Geant4 Gamma Transport

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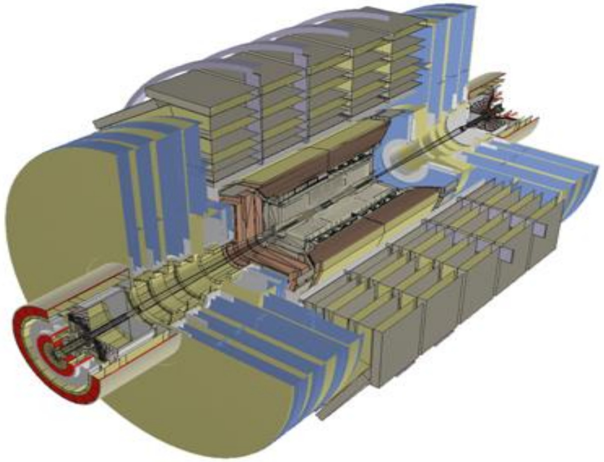
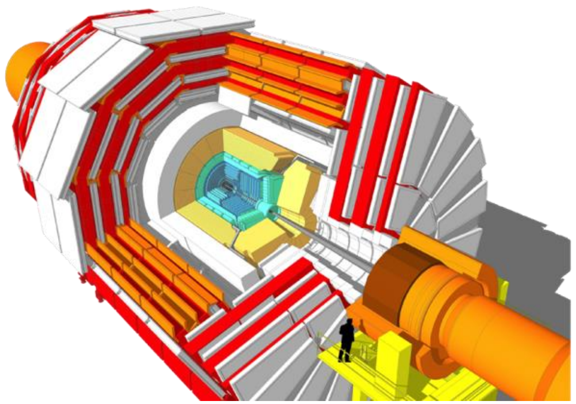
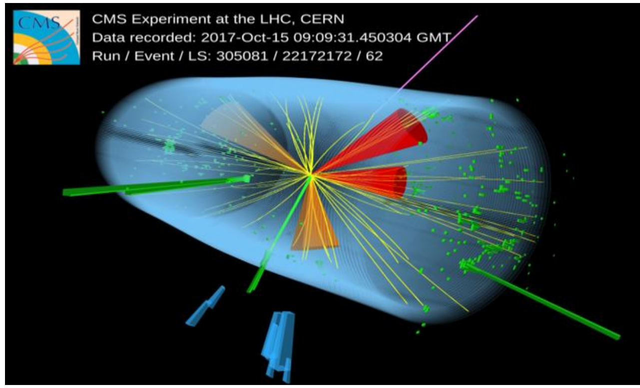
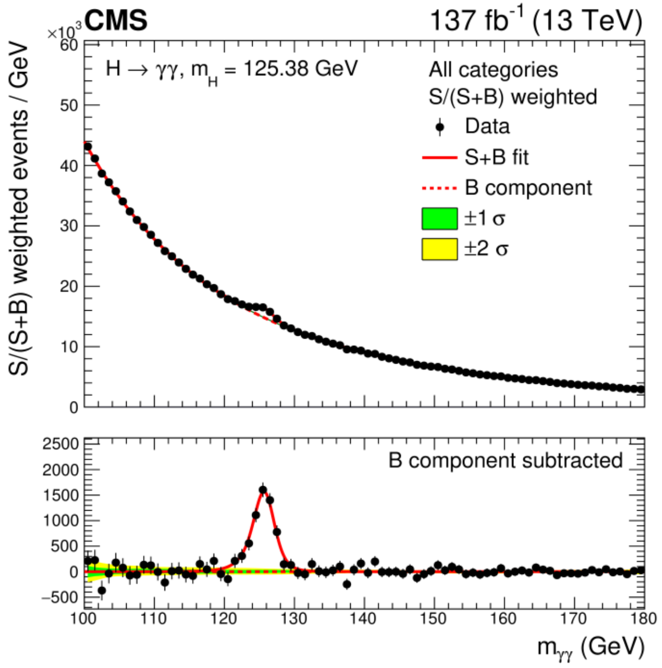
Outline

