# Cosmogenic Simulations with Geant4 and FLUKA

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# what do we want?

## for low background underground experiments

**How many neutrons will not be able to be vetoed in an experiment?**

- depends on neutron flux in cavern
- also depends on electromagnetic signatures and their time-space correlation

# what are the problems?

**for low background underground experiments**

- measurements are difficult for a variety of reasons
  - data slow to come in
  - suitable locations hard to find
  - correlations in time and space almost impossible to measure
- often small effects in tails of distributions can be important

- still there are a number of experiments with useful data (NMM,LVD,Borexino,KAMLAND...)
- need more physics (particle transport equations or track-by-track simulation)
- correlations difficult with particle transport so usual approach is simulation

# standard software

- for cosmogenics this means studying $\mu^{+/-}$ cascades virtually, then using data to verify
- Geant4 and FLUKA are widely used for this purpose in underground science

## Geant4

- http://geant4.cern.ch
- latest version: v4.9.4.p01
- does not yet include latest update to $\mu$-nuclear interaction

## FLUKA

- http://www.fluka.org
- latest version: v2011.2.6

# standard software (2)

## Geant4 (our version: v4.9.3+)

- open source
- particle tracking and microscopic interactions included
- modular and customizable by users

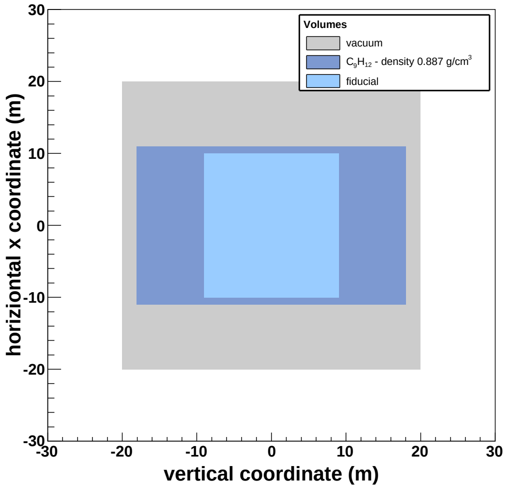
## FLUKA (our version: v2011.2.5)

- closed source
- neutron tracking with energy groups
- switches for features like light ion tracking

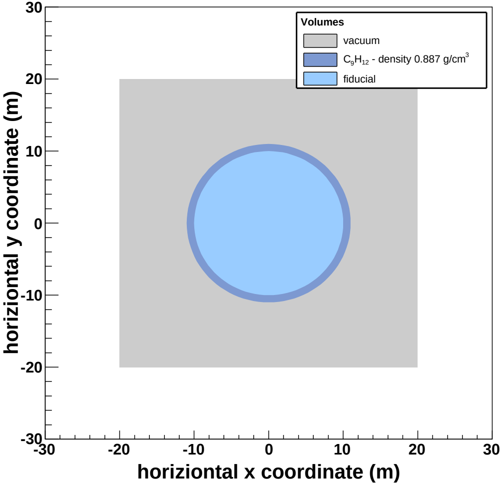
# simulating cosmogenics

- from discussion at the previous AARM workshop a series of simulations were suggested with simple geometry but varied materials and $\mu$ energies
- with $\mu^{+/-}$ incident on a cylinder radius 11m and thickness 3200 g/cm$^2$ with axis along $\hat{z}$
- neutron counting confined to inner 10m radius and 1600 g/cm$^2$ to select an equilibrated volume

# simulating cosmogenics (2)



# simulating cosmogenics (3)



# materials

| Material Name | Chemical Composition | Density (g/cm$^3$) |
|---|---|---|
| Liquid Scintillator | $C_9H_{12}$ | 0.887 |
| Water | $H_2O$ | 1.0 |
| Salt | NaCl | 2.17 |
| Carbon | C | 2.267 |
| Calcium Carbonate (calcite) | $CaCO_3$ | 2.71 |
| Iron | Fe | 7.874 |
| Lead | Pb | 11.342 |

Table: Table of materials and densities

# statistics

| Material Name | Energy (GeV) | Geant4 Primaries ($\mu^-/\mu^+$) | FLUKA Primaries ($\mu^-/\mu^+$) |
|---|---|---|---|
| Liquid Scintillator | 10 | 600k/600k | 1.2M/- |
| Liquid Scintillator | 30 | 100k/100k | 1.2M/- |
| Liquid Scintillator | 100 | 200k/200k | 1.2M/- |
| Liquid Scintillator | 280 | 1.2M/1.3M | 1.2M/- |
| Liquid Scintillator | 1000 | 10k/- | 1.2M/- |
| Lead | 10 | 550k/550k | 800k/- |
| Lead | 30 | 550k/550k | 1.1M/- |
| Lead | 100 | 530k/510k | 1.2M/- |
| Lead | 280 | 530k/510k | 500k/- |
| Lead | 1000 | 441k/222k | -/- |

