Cosmogenic isotope production in DEAP-3600

June 23, 2020

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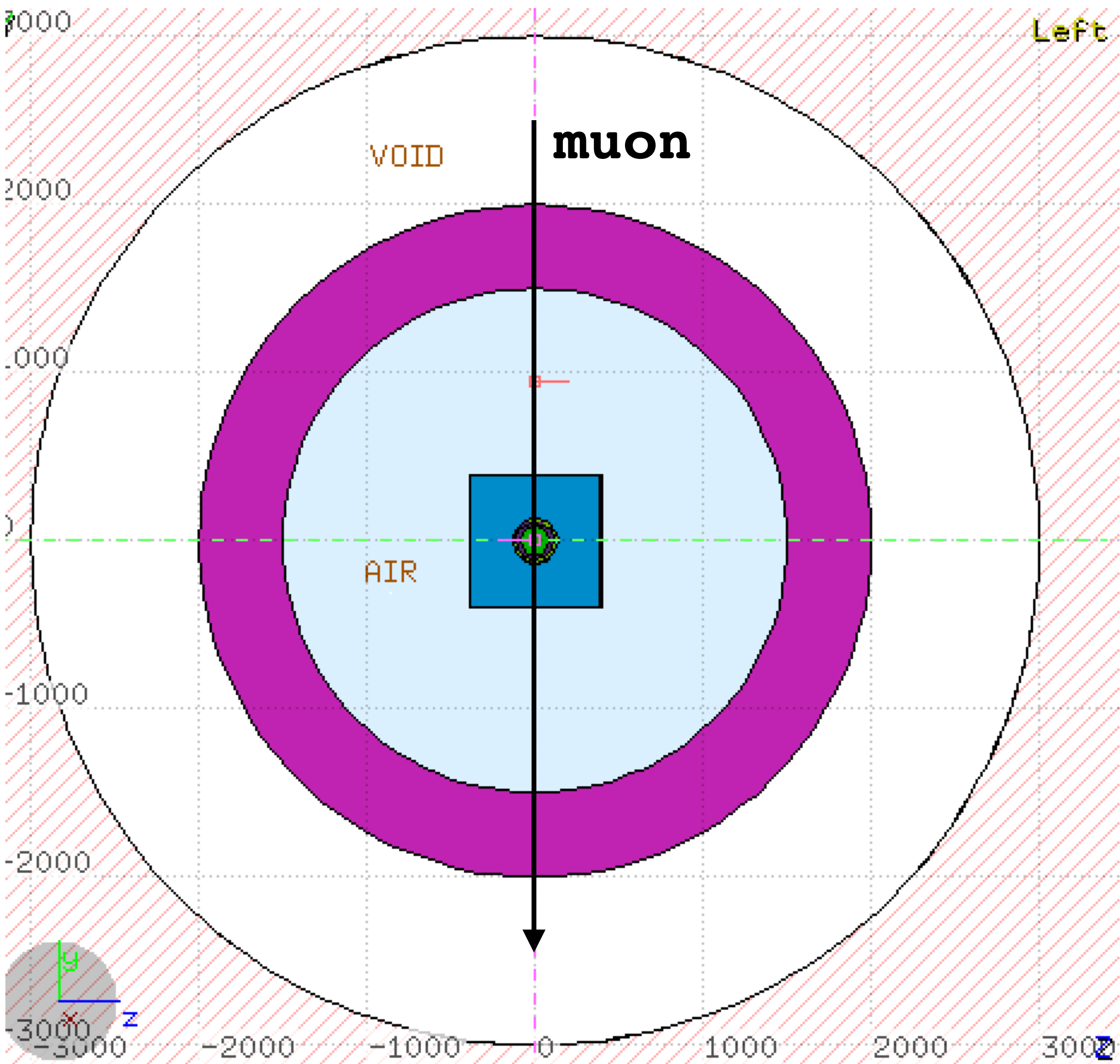
Outline

- FLUKA simulation
  - Detector geometry/materials
  - Muon energy spectrum
- Geometrical factors
- Some results:
  - Water
  - Stainless steel
  - High density polyethylene
  - Acylic
  - LAr

