Muon-induced background in a next-generation dark matter experiment based on liquid xenon

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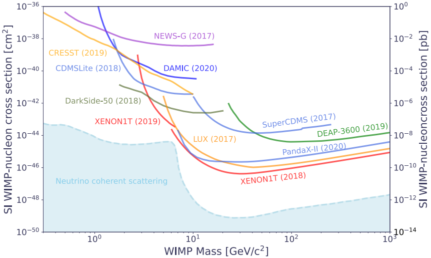
Motivation

Focus on cosmogenic background

- Study for next generation direct dark matter search, hitting the neutrino floor
- Aimed at **dual phase xenon TPC**
- Background from **neutrons induced by cosmic ray muons**
- Key question:
  Is **depth of about 3 km w.e. sufficient** for the next generation (G3) dark matter experiment?

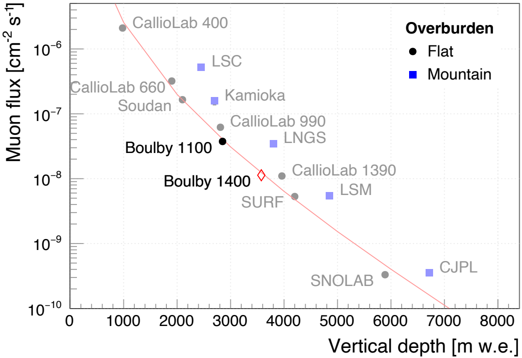


PDG RPP 2021

Boulby Mine model case

- Work part of feasibility study for next generation DM experiment at Boulby mine
  - Funded by UKRI-STFC
- **Two locations** considered:
  - **currently used** level (2850 m w.e.)
  - **deeper** new location (different rock composition)
- Results relevant to sites of **similar depth**

Two depths at Boulby Mine



1. close to current experimental lab
   - **2850 m w.e.**
   - in **NaCl**
2. deeper potential site for future experiments
   - **3575 m w.e.**
   - in **polyhalite**

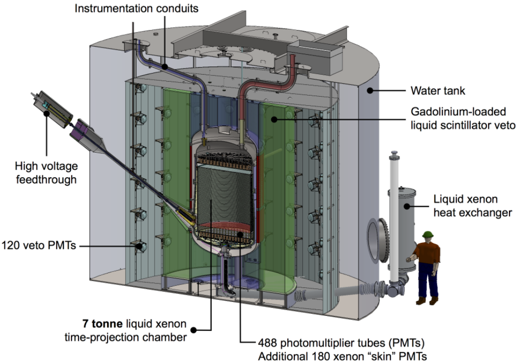
- Red line calculated for flat overburden and standard rock (Z = 11, A = 22)

Simulation of cosmic ray muon background

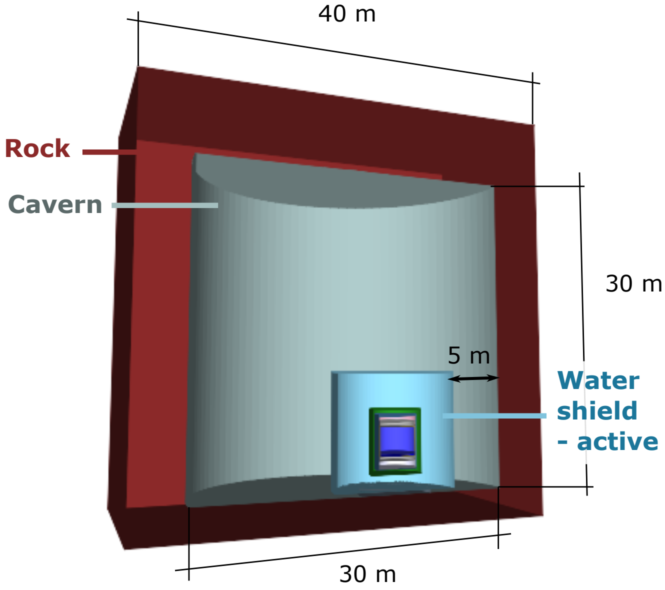
Geometry based on LZ design

- LZ scaled up 10$\times$ $\rightarrow$ **71 tonne active LXe**
- Water shield, liquid scintillator, two-phase Xe TPC with LXe skin

