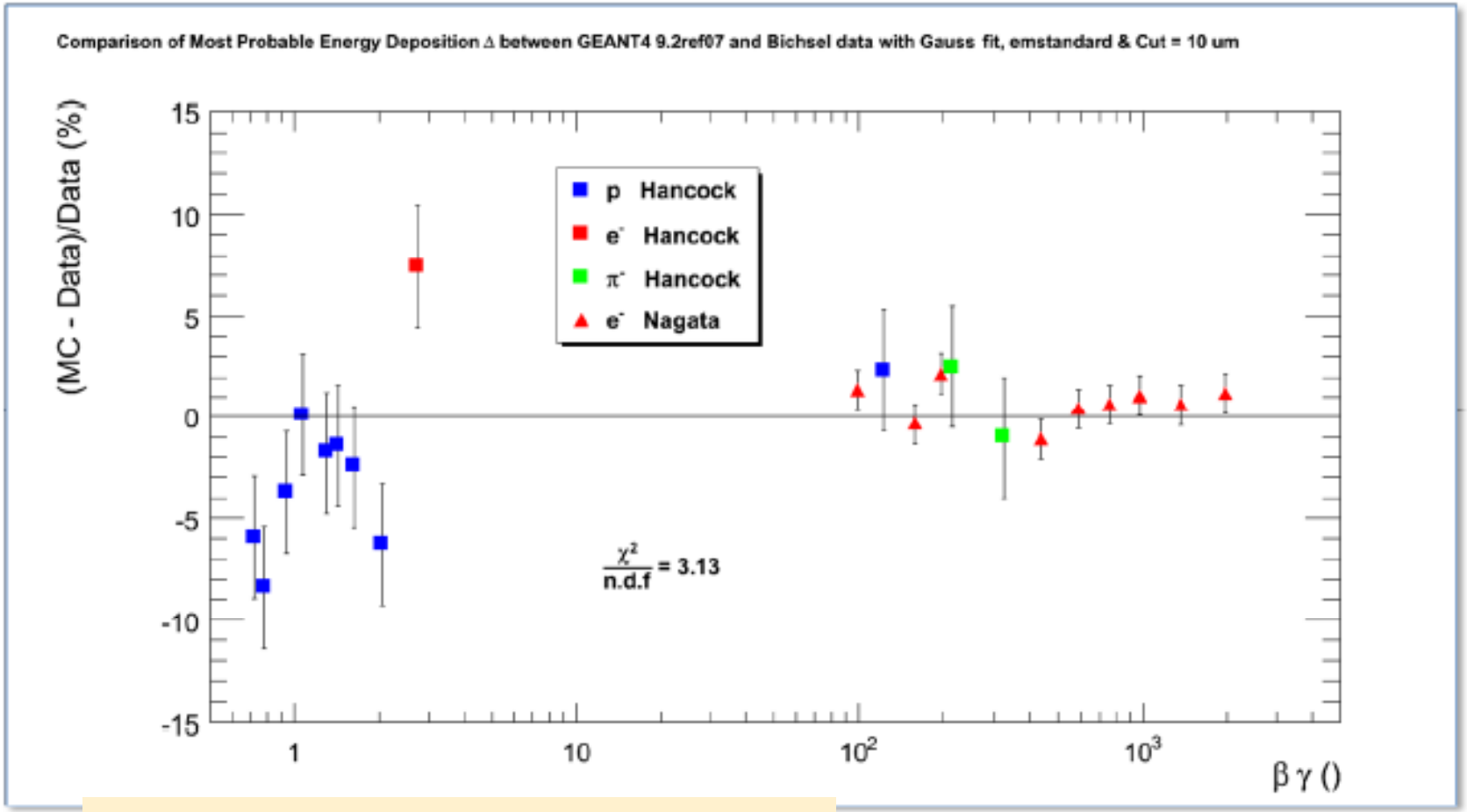
Proton stopping power comparison:

