Applications of Geant4 simulation methods in studies of nuclear processes

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Outline

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- Low-background underground laboratory
- Measurements of the cosmic-ray muon intensity
- Simulations of the cosmic-ray induced background
- Simulations in gamma spectroscopy measurements
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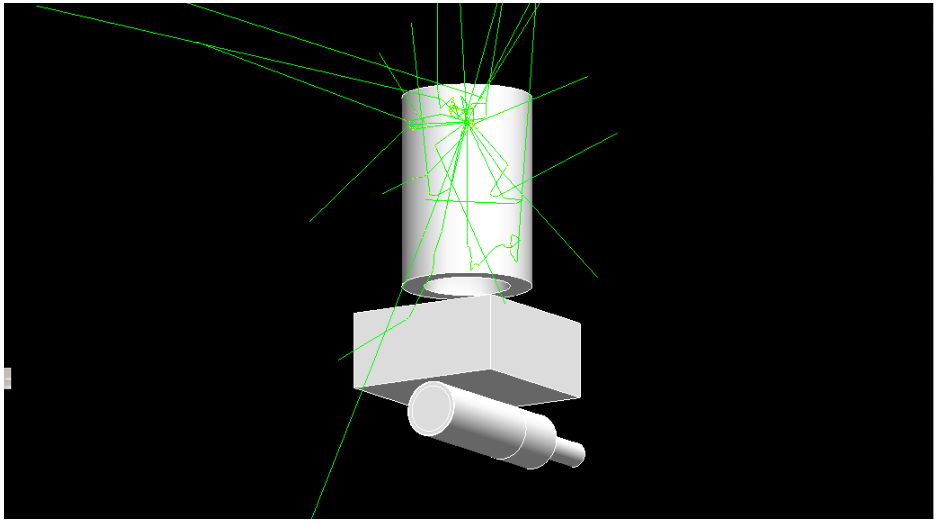
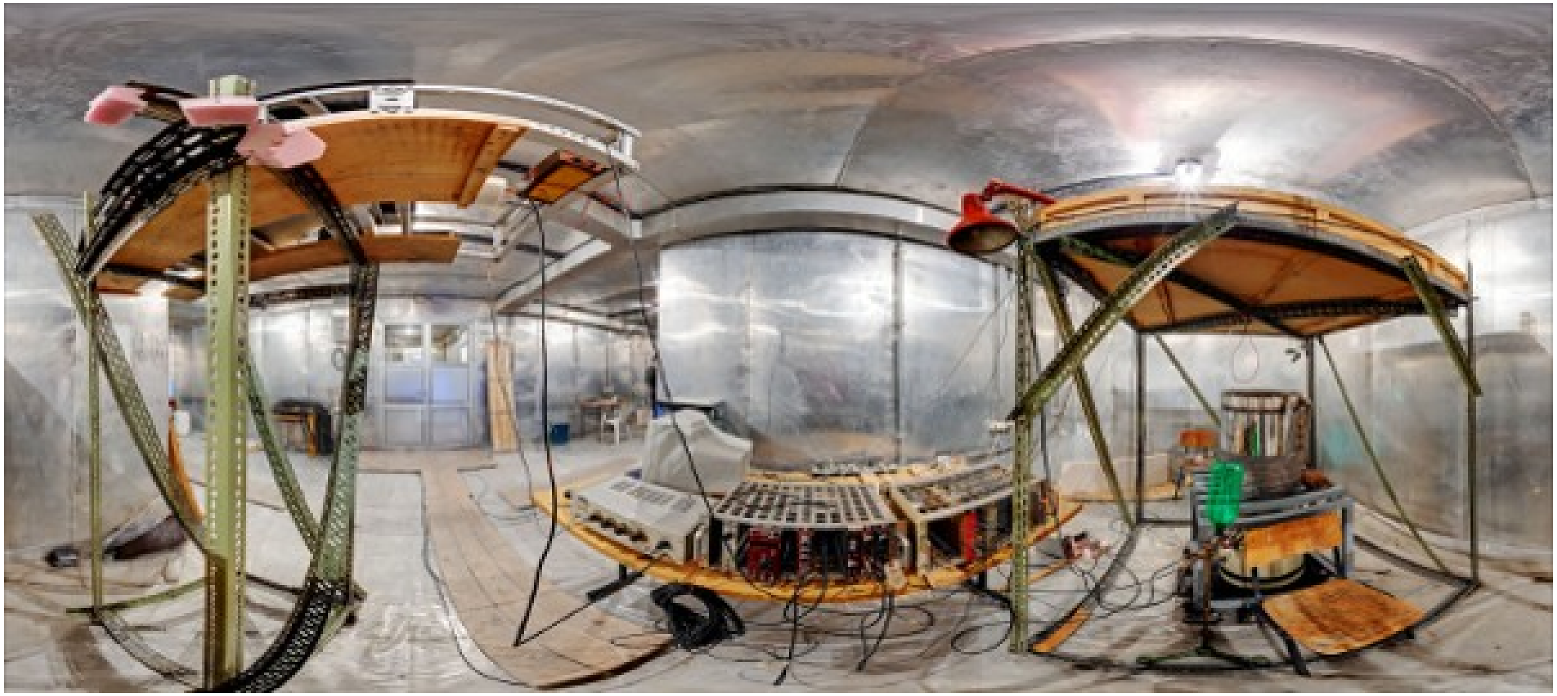
Introduction

