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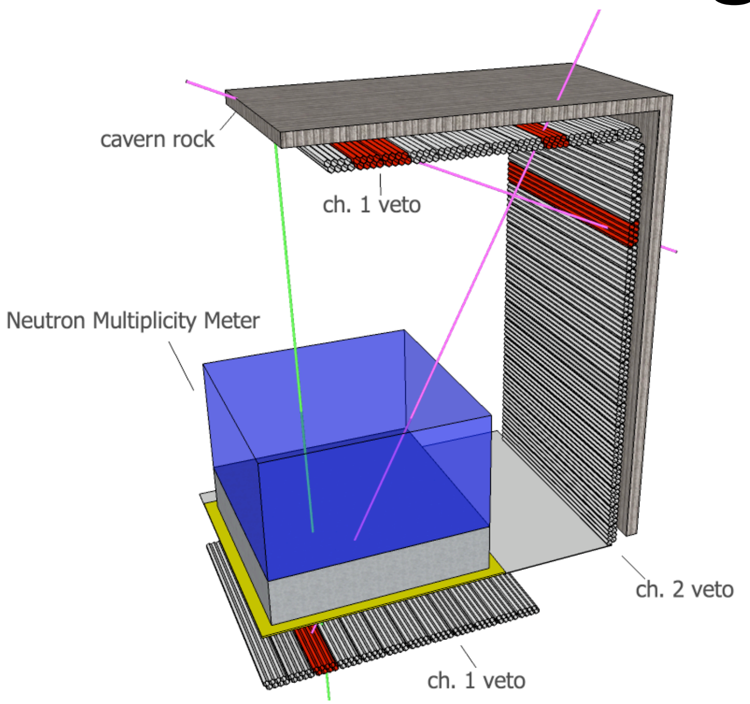
A Comprehensive Comparison for Simulations of Cosmic Ray Muons Underground

A.N. Villano[1], A. Empl[2], A. Kennedy[1], S. Lindsay[2]

(for the AARM collaboration)

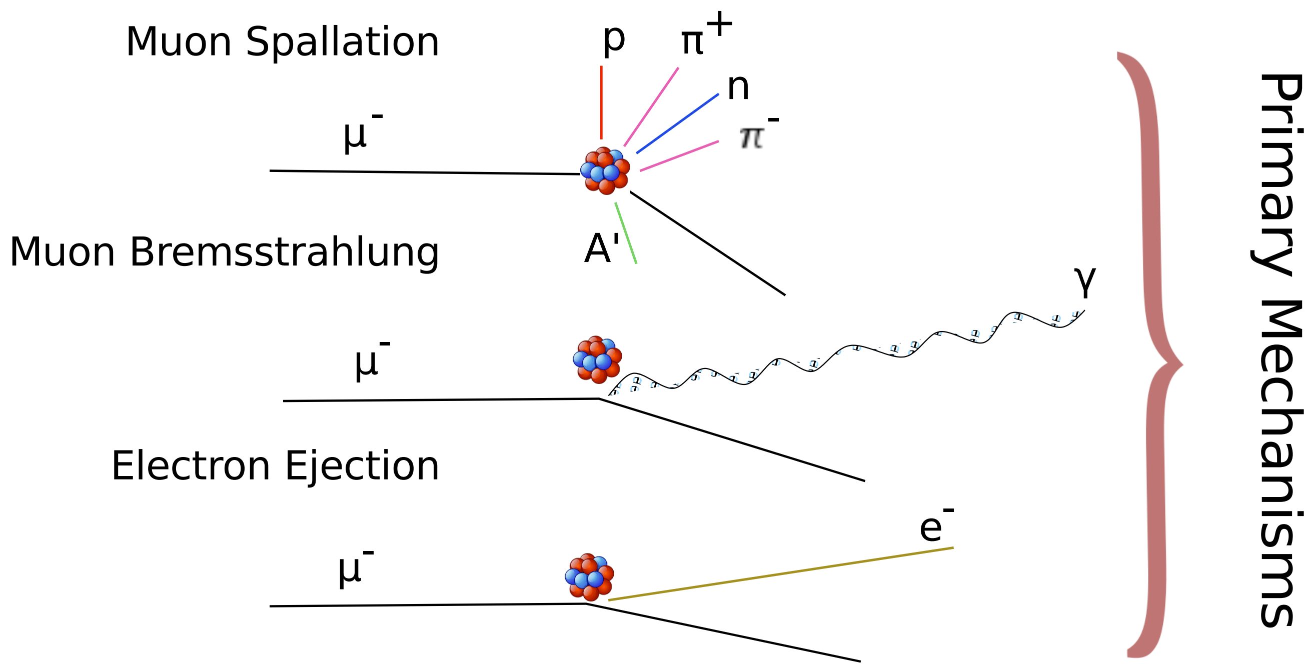
[1]University of Minnesota
[2]University of Arkansas, Little Rock

