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*Title:* A Range Muon Tomography Performance Study

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*Intended for:* 2010 Nuclear Science Symposium and Medical Imaging Conference, 30 October - 6 November, 2010, Knoxville, Tennessee

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Form 836 (7/06)

# A Range Muon Tomography Performance Study

Leticia Cu´ellar, Konstantin Borozdin, Kiwhan Chung, Andrew Green, Nicolas Hengartner, Christopher Morris, Larry Schultz, Nathan Reimus, Jonathan Roybal, Jeff Bacon, Wendy Vogan-McNeil

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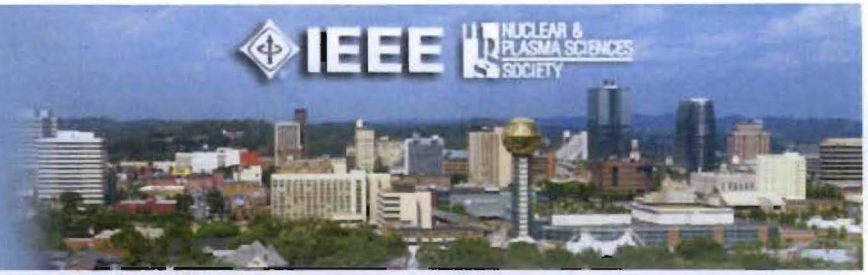
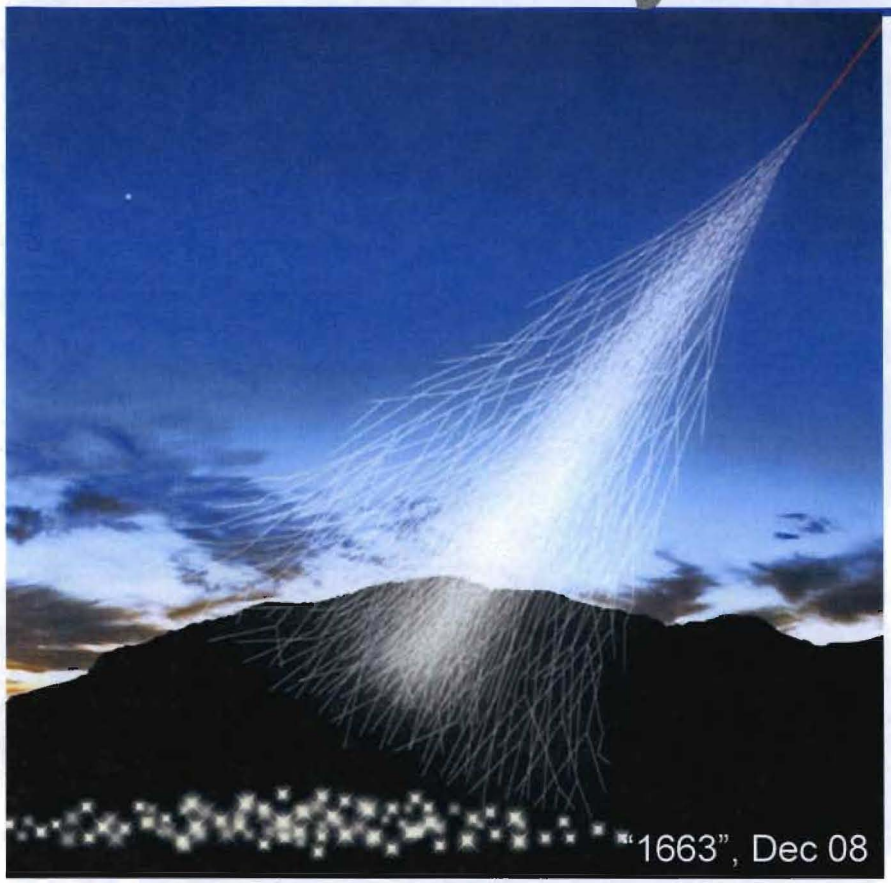
2010 Nuclear Science Symposium,
Medical Imaging Conference and
17th Room Temperature Semiconductor Detector Workshop

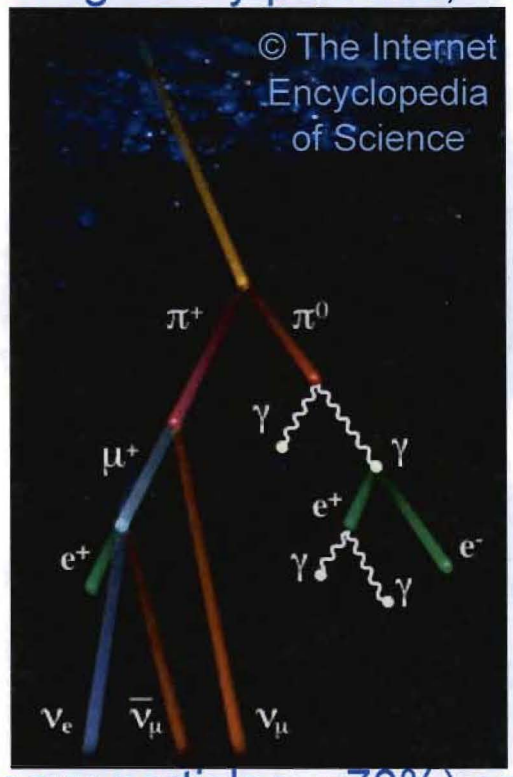
October 30, 2010 – November 6, 2010 – Knoxville, Tennessee



# Cosmic Rays in the Atmosphere




Mostly protons and α (charged, strongly interacting heavy particles, ~99%)

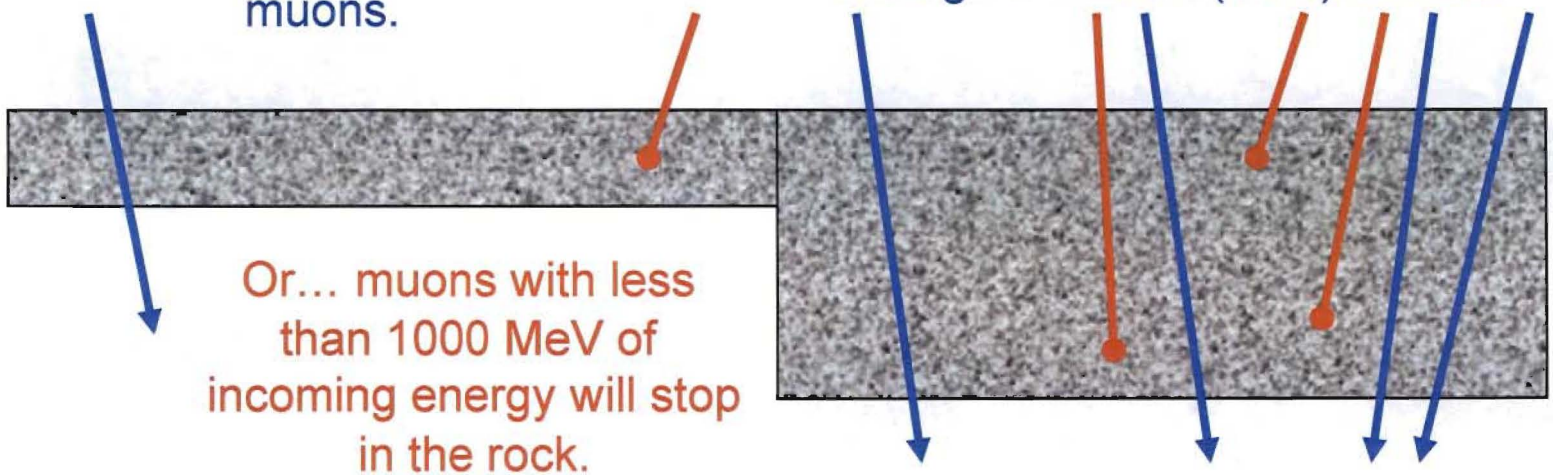



Mostly muons (charged, EM-interacting heavy particles, ~70%) and electrons (charged, EM-interacting, light particles, ~30%). Neutrinos are weakly interacting and can be ignored.

