Recent Progress of Geant4 Electromagnetic Physics for Simulation of Calorimeters

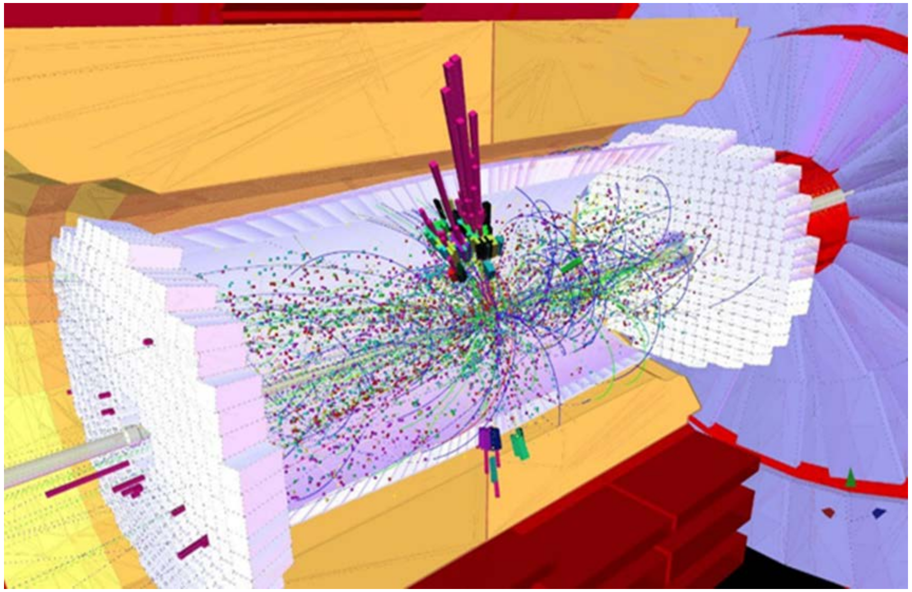
V. Ivanchenko[1,2], S.Incerti[3,4] and M.Novak[1] for Geant4 EM working groups

[1]CERN, Geneva, Switzerland
[2]Tomsk State University, Tomsk, Russia
[3]Univ. Bordeaux, CENBG, Gradignan, France
[4]CNRS, IN2P3, CENBG, Gradignan, France

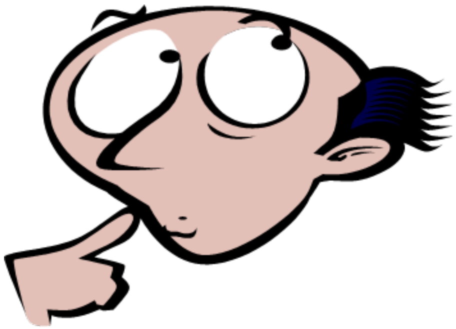
Calorimetry for the High Energy Frontier
Lyon, France
2-6 October 2017

Outline

- Geant4 electromagnetic (EM) physics
  - History
  - EM sub-packages and infrastructure
  - Calorimetery simulation
- Highlights on improvements for Geant4 10.4
  - PAI and Urban models
  - GS model update
- Configuration of EM physics
- Summary and plans



Geant4 EM libraries



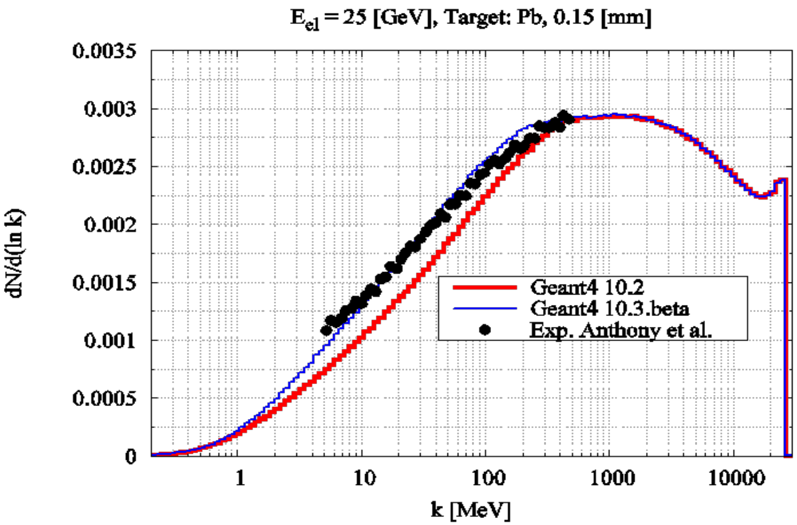
- Low-energy
  - Livermore library γ, e- from 10 eV up to 1 GeV
  - Livermore library based polarized processes
  - PENELOPE code rewrite , γ, e- , e+ from 100 eV up to 1 GeV (2008 version)
  - hadrons and ions up to 1 GeV
  - atomic de-excitation (fluorescence + Auger)
- Geant4-DNA
  - microdosimetry models for radiobiology (Geant4-DNA project) from 0.025 eV to 100 MeV
- Adjoint
  - Reverse Monte Carlo processes and models to track from the volume of interest back to source of radiation
- Utils
  - general EM interfaces
- 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
- X-rays
  - X-ray and optical photon production processes
- High-energy
  - processes at high energy (E>10GeV)
  - physics for exotic particles
- Polarisation
  - simulation of circular polarized beam transport
- Optical
  - optical photon interactions

