Developments of Geant4 physics models and user applications

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8th International Conference on Particle Physics and Astrophysics

27 -30 October 2026, Moscow

Introduction

- Laboratory of data analysis for HEP from Tomsk State Research University
  - Was created in 2017
  - Initial goals were collaboration with CERN experiments and projects
    - ATLAS, CMS, Geant4, TOTEM
  - https://hep.tsu.ru/
- Current scientific program
  - Development of data analysis methods for HEP and beyond
  - Analyses on meteo and space data using ML
  - SPD experiment at NICA
    - Electronics
    - Geometry description
    - Simulation software development
  - Simulation of radiation effects for medicine

- Contribution to Geant4 toolkit
  - Geometry developments
  - Electromagnetic physics (EM)
  - Hadronic Physics
  - Geant4-DNA
- Developments of Geant4 applications
  - Medical applications
  - Education

In this talk we discuss recent results on Geant4 physics and applications obtained

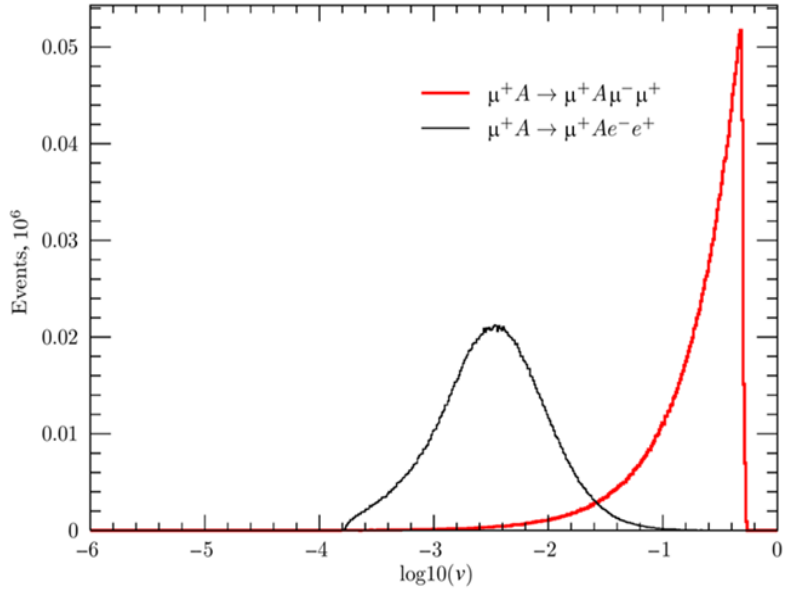
Outline

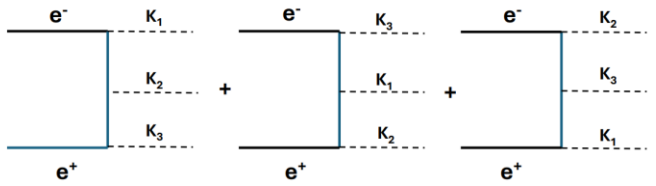
- Electromagnetic physics of Geant4
  - EM models for HEP
  - EM for medicine and Geant4-DNA
- Hadronic physics of Geant4
  - Hadronic cross sections
  - G4PARTICLEXS data set
  - Geant4 de-excitation module
- Examples of Geant4 applications
- Project GEANT4RU
- Summary

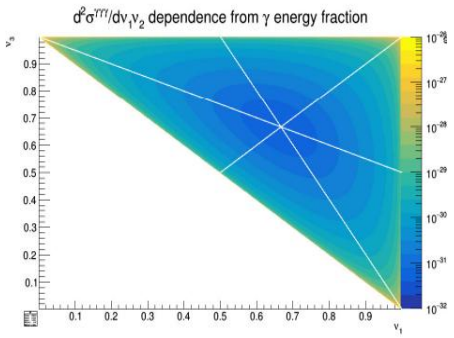


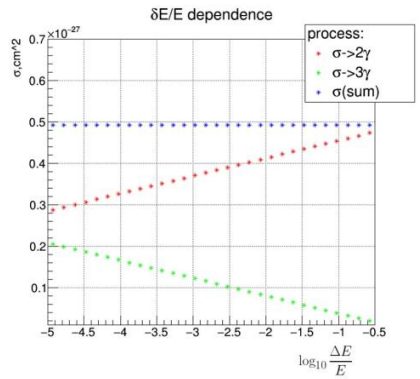
EM model developments for HEP

- Main developments for HEP are carried out to add next to leading order corrections and addition of rare EM processes
  - Precise physics analysis for Run4 and other HEP experiments
- Ionisation and multiple scattering for “unknown” changed particles
  - For exotica analysis
  - Only G4DynamicParticle is used in these Geant4 processes
- Production of $\mu^+\mu^-$ pairs by muons
  - Muon pair production has 10^{-5} smaller cross section
  - Seen in SND@LHC experiment in forward 100 m from ATLAS IP
    - S.R. Kelner et al., Phys. Atom. Nuclei 63 (2000) 1603–1611.
    - A. Bagulya et al., Russian Physics Journal 67 (2024) 2379–2382.
- 2- and 3-γ positron annihilation including positronium formation
  - ~10^{-3} effect on HEP shower shape
    - V.N. Baier et al., Physics Reports 78 (1981), 293-393.
    - A. Ore and J. L. Powell, Phys. Rev. 75 (1949) 1696
    - J. Allison et al., Radiation Physics and Chemistry 251 (2027) 114505

