

Imaging Maya Pyramids and Other Large Things with Cosmic Ray Muons



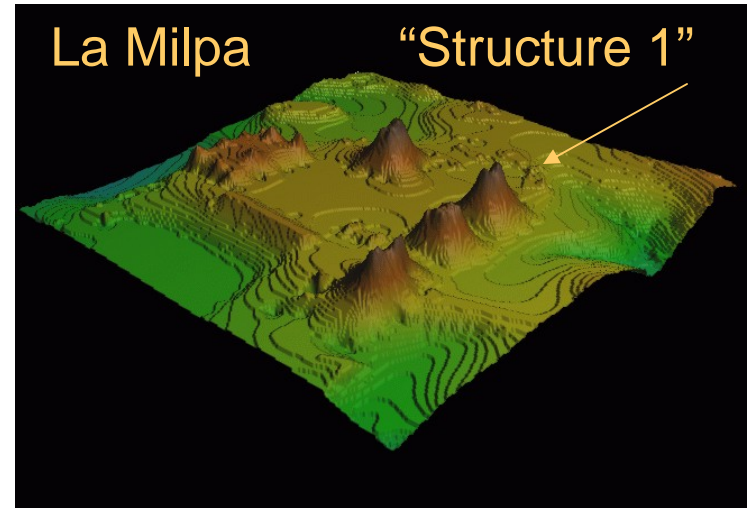
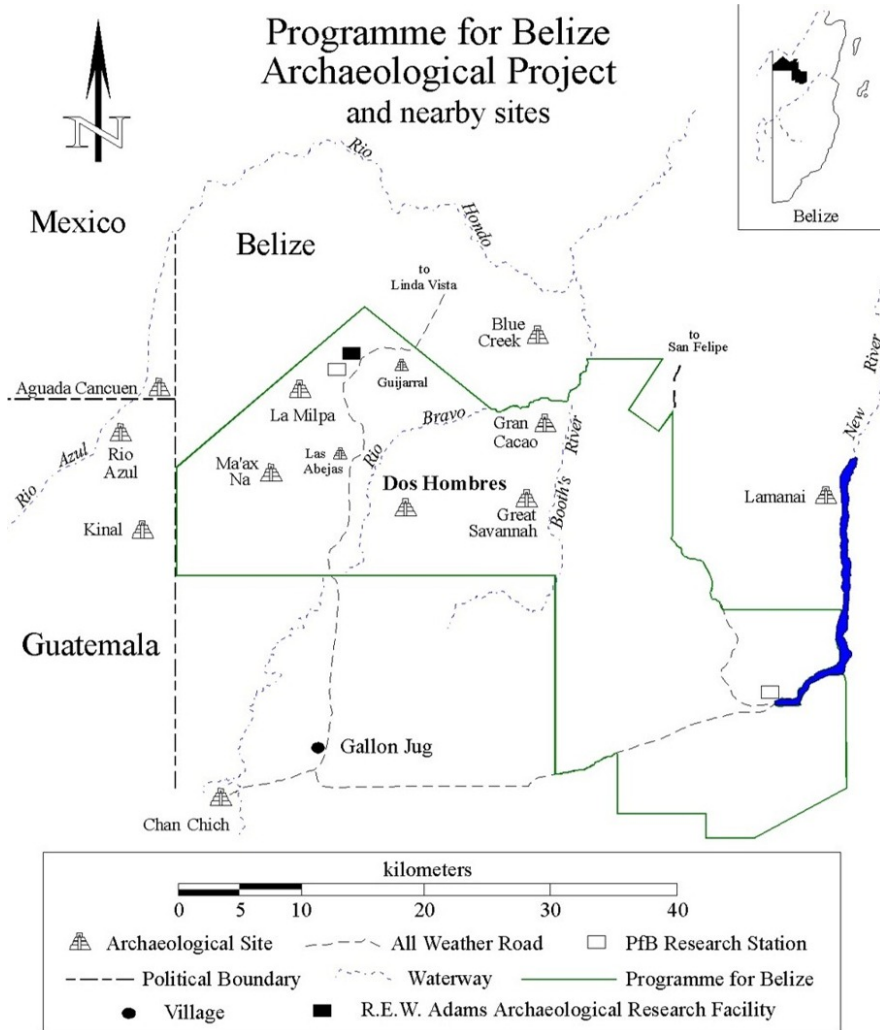
An Application of the Tools of High Energy Physics



The Maya: Extraordinary American Culture

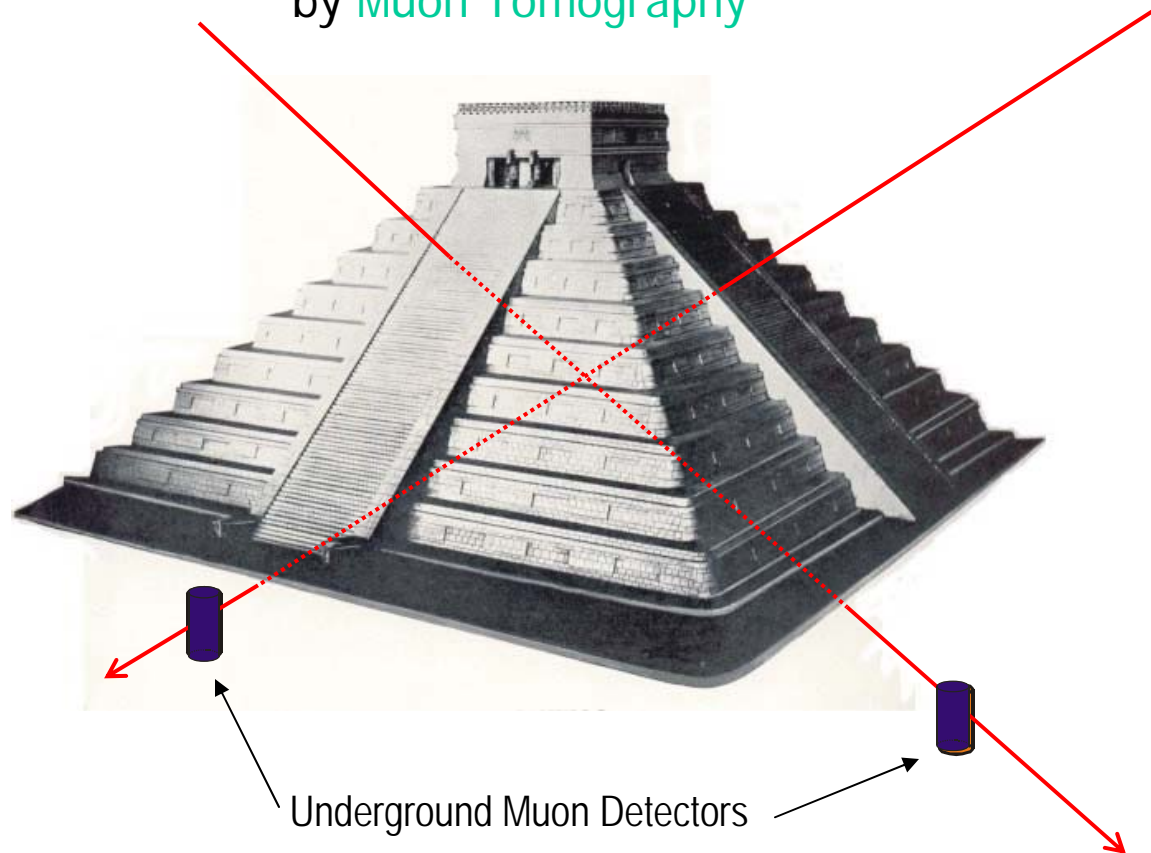


Much Still to be Learned About the Maya: UT Mesoamerican Archeological Lab in Belize



What is the internal structure?

Measure Spatial Distribution of Material *Inside*
by **Muon Tomography**



This is Proven Technology

- Luis Alvarez* invented muon tomography in 1960's to study the 2nd Pyramid of Chephren
- Spark chambers used to track muons from Belzoni Chamber
- System worked well—could see structures of caps
- Main discovery: No other chambers exist

* L.W. Alvarez, et al, *Search for Hidden Chambers in the Pyramids Using Cosmic Rays*, Science 167, 832-839, 1970.

