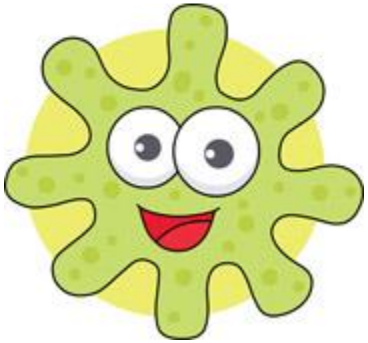
Progress of Geant4 Electromagnetic Physics Developments and Applications

V. Ivanchenko CERN & Tomsk State University, Russia
On behalf of the Geant4 Collaboration

CHEP 2018 Conference
Sofia (Bulgaria) - July 9-13, 2018

A.Bagulya, S. Bakr, M. Bandieramonte, D. Bernard, J.M.C. Brown, H. Burkhardt, P. Dondero, S. Elles, V.Grichine, S. Guatelli, F. Hariri, A. Howard, V.N.Ivanchenko, S. Incerti, S.J. Jun, O. Kadri, M.Maire, A. Mantero, M. Novak, D. Sawkey, I. Semeniouk, A.Sokolov, L. Urban

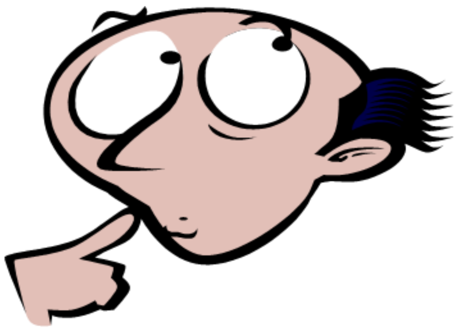
Outline



- Geant4 electromagnetic physics (EM)
- Main challenges for Geant4 EM
- Highlights on EM physics in Geant4 10.4 and 10.5beta
- Prospects and plans

Electromagnetic (EM) physics sub-libraries of Geant4 provide simulation of EM interactions of gamma, charged leptons, hadrons and ions for all kind of simulation applications

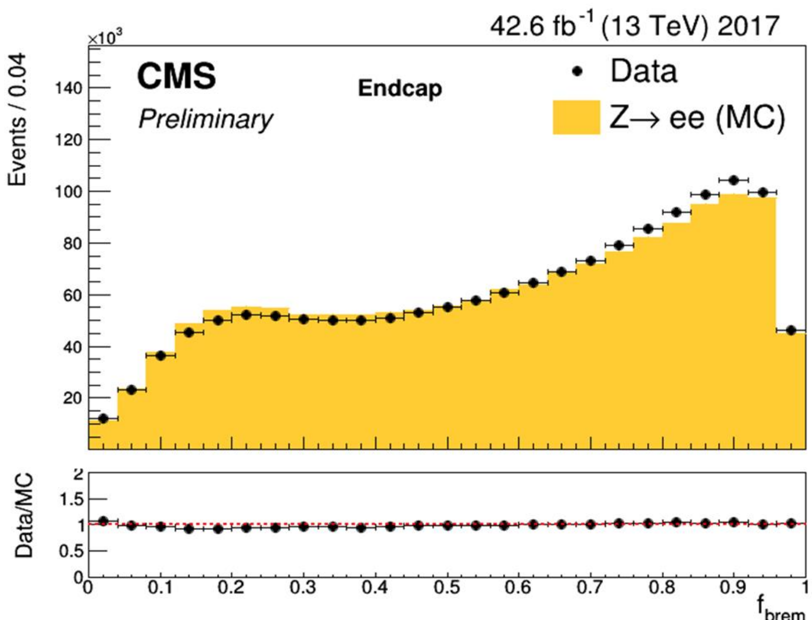
EM Physics of Geant4



- Standard EM development was concentrated on HEP
  - Important physics sub-packages for LHC experiments
- For many years EM low-energy sub-package was developed separately
  - Focused on medical and space science requirements
- From Geant4 9.6 the unification of EM processes and models was completed and EM packages cover all application areas
  - Low and High energy models selectable on the fly
  - Angular generators for sampling of final states interchangeable
  - Atomic de-excitation module is common
- We report today on EM physics progress for Geant4 10.4
  - Several model improvements for HEP and others
    - Main results (like EM shower resolution) are stable for Geant4 10.X
  - EM physics is fully multi-threading compliant
    - All data tables are shared between threads
  - Code is C++11 compliant
- We will also discuss upgrades available with Geant4 10.5beta

