Geant4 Standard and Low Energy EM libraries

V. Ivanchenko & S. Incerti for the Geant4 Collaboration

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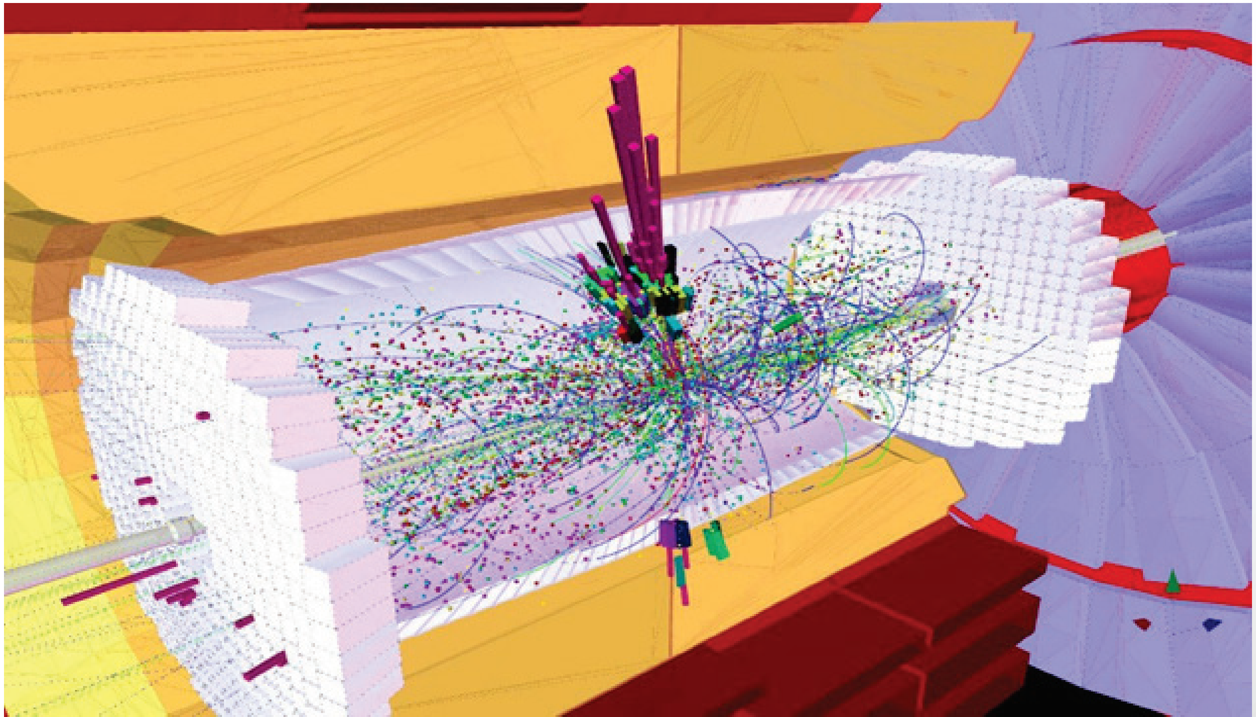
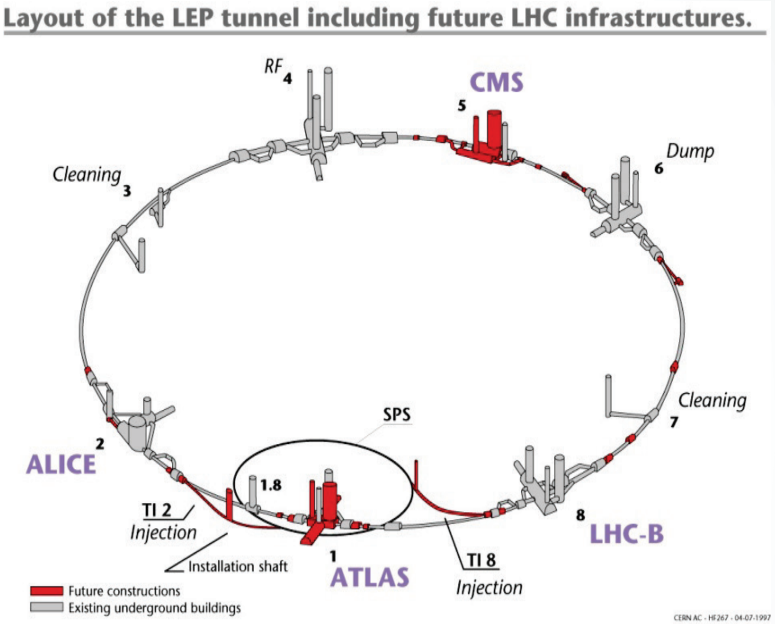
Outline

- Geant4 history
- Geant4 version 10.X
- Electromagnetic (EM) physics libraries
- Electron transport
- Configuration of EM physics
- Current EM developments
- Summary



Geant4 History

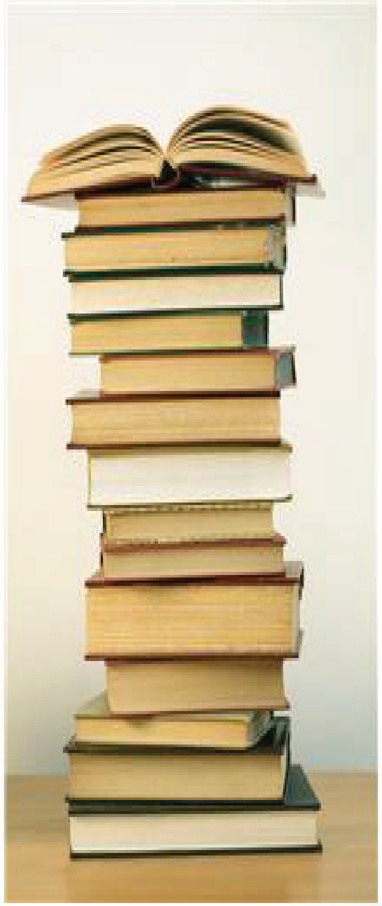
- Dec 1994 - Project start
- ...
- Dec 1998 - First Geant4 public release - version 1.0
- ...
- Dec 2010 - Geant4 version 9.4 – RUN 1 LHC
- ...
- Dec 2012 - Geant4 version 9.6 – consolidation of 9.X
- Dec 2013 - Geant4 version 10.0 - multi-threading
- ....
- Dec 2016 – Geant4 10.3



