Review of Monte Carlo simulations and muon-induced neutrons

Marco Selvi – INFN Bologna

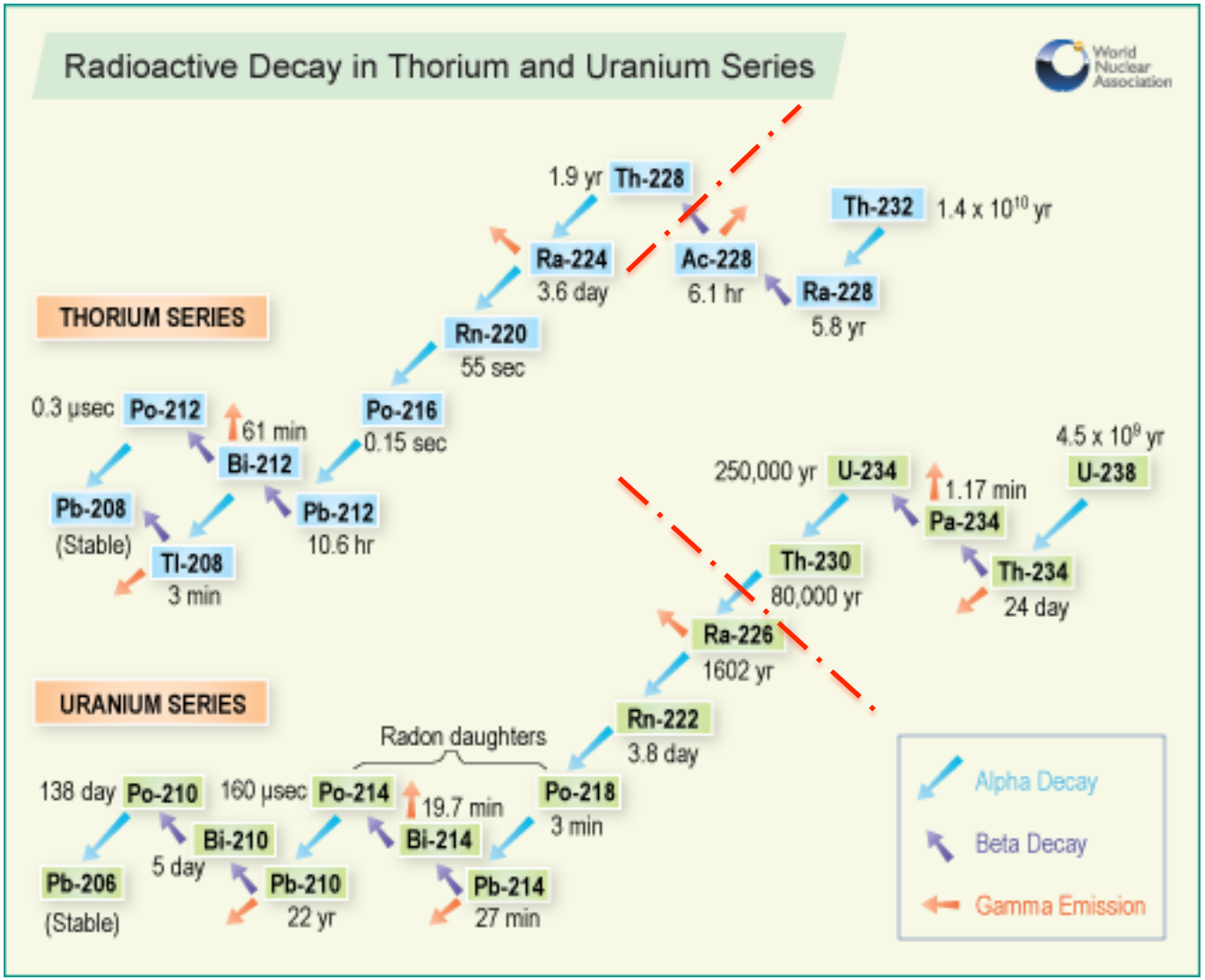
Low Radioactivity Techniques
Workshop – April, 12th 2013 - LNGS

Outline

- e.m. background:
  - Gammas, betas from radioactivity
  - Intrinsic contaminants
- Radiogenic neutrons:
  - Spontaneous fission
  - (α,n)
- Cosmogenic neutrons:
  - Muon-induced neutrons

e. m. background

U and Th chains



Radioactive decays in GEANT4

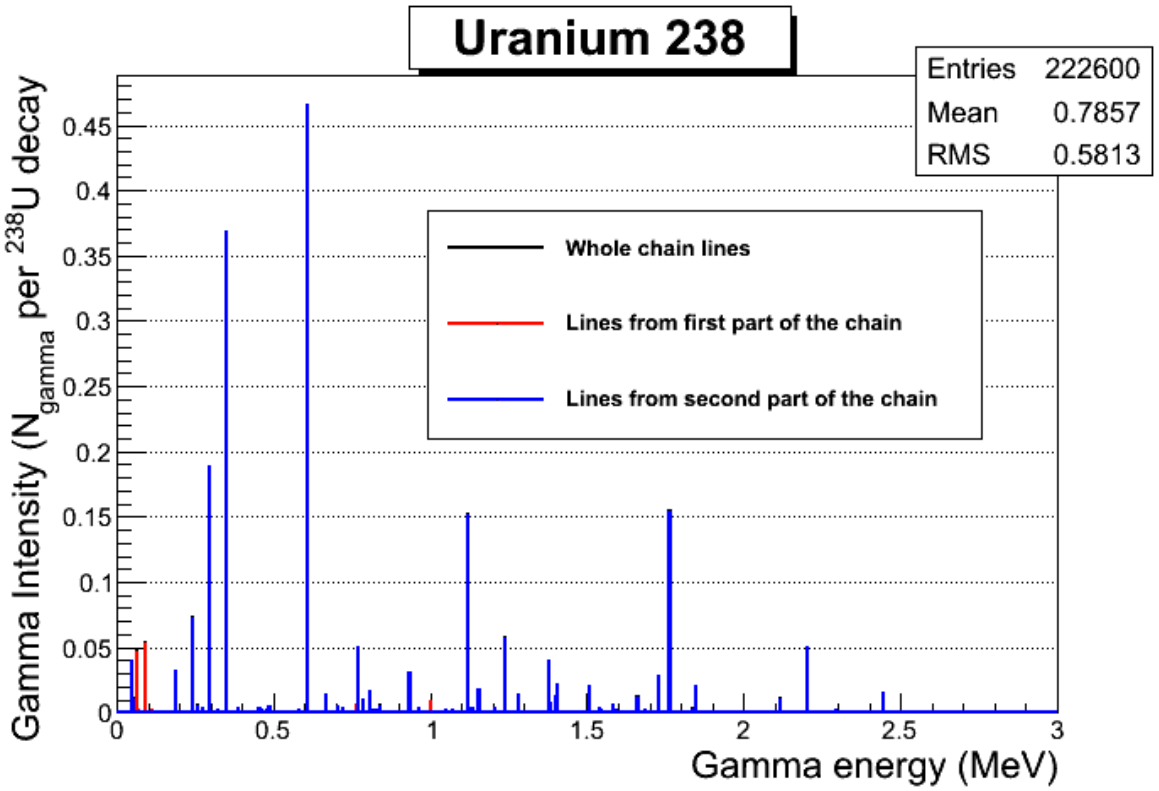
- G4RadioactiveDecay: process to simulate radioactive decay of nuclei
- α, β+, β- decay, electron capture (EC) implemented
- Empirical and data-driven:
  - data files taken from Evaluated Nuclear Structure Data Files (ENSDF)
  - Half lives, nuclear level structure for parent and daughter nuclides, decay branching ratios, energy of decay process
- If daughter of nuclear decay is an isomer, prompt-de-excitation is done with G4PhotonEvaporation process

^{238}U chain

Uranium 238

Table 1: Uranium 238 chain	
Part of the chain	**Gamma yield (gammas per parent decay)**
First part: U238[0.0] → Ra226[0.0]	0.14
Second part: Ra226[0.0] → Pb206[0.0]	2.09
Whole chain: U238[0.0] → Pb206[0.0]	2.23

Fig. 1: gamma lines from uranium 238

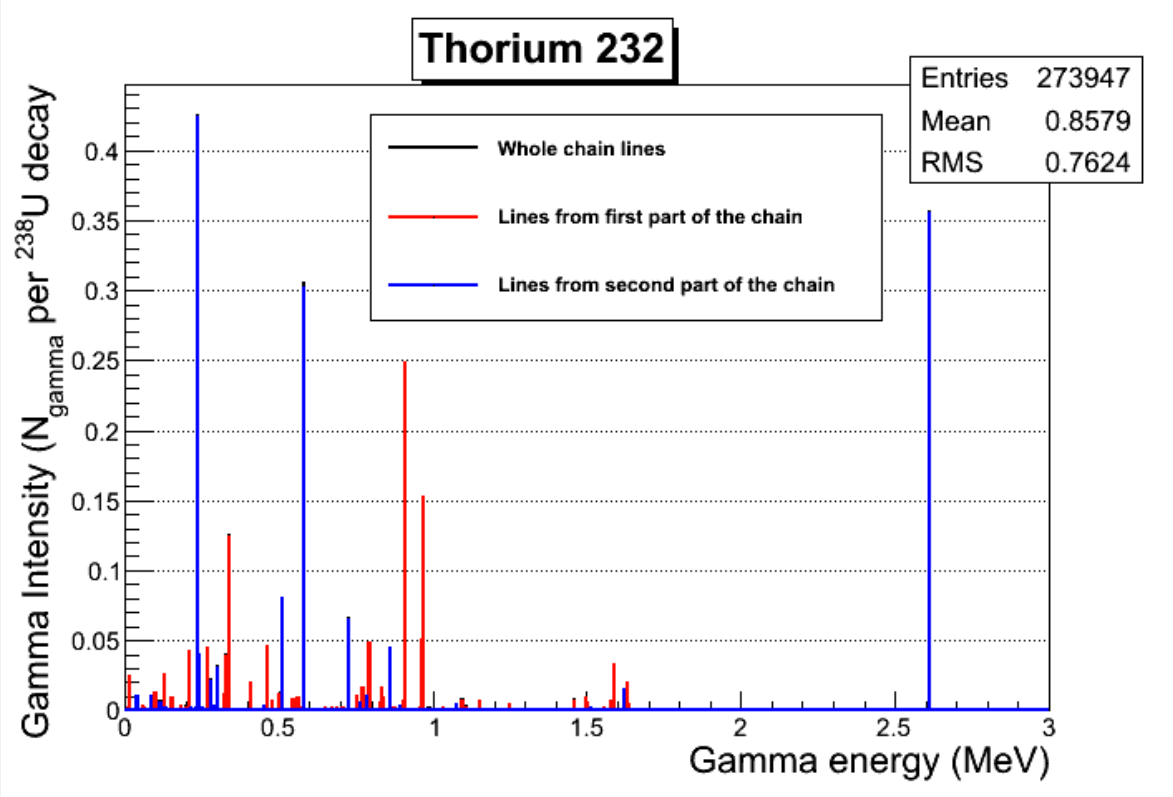


^{232}Th chain

Thorium 232

Table 2: Thorium 232 chain	
Part of the chain	**Gamma yield (gammas per parent decay)**
First part: Th232[0.0] → Th228[0.0]	1.27
Second part: Th228[0.0] → Pb208[0.0]	1.47
Whole chain: Th232[0.0] → Pb208[0.0]	2.74