Current accuracy of Geant4 EM

- Since Geant4 9.6
  - Accuracy of EM cross sections, shower response and resolution O(%)
  - EM shower shapes are monitored in regression on level $O(10^{-3})$
- Some discrepancies observed with LHC data do not clearly indicate the level of inaccuracy of the current EM physics but may be attributed to
  - Inaccuracy of geometry descriptions of detectors
  - Inaccuracy of simulation of digitization including pileup effects
- For more details see materials of the LPCC workshop



Recent example of Run-2 simulation:

CMS-DP-2018/017: Electron and Photon performance in CMS with the full 2017 data sample

Less agreement with data for the endcap than for the barrel

The fraction of the momentum lost to bremsstrahlung measured in the tracker, defined as f_{brem} for ECAL endcap .

Main challenges for EM physics in future experiments

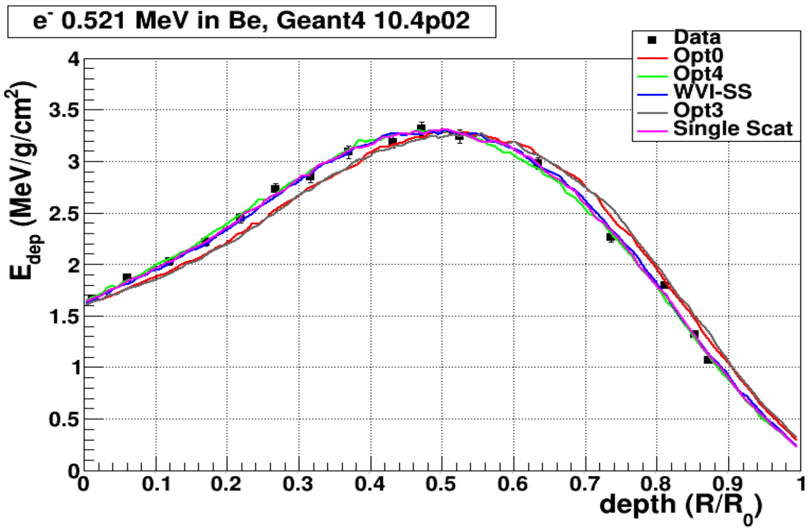
- LHC Run-3 and HL-LHC physics analysis
  - Will require higher statistics of simulation
  - Current EM physics modelling uncertainties may contribute to systematic uncertainty of physics observables
  - Rare EM processes with O(%) cross section and below may potentially create non-standard event patterns
- In dark matter search experiments rare EM processes are background
- For FCC design we need reliable EM simulation up to 100 TeV
  - LPM suppression for gamma conversion and bremsstrahlung
  - Nuclear recoil effects
  - Nuclear and atomic form-factors
  - Specific EM processes for study of interaction region design
- Current priorities in Geant4 EM physics developments:
  - Review and update of all models according to the best state of art
  - Focus on model extensions to implement next to leading order corrections for cross sections
  - Add sampling of second order final states
    - extra recoil atomic electron , extra gamma or e+e- pair, recoil nucleus

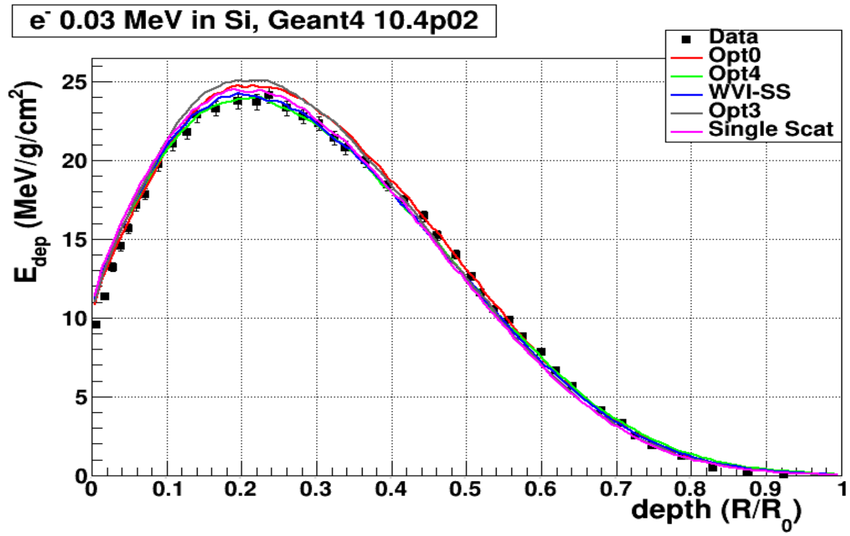
Most important updates for Geant4 10.4 (December 2017)