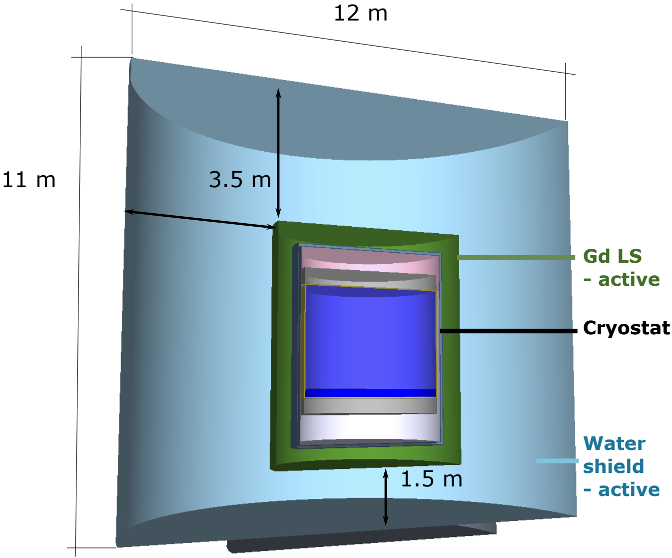
LZ detector



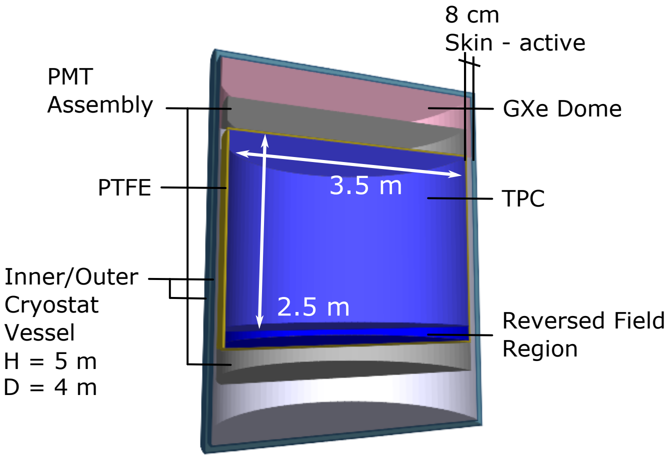
Cavern



Detector



TPC



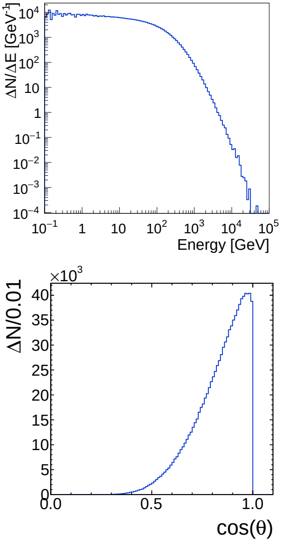
8 cm
Skin - active
PMT
Assembly
GXe Dome
PTFE
3.5 m
TPC
Inner/Outer
Cryostat
Vessel
H = 5 m
D = 4 m
2.5 m
Reversed Field
Region

Muons

- MUSUN/MUSIC [*] — surface $\rightarrow$ underground μ propagation
- Flat overburden
- Uniform rock composition
- Calculated flux:
  2850 m w.e., NaCl: $3.75 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  3575 m w.e., polyhalite: $1.13 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Approximation: same distributions for both depths
  - Mean energy: 261 GeV (median 134 GeV)
  - Median zenith: 30.1°