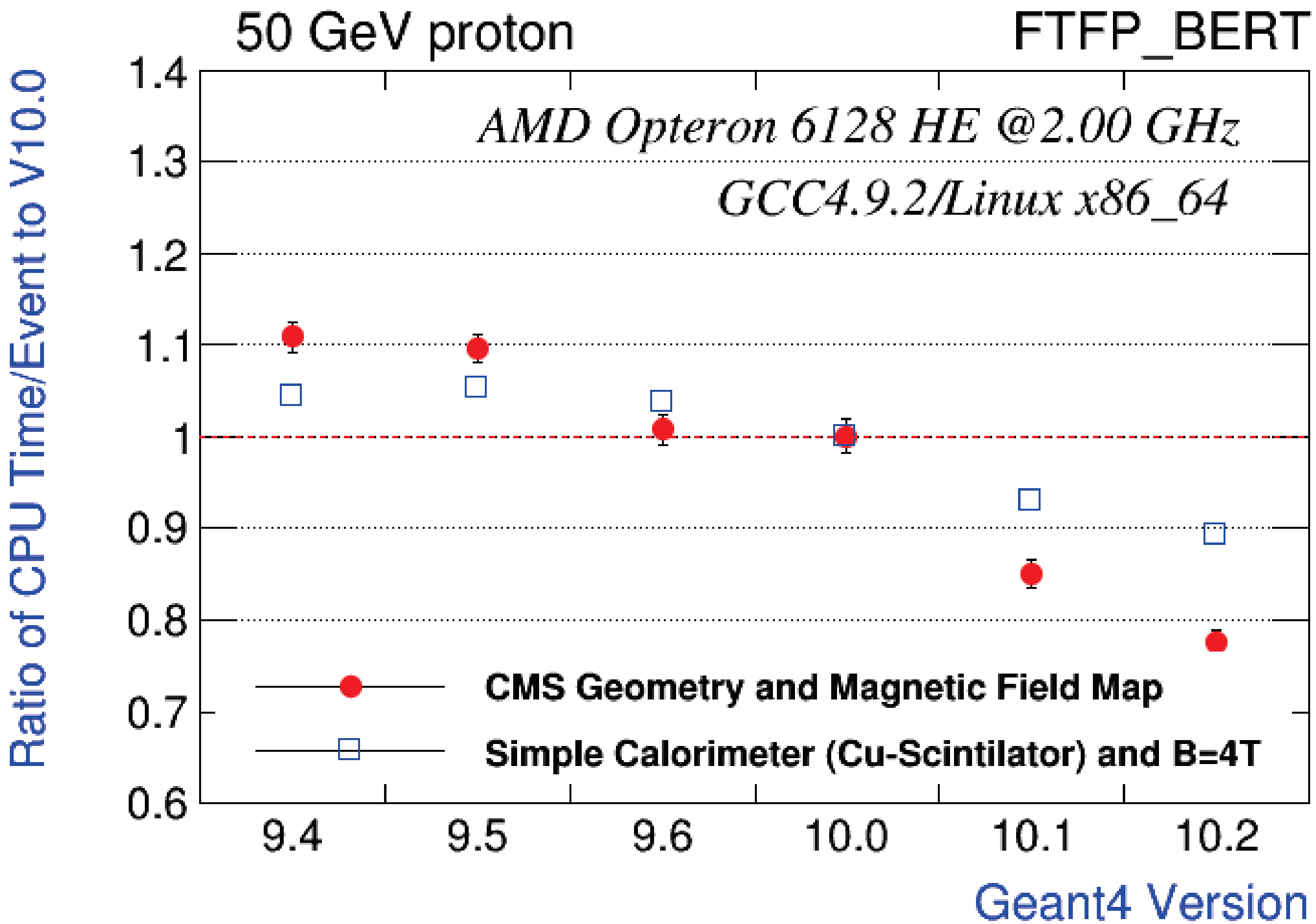
- Geant4 developments were strongly supported by HEP community
  - LHC experiments always were the goal
  - Space and medical user communities also contribute significantly to Geant4 developments
  - 1st general Geant4 paper A 506 (2003) 250-303 has >10000 citations
- Geant4 approach to collect alternative models and approaches applicable for different use cases

Geant4 Version 10 Series

- Geant4 version 10.0 was released on December 2013
  - The first major release since June 2007.
    - 9.X seria was focused on RUN-1 of LHC
  - One of highlights was its multithreading capability.
  - Many users have successfully migrated to version 10 series and started to use it in multithreaded mode.
    - CMS is ahead of other experiments:
      - ~10^{10} events produced using Geant4 10.0p02-seq
      - current CMS development 10.2.p02-MT
    - ATLAS, LHCb, ALICE are in process of adoptation 10.1 for production
  - Detail of version 10 is fully described in our third general paper.
    - J. Allison *et al.*, "Recent Developments in Geant4", NIM A 835 (2016) 186-225
- Since the 10.0 release, the Geant4 Collaboration continues its efforts to improve the performance in both physics and computing, enrich the functionalities and offer user support.

