Geant4 electromagnetic physics progress

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Outline

- Electromagnetic (EM) physics sub-libraries in Geant4 10.5
- EM physics developments for Geant4 10.6
- New instruments for customization of EM physics in Geant4 10.6
- Summary

- List of authors:

A. Bagulya, S. Bakr, M. Bandieramonte, D. Bernard, M.-C. Bordage, H. Burkhardt, P. Dondero, V. Grichine, S. Guatelli, I. Hrivnacova, V. N. Ivanchenko, S. Incerti, O. Kadri, D. Konstantinov, I. Kyriakou, M. Maire, A. Mantero, J. Ramos-Mendez, M. Novak, L. Pandola, D. Sakata, D. Sawkey, I. Semeniouk, W. G. Shin, N. H. Tran, L. Urban

Updated EM models in Geant4 10.5

- Models of single and multiple scattering for e+-
  - Improved sampling of displacement for the G4UrbanMscModel
  - Added Mott corrections to G4WentzelVIModel used for simulation of multiple scattering of e+- above 100 MeV
  - G4ScreenedMottCrossSection - use G4MottData shared between threads and implemented more optimal computations
  - G4GoudsmitSoundersonMscModel - fix initialisation and added extra access method to transport cross section
- Gamma models and bremsstrahlung
  - G4ModifiedTsai - use as the default angular generator for bremsstrahlung and pair production, added new method SamplePairDirection, improved performance
    - Since Geant4 9.6 G4DipBustGenerator was the default
  - G4BetheHeitlerModel, G4PairProductionRelModel - improved
    - screening function approximation, Landau-Pomeranchuk-Migdal function approximation, selection of elements in compounds
  - G4SeltzerBergerModel - added optional mechanism of sampling final state using sampling table

New standard EM models in 10.5

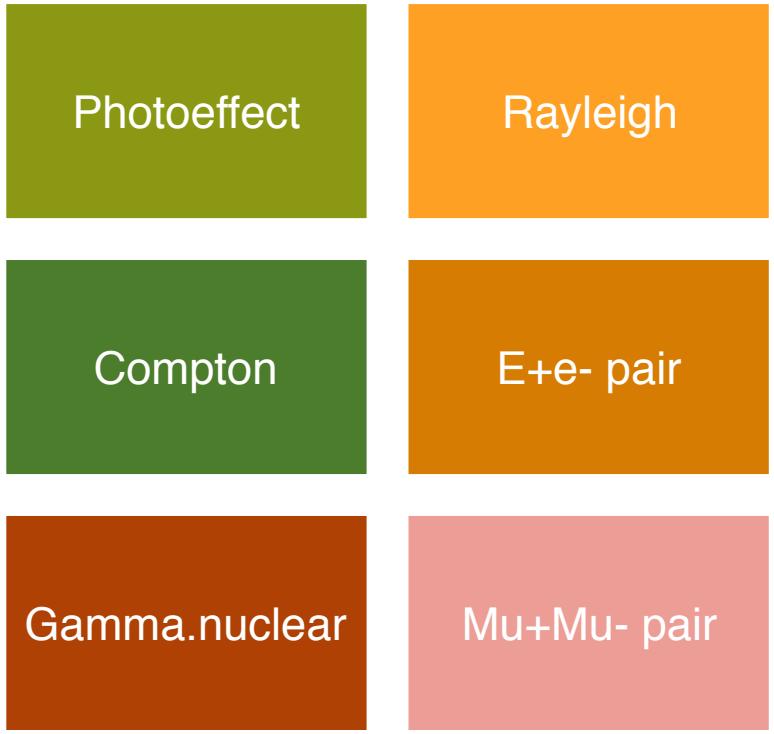
- Electron/positron bremsstrahlung - G4BetheHeitler5DModel
  - Accurate sampling of final state (~100x slower)
  - Nuclear recoil and polarisation are taken into account
- Proton/hadron ionisation
  - Added possibility to use ICRU90 data for stopping powers
  - Geant4/GATE project
- Ion ionisation based on Lindhard-Sorensen theory
  - G4LindhardSorensenModel – parameterisation above 10 MeV
  - G4AtimaEnergyLossModel – implementation of ATIMA code in C++
  - G4AtimaFluctuations – relativistic ion energy loss fluctuations
- 3-gamma annihilation model
  - G4eplusTo2GammaOKVIModel and G4eplusTo3GammaOKVIModel classes implement 2-gamma and 3-gamma positron annihilation in fly and at rest
  - Probability of 3-gamma final state depends on cut for 3d gamma energy

