Muography at 1 km Depth - Results

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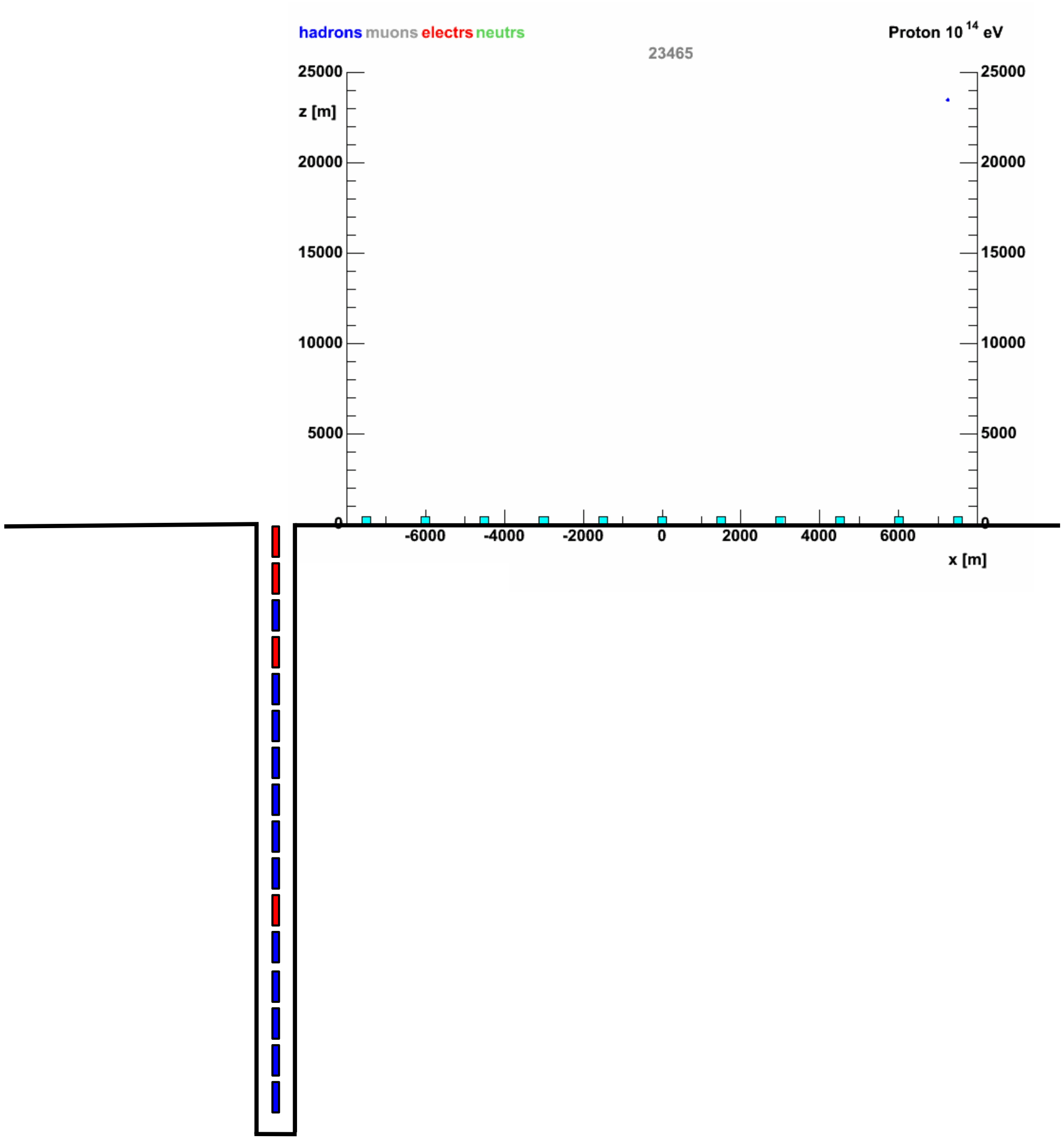
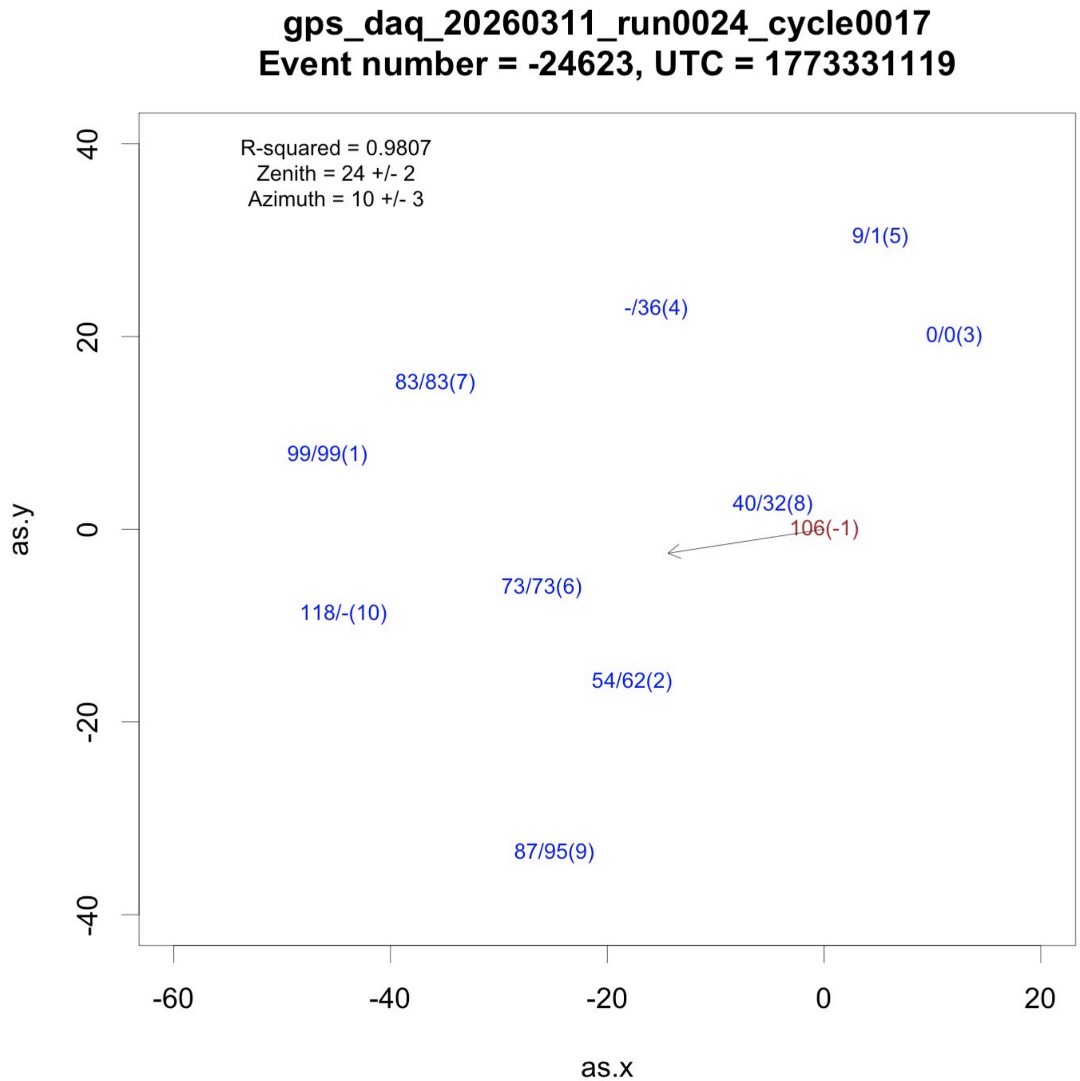
Air shower muography