Cosmogenic Neutrons



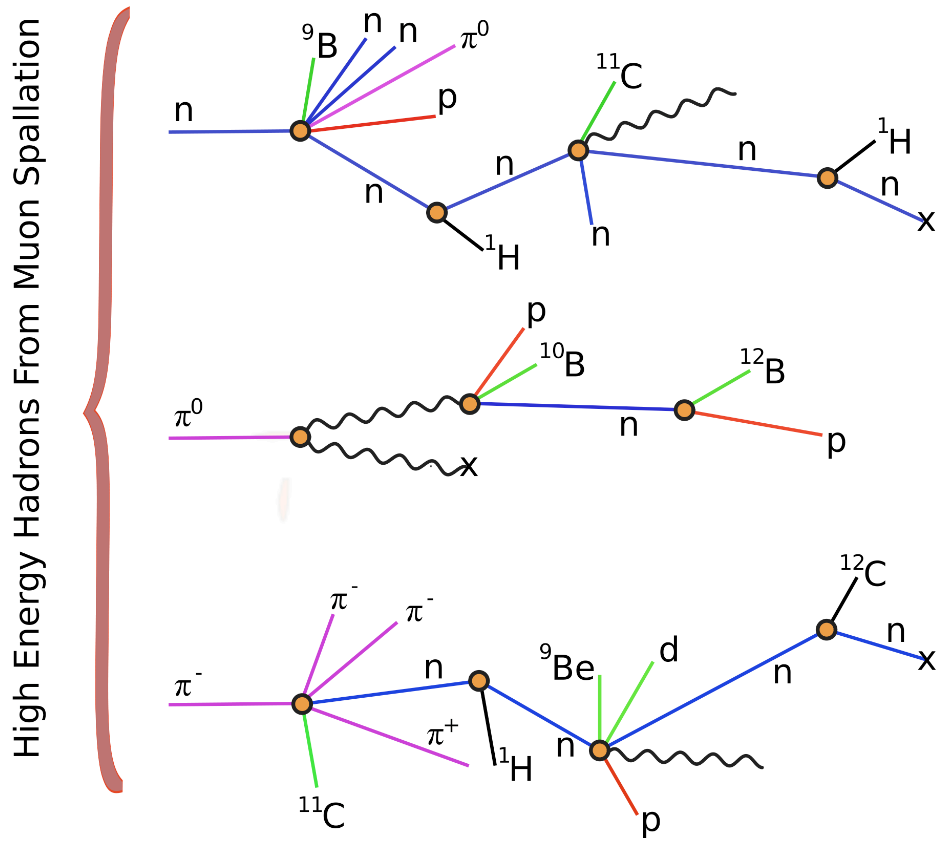
- cosmogenic events can produce important backgrounds for DM detectors like CDMS (right) and other rare searches
- there are efforts to make measurements of cosmic-ray-correlated neutrons underground (left: poster contribution by A.N. Villano and R. Bunker)
- It is necessary to understand in detail all possible events and how they are simulated in practice with modern particle transport codes (here: Geant4 and FLUKA)

Muon Primaries



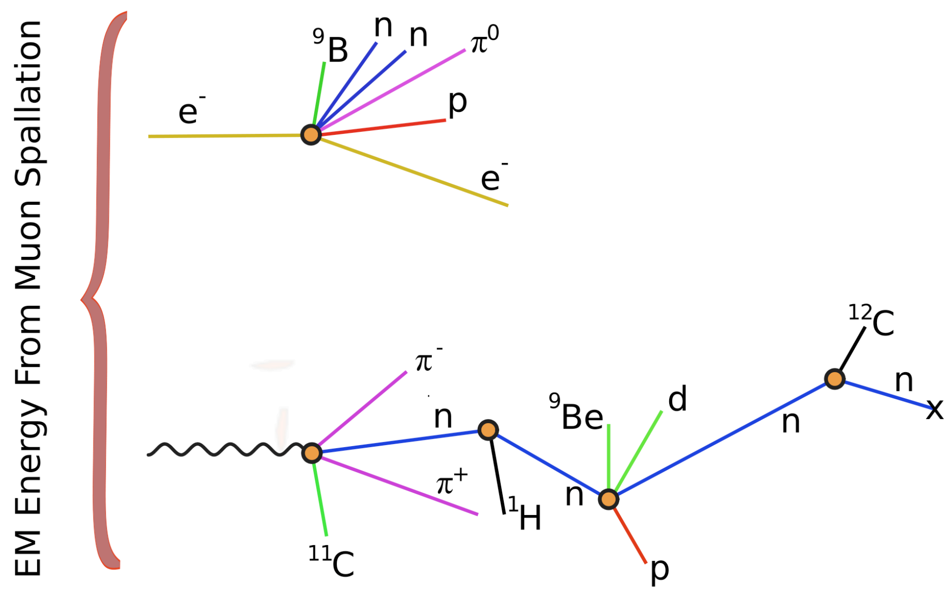
- primary muon spallation can leave residual activation which is a worry for exp.
- bremsstrahlung happens with photon spectrum which is biased "softer"
- electron ejection will most likely result in rapid electron energy loss and is not as important