Optimization and speed-up for 10.6

- EM physics software was reviewed and several optimizations were introduced into the toolkit:
  - At any step of each track EM energy loss, ranges, cross sections are recomputed using internal tables
  - Energy scales of tables are logarithmic over particle kinetic energy
    - Main optimization is in computing logarithm only once if the energy is the same
    - This also allows substantial simplification of the interpolation code and reducing the number of lines of the code called at a step practically 10 times
- Benchmark results for CMS geometry without hit creation:
  - ~8% faster for Mac Book Pro (Mac OS 10.13.2) 2.8 GHz i7
  - ~5 % faster for AMD (SLC6 gcc8.2.0) 3.5 GHz

G4GammaGeneralProcess

- G4GammaGeneralProcess



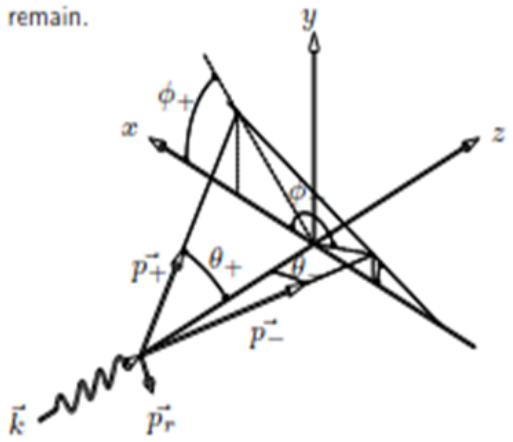
- SteppingManager sees only 1 physics process
  - Only 1 mean free path
  - Plus transportation
- Enabled via UI command
  - In 10.6 will be optional in general (UI command may be used to enable)
  - Will be default for Opt1 EM physics
- Reduced number of instructions
  - Gain in CPU ~5%
  - Extra PhysicsTables shared between threads – a bit more memory
- Final numbers for CPU/memory should be checked by users

Gamma conversion to lepton pair model

by D. Bernard and I. Semeniouk (LLR, CNRS/IN2P3, Ecole Polytechnique)

A 5D phase space

- 3 particle final state, $4 - 1 = 3$ free parameters for each one,
- energy-momentum conservation fixes 4 of them.
- $3 \times 3 - 4 = 5$ variables remain.



- $+, -, r$ = positron, electron, recoil. ϕ azimuthal, θ polar angles.
- $\Omega \equiv (\phi_+,\ \phi_-,\ \theta_+,\ \theta_-,\ x_+ \equiv E_+/E_\gamma)$

