Recent Improvements in Geant4 Electromagnetic Physics Models and Interfaces

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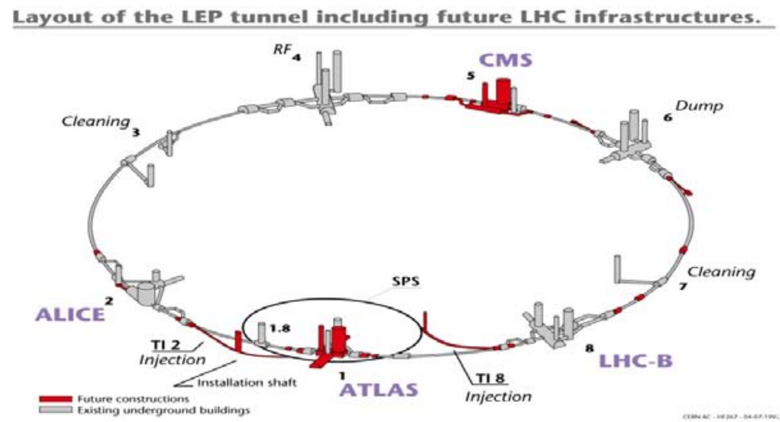
Geant 4

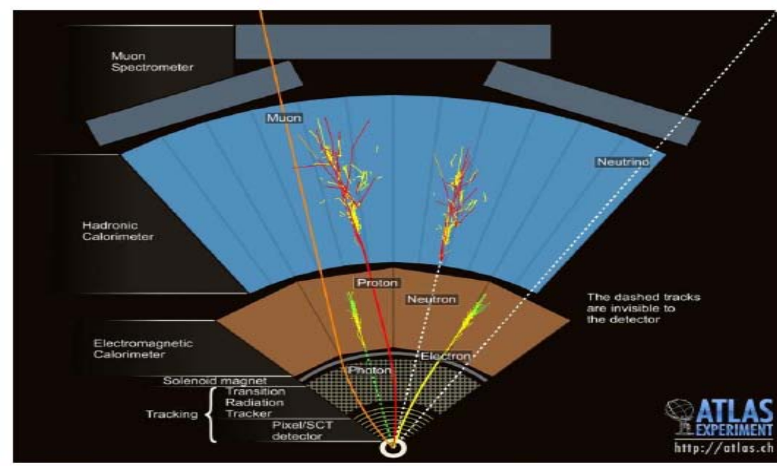
Outline

- Introduction
  - Electromagnetic (EM) sub-packages
- Unification of standard and low-energy sub-packages
  - EM physics design
  - New validation results
- Overview of recent model developments
  - High energy models
  - Multiple scattering
  - Ion ionisation
- Upgrade of user interfaces
  - Physics Lists components
  - Helper classes
- Summary

Geant4 Electromagnetic Physics

- Used for many years for production by large HEP experiments
  - BaBar,
  - ATLAS, CMS, LHCb,..
- Many common requirements for HEP, space, medical and other applications
- EM web page (common for Standard and Low-energy working groups):





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

Geant4 EM packages

- ***Standard***
  - γ, $e^{\pm}$ 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
- ***High-energy***
  - Processes at high energy (E>10GeV)
  - Physics for exotic particles
- ***Polarisation***
  - Simulation of polarized beams
- ***Optical***
  - Optical photon interactions

- Low-energy
  - **Livermore LPDL and EEDL data** γ, e^- from 250 eV up to 1 GeV
  - **Livermore LPDL data based polarized processes**
  - **PENELOPE code rewritten in C++, γ, e^- , e^+ from 250 eV up to 1 GeV**
  - **hadrons and ions up to 1 GeV**
  - **Microdosimetry (Geant4-DNA project) from 7 eV to 10 MeV**
  - **Atomic deexcitation**
- Adjoint
  - **New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation**
- **Utils – general EM interfaces**

Unification of standard and low-energy sub-packages

Why Unification of EM Physics?

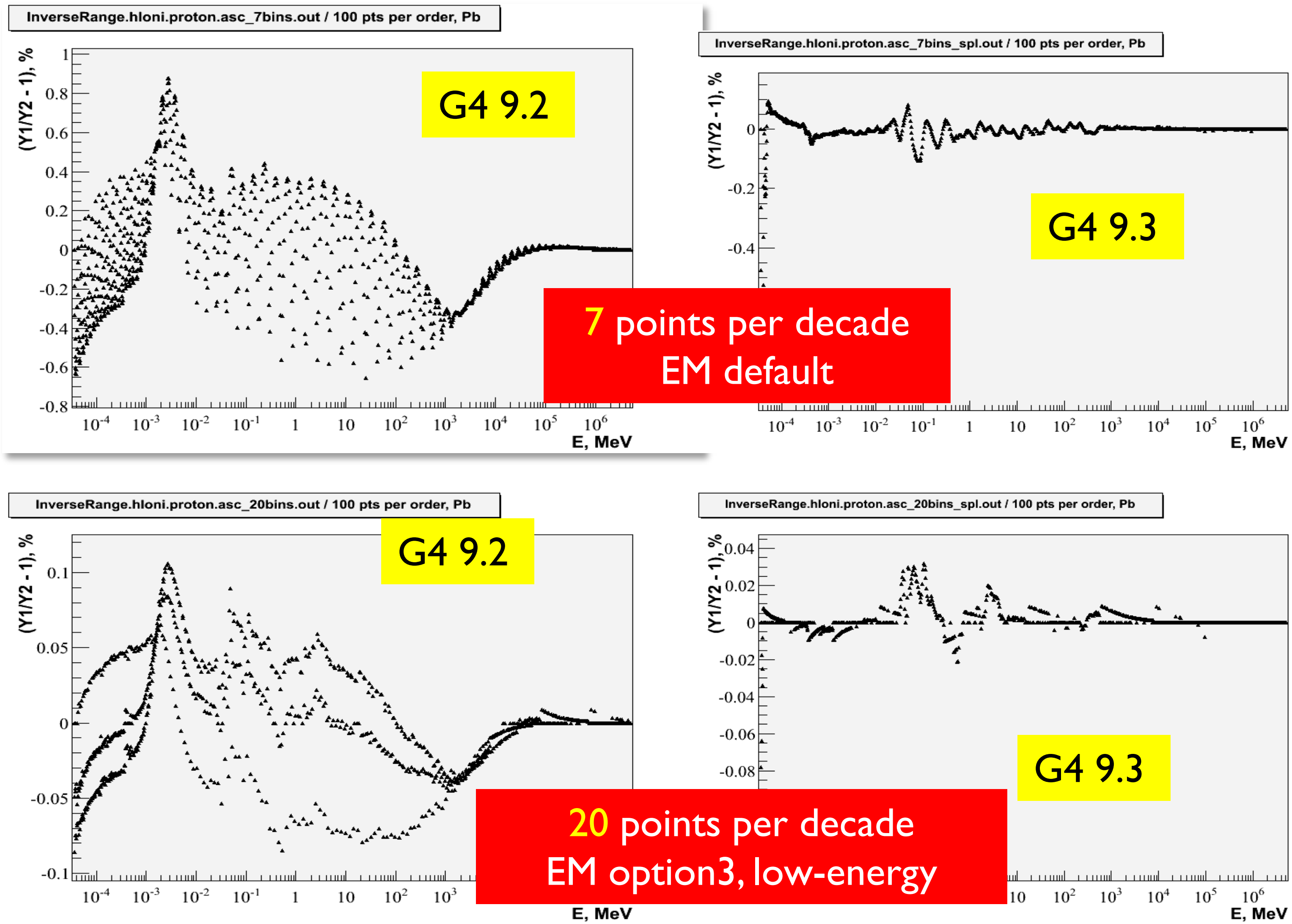
- Standard EM developments was concentrated on HEP and in a great part to LHC experiment
  - LHC experiments are successfully taking and analyzing data now
  - Standard EM package and Physics Lists did not use low-energy models
- For many years EM low-energy sub-package was developed separately
  - Focused on medical and space science requirements
- The were many recommendation extend Geant4 EM physics using the best features of both packages
- Migration to common design for the low-energy package have been done for Geant4 9.3