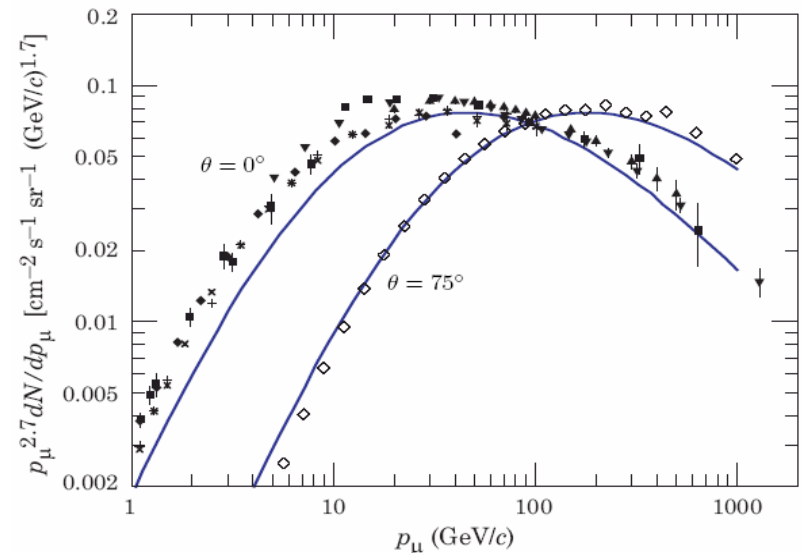
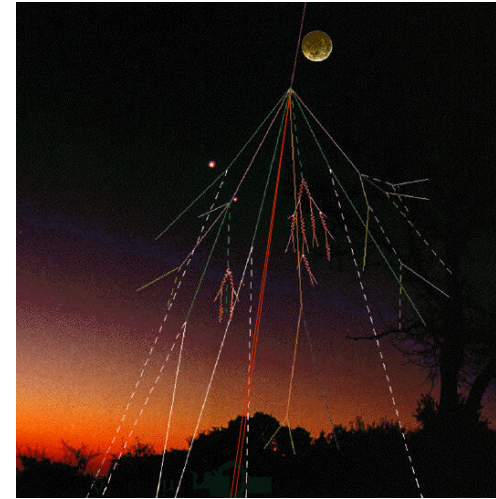


Muons (and Neutrinos) are the Main Component of Cosmic Rays at the Earth's Surface and Below

- Primary cosmic rays interact in upper atmosphere $\Lambda_{\text{int}} \approx 50 \text{ gm/cm}^2$
 - Mainly high energy protons
 - Showers of π 's/K's created
 - Decay within 10's – 1000's $c\tau_{\pi} = 7.8 \text{ m}$ meters or collide with nuclei $c\tau_K = 3.7 \text{ m}$ in air

- Muons are produced in decays of π /K
 - Do *not* have nuclear interactions
 - Lifetime much longer than π /K *and* dilated by relativity $c\tau_{\mu} = 660 \text{ m}$

- Approximate muon rate at Earth's surface: $\sim 1 / \text{cm}^2 / \text{sr} / \text{minute}$



Muon Interactions in Matter

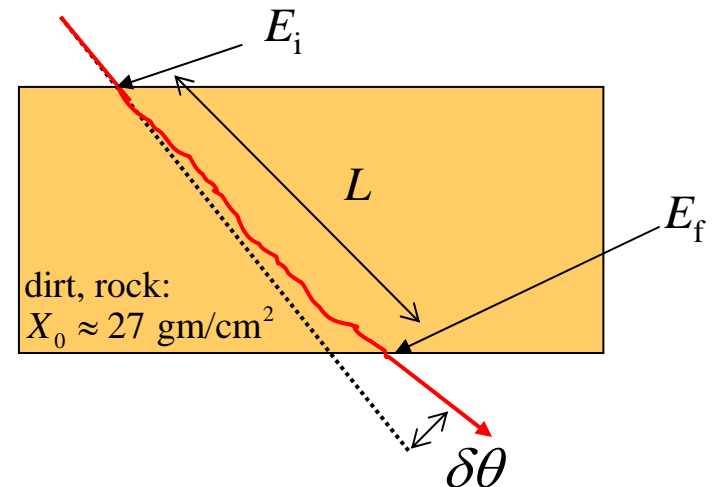
- Muons are weakly interacting; they do *not* have strong nuclear interactions
- Energy loss: predominately by ionization

$$\frac{dE}{dx} \approx 2 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m in rock}$$

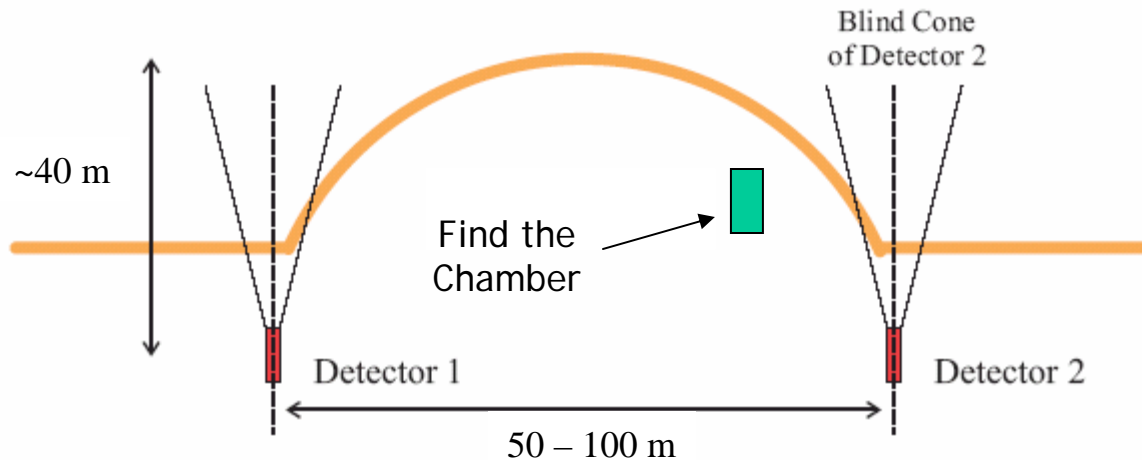
- Multiple-Coulomb Scattering

$$\delta\theta \approx \frac{13.6 \text{ MeV}}{\sqrt{E_i E_f}} \sqrt{\frac{L}{X_0}}$$

$$E_i - E_f \approx L \frac{dE}{dx}$$



Arrangement Involving Cylindrical Detectors

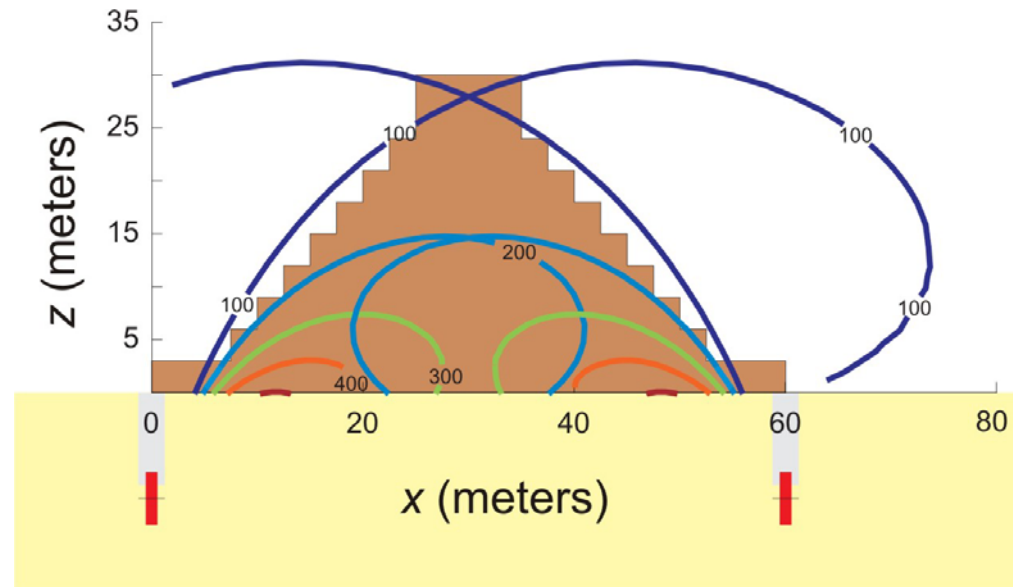


- Use 2 or more detectors
 - Compensates for “blind cone” inherent in cylindrical detectors
 - Improved stereo sampling of target volume
 - Symmetry of cylindrical detectors good for measuring null image
- Minimizes excavation

Basic Rates/Exposure Times

- Extreme Case:
 - 1 m³ void at 50 m
 - Solid angle $\Delta\Omega = 1/50^2$
 - Active area $A = 3 \text{ m}^2$
 - Resulting rate per $\Delta\Omega$ bin:
~ 100/day/detector
 - Contrast ~ 1.5 x 1/50
 - 1 σ measurement needs 1000 events per $\Delta\Omega$ bin
- Second detector may see higher rates for same void
- Bottom line:
 - 1 σ survey requires ~10 days
 - 3 σ survey requires ~ 3 months

Contours of Equal Counting Rate for 2 Detectors (counts/day/pixel)



Muon Detector System

- Mechanical Structure
 - Supports detector components
 - Provides environmental protection
- Muon Tracking System
 - Scintillator-WLS fiber-PMT technology
 - 3 stereo layers: $\pm 30^\circ$ helices, 0° , 448 strips total
- Electronics
 - Front-end boards (FEB) time hit strips
 - Trigger/Data-acquisition (DAQ) system
- Software



Built and tested at UT:

1.6 m × 4.2 m
1 ton

Under development.