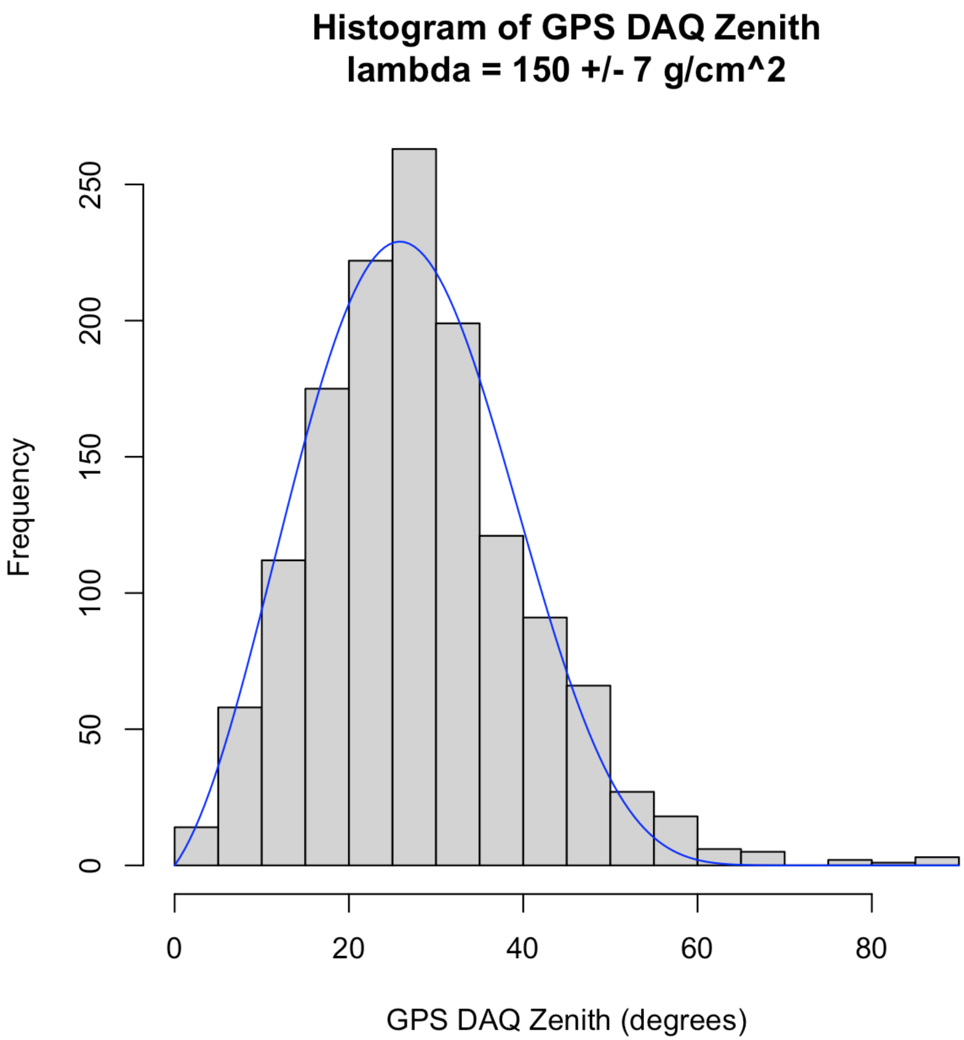
- To do muography you need θ, ϕ and depth of detection.
- Depth is easy and cheap to measure if θ, ϕ could be measured in some other way.
- Muons often arrive together in a pancake structure spread over length scales of ~100 m (air shower)
- At depths > 25 m all muons are associated with a shower on the surface
- **Will it work?**