# Muons Penetrate Significant Depths

2 meters (6.5 ft) of rock removes about 1000 MeV* of energy from muons.

The average energy of a cosmic ray muon is 3000 MeV and will pass through 6 meters (20 ft) of rock.



Or… muons with less than 1000 MeV of incoming energy will stop in the rock.

Or… half of the cosmic ray muon flux will stop in 6 meters of rock.

* *MeV → Million electron Volts*

# Attenuation Radiography with Muons

## *Searching for Hidden Chambers in Pyramids*

Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

Luis Alvarez, et. al.
*Science* **167**, 832 (1970)

Arturo Menchaca, et. al.
current effort, see

***http://www.msnbc.msn.com/id/4540266/***

## *Predicting Volcanic Eruptions*

Tanaka, Nagamine, et. al.
*Nuclear Instruments and Methods A*
**507**:3, 657 (2003)

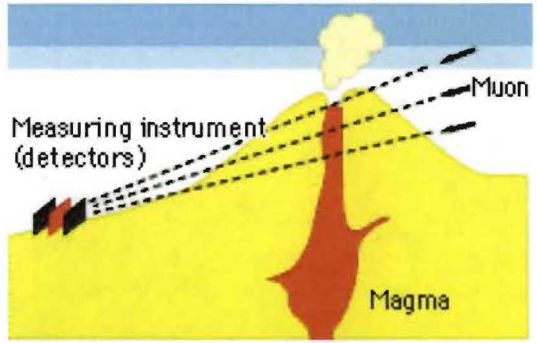
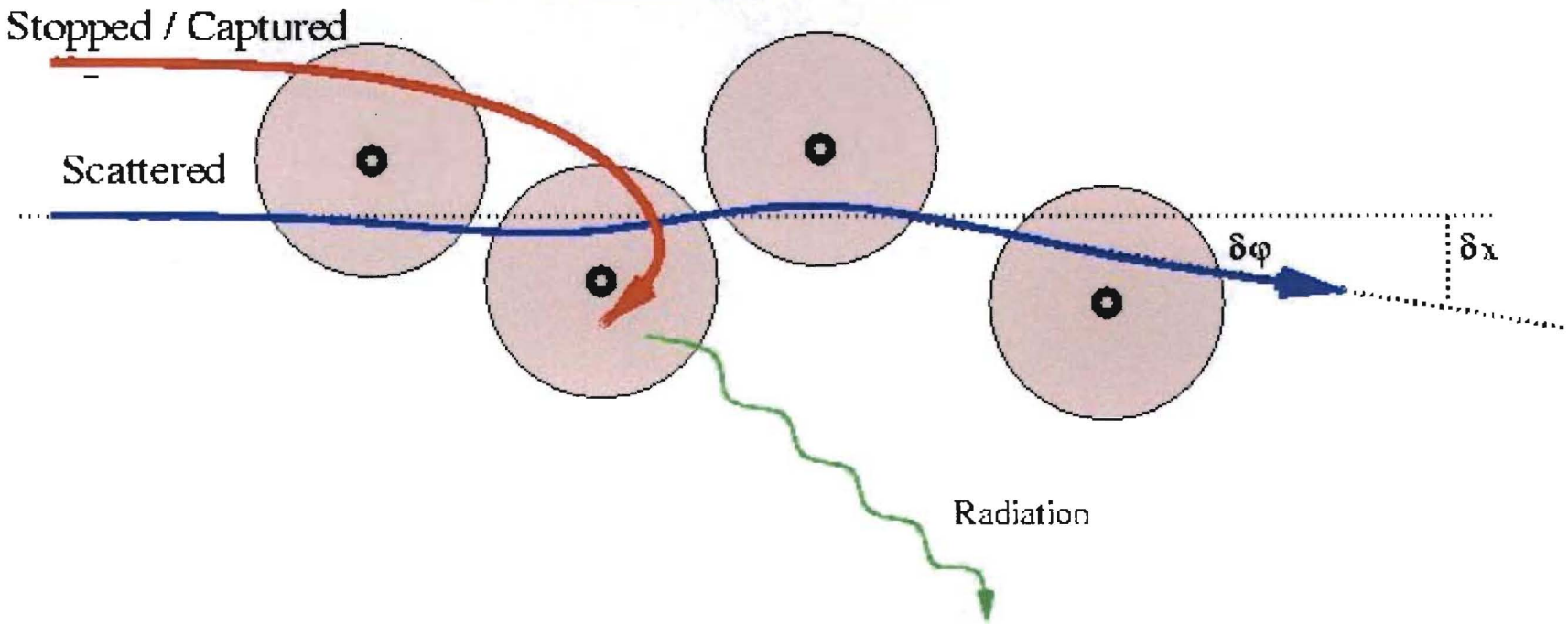


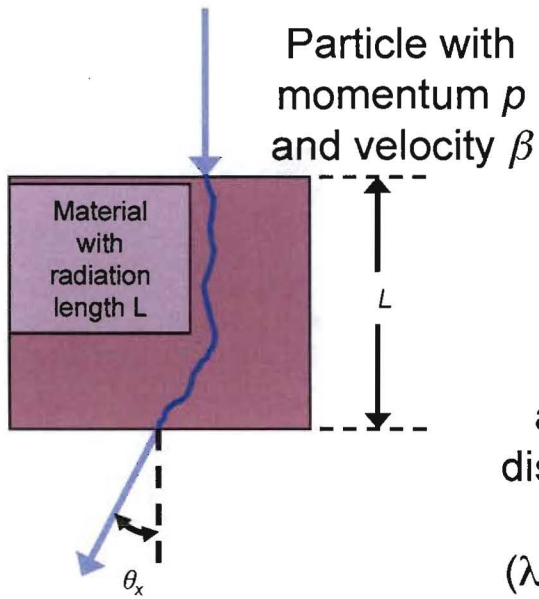

Figure 4: Analyzing the internal structure of a volcanic zone using muons

# Charged Particle Interaction in Matter




Both muons and electrons are scattered and stopped in matter. Higher energy (hard, mostly muons) component of cosmic-rays goes through, while lower energy (soft, mostly electrons) component stops in objects.
Detecting both we can measure scattering density and stopping power of different objects.