- Introduction to Geant4
- Geant4 physics
- Electromagnetic (EM) gamma processes
- Gamma nuclear process
- Summary









The Geant4 toolkit

https://geant4.web.cern.ch/

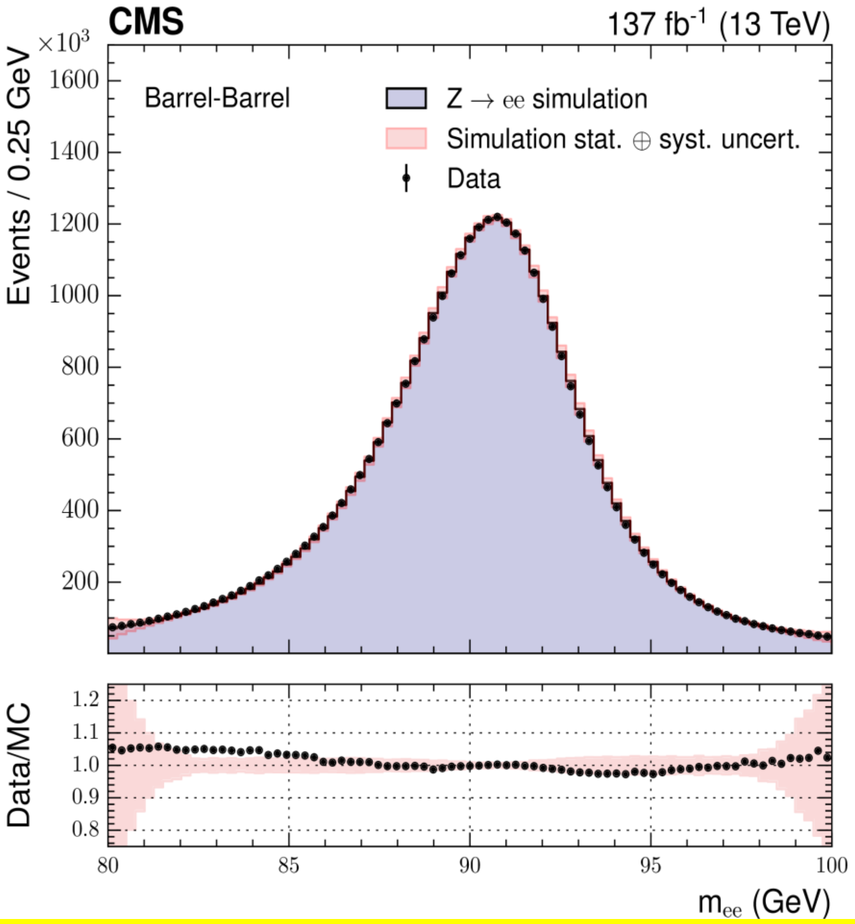
- Geant4 History
  - Early discussions at CHEP 1994 @ San Francisco CERN & Japan seeded R&D proposal
  - Dec '94 –R&D project start
  - Dec '98 -First Geant4 public release -version 0.0
  - 1999: Used to simulate X-ray mission in ESA's XMM mission
  - 2001: Babar (SLAC) uses Geant4 in production
  - …..
  - 2004: ATLAS, CMS, and LHCb start using Geant4 in production
  - Dec 2013 – version 10.0 – 1st with multi-threading
  - Dec 2020 - version 10.7 completed 10 series
  - Dec 2021 – Geant4 11.0
- Main publications
  - Nucl. Instr. Meth. **A 506**, 250-303 (2003).
  - IEEE Trans. Nucl. Sci. **53**, 270-278 (2006).
  - Nucl. Instr. Meth. **A 835**, 186-225 (2016).