Fitting Air Shower Events



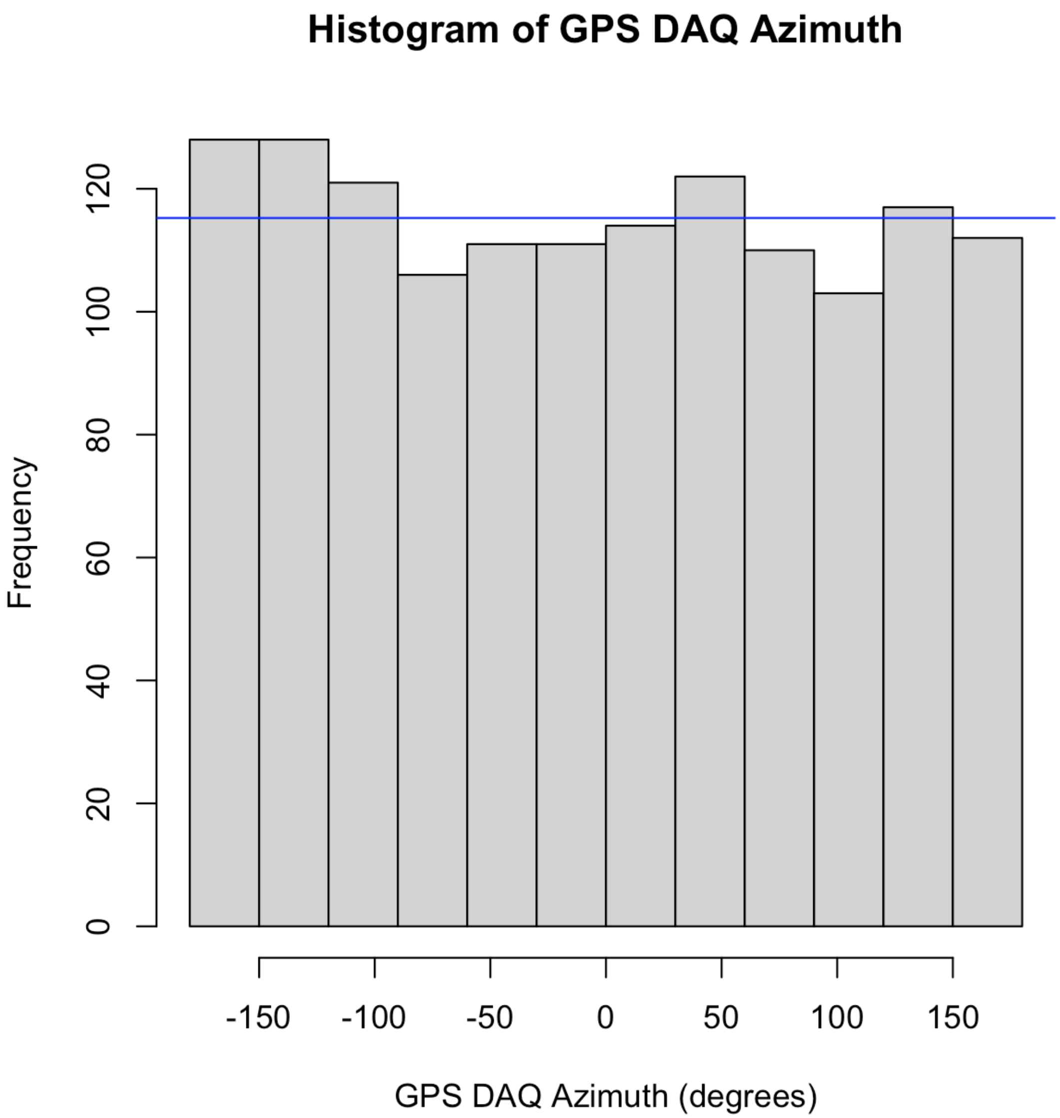
- The plot to the left shows data from an air shower that hit all 10 detectors.
- Each detector reports the time, in ns, when SiPMs on either side went over threshold.
- The borehole detector was 20.3 m underground.
- All times are referenced to the earliest hit.
- You can “see” the hits progressing from right to left.
- Using all (x,y,z,t) coordinates we do a simple linear fit to zenith and azimuth and also obtain fitting errors.

Zenith Distribution



- According to the literature the distribution of zenith angles for extensive air showers follows a $e^{-\frac{X}{\lambda cos\theta}}$ multiplied by geometric factors where *X* is the vertical depth in the atmosphere , 997 g/cm^2, and λ attenuation length is fit to 150 +/- 7 g/cm^2.