# Physics of interaction: multiple scattering




Particle with momentum $p$ and velocity $\beta$

Scattering distribution is approximately Gaussian

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

and the width of the distribution is related to the material ($\lambda$ is a radiation length)

$$\theta_0 = \frac{13.6}{p\beta}\sqrt{\frac{L}{\lambda}}$$

Scattered particles carry information from which material may be identified.

| Material | $\lambda$, cm | $\theta_0$, mrad* |
|---|---|---|
| Water | 36 | 2.3 |
| Iron | 1.76 | 11.1 |
| Lead | .56 | 20.1 |

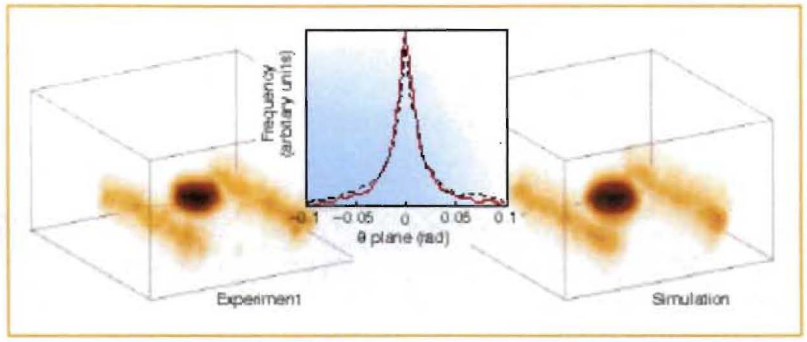
*10 cm of material, 3 Gev muons

# Cosmic-Ray Muon Tomography

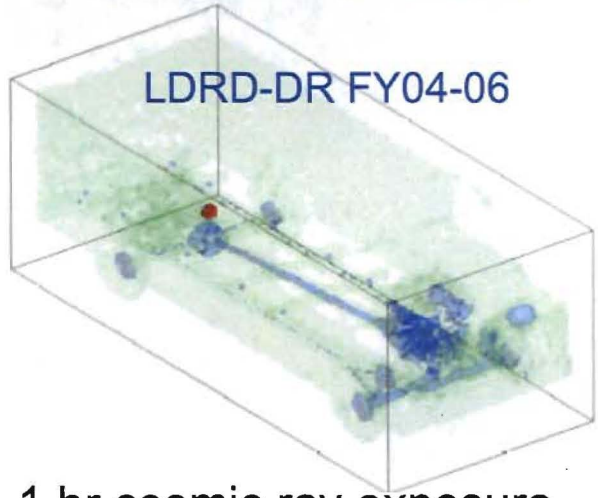
## Radiographic imaging with cosmic-ray muons

Natural background particles could be exploited to detect concealed nuclear materials.

Despite its enormous success, X-ray radiography[1] has its limitations: an inability to penetrate dense objects, the need for multiple projections to resolve three-dimensional structure, and health risks from radiation. Here we show that natural background muons, which are generated by cosmic rays and are highly penetrating, can be used for radiographic imaging of medium-to-large, dense objects, without these limitations and with a reasonably short exposure time. This inexpensive and harmless technique may offer a

