Measurement and simulation of the muon-induced neutron yield in lead

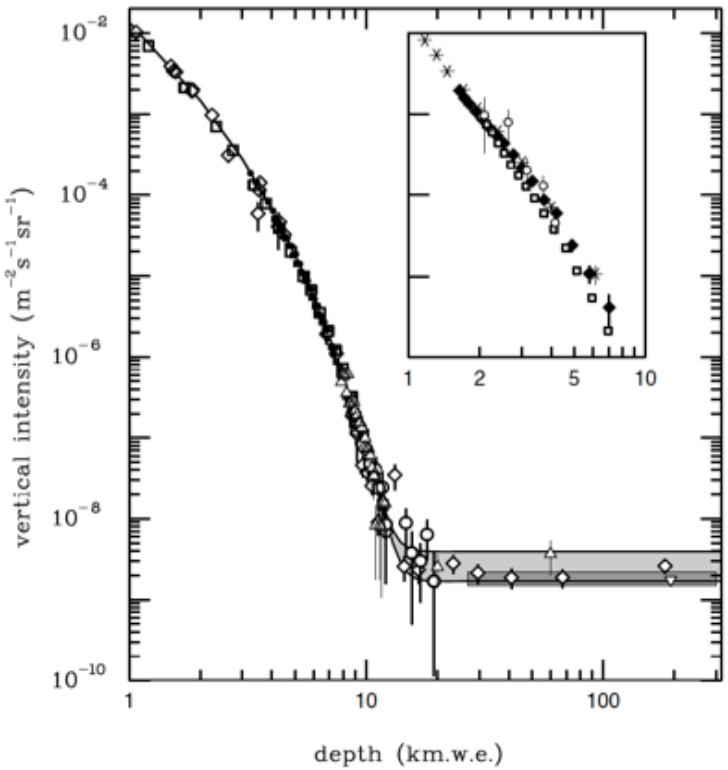
Lea Reichhart

LRT – 12/04/2013

Muons and muon induced neutrons underground

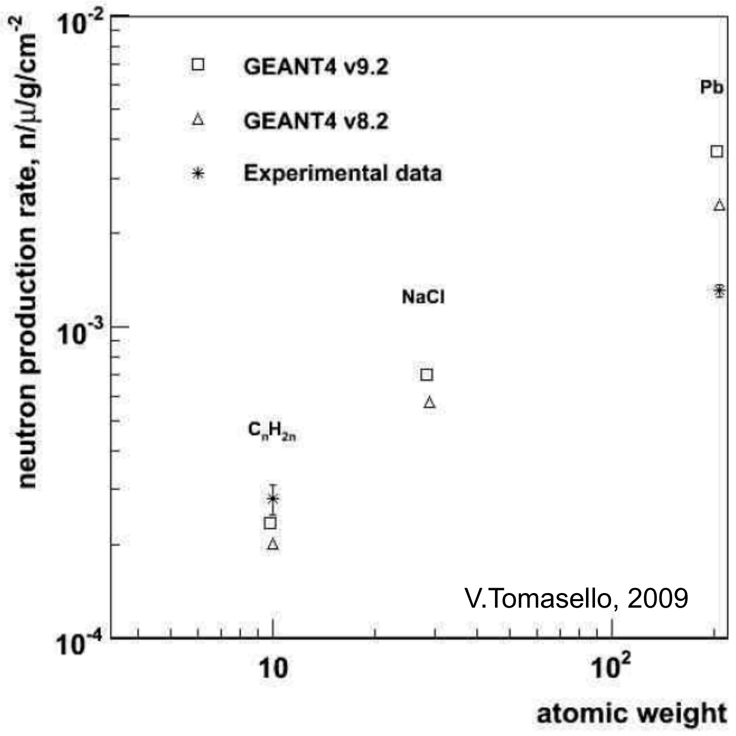
High energy cosmic-ray muons penetrating the rock produce neutrons via four main processes:

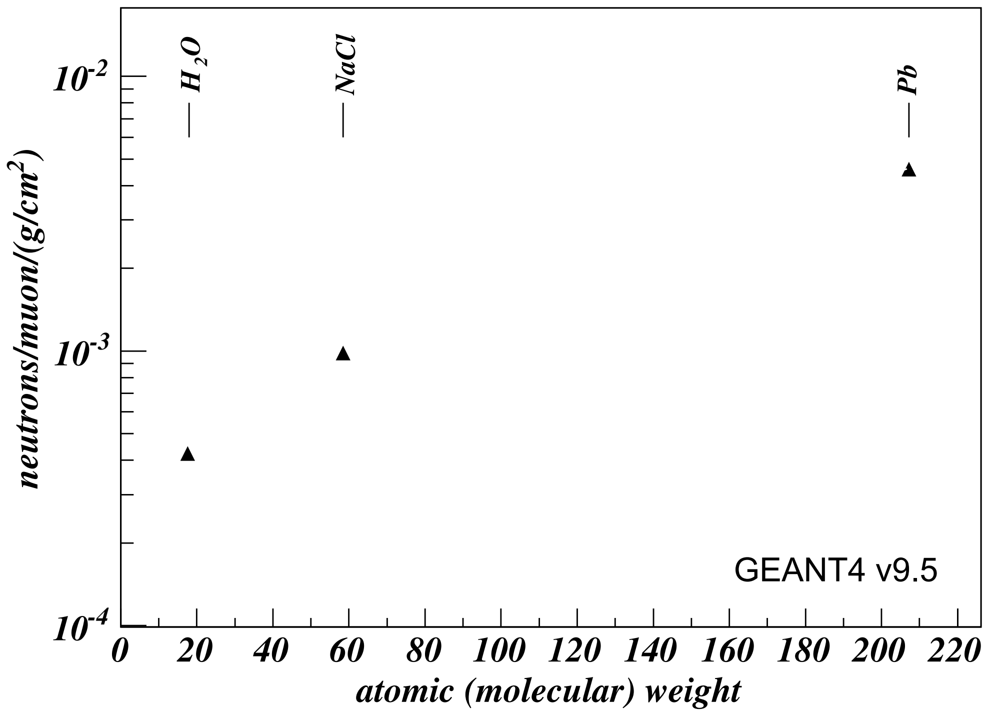
- Muon spallation – muon nuclear interaction via the exchange of a virtual photon resulting in nuclear disintegration
- Muon capture – only relevant at shallow depths <100 m w.e.
- Photo-nuclear interactions in muon triggered electromagnetic showers
- Hadron production in hadronic cascades initiated by the muon



High Energy Cosmic Rays, T.Stanev, Springer, 2010

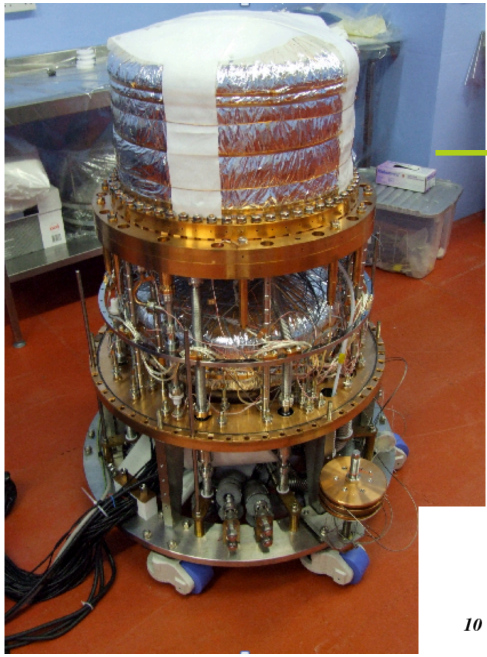
Muons and muon induced neutrons underground