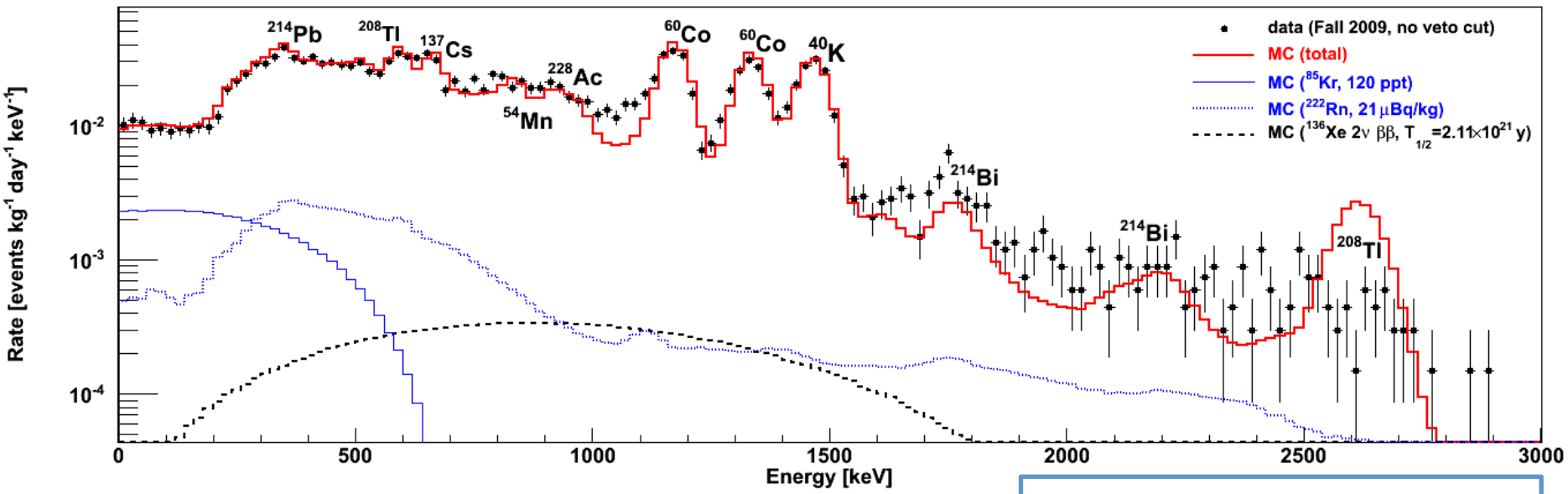
Fig. 2: gamma lines from thorium 232



MC-DATA comparison in XENON100

- Monte Carlo simulations of XENON100 e.m. background in good agreement with measured data
- Background is well understood in the full energy range

30 kg fiducial volume, single scatter, No veto cut, BEFORE S2/S1 discrimination

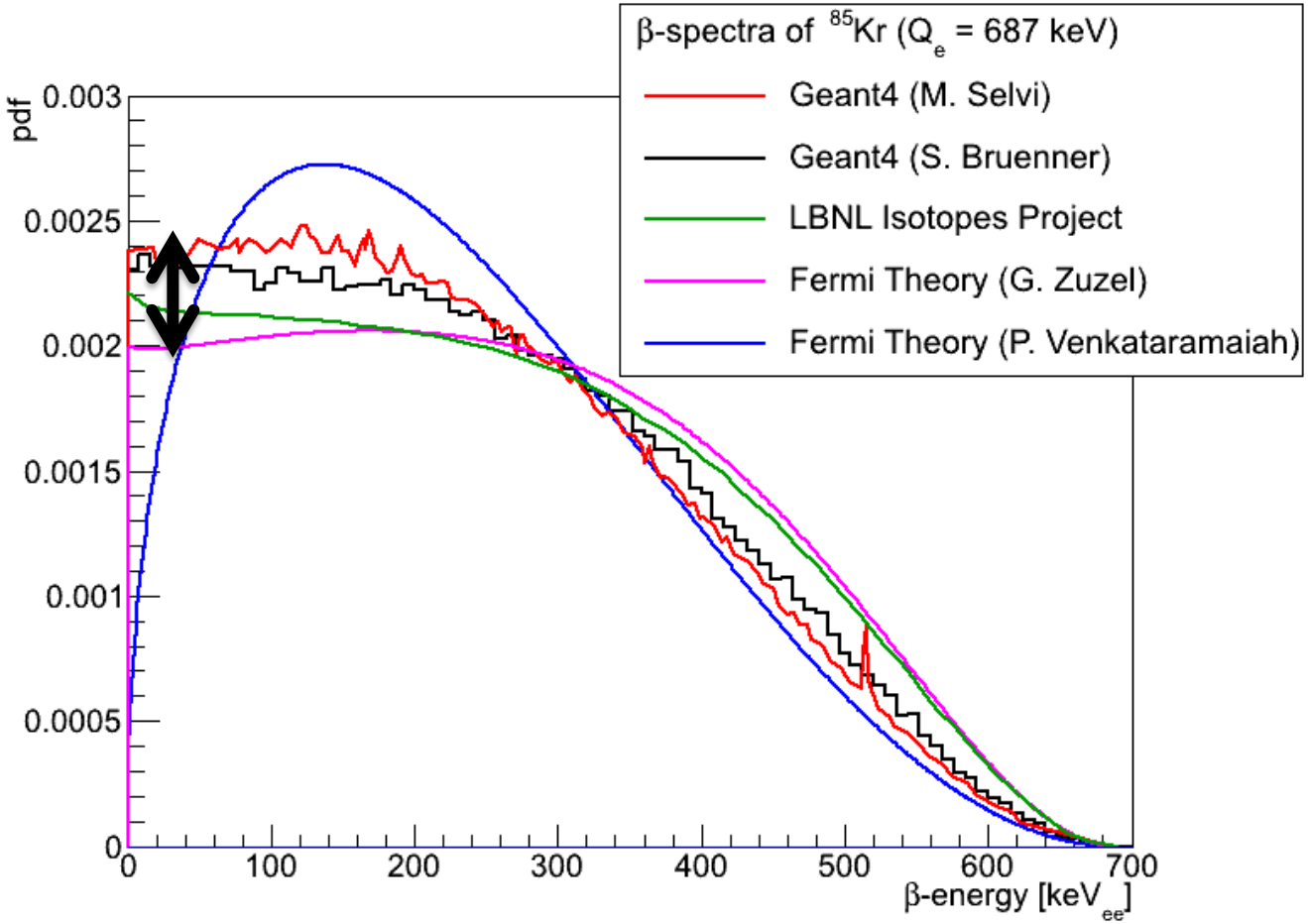


Phys. Rev. D83: 082001, 2011

It's not a fit to the data,
we used the screened contaminations of the materials as input for the MC simulation and superimpose with data.

