UHE Cosmic Ray Energy Spectrum from the Telescope Array Experiment & Search for Simultaneous Showers in High Resolution Fly's Eye Data

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Ph.D. Defense
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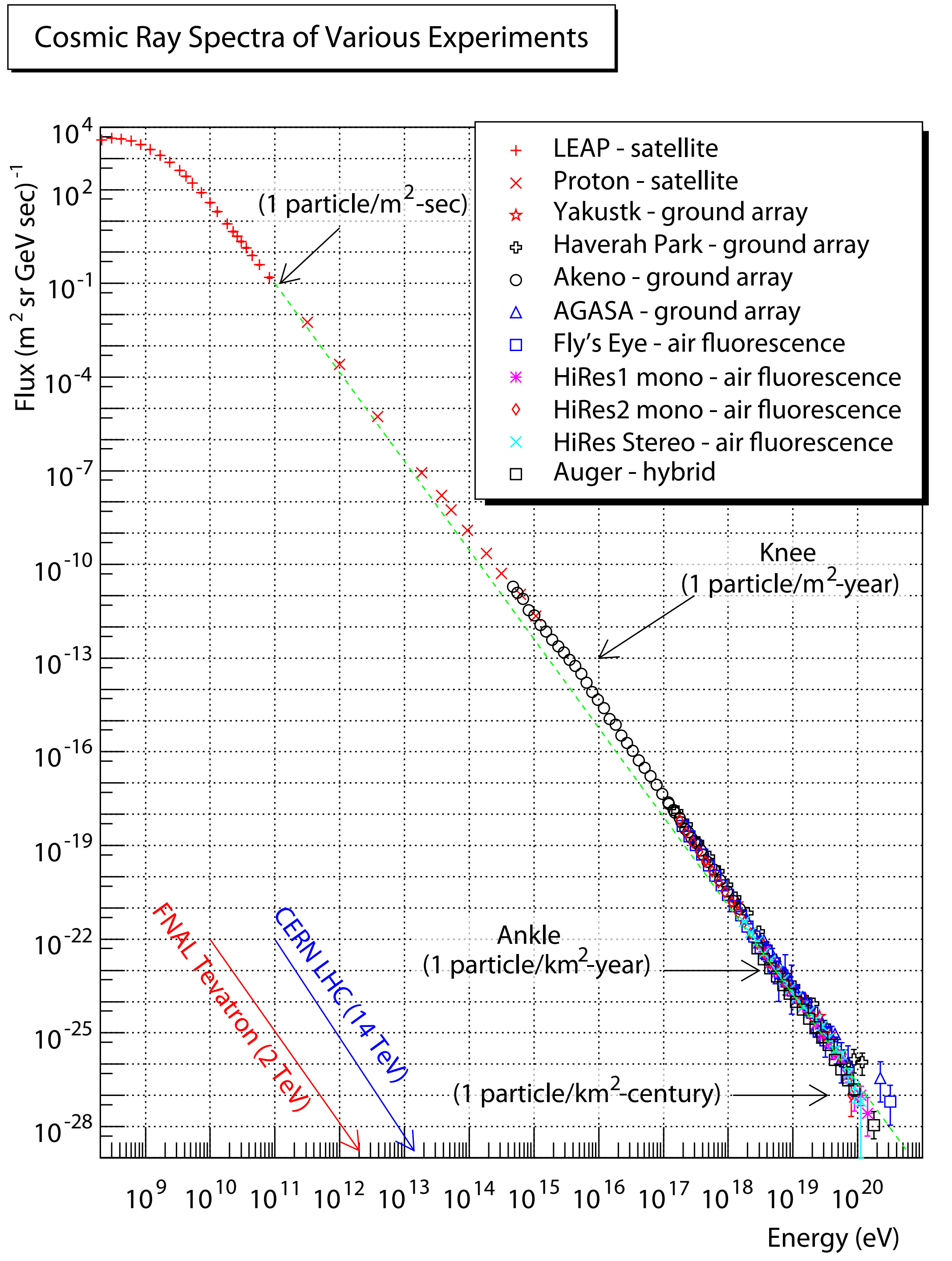
Outline

- Cosmic Ray Physics
- Overview of HiRes and Telescope Array
- Energy Spectrum
  - Analysis
  - Results
  - Summary
- Simultaneous Showers
  - Theory and Modeling
  - Analysis
  - Results
  - Summary

Cosmic Rays

- 1912: Victor Hess discovers cosmic rays
- Observed over wide range of energies
- Slope barely deviates over 10 orders of magnitude
  - power law of -3
  - primary feature: the Knee (~5×10^{15} eV)



Cosmic Ray Energy Limit

- 1964: Penzias and Wilson observe Cosmic Microwave Background (CMB)

- 1966: end of the cosmic ray spectrum proposed
  - Greisen and, independently, Zatsepin and Kuzmin

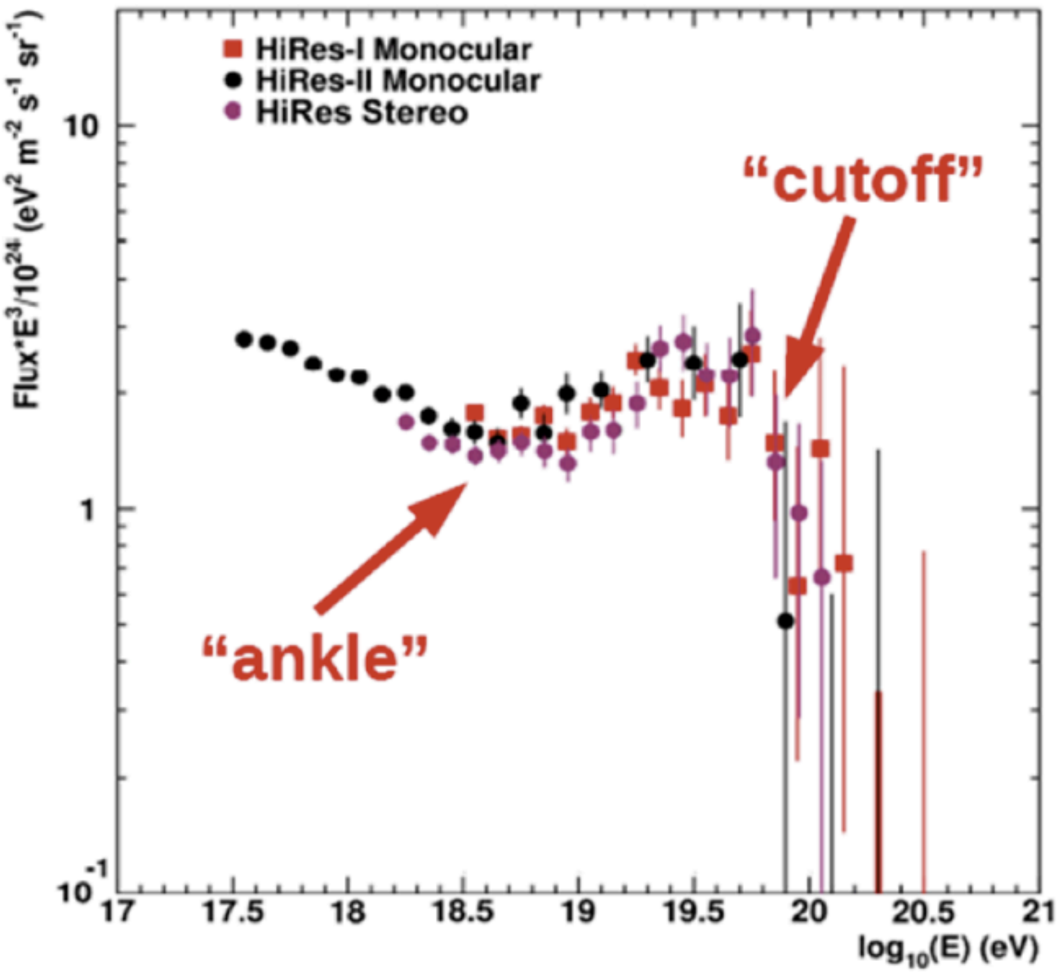
$$p + \gamma \rightarrow \Delta^{+}(1232\ \mathrm{GeV}) \rightarrow p + \pi^{\circ}$$

- GZK cutoff at 6×10^{19} eV (reaction threshold)
  - due to UHECR proton interacting CMB Radiation

K. Greisen. End to the cosmic-ray spectrum? Phys. Rev. Lett., 16(17):748–750, Apr 1966.
G. T. Zatsepin and V. A. Kuz'min. Upper limit of the cosmic-ray spectrum. Sov. Phys. JETP Lett., 4:78, 1966.

UHE Cosmic Rays

- HiRes (Utah) first to observe GZK
- Ultra-High Energy (UHE) regime
  - E ≳ $10^{17.0}$ eV
  - Flux × E^3
- Two features
  - ankle and GZK indicative of protonic composition



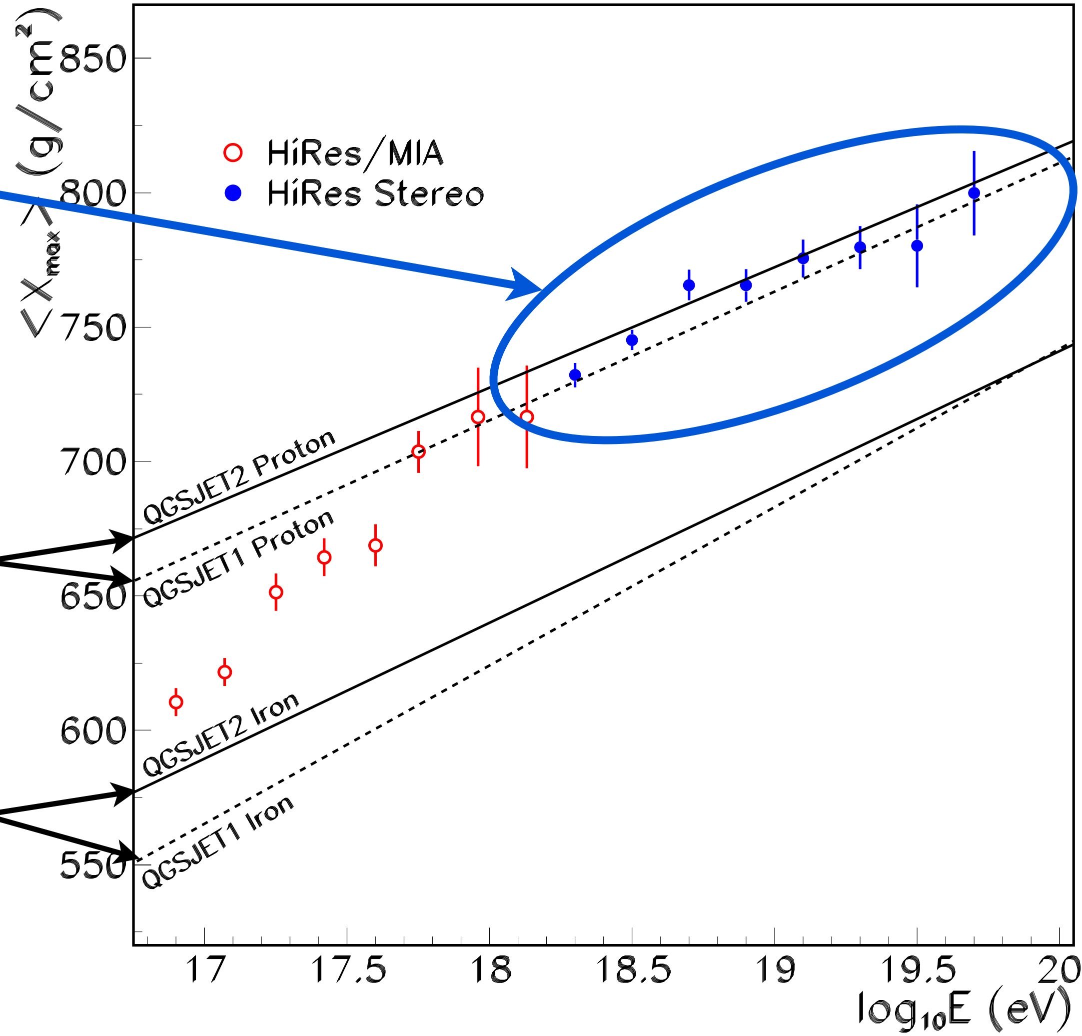
R. Abbasi et al., Measurement of the flux of ultra high energy cosmic rays by the stereo technique, Astroparticle Physics 32 (2009).
R.U. Abbasi et al., First observation of the Greisen-Zatsepin-Kuzmin suppression, Phys. Rev. Lett. 100 (2008), no. 10, 101101.

UHE Cosmic Rays Composition

- HiRes composition consistent with proton ≥ 10^{18} eV

Proton Monte Carlo

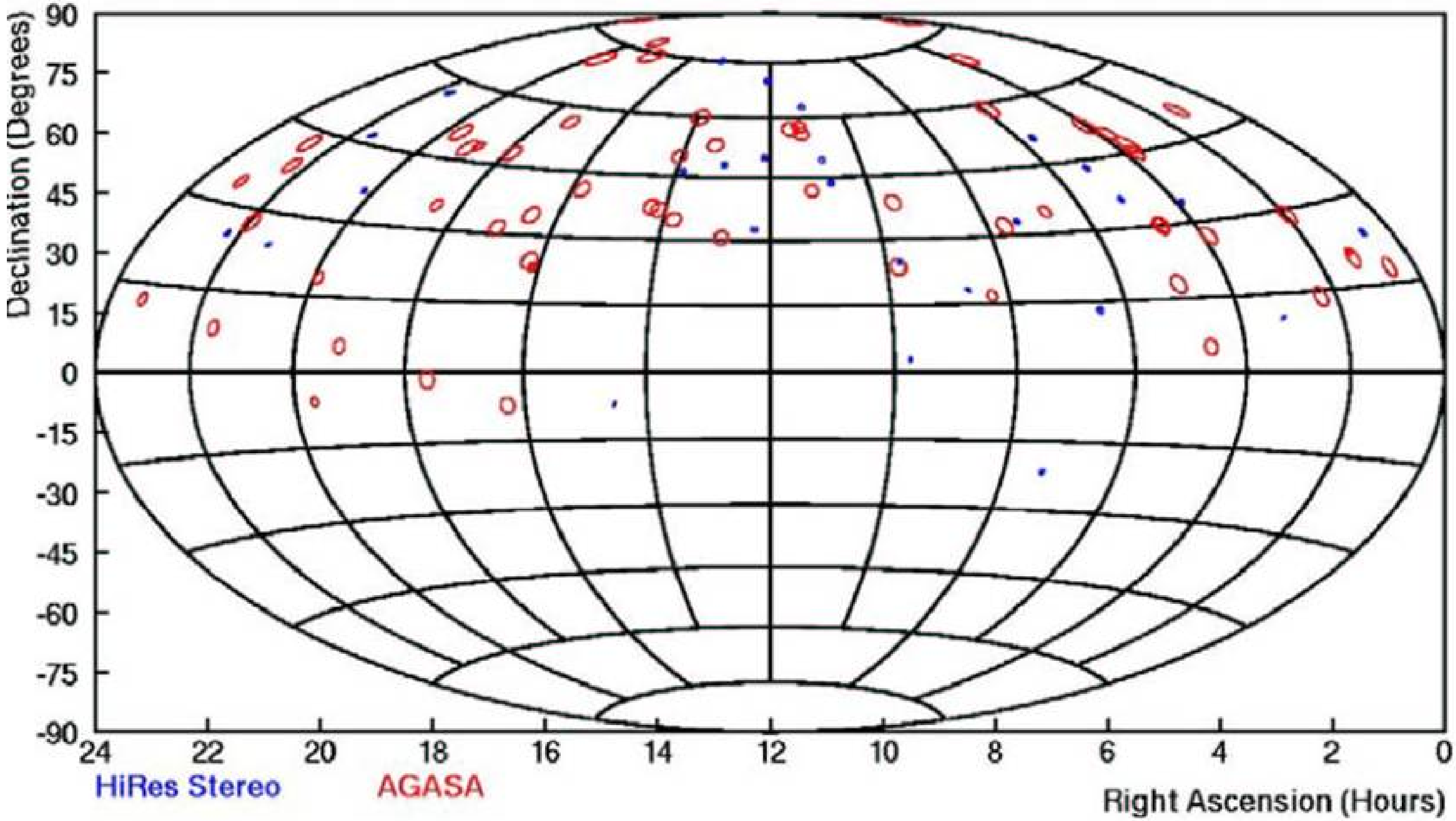
Iron Monte Carlo



R. U. Abbasi et al. (The High Resolution Fly's Eye Collaboration), Evidence for Proton-Dominated Cosmic Ray Composition above 1.6 EeV, Phys. Rev. Lett. 104 (2010).

- energy spectrum → acceleration mechanism?
- composition → where does acceleration taking place?
- current results: UHECR extra-galactic protons(?)
- anisotropy search → no significant results
- **Source is unclear**

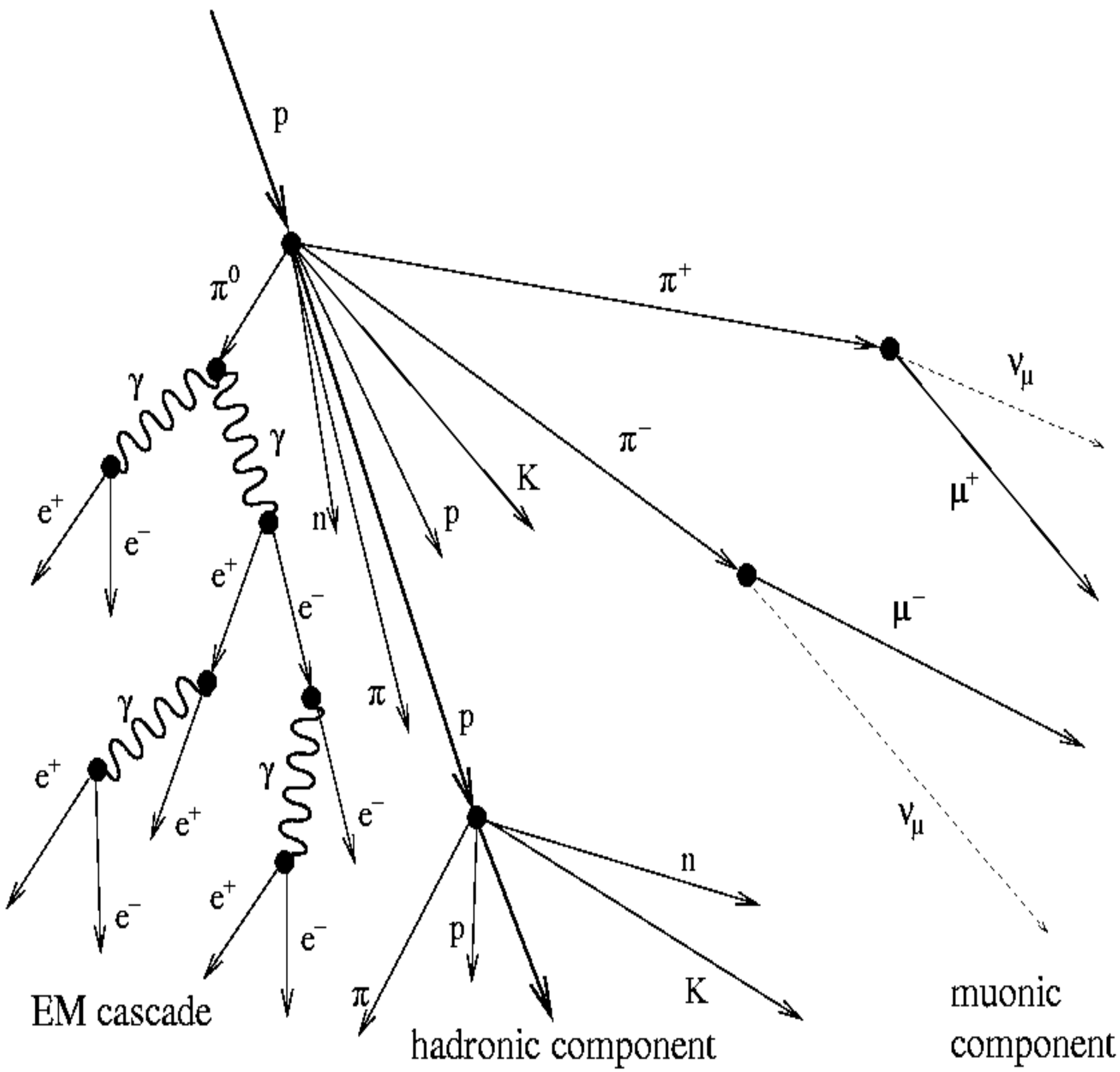
68% Angular Resolution for AGASA and HiRes Events > 4 × 10^{19} eV



Observation of UHE Cosmic Rays

- Very rare
  - Can't make direct measurements using satellite- or balloon-sized instruments
- Detection method is conventionally known as calorimetry
  - Measure energy deposited into atmosphere
- Methods:
  - Fluorescence telescopes
  - Ground arrays (scintillators, water tanks, etc.)
  - Čerenkov detectors

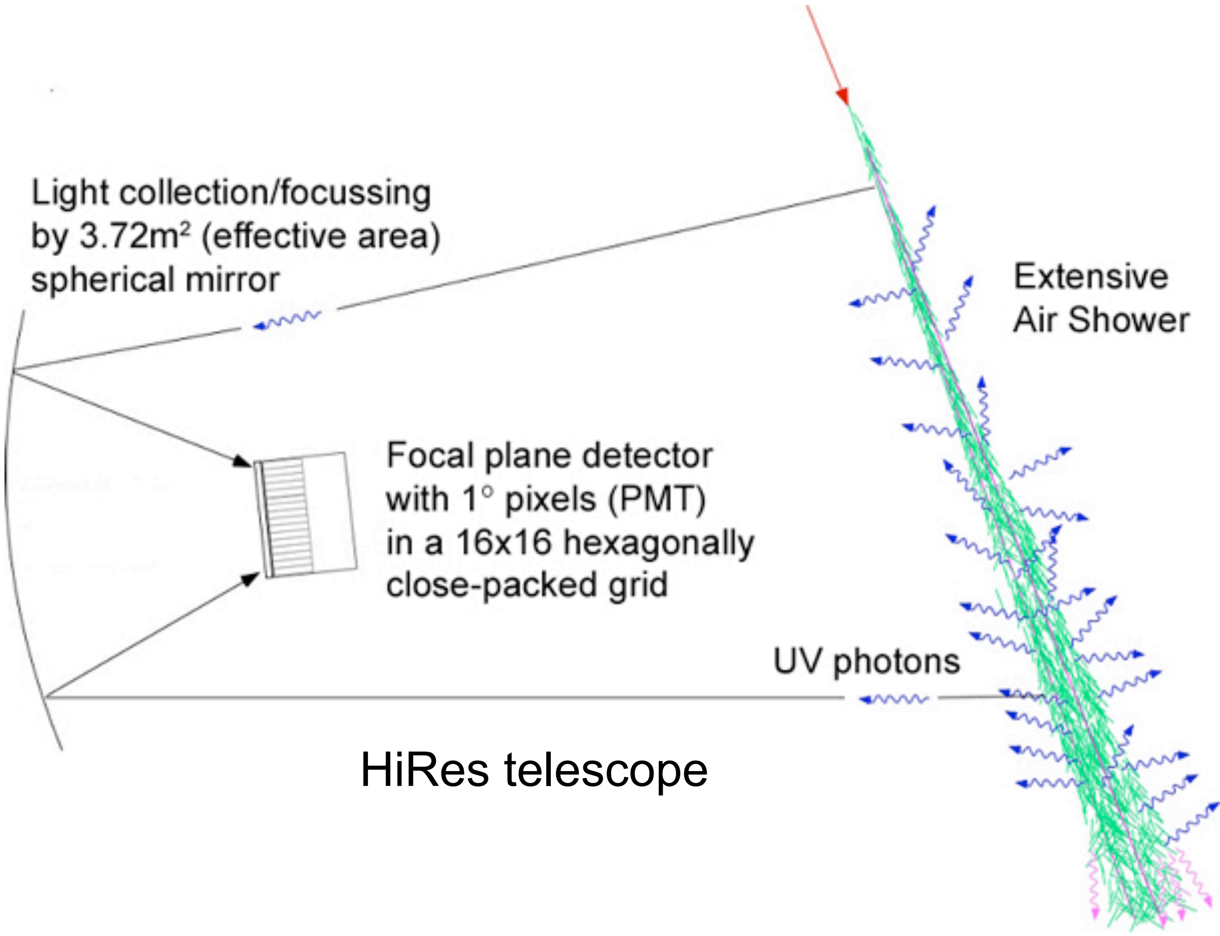
Extensive Air Showers



- Primary particle enters atmosphere interacting with a nucleus, creating many secondaries
- Which go on to collide, repeating interaction, resulting in extensive air showers
- shower dominated by electromagnetic particles (e and γ) after first few interactions

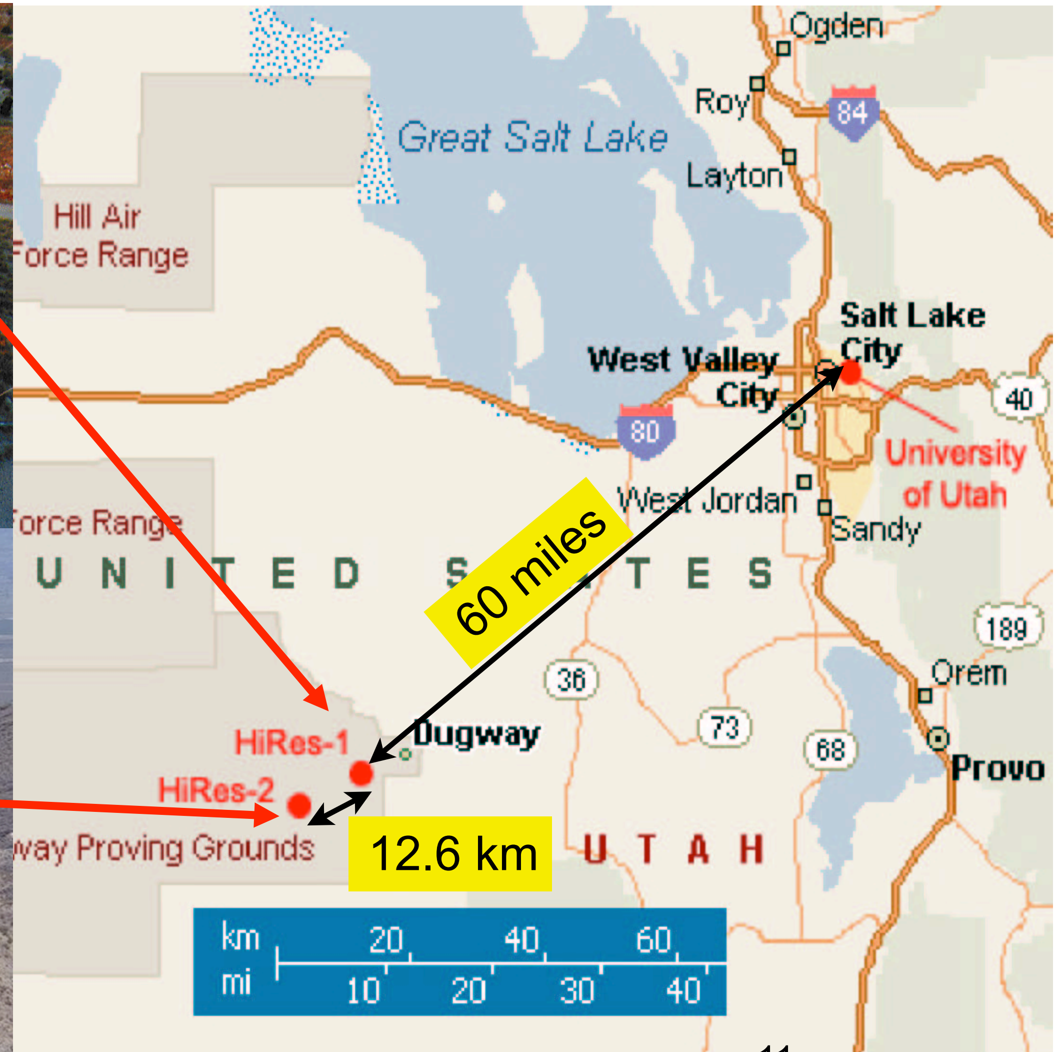
Fluorescence Observation

- Fluorescence telescopes observe the UV light
- Consist of:
  - mirror focuses light
  - camera of photomultiplier tubes, convert light to electrical signal
  - UV bandpass filter removes most visible



HiRes telescope

The High-Resolution Fly's Eye



HiRes Author List

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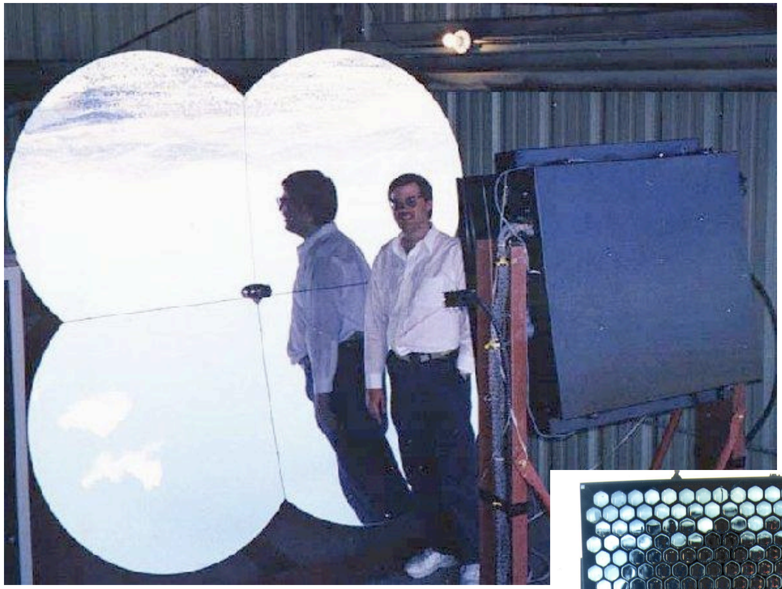
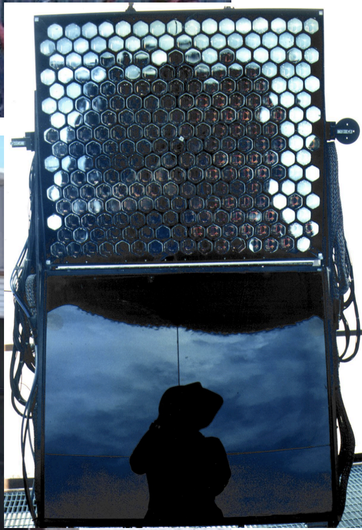
University of Utah

HiRes Sites

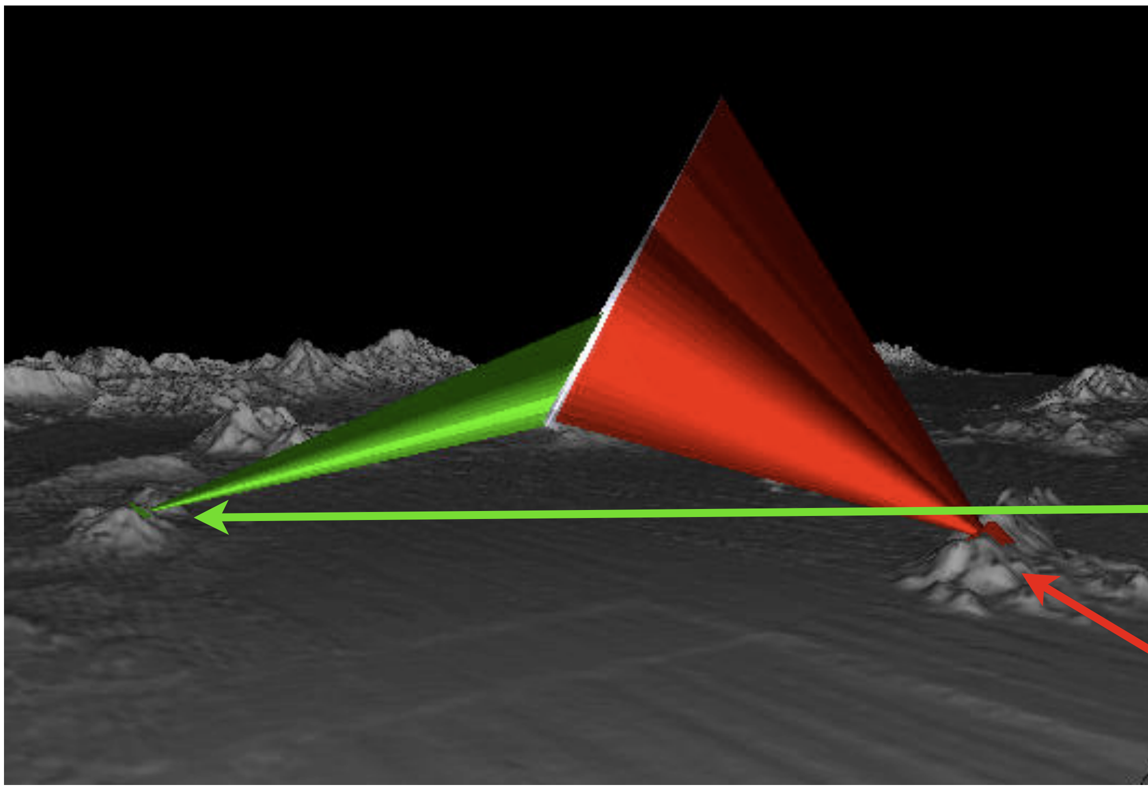
HiRes-1: atop Little Granite Mountain
- 20 telescopes, “ring-1”
  - (3°< elevation <17°)
- 2 “ring-2” telescopes for stereo
  - (17°< elevation <31°)
- Sample-and-hold electronics
  - (pulse height and trigger time)

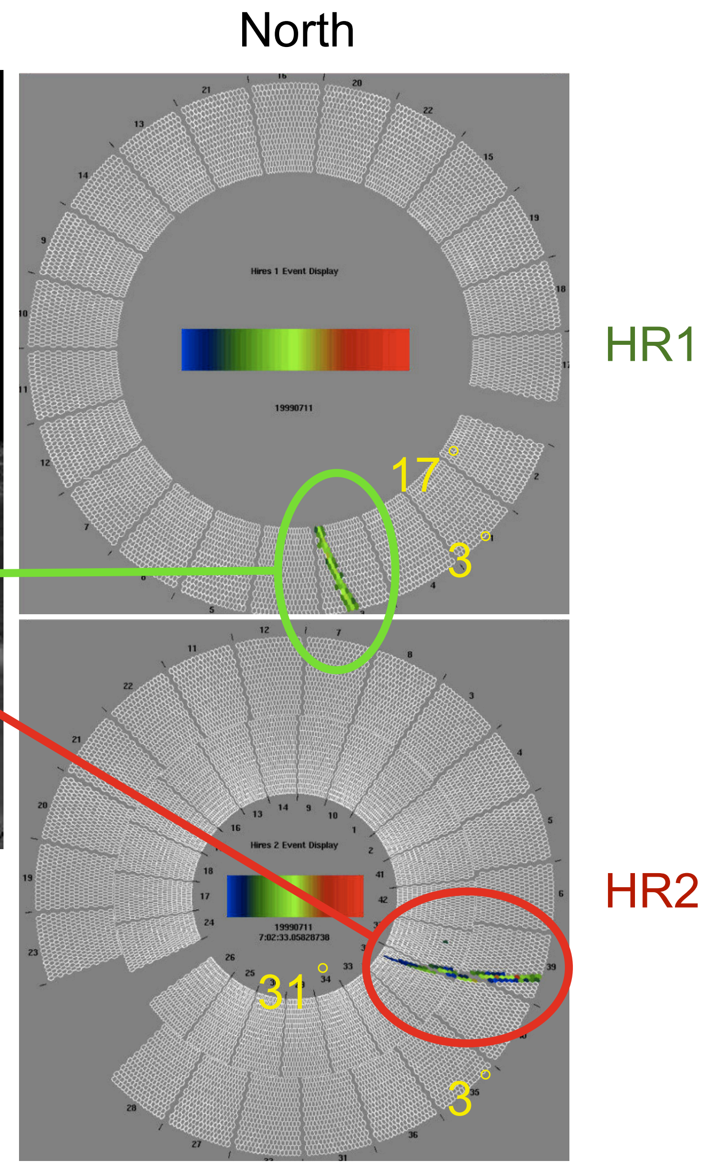


HiRes-2: atop Camel’s Back Ridge
- 12.6 km SW of HiRes-1
- 42 telescopes, 2 full rings
  - (3°< elevation <31°)
- FADC electronics
  - (100 ns period)