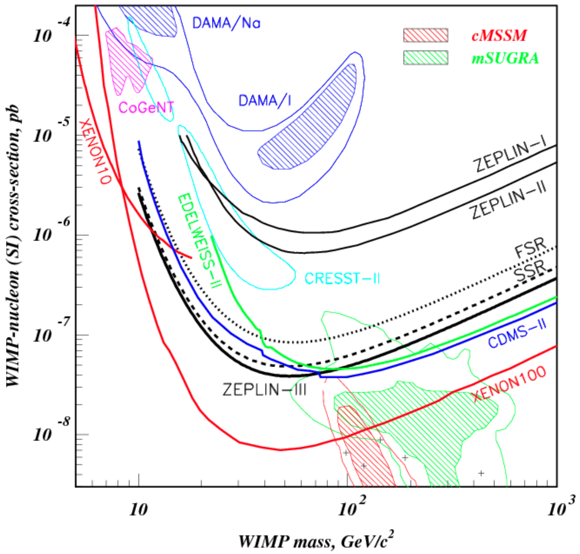
- Strong discrepancies of neutron yield for lead from measurements as well as under/over prediction of Monte Carlo simulations.
- Increased neutron production yield for lead in comparison to other common shielding materials.

ZEPLIN-III dark matter search



~12 kg liquid/gas DUAL PHASE xenon detector with an array of 31 PMTs

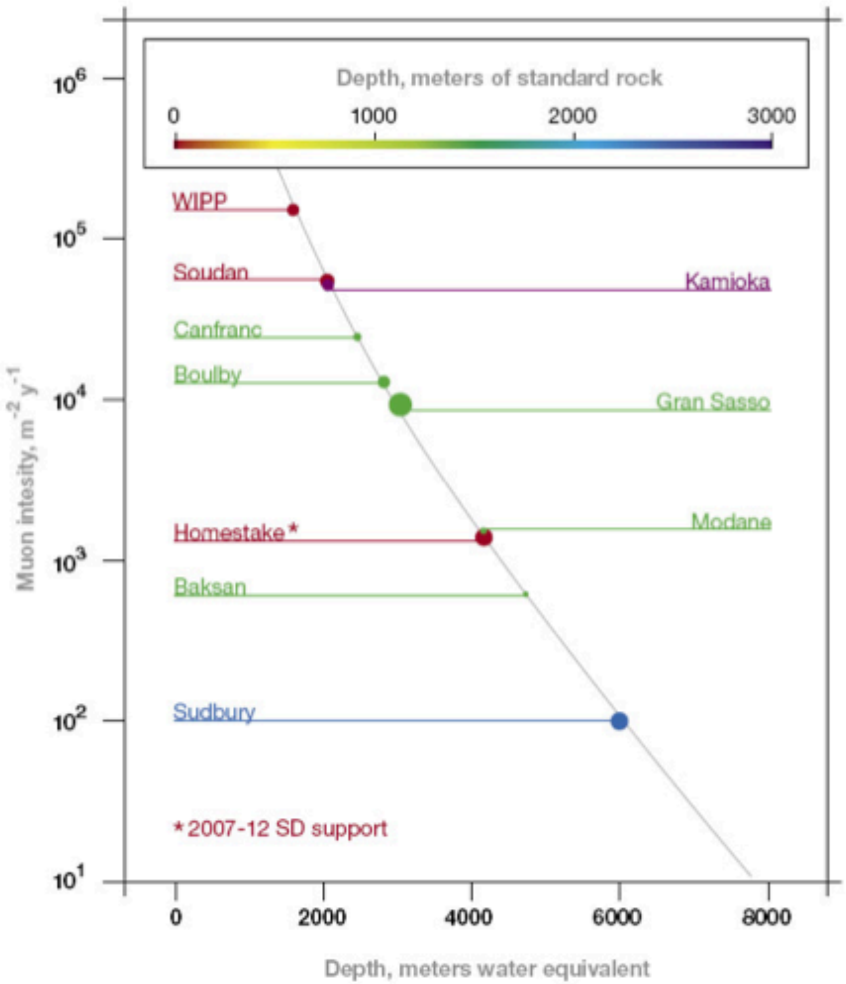
- Target: ~60 tonne lead castle

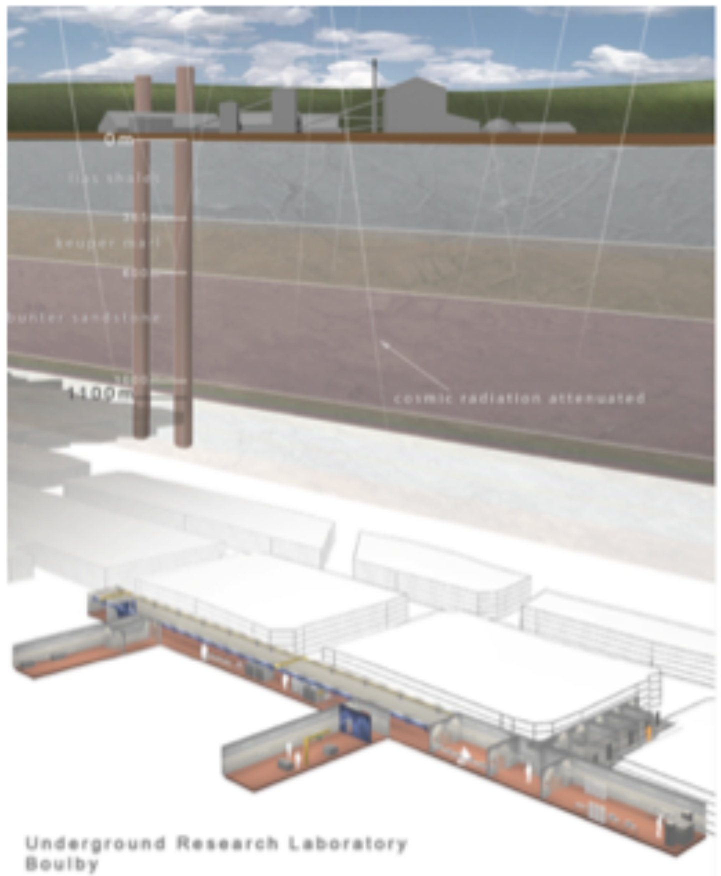


- **Second Science Run**:
  - Spin-independent:
    $\sigma < 3.9 \times 10^{-8}$ pb
    (at 52 GeV/c^2)
  - Spin-dependent:
    $\sigma_n < 8.0 \times 10^{-3}$ pb
    (at 50 GeV/c^2)

