Imaging Maya Pyramids with Cosmic Ray Muons

An Application of the Tools of High Energy Physics

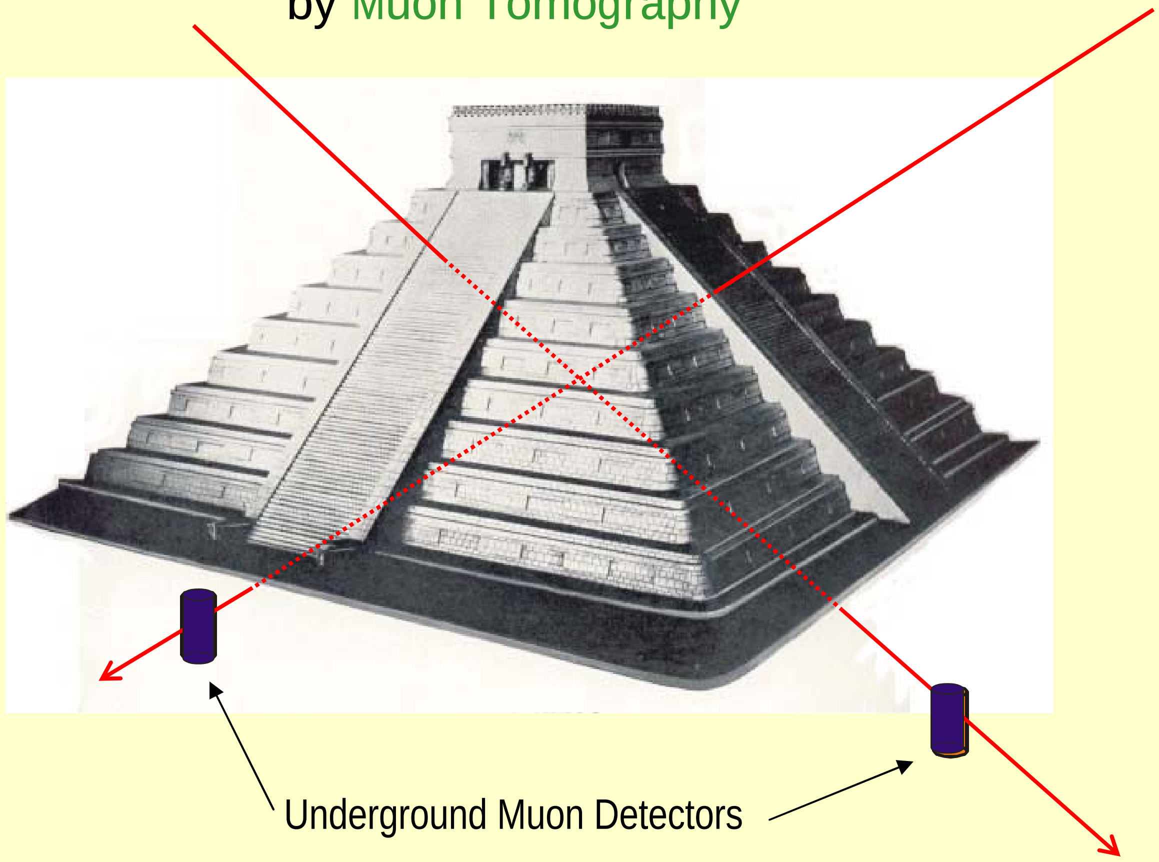
The Maya: Extraordinary American Culture

Some Background

- 1839-*ff*: John Lloyd Stephens with Frederick Catherwood, artist
  - *Incidents of Travel in Central America, Chiapas, and Yucatan* (1841)
  - *Incidents of Travel in Yucatan* (1843)
- Linda Schele (1942 – 1998) UT Austin
  - *The Code of Kings* (1998) with Peter Mathews

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
  - Mainly high energy protons
  - Showers of π's/K's created
  - Decay within 10's – 1000's meters or collide with nuclei 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
- Approximate muon rate at Earth's surface:

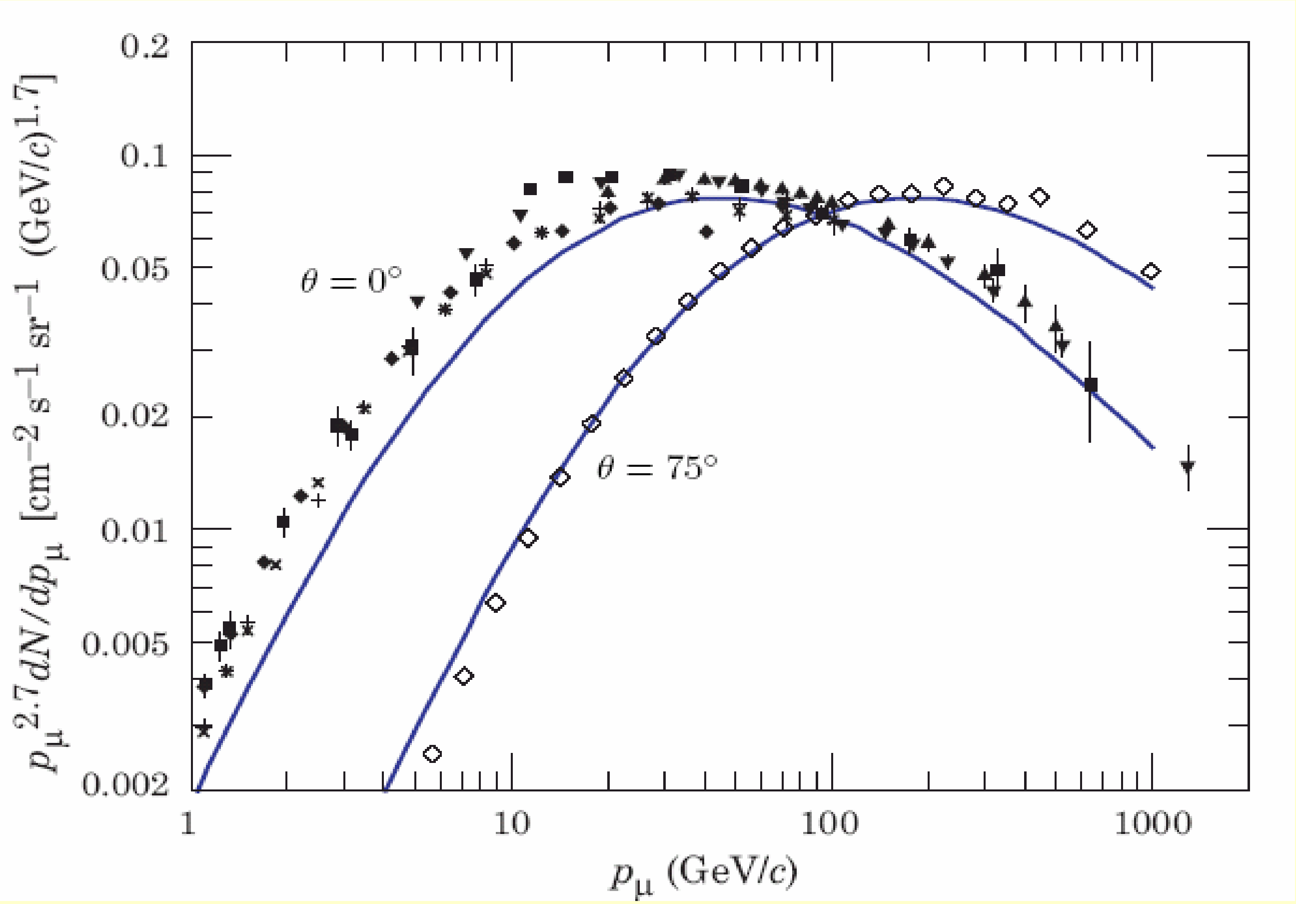
$$\Lambda_{\text{int}} \approx 50\ \text{gm/cm}^2$$

$$c\tau_\pi = 7.8\ \text{m}$$
$$c\tau_K = 3.7\ \text{m}$$

$$c\tau_\mu = 660\ \text{m}$$

$$\sim 1/\text{cm}^2/\text{sr/minute}$$

Muon Flux at Surface



Muon Interactions in Matter

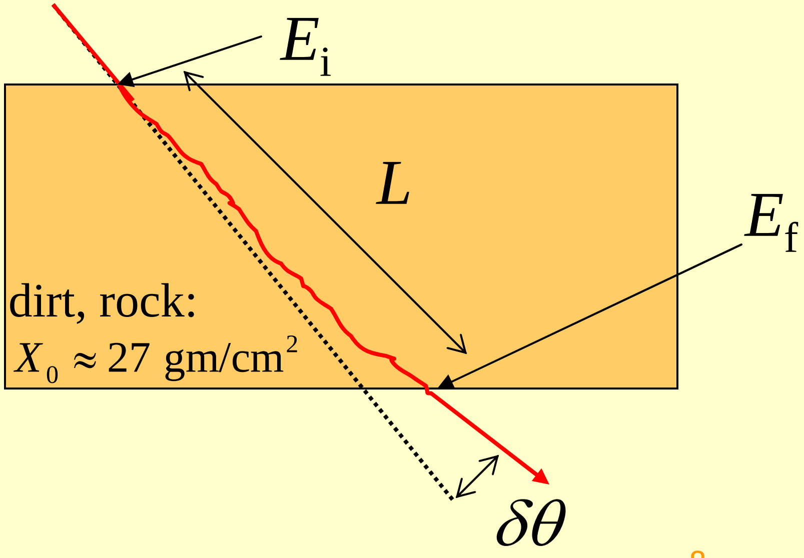
- Energy loss: predominately by ionization

$$\frac{dE}{dx} \approx 2.3 \text{ MeV/gm/cm}^2 \approx 0.6 \text{ GeV/m in rock}$$