Stereo Observation

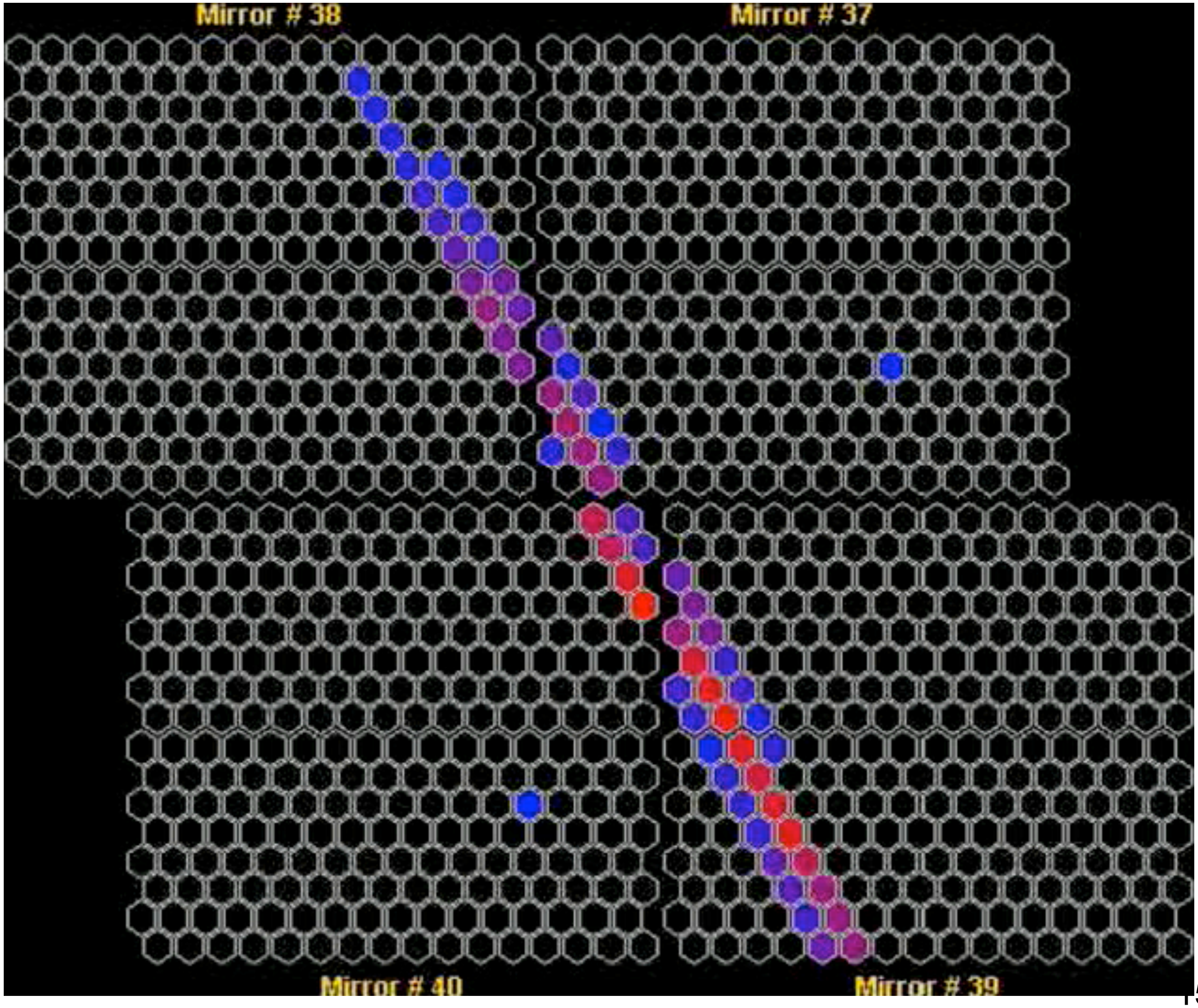




- Event Displays at right
  - Outer ring at 3° above horizon
  - Zenith is at center of displays
  - Color indicates intensity of light

Observation of EAS

(playback at 1/500,000 speed)



HiRes-2 Event

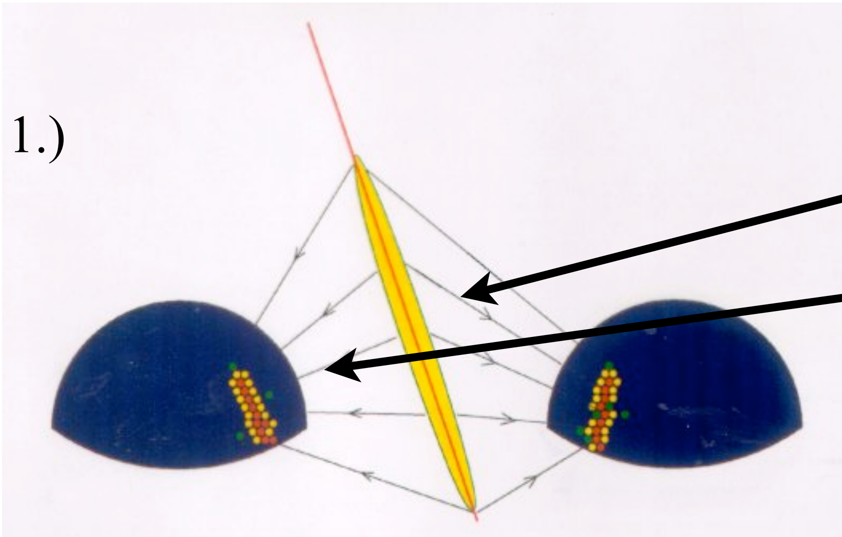
Observation of EAS

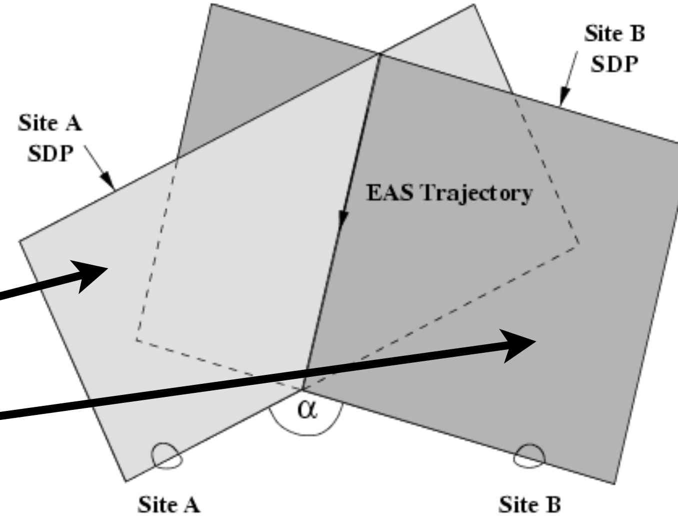
(playback at 1/500,000 speed)

HiRes-2 Event

Reconstruction of EAS

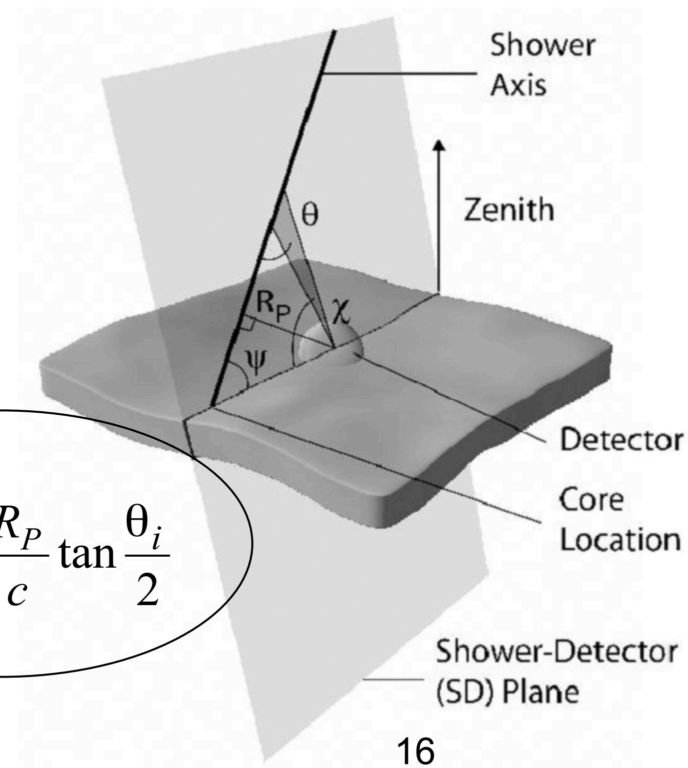
1.)





- Trajectory can be determined in two ways:
  1. If observed by both sites, intersect the two Shower-Detector Planes
     - provides more precise geometrical (hence, energy) reconstruction
  2. Else, use the arrival time of light at the detector

2.)



$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

Measuring the Energy

Gaisser-Hillas:

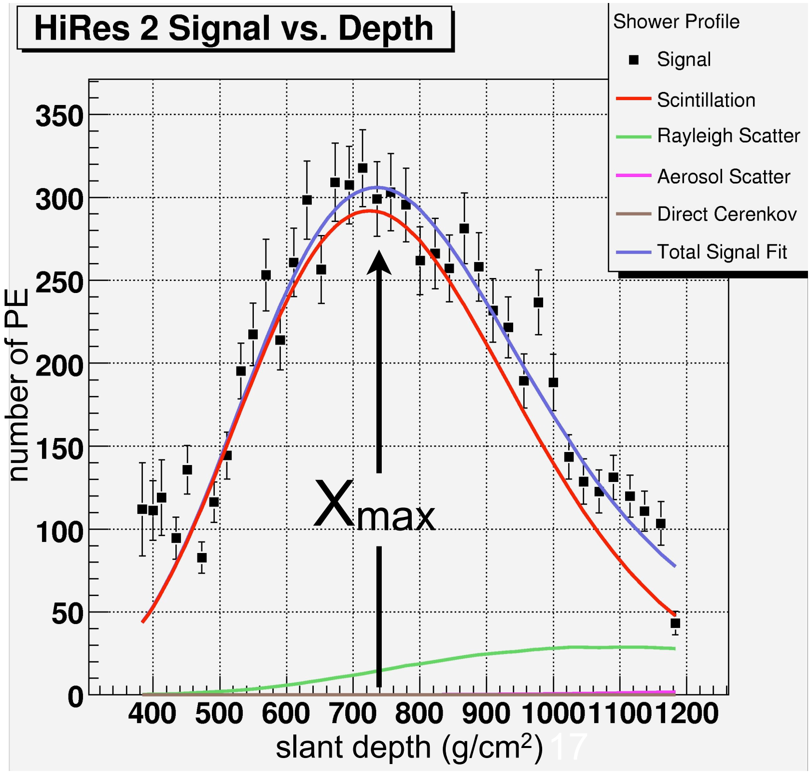
$$N(X) = N_{max} \left(\frac{X - X_0}{X_{max} - X_0} \right)^{\left(\frac{X_{max} - X_0}{\lambda} \right)} \exp\left(\frac{X_{max} - X}{\lambda} \right)$$

Event by event:

- X_{max} in g/cm²
- Total energy of the primary particle
- Arrival direction

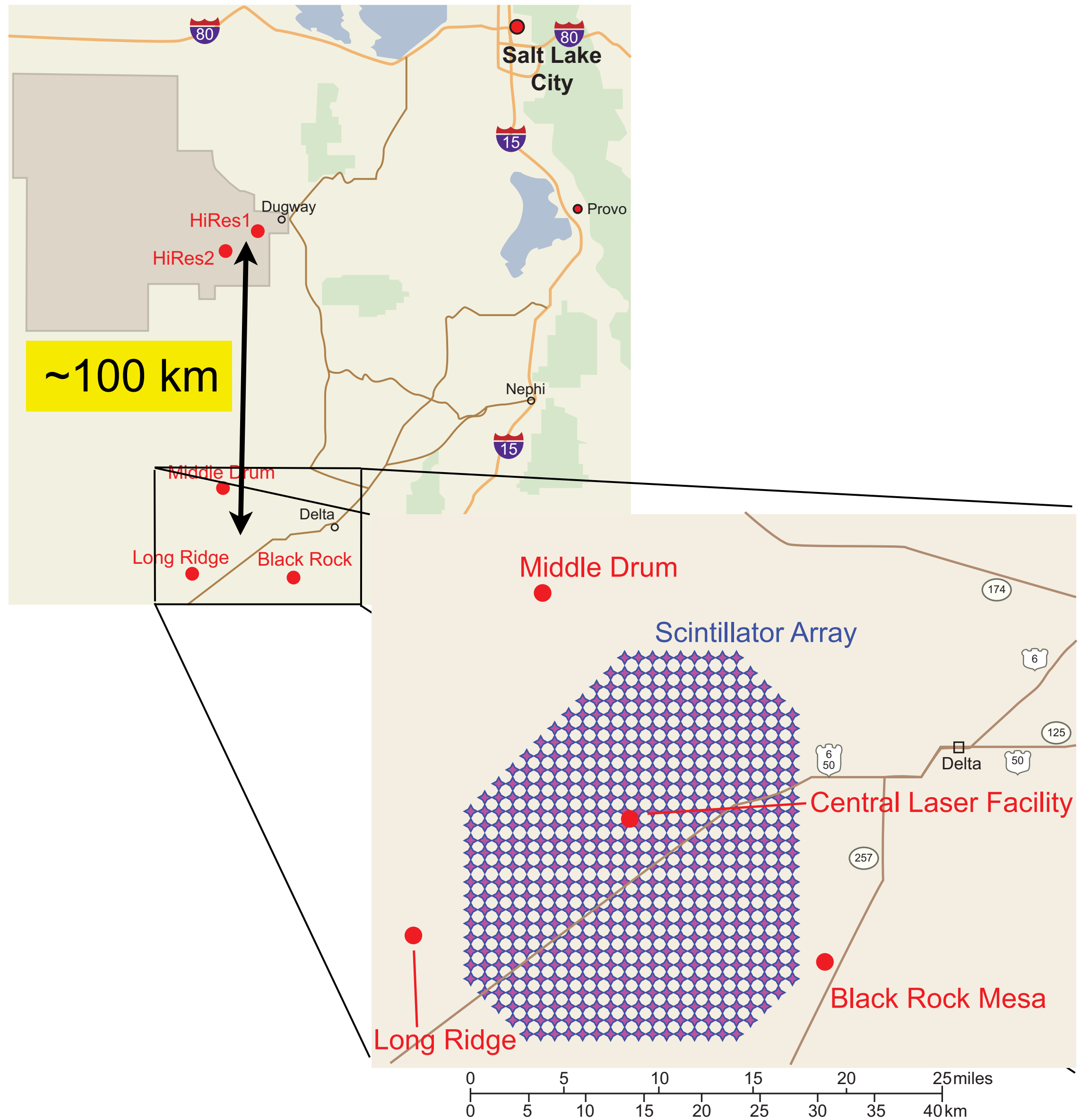
Statistically:

- composition
- *p*-air inelastic cross-section
- flux



New Experiment: Telescope Array

- HiRes concluded operations 4/2006
- Collaboration between HiRes and AGASA groups



TA Author List

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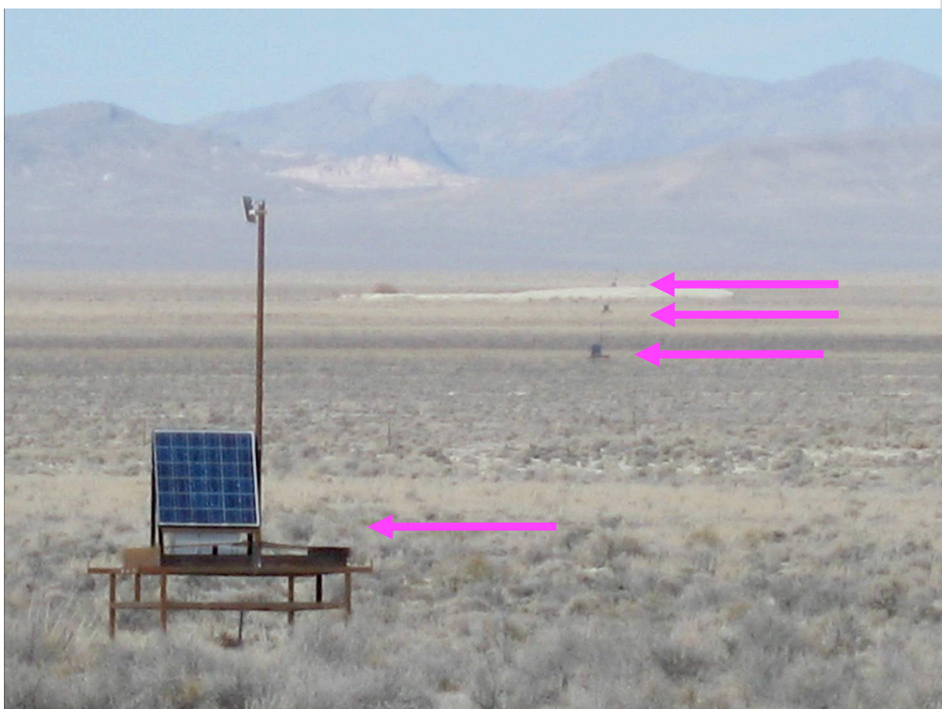
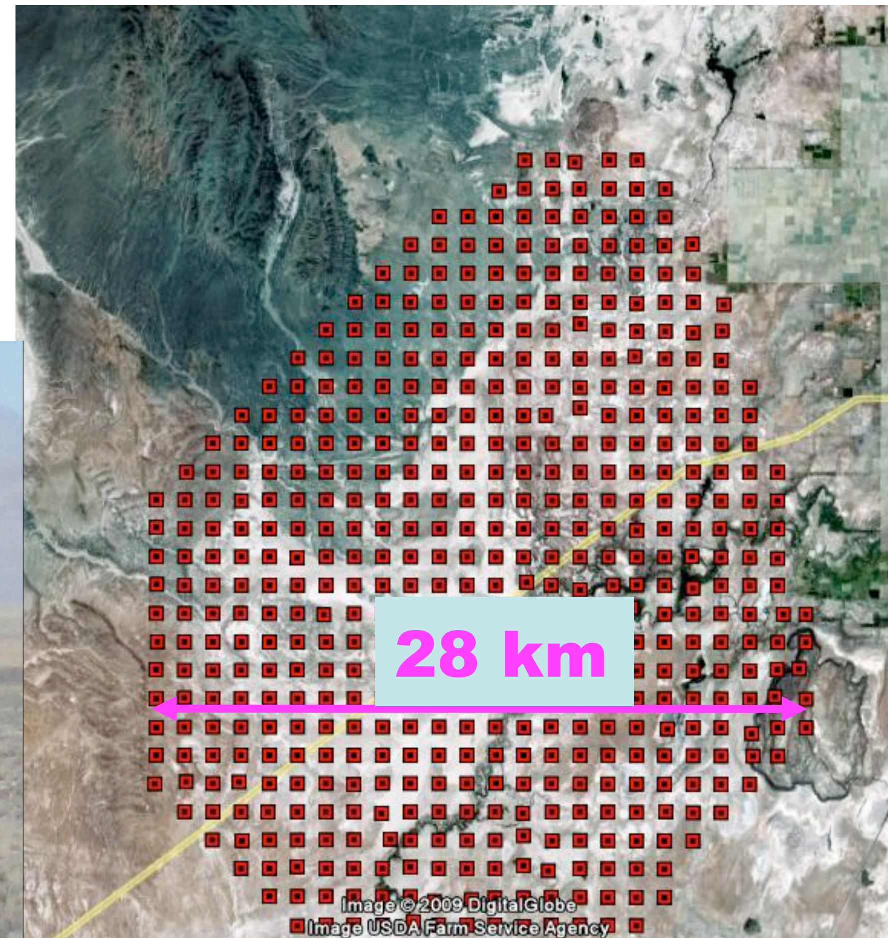
Physics Goals of Telescope Array

Observed	HiRes	AGASA	Auger
GZK	✓		✓ ✓
Point Sources		✓	
AGN Correlation			✓
Proton Composition	✓		
Iron Composition			✓

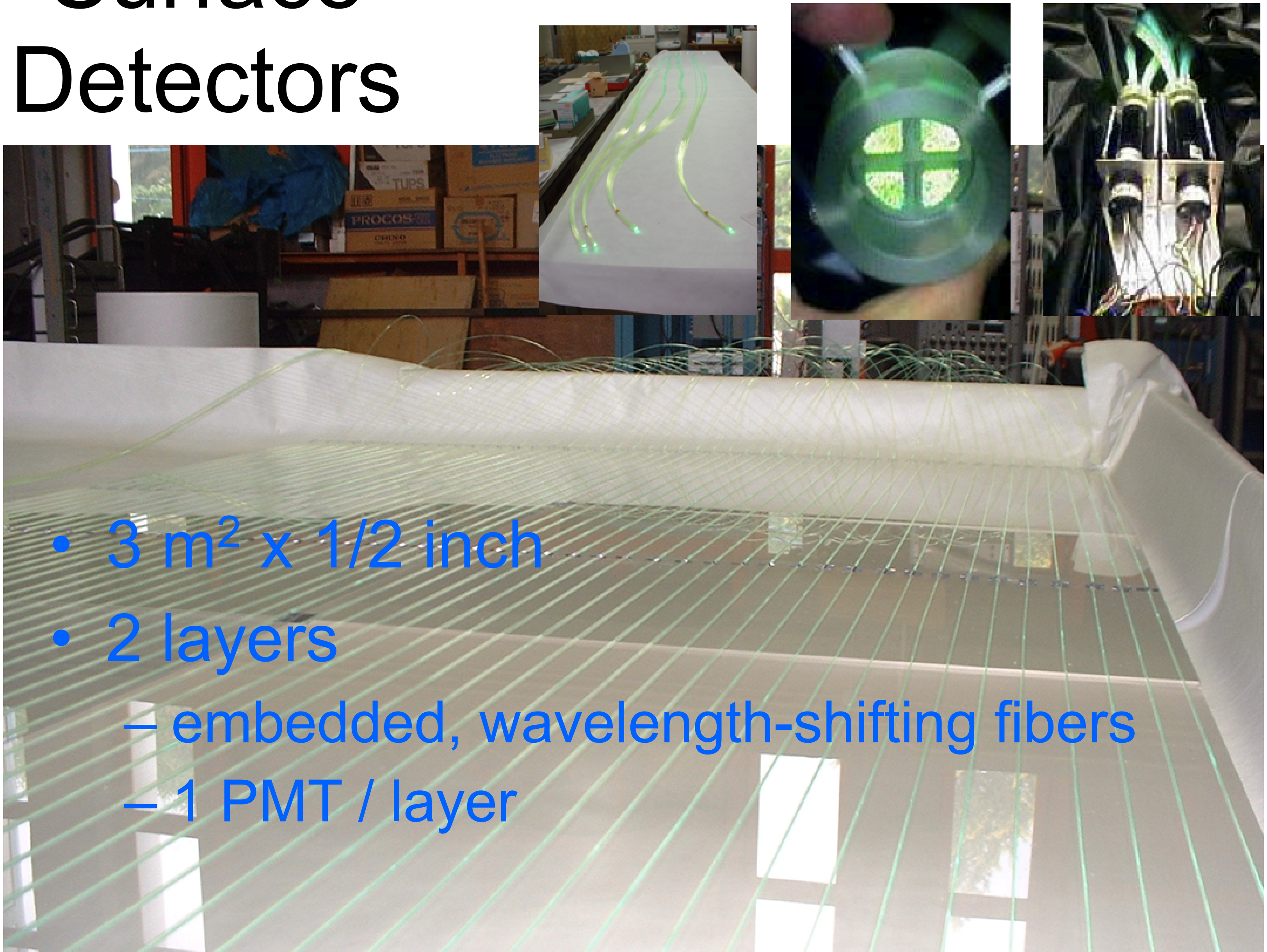
TA Surface Detectors

- Scintillation Array
  - 1.2 km separation, square grid
  - ~7× AGASA area





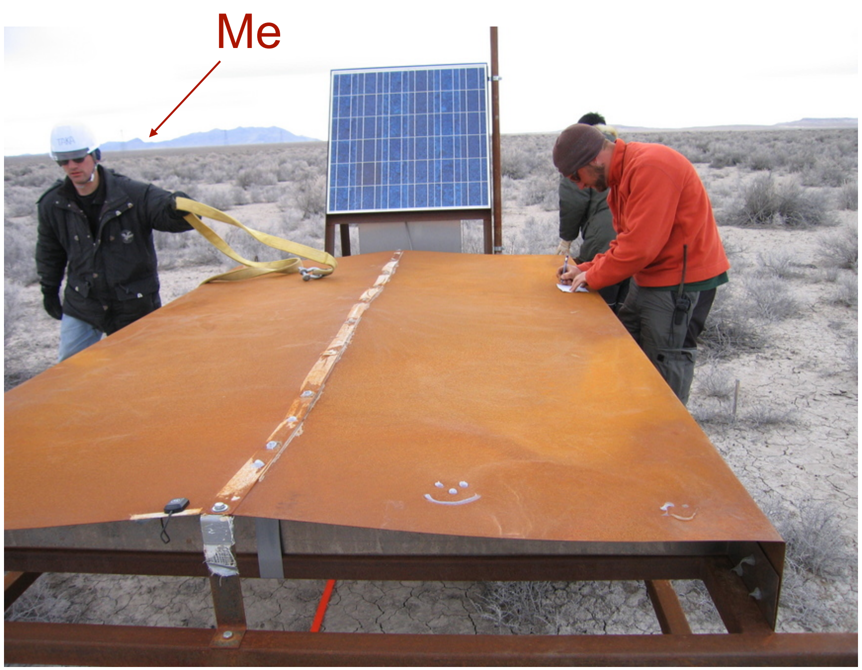
Surface Detectors



- $3\ m^2$ x 1/2 inch
- 2 layers
  - embedded, wavelength-shifting fibers
  - 1 PMT / layer

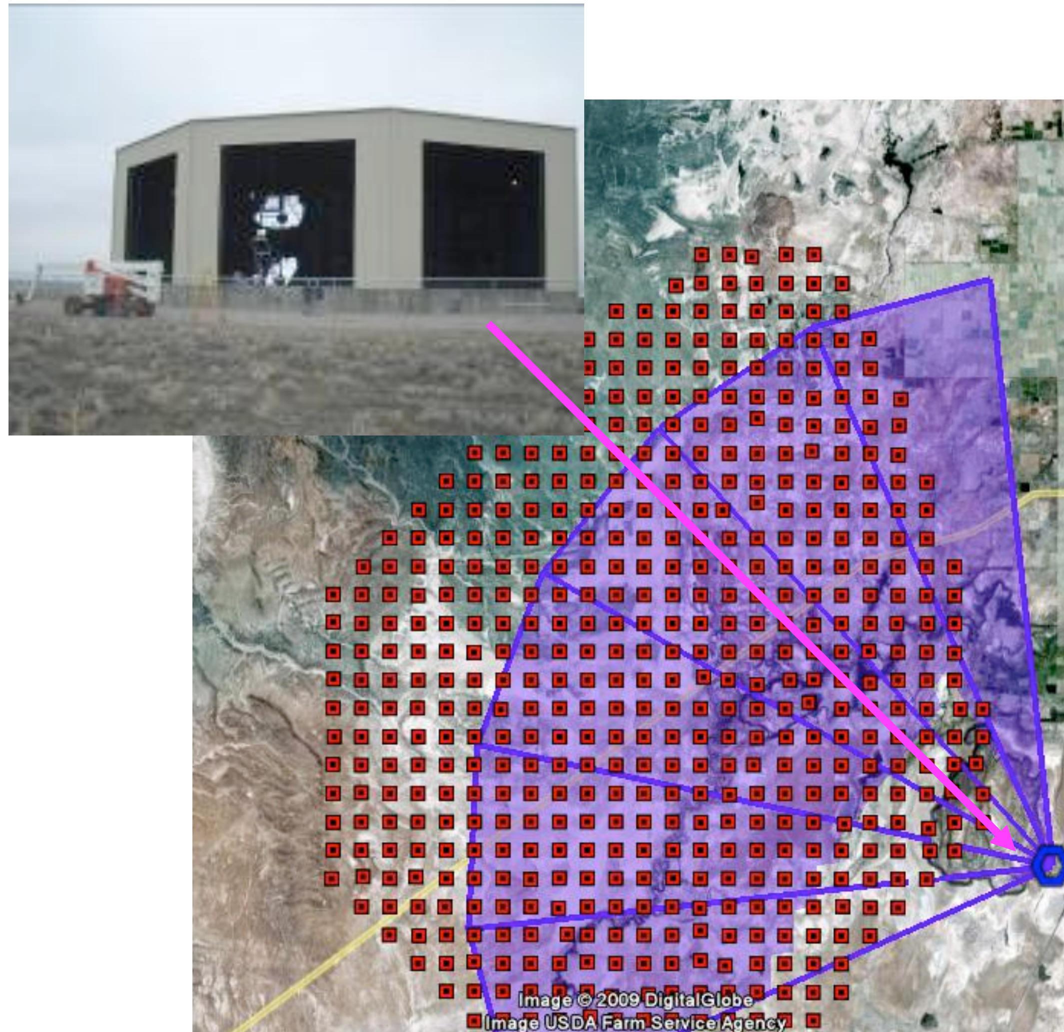
SD Deployment

- Sept. 2006 - March 2007
  - 485 of 507 deployed



TA Fluorescence Detectors

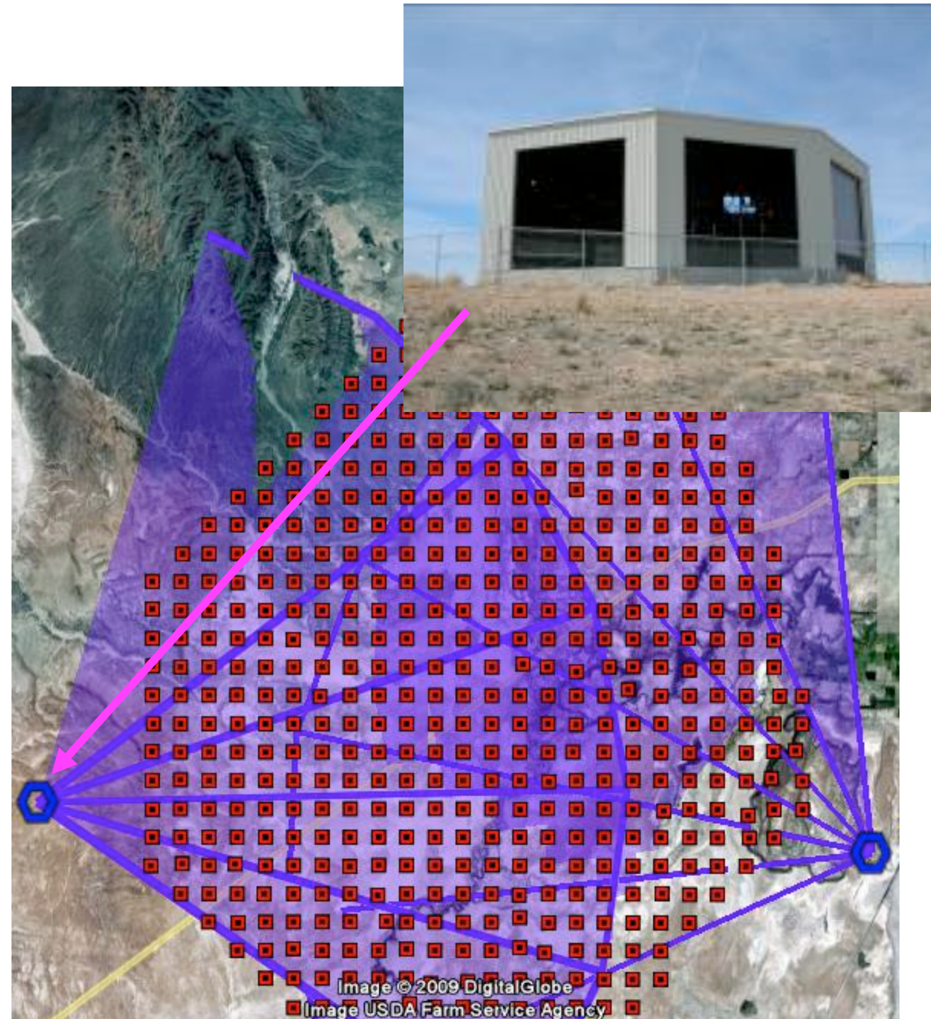
- 3 HiRes-like fluorescence detector sites
  – Black Rock Mesa



10^{19} eV range

TA Fluorescence Detectors

- 3 HiRes-like fluorescence detector sites
  - Black Rock Mesa
  - Long Ridge

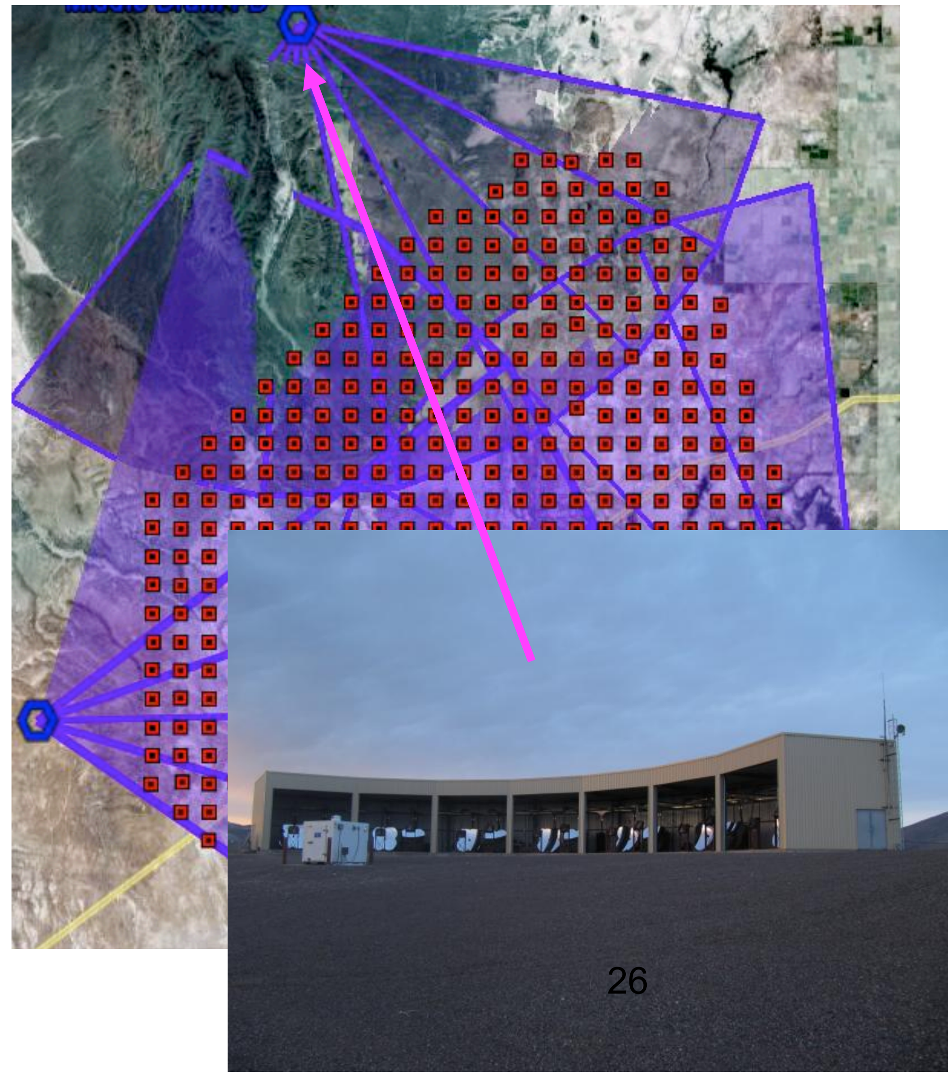


10^{19} eV range

TA Fluorescence Detectors

- 3 HiRes-like fluorescence detector sites
  - Black Rock Mesa
  - Long Ridge
  - Middle Drum