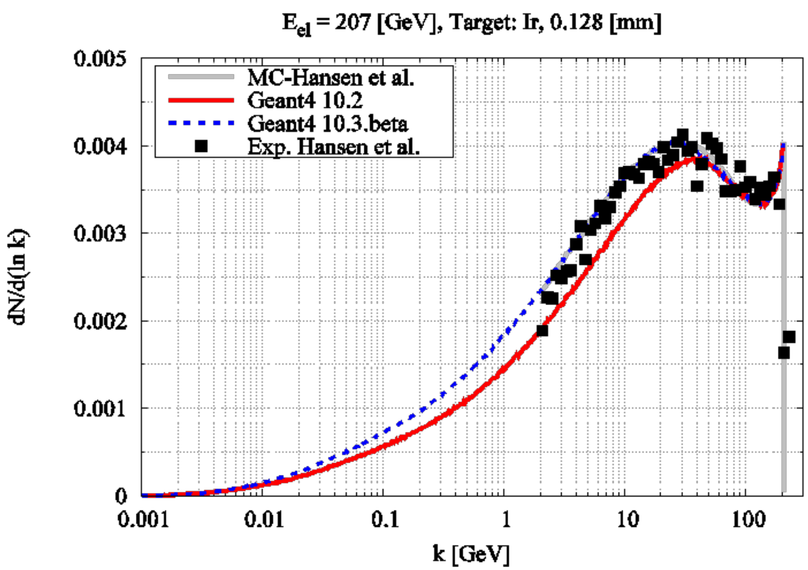
EM physics consolidation

- For Geant4 9.6 the consolidation of all EM sub-libraries was completed
  - Low- and high- energy models may work together in the same run
  - Components from different sub-libraries interchangeable, so for HEP applications low-energy models can be used, for example,
    - Models for sampling of angular distributions
    - Atomic de-excitation module
      - Is also used by radioactive decay module
- Migration to multi-treading for 10.X was going smoothly for EM physics because of the common approach
  - Geant4 EM is fully multi-threaded
    - All EM tables and material properties are defined in the master thread and in run time are shared between threads
  - Geant4 10.3 is the recent public release
  - Geant4 10.4 will be available December 2017
    - Some expected results will be shown below

EM physics developments included in the recent public version Geant4 10.3

- Upper energy limit of EM physics is extended from 10 TeV to 100 TeV
  - Essential for FCC R&D
- Implementation of LPM suppression in e+- bremsstrahlung is revised
  - Better agreement with CERN and SLAC experimental data:
    - Anthony P L et al. 1997 Phys. Rev. D **56** 1373
    - Hansen H D et al. 2004 Phys. Rev. D **69** 032001
    - Affect CMS shower shape on level ~10^{-3}
- Goudsmit-Saunderson multiple-scattering model is fully revised
  - Angular distribution is improved, as well as computing performance
- New direct e+e- pair production process by e+-
- Added optional variants of EM form-factor parameterisation



