Simulation of Muon-Induced Neutrons for the Neutron Multiplicity Meter in the Soudan Cavern

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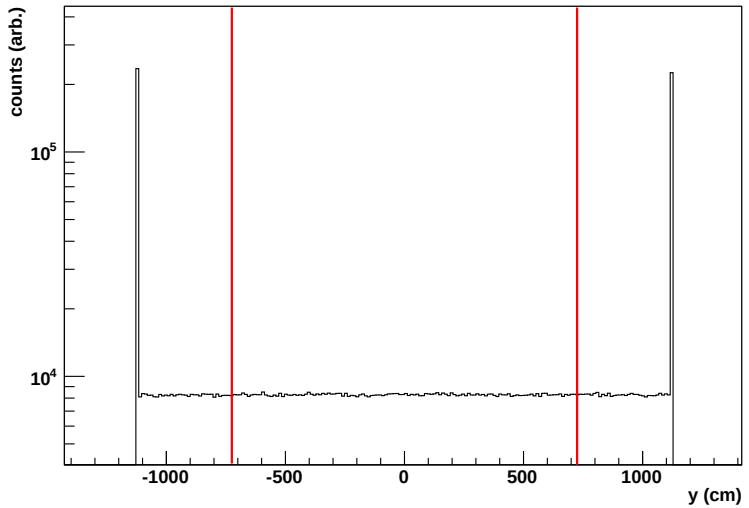
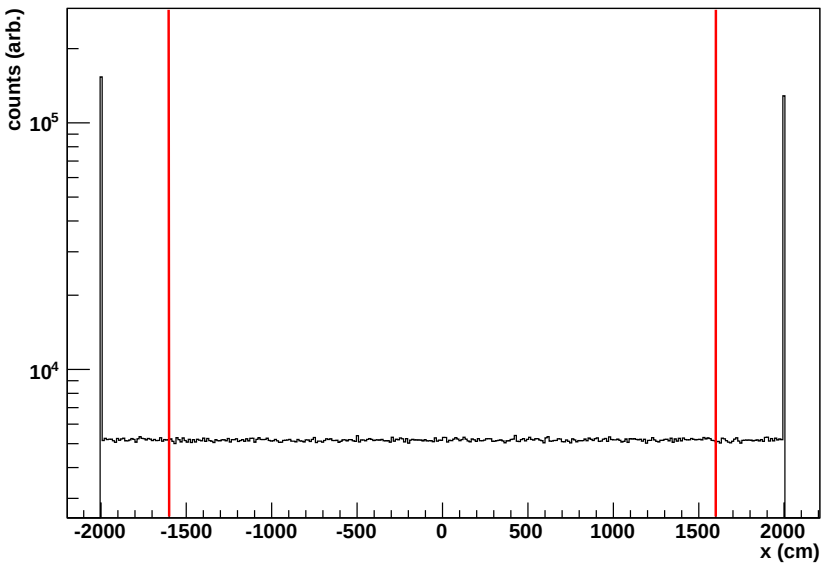
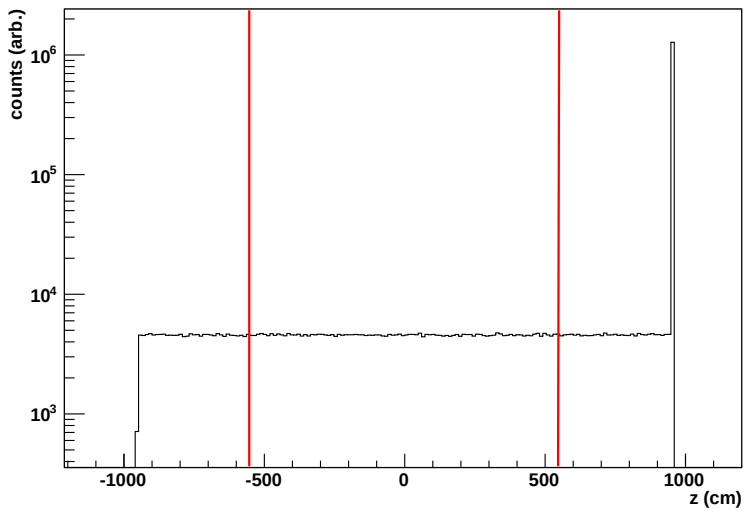
Muons from MUSIC/MUSUN