^{85}Kr beta spectrum

Uncertainty in the low energy region : about 20 %

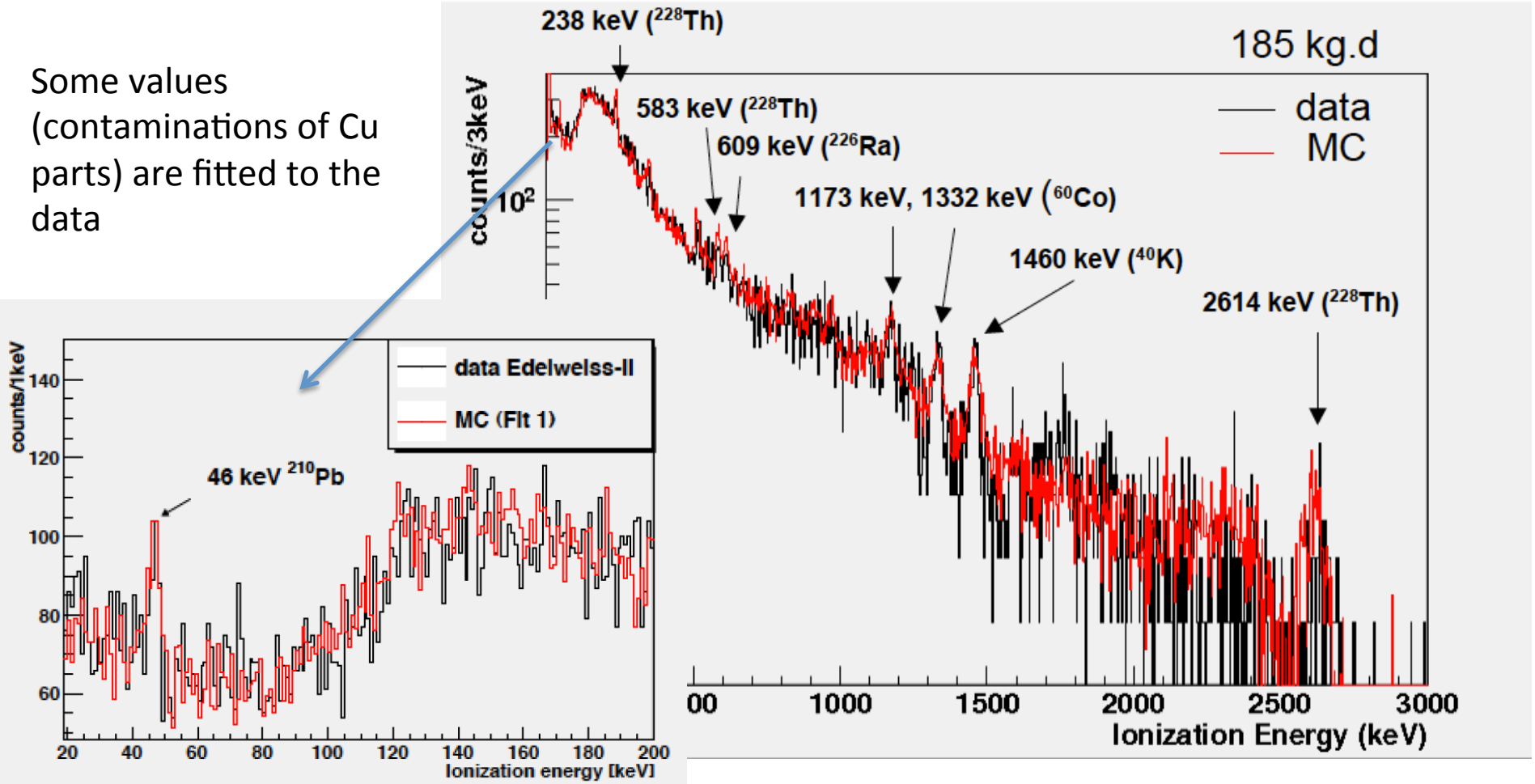


Plot by S. Lindemann - MPIK

MC-DATA comparison in EDELWEISS-II

The decays of ^{226}Ra, ^{228}Ra, ^{60}Co, ^{40}K, ^{54}Mn and ^{210}Pb were simulated in the detector casings, the copper plates at 10 mK, the bars supporting the plates, the screen and plate at 10 mK, cryostat, the dilution chamber, 1K connectors, the coaxial cables and the lead shielding

Some values (contaminations of Cu parts) are fitted to the data



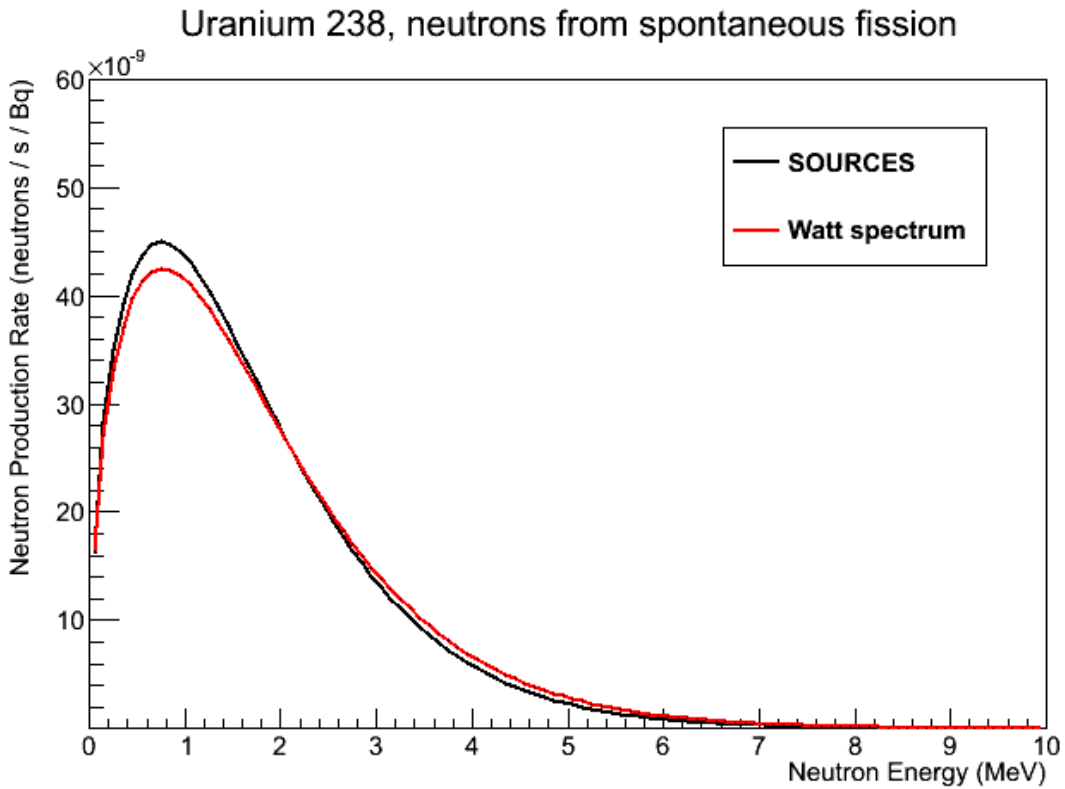
Radiogenic neutrons

Radiogenic neutrons

- SOURCES-4A (modified version – Sheffield group):
  Wilson et al. Sources4A. Technical Report, LA-13639-MS (1999);
  Tomasello et al., NIMA 595 (2008) 431.
  Cross-sections from EMPIRE.
- Zhang-Mei-Hime code
  NIM A606, 651 (2009)
  http://neutronyield.usd.edu
  Cross-sections from TALYS.

Neutrons from spontaneous fission

Watt's spectrum: $N(E) = C * e^{(-E/a)} * \sinh(\sqrt{b*E})$
with a = 0.7124 MeV, b = 5.6405 MeV^{-1}.
C is the normalization factor.
H. Wulandari et al., Astrop. Phys. 22 313 (2004).



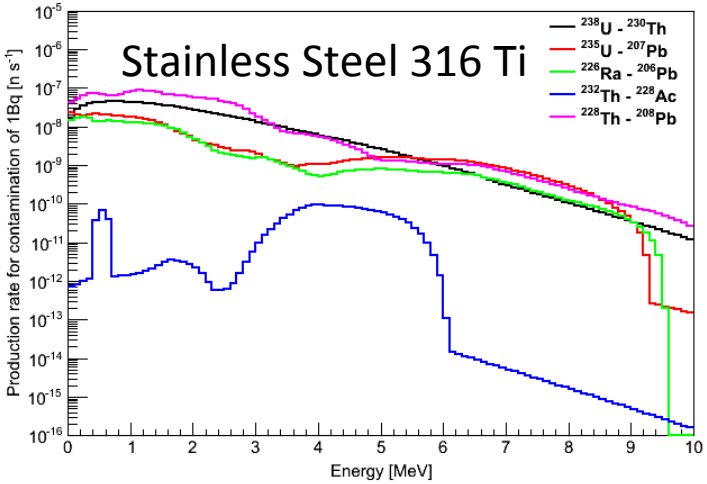
1 kg of Uranium
emits 13.53 n/s
(taken from
http://www.wise-uranium.org/ranc.html),
→ 1.1 10^{-6} n/s @ 1 Bq
independent from the material

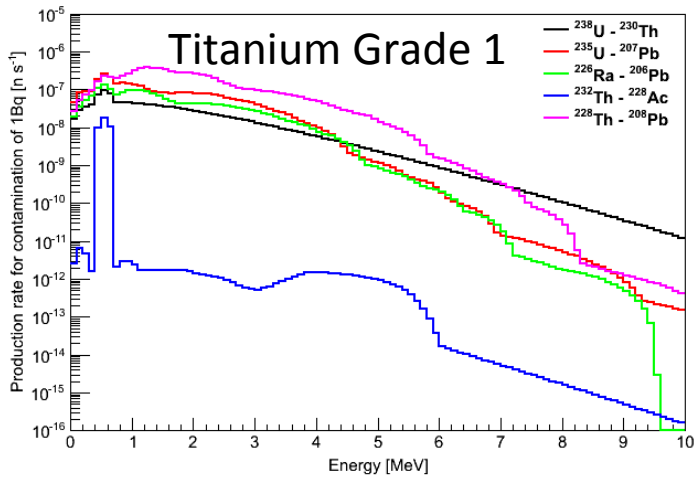
Neutron production with SOURCES

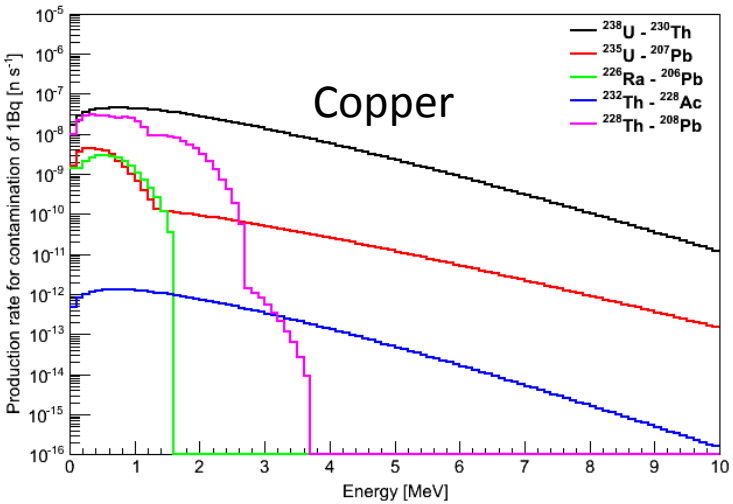
Table 1: Neutron production rate due to (α,n) and spontaneous fission reactions calculated with SOURCES-4A. Included is the systematic unc