- Geant4 is a toolkit for fast and accurate Monte Carlo simulations of the passage of particles through matter
- It contains a complete set of routines for modeling the particle trajectories and interactions:
  - definition of the detector geometry and materials
  - implementation of physics processes
  - generation of primary events
  - evaluation of the detector response
- Applied in high energy and nuclear physics, medical and space science

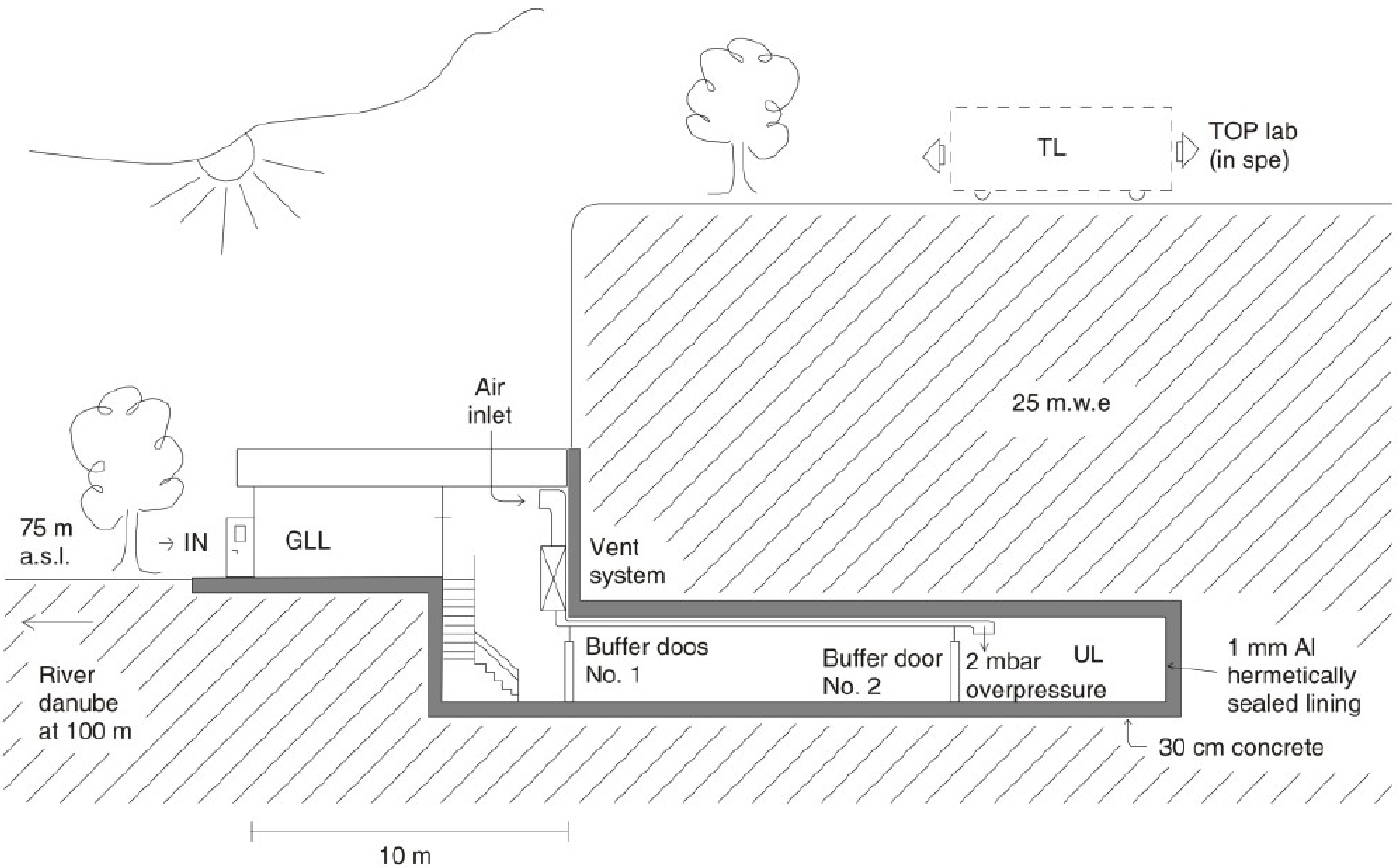


Low-background underground laboratory

- Dedicated facility for gamma spectroscopy measurements and measurements of the cosmic-ray muon intensity
- At the intersection of the two research subjects, the study of muon-induced background in gamma spectroscopy is of particular interest