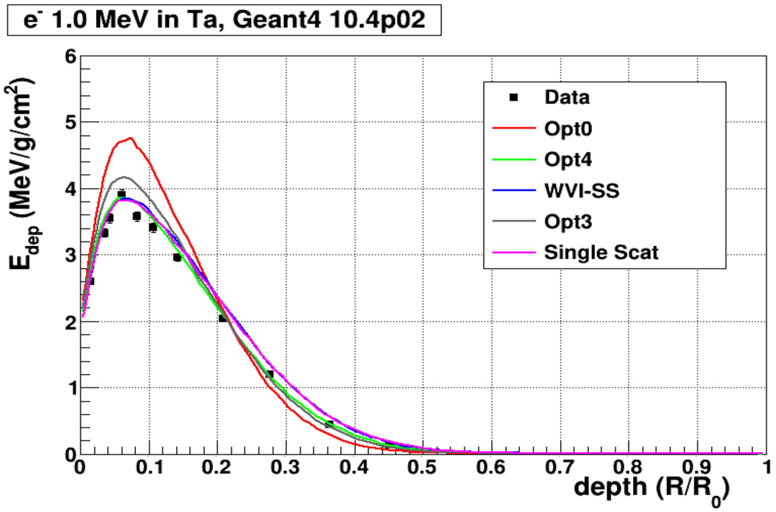
- Extended Geant4 Goudsmit-Saunderson (GS) model of multiple scattering of electrons and positrons
  - Mott corrections are fully implemented
  - Error free stepping option is available with Opt4 EM physics (EMZ)
- Tuned Urban model of energy loss fluctuations
- Improved photo-electric model and Rayleigh scattering
- Improved computations of LPM suppression corrections
  - Gamma conversion and bremsstrahlung
- Improved model for gamma conversion into $\mu^+\mu^-$ pair
- Provided 1st Geant4 example for light dark matter particle transport
- Improved interfaces for management of EM parameters
  - Models may be activated per detector region in easy way
- Improved handling of material properties for optical processes

Energy deposition in semi-infinite media

SANDIA REPORT SAND79-0414.UC-34a



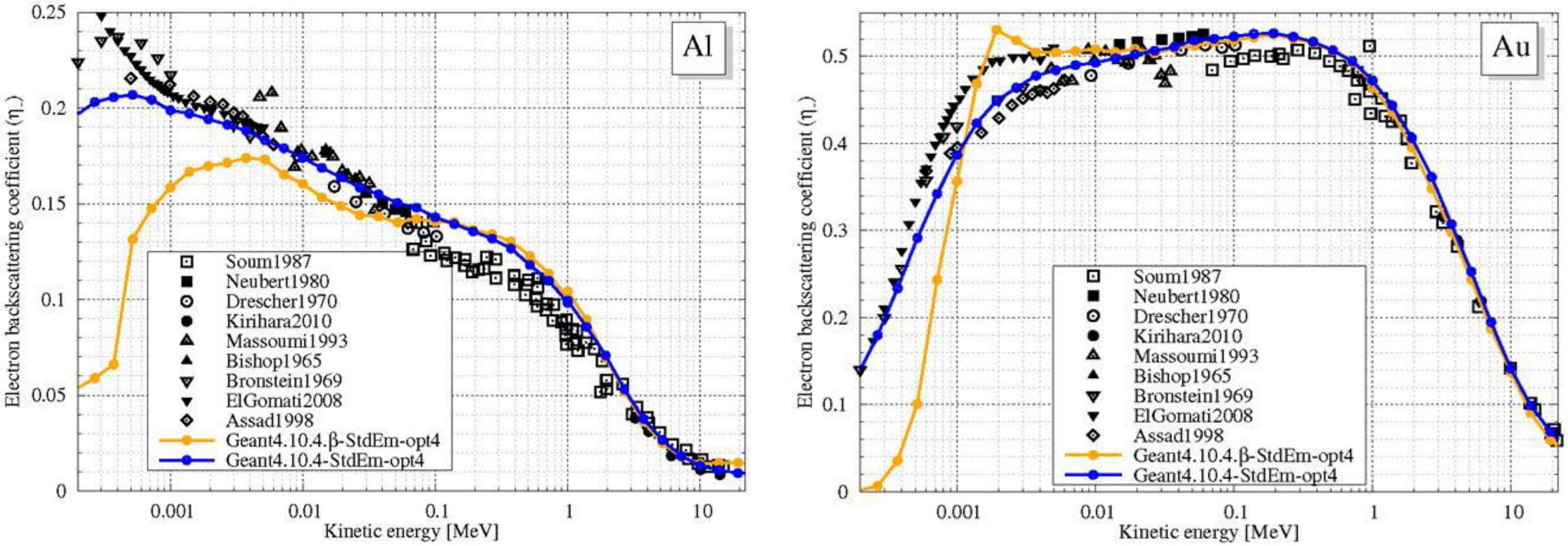




- Recent GS model now describes data for both low and high density media
- Opt0 (default) is not so accurate but is fast
- Opt4 (EMZ) is recommended as an alternative if increased precision is needed but is slower