- Multiple-Coulomb Scattering

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

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

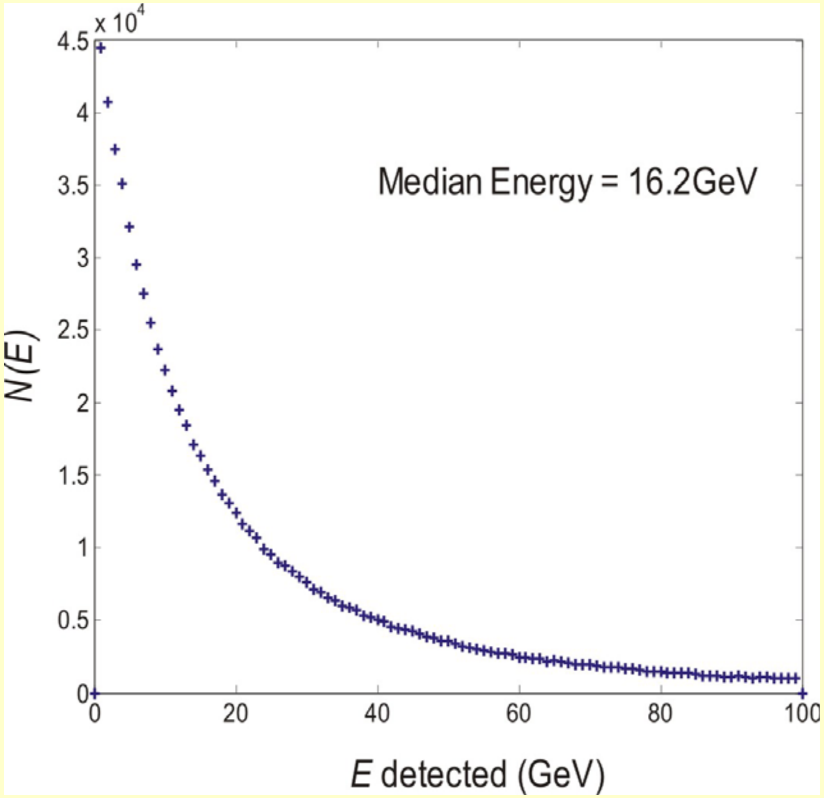


Muons at the Detector

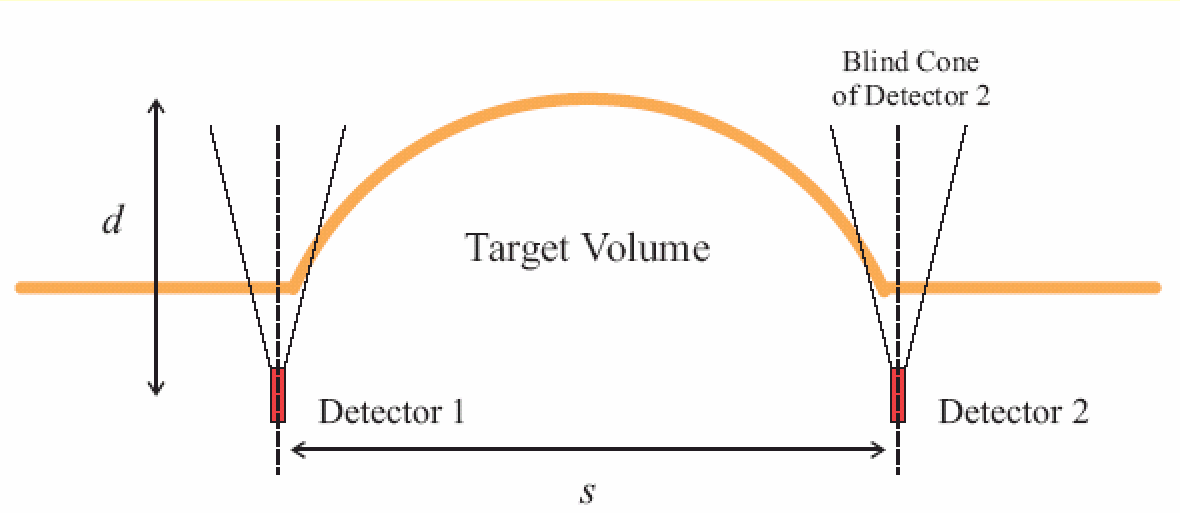
- Typical detected energy spectrum shown:
- Coulomb scattering large for tracks near end of range; nearly *independent* of scattering material and initial muon energy

$$\delta\theta \approx \frac{0.055}{\sqrt{E_f\,(\mathrm{GeV})}} \quad \text{for } E_f << E_i$$

- May need to "harden" the spectrum to reduce blurring (Alvarez used iron absorber)



Arrangement Involving Cylindrical Detectors

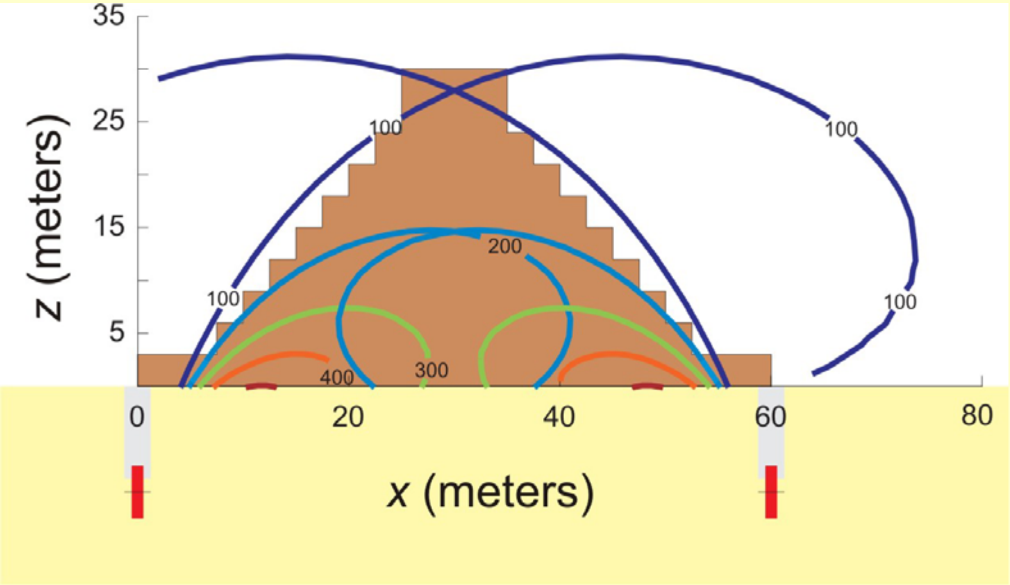


- Use 2 or more detectors
  - Compensates for "blind cone" inherent in cylindrical detectors
  - Improved stereo sampling of target volume
  - Symmetry of cylindrical detectors good for measuring "average" image
- Minimizes excavation

Basic Rates/Exposure Times

- Extreme Case:
  1 m^3 void at 50 m
  - Solid angle $\Delta\Omega = 1/50^2$
  - Active area $A = 3\ m^2$
  - 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)

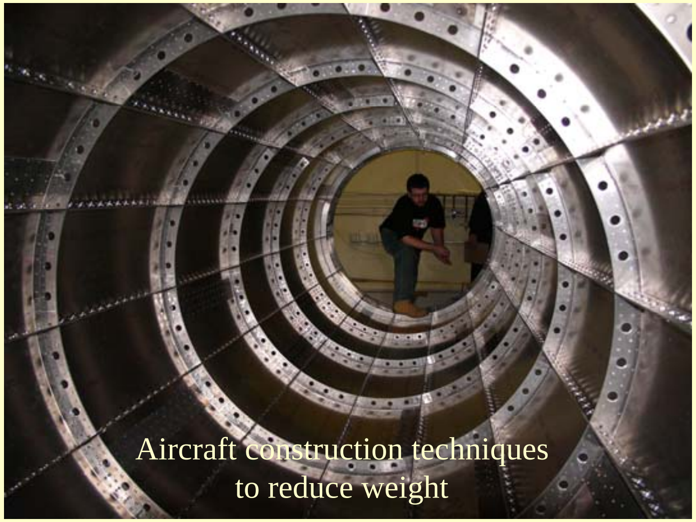


Detectors

- Cylindrical structure
  - 1.5 m diameter
  - 4.5 m long
- Muon tracking
  - 3 stereo layers
  - WLS-scintillator technology
  - PMT readout
- Threshold energy selection
  - Use inner volume as a Cherenkov radiator
  - PMT readout
- Other systems
  - Electronics
  - Mechanical
  - Power/communications

