Neutron Background to Atmospheric Neutrino Analyses

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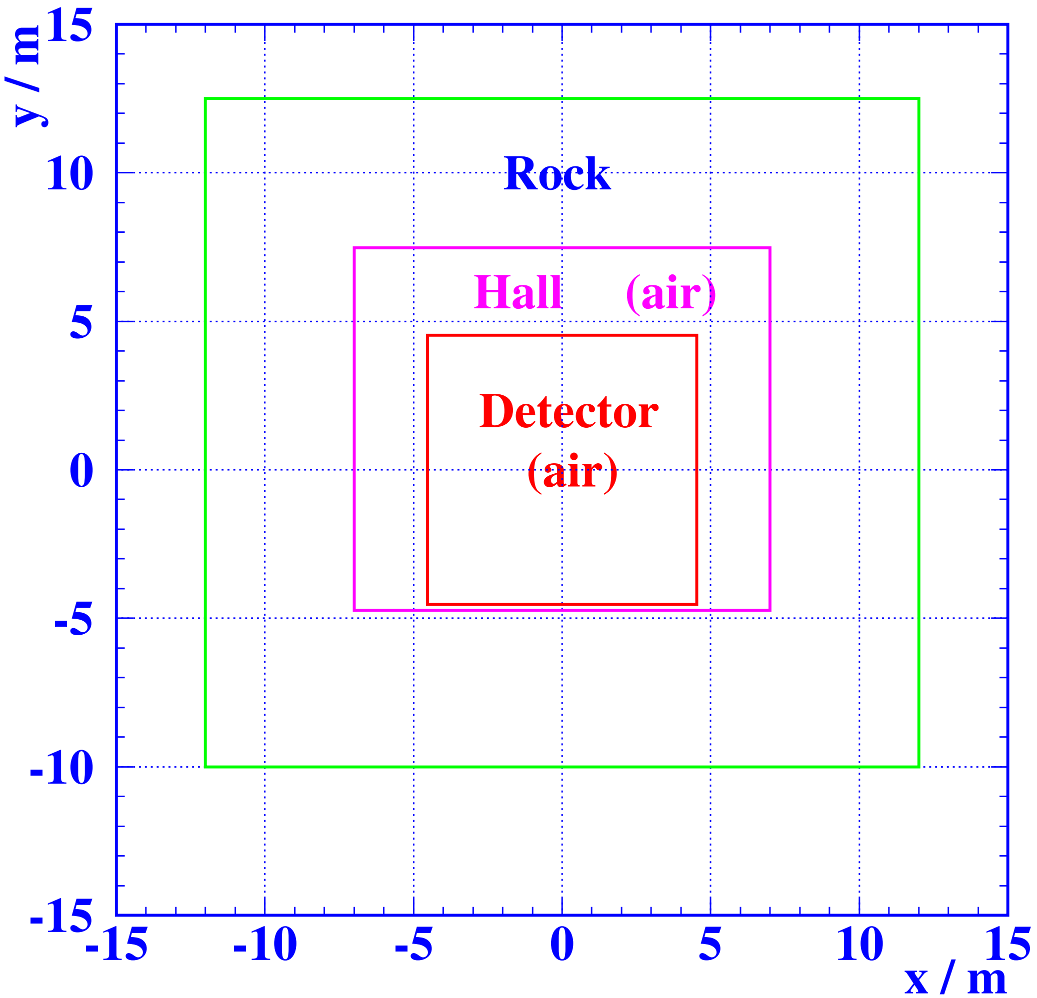
- Neutrons produced from interactions of cosmic muons in rock are potential background in atmospheric neutrino event samples
  Particularly if muon not seen in detector
- Attempts to estimate rate of neutrons incident on MINOS FD from Soudan 2 data or MC calculations performed by other experiments gave rates from 200 – 30000 n/year with $E_{\rm n} >$300 MeV
- Therefore used simple GEANT4 simulation to estimate neutron rate

