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Form 836 (7/06)

ABSTRACT

Non-Invasive Imaging of Reactor Cores Using Cosmic Ray Muons

Edward C. Milner

for the Los Alamos National Laboratory P-25 Muon Tomography Team

July 29, 2011

Cosmic ray muons penetrate deeply in material, with some passing completely through very thick objects. This penetrating quality is the basis of two distinct, but related imaging techniques. The first measures the number of cosmic ray muons transmitted through parts of an object. Relatively fewer muons are absorbed along paths in which they encounter less material, compared to higher density paths, so the relative density of material is measured. This technique is called muon transmission imaging, and has been used to infer the density and structure of a variety of large masses, including mine overburden[1], volcanoes[2], pyramids[3], and buildings[4]. In a second, more recently developed technique, the angular deflection of muons is measured by trajectory-tracking detectors placed on two opposing sides of an object. Muons are deflected more strongly by heavy nuclei, since multiple Coulomb scattering angle is approximately proportional to the nuclear charge. Therefore, a map showing regions of large deflection will identify the location of uranium in contrast to lighter nuclei. This technique is termed muon scattering tomography (MST) and has been developed to screen shipping containers[5] for the presence of concealed nuclear material. Both techniques are a good way of non-invasively inspecting objects. A previously unexplored topic was applying MST to imaging large objects. Here we demonstrate extending the MST technique to the task of identifying relatively thick objects inside very thick shielding. We measured cosmic ray muons passing through a physical arrangement of material similar to a nuclear reactor, with thick concrete shielding and a heavy metal core. Newly developed algorithms were used to reconstruct an image of the "mock reactor core", with resolution of approximately 30 cm.

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[1] E.P. George, Commonwealth Engineer, 455 (July 1, 1955).
[2] K. Nagamine, M. Iwasaki, K. Shimomura, K. Ishida, NIM Phys. Res. A **356**, 585-595 (1995).
[3] L. W. Alvarez, J. A. Anderson, F. Elbedwe*, J. Burkhard, et al., Science (USA) **167** (3919), 832 (1970).
[4] C. Hui, MA Thesis, The University of Texas at Austin, (2007).
[5] C. Morris, C. Alexander, J. Bacon, K. Borozdin, et al., Science & Global Security **16** (1), 37-53 (2008).

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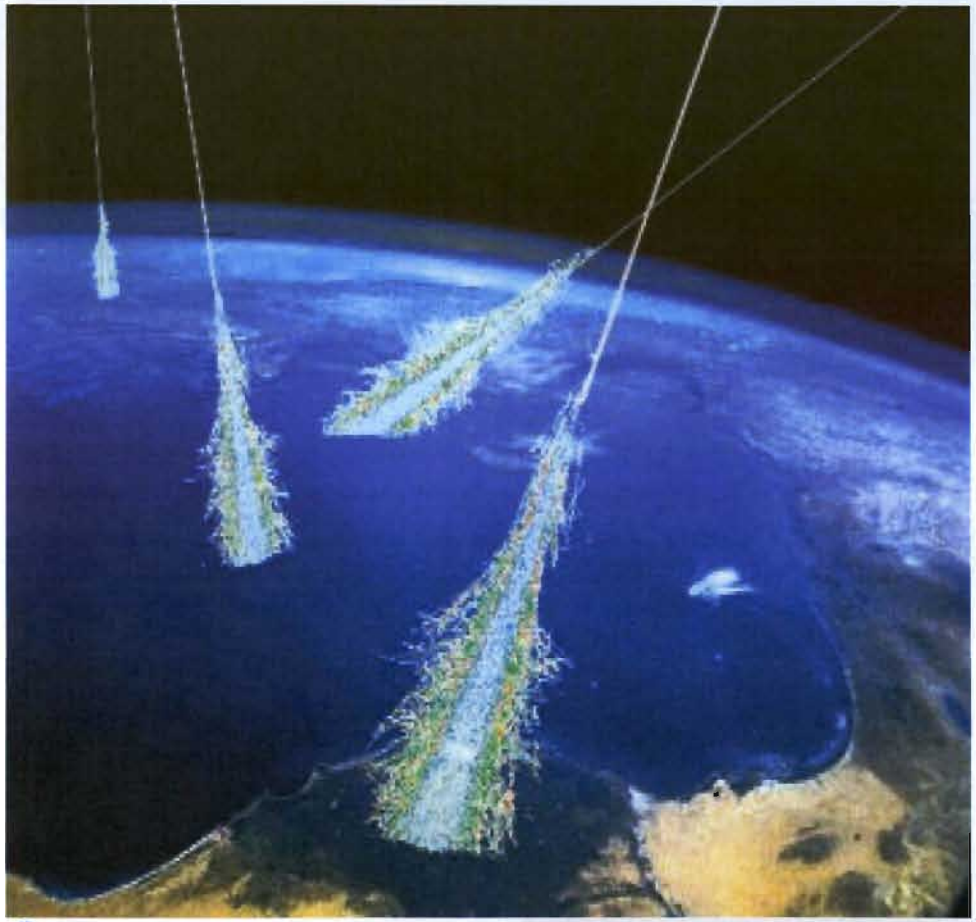
Cas Milner

Los Alamos National Laboratory

P-25, Sub-Atomic Physics Group

High energy cosmic rays interacting in the atmosphere generate extensive showers of secondary particles.