Main Benefits of the Unification

- Possible to combine low-energy and high-energy models
- Number of long-stand issues of the low-energy package were fixed by migration
- CPU performance of the low-energy package was slightly improved
- User interfaces were improved
- Easy access to cross sections and stopping powers is provided
- New model developments were facilitated
- All EM components can use any new features from Geant4 kernel in more easy way

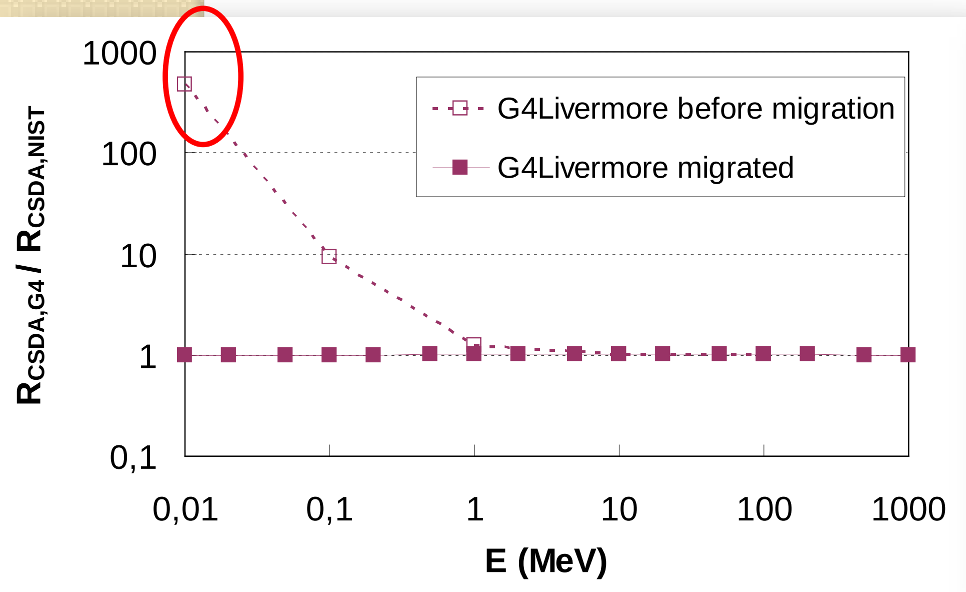
Spline method for interpolation of stopping powers and ranges improving accuracy of proton transport in Lead

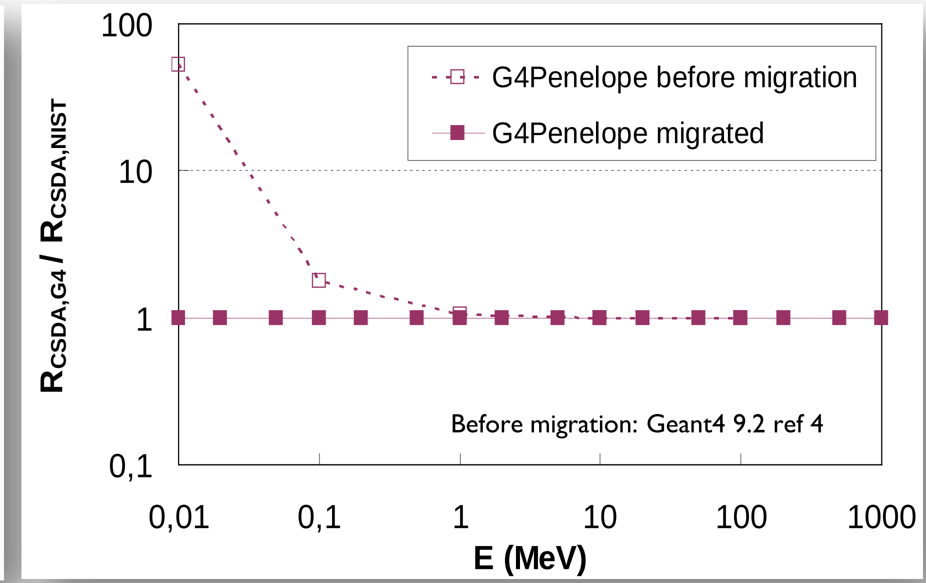
Automatically available to all EM processes