G4 NIST/ G4 ICRU/ SRIM-06/ NIST data

(V.Ivanchenko, Geant4 Space User Workshop, San Diego, 2007)



Recent validation of Geant4 simulation of response of thin (300 um) Silicon detector



F.Dupertuis, CERN summer student, 2009

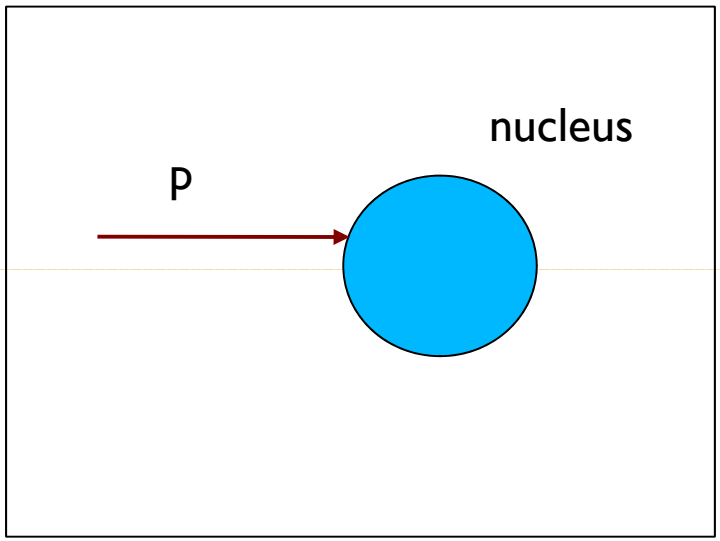
Hadronic physics for medical applications

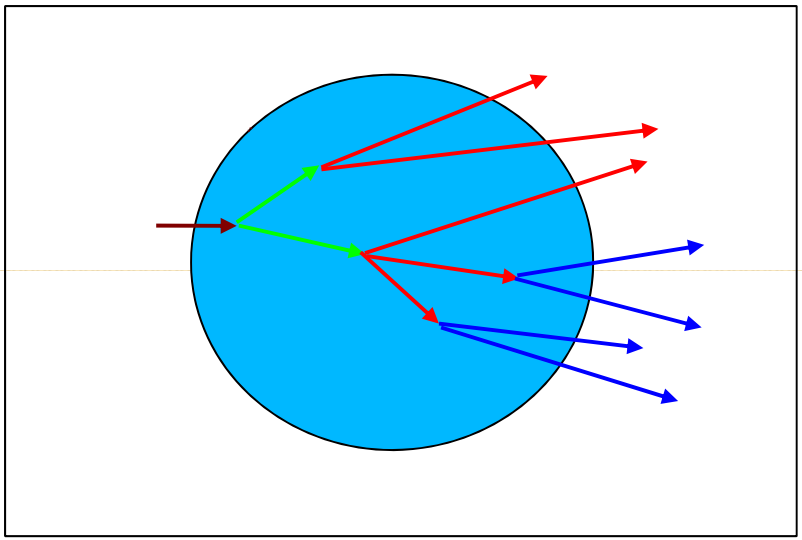
General comment:

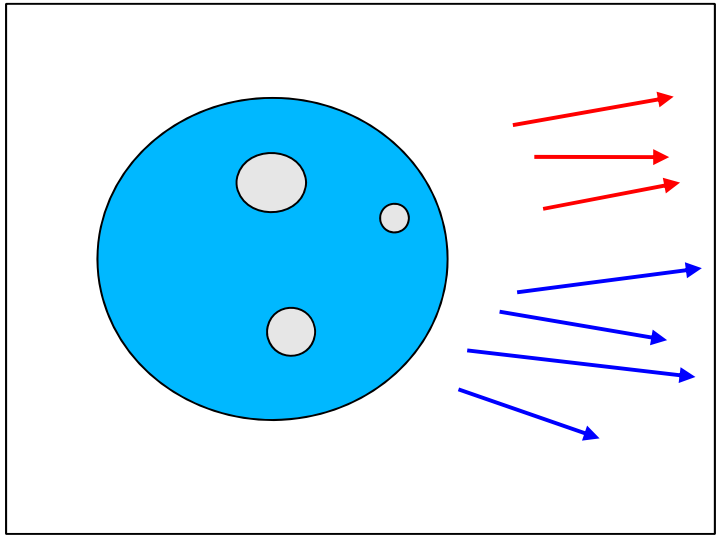
Theory of inelastic hadronic interactions is not established from 1st principles, so phenomenology and parameterisations based on data are used, naturally different competitive models are being developed inside Geant4