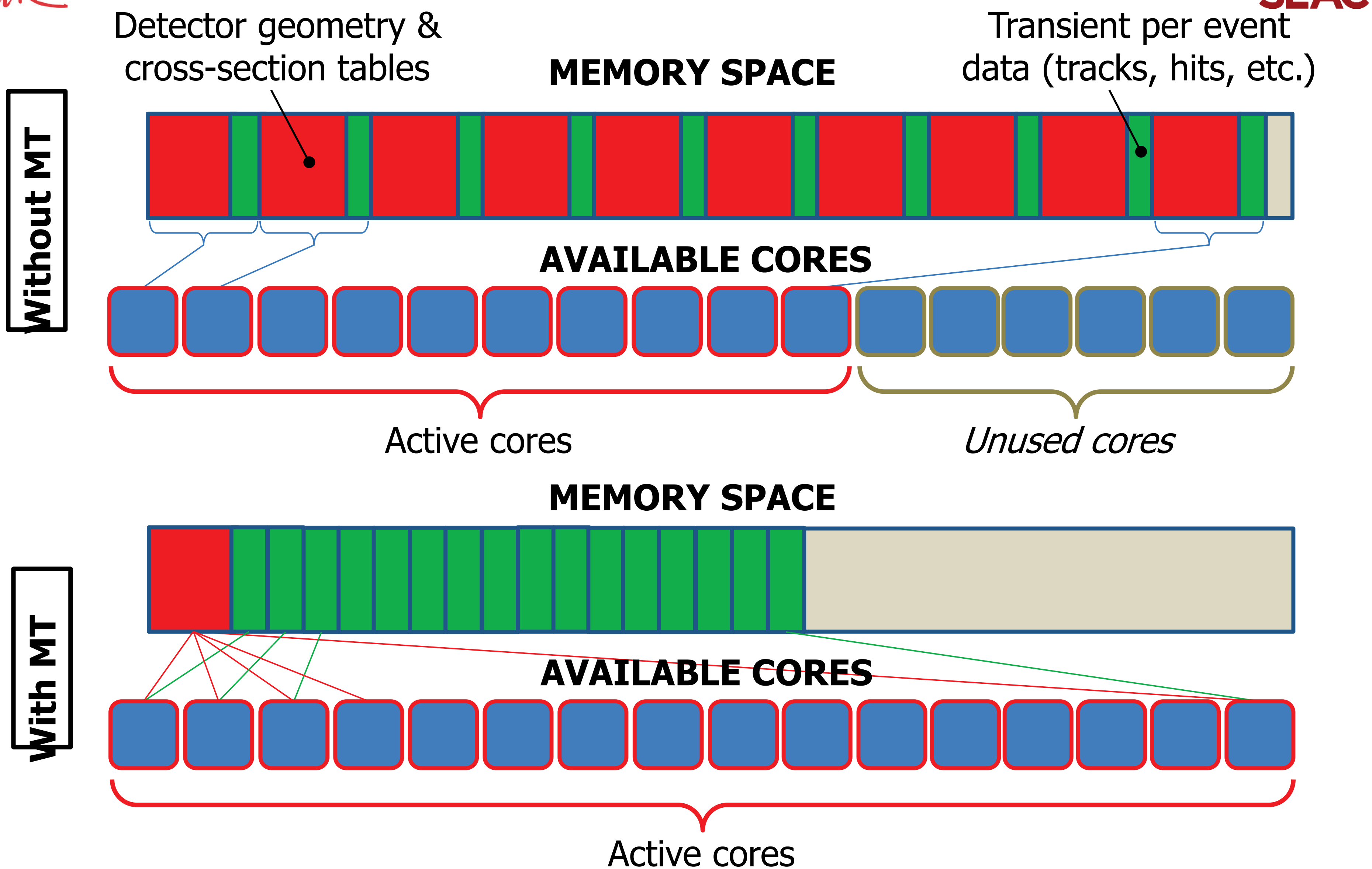


First of all, we are making it faster!

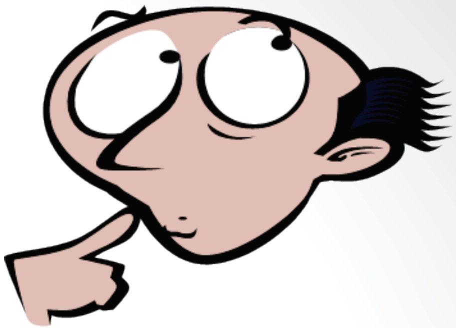


ATLAS : "The 10% CPU improvement we gain from the move from G4 9.6 to 10.1 is invaluable to the collaboration."

Memory usage in multithreaded mode



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 10 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

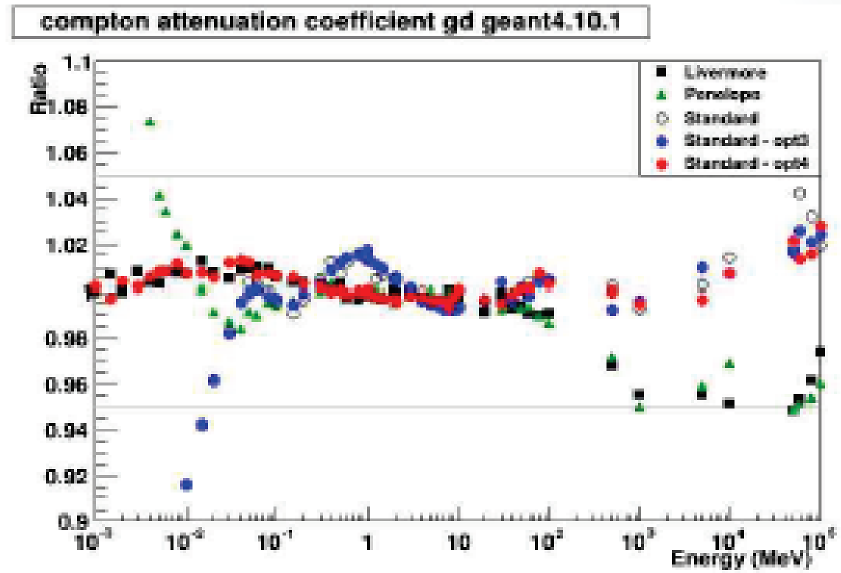
Located in $G4INSTALL/sources/processes/electromagnetic