Table: Table of simulation statistics

# our goals

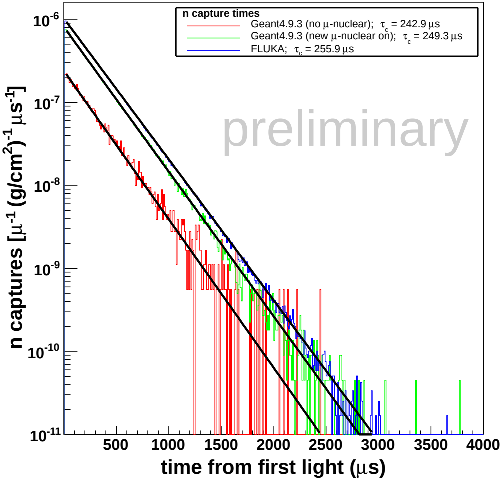
## AARM Feb. 2011 charge

- count neutrons in materials without double counting
- obtain information about reaction mechanisms, $\mu$ spallation, $\pi$ spallation ...
- simulations at rock/cavern boundaries with empty cavern

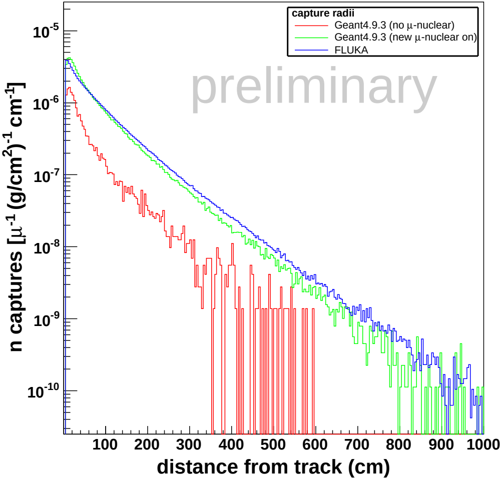
## further goals

- find the specific reasons for differences in Geant4 and FLUKA
- understand the microscopic processes and how they are handled in both codes for large cascades
- through these excersizes find the most efficient way to make use of various data that has been taken at underground sites

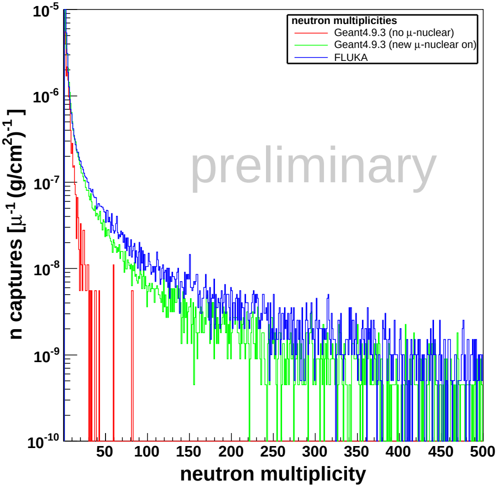
# scintillator with 280 GeV $\mu^-$



# scintillator with 280 GeV $\mu^-$ (2)



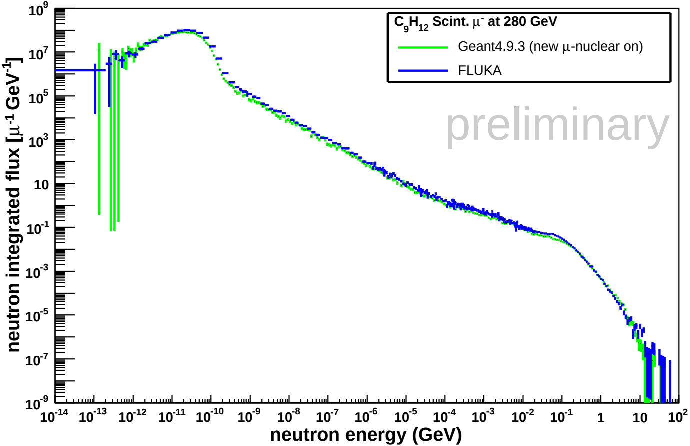
# scintillator with 280 GeV $\mu^-$ (3)



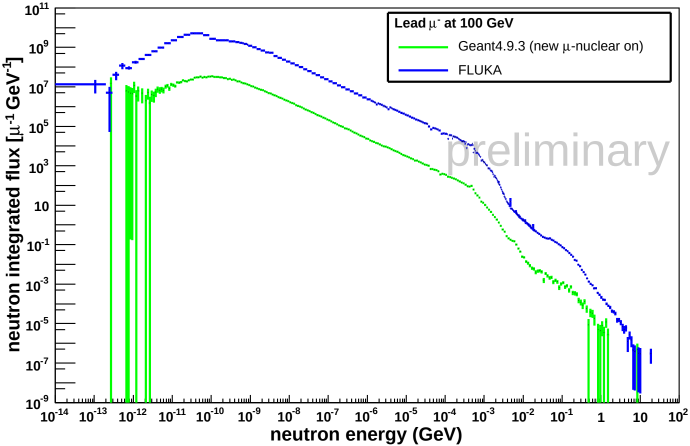
# scintillation results

- it is clear that the $\mu$-nuclear interaction is very important to produce accurate neutron spectra, especially for capture multiplicity
- the CDMS collaboration found that the $\mu$-nuclear interaction included in Geant v4.9.3 *was not* producing enough neutrons but the new version of the interaction comes closer
- with the Geant v4.9.3+ we still have under-prediction of neutrons from capture
- there might be a slight mismatch in neutron capture time between Geant v4.9.3 and FLUKA
- simulation data will be used to isolate simulation differences