Backscattering validation results

CHEF-2017 Conference (JINST 13 C02054, 2018)



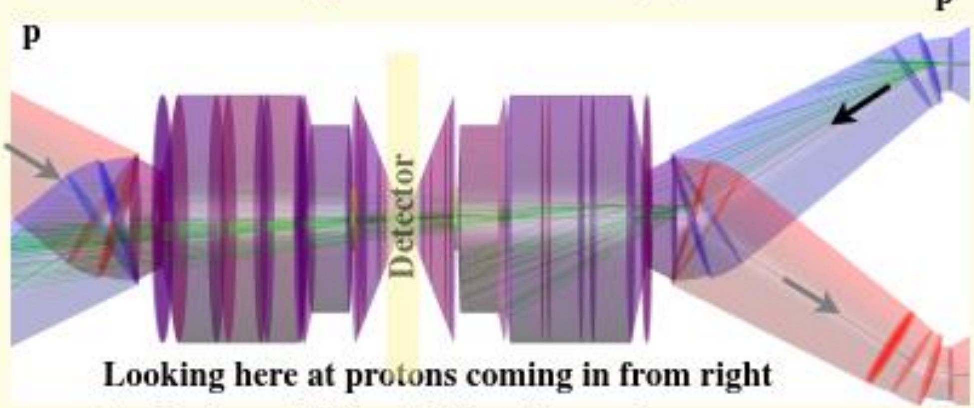
- Validation of electron backscattering from light (Al) and heavy (Au) targets versus data from different experiments.
- Old Opt4 (EMZ) EM configuration uses the Urban model (yellow), the final variant of Opt4 uses GS with “error-free” stepping (blue)
- Simulation with GS is substantially more accurate below 10 keV

FCC design efforts bring new requirements to Geant4 EM and SR model is upgraded for 10.4

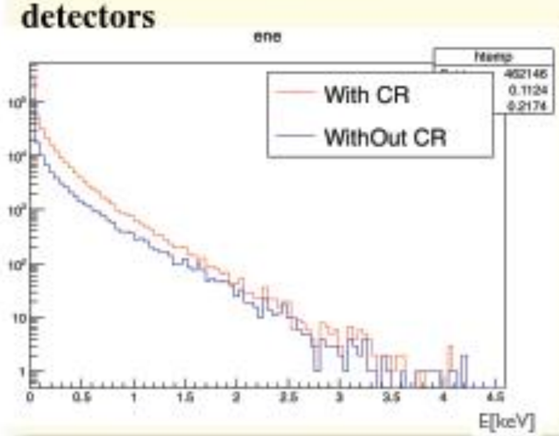
SR (synchrotron radiation) as major constraint both hh and ee
100 MW ee, 5 MW in pp -- on cold surface & backgrounds in detectors (ee)

Example of use of G4 upgraded for FCC

SR of protons and high precision um over km tracking to predict the rate and spectrum of photons into detectors



Looking here at protons coming in from right tracked over 700 m to IP and beyond generating SR photons shown in green transverse scale × 1000