Hadronic Cascade



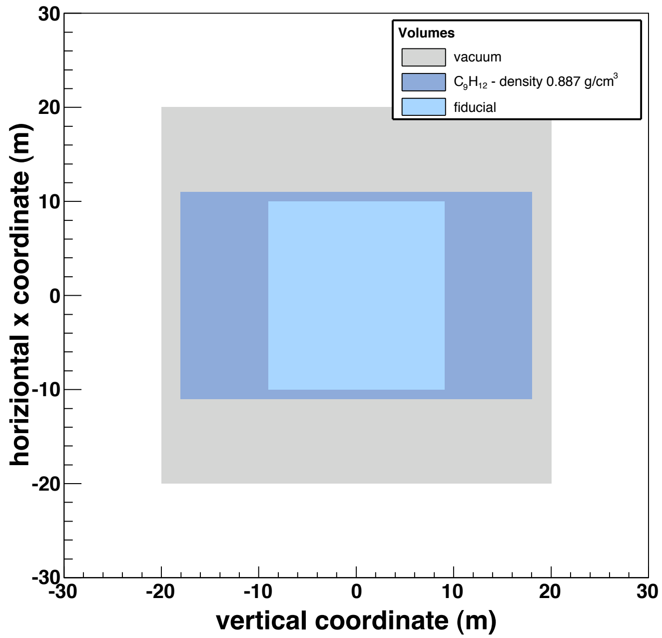
- neutrons are most stable uncharged which are not impeded especially by highly electron-dense materials
- produced copiously from hadronic interactions with nuclei at HE
- should be counted correctly in two important cases:
  - direct simulation comparisons
  - simulation/experiment comparisons

Electromagnetic Cascade

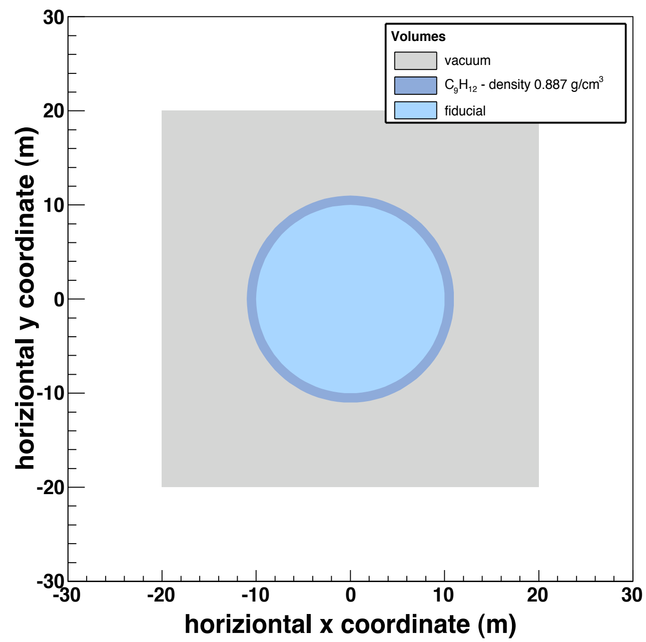


- electrons and photons can also create interesting showers
- electrons produce a small contribution to showers
- photons can contribute to nuclear breakup but mechanism different from muon nuclear → needs independent checking
- photons can also, therefore, produce activation products – 30% of cosmogenic neutrons in scintillator comes from $^{12}C(g,n)$

Simple Geometry Simulations



- muons/anti-muons enter geometry from side
- materials include water, scintillator, calcium carbonate, iron, lead
- energies 10, 30, 100, 280, 1000 GeV