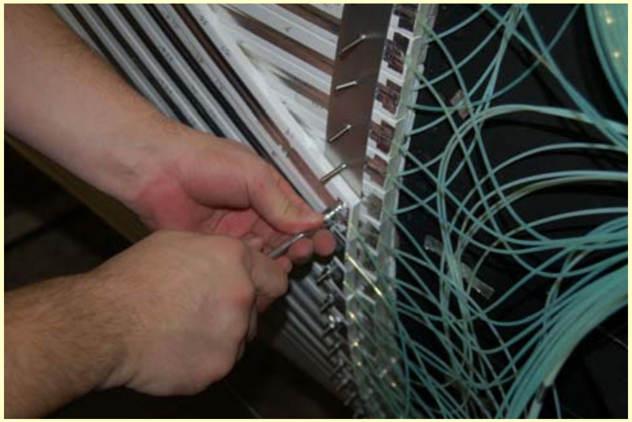
Frame


Completed frame during lay-up of scintillator strips


Aircraft construction techniques to reduce weight


PMTs and electronics will be mounted in end-rings

Tracking System Elements

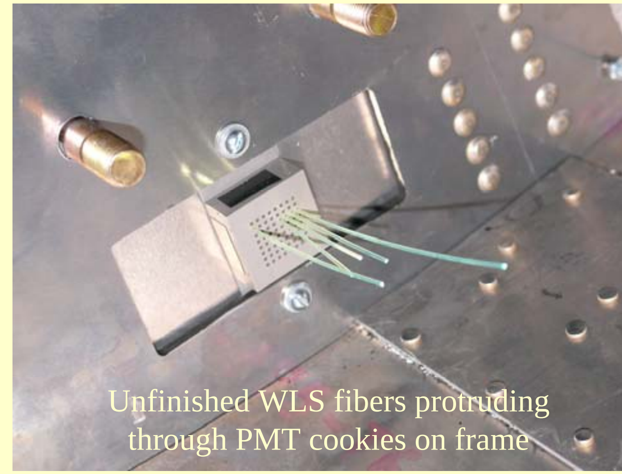


"MINOS" scintillator
- 30 mm wide
- 10 mm thick

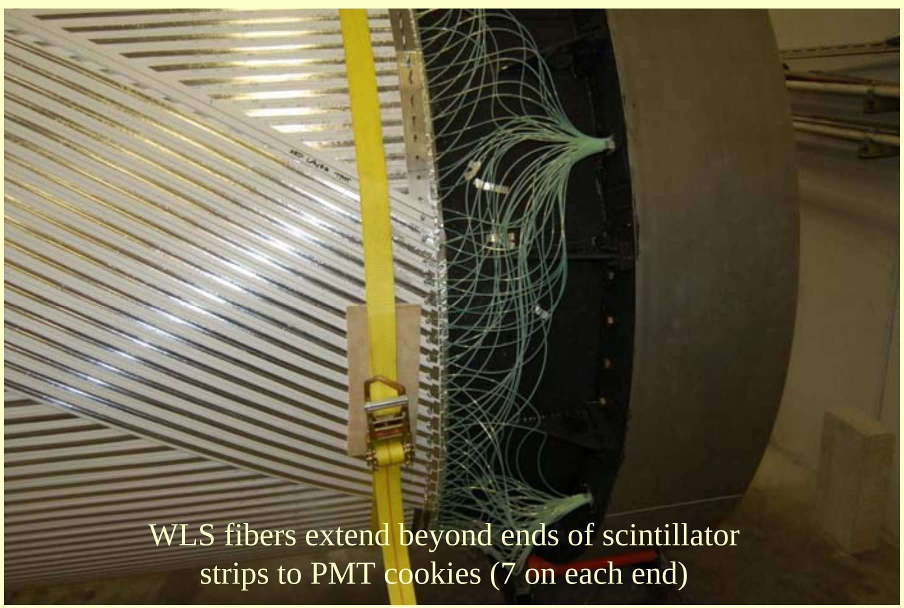
WLS fiber readout

2 helical layers
1 axial layer (center)

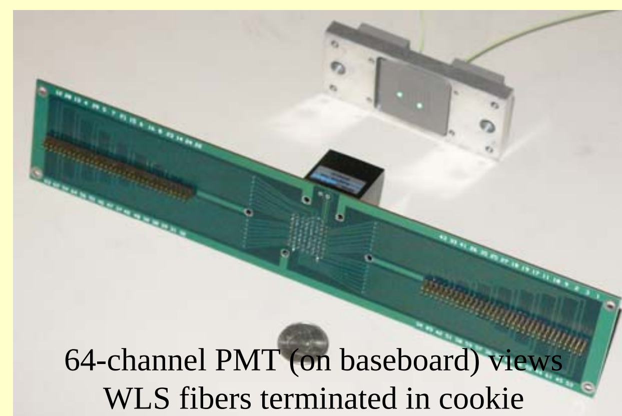
441 total strips



Unfinished WLS fibers protruding through PMT cookies on frame

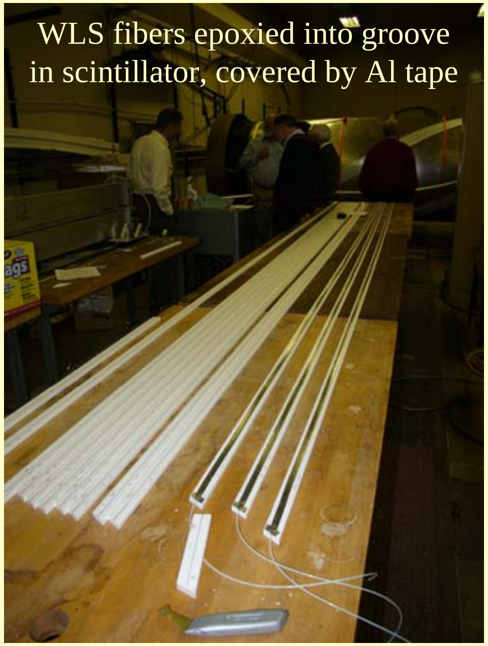


WLS fibers extend beyond ends of scintillator strips to PMT cookies (7 on each end)



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

Scintillator Installation


WLS fibers epoxied into groove in scintillator, covered by Al tape


1^{st} end of strip secured with machine screw, temporary straps applied


Helical wrap applied with twist; temporary straps tensioned

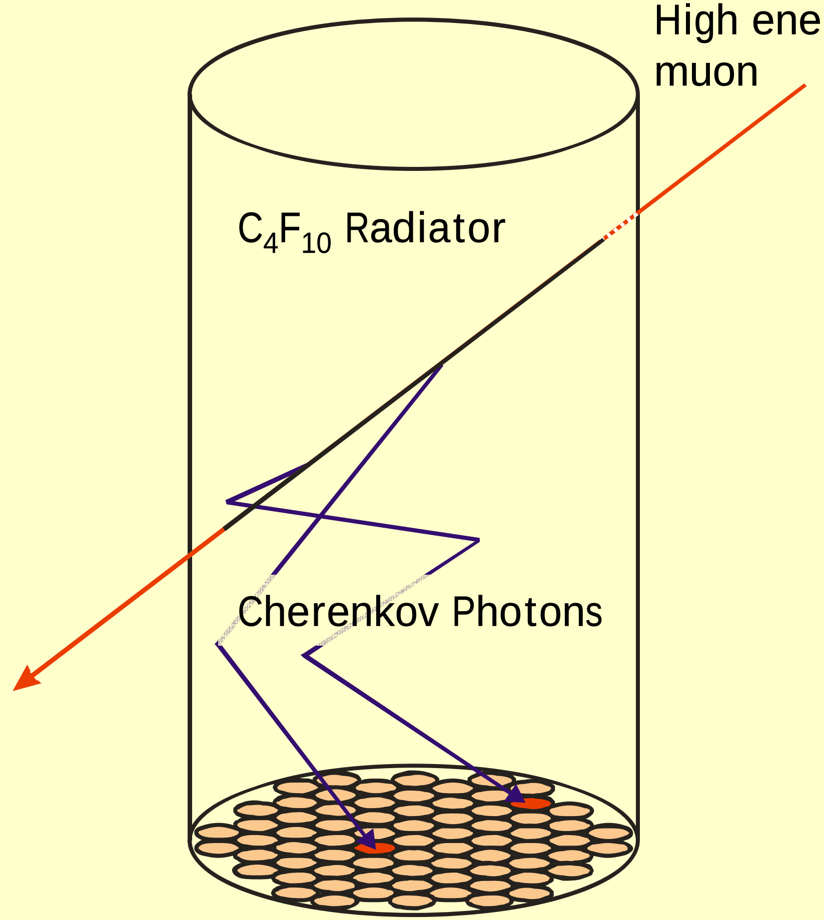

Strip attached along full length with double-sided adhesive tape


Secure 2^{nd} end of strip

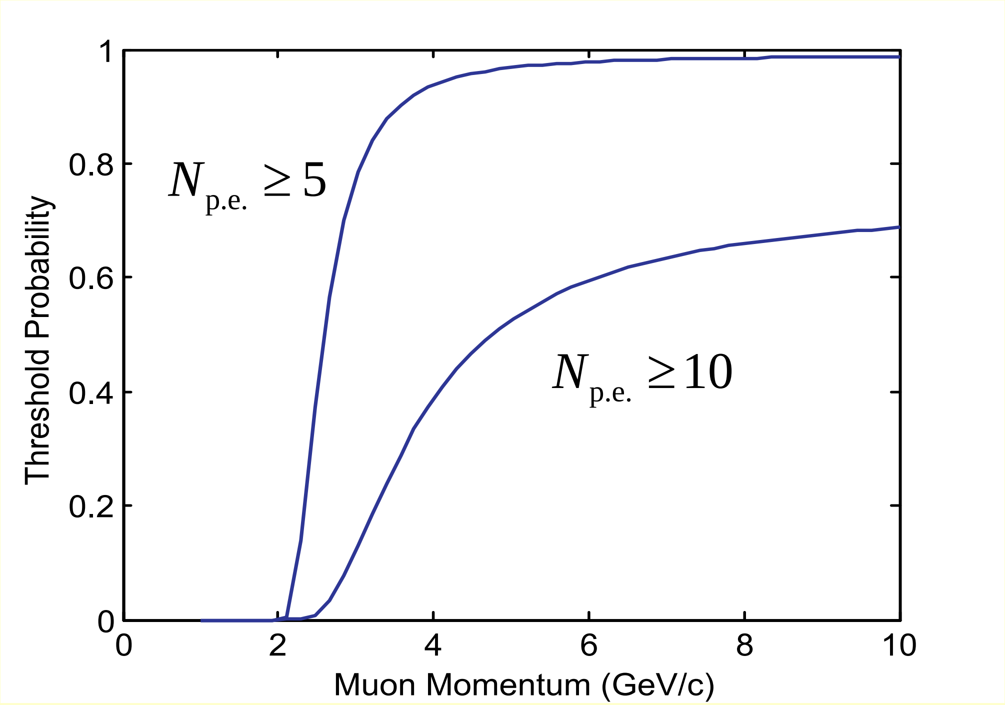

Plug fiber into PMT cookie

Cherenkov Threshold Implementation

- Fill central cylindrical volume of detector with Cherenkov radiator gas: C_4F_{10}
  - Muon threshold ~ 2 GeV
  - β = 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