10^{19} eV range



Middle Drum FD

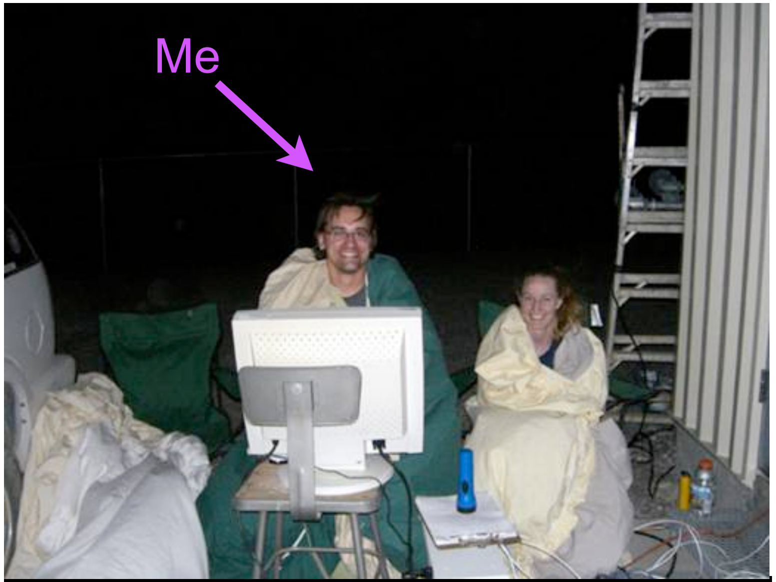
- 14 telescopes refurbished from HiRes-1
  - Reduced cost
  - Quick construction
- Changes
  - 2-rings (3-31° in elevation) like HiRes-2
  - longer tracks
  - ~120° in azimuth

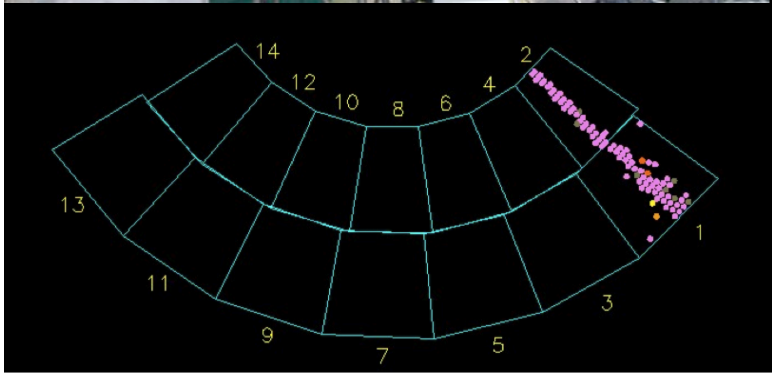
Middle Drum FD

- Sample-and-Hold electronics
  - 5.6 μs gate
  - "floating" tube thresholds to maintain individual firing rate of ~200 Hz
- 256 PMT cameras
  - 1° pixel
  - UV bandpass filter
- Same equipment used at HiRes-1
  - same calibration
  - direct link between HiRes-1 and Middle Drum

Refurbishment

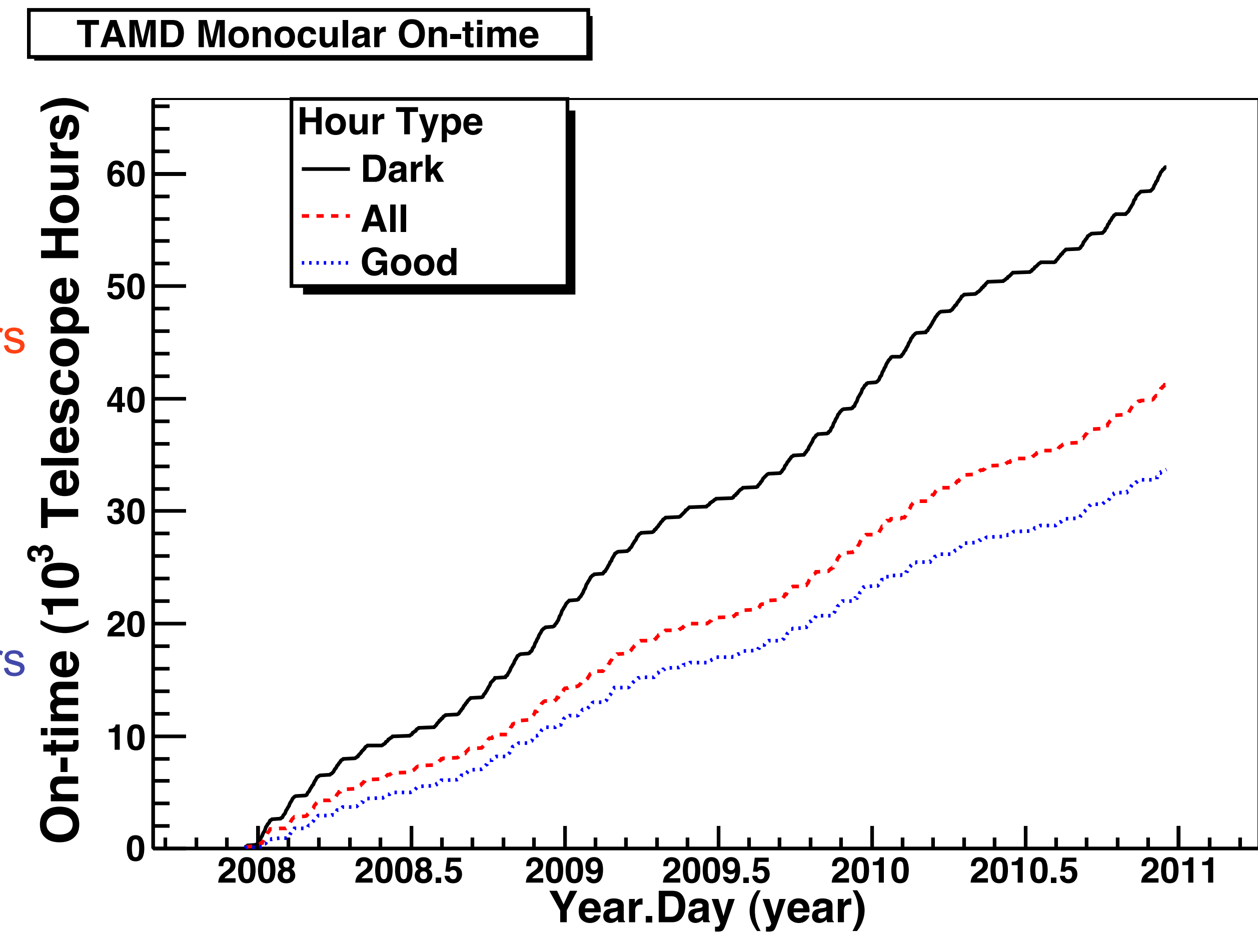
- I led a team of 3 students
  - 1 junior grad
  - 2 undergrads
- Process took 7 months, 2006-7
- Installation from June 2007 - October 2007
- Routine operations from November 2007
- First laser events shown at July 2007 ICRC (Mexico)





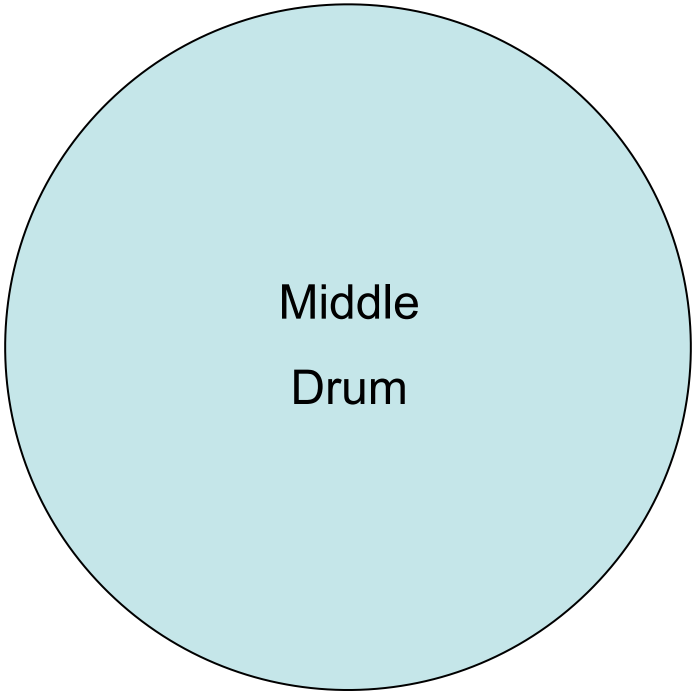
Middle Drum 3-Year On-Time

- 1-year spectrum shown in 2009 ICRC (Poland)
- December 16, 2007 – December 16, 2010
- All Weather: 41,261 integrated telescope hours
  - ~2,947 site hours (~68% of available)
  - moonless nights
- Good Weather: 33,686 integrated telescope hours
  - ~2,406 site hours (~82% of collected)
  - clear, moonless nights
- ~9% duty cycle



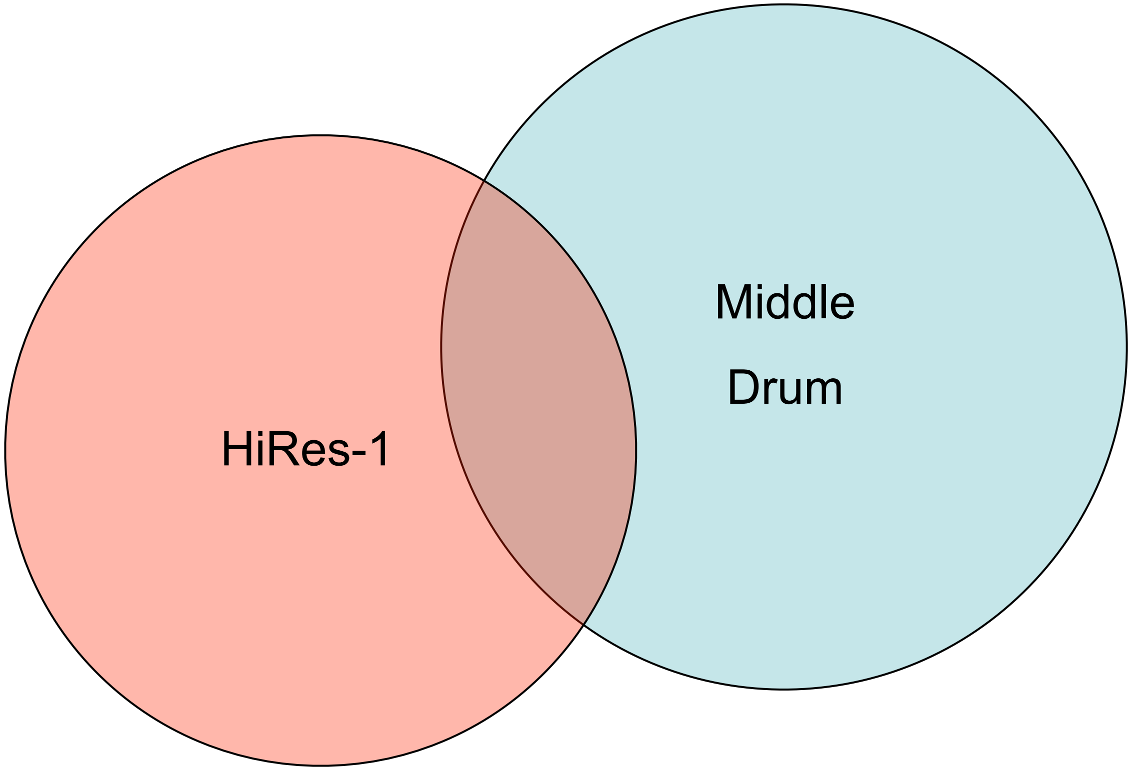
My Spectrum Goals

- Produce a spectrum



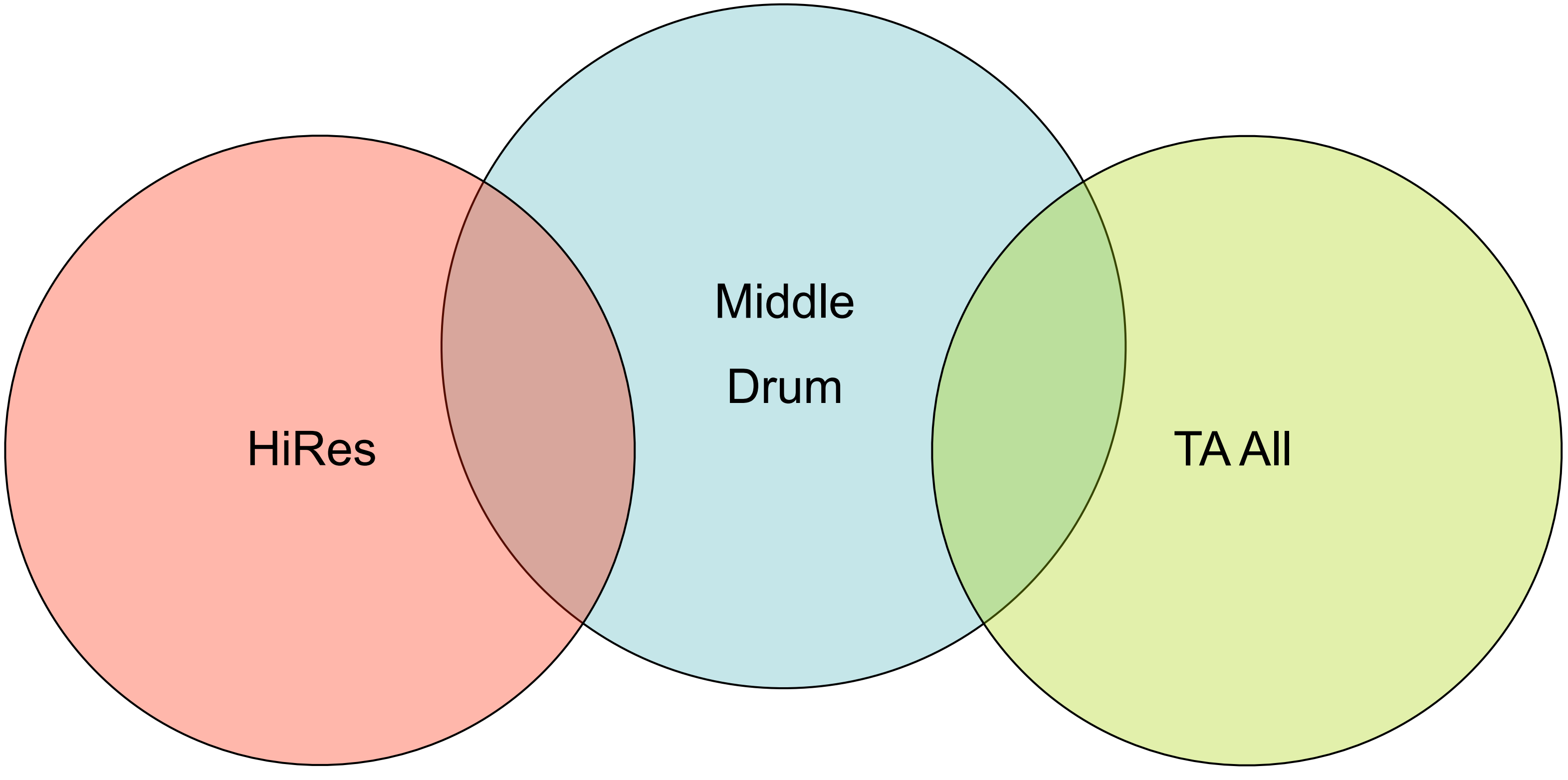
Goals

- Transfer spectrum energy scale of HiRes-1 to TAMD



Goals

- Lay groundwork for TA energy scale



Calculating the Spectrum

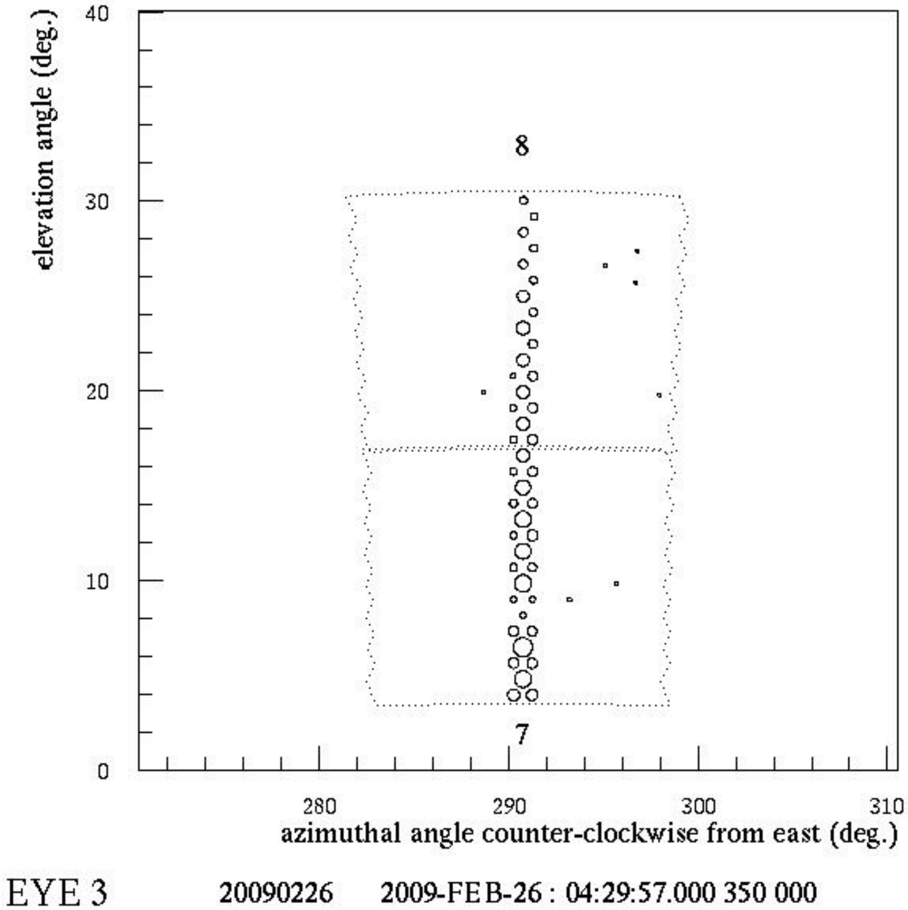
- Energy spectrum is the flux of particles as a function of energy

$$J\ (m^{-2}\ s^{-1}\ sr^{-1}\ eV^{-1}) = \frac{N}{(A\Omega)\ \Delta t\ \Delta E}$$

- Need:
  - number of particles at each energy
  - detector on-time
  - aperture
- Use 1/10th-decade energy bins in spectrum
  - $10^{19\text{-}19.1}$ eV, $10^{19.1\text{-}19.2}$ eV, $10^{19.2\text{-}19.3}$ eV, etc.

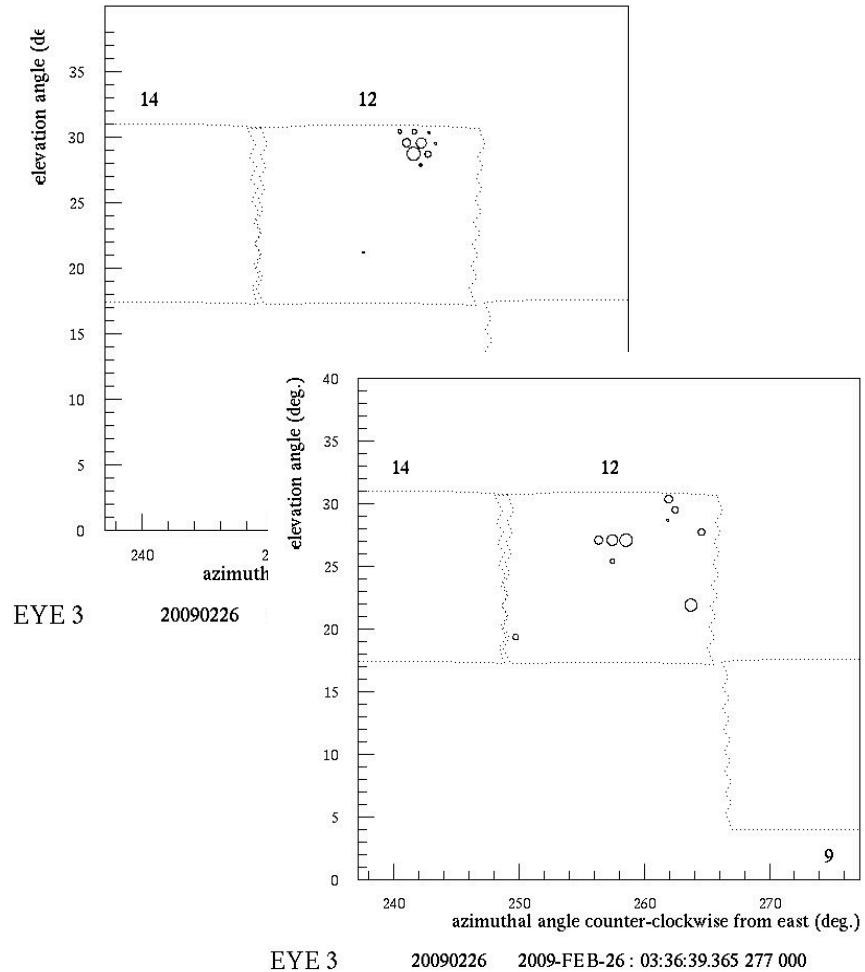
HiRes-1/TAMD Event Selection

- Most events from lasers
  - CLF
  - Lidar at Black Rock
- Removed through GPS time-stamps



Noise Removal

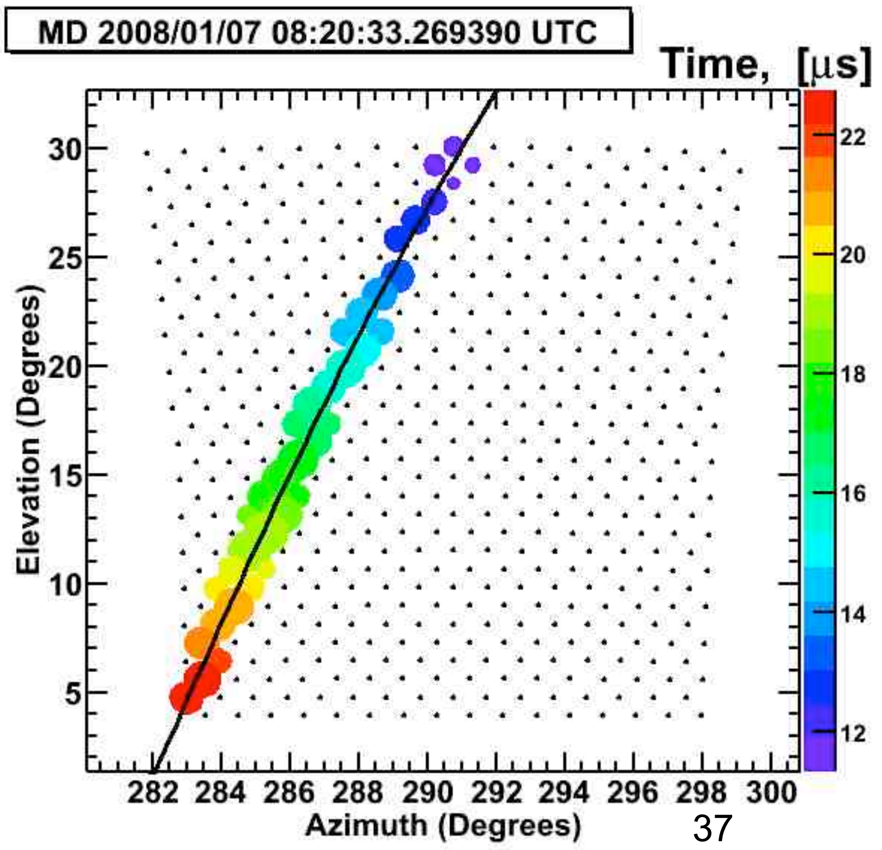
- Most remaining events are
  - Airplanes
  - Noise
- Removed using a Rayleigh Filter
  - Looking for time-ordered, line-like structures
  - Removes events with high random-walk (e.g. airplanes, noise)



HiRes-1/TAMD Event Selection

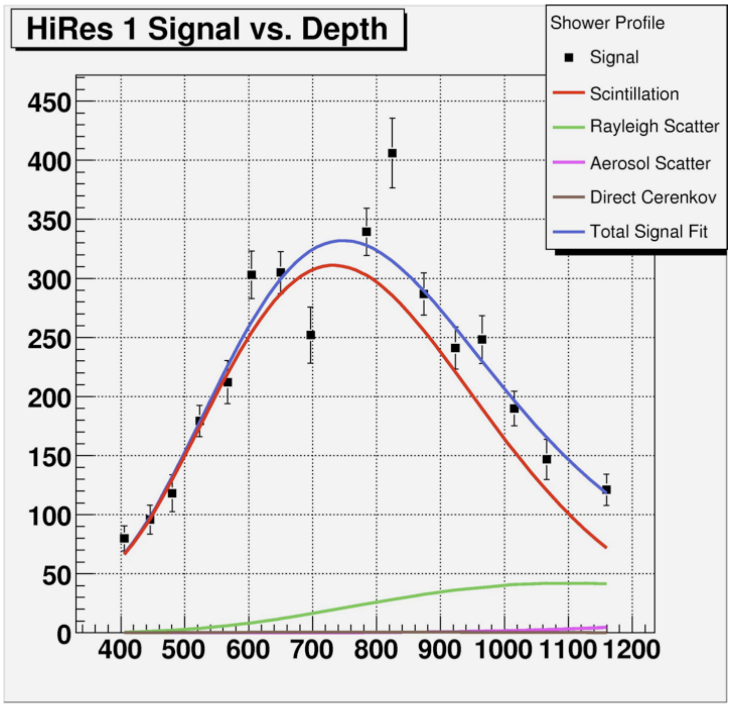
Circle area ∝ signal size

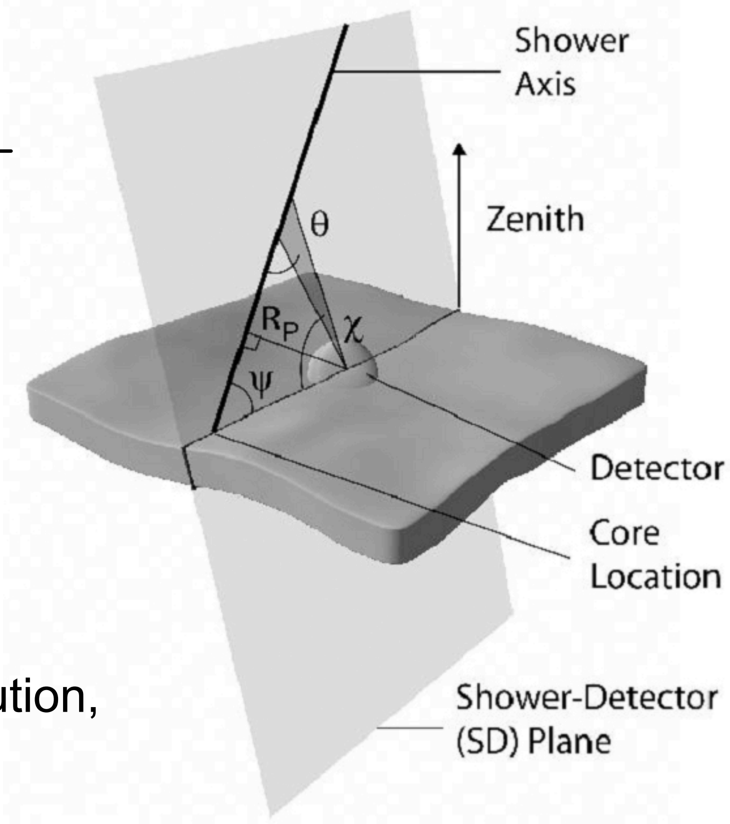
Fit survivors to a plane



Profile-Constrained Timing Fit

$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$





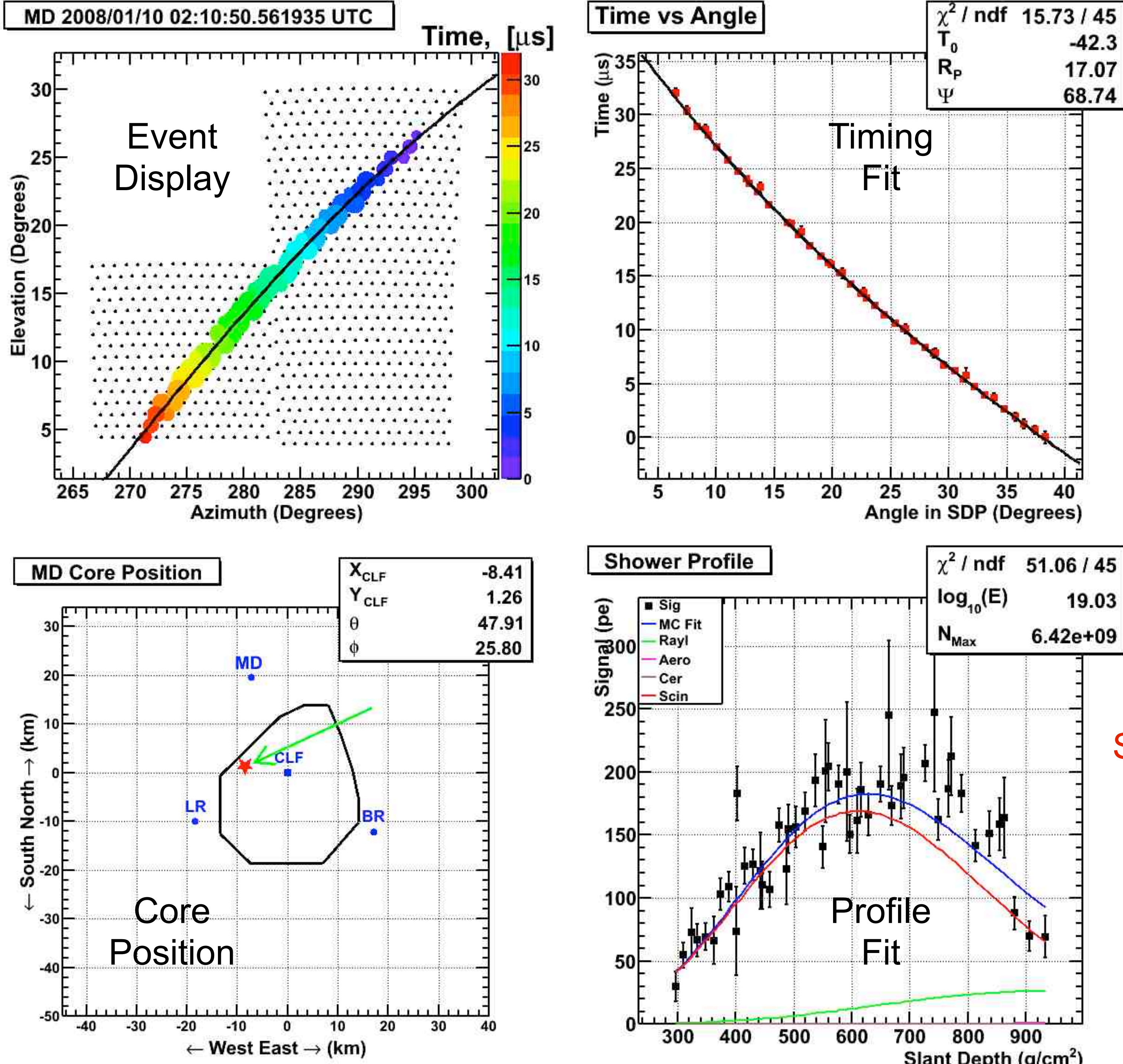
Better resolution, aperture

$$N(X) = N_{max}\left(\frac{x - X_0}{X_{max} - X_0}\right)^{\left(\frac{X_{max} - X_0}{\lambda}\right)} \exp\left(\frac{X_{max} - x}{\lambda}\right)$$

HiRes-1/TAMD Quality Cuts

After fitting, **Reject** events **IF**

1. Track "angular length" < 7.9°
   - Not long enough to determine a good geometry fit
2. Depth of first observed tube (X_F) > 1000 g/cm^2
   - The shower starts too deeply into the atmosphere
3. Effective mirror area correction factor < 0.9 m^2
   - Most of the light must be observed away from the mirror edge or tube edge
4. In-plane angle (Ψ) > 120.0°
   - Rejects events with large Čerenkov contamination

