

Simulation of background sources in the GeMPI detectors and proposal of a new shield design for future GeMPI-like detectors

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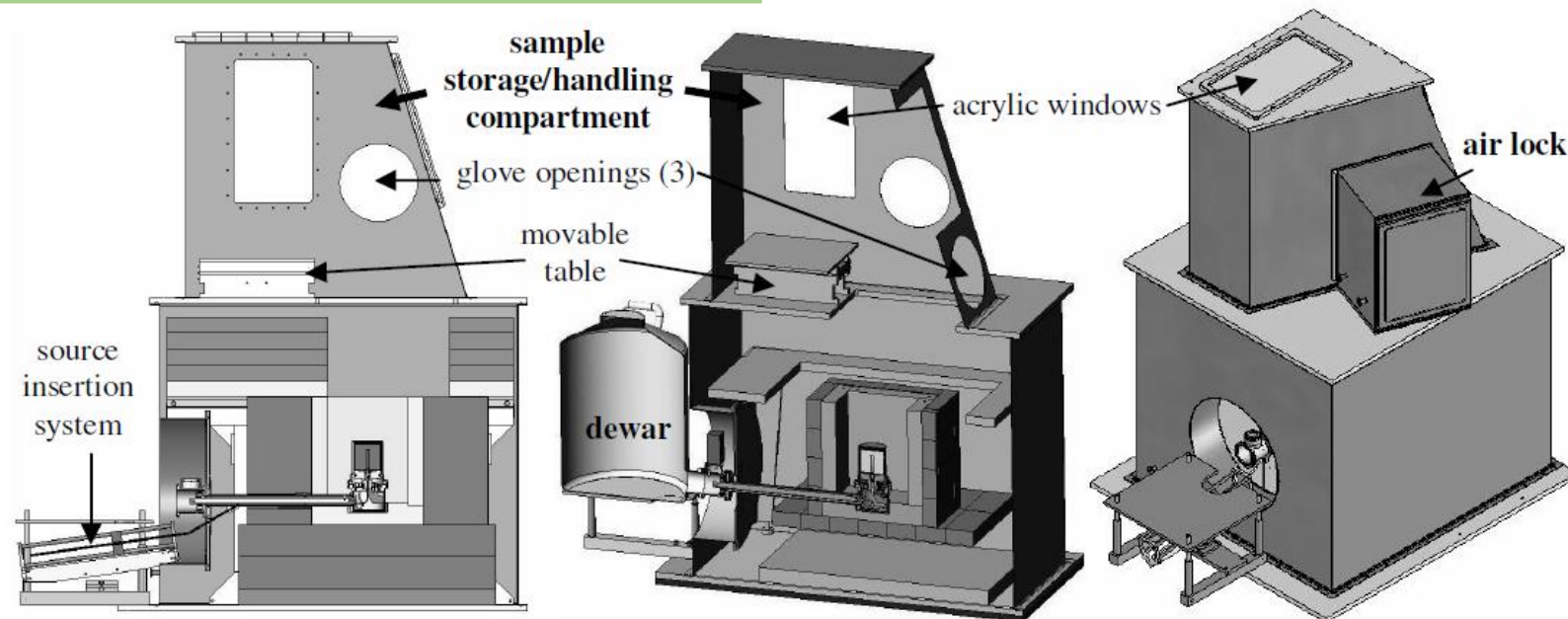
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GeMPI detectors at the LNGS underground laboratory

- 4 setups with highly sensitive **Germanium spectrometers** (active mass: 2.2 – 2.4 kg) (3* MPIK, 1* LNGS)
- Used for screening of materials for low background experiments
- Located at a depth of **3800 m w.e.**
- Sensitivity for U and Th: **10 μ Bq/kg** (most sensitive Ge spectrometers worldwide)

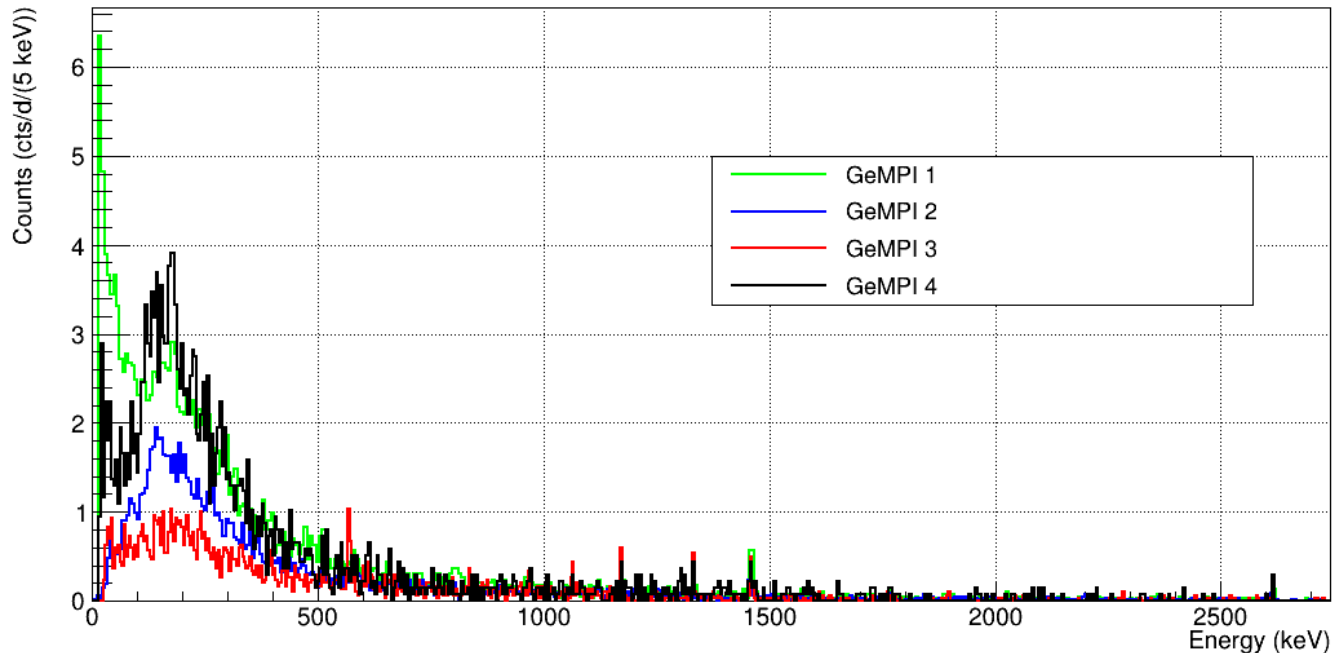
Basic detector design:

- 20 cm lead shield
- 5 cm copper shield
- Sample chamber flushed with Nitrogen gas
- Ge diode inside ultra low background copper cryostat



[1]

Background spectra of GeMPI detectors



Detector	Bkg. Count rate [40, 2700] keV (cts/d/kg)
GeMPI 1	71 ± 1
GeMPI 2	38 ± 1
GeMPI 3	24 ± 1
GeMPI 4	65 ± 1

- Very low background achieved \leftrightarrow current sensitivity for U and Th: $10 \mu\text{Bq/kg}$
 - \rightarrow Improvement of sensitivity possible through further reduction of background
 - \rightarrow Understanding of background through Monte Carlo simulations

Potential sources of background

Cosmic ray muons

- Greatly reduced flux compared to sea level ($\times 10^{-6}$): $(3.41 \pm 0.01) \times 10^{-4} m^{-2} s^{-1}$ [2]
- High mean energy: **262 GeV**
- Possible muon veto system in future GeMPI generations ?

Muon-induced neutrons from surrounding rock

- Induced by cosmic ray muons
- Very small flux: $(4.27 \pm 0.01) \times 10^{-6} m^{-2} s^{-1}$ [3]
- Energies **up to 1 TeV** [3]
- Possible neutron shield (made from PE) in future GeMPI generations ?