- Object oriented design and C++ allow to have a flexible code organisation
  - New components may be added without affecting other part of exiting code
  - User may be a developer
- Geant4 developments are strongly supported by HEP community
  - Support of the LHC experiments for the Geant4 Collaboration is the top priority
- Other communities also significantly contribute to Geant4 developments
  - Space science
  - Medical
  - Nuclear physics
- All Geant4 user communities benefit of common developments of the toolkit

Geant4 physics

- Main physics processes are
  - Electromagnetic
  - Hadronic
  - Decay
  - Optical
- Combined approach
  - Theory based cross sections and final state sampling
  - Parametrisations based on evaluated data and theoretical computations
  - Data driven models and cross sections
- Geant4 distribution includes
  - Source code
  - Example applications (~300)
  - Data files for EM and hadronic physics

- Abstract interfaces for physics allows integrating all physics components in one run
- Main entities for Geant4 physics
  - Particles
  - Processes
  - Models
- EM cross sections and final state generators are coupled together in EM process and model classes
- Hadronic cross sections are implemented in separate classes independent on final state generators
  - Alternative final state generators may use the same cross sections
- Accuracy of gamma cross sections and final state sampling is defined by the accuracy
  - of theory and values of high-level corrections not considered in a model – HEP
  - Of evaluated data – low-energy



http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-19-015/index.html

Geant4 gamma processes

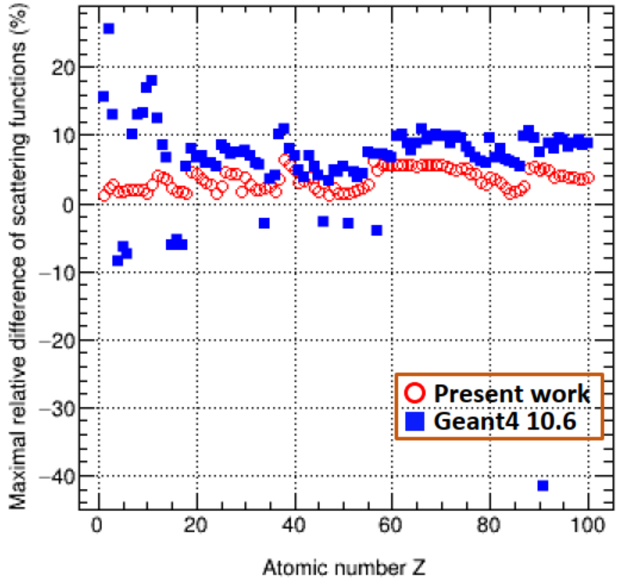
- EM gamma processes
  - Photo effect
  - Compton scattering
  - Gamma conversion
  - Rayleigh scattering
  - Gamma conversion into muon pair
- Different sub-libraries
  - Standard – HEP oriented
  - Livermore – data driven models based on EPDL97 evaluated data (D. Cullen, J.H. Hubbell, L. Kissel, The Evaluated Photon Data Library 97. UCRL-50400. 1997)
  - Penelope-2008 rewritten in C++ (F. Salvat, J.M. Fernandez-Varea, J. Sempau, OECD-NEA Report 6416 (2009))
  - Polarisation – for transport of circular polarized beams

- Recent developments for EM gamma physics
  - 5D model for gamma conversion – Geant4 10.5
  - Extension gamma conversion to muon pair down to production threshold – Geant4 10.6 (V.Ivantchenko et al., EPJ Web of Conferences 214, 02046 (2019))
  - Migration of the Livermore gamma models to EPICS2017 cross sections – Geant4 11.0 (Zhuxin Li et al., Physica Medica 95, 94-115 (2022))
  - Providing optional linear gamma polarization option for all gamma processes – 11.0
  - Providing simulation of Quantum entanglement in positron annihilation (D.P. Watts et al. Nature Commun. 12 (2021) 1, 2646; arXiv: 2012.04939v1)
- Geant4 11.0 developments for gamma-nuclear
  - Implemented IAEA-2019 DB based cross section in the Giant resonance energy region (B. Kutsenko, https://cds.cern.ch/record/2778865/files/Kutsenko_report.pdf)