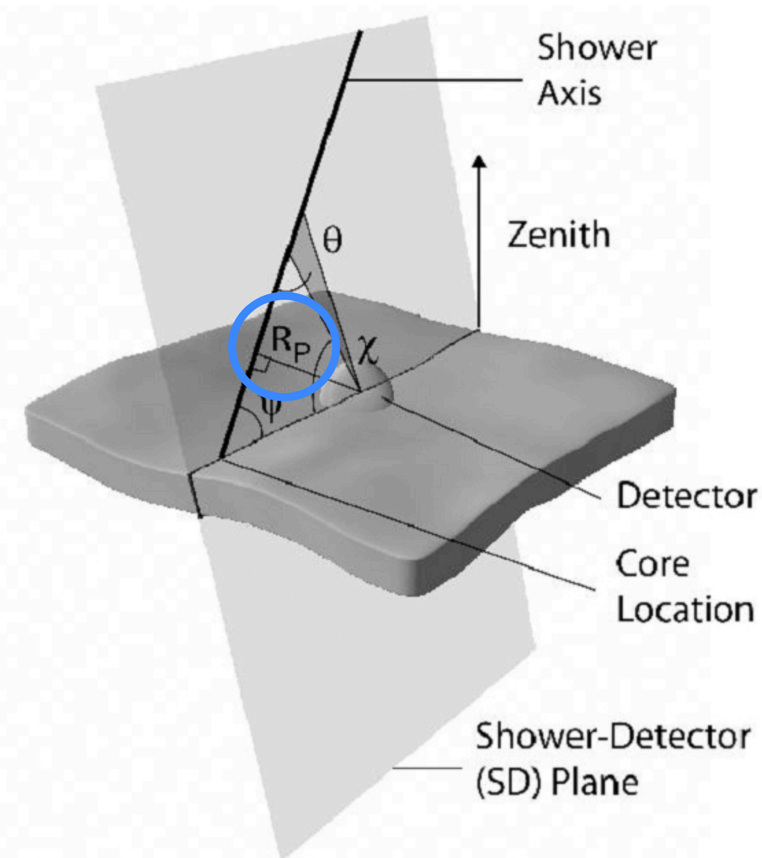


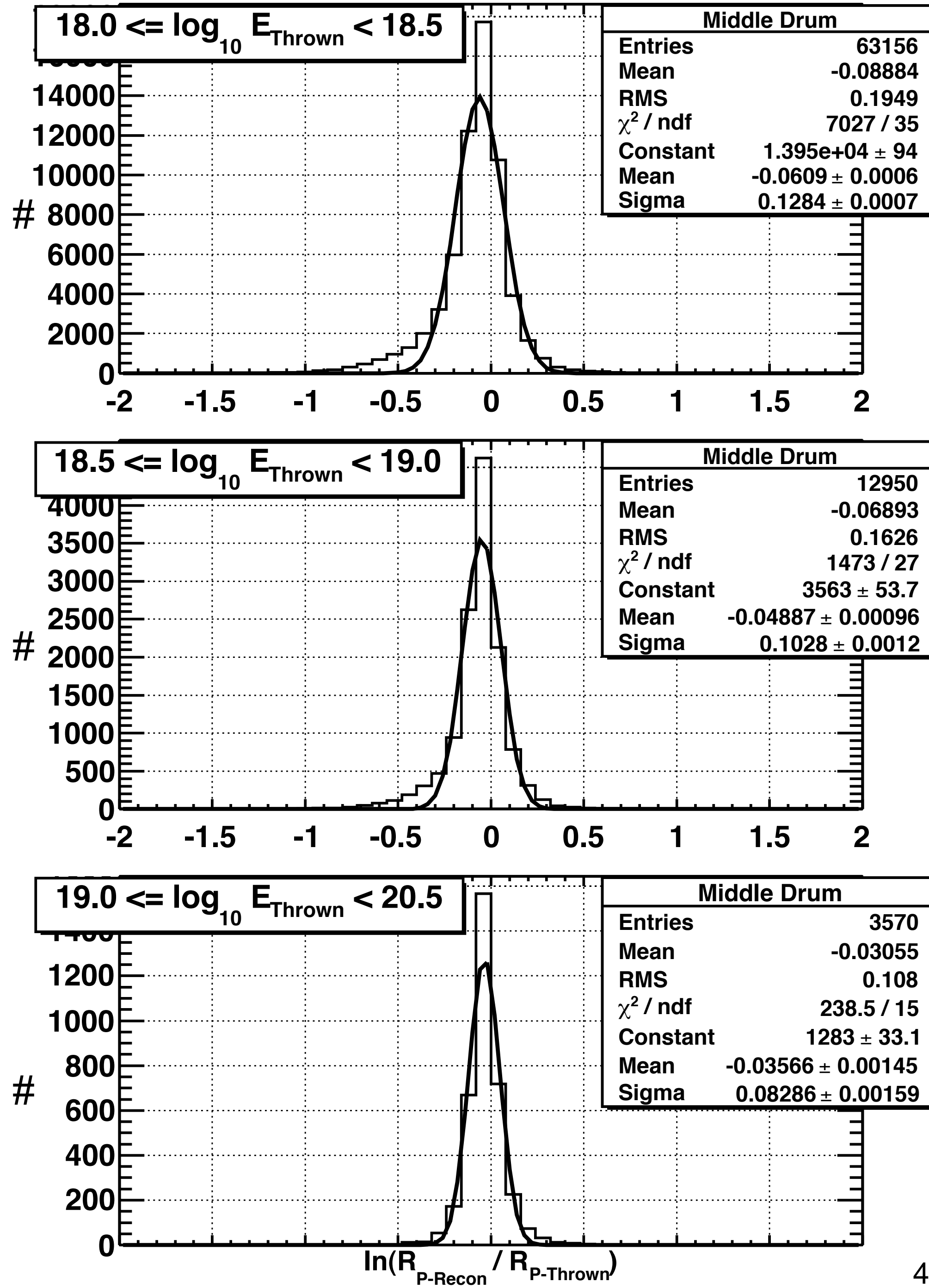
Used in Spectrum

TAMD Resolution

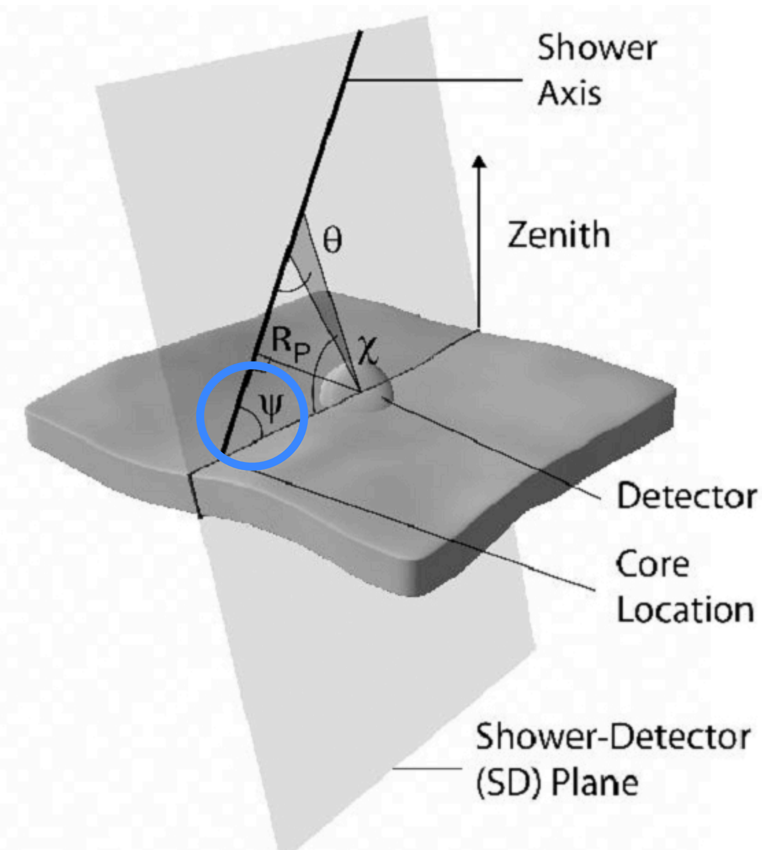
- **Quality assurance**
  - how well can we reconstruct the events
- MC resolutions of reconstruction variables
- 3 energy ranges
  - $10^{18.0} – 10^{18.5}$ eV
  - $10^{18.5} – 10^{19.0}$ eV
  - $> 10^{19.0}$ eV

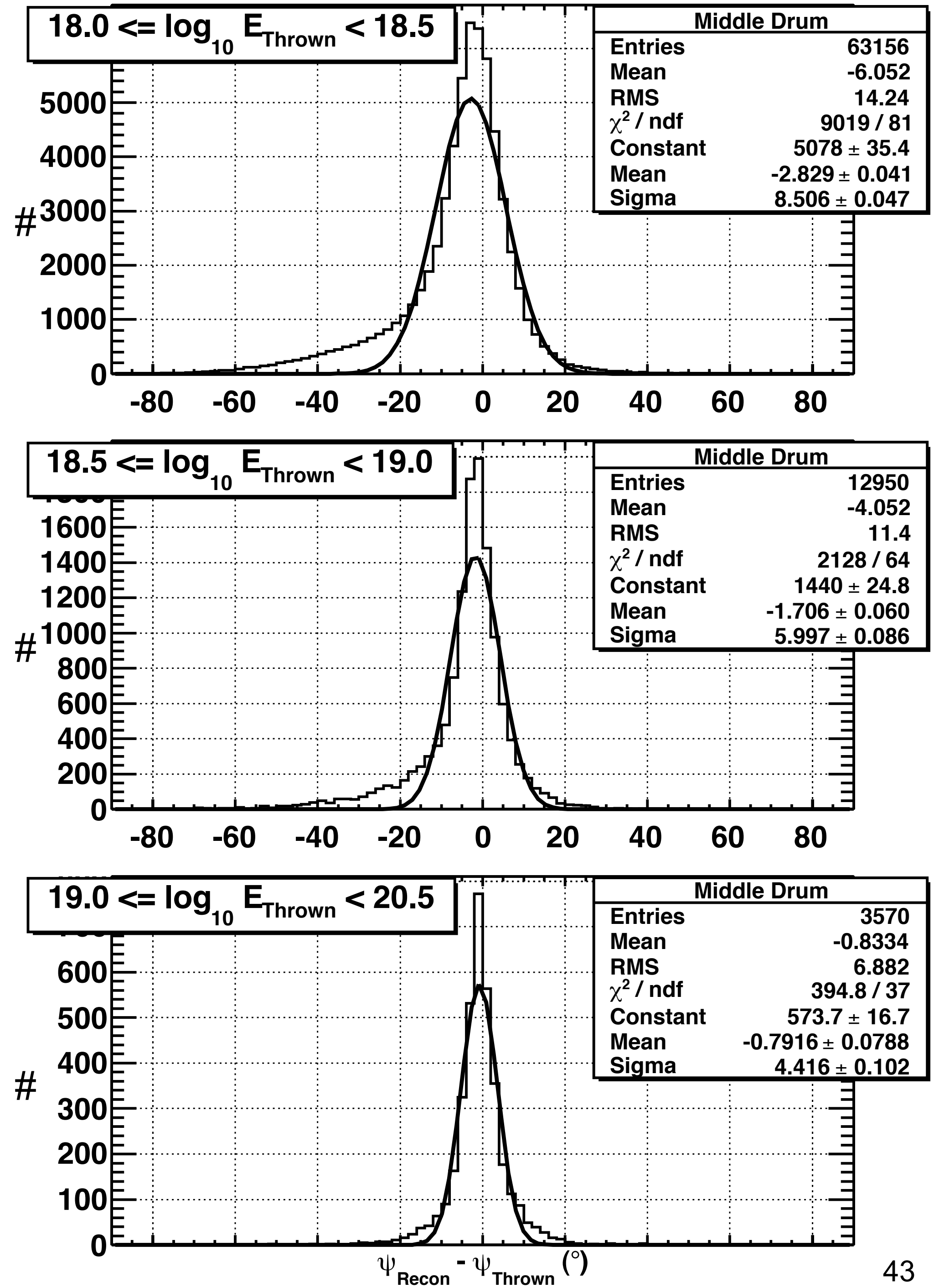
$\ln(R_{P\text{-}Recon} / R_{P\text{-}Thrown})$





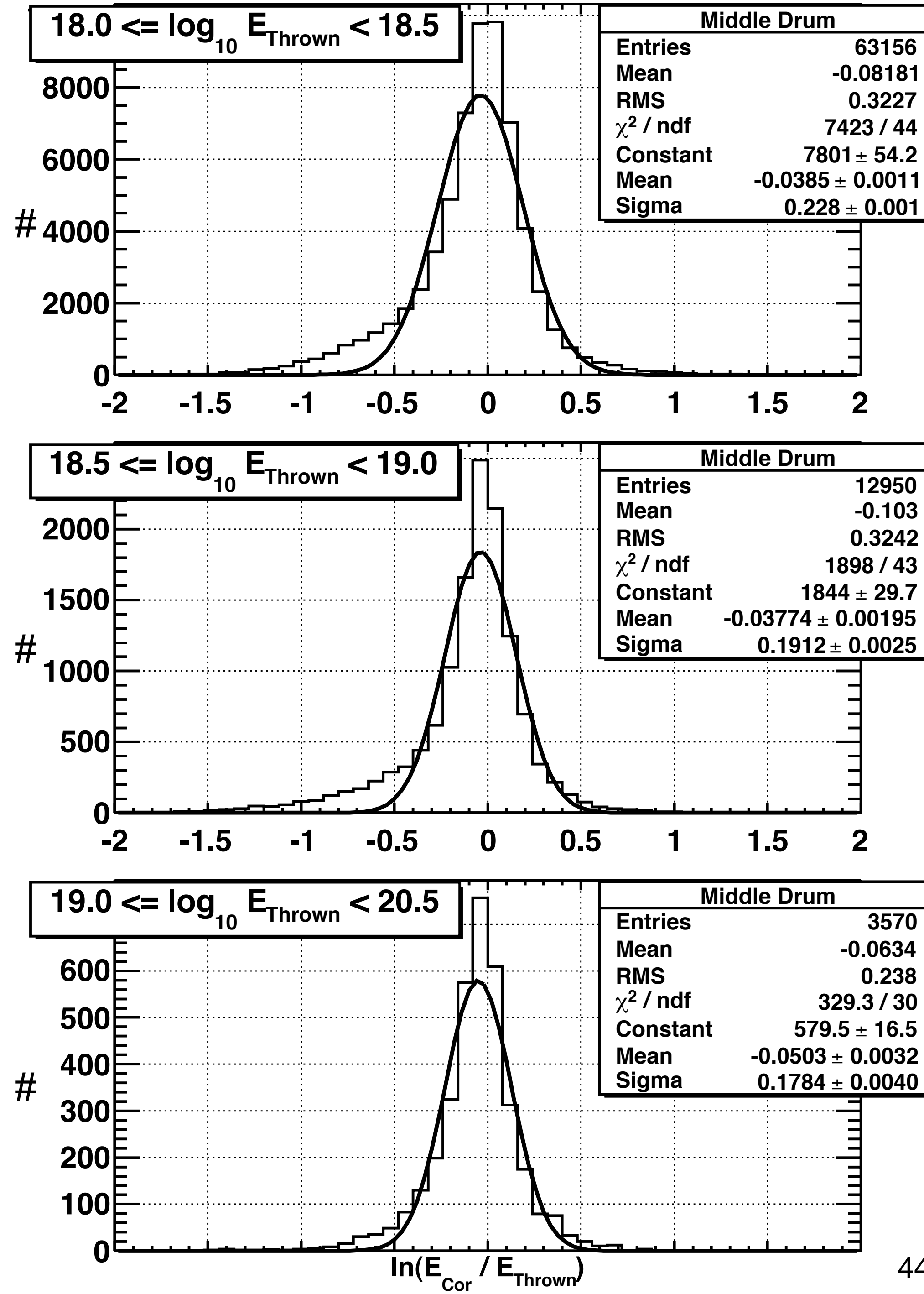
ΔΨ


Shower
Axis
Zenith
θ
R_P
χ
ψ
Detector
Core
Location
Shower-Detector
(SD) Plane


18.0 <= $\log_{10}$ E_{Thrown} < 18.5
Middle Drum
Entries 63156
Mean -6.052
RMS 14.24
χ^2 / ndf 9019 / 81
Constant 5078 ± 35.4
Mean -2.829 ± 0.041
Sigma 8.506 ± 0.047
18.5 <= $\log_{10}$ E_{Thrown} < 19.0
Middle Drum
Entries 12950
Mean -4.052
RMS 11.4
χ^2 / ndf 2128 / 64
Constant 1440 ± 24.8
Mean -1.706 ± 0.060
Sigma 5.997 ± 0.086
19.0 <= $\log_{10}$ E_{Thrown} < 20.5
Middle Drum
Entries 3570
Mean -0.8334
RMS 6.882
χ^2 / ndf 394.8 / 37
Constant 573.7 ± 16.7
Mean -0.7916 ± 0.0788
Sigma 4.416 ± 0.102
#
$\psi_{Recon} - \psi_{Thrown}$ (°)

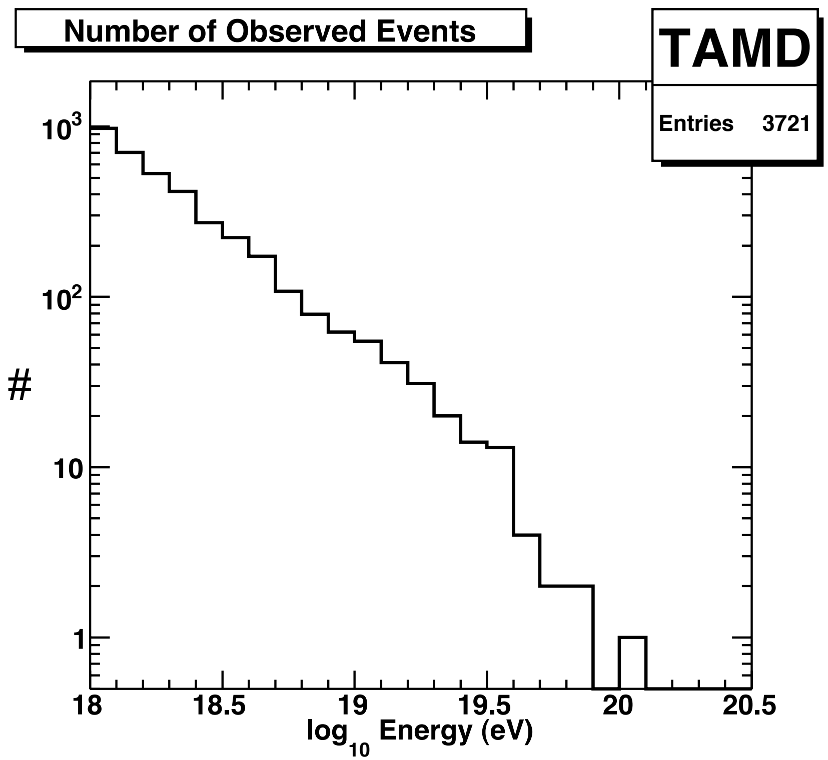
ln(E-Recon/ E-Sim)

- Energy Resolution ~20%
- Comparable to bin size



Events Collected

- Number of TAMD events ~1/3 HiRes-1 total



log_{10} Energy (eV)	HiRes-1	Integrated HiRes-1	TAMD	Integrated TAMD
18.05			974	3721
18.15			703	
18.25			530	
18.35			415	
18.45			272	
18.55	632	2473	222	827
18.65	416		173	
18.75	329		108	
18.85	288		79	
18.95	192		62	
19.05	168	616	55	183
19.15	131		41	
19.25	116		31	
19.35	72		20	
19.45	42		14	
19.55	37	87	13	22
19.65	19		4	
19.75	20		2	
19.85	8		2	
19.95	2		0	
20.05	1		1	

Calculating the Spectrum

- Energy spectrum is the flux of particles as a function of energy

$$J\ (m^{-2}\ s^{-1}\ sr^{-1}\ eV^{-1}) = \frac{N}{(A\Omega)\ \Delta t\ \Delta E}$$

- Need:
  - number of particles at each energy
  - detector on-time
  - aperture
- Use 1/10th decade energy bins in spectrum
  - $10^{19-19.1}$ eV, $10^{19.1-19.2}$ eV, $10^{19.2-19.3}$ eV, etc.

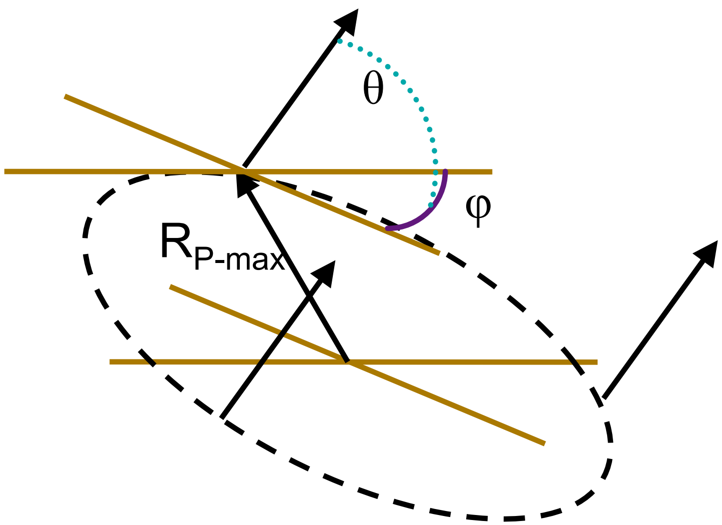
Aperture

Aperture: effective area × solid angle acceptance

Use Monte Carlo simulation to calculate

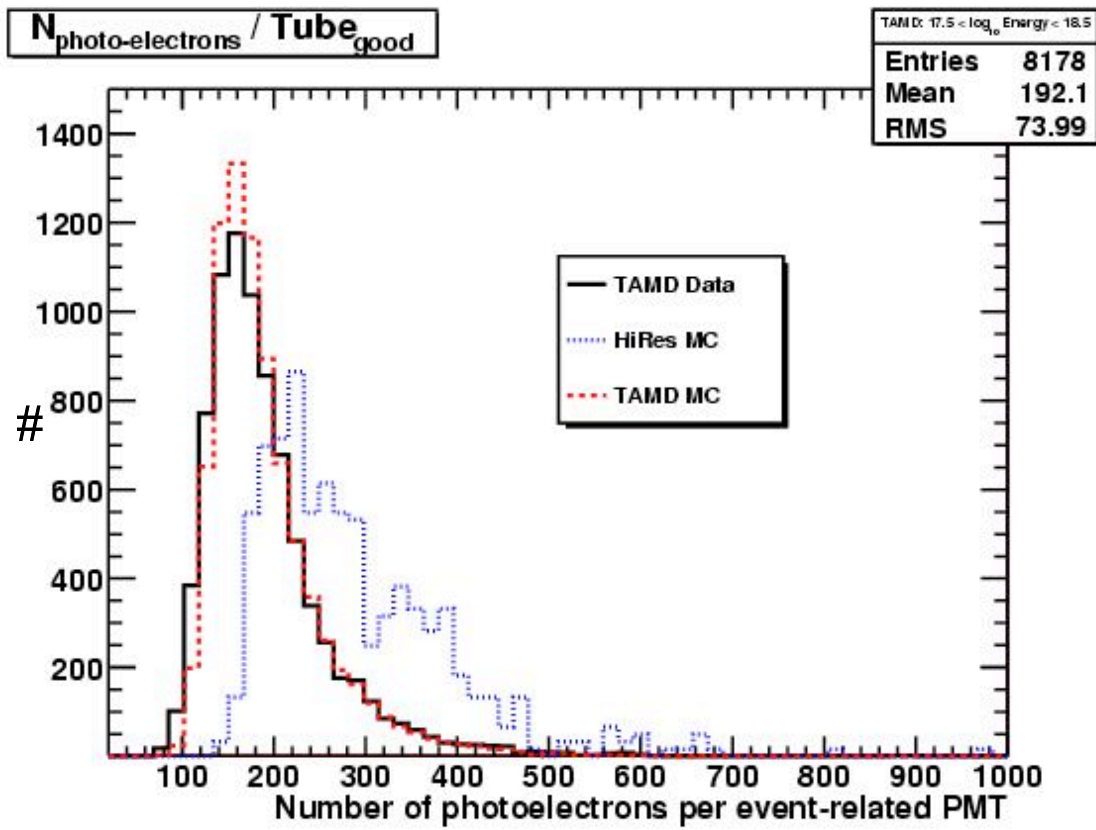
$$(A\Omega)_0 \text{ (km}^2 \text{ ster)} = (2\pi)\, \pi\, R^2_{P\text{-max}}$$

$$(A\Omega) = (A\Omega)_0 \frac{N_{Accepted}}{N_{Simulated}}$$



Monte Carlo Consistency Fix

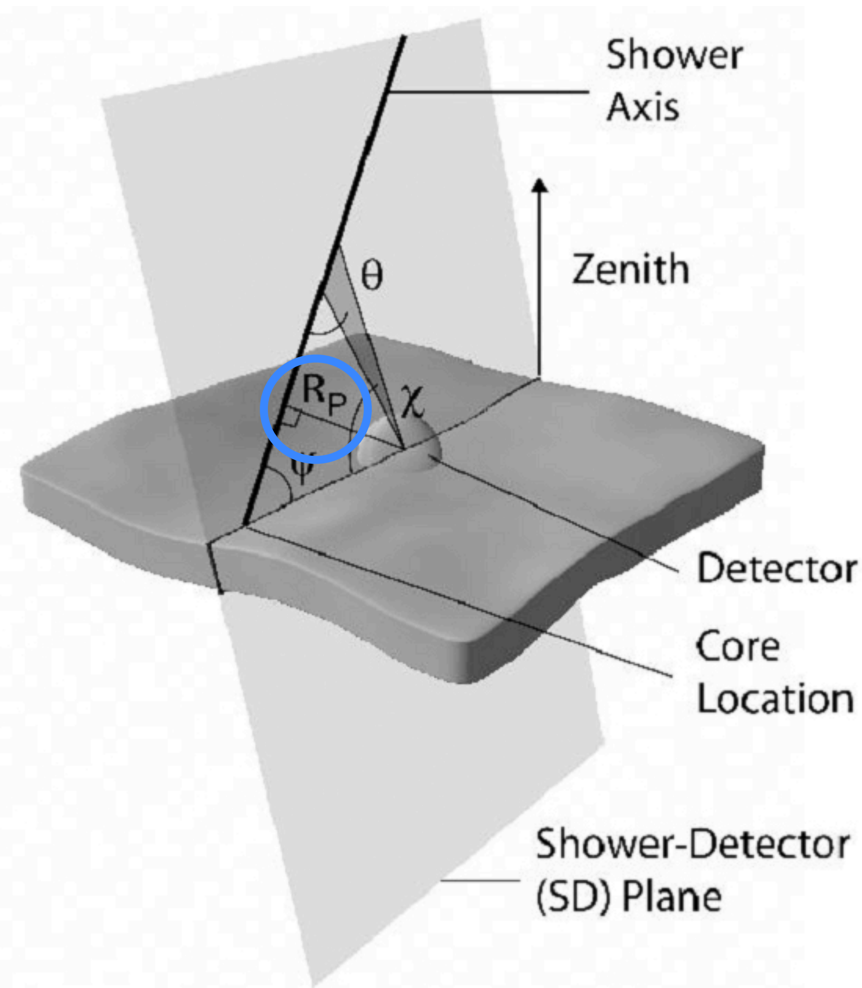
- MC (blue) using HiRes-1 aerosol (VAOD) and thresholds
  - with TAMD geometry
- Adjusted 2 values for HiRes-1
  - Atmosphere aerosol content
  - Tube gain/threshold
- Same desert, same aerosol content
- MC (red) using thresholds recorded from data at TAMD
  - ~20% lower than at HiRes-1
  - fewer artificial light sources



Data-MC Comparisons

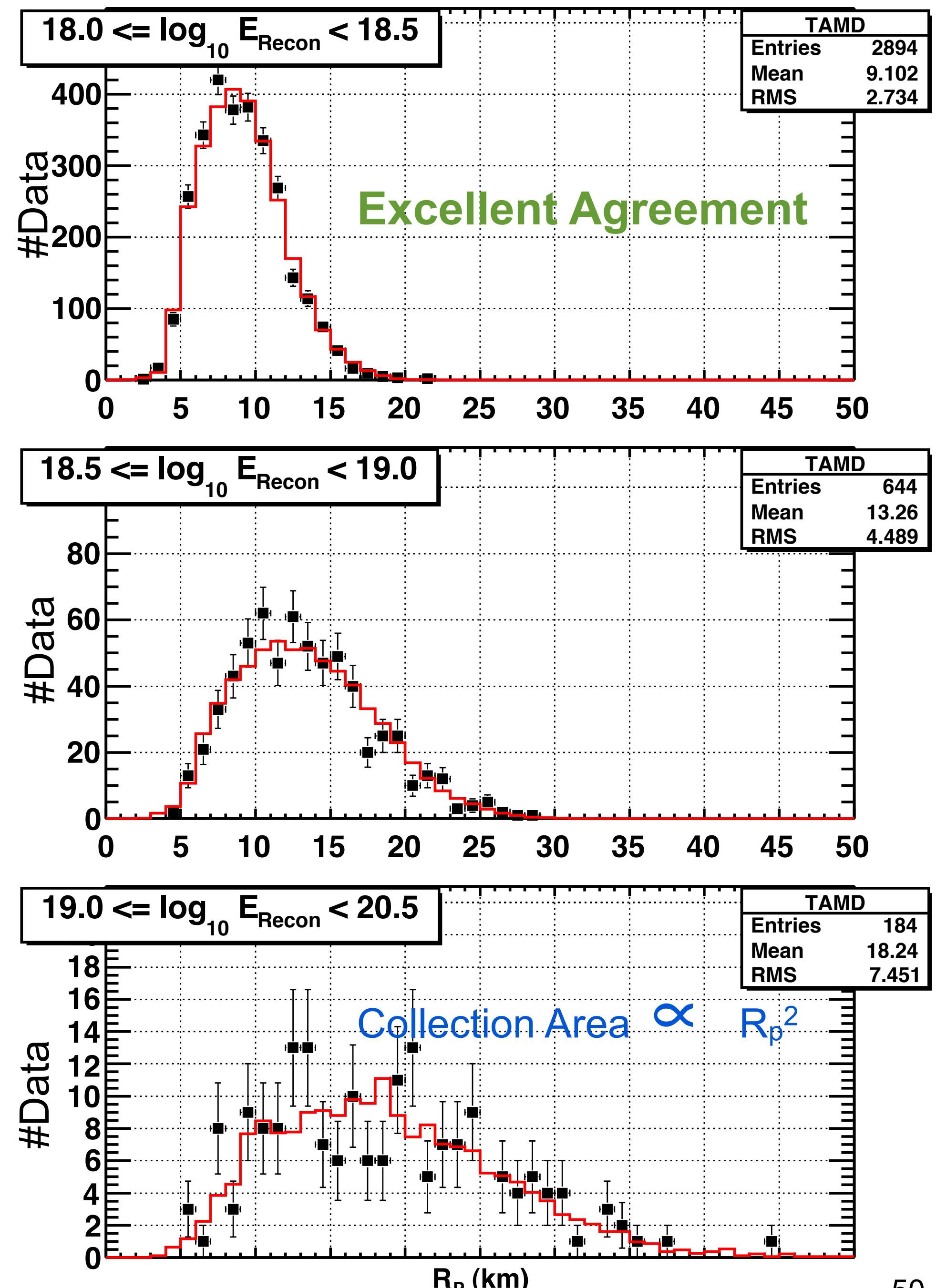
- Use Data-MC comparisons to verify reliability of the aperture calculation
- 3 energy ranges are shown
  - $10^{18.0} - 10^{18.5}$ eV
  - $10^{18.5} - 10^{19.0}$ eV
  - $> 10^{19.0}$ eV
  - check energy evolution