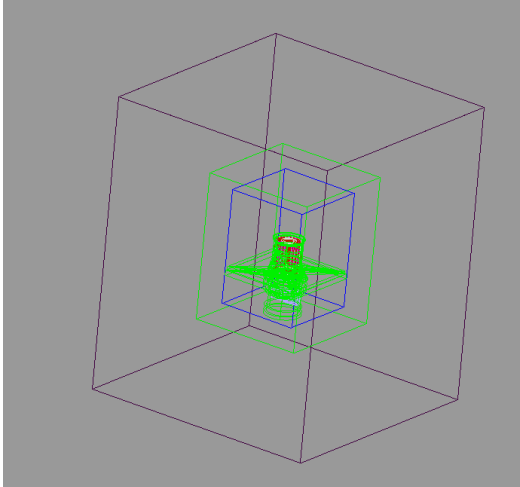
Neutrons from natural radioactivity

- Neutrons from (α, n) -reactions and rad. U and Th decays in the surrounding rock
- Flux between $(0.5 \pm 0.1) \times 10^{-2} m^{-2} s^{-1}$ and $(3.0 \pm 0.1) \times 10^{-2} m^{-2} s^{-1}$ [4]
- Energies of **a few MeV** [4]
- Possible neutron shield (made from PE) in future GeMPI generations ?

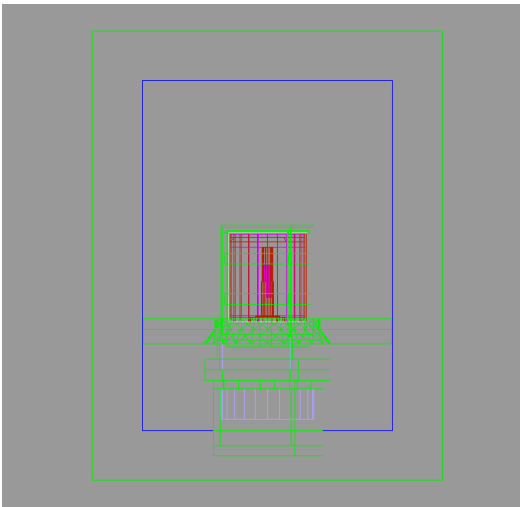
Contaminations of shielding materials

- Shielding materials (Pb, Cu, PE etc.) can contain tiny radioactive contaminations
- Contaminations include: Th232, U238, Co60, K40, Pb210
- Isotope with highest background contribution: **Pb210** in lead shield

Detector modelling and particle simulation with Geant4-based toolkit MaGe



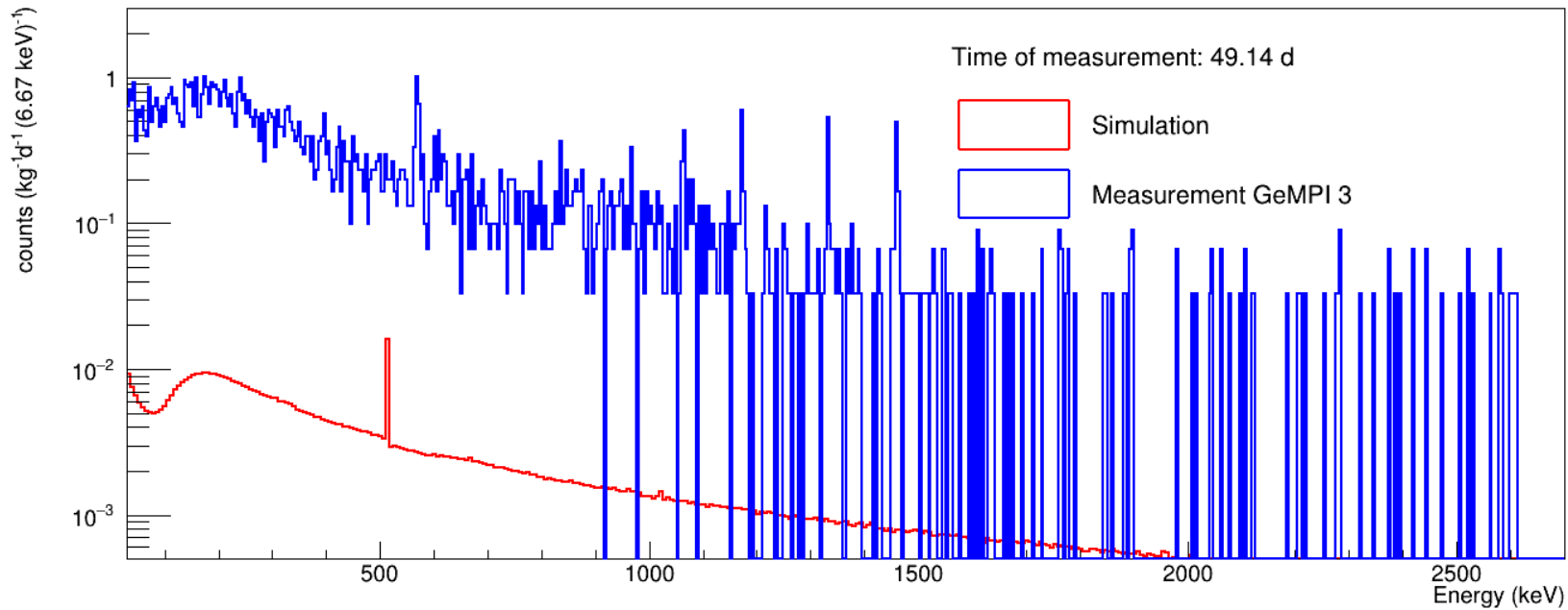
- MaGe based on Geant4, developed for Majorana and Gerda experiment [5]
- Detector geometries implemented using measurements from detector construction
- All 4 detectors share a very similar design → Simulations only done on one detector geometry (except for simulation of material contaminations)



Input for simulations

- For muons and neutrons:
Energy and angular distributions in the LNGS laboratory
(Muon distributions courtesy of the XENON collaboration)
- For contaminations of materials:
Material screening measurements of activities of radioactive isotopes in the materials (when available)