Electron Low-energy Ionisation

- Electron CSDA range vs NIST
- Ionisation in liquid water
- Non-migrated and migrated Livermore and Penelope alternatives
- Wrong computation below 1 MeV is fixed by migration to the new design





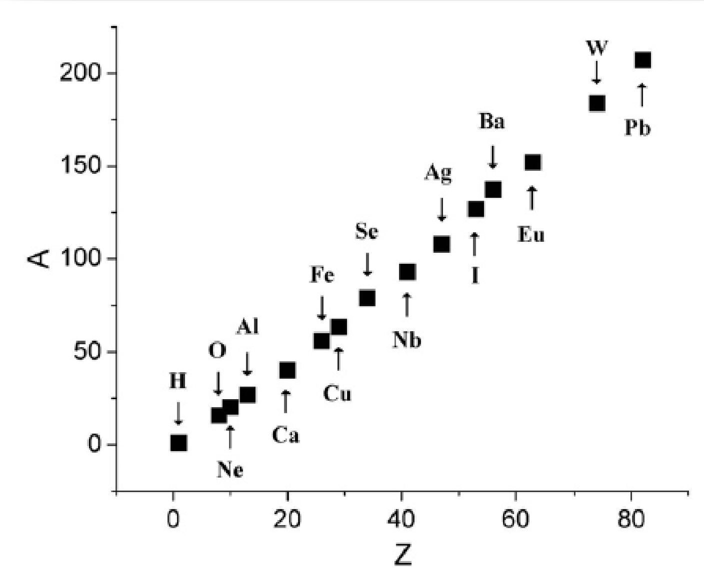
Geant4 EM Physics Design

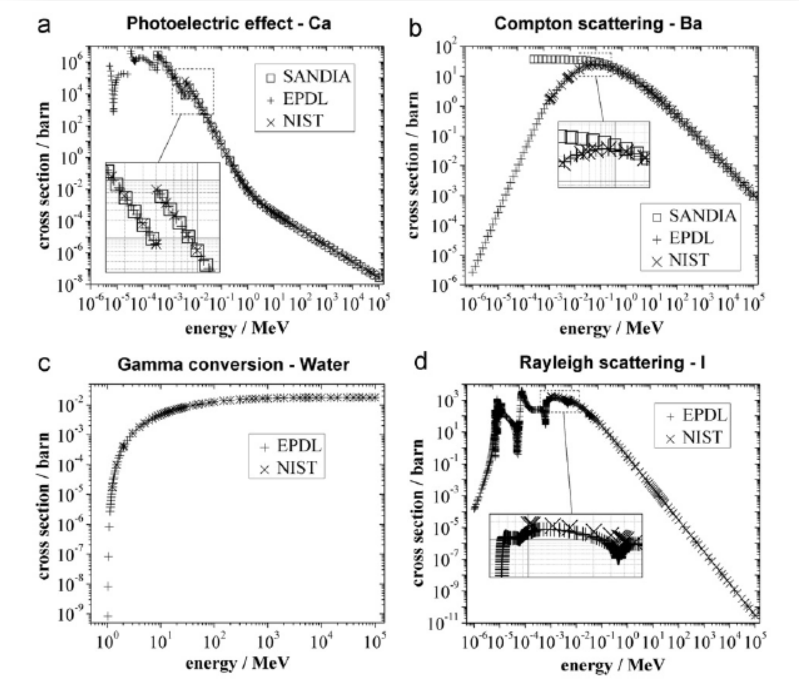
J.Apostolakis et al., Rad. Phys. Chem. 78 (2009) 859

- Geant4 physics is implemented via G4VProcess interface
- EM processes are implemented via 3 base classes, which responsible for all management functions and interaction with Geant4 kernel:
  - G4VEnergyLossProcess
  - G4VEmProcess
  - G4VMultipleScattering
  - All concrete processes inherit from one of these interfaces
- EM process may have one or many models for energy range and geometry region following G4VEmModel interface
  - Only implementation of physics:
    - Cross section and stopping power computation
    - Sampling of final state
- Alternative models allowing flexible construction of optimal physics per use-case
- Consolidation of EM design provides more possibilities for validation