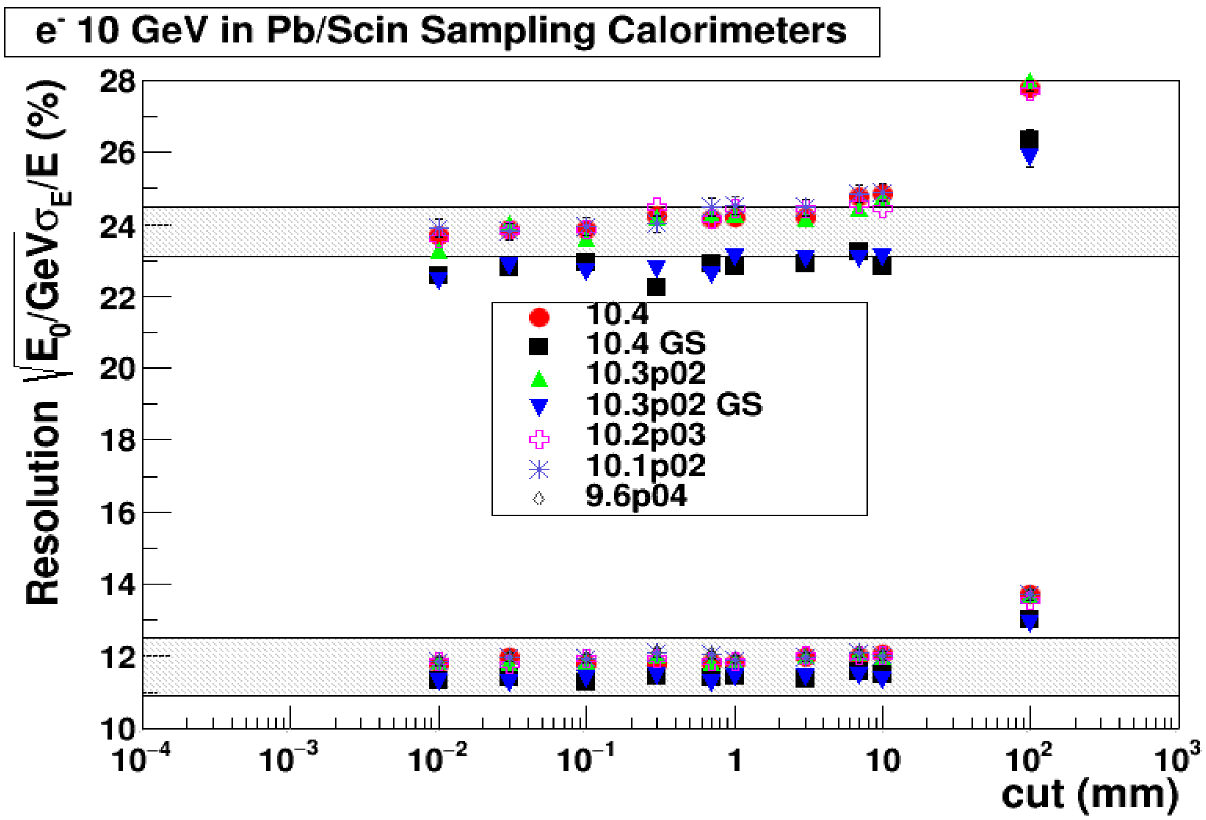


EM physics developments for 10.4

- New interfaces are added allowing user defined density effect parameterisation
  - G4Material::GetIonisation()>SetDensityEffectParameters(
    G4double cd, G4double md, G4double ad, G4double x0, G4double x1, G4double x2);
  - G4Material::GetIonisation()->SetDensityEffectParameters(
    const G4Material* base_mat);
- Models of fluctuation of energy loss updated
  - Urban model of fluctuations and the PAI model
  - Fixed low-energy hadron transport
  - Nuclear stopping fixed
- Models of single and multiple scattering for e+- below 100 MeV
  - Added Mott corrections to GS model and to single scattering
    - Will be discussed below
  - Updated relativistic scattering model
- Extended service for configuration of EM physics

Resolution of Pb/Sc calorimeters

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



- A classical benchmark (ZEUS test-beam) for two sampling calorimeters with different sampling fractions
  - The same simulation conditions for two setups
- Geant4 results are stable between different releases
  - Goudsmit-Saunderson (GS) model of multiple scattering is slightly less accurate compared with the default Urban model

Simulation of Calorimeters

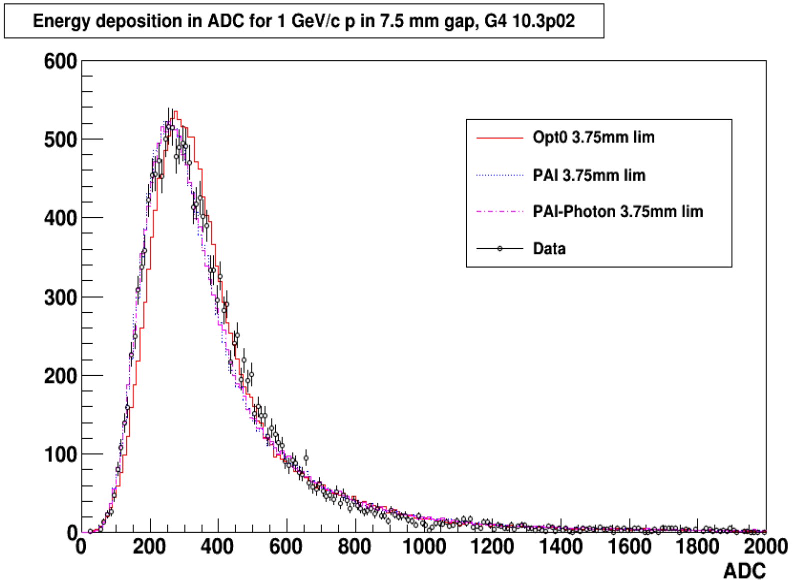
- Geant4 9.6 and 10.X provide stable and accurate simulation of EM shower shape for traditional calorimeters
  - See CMS and ATLAS reports at LPCC workshop 2017: https://indico.cern.ch/event/614935/
    - My personal conclusions:
      - If amount of material in front of a calorimeter is limited (CMS Ecal barrel) Geant4 reproduce EM shower well for run-1 and run-2
      - Less agreement for CMS EE and ATLAS calorimeters
  - The most important Geant4 processes are stable:
    - Ionisation, energy loss fluctuations, bremsstrahlung, multiple scattering
- Many use cases when tiny steps of charged particles are used
  - Fine grain structure of sensitive layers
  - Thin Silicon detectors or thin gas gaps
- Designs of new calorimeters bring new requirements for simulation
  - Simulation results should be stable versus cut or step limit
  - Accurately predict peak, width and tail of a signal
  - Accurately predict particle flux in thin layer after heavy absorber
  - Accurately predict backscattering from heavy absorber
- Critical improvements will be available with Geant4 10.4
  - GS model with error free stepping
  - Improved Urban model of energy loss fluctuations