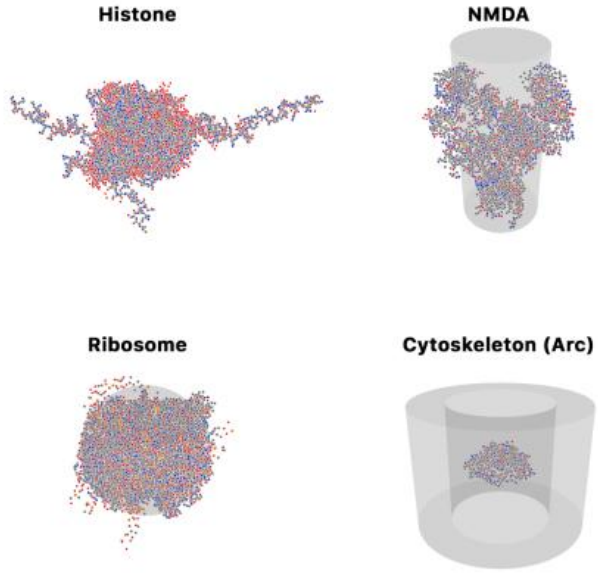




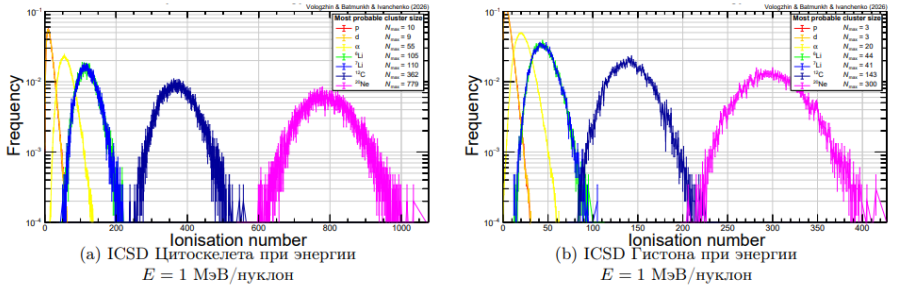




EM for medicine and Geant4-DNA



- Geant4 EM sub-libraries are applicable for applications other than HEP
- G4MED group for validation of Geant4 for medical applications
  - Medical Physics 45, e722–e739 (2018)
  - Medical Physics 48, 19-56 (2021)
  - Medical Physics Special report, 1-55 (2025)
- Geant4-DNA project
  - Simulation of alpha emitters for radiation therapy
  - Development of models for ion ionization
  - Validation of detailed track structures
  - Assessment of geometrical approximations for biomolecules



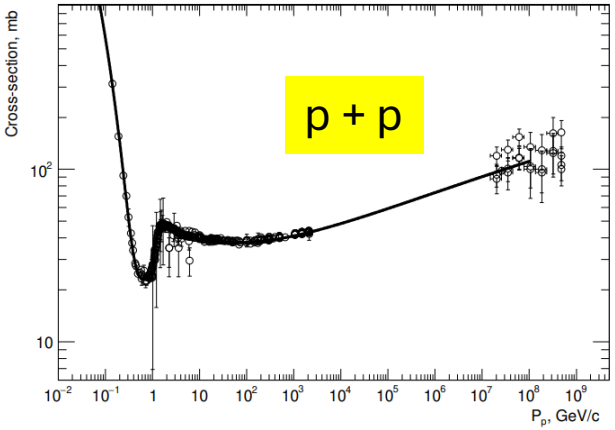
(a) ICSD Цитоскелета при энергии $E = 1$ МэВ/нуклон
(b) ICSD Гистона при энергии $E = 1$ МэВ/нуклон
(c) ICSD NMDA-рецептора при энергии $E = 1$ МэВ/нуклон
(d) ICSD Рибосомы при энергии $E = 1$ МэВ/нуклон

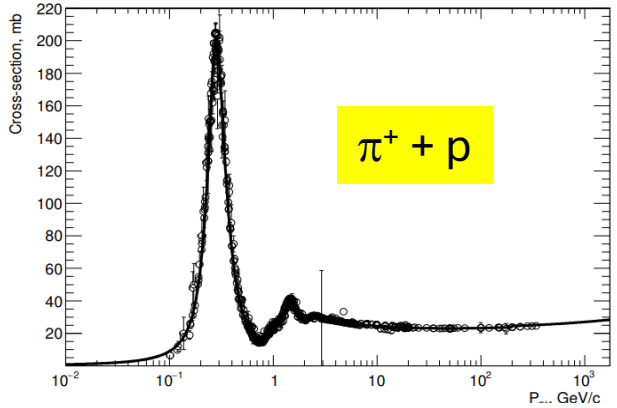
Hadronic cross sections

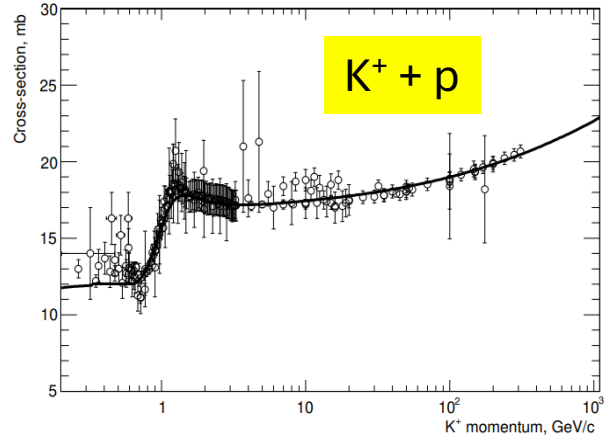
- Hadronic cross sections Geant4 are independent from models
  - Cross section can be based on theory and on data
- Evaluated data
  - JEFF-3.3 -> G4NEUTRONHPDATA - neutrons below 20 MeV
  - TENDL-2019 -> G4PARTICLEHPDATA – p, d, t, He3, He4 below 200 MeV
  - V.S. Barashenkov cross sections 1989 – n, p, pi+, pi- 20 MeV – 20 GeV
- Glauber-Gribov model
  - R. Glauber УФН 103, 642 (1971)
  - V.N. Gribov, JETP 56, 892 (1969)
  - V.M. Grichine, Eur. Phys. J. C 62 399 (2009)

$$\sigma_{tot}^{hA} = 2\pi R^2 \ln\left[1 + \frac{A\sigma_{tot}^{hN}}{2\pi R^2}\right]$$

- Contribution of TSU group to Geant4 approach for cross sections:
  - *Известия вузов. Физика. 67, 80 (2024). DOI:10.17223/00213411/67/12/10*
  - *Russ Phys J 68, 658 (2025). DOI:10.1007/s11182-025-03479-z*
  - *УФН 196, 115 (2026). DOI: 10-3367/UFNr.2025.09.040030*
  - *Physics-Uspekhi 69 (2026). DOI: 10-3367/UFNe.2025.09.040030*
  - *Russ Phys J 69, 411 (2026). DOI: 10.1007/s11182-026-03729-8*