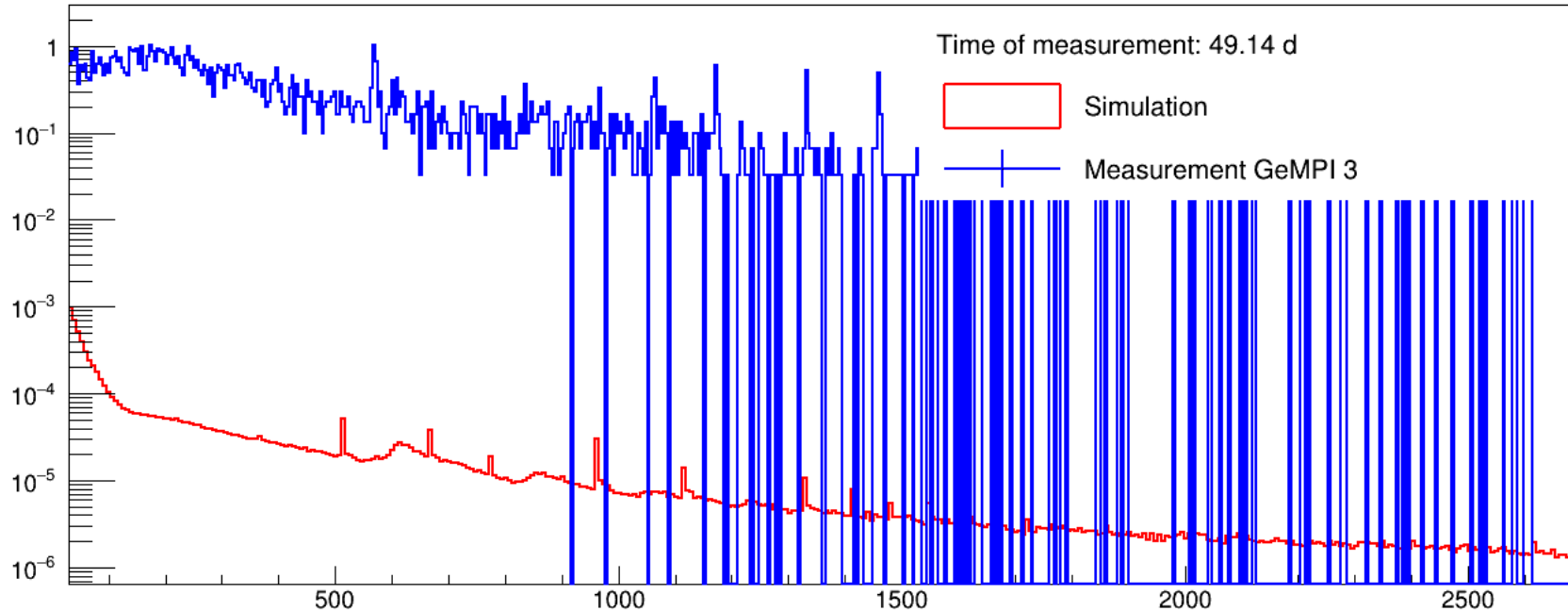
Results: Muon-induced background



- Muons only contribute to a small part of the GeMPI background
- Muon veto system in future GeMPI generations not necessary

Count rate from simulations [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
0.8 ± 0.1	3.3 ± 0.6

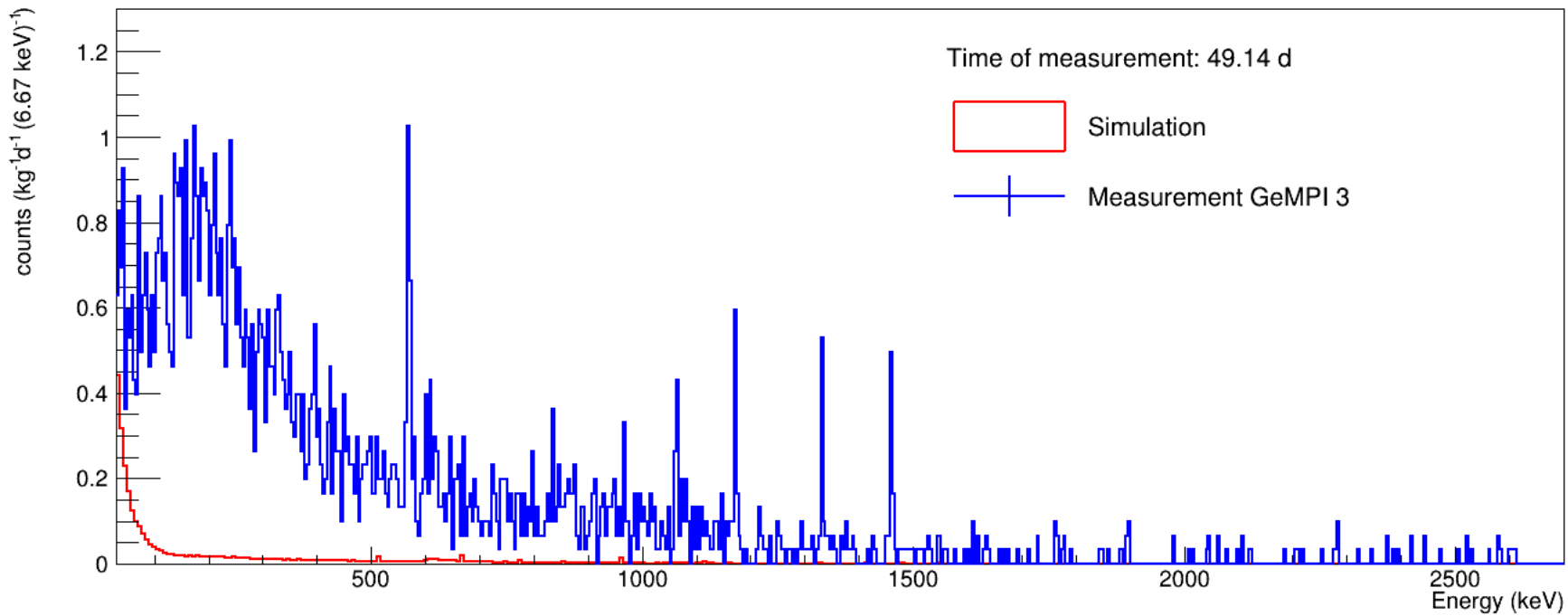
Results: Neutron background - Neutrons from muon interactions in surrounding rock



- Muon-induced neutrons only contribute a tiny part to the GeMPI background (despite very high energies)

Count rate from simulations [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
0.0008 ± 0.0002	0.003 ± 0.001

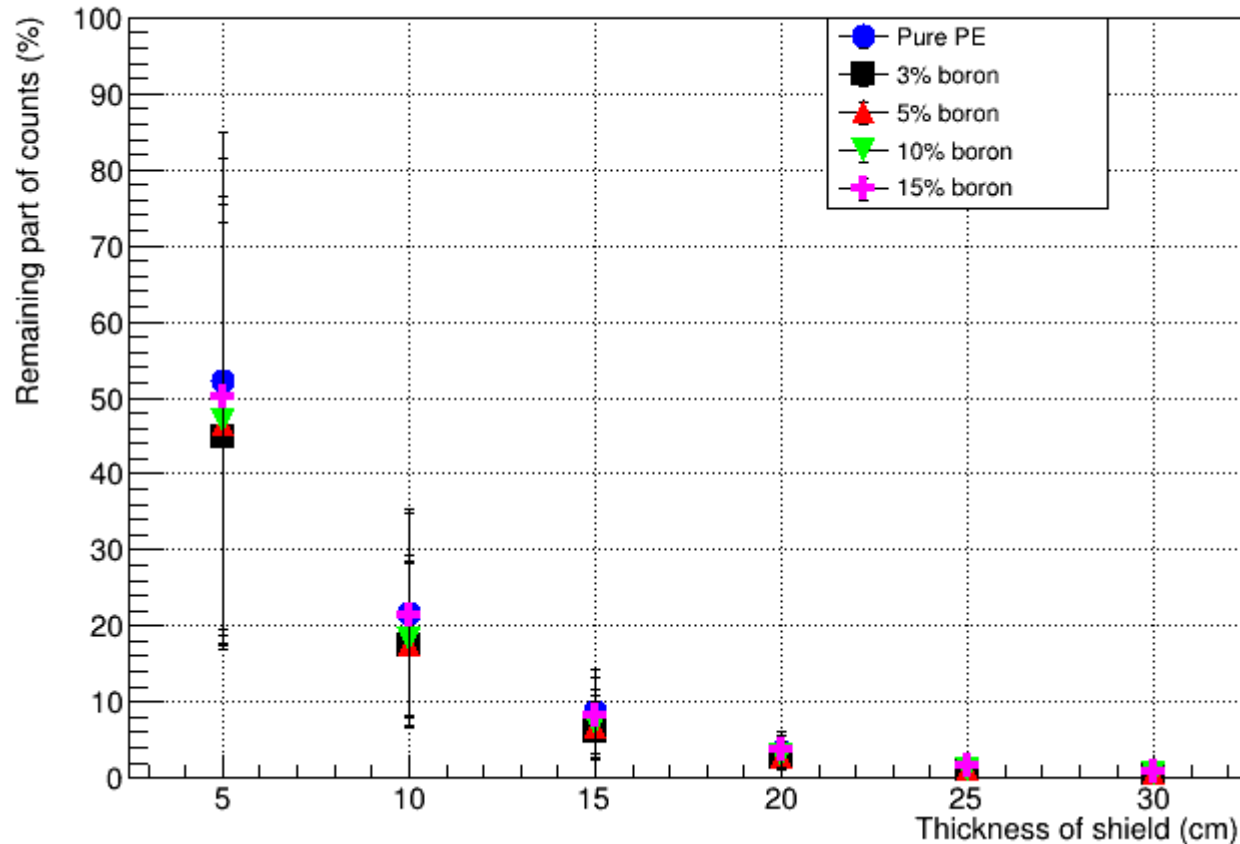
Results: Neutron background - Neutrons from nat. radioactivity in surrounding rock