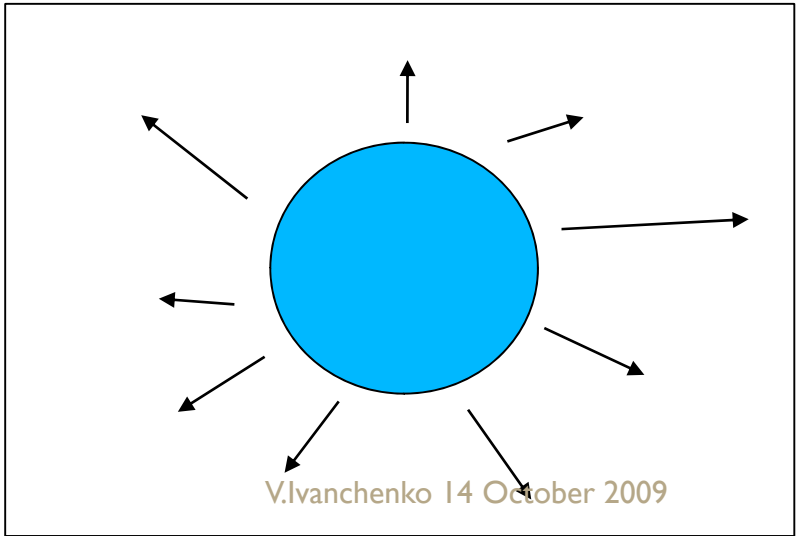
Geant4 include number of professionals with 10-30 years of expertise in specific hadronic models

Cascade models (100 MeV – 3 GeVs)