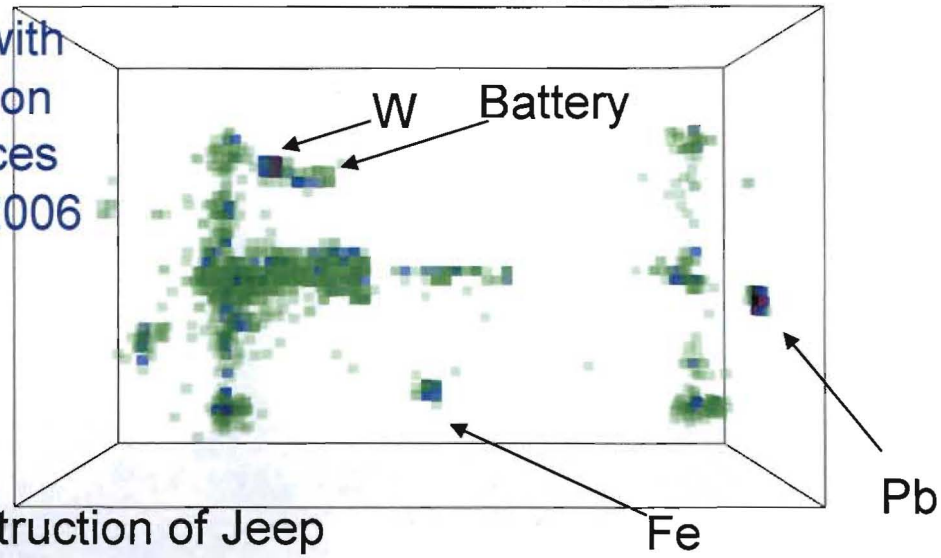



Borozdin et al. Nature, 422, 277, 2003



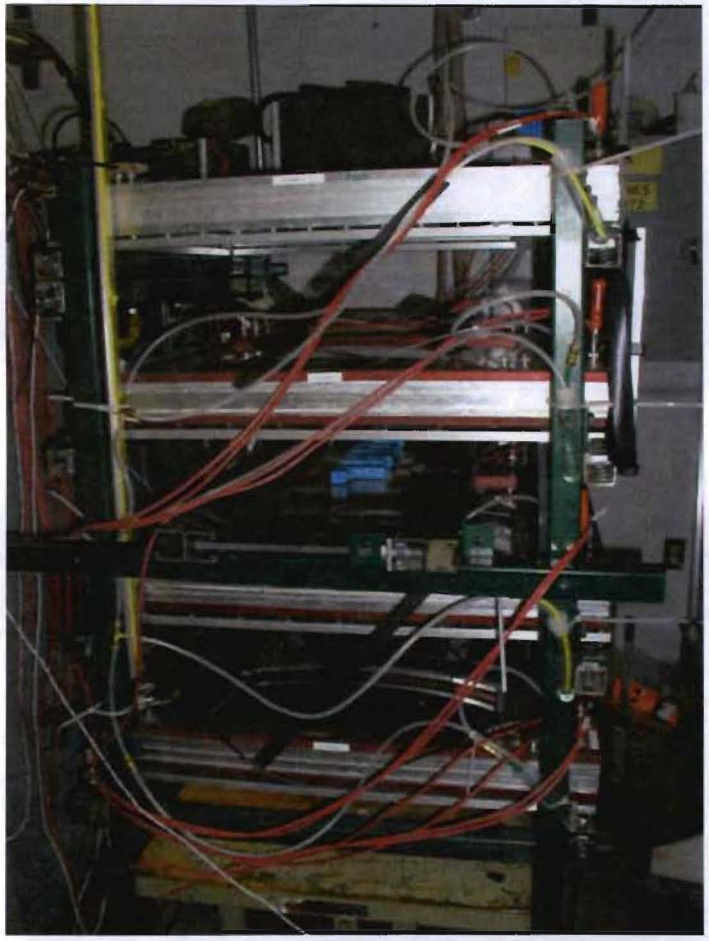

1 hr cosmic ray exposure simulation

Work with Decision Sciences Since 2006



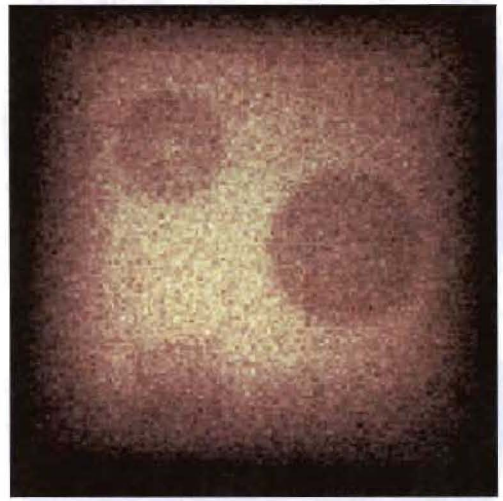

Reconstruction of Jeep with 3 objects

# Attenuation in Small Objects



Iron

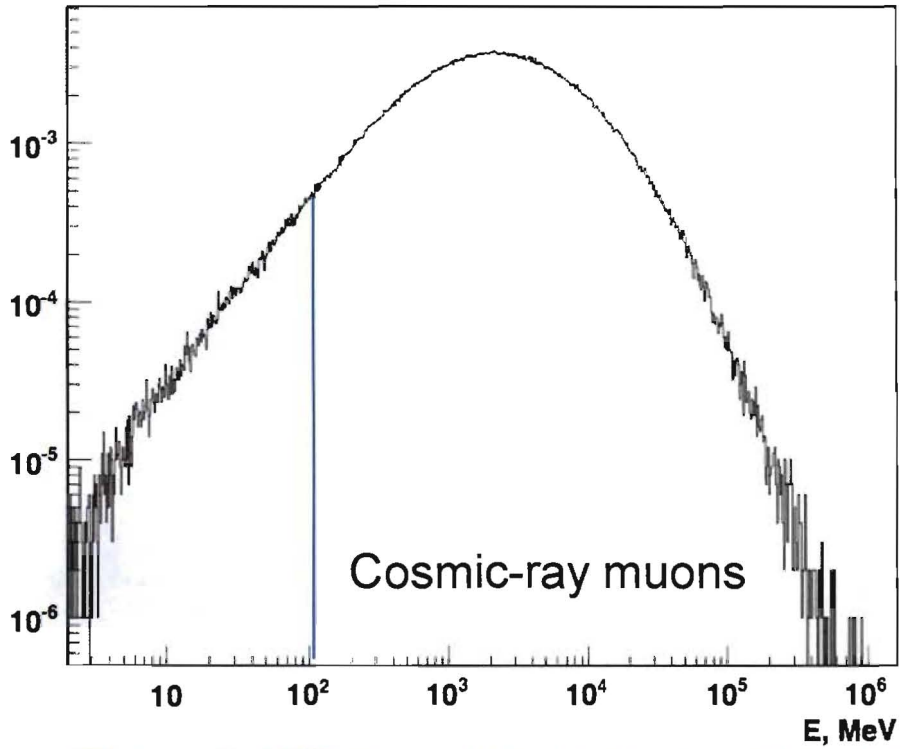
Aluminum

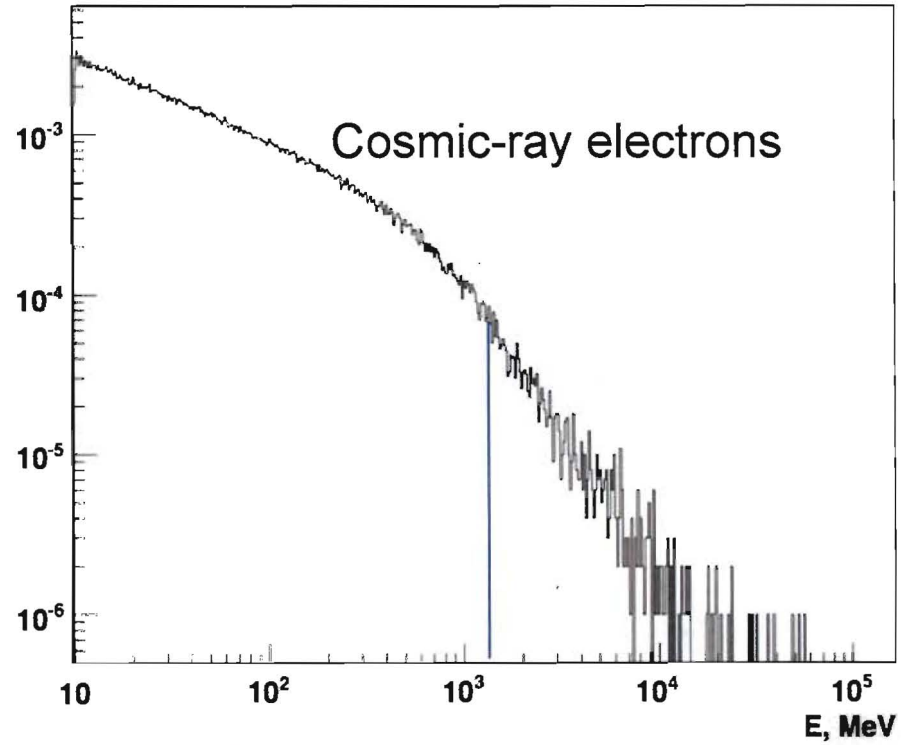


Tungsten

Image of muon "shadows" created by three objects.

# Energy Spectra




The main difference between muons and electrons is their mass

- muons are ~200 times heavier

Because of this difference, muons lose energy much slower for broad range of energies

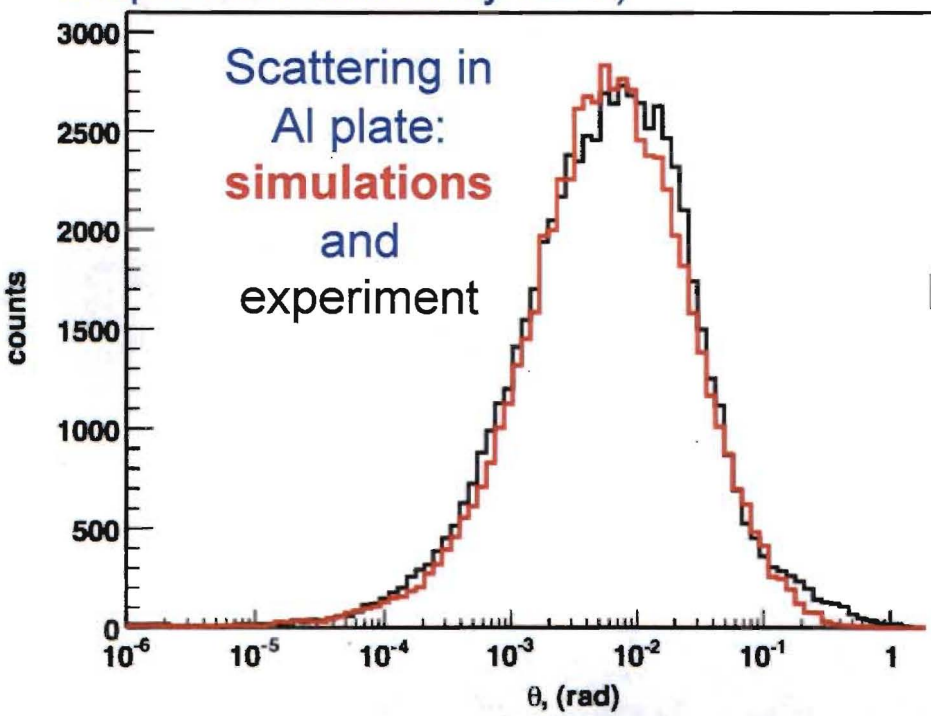
Distribution of energies means distribution of ranges

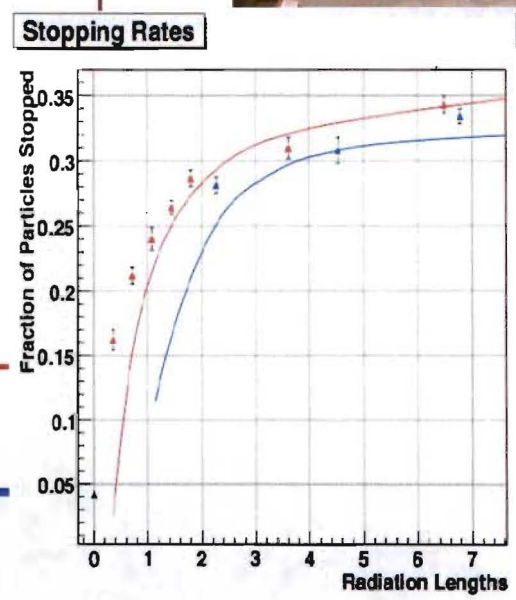
# μ/e mixture in modeling and experiment