Low-background underground laboratory

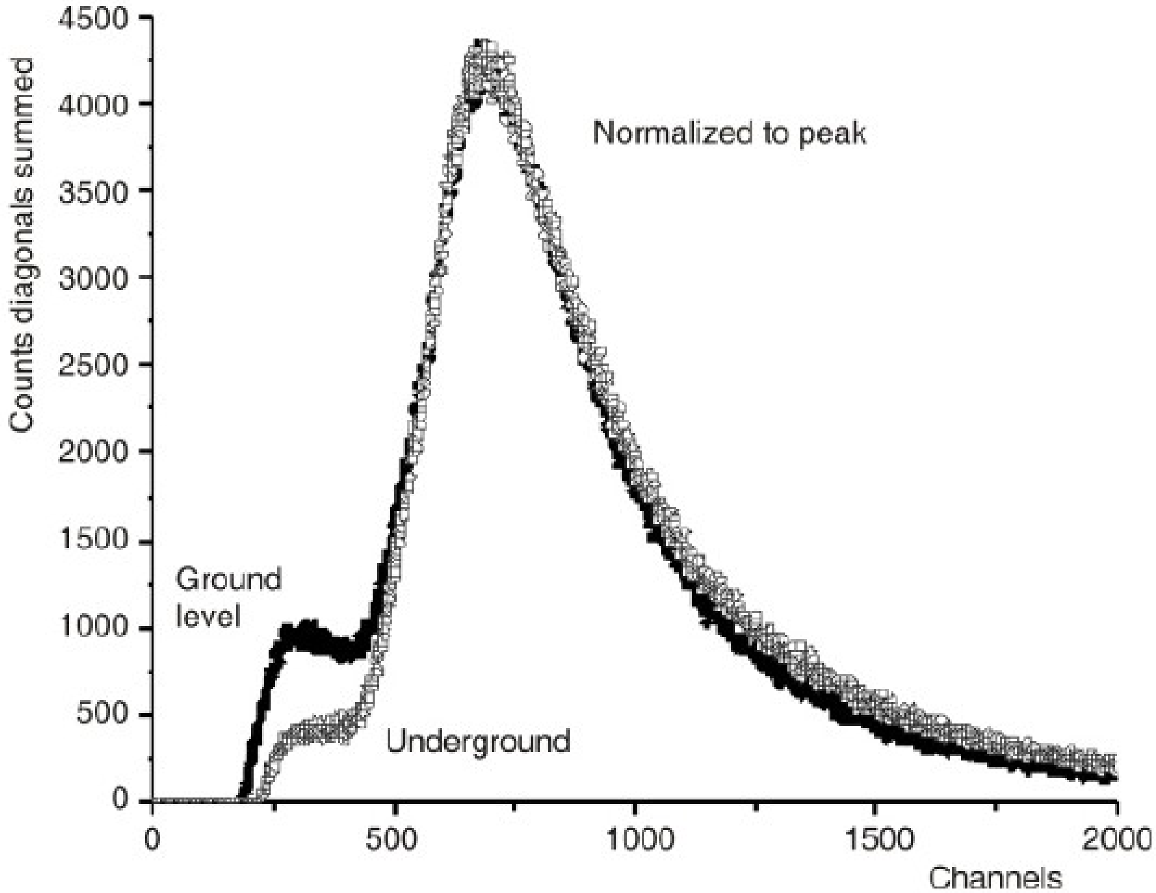


Measurements of the cosmic-ray muon intensity

- Measurements have been continuously performed since 2002, simultaneously at the ground and the underground level
- The experimental set-up consists of four plastic scintillators, which can be arranged flexibly
- Every event is recorded with the time of occurance and its amplitude