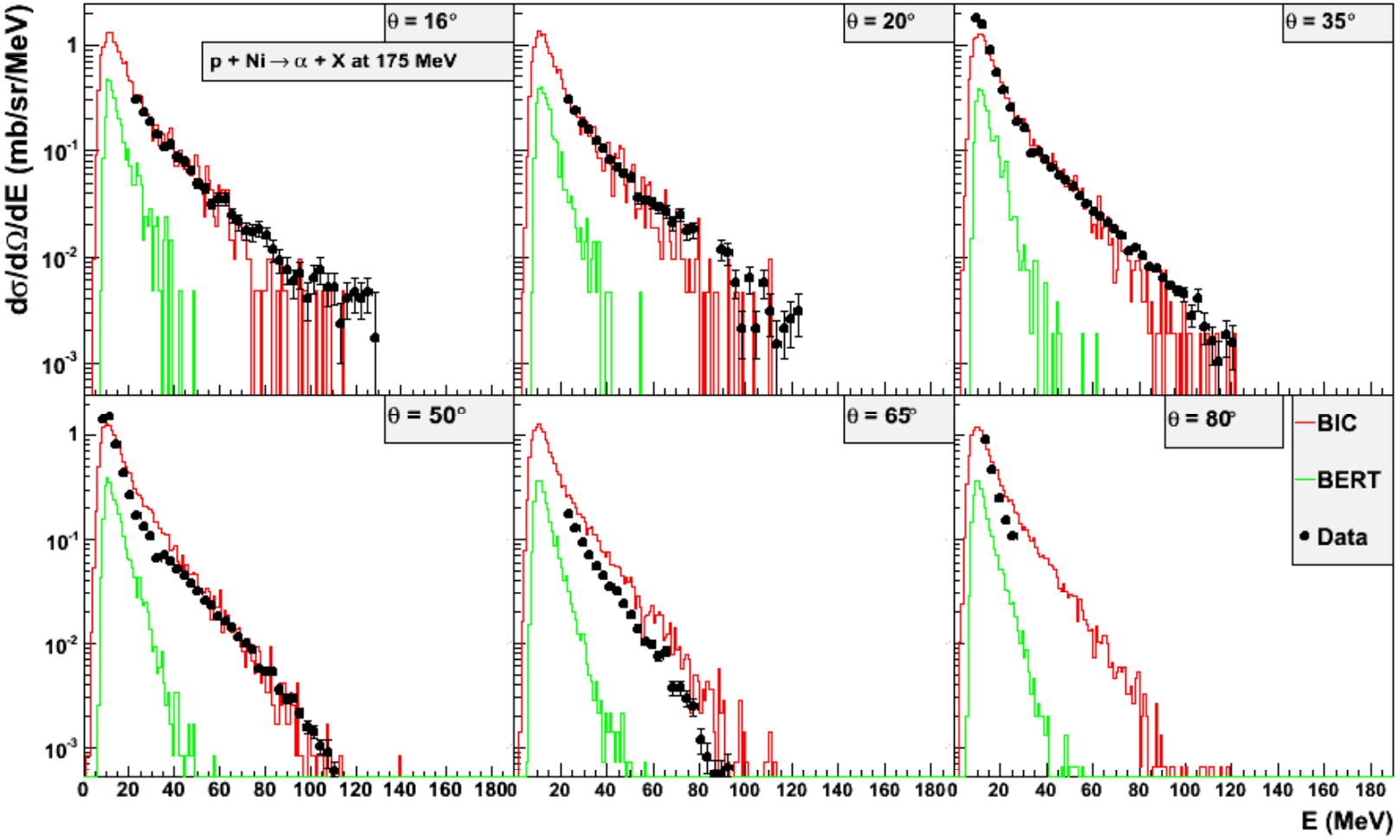
Bertini Cascade Model (favorite for LHC)

- The Bertini model is a classical cascade:
  - it is a solution to the Boltzman equation on average
  - no scattering matrix calculated
  - can be traced back to some of the earliest codes (1960s)
  - Original author Stepanov (ITEP, Moscow)
  - Current responsible D.Wright (SLAC, Stanford, CA)
- Core code:
  - elementary particle collider: uses modified free-space cross sections to generate secondaries
  - cascade in nuclear medium
  - pre-equilibrium and equilibrium decay of residual nucleus
  - 3-D model of nucleus consisting of shells of different nuclear density
- In Geant4 the Bertini model is currently used for p, n, π, K^+, K^-, K^0_L, K^0_S, Λ, Σ^+, Σ^-, Ξ^-, Ξ^0, Ω^-
  - valid for incident energies of 0 – 10 GeV
  - more precise for A > 10

Binary Cascade – today favorite for medical applications (G.Folger et al.)

- Modeling sequence similar to Bertini, except that
  - Nucleus consists of nucleons
  - hadron-nucleon collisions
    - handled by forming resonances which then decay according to their quantum numbers
    - Elastic scattering on nucleons
  - particles follow curved trajectories in nuclear potential
  - Geant4 native PreCompound model is used for nuclear de-excitation after cascading phase
- In Geant4 the Binary cascade model is currently used for incident p, n and π
  - valid for incident p, n from 0 to 10 GeV
  - valid for incident π^+, π^- from 0 to 1.3 GeV
- A variant of the model, G4BinaryLightIonReaction, is valid for incident light ions
  - or higher if target is made of light nuclei
- Alternative new model QMD (T.Koi) was recently released
  - May be recommended for light media

Hadronic validation: ^{4}He ion emission in proton nuclear reaction



Chiral Invariant Phase Space (CHIPS)