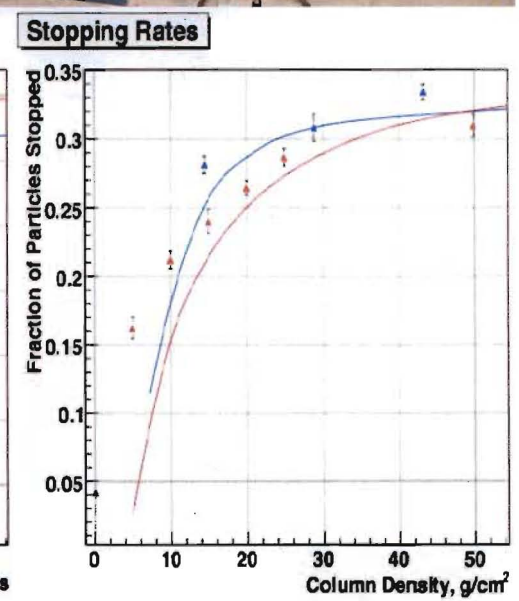
*Experiment:* 30.9 events/s

*Simulation:* 24.8 events/s from muons (1.7 mu/cm$^2$)
+ 6.2 events/s from electrons (1.7 e/cm$^2$)

Total: 31+/- 6 events/s (with assumed data acquisition efficiency 87%)



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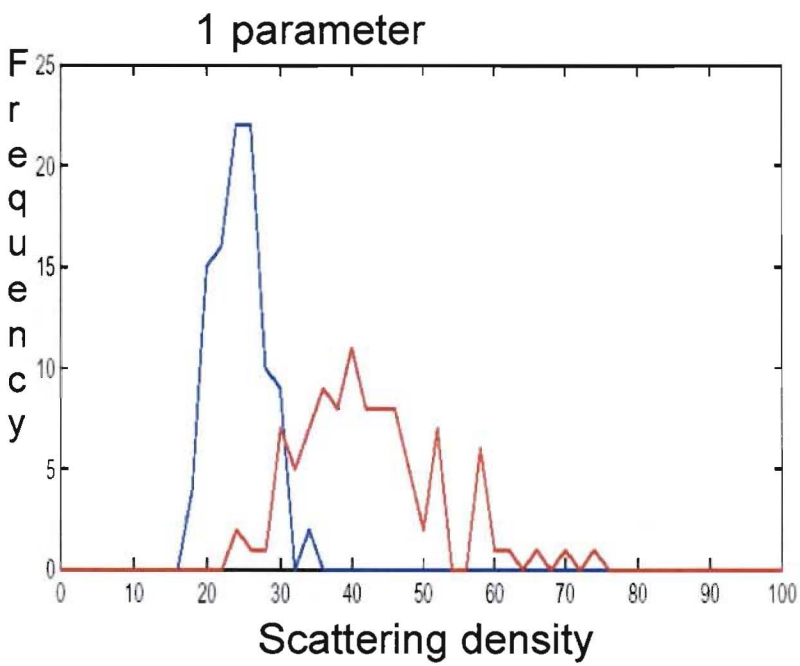
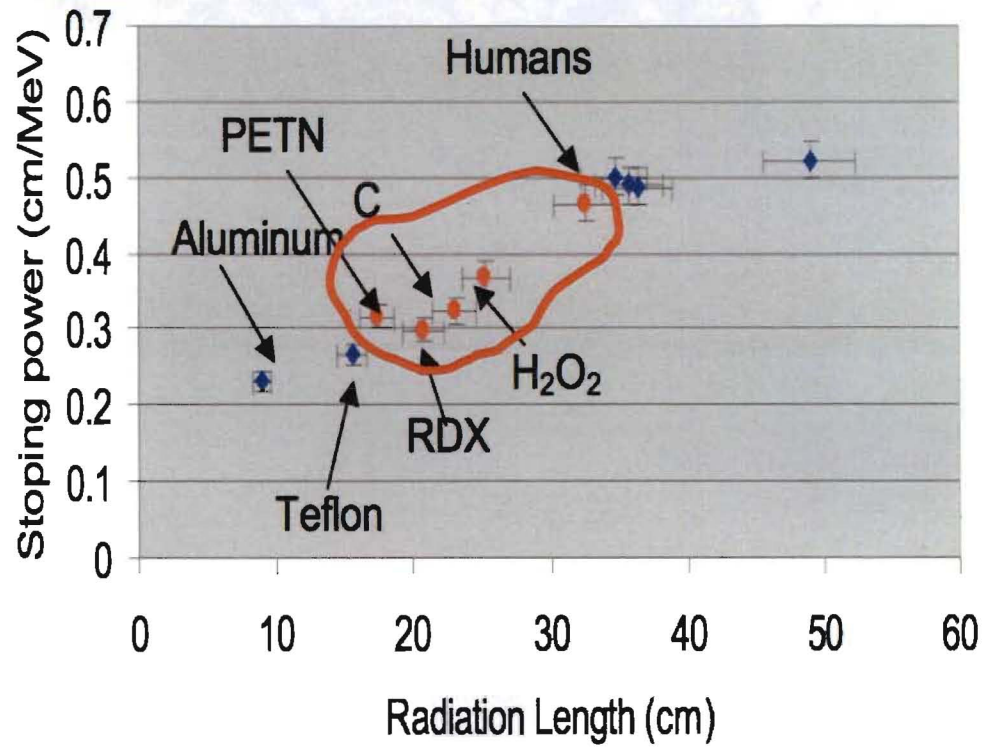
# 1-parameter vs. 2-parameter discrimination




There could be less false positives in 2-parameter space

Not so effective, if both parameters are strongly correlated (mass and density)

Doesn't work, if there is no correlation at all (mass and color)

# ML Stopping Reconstruction

Particle i with energy E traverses the volume if its energy exceeds the resistance $R_\gamma$ along the path $\gamma_i$ . Voxelize the area to be imaged. Approximate, for each ray $i = 1, \ldots, M$:

$$R_{\gamma_i} \approx L_i^t \rho = \sum_{k=1}^{N} L_{ik} \rho_k .$$

Maximize likelihood function w.r.t. ρ:

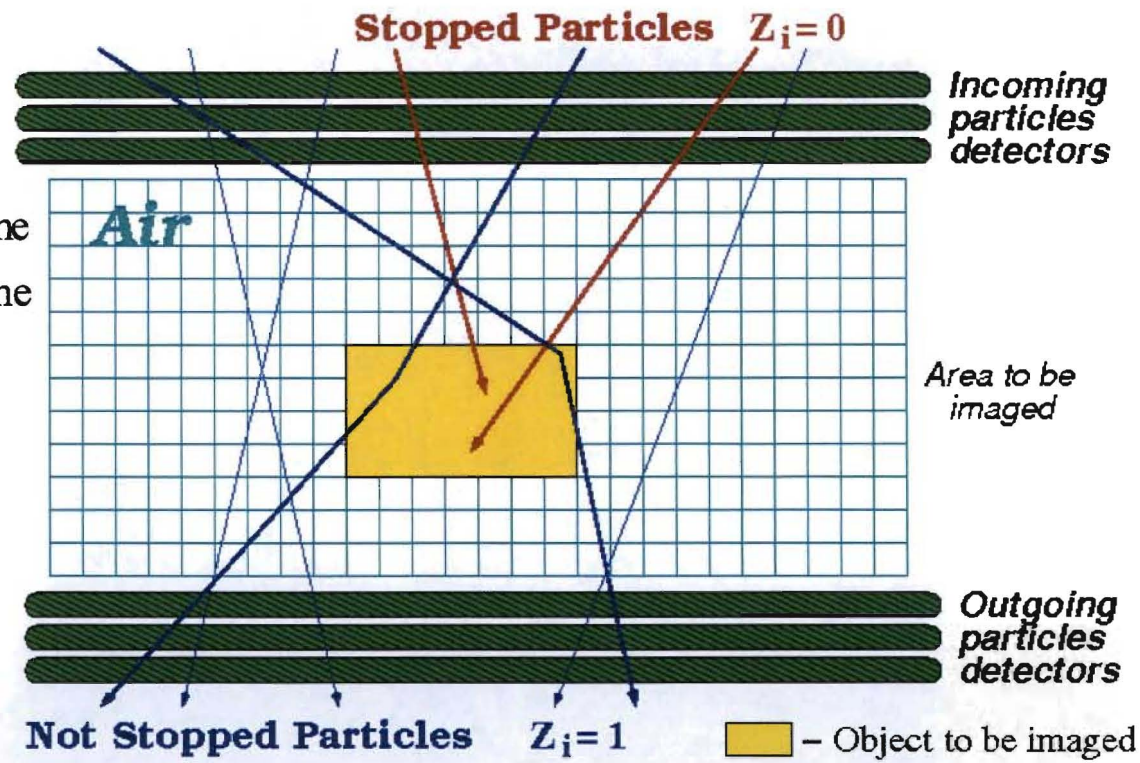
$$\boldsymbol{L}(\rho) = \prod_{i=1}^{M} [1 - H(L_i^t \rho)]^{Z_i} \, H(L_i^t \rho)^{1-Z_i}$$