Consolidation of EM physics

- Standard EM development was concentrated on HEP
  - Important physics sub-package for LHC experiments
- For many years EM low-energy sub-package was developed separately
  - Focused on medical and space science requirements
- The were many recommendations to extend Geant4 EM physics using the best features of both packages
  - Before Geant4 9.3 there were technical limitations to use in one run both standard and low-energy models
- For Geant4 9.6 unification of EM processes and models was completed
  - Angular generators for sampling of final states
  - Atomic de-excitation module is common
    - It is used by standard, low-energy EM models and also by radioactive decay and nuclear de-excitation module
  - Built-in biasing
- Using common validation suite it becomes possible to improve physics performance of both standard and low-energy models
  - Applicability range of models is better defined
- Migration to multi-treading for 10.0 was goind smoothly for EM physics because of the common approach

Geant4 physics model approach

- Geant4 EM and hadronics allowing co-existence of several models within Geant4 distribution
  - Model interface allowing easy developemt of new models
  - Verification suite provides validation of models and identification of applicability limits
- We are trying to keep EM models used for LHC stable
  - Any change in default models should justified by some data
  - CPU and memory should not degradate
- Alternative models may be modified with less restrictions



Compton scattering cross section for all elements above 1 keV agree to each other within 5%

Alternative Compton scattering models take into account atomic electron PDF functions and gamma polarisation

CPU performance and applicability ranges of gamma models

1 MeV gammas in Al

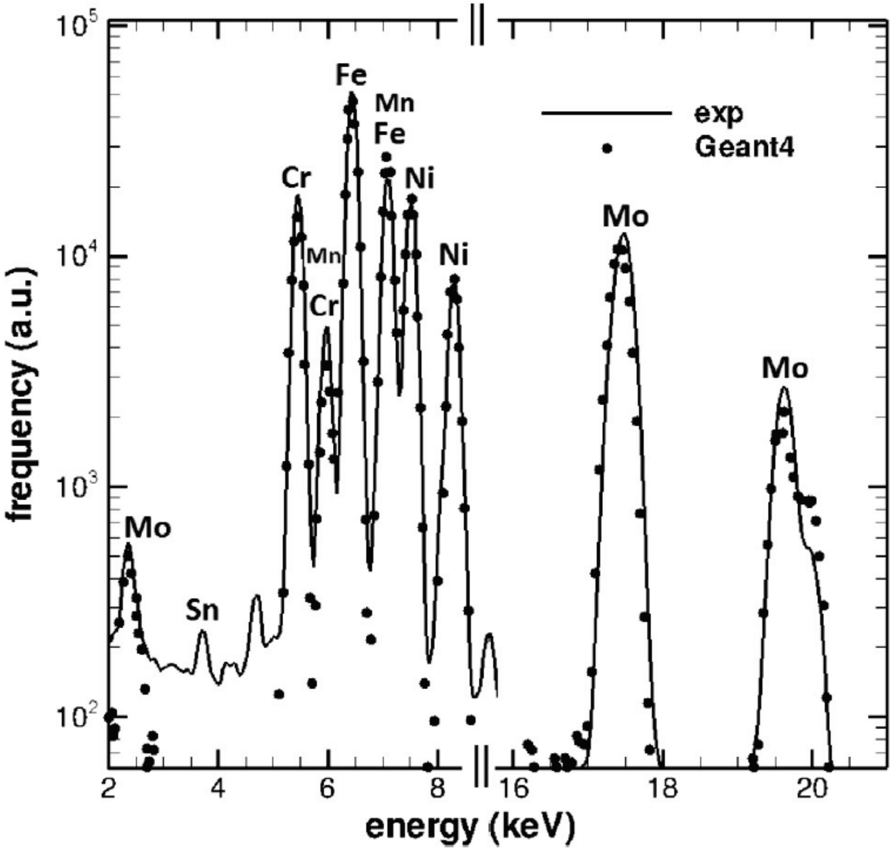
Model	E_{min}	E_{max}	CPU
G4LivermoreRayleighModel	100 eV	10 PeV	1.2
G4PenelopeRayleighModel	100 eV	10 GeV	0.9
G4KleinNishinaCompton	100 eV	10 TeV	1.4
G4KleinNishinaModel	100 eV	10 TeV	1.9
G4LivermoreComptonModel	100 eV	10 TeV	2.8
G4PenelopeComptonModel	10 keV	10 GeV	3.6
G4LowEPComptonModel	100 eV	20 MeV	3.9
G4BetheHeitlerModel	1.02 MeV	100 GeV	2.0
G4PairProductionRelModel	10 MeV	10 PeV	1.9
G4LivermoreGammaConversionModel	1.02 MeV	100 GeV	2.1
G4PenelopeGammaConversionModel	1.02 MeV	10 GeV	2.2
G4PEEFluoModel	1 keV	10 PeV	1
G4LivermorePhotoElectricModel	10 eV	10 PeV	1.1
G4PenelopePhotoElectricModel	10 eV	10 GeV	2.9

ref → G4PEEFluoModel

Validation details at url:

https://geant4.cern.ch/collaboration/working_groups/electromagnetic/indexv.shtml

PIXE x-Ray radiation from complex sample: any EM Physics List – based on the same atomic data



NIM B 316 (2013) 1-5

Stainless steel sample simulation compared to experimental values, taking into account Aluminum ‘‘funny filter’’ of 250 um and 0.26% hole-detector surface proportion.