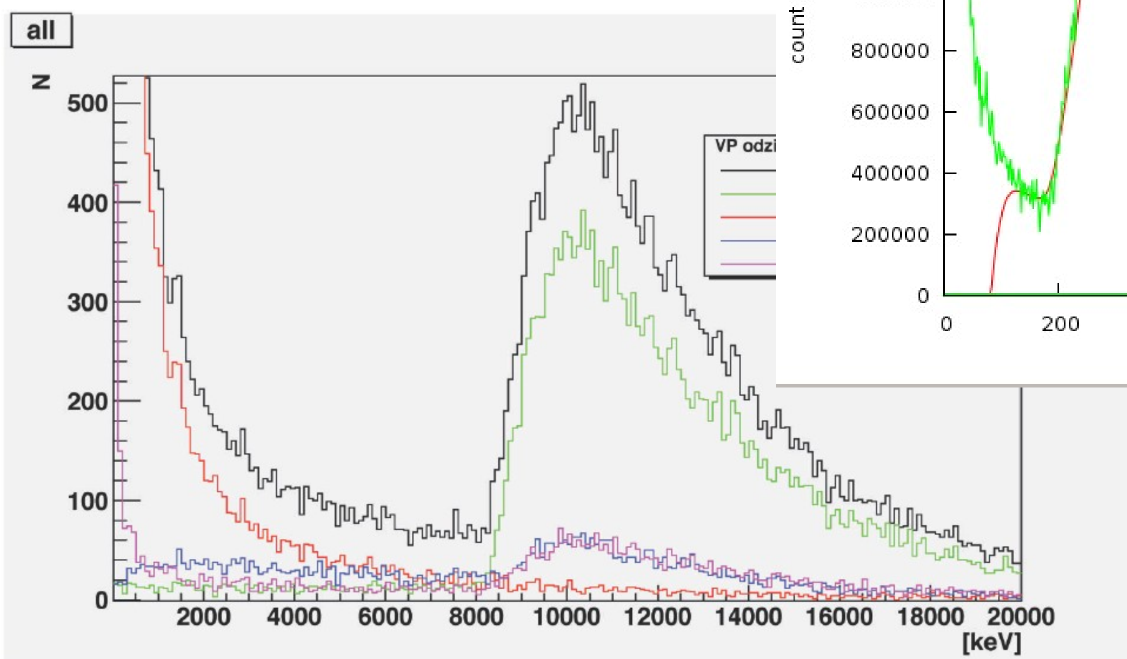
Measurements of the cosmic-ray muon intensity

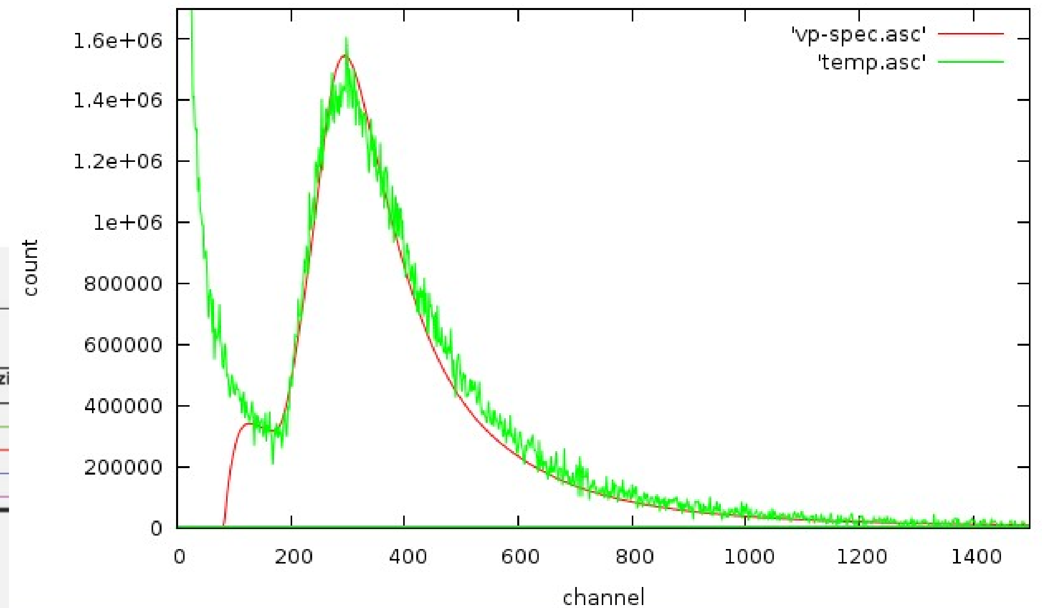
- Spectra of large plastic scintillators (100 x 100 x 5)