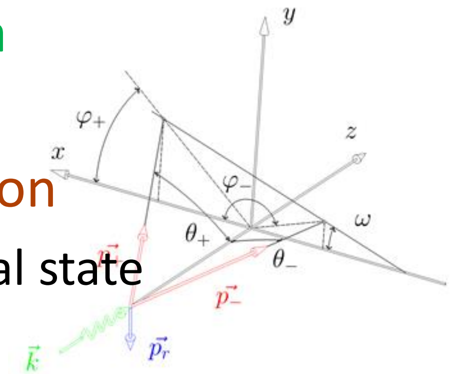


SR photon spectrum coming into detector region depending on crossing angle

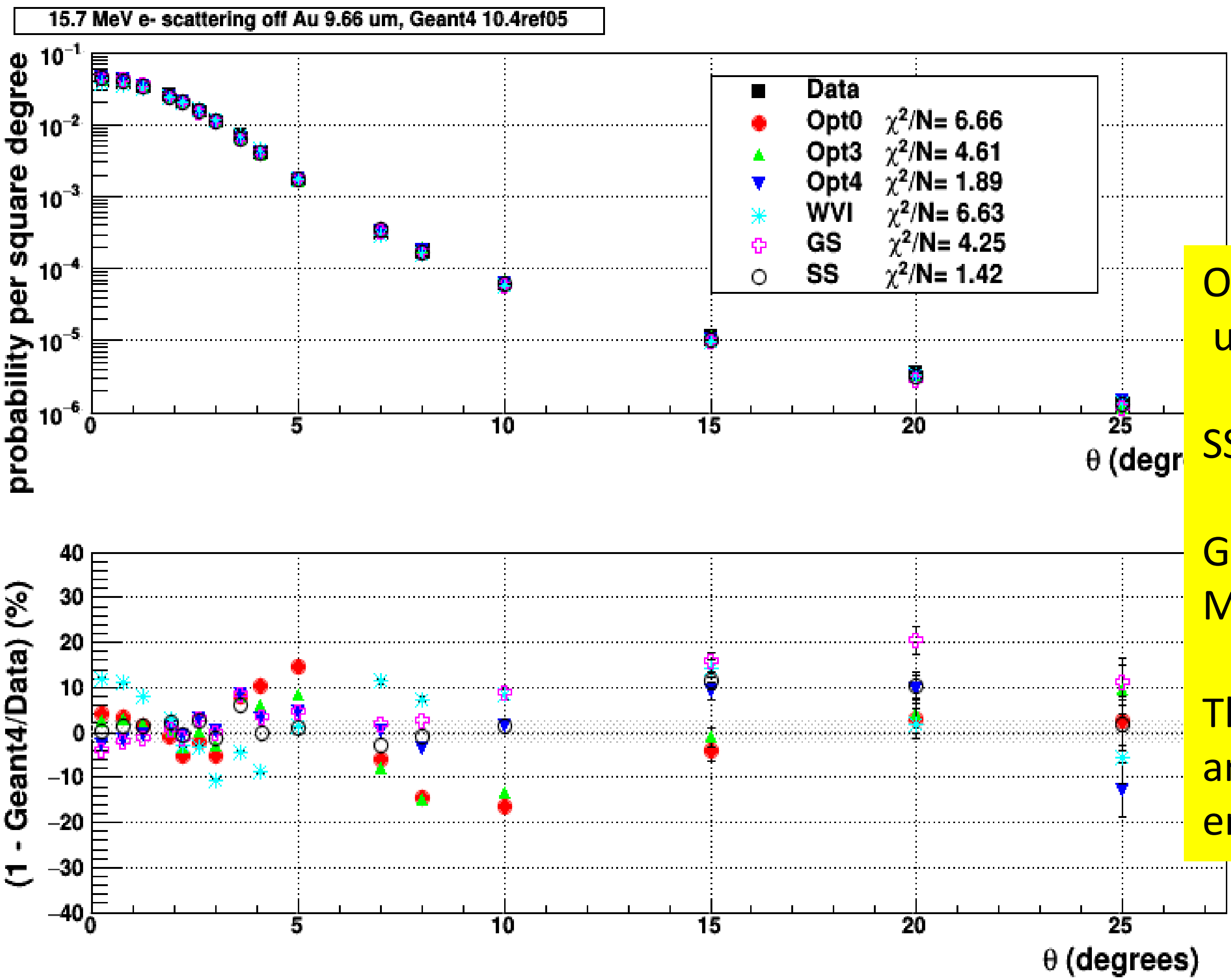
Ref :
Synchrotron Radiation Backgrounds for the FCC-hh Experiments, IPAC2017 paper and F. Collamati / INFN-Rom presentation 10/2017

Most important updates for Geant4 10.5beta (June 2018)

- Inclusion of Mott corrections in WentzelVI and single scattering models used for high energy e+e-
- Improved displacement sampling in Urban multiple scattering model
- Improved final state sampling for default gamma conversion models
- A new alternative 5D model for gamma conversion
  - Accurate simulation of angular correlations for final state
  - Triplet production (recoil e-)
  - Linear polarization of gamma may be taken into account
- A new relativistic model for ion ionisation