GEANT4 Simulation

- Very simple geometry:
- 'Detector' = box of air $9.06 \times 9.06 \times 34.0$m
- Surround by
  HALL (air)
  ROCK (concrete: A=22.9 Z=11.4 ρ=2.5g/cc)
  Dimensions and materials as in GMINOS

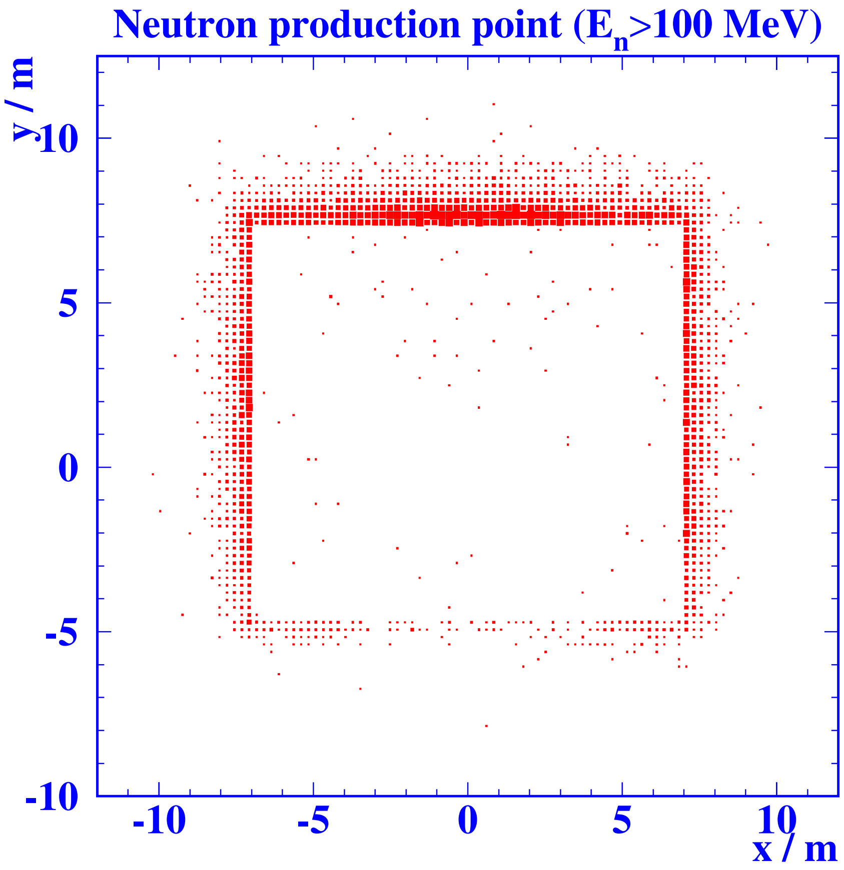


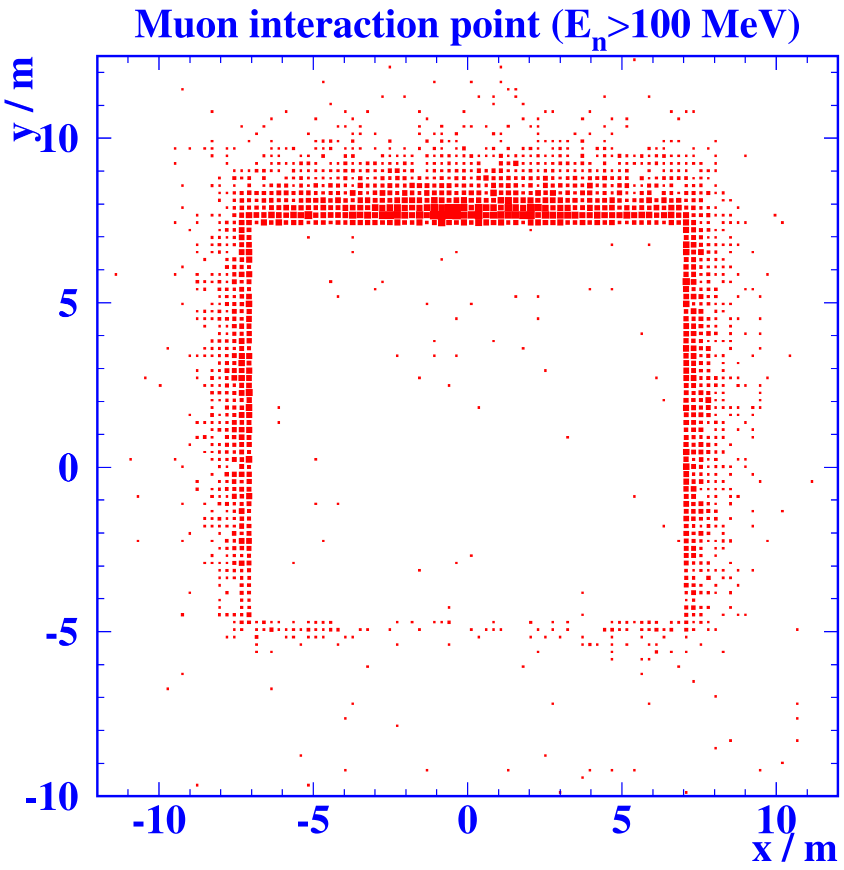
GEANT4 Simulation

- Cosmic muon flux as in atmospheric ν background studies
- Take muons incident on box 5m from detector, and extrapolate back so they traverse (at least) 5m rock
- Physics processes as in example N04 (usual em, hadronic int., decays etc.) with addition of muon nuclear interactions
- Track muon until reaches detector, decays or leaves ‘world’. If there has been a muon nuclear interaction, continue tracking and save all particles entering detector volume; otherwise kill event
- Save ONLY events with at least one neutron entering detector; for these, output all particles which enter detector
- Separate step: feed these particles into GMINOS detector simulation and reconstruct