Current PIXE implementation done for K- , L- and M- shells

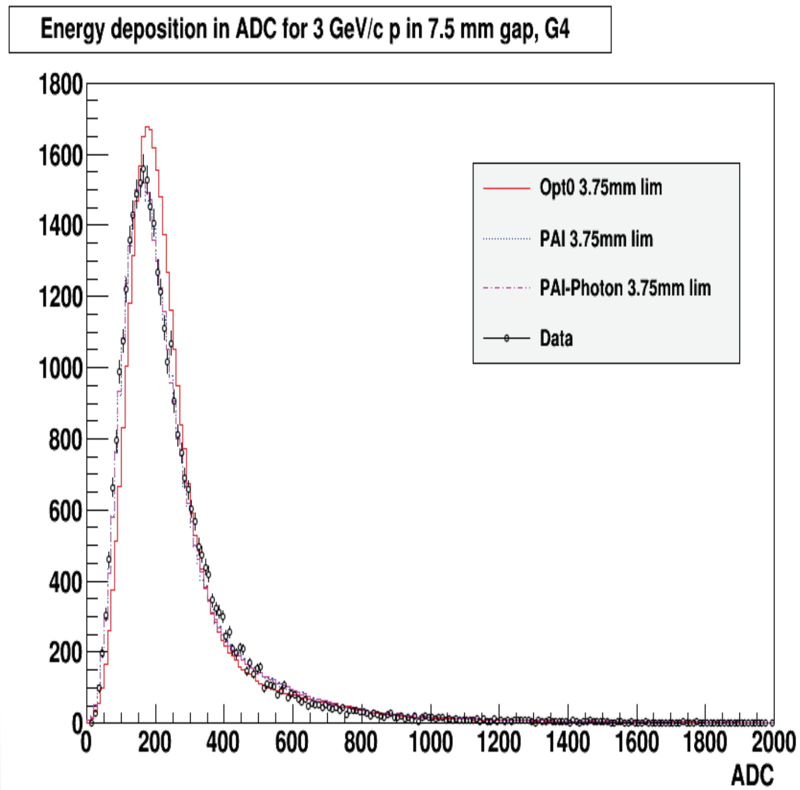
Electron transport

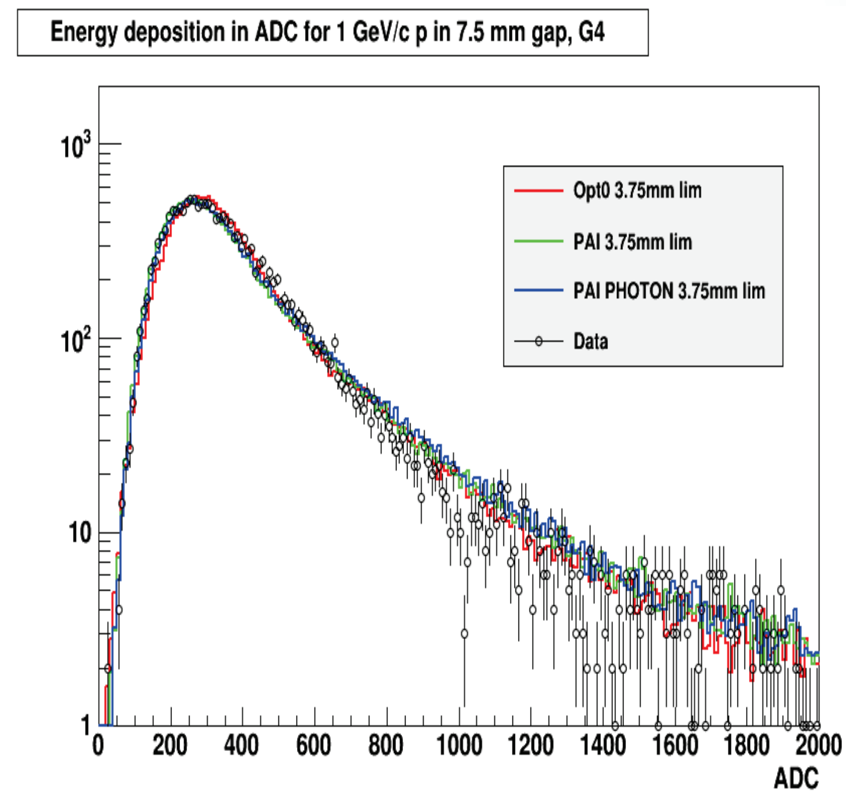
- Condence history approach allowing to have a trade of CPU performance versus accuracy of simulation
  - Continuesenergy loss + fluctuations of energy loss
  - Multiple scattering
  - Optimisation of energy cuts and step limits are necessary to get desired accuracy
- Types of step limits in Geant4
  - Cut in rage transformed into production thresholds for delta-electrons and bremsstrahlung gamma
    - May be defined per G4Region
  - Step limit function from ionisation models (20% of range if not the last step)
  - Spec limit from multiple scattering model
  - User step limit per particle type
    - May be recommended for TPC and some other gaseous detectors

Energy deposition in ALICE TPC test-beam

Two alternative models of flluctuations of energy loss:

- Default Urban model required step limit half cell size
- PAI model more accurate but slower and not sensitive to step limitation