- Neutrons from natural radioactivity make up a significant part of the GeMPI background
- Future GeMPI generations should include a Polyethylene neutron shield

Count rate from simulations between [40, 2700] keV (cts/d/kg)	Percentage of total bkg. rate [GeMPI 3] (%)
3.1 ± 2.0	12.9 ± 8.2

Results: Simulations of possible neutron shields



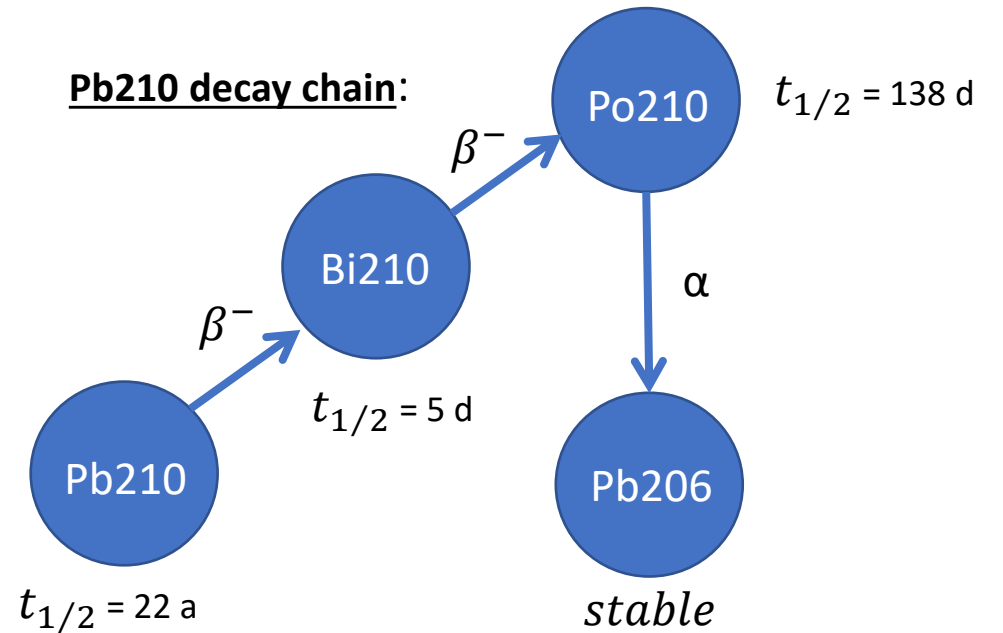
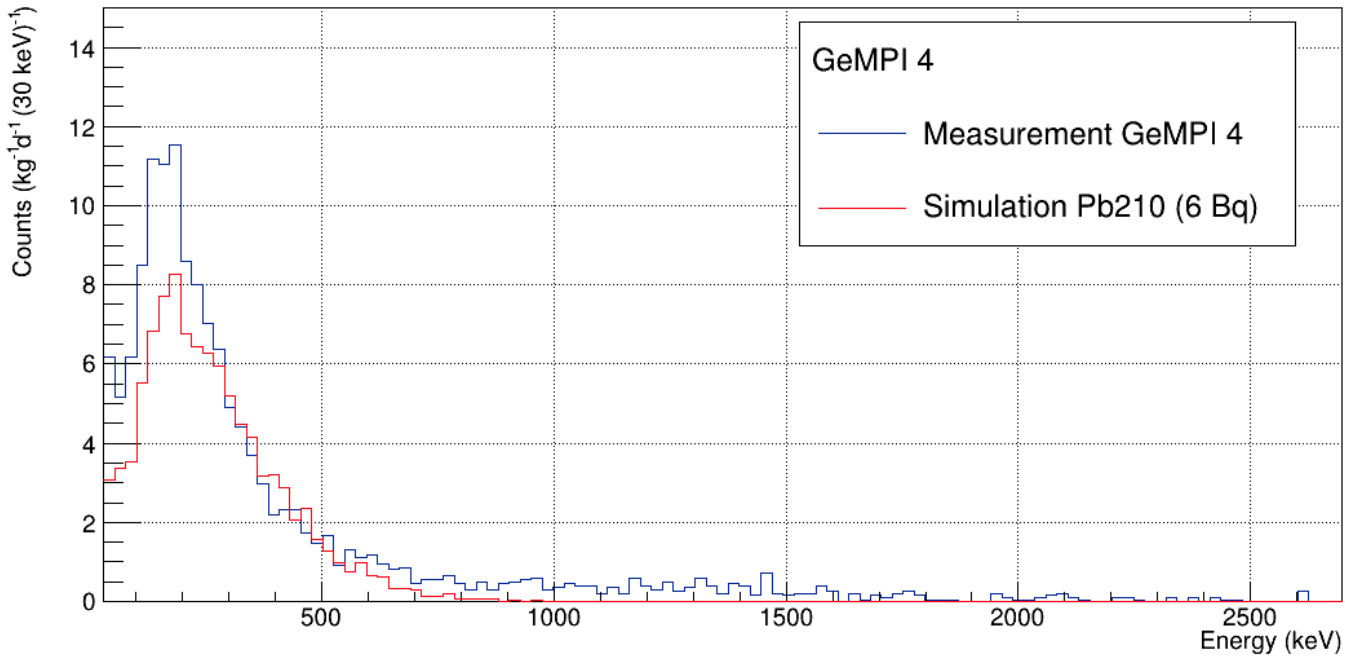
- Hydrogen (in PE) ideal for deceleration of fast neutrons
- Boron has high cross section for thermal neutron capture

→ Simulation of neutron shield made from borated PE with different boron contents

- At a thickness of 15 cm:
 - neutron contribution comparable to muon contribution
 - different boron contents do not have a significant influence on the effectiveness of the shield

→ 15 cm shield of pure PE for future GeMPI generations

Results: Residual contribution of Pb210 in lead shield



	GeMPI 1	GeMPI 2	GeMPI 3	GeMPI 4
Pb210 Cont. (Bq/kg)	~ 6	~ 3	~ 1.7	~ 6
Contr. to Bkg. [40, 2700] keV (cts/d/kg)	45 ± 4	23 ± 2	13 ± 1	45 ± 4
Percentage of total bkg. rate (%)	63 ± 5	60 ± 5	54 ± 4	69 ± 6