Azimuth Distribution



- For such small zenith angles we don't expect much variation in the azimuth distribution

Decadal Rate Analysis – All Particles

All particle table		Lambda (g/cm^2)
Primary Energy Range (eV)	CORSIKA rates per borehole detector (per hour)	
1E11 - 1E12	0	~110
1E12 - 1E13	0.12 +/- 0.06	~120
1E13 - 1E14	0.8 +/- 0.2	~130
1E14 - 1E15	1.2 +/- 0.2	~140
1E15 - 1E16	0.4 +/- 0.1	~150
1E16 - 1E17	0.11 +/- 0.04	~165
CORSIKA Total	**2.7 +/- 0.3**	
Experimental Results	**1.2 +/- 0.1 (DRS-DAQ)** **0.98 +/- 0.06 (GPS-DAQ)**	

- Predicted rates of detection (borehole + 4 air shower detectors) by decade of primary proton
- DRS-DAQ had a much lower threshold than the GPS-DAQ
- Predicted rate is too high by about 2
- Our detectors are largely insensitive to gammas though…

Decadal Rate Analysis – No gammas

No gamma table		Lambda (g/cm^2)
Primary Energy Range (eV)	CORSIKA rates per borehole detector (per hour)	
1E11 - 1E12	0	~110
1E12 - 1E13	0	~120
1E13 - 1E14	0.5 +/- 0.1	~130
1E14 - 1E15	0.41 +/- 0.07	~140
1E15 - 1E16	0.3 +/- 0.1	~150
1E16 - 1E17	0.07 +/- 0.03	~165
CORSIKA Total	**1.3 +/- 0.2**	
Experimental Results	**1.2 +/- 0.1 (DRS-DAQ)** **0.98 +/- 0.06 (GPS-DAQ)**	

- The table shows the predicted rates of detection assuming **no** sensitivity to gammas
- Predicted rate is now in rough agreement with observed rate
- The Λ is in rough agreement.
- Converting gammas, with ¼" Pb for instance, could yield 2x rate increase

Angular Resolution - CASA

- The Chicago Air Shower Array (CASA) from the 1990s was a scintillator-based detector of the scale we are contemplating.

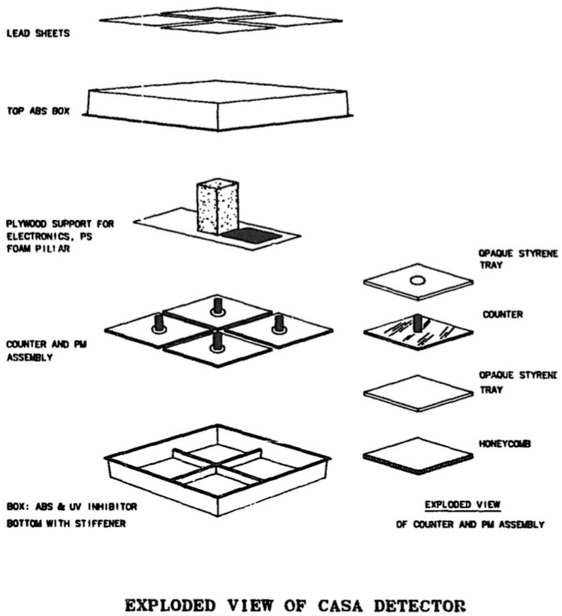


FIGURE 2
Construction diagram of a CASA station and counter.

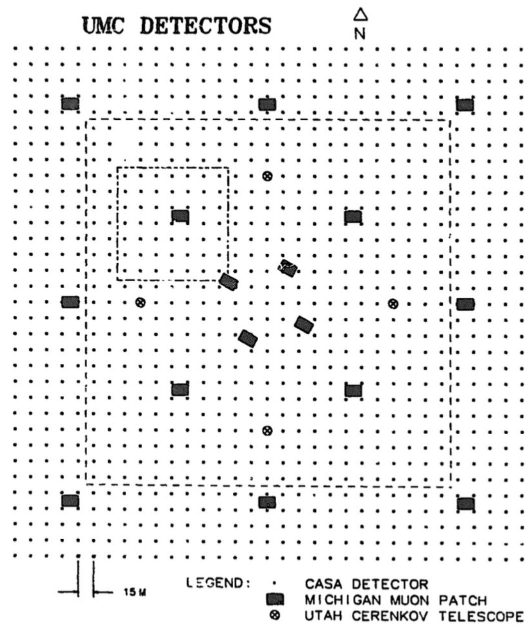


FIGURE 1
Plan view of the Utah-Michigan-Chicago detectors at Dugway, Utah. The line boundaries are discussed in the text. The Fly's Eye II experiment is not shown.