D. Yu. Akimov *et al.*, PLB 709:14-20, 2012.

Boulby Mine Laboratory



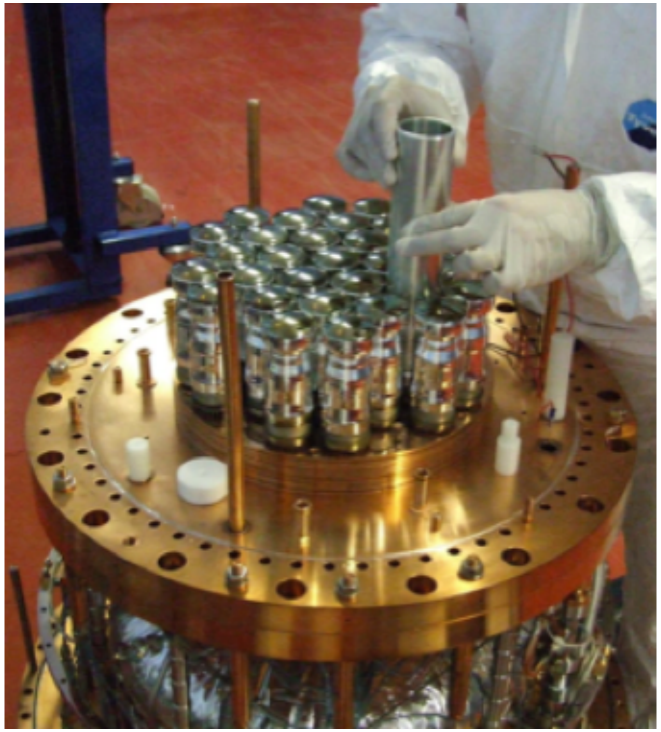


Located in Boulby Mine, north east England
1100 m underground (2850 m w.e.)
Reduces muon flux by ~10^6

ZEPLIN-III - 2nd science run upgrades

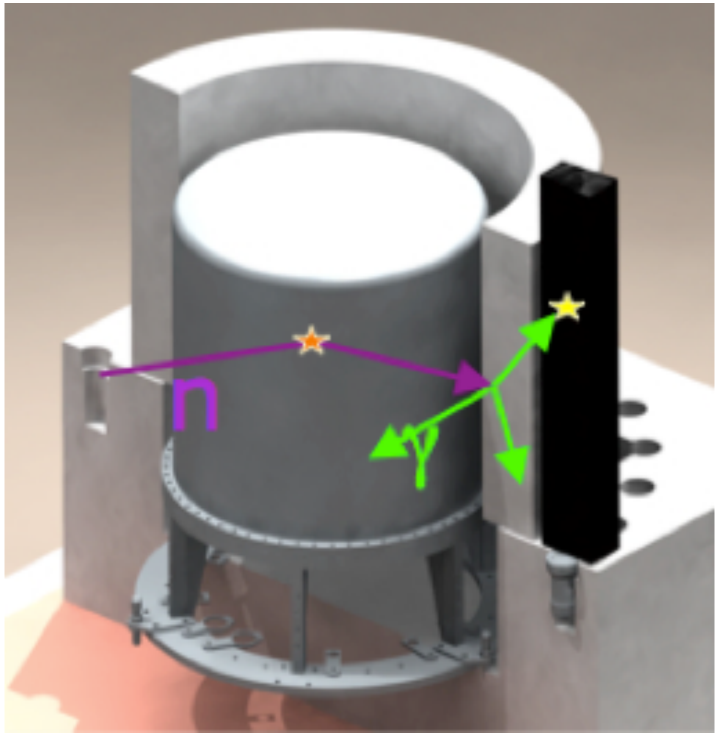
1st UPGRADE:

31 Ultra-low background PMTs



2nd UPGRADE:

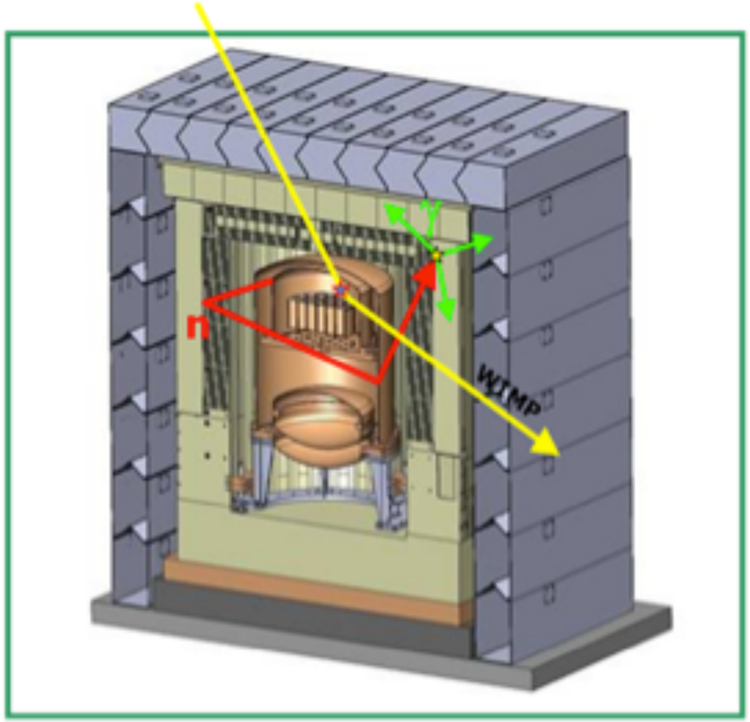
Active VETO detector

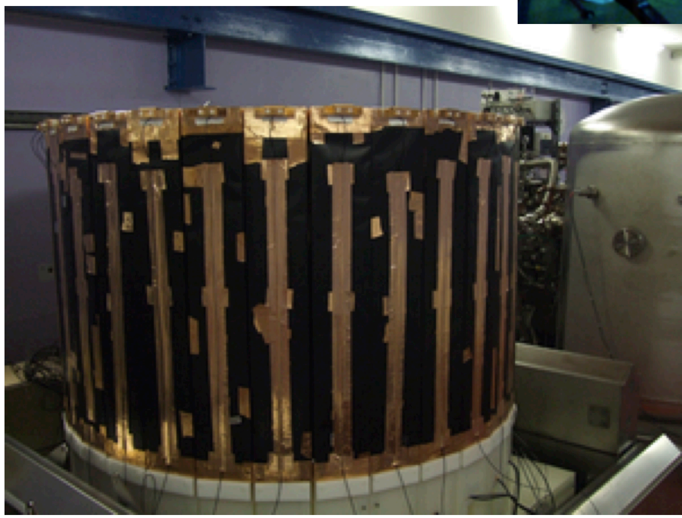


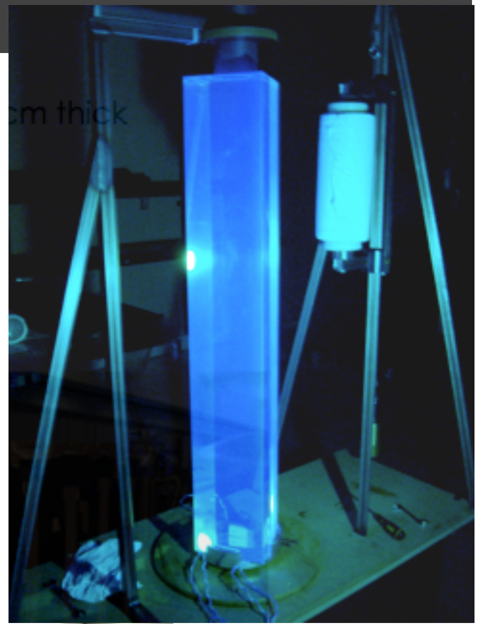
- Other UPGRADES
  - Complete remote operations → duty cycle up to 96%
  - New source delivery system

ZEPLIN-III veto detector

- 1 tonne plastic scintillator in 52 modules (UPS-923A)
- Scintillator 15cm thick, Gd loaded polypropylene 15cm thick
- Dedicated DAq and monitoring system
- Radiation budget very low