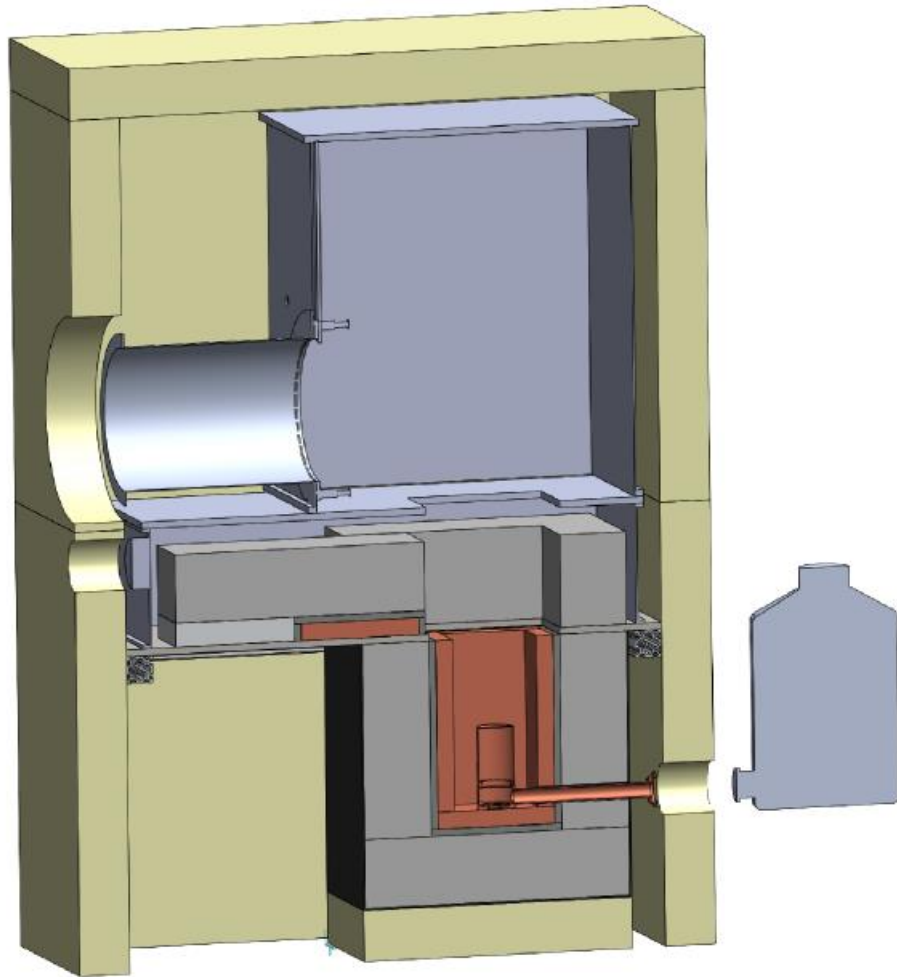
Results: Possible ways to reduce contribution from Pb210 in lead shield

- Pb210 contamination in lead shield is biggest contributor to background despite copper shield
- need different shield design to reduce contribution

- Simulations show that Pb210 contaminations in first two cm's of lead shield have the biggest impact (see table)
- Replace first two cm of lead shield with a very pure layer

Layer	Percentage of total Pb210 contribution coming from layer (%)
0 – 1 cm	85 ± 4
1 – 2 cm	11 ± 1
2 – 3 cm	3 ± 1
3 – 4 cm	< 1
4 – 5 cm	< 1

Results: Suggested shield design with 2 cm of very pure lead as inner layer

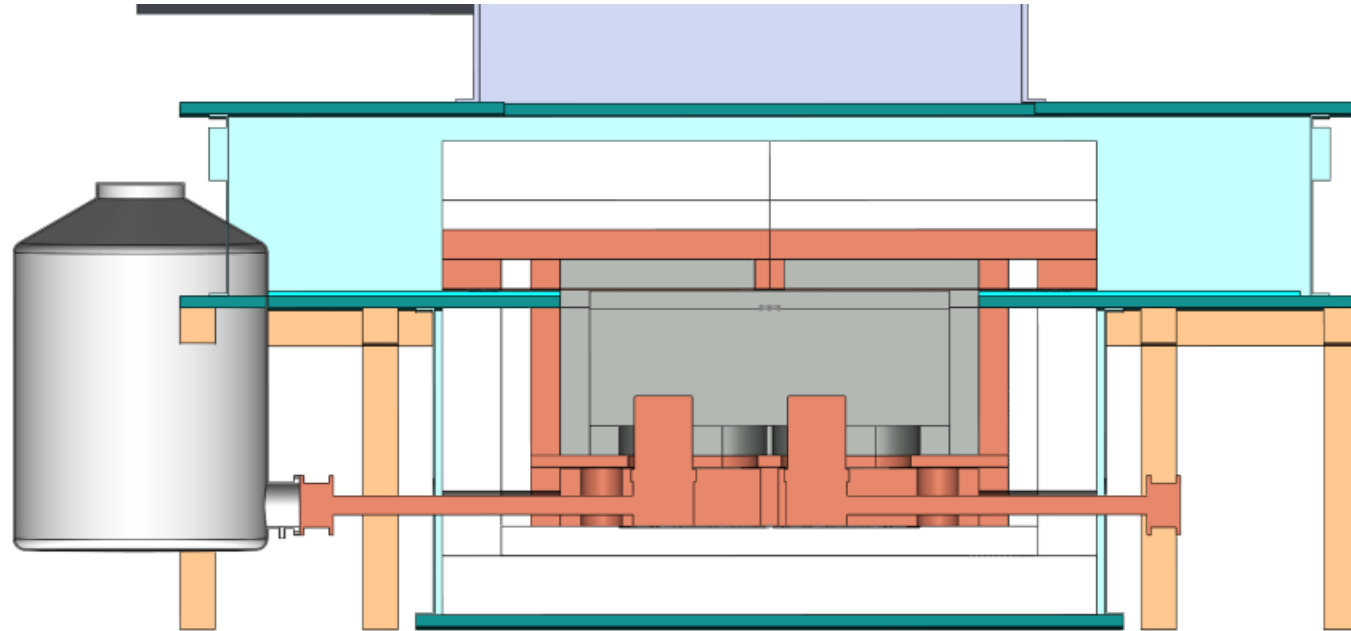


- **Results suggest for future GeMPI detectors:
2 cm layer of very pure Pb as inner shield:**

Assuming 0.5 Bq/kg Pb210 in new inner layer and 10 Bq/kg in outer layer

→ Reduction of Pb210 contribution to (3.12 ± 0.59) cts/d/kg in the interval [40, 2700] keV

Additional improvement: Two Germanium crystals in the sample chamber



- A second Germanium crystal doubles the active volume inside the sample chamber
→ Doubles the efficiency for detection of contaminations in the samples