0.6 m × 1.4 m
0.1 ton



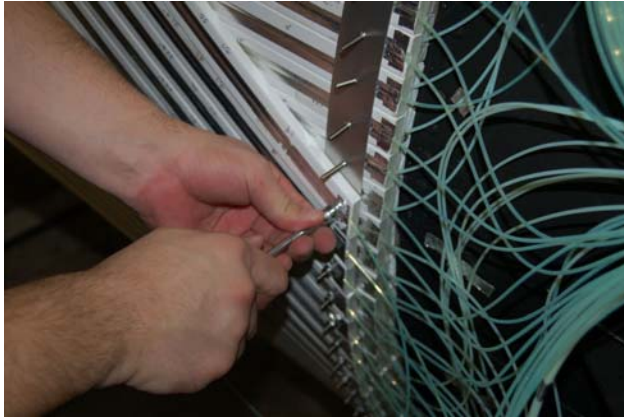
UT Prototype Detector

- Built by H. Stevens and students
- Mechanical assembly completed in April 2006
- First events recorded in fall 2007
- Moved to vertical orientation in March 2007
- Run with test targets (Pb-loaded bricks) during summer 2007 to present



February 2008

Tracking System Elements

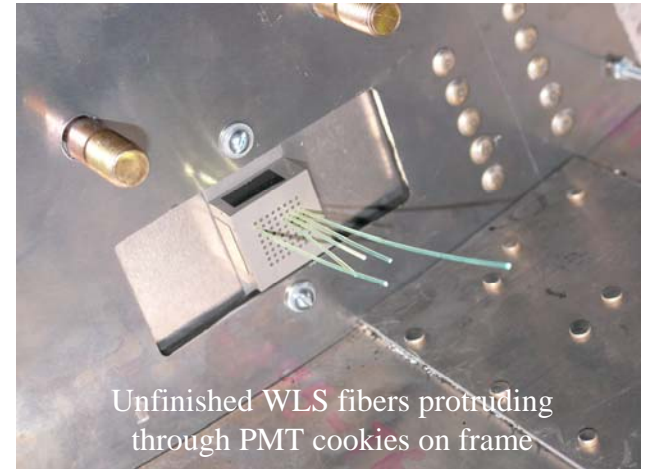


“MINOS” scintillator
30 mm wide
10 mm thick

WLS fiber readout

2 helical layers
1 axial layer (center)

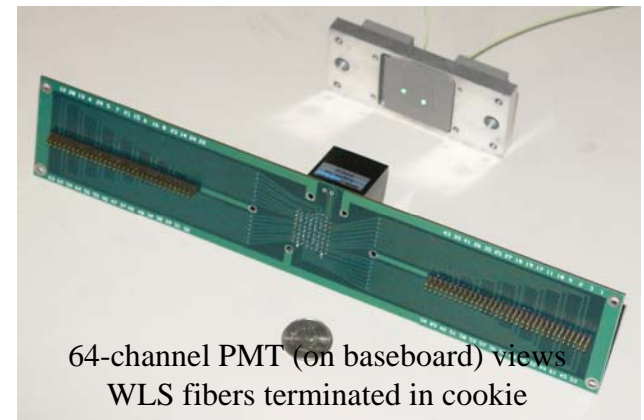
441 total strips



Unfinished WLS fibers protruding
through PMT cookies on frame



WLS fibers extend beyond ends of scintillator
strips to PMT cookies (7 on each end)



64-channel PMT (on baseboard) views
WLS fibers terminated in cookie



Scintillator Hits Are “Reconstructed” into Tracks

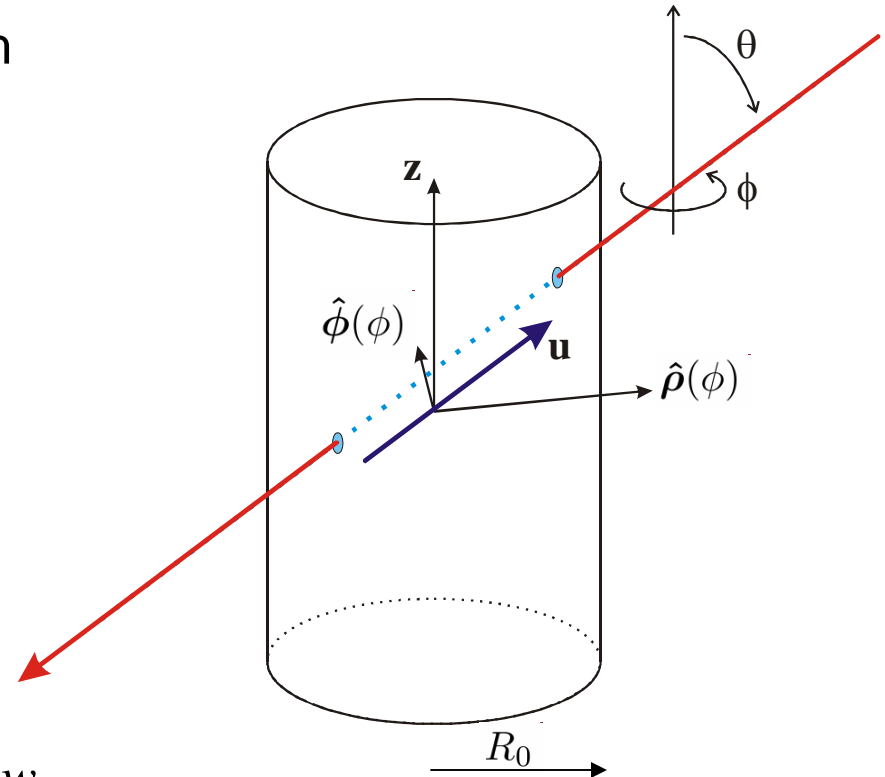
- Entrance and exit locations each found by overlap of 3 strips, one from each layer: “triplets”

- Tracks described by 4 parameters: $\phi, \cot \theta, b, z$

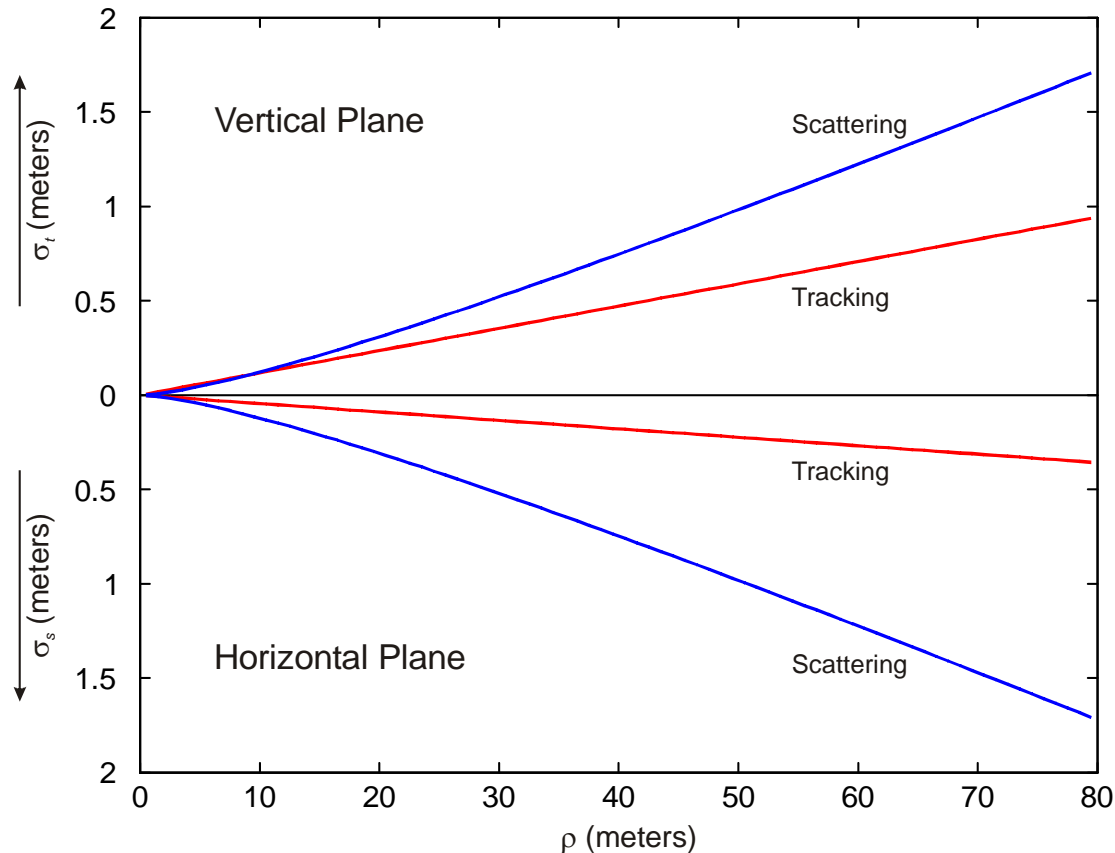
- Direction:
$$\hat{\mathbf{u}} = \frac{\hat{\rho}(\phi) + \cot \theta \hat{\mathbf{z}}}{(1 + \cot^2 \theta)^{1/2}}$$

- Point-of-closest-approach:
$$\mathbf{X}_t = -b \hat{\phi}(\phi) + z \hat{\mathbf{z}}$$

- Resolution determined by width w of scintillator strips



Tracking Resolution Dominated by Scattering (in dense material)