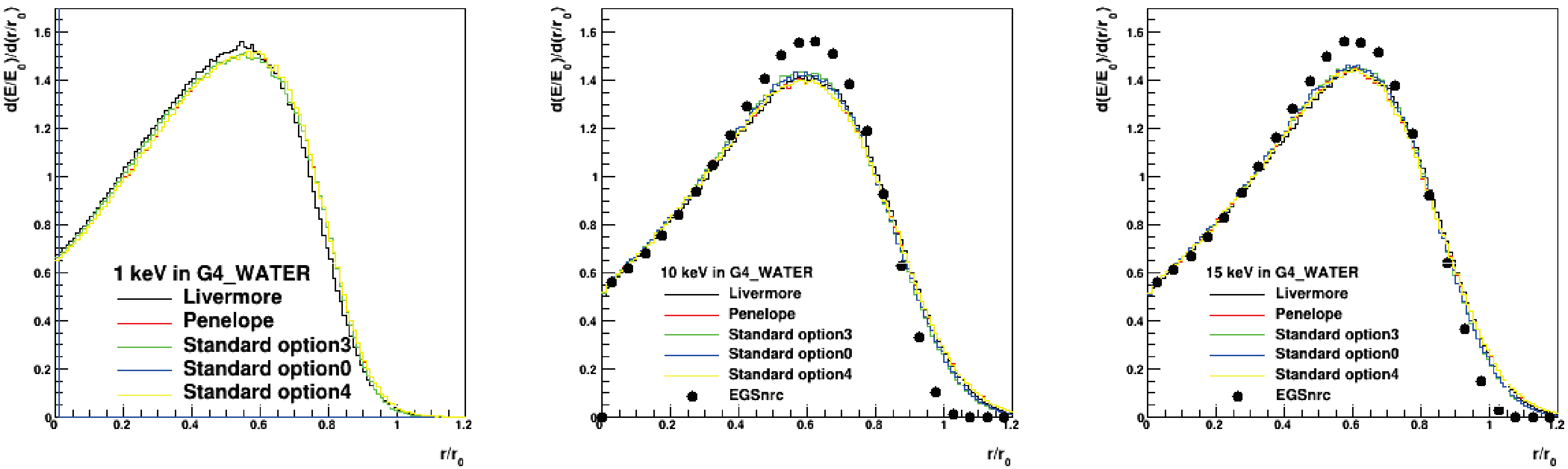
Data: Nucl. Instr. Meth. A, 565, 551-560 (2006),
Int. J. Mod. Phys. *E,* 16, 2457-2462 (2007). Geant4 10.2p02

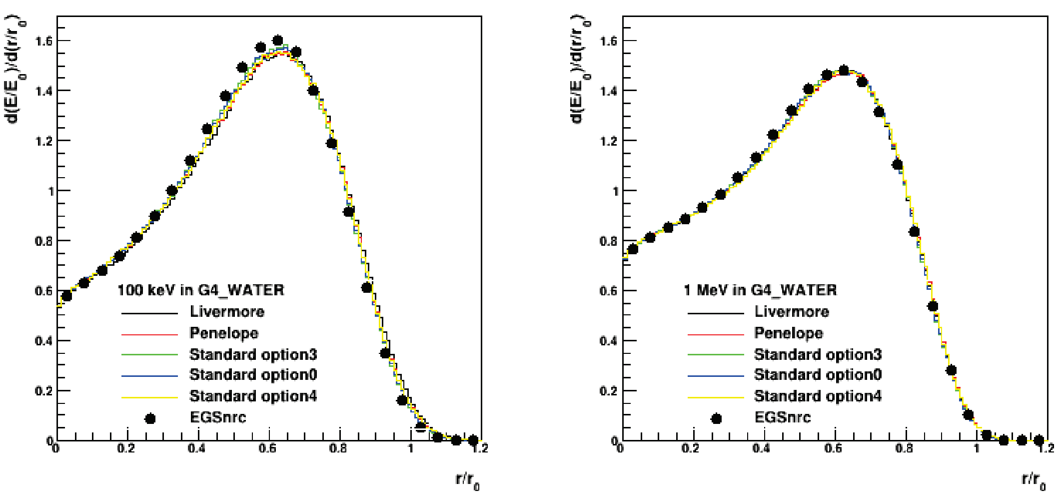
MSC and Single Scattering Models

Model	Particle type	Energy limit	Specifics and applicability
Urban (L. Urban 2006)	Any	-	Default model for $e^{\pm}$ below 100 MeV and for ions, tuned to data, used for LHC production.
WentzelVI & Coulomb Scattering (V.Ivanchenko 2009) LowEnergyWentzelVI (2014)	Any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons but applied also for e± above 100 MeV; low-energy variant of the model is applicable for low-energy e-
Goudsmit-Saunderson (O.Kadri 2009, revised by M.Novak for 10.2	e^{+}, e^{-}	< 1 GeV	Theory based cross sections (Goudsmit and Saunderson 1950); ELSEPA code computations, EGSnrc aproach. precise electron transport
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e^{+}, e^{-}	-	Model based on Wentzel formula + relativistic effects + screening effects for projectile & target. From the work of P. G. Rancoita, C. Consolandi and V. Ivantchenko.
Screened Nuclear Recoil (Mendenhall and Weller 2005) TestEm5	p, ions	< 100 MeV/A	Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space applications

Current default for HEP applications is a combined multiple and single scattering model:
G4WentzelVIModel + G4eCoulombScatteringModel
Applied for high energy e+-, muons, hadrons
Recoil nucleaus is simulated if it s kinetic energy is above energy threashold