Measurements of the cosmic-ray muon intensity

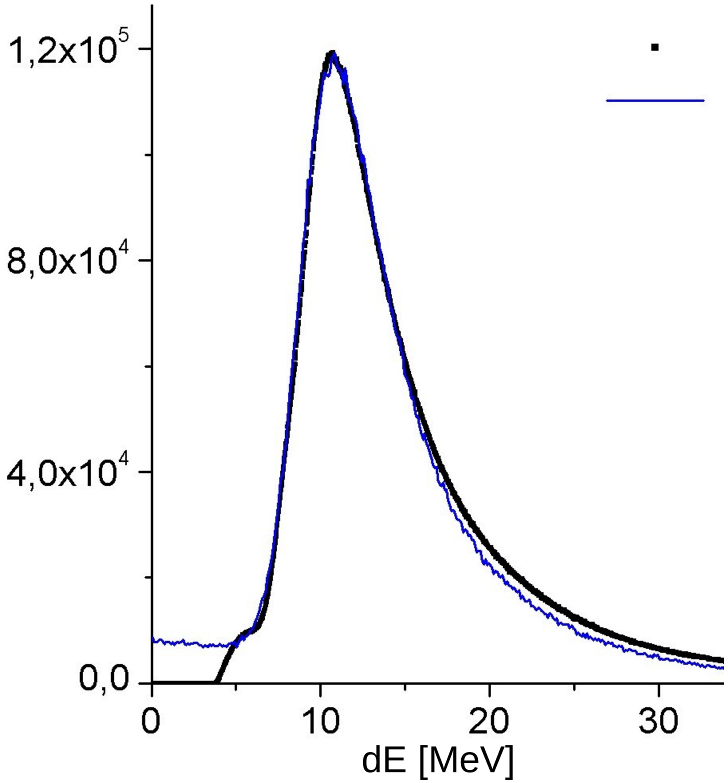
- Interpretation of the experimental spectra and their features has been done using Geant4 and CORSIKA
- <u>Ground level</u>





Measurements of the cosmic-ray muon intensity

- Underground only muons are present
- Muon distribution was sampled at the surface, then only muons that survive passage through 25 m.w.e depth are taken into account

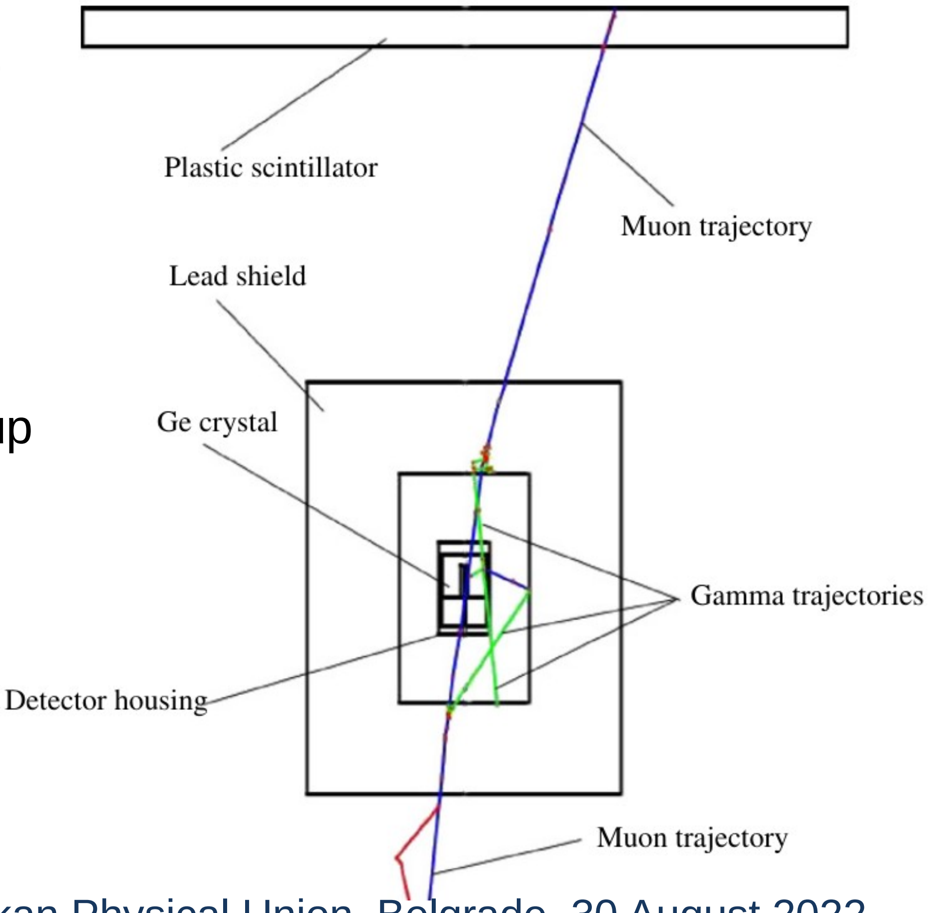


The precise values of the muon flux at ground level and at the depth of 25 m.w.e. were measured