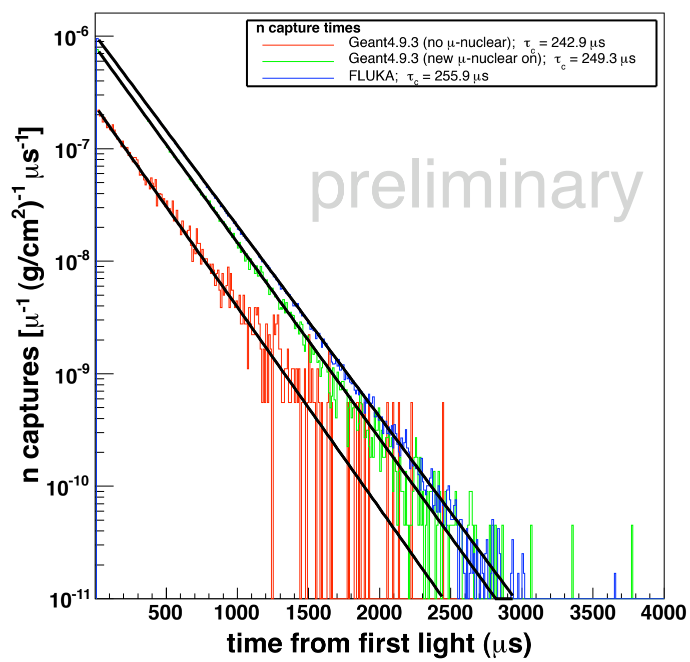


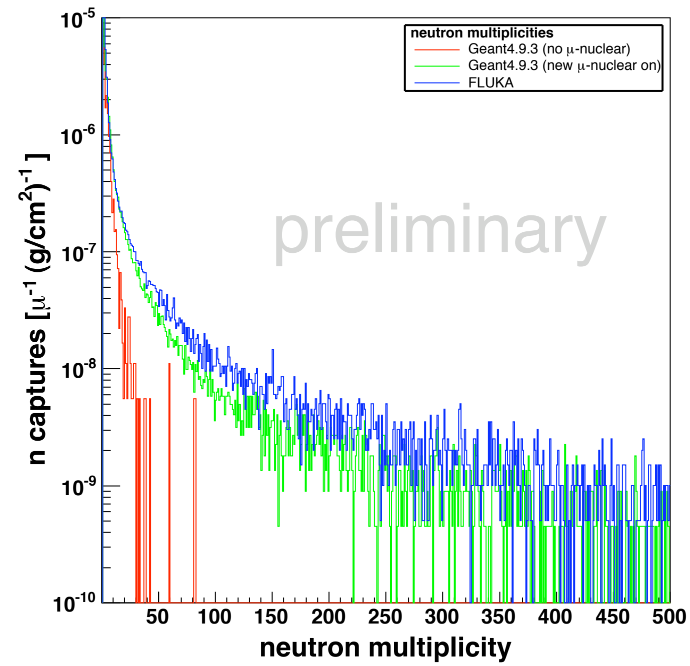
- geometry is cylindrical surrounded by vacuum and fiducialized
- length is dependent on material density in terms of thickness (g/cm^2)

Software Versions and Models

- FLUKA: 2011.2 patch level 17 (Dec 2012)
  - A. Empl working with Borexino/Darkside on several isotope issues
- Geant4.9.5 (updated μ-nuclear process)
  - "Shielding" high precision physics list
  - This simulation can be used to benchmark other physics lists or custom lists
  - Staying ~ 1 version behind to have bugs realized before incorporation

Modeling Showers





- early on, clear that muon nuclear interaction played major role
- produces at least 4x the neutrons that gamma and electron cascades produce alone
- indeed it had undergone some recent corrections in Geant4.9.3 → Geant4.9.5 and this corrected cross section (ported to Geant4.9.3) used above