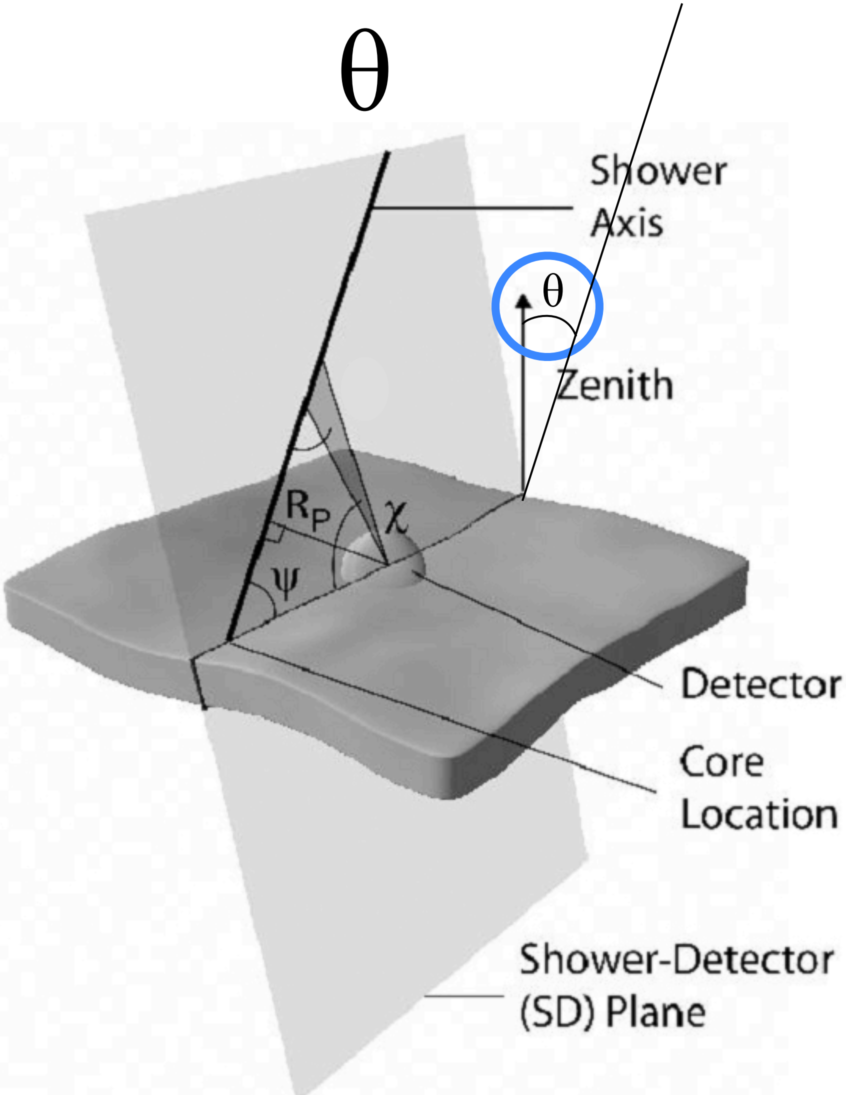
R_P

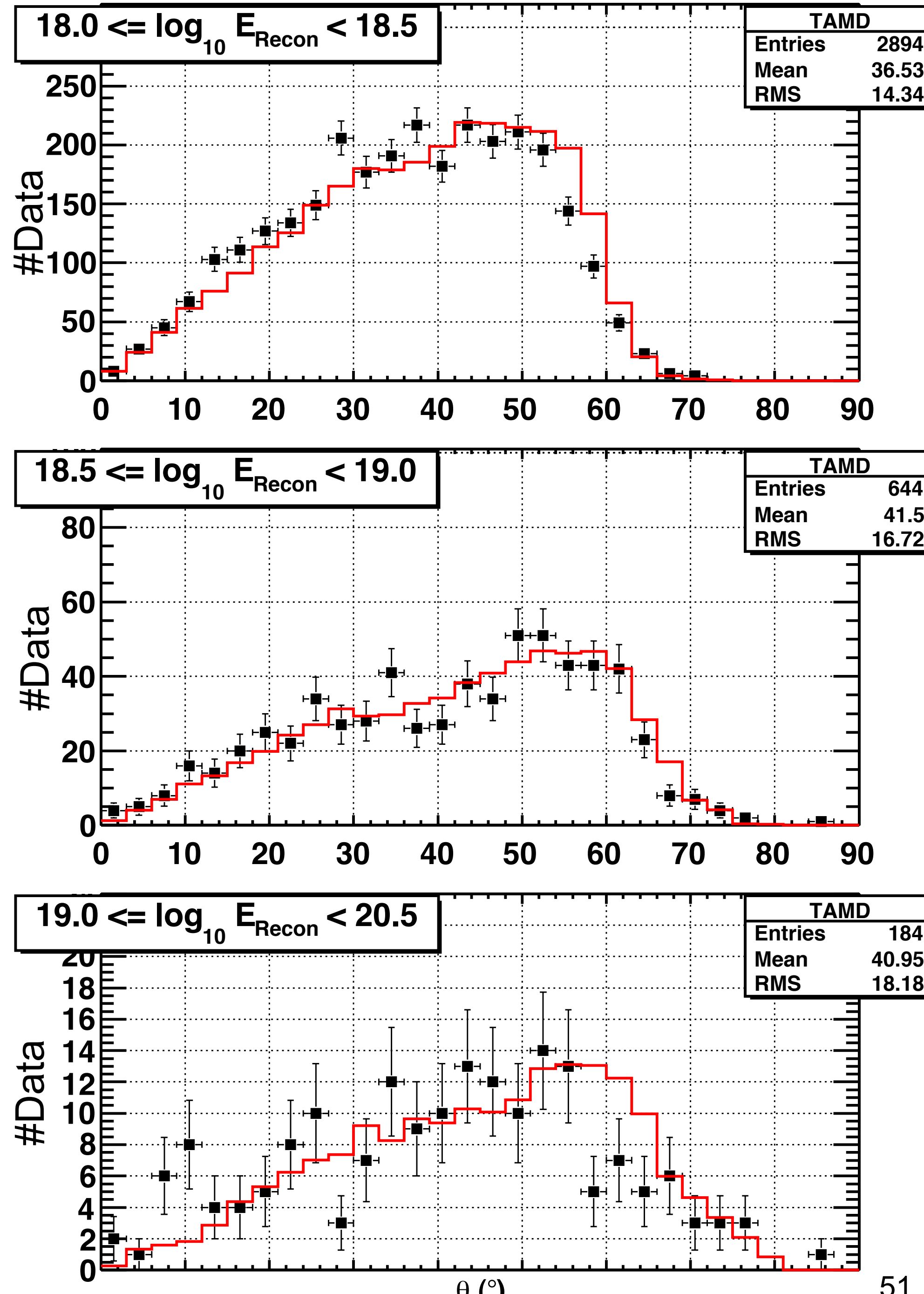


Black points = Data

Red histogram = MC



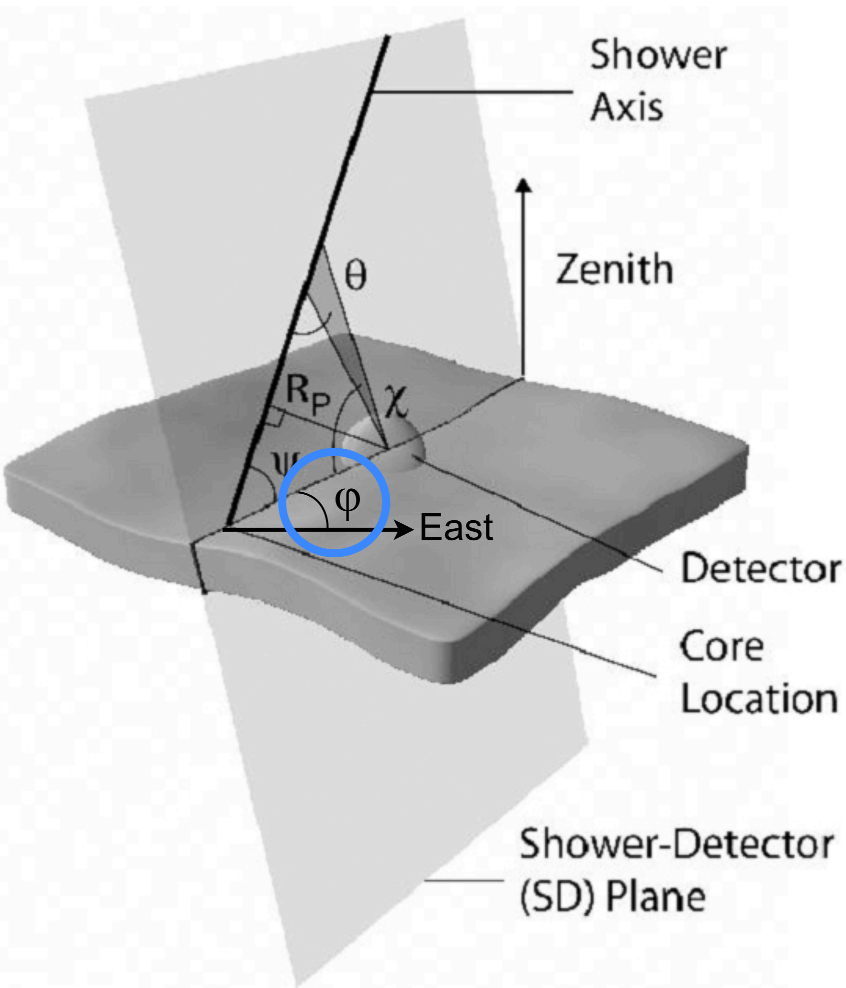


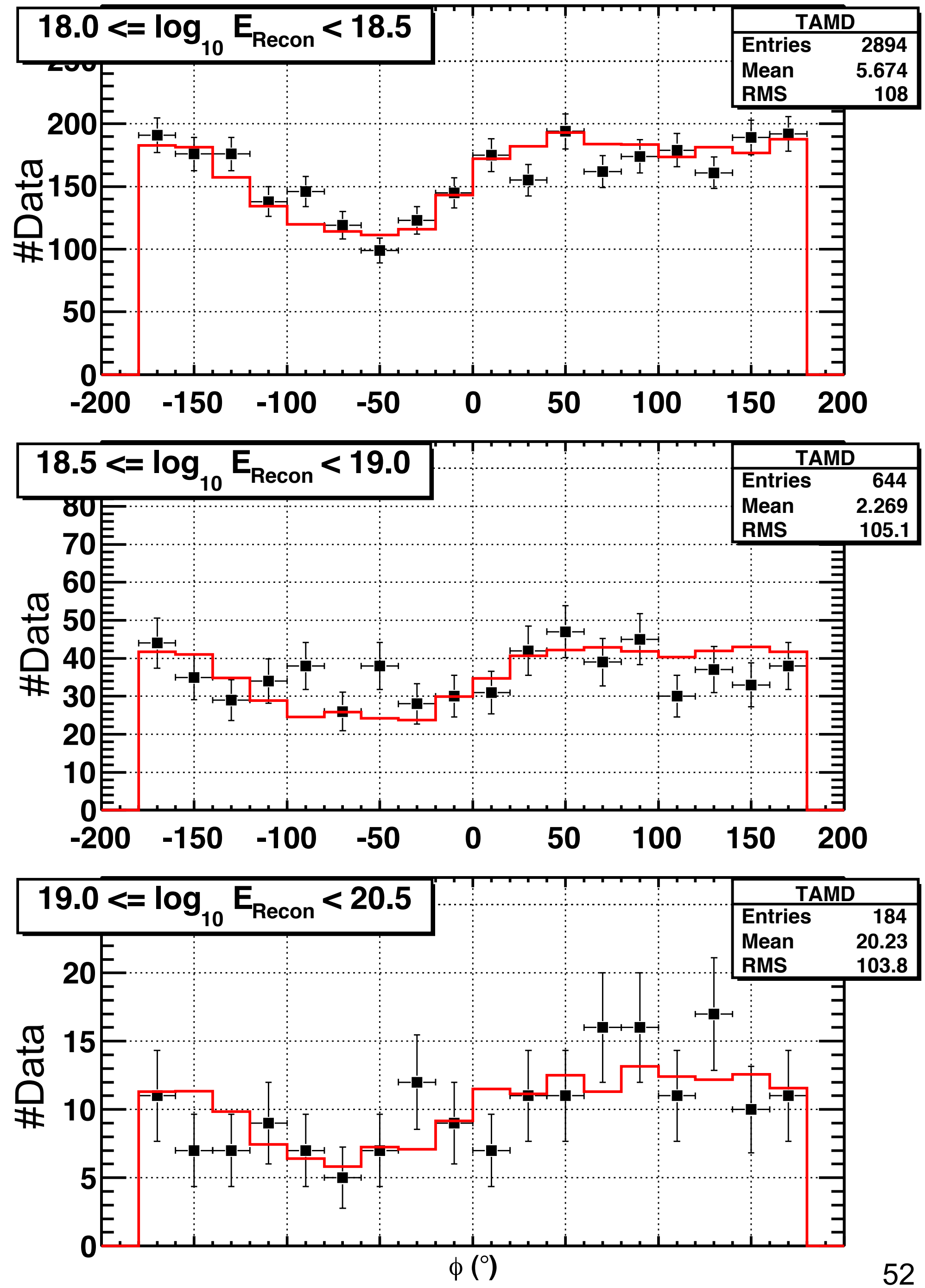


Black points = Data

Red histogram = MC

φ



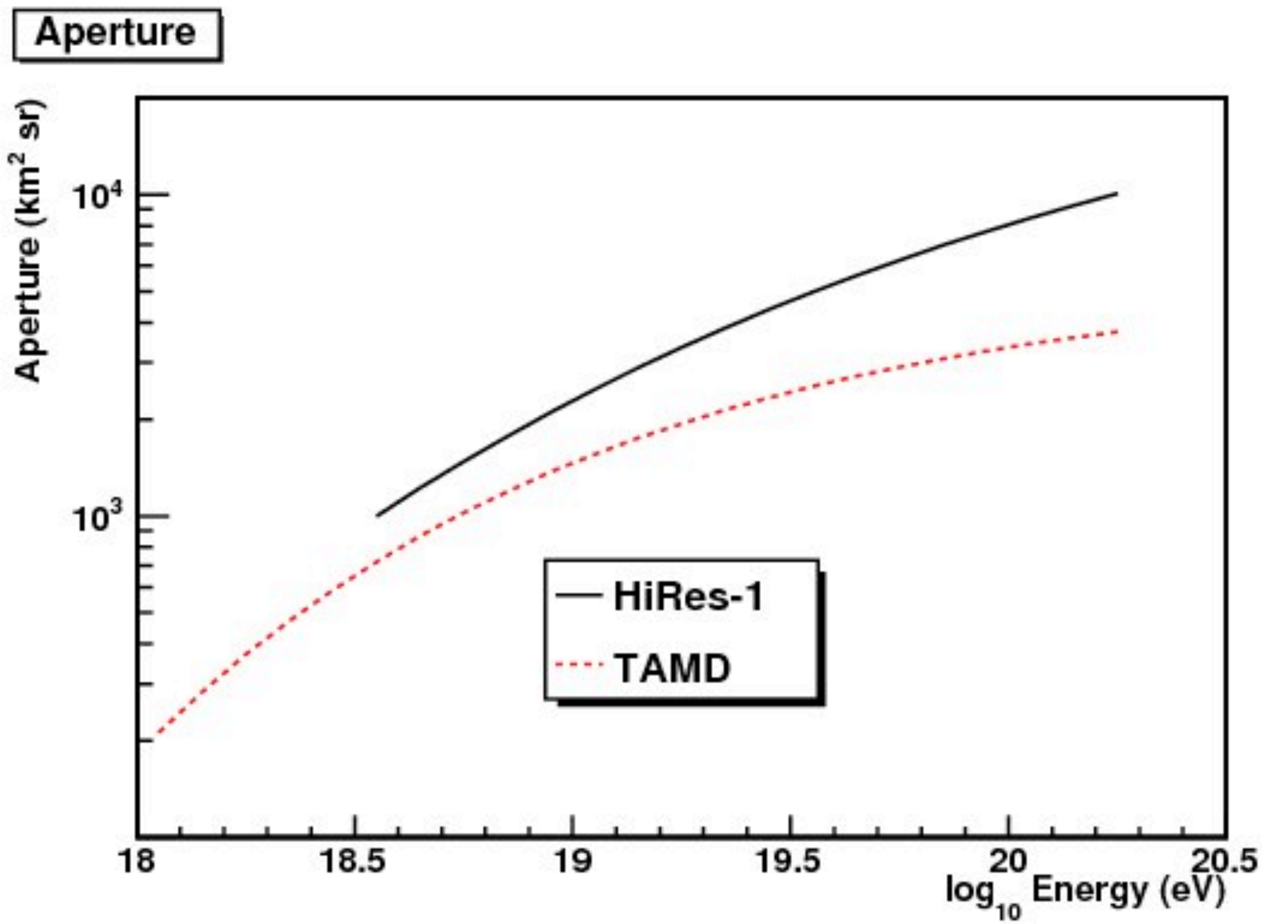


Black points = Data

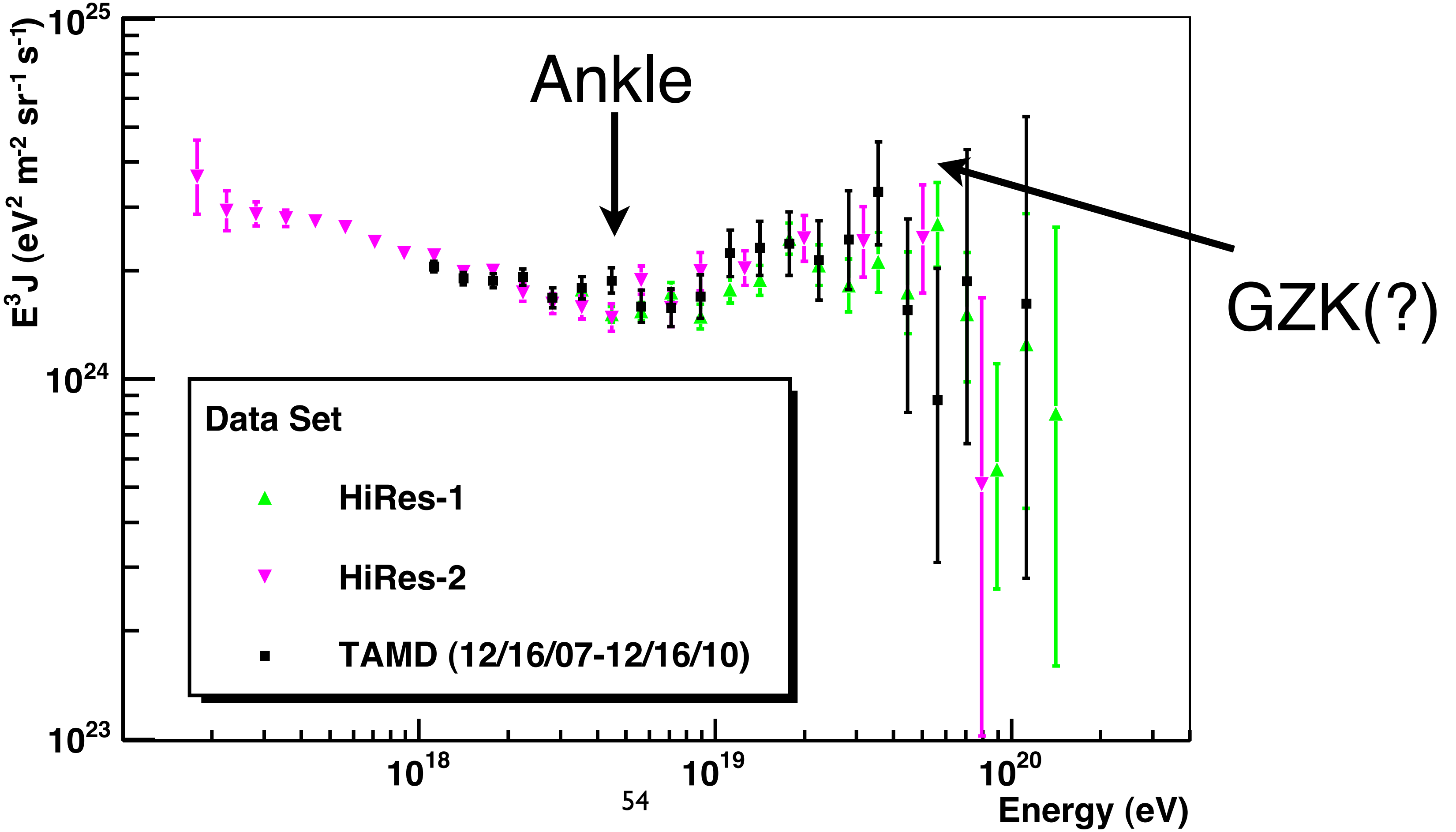
Red histogram = MC

Exposure Difference

- High energy aperture ≈ 1/2 (HiRes-1): E > 10^{19} eV
- TAMD has ~1/3 the exposure of HiRes-1



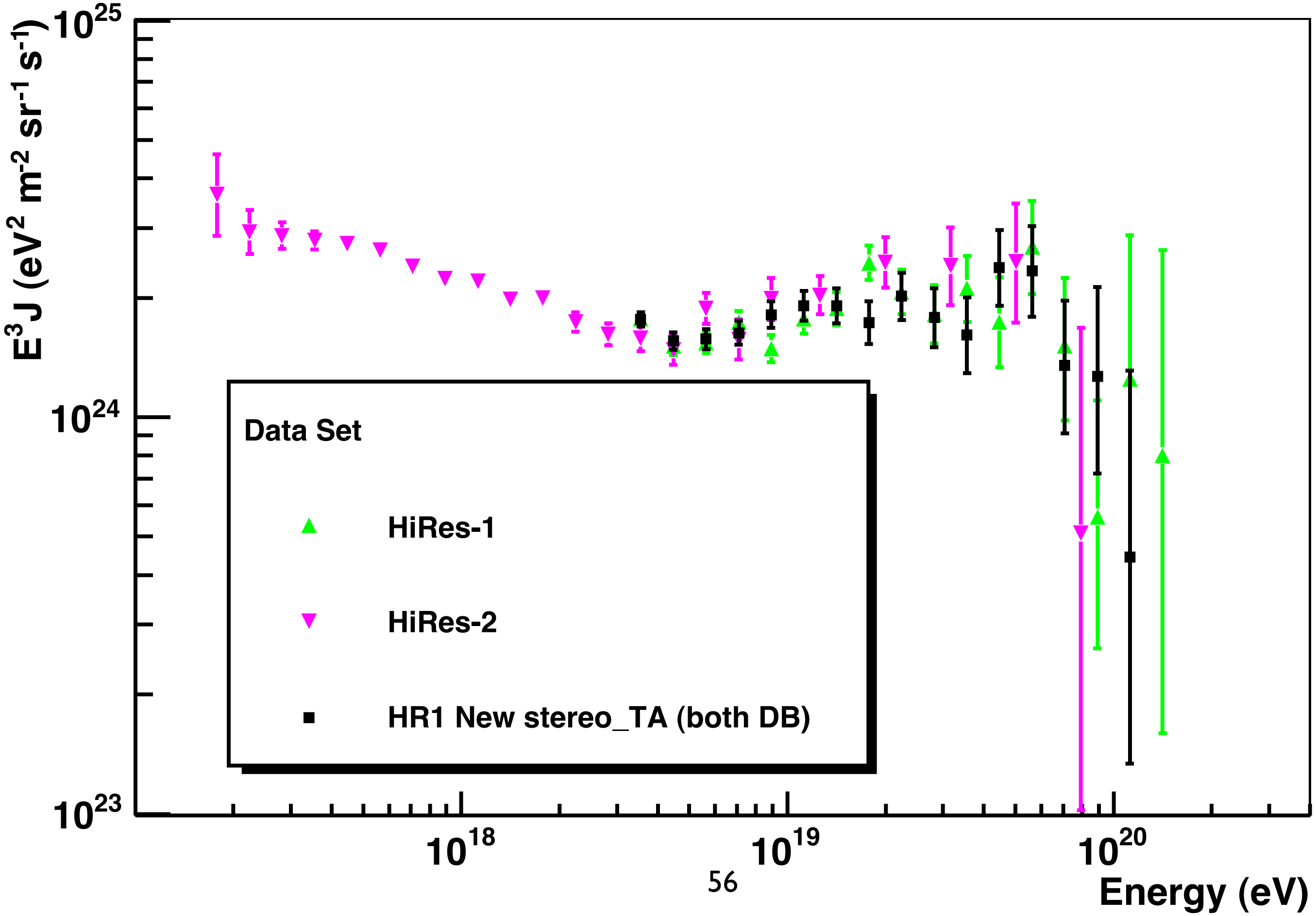
- TAMD 3-year energy spectrum in EXCELLENT agreement with HiRes in both shape AND normalization
- Indicates HiRes-1 and TAMD have same energy scale
- Different energy scale would be reflected in change of normalization or shift of spectral features in energy - we see neither



New Systematic Check of HiRes-1 Energy Spectrum

- Studied effect of using the nightly atmospheric and electronic calibration databases on the data reconstruction
- HiRes-1 published spectrum used
  - average atmosphere
  - average electronic calibration

- HiRes-1 energy spectrum re-analyzed
- utilized every optometric calibration
- nightly atmospheric and electronic calibration database
- EXCELLENT agreement with previously published spectrum shows robustness with respect to most details of study



Energy Spectrum Summary

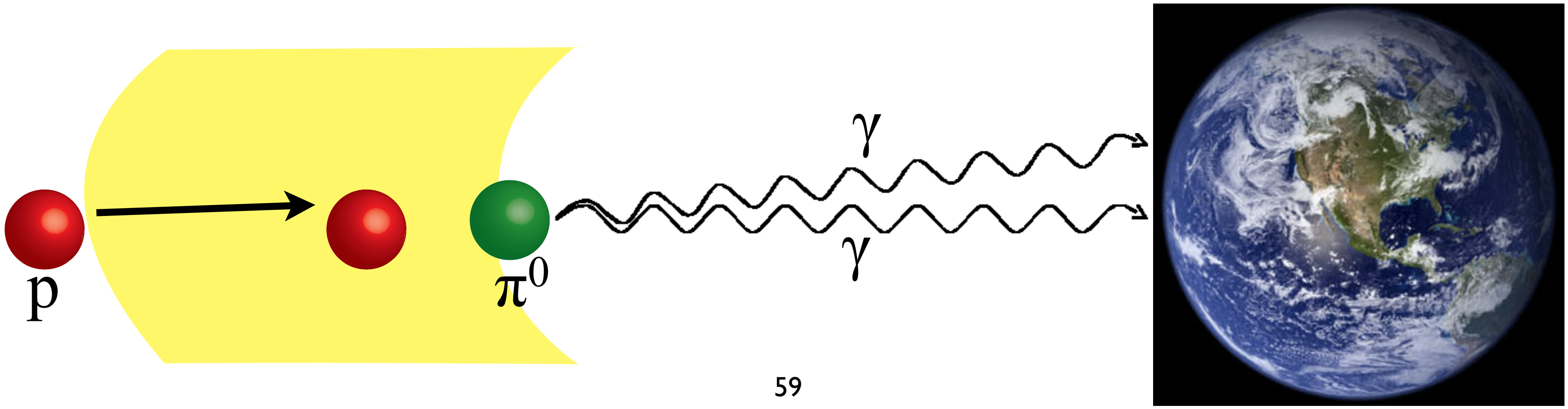
- Measured energy spectrum from the TA experiment with first 3 years of MD data
- Direct link between TAMD and HiRes energy scales
- Good resolution over energy range of spectrum
- Excellent Data-MC comparisons
- No systematic bias using average atmosphere and electronic calibration

Act II

Exotic Event Search

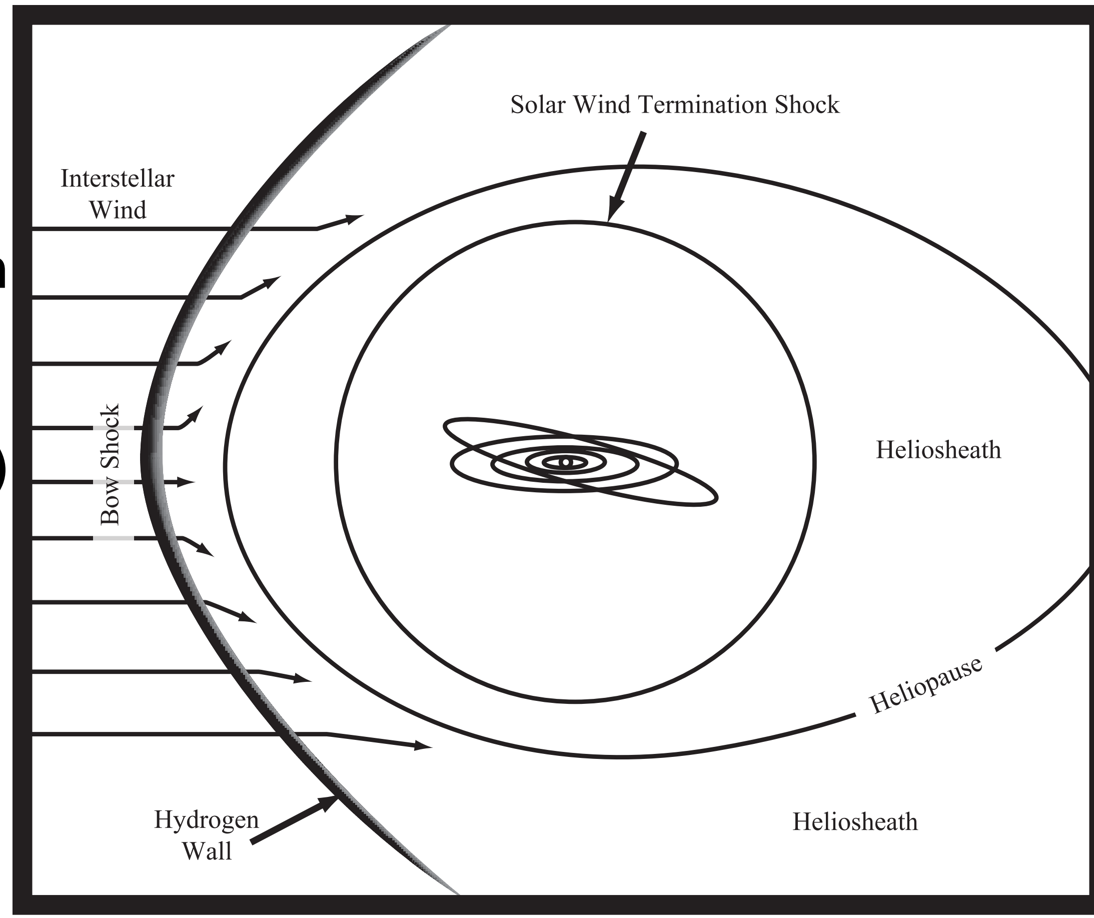
Cosmic-ray Heliospheric Interactions

- Hypothesis: hadronic decay in heliosphere produces...
- Neutral pion decay which...
- May be observable.



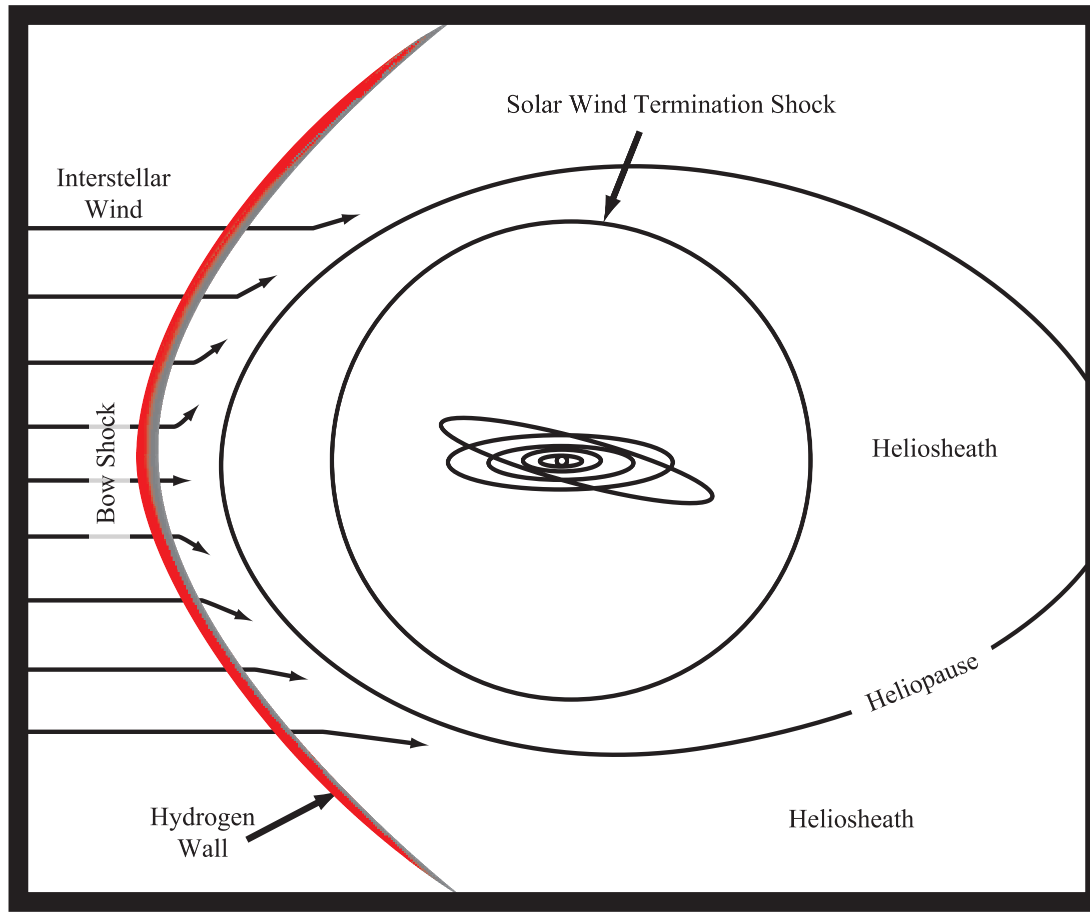
Heliosphere

- Gigantic magneto-bubble
  - almost pure vacuum
  - holds only solar wind (+planets, etc.)
  - Limits effect of Interstellar Wind
- 3 areas of "high" concentration



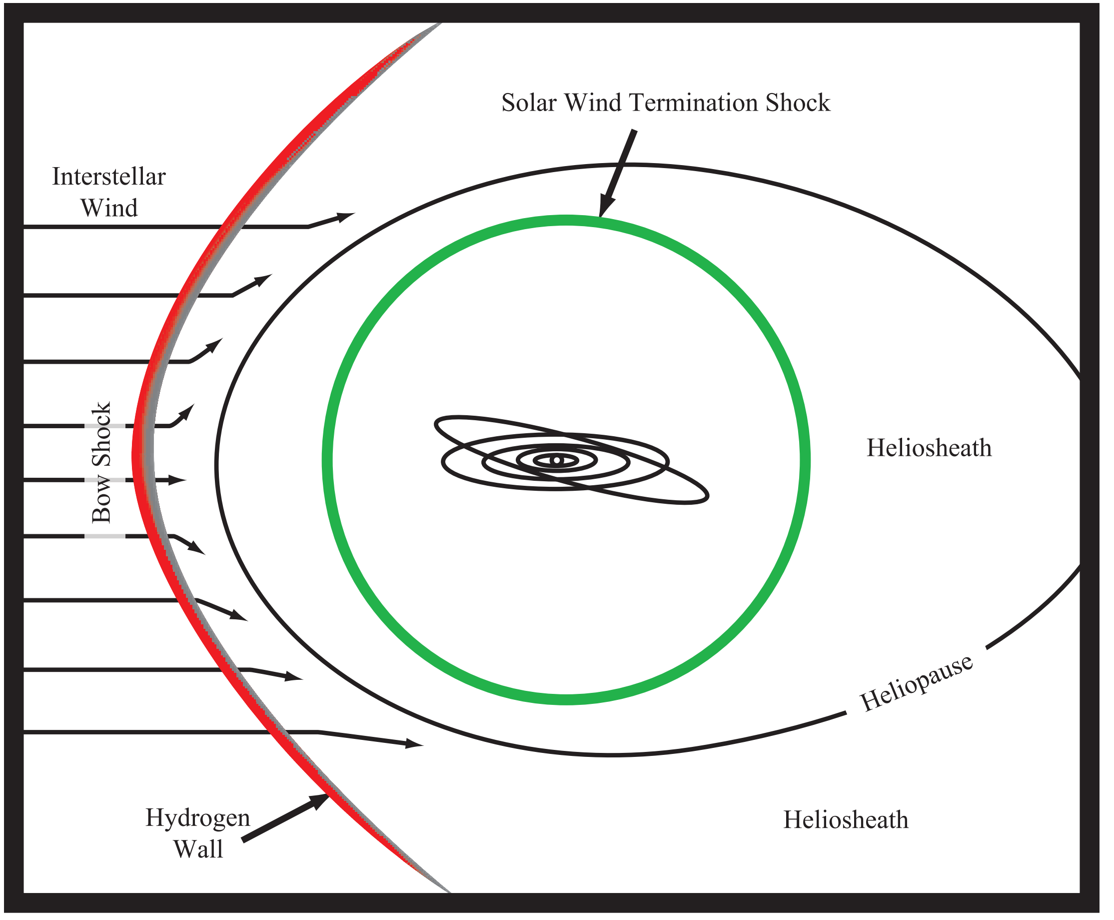
Heliosphere

Hydrogen Wall



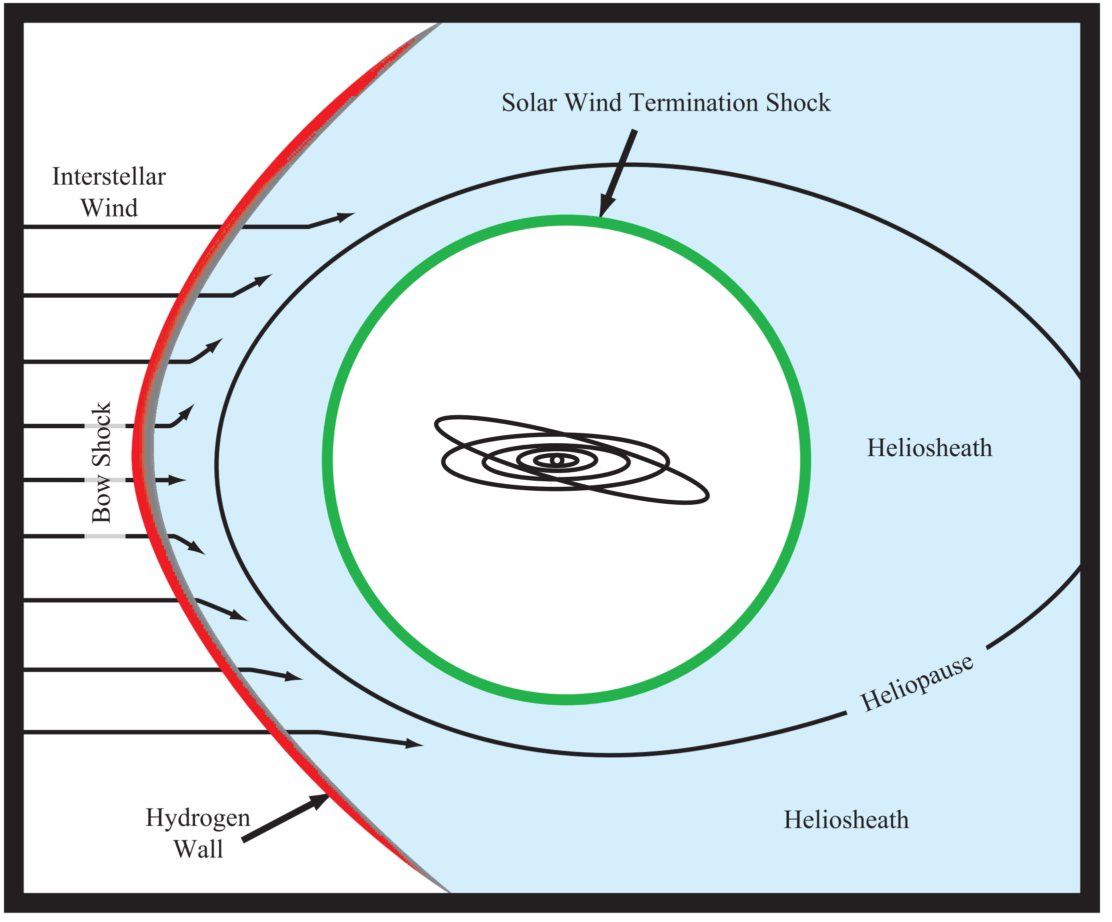
Heliosphere

Termination Shock



Heliosphere

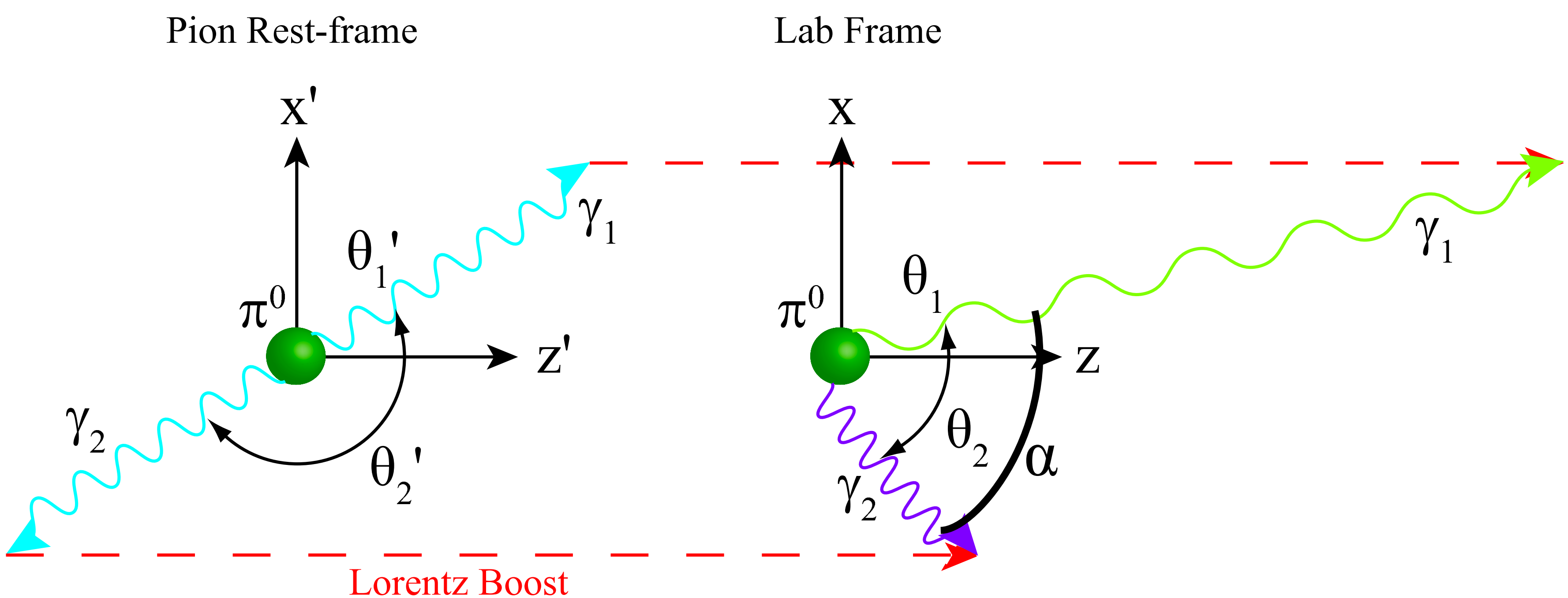
Heliosheath



CR-Heliosphere Ion Interaction Probability

	Density (particle/cm^3)	Interaction Length (AU)	Region Thickness (AU)	Interaction Probability
Hydrogen Wall	0.3	4.84×10^{11}	20	1.08×10^{-11}
Termination Shock	0.1	1.45×10^{12}	0.5	8.98×10^{-14}
Heliosheath	0.001	1.45×10^{14}	59	1.06×10^{-13}