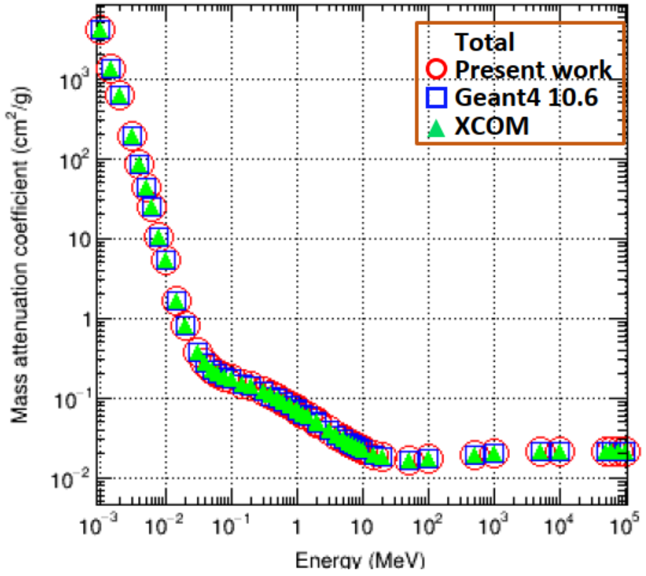
Implementation of the EPICS2017 database for photons in Geant4

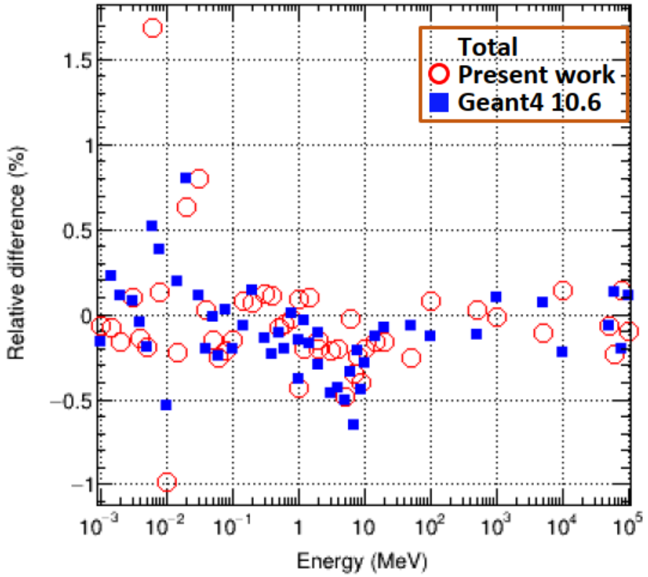
Zhuxin Li et al., Physica Medica 95, 94-115 (2022)