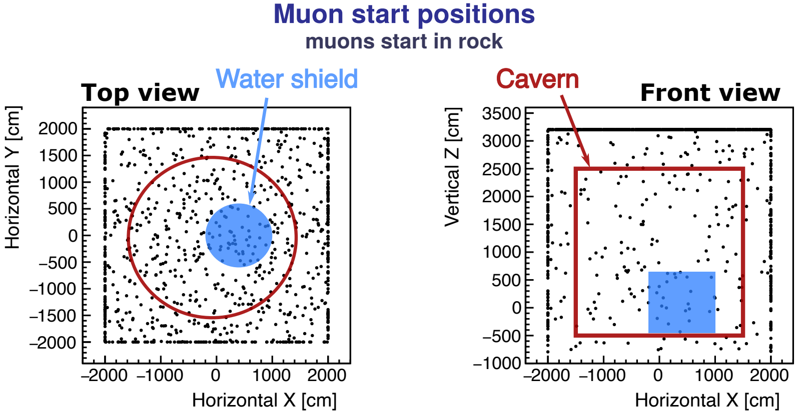
As generated

1M events



Simulated sample

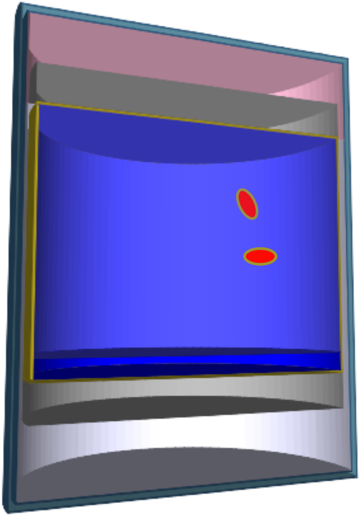
- GEANT4 v10.5, `Shielding` physics list
- Simulated 800M muons for each site
- Equivalent to **29 years** (NaCl) and **97 years** (polyhalite)



Analysis

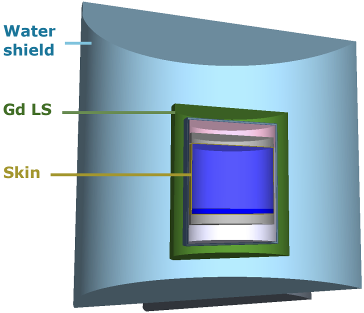
Event selection

- Based on true energy depositions — no signal propagation and processing was simulated
- Single Xe recoil above 1 keV – within 1 ms
- $>$5 cm away from boundary of active volume
- No other recoil above 0.5 keV – considered resolvable from ionisation charge; sign of multiple neutron scatters
- No other depositions above 10 keV (non-NR)



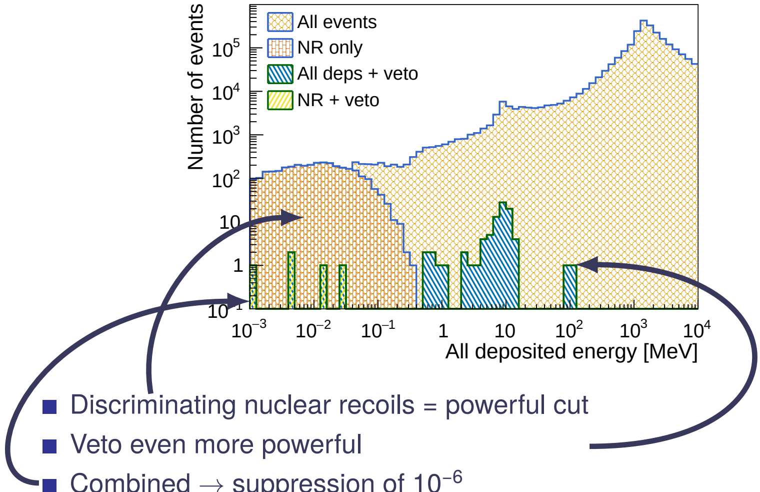
Veto

- 0.5 ms before and after TPC signal
- Thresholds:
  - skin: 100 keV
  - LS: 200 keV
  - WS: 200 MeV (from Cherenkov radiation)



Results

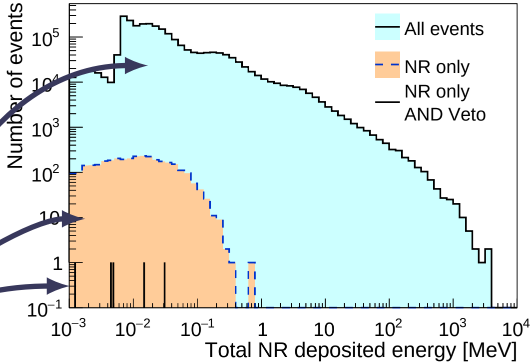
Energy depositions in TPC (NaCl)



- Discriminating nuclear recoils = powerful cut
- Veto even more powerful
- Combined $\rightarrow$ suppression of 10^{-6}

* only events with NR activity shown

Energy depositions from NR in TPC (NaCl)