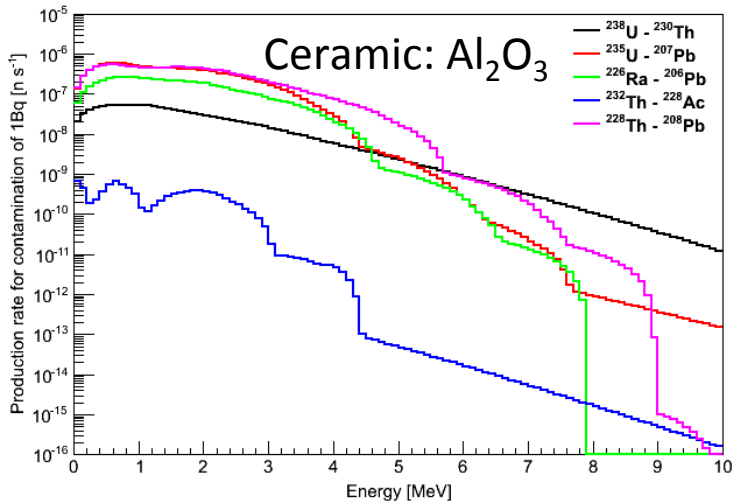
Material	Neutron production for contamination of 1Bq [$n \cdot s^{-1}$]				
	^{238}U - ^{230}Th	^{235}U - ^{207}Pb	^{226}Ra - ^{206}Pb	^{232}Th - ^{228}Ac	^{228}Th - ^{208}Pb
stainless steel 316Ti	$(1.1\pm0.2)\cdot10^{-6}$	$(4.1\pm0.7)\cdot10^{-7}$	$(3.1\pm0.5)\cdot10^{-7}$	$(1.8\pm0.3)\cdot10^{-9}$	$(2.0\pm0.3)\cdot10^{-6}$
stainless steel 304L	$(1.1\pm0.2)\cdot10^{-6}$	$(3.4\pm0.6)\cdot10^{-7}$	$(2.8\pm0.5)\cdot10^{-7}$	$(4.9\pm0.8)\cdot10^{-11}$	$(2.0\pm0.3)\cdot10^{-6}$
titanium	$(1.2\pm0.2)\cdot10^{-6}$	$(3.3\pm0.6)\cdot10^{-6}$	$(2.0\pm0.3)\cdot10^{-6}$	$(3.8\pm0.7)\cdot10^{-8}$	$(7.7\pm1.3)\cdot10^{-6}$
copper	$(1.1\pm0.2)\cdot10^{-6}$	$(3.3\pm0.6)\cdot10^{-8}$	$(2.5\pm0.4)\cdot10^{-8}$	$(3.0\pm0.5)\cdot10^{-11}$	$(3.6\pm0.6)\cdot10^{-7}$
PTFE	$(7.4\pm1.3)\cdot10^{-6}$	$(1.3\pm0.2)\cdot10^{-4}$	$(5.5\pm0.9)\cdot10^{-5}$	$(7.3\pm1.2)\cdot10^{-7}$	$(1.0\pm0.2)\cdot10^{-4}$
Cirlex	$(1.3\pm0.2)\cdot10^{-6}$	$(2.2\pm0.4)\cdot10^{-6}$	$(3.5\pm0.6)\cdot10^{-6}$	$(4.1\pm0.7)\cdot10^{-8}$	$(2.4\pm0.4)\cdot10^{-6}$
Kovar	$(1.1\pm0.2)\cdot10^{-6}$	$(1.3\pm0.2)\cdot10^{-7}$	$(1.2\pm0.2)\cdot10^{-7}$	$(3.0\pm0.5)\cdot10^{-11}$	$(1.0\pm0.2)\cdot10^{-6}$
quartz (fused silica, SiO_2)	$(1.2\pm0.2)\cdot10^{-6}$	$(1.9\pm0.3)\cdot10^{-6}$	$(8.8\pm1.5)\cdot10^{-7}$	$(6.8\pm1.2)\cdot10^{-9}$	$(1.9\pm0.3)\cdot10^{-6}$
ceramics, aluminum oxide (Al_2O_3)	$(1.2\pm0.2)\cdot10^{-6}$	$(1.3\pm0.2)\cdot10^{-5}$	$(6.0\pm1.0)\cdot10^{-6}$	$(9.2\pm1.6)\cdot10^{-9}$	$(1.4\pm0.2)\cdot10^{-5}$
ceramics, titanium oxide (Ti_2O3)	$(1.2\pm0.2)\cdot10^{-6}$	$(1.8\pm0.3)\cdot10^{-6}$	$(1.1\pm0.2)\cdot10^{-6}$	$(2.1\pm0.4)\cdot10^{-8}$	$(3.9\pm0.7)\cdot10^{-6}$
polyethylene (C_2H_4)	$(1.2\pm0.2)\cdot10^{-6}$	$(1.6\pm0.3)\cdot10^{-6}$	$(7.5\pm1.3)\cdot10^{-7}$	$(3.1\pm0.5)\cdot10^{-8}$	$(1.4\pm0.2)\cdot10^{-6}$
PEN (polyethylene naphtalate, $[C_{14}H_{12}O_4.C_2H_6O_2]_n$)	$(1.3\pm0.2)\cdot10^{-6}$	$(2.0\pm0.3)\cdot10^{-6}$	$(9.4\pm1.6)\cdot10^{-7}$	$(3.7\pm0.6)\cdot10^{-8}$	$(1.7\pm0.3)\cdot10^{-6}$
PMMA, acrylic plastic (polymethyl methacrylate, $[C_5H_8O_2]_n$)	$(1.3\pm0.2)\cdot10^{-6}$	$(1.8\pm0.3)\cdot10^{-6}$	$(8.8\pm1.5)\cdot10^{-7}$	$(3.5\pm0.6)\cdot10^{-8}$	$(1.6\pm0.3)\cdot10^{-6}$
PEEK (polyether ether kethone, $[OC_6H_4OC_6H_4COC_6H_4]_n$)	$(1.3\pm0.2)\cdot10^{-6}$	$(2.4\pm0.4)\cdot10^{-6}$	$(1.1\pm0.2)\cdot10^{-6}$	$(4.6\pm0.8)\cdot10^{-8}$	$(2.1\pm0.4)\cdot10^{-6}$
LNGS concrete	$(1.2\pm0.2)\cdot10^{-6}$	$(1.5\pm0.3)\cdot10^{-6}$	$(7.1\pm1.2)\cdot10^{-7}$	$(7.8\pm1.3)\cdot10^{-9}$	$(1.5\pm0.3)\cdot10^{-6}$

Neutron production with SOURCES









Cross checks of (alpha,n) neutrons

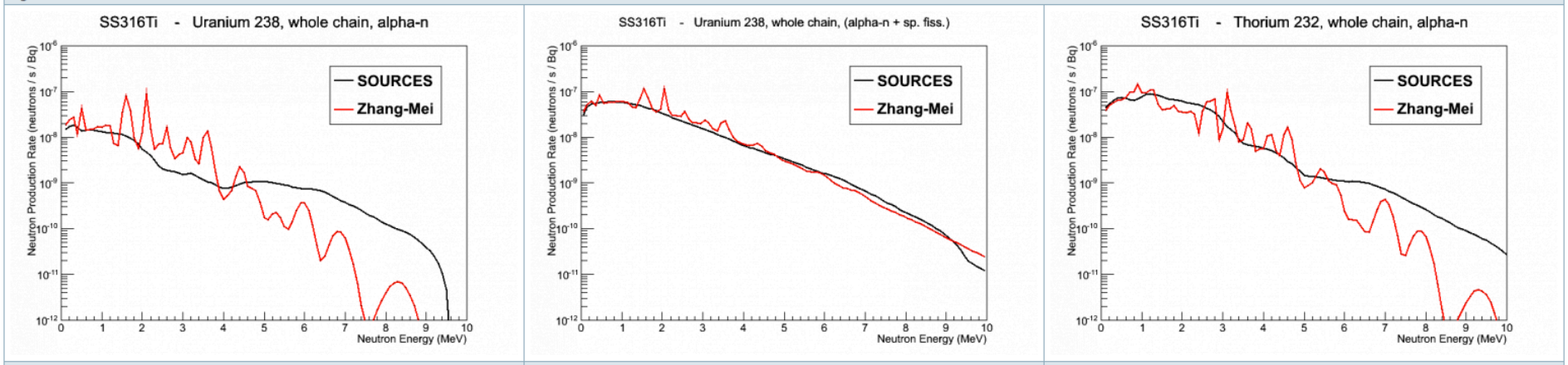
Comparison of the neutrons produced by (alpha,n) interactions between SOURCES and the code by Zhang, Mei and Hime.

Table 1: total neutron yield (neutrons/Bq s)									
Material	U238 (only alpha,n)			U238 (alpha,n + s.f.)			Th232		
	SOURCES	Zhang-Mei	Diff %	SOURCES	Zhang-Mei	Diff %	SOURCES	Zhang-Mei	Diff %
SS316Ti	3.16e-07	6.57e-07	-70.1%	1.42e-06	1.75e-06	-21%	1.98e-06	2.05e-06	-3.49%
TiGrade1	2.14e-06	3.58e-06	-50.5%	3.24e-06	4.67e-06	-36.3%	7.7e-06	6.76e-06	12.9%
copper	2.46e-08	3.06e-08	-21.6%	1.12e-06	1.13e-06	-0.294%	3.56e-07	3.01e-07	16.6%
PTFE	6.09e-05	5.91e-05	2.88%	6.2e-05	6.02e-05	2.84%	0.000104	6.06e-05	52.9%
Al2O3	6.17e-06	6.94e-06	-11.6%	7.28e-06	8.03e-06	-9.87%	1.39e-05	8.59e-06	47.1%
Ti2O3	1.17e-06	2.51e-06	-72.8%	2.27e-06	3.6e-06	-45.3%	3.89e-06	4.62e-06	-17.3%
Poly	8.83e-07	8.31e-07	6.09%	1.99e-06	1.93e-06	3.06%	1.39e-06	7.56e-07	59.3%

The total neutron yields are within a factor 2.