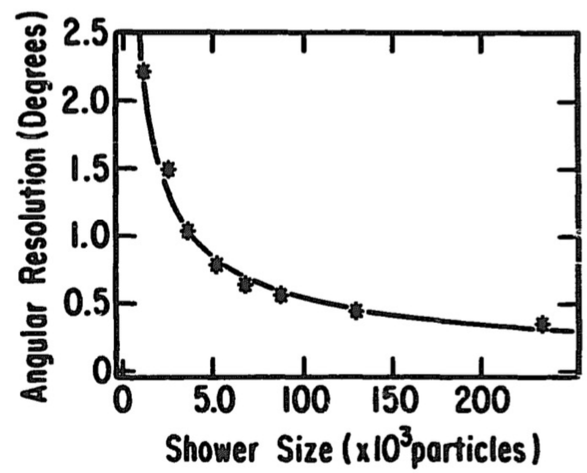
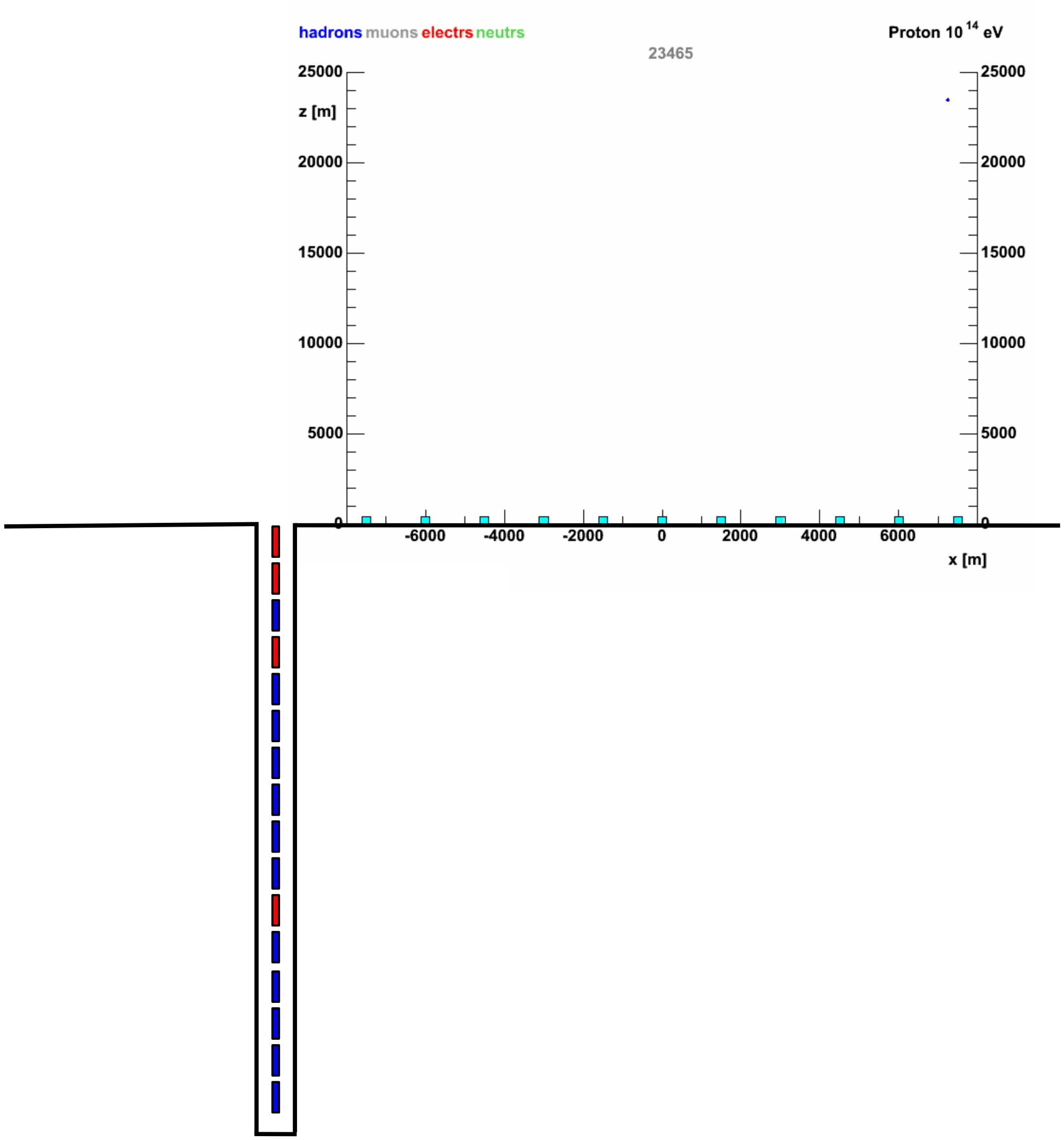


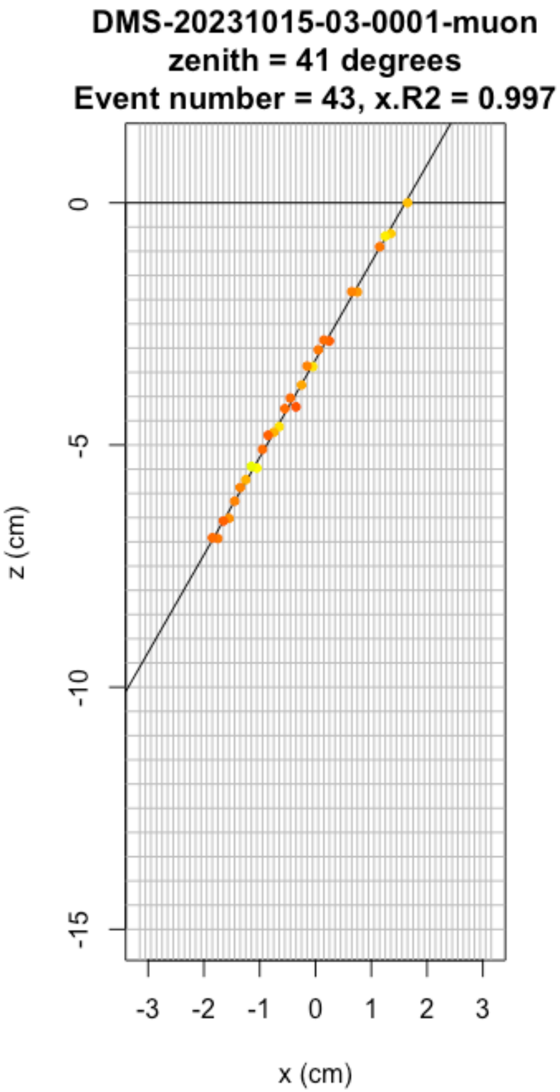
FIGURE 12
Angular resolution versus shower size (preliminary).