Compton scattering



Gamma attenuation

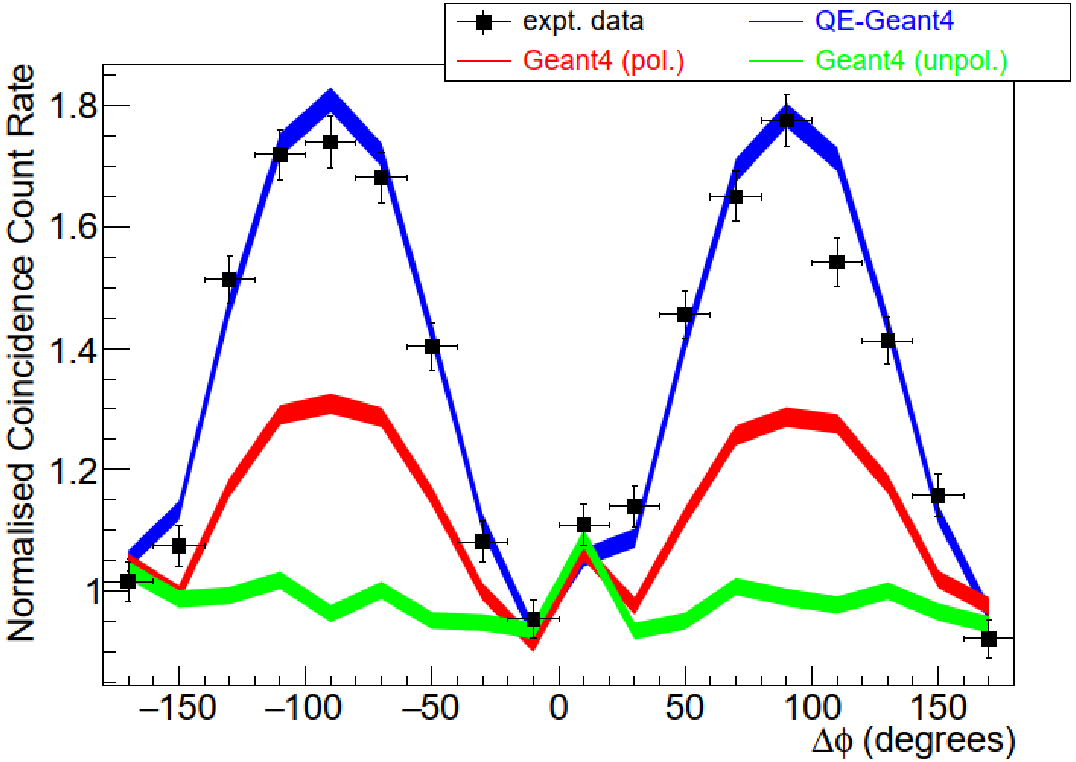


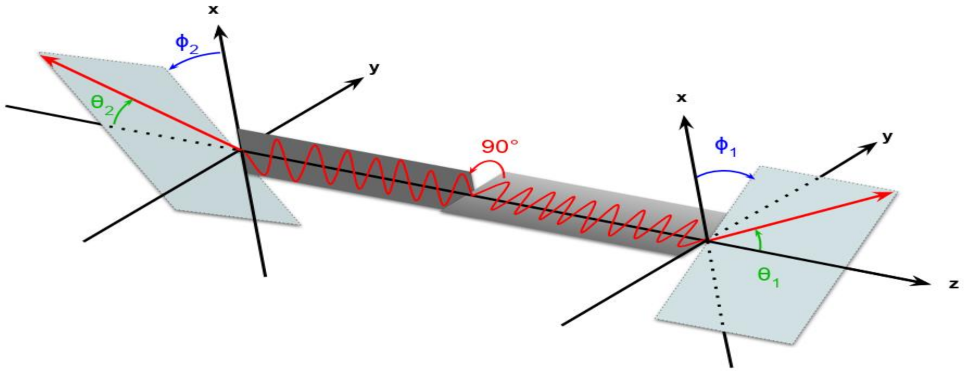


- EPICS-2017 data for cross sections and form factors are parameterized or used as a data table
  - In average accuracy of the new parameterisation is better for about 30%
- Validation performed versus XCOM and SCOFIELD
  - D.E. Cullen, A survey of photon cross section data for use in EPICS2017. IAEA-NDS-225, rev 1, 2018