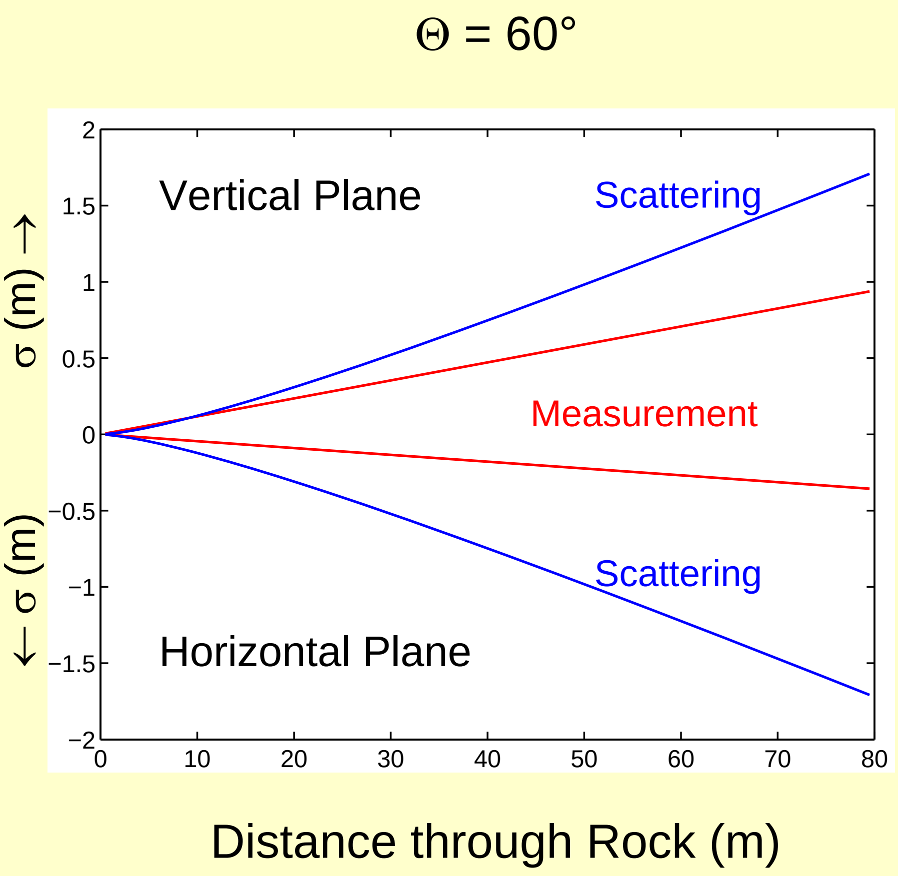


Expected Cherenkov Threshold Curves



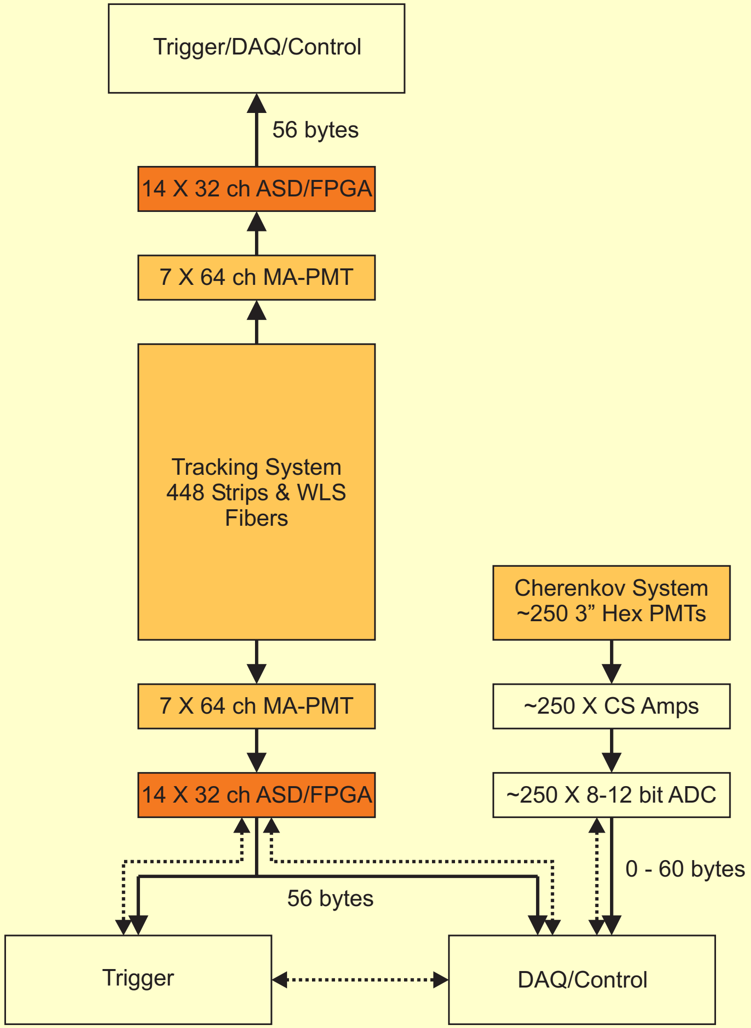
Tracking Resolution

- Measurement errors
  - Determined by strip width and stereo angle
  - σ < 1m in both planes
- Multiple-scattering
  - Will dominate tracking errors for *R* > 40 m
  - Higher Cherenkov threshold can mitigate
  - GEANT simulations in progress



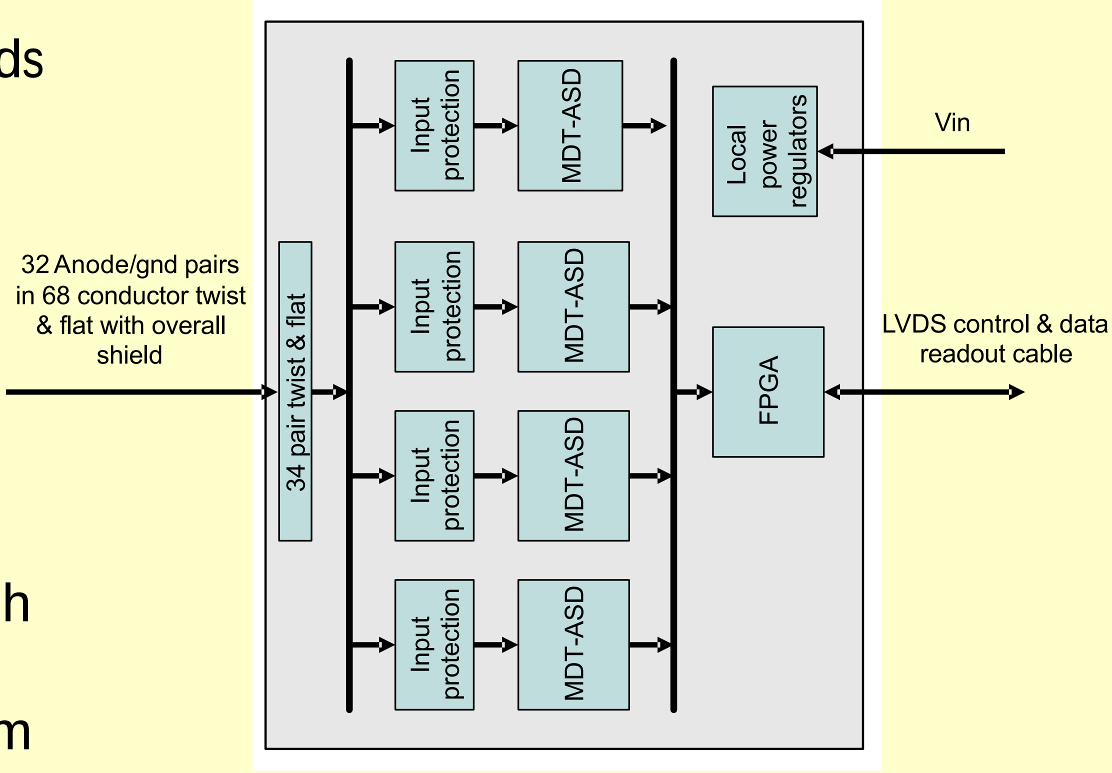
Detector Electronics Systems

- Data from detector
  - Tracking: 2X448 “hit” bits
  - Cherenkov: Analog out
- Trigger
  - Based on tracking information only
  - Programmable logic
- DAQ
  - All tracking bits
  - Cherenkov hits *above* pedestal
- Control
  - Trigger/DAQ control
  - Monitor all detector systems