Neutral Pion Decay



$$\cos \theta'_2 = - \cos \theta'_1$$

Use relativistic kinematics to convert from rest-frame to lab-frame

Photon Opening Angles

$$\tan\theta_1 = \frac{P_{1x}}{P_{1z}} = \frac{\sin\theta'_1}{\gamma(\beta + \cos\theta'_1)}$$

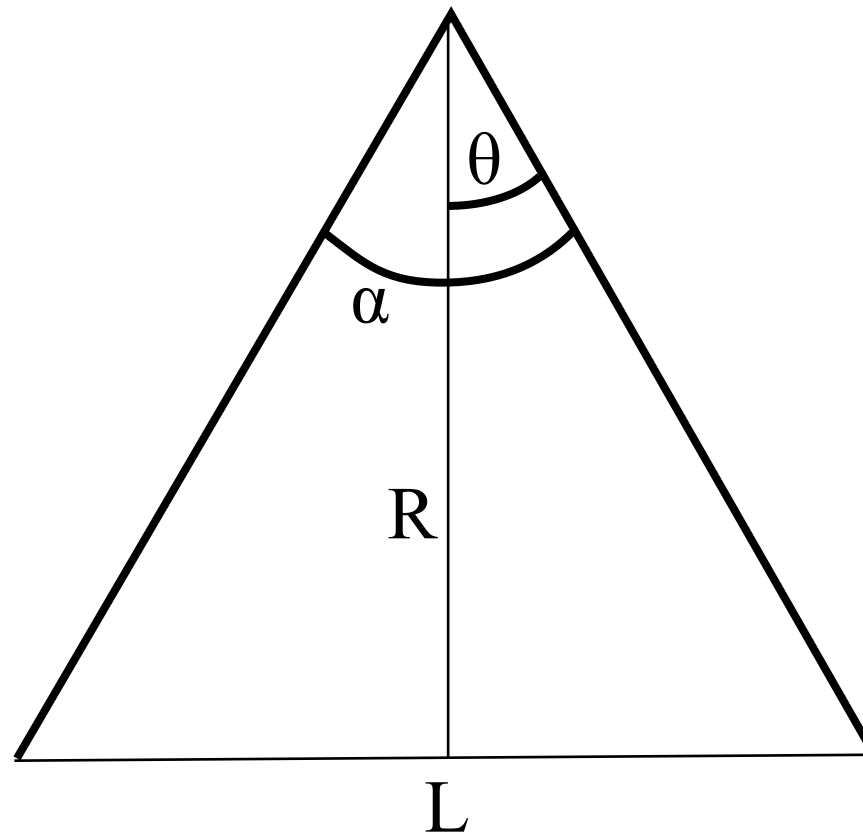
$$\tan\theta_2 = \frac{P_{2x}}{P_{2z}} = \frac{\sin\theta'_2}{\gamma(\beta + \cos\theta'_2)}$$

$$\alpha = |\theta_1| + |\theta_2|$$

$\log_{10} E_{pion}$ (eV)	$\log_{10} \alpha$ (degrees)
17	~ -4
21	~ -11

Perpendicular Spread

- Perpendicular spread between photons
- $R \sim 75\text{-}100$ AU
- $\alpha \sim 10^{-4} - 10^{-11}$ degrees
- $L_{\perp} \approx R\,\alpha$



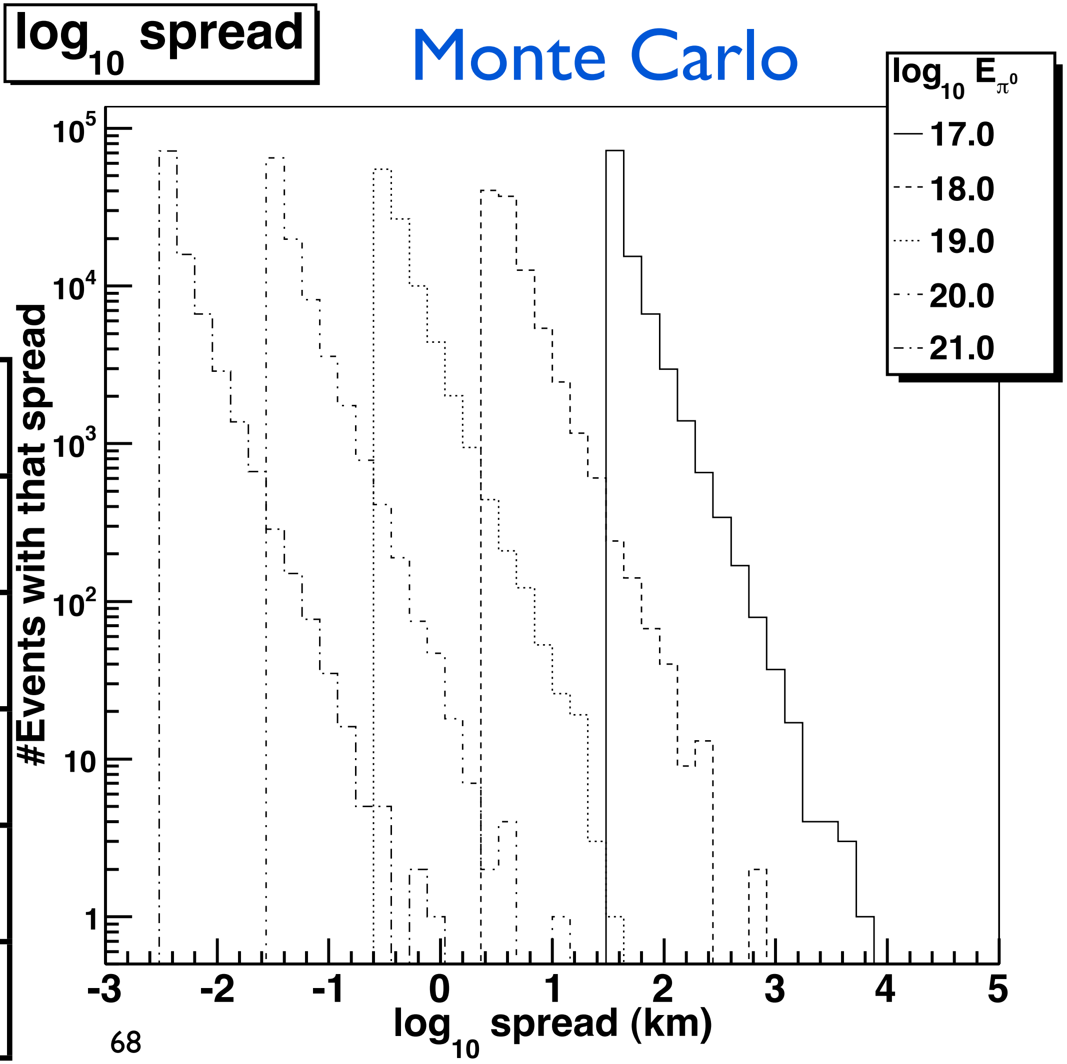
1 AU = 1.5×10^{8} km
(Earth-Sun distance)

Spread Between Showers

Minimum spread between showers gets narrower as pion energy increases

Pion Energy	Spread
10^{17} eV	30,000 m
10^{18} eV	3,000 m
10^{19} eV	300 m
10^{20} eV	30 m
10^{21} eV	3 m

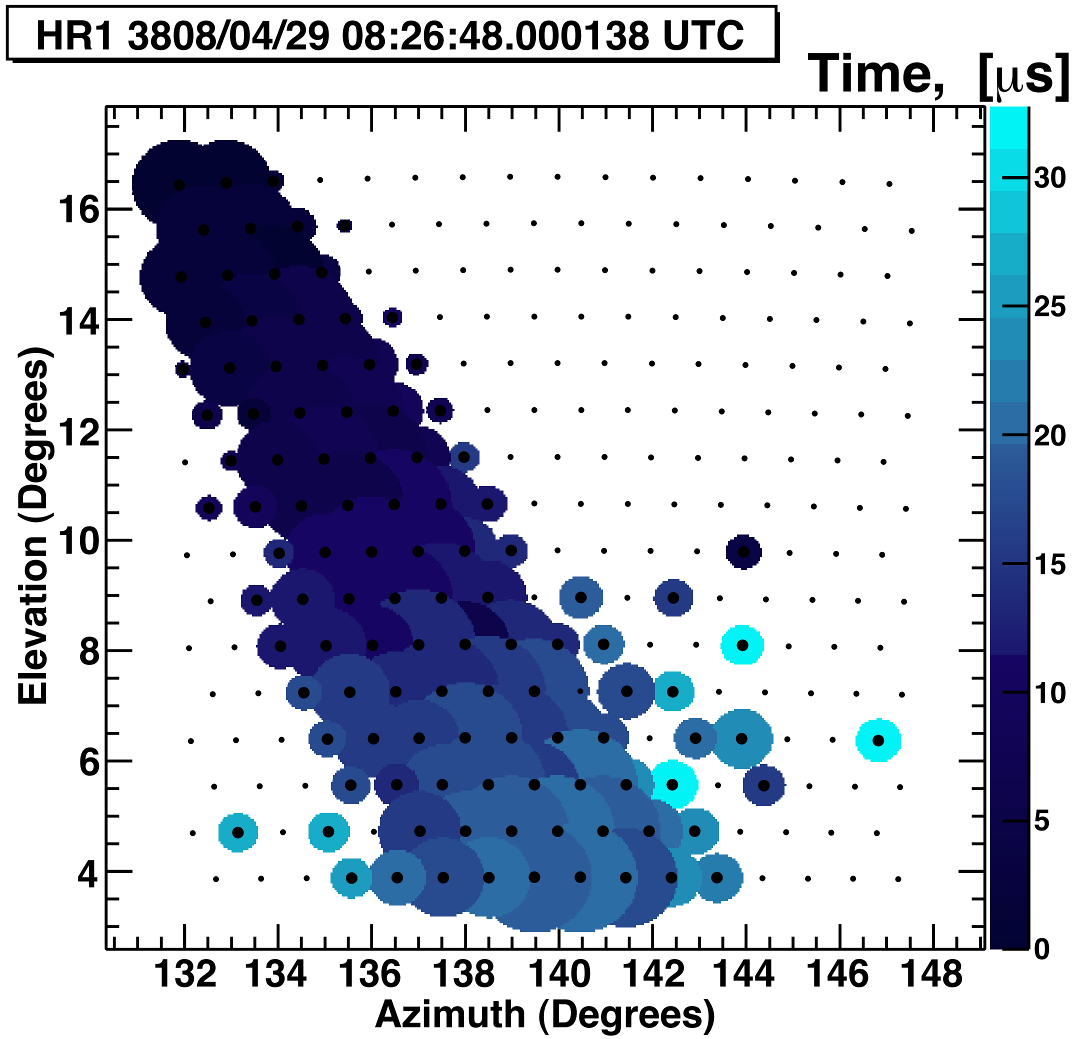
Monte Carlo



Signature of π^0-decay Double Showers

Monte Carlo simulation shows 3 classes of events

Single Event, Single Telescope

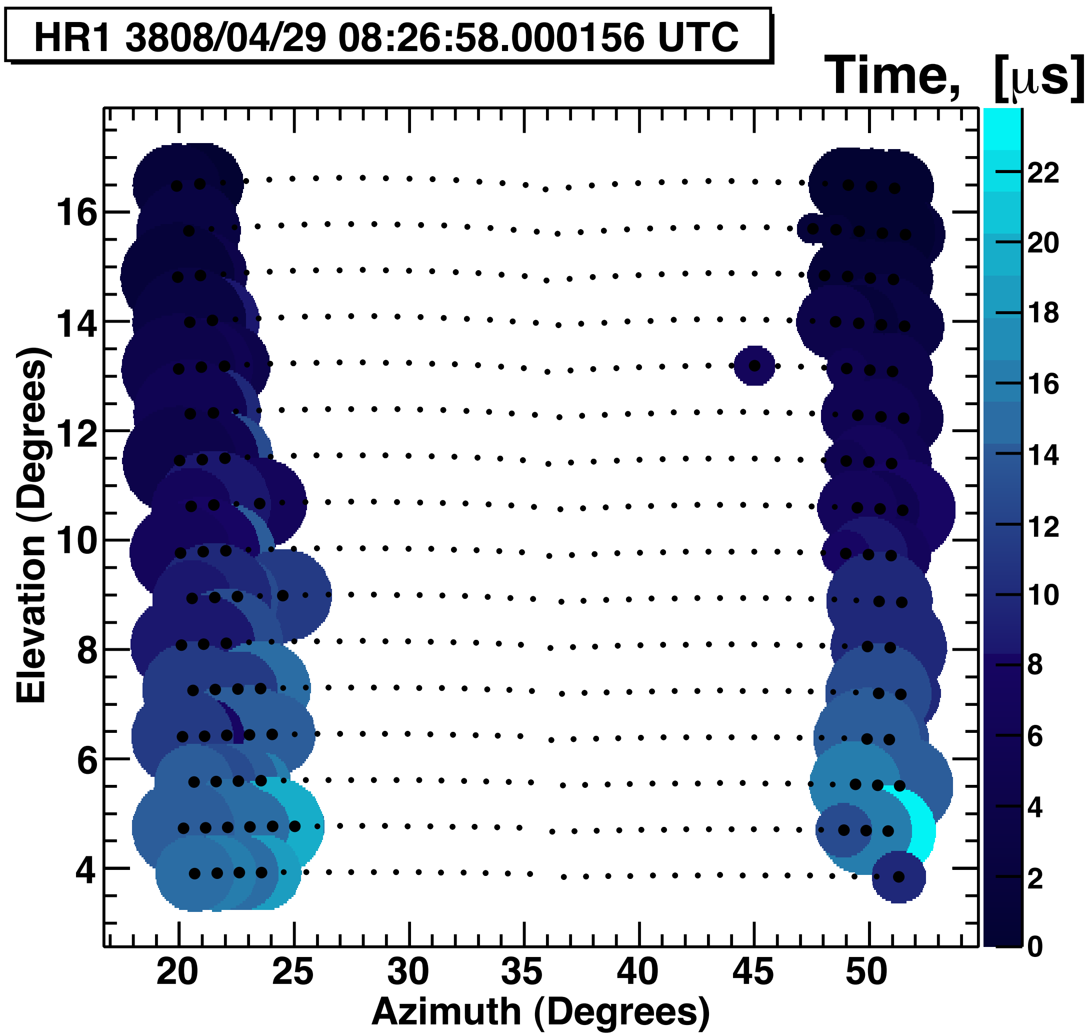


Event = grouping of data within 100 μs

Signature of π^0-decay Double Showers

Monte Carlo simulation shows 3 classes of events

Single Event, within Multiple Telescopes



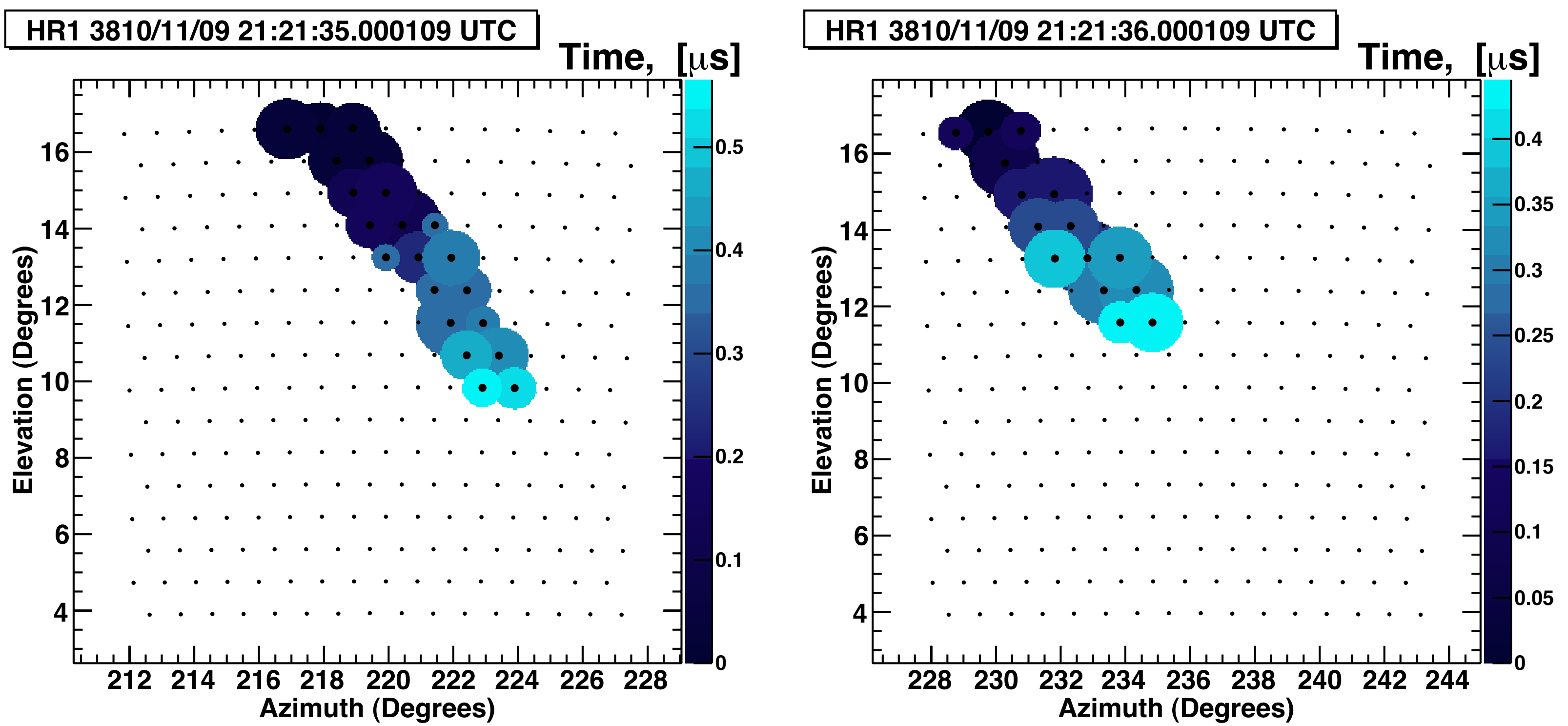
Signature of π^0-decay Double Showers

Monte Carlo

simulation shows

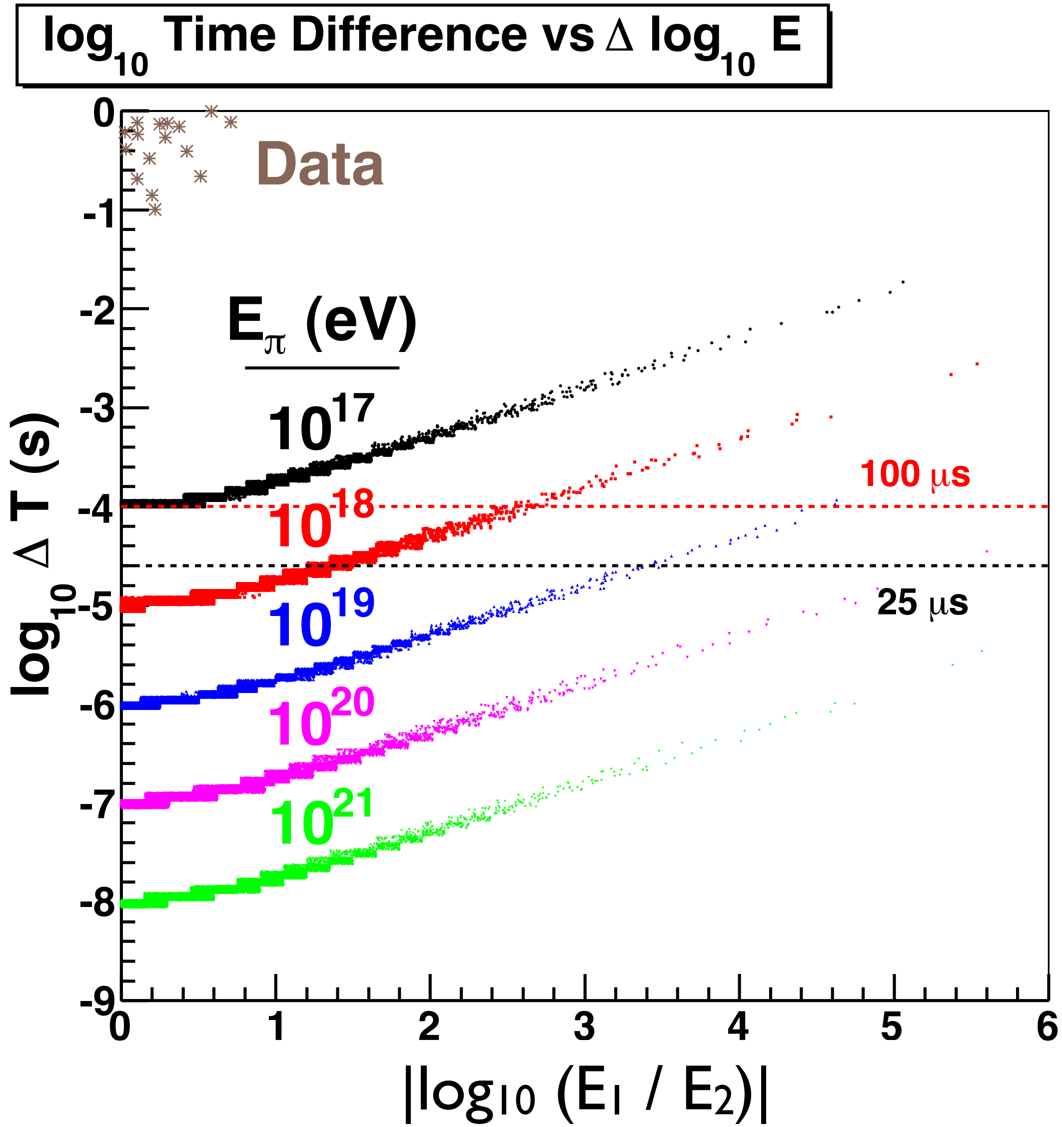
3 classes of events

Multiple Events



Distinguishing Multiple-Event Showers

- MC: Colored Bands
- Data: Brown Points
- Photon times and energies
- Data inconsistent with simulated double-showers

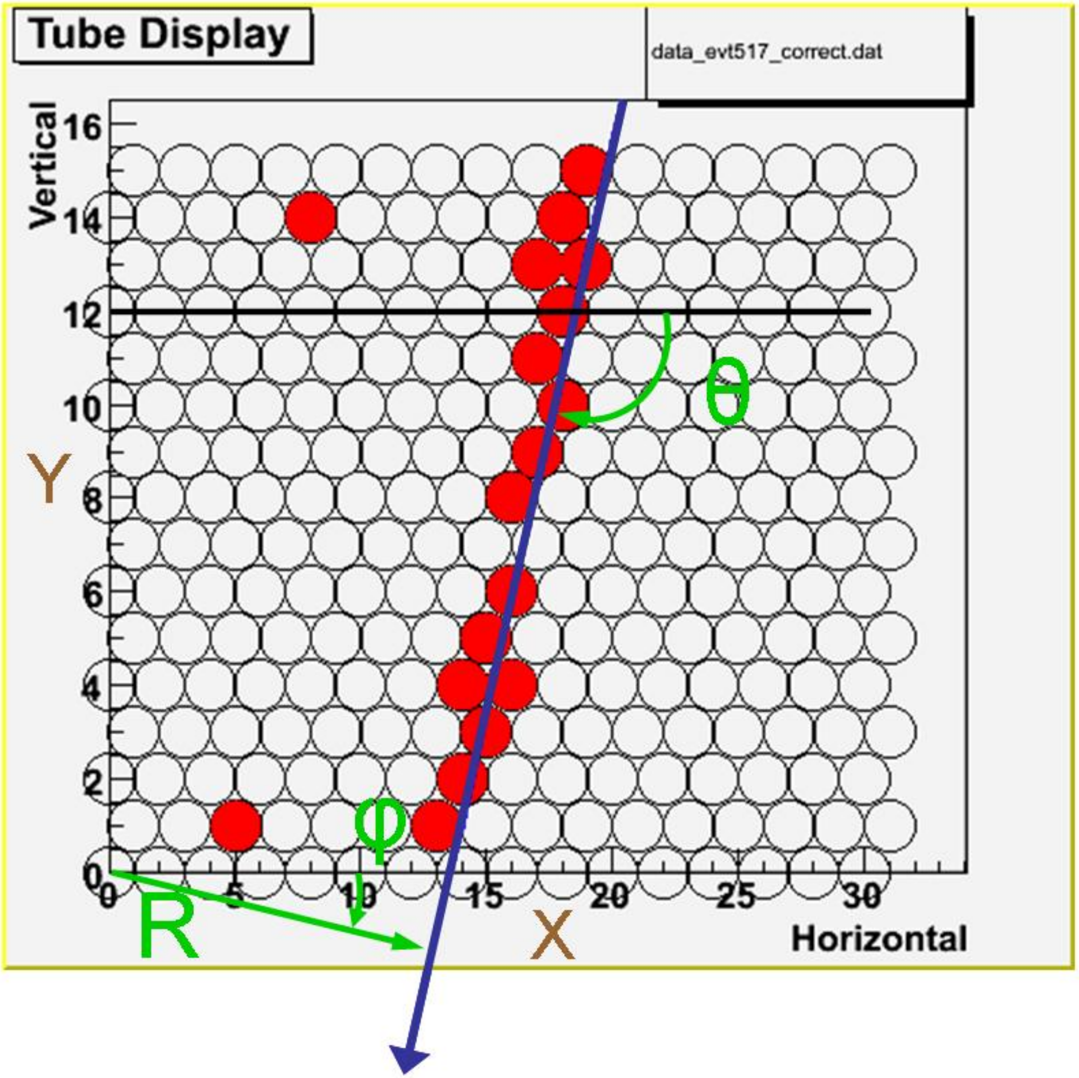


Single-Event Double-Shower Search

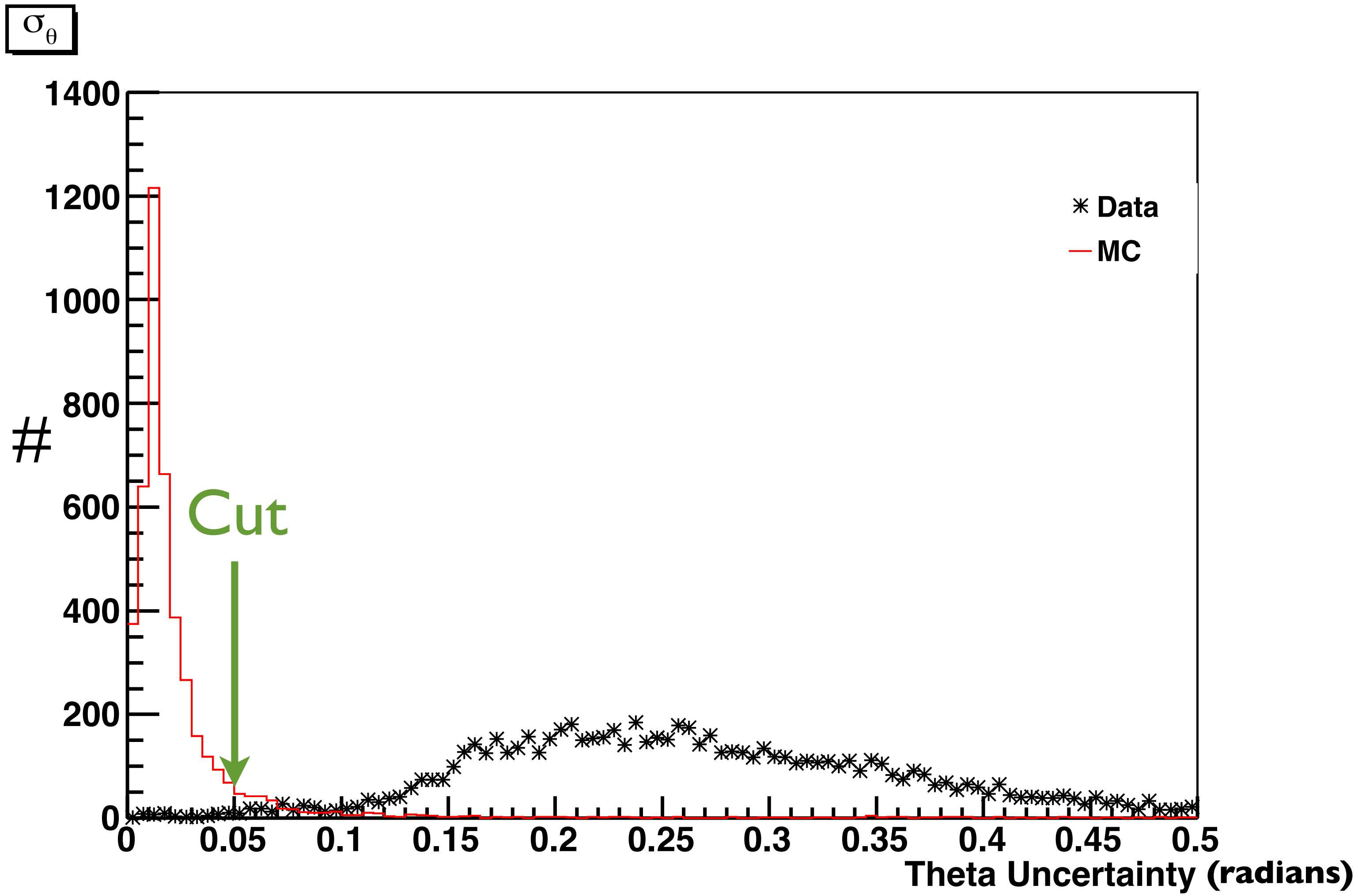
- Used HiRes-1 data set since it is the largest available at the time this project was started
- Created new programs to search for two, simultaneous, time-coincident showers
- Modified the standard Monte Carlo to allow two showers to be within a single event

Noise Removal

- Use Hough Transform to remove non-linear events
  - noise
  - airplanes
  - muons
- Used in computer image processing
- Utilized by R. Abbasi for anisotropy studies of HiRes data

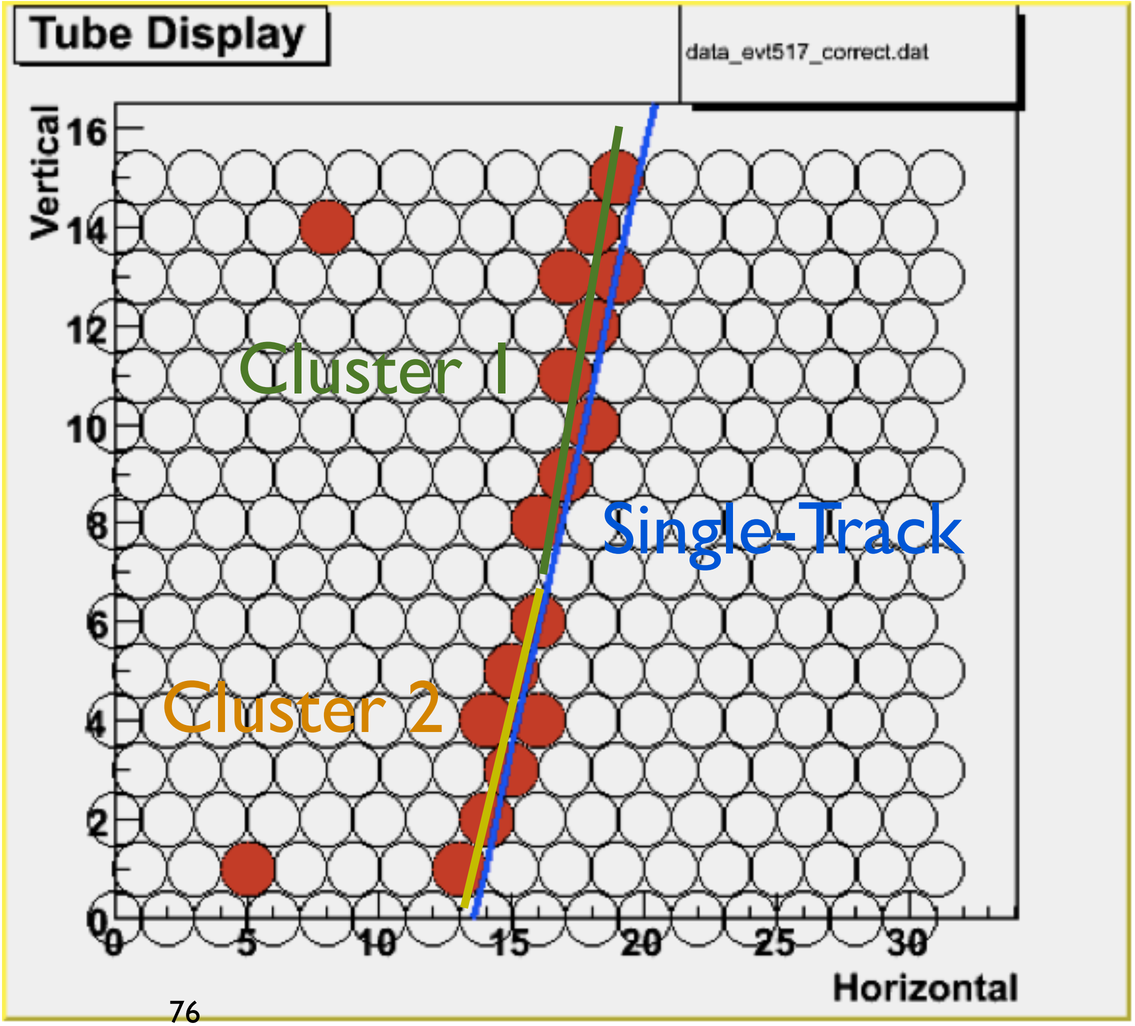


Line Quality



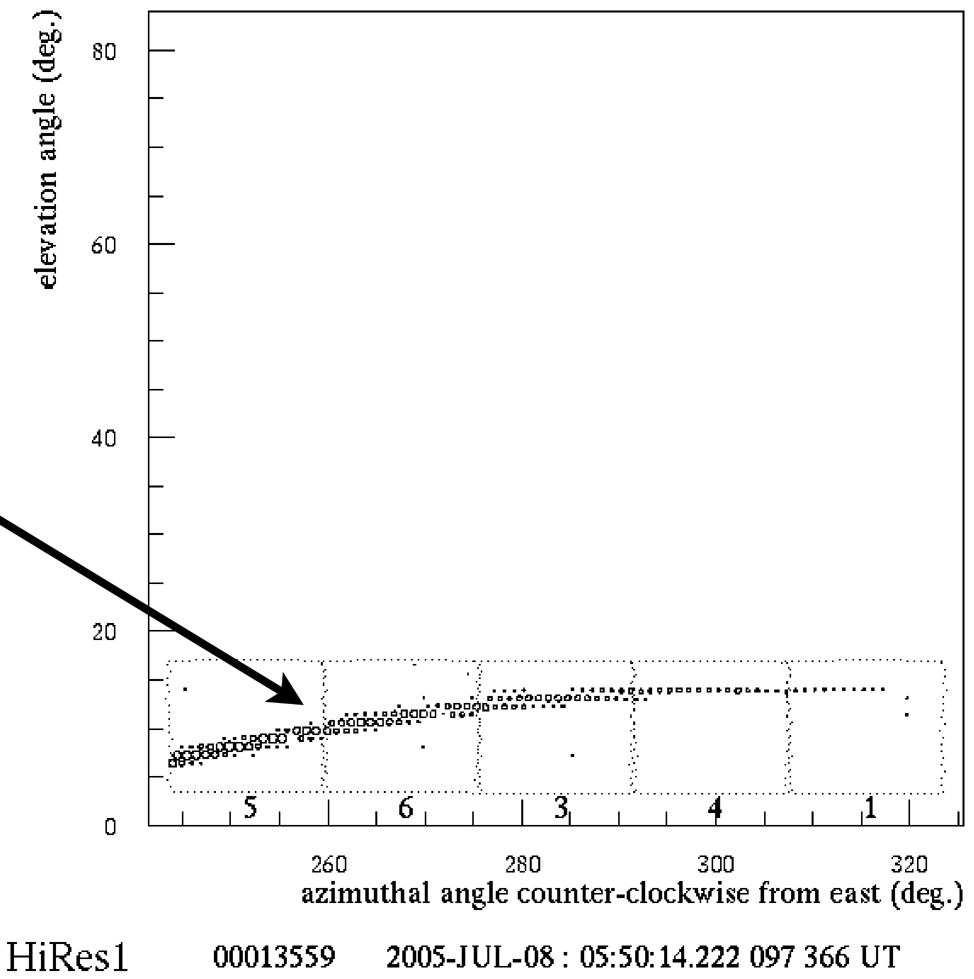
Looking for Multiple Showers

- Group triggered tubes into clusters
  - trigger time within 2 μs
  - pointing angle within 1.2°
- Determine shower-detector plane for each cluster