Average tracking errors:
(prototype detector)

$$\langle \sigma_\phi \rangle = 5.0 \text{ mrad}$$

$$\langle \sigma_{\cot\theta} \rangle = 0.013$$

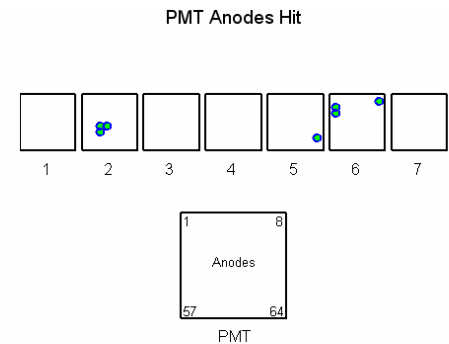
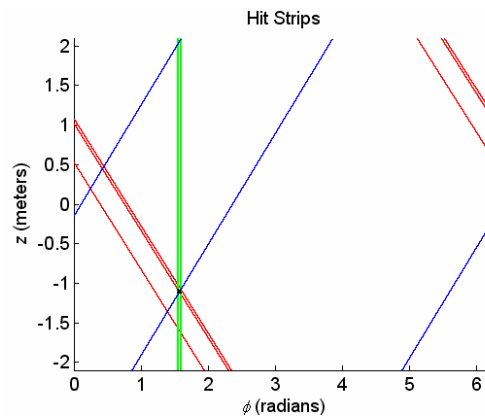
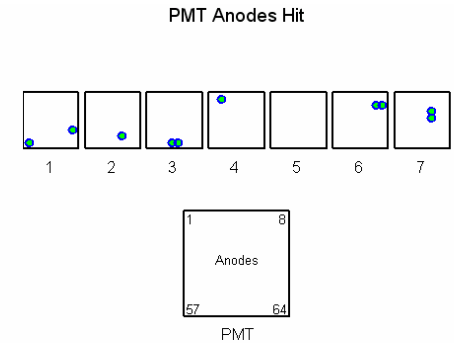
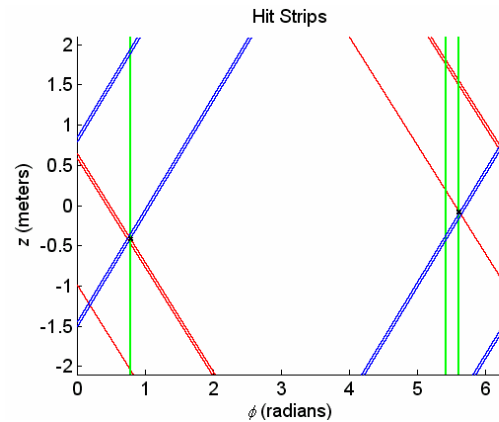
$$\langle \sigma_b \rangle = 3.5 \text{ mm}$$

$$\langle \sigma_z \rangle = 8.9 \text{ mm}$$



Typical Events

- Reading out both ends, independently
- Overall detection efficiency ~50%
- Trigger passes all data to DAQ computer
- PMT cross-talk common, but has minor effect on tracking



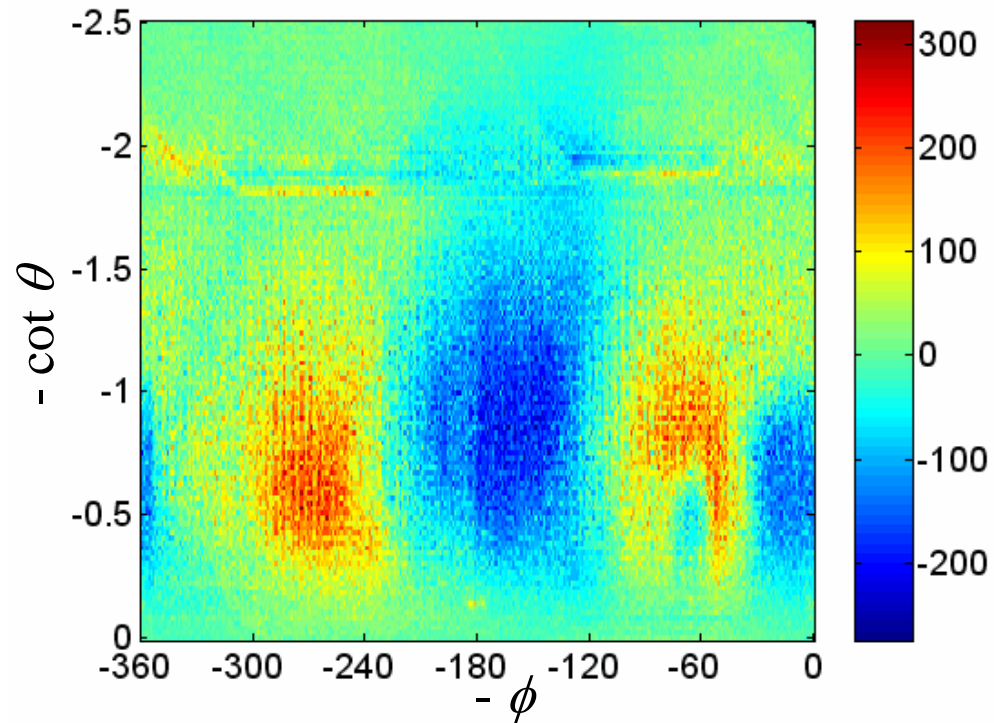
Collecting Data

- Saw crude image of surrounding buildings in first 2-minute run
- Collects ~ 1M tracks per hour
- Currently recording all raw data ~ 1GB/hour
- Tracking software works well—can easily stay ahead of DAQ system
 - Raw data are reduced to track lists for image analysis
 - Will soon switch over to recording tracks only
- Set up test targets of Pb-loaded concrete bricks to test tracking and imaging capabilities