Define H(*x*) = **P**(E ≤ x) and

$$Z_i = \begin{cases} 0 & \text{if particle is stopped in the volume} \\ 1 & \text{if particle goes through the volume} \end{cases}$$

Estimate stopping densities:

$$\{\rho_k\}_{k=1}^{N} .$$

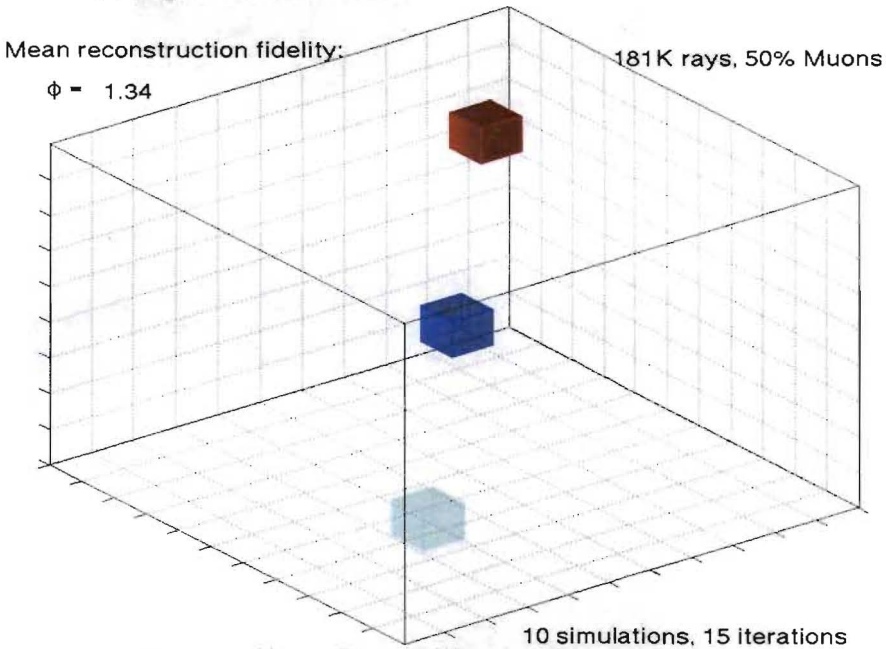


# Reconstruction of simple scenes

**Monte Carlo simulations: assume energy distribution is a log-normal mixture, and a 2 MeV/g/cm energy loss.**

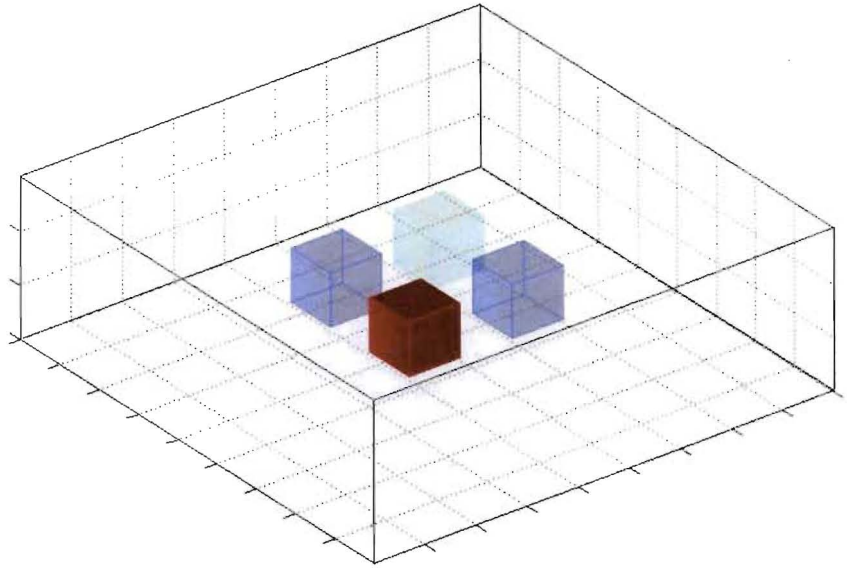
**Geant 4 simulations: reconstruction assumes energy distributions is a log-normal mixture.**

Stopping Reconstruction for Monte Carlo Simulations




| | Al | Fe | W |
|---|---|---|---|
| Actual | 5.40 | 15.75 | 38.60 |
| Estimated mean | 3.14 | 9.77 | 31.30 |

Mean Stopping Reconstruction for Geant Simulations



| Estimated ρ | H20 | TNT | Al | Fe |
|---|---|---|---|---|
| Mean | 3.24 | 5.27 | 10.04 | 37.10 |
| Std. Dev. | 0.51 | 0.91 | 1.80 | 7.21 |