A.Dragić et al. Nucl. Instrum. Meth. A 591 (2008) 470

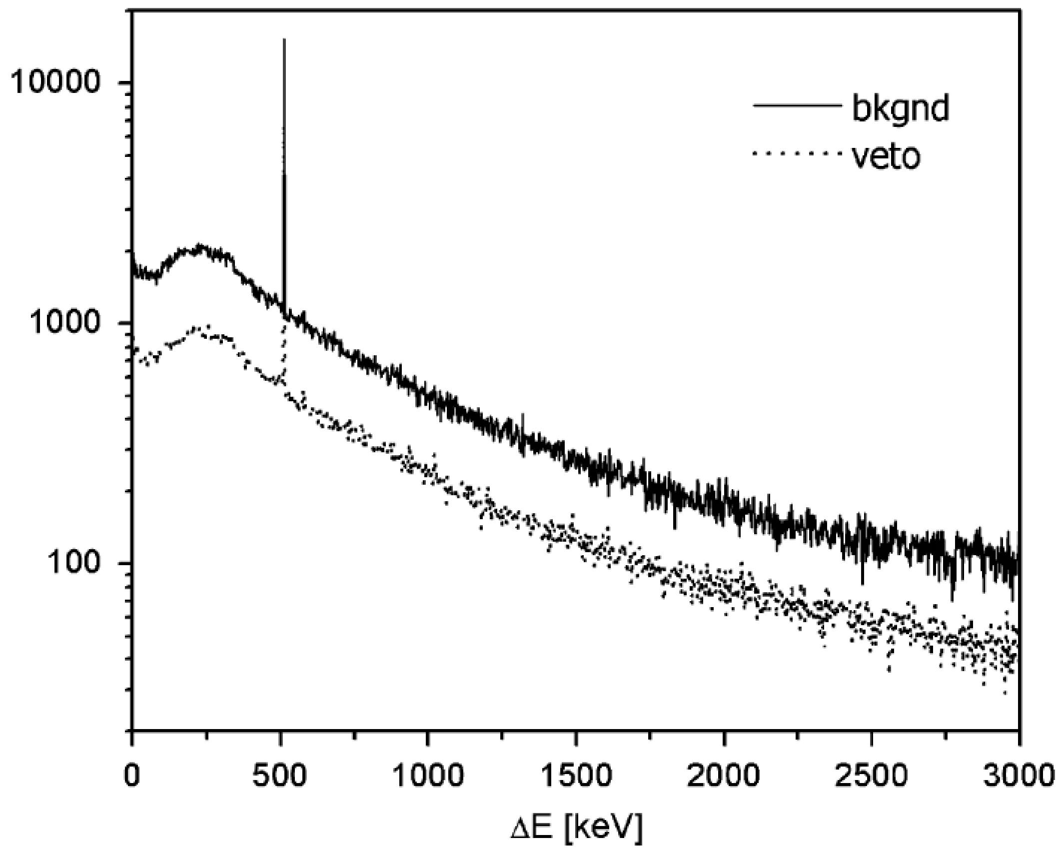
Simulations of the cosmic-ray induced background

- Cosmic-ray muons contribute to the background, either directly or by generating secondary particles, particularly neutrons
- Simulation of the coincident responses of the plastic scintillator and the HPGe detector to the cosmic-ray muons
- Results yielded an estimation of the background reduction by a veto scintillator in the given set-up



Simulations of the cosmic-ray induced background

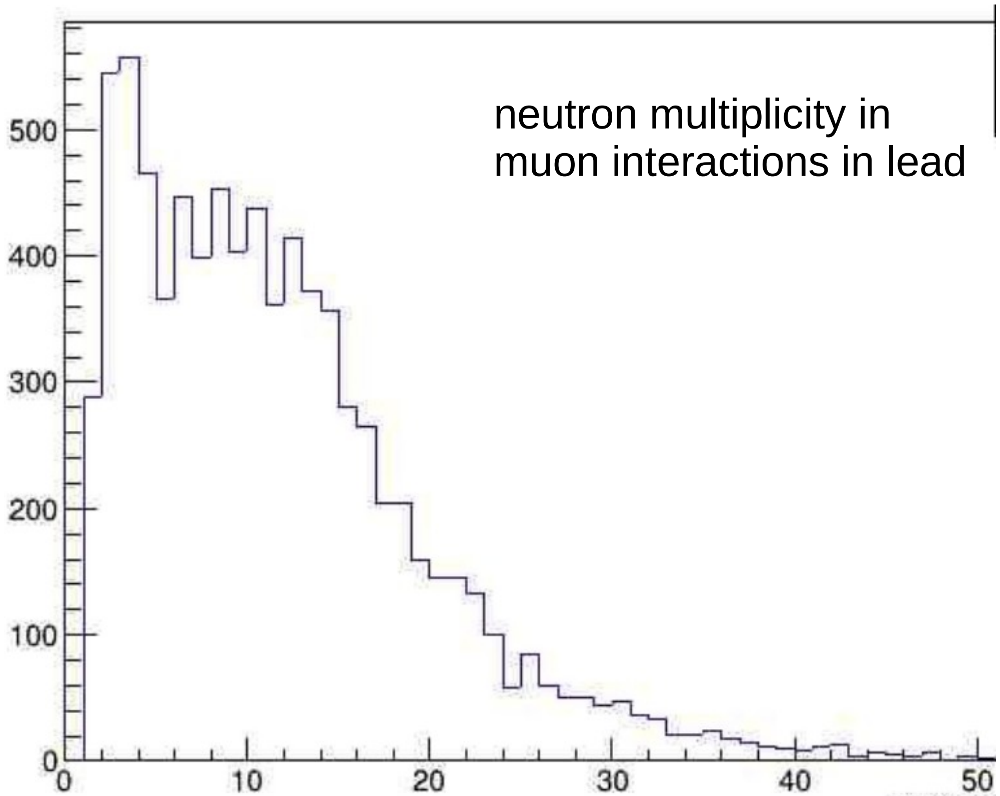
- Muon induced background (prompt), with estimated veto reduction