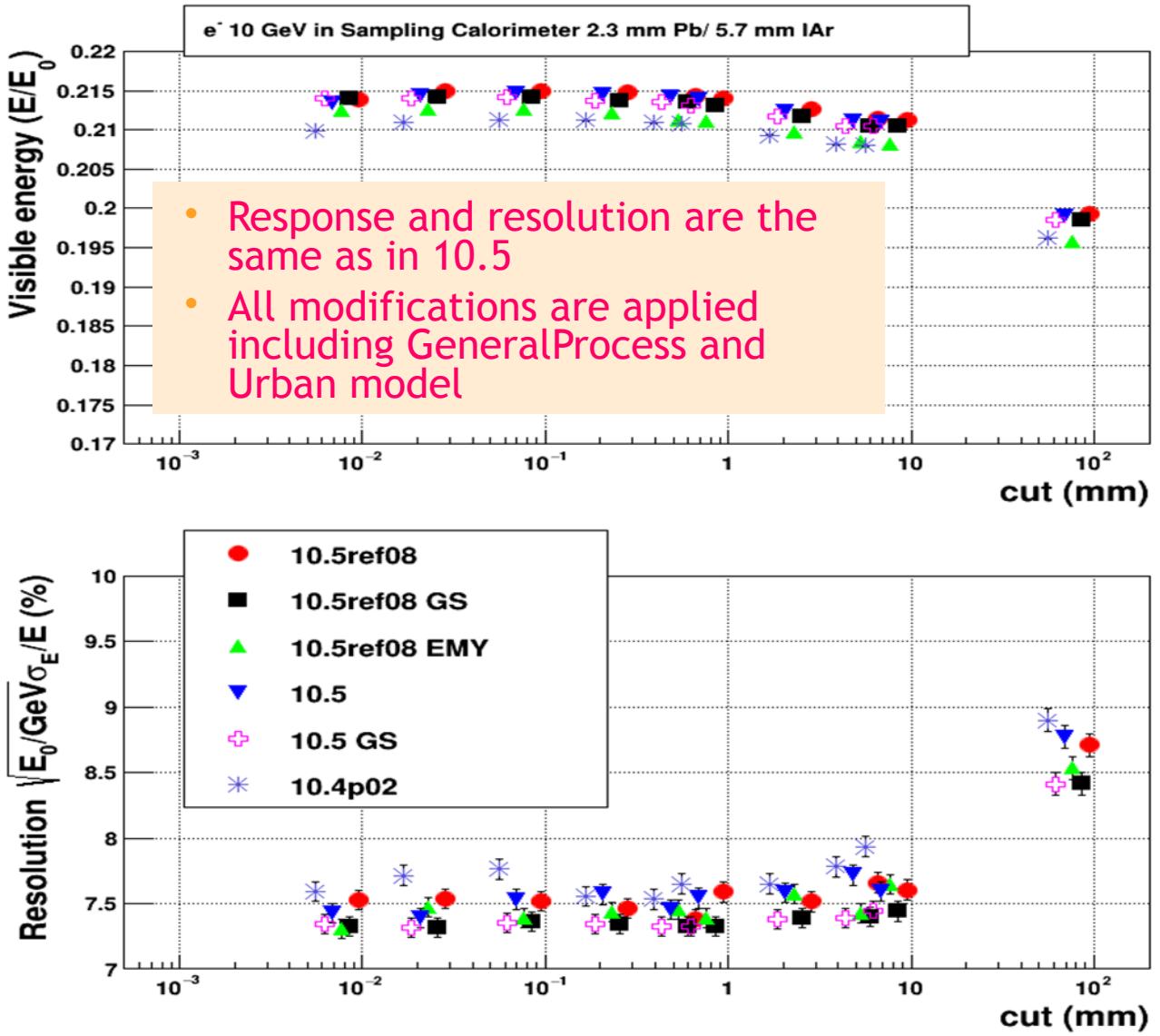
The model was developed for e+e- pair production but is applicable to muon pair production

Linear polarization of incoming gamma, nuclear recoil, and triplet production are taken into account

In 10.6 can be applied for full energy range from threshold and for muon pair production arXiv:1910.12501

- List of publications (+references inside)
  - P. Gros and D. Bernard, Astropart. Phys. 88, 60 (2017)
  - D. Bernard, Nucl. Instrum. Meth. A 899, 85 (2018)
  - V. Ivanchenko et al., EPJ Web of Conferences 214 02046 (2019)

Cut dependence of ATLAS type simplified calorimeter response



- Response and resolution are the same as in 10.5
- All modifications are applied including GeneralProcess and Urban model

New instruments for customization of EM physics in Geant4 10.6

NIEL Calculator For Radiative Background Studies

- Before Geant4 10.6 user had to correctly combine tracking cuts and production thresholds in EM physics definition
  - In that case non-ionizing energy loss (NIEL) is available in Geant4 user actions from the G4Step object
  - This method seems to be much more complicated and less obvious to a user
- As a result of several discussion inside CERN-SFT group and with FLUKA developer it was decided to provide an alternative method
- We introduced G4NIELCalculator helper class in 10.6
  - This class calculate NIEL at a step independently on cuts
  - Example how to use is in TestEm1
  - This class uses G4VEmModel which provides NIEL computation
  - The default model – G4ICRU49NuclearStoppingModel

Configuration of EM physics

- A set of EM physics constructors are provided together with each recent Geant4 version
  - The default (Opt0) EM physics is optimized for use in HEP
  - There are variants Opt1 (EMV) and Opt2 (EMY) with simplified multiple scattering and other options
  - The alternative Opt4 (EMZ) physics is combination of the most accurate EM models
    - It is recommended for R&D and detector performance studies
    - For 10.6 will use 5D gamma conversion model
- On top of any EM physics configuration it is possible to customize EM parameters via UI commands and C++ interface
  - G4EmParameters class may be called
  - EM physics configuration and photo-absorption ionization (PAI) model may be defined for one or more G4Region(s)
    - This feature is already used by ALICE and CMS

How to speed-up simulation of an actual detector?