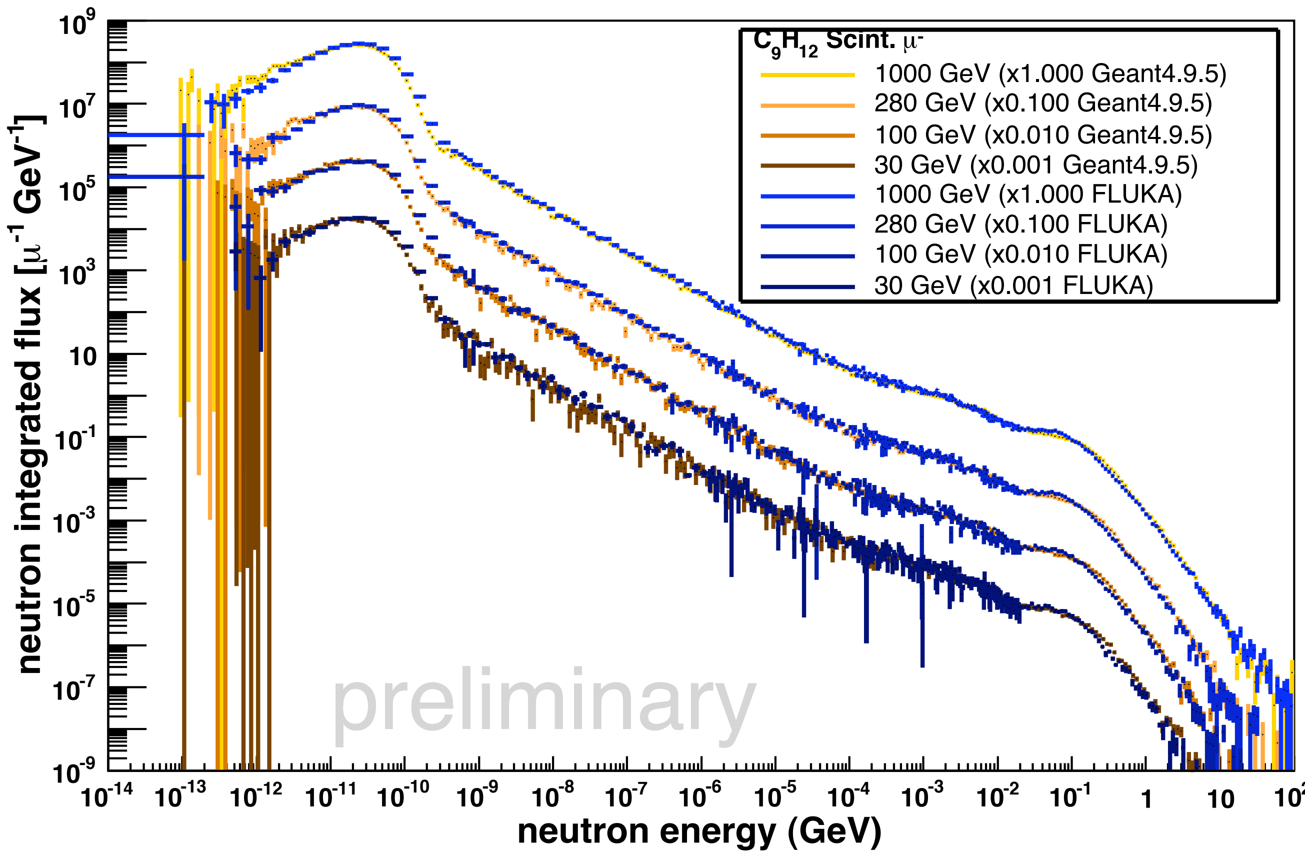
Materials and Statistics

Material	Density (g/cm^3)	Geant4 Counts (1 Tev, 280,100,30 GeV)	FLUKA Counts
Scintillator	0.887	1M, 797K, 1M, 1M	~3M
Water	0.997	1M, 600K, 1M, 1M	~3M
Calcium Carbonate	2.710	998K, 1.1M, 1M, 1M	~3M
Iron	7.874	98K, 918K, 956K, 1.3M	~3M
Lead	11.342	404K, 195K, 796K, 996K	~500K