Geant4 EM photon models validation

G.A.P. Cirrone et al., NIMA 618 (2010) 315–322

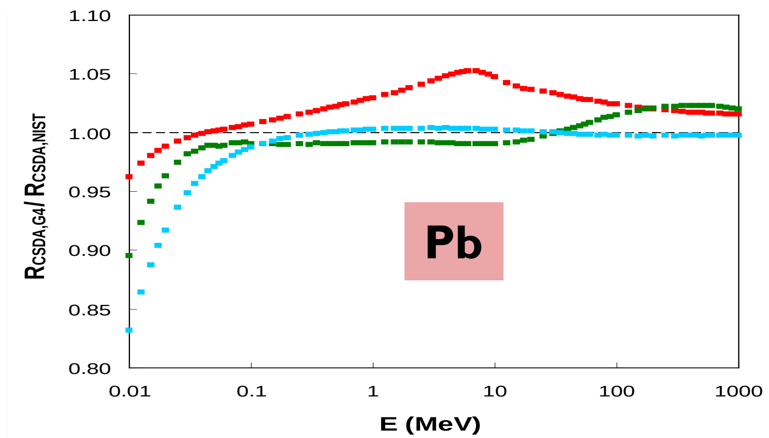


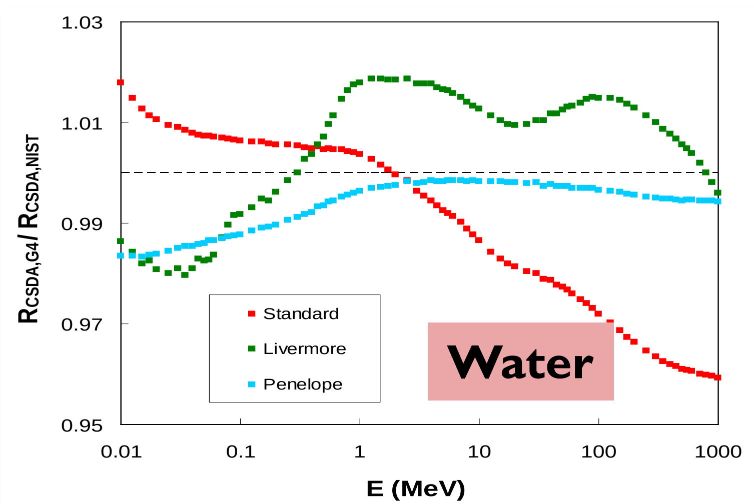


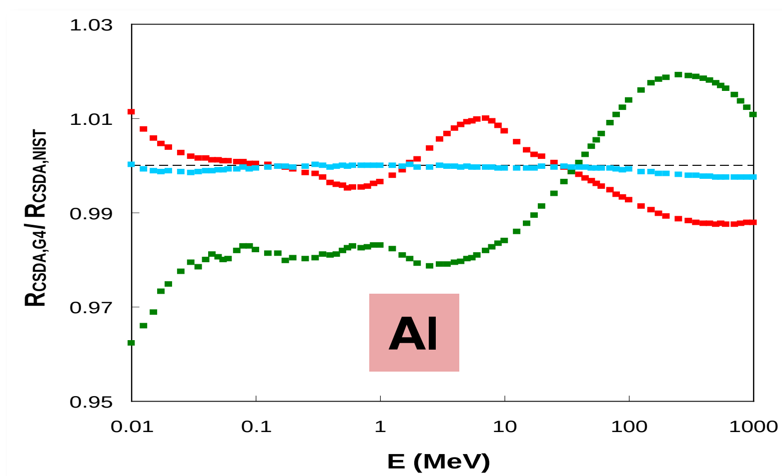
- Systematic validation of cross-sections for electromagnetic photon models of migrated models
  - Standard, Livermore, Penelope models (Geant4 9.3)
  - Photoelectric, Compton, gamma conversion, Rayleigh models
  - EDPL97, SANDIA, NIST data libraries

Electron ranges Geant4 (9.3beta) versus NIST ESTAR data

- Penelope results are more close to NIST
  - the difference <5% in the energy range 0.1 MeV – 1 GeV
  - except for Pb below 0.1 MeV, where EM standard is best







Overview of recent model developments

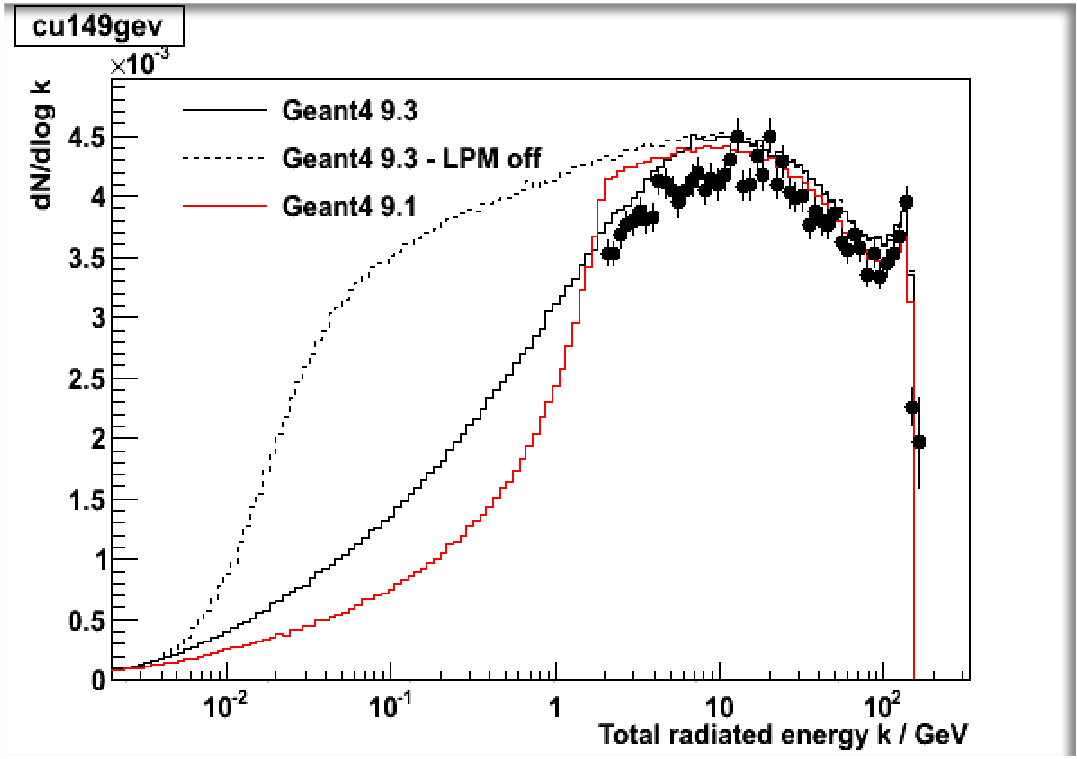
New bremsstrahlung models

V.Ivanchenko et al., PoS (ACAT2008) 108

A.Schaelicke et al., in proceedings of NSS IEEE 2008

- Bethe-Heitler formula with corrections
- Complete screening with Coulomb correction
  - Valid for E > 1 GeV
- **Density & LPM-Effect**
  - **consistent combination a'la Ter-Mikaelian**
- **Hadron bremsstrahlung for LHC experiments**

149 GeV e^- at Cu target (4%X_0)



Data from the CERN experiment: H.D.Hansen et al, PR D 69, 032001 (2004)