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



Opt4 Physics List uses the GS model

SS is single scattering

GS and SS are using Mott corrections

These improvements are also valid for all energies

Prospects and plans

- Geant4 10.4 offers several new developments
  - New options for EM model configuration
  - New GS model for e+-, improved Opt4 EM physics
  - Several form factor parameterisations
- Geant4 10.5beta offers further improvements
  - Mott corrections for e+e- scattering are available and are used for all energies by default
  - Improved lateral displacement sampling in the Urban multiple scattering
  - New 5D model for gamma conversion
    - Triplet production, accurate angular correlations, and polarization
  - New relativistic ion ionisation model
- We plan to cover next to leading order corrections to all models important for HEP
- Will develop necessary features for FCC design

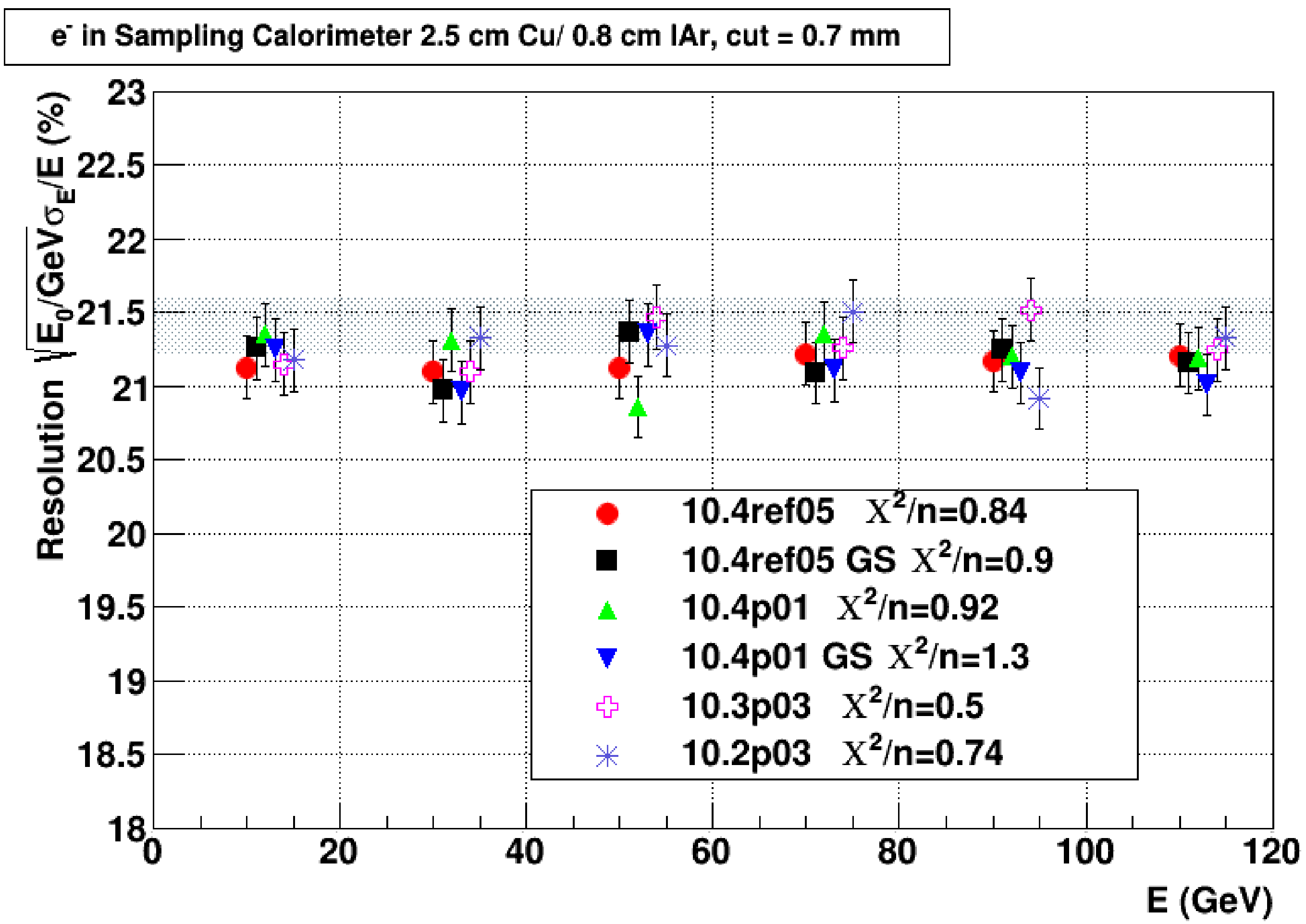
Thank you for your attention!