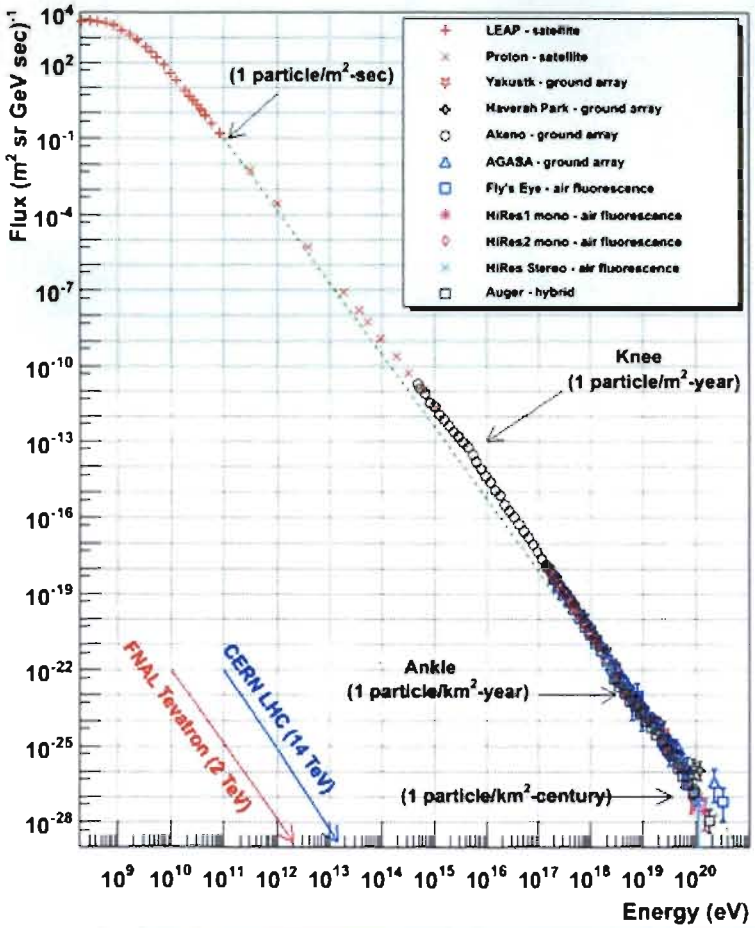
Source: Simon Swordy, U. Chicago

- Flux at sea level
  - ~ 10,000 /m^2 /minute
  - ~ 1 /60 cm^2 /s
  - ~ 1 / "hand" /s)
- $p + N_2 \rightarrow$ hadronic showers:

  $E^2 = \underline{m}^2c^4 + p^2c^2$
- Primary "sources" somewhat obscure
- Some primaries have **<u>very high</u>** energy
- High energy component of secondary flux is very useful

The primary cosmic ray energy spectrum is well known.

Cosmic Ray Spectra of Various Experiments

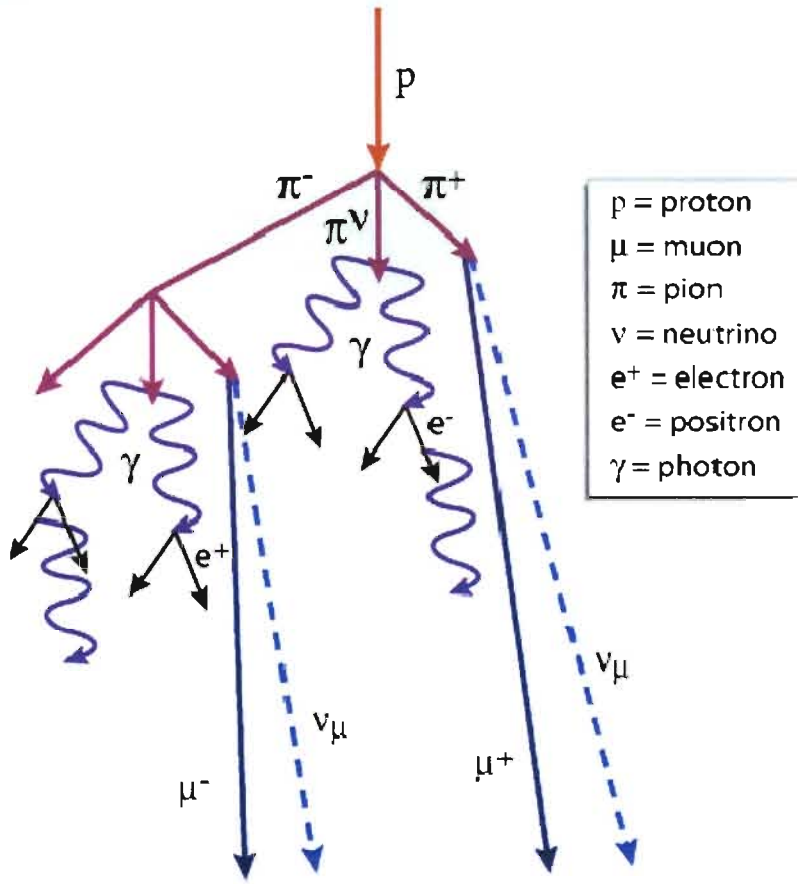


- Useful flux in the GeV to TeV range
- Flux scales as ~ E^{-2}

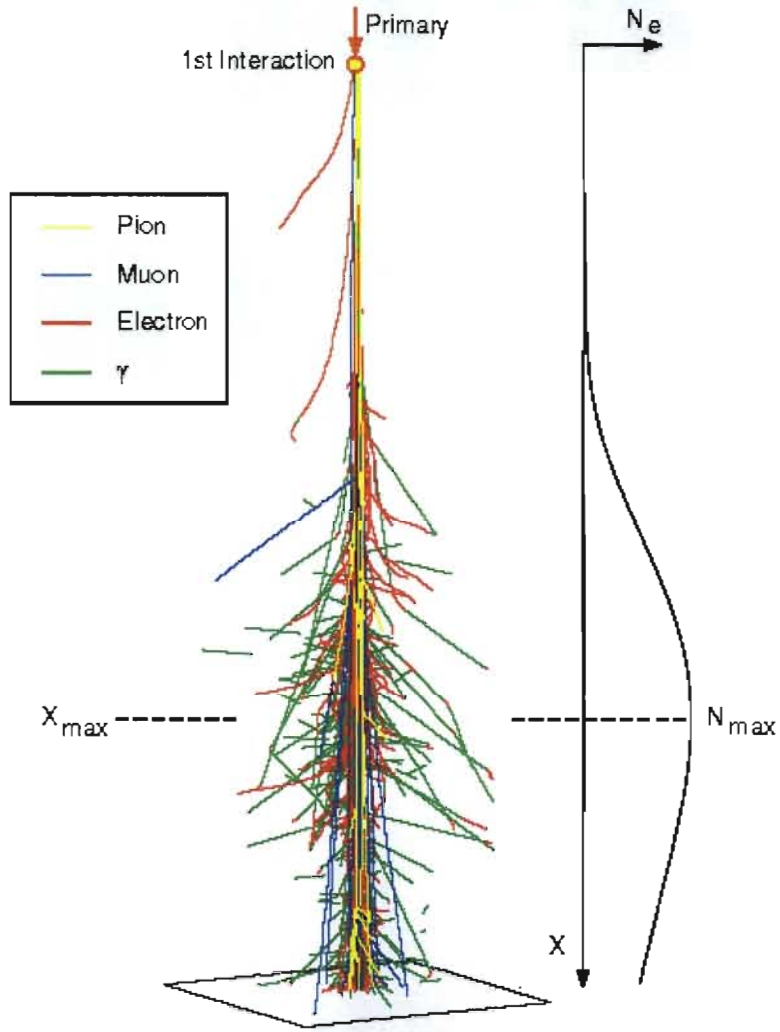
Ref: W.F. Hanlon, Ph.D. Dissertation, U. Utah, 2008.

The secondary cosmic ray particle showers are primarily hadronic, with significant decay muon content.

- High production of π^o, π^+, π^-, K, etc.
- Muons (μ) produced in $\pi^{+/-}$, K, etc. decay
- Muon component of shower is penetrating and long lived
  - $\tau \sim 2.2$ μs in μ rest frame of reference, but much longer in our frame of reference



Muons are penetrating, making radiography of thick objects possible.