Geant Simulations: 100

Particles: 50% muons
50% electrons
Exposure time: 1 minute

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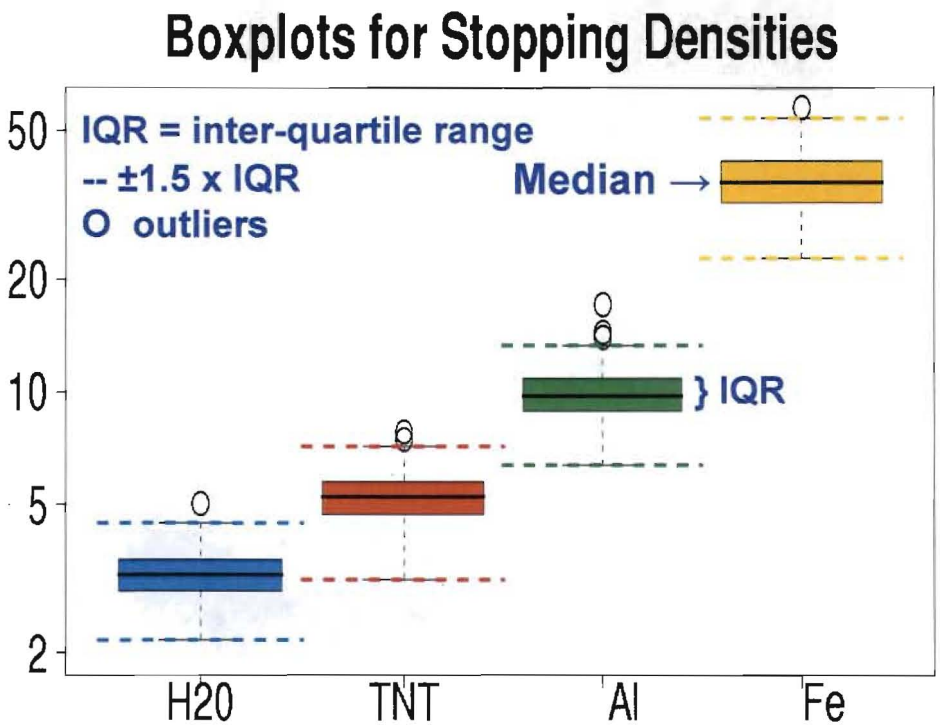
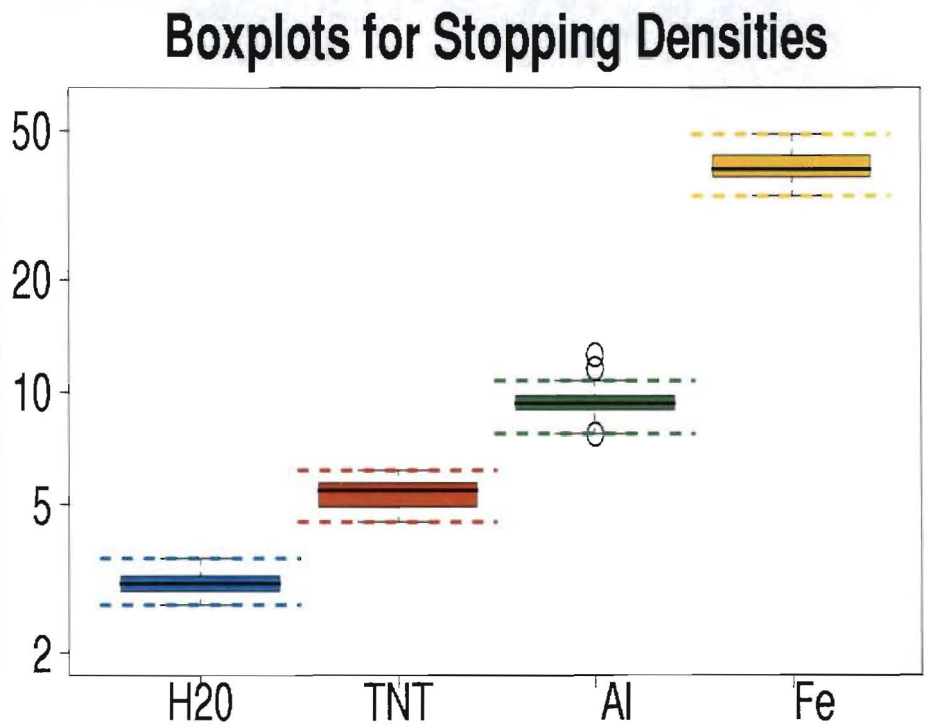
# Stopping density estimations



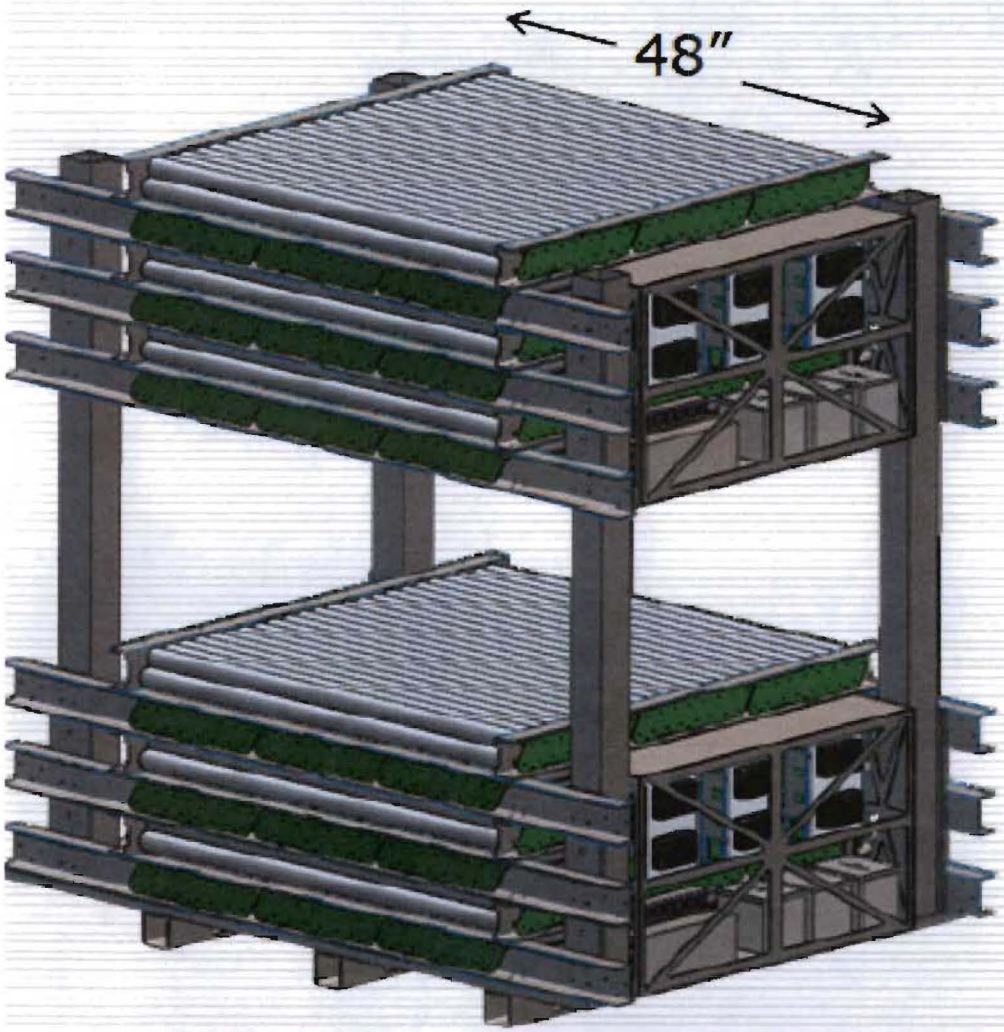

Exposure time: 1 minute (50 simulations)




Exposure time: 2 minutes (50 simulations)

**Boxplots: compare empirical distributions without making assumptions on the underlying statistical distribution.**

# Mini muon tracker design




- Supermodules 1,2 are independent units
- Top SM can be repositioned up/down
- Electronics boxes hold:
  - LV, HV supplies
  - Power distribution
  - LVDS/ECL converter boards
- Good grounding & shielding
  - Steel cover strips not shown here
- 48" C-channel module
- Mobile via forklift or palate jack

# Detector and electronics

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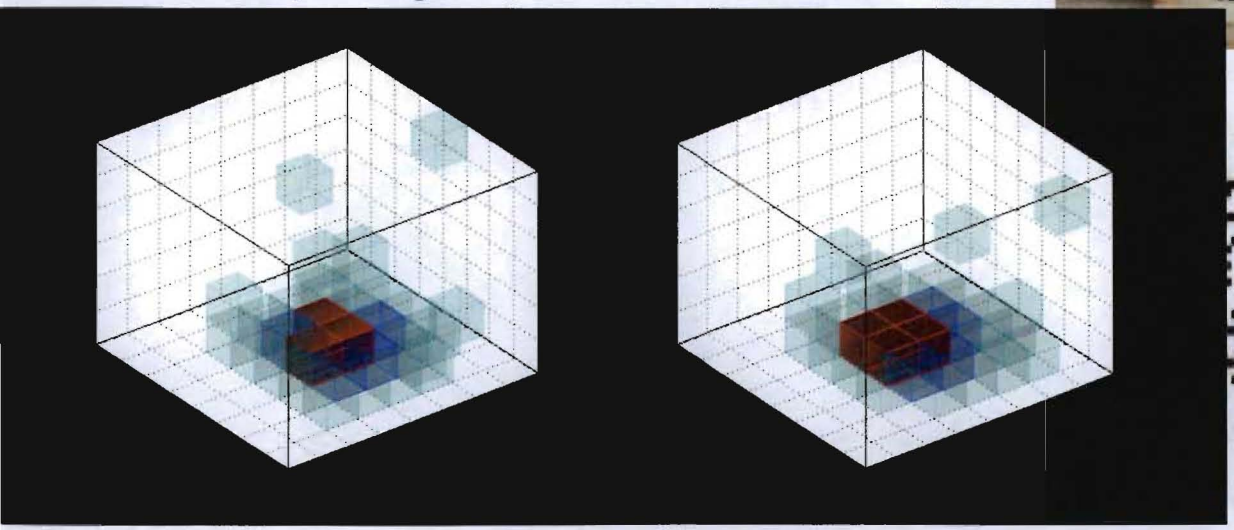
# Experiments