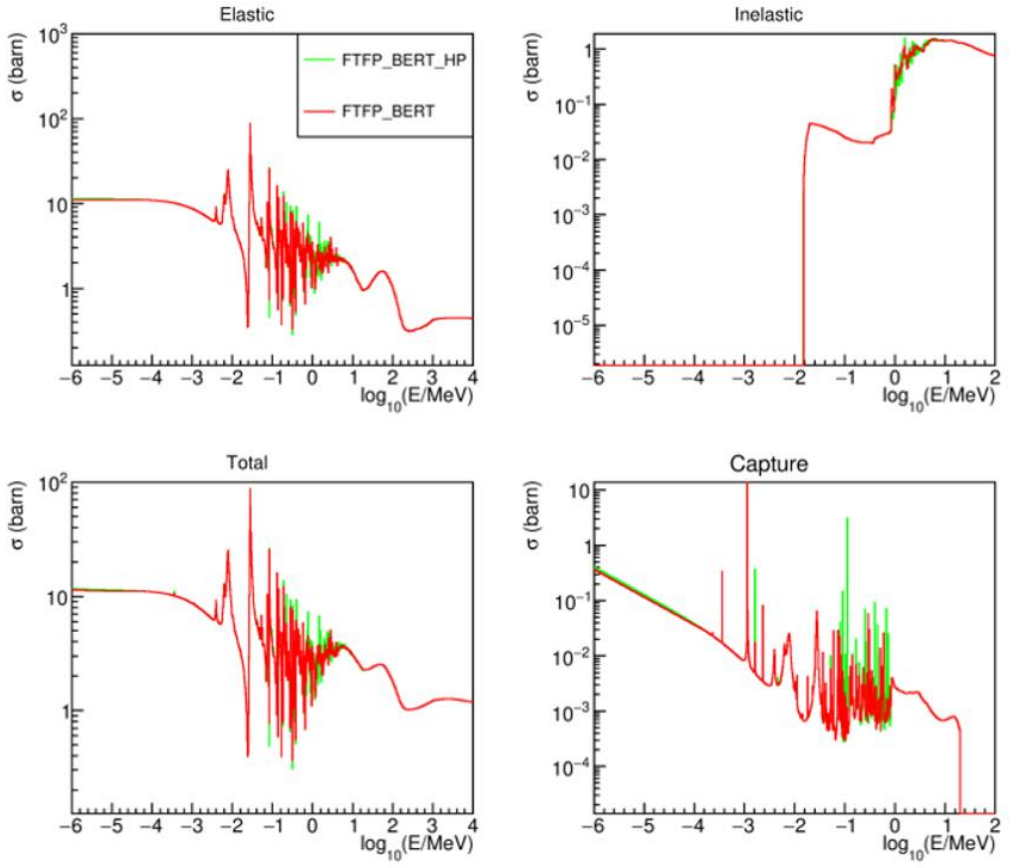






G4PARTICLEXS data structure

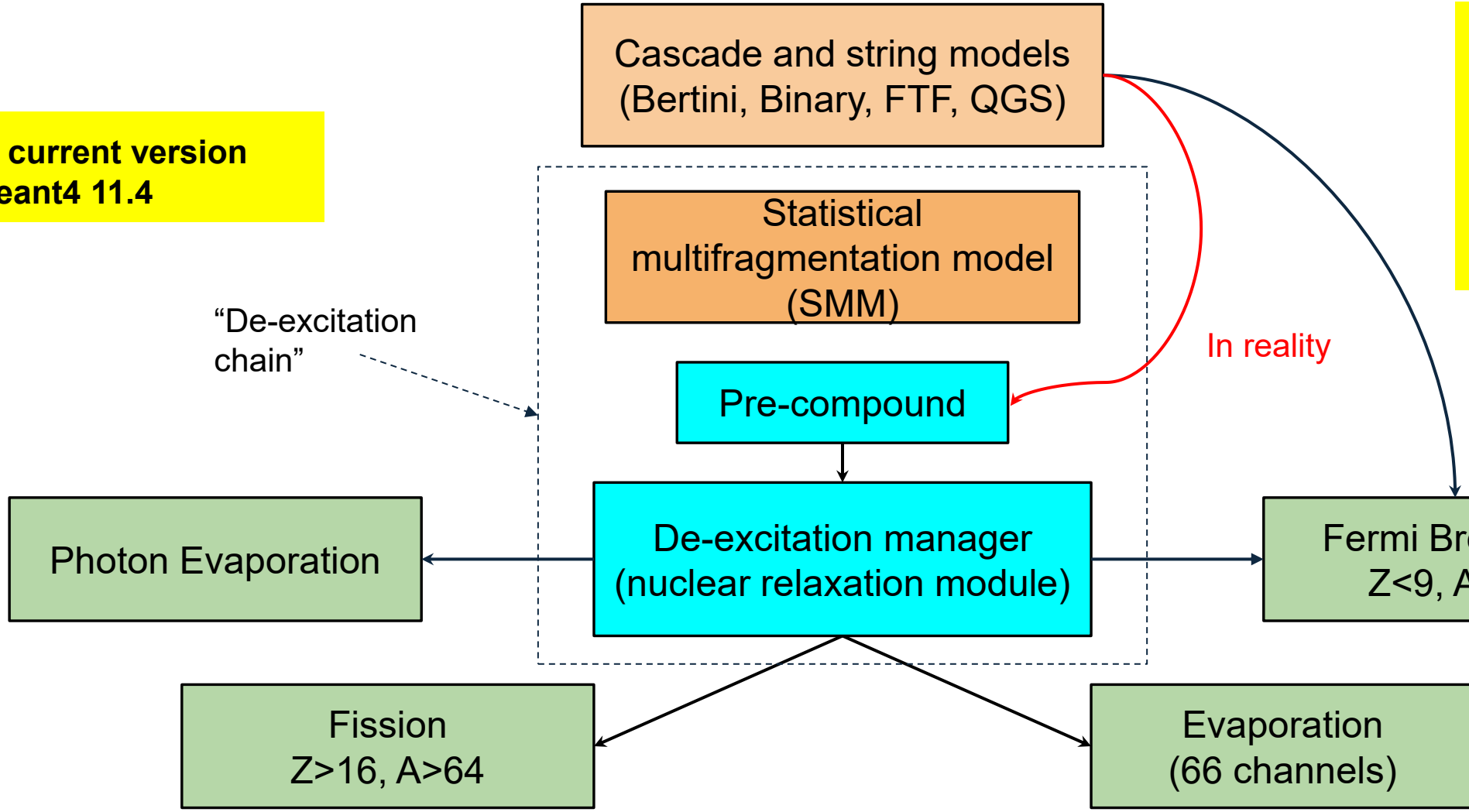
- For p, n, $\pi^{\pm}$
  - E < 20 MeV – parameterization
  - 20 MeV < E < 91 GeV Barashenkov
  - 91 GeV < E – Glauber-Gribov
- For low energy neutrons
  - G4PARTICLEHPDATA dataset is converted from JEFF-3.3
  - G4PARTICLEXSDATA produced from HP dataset
  - A new method for making this data was reported at CHEP 2026
    - Introduced extra R-files for the resonance region (different for each isotope)
    - Access to any neutron cross section is faster then in the case of HP sub-library