- Many NR from muon Coulomb scattering
- NR-only signals at low energy
- Few events survive veto

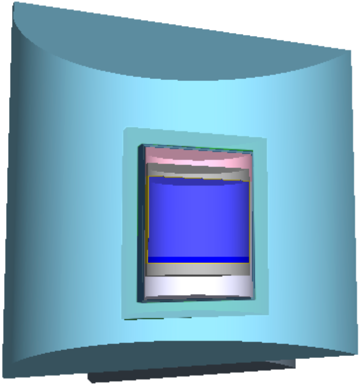
Single background event

- **No events** passed full selection in **NaCl**
- **One background event** passed in **polyhalite**

Depth/Rock material	Observed events	Rate [/10 yrs/71 t]	90% CL
2850 m w.e./NaCl (29 yr)	0		<0.84
3575 m w.e./polyhalite (97 yr)	1	0.10	0.01–0.45

Approximated option without liquid scintillator

- Is LS needed to help rejecting muon-induced background?
- No new simulations, simply reanalysed
- LS treated as part of water shield
- Veto: LXe skin and combined LS+WS



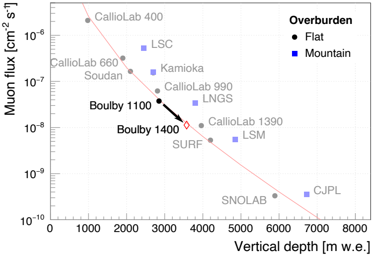
Additional background event when no scintillator used

- **No events** passed full selection in **NaCl**
- **Two background events** passed in **polyhalite**

Depth/Rock material	Observed events	Rate [/10 yrs/71 t]	90% CL
2850 m w.e./NaCl	0		$<$0.84
3575 m w.e./polyhalite	2	0.21	0.05–0.61

Note on uncertainties

- Only statistical errors considered
- Additional factor 2 uncertainty comes from neutron production in GEANT4
  - discrepancies between past measurements and G4 simulations
  - assumed conservative (most discrepancies observed for heavy elements)
- Muon flux can be determined to within 10%
- Difference in spectra for 2 sites not taken into account
  - mean energy 261 GeV $\rightarrow$ 282 GeV
  - neutron production increase by 7%



Conclusion

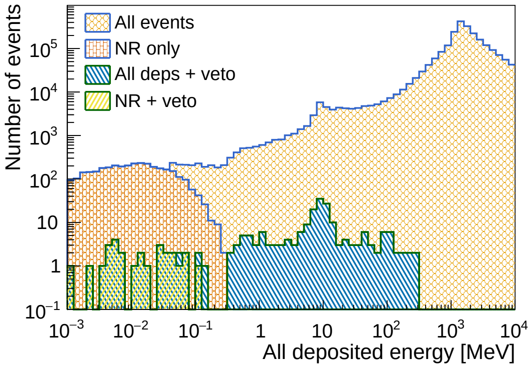
- Only few background events observed
- LS does not play major role in rejecting cosmogenic background but may be needed for rejection of radiogenic backgrounds
- Events from delayed neutrons from cosmogenic ^{17}N in PTFE
  - used 3 cm thick PTFE field cage $\rightarrow$ 2.8 t
  - can be reduced if needed
- Rate lower than other expected backgrounds
- **3 km w.e. deep enough** for cosmogenic background

BACKUP

Effect of veto on energy depositions in TPC

Energy depositions in TPC (NaCl)