The Simulation Data

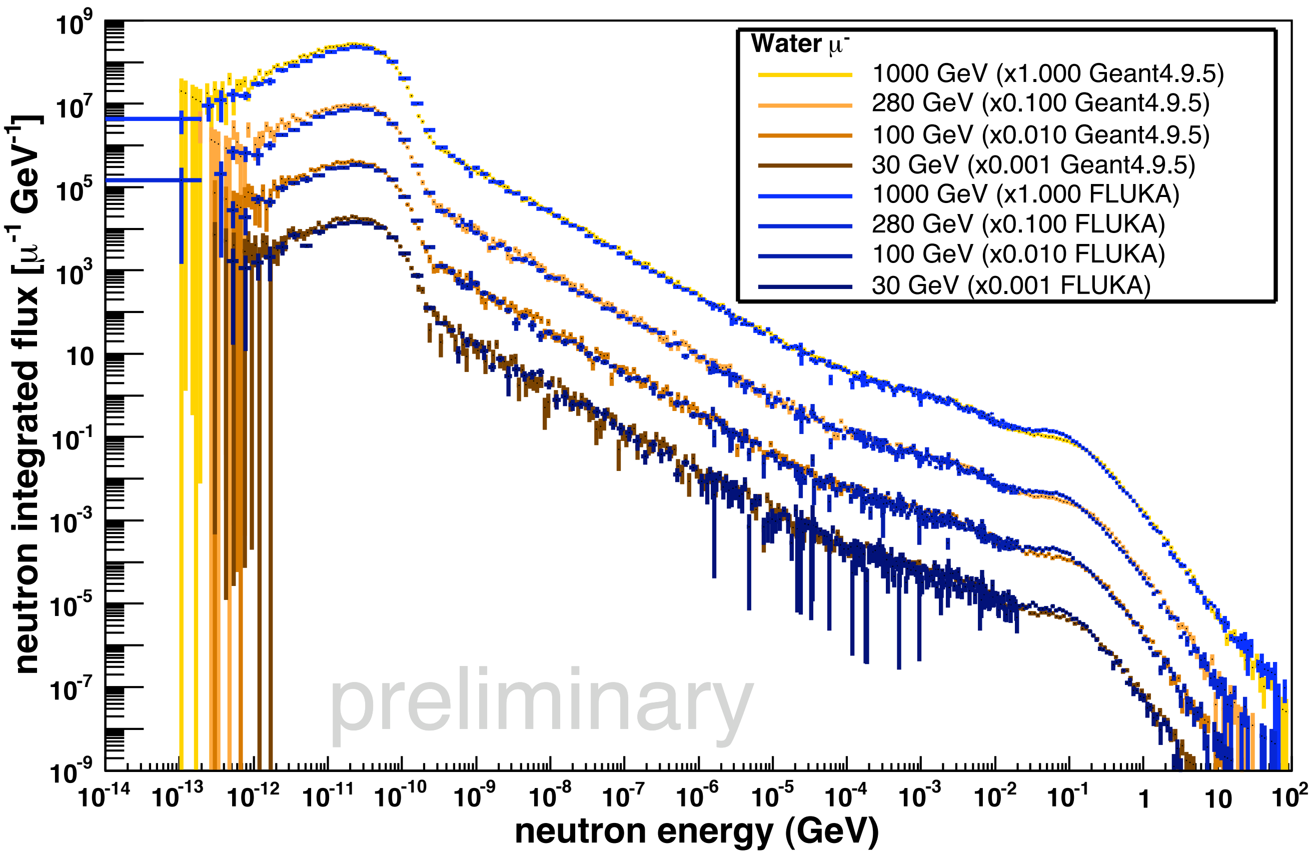
- The statistics mentioned previously are sufficient for many neutron event studies – more will be gathered for studies of smaller effects
- Neutron capture and flux properties being analyzed for these proceedings
- Comparison to data very important which will be addressed in increasing detail, starting with these proceedings
- Really, want a way to look at showers which is sensitive to the (sometimes subtle) differences between similar transport codes
- Non-underground particle physics/nuclear physics data will be reviewed in terms of impact on the models for these simulations

Scintillator (C_9H_{12})



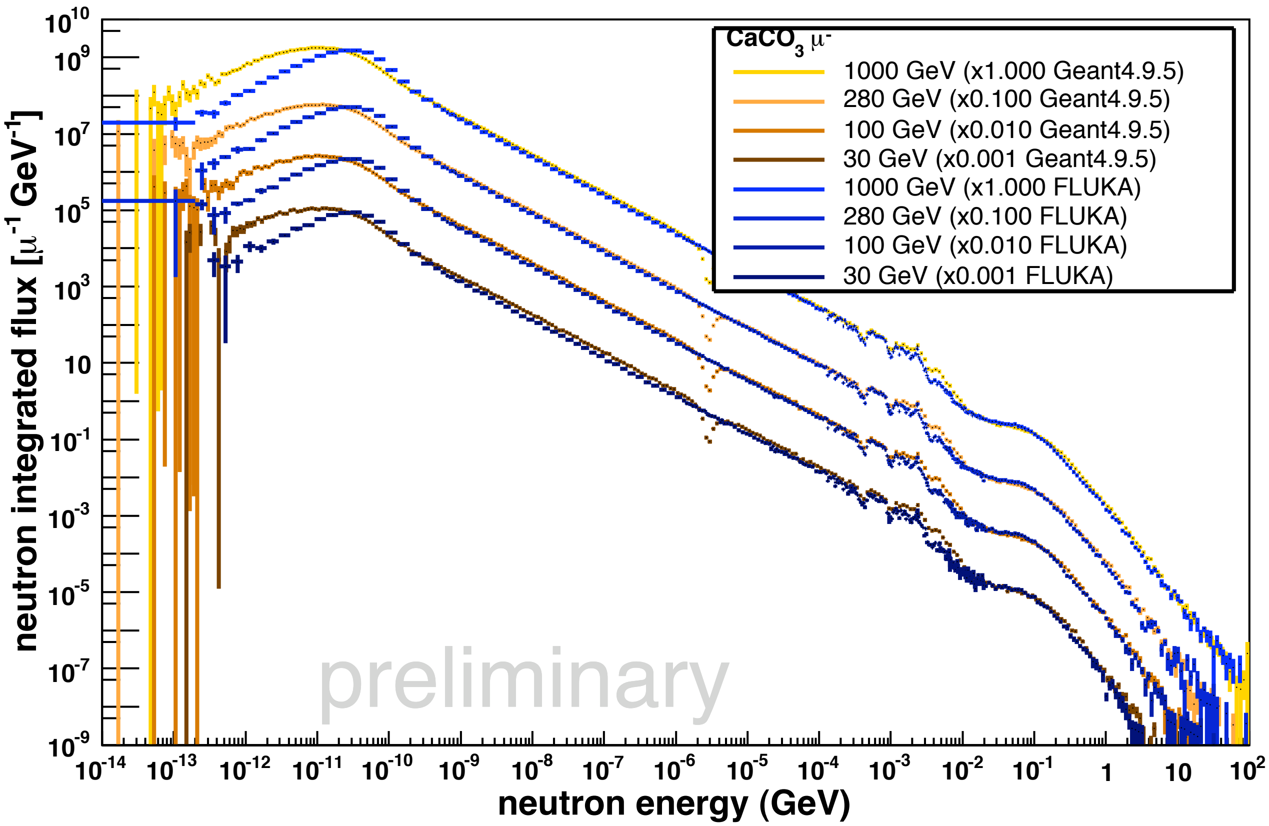
- even with Geant4.9.3 have had excellent gross agreement with scintillator, this continues
- some areas like near the 100 MeV rolloff have discrepancies to be examined