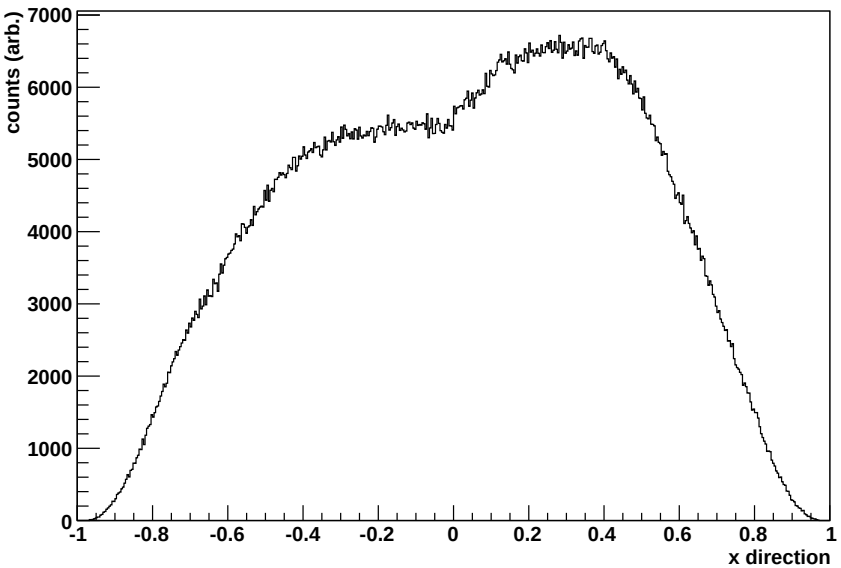
- 60 million muon tracks generated on cube
- +x direction = NORTH
- +y direction = WEST
- +z direction = UP

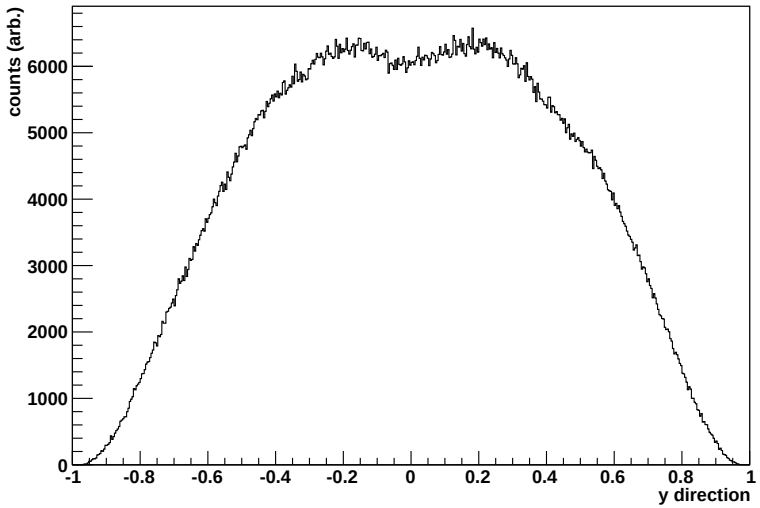


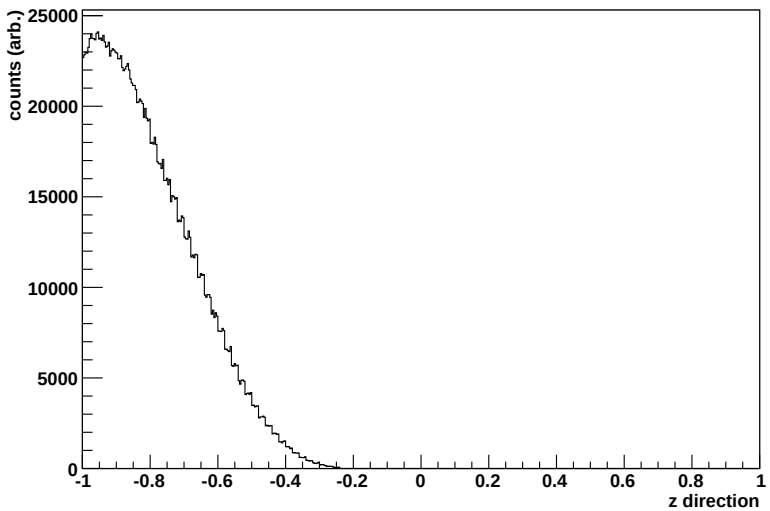




Muons from MUSIC/MUSUN







Implementation into NMDSim

- Geant4.9.5.p01 with Shielding physics list (and patch)
- NMM Detector simulation has +x as WEST, symmetric in y (+NORTH)→ exchange x,y coordinates
- NMM offset in detector coordinate system (x,y,z) = (5.94,1.98,1.81) meters
- Muon propagate through 4 meters of Soudan Rock
- Save particle tracks as they pass through rock/cavern boundary inward only