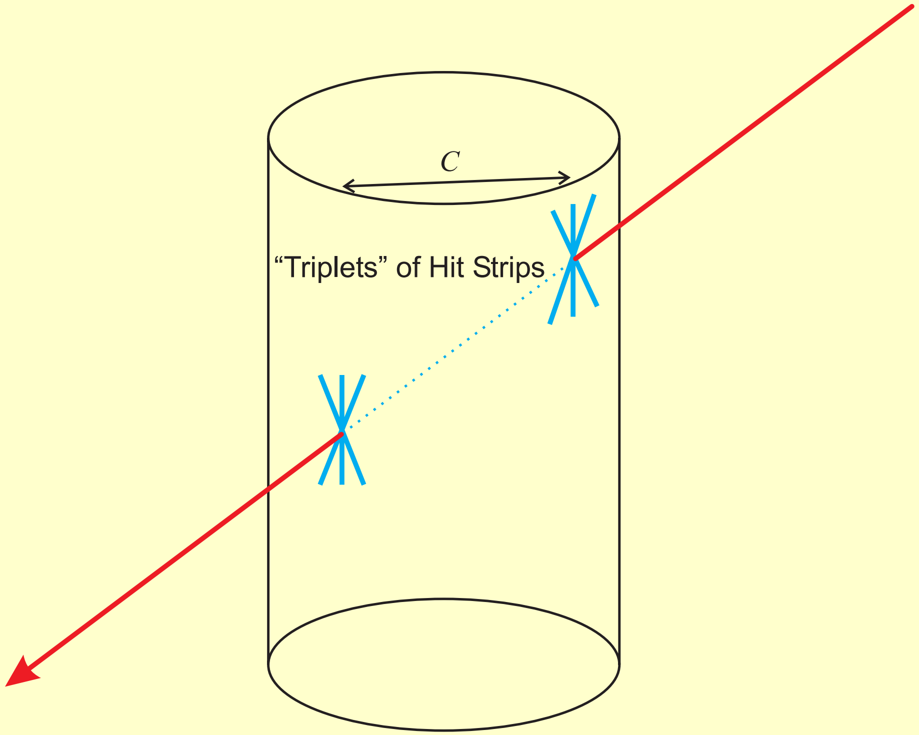
Tracking PMT Front-end Boards

- Based on Harvard design for Atlas Muon System (LHC)
- Complete set of boards assembled
- Now running FEBs with National Instruments "Compact RIO" system



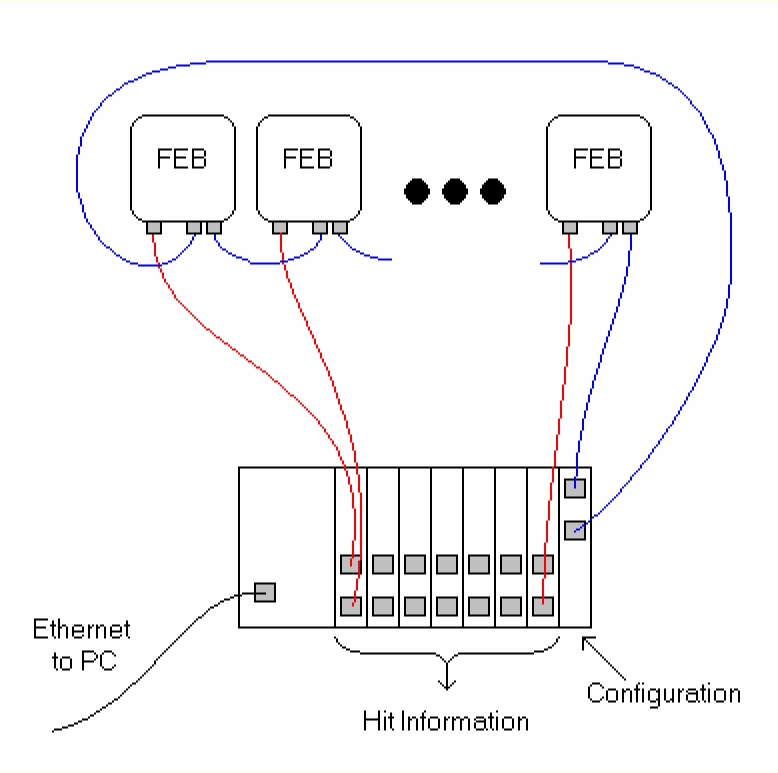
Trigger Requirements

- Use only tracking information
- Require:
  - >/= 2 Hit "Triplets"
  - Chord $c > c_{\text{min}} = 1.2\ R$
- Flexible definition of Triplet
  - Coincidence gate: 25—50 ns
  - Number/pattern of hits to balance:
    - Noise – singles rates
    - Inefficiencies
- Typical rates:
  - True events ~ 500 Hz
  - CR singles:
    - ~ 5 KHz full detector
    - ~ 30 Hz per strip



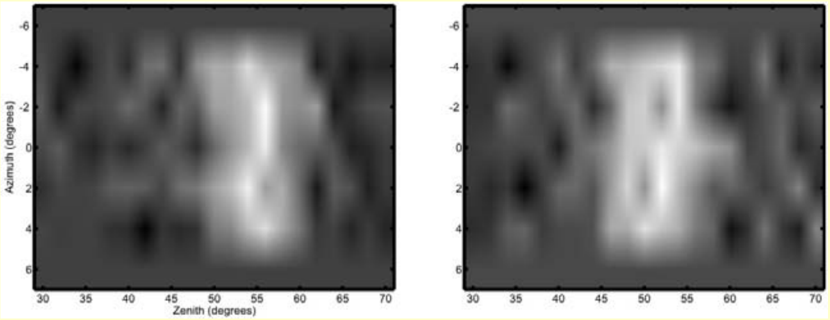
Data Acquisition/Trigger

- Use National Instruments "CompactRIO" system
  - FPGA processor for trigger
  - 8 I/O modules
    - 7 communicate with the 14 FEBs on a single end
    - 1 configuration control
- NI software
  - LabView FPGA for programming cRIO and FEBs
  - LabView for Online environment and monitoring

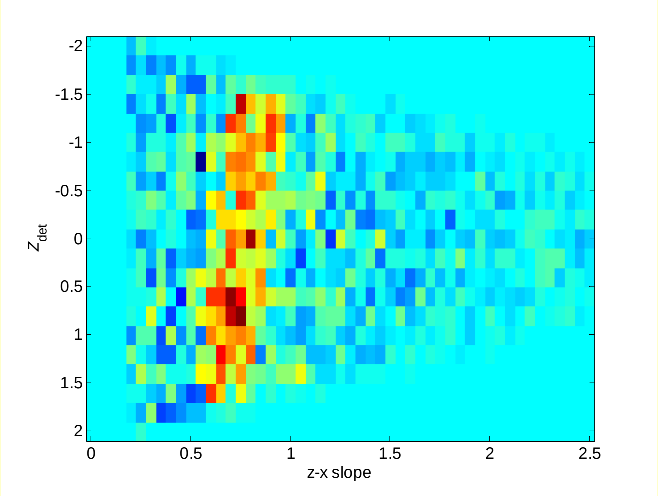


Imaging

- Have begun studies of imaging with a single detector
  - Stereo pairs of spherical projections
  - Radon transformations
- Collaboration expected with UT CS experts
- Extensive sets of tools available:
  - MATLAB
  - LabVIEW



Simulated tunnel 20m distant in one week of running



$$z_{\det,i} = z_{\text{tunnel}} - x_{\text{tunnel}} \left(\frac{p_{z,\det}}{p_{x,\det}} \right)_i$$