Quantum entanglement in positron annihilation

D.P. Watts et al. Nature Commun. 12 (2021) 1, 2646; arXiv: 2012.04939v1



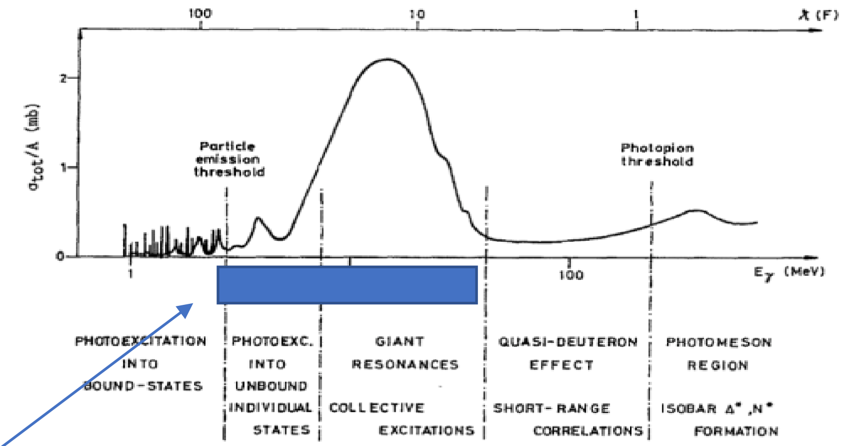


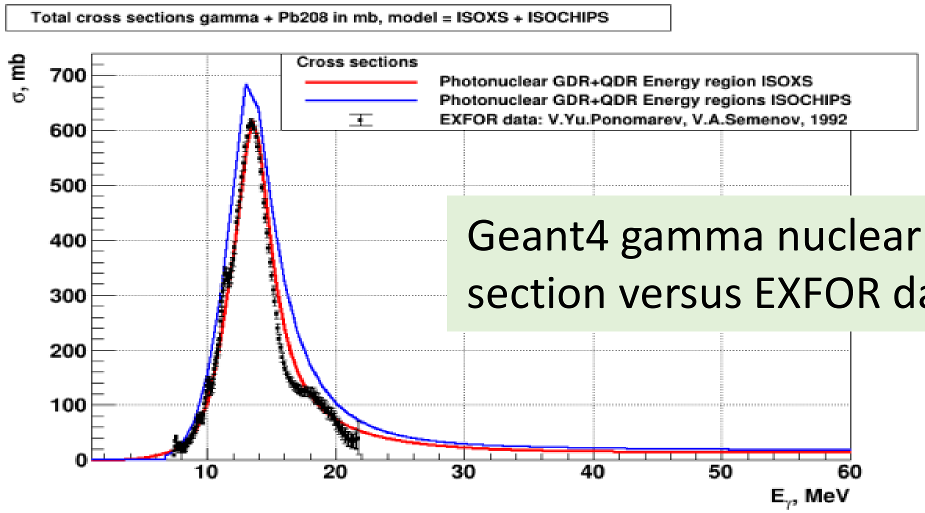
- There is angular correlation for Compton scattering of two photons in PET device
- The developed method may be potentially used in HEP (Higgs->2γ decay) and other applications

Gamma-nuclear cross section

https://cds.cern.ch/record/2778865/files/Kutsenko_report.pdf

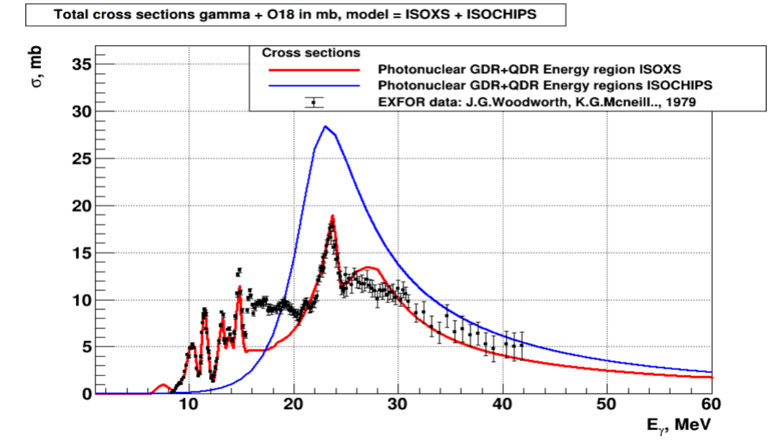
- Several different mechanisms are responsible for gamma-nuclear cross section
  - For a long time in Geant4 CHIPS parameterization was used for full energy range above 10 MeV (NIM A 835, 186-225 (2016))
- Recently a new evaluation of the data was published (T. Kawano et al, IAEA photo nuclear data library2019.Nuclear Data Sheets,163,109-162 (2020))
  - A new data set has been included into Geant4 11.0 per natural isotope
  - Data tables from threshold to 130 MeV
  - CHIP interpolation above 150 MeV
  - Linear interpolation in the transition energy range