Material	Percentage (%)
SiO_2	51.0
Al_2O_3	15.0
CaO	9.0
FeO	8.6
MgO	6.5
H_2O	2.7
Fe_2O_3	2.6
Na_2O	2.5
TiO_2	1.1
K_2O	0.4
CO_2	0.3
MnO	0.2
P_2O_5	0.1

K.Ruddick, *MINOS Internal Note*, NuMI-L-210 (1996)

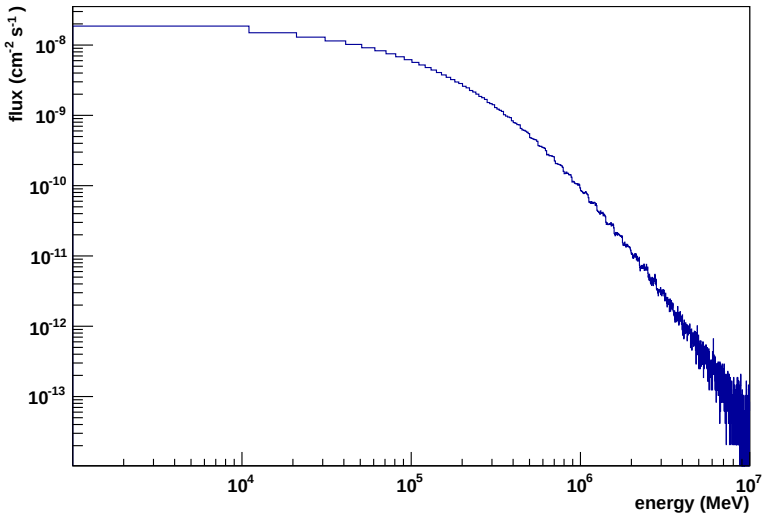
Muons/Neutrons Crossing into Cavern

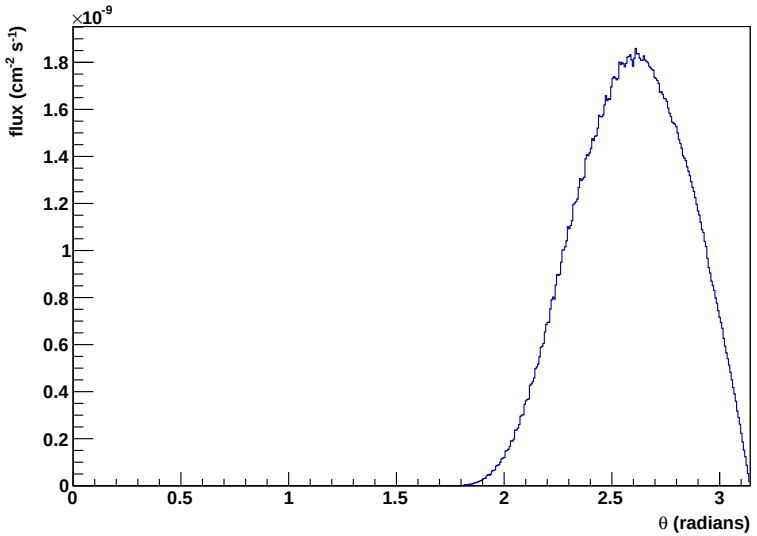
- Muon passing through top sheet
  - z $>$ 5499
  - PDG $= \pm$ 13
- Neutron passing through top sheet
  - z $>$ 5499
  - PDG $=$ 2112
  - TID $\neq$ lastTID
  - PID $\neq$ lastTID
  - Same effect as "killing" neutron track at rock/cavern boundary
  - EID $=$ lastEID $\rightarrow$ increment multiplicity
- Simulation time $t = \frac{N}{A\mathcal{F}_V}$
  - N is the total number of muons crossing top sheet
  - A is the area of the top sheet, 32x14.5 m^2
  - $\mathcal{F}_V$ is the flux through a horizontal sheet at Soudan, $(2.0 \pm 0.2) \times 10^{-7} cm^{-2}\ s^{-1}$