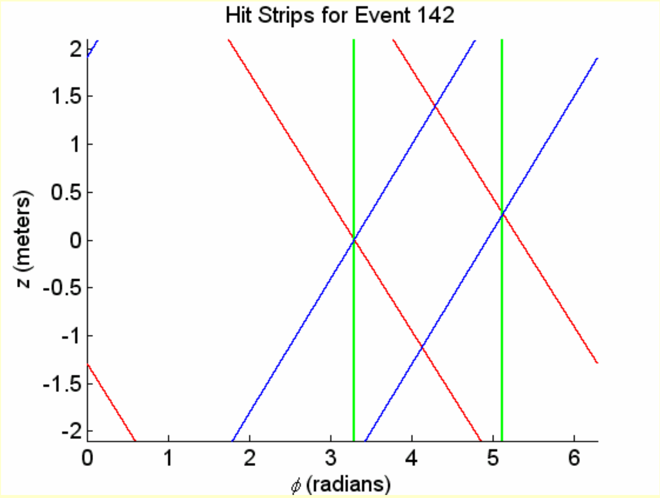
Detector Summary

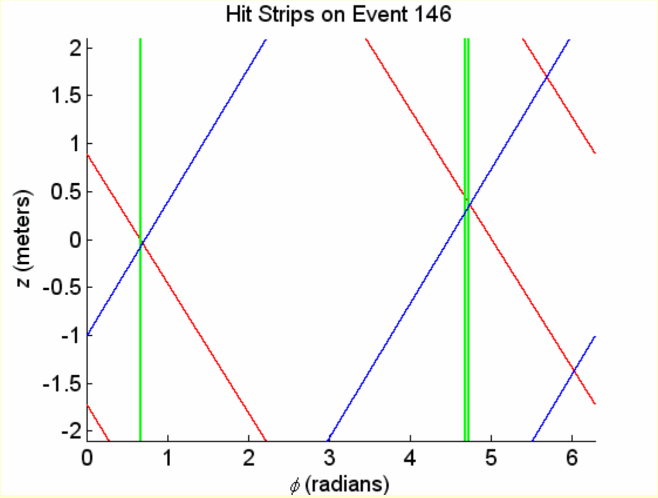
- 2 units to be built (for 3-D reconstruction)
  - 1.5 m diameter
  - 4.5 m long (for convenience in fabrication/operations)
- Tracking
  - 3 stereo (0°, ±30°) layers of scintillator/WLS fibers
  - 30 mm strip width; up to 448 strips per detector unit, readout both ends
  - PMT readout; 28 Hamamatsu M-64's total (no multiplex)
- Cherenkov threshold discrimination
  - Reflective inner cylinder with C_4F_{10} radiator
  - PMT detection on bottom face of cylinder
  - Typical thresholds ~ 5 – 10 photoelectrons
- Data acquisition/trigger: ~100 bytes/event, 10—100 Hz rates
  - Commercial DAQ: NI LabView
  - Simple majority-logic/event-topology-based trigger
  - Local data storage with periodic readout to base station

March 2006

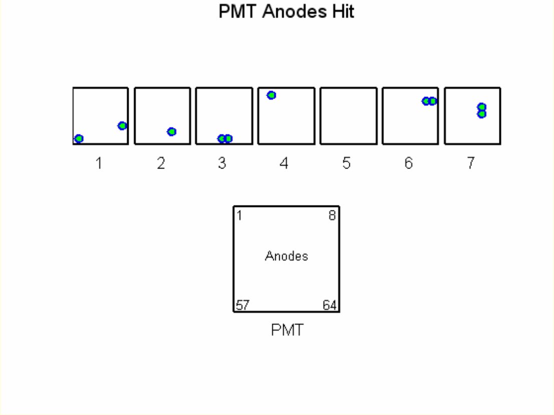
Started Running in Fall 2006

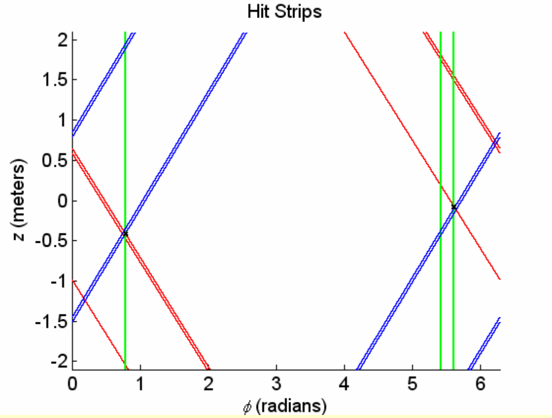
- Detector in Horizontal Orientation
  - Reading out both ends
  - Clocks *not* synchronized
  - Detected/tracked cosmic ray rate ~200 Hz per end
- Some technical details:
  - Singles rates < 100 Hz/strip
  - Minor light-leaks found using data (and fixed)
  - DAQ passing all data to analysis software

