

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

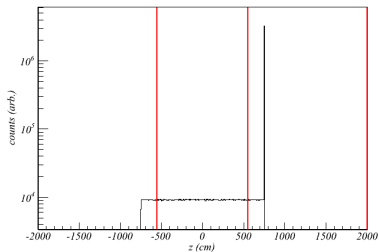
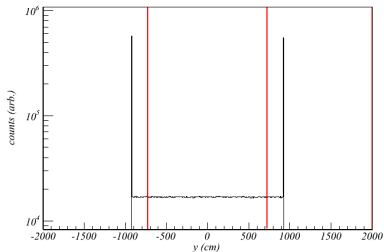
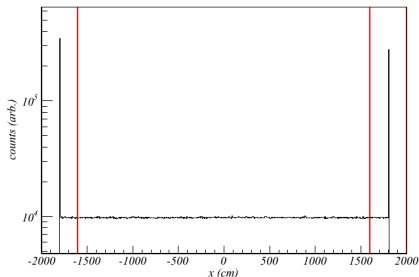
Melinda Sweany

Lawrence Livermore National Laboratory

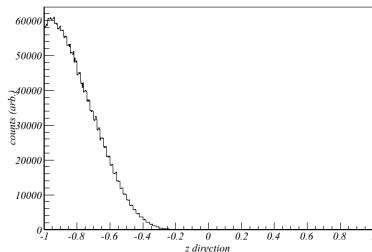
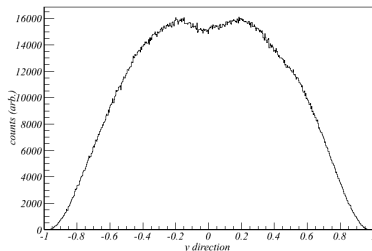
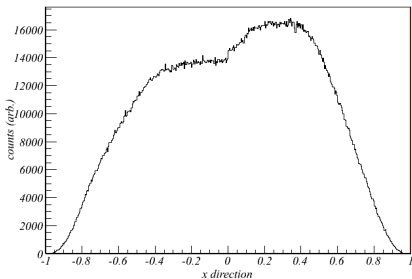
April 5, 2012

Muons from MUSIC/MUSUN

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



Muons from MUSIC/MUSUN

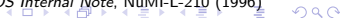


Implementation into NMDSim

- ▶ 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 2 meters of Soudan Rock
- ▶ Save particle tracks as they pass through rock/cavern boundary inward only
- ▶ ~ 3 hours cluster time for 2 million muon tracks

Material	Percentage (%)
SiO ₂	51.0
Al ₂ O ₃	15.0
CaO	9.0
FeO	8.6
MgO	6.5
H ₂ O	2.7
Fe ₂ O ₃	2.6
Na ₂ O	2.5
TiO ₂	1.1
K ₂ O	0.4
CO ₂	0.3
MnO	0.2
P ₂ O ₅	0.1

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



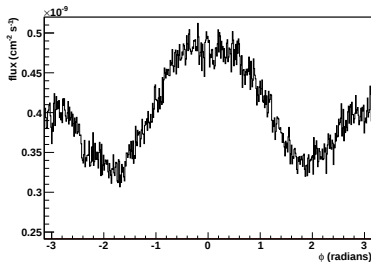
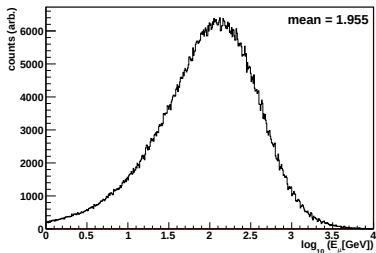
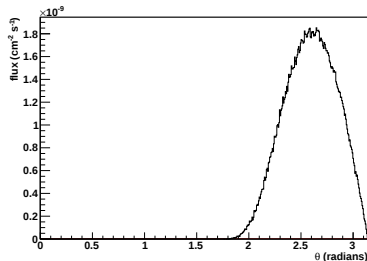
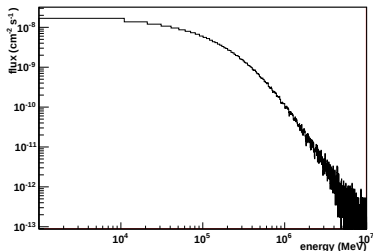
Muons/Neutrons Crossing into Cavern

- ▶ Muon passing through top sheet
 - ▶ $z > 5499$
 - ▶ $\text{PDG} = \pm 13$
- ▶ Neutron passing through top sheet
 - ▶ $z > 5499$
 - ▶ $\text{PDG} = 2112$
 - ▶ $\text{TID} \neq \text{lastTID}$
 - ▶ $\text{PID} \neq \text{lastTID}$
 - ▶ Same effect as “killing” neutron track at rock/cavern boundary
 - ▶ $\text{EID} = \text{lastEID} \rightarrow \text{increment multiplicity}$
- ▶ 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, $32 \times 14.5 \text{ m}$
 - ▶ $\mathcal{F}_V$ is the flux through a horizontal sheet at Soudan, $(2.0 \pm 0.2) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$

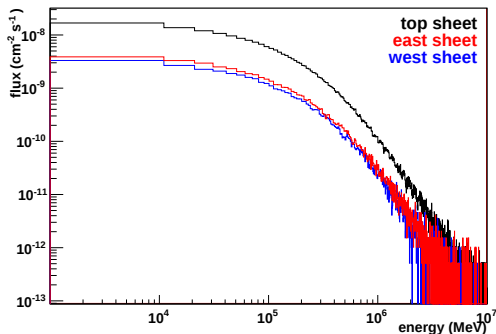
K.Ruddick, *MINOS Internal Note*, NuMI-L-210 (1996)