Backup includes some practical details

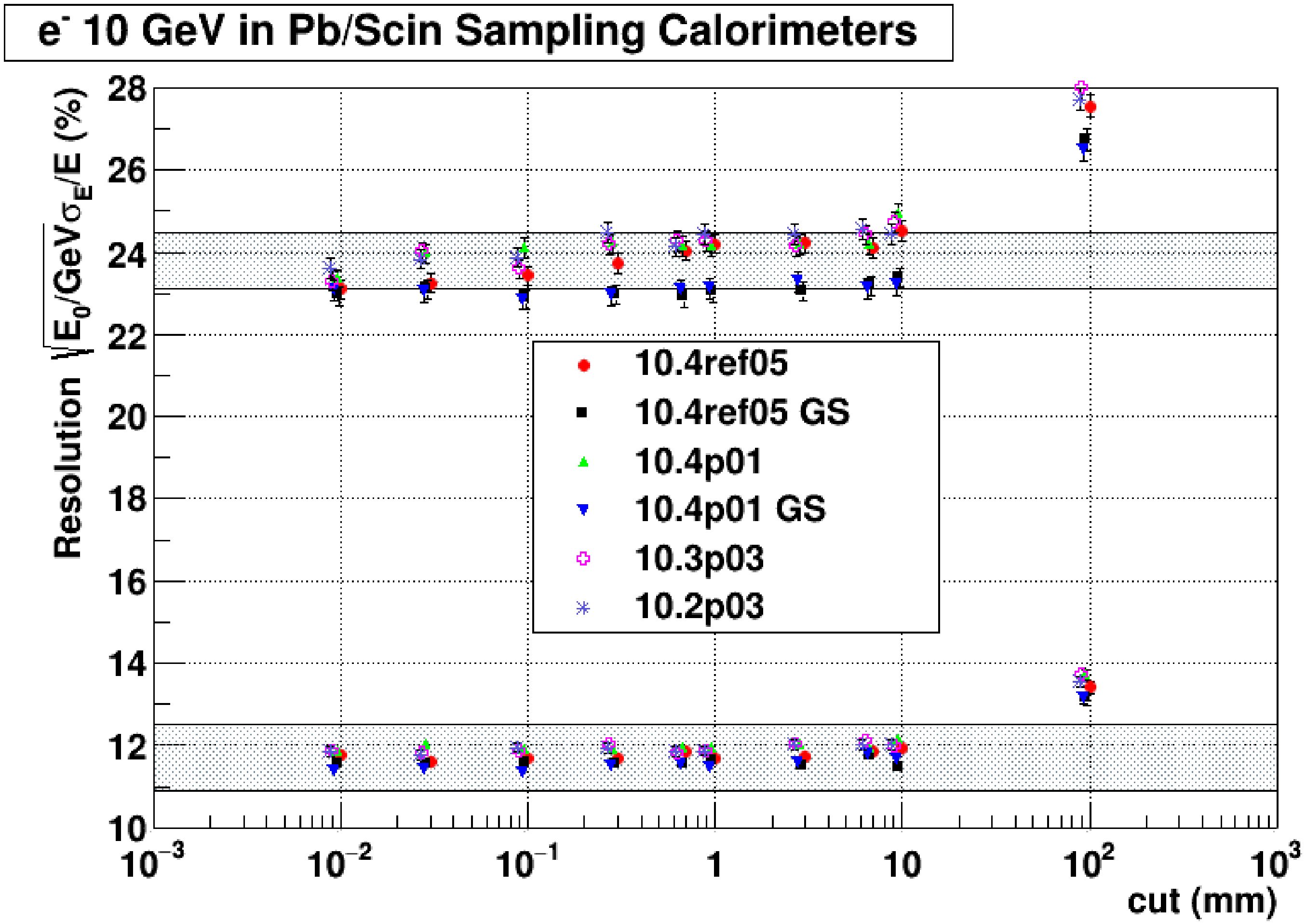
Geant4 EM main references

- **Recent progress of Geant4 electromagnetic physics for calorimeter simulation**. *S. Incerti, V. Ivanchenko and M. Novak*, 2018 Published in JINST 13 C02054.
- **Recent progress of GEANT4 electromagnetic physics for LHC and other applications.** *A. Bagulya et al.,* 2016. Published in J. Phys: Conf. Ser. 898: 042032, 2017.
- **Geant4 Standard and Low Energy electromagnetic libraries.** *V. Ivanchenko and S. Incerti* 2016. Published in EPJ Web of Conferences 142: 01016, 2017.
- **Recent Developments in Geant4.** *J. Allison et al., by the Geant4 Collaboration.*, Nucl. Instrum. Meth. A 835, 186-225, 2016.
- **Progress in Geant4 electromagnetic physics modeling and validation.** *J. Apostolakis et al.,* 2015. Published in J. Phys: Conf. Ser. 664: 072021, 2015.
- **Recent Improvements in Geant4 Electromagnetic Physics Models and Interfaces**. *V. Ivanchenko et al.,* Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 2, pp.898-903, 2011.
- **Geometry and physics of the Geant4 toolkit for high and medium energy applications.** *J. Apostolakis et al.*, Radiation Physics and Chemistry 78: 859-873, 2009.