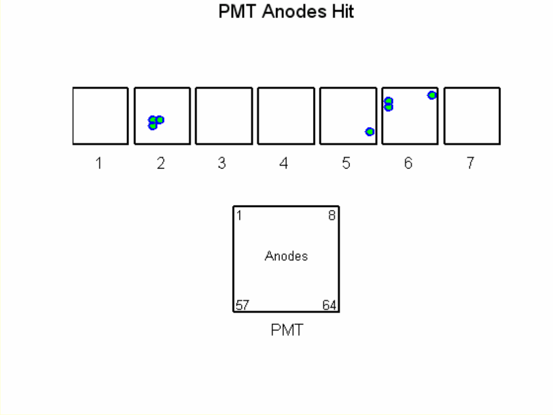


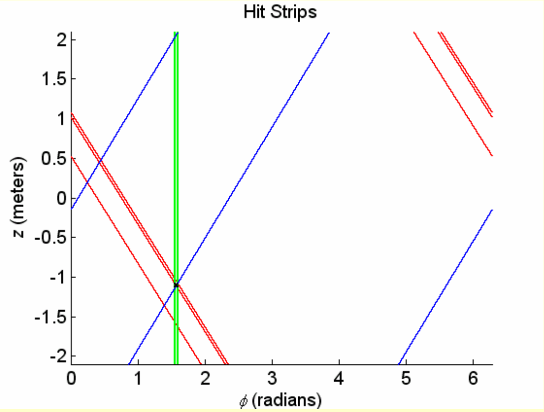


Some Events



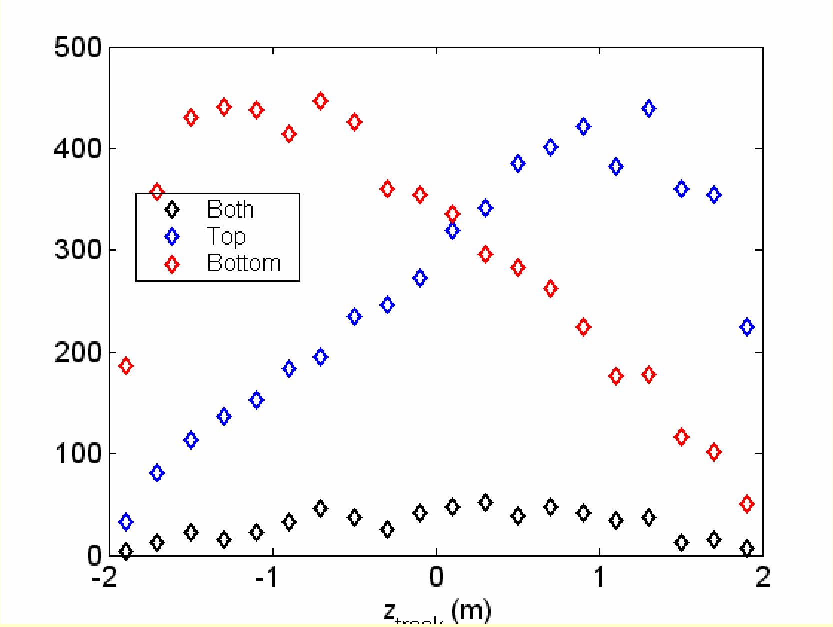


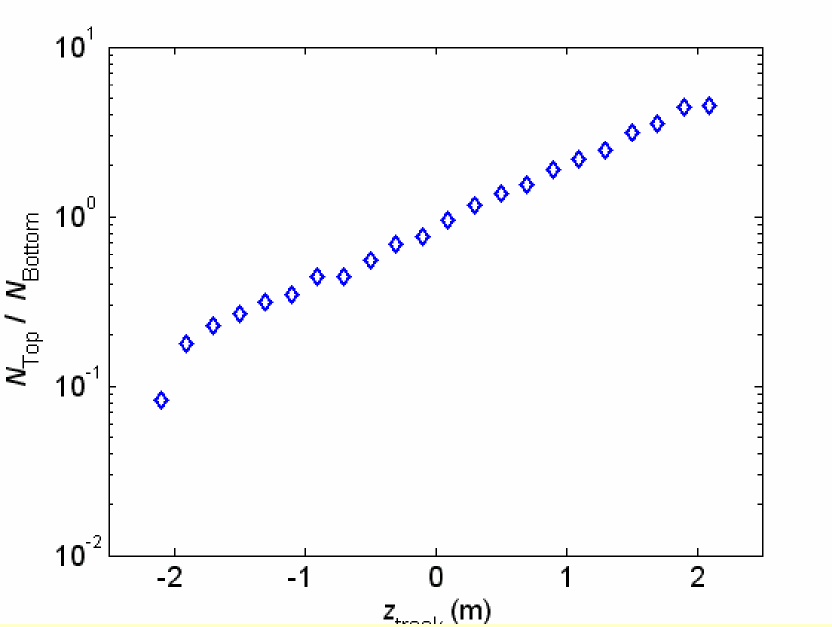




PMT cross-talk common, but has minor effect on tracking

Attenuation is an Issue





$$\varepsilon_{\det} = \eta_s^6 = p_s^6 \exp(-6d / L_0)$$

$$p_s^6 \sim 0.5 \qquad L_0 \approx 3.6L$$

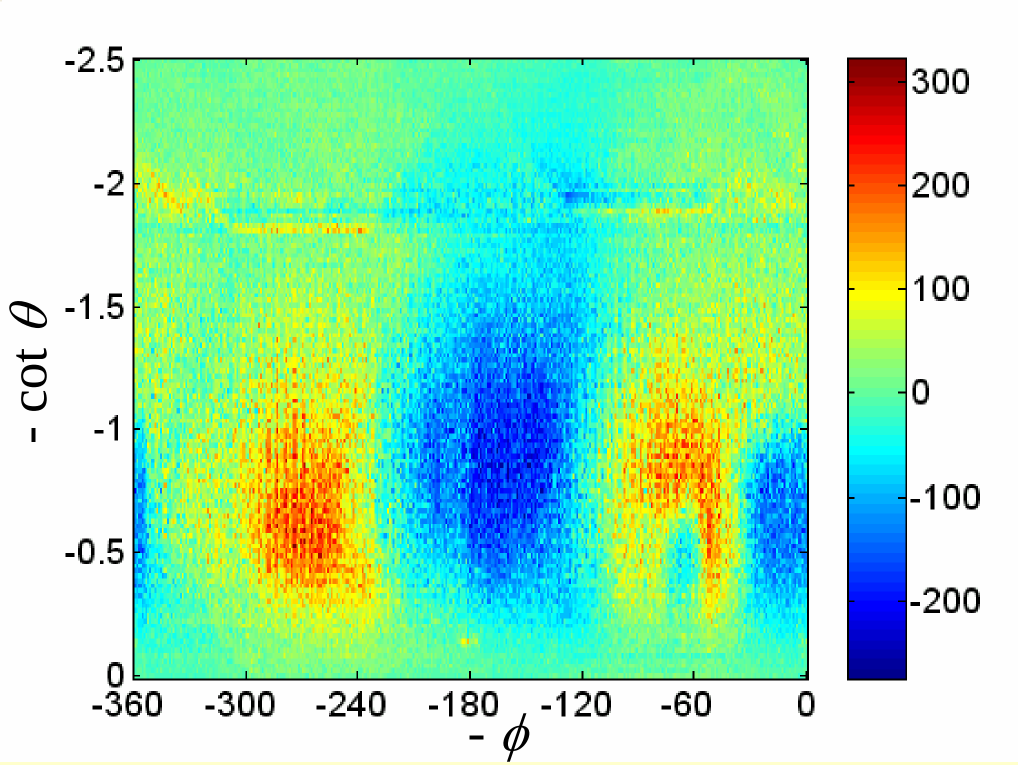
March 2007

Collecting Data

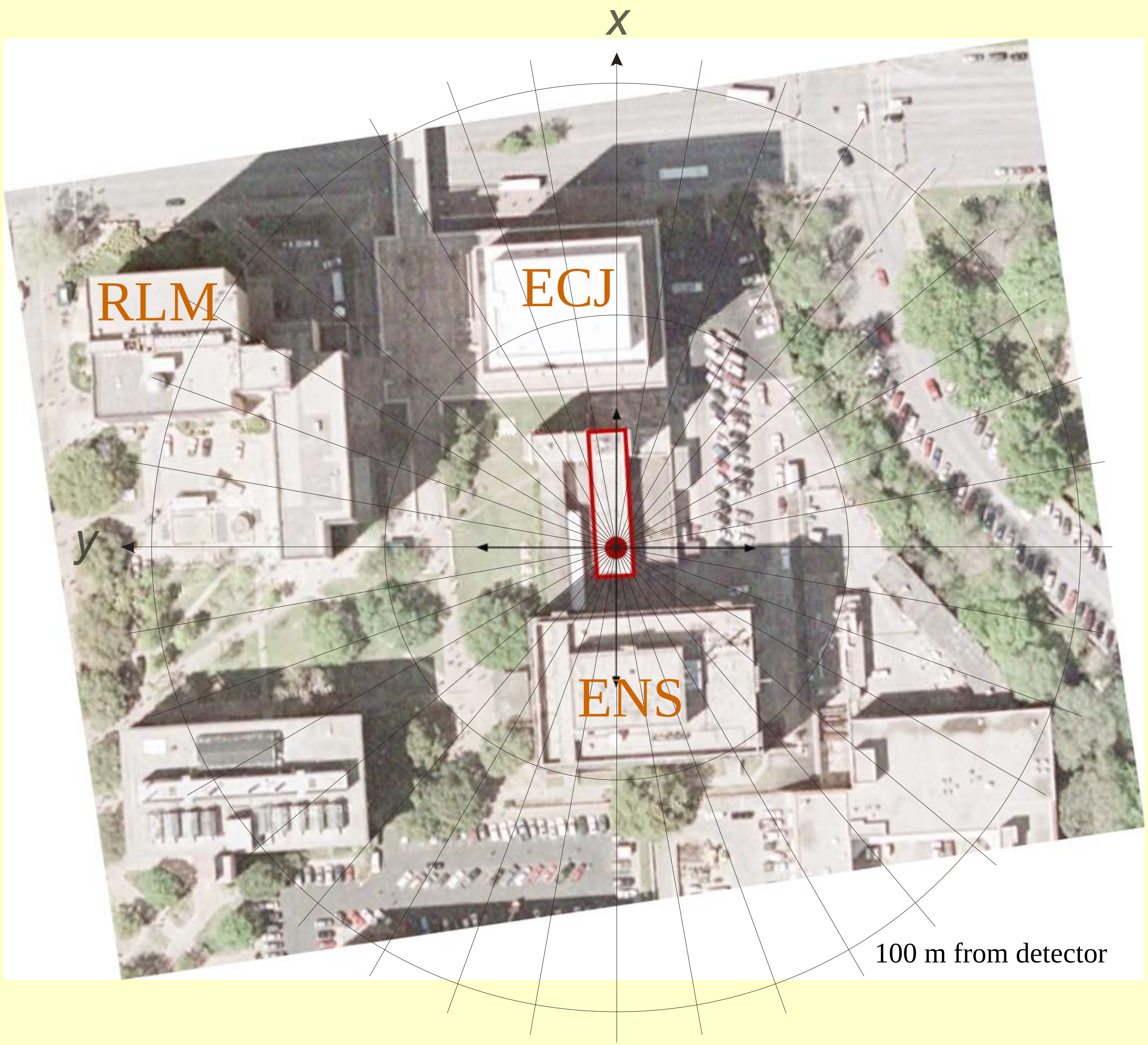
- Saw crude image of surrounding buildings in first 2-minute run
- Collecting ~ 1M tracks per hour
- Currently recording all raw data ~ 1GB/hour
- Tracking software works well—can stay ahead of DAQ system
- We are learning about imaging
- Have just set up a pile (~1 m deep) of Pb bricks to see if we can find it with muons.