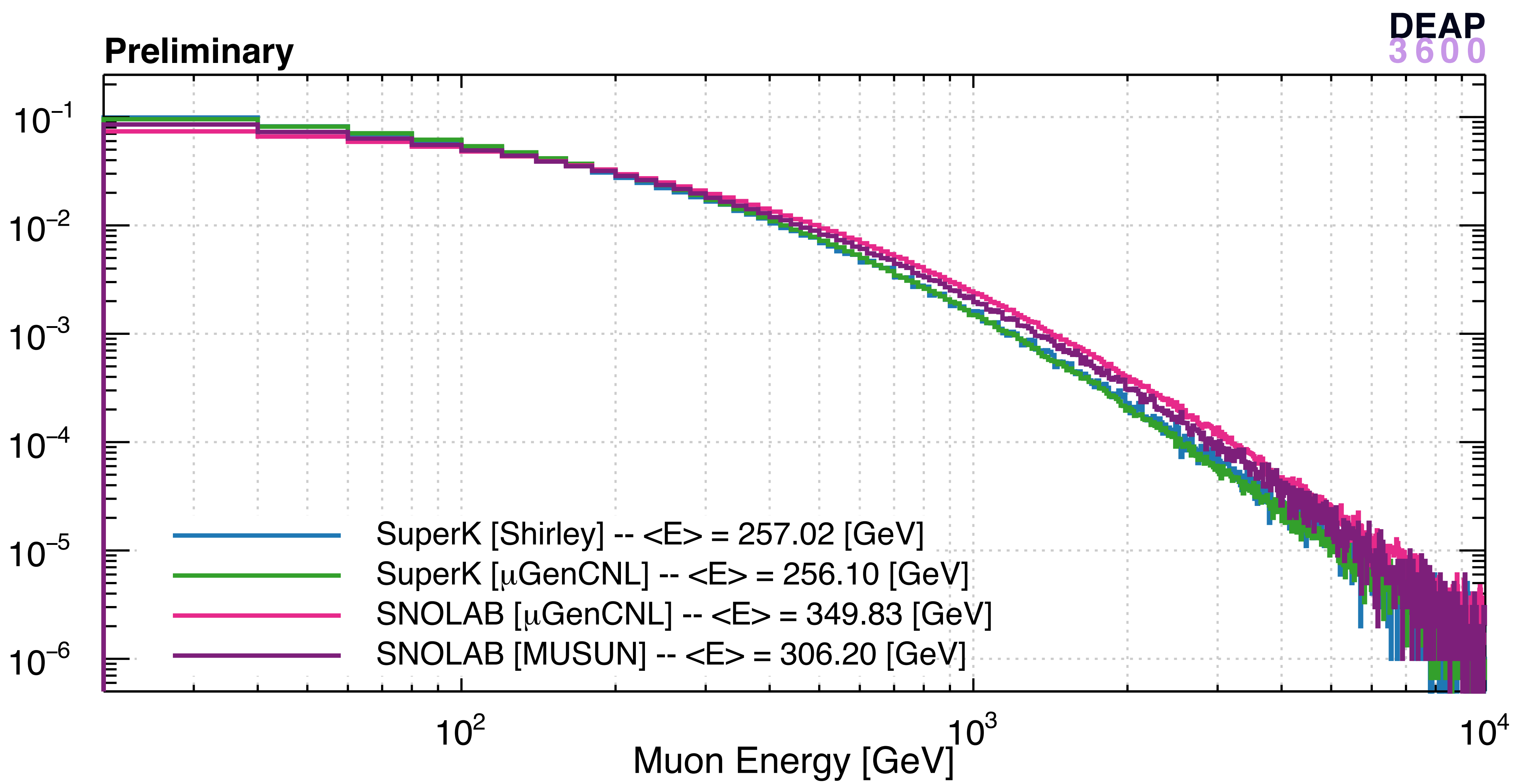
FLUKA Simulation



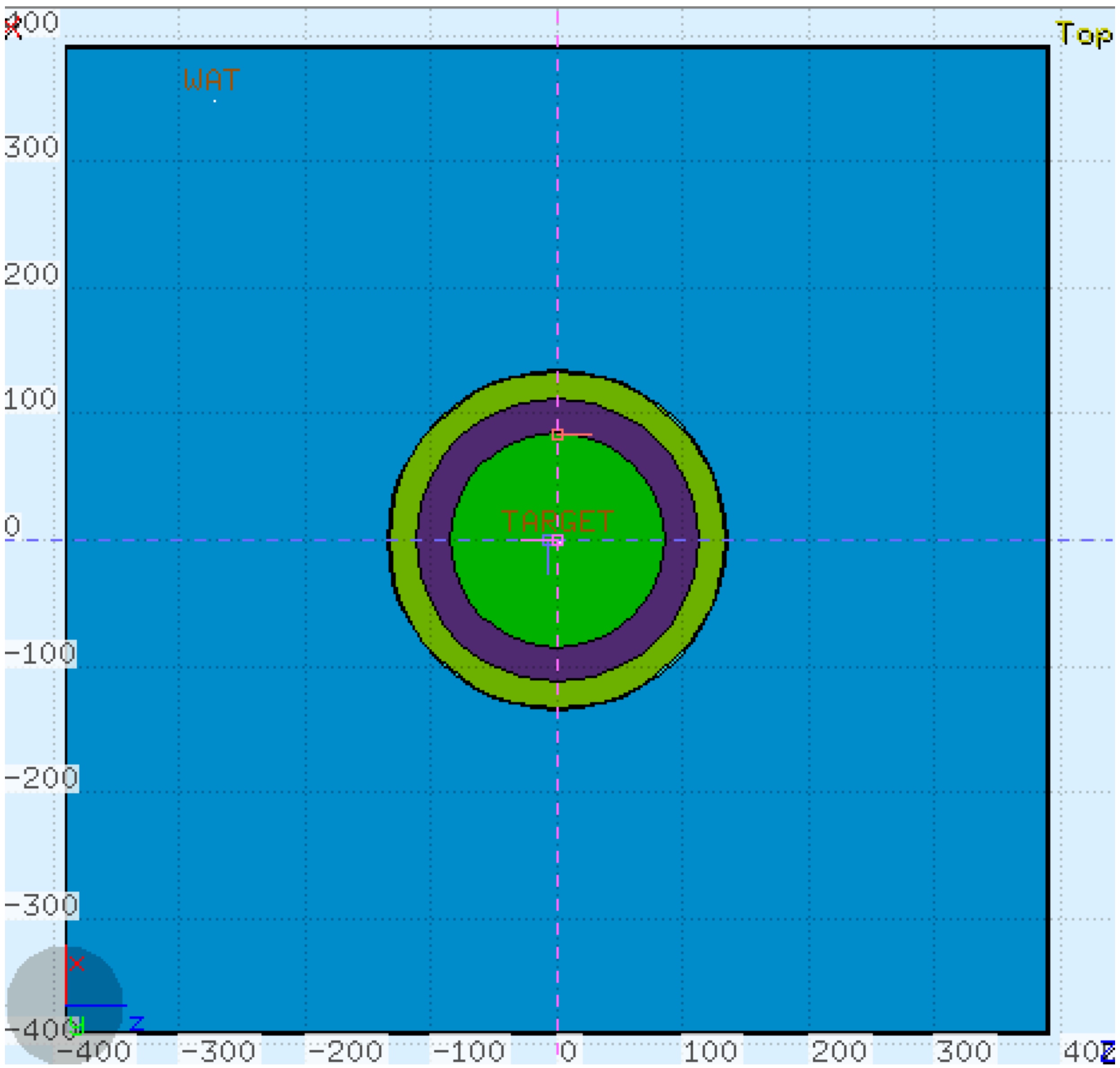
- Muons fired vertically downward from outside of rock volume
- Energy taken from μGenCNL @ SNOLAB depth
- Production of all residual isotopes scored in Water, Stainless Steel, HDPE, Acrylic, and LAr.
- Identical approach to: https://arxiv.org/pdf/1402.4687.pdf (SuperK) https://journals.aps.org/prc/pdf/10.1103/PhysRevC.99.055810 (DUNE)
  - Choices for implementation of geometry, materials, scoring, etc resulted from useful correspondence with an author of the above papers (FLUKA expert)
- Isotopes produced mainly by muon secondaries rather than muons themselves