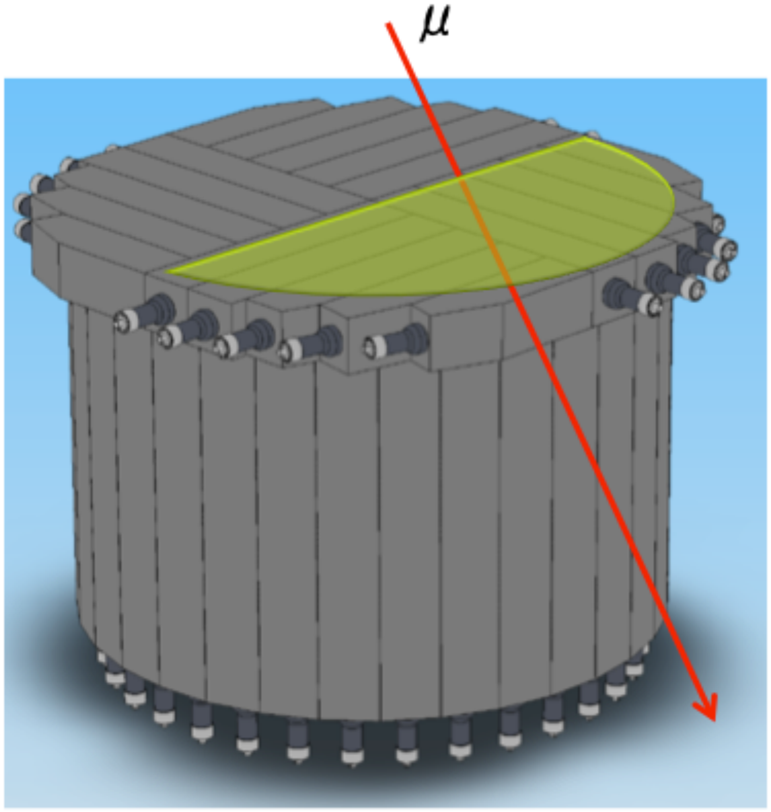


D. Yu. Akimov *et al.*, Astroparticle Phys. 34 (2010) 151-163.
C. Ghag *et al.*, Astroparticle Phys. (2011) Vol.35 (2) pp. 76-86.

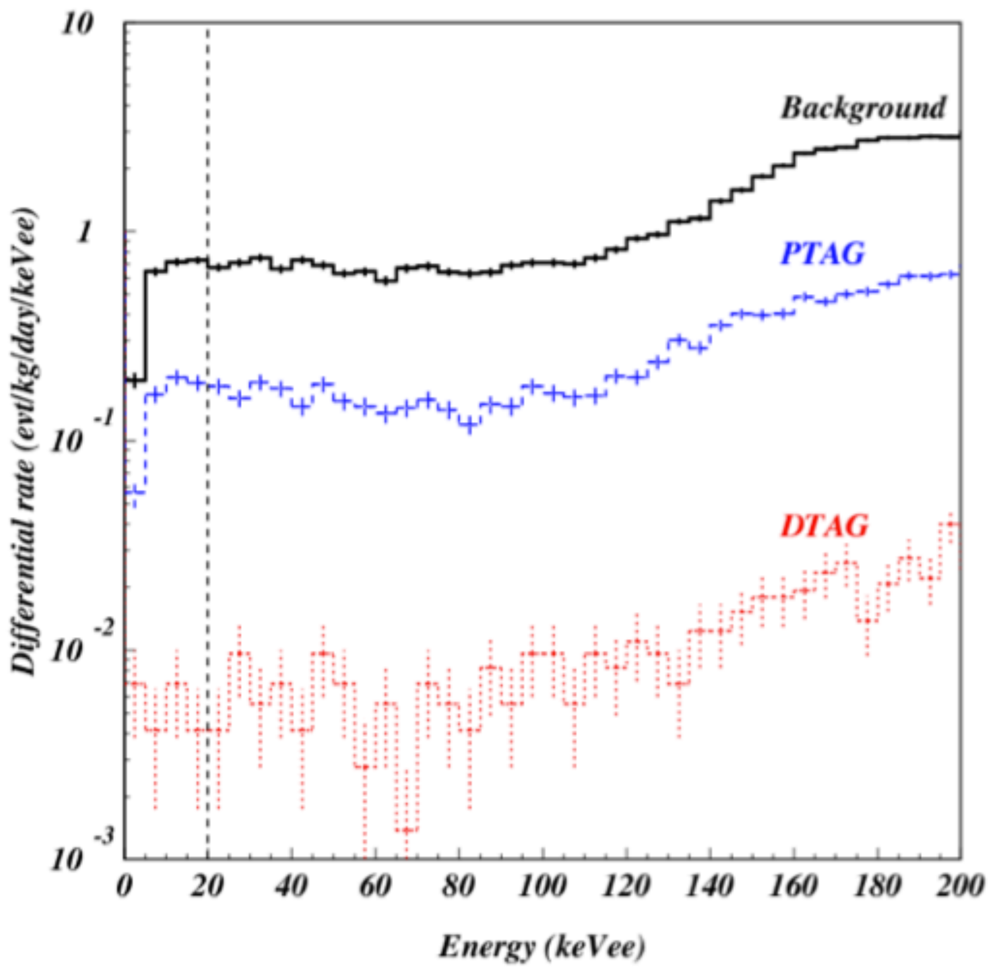
ZEPLIN-III veto detector

- Trigger setup
  - Slave mode – veto triggered from ZEPLIN-III

  - Master mode
    – independent trigger
    - Majority trigger
    - Muon trigger
      Sum signal from roof modules



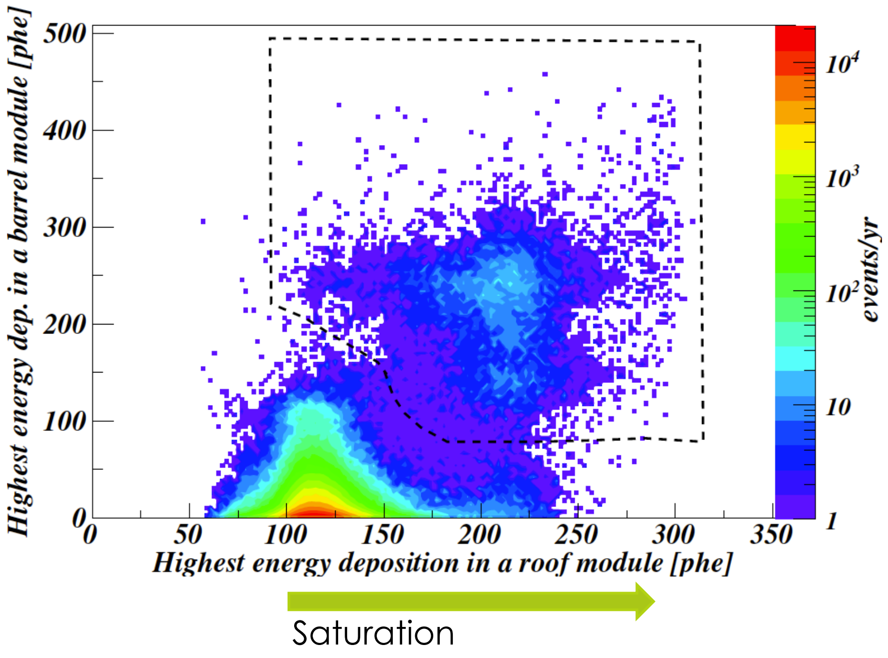
VETO performance



- Prompt gamma-ray tagging (PTAG) ~28%
- Delayed neutron tagging (DTAG) ~61%
- Constant tagging fractions over all energies → Possibility of studying non-trivial events without sacrificing WIMP search data