Muon Interaction Vertex

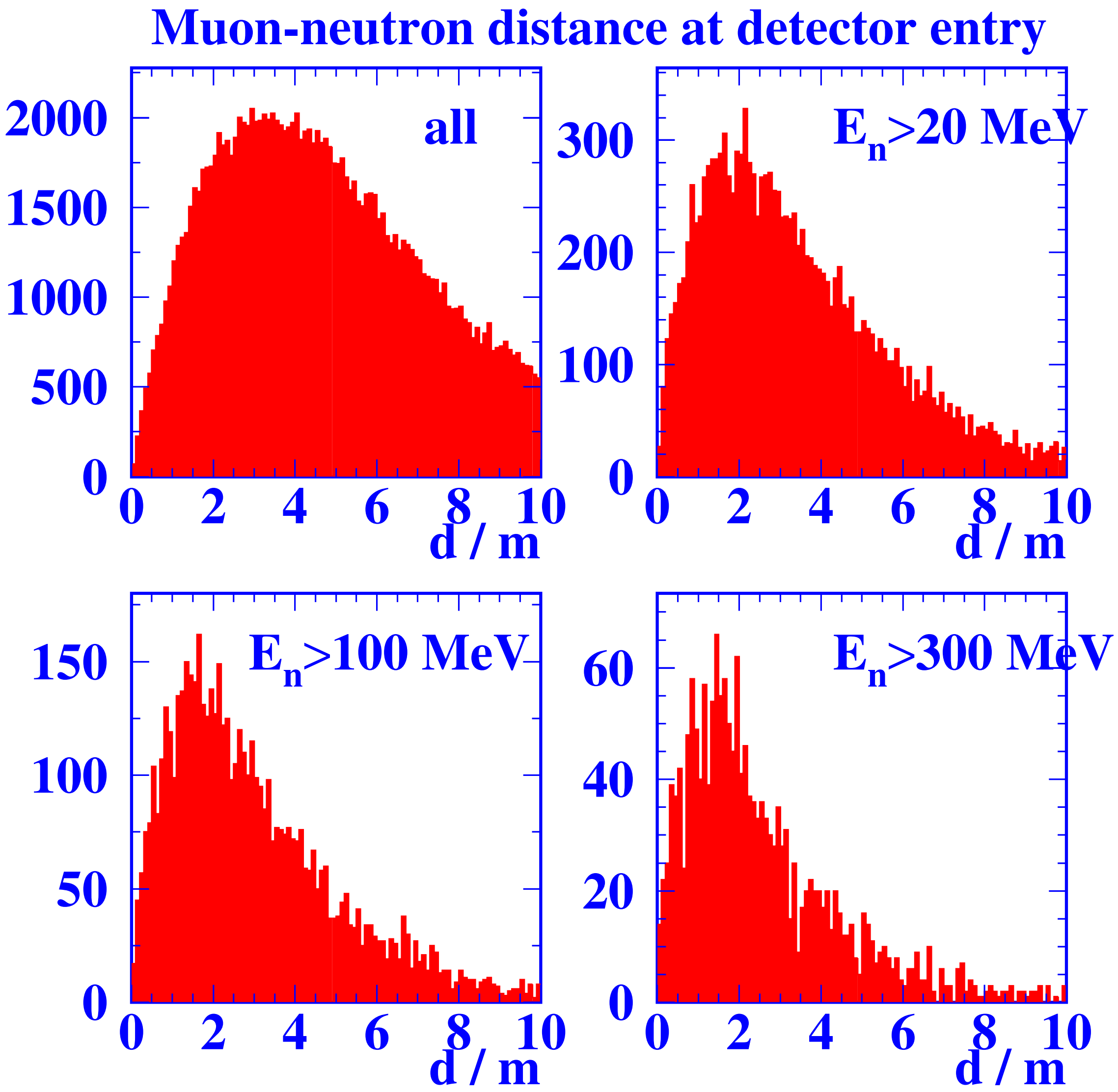
- High energy neutrons reaching detector almost all produced within last $\sim$2 m of rock





Muon-neutron Separation

- Separation between muon and neutron at detector entry typically metres, decreasing with energy
- For $E_\mathrm{n} > 100$ MeV (300 MeV), approx. 18% (13%) of neutrons enter detector more than 5 m from muon