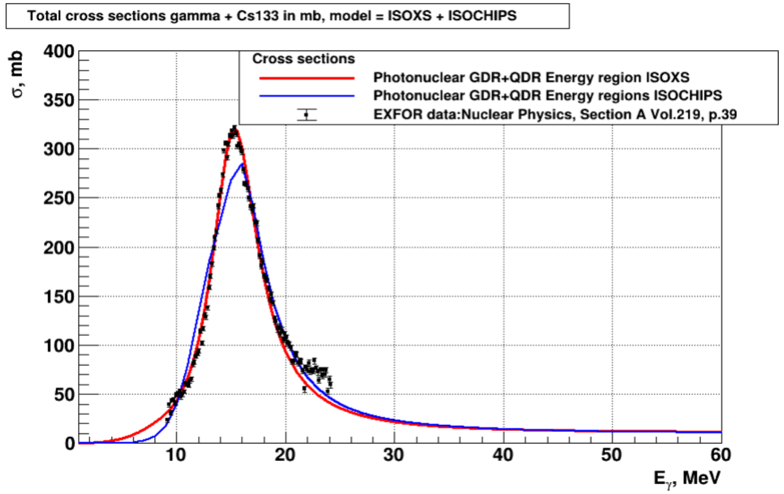


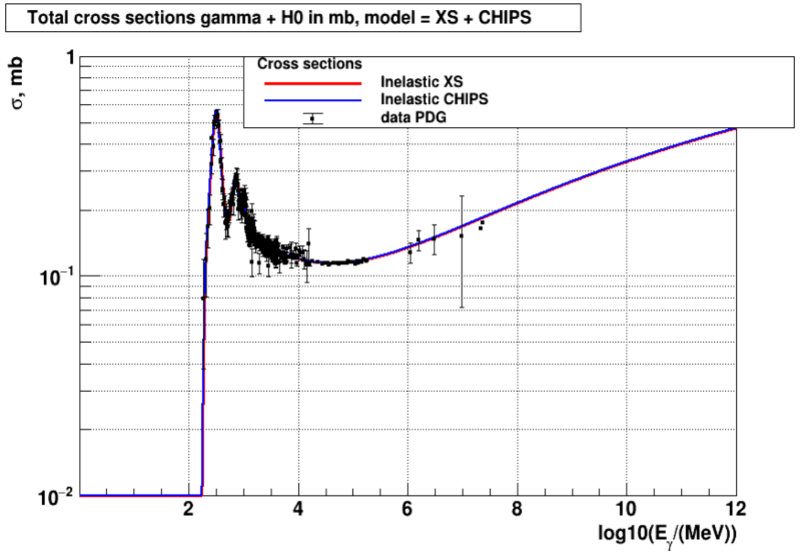


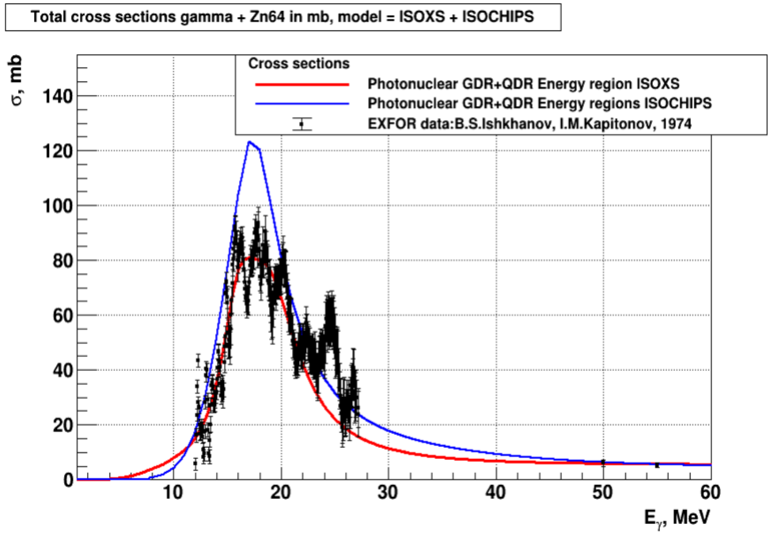
Geant4 gamma nuclear X-section versus EXFOR data