Muon event selection

Data

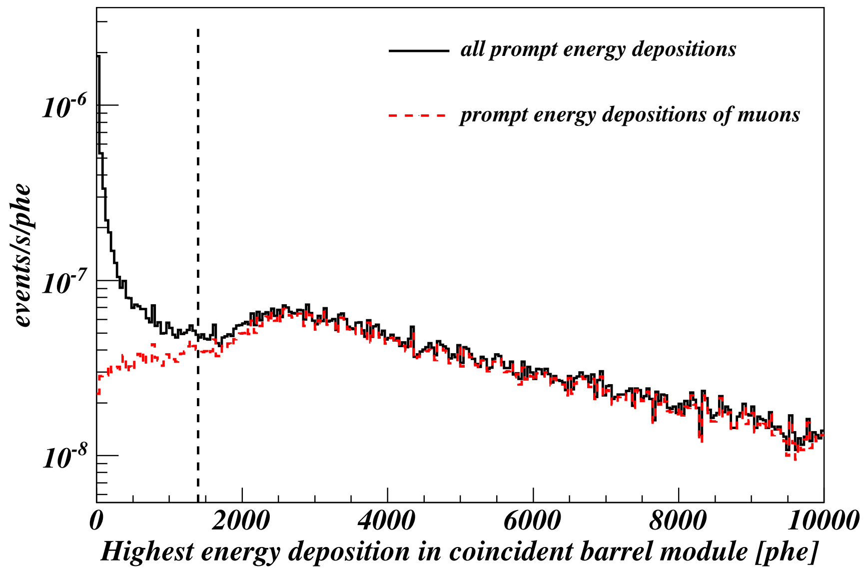


Total of 7979 muons selected corresponding to 32.3±0.4 muons/day.

Overall detection efficiency (from simulations) for pure muon events 36.8±0.6%.

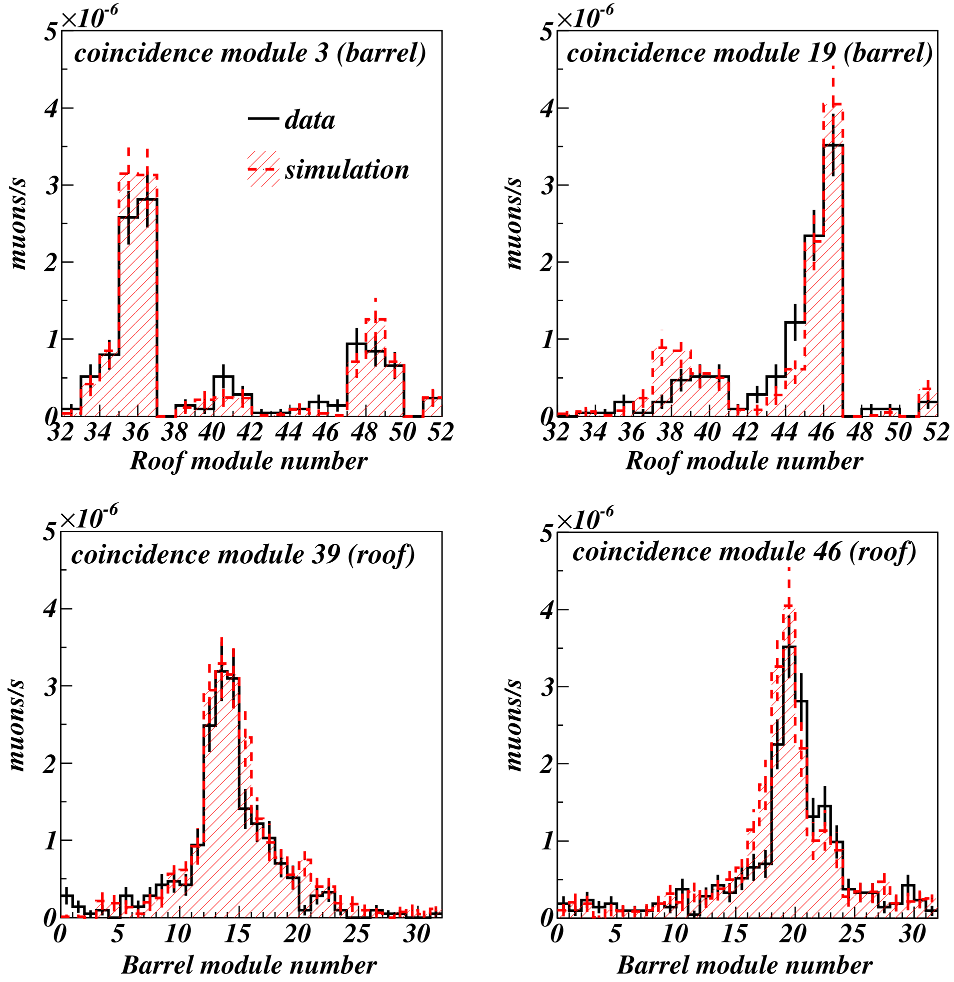
Simulations

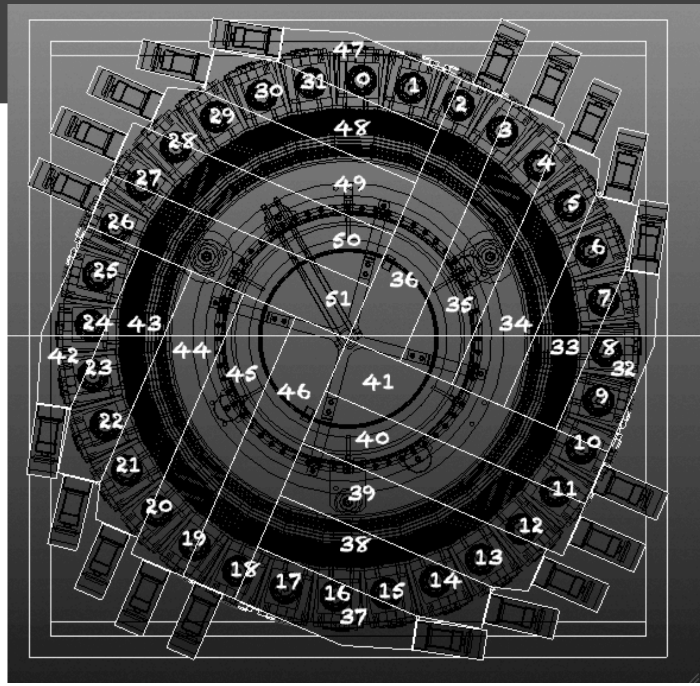
Muon propagation – MUSIC
Muon sampling – MUSUN
20 milllion muons
Mean muon energy 260 GeV
~3.1 years simulation live-time (~4.5 x data)



Monte Carlo simulations with GEANT4 version 9.5, p01 using the Shielding physics list (FTF + BERT)
+ implementation of thermal scattering of neutrons off chemically bound atoms below 4 eV
→ Important for thermalisation in the plastic

Muon event selection





Comparing measured rates to Monte Carlo predictions of flux through a normalised sphere