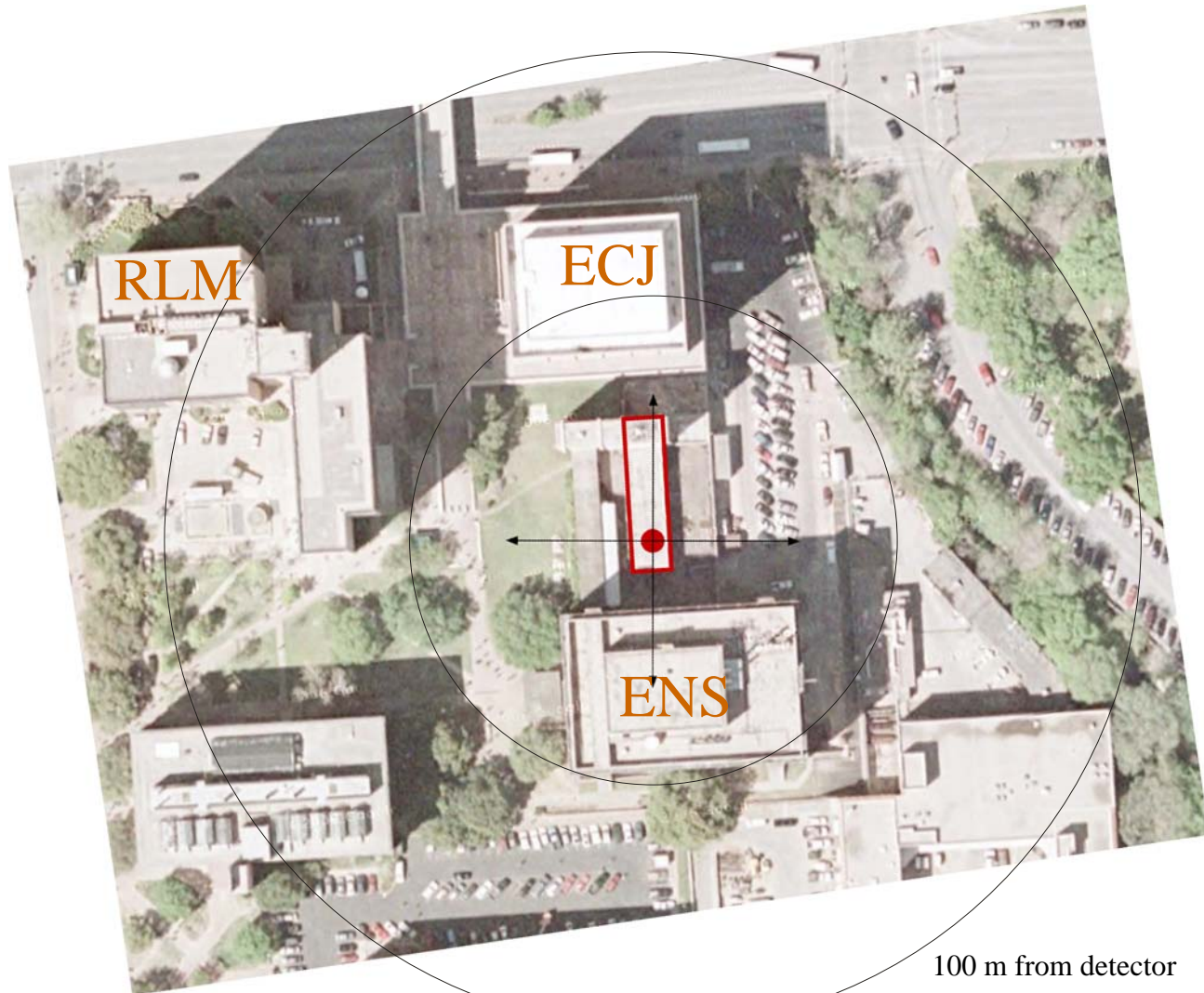


6 Hours of Data

$$N_{i,j} - \langle N_{i,j} \rangle$$



Our Neighborhood

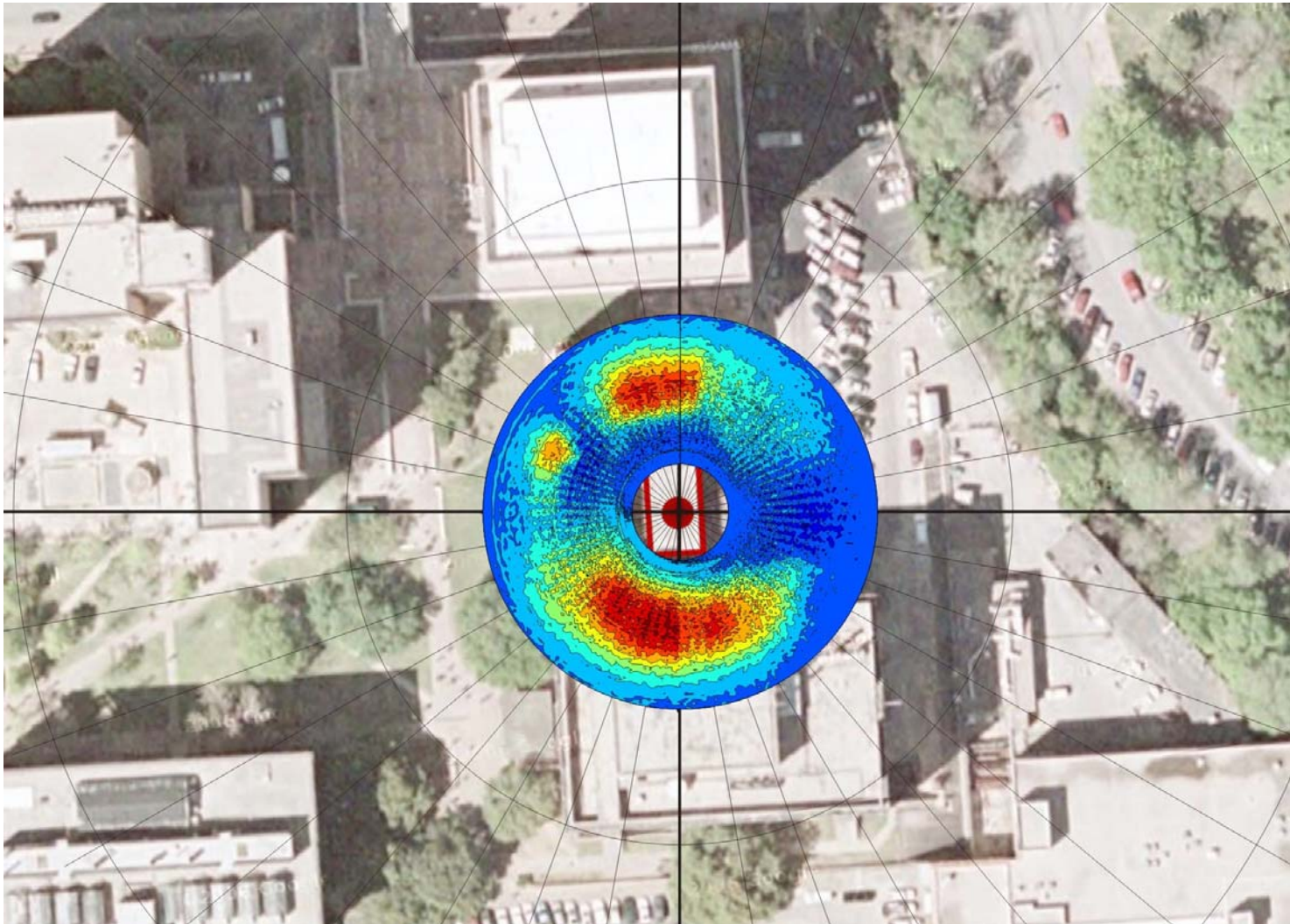


100 m from detector

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Muon "Deficit" θ vs ϕ



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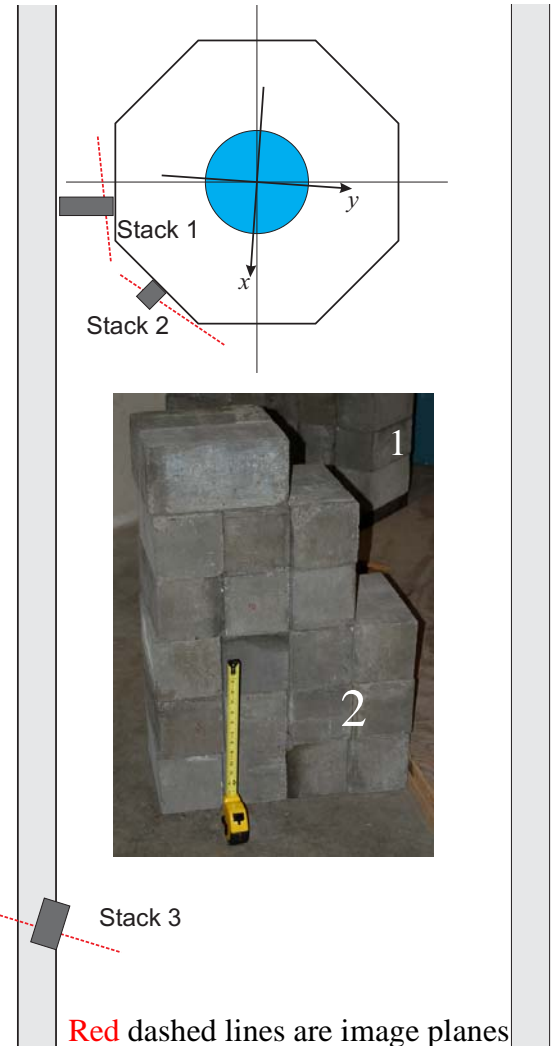
Test Targets: Stacks of Bricks

- Pb-loaded concrete bricks
 - Density = 4.8 gm/cm^3
 - Energy loss:
~ 0.7 GeV/m
- Stacks 1 & 2 run simultaneously
 - 2 m from detector axis
- Stack 3 located on 3-foot thick concrete roof
 - 12 m from detector axis



Detector is 8 m below roof vent

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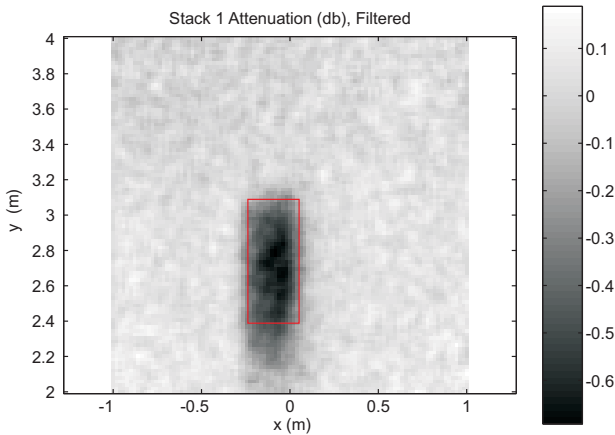