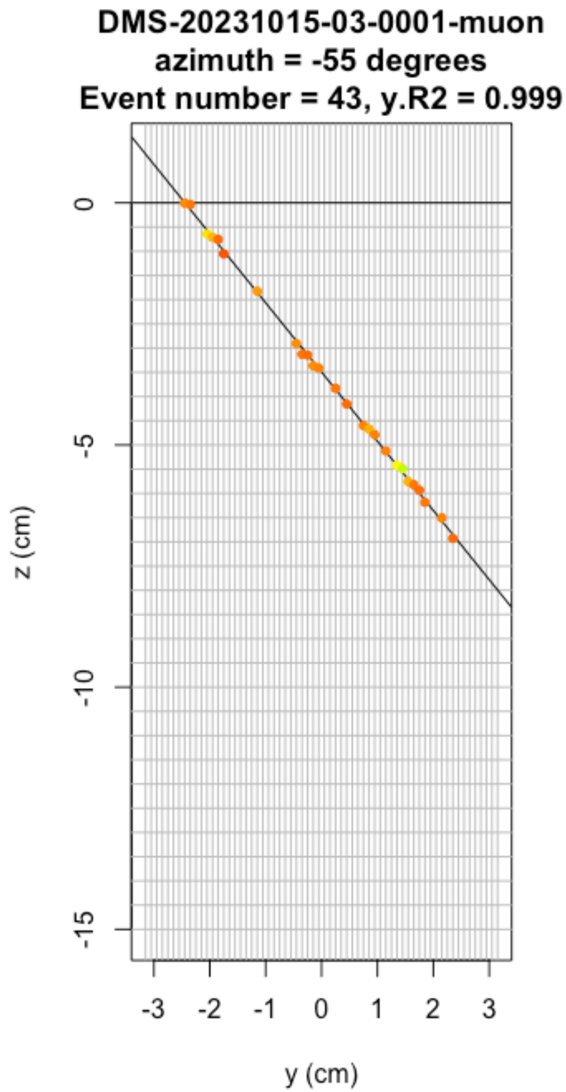
Angular Resolution



- We replaced one of the borehole detectors with our directional, gas-based, borehole detector.

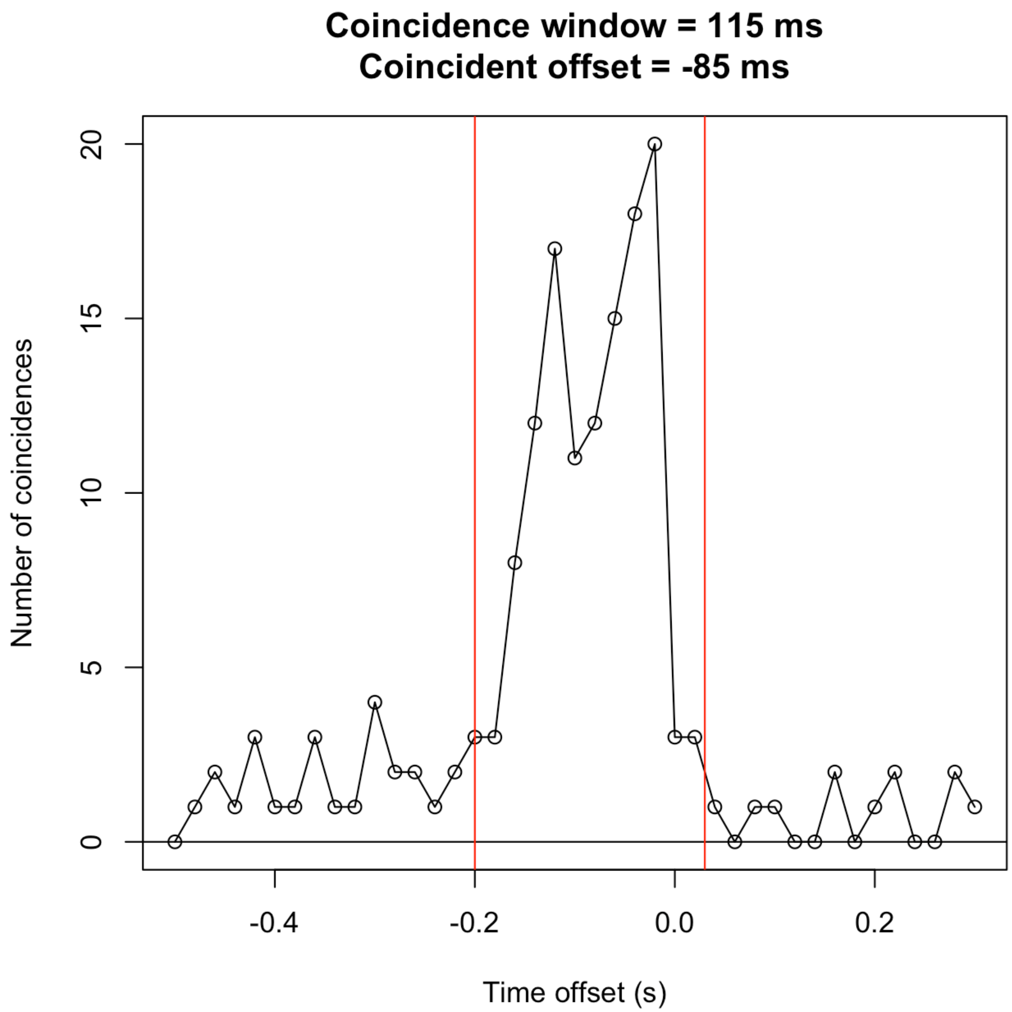
Angular Resolution of KoDark Gas Detector