- In Geant4 10.6 following customization options for EM physics are recommended:
  - Production thresholds (cuts in range) per G4Region
  - Tracking cuts per particle type
  - General process for gamma may be enabled
- Different multiple scattering parameters may be tuned per G4Region (per sub-detector)
  - Range Factor, Geom Factor, Stepping algorithm, Lateral displacement
  - New in 10.6: Safety Factor , Lambda Limit
- User may design EM physics constructor with multiple scattering models separately defined per G4Region or use G4EmConfigurator interface

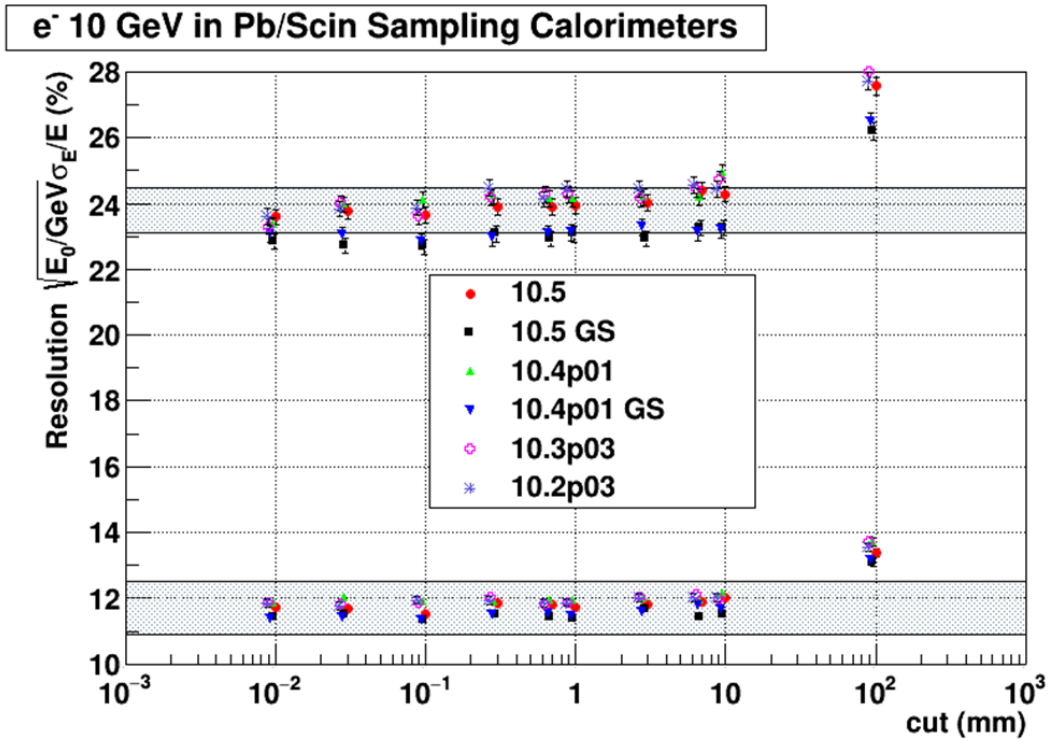
Summary

- Several EM physics models were enhanced
  - Improvements are available in the default and in other EM physics including Opt4 (EMZ) EM physics constructors
    - Calorimeter response may be slightly changed (<1%)
  - NIEL calculator allows making various studies of radiation damage
- With Geant4 10.6 several new features will be provided allowing to gain detector simulation performance
  - Default EM physics become faster
  - General gamma process option may be applied
  - Extended interface to configure EM physics per detector region