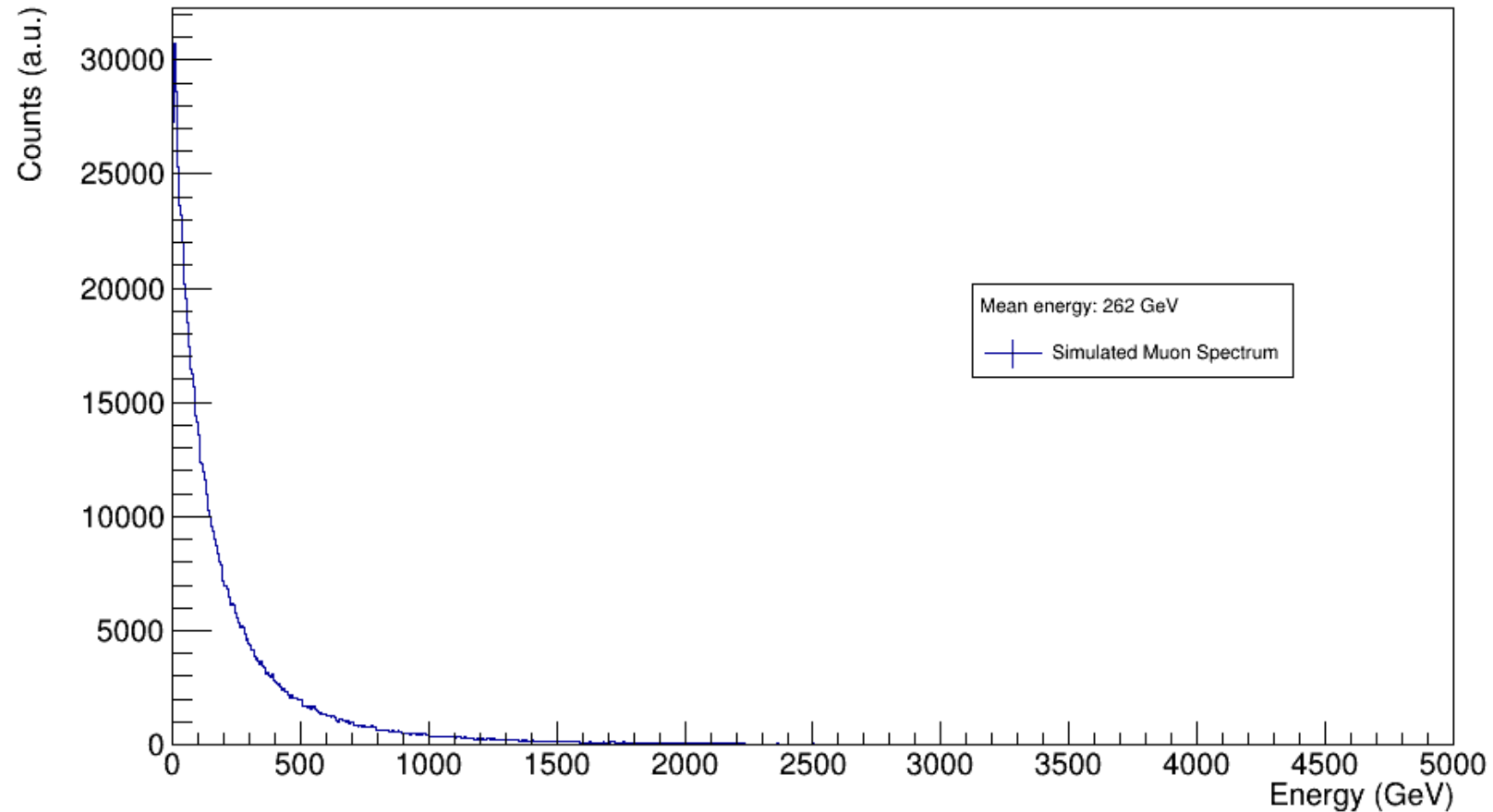
Summary and outlook

- **Simulation of background components of GeMPI detectors:**
 - Pb210 in lead shield is main background source (~ 60%)
 - Muon contributions are very small (1% – 3%)
 - Neutrons contribute up to 15%
- **Consequences for next generation of GeMPI detectors:**
 - 2 cm inner layer of very pure lead to reduce impact of Pb210 in outer lead
 - 15 cm layer of pure PE as neutron shield integrated in the walls of the laboratory
 - no muon veto necessary
 - Background count rate of 15 cts/d/kg between 40 keV and 2700 keV seems feasible (GeMPI 3: 24 +- 1 cts/d/kg)
 - Additionally a second Ge crystal will be included in the next GeMPI detector
- **Next steps:**
 - Procurement of radio pure Pb & Cu
 - Work on shield and detector design of a new material screening station at LNGS

BACK - UP

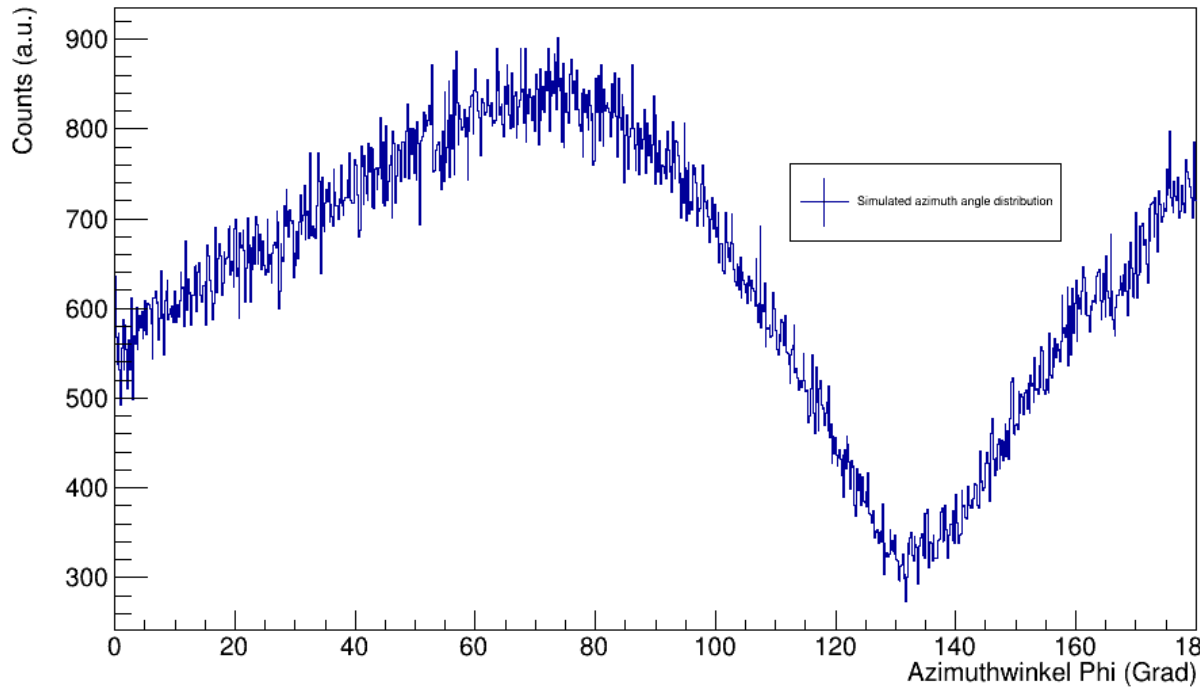
Energy distribution of muons in the LNGS laboratory

Simulated Muon Spectrum from Xenon (Jose Cuenca)

