Cosmic Ray Muon Tomography for the Detection of High-Z Objects

Richard C. Schirato
Los Alamos National Laboratory

For the MuRad Collaboration:
, Charles Alexander[a], Thomas Asaki[a], Jeffrey Bacon[a], Gary Blanpied[b], Konstantin Borozdin[a], Alberto Canabal-Rey[ag], Matt Cannon[ac], Rick Chartrand[a], Guangliang Chen[d], Deborah Clark[a], John Dennis[c], Camilo Espinoza[a], Esteban Figueroa[a], Andrew Fraser[a], Mark Galassi[a], John Gomez[a], Jackie Gonzales[a], Andrew Green[a], Nicolas Hengartner[a], Gary Hogan[a], Alexei Klimenko[a], Gilad Lerman[d], Patrick McGaughey[a], Jason Medina[a], Christopher Morris[a], Keith Mosher[a] ,Christopher Orum[a], Fawn Pazuchanics[a], William Priedhorsky[a], Andrew Sanchez[a], Alexander Saunders[a], Richard Schirato[a], Larry Schultz[a], Michael Sossong[a], Matthew Sottile[a], Margaret Teasdale[af], Jason Tenbrink[a], Kevin Vixie[a], Brendt Wohlberg[a]

[a]Los Alamos National Laboratory, [b]University of South Carolina, [c]Rice University, [d]University of Minnesota, [e]University of New Mexico, [f]University of Hawaii, [g]New Mexico State University

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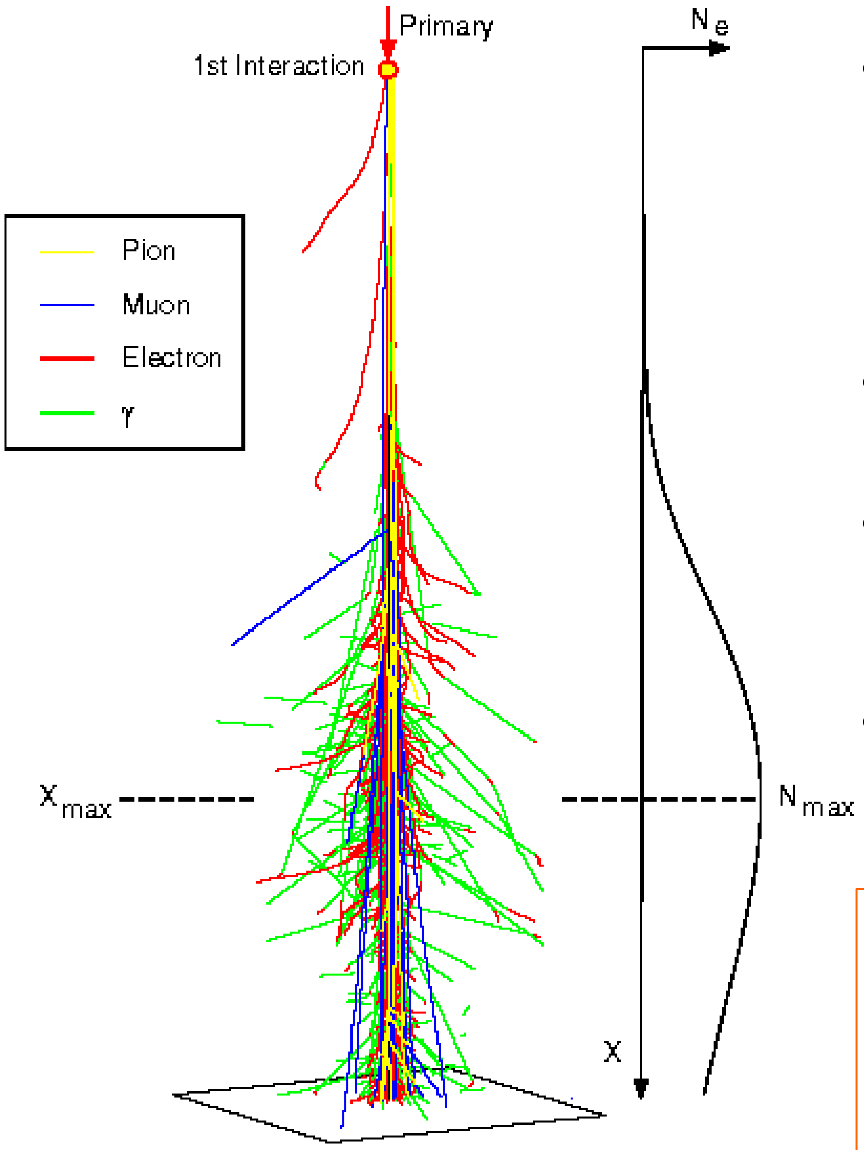
Motivation

- Terrorists or smugglers may try to move a variety of threat materials such as Special Nuclear Material (SNM) or radioactive sources across borders.
- To prevent detection by passive means, these items will need to be shielded, so there will also be Lead or other high Z/ high density shielding material present.
- A characteristic of high Z (atomic number) materials is that incident energetic charged particles will experience relatively more multiple Coulomb scattering than lower Z material.
- Our proposed method of detecting SNM or shielding material is to measure the multiple scattering of charged particles that pass through a cargo container or vehicle.
- Advantages of Cosmic Ray Muon Tomography
  - No artificial sources of radiation required
  - Very penetrating
  - Allows for automatic detection

Cosmic Ray Muons

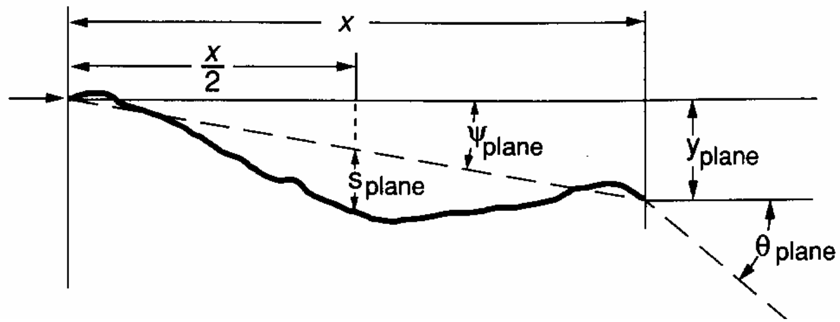


- Primary cosmic rays interact in the upper atmosphere, producing particles including pions (τ=26 ns) which decay into muons (τ=2.2 μsec).
- Muons interact only through the Coulomb and weak forces.
- Since $m_\mu >> m_e$, *bremstrahlung* processes are suppressed
- Muons arrive at a rate of ~10,000 $m^{-2}min^{-1}$ at sea level.