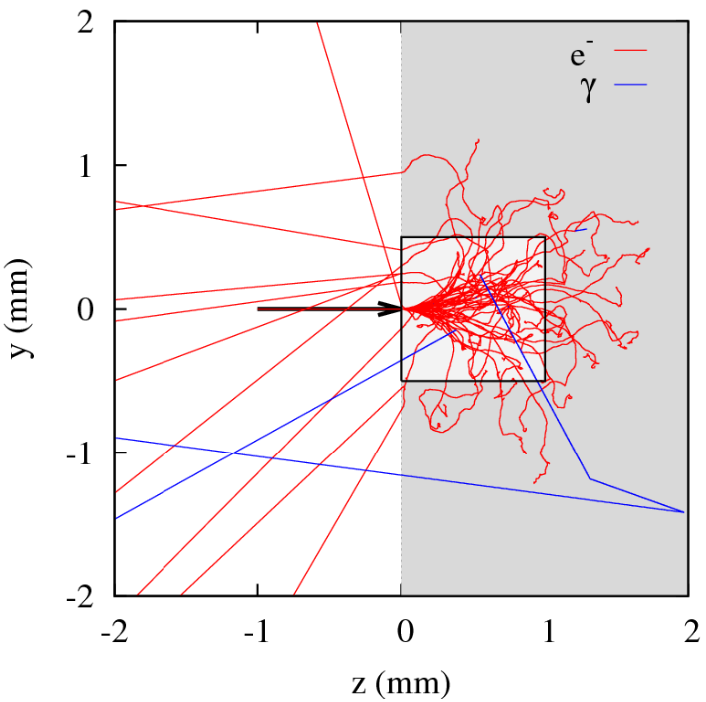
Multiple scattering development

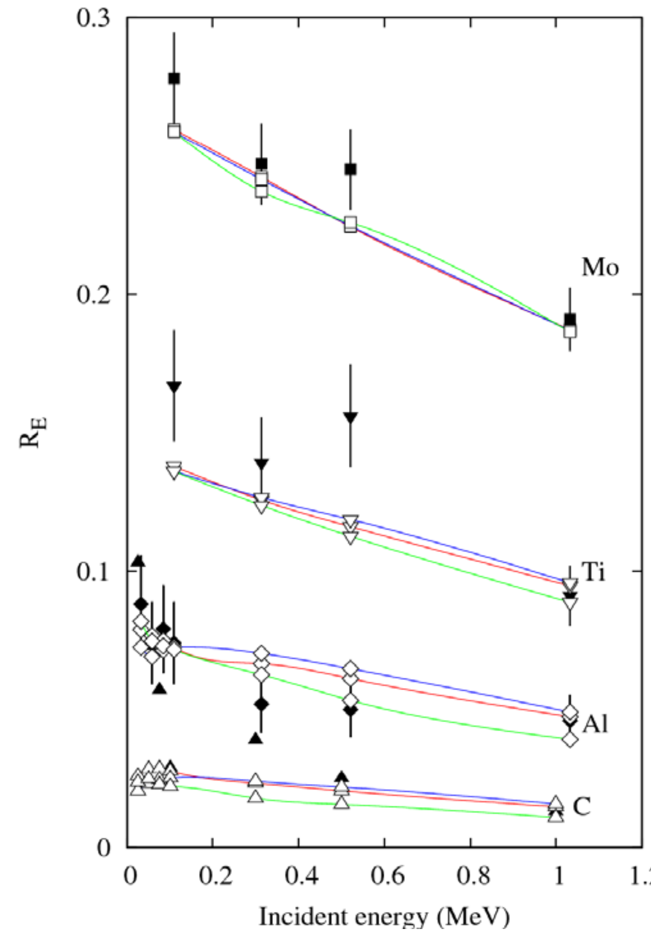
L..Urban, CERN-OPEN-2006-077

- The model of multiple scattering of L.Urban is main default for long time up to now
- Provides accurate simulation for LHC and other HEP applications
- Flexible step limitation algorithm applicable for tracking in field
- Include parameterisations for central part of and tail of scattering angle
  - This providing CPU effective computations
  - Limitation overall accuracy

Backscattering simulation with L.Urban model (Geant4 9.3)

Electron Energy and Charge Albedos
SANDIA Report SAND80-0573 (1984)
Electron energy 0.1 – 1 MeV





Multiple scattering developments

J. Phys: Conf. Ser. 219 (2010) 032045

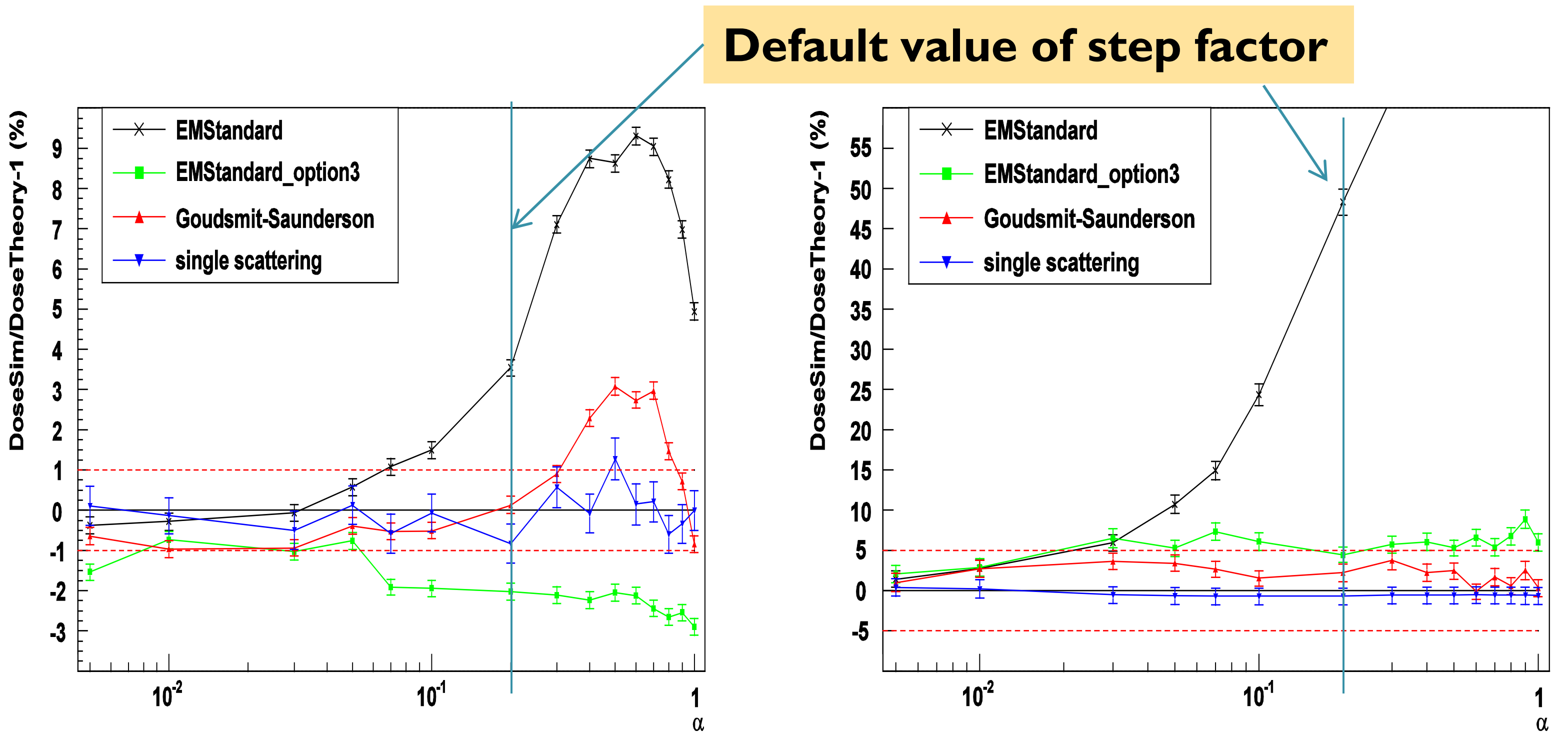
- There are natural limitations of the accuracy of the L.Urban model
  - Parameterisations versus available data on electrons scattering
  - Optimisation of CPU performance for HEP applications
- Geant4 design allowing to have alternative models
  - Specialisation per particle type and use-case
- Recently number of new models become available:
  - Goudsmit-Saunderson – fully theory based ($e^{\pm}$)
  - Single Coulomb scattering model and WentzelVI multiple scattering ($\mu^{\pm}$, hadrons)