Option **without LS**

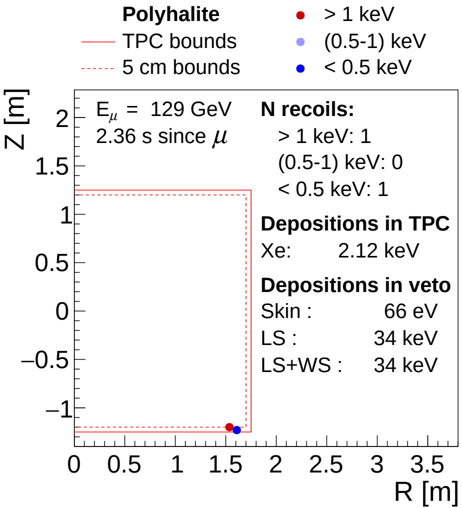


- More activity/lower veto efficiency

* only events with NR activity shown

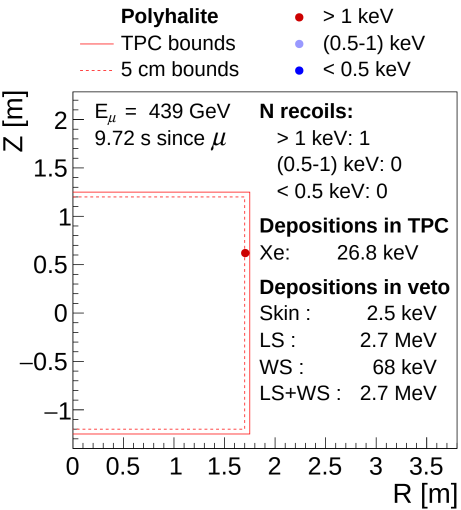
Example event displays

Example event — passing I



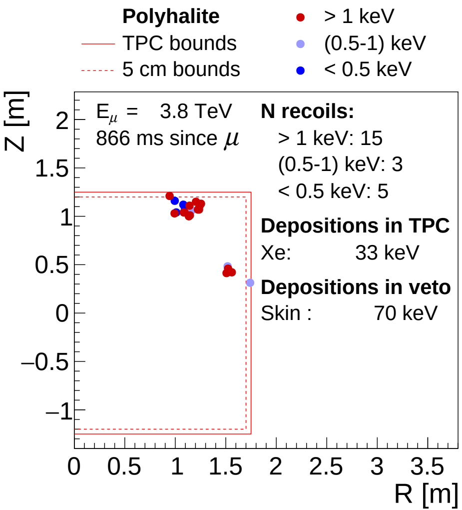
- Single detectable recoil
- Within fiducial volume
- Small depositions in veto systems
- Delayed neutron emission from PTFE

Example event — passing II



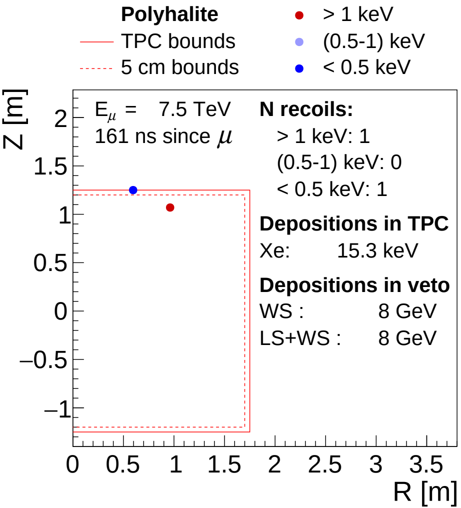
- Single recoil
- Vetoed by LS
- But survives in no-LS case