Results

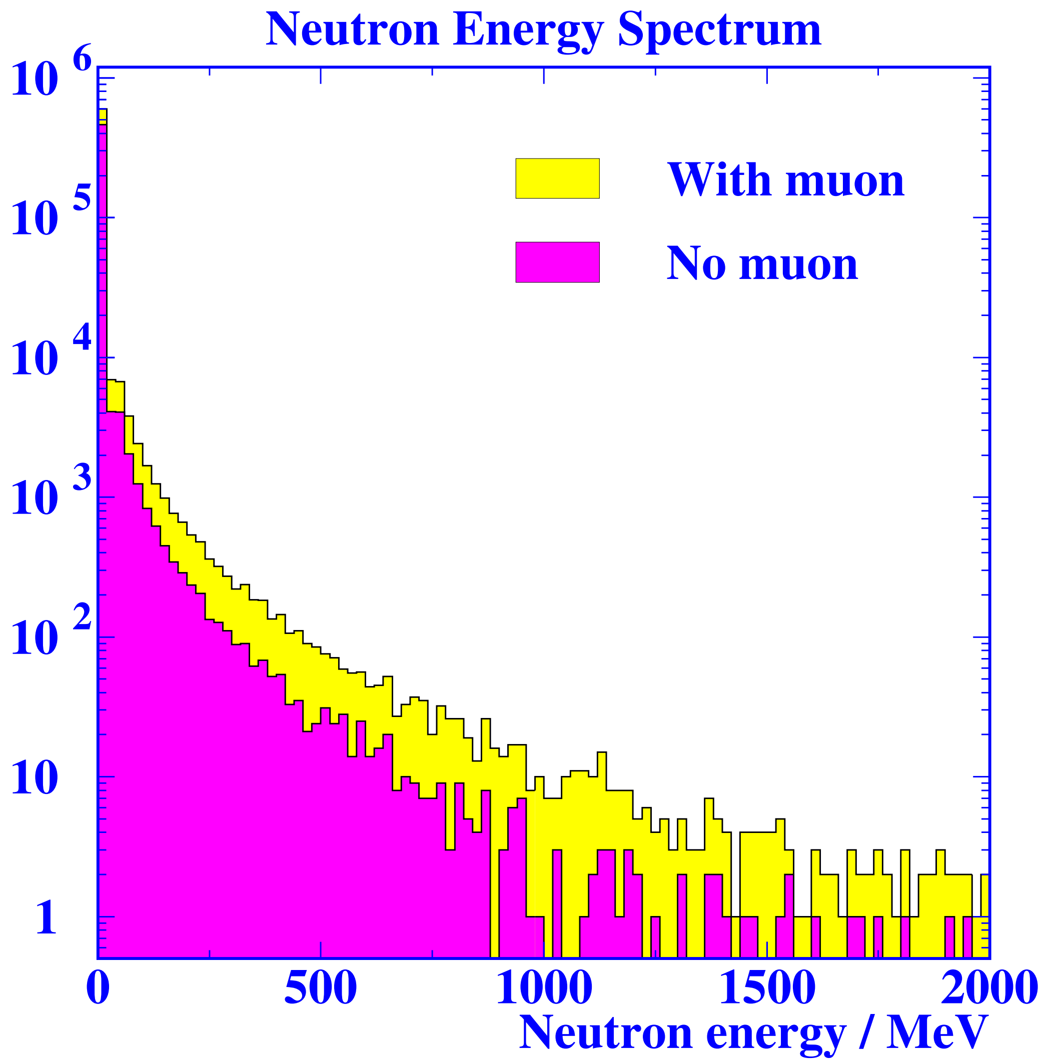
- Results based on 330M muons ($\equiv$ 4.7 years)
- Approx 0.9% give $\geq$ 1 neutron incident on detector volume
  In these, mean number of particles hitting detector = 14.4$\pm$0.2, but some events have 10000 or more (mostly low energy photons)
- Number of neutrons per muon with $E_{\rm n}$ $>$20 MeV = 29822/30M = 0.001
- How does this compare with other simulations? Comparison difficult as I only save events with neutron incident on detector
- hep-ex/0403009 (Canfranc) quote mean number of neutrons per muon with $E_{\rm n}$ $>$20 MeV = 0.007
- But number of neutrons $\sim$ $E_\mu^{0.75}$ $\Rightarrow$ expect Soudan/Canfranc $\sim$ 0.5
- Only $\sim$30% of generated muons point to my detector volume $\rightarrow$ multiply my rate by $\sim$ 3
- Hence rates roughly consistent

Neutron Energy Spectrum

- 19% of neutron events have muon incident on the detector
- These tend to be higher energy neutrons
- With muon:

  $< E_{\mathrm{n}} >$ = 14.8 MeV
- No muon:

  $< E_{\mathrm{n}} >$ = 3.7 MeV



Neutron Energy Spectrum

Neutron Rates at Far Detector from GEANT4 Simulation

	$E_{\rm n} > 100$ MeV	
	Events/y $[10^3]$	Neutrons/y $[10^3]$
Accompanied by muon	9.68±0.05	13.75±0.06
Without muon	8.10±0.04	10.01±0.05
Total	17.79±0.06	23.76±0.07
	$E_{\rm n} > 300$ MeV	
	Events/y $[10^3]$	Neutrons/y $[10^3]$
Accompanied by muon	3.52±0.03	4.46±0.03
Without muon	1.83±0.02	2.05±0.02
Total	5.54±0.04	6.51±0.04