Goudsmit-Saunderson Model

O.Kadri et al., NIM B267 (2009) 3624

- Angular distribution from Goudsmit-Saunderson theory
  - Thanks to F.Salvat provided ELSEPA code
- Lewis moments and displacement sampling according EGSnrc prescriptions
  - Thanks to I.Kawrakov
- Step limitation and path length corrections from L.Urban model
- The goal of the model is achieve maximum precision for electron transport
  - It is still significantly slower than the L.Urban model (about factor 2)

Recent Fano Cavity Validation Results (Geant4 9.4beta)

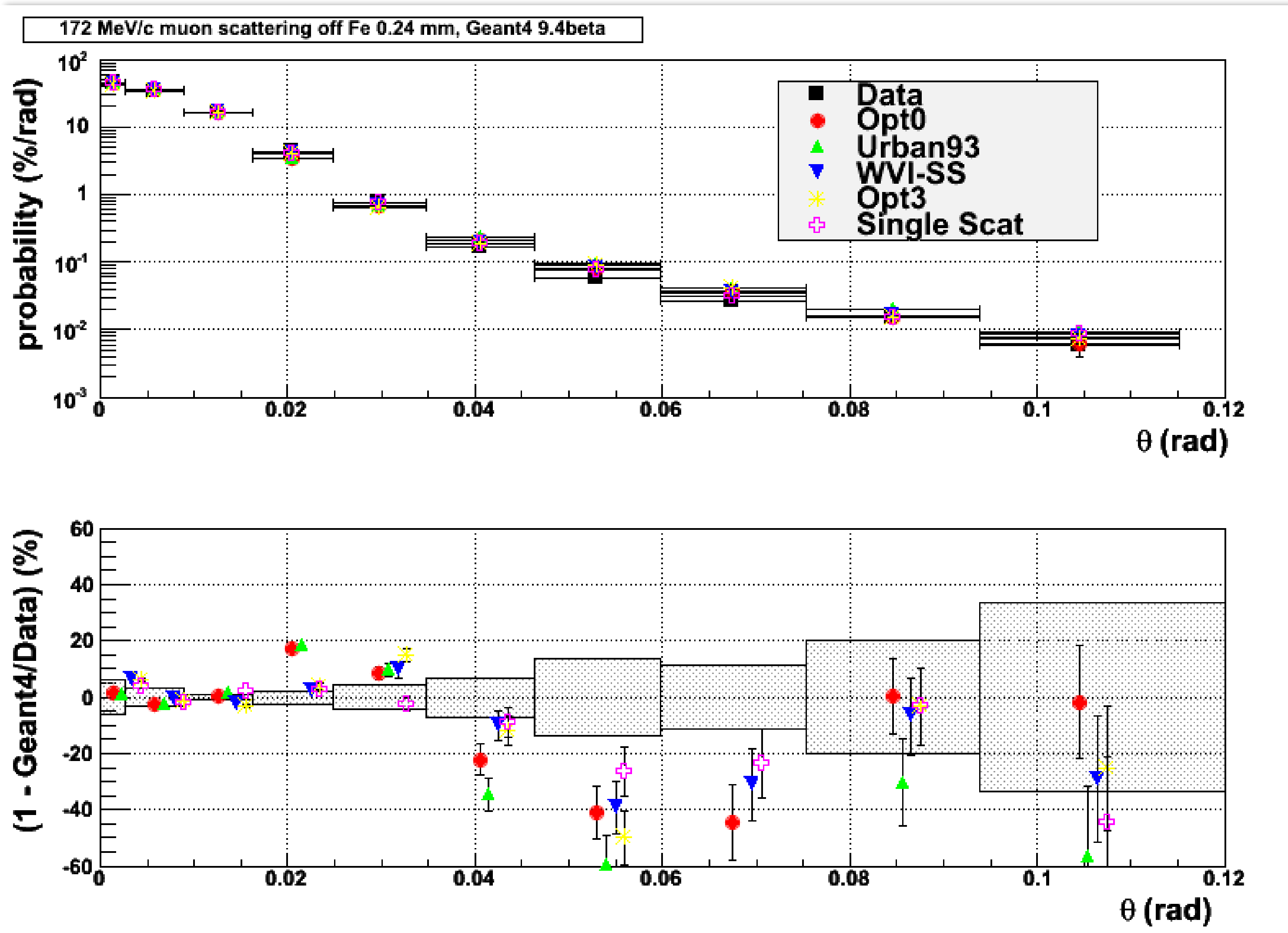


- Dependence of ionisation dose inside the cavity demonstrates precision of MeV electron transport
  - *S.Elles et al., J. Phys: Conf. Ser. 102 (2008) 012009*