Example event — NOT passing I



- No veto
- Multiple scatters
- Easy to reject

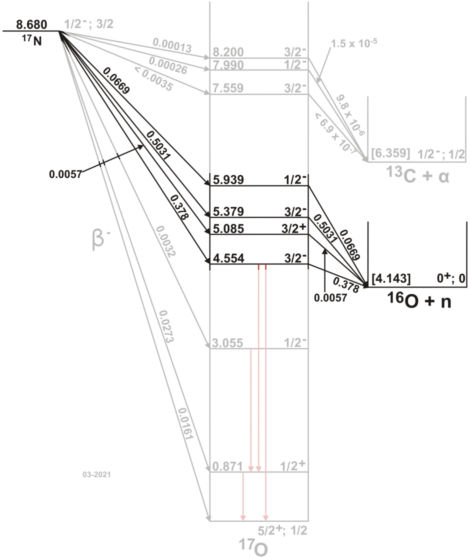
Example event — NOT passing II



- Large signal in WS
- $\rightarrow$ vetoed single recoil

Delayed neutron emission

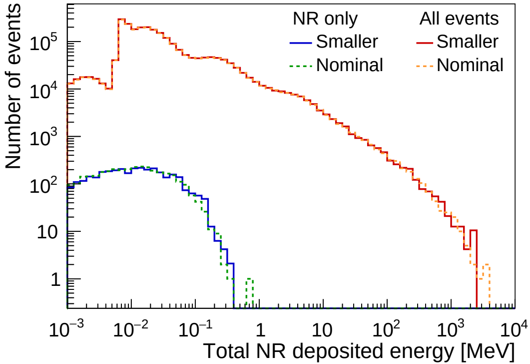
Cosmogenic ^{17}N in PTFE



- Significant contribution to background candidates from **neutrons from PTFE**
- Many candidates passing selection except for multi-scatter requirement
- **Delayed** neutrons from ^{17}N
- ^{17}N from π, n, γ and μ interactions with ^{19}F
- **^{17}N half-life 4.2 s**
- 3 cm thick PTFE in our simulation $\rightarrow$ 2.8 t

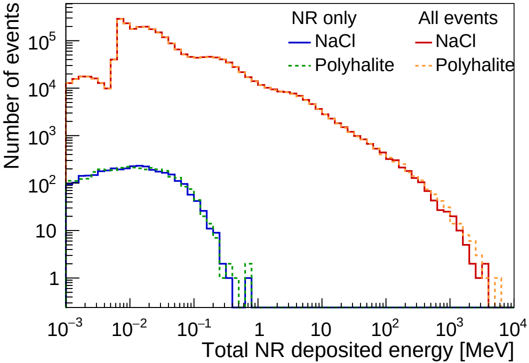
Cavern size and material comparison

Cavern size doesn't make difference

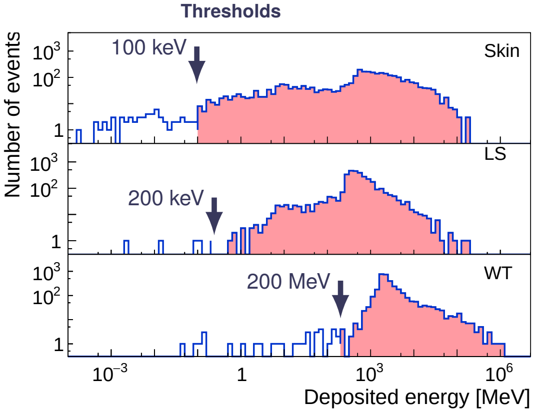


- Does cavern size and layout make difference?
  - neutrons produced preferentially in muon direction
- Simulations repeated for cavern of **smaller size** (by 40%)
- **No difference** observed in spectra of depositions in TPC

Rock material doesn't make difference



Energy depositions in veto systems

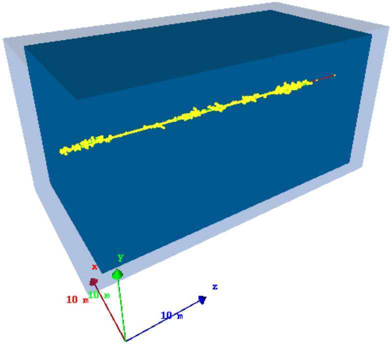


- Shown depositions coincident with NR-only events in TPC

Muon induced neutron production in GEANT4

Geant4 neutron production

Simulated mono-energetic muons in simplified geometry.
Recorded neutrons produced within tested material.