Using a mini muon tracker developed at the Los Alamos National Laboratory we performed experiments of . simple landscapes of various materials, including TNT, 9501, lead, tungsten, aluminium, and water. Most common scenes are four two inches thick step wedges of different dimensions: 12"x12", 12"x9", 12"x6", and 12"x3"; and a one three inches thick hemisphere of lead with spherical hollow, and a similar full lead sphere.

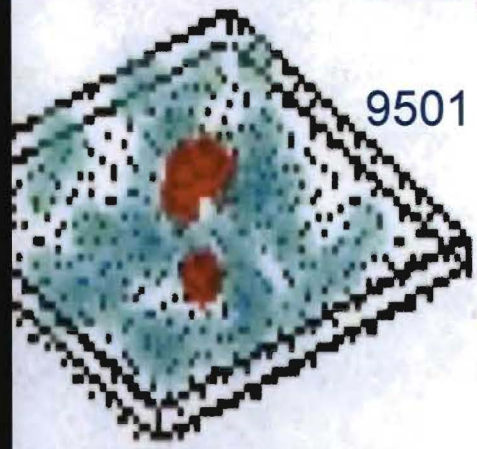
The MMT at the chamber-15 firing site inside its weather-proof shed. The DAQ rack is in the "bunker" building close by.

W stepwedge



Lead bricks





9501 explosive

# Conclusions

- Analysis of stopped charged particles provides a complimentary view to scattering tomography and helps to resolve medium and low-Z materials.
- Using scattering and stopping together we can discriminate better between different materials and detect potential threats in shorter time.
- Stopped particles can be measured with the same muon tomography apparatus.
- We developed reconstruction techniques for attenuation cosmic-ray tomography and demonstrated their performance in simulations.
- We build a mini-muon tracker and performed a series of demonstration experiments with various simple objects.

# A Range Muon Tomography Performance Study for the Detection of Explosives

L. Cuéllar, K. N. Borozdin, K. Chung, J. A. Green, N. W. Hengartner, C. Morris, and L. J. Schultz,
*Member, IEEE, N.P. Reimus, J.D. Bacon, W. Vogan-McNeil*

***Abstract*—Soft cosmic ray tomography has been shown to successfully discriminate materials with various density levels due to their ability to deeply penetrate matter, allowing sensitivity to atomic number, radiation length and density. Because the multiple muon scattering signal from high Z- materials is very strong, the technology is well suited to the detection of the illicit transportation of special and radiololgical nuclear materials. In addition, a recent detection technique based on measuring the lower energy particles that do not traverse the material (range radiography), allows to discriminate low and medium Z-materials. This is shown in [4] using Monte Carlo simulations. More recently, using a mini muon tracker developed at Los Alamos National Laboratory, we performed various experiments to try out the radiation length technology. This paper presents the results from real experiments and evaluates the likelihood that soft cosmic ray tomography may be applied to detect high-explosives.**

## I. Introduction

SOFT cosmic rays are subatomic particles that collide with the upper atmosphere to produce pions that decay to muons, electrons and positrons. Most muons reach the earth's crust where they penetrate deeply into matter [3]. Electrons also reach the crust but because they are less energetic, they stop faster. These muons and electrons can serve as probes for tomographic imaging. Multiple muon scattering has been succesfully applied to identify high Z- objects like shielding materials and special nuclear and radioactive materials. However, imaging of low-Z materials using multiple muon scattering are very noisy due to the low signal-to-noise ratio of these materials [5] and [6]. An alternative tomographic imaging technique, based on range radiography seems promising [4]. This technique exploits the fact that lower energy particles are more likely to stop while traversing an object. Image reconstruction with this technique on simple synthetic landscapes using data from Geant Monte Carlo simulations [1], [2] are encouraging.

The challenge is to mature this technology and transition it from working *in Silico* to enabling imaging of real scenes. To this end, Los Alamos National Laboratory has build a portable *mini muon tracker* (MMT). This muon tracker is constructed from sealed aluminum drift tubes, which are grouped into twenty-four 4 feet$^2$ squared planes. The MMT can be moved via a pallet jack or a fork lift. This paper presents the results of our first data collected from that instrument. The aim in each of the analyzed examples is to identify explosives hidden within the scene. The examples we consider range in complexity of the background clutter.

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Fig. 1. Final Mini Muon Tracker mechanical design

Fig. 2. Completed Mini Muon Tracker to enable full track reconstructtion of cosmic ray muons and electrons.

## II. Experiments

All experiments performed are simple landscapes of various materials placed on top of a $\frac{3}{4}''$ plywood table. Materials include TNT, 9501, Lead, Tungsten, Aluminum, and water. Most common scenes are four two inches thick step wedges of different dimension: $12' \times 12''$ , $12'' \times 9''$, $12'' \times 6''$ and $12'' \times 3''$, one three inches thick hemisphere of lead with sperical hollow, and a similar full lead sphere.

## III. Image Reconstruction

We are currently in the process to apply our image reconstruction technique based on stopping to all these scenes. Results should be available and ready to report by the time of the Nuclear Science Symposium.

## References


[1] S. Agostinelli, *et al.* GEANT4 A simulation toolkit. Nuclear Instruments and Methods in Physics Research Section A, **506**, 3, pp. 250-303, July, 2003.

[2] J. Allison, *et al.* GEANT4 developments and applications, IEEE Transactions on Nuclear Science, **53**, 1, pp. 270-278, 2006.

[3] K. N. Borozdin, G. E. Hogan, C. Morris, W. C. Priedhorsky, A. Saunders, L. J. Schultz, M. E. Teasdale. Surveillance: Radiographic imaging with cosmic-ray muons, Nature **422**, 6929, pp. 277-278. March, 2003.

[4] L. Cuéllar, K.N. Borozdin, L. Schultz, A. Green, N. Hengartner. Soft Cosmic Ray Tomog raphy for Detection of Explosives, 2009 IEEE Nuclear Science Symposium and Medical Imaging Conference Record, October, 2009.

[5] L. J. Schulz, K. N. Borodzin, A. Fraser, A. Klimenko, N. W. Hengartner, C. Morris, C. Orum, M. Sossong. Statistical Tomographic Reconstruction for Cosmic Ray Muon Tomography, IEEE transactions on Image Processing, **16**, 8, pp. 1985-1993, August, 2007.

[6] L. J. Schultz, G. Blanpied, K. N. Borozdin, A. Fraser, A. Klimenko, N. Hengartner, C. Morris, C. Orum, and M. Sossong. ML/EM Reconstruction Algorithm for Cosmic Ray Muon Tomography, IEEE Nuclear Science Symposium Conference Record, 8, pp 2574-2578, October, 2006.