Hadronic Interaction Models

- Approx. 64% of neutrons with $E_{\mathrm{n}} > 100$ MeV incident on detector are from secondary interactions

  $\Rightarrow$ Results sensitive to modelling of hadronic interactions

- Main simulation (results on previous slide) used (energy-dependent) parameterized models for inelastic hadronic processes ($\equiv$ LHEP physics list)

- Replace with different physics lists:
  - QGSP: theory-driven quark-gluon string model
  - QGSP_BERT: as QGSP but Bertini cascade for pions and nucleons below 3 GeV
  - QGSP_BIC: as QGSP but Bertini cascade for nucleons below 3 GeV

Hadronic Interaction Models

- Ratio of neutron fluxes to default simulation:

	$E_\mathrm{n} > 100$ MeV		$E_\mathrm{n} > 300$ MeV	
	Events/y	Neutron/y	Events/y	Neutrons/y
QGSP	0.86±0.02	0.87±0.02	0.81±0.03	0.85±0.03
QGSP_BERT	1.31±0.02	1.39±0.02	1.28±0.04	1.33±0.04
QGSP_BIC	1.20±0.02	1.22±0.02	1.24±0.04	1.26±0.04

- See variations up to 30–40%

- There are also uncertainies in the muon-nuclear interaction model, rock composition/density etc.

  Estimated rates probably reliable to ∼50%

Neutrons in Soudan 2

- Is GEANT4 estimate consistent with neutron rate observed in Soudan 2?
- In February, estimate from Soudan 2 data gave 200 n/y at MINOS WITH VISIBLE ENERGY $E_{\rm vis} > 300$ MeV
- But how does visible energy relate to neutron energy?
- Try to make estimate of rate with VISIBLE energy above 300 MeV
- Using GMINOS simulation of events output from G4 program, sum energy of secondary particles above Soudan 2 thresholds (e/γ 100 MeV/c, π 150 MeV/c, p 500 MeV/c)
- Most events have many particles, so consider 'visible energy' originating from highest energy neutron
- Number of events/year with $E_{\rm vis} > 300$ MeV = 1741