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

Muons Crossing into Cavern - 43 days so far



Muon Vertical/Horizontal Flux



$$\mathcal{F}_V = 2.0 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$

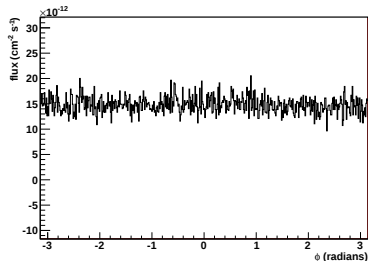
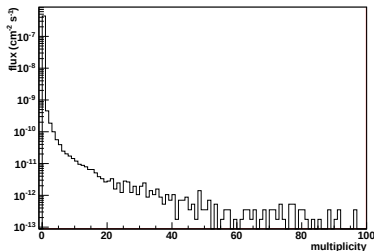
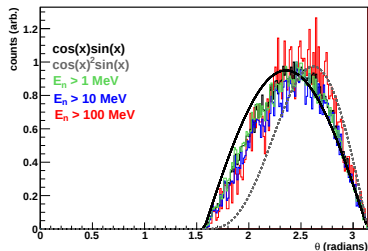
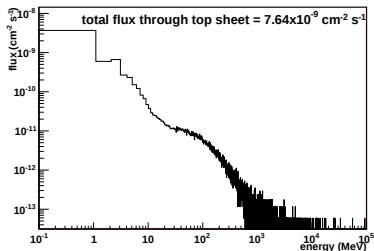
$$\mathcal{F}_H = 4.1 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\frac{\mathcal{F}_H}{\mathcal{F}_V} = 0.21$$

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

$$\alpha = 3 \rightarrow \frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{2}{3\pi} = 0.21$$

Neutrons Crossing into Cavern - 43 days so far



Neutron Flux Ratios

$$\mathcal{F}_V(T) = 7.64 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\mathcal{F}_V(B) = 7.64 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\mathcal{F}_H(W) = 7.06 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\mathcal{F}_H(E) = 6.97 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\mathcal{F}_H(N) = 7.29 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\mathcal{F}_H(S) = 7.13 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$$

$$\frac{\mathcal{F}_H}{\mathcal{F}_V} \sim 1$$

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

$$\alpha = 0 \rightarrow \frac{\mathcal{F}_H}{\mathcal{F}_V} = \frac{2}{3\pi} = 0.5$$

Neutrons Flux as a Function of Energy

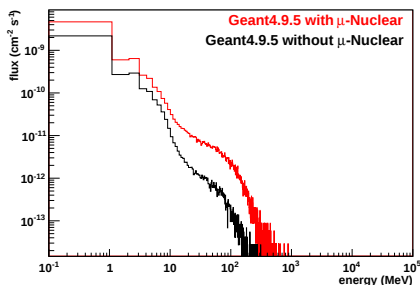
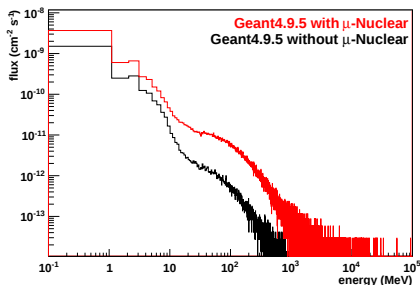
Wall	Total	>1 MeV	>10 MeV	>100 MeV
Top	7.64	3.95	1.73	0.796
Bottom	7.64	2.87	0.703	0.122
West	7.06	3.29	1.13	0.362
East	6.97	3.36	1.18	0.382
North	7.29	3.37	1.16	0.392
South	7.13	3.35	1.17	0.382
All	43.7	20.2	7.01	1.64
Mei and Hime	16.9	5.84	4.73	1.073

Do To List:

- ▶ MUSUN/MUSIC Muon files with Geant4.9.5:
 - ▶ Muon energy, angular distribution
 - ▶ Flux through top sheet to set timebase
 - ▶ Neutron energy, angular, multiplicity distribution from cavern walls
 - ▶ Neutron flux through top of cavern
 - ▶ Neutron flux detected with simulated NMM
 - ▶ Neutron flux coincident with showers, passing/not passing muon cut
 - ▶ Compare with new higher stats data and Mei and Hime and/or FLUKA prediction
- ▶ Original implementation
 - ▶ Re-run Mei and Hime parameterization with Geant4.9.5 and Shielding physics list
 - ▶ Compare with new higher stats data

A Happy Accident?

- ▶ Geant4.9.5 shielding list does not intrinsically include μ -Nuclear process
- ▶ In .mac file: */physics_engine/tailor/MuonNuclear on*
- ▶ Now have ~ 182 days of simulation time without μ -Nuclear



Neutrons Flux as a Function of Energy - No μ -Nuclear

Wall	Total	>1 MeV	>10 MeV	>100 MeV
Top	2.66	1.15	0.189	0.0457
Bottom	3.28	1.10	0.102	0.0071
West	2.70	1.10	0.142	0.0241
East	2.55	1.08	0.145	0.0251
North	2.72	1.11	0.142	0.0240
South	2.64	1.09	0.141	0.0233
All	16.6	6.63	0.861	0.149
Mei and Hime	16.9	5.84	4.73	1.073

Detected Multiplicity Comparison