- Highly penetrating
  - Muons interact only through the Coulomb and weak force
  - Mass ~200x e^- mass, so e^- deflection is very small
- 3 GeV muons have a range of ~17 m in concrete

Cosmic ray muons have been used to probe the interior of mountains, pyramids and shipping containers.

- **Measurement of mine overburden (under a mountain!)**
  - E.P. George, Commonwealth Engineer, 455 (July 1, **1955**).
- **Search for structure in the Second Pyramid (Kephren) at Giza**
  - L. W. Alvarez, J. A. Anderson, F. Elbedwe, J. Burkhard, et al., Science (USA) 167 (3919), 832 (**1970**).
- **Location of lava inside volcano**
  - K. Nagamine, M. Iwasaki, K. Shimomura, K. Ishida, NIM Phys. Res. A 356, 585-595 (**1995**).
- **Imaging interior of buildings on UT campus**
  - C. Hui, MA Thesis, The University of Texas at Austin, (**2007**).
- **Detection of dense metal objects in shipping containers**
  - C. Morris, C. Alexander, J. Bacon, K. Borozdin, et al., Science & Global Security 16 (1), 37-53 (**2008**).

There are two techniques for imaging the interior of large objects with cosmic ray muons.

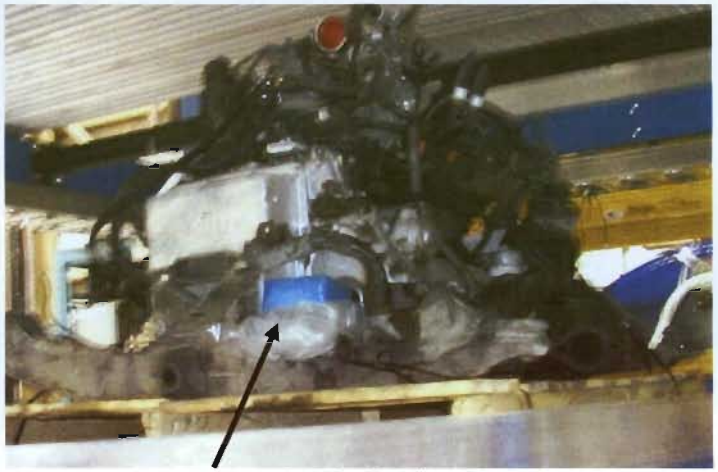
- **Muon transmission imaging**
  - Measure muons transmitted through object.
  - More muons successfully pass through paths in which they encounter less material (integrated density and length), compared to higher density paths.
  - Muon intensity data from a variety of directions and detector positions is used to reconstruct a 3-dimensional image of the relative density of material.
- **Muon scattering tomography imaging**
  - Angular deflection of muons passing through the reactors is measured by detectors placed on two opposing sides of an object.
  - Muons are deflected more strongly by heavy nuclei like uranium, than by relatively lighter nuclei like the iron in steel or the elements in concrete.
  - A three-dimensional map showing the regions of large deflections will identify the location of uranium.

At LANL, we have developed Muon Tomography for detecting concealed high-Z material (uranium, etc.)

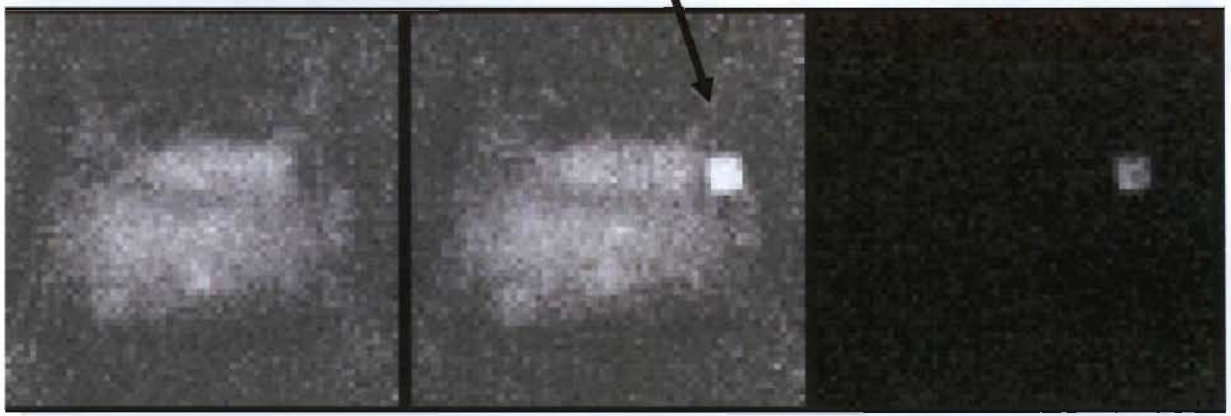
- **Measure deflection of cosmic muons**
  - tracking before and after passing through object
  - Generate muon "scattering density" image
    - » "High-z" materials (like uranium) deflect muons strongly
- **Advantages over other methods:**
  - No artificial radiation
  - Simple technology
  - Inexpensive
  - Can penetrate thick cargoes
  - Automatic Identification

Source: Decision Sciences Corporaton (licensee)

It really works!