WentzelVI model

- Is much more simple but fully theory based
  - Wentzel differential cross section with mass, spin and form-factor corrections
- Dynamically (depending on momentum) the angular limit for single scattering is selected
  - May be applied for transportation in vacuum or low-density media
  - Has original step limitation
- Can be used together with hadron elastic scattering for HEP applications

MuScat test results for 9.4beta

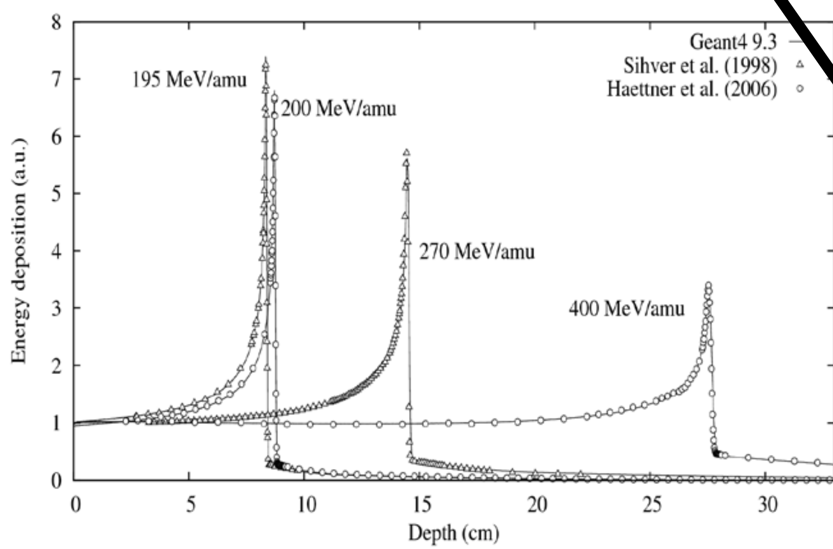


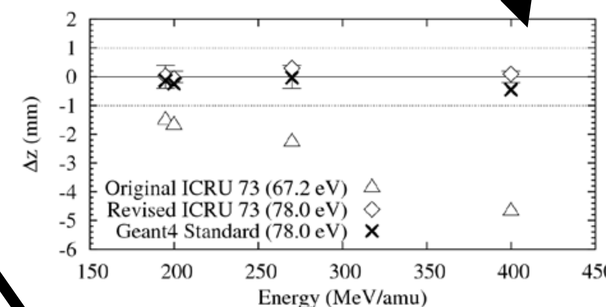
Recent improvements of ion transport in Geant4

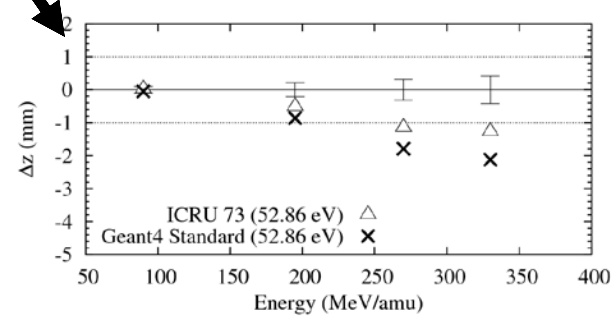
Validation of ICRU 73-based ion model in Geant4

A. Lechner et al., NIM B268 (2010) 2343

- Validation of ^{12}C Bragg peak simulation in water and polyethylene (90-400 MeV/amu) for G4ionIonisation process
- Experimental **Bragg peak position** can be reproduced within **0.2%** of ion range in case of **water**, and within **0.9%** in case of **polyethylene**.



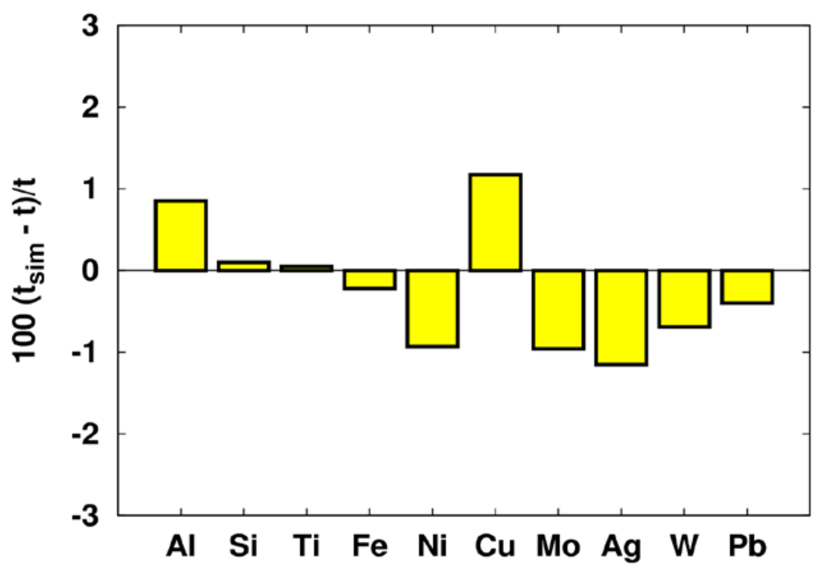


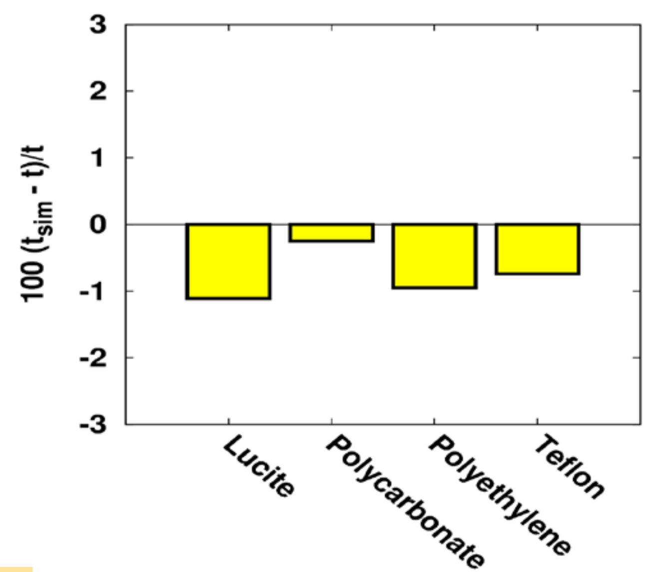


See paper for details. Experimental data by courtesy of D. Schardt and U. Weber.