Water (H_2O)



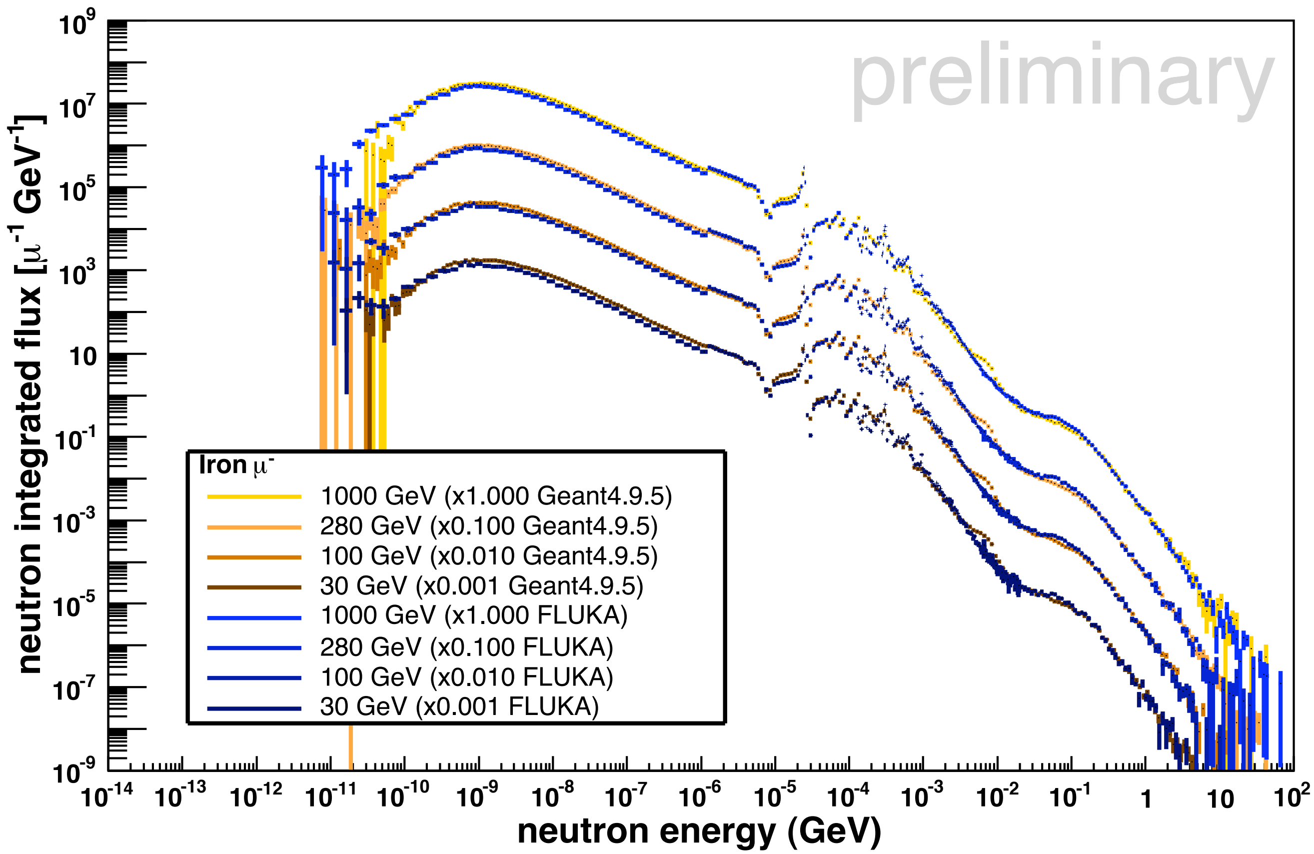
- good overall agreement with water
- some areas like near the 100 MeV rolloff have discrepancies to be examined