Red dashed lines are image planes

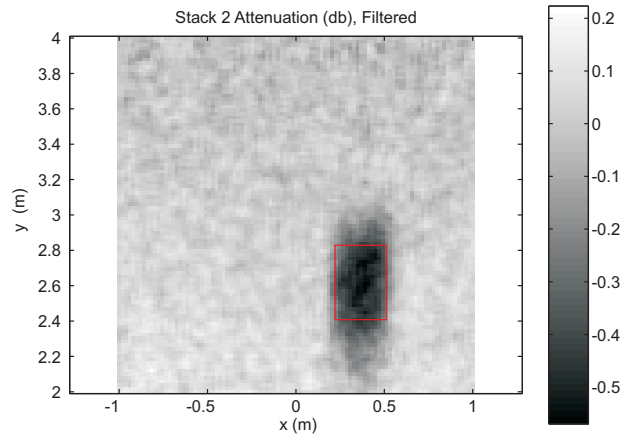
Images

Running time ~ 2 months

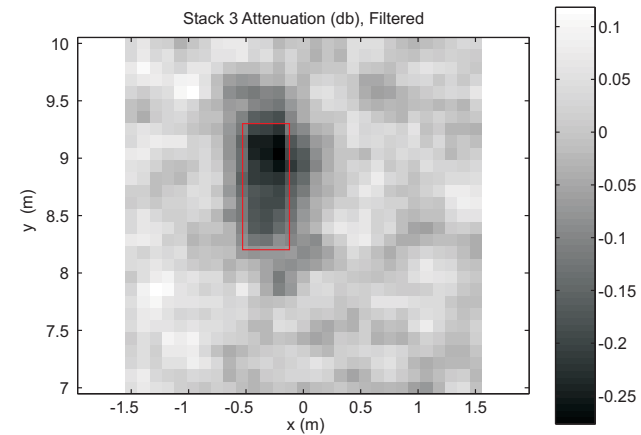
- 1 mo. with stack
- 1 mo. without



Stack 1
2.4 m to detector axis
 $\Delta E = 0.9$ GeV



Stack 2
2.4 m to detector axis
 $\Delta E = 0.6$ GeV

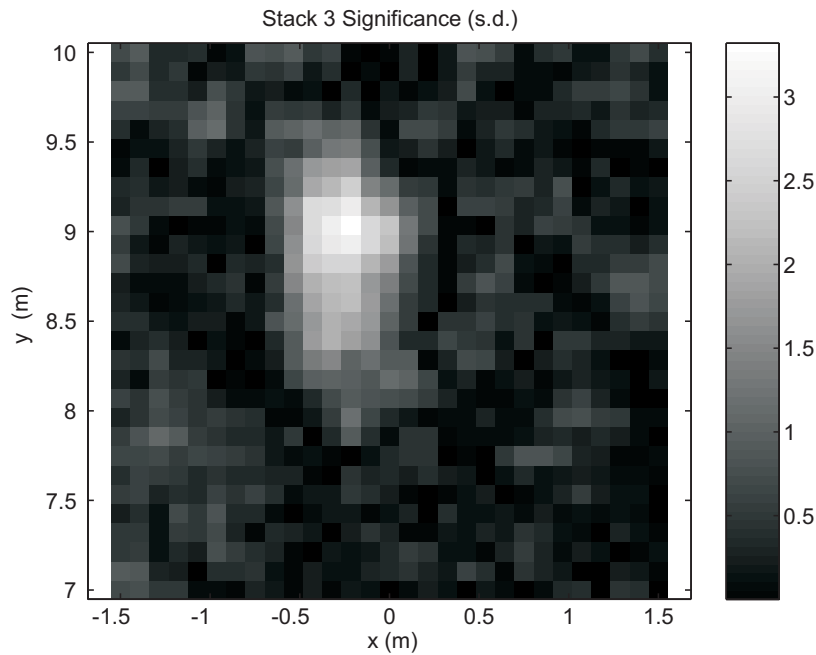


Stack 3
12.2 m to detector axis
 $\Delta E = 0.6$ GeV

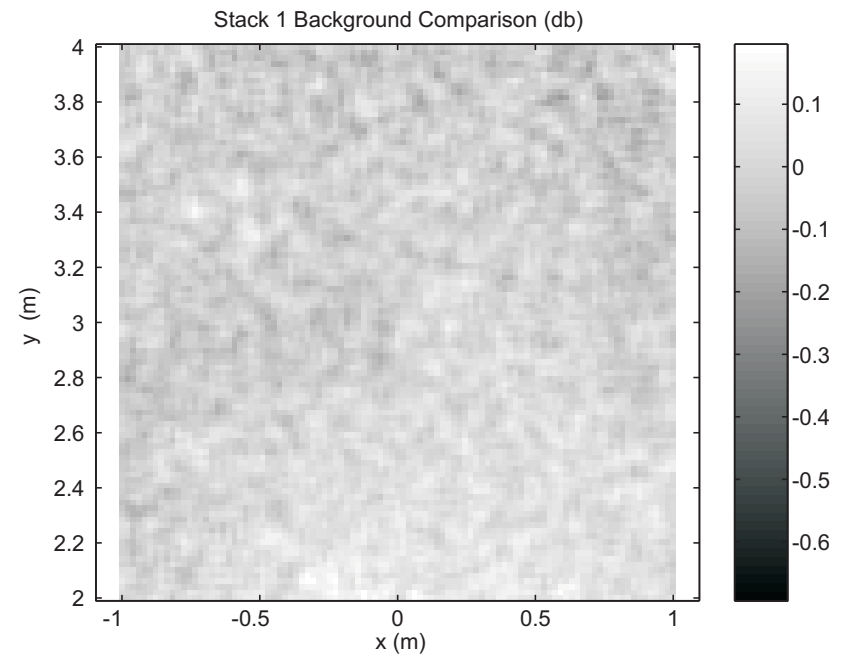
Rates, contrast and resolution all consistent with expectations



Statistics and Stability



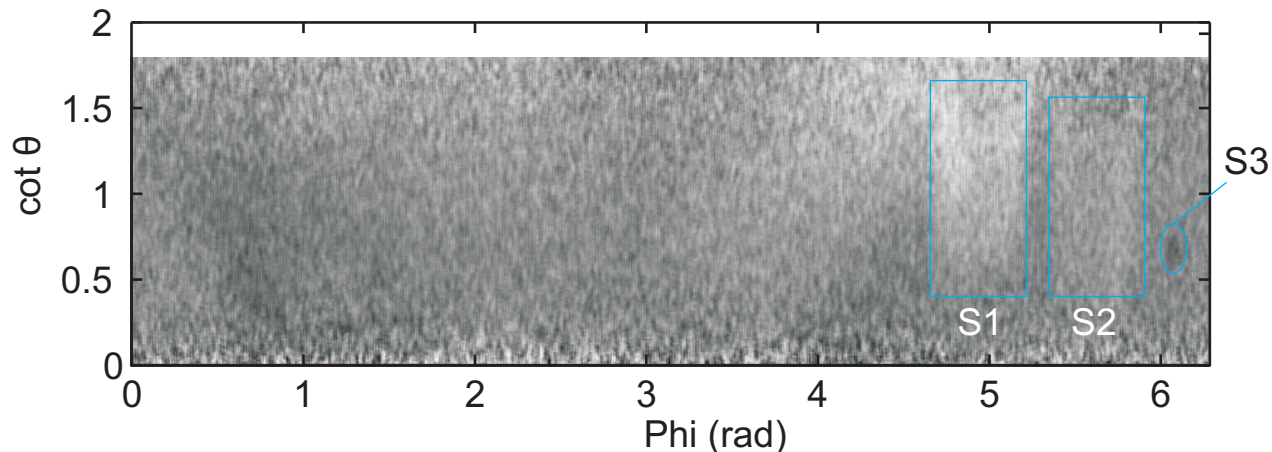
Statistical significance of
signal from Stack 3



Compare background runs
separated by > 1 month

Could We Have Found the Stacks Without Knowing Where They Were?

- Plot attenuation in bins of $(\phi, \cot \theta)$ (an image effectively focused at infinity)
 - Look for changes over 1 month runs
 - Poor “focus” for nearby objects
- The 3 stacks are clearly seen
 - Projections can then be made for detailing the objects using the other two track parameters measured
- Change-detection is verified!
- Full 3-d tomography should be feasible—needs work



Data Analysis Issues

- Discrete detector tracking elements lead to artifacts in reconstructed images
 - 55,360 allowed triplets \Rightarrow $\sim 10^9$ unique reconstructed tracks
 - Not a problem for change-detection
 - A big problem for viewing static images
 - Will be solved by computing appropriate track weights
- 3D reconstruction?
 - Stereo permits a “focus” that can resolve range
 - Multiple detectors planned to better survey volumes of interest
 - We can use help in developing 3D codes!

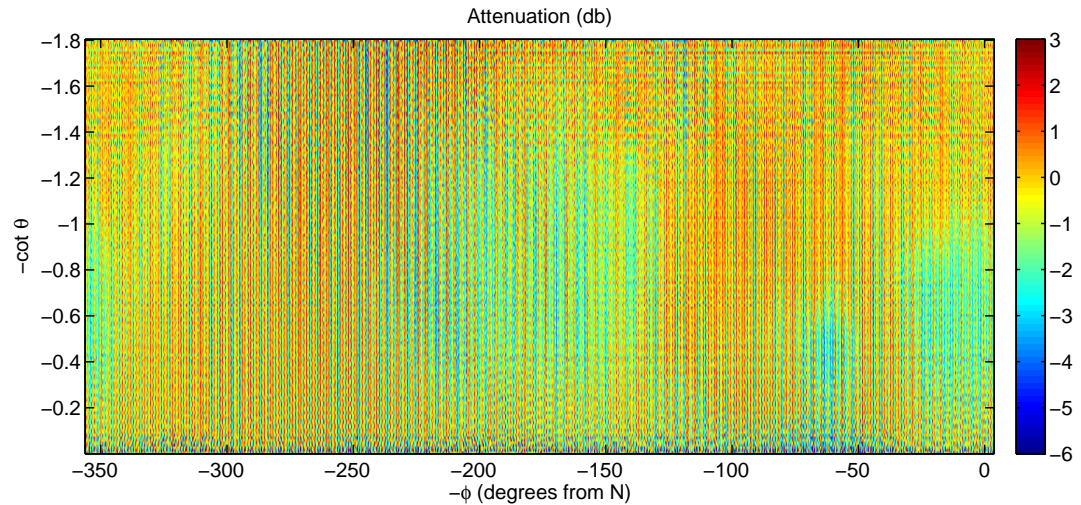


“Cylinder” Plots from Data

Reconstructed data:

Binned at 1σ

Dynamic range limited



Above data dithered:

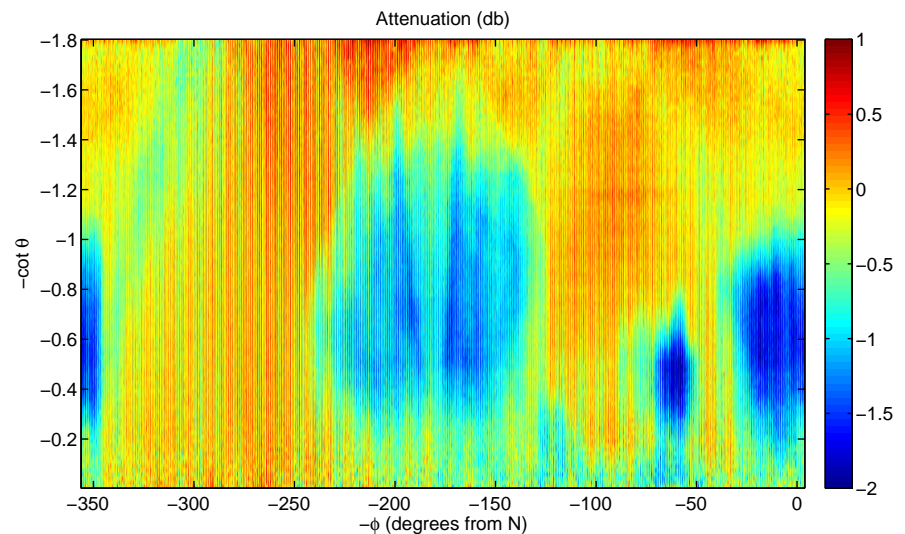
Gaussian + uniform over bin

Re-binned at new 1σ

Note smaller contrast now visible

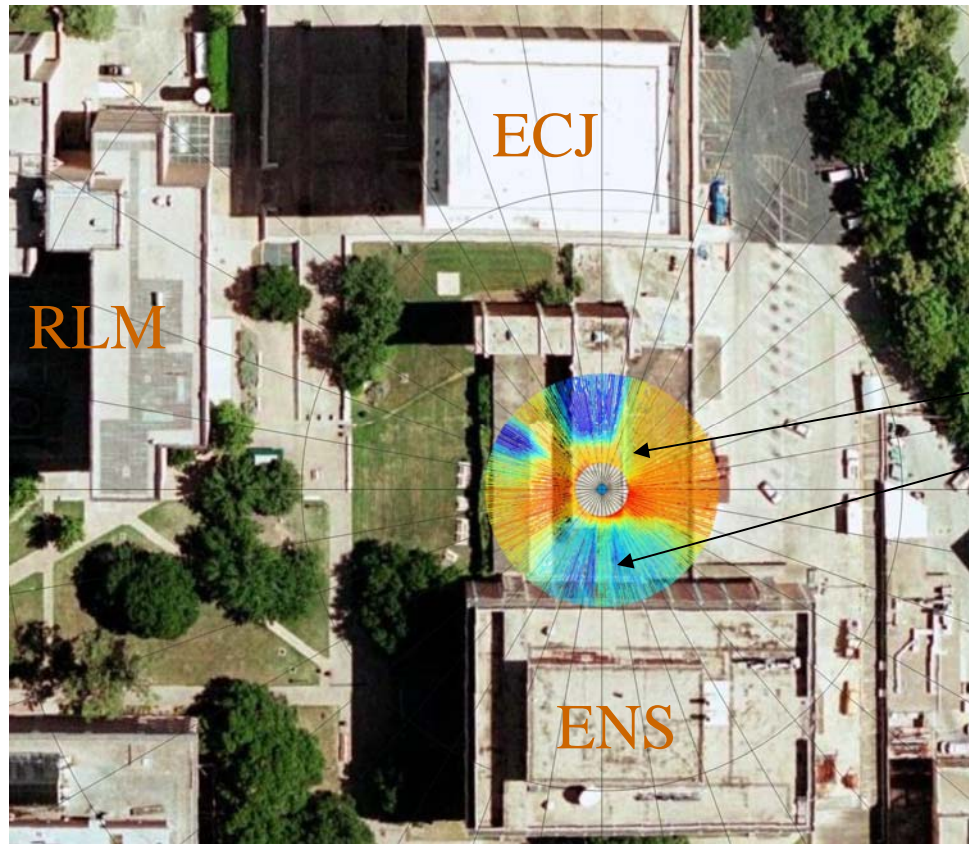
Banding still apparent

Blue patches are muon “shadows”



Nevertheless...

We are starting to see “inside” static scenes



Some details:
Outer shielding of lab
Corridor in ENS

Muon “shadows” projected onto lab roof from ~24 hours of data



Other Potential Applications

- Muon Tomography is good for monitoring large underground volumes ($\sim 100 \text{ m}^3$), provided:
 - You are interested in structures of scale 1 m – 10 m
 - You can afford to wait for weeks to months to acquire the data
 - The volume of interest is between your detector and the sky
- Geological studies of aquifers
- Monitoring of geology surrounding underground sites, e.g. underground nuclear waste storage
- Bank vaults?!

Summary

- Muon tomography is feasible
 - Proven in Alvarez experiment
 - New technologies enable simplified detector design
 - WLS/scintillator tracking well-developed/good match
 - UT prototype detector providing useful data for developing reconstruction software—we would welcome collaborators!
- Excellent project for engaging students
- Other applications are possible
- Maybe we can help to learn more about the Maya!



Contributors

- UT Physics
 - Jared Bennett, Mark Cartwright
 - Brian Drell, JJ Hermes
 - Becket Hui, Jeremy Johnson
 - K. Krishnakumar, Nicholas Raspino
 - Cesar Rodriguez, Anandi Salinas
 - Mark Selover, Derrick Tucker
 - Brad Wray, Eric Wright
 - H. Adam Stevens
 - Austin Gleeson, RFS
- UT Electrical & Computer Eng.
 - Bill Bard, Lizy John
 - Carlos Villarreal
 - Elizabeth Van Ruitenbeek
 - Daniel Garcia, Nakul Narayan
- Fermilab—Scintillator Production
 - Anna Pla-Dalmau
- Harvard HEPL—Front-end Electronics
 - John Oliver, Sarah Harder
- Other physicists who participated in the early stages
 - Prof. Rich Muller, UC Berkeley
 - Dr. Dick Mischke, LANL
- UT Mesoamerican Archaeological Research Laboratory (MARL)
 - Prof. Fred Valdez, Director
- National Instruments
 - Hugo Andrade, Joe Peck



The Real World



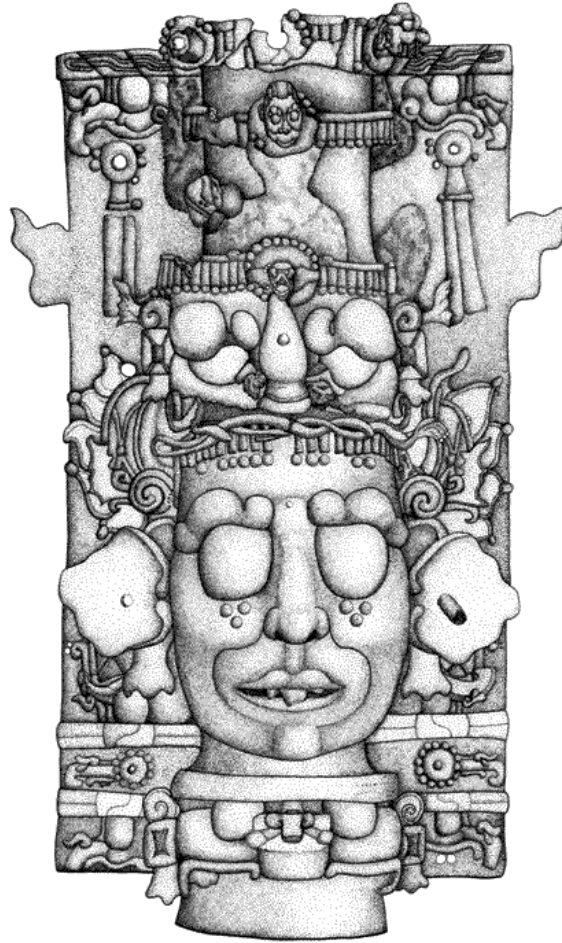
➤ Funding

- Sandia National Lab provided detector development funds
- UT funds supporting studies, students
- Physics Department machine shop and electronics shop support
- National Instruments provided assistance with DAQ
- Private donors being sought to fund “jungle-related” costs

➤ Logistics

- First establish feasibility at UT: underway
- Support in Belize: transportation, excavation, operations