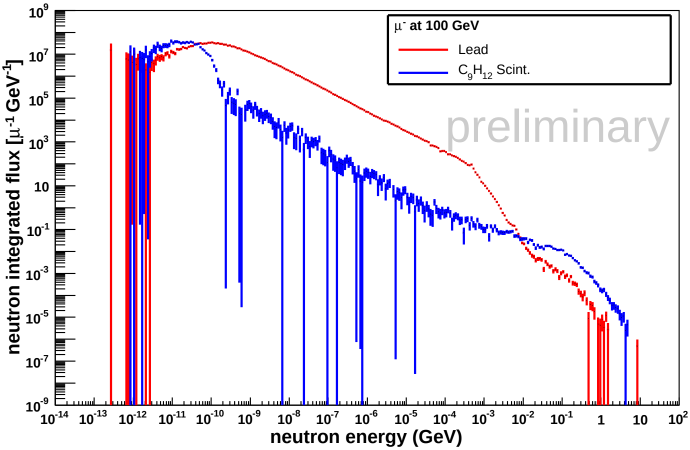
# energy flux comparison



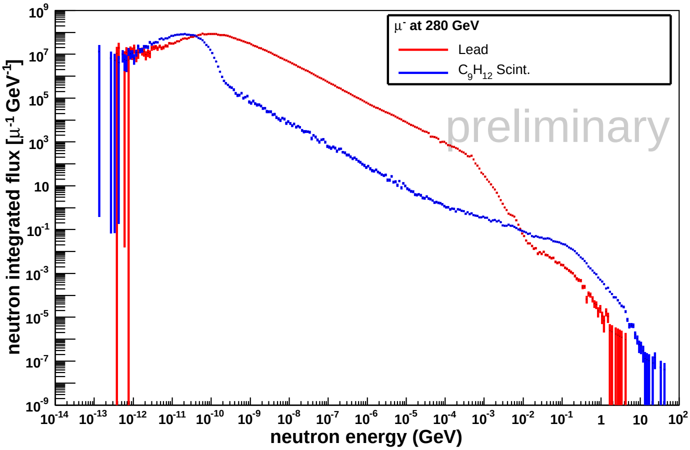
# energy flux comparison (2)



# energy flux comparison (3)



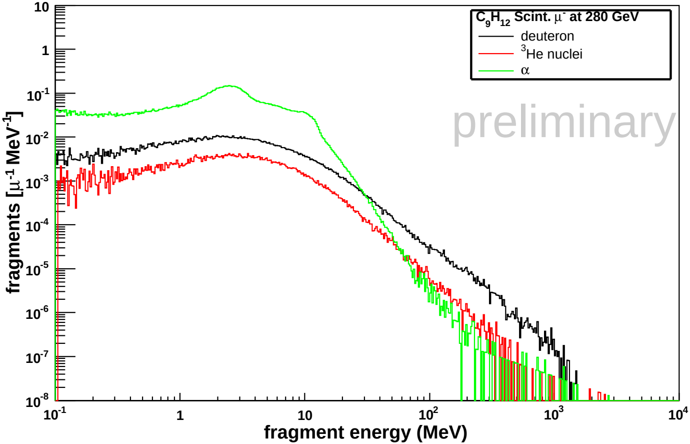
# energy flux comparison (4)



# energy flux results

- for 280 GeV scintillator the energy flux agrees quite well with some minor Geant v4.9.3+ under-prediction in the 1 GeV neutron energy range
- for 100 GeV lead the energy flux disagrees by a large factor
- it is clear that at the high energy for Geant v4.9.3+ the scintillator and lead spectra do not overlap and scintillator actually out-produces lead
- these results are **preliminary** and will be scrutinized in detail before any judgment about either FLUKA or Geant is made

# fragment analysis with 280 GeV $\mu^-$



# fragment analysis results

- light fragments are not produced by default in FLUKA and it is not clear that the deuteron is treated correctly if it is produced
- since deuterons are very loosely bound when production of neutrons is concerned high energy deuterons are also of concern
- preliminary investigations show that according to Geant deuterons can be more abundant than the He isotopes at high energies even when the primary nucleus is an $\alpha$-cluster nucleus (Carbon).

# summary

- Geant (v4.9.3+) and FLUKA (v2011.2.5) are used to produce cosmogenic simulations in a cylindrical geometry
- materials and energies are varied in these simulations **lots of statistics coming in with SLAC batch farm!**
- it is clear that Geant v4.9.3 was under-producing compared to FLUKA and the new $\mu$-nuclear interaction addresses that to a large extent
- this new interaction is in the "special" Geant v4.9.3+ but not yet in general release (v4.9.5)
- going forward to produce large statistics with above versions and all materials
- more detailed flux/production mechanism analysis expected end of this year