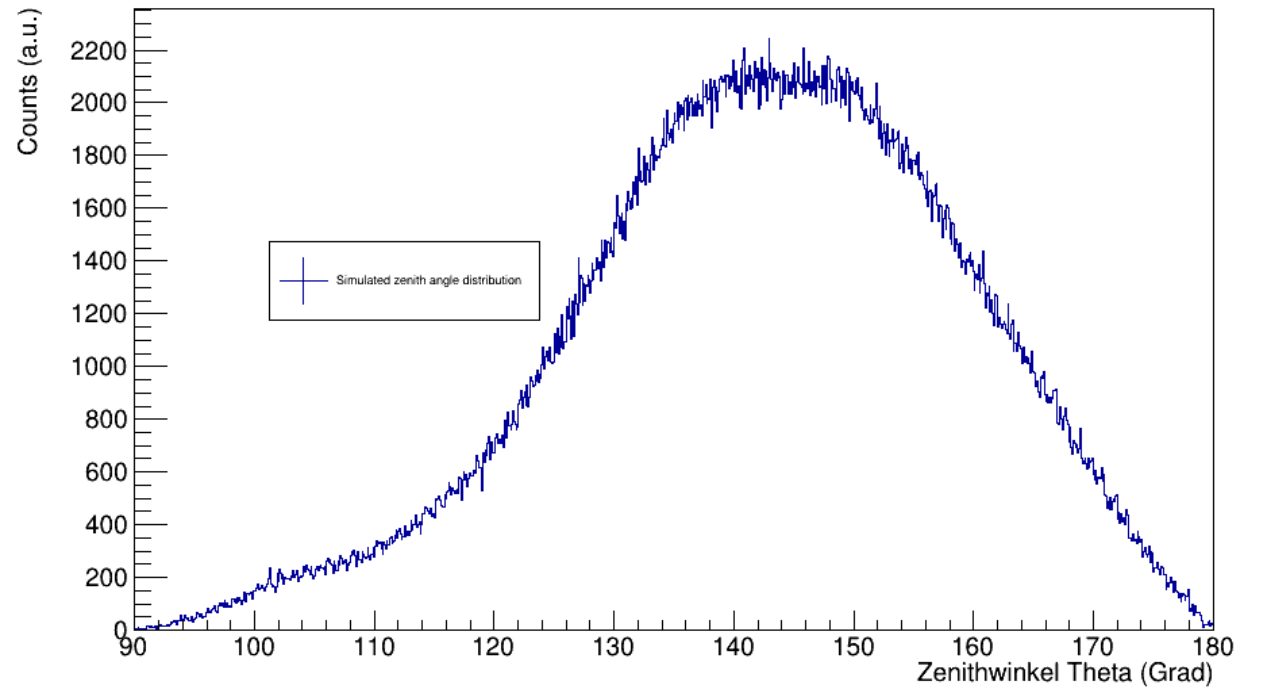


Angular distribution of muons in the LNGS laboratory

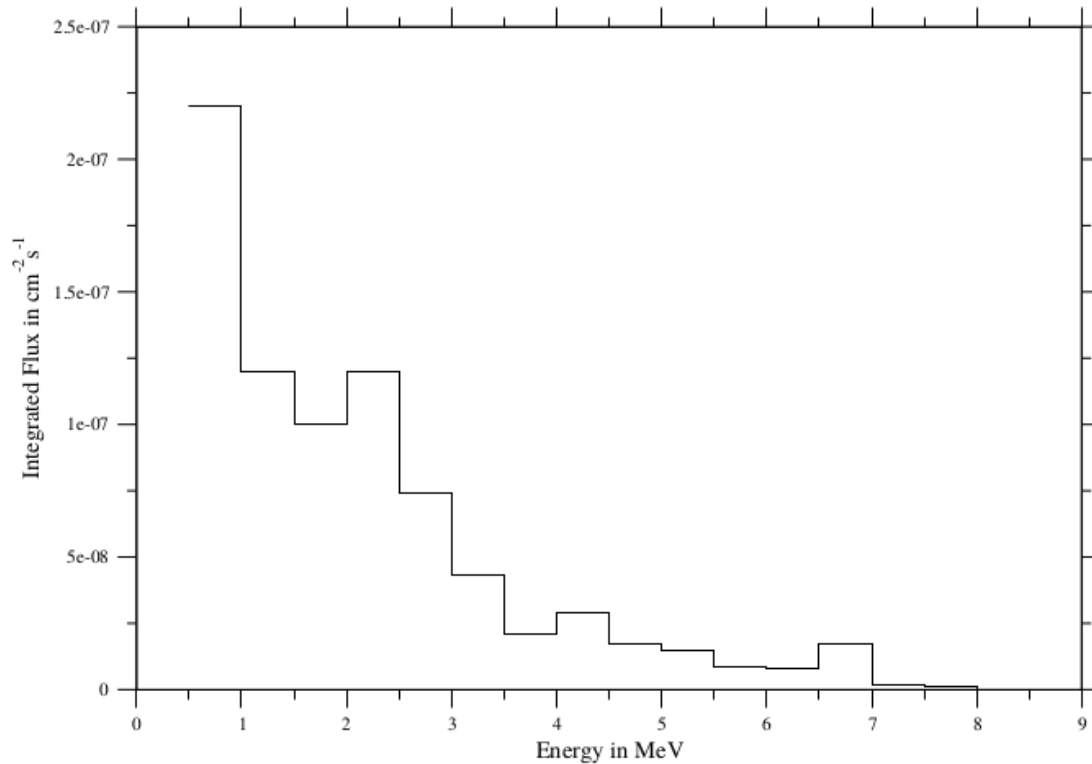
Azimuthal angle



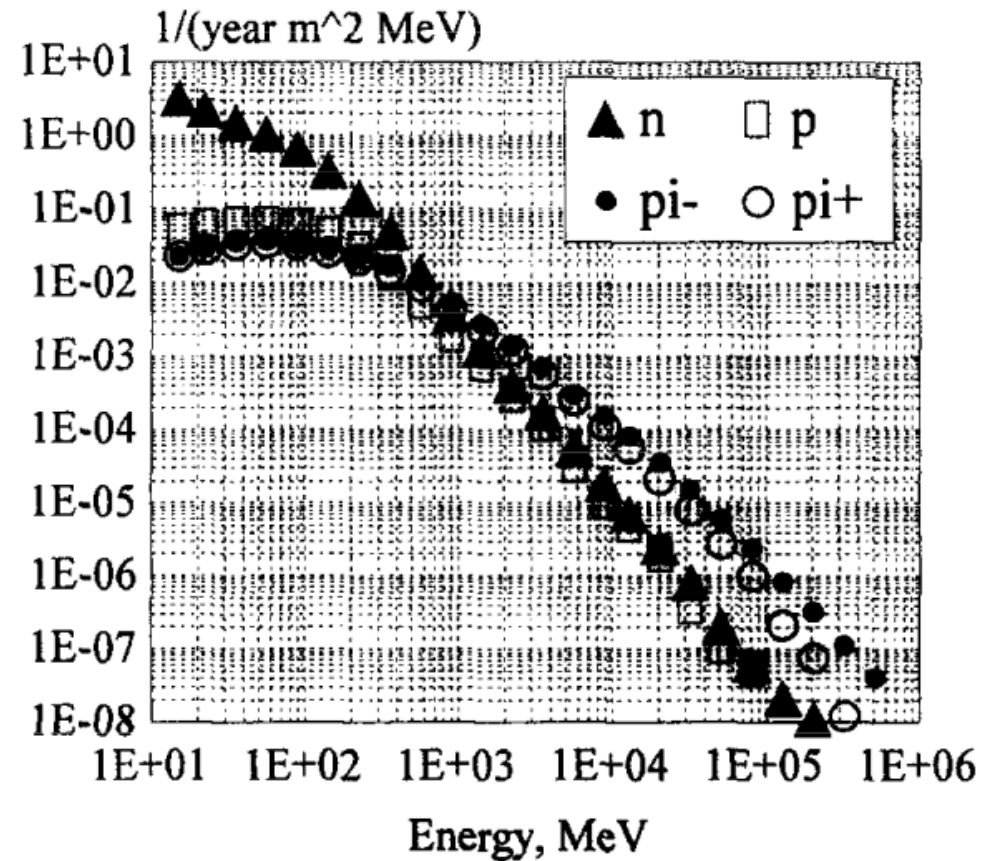
Zenith angle



Energy distribution of neutrons in the LNGS laboratory

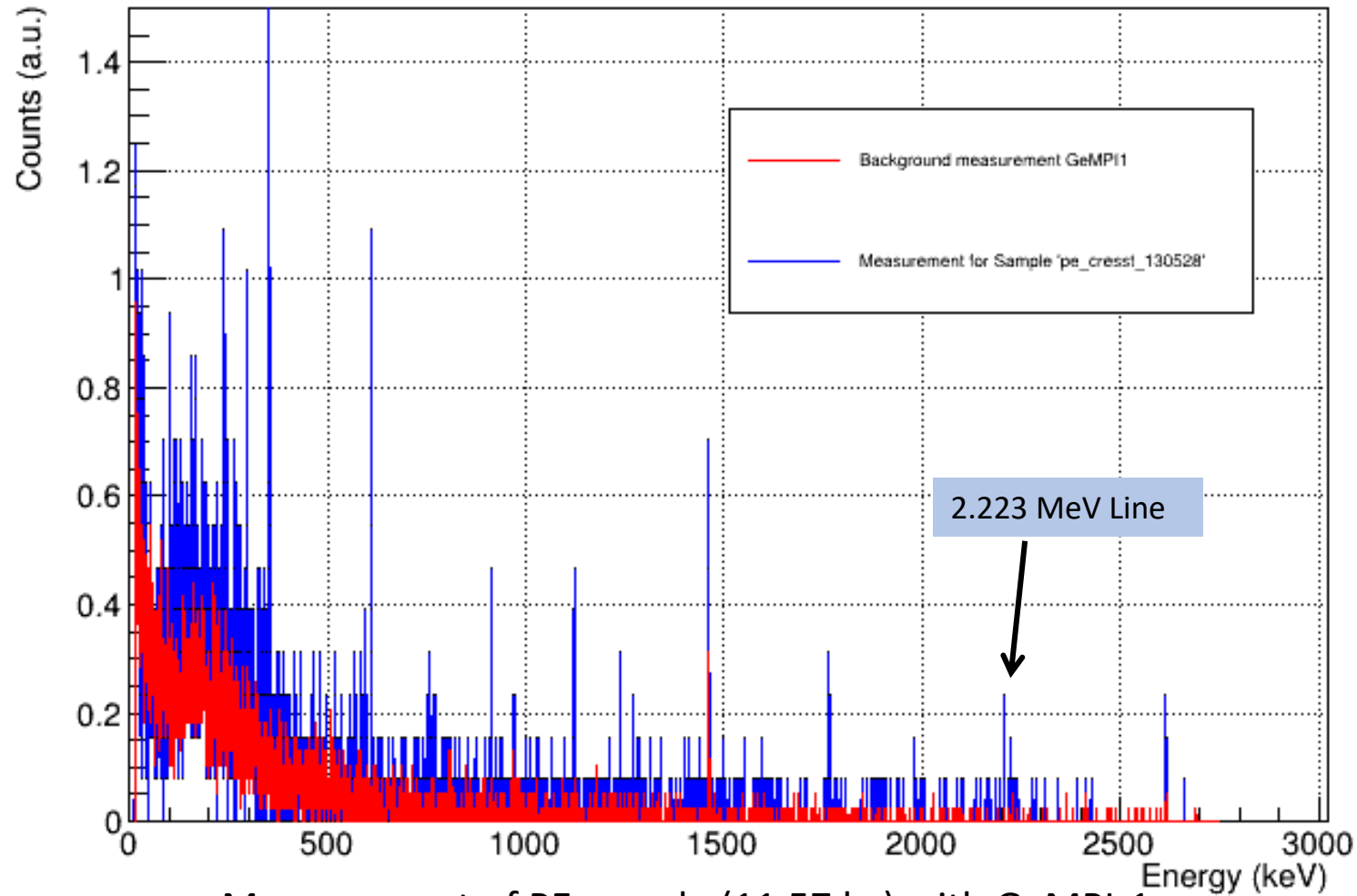


Neutrons from nat. radioactivity

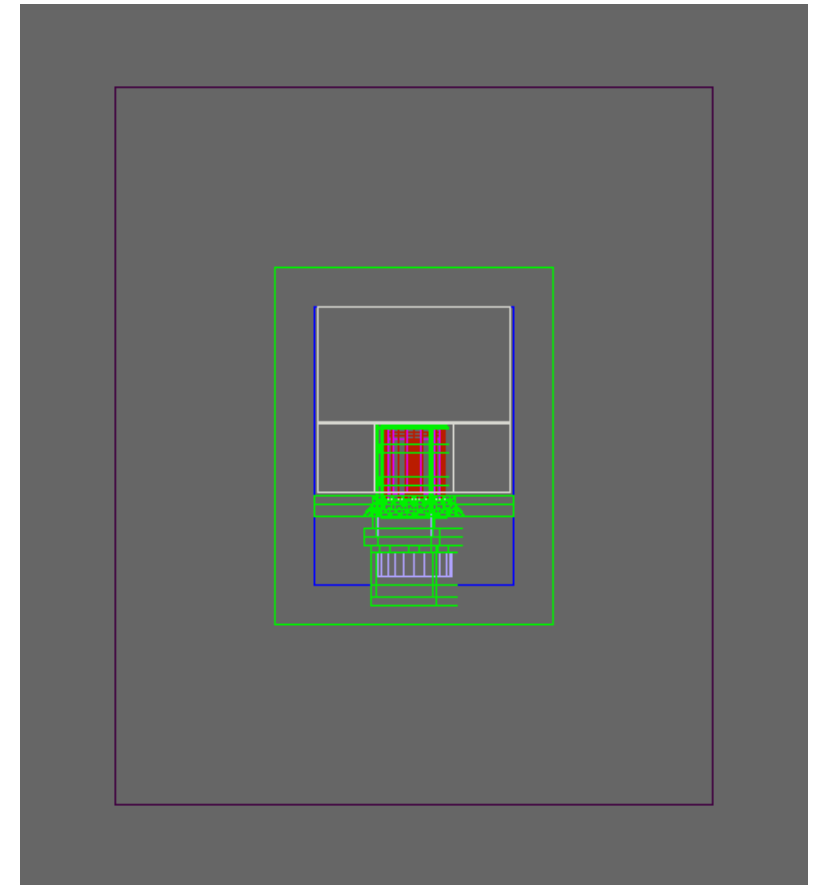


Muon-induced neutrons

Determination of flux of neutrons from nat. radioactivity



Measurement of PE sample (11.57 kg) with GeMPI-1 for Cress-Experiment



PE sample (white) in MaGe geometry

PE-Sample – Measurement and simulation

	Counts in 2.223 MeV line ($d^{-1}kg^{-1}$)	Part of measured value (%)
Measurement	0.095 ± 0.058	
Muon-induced neutrons (shield)	0.003 ± 0.001	3.16 ± 1.05
Muon-induced neutrons (rock)	0.0002 ± 0.0001	0.21 ± 0.11
Neutrons from nat. radioactivity*	0.058 ± 0.003	61.05 ± 3.16

*simulated with $0.7 * 10^{-6} \frac{n}{s cm^2}$

→ Remaining counts in line have to be induced by „missing“ flux from neutrons from natural radioactivity

☐ Can be used to indirectly determine this „missing“ flux

☐ Factor (1.6 ± 1.0) for flux of neutrons from nat. radioactivity

Increase of thickness of copper layer

Isotope	Assumed activity [$\mu\text{Bq/kg}$]	Background contribution for 5 cm Cu layer [counts/d/kg]	Background contribution for 10 cm Cu layer [counts/d/kg]