Electron energy resolution in simplified ATLAS HEC as a function of beam energy for different Geant4 versions and EM physics



Electron energy resolution in simplified Pb/Sc calorimeters of two configurations as a function of the cut in range for different Geant4 versions and EM physics configurations



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 substantially slower than the default
    - Is recommended for R&D and detector performance studies
- 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 PAI ionization model may be defined for or more G4Region(s)
    - This feature is used by ALICE and CMS

EM Physics builders for HEP

- Urban multipe scattering for e^{+-} below 100 MeV only
  - WentzelVI + Single scattering above 100 MeV
- WentzelVI + single scattering for muons and hadrons
- Urban multiple scattering model for ions

Constructor	Components	Comments
G4EmStandardPhysics	Default (QGSP_BERT, FTFP_BERT…)	ATLAS, and other HEP productions, other applications
G4EmStandardPhysics_option1	Fast due to simple step limitation, cuts used by photon processes (FTFP_BERT_EMV)	Similar to one used by CMS, good for crystals, not good for sampling calorimeters
G4EmStandardPhysics_option2	Fast due to simple step limitation, updated photon models and bremsstrahlung angular generator	Similar to one used by LHCb

EM Physics for Accurate Simulations

- Focus on accuracy instead of maximum simulation speed
- Ion stopping model based on the ICRU'73 data
  - Step limitation for multiple scattering using UseDistanceToBoundary option
- 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 for all particles	Proton/ion therapy
G4EmStandardPhysics_option4	The best combination of models per particle type and energy range, Goudsmit-Saunderson multiple scattering model for e+- below 100 MeV with error free stepping approach	Goal to have the most accurate EM physics
G4EmLivermorePhysics	Livermore models for γ, e^- below 1 GeV, Standard models above 1 GeV	Livermore low-energy electron and gamma transport
G4EmPenelopePhysics	Penelope models for γ, $e^{\pm}$ below 1 GeV, Standard models above 1 GeV	Penelope low-energy $e^{\pm}$ and gamma transport

Special EM Physics List Constructors

Constructor	Components	Comments
G4EmStandardPhysicsGS	Goudsmit-Saunderson multiple scattering model for e+- below 100 MeV	May be considered as an alternative to standard Opt0
G4EmStandardPhysicsWVI	WVI + SS combination	Is good for high energy interactions
G4EmStandardPhysicsSS	Single elastic scattering for all charged particles	Mainly for validation and verification
G4EmLowEPPhysics	Monarsh University Compton scattering model, WVI-LE model, potentially GS model	Used new low-energy models
G4EmLivermorePolarized	Polarized gamma models	An extention of Livermore physics

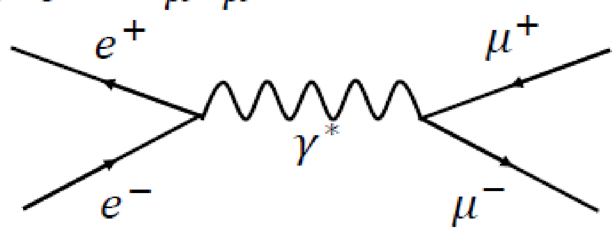
High energy positron annihilation

- High energy positron annihilation
  - — In high energy physics, incident e^+ would annihilate with atomic e^- by the following processes[1].
  - — these processes may provide a background to the interaction region of linear collider(for example, CLIC) or to search for new physics at LHC.

Processes

$$e^+e^-$$
$$\rightarrow \gamma\gamma$$
$$\rightarrow \mu^+\mu^-$$
$$\rightarrow \pi^+\pi^-$$
$$\rightarrow \pi^+\pi^-\pi^0$$
$$\rightarrow K^+K^-$$
$$\rightarrow K_L K_S$$
$$\rightarrow \eta\gamma$$
$$\rightarrow \pi^0\gamma$$

ex) $e^+e^- \rightarrow \mu^+\mu^-$



PDG data