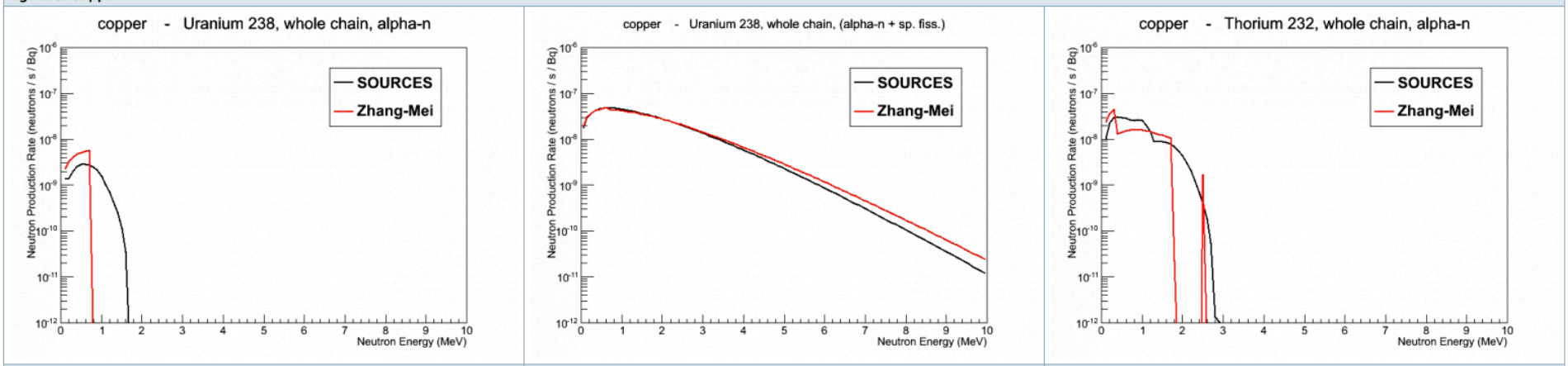
Cross checks of (alpha,n) neutrons

Figure 1: Stainless steel SS316Ti



Uranium (only alpha,n) | **Uranium (alpha,n + s.f.)** | **Thorium**

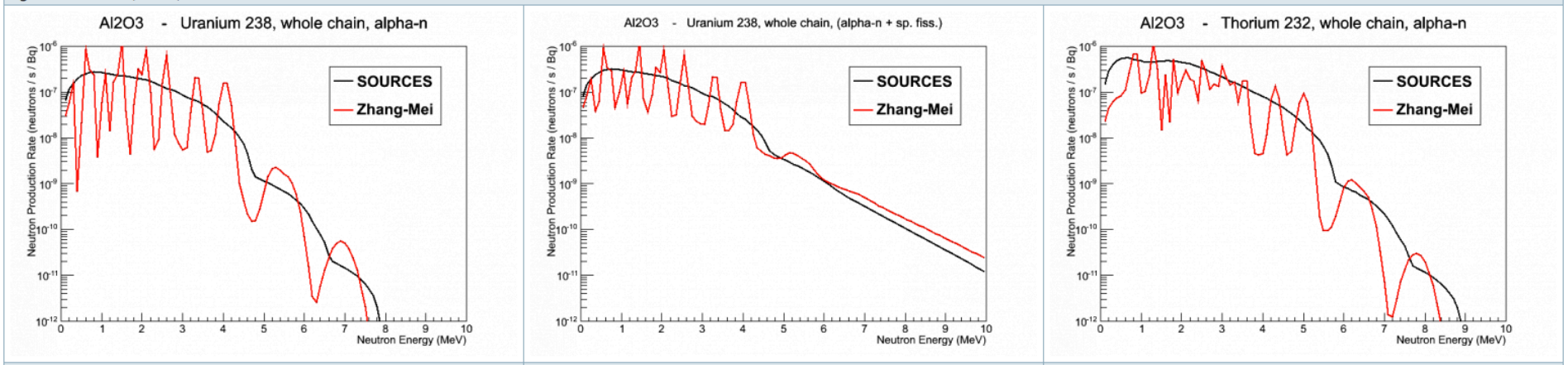
Figure 3: Copper



Uranium (only alpha,n) | **Uranium (alpha,n + s.f.)** | **Thorium**

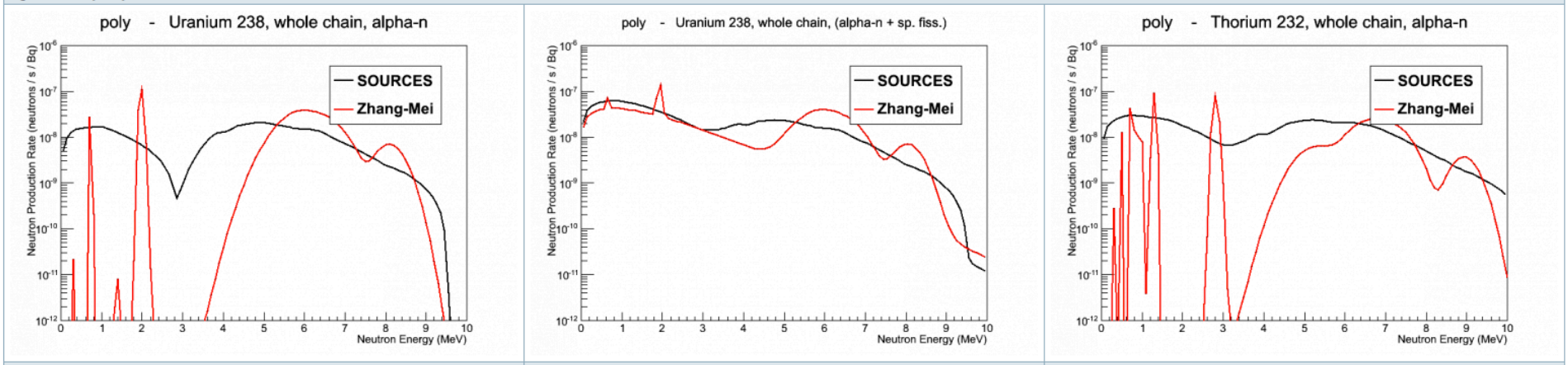
Cross checks of (alpha,n) neutrons

Figure 5: Ceramic (Al2O3)



Uranium (only alpha,n) | **Uranium (alpha,n + s.f.)** | **Thorium**

Figure 7: Polyethylene (Cn H2n)



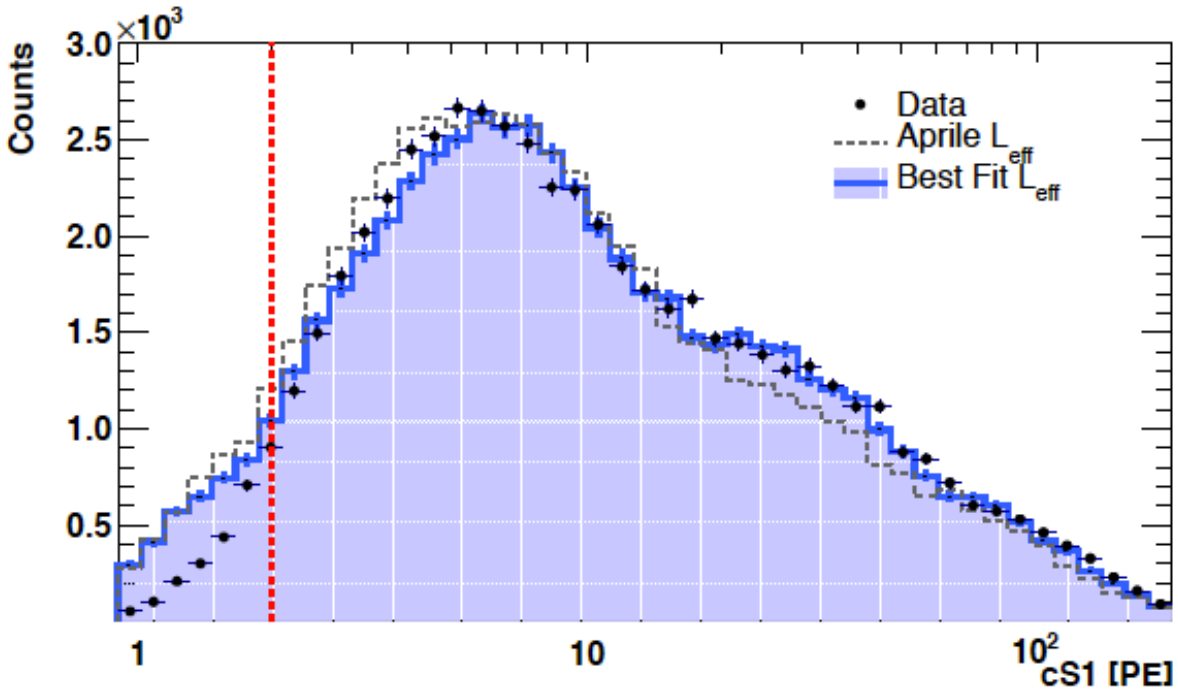
Uranium (only alpha,n) | **Uranium (alpha,n + s.f.)** | **Thorium**

Neutron propagation and interaction

Response of the XENON100 Dark Matter Detector to Nuclear Recoils – arXiv:1304.1427

Neutrons from AmBe calibration source.
Comparison between data and the GEANT4 simulation shows a good agreement.

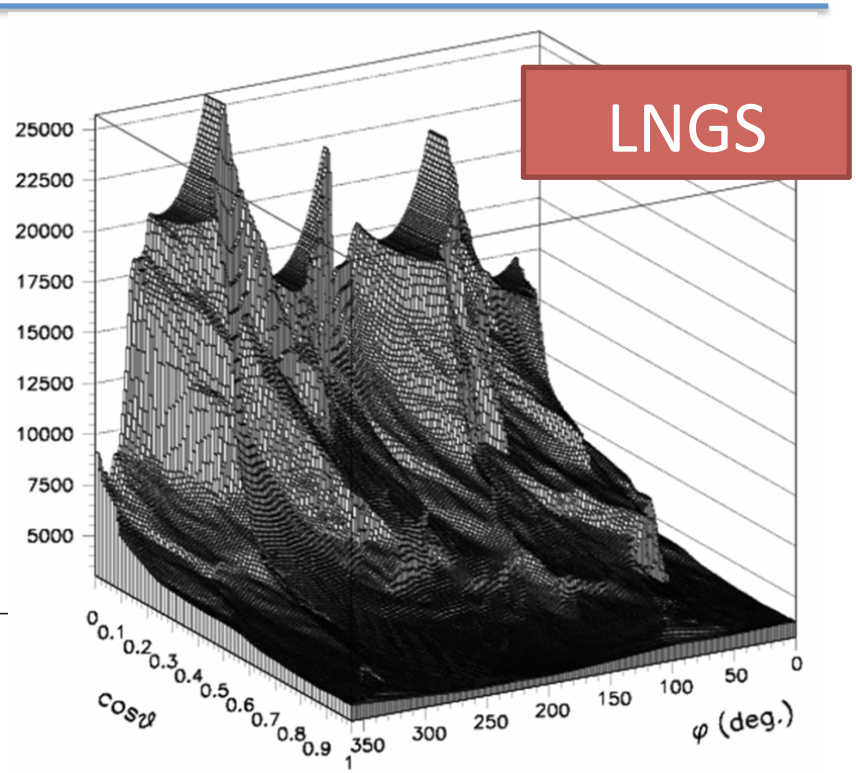
"HP" physics list was used for neutron propagation and interaction, using the ENDF/B-VI/B-VII databases provided in the data files G4NDL 3.13.