- Origin: M.V. Kosov (CERN, ITEP)
- Use:
  - capture of negatively charged hadrons at rest
  - anti-baryon nuclear interactions
  - gamma- and lepto-nuclear reactions
  - back end (nuclear fragmentation part) of QGSC model
  - For coming g4 9.3 simulation of primary p, n will be available
- Base element is quasmon: an ensemble of massless partons uniformly distributed in invariant phase space
  - 3D bubble of quark-parton plasma
  - Can be any excited hadron system or ground state hadron
  - Quark fusion hadronization: two quark-partons may combine to form an on-mass-shell hadron
  - Quark exchange hadronization: quarks from quasmon and neighbouring nucleon may trade places

Liege Cascade (INCL) model

- Well established code in nuclear physics
  - Well tested for spallation studies
  - Uses ABLA code for nuclear de-excitation
- Valid for p, n, pions up to 2-3 GeV
  - Not applicable to light nuclei (A< 12-16)
- Authors collaborate with Geant4 to re-write code in C++
  - First version will be released with 9.2 in December 2008
  - ABLA is included as well
  - Helsinki University group is responsible

Low energy neutron transport NeutronHP

- Data driven models for low energy neutrons, E< 20 MeV, down to thermal
  - Elastic, capture, inelastic, fission
    - Inelastic includes several explicit channels
  - Based on data library derived from several evaluated neutron data libraries
  - Data on cross sections and final state in $G4NEUTRONHPDATA
  - Responsible T.Koi (SLAC, Stanford, CA)

Radioactive decay

- To simulate decay of radioactive nuclei
- Empirical and data-driven models
- Models of α, $\beta^{\pm}$ decays, and e^{-} capture are implemented
- Data derived from Evaluated Nuclear Structure Data File (ENSDF)
  - Nuclear half-lives, level structure, nuclear decay branching ratio, Q-value of decays, the data directory $G4RADIOACTIVEDATA
- If the daughter of a nuclear decay is an excited isomer, its prompt nuclear de-excitation is treated using photon evaporation code – data-base of γ lines and nuclear levels in $G4LEVELGAMMADATA

Configuration of Geant4 physics for medical applications

Reference Physics Lists

- Reference physics lists attempt to cover a wide range of use cases
  - Extensive validation by LHC experiments for simulation hadronic showers
    - QGSP_BERT, or QGSP_BERT_EMV current favorite for LHC
    - New FTF_BIC is a promising alternative
    - QGSP_BERT_EMY – first variant for medical users
  - user feedback is welcome
- Reference Physics Lists use modular design including following constructors (builders):
  - EM (default is standard EM)
  - Extra EM (gamma- and electro- nuclear processes)
  - Decay
  - Hadron elastic scattering
  - Hadron inelastic Interaction
  - Ion-nuclear interactions
  - User can add extra physics constructor – StepLimiter, Optical…