Geant4 11.4 – G4PARTICLEXS4.2 data set

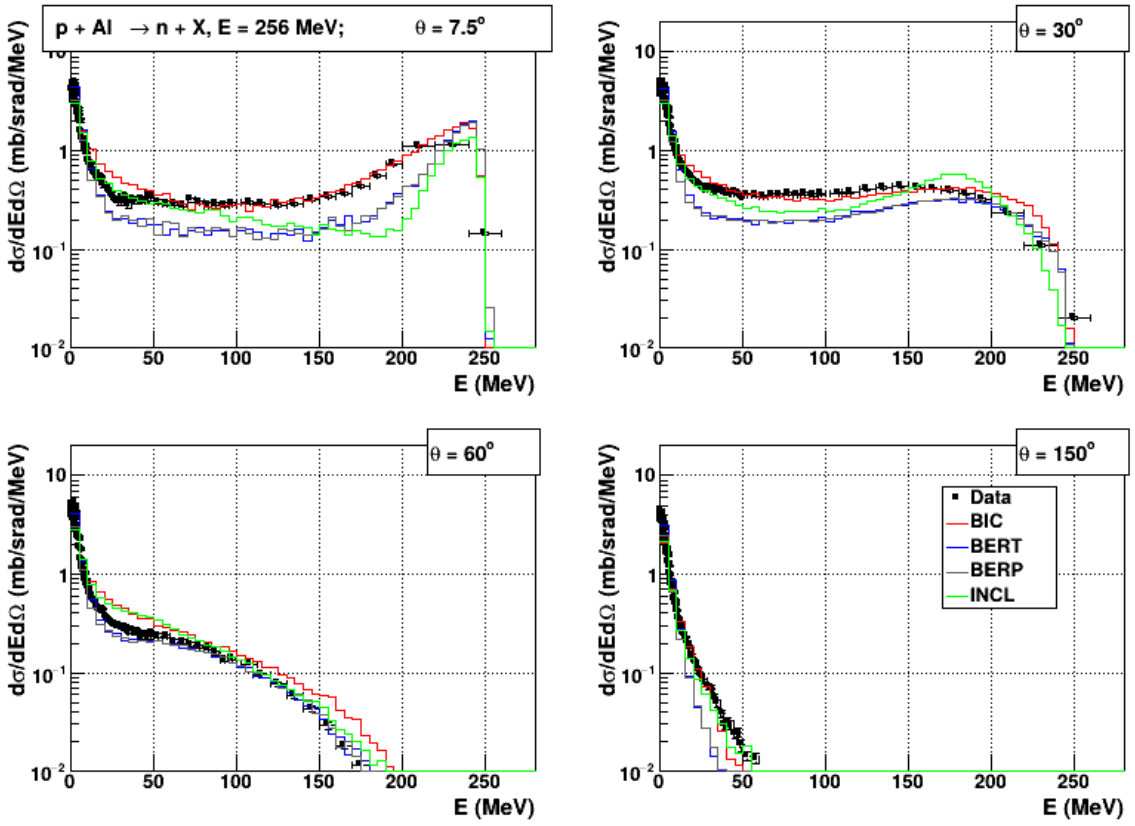
Hadronic physics models structure – TSU group contributes to different aspects of Geant4 hadronic physics