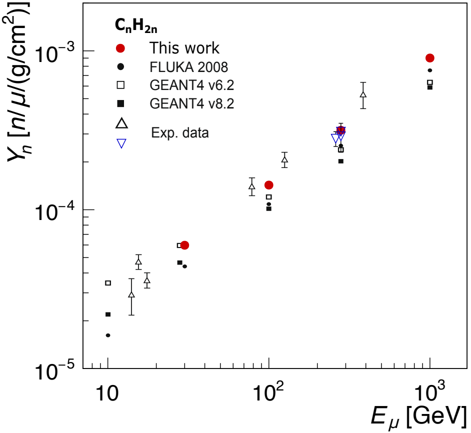


Neutrons in various materials for **280 MeV muons**

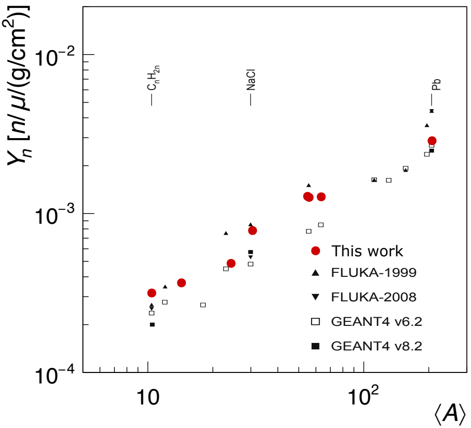
GEANT4 v10.5, `Shielding` physics list

Material	Neutron yield [$\times 10^{-3}$ n/μ/(g/cm^2)]	Material	Neutron yield [$\times 10^{-3}$ n/μ/(g/cm^2)]
C_nH_{2n}	0.31±0.01	Mg	0.49±0.02
H_2O	0.37±0.01	Ti	1.39±0.06
polyhalite	0.46±0.02	Mn	1.46±0.04
PTFE	0.65±0.03	Fe	1.31±0.05
NaCl	0.81±0.03	Cu	1.30±0.05
		Pb	3.27±0.13

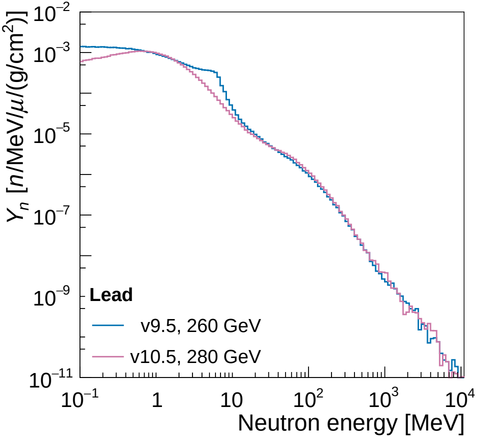
Neutron yield in polyethylene vs muon energy



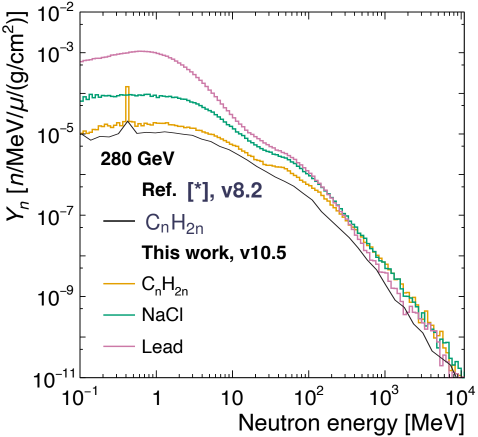
Neutron yield vs atomic weight of material – $E_\mu = 280$ GeV



Neutron production spectra in lead – GEANT4 v9.5 v v10.5



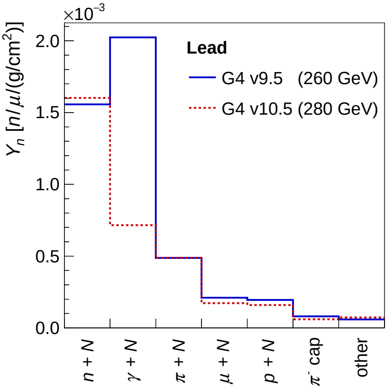
Neutron production spectrum in various materials – Geant4 v10.5



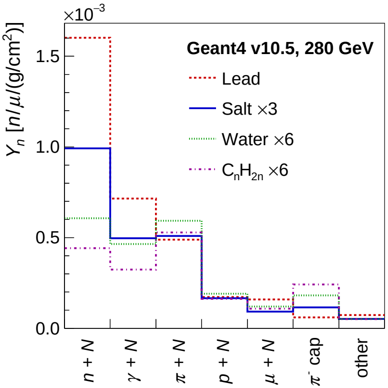
* Astropart.Phys. 31 (2009), 366

Neutron production processes

GEANT4 v10.5 v v9.5, lead

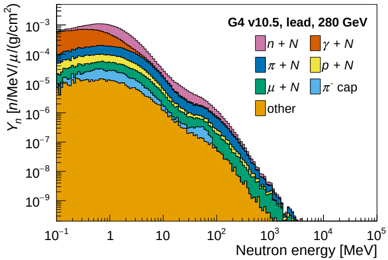


GEANT4 v10.5, $E_\mu = 280$ GeV
multiple materials



Neutron production spectrum by process

GEANT4 v10.5, $E_\mu = 280$ GeV



GEANT4 v9.5, $E_\mu = 260$ GeV