Neutrons in Soudan 2

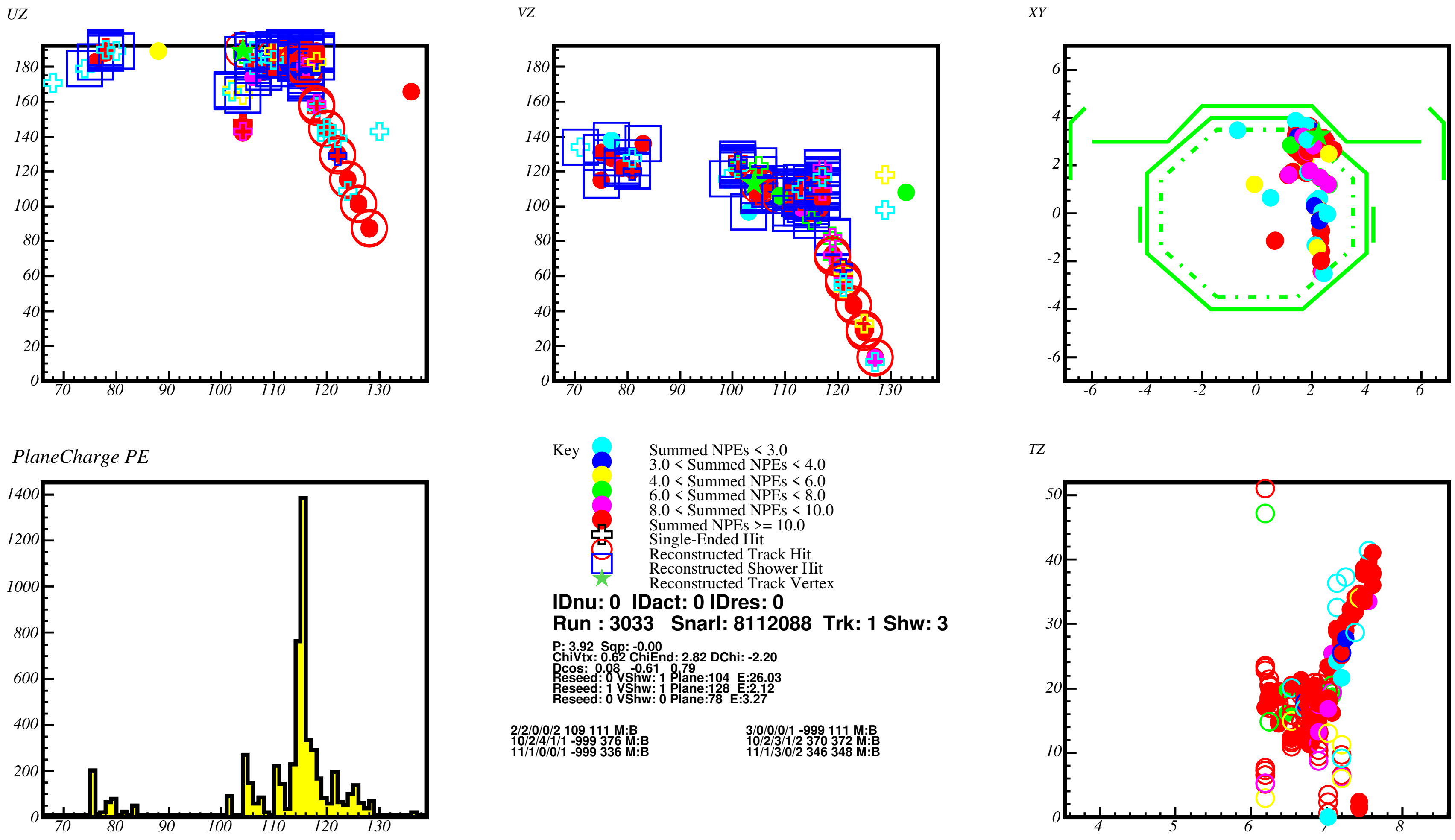
- But many of these events also have visible muon and/or another neutron and would have been rejected as ν events by scanning at Soudan 2
- If also demand muon misses detector and no 'visible energy' from other particles, number of events/year reduced to 320
- Within factor of 2 of my estimation from Soudan 2 data ($\sim$200 events/year)

Detector Simulation

- Events with a neutron $>$100 MeV processed through GMINOS
  83803 events from 330M muons
- Reconstructed with AtNu reconstruction (Andy Blake)
  $\Rightarrow$ no event passes early stages of ν_μ CC event selection