$$p + A \rightarrow p + X + \pi^+ + \pi^-$$

$$\pi^{+/-} \rightarrow \mu^{+/-} + \nu_\mu$$

Muon Interactions with Matter



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

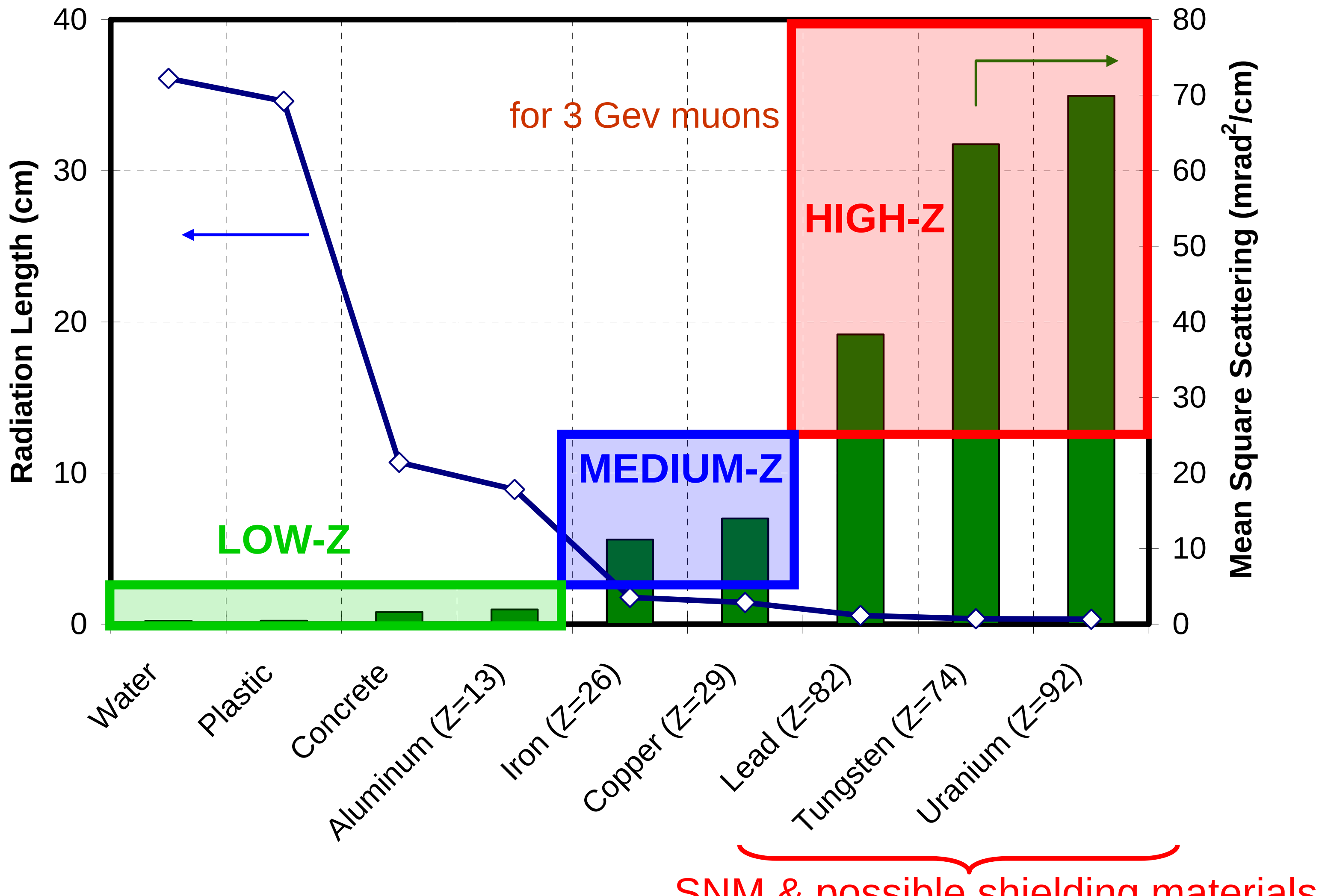
$$\theta_0 = \frac{13.5}{p\beta}\sqrt{\frac{x}{X_0}}$$

- Energy loss[1]
  - Most sensitive but expensive and complex
- Range (attenuation)[1]
  - Useful for archeological and geological objects
- **Multiple scattering[2-4]**
  - Requires relatively fewer particles for detection

1. **Livingston MS, Bethe HA. *Rev. Mod. Phys.* 9: 245 (1937)**
2. **Rossi B. *High-Energy Particles*. New Jersey: Prentice-Hall (1952)**
3. **Bethe HA. *Physical Review* 89: 1256 (1953)**
4. **Moliere G. *Zeitschrift fur Naturforschung Section A-A Journal of Physical Sciences* 2: 133 (1947)**

Scattering is Material Dependent

(atomic number and density)



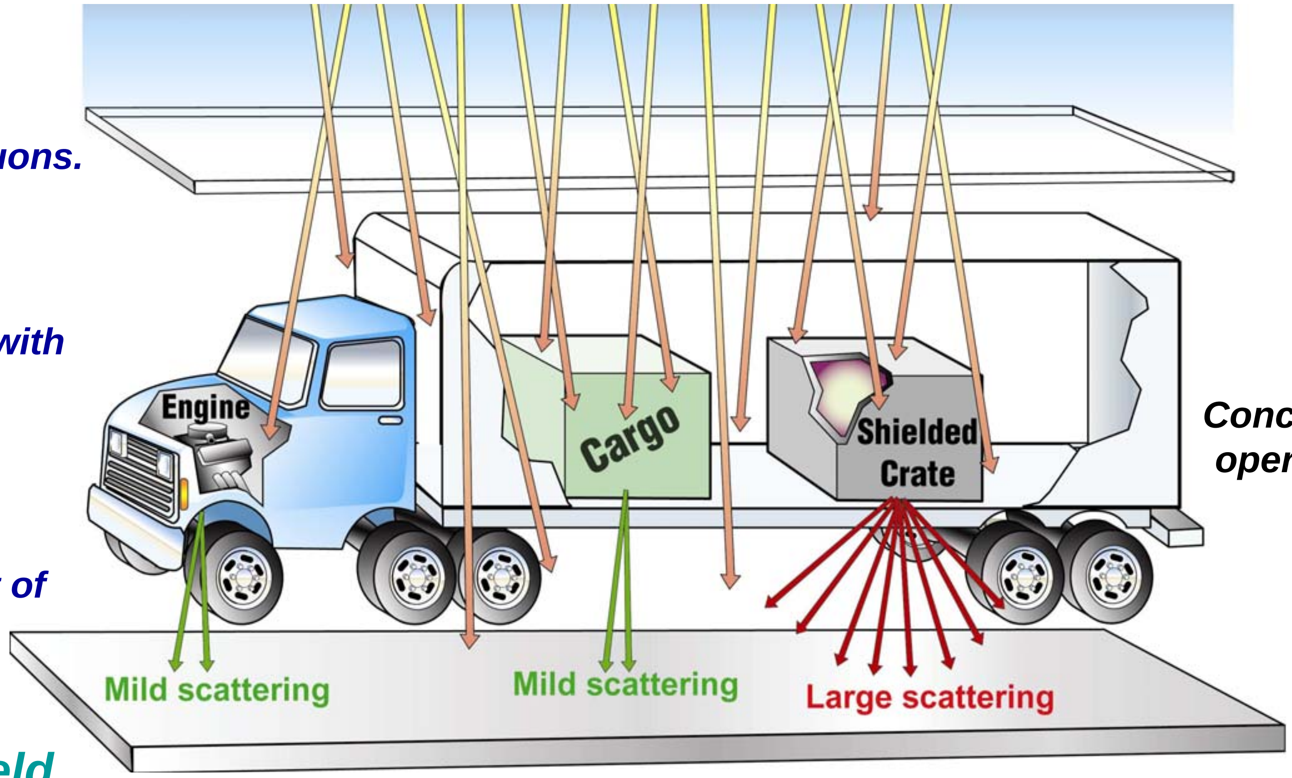
Detection Concept

The Signal:
Measured scattering of muons.