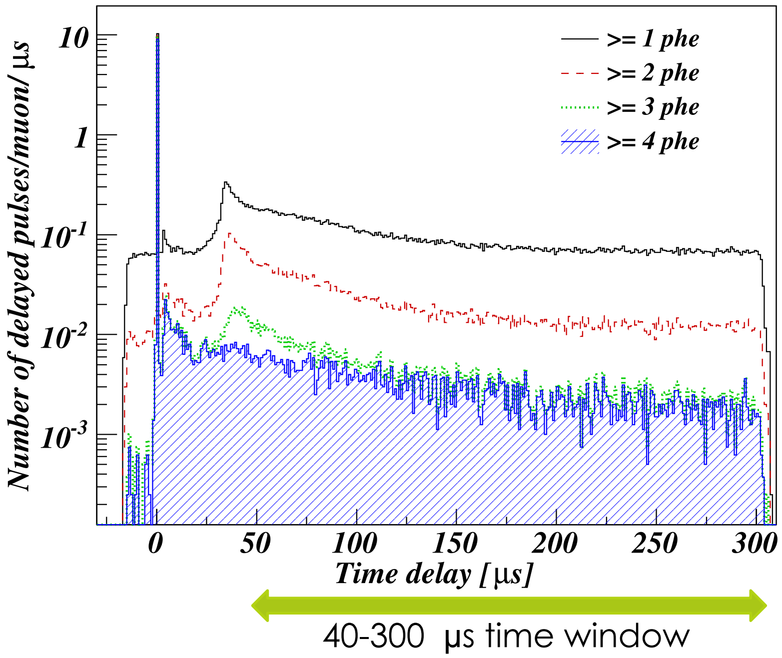
→ $(3.75\pm0.09)\times10^{-8}$ muons/s/cm^2

Prev. measurements (H. Araujo et al., 2008):
$(3.79\pm0.15)\times10^{-8}$ muons/s/cm^2

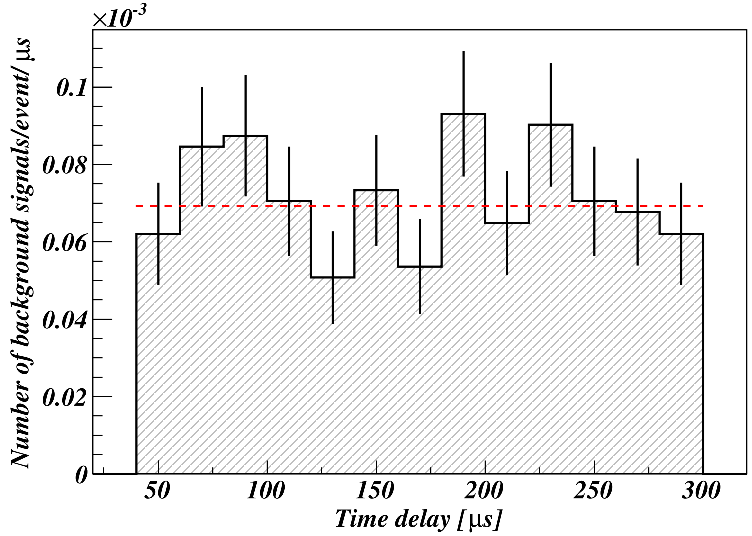
Muon-induced neutron yield

Measurement of neutrons via detection of γ-rays emitted in radiative neutron capture (predominately on H)

Pulse rate above threshold

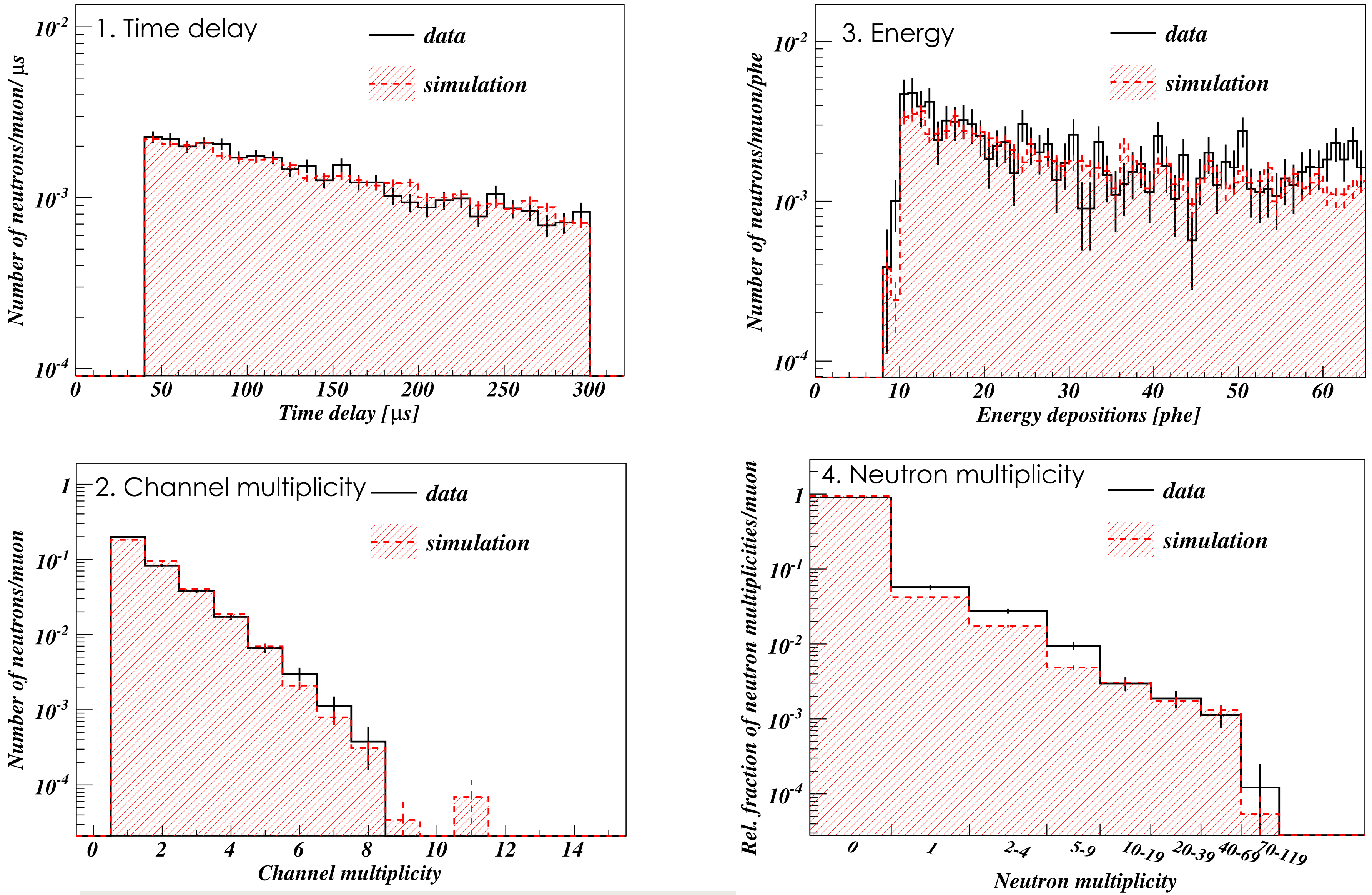


Single scintillator background >=10 phe



Selection criteria:	Threshold on individual pulse
Single scintillator events	>=10
Channel multiplicity 2	>=4
3	>=2
>=4	>=1