C. Champion, G. Depaola, S. Incerti, V. Ivanchenko, A. Lechner, F. Longo, M. Maire, A. Mantero, L. Pandola

New EM physics builders

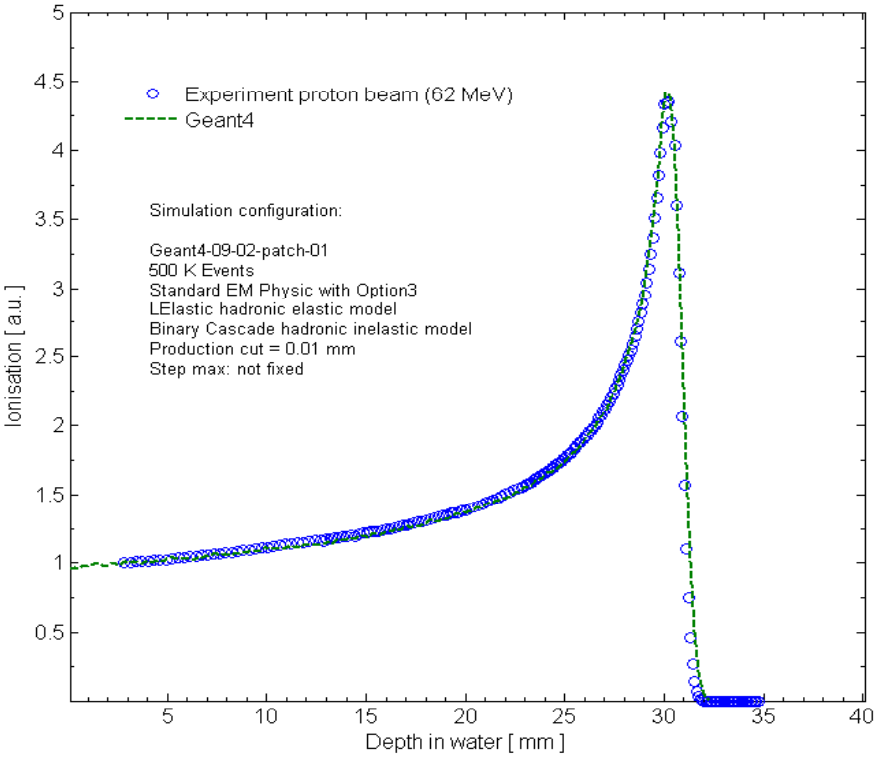
- Combined standard/low-energy EM physics:
  - Low energy processes below 1 GeV
    - G4EmLivermorePhysics
    - G4EmPenelopePhysics
  - Standard models above 1 GeV
- Prototype builders
  - G4EmLivermorePolarizedPhysics
  - G4EmDNAPhysics
- Documentation
  - Extended examples
  - Advance examples: microbeam, microdosimetry
  - Low-energy group web
- Obsolete low-energy classes will be kept for some time
  - will warn and ask users to switch to new process

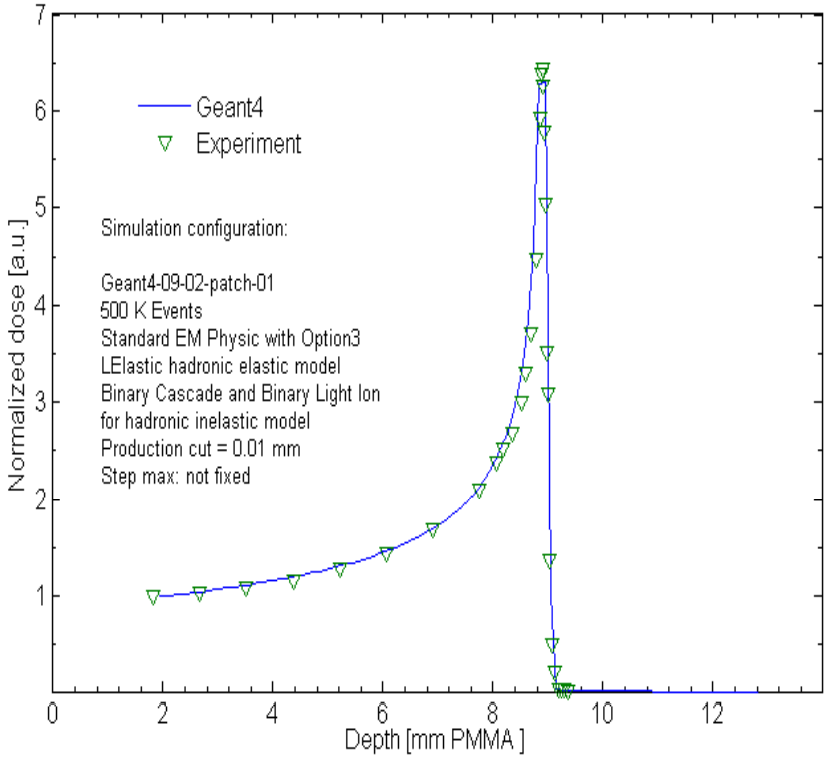
G.A.P.Cirrone, G.Cuttone, F.Di Rosa, Z.Quiwei, F.Romano