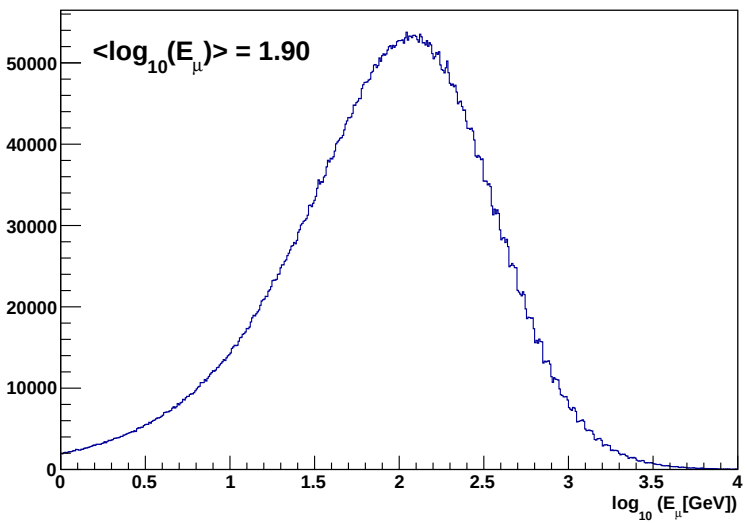
K.Ruddick, *MINOS Internal Note*, NuMI-L-210 (1996)

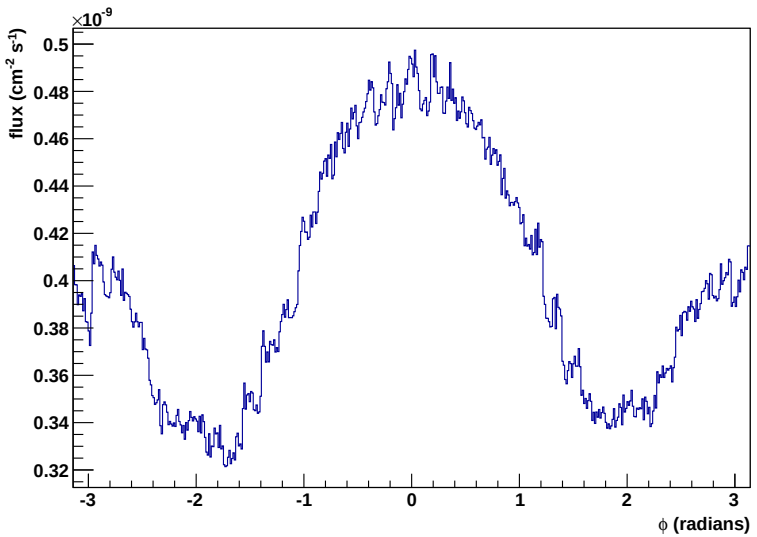
R.Nelson, *B.S. Dissertation, University of California at Santa Barbara* (2003)