Objective:
penetrating radiography with no artificial dose

Application:
Prevent illicit movement of nuclear materials

The heavier the shield, the easier the detection



Concept of operation

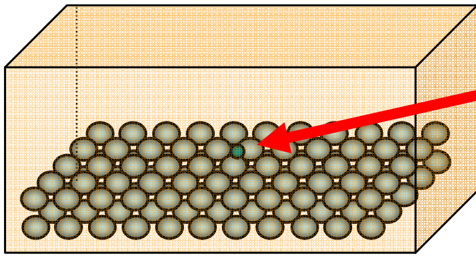
Simulations of Car and Container Radiography

Geant4 Monte Carlo simulations

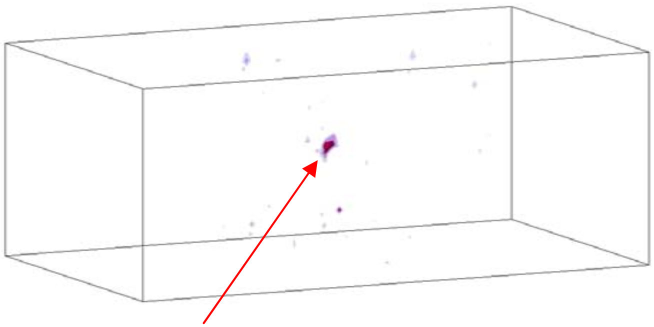
60 second simulated exposure

Ray-crossing algorithm

Uranium in a cargo of automobile differentials



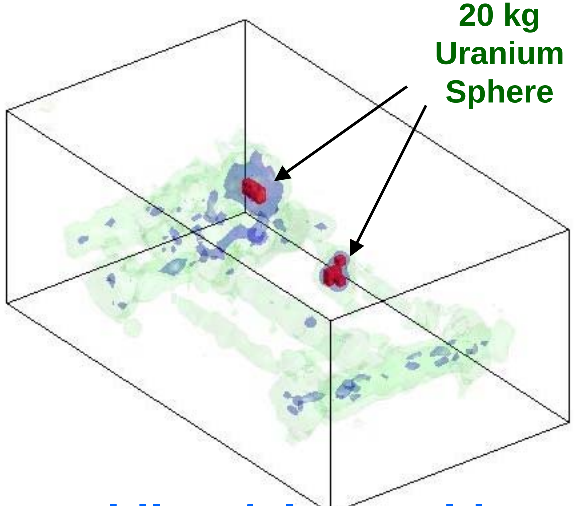
20 kg Uranium Sphere



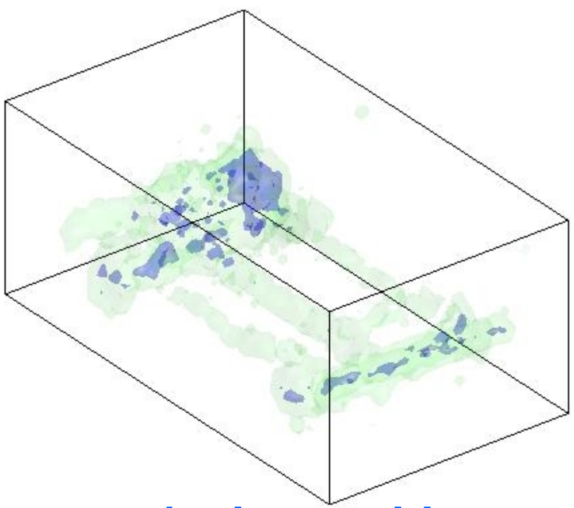
Uranium ball

Maximum Likelihood image reconstructions:

20 kg Uranium Sphere

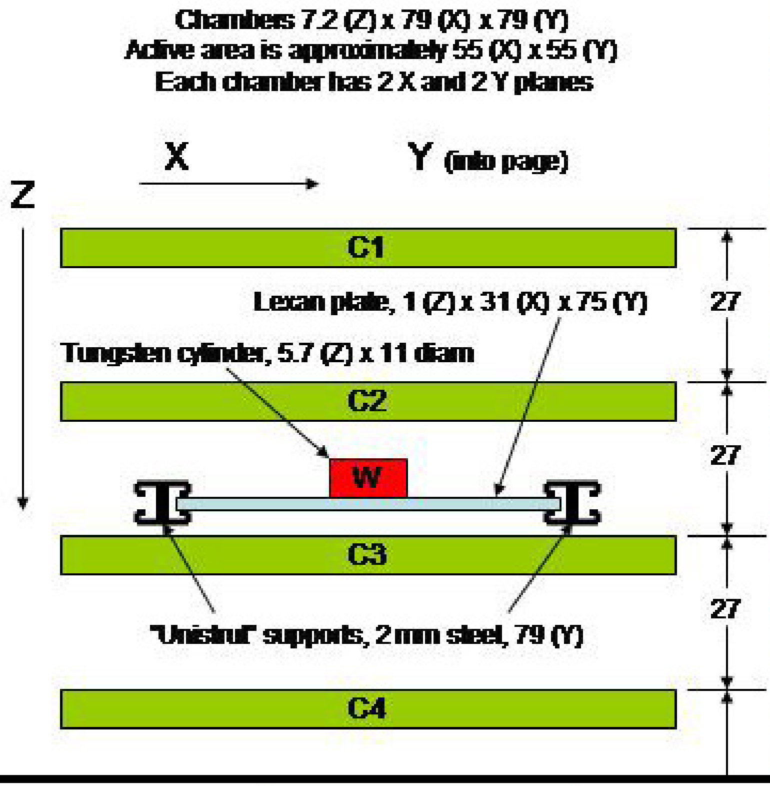


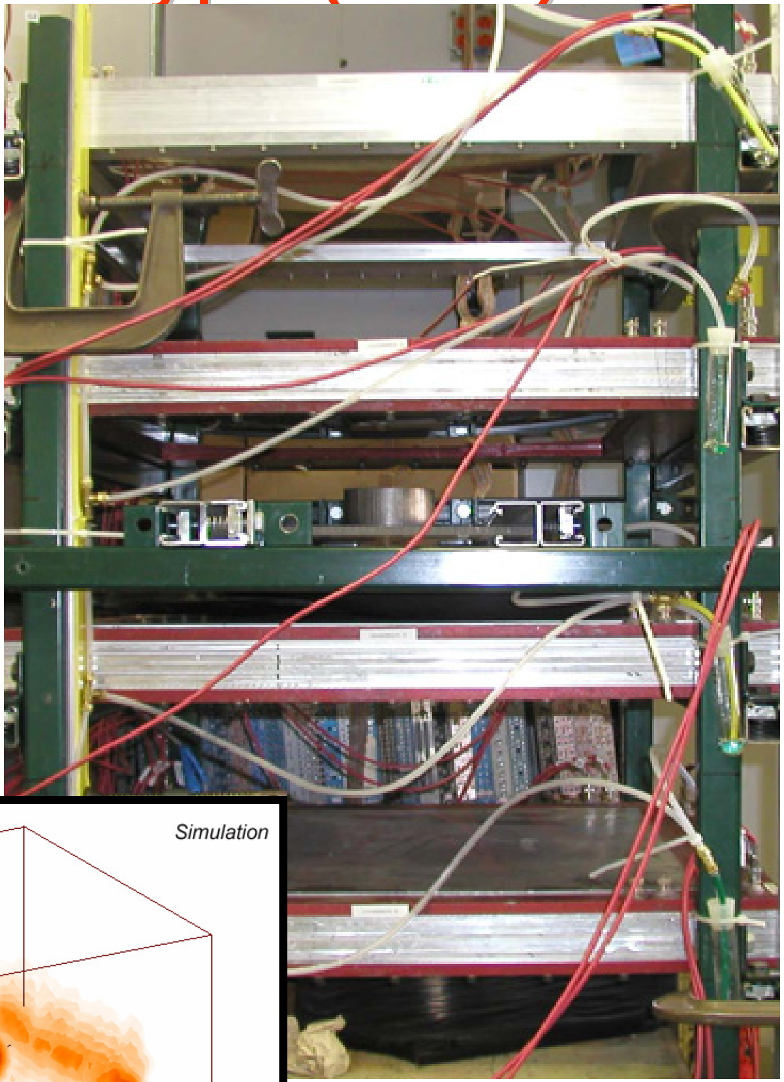
Automobile w/ threat objects

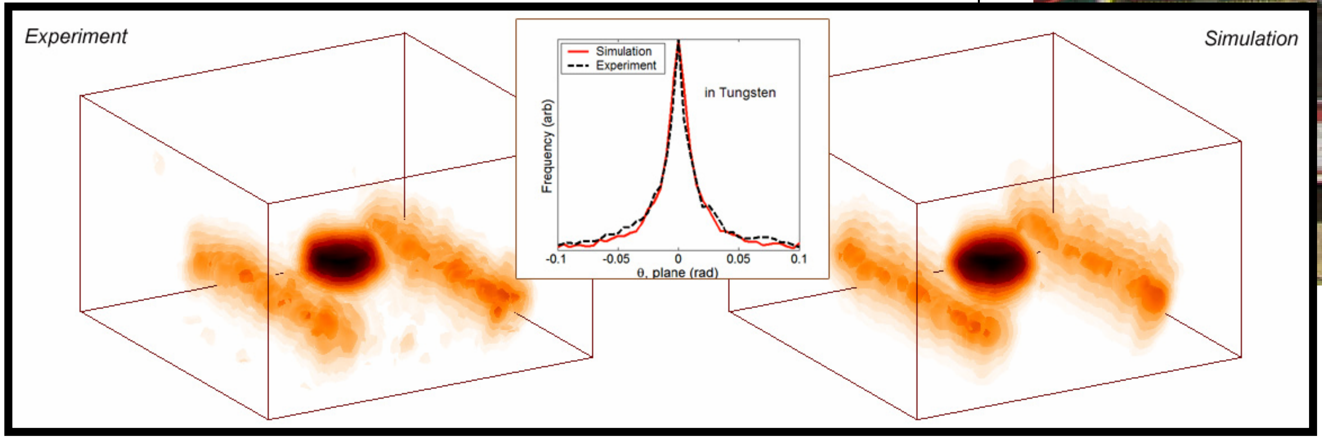


w/o threat objects

Wire Chamber Prototype (WCP)



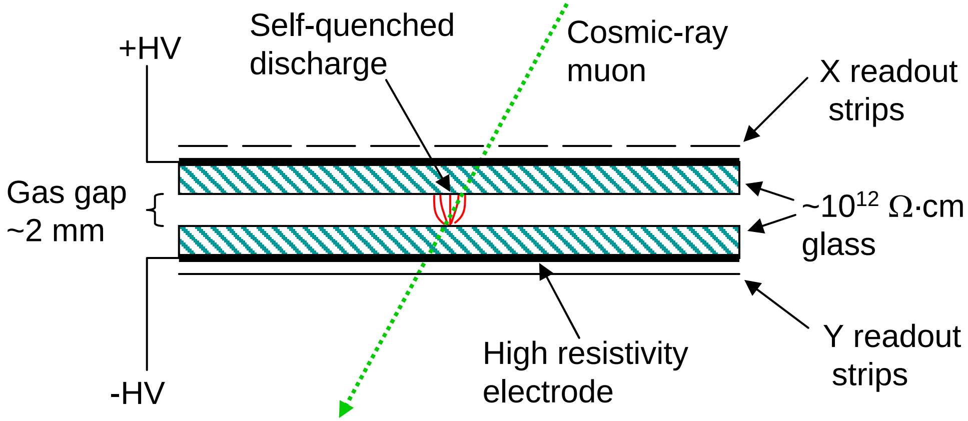




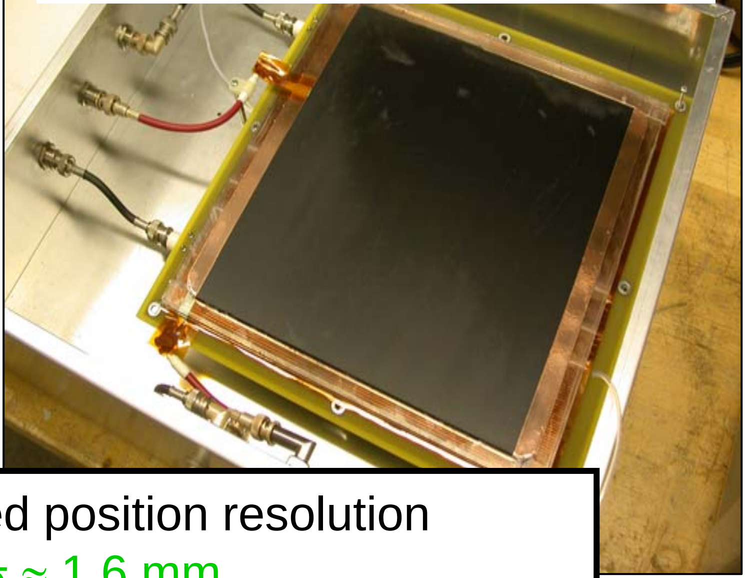
- Proof of principal
- Detector resolution measurements

RPC with Delay-Line Read-Out

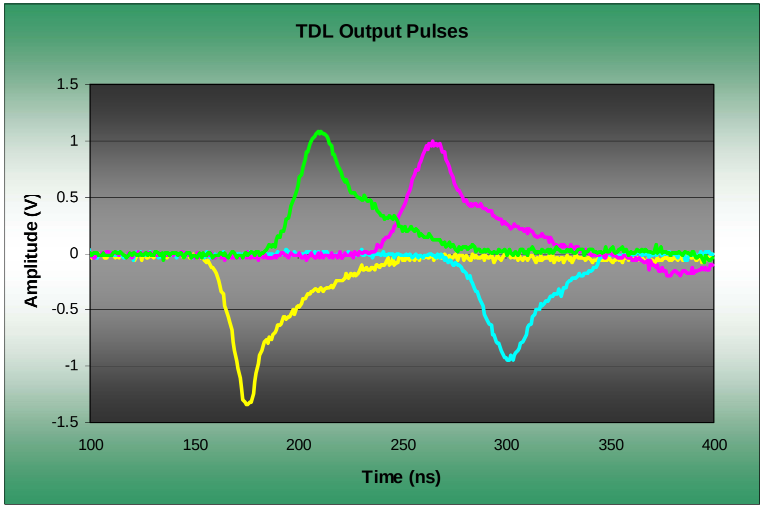
Resistive Plate Chamber Concept:

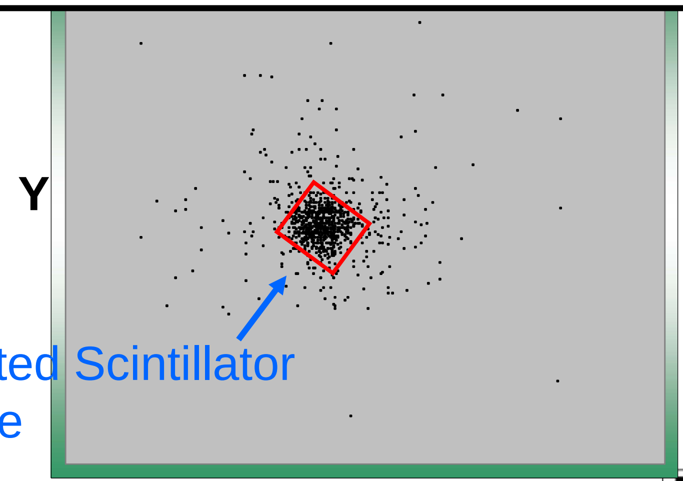


Prototype 10.5” x 10.5” RPC



- Measured position resolution $\sigma \approx 1.6$ mm
- Double scintillator coincident map:

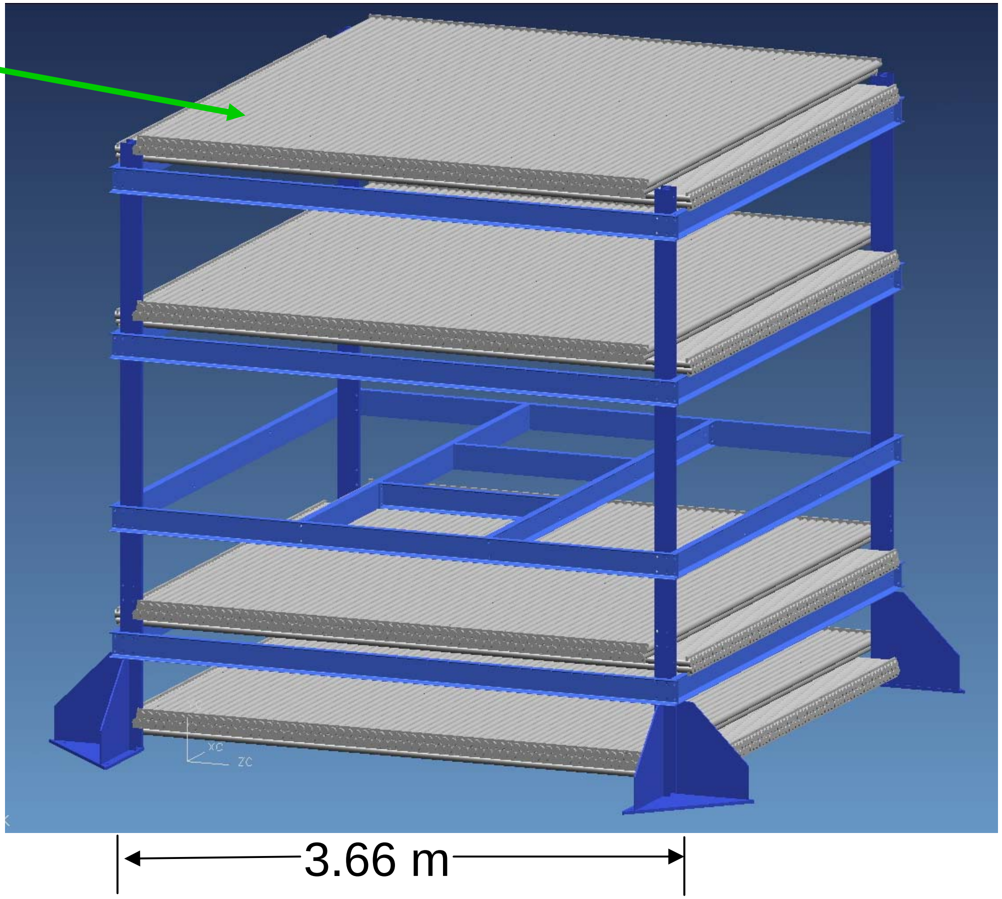




Projected Scintillator Outline

Large Muon Tracker (LMT)

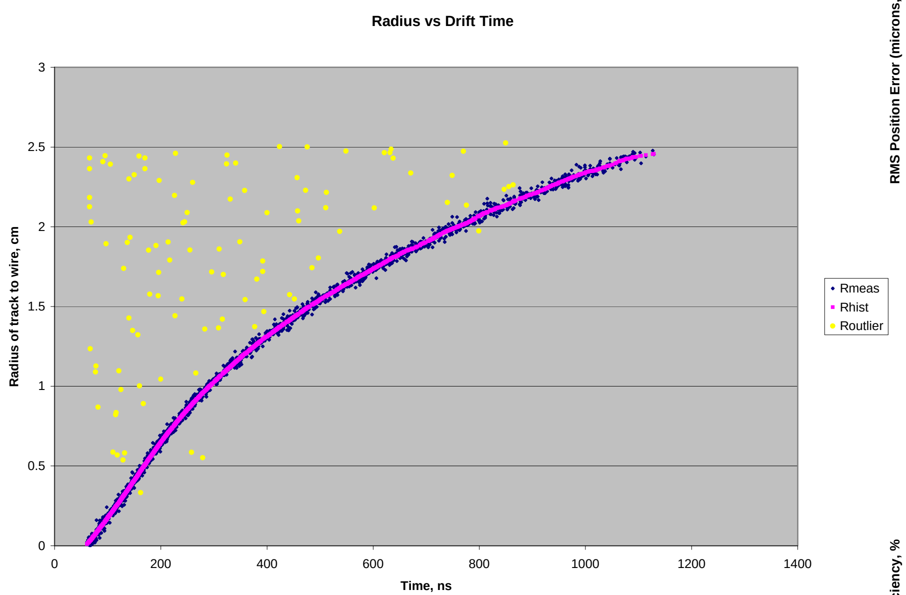
- Drift tube detectors
  - 12' long, 2" OD
- Reconfigurable
- Initial Configuration:
  - 4 xy planes
  - 64 tubes per x or y
  - 512 channels total