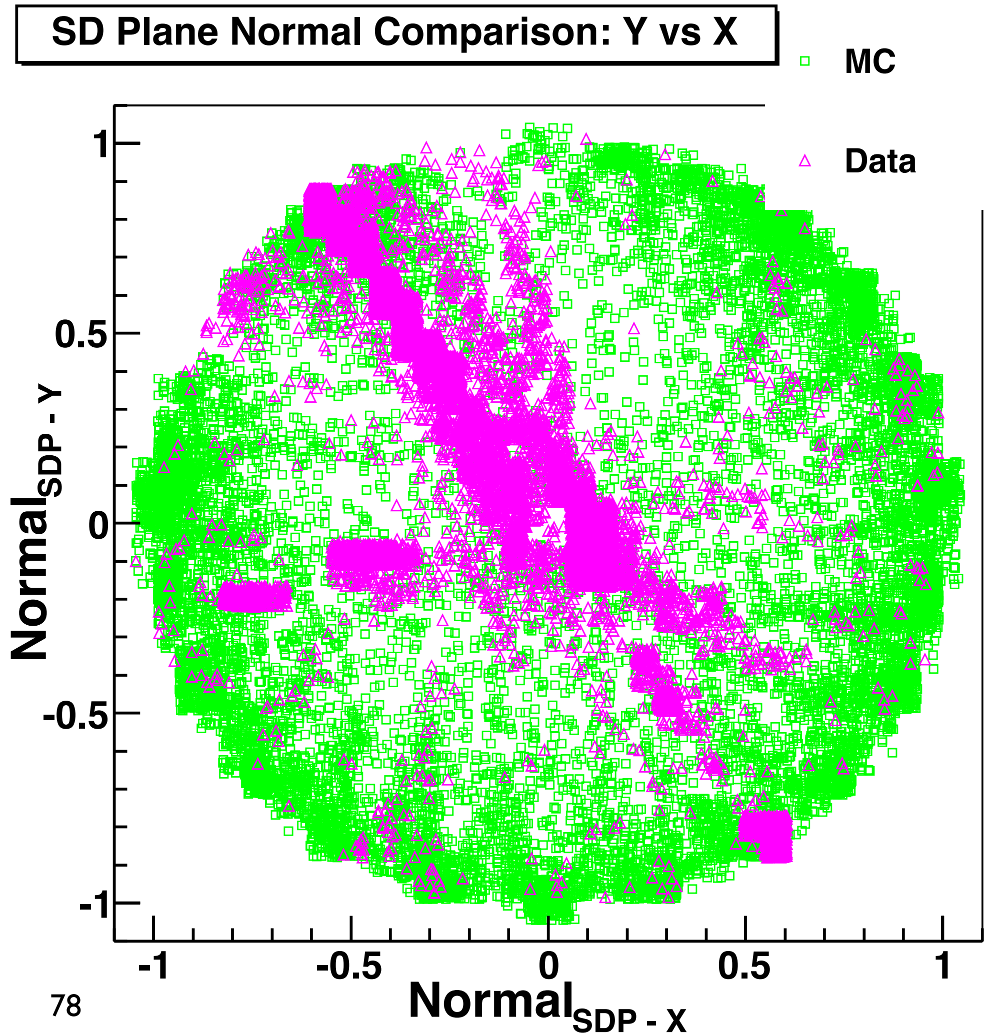
Event Sorting

- Most remaining events are artifacts
  - HR2SLS
  - Flashers
  - Terra Laser
  - Inter-site Flasher
- Removed by
  - time-stamp
  - position
  - angle of trajectory
  - repetition



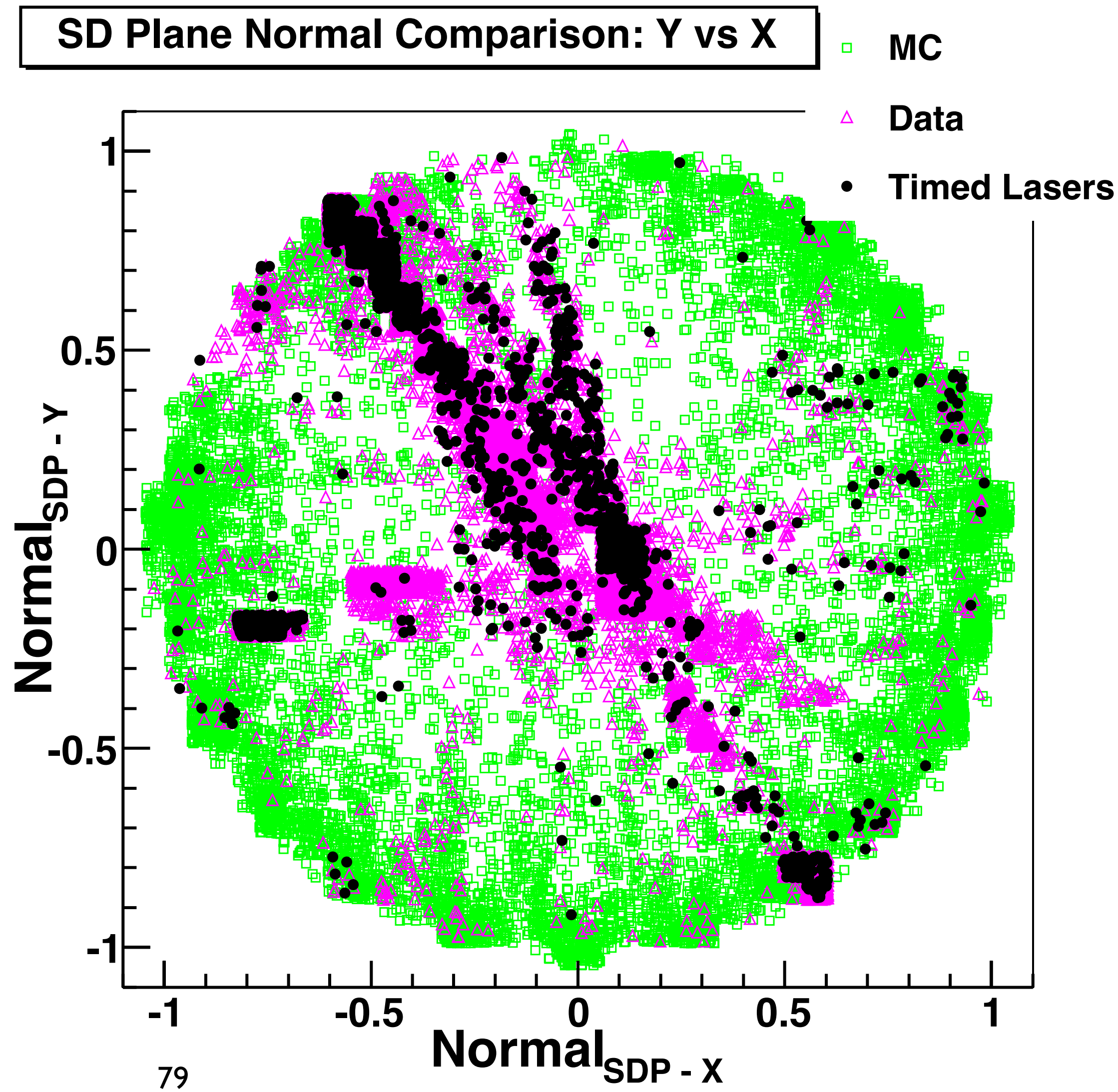
Preliminary Double-Shower Candidates

- Monte Carlo simulations uniformly distributed around detector
- Data had patterns



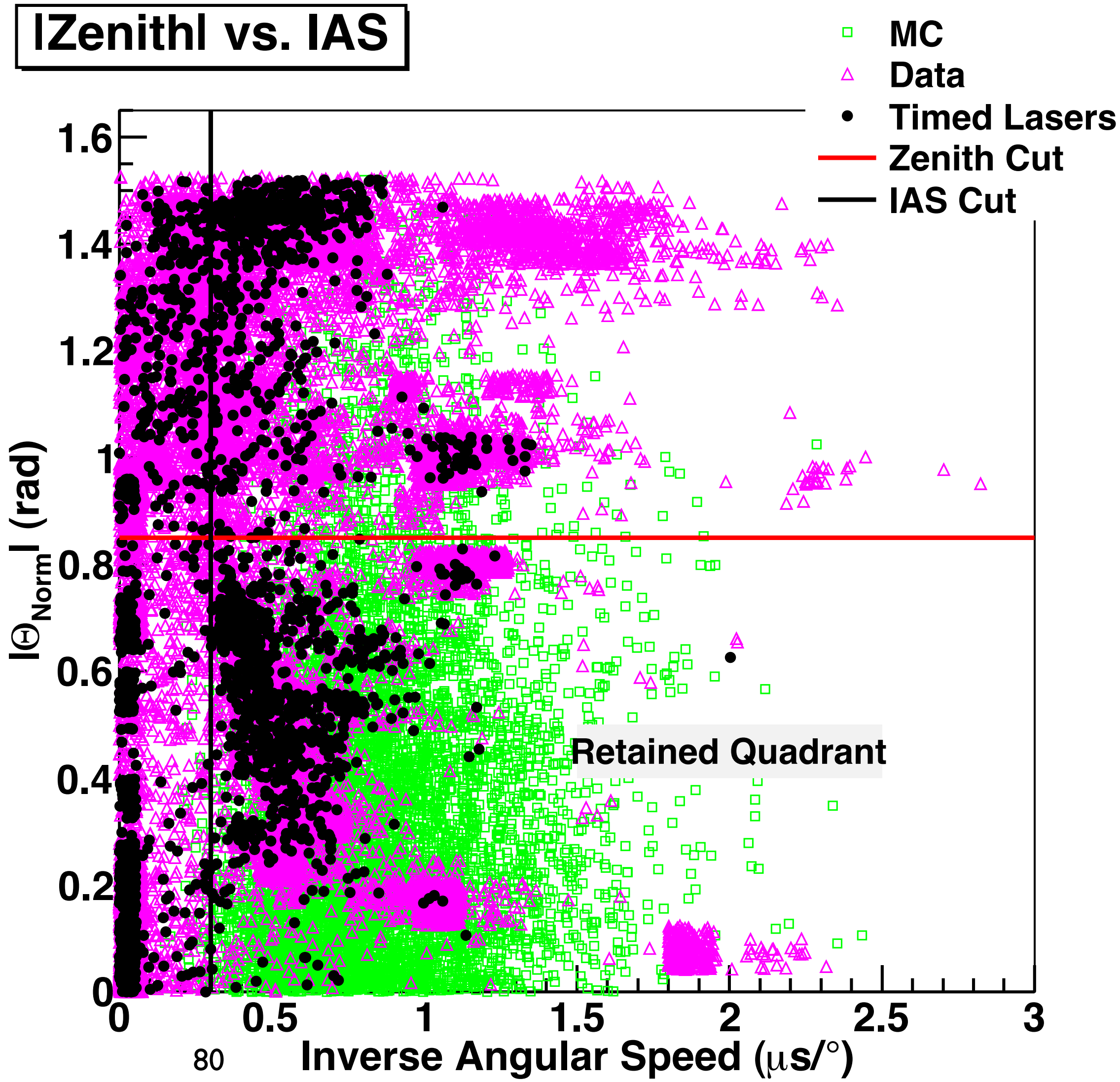
Resolving Data Doubles

- Data events primarily correlated wtih known laser events with known time-stamps



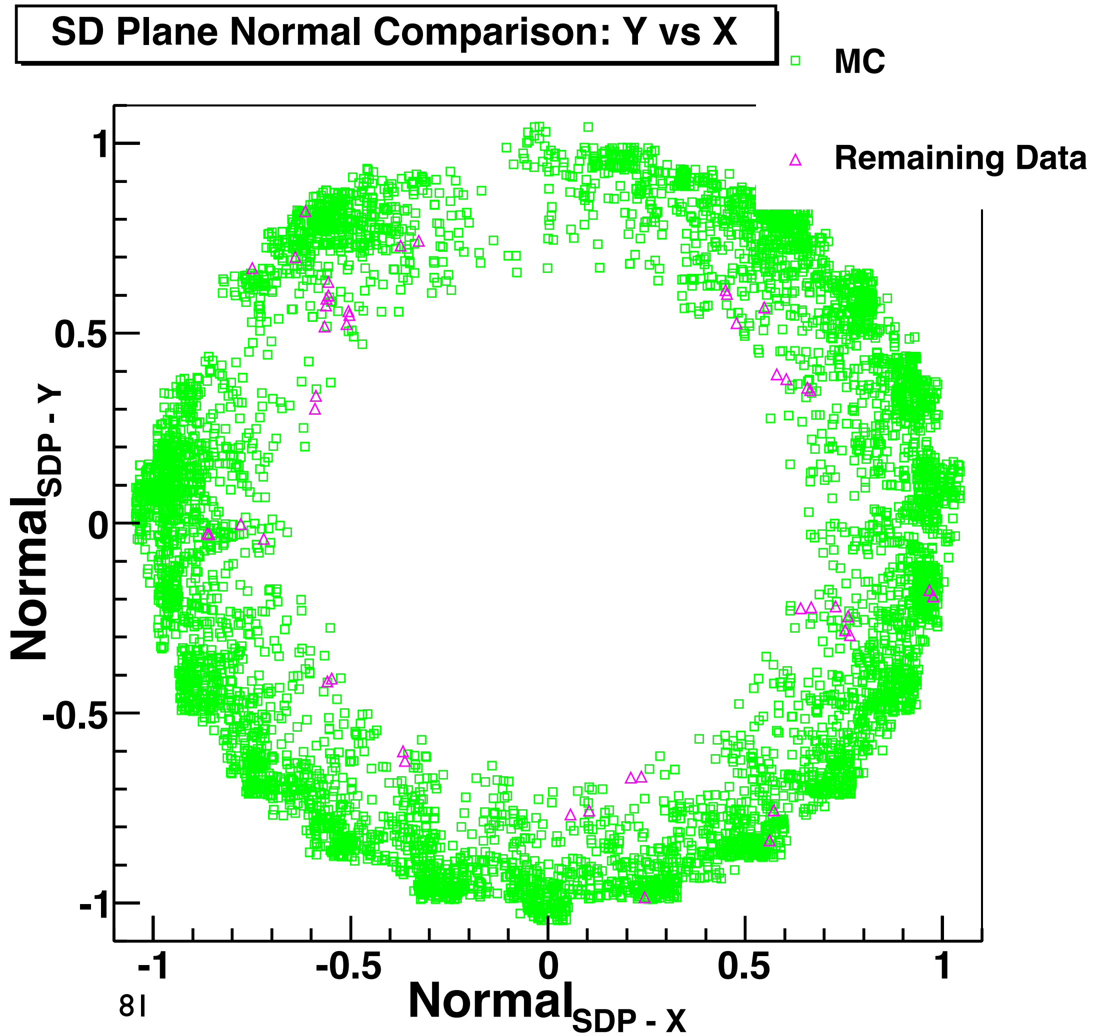
Resolving Data Doubles

- Known lasers had well-defined zenith angles or inverse angular speeds
- Removed MC and data events if **both** tracks have
    - inverse angular speed < 0.3 μs/degree
    - zenith angle, θ, > 0.85 radians (~49°)



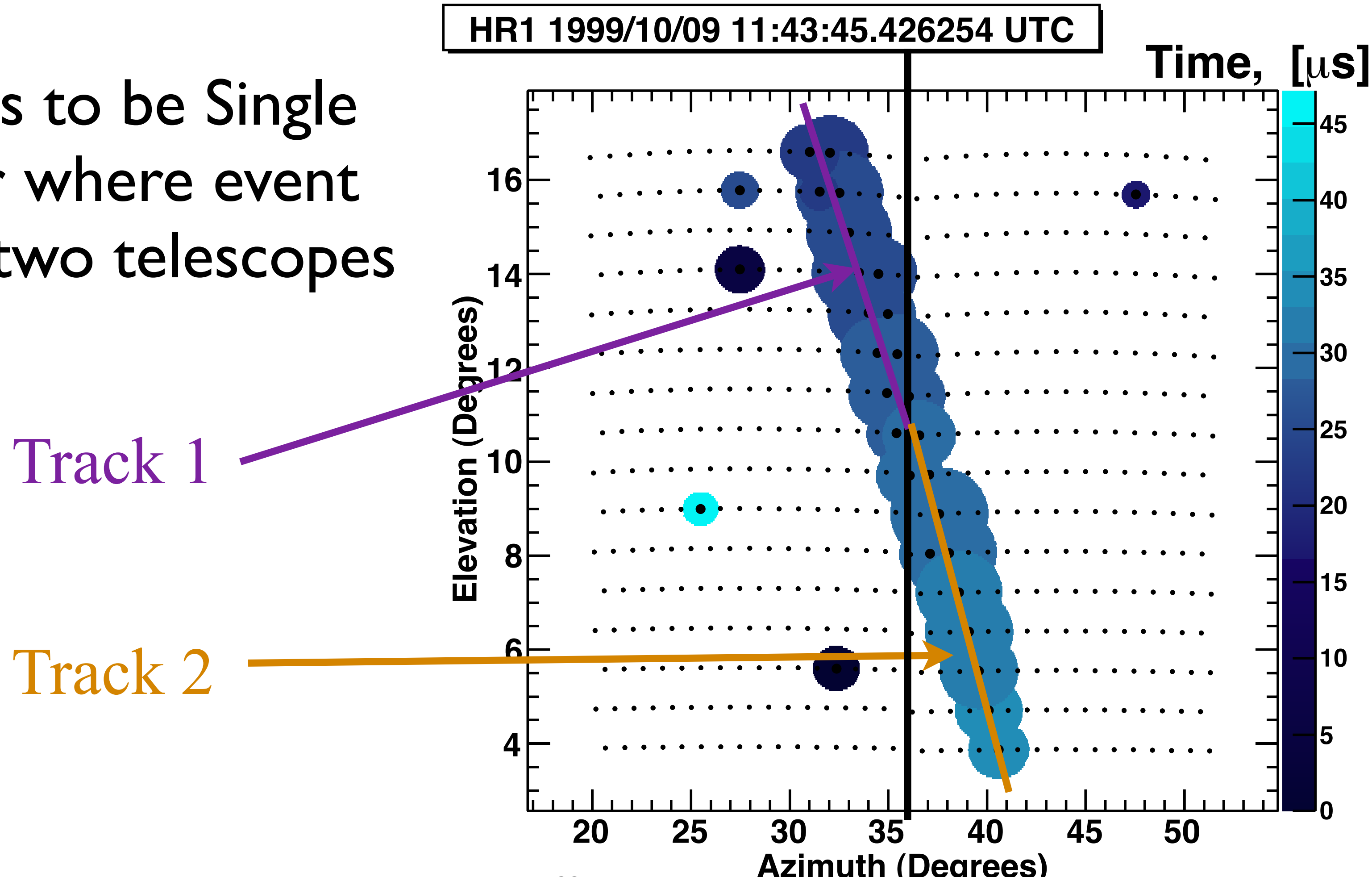
Final Double-Shower Candidates

- 23 Data events remain
  - 46 clusters
- 82% MC retained



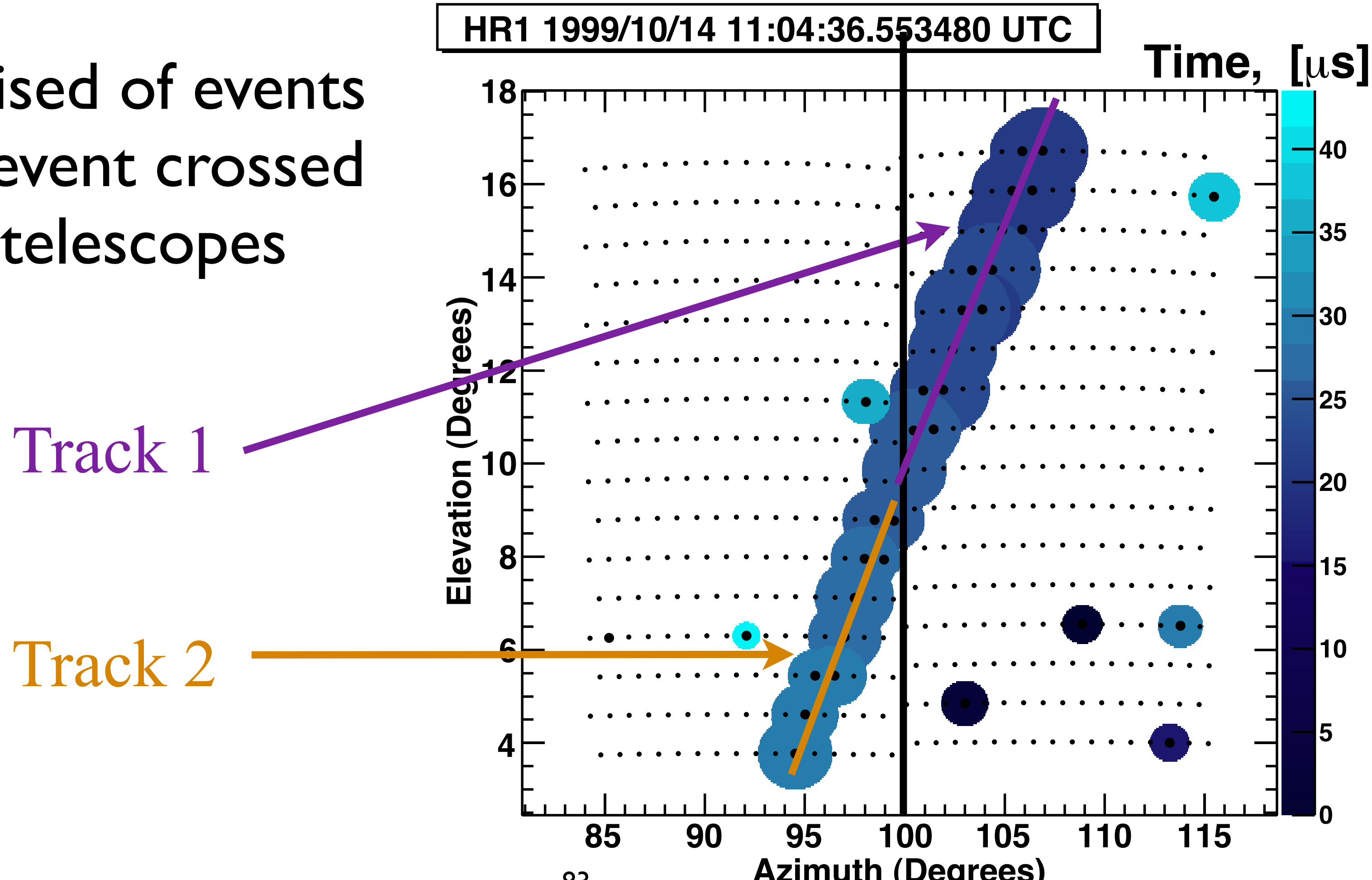
Remaining Data Candidate Examples

Appears to be Single Shower where event crossed two telescopes



Remaining Data Candidate Examples

Comprised of events where event crossed two telescopes

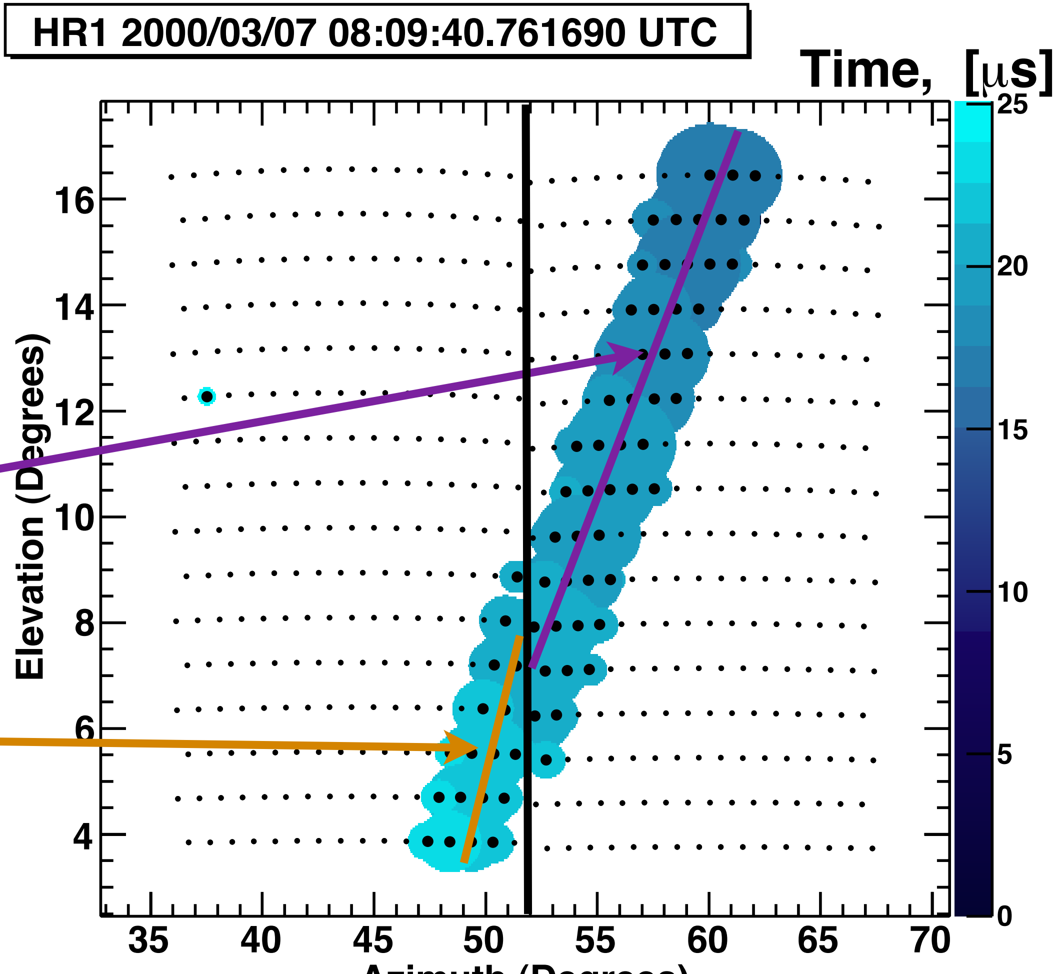


Remaining Data Candidate Examples

Comprised of events where event crossed two telescopes

Track 1

Track 2



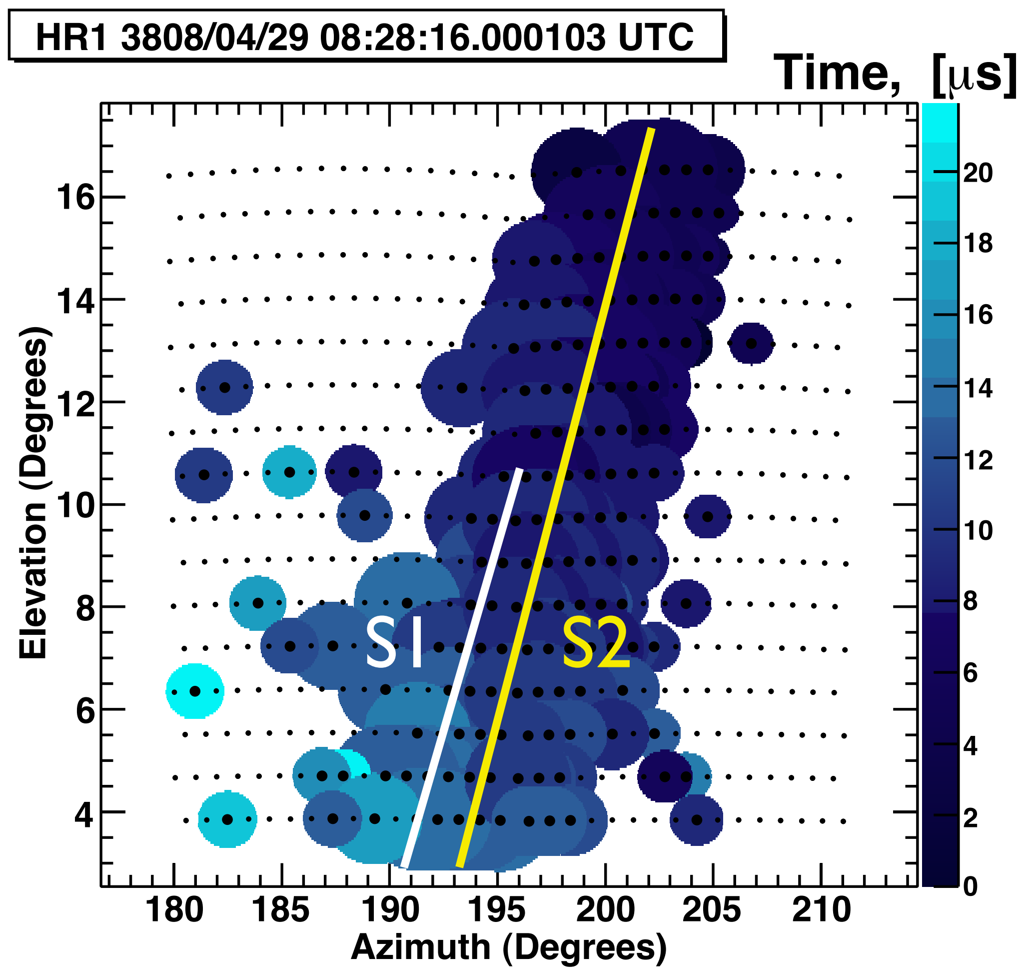
Objectively distinguish?

How Close Is Too Close?

Double-shower
Monte Carlo

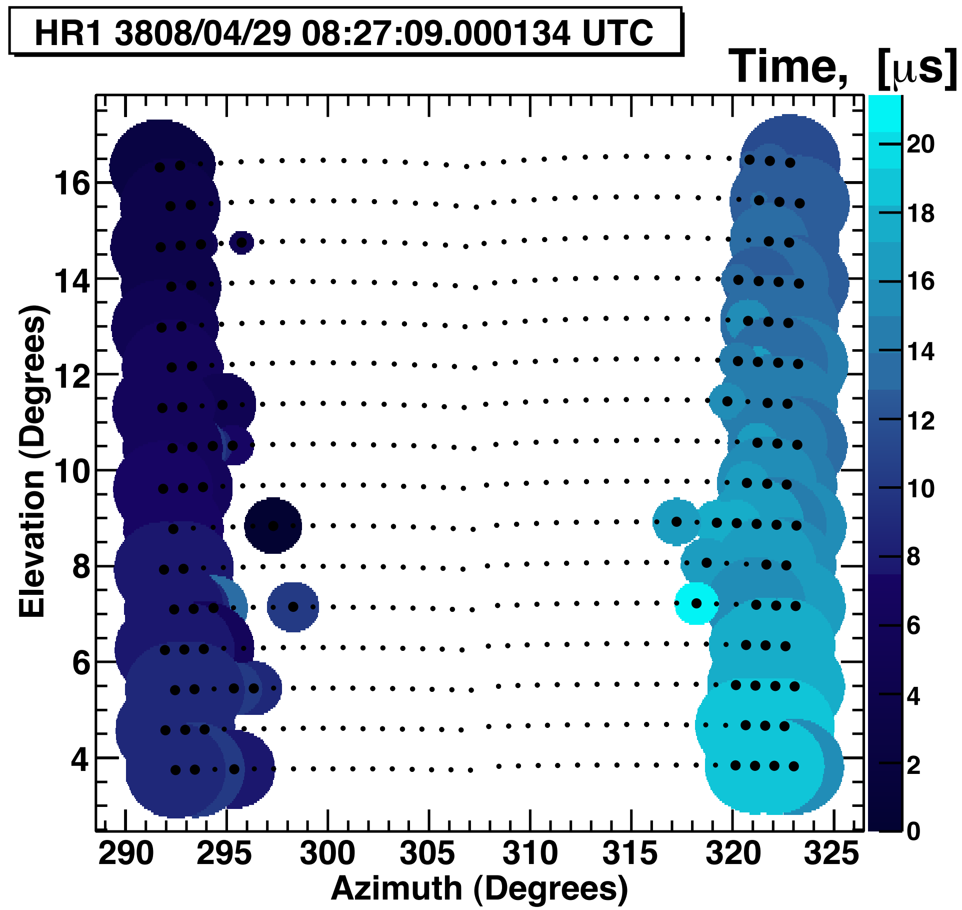
Overlapping tracks from detector's standpoint