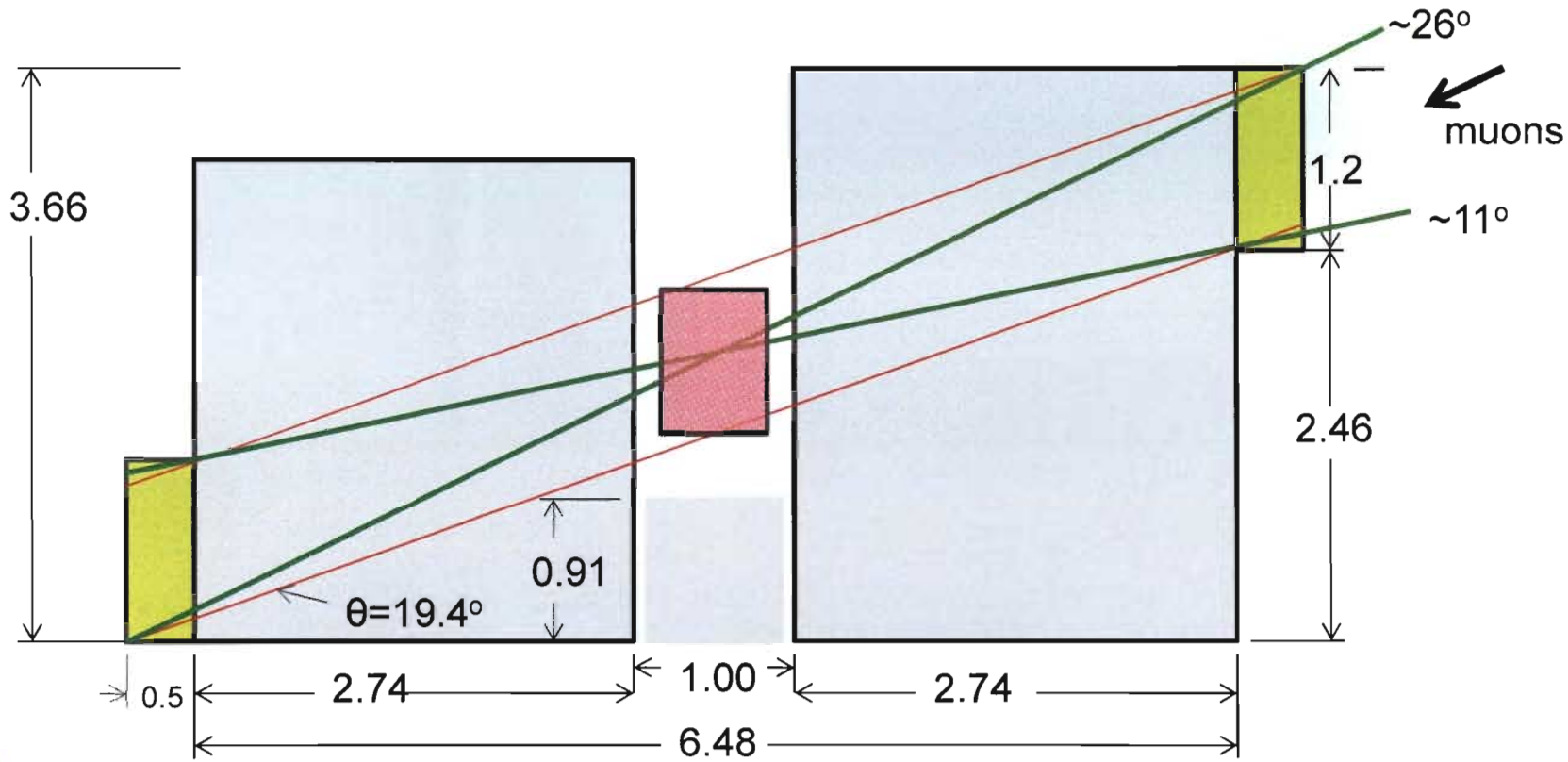
Lead Brick



We have extended Muon Tomography to the task of imaging thick objects in very thick shielding.

- Concrete
- Muon mini-tracker (MMT) set
- Target region

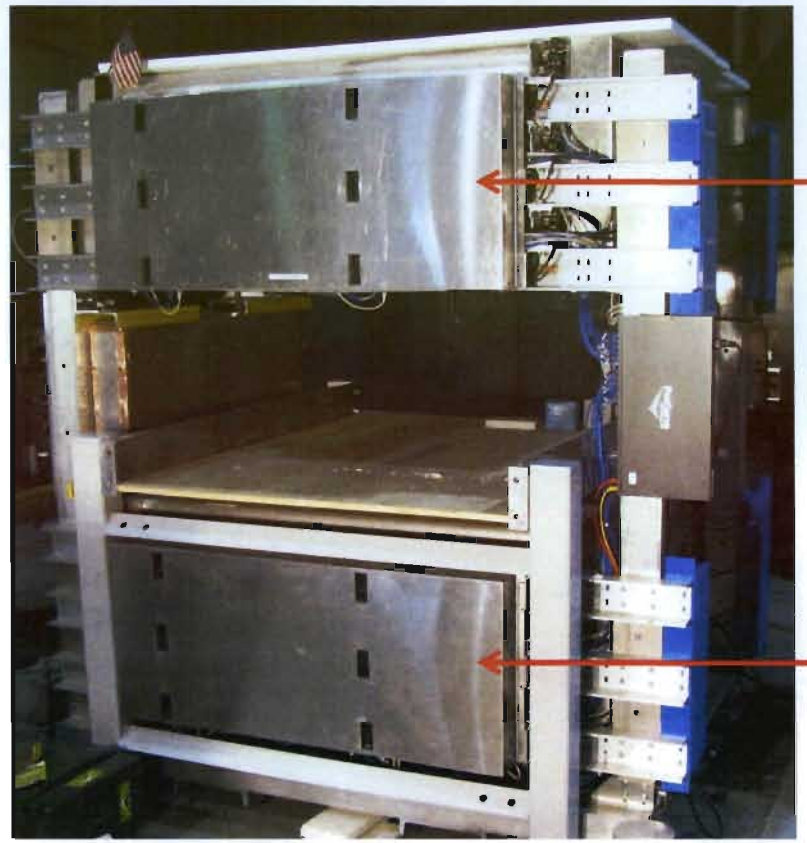
All distances in meters (m)
Angles are in degrees, and are with respect to horizon.