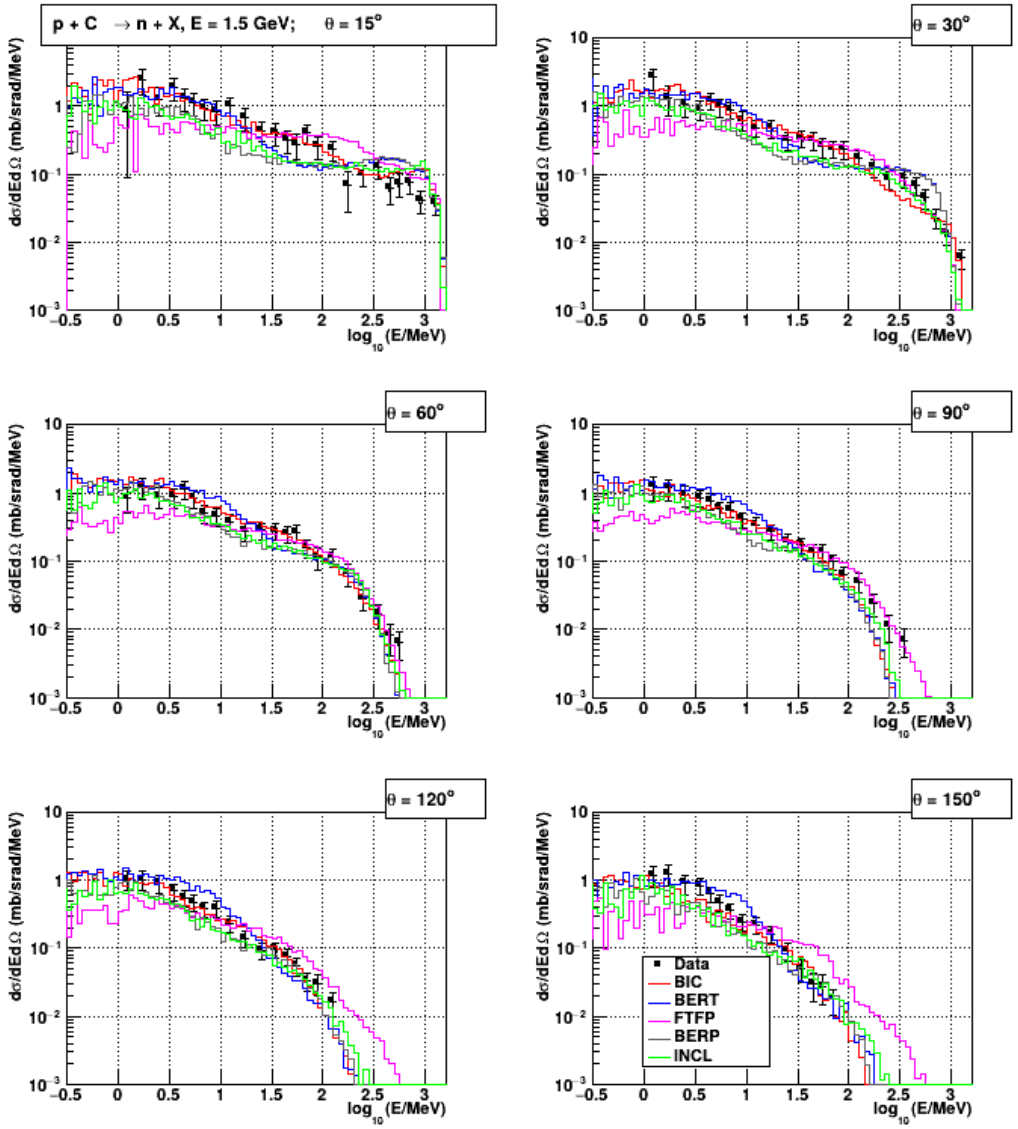
In current version Geant4 11.4



For Physics lists, in which native de-excitation is used: FTFP_BERT, QGSP_BIC, QBBC, etc.