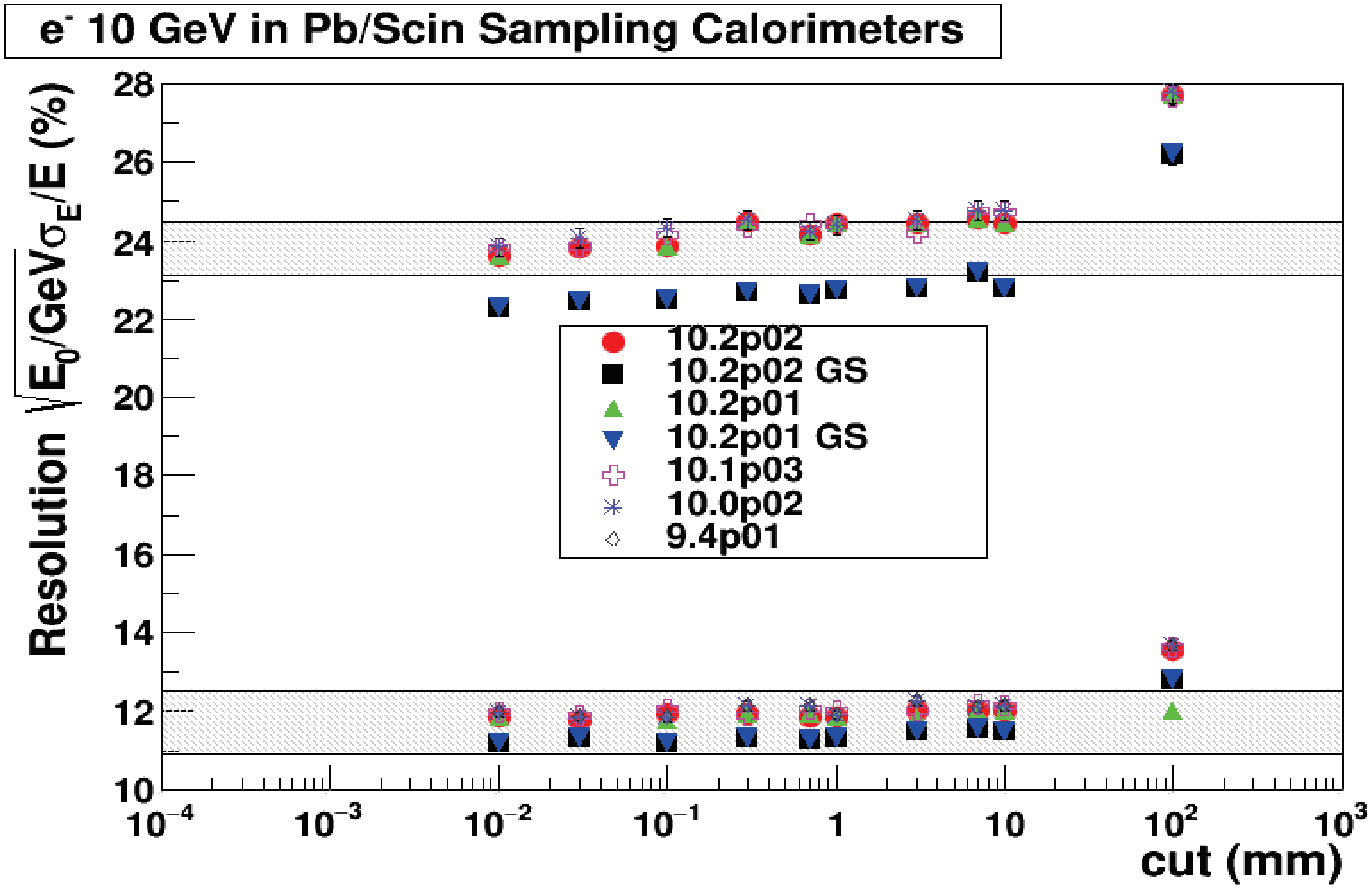
Dose point kernel in water Geant4 10.0 versus EGSnrc – electron transport characterisation





- Results for different EM configurations are similar
- Geant4 predicts longer tail for 10 and 15 keV than EGSnrc

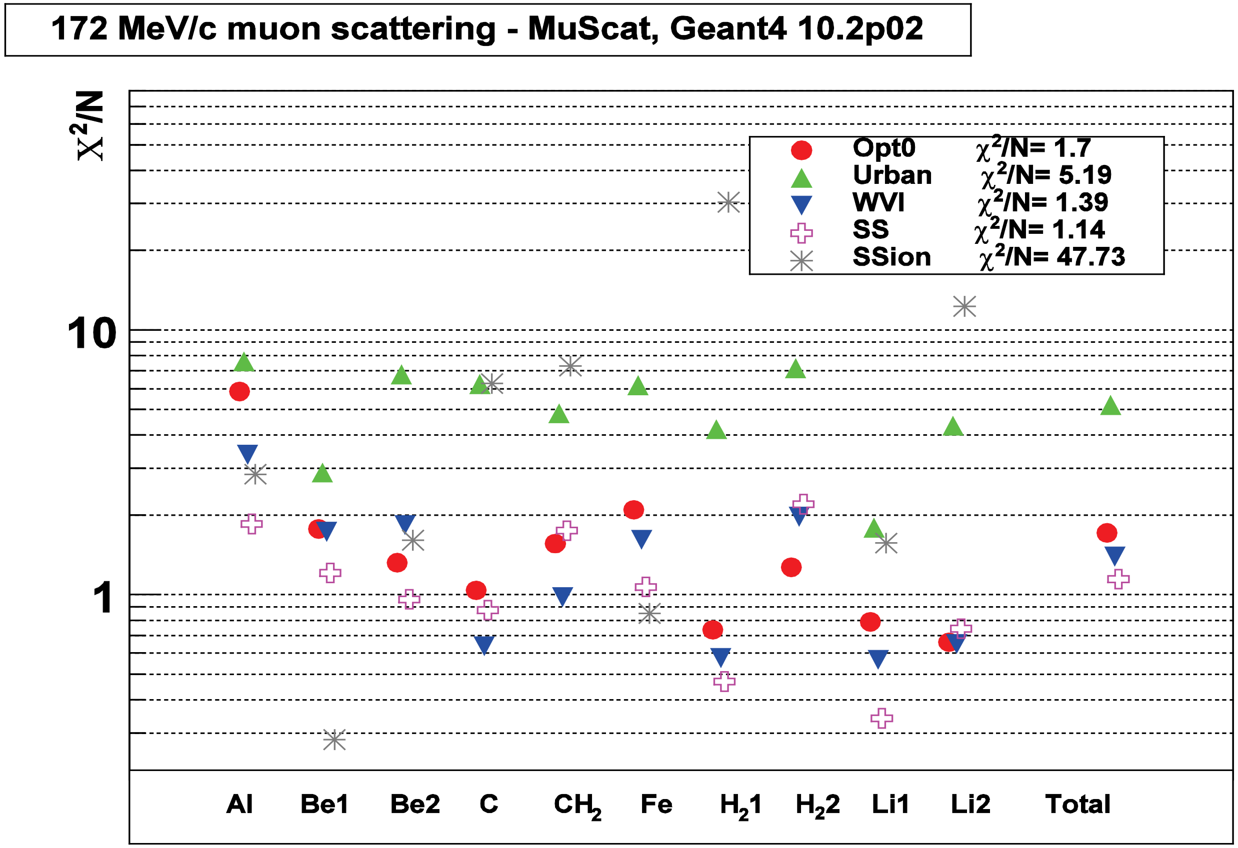
ZEUS test-beam calorimeters



Two different sampling calorimeters are simulated with the same conditions
Results are stable versus cut in range and Geant4 version
New GS model is competative to the default Urban model

MuScat benchmark

Nucl. Instr. Meth. B 251 (2006) 41



Single scattering and WentzelVI models are closer to the data than the Urban model.