Muon-induced neutron yield



Muon-induced neutron yield

		Data			Simulation
Channel mult.	Threshold	Events/muon	Background rate	n/muon (bkg.corr.)	n/muon
1	$\geqslant 10$	0.216 ± 0.005	0.019 ± 0.001	0.197 ± 0.005	0.145 ± 0.002
2	$\geqslant 4$	0.088 ± 0.003	0.0049 ± 0.0005	0.083 ± 0.003	0.076 ± 0.001
3	$\geqslant 2$	0.039 ± 0.002	0.0019 ± 0.0003	0.037 ± 0.002	0.0321 ± 0.0009
$\geqslant 4$	$\geqslant 1$	0.029 ± 0.002	0.0008 ± 0.0002	0.028 ± 0.002	0.0231 ± 0.0008
Total		0.372 ± 0.007	0.026 ± 0.001	0.346 ± 0.007	0.275 ± 0.003

➡ under production by simulation by ~20%

	Production material of	
Material	all neutrons	detected neutrons
Lead	0.2%	95.0%
Rock	99.8%	1.4%
Steel	-	1.2%
C_8H_8	-	0.9%
Copper	-	0.8%
CH_2	-	0.5%
Gd-epoxy	-	0.1%
Liquid Xe	-	0.1%

Production material

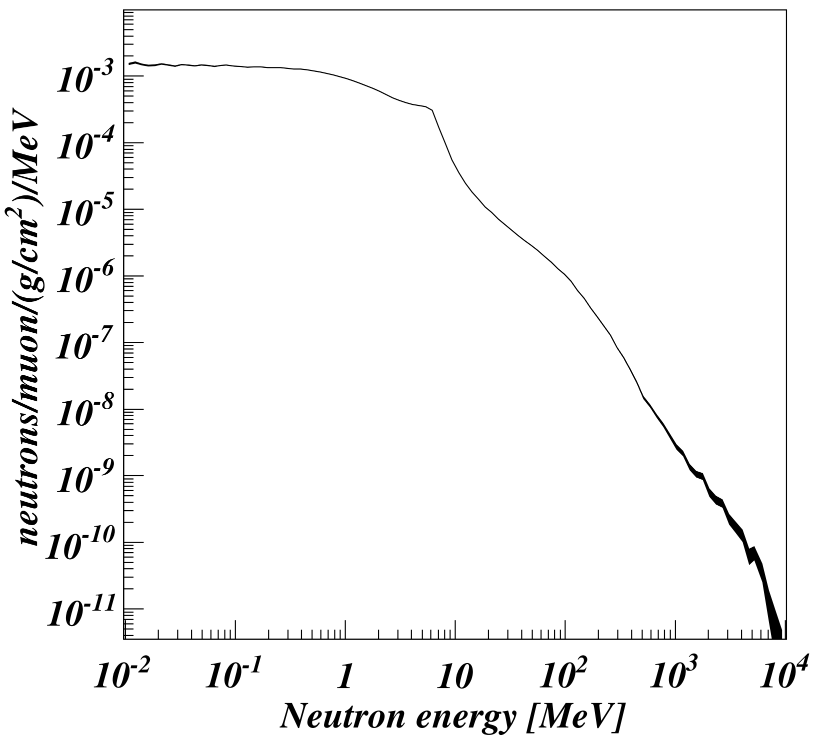
	Capture element of	
Element	all neutrons	detected neutrons
H	-	71.1%
Fe	-	11.5%
Cl	94%	7.0%
Gd	-	7.0%
Pb	-	1.3%
C	-	1.1%
Cu	-	0.6%
Na	6%	0.2%
Mn	-	0.2%

Capture element

Muon-induced neutron yield in lead

Mon-energetic 260 GeV μ^-- beam incident on centre of lead block of 3200 g/cm^2

-count only central half length – avoid surface/edge effects
-neutron rejection in neutron inelastic processes – avoid double counting



Neutron production rate of
$(4.594 \pm 0.004) \times 10^{-3}$ neutrons/muon/(g/cm^2)

Ratio data/simulation = 1.26 ± 0.05

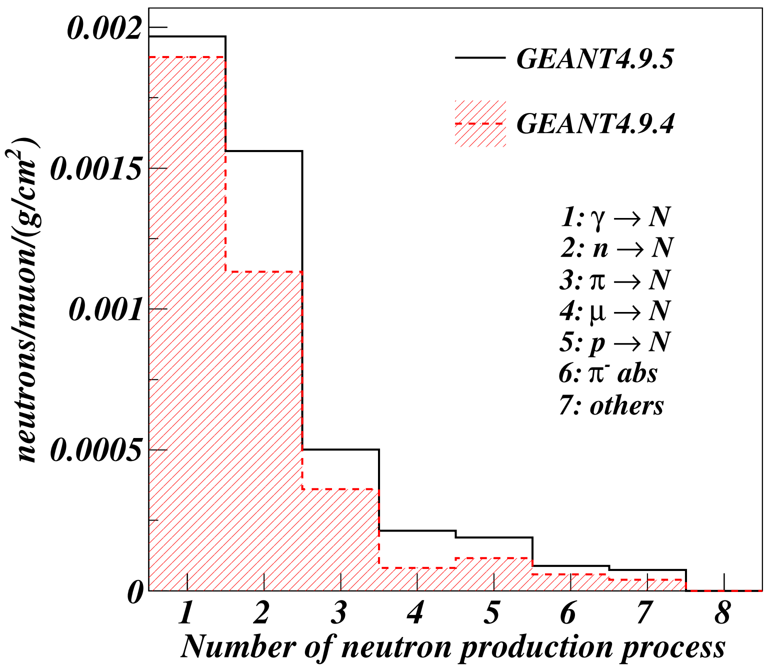
Suggests a true production rate by 260 GeV muons of

$(5.8 \pm 0.2) \times 10^{-3}$ neutrons/muon/(g/cm^2)

assuming neutron transport and detection were modeled accurately

Muon-induced neutron yield in lead – changes from simulations

GEANT4 version	physics list	muon-induced neutron yield [neutrons/muon/(g/cm^2)]
8.2	custom built	$(2.846 \pm 0.006) \times 10^{-3}$
9.4	custom built	$(3.304 \pm 0.003) \times 10^{-3}$
9.4	QGSP_BIC_HP	$(3.376 \pm 0.003) \times 10^{-3}$
9.4	Shielding	$(3.682 \pm 0.003) \times 10^{-3}$
9.5	QGSP_BIC_HP	$(3.993 \pm 0.004) \times 10^{-3}$
9.5	QGSP_BERT_HP	$(4.369 \pm 0.004) \times 10^{-3}$
9.5	FTFP_BERT	$(4.467 \pm 0.004) \times 10^{-3}$
9.5	Shielding	$(4.594 \pm 0.004) \times 10^{-3}$



- steady increase with every successive version of GEANT4
- Greatest yields and increase (going from v9.4 to v9.5) for Shielding physics list
- ~38% higher production yield for neutron inelastic process
- New muon-nucleus interaction model (G4VDMuonNuclearModel)
- Additional changes in FTF model

Conclusions

- Muon-induced neutron production yield in lead by 260 GeV muons:

$(5.8 \pm 0.2) \times 10^{-3}$ neutrons/muon/(g/cm^2)

- Simulations reproduce very well the experimental data.

- Absolute simulated rates are very close to the data – an underproduction by only ~20% is observed.