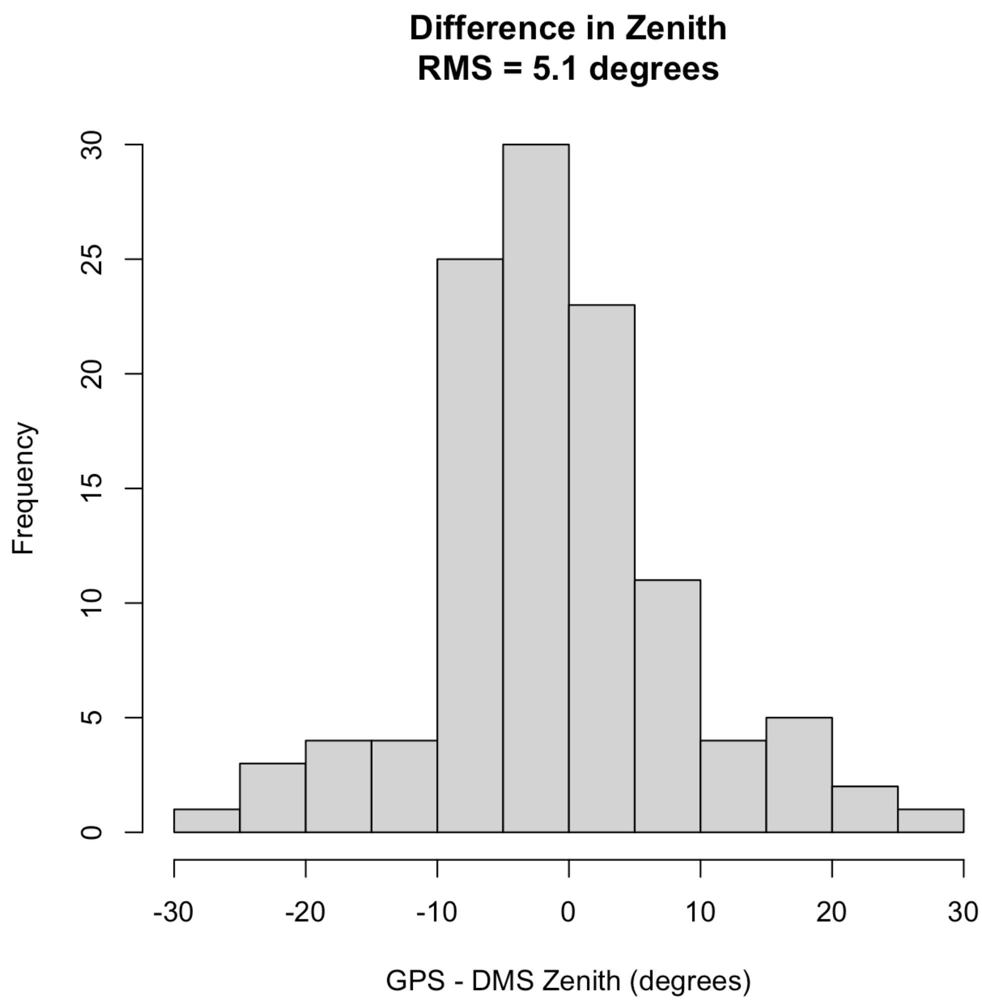
- More details about this detector can be found in Jean-Luc Gauvreau's Muographers 2024 talk.
- As discussed there this detector has ~1 mrad angular resolution.
- Deployed for this exposure at a depth of 20.3 m.
- Used GPS on each computer to sync the data sets in time.

Timing



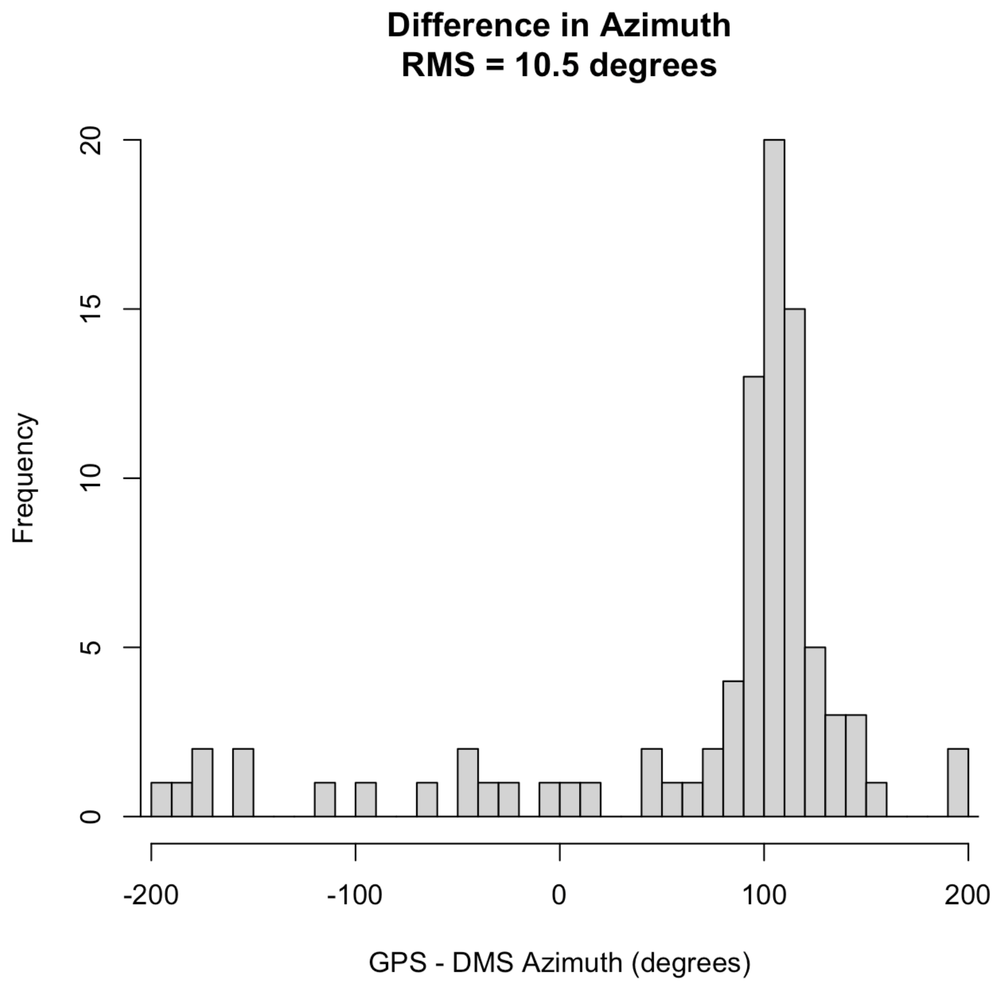
- Because of timing issues with the gas detector DAQ we were only able to obtain ~0.1 s timing resolution.
- We still see a clear peak
- There are 123 events in the acceptance window with a noise of 13.