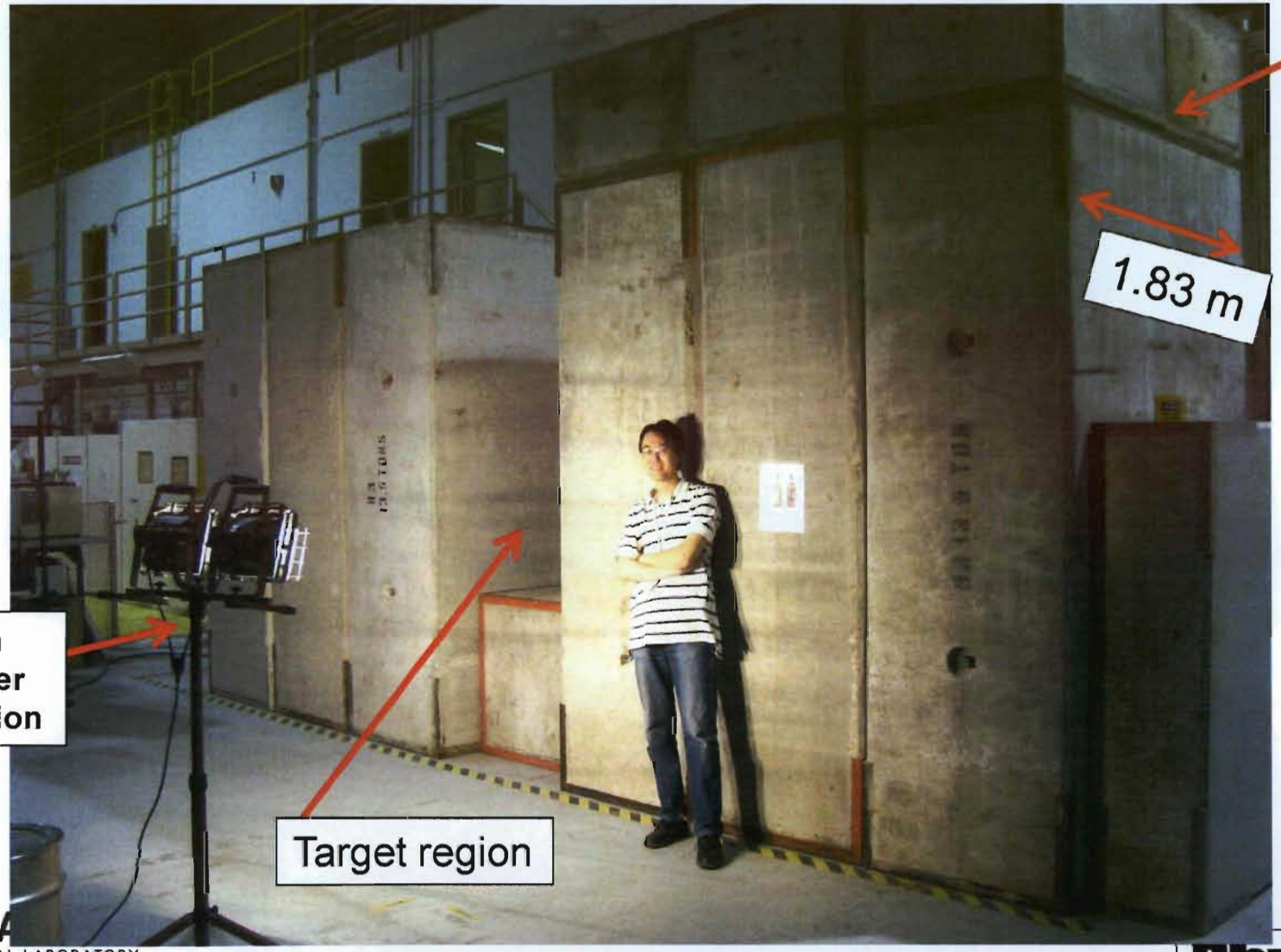
East →

The experiment budget was modest, using previously constructed equipment.

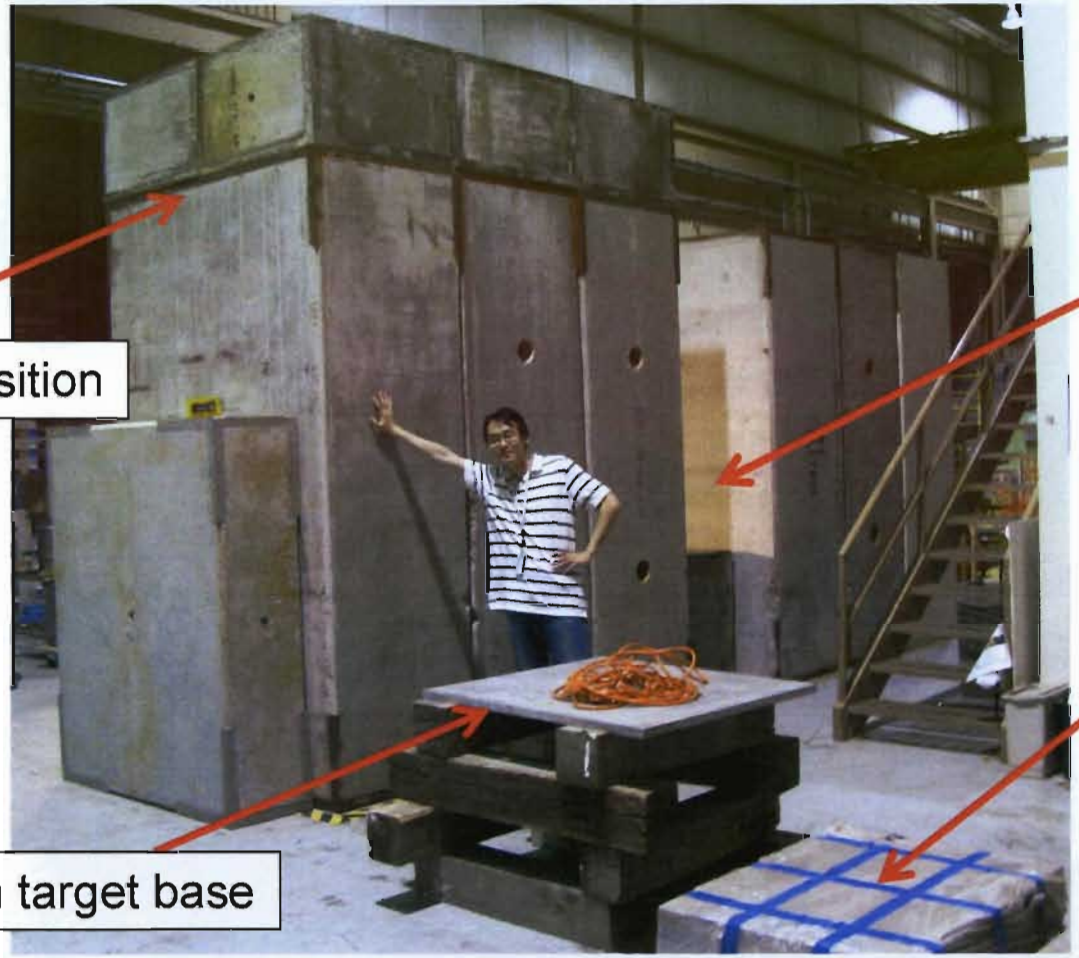
- Two sets of trackers (MMT – Muon Mini-Tracker)
- Each tracker set has 3 x-y pairs planes, for a 6-fold tracking coincidence, in and out.
- Tracker sets moved to "mock reactor".
- One set placed high onshielding, to track incoming muons.
- Other set placed low on the "exit" side of the shielding.