Double differential cross section of neutron production by proton beam

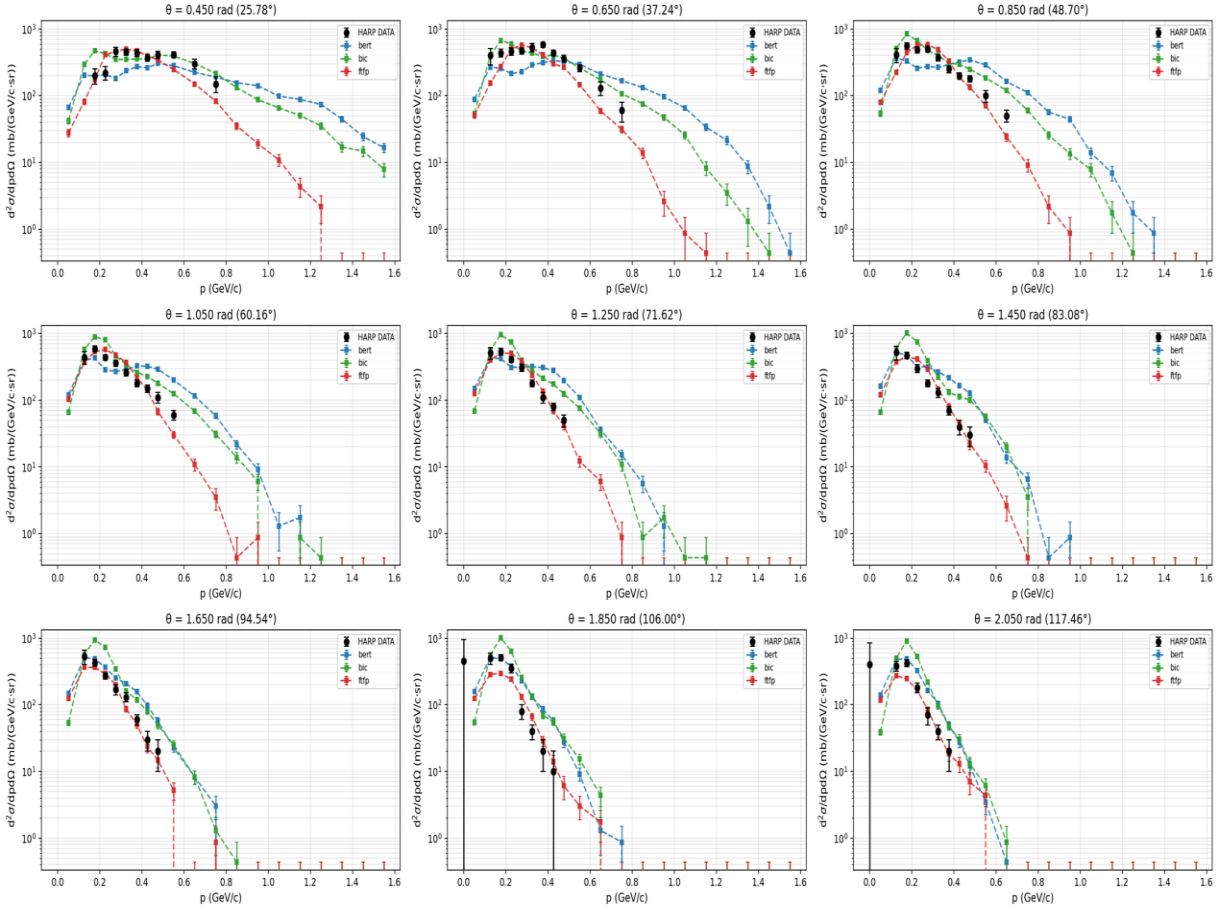




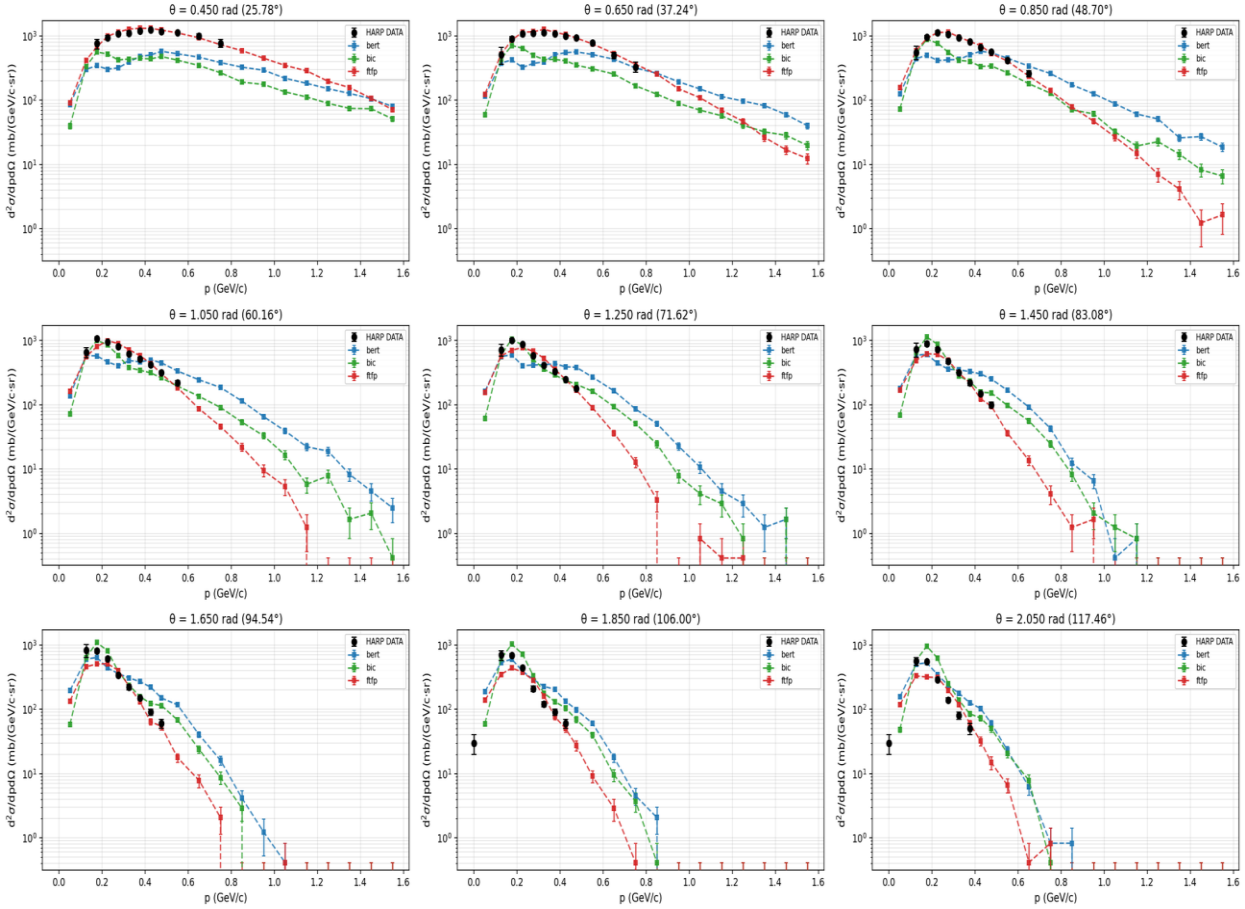
The Binary cascade better reproduce the data at low beam energy and provide similar predictions at 1.5 GeV as the Bertini cascade and INCL++. FTF string model is not as accurate as cascades at 1.5 GeV

Double differential cross section p + Cu ->X + π^+ for E_{kin} = 3 GeV and 8 GeV
HARP data versus Geant4 cascade and string model predictions for 26-118 degrees

Protons 3 GeV



Protons 8 GeV

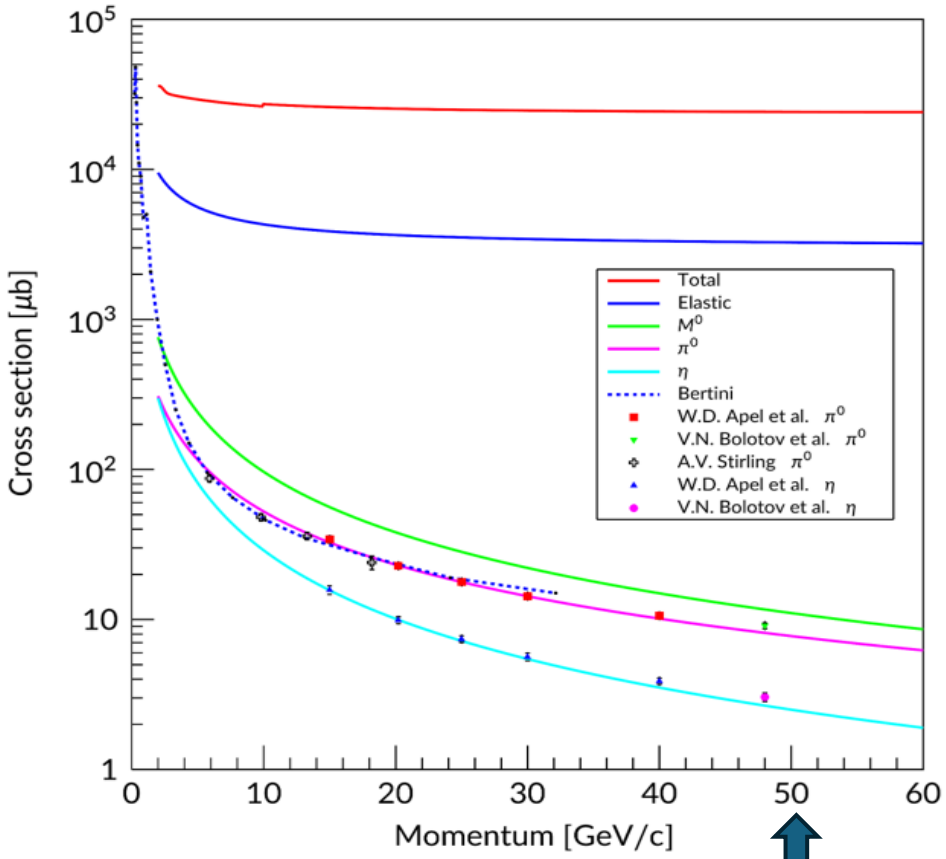


FTF string model (red) fit the data at 8 GeV and is competitive to the cascades (blue – Bertini, green - Binary) at 3 GeV

Charge Exchange processes for light mesons

- Considered meson-nucleon reactions
  - $\pi^- + p \rightarrow M^0 + n$, $M^0 = \pi^0, \eta, \eta', \omega(782), f2(1270)$
  - $\pi^+ + n \rightarrow M^0 + p$
  - $K^- + p \rightarrow K^0 + n$
  - $K^0_L + p \rightarrow K^+ + n$
  - $K^0_L + n \rightarrow K^- + p$
- The main goal of this development is to provide simulation of background for NA64 experiment at 50 GeV for the dark matter search in invisible decay of neutral mesons produced in reaction
  - $\pi^- + A \rightarrow M^0 + A'$
- A new dedicated Physics List component is created to be applied on top of any Geant4 Physics List
  - Enabled for meson energy above 12 GeV to avoid double counting with the Bertini cascade
  - Charge exchanged cross section may be enhanced by a factor
    - Factors for pions and kaons are independent
- Comp. Phys. Comm. 321 (2026) 110033. DOI:10.1016/j.cpe.2026.110033