Zenith Resolution



- Zenith angles measured from the GPS DAQ and the DMS DAQ from simultaneous events were subtracted.
- The RMS resolution in zenith was 5.1 degrees near the peak.
- The borehole detector could be tilted at a few degrees. We know the borehole is not perfectly straight.

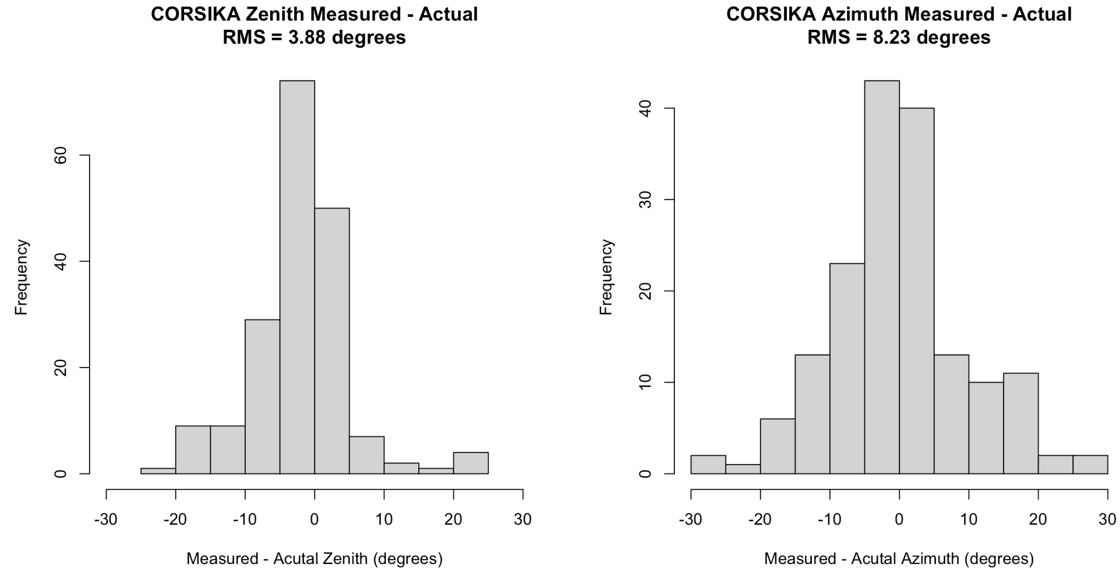
Azimuth Resolution



- We don’t control the azimuth of the borehole detector so that is a free parameter.
- The RMS resolution of the difference in azimuth was 10.5 degrees near the peak.
- Azimuth is more difficult to measure for low zenith tracks owing to the smaller difference in arrival times.

CORSIKA Resolution

- Air showers have a thickness of several m which yields a fundamental limit on resolution.
- Each CORSIKA event was fit using the above algorithm and compared to the true values.
- The bulk of the measured error is due to air shower physics.
- The residual error is roughly in agreement with predicted timing errors
- We are “lever arm” limited with this test array.



Resolution matrix	Zenith RMS (degrees)	Azimuth RMS (degrees)
Experiment	5.1	10.1
CORSIKA	3.88	8.23
Residual	3.31	5.85

- Simulations of a large km-scale detector with 1600 detectors spread over a circle of radius 1 km and borehole detectors at 1 km suggest errors down to ~1-2 degrees in zenith / azimuth.

Conclusion

- We constructed the array test-bed at Occidental College in order to verify this concept.
- To first order it has passed several tests,
  - ✓ Technically possible
  - ✓ Coincidences observed
  - ✓ Zenith distribution
  - ✓ Rate
  - ✓ Angular resolution
- With the hardware, GPS-DAQ and these tests we feel confident to move on to a bigger detector. We are planning to build much larger prototypes over the next 3 years
- We look forward to presenting results at next Muographers Conference.

The End

CORSIKA – Preliminary Results

- Generated 40M showers so far
- 10^{12} eV < E_0 < 10^{16} eV
- 1600 m^2 of detectors spread over a circle of radius = 1 km, i.e. optimized for 1 km depth detections
- Calculated fraction of muons at depth associated with showers hitting 3 separate detectors or more
- For 1600 1 m by 1 m stations at 1km the result is about 20%
- Considered stations 1 m by 1 m up to 4 m by 4 m keeping total scintillator area fixed
- There does not appear to be much dependence on station size