S1 - 15 km away
S2 - 14 km away
2 deg. opening angle

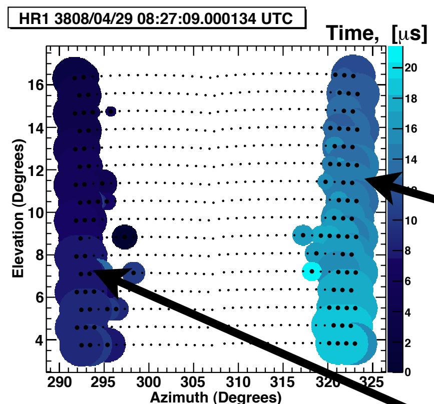


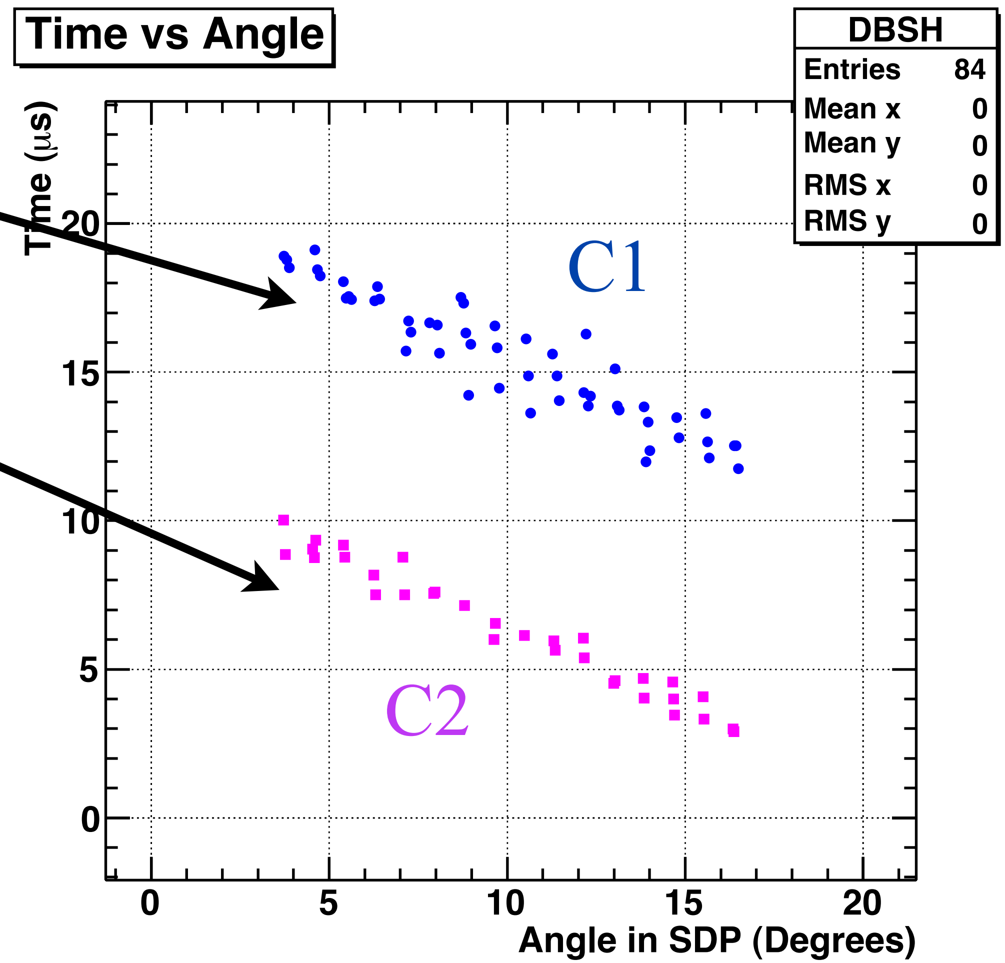
Distinguishing Tracks

- Monte Carlo simulation example of double-showers
  - Distinct tracks



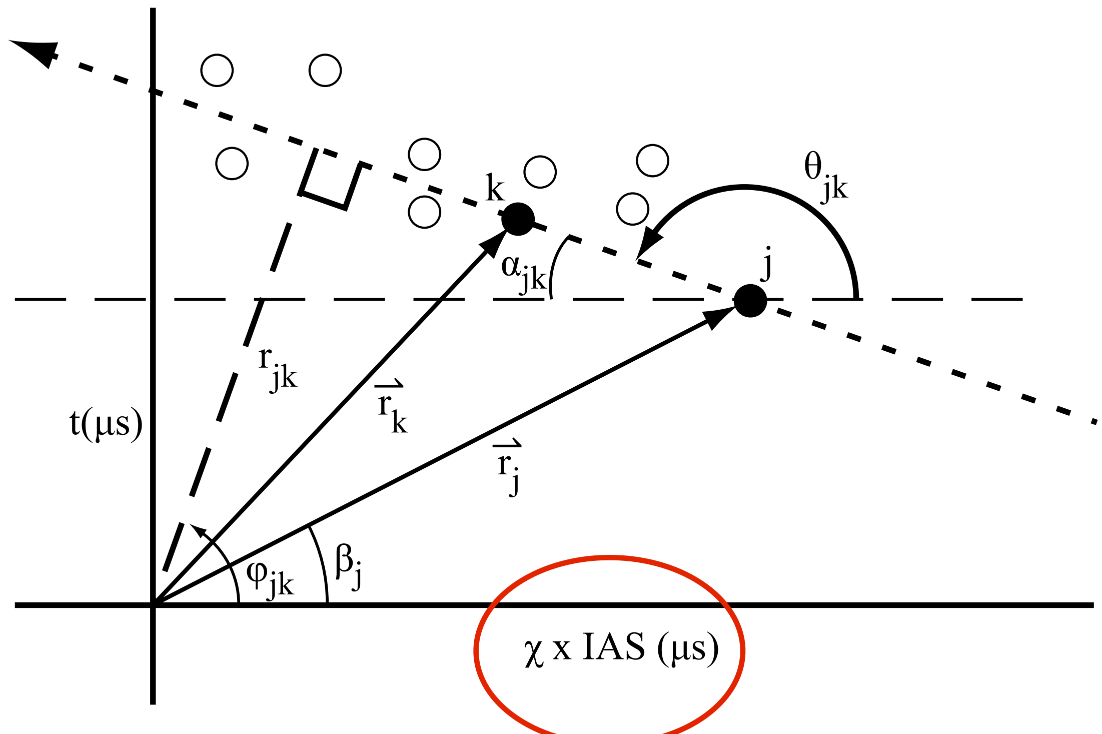
Time-vs.-Angle Plot





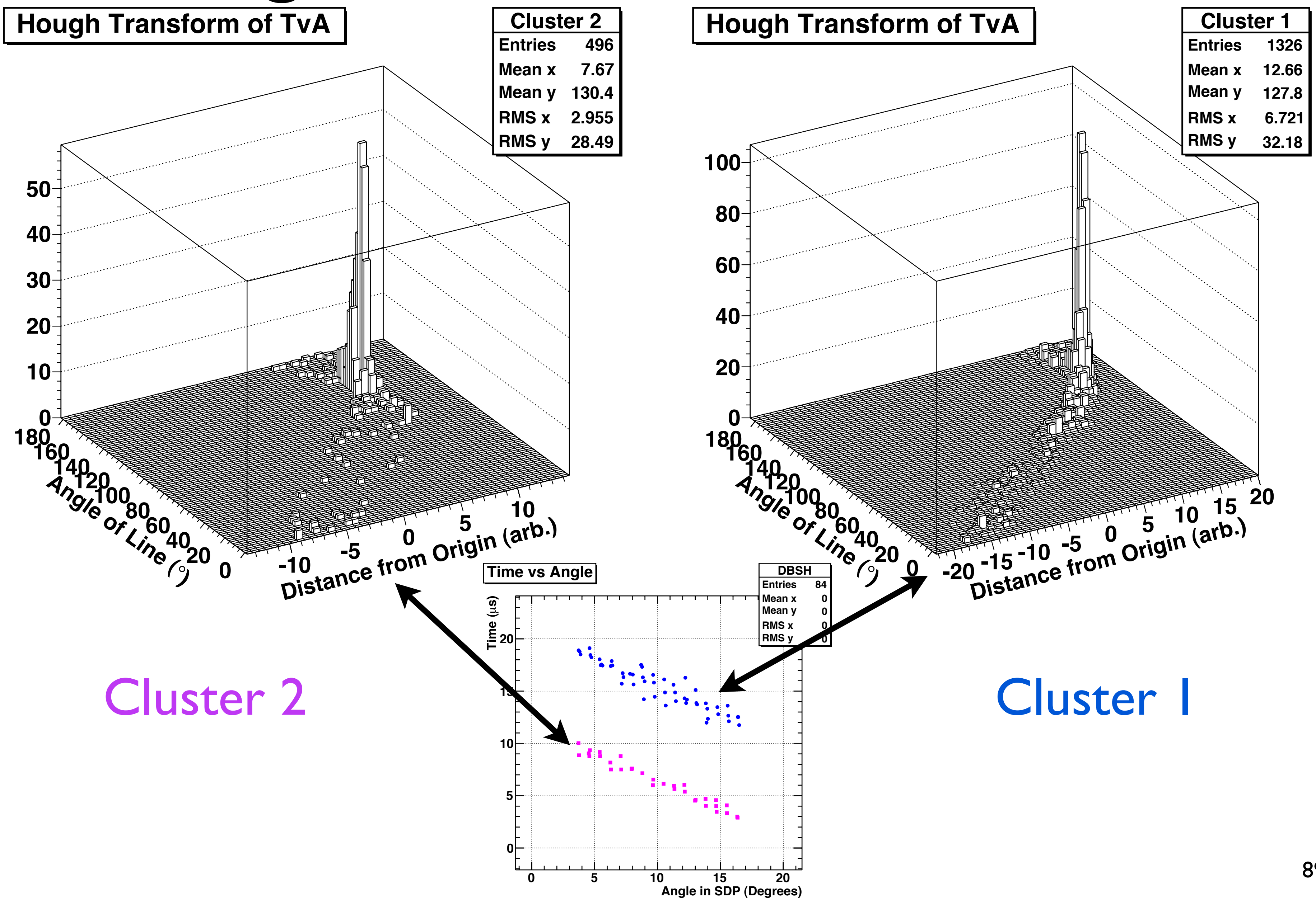
Each tube in an event has a trigger time and an angle in the shower-detector plane

Time-vs.-Angle Hough Transform



Each pair of tubes can then be used to create a line (Hough Transform)

Hough Transform Distribution



Refining the Mean

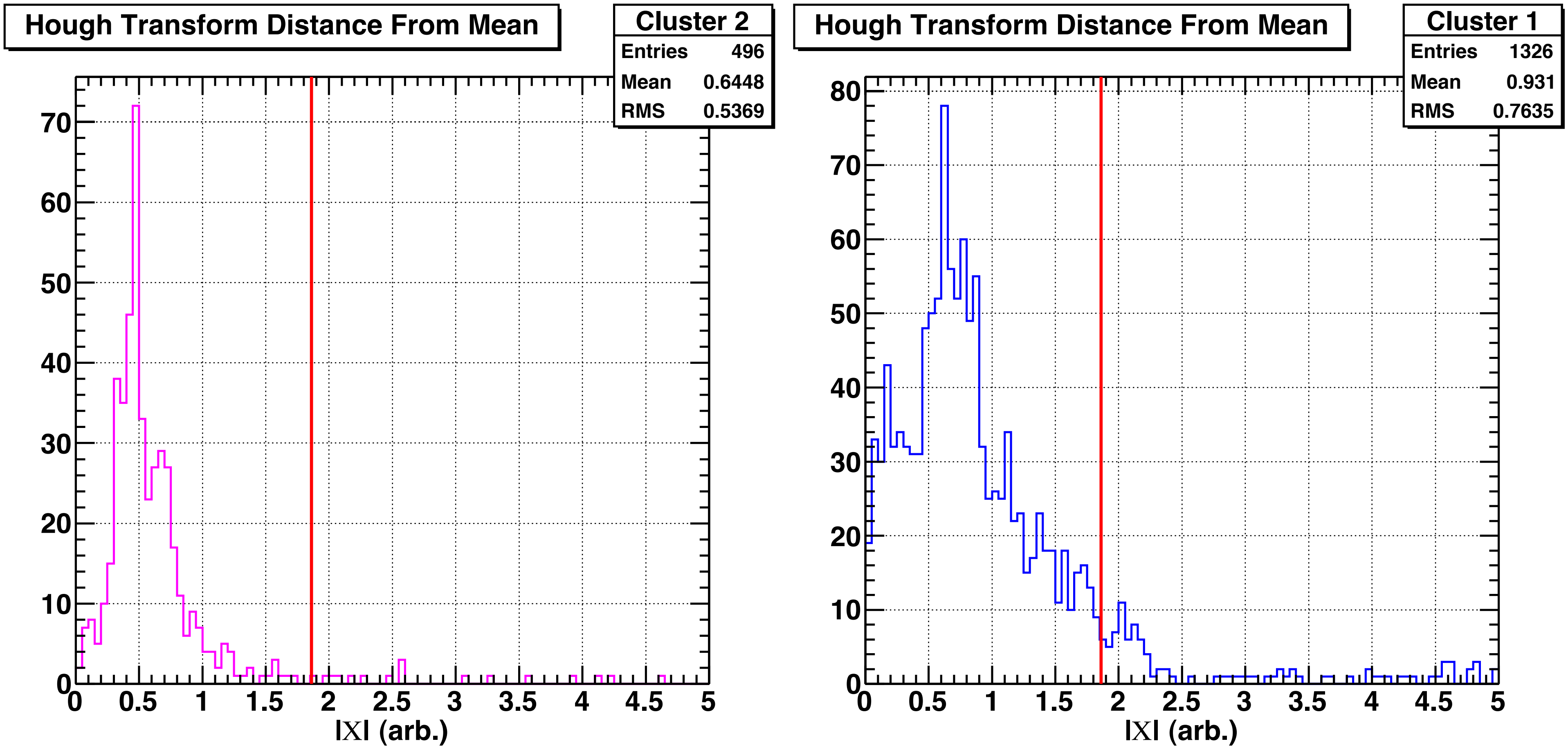
- To obtain a refined mean, remove outliers
- Determine the mean separation in 2-dimensions

$$X_{\theta\text{-}jk} = \frac{\theta_{jk} - \bar{\theta}}{\sigma_\theta} \qquad X_{r\text{-}jk} = \frac{r_{jk} - \bar{r}}{\sigma_r}$$

- Determine the difference between the individual points and the mean
  - Equivalent to the normalized RMS deviation

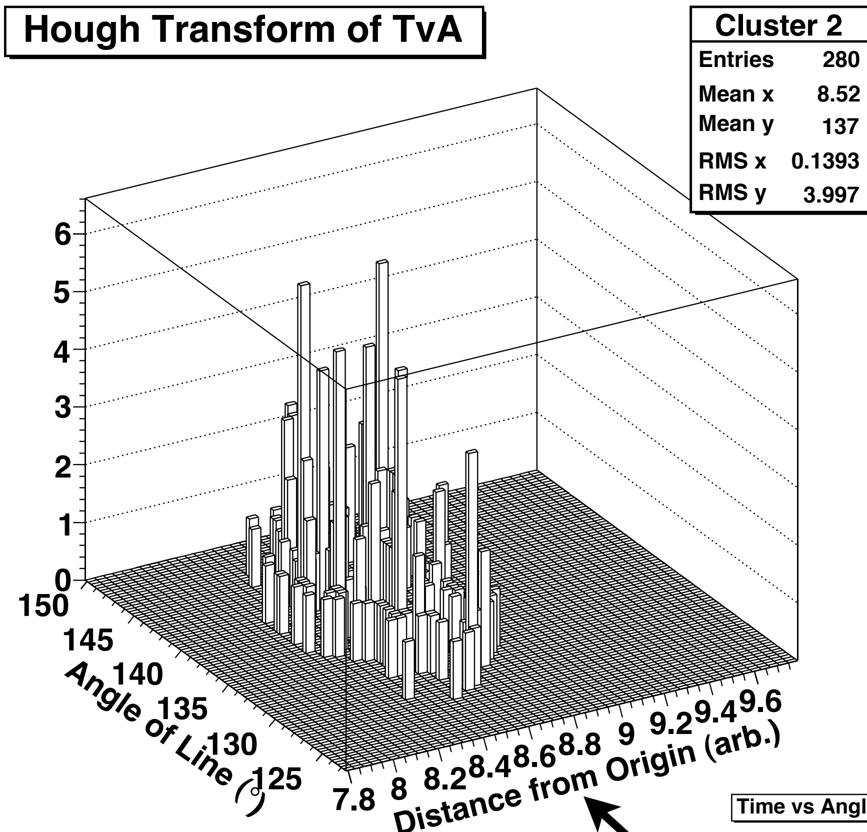
$$|X_{jk}| = \sqrt{X^2_{\theta\text{-}jk} + X^2_{r\text{-}jk}}$$

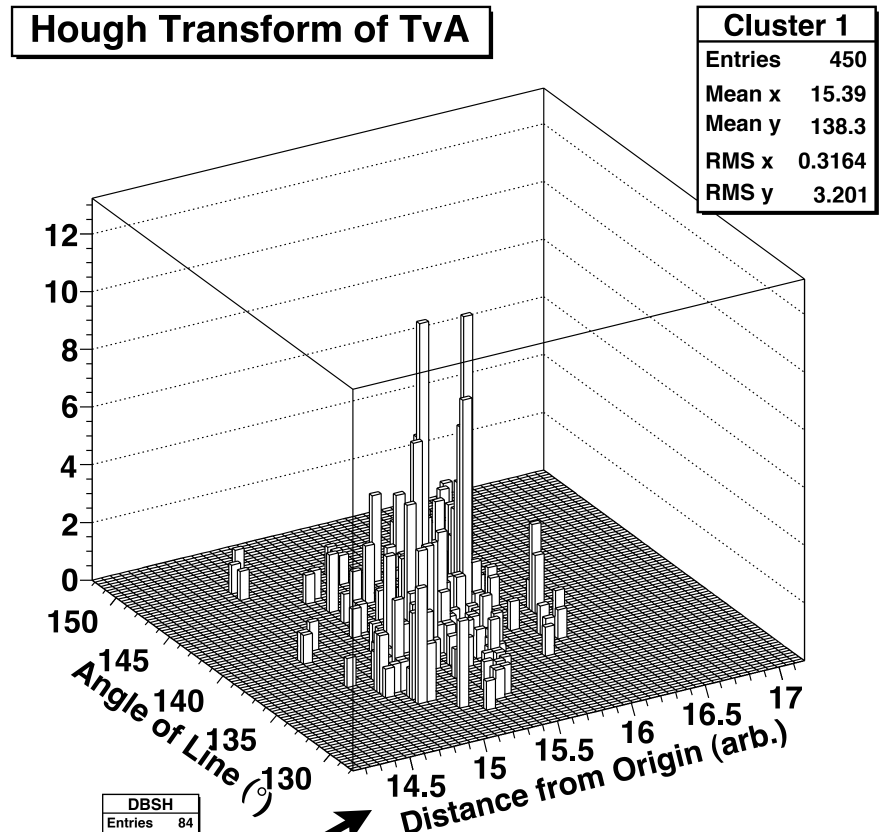
Refining the Mean

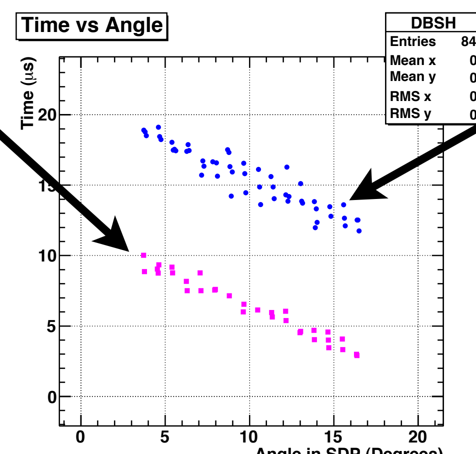


Remove points greater than ~2σ from mean

Refined Angle and Distance







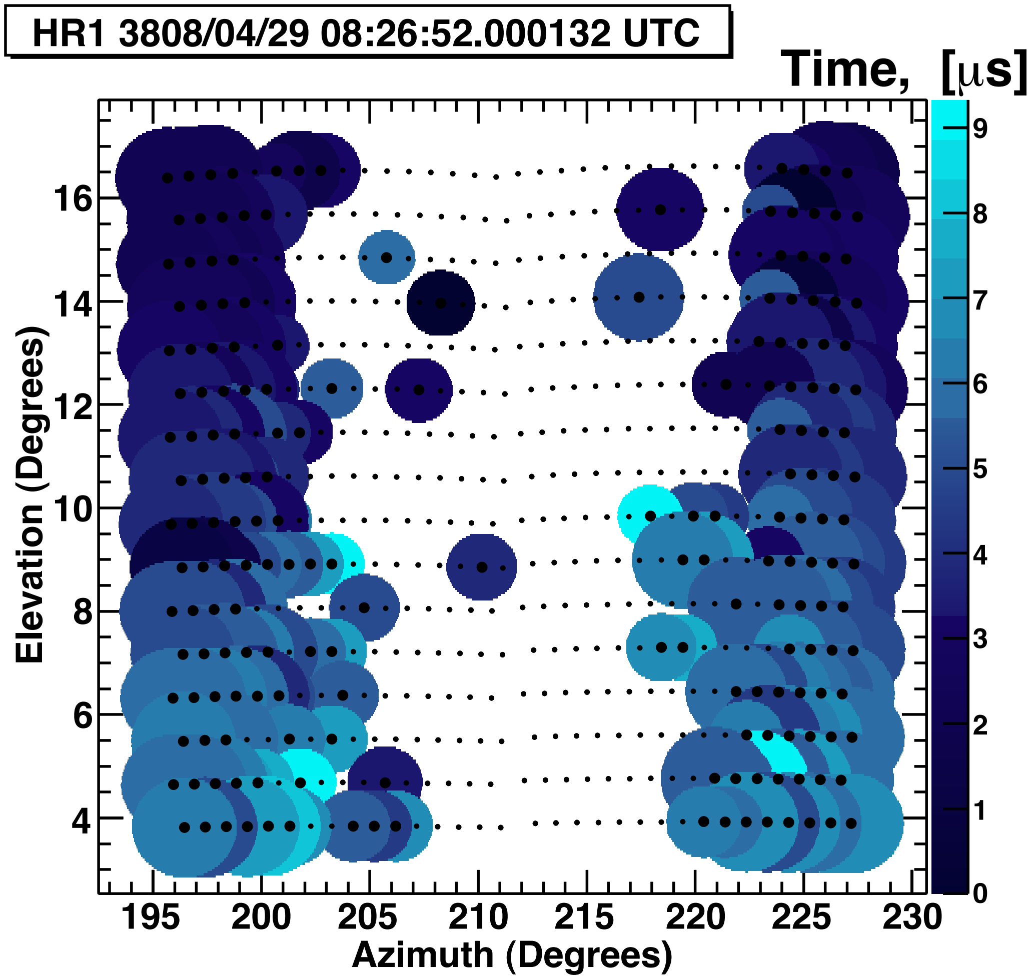
Cluster 2

Cluster 1

19.9σ

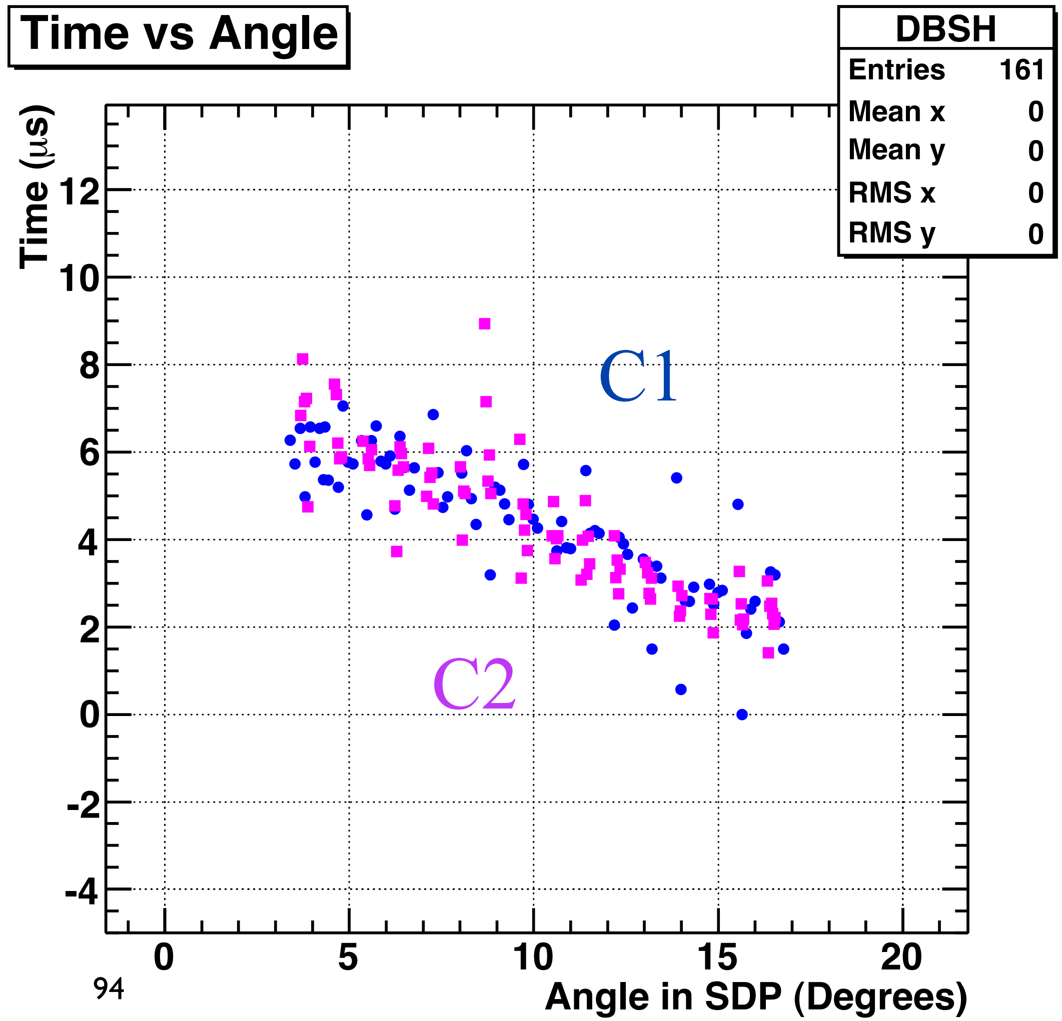
Distinguishing Similar Tracks

These MC tracks are distinct in the event display

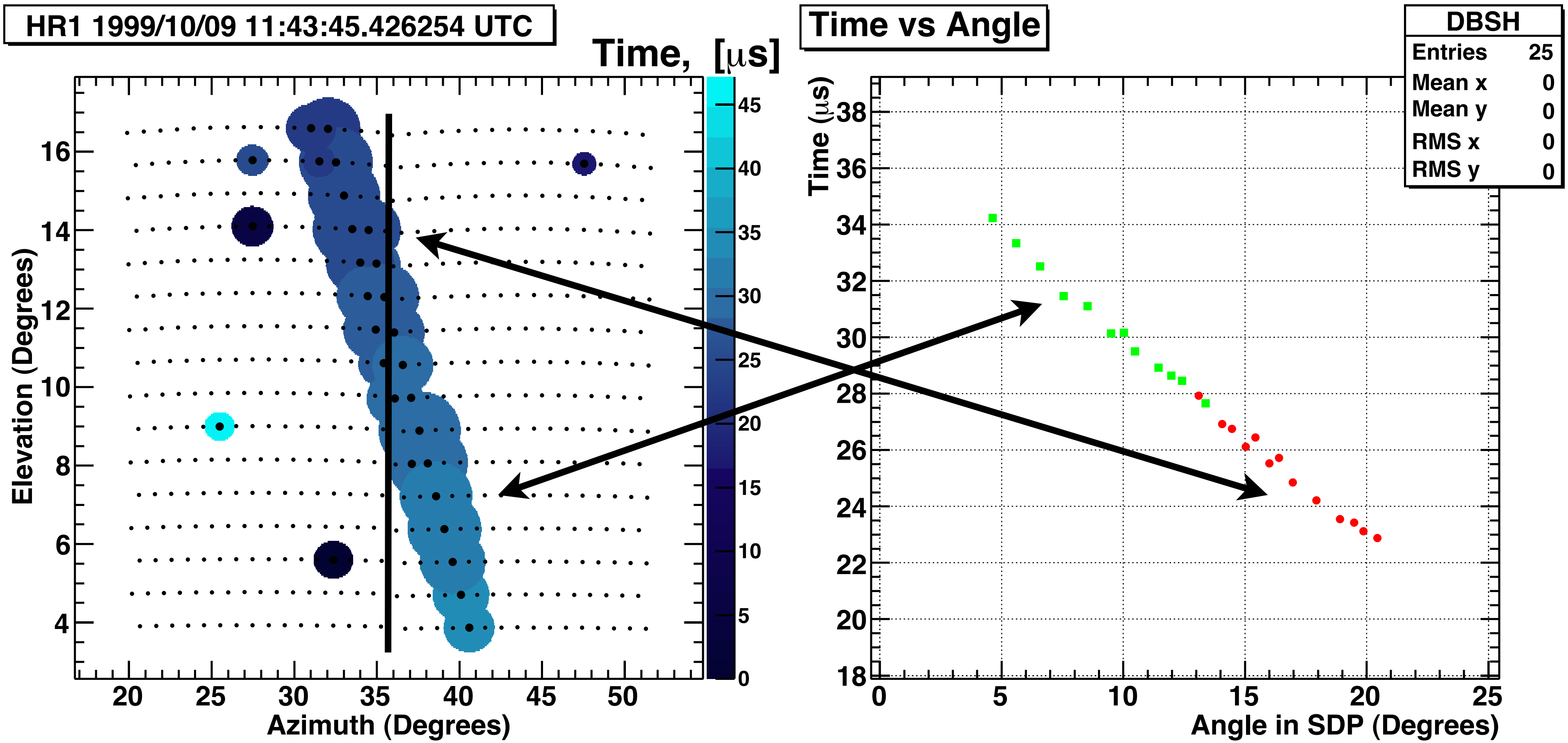


Distinguishing Similar Tracks

However, they appear to have the same time-versus-angle distribution

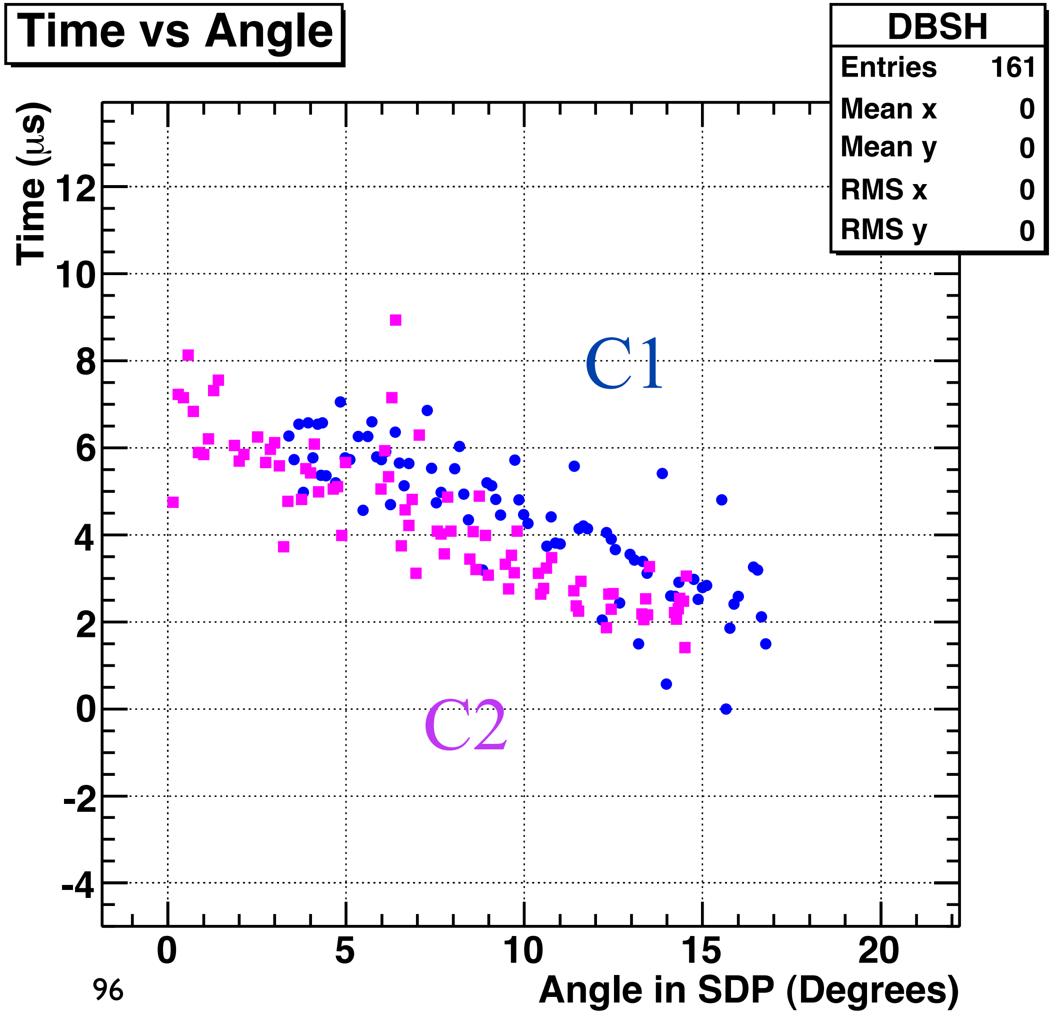


Data Candidate



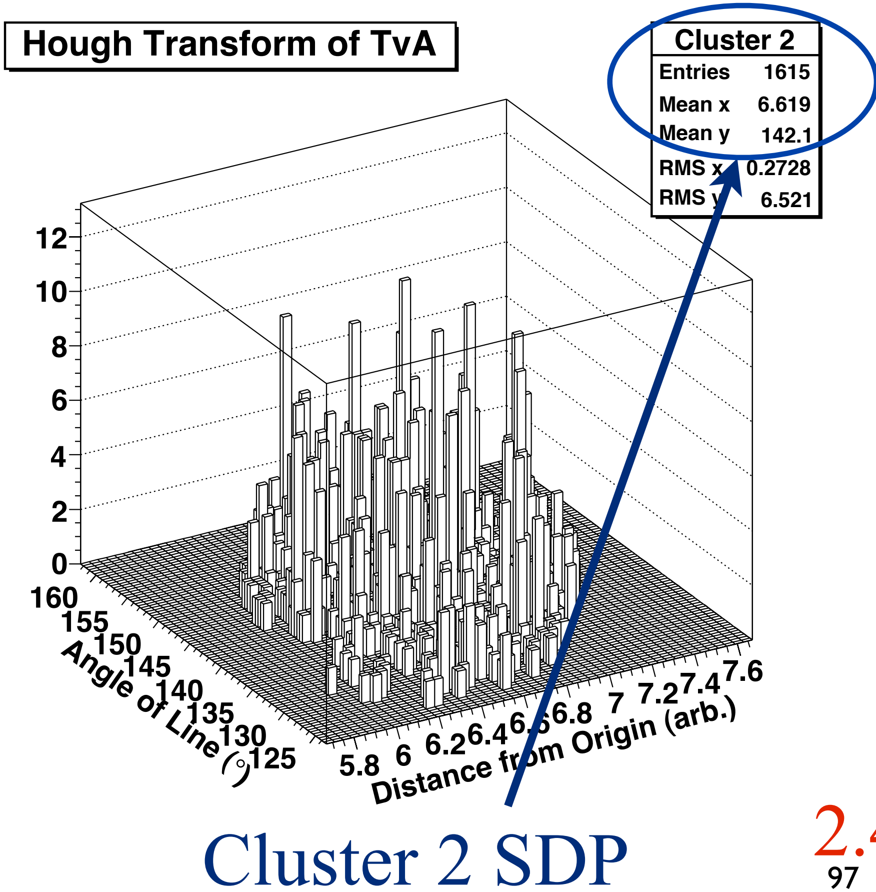
Distinguishing Similar Tracks

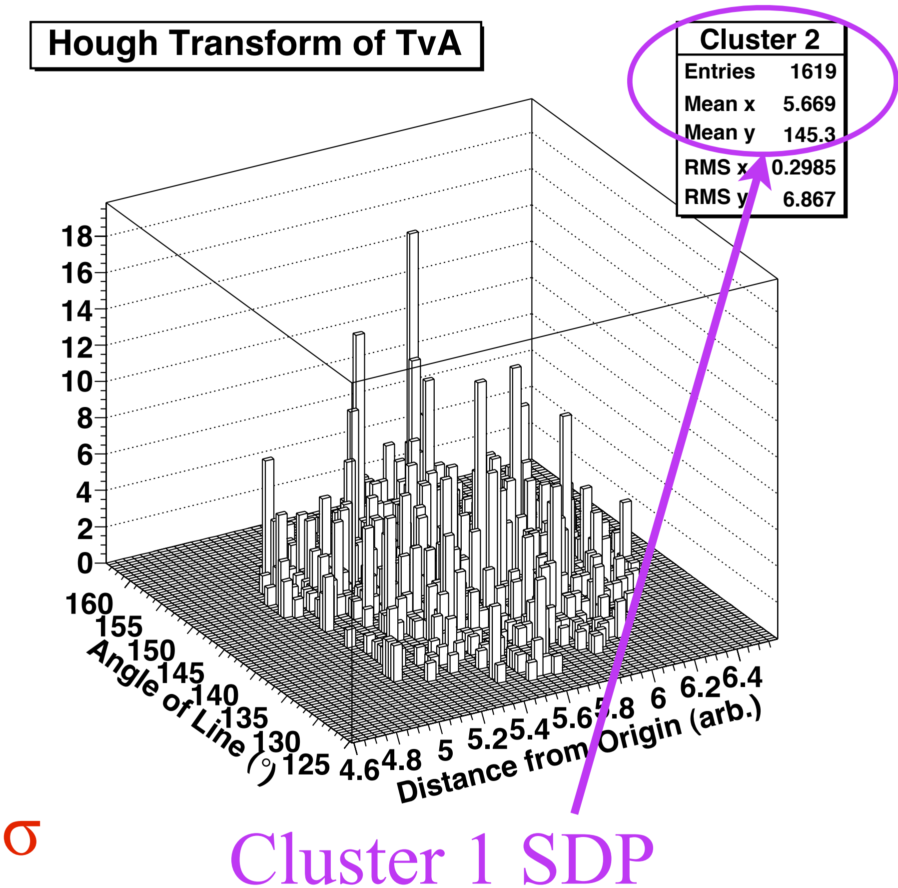
Resolved these by using the shower-detector plane of the first (blue) cluster to determine the angle of the second cluster



Distinguishing Similar Tracks

Same process to find angle and distance means