D.R.Joković et al. Appl. Radiat. Isotopes 67 (2009) 719

Simulations of the cosmic-ray induced background

- Cosmic-ray muons contribute to the background through production of particles, mainly neutrons, in detector surroundings (lead, rock)
- Muon induced neutron production in the lead shield of the HPGe detector



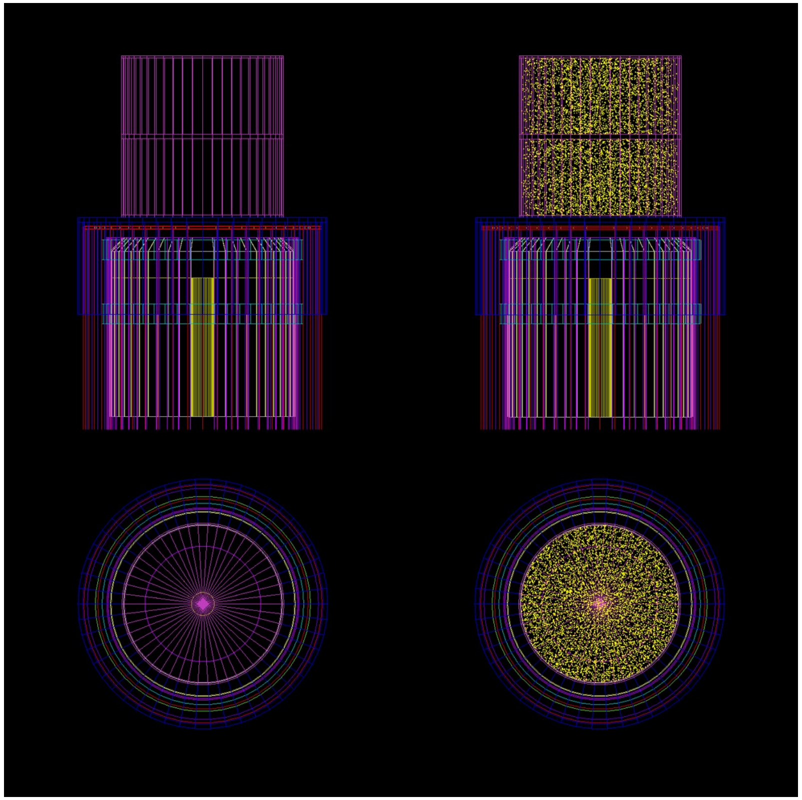
neutron yield

$$Y_n = \frac{934000}{302\, g/cm^2} = 3.09 * 10^{-5} \frac{1}{g\, cm^{-2}}$$

N.Lalić, MSc. thesis (2019)