^{60}Co	33	3.8 ± 0.3	5.2 ± 0.5
^{238}U	16	1.9 ± 0.1	2.1 ± 0.1
^{232}Th	19	4.8 ± 0.4	5.4 ± 0.5
^{40}K	88	0.8 ± 0.1	0.9 ± 0.1
Total	-	11.3 ± 0.9	13.6 ± 1.2

Composition of Bkg. Spectrum of GeMPI 3

Source	Integrated background count rate [40, 2700] keV [cts/d/kg]	Percentage of detector background [%]
Muons	0.8 ± 0.1	3.3 ± 0.6
Neutrons	3.1 ± 2.0	12.9 ± 8.2
^{210}Pb in lead shield	13.0 ± 1.0	54.0 ± 4.0
^{60}Co in copper	3.3 ± 0.9	13.6 ± 3.7
^{238}U in copper	1.8 ± 2.2	7.5 ± 9.0
^{232}Th in copper	0.6 ± 0.3	2.3 ± 1.2
^{40}K in copper	1.6 ± 0.5	6.7 ± 2.2
^{207}Bi on crystal surface	2.0 ± 0.5	8.3 ± 2.1
Total	26.2 ± 7.5	108.6 ± 30.0

References

- [1] „Low level germanium gamma-ray spectrometry at the $\mu\text{Bq}/\text{kg}$ level and future developments towards higher sensitivities“ - Heusser G., M. Laubenstein, H. Neder
- [2] „The neutron background of the XENON100 dark matter experiment“ – XENON collaboration
- [3] „Production and transport of hadrons generated in nuclear cascades initiated by muons in rock“ - A. Dementyev, V. Gurentsov, O. Ryazhskaya, N. Sobolevsky
- [4] „Neutron Flux at the Grand Sasso Underground Laboratory Revisited“ - H. Wulandari, J. Jochum, W. Rau, F. von Feilitzsch
- [5] „MAGE- a GEANT4-based Monte Carlo framework for low-background experiments” – Yuen-Dat Chan, Jason Detwiler, Reyco Henning, Victor Gehmann