Backup Material

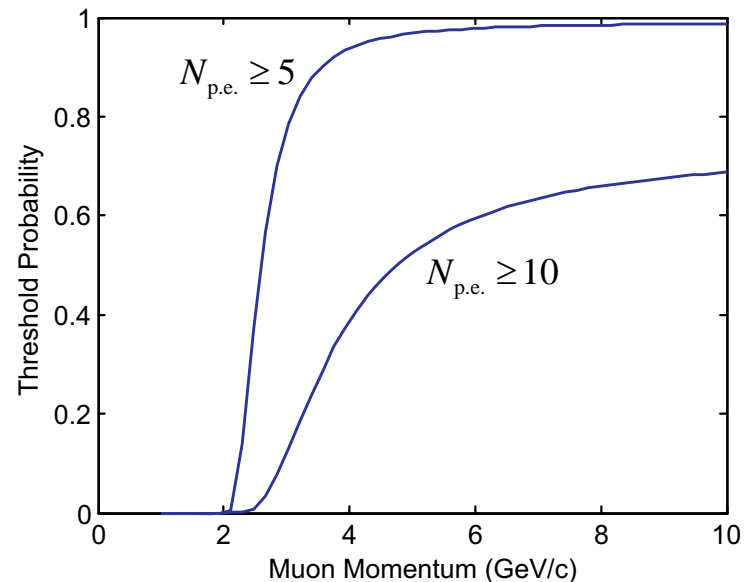


Discrimination Against Low-energy Muons

- Multiple-Coulomb scattering is large for muons near the end of their range
- Require minimum value for detected E_f ; options:
 - Energy loss in iron absorber:
 - Heavy ~ 1m thickness
 - Requires additional tracking layers
 - Detect Cherenkov radiation
 $\Rightarrow v > c / n_{\text{gas}}$
- Cherenkov threshold can be imposed/adjusted at data analysis stage

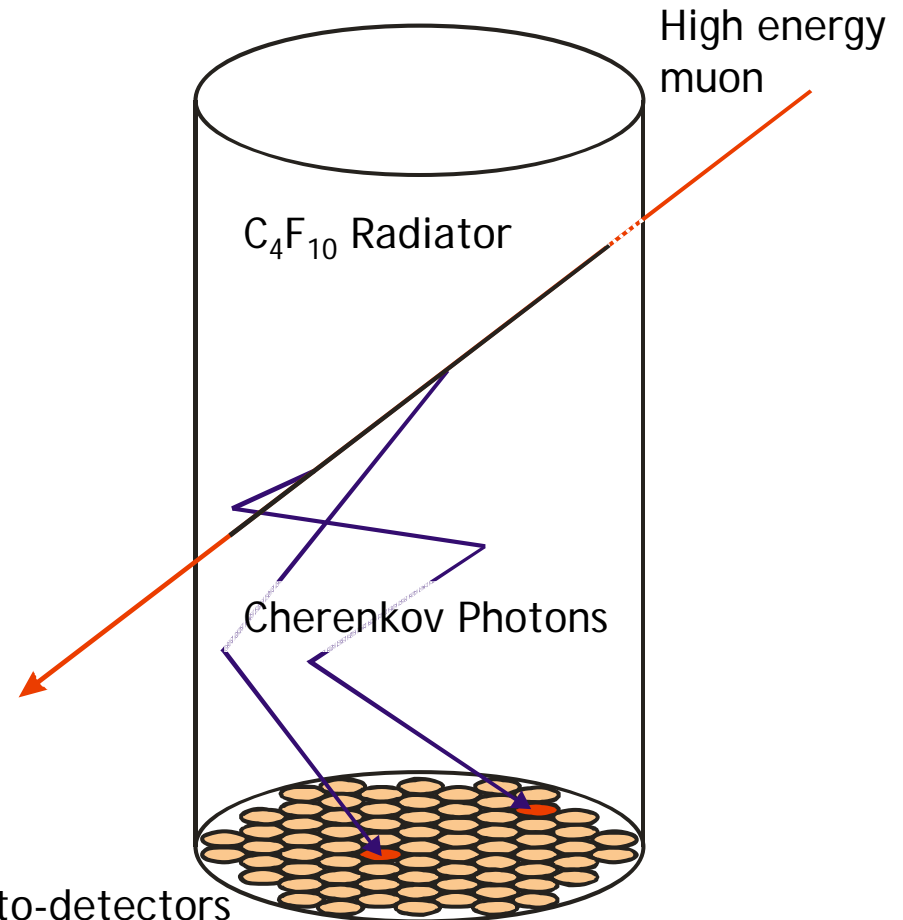
$$\delta\theta \approx \frac{0.055}{\sqrt{E_f \text{ (GeV)}}} \text{ for } E_f \ll E_i$$

Cherenkov threshold curves:



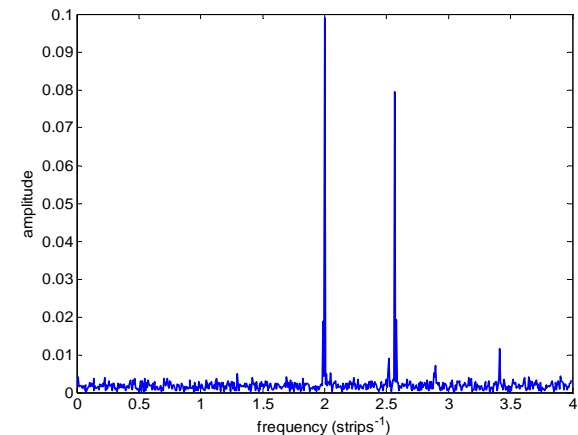
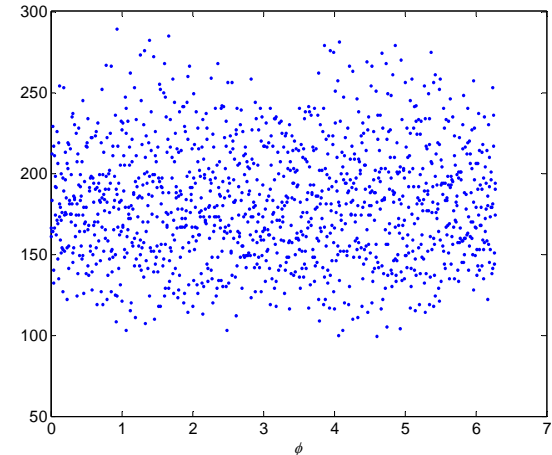
Cherenkov Threshold Implementation

- Fill central cylindrical volume of detector with Cherenkov radiator gas: C_4F_{10}
 - Muon threshold ~ 2 GeV
 - $\beta = 1$ p.e. yield: ~ 35 /meter of radiator
 - C_4F_{10} is a freon used for fire suppression
- Make inner surface of cylinder optically reflecting
- Place array of photon detectors on *bottom* of cylinder
- Development is deferred at present



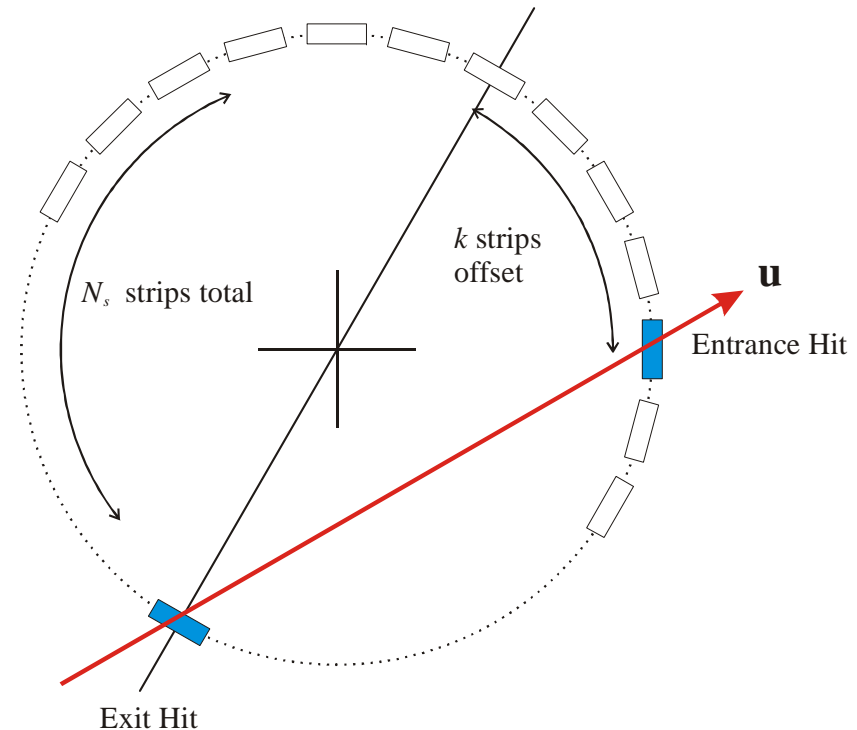
Simulation to Understand the Character of the Banding in ϕ

- Non-statistical spread in 1σ -binned histograms
 - 1300 bins in $\phi \sim 1\sigma$
 - $\sim 2x$ greater fluctuations than statistics of simulation alone
- Strong, high-frequency Fourier components
 - FFT “found” correct strip pitch to 4 significant figures!
 - Impossible to smooth the ϕ distribution using FFT results



Strong Fourier Component at $1/2N_s$ Is No Surprise

- ϕ banding: a kind of Moiré interference, similar to looking through a cylinder composed of slats
- Reconstruction assumes track goes through strip center
- Figure indicates only the axial strips
 - Possible $\phi_{\mathbf{u}}$ quantized into $2N_s$ values
 - Helical layers spread out allowed values
 - Acceptance is a $f(k, \cot\theta, z)$



$$\phi_{\mathbf{u}} = \phi_{\text{exit}} + \pi \pm \frac{k}{2N_s} 2\pi$$

Muon Shadow Detail