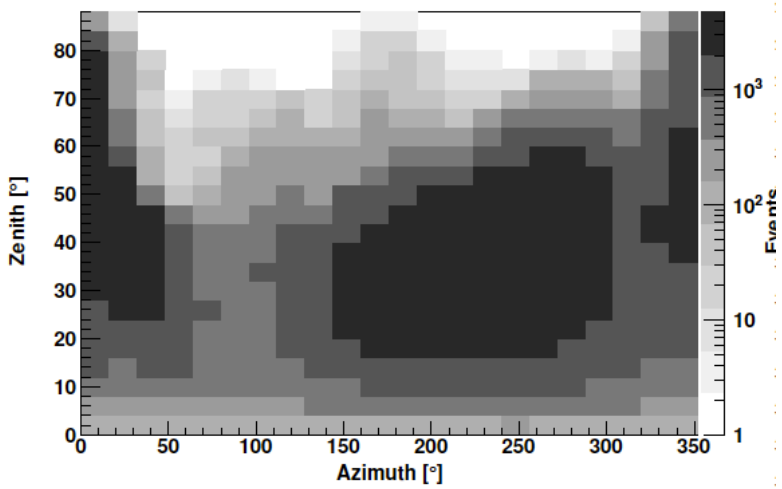


Muon-induced neutrons

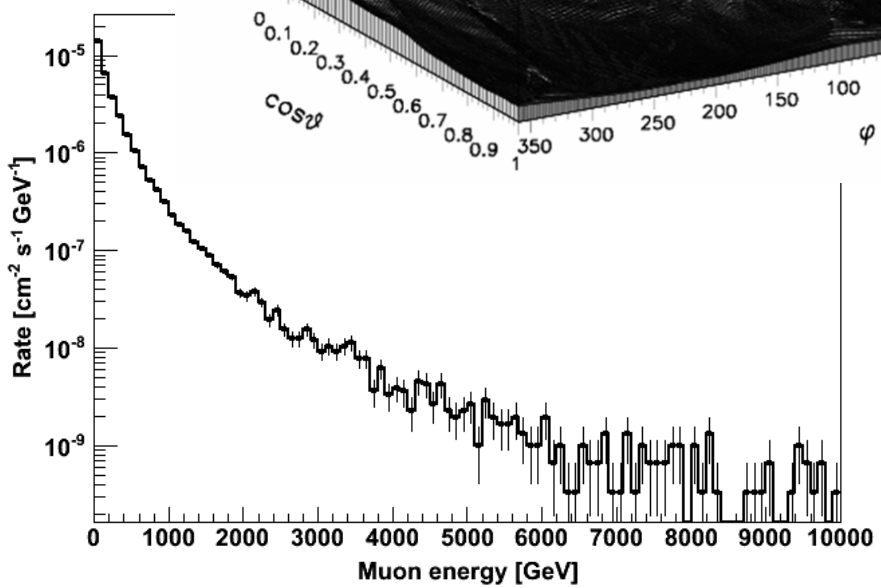
Ingredients

- Muon flux, energy spectrum and angular distribution (site dependent)
  → MUSIC, MUSUN
  V. Kudryavtsev, Comp. Phys. Comm. 180 (2009) 339



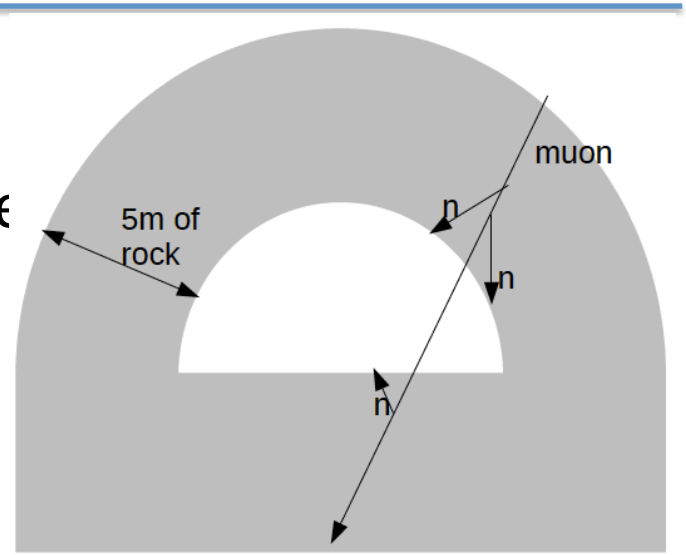


(b) angular spectrum



Ingredients

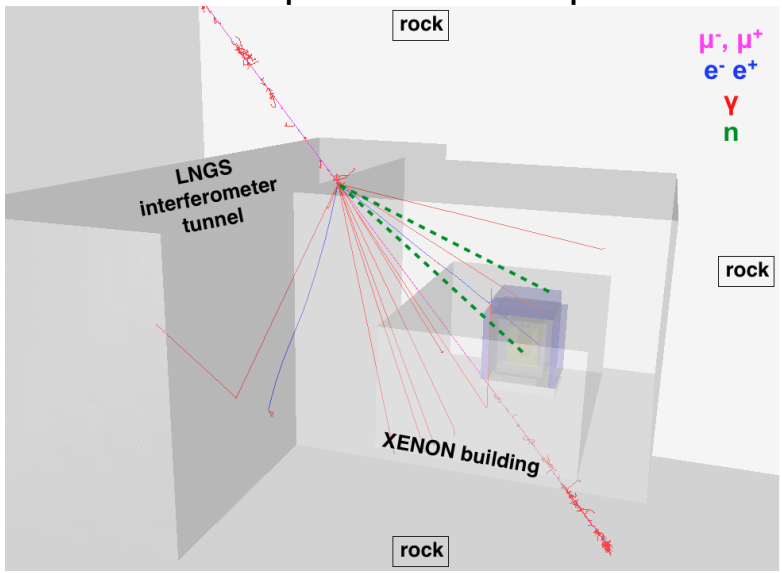
- Put a few meters of rock thickness around the hall to fully develop the muon-induced showers.



- Rock composition

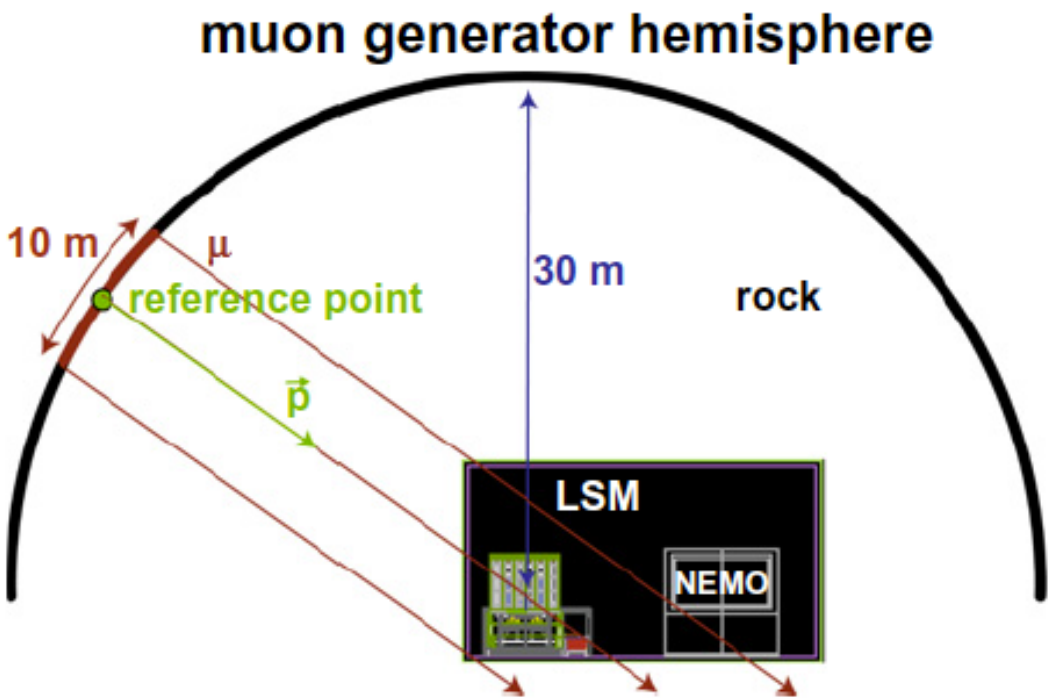
Element	Percentage in weight LNGS	LSM
H	0	1
C	12	5.94
O	51	49.4
Na	0	0.44
Mg	8.4	0.84
Al	0.6	2.58
Si	1	6.93
P	0	0.06
K	0	0.21
Ca	27	30.6
Ti	0	0.07
Mn	0	0.03
Fe	0	1.9