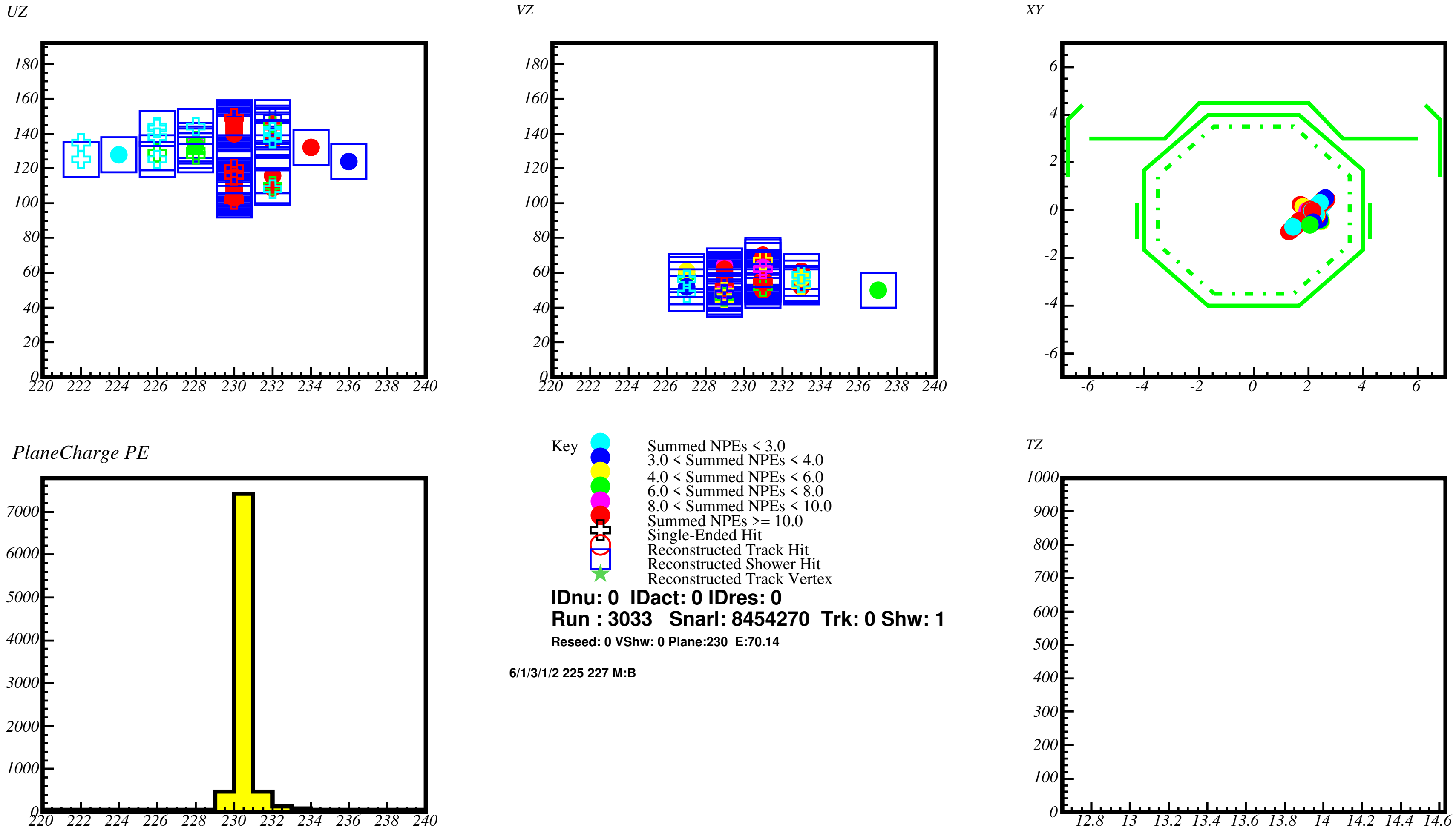
Typical Event...

312 GeV μ^- interacts $\sim$30 cm from rock-hall interface producing high multiplicity shower: 423 particles incident on detector



Another Typical Event...

82 GeV μ^- interacts few cm from rock-hall interface; 13 partcles hit detector



Summary

- Used simple GEANT4 job to study neutron background to atmospheric neutrino analyses from cosmic muon interactions in rock
- Results indicate rates of about 6500 (2000) neutrons per year with $E_{\mathrm{n}} >$300 MeV including (excluding) those with muon incident on detector
- These rates are consistent, within factor 2, of rough estimate using Soudan 2 data.
- Output of GEANT4 simulation input to GMINOS and reconstructed
  $\Rightarrow$ No event passes early stages of ν_μ CC selection
- Results written up:
  NuMI-NOTE-SIM,ATM_NU-1085