Backup

Resolution of Pb/Sc calorimeters

Bernardi E. et al. 1987 Nucl. Instrum. Meth. A 262, 229

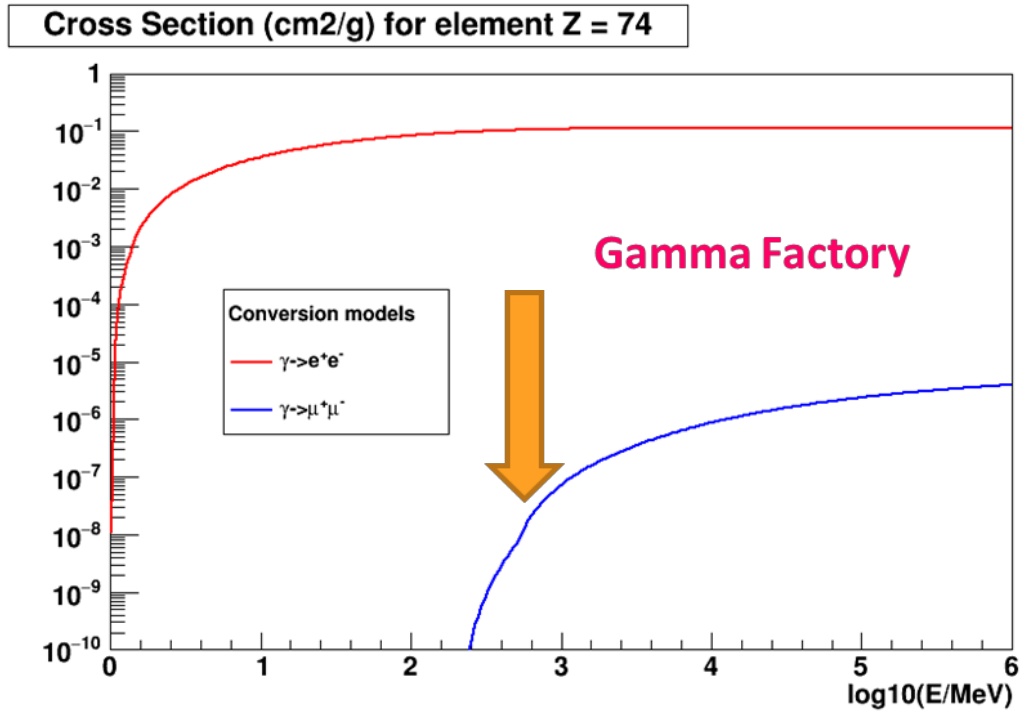


- Resolution for 10.5 is narrower but within data errors
  - Effect is larger for lower sampling fraction (thicker scintillator)
  - Due to G4UrbanMscModel modification of lateral displacement sampling algorithm to provide more accurate backscattering

Muon part production cross section near the threshold

- The Gamma Factory project is under development to design a muon source for the muon collider
- In order to extend current model down to the threshold an update of the G4GammaConversionToMuonPair was done
  - Approximation used in Geant4 Bethe-Heiltler 5D model for e+e- pair production is applied to the muon pair production

- Accuracy of cross section for E >10 GeV is about 3 %
  - Accuracy is lower near the threshold



Low Energy EM & DNA Physics in 10.5

- Added new JAEA model of gamma elastic scattering (M.Omer and R.Hajima)
- Geant4-DNA
  - Published Special Report in Medical Physics journal describing all physics models and applications for track structure simulations (covers 2008-2018 period)
    - Med. Phys. 45, e722-e739 (2018)
  - New constructors
    - Physics (G4EMDNAPhysics_option8) – electron elastic scattering based on CPA100 approach
    - Chemistry (G4EmDNAChemistry_option1) – alternative set of values (diffusion constants, reaction rates) from RITRACKS / NASA software
  - New examples
    - **splitting**: illustrating computing speedup in ionisation
    - Updated **svalue** example for the calculation of S values in nuclear medicine

Low Energy EM & DNA Physics in 10.6

- Extension Geant-val GRID validations with set of 18 EM tests
  - https://geant-val.cern.ch/
- Built-in bremsstrahlung splitting is now available
- Low energy models:
  - New models for electrons in DNA material
  - Physics - relativistic extension of DNA Option 4 up to 1 MeV is underway
- Making chemistry more accurate and faster for 10.6:
  - Influence of physics models and chemistry parameters on the simulation of radiochemical yields (Wook Geun Shin et al.)
  - Porting of TOPASnBio IRT & alternative versions to Geant4 is on-going in collaboration with TOPAS developers
  - Evaluation of DNA damage in a fractal nucleus geometry
  - New examples:
    - Evaluation of proximity functions "microprox"
    - Various DNA geometries "dnadamage1"
  - New constructor G4EmDNAChemistry_option2