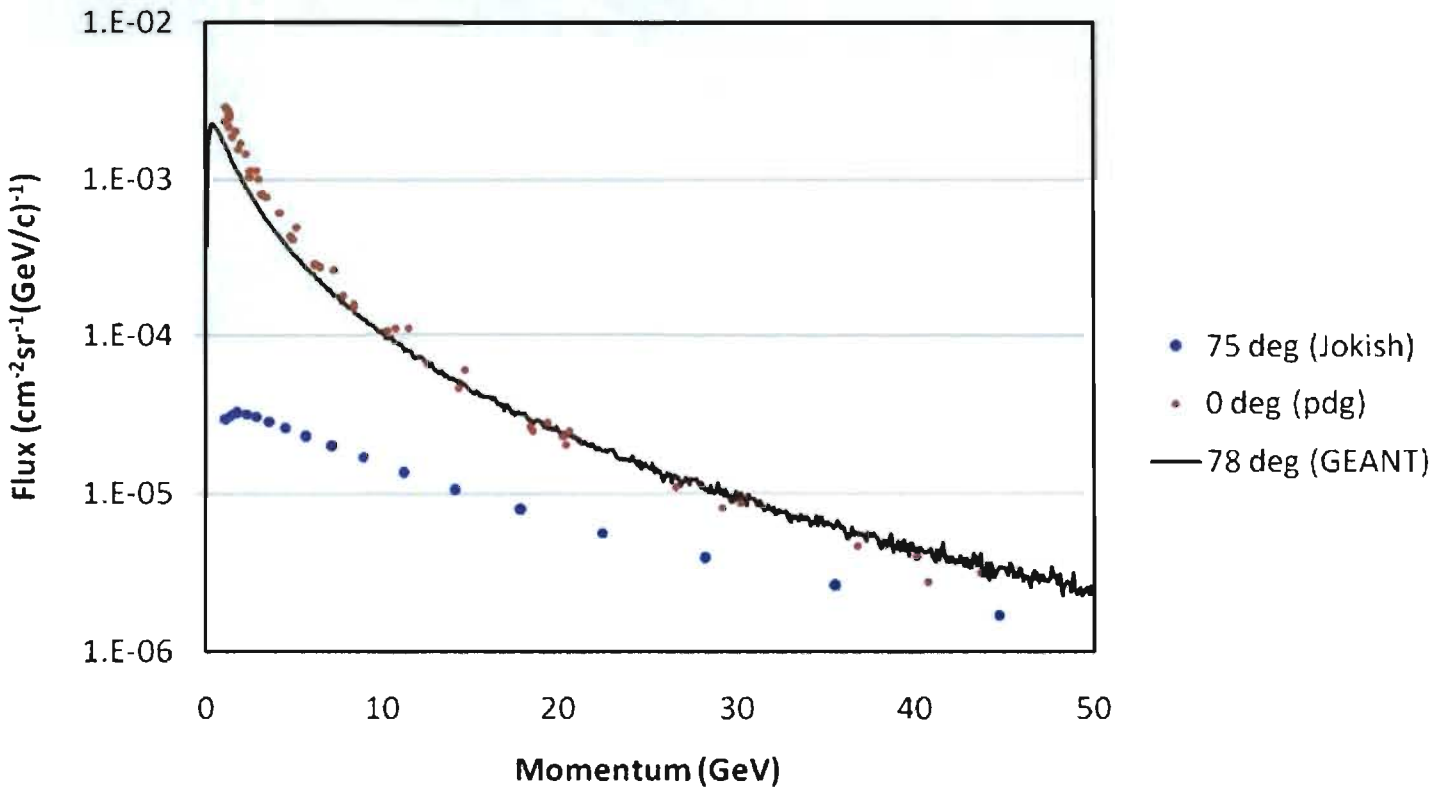
Concrete shielding was 18 feet – similar to a reactor shield.



Lead-brick target material ready for stacking.



The near-horizontal muon spectrum differs significantly from the vertical spectrum.

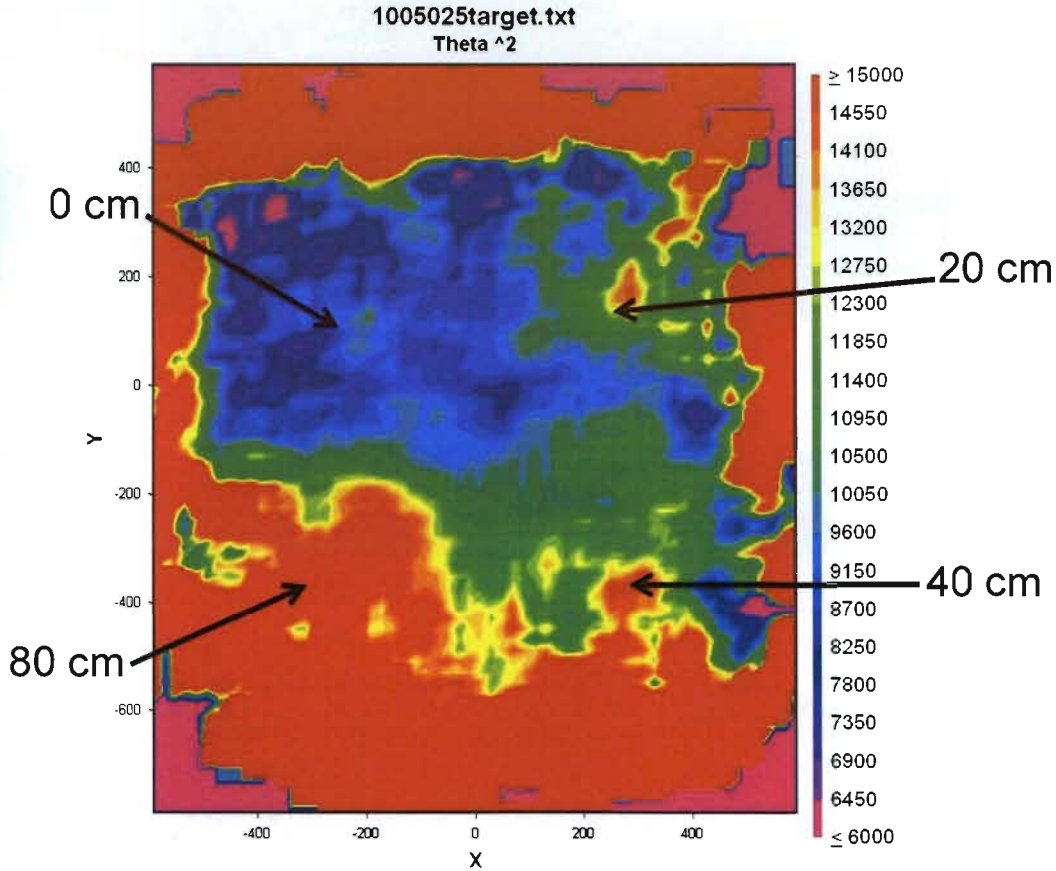


Ref: H. Jokisch, K. Carstensen, W. Dau, H. Meyer, O. Allkofer, *et al.*, Cosmic Ray Muon Spectrum Up to 1-TeV at 75-Degrees Zenith Angle, PHYSICAL REVIEW D (**1979**) Vol.19, iss.5, p.1368-1372F

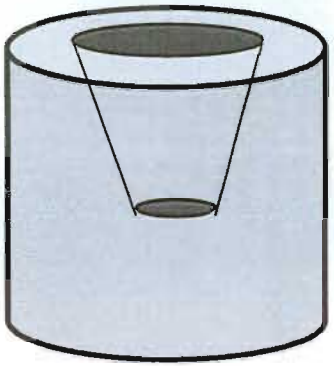
Data analysis resulted in images of high-Z material.