ON IMPROVEMENTS PREPARED FOR GEANT4 10.4

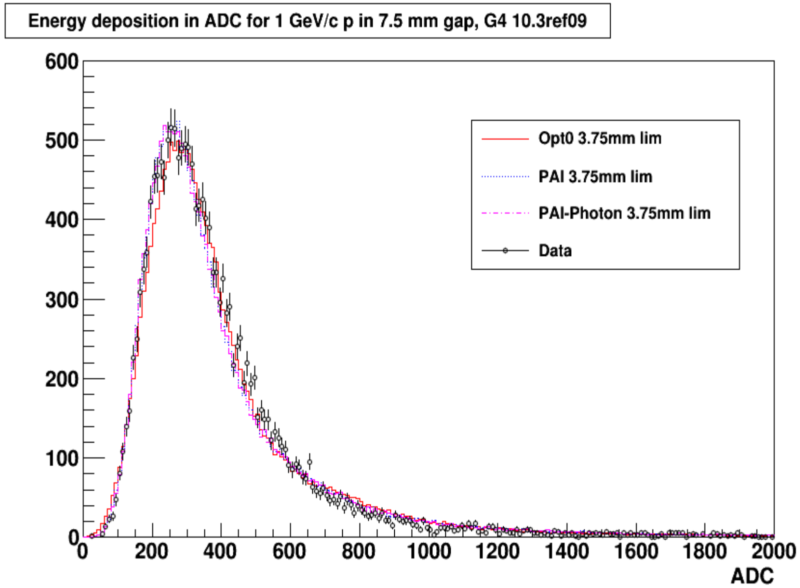
ALICE TPC benchmark

Nucl. Instr. Meth. A, **565**, 551-560 (2006)
Int. J. Mod. Phys. E, **16,** 2457-2462 (2007)