Depth dose distributions with the new version of the hadrontherapy example

Collection volume case	Slices of 200 μm in thickness
Production cut	≤ of the half of slice dimension (≤ 100 μm) But best agreement with 10 μm
Step max	No need to set the step max if production cut is ≤ 100 μm
Electromagnetic models	G4EmStandardOption3 (also Low-energy Livermore but too time consuming)
Hadronic models	Binary Cascade (protons and neutrons) + BinaryLigthIon or QMD (for ion-ion interaction)
Package	QGSP_BIC_EMY - G4EmStandardPhysicOption3 must is forced

Depth dose in water for proton and carbon beams for 62 MeV case



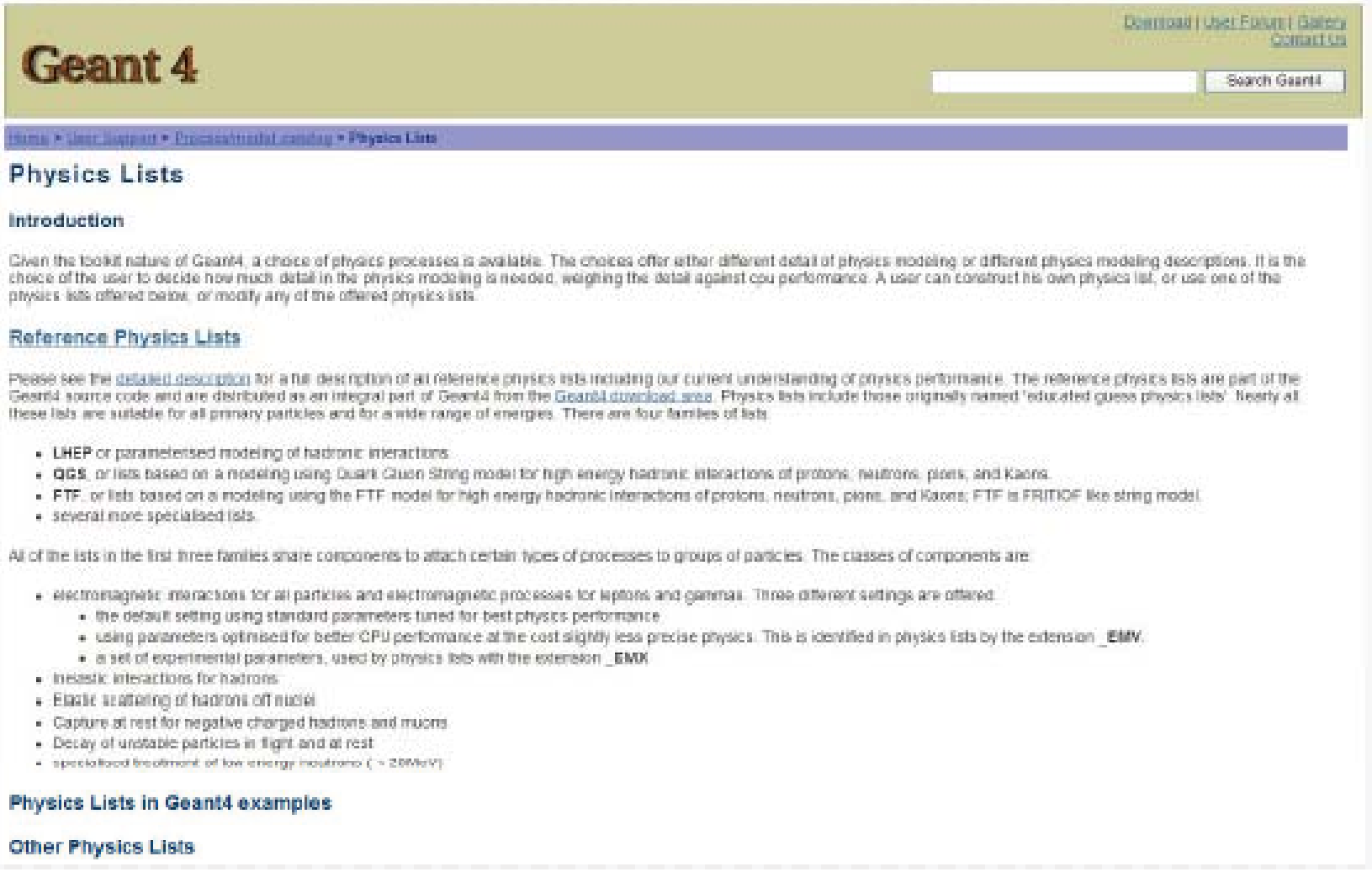


Comments on user support

How to start Geant4 simulation?