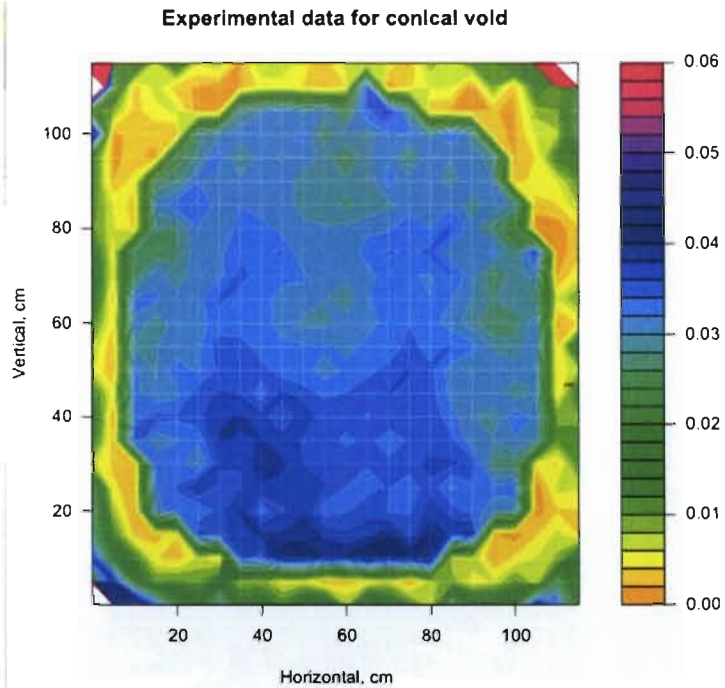
- **Deflection angle squared at target mid-plane**
  - Accept tracks passing within 10-cm of each other at mid-plane
  - Deflection = (angle-out – angle-in)^2
  - Plot average deflection for each x-y pixel (10 cm x 10-cm) at mid-plane
- **Compare to simulation Monte Carlo**
  - GEANT4 model of experiment
  - Use near-horizontal spectrum (rather than standard vertical spectrum)
- **Calculate mass of target**
  - Model input spectrum
  - Estimate mass based on scattering

A target of 80-, 40-, and 20-cm of lead (Pb) was imaged.

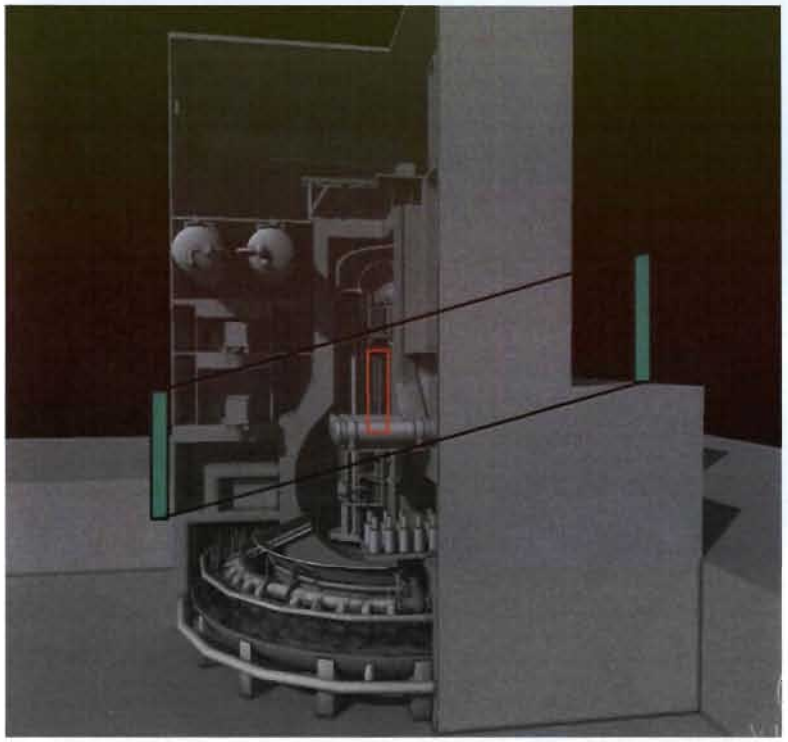


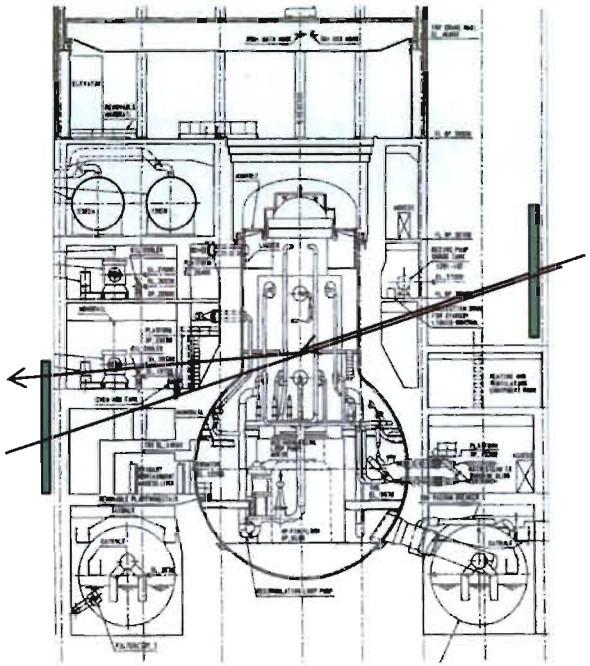
An 80-cm thick Pb target, with "conical void" was imaged.





Our demonstration measurement could be scaled-up, to image the fuel in the Fukushima Daiichi reactors.





We have established Muon Tomography as a technique for non-invasively imaging large objects.

- **Thick targets imaged inside very thick concrete shield**
  - 3 m of concrete – similar to Boiling Water Reactor (BWR)
  - 80-cm of Pb – similar to areal-density thickness of reactor fuel
  - ~ weeks to image each target
- **Scale-up to reactor**
  - Detectors would be on building exterior, ~50 m apart
  - Maintain same solid angle with detectors 5 m x 5 m (commercially available)
  - Measure image of location of fuel
  - Measure amount of fuel remaining in the reactor pressure vessel (RPV)
    - Consistent with known quantity? **Remove intact RPV for disposal**
    - Less than known fuel quantity? **Melt down. Complicated remediation.**
- **Next: full scale demonstration at functioning US reactor?**

Appendix slides

The history of cosmic rays spans one hundred years.