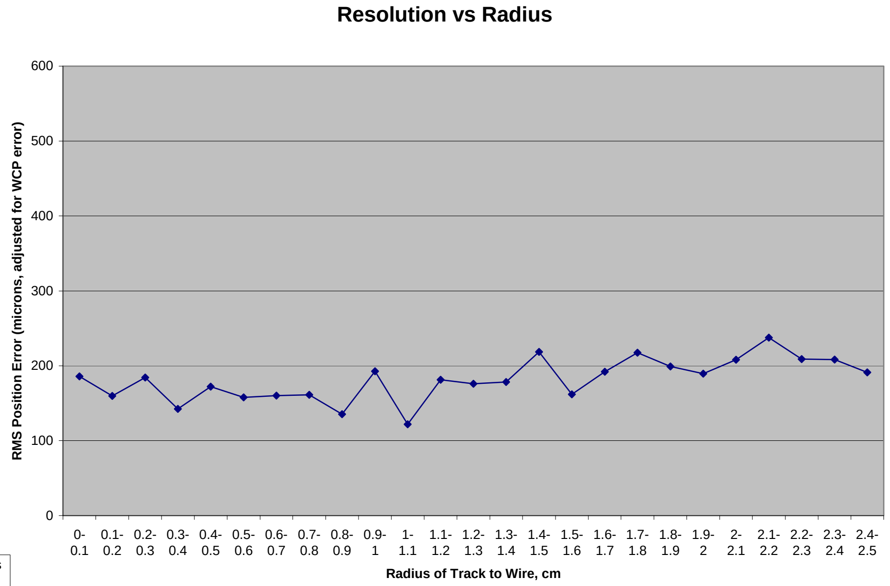
- **Goals:**
  - **Demonstrate at a representative scale.**
  - **Establish robust detector performance and calibration methods.**
  - **Demonstrate detection of realistic sized objects of interest in cluttered background.**

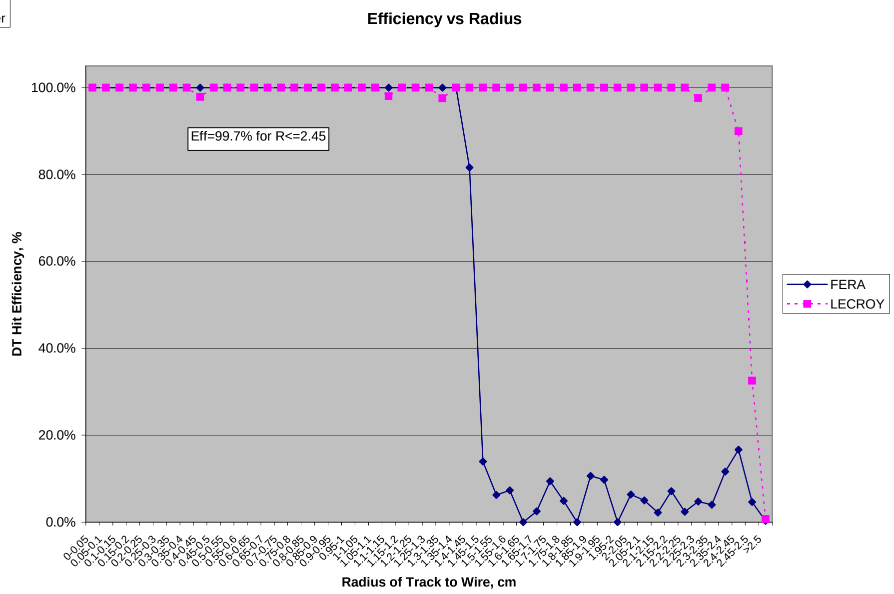
Drift Tube Resolution & Efficiency

- 1 m, 2 inch O.D. drift tube
- Incident muons tracked into tube with wire chamber system