Cosmogenic backgrounds from FLUKA

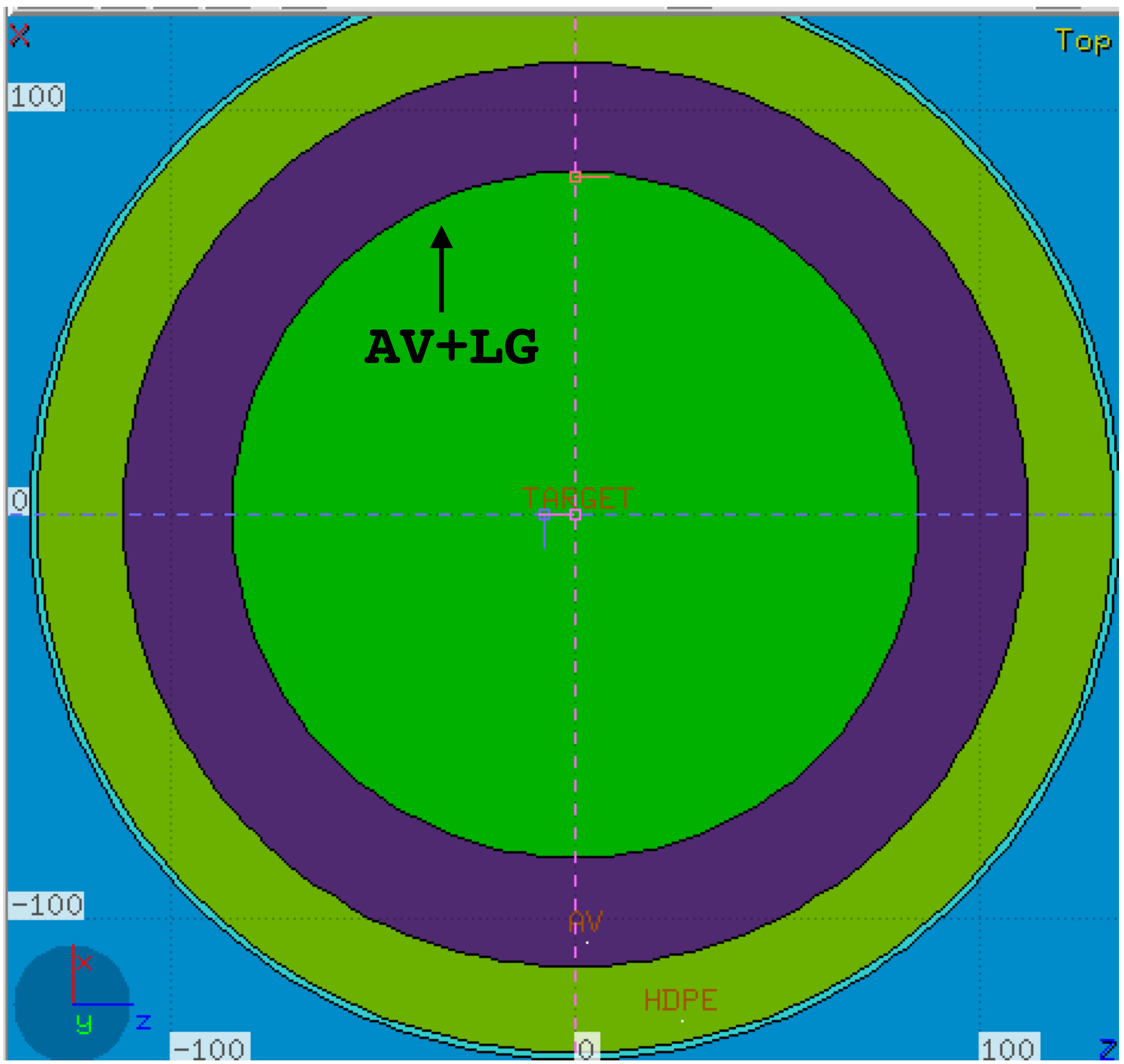
- First input into simulation is the muon energy spectrum