Validation of ^{12}C CSDA Ranges in Elemental Media and Compounds

- **Results:**
  - Calculation of absorber thickness ($\mathbf{t}_{sim}$) required in the simulation to achieve the <u>same residual CSDA range</u> in water as in the experiment.
  - Figures: <u>Percentage difference</u> of $\mathbf{t}_{sim}$ and $\mathbf{t}$ in elemental (left) and compound (right) targets.





Data H.Bichsel et al., Radiat. Res. 153 (2000) 208

Upgrade of user interfaces

EM Physics List Constructors for HEP

- Main user interface – version for g4 9.3 described below
- Used by Geant4 validation suites
  - Are robust due to intensive tests by Geant4 team
  - well known precision and limitations
- Providing several alternatives focused to different application domain

Constructor	Components	Comments
G4EmStandardPhysics	Default (QGSP_BERT, FTFP_BERT…)	ATLAS, LHCb and other HEP productions, other applications
G4EmStandardPhysics_option1	Fast due to simple step limitation, cuts used by photon processes (QGSP_BERT_EMV, …)	CMS production, good for crystals not good for sampling EM calorimeters
G4EmStandardPhysics_option2	Experimental: WentzelVI model of multiple scattering (QBBC, …)	Used for testing of new models

Combined EM Physics List Constructors

- Are available after migration to common EM design (g4 9.3)
- For today focus more to precision than to maximum simulation speed
- Ion stopping model based on the ICRU'73 data
- Step limitation for multiple scattering using distance to boundary
- Strong step limitation by the ionisation process defined per particle type
- Recommended for hadron/ion therapy, space applications

Constructor	Components	Comments
G4EmStandardPhysics_option3	Urban MSC model (QGSP_BIC_EMY, Shielding)	Proton/ion therapy
G4EmLivermorePhysics	GodsmitSaunderson MSC model Livermore models for γ, e^- below 1 GeV, Standard models above 1 GeV	Livermore low-energy electron and gamma transport
G4EmPenelopePhysics	GodsmitSaunderson MSC model Livermore models for γ, $e^\pm$ below 1 GeV, Standard models above 1 GeV	Penelope low-energy $e^\pm$ and gamma transport

Optional EM Constructors

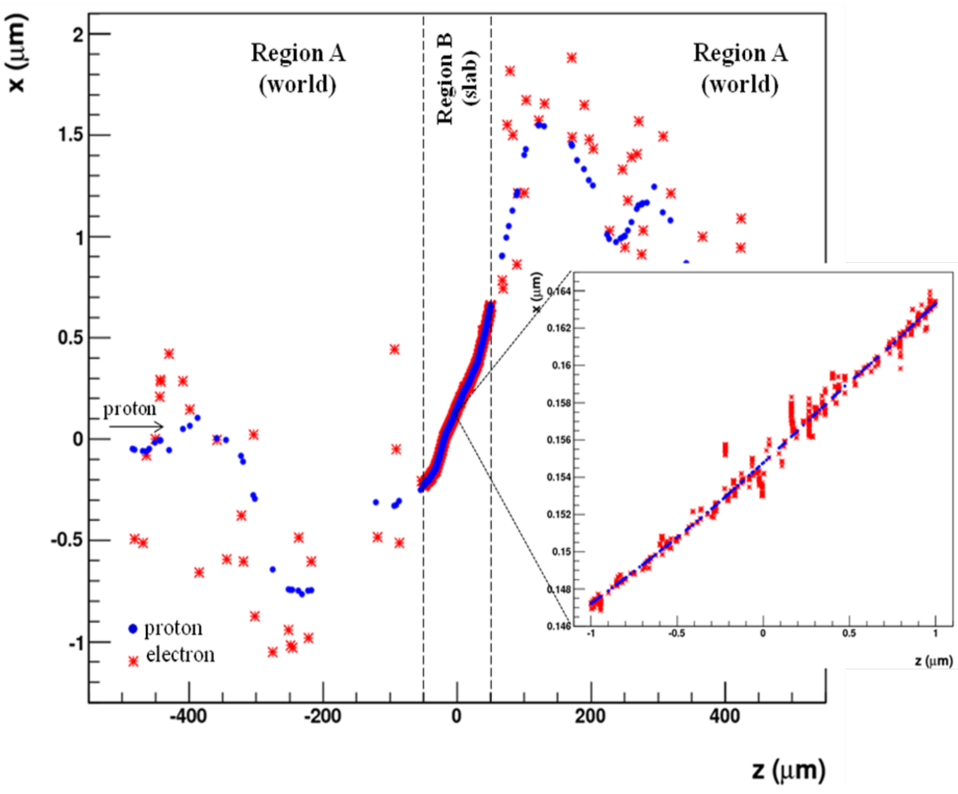
- G4EmLivermorePolarizedPhysics
  - Polarisation in gamma processes
- G4EmExtraPhysics:
  - G4SynchrotronRadiation by default disabled, may be enabled via UI command
  - Gamma and electro nuclear physics by CHIPS
- G4OpticalPhysics
  - includes all optical processes
- G4EmDNAPhysics
  - Include very low-energy processes for liquid water

User Interfaces and Helper Classes

- G4EmCalculator – easy access to cross sections and stopping powers (TestEm0)
- G4EmProcessOptions – c++ interface to EM options alternative to UI commands
- G4EmSaturation – Birks effect
- G4ElectronIonPair – sampling of ionisation clusters in gaseous or silicon detectors
- G4EmConfigurator – add models per energy range and geometry region

DNA Models per G4Region

- Standard EM physics constructor as a base
- G4EmConfigurator is used to add DNA models
- DNA models are enabled only in the small G4Region for energy below 10 MeV
- CPU performance optimisation



Summary

- Unification of Geant4 EM physics was achieved for the version 9.3
- An improved approach for high energy bremsstrahlung has been implemented
- Multiple scattering model specialisation per particle type and use-case is achieved
- New model for ion ionisation based on ICRU73 report is available
  - Accuracy of 1% is achieved for range of carbon ions
- Physics constructors combining standard and low-energy models are available since Geant4 9.3

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