10.3p02



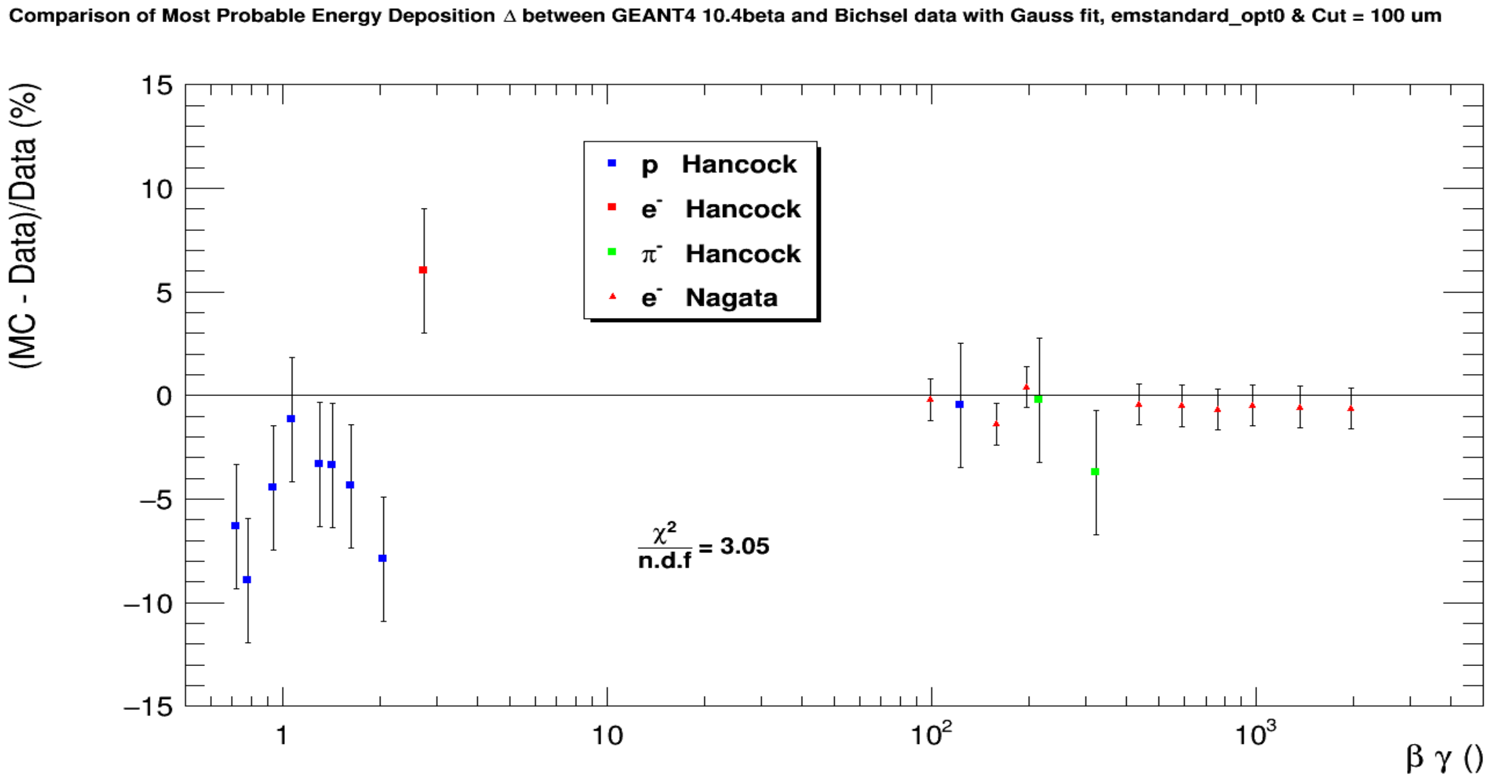
10.4



- Two Geant4 models of fluctuations of energy loss
  - The Urban model is default, it is based on parameterizations
    - Provide the best CPU performance
    - Needs optimal step limit - 2 steps in sensitive volume
  - PAI model uses photoelectric cross sections
    - Stable versus cuts and step limits
- Proton 1 GeV/c beam, peak position is normalized to 3 GeV/c data
  - Light TPC gas Ne + CO_2
  - Urban model slightly improved for 10.4

Energy depositions in Si detectors

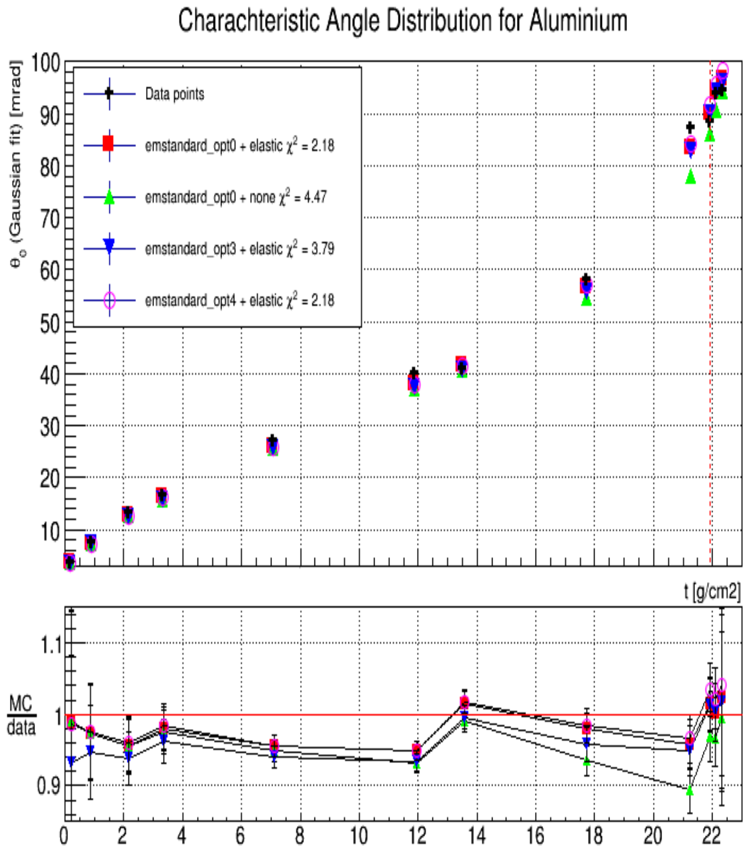
H. Bichsel data collection: Rev. Mod. Phys. **60**, 663, 1988



- Geant4 results for 0.3 and 1.4 mm thick Silicon detectors
  - Both Urban and PAI models reproduce well data for relativistic beams
  - Less accurate for e- and proton data for $\beta\gamma \sim 1$
    - There are questions to experiments directly
- **It would be very interesting to have similar data for modern Si sensors**