EM MODEL CONFIGURATIONS

Reference Physics Lists and EM constructors

- Geant4 provide set of reference Physics Lists
  - These physics configuration are validated by Geant4 team
  - Allowed cross experiments validations
  - Current default is FTFP_BERT
- To get optimal CPU/accuray balance EM physics requires extra configuration on top
  - Cuts may be defined per G4Region
  - There are several predefined EM physics configurations which are also under regular validation
  - FTFP_BERT_EMV, FTFP_BERT_EMY....
- A concrete experiment may need more, for example, CMS production:
  - For RUN-1,2 QGSP_FTFP_BERT_EML was used
  - For RUN-2 2017 FTFP_BERT_EMM is prepared
  - EML and EMM are different EM configurations
    - EMM provided improved accuracy in HCAL

Electromagnetic parameters

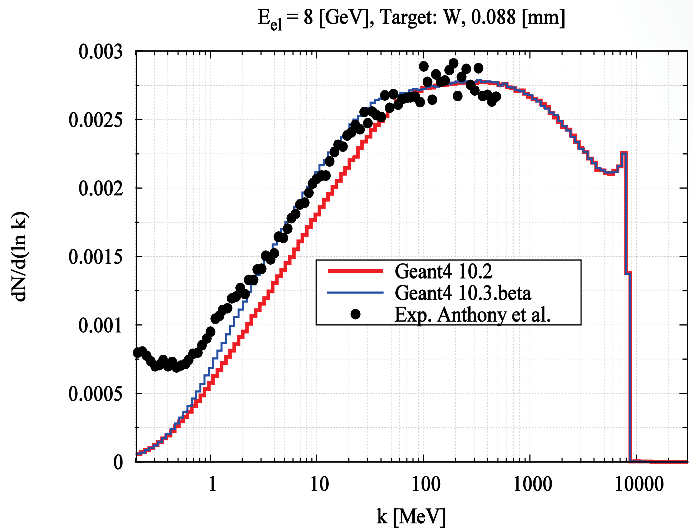
- In previous versions of Geant4 EM parameters were defined via UI commands and C++ interface G4EmProcessOptions
  - Via this class each EM process was accessed one by one in order to set parameter value
- After Geant4 10.0 we face some limitation in MT mode and switch to G4EmParameters class
  - EM process or model at initialization read these parameters
  - Now UI command order become 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
- Now parameter configuration is working fine in general but we may be provide too much freedom for customisation?

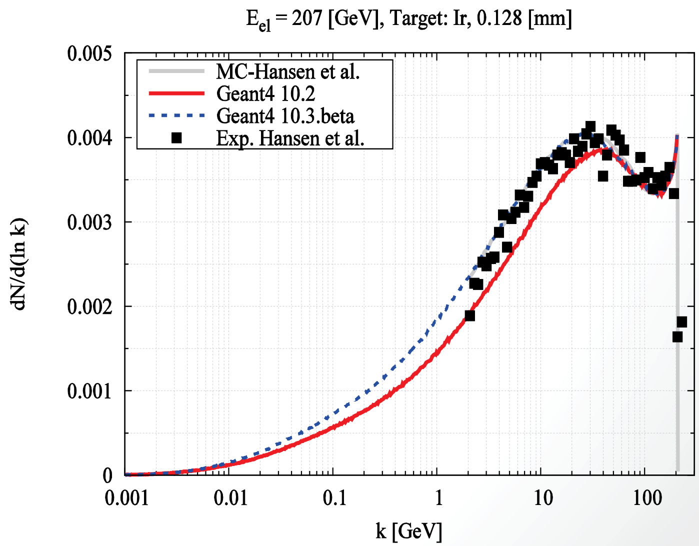
EM physics configuration

- Until Geant4 10.2 we had a limitation Geant4 EM physics should be customised by a user for any special needs:
  - Different models for G4Region
  - Different model options for G4Region
  - Standard/DNA models
- This customisation can be done properly only by an expert user and make problems even for top experts
- For 10.2 we provide new UI commands:
  - /process/em/AddPAIREgion all myregion PAI
  - /process/em/AddMicroElecRegion myregion
  - /process/em/AddDNARegion myregion DNA_Opt0
- For 10.3 we provide new UI command:
  - /process/em/AddEmRegion myregion G4EmStandard_Opt3
- This is not PhysicsList per G4Region but EM physics configuration per G4Region
  - By this new command we do not fully emulate Opt0, Opt1.. But mainly msc models and atom de-excitation

Recent EM physics developments

- Implementation of LPM suppression in e± bremsstrahlung is revised
  - Better agreement with CERN and SLAC experimental data
- Upper energy limit of EM physics is extended from 10 TeV to 100 TeV.
  - Essential for FCC R&D
- 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 formfactor parameterisation





Summary

- For today all EM physics libraries are following the same interface
  - All EM models are migrated to the multi-treaded mode
  - Models may co-work for different particle type, energy interval and detector region
- Geant4 recommendation:
  - Use version 9.6 or better to switch to 10.X, which may be also used squential mode
- Current development is ongoing for 10.X seria
  - Extentions for high energy – current upper limit is 100 TeV
  - Extended set of UI commands and c++ interface to configure EM physics per region
  - Many improvements for very low energy EM physics (not part of this talk)
  - Some improvements for moderate energies
    - Multiple and single scattering model
  - We permanently work on extention of validation and code quality

THANK YOU FOR YOUR ATTENTION