Muons Crossing into Cavern - 120 days

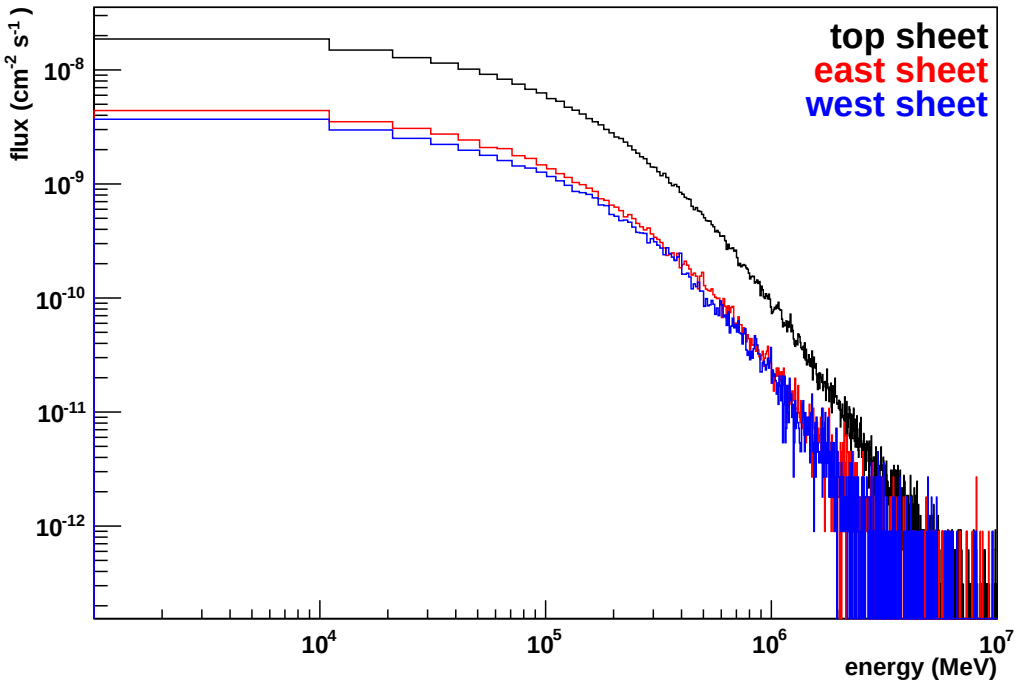








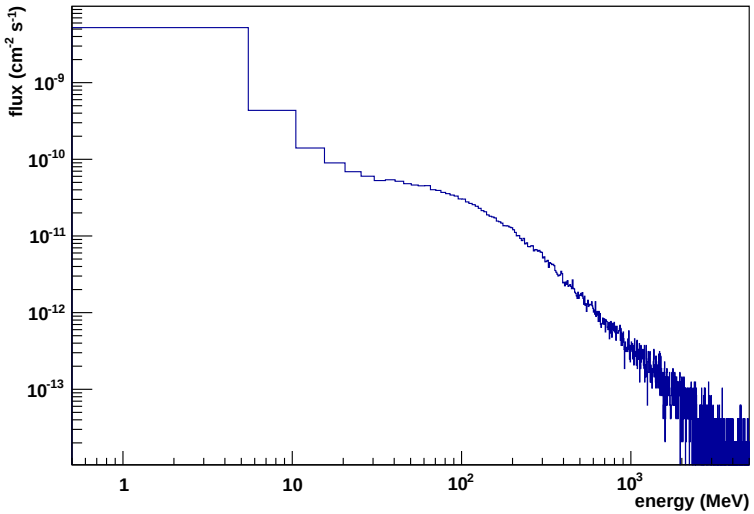
Muon Vertical/Horizontal Flux

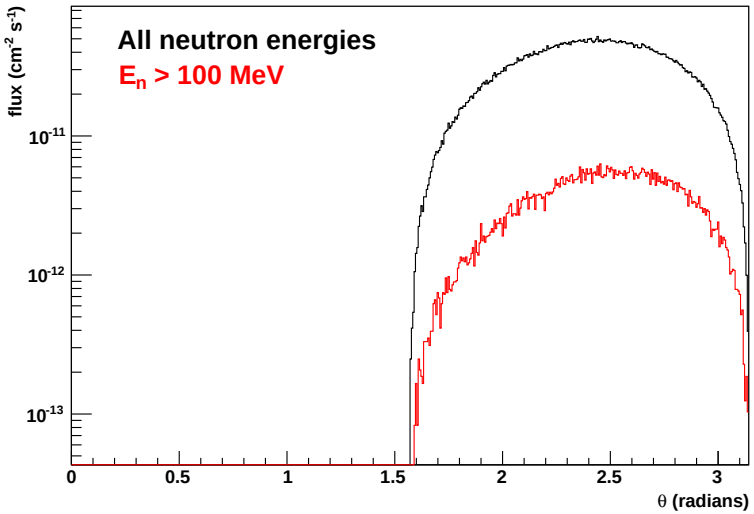


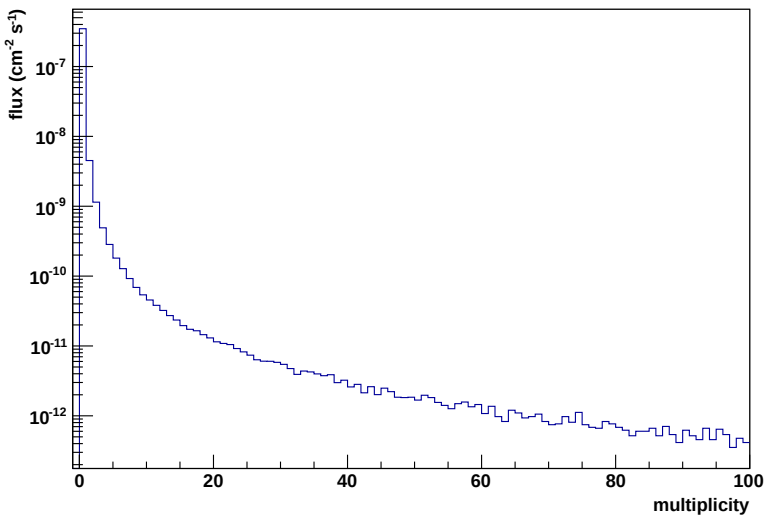
$$\mathcal{F}_V = 2.0\text{x}10^{-7}\text{cm}^{-2}\ \text{s}^{-1}$$
$$\mathcal{F}_H = 4.1\text{x}10^{-8}\text{cm}^{-2}\ \text{s}^{-1}$$
$$\frac{\mathcal{F}_H}{\mathcal{F}_V} = 0.21$$

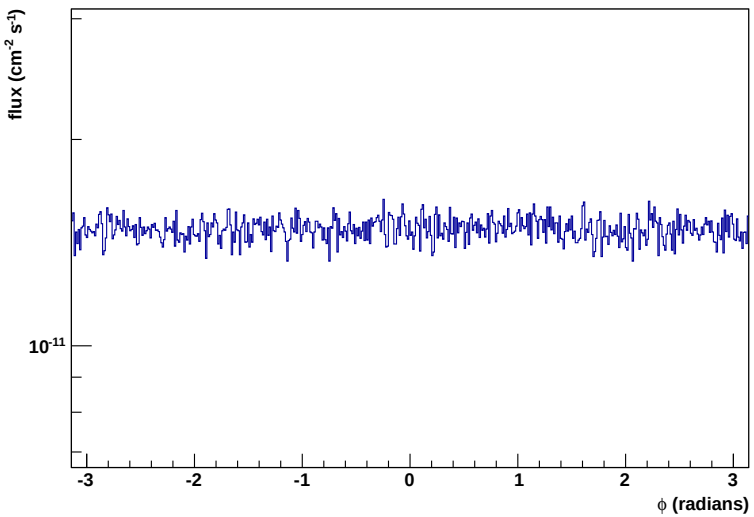
$$\frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{\alpha+2}{4\sqrt{\pi}} \frac{\Gamma(\frac{\alpha}{2}+\frac{1}{2})}{\Gamma(\frac{\alpha}{2}+2)}$$
$$\alpha = 3 \rightarrow \frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{2}{3\pi} = 0.21$$

Neutrons Crossing into Cavern - 120 days









Neutron Flux Ratios

$$\mathcal{F}_V(\mathrm{T}) = 7.401\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\mathcal{F}_V(\mathrm{B}) = 7.042\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\mathcal{F}_H(\mathrm{W}) = 