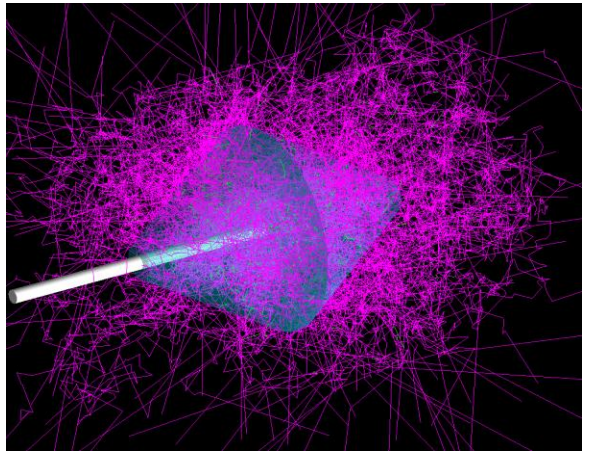
Cross section $\pi^- + p$

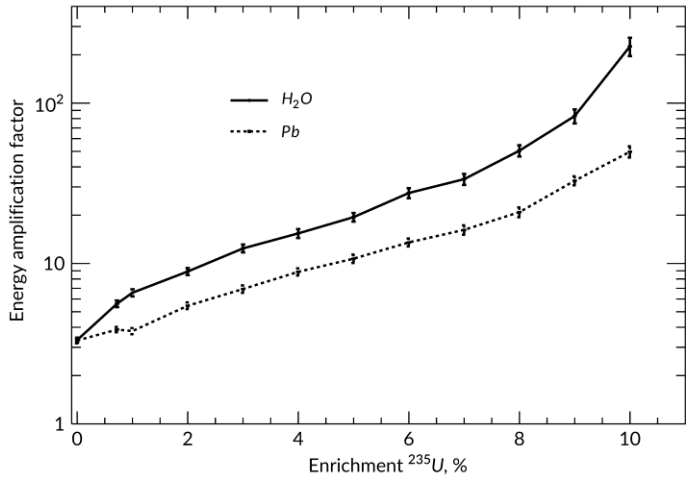


NA64

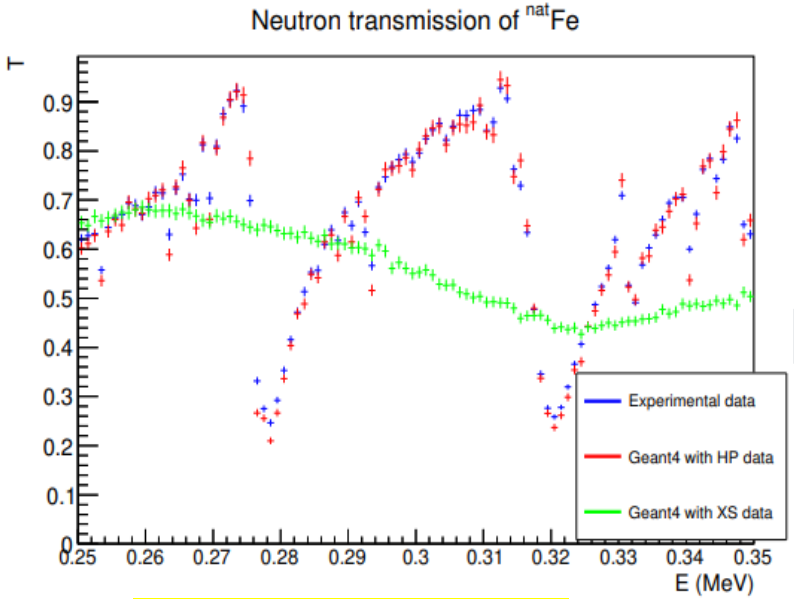
Examples of Geant4 applications

- «Моделирование выхода медицинских изотопов на электро-ядерной установке». Краткие сообщения по физике ФИАН 11 (2024).
- “GEANT4 simulation of accelerator driven system”. Russ Phys J, (2025). DOI : 10.1007/s11182-025-03495-z