1912 Victor Hess discovers cosmic rays at 5000 m in balloon flight

1927 Skobeltzyn sees cosmic rays in cloud chamber

1932 Anderson discovers anti-electron in cloud chamber

1937 Neddermeyer and Anderson discover cosmic ray muons in cloud chamber

1938 Pierre Auger discovers cosmic ray extensive air showers (Jungfraujoch, ~3500m)

1946 First air shower experiments (Rossi [USA] and Zatsepin [USSR])

1949 Fermi's theory of cosmic ray acceleration by magnetic fields

1962 First ~10^{20} eV cosmic ray detected (Linsley, *et al.*, Volcano Ranch, NM)

1966 Proposal of GZK cutoff energy for cosmic rays (< 5 x 10^{19} eV)

1967 Alvarez group inspects Chephren Pyramid using muon radiography

1991 Fly's Eye (USA) detects highest-energy cosmic ray (above GZK)

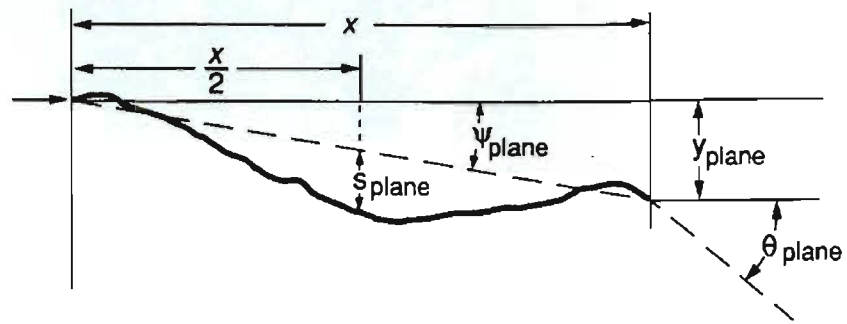
1994 AGASA (Japan) high-energy event (above GZK)

2005 Auger Project (Argentina) begins operation

Multiple scattering distinguishes materials.

- **Range (absorption)**
  - Useful for uniform objects (pyramids, volcanoes)
- **Multiple scattering**
  - Cost effective and simple
  - Scattering length (x) depends on material:

Material	dE/ dx	χ
	MeV-cm^2/gm	cm
H_2O	2.06	36
Fe	1.87	1.76
Pb	1.54	0.56



$$y_{\text{plane}} = z_1\, x\, \theta_0 (1-\rho_{y\theta}^2)^{1/2}/\sqrt{3} + z_2\, \rho_{y\theta}\, x\, \theta_0/\sqrt{3}$$

$$= z_1\, x\, \theta_0/\sqrt{12} + z_2\, x\, \theta_0/2\ ;$$

$$\theta_{\text{plane}} = z_2\, \theta_0\ .$$

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

$$\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{l}{\chi}}$$

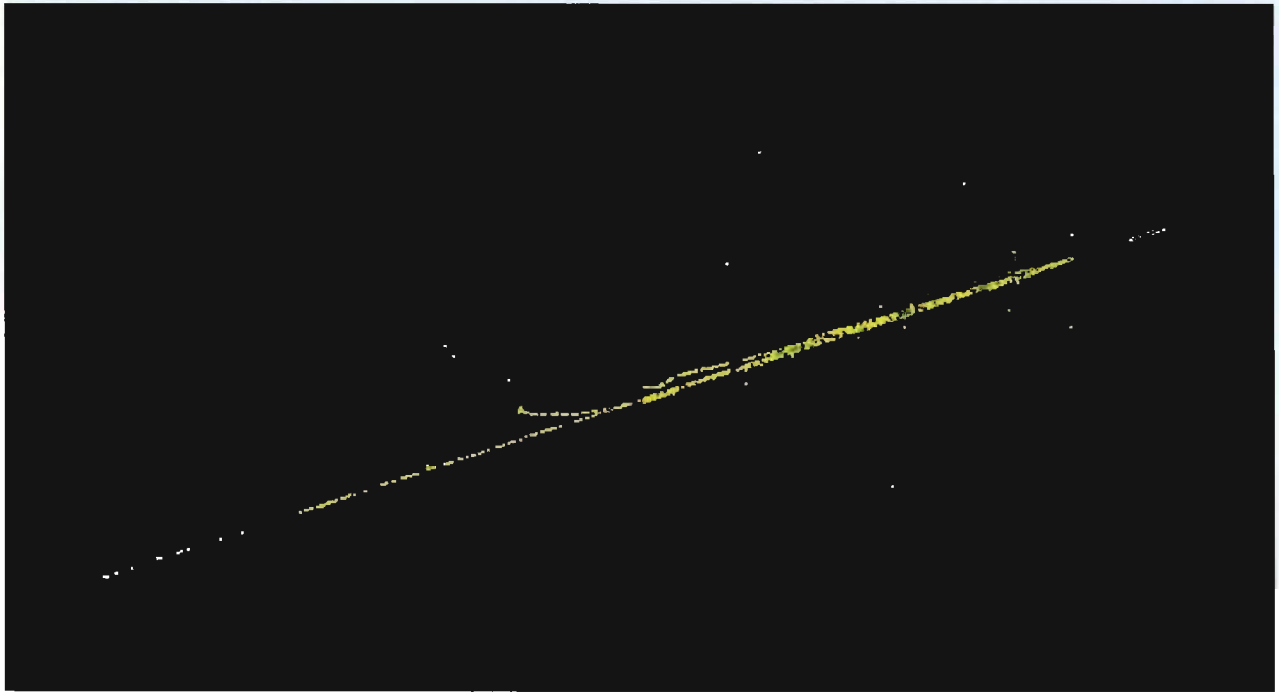
since each measurement of θ_x and θ_y measures θ_0

$$\frac{\Delta l}{l} = \sqrt{\frac{2}{N}}$$

where N is the number of detected muons

Fermi and Rossi, 1940

A Monte Carlo model of the demonstration experiment is being developed in GEANT4.



Slide headers

1. High energy cosmic rays interacting in the atmosphere generate extensive showers of secondary particles.
2. The primary cosmic ray energy spectrum is well known.
3. The secondary cosmic ray particle showers are primarily hadronic, with significant decay muon content.
4. Muon cosmic rays are deeply penetrating – through the atmosphere and terrestrial material.
5. Cosmic ray muons have been used to probe the interior of mountains, pyramids and shipping containers.
6. There are two techniques for imaging the interior of large objects with cosmic ray muons.
7. At LANL, we have developed Muon Tomography for detecting concealed uranium (plutonium, thorium, etc.)
8. We have extended Muon Tomography to the task of imaging thick objects in very thick shielding.
9. The experimental set-up was an approximation to a nuclear reactor.
10. The experiment budget was modest, using previously constructed equipment.
11. The near-horizontal muon spectrum differs significantly from the vertical spectrum.
12. Data analysis resulted in images of high-Z material.
13. A target of 80-, 40-, and 20-cm of lead (Pb) was imaged.
14. An 80-cm thick Pb target, with a “conical void” was imaged.
15. Our demonstration measurement could be scaled-up, to image the fuel in the Fukushima reactors.
16. We have established Muon Tomography as a technique for non-invasively imaging large objects.