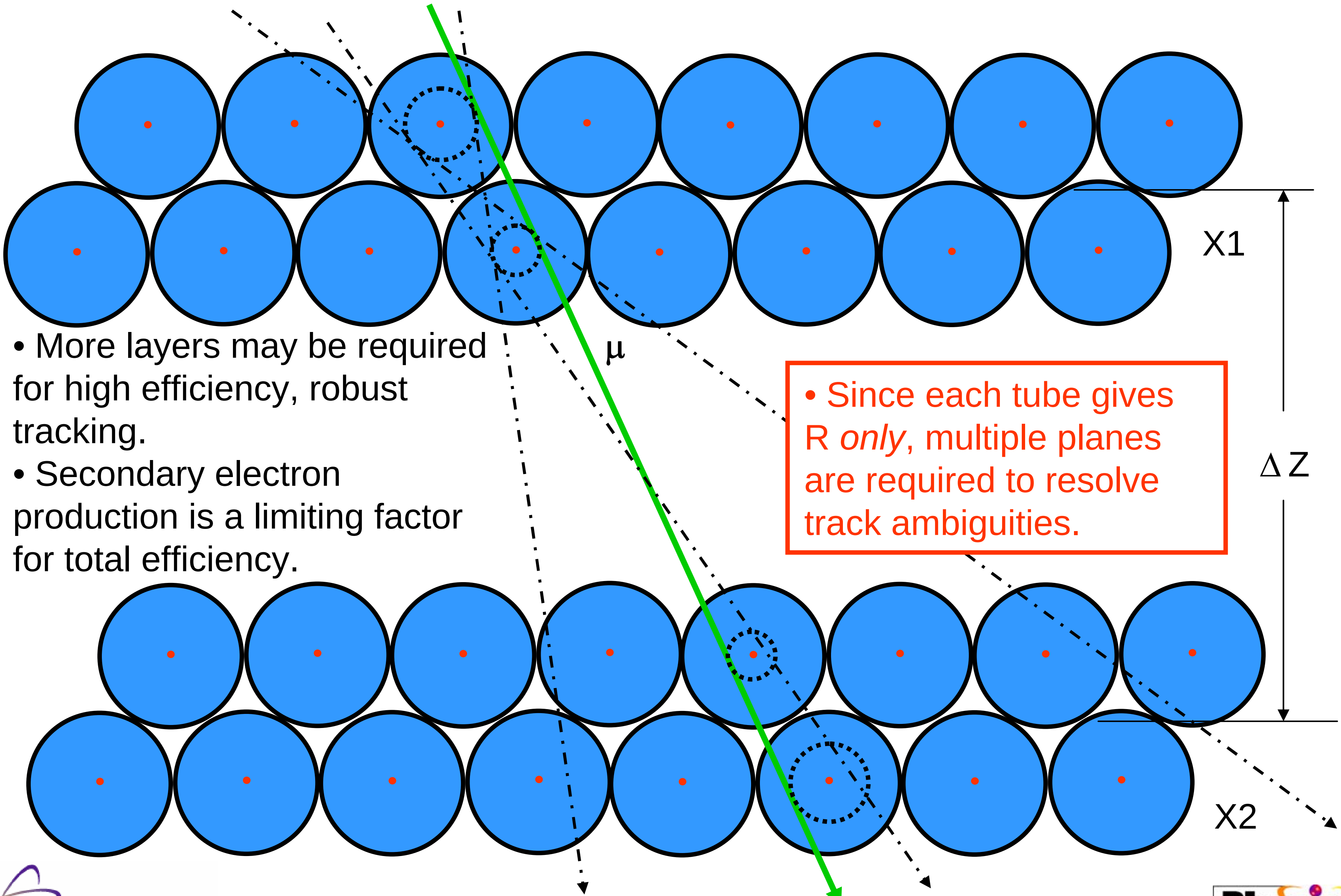


Gas Mixture & Voltage:
84/10/6 Ar/CO_2/Iso-B, 1650V





X-Coordinate Plane Drift Tube Layout

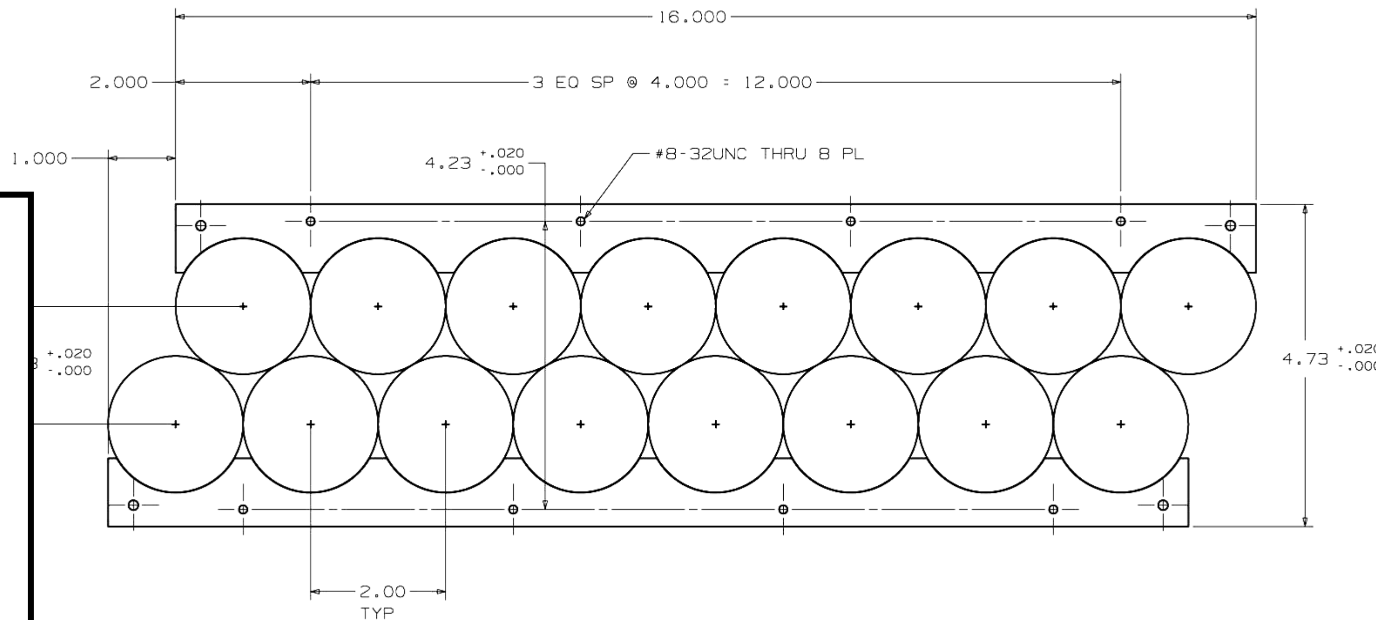


- More layers may be required for high efficiency, robust tracking.
- Secondary electron production is a limiting factor for total efficiency.

- Since each tube gives R *only*, multiple planes are required to resolve track ambiguities.

Drift Tube Module Fabrication

- Two close-packed layers are bonded together to increase stiffness
- 16 tubes/module
- 0.035 inch Al
- module: < 60 lbs
- 20 micron tungsten wire for proportional mode

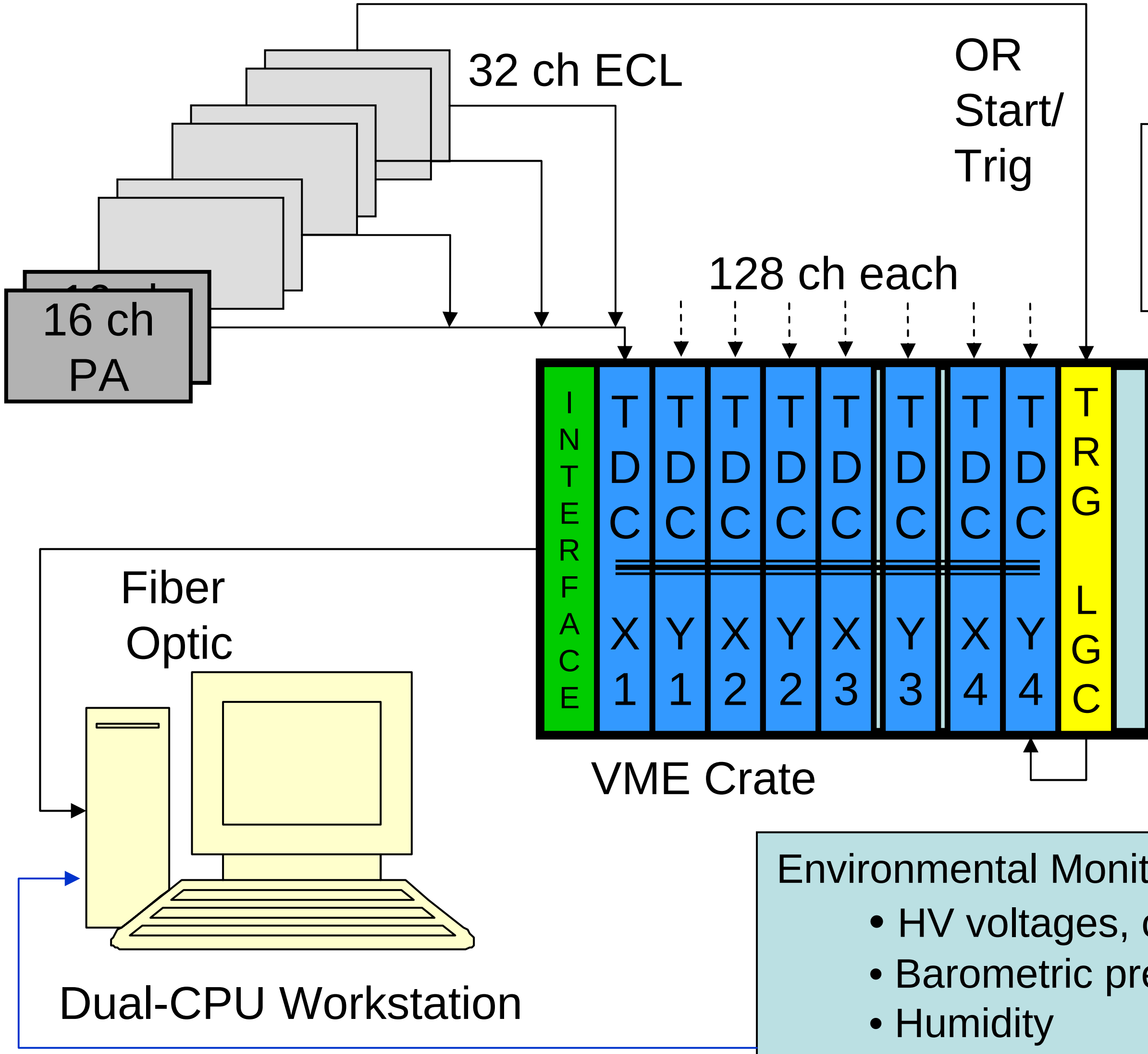


Large Muon Tracker (LMT) at LANL

- 512 channels
- Drift gas: 60% Ar/ 40% Isobutane
- 1 m between adjacent planes
- 1.5 m tall sample area
- $1m^2$ scintillator paddles below layer 3