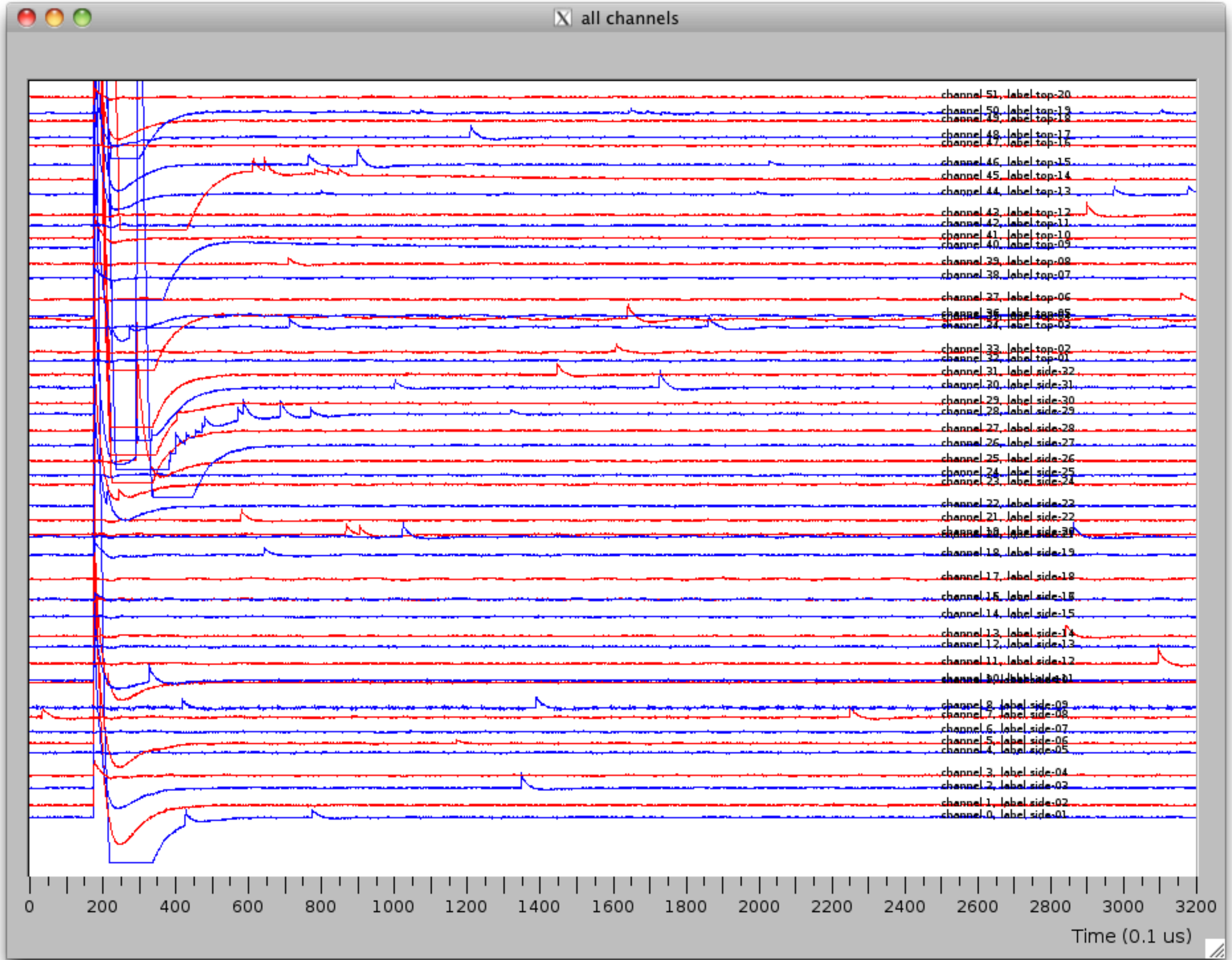
L. Reichhart[*,a], A. Lindote[b], D.Yu. Akimov[c], H.M. Araújo[d], E.J. Barnes[a,1], V.A. Belov[c], A. Bewick[d], A.A. Burenkov[c], V. Chepel[b], A. Currie[d], L. DeViveiros[b], B. Edwards[e,2], V. Francis[e], C. Ghag[a,f], A. Hollingsworth[a], M. Horn[d,2], G.E. Kalmus[e], A.S. Kobyakin[c], A.G. Kovalenko[c], V.A. Kudryavtsev[g], V.N. Lebedenko[†d], M.I. Lopes[b], R. Lüscher[e], P. Majewski[e], A.St J. Murphy[a], F. Neves[b], S.M. Paling[e], J. Pinto da Cunha[b], R. Preece[e], J.J. Quenby[d], P.R. Scovell[a,3], C. Silva[b], V.N. Solovov[b], N.J.T. Smith[e,4], P.F. Smith[e], V.N. Stekhanov[c], T.J. Sumner[d], C. Thorne[d], R.J. Walker[d,5]

[a] *School of Physics & Astronomy, SUPA University of Edinburgh, UK*
[b] *LIP–Coimbra & Department of Physics of the University of Coimbra, Portugal*
[c] *Institute for Theoretical and Experimental Physics, Moscow, Russia*
[d] *High Energy Physics Group, Blackett Laboratory, Imperial College London, UK*
[e] *Particle Physics Department, STFC Rutherford Appleton Laboratory, Chilton, UK*
[f] *High Energy Physics Group, Department of Physics & Astronomy, University College London, UK*
[g] *Department of Physics & Astronomy, University of Sheffield, UK*

http://arxiv.org/abs/1302.4275

BACKUPS

Muon-induced neutrons



Backgrounds

Table 2
Radiological content with statistical uncertainties where appropriate of veto components as assayed either by direct observation of γ-ray emission (HPGe) or through mass-spectroscopy techniques (ICP-MS/OES). See text for further details.

Component	Mass (kg)	Radiological content		
		U (ppb)	Th (ppb)	K (ppm)
HPGe measurements				
Plastic scintillator	1057.0	0.2 ± 0.3	0.1 ± 0.7	0.2 ± 0.6
PTFE inner wrap	8.9	1.3 ± 0.2	0.2 ± 0.5	1.2 ± 0.4
Silicone	0.1	2.9 ± 0.4	0.5 ± 0.8	5.7 ± 1.1
PTFE tape	3.1	3.2 ± 1.3	6.1 ± 1.1	3.9 ± 1.0
Veto PMTs	6.2	38.0 ± 0.8	21.1 ± 1.2	65.5 ± 2.4
PMT preamplifiers	0.7	8.4 ± 1.7	13.2 ± 2.2	10.1 ± 1.7
PMT base	5.5	12.7 ± 1.4	14.8 ± 2.4	20.2 ± 2.4
Epoxy	70.0	2.5 ± 0.6	0.9 ± 0.3	0.6 ± 0.1
Gd oxide	8.0	0.9 ± 0.1	1.2 ± 0.3	1.7 ± 1.1
ICP-MS/OES				
Copper tape	26.0	1.9 ± 0.2	2.9 ± 0.4	14.0 ± 2.0
PTFE inner wrap	8.8	2.0 ± 1.0	5.0 ± 1.0	<4
Veto PMTs	6.2	30.2 ± 2.2	30.0 ± 3.7	60 ± 2.2
PMT preamplifiers	0.7	10.3 ± 0.5	29.7 ± 3.2	24 ± 3.7
PMT base	5.5	13 ± 3.4	19 ± 2.0	21 ± 3.0
Polypropylene	510	<1	<1	<5
PMT mounting	15.8	30 ± 7.8	<10	<10
Cabling	30.2	110 ± 5.4	20 ± 3.2	29 ± 7.3
Connectors	2.1	<10	<10	<4
Optical gel	0.3	<1	<1	<1
Gd oxide	8.0	2.5 ± 0.5	3.4 ± 0.7	<4