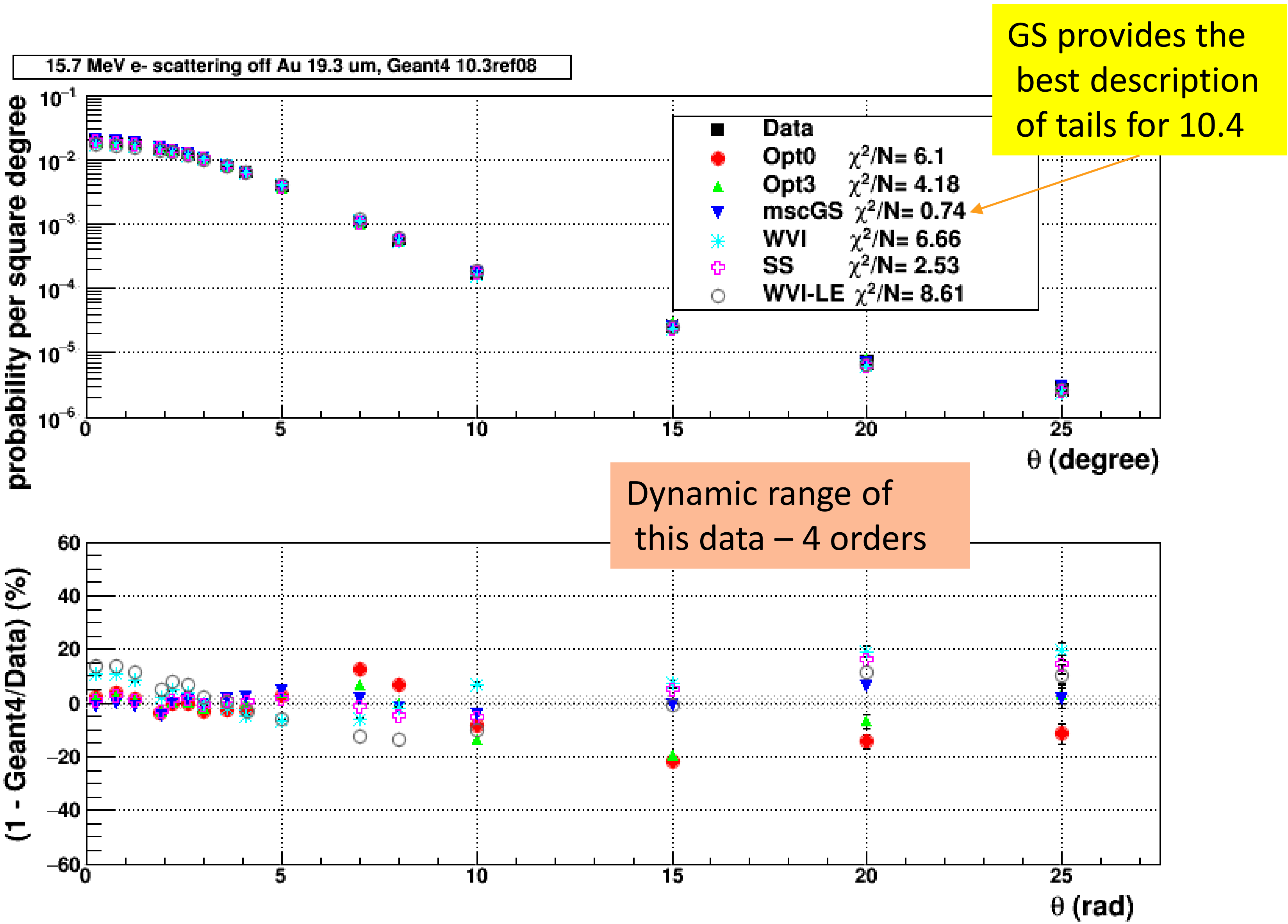
Geant4 Multiple and Single Scattering

- Combined multiple and single scattering Wentzel-VI models
  - Single scattering for large angles
  - Multiple scattering for small angles
  - For muons and hadrons
  - For e+- above 100 MeV
- Urban multiple scattering
  - By default for e+- below 100 MeV by default
  - For ions
- New GS model
  - Used for e+- below 100 MeV
  - Used single scattering regime in vicinity of geometry boundary
  - Mott corrections since 10.4