- Detailed description of the experimental hall



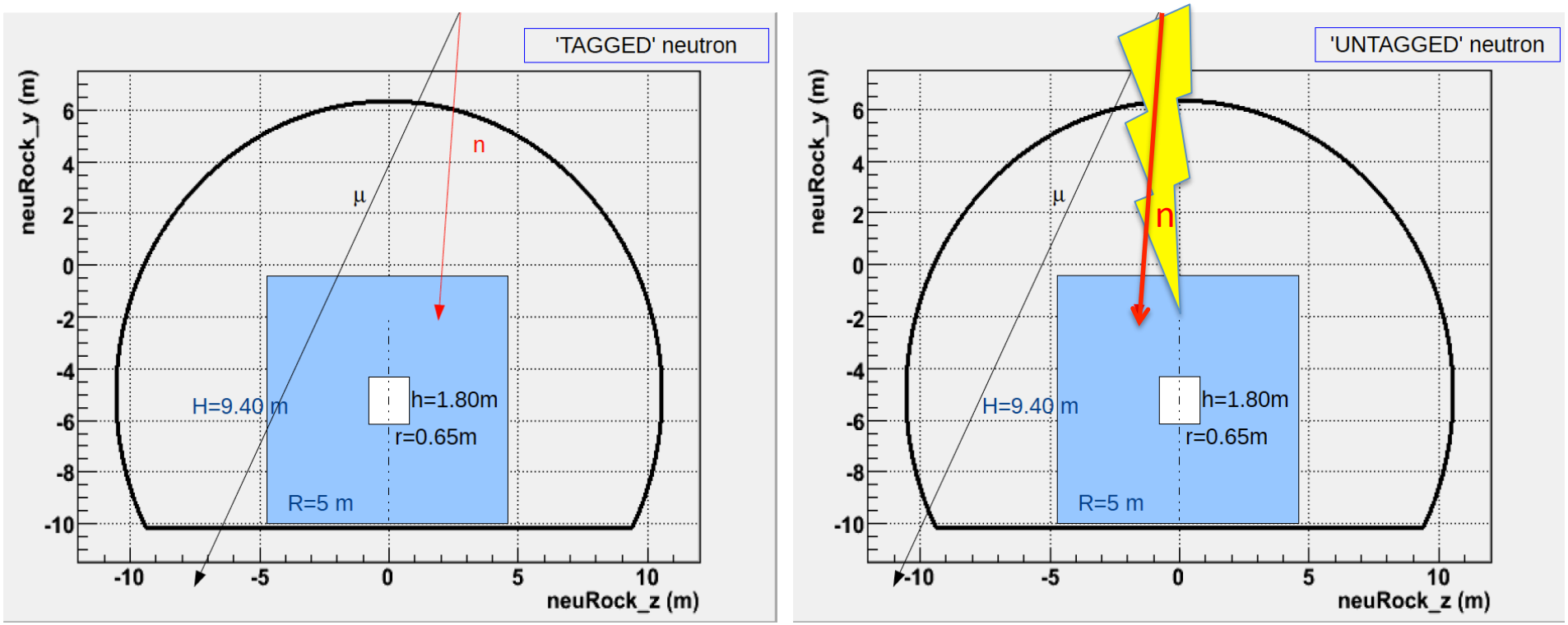
Ingredients

- Generate muons over a large area: radius up to 10-30 meters from the experimental site



Ingredients

- Propagate all the secondary particles , not just the neutrons (in particular for active veto)



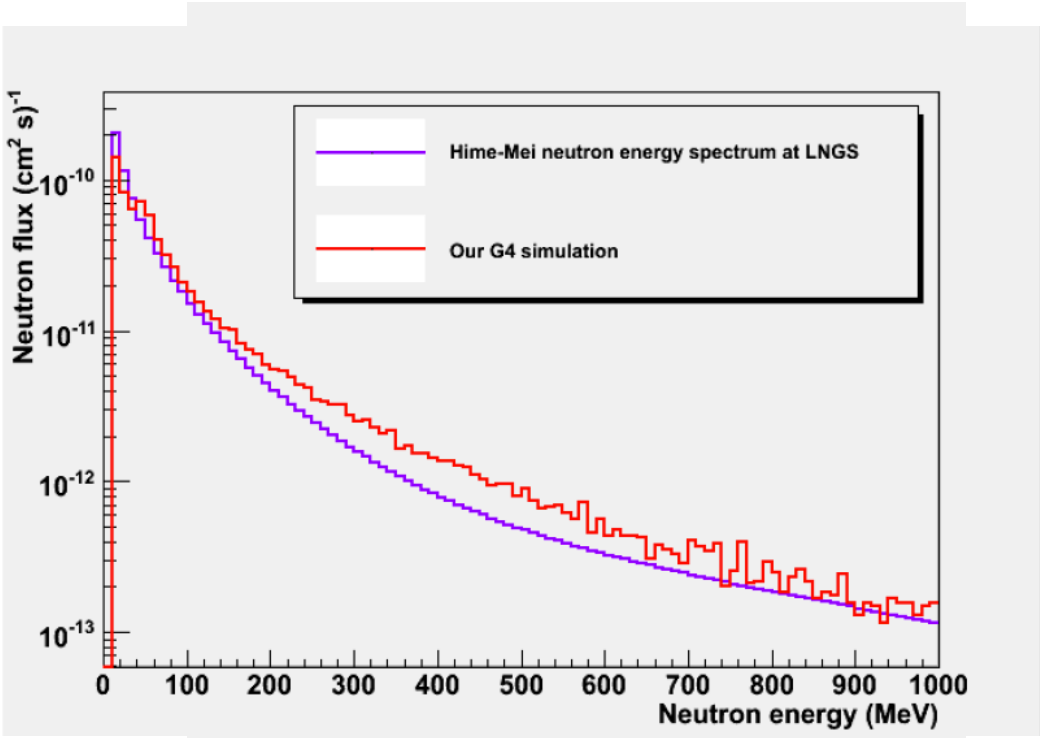
Neutron flux underground

100M muons were generated with GEANT4 9.3 (physics list QGSP_BIC_HP) with the proper energy and angular distribution at LNGS. They were sampled over a large area: a circle with 30m radius, corresponding to about 1250 days at Gran Sasso.

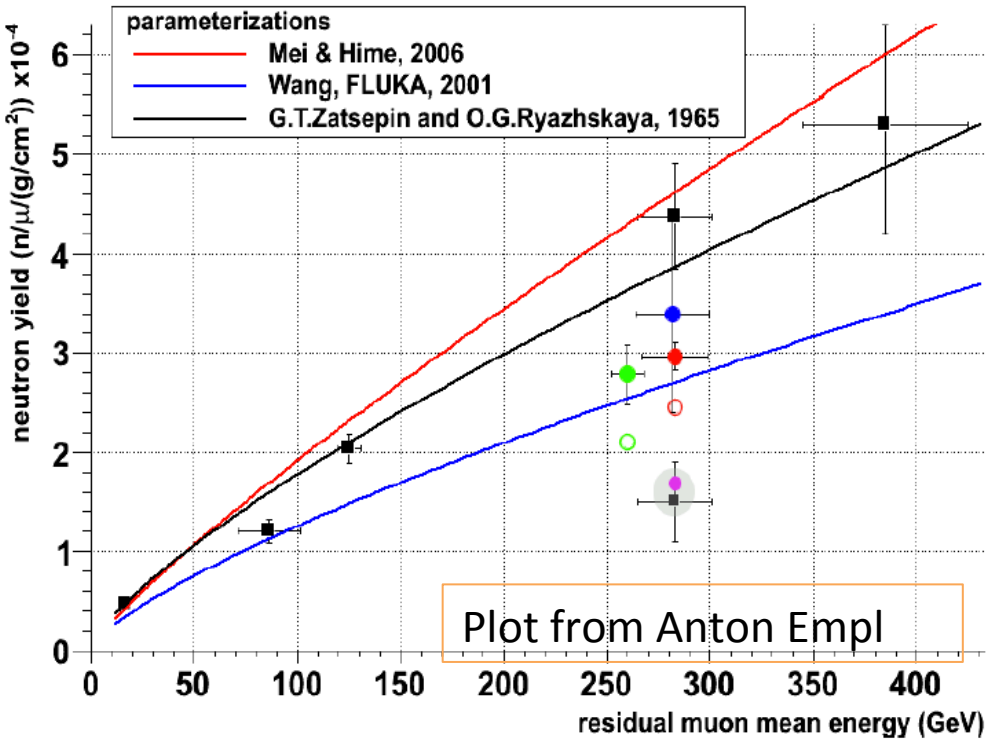
Muons are propagated through the LNGS rock, all the neutrons produced by direct spallation, e.m. and hadronic cascades are followed and their entrance point and momentum at the hall surface is recorded.

The total flux from the MC is:
E_n> 10 MeV: 1.3 10^{-10} $(cm^2\ s)^{-1}$
E_n> 100 MeV: 3.7 10^{-11} $(cm^2\ s)^{-1}$

FLUKA (+some "doping") simulation:
Mei and Hime, Phys. Rev. D 73, 053004 (2006):
E_n> 10 MeV: 7.3 10^{-10} $(cm^2\ s)^{-1}$
About 6 times higher !



n-yield in liquid scint. : data vs FLUKA



solid **black** symbols: Malgin and Ryazhskaya, Yad. Fiz. 71, 1800 (2008)
Phys. At. Nuclei 71, 1769 (2008)

Measurements made by physicists of the Laboratory of Electron Methods for Neutrino Detection, Inst. for Nuclear Research, Moscow and by members of the LSD and LVD collaborations. The black line is not a fit to the data but an early prediction.

Solid **blue** symbol:
PhD R. Persiani, Bologna (2011)
Presentation at AARM meeting (2012)
Recent result from LVD

Solid and open **green** symbols:
Phys. Rev. C 81, 025807 (2010)
Results from KamLAND on cosmogenic neutron and isotope production. The open symbol corresponds to results from a FLUKA simulation.

Solid and open **red** symbols:
PhD A. Chavarria, Princeton (2012)
A first result from Borexino on the neutron yield. The open symbol corresponds to the FLUKA predicted yield - however, note slides on ^{11}C production.

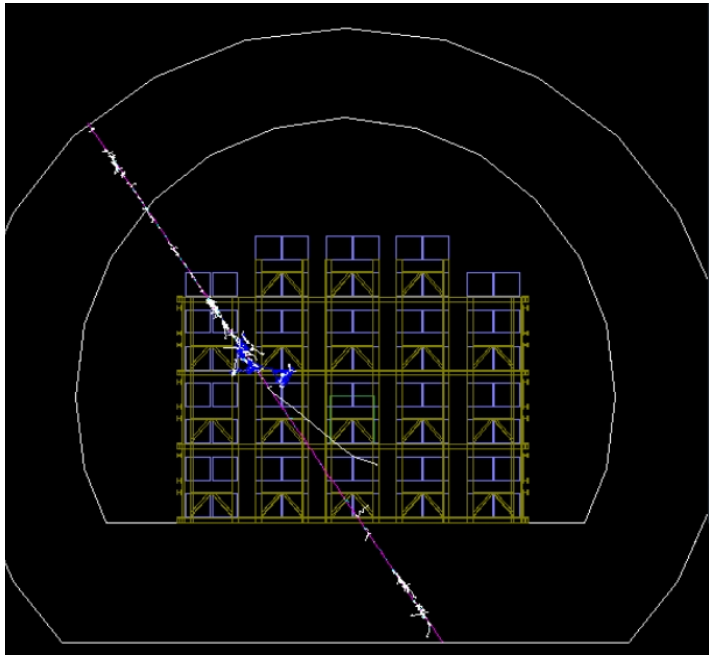
Gray shaded:
Early results (1999) reported from LVD (black) and CTF (purple symbol).