Detector Geometry



Y-Z View of entire water tank and detector

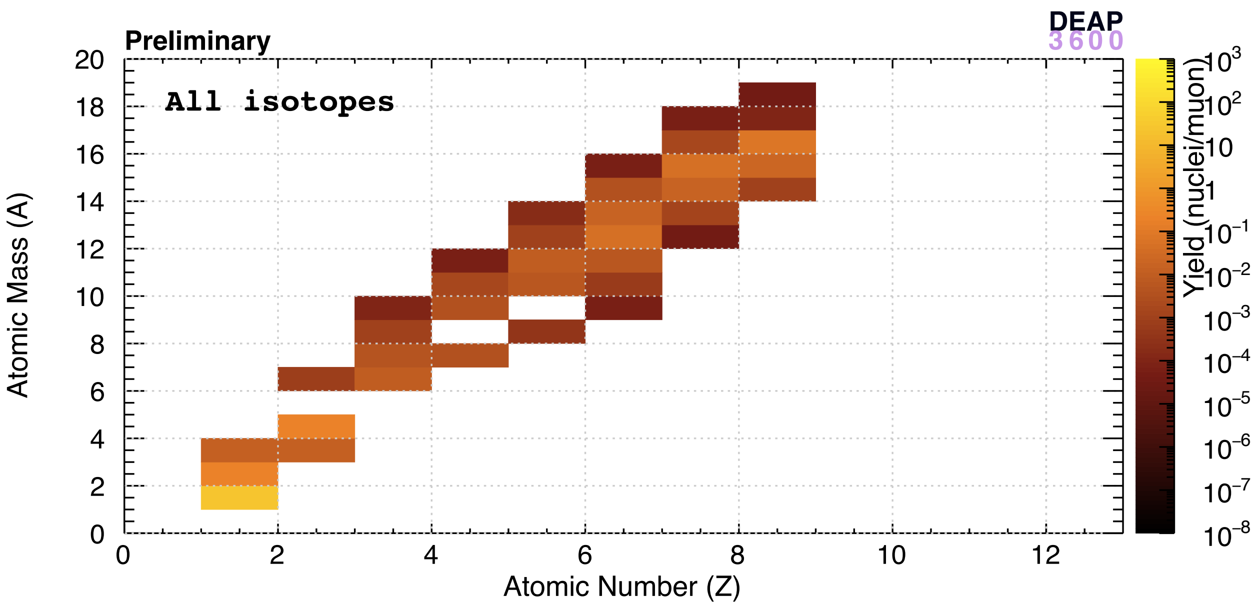


Y-Z view of simplified detector geometry

Geometrical factors

- Each muon will travel through a characteristic length of each material in these simulations
- Since the muons are all vertically incident, this length can be safely assumed to be the muon's chord length
  - Water = 508.00 cm
  - Stainless Steel = 1.83 cm
  - HDPE = 42.38 cm
  - Acrylic = 53.96 cm
  - LAr = 160.00 cm (using a fiducial volume)
- These lengths are useful for re-scaling the delayed neutron yields such that a total annual yield for each material can be calculated using a reconstructed path lengths for muons through each material from a realistic angular distribution
- The muon flux through each material is also different:
  - Muons the pass through LAr must have also passed through water,SS,HDPE, and acrylic
  - However, not all muons that pass through HDPE (for example) also pass through acrylic and LAr

Water



Isotope		Yield (per μ)
^{9}Li	($t_{1/2}$ = 178 ms)	→ 5.0E-5
^{11}Be	($t_{1/2}$ = 13.76 s)	→ 6.0E-5
^{8}He	($t_{1/2}$ = 17.3 ms)	→ 4.16E-7
^{17}N	($t_{1/2}$ = 4.17 s)	→ 5.71E-5

Total yield = 1.67E-4 neutrons/μ

or,

Total yield = 3.30E-7 neutrons/cm

Expect ~2.5 delayed neutrons in water in 1 live-year

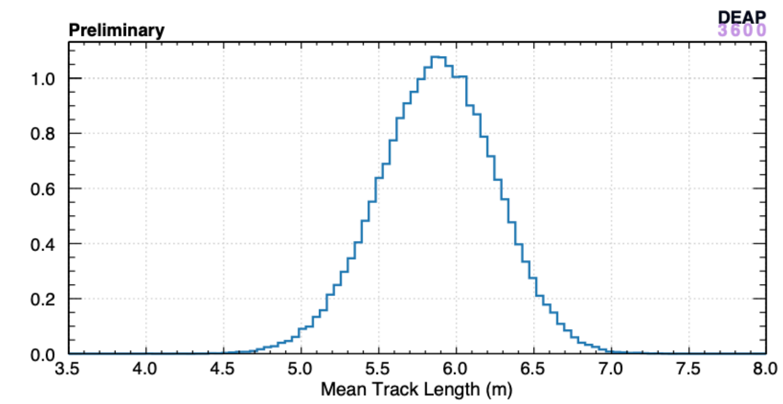
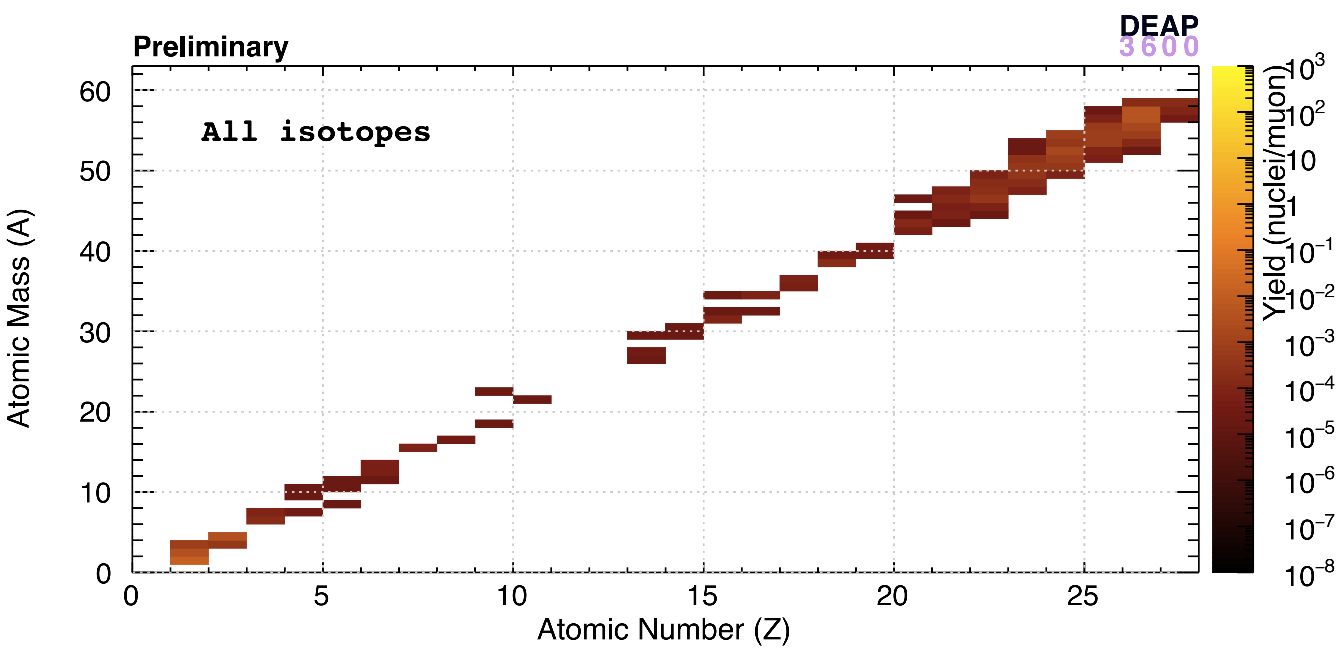


Figure 3.4: Mean muon path length from 100k psuedo experiments.

Muon track length through water (mean = 587 cm)

Stainless Steel

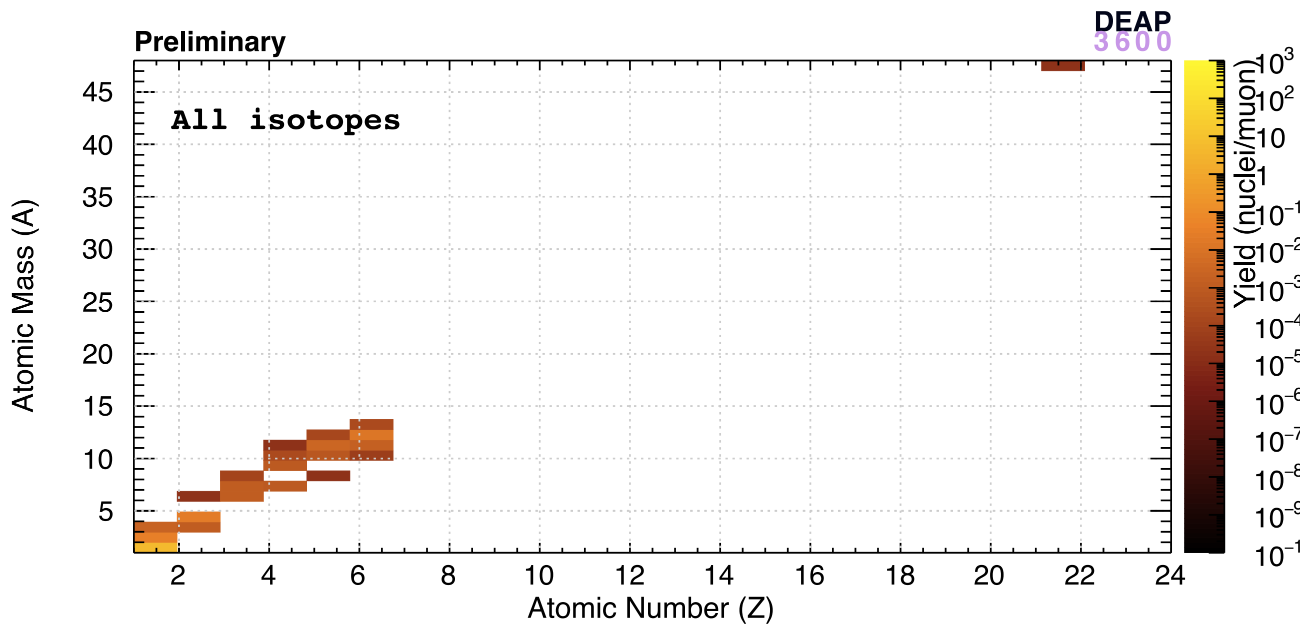


Isotope	Yield (per μ)
^{22}F ($t_{1/2}$ = 4.23 s)	→ 2.20E-6

Total yield = 2.20E-6 neutrons/μ
or,
Total yield = 1.20E-6 neutrons/cm

Expect ~3.14E-3 delayed neutrons in stainless steel in 1 live-year

High density polyethylene



Isotope	Yield (per μ)
^{11}Be ($t_{1/2}$ = 13.76 s) →	2.0E-5

Muon track length through
HDPE ~63.24 cm

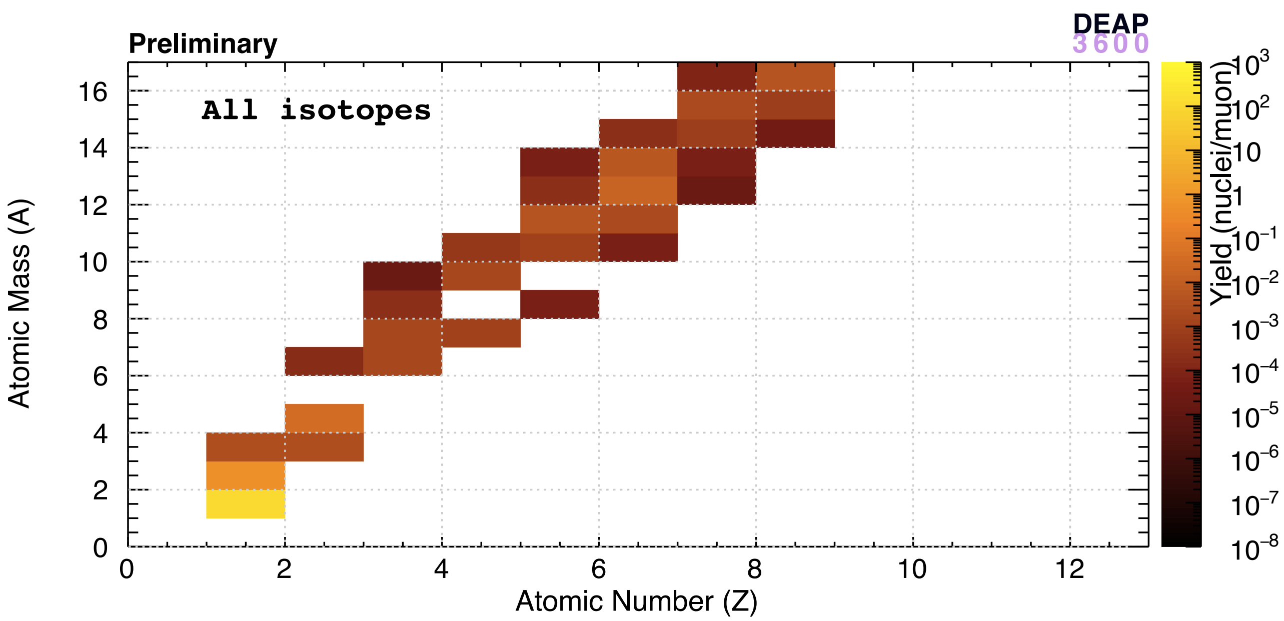
Total yield = 2.0E-5 neutrons/μ

or,

Total yield = 4.72E-7 neutrons/cm

Expect ~1.97E-2 delayed neutrons in HDPE in 1 live-year

Acrylic



Isotope Yield (per μ)

^{9}Li ($t_{1/2}$ = 178 ms) → 1.9E-5

^{5}B ($t_{1/2}$ = 17.3 ms) → 1.56E-7

^{17}N ($t_{1/2}$ = 4.17 s) → 1.56E-7

Muon track length through acrylic ~19.81 cm

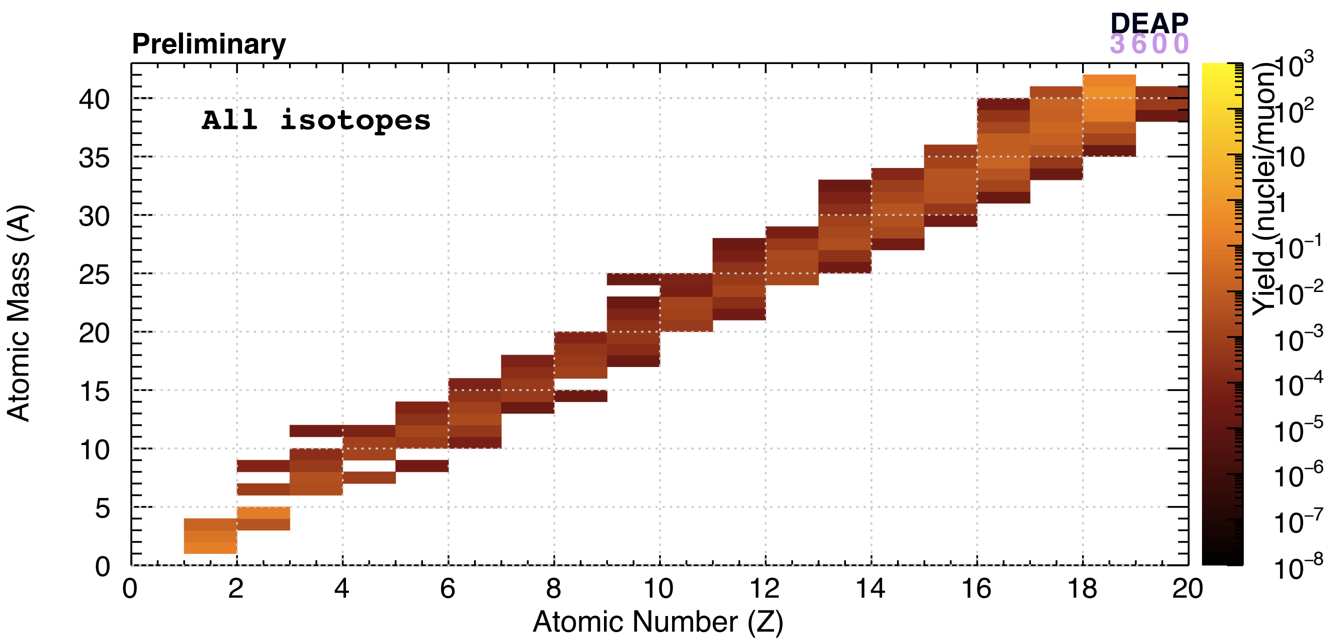
Total yield = 2.91E-5 neutrons/μ

or,

Total yield = 5.41E-7 neutrons/cm

Expect ~5.0E-3 delayed neutrons in acrylic in 1 live-year

Delayed LAr neutrons



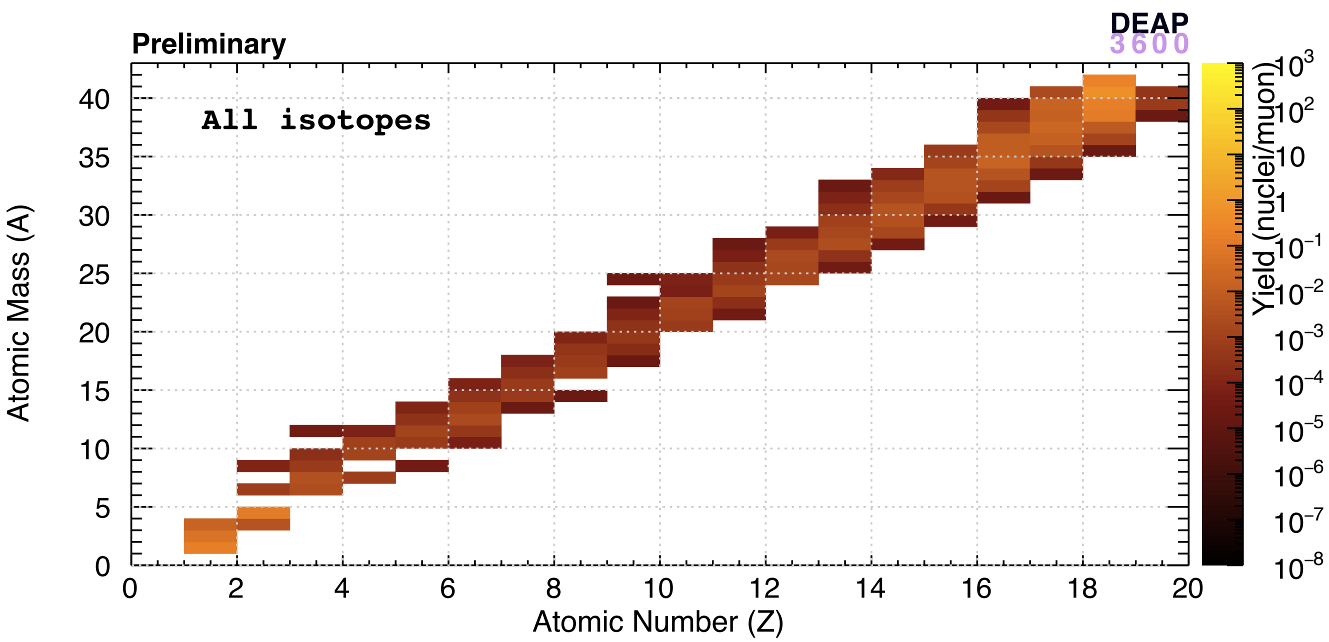
Total yield = 2.97E-4 neutrons/μ
or,
Total yield = 1.86E-6 neutrons/cm

Isotope		Yield (per μ)
^{8}He	($t_{1/2}$ = 119 ms) →	1.59E-5
^{9}Li	($t_{1/2}$ = 178 ms) →	1.2E-4
^{11}Li	($t_{1/2}$ = 8.75 ms) →	3.44E-5
^{11}Be	($t_{1/2}$ = 13.76 s) →	7.99E-5
^{13}B	($t_{1/2}$ = 17.3 ms) →	1.0E-4
^{17}N	($t_{1/2}$ = 4.17 s) →	7.60E-5
^{22}F	($t_{1/2}$ = 4.23 s) →	2.2E-6
^{24}F	($t_{1/2}$ = 382 ms) →	1.2E-6
^{27}Na	($t_{1/2}$ = 301 ms) →	2.6E-8
^{31}Al	($t_{1/2}$ = 644 ms) →	1.28E-6
^{32}Al	($t_{1/2}$ = 31.9 ms) →	1.4E-7

Expect ~5.61E-2 delayed neutrons in LAr in 1 live-year

Muon track length through LAr ~112.12 cm

β-decaying isotopes in LAr



Total yield = 0.4705 isotopes/μ

or,

Total yield = 0.0029 isotopes/cm

Expect ~190 isotopes in LAr in 2.1 live-years

Isotope		Yield (per μ)
^{41}Ar	($t_{1/2}$ = 6576 s) →	0.2113
^{40}Cl	($t_{1/2}$ = 1.35 m) →	0.0023
^{39}Cl	($t_{1/2}$ = 3372 s) →	0.0159
^{39}Ar	($t_{1/2}$ = 269 y) →	0.1626
^{38}Cl	($t_{1/2}$ = 2234 s) →	0.0123
^{37}S	($t_{1/2}$ = 303 s) →	0.0016
^{37}Cl	($t_{1/2}$ = 3E5 y) →	0.0134
^{35}S	($t_{1/2}$ = 87 d) →	0.0108
^{34}P	($t_{1/2}$ = 12.43 s) →	0.0014
^{33}P	($t_{1/2}$ = 25 d) →	0.0043
^{32}P	($t_{1/2}$ = 14 d) →	0.0050
^{31}Si	($t_{1/2}$ = 157 m) →	0.0018
^{28}Al	($t_{1/2}$ = 2.2 m) →	0.0019
^{10}Be	($t_{1/2}$ = 1.5E6 y) →	0.0010
^{3}H	($t_{1/2}$ = 12 y) →	0.0161

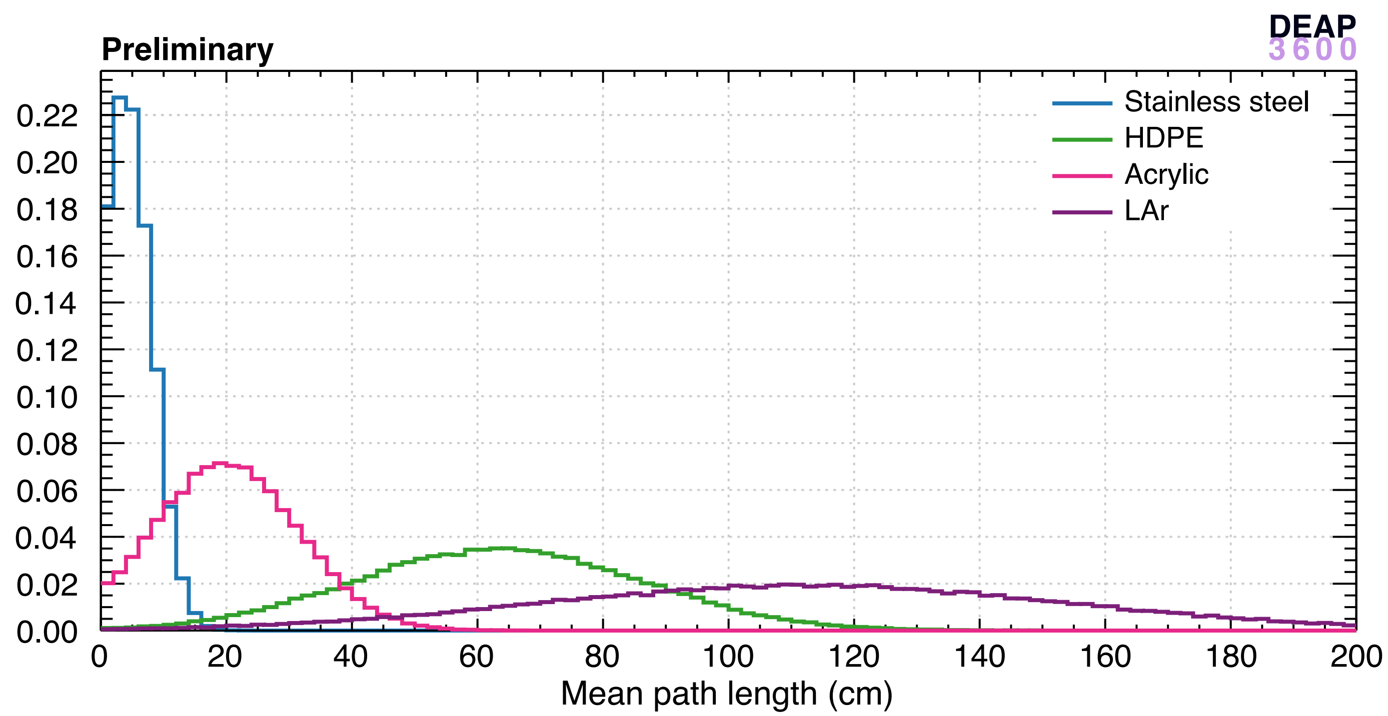
Conclusions

- FLUKA studies provide estimates for isotope yields in detector materials
- For underground Ar, minimal activation as expected

Backup

Final refinements

- Using simple MC techniques, reasonable PDFs for the muon path length in each material can be determined:

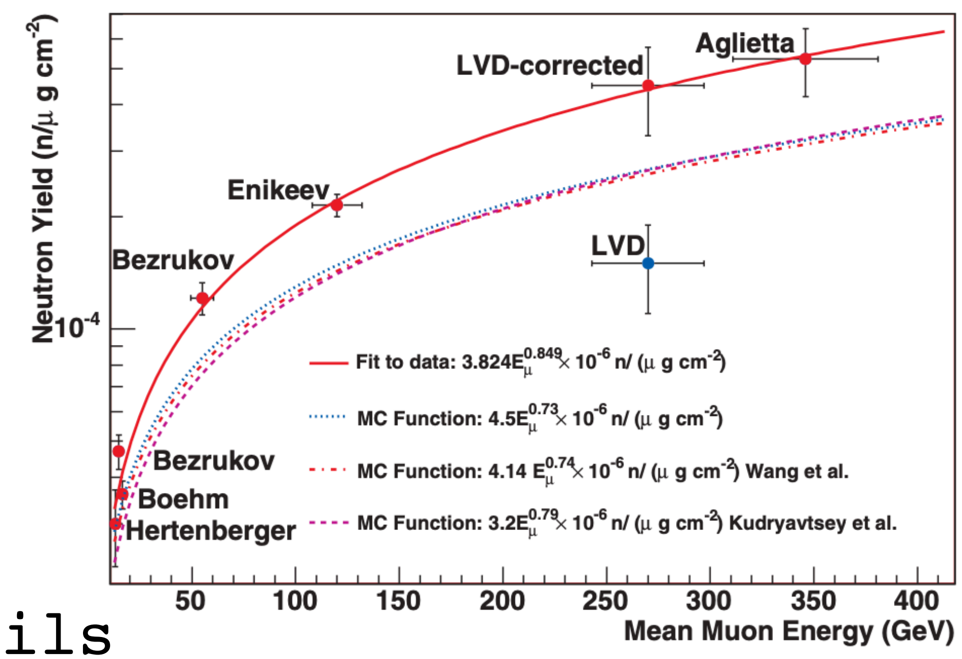


- Each yield from FLUKA has a statistical uncertainty which can be combined with the uncertainty from the path length PDFs to create reasonable 1σ intervals… or upper limits at 90% confidence which is likely how the high energy neutron study results will be expressed

- Question: Can the neutron yields from water, SS, and HDPE be totally neglected? First thought is to run a quick MC. Could weight the yields by the mean impact factor of neutrons generated from the various sources?

Spallation Neutrons

- One facet of the FLUKA simulations is that I should be able to reproduce the spallation neutron yields reported by both Mei & Hime (https://doi.org/10.1103/PhysRevD.73.053004) and Li & Beacom (PHYSICAL REVIEW C **89**, 045801 (2014))
- For reference:
  - Mei & Hime predict **5.3E-4** (n/(muon g cm^{-2}))
  - Li & Beacom predict **2.03E-4** (n/(muon g cm^{-2}))



These numbers are not corrected for details like the rock composition or the mean muon energy at SNOLAB but they provide a very good idea of what to expect