6 Hours of Data

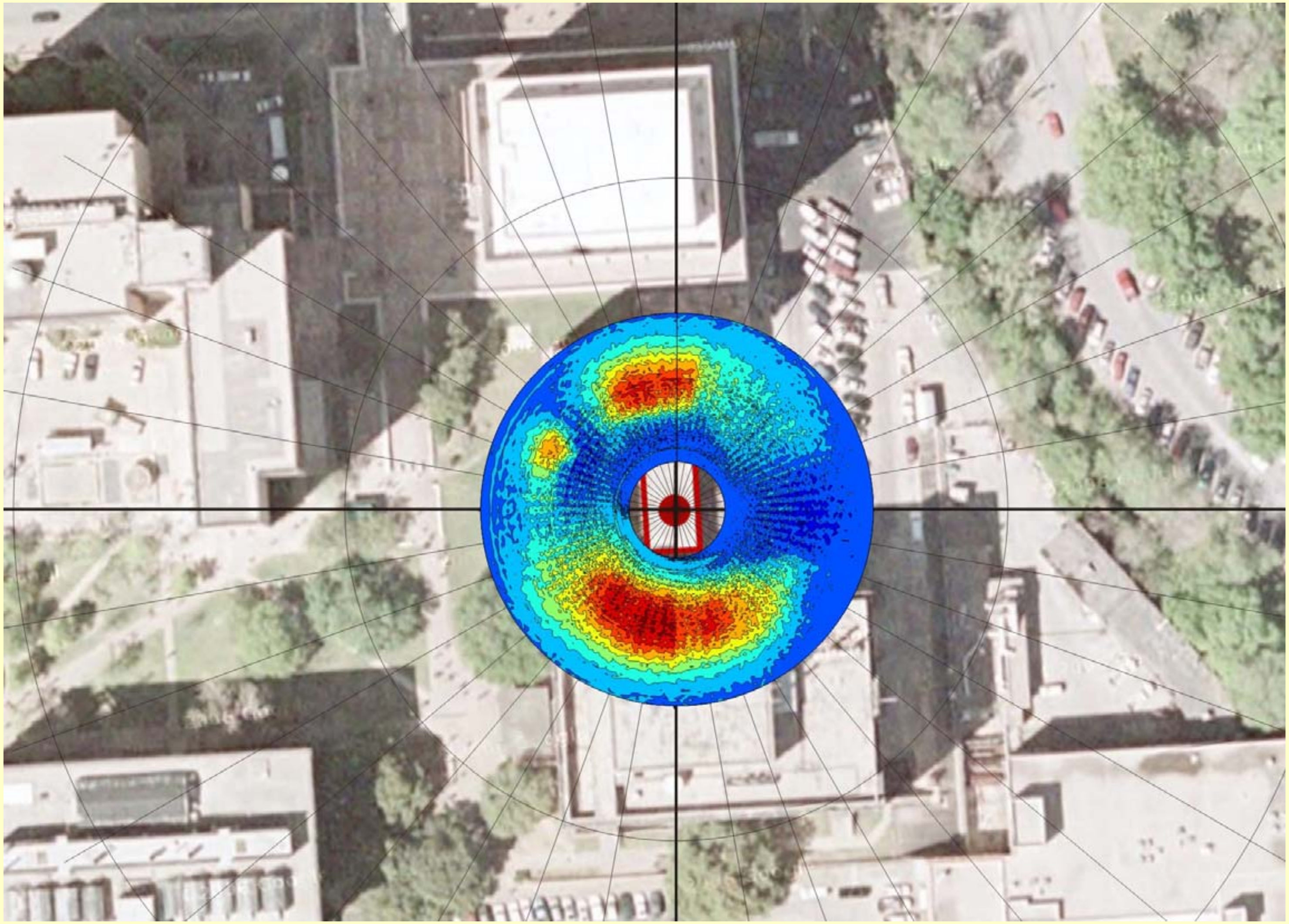
$$N_{i,j} - \langle N_{i,j} \rangle$$



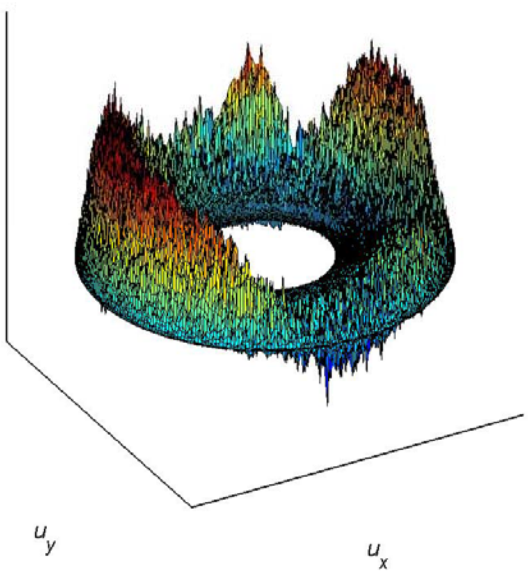
Our Neighborhood



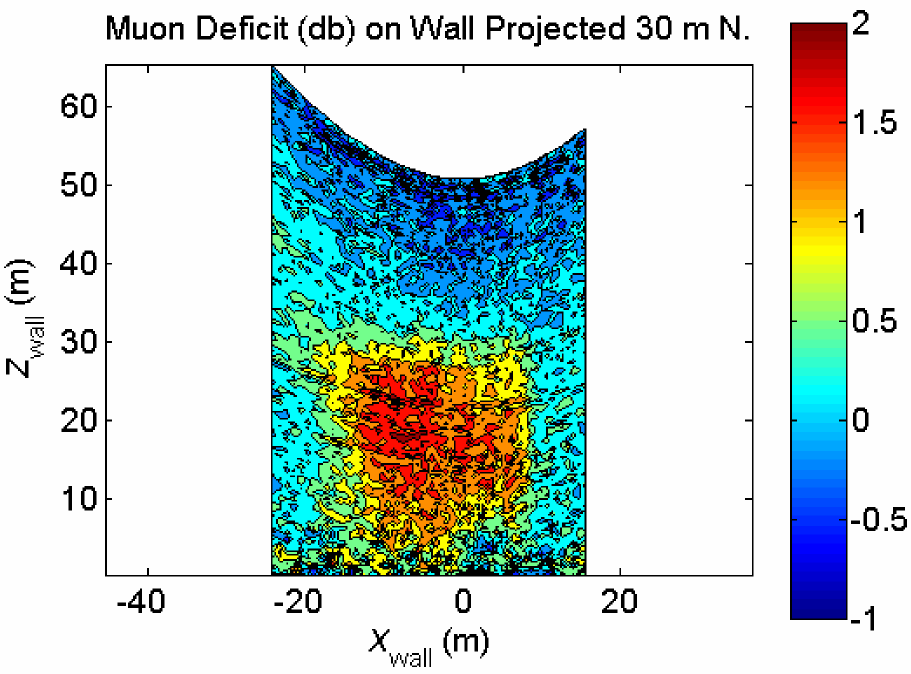
Net Muon "Deficit" in θ versus ϕ



Other Views



u_y
u_x



Muon Deficit (db) on Wall Projected 30 m N.
60
50
40
30
20
10
Z_{wall} (m)
-40
-20
0
20
X_{wall} (m)
2
1.5
1
0.5
0
-0.5
-1

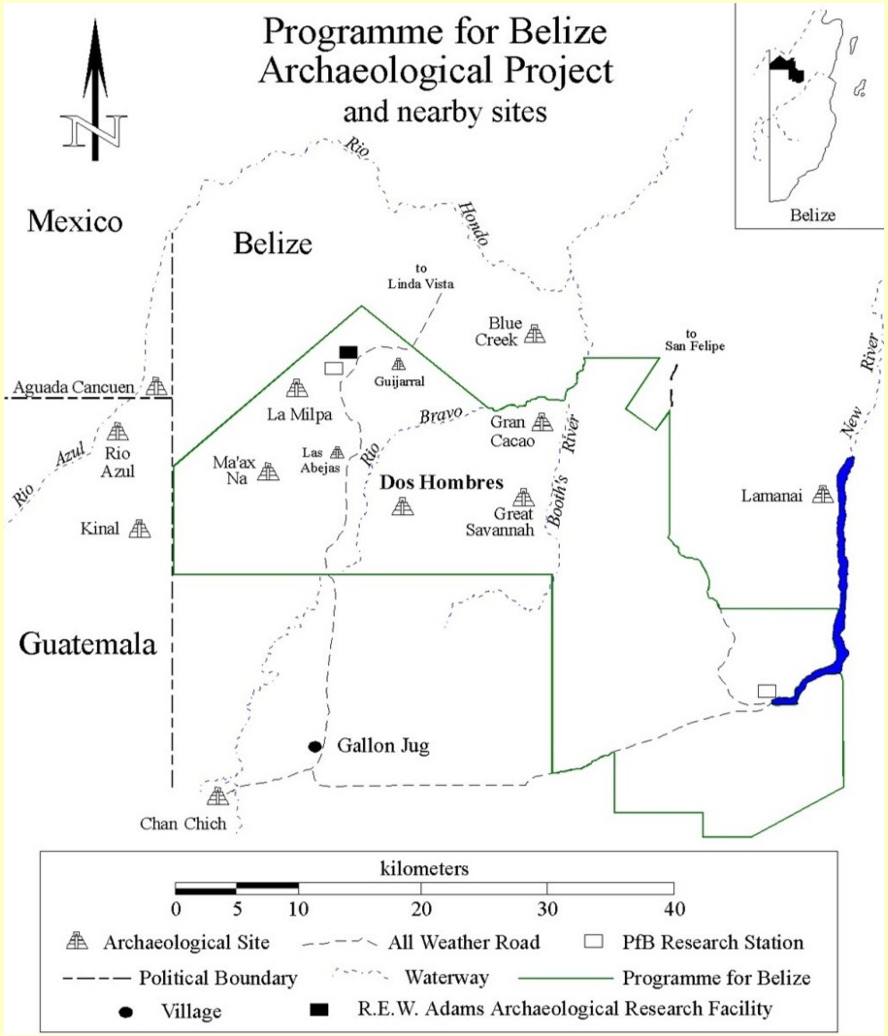
The Real World

- 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

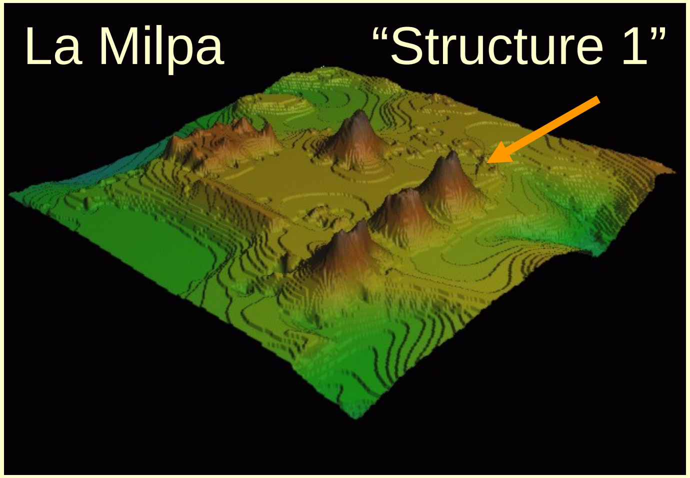
People & Things

- UT Physics
  - Jared Bennatt, Mark Cartwright
  - Brian Drell, JJ Hermes
  - Becket Hui, Jeremy Johnson
  - K. Krishnakumar, Nicholas Raspino
  - Cesar Rodriquez, 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
- National Instruments
  - Hugo Andrade, Joe Peck
- Fermilab—Scintillator Production
  - Anna Pla-Dalmau
- Harvard HEPL—Front-end Electronics
  - John Oliver, Sarah Harder
- Other physicists who contributed in the early stages
  - Prof. Rich Muller, UC Berkeley
  - Dr. Dick Mischke, LANL
- UT Mesoamerican Archaeological Research Laboratory (MARL)
  - Prof. Fred Valdez, Director

UT Mesoamerican Archaeological Research Laboratory



Potential Target Structure



- La Milpa site has relatively good access/infrastructure
- Developing simulation tools to optimize detector design and placement
- Plan excavations for deployment

Other Potential Applications

- Muon Tomography is good for monitoring large underground volumes (~100 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
  - Shapes of underground cavities
  - Time-dependence of water levels
- Monitoring of geology surrounding underground sites, e.g. underground nuclear waste storage

Summary

- Muon tomography is feasible
  - Proven in Alvarez experiment
  - New technologies enable simplified detector design
  - WLS/scintillator tracking well-developed/good match
  - Cherenkov threshold detector is indicated
    - New approach to problem of low-energy multiple-scattering
    - Well-understood physics/technology
    - Simplifies system design
- Excellent project for engaging students
- Other applications are possible
- Maybe we can help to learn more about the Maya!