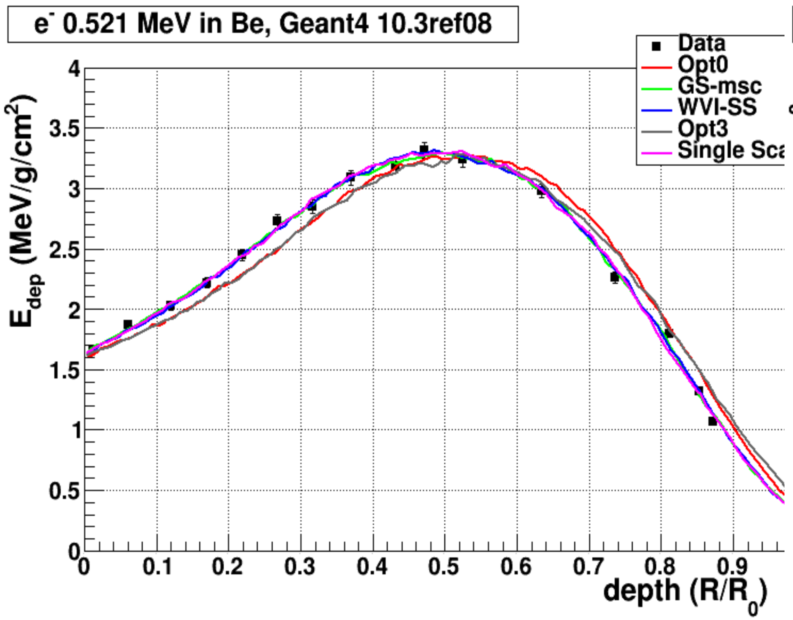
Proton multiple scattering benchmark
Nucl. Instr. Meth. B 74, 467 (1992)

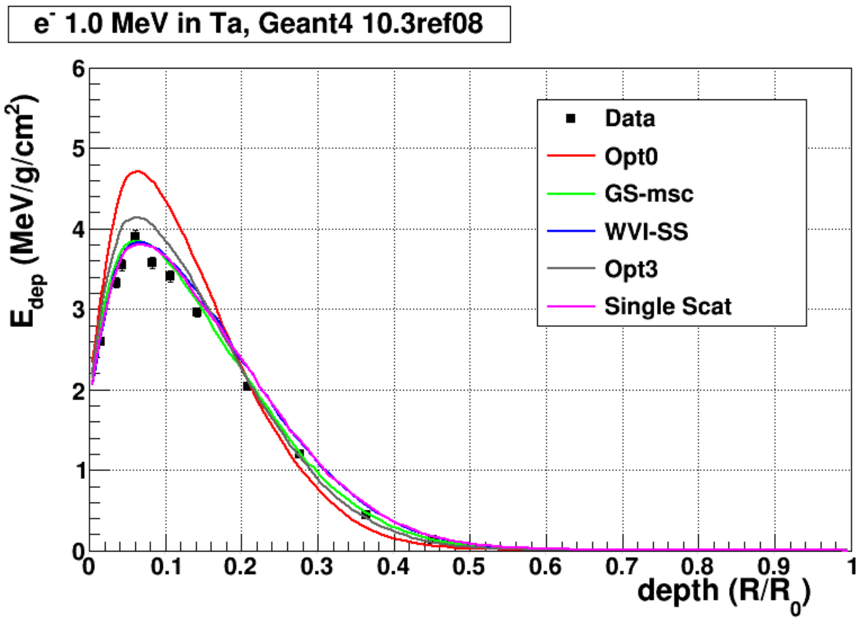
Hanson data for electron scattering off Gold target (*Phys. Rev.* **84**, 634-637, 1951)