Initial Configuration July 2005

Simplified Data Acquisition System

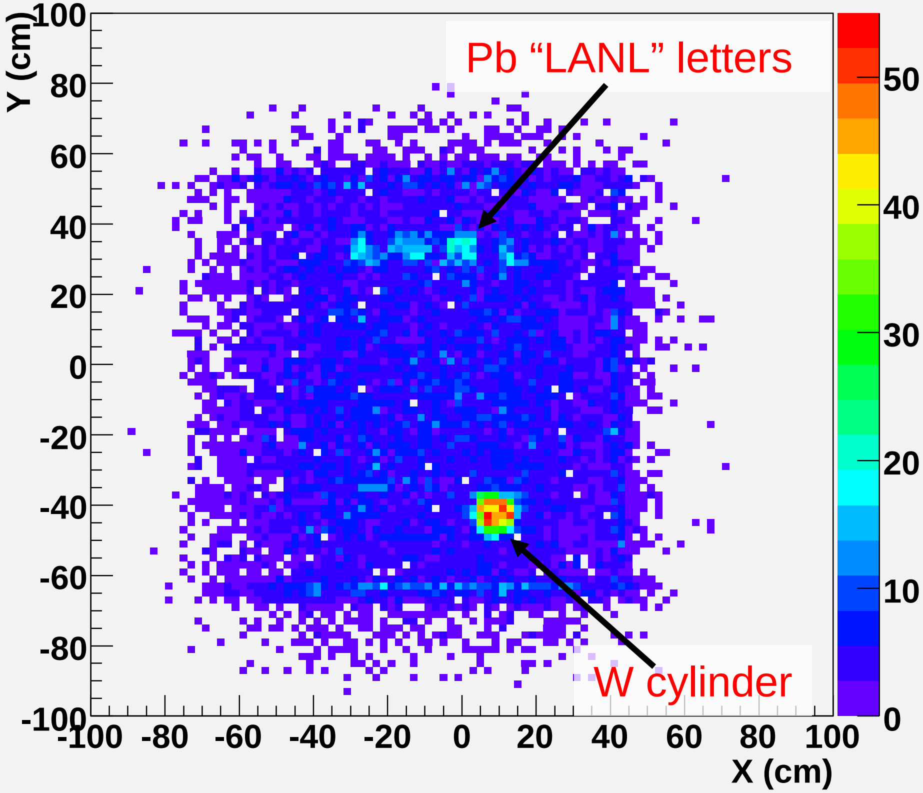


- **Used COTS electronics where possible**

Environmental Monitor:
- HV voltages, currents
- Barometric pressure
- Humidity
- Temperature

Initial Object Scan with LMT

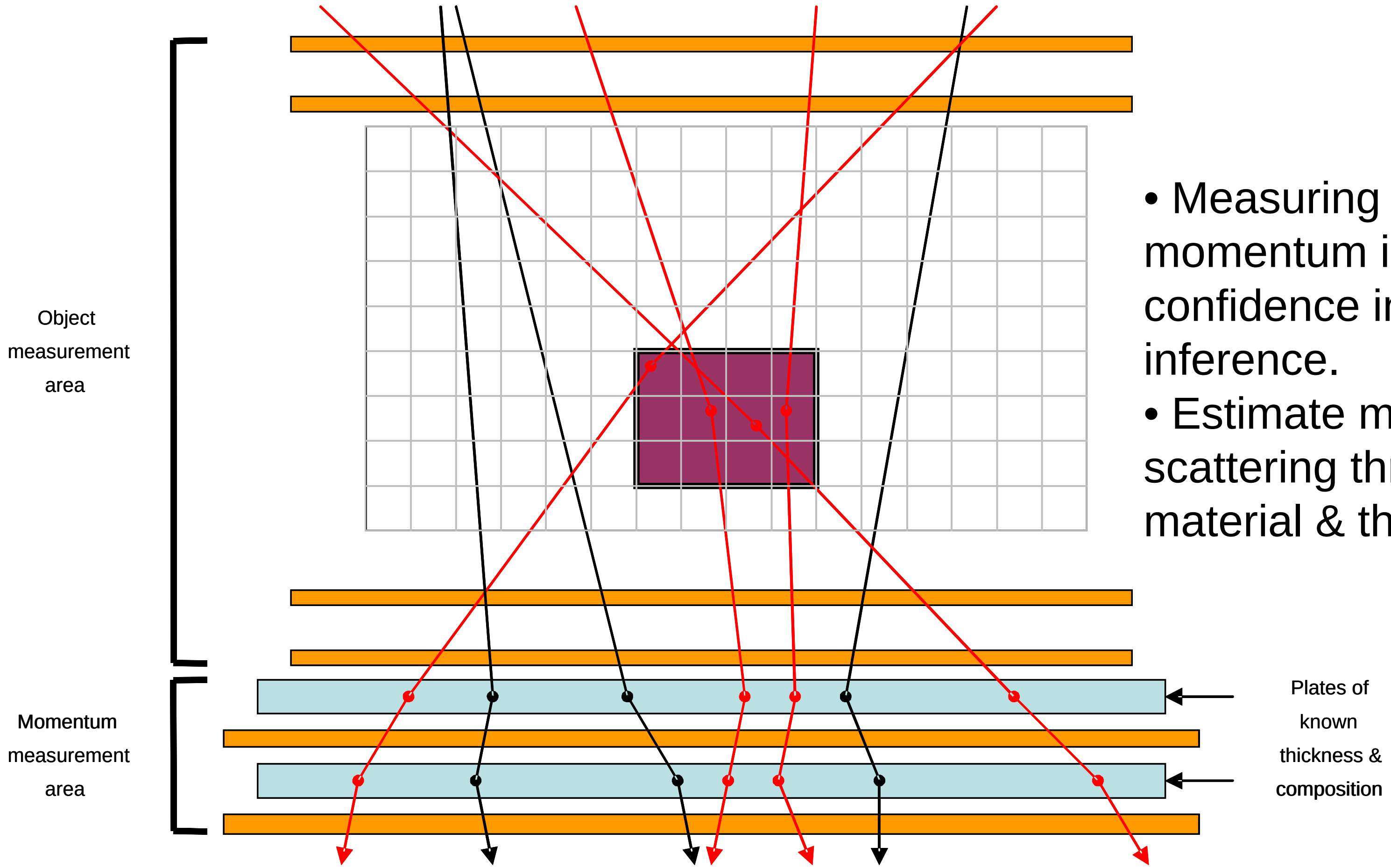
Density of points of closest approach (PoCA)



- Scattering angle > 50 mrad
- Track resolution ~1mm at that time (intrinsic tube resolution is ~200μm)
- Has improved with further muon track calibration to ~0.5mm

July 2005

Momentum Measurement



- Measuring particle momentum increases confidence in material inference.
- Estimate momentum from scattering through *known* material & thickness.

• Scattering in slabs below fiducial region is function of particle momentum.

Summary

- Simulations and proof of concept experiments suggest that cosmic ray muon tomography shows promise for the detection of shielded SNM and radioactive sources.
- Reconstruction/detection algorithms are being developed and tested.
- A representative-scale experimental demonstration based on drift tube technology is on-going.

- Current/Future work:
  - Fabricate additional detector modules
    - Increase solid angle/acceptance
    - Improve z-coordinate discrimination
    - Reduce exposure time
  - Incorporate momentum measurement
  - Perform series of demonstration experiments on objects with clutter