Simulations in gamma spectroscopy measurements

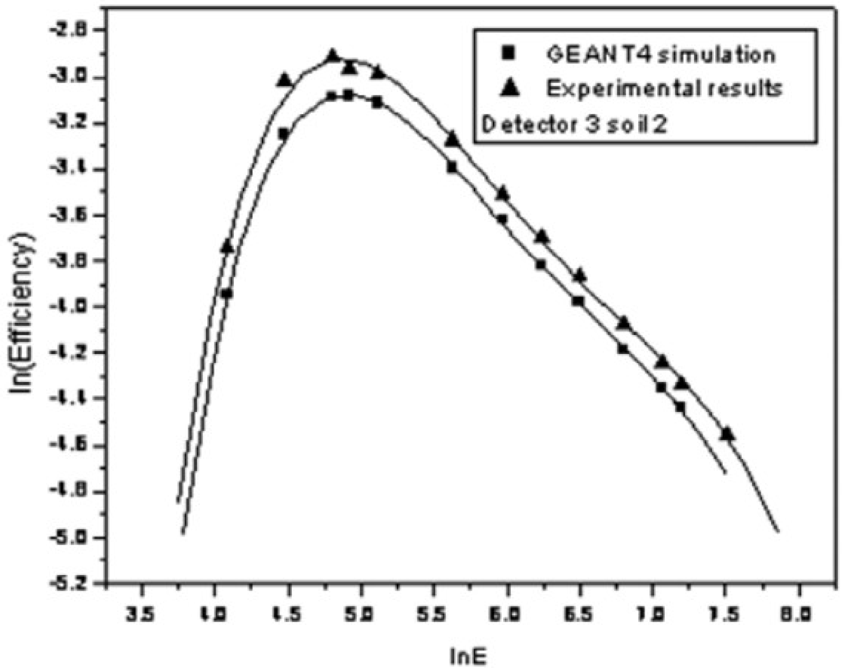
- Geant4 has been widely applied in efficiency calibration of HPGe detectors
- Physics lists including low-energy electromagnetic processes, for simulations with high accuracy
- Accurate detector description and parametrisation is of utmost importance
- Inhomogeneity of a sample adds uncertainty to the calibration

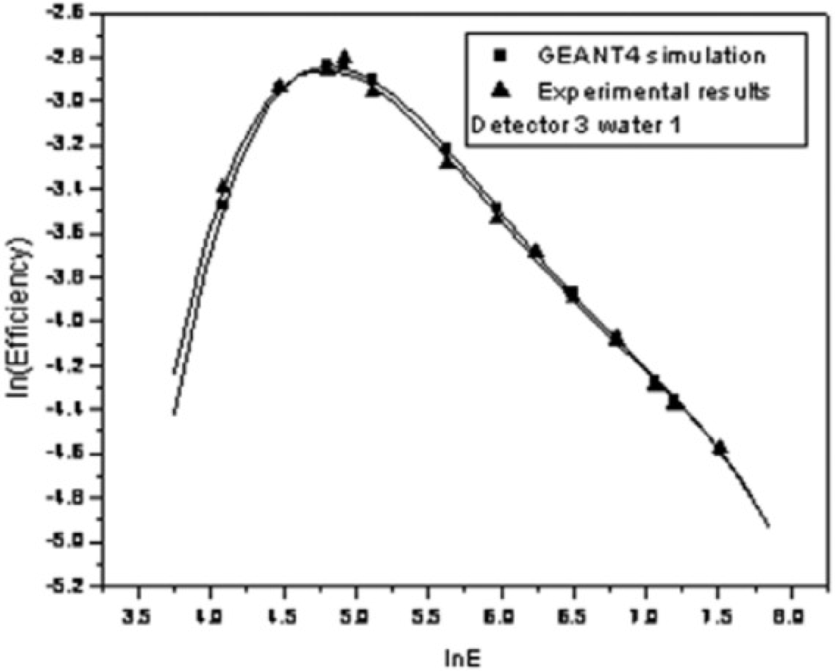


- Fast and flexible method for efficiency calibration of any detector-sample geometry and configuration

Simulations in gamma spectroscopy measurements

- Calibration of HPGe detectors for cylindrical samples





J.Nikolic et al. J. Radiol. Prot. 34 (2014) N47

Simulations in gamma spectroscopy measurements

- Contribution of inelastic neutron scattering on Ge nuclei to the low-energy part of gamma spectra of HPGe detectors

- Probabilities of photon detection and photon escape from Ge crystal

E [keV]	Reaction	I [s^{-1}]	p_{peak}	$1-p_{tot}$
562.8	$^{76}Ge(n,n')^{76}Ge$	0.00197	0.307	0.376
595.8	$^{74}Ge(n,n')^{74}Ge$	0.01235	0.295	0.383
691.3	$^{72}Ge(n,n')^{72}Ge$	0.00556		
834	$^{72}Ge(n,n')^{72}Ge$	0.00402	0.230	0.429
1039.6	$^{70}Ge(n,n')^{70}Ge$	0.00150	0.197	0.459
1204.2+1215.4	$^{74}Ge(n,n')^{74}Ge + ^{70}Ge(n,n')^{70}Ge$	0.00175		

M.Krmar et al. Nucl. Instrum. Meth. A 709 (2013) 8

Conclusion

- Geant4 based simulations have been used in various applications (measurements of the cosmic-ray muon flux, gamma spectroscopy)

  - testing of the experimental set-up, layout
  - evaluation of the detector response
  - interpretation of the experimental spectra, calibration

- Further studies include
  - measurements of the cosmic-ray muon and electromagnetic components
  - simulations of the cosmic-ray induced production of nuclei in rock or soil
  - studies of the scintillator-HPGe system in the underground (coincidence and anticoincidence), e.g. for measurements of neutron production