Calcium Carbonate ($CaCO_3$)



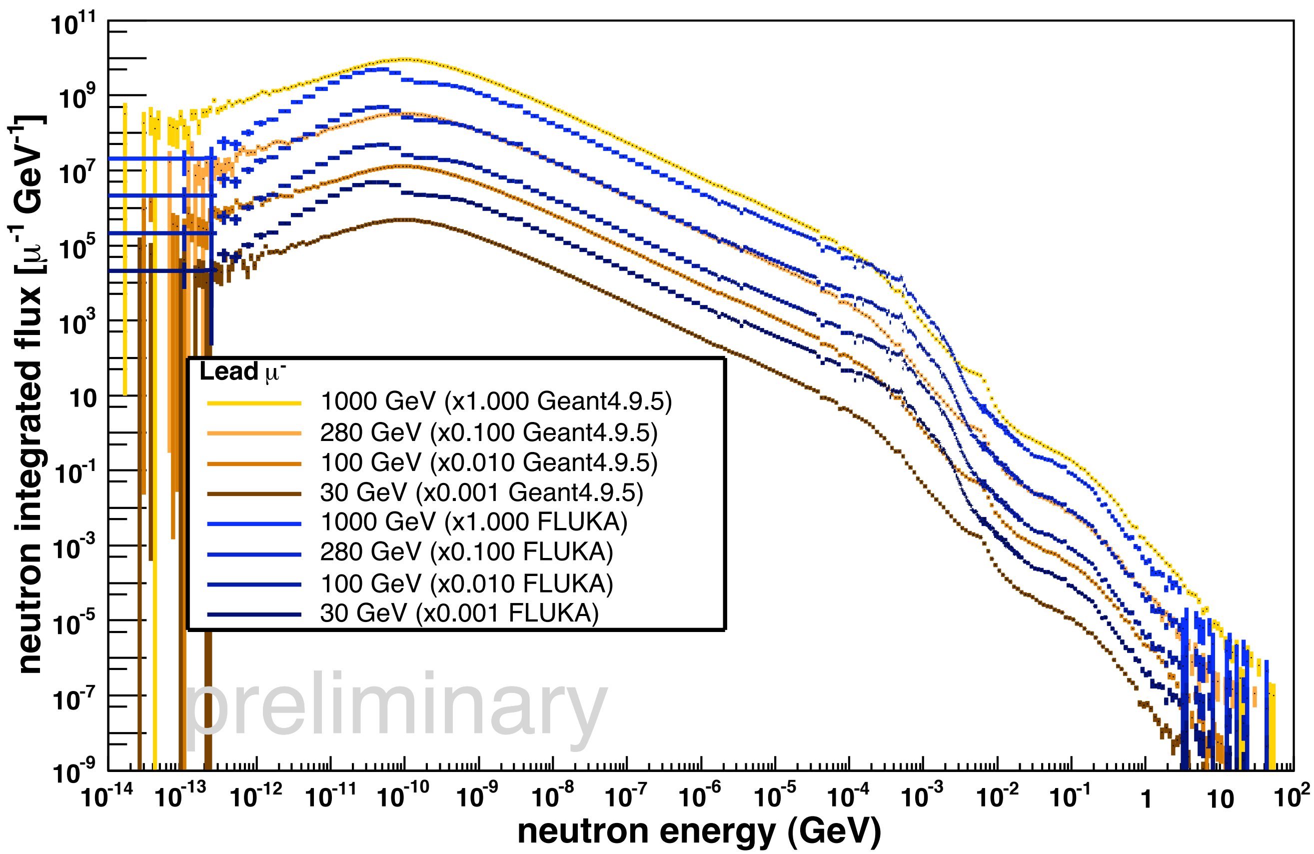
- some structures matched and some present in Geant4 and not FLUKA, this is being examined
- ultra low energy features discrepant but need to look at with better probe

Iron



- structures reproduced, throughout
- statistics a bit lacking at ultra low energies: overall fewer neutrons produced from iron

Lead



- not x100 factors at 280 GeV as was found in previous Geant4.9.3 study but clearly normalizations are to be checked carefully
- structures at high energies not quite the same in both codes: significant checking for lead

Automation/Vetting

- Can simulate both Geant4 and FLUKA in ~ 2 weeks with ~ millions of primaries for each case
- A wealth of information is available, including fine details of showers
- The first suggestion by Vitaly Kudryavtsev for observables is currently utilized and has been extended to form an optimized set
- This can occur for any version of Geant4/FLUKA with minimal changes to the code