See also N. Agafonova, A. Malgin arXiv:1304.0919
Universal formula for the muon-induced neutron yield

FLUKA vs GEANT4

… see A. Villano talk in a while :
A Comprehensive Comparison for Simulations of Cosmic Ray Muons Underground

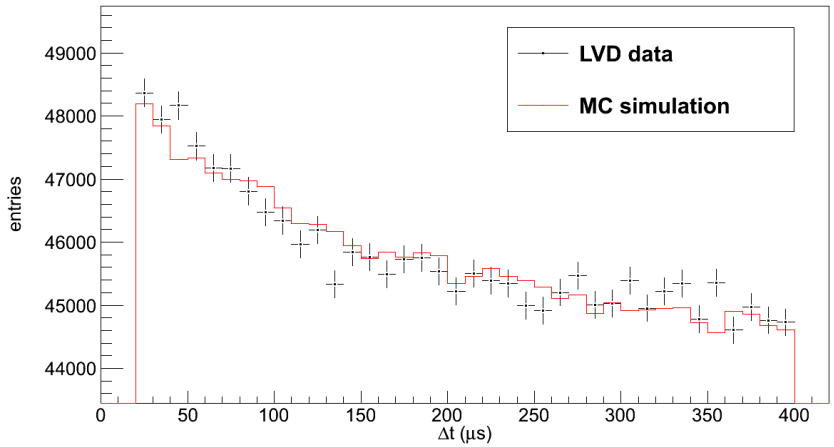
LVD



Monte Carlo simulation done in GEANT4 9.3, with the QGSP_BIC_HP physics list.

Background evaluation independent from the muon-correlated data.

Agreement with the experimental data increasing the MC by a factor 1.4.



The MC also tells us that 80% of the neutrons are produced in the iron of the support structure:

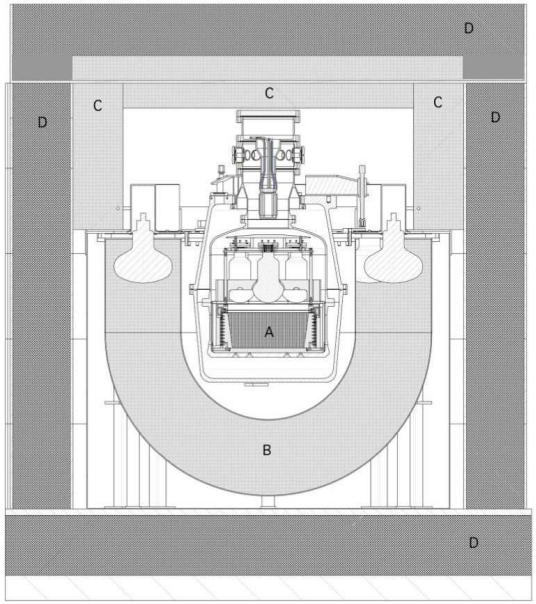
$Y_{LS} = (2.9 \pm 0.6) \times 10^{-4}$ n/(g/cm^2)

$Y_{Fe} = (1.5 \pm 0.3) \times 10^{-3}$ n/(g/cm^2)

More details in Rino Persiani's poster:
Measurement of the neutron yield induced by muons in liquid scintillator and iron at LNGS with LVD experiment

ZEPLIN II and III

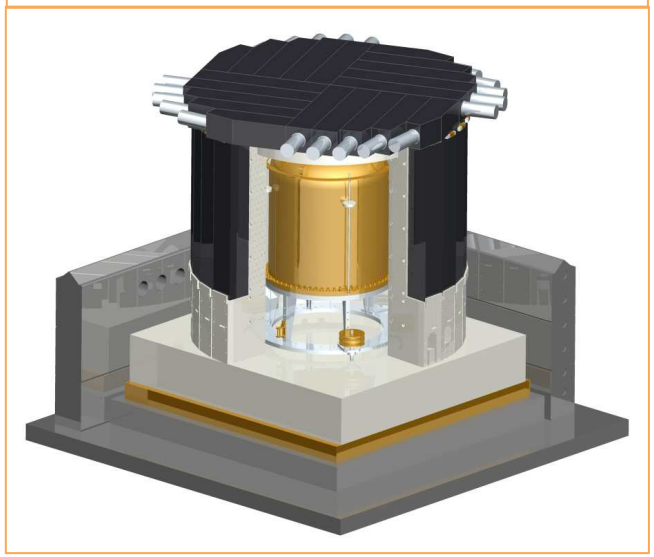
ZEPLIN-II measurement: Astrop. Phys. 29 (2008) 471
Details of the MC simulation: Astrop. Phys. 31 (2009) 366



Neutrons detected vie their capture in Gd-loaded liquid scintillator detector

MC simulation developed in GEANT4 8.2, with a custom physics list

Wait for Lea Reichhart's talk about the results of ZEPLIN-III



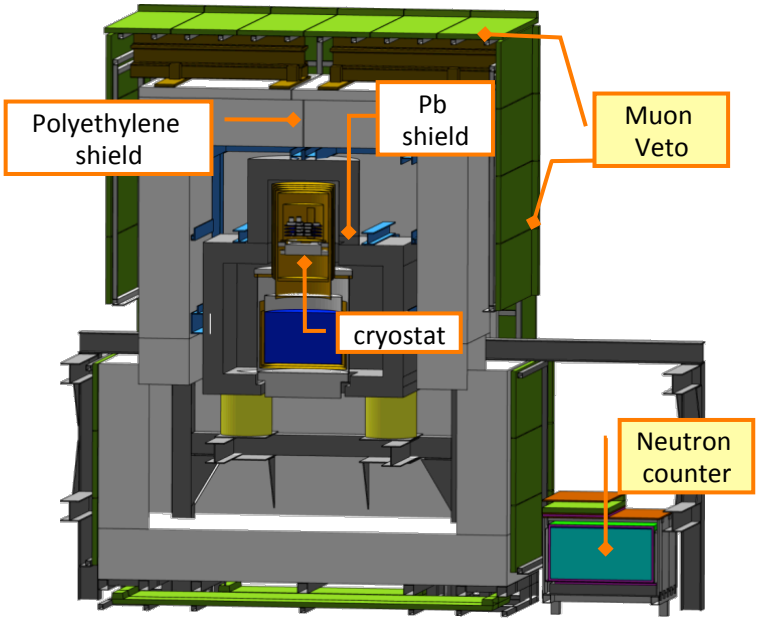
Neutron production mainly in the lead of the shield:

- DATA: 0.079 ± 0.003 n/μ
- MC: 0.143 ± 0.010 n/μ

MC simulation is a factor 1.8 higher than the DATA

EDELWEISS – Gd Neutron counter

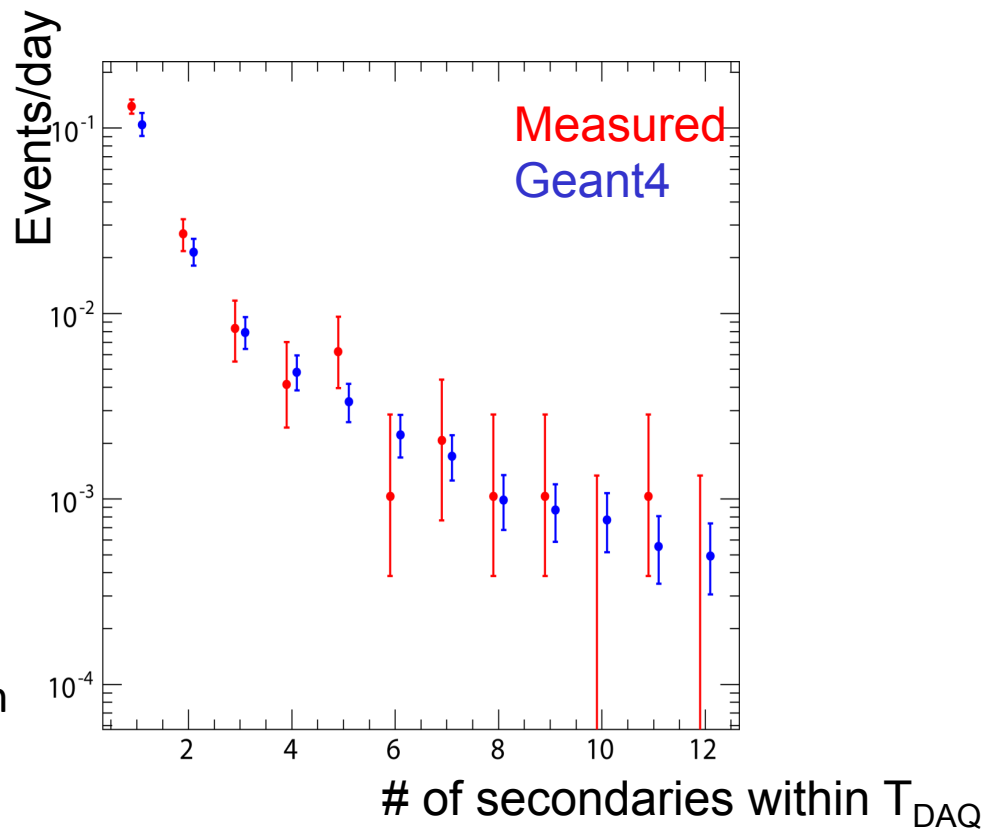
Muon-veto performance in
Astrop. Phys. 44 (2013) 28–39



- Geant4 9.2p01
- Physics list is based on QGSP_BIC_HP
- Detailed 3D geometry of the setup
- Custom Gd neutron capture spectrum
- Same cuts as in the measurement, …

⇒ Agreement within 20%

See V. Kozlov poster:
Measurement and modeling of muon-induced neutrons in LSM in application for direct Dark Matter searches



Conclusions

- MC simulations of e.m. backgrounds can reproduce the experimental data with a very high precision level.
- Radiogenic neutrons: comparison between two independent codes show results compatible inside a factor 2
- Muon-induced neutrons:
  - more experiment are doing measurements interpreted with detailed Monte Carlo simulations,
  - uncertainties still quite large, but the discrepancy is decreasing (inside a factor 2)
  - GEANT4: variations in the neutron yield modifying the code version or the physics list

Thanks !