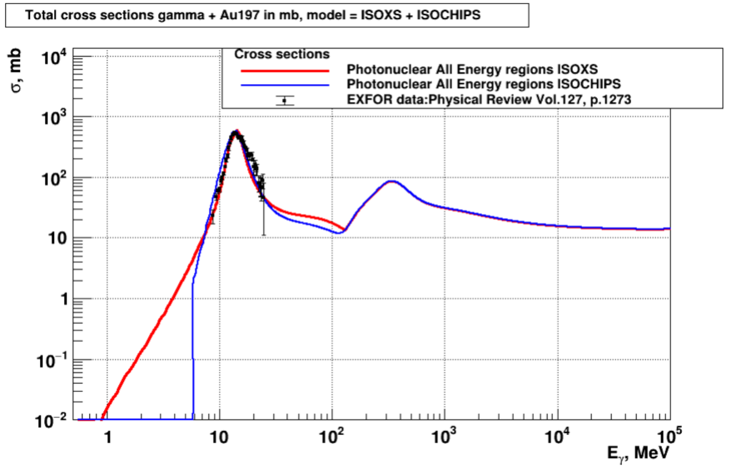
Gamma-nuclear cross section











- Tabulated data for low-energy is the best approach
- New ICRU-2019 data are available for a good part of natural isotopes
- Validation was performed versus EXFOR data and PDG data

Thank you!

Summary

- The Geant4 toolkit [1-3] is the main engine for the Monte Carlo simulation of particle transport for experiments at the Large Hadron Collider. The toolkit was designed also considering many other applications domains, including medical, space, and nuclear physics. Geant4 is a free, open-source software, which is maintained by the international collaboration [4]. Geant4 is based on an object-oriented approach and is implemented in C++.
- The Geant4 components for the gamma transport include photo-electric effect, gamma conversion, Compton scattering, Rayleigh scattering, and gamma-nuclear. There are one or several alternative models used for different energy ranges and having different accuracy. For the main electromagnetic gamma processes there are three groups of models: standard [1], Livermore (based on EPDL97 [5]), and Penelope (rewrite of Penelope-2008 [6]).
- For Geant4 10.5 (December 2018), 5-D gamma conversion model to electron-positron pair has been implemented [7], later the model of muon pair conversion was extended down to the threshold [7], and for the recent release 11.0 (December 2021) production of tau-lepton pair was added. For the recent Geant4 11.0, Livermore gamma models were improved by optional addition of EPICS2017 data [8], which includes more accurate cross sections and form factors. The handling of the linear polarization of gamma may be enabled on top of any physics configuration. For the first time the simulation of quantum entanglement in positron annihilation has been implemented [9].
- Geant4 gamma-nuclear cross section was parameterized in the full energy range and used for a long time. It has been updated [10] for Geant4 11.0 using the recent data from the IAEA database [11, 12]. New data are included into Geant4 G4PARTICLEXS4.0 dataset for all isotopes. For isotopes, which are not present in the IAEA database, the previous Geant4 parameterisation is used. In the new gamma-nuclear cross section class, a data table is built below 130 MeV. This is then connected to the existing Geant4 parameterisation, which are applied above 150 MeV, via linear interpolation at in the transition energy range. This approach allows a good reproduction the cross section in the energy ranges of the Giant resonance, the delta-isobar, and above.

- References

1. The Geant4 Collaboration (S. Agostinelli et al.), Nucl. Instr. Meth. A 506, 250-303 (2003).
2. J. Allison et al., IEEE Trans. Nucl. Sci. 53, 270-278 (2006).
3. J. Allison et al., Nucl. Instr. Meth. A 835, 186-225 (2016).
4. https://geant4.web.cern.ch/
5. D. Cullen, J.H. Hubbell, L. Kissel, The Evaluated Photon Data Library 97. UCRL-50400. 1997, 6.
6. F. Salvat, J.M. Fernandez-Varea, J. Sempau, OECD-NEA Report 6416 (2009).
7. V. Ivanchenko et al., EPJ Web of Conferences 214, 02046 (2019).
8. Zhuxin Li et al., Physica Medica 95, 94-115 (2022).
9. D.P. Watts, J. Bordes, J.R. Brown et al., Nat. Commun. 12, 2646 (2021).
10. B. Kutsenko, https://cds.cern.ch/record/2778865/files/Kutsenko_report.pdf
11. https://www-nds.iaea.org/photonuclear
12. M. Wiedekin, D. Filipescu, and P. Dimitriou, IAEA Report INDC(NDS)-0777, IAEA, Vienna, 2019.