- Geant4 provides more than 70 examples
  - Basic functionality - *novice*
  - Addressing specific use-case - *extended*
    - Hadr00, Hadr01 for hadronic physics configuration
  - Produced from concrete user applications – *advanced*
- User HyperNews Forum – the best place for direct discussions
  - User-developer
  - User-user
- Bug-report and tracking system – for real bugs (not a place for requirements)
- Technical Forum – group of users may report to Geant4 and submit new requirements

Reference Physics Lists – ready to use



Geant 4

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Physics Lists

Introduction

Given the toolkit nature of Geant4, a choice of physics processes is available. The choices offer either different detail of physics modeling or different physics modeling descriptions. It is the choice of the user to decide how much detail in the physics modeling is needed, weighing the detail against cpu performance. A user can construct his own physics list, or use one of the physics lists offered below, or modify any of the offered physics lists.

Reference Physics Lists

Please see the detailed description for a full description of all reference physics lists including our current understanding of physics performance. The reference physics lists are part of the Geant4 source code and are distributed as an integral part of Geant4 from the Geant4 download area. Physics lists include those originally named 'educated guess physics lists'. Nearly all these lists are suitable for all primary particles and for a wide range of energies. There are four families of lists:

- **LHEP** or parameterised modeling of hadronic interactions
- **QGS**, or lists based on a modeling using Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions, and Kaons.
- **FTF**, or lists based on a modeling using the FTF model for high energy hadronic interactions of protons, neutrons, pions, and Kaons; FTF is FRITIOF like string model.
- several more specialised lists.

All of the lists in the first three families share components to attach certain types of processes to groups of particles. The classes of components are:

- electromagnetic interactions for all particles and electromagnetic processes for leptons and gammas. Three different settings are offered:
  - the default setting using standard parameters tuned for best physics performance
  - using parameters optimised for better CPU performance at the cost slightly less precise physics. This is identified in physics lists by the extension **_EMV**.
  - a set of experimental parameters, used by physics lists with the extension **_EMX**
- Inelastic interactions for hadrons
- Elastic scattering of hadrons off nuclei
- Capture at rest for negative charged hadrons and muons
- Decay of unstable particles in flight and at rest
- specialised treatment of low energy neutrons (< 20MeV)

Physics Lists in Geant4 examples

Other Physics Lists

Documentation on EM physics

- The electromagnetic web pages have been completely reorganized:
  - EM Home page easily accessible from G4 web

    http://geant4.web.cern.ch/geant4/collaboration/EMindex.shtml
  - EM TWiki pages have been created (C.Zacharatou)

    https://twiki.cern.ch/twiki/bin/view/Geant4/ElectromagneticPhysics
  - Pages are maintained by common efforts of both EM groups
    - User contribution welcome

C. Zacharatou

Documentation of the Electromagnetic Physics

CERN Twiki

https://twiki.cern.ch/twiki/bin/view/Geant4/ElectromagneticPhysics

Electromagnetic Physics

- Publications, preprints
- Meetings
- Release notes
- Validation & verification

Low Energy EM WG

- Processes
  - Penelope
  - Livermore
  - Geant4-DNA
- Physics lists
- Space physics
- Workplan
- Mini Working Groups
- External collaborators

Medical Physics

- DICOM
- Physics
- Biasing, CPU, Reverse MC
- Interfaces
- CT/pCT
- Photon/Electron therapy
- Brachytherapy
- Hadron therapy
- Microdosimetry

Thank you for your attention!