Energy deposition in semi-infinite media

SANDIA REPORT SAND79-0414.UC-34a



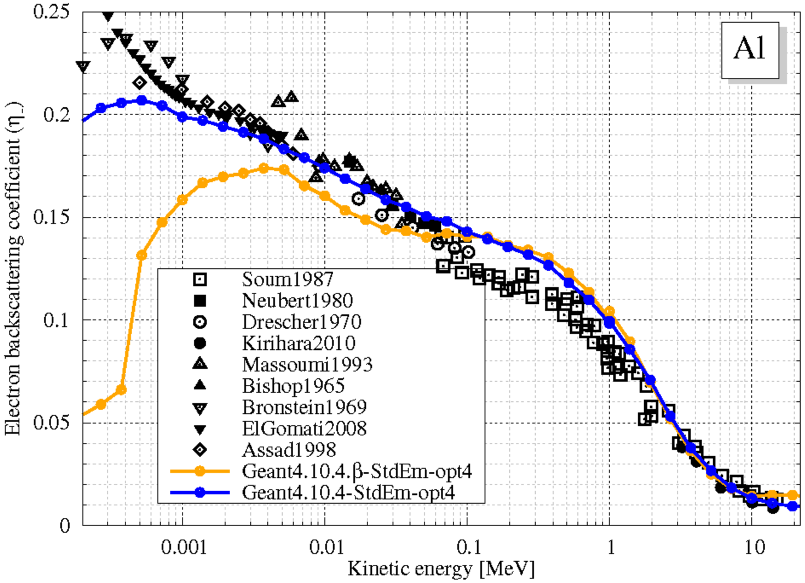


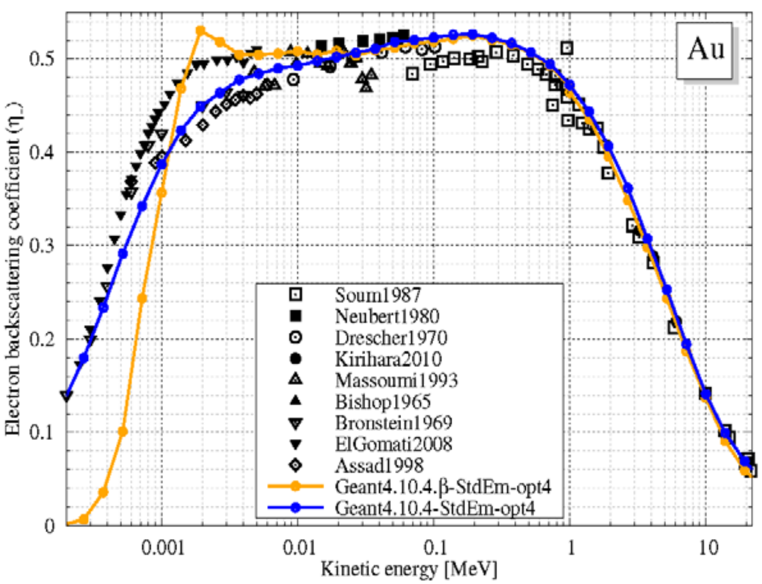
- This benchmark is used for control of Geant4 electron transport since 2009
  - Nucl. Instrum. Meth. B 267 3624-32, 2009
- Recent GS (Geant4 10.4) model describes now data for both low-density and high density data as WVI and SS models
  - This test directly couples with the problem of accurate simulation of electron transport in sampling calorimeters

Backscattering benchmark

10.4beta – Urban model in Opt4
10.3ref09 – GS model in Opt4

10.4beta – Urban model in Opt4
10.3ref09 – GS model in Opt4





Backscattering description below 100 keV is improved significantly
This is essential for many applications including HEP (high granular calorimeters)

CONFIGURATION OF EM PHYSICS
KANGAROO APPROACH

Electromagnetic parameters

- In previous versions of Geant4 (before 10.2) EM parameters were defined via UI commands and C++ interface G4EmProcessOptions
  - Via this class each EM process was accessed one by one in order to set parameter value
- After Geant4 10.0 we face some limitation in MT mode and switch to G4EmParameters class
  - EM process or model at initialization reads these parameters
  - Since 10.3 UI command order becomes not so important as before
    - Commands should be issued in PreInit and/or Idle states from the master thread
  - Information on set of parameters is available via Dump method
- With Geant4 10.3 parameter configuration is working via G4EmParameters interface
  - G4EmProcessOptions become obsolete

EM physics list constructors

- Several EM physics constructors (Physics List components) are provided
  - G4EmStandardPhysics – default
  - G4EmStandardPhysics_option4 (EMZ) – a combination of the most accurate EM models
  - G4EmStandardPhysicsGS – alternative multiple scattering
  - G4EmStandardPhysicsSS – single scattering (very CPU demanding)
  - Full list for constructors: http://geant4.cern.ch/collaboration/working_groups/electromagnetic/physlist.shtml
- On top of any of EM physics configuration it is possible to setup extra options, in particular:
  - Define cuts – production thresholds
  - Enable full atomic de-excitation cascade
  - Change lowest electron energy (tracking cut)
    - The default value is 1 keV

EM physics list constructors

- In past, the only possibility for users to add a special feature/model was to make custom EM physics list
  - For CMS production in 2017 Opt1 EM physics is used everywhere but Opt0 inside Hcal
  - For ALICE a similar approach is prepared
- With Geant4 10.3 a new possibility to customize EM configuration per detector region is available
  - New UI commands and C++ interfaces are provided
    - Alternative Physics Lists per region
      - /process/em/AddEmRegion myregion G4EmStandard_Opt4
    - PAI ionisation model per particle and region
      - /process/em/AddPAIRegion all myregion PAI
    - MicroDosimetry models per region below 100 MeV
      - /process/em/AddMicroElecRegion myregion
      - Single elastic and inelastic scattering in Silicon (very slow)
- This may be recommended both for test-beam simulations and for big experiment productions

Summary and Plans

- We recommend using recent versions of Geant4
  - Geant4 9.6 – last sequential version
  - Geant4 10.3 – recent public version
  - Stable results for shower shapes
- New instruments to configure EM physics are available with Geant4 10.3
  - Fine grain calorimeters may be simulated with specific configurations of EM physics
- Plans for next Geant4 releases
  - Include simulation of 1st order radiative corrections into main processes
  - Improve sampling of final state for interactions with atomic electrons
  - Improved CPU performance of EM models
- **Number of experiments which are used of EM physics validation is limited**
  - **New accurate test-beam results may be useful**