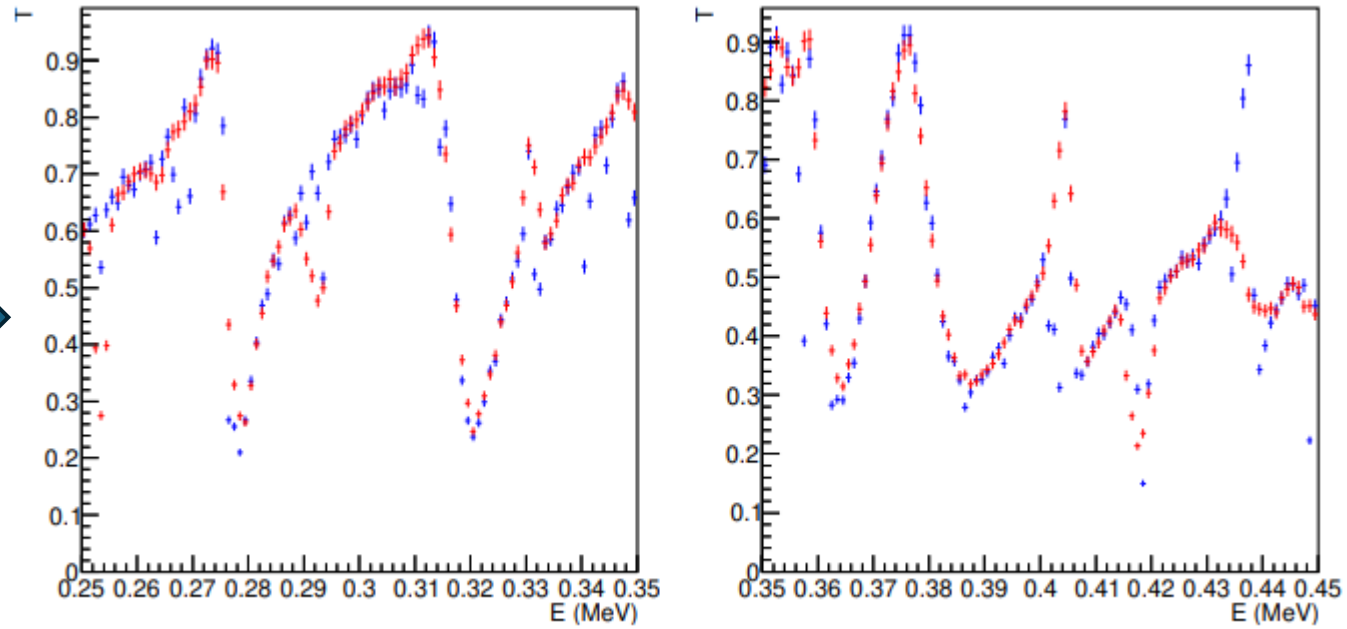




Comparisons of neutron transmission probability based on nELBE data



G4PARTICLEXS4.1

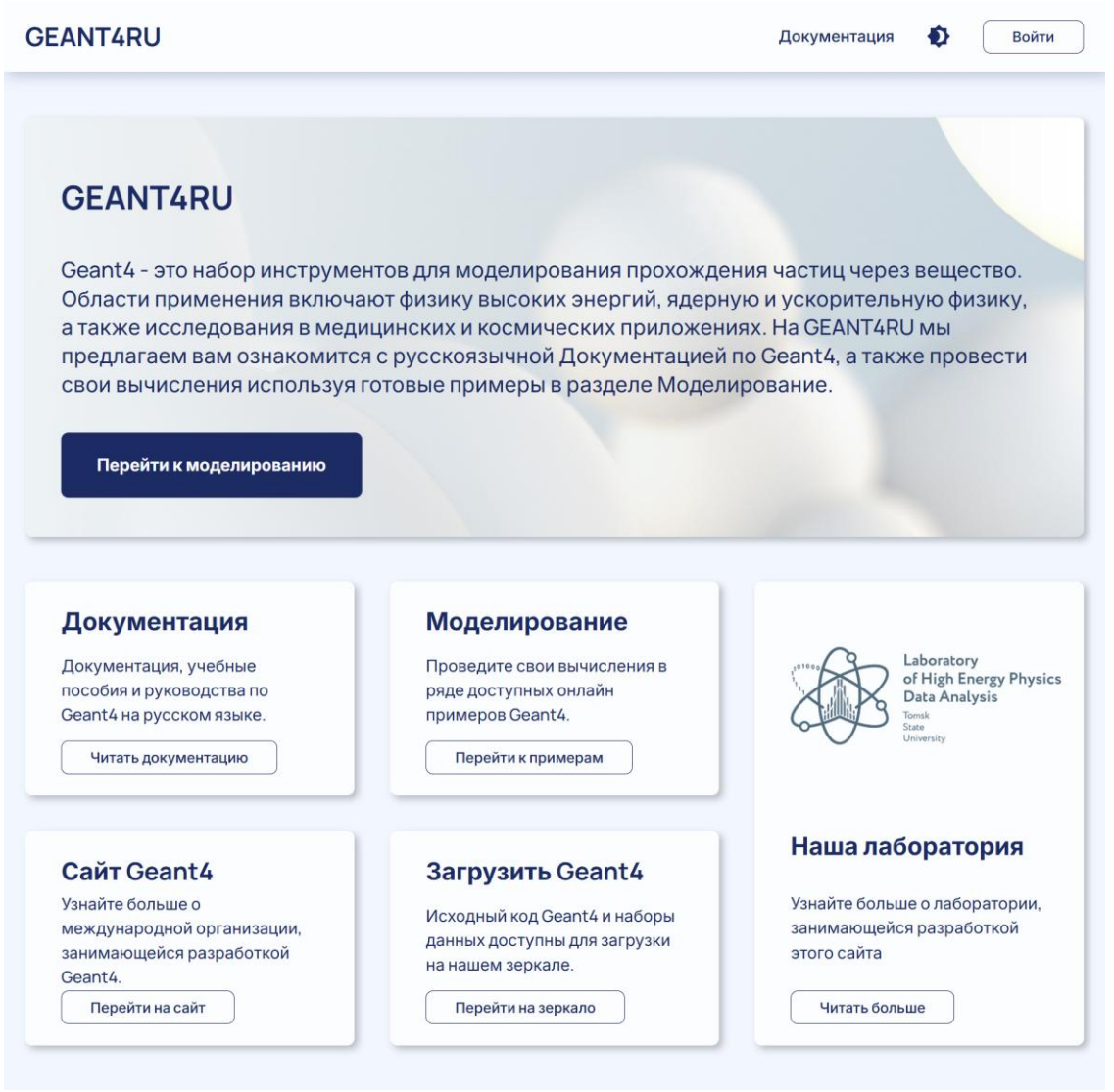


G4PARTICLEXS4.2, 4.3

- Data:
  - EPJ Web of Conferences 239, 01006 (2020). DOI:10.1051/epjconf/202023901006
  - Research Data for ANE 218 (2025) 111363) (2025). DOI:10.14278/rodare.3963
- New versions of G4PARTICLEXS4.2 and 4.3 allows to have an accurate transmission probability for the Geant4 default Physics Lists (FTFP_BERT, QBBC, and others) – CHEP 2026 report

Project GEANT4RU

- The project was lunched by TSU
  - Help for Russian users of Geant4
  - Support education programs
- Beta version is already available
  - https://geant4.hep.tsu.ru
- Components
  - Russian manuals
  - Useful links
  - Online computations
    - Attenuation coefficients for gamma
    - dEdx for charged particles
    - Ranges for charged particles
    - Hadronic cross sections
    - Shower profile in a uniform media



Summary

- Several developments for the Geant4 toolkit was carried out by TSU group
  - Rare QED processes
  - Geant4-DNA
  - Cross sections
  - Pre-compound/de-excitation of nuclei
- We assume that our developments will be useful for NICA and other applications
- Obtained results are verified using published data
  - Several applications are created
- The beta-version of GEANT4RU portal is available

Geant4 11.4.3 validation results

GEANT4RU-beta

The work is supported by a grant from the Government of the Russian Federation

(Agreement No. 075-15-2025-009 of 28 February 2025)