6.658\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\mathcal{F}_H(\mathrm{E}) = 6.749\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\mathcal{F}_H(\mathrm{N}) = 6.6848\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\mathcal{F}_H(\mathrm{S}) = 6.506\mathrm{x}10^{-9}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\frac{\mathcal{F}_H}{\mathcal{F}_V} \sim 1$$

$$\frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{\alpha+2}{4\sqrt{\pi}} \frac{\Gamma(\frac{\alpha}{2}+\frac{1}{2})}{\Gamma(\frac{\alpha}{2}+2)}$$
$$\alpha = 0 \rightarrow \frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{2}{3\pi} = 0.5$$

Neutrons Flux as a Function of Energy

Wall	Total	>100 keV	>1 MeV	>10 MeV	>100 MeV
Top	7.401	2.179	2.179	1.603	0.7609
Bottom	7.042	2.516	1.935	0.6188	0.1107
East	6.749	3.105	2.559	1.173	0.4042
West	6.658	2.962	2.419	1.048	0.3473
North	6.684	2.962	2.415	1.056	0.3522
South	6.506	2.914	2.392	1.034	0.3418
Sum	41.04	16.64	13.90	6.533	2.317
Average	7.0	2.6	2.2	1.1	0.5
M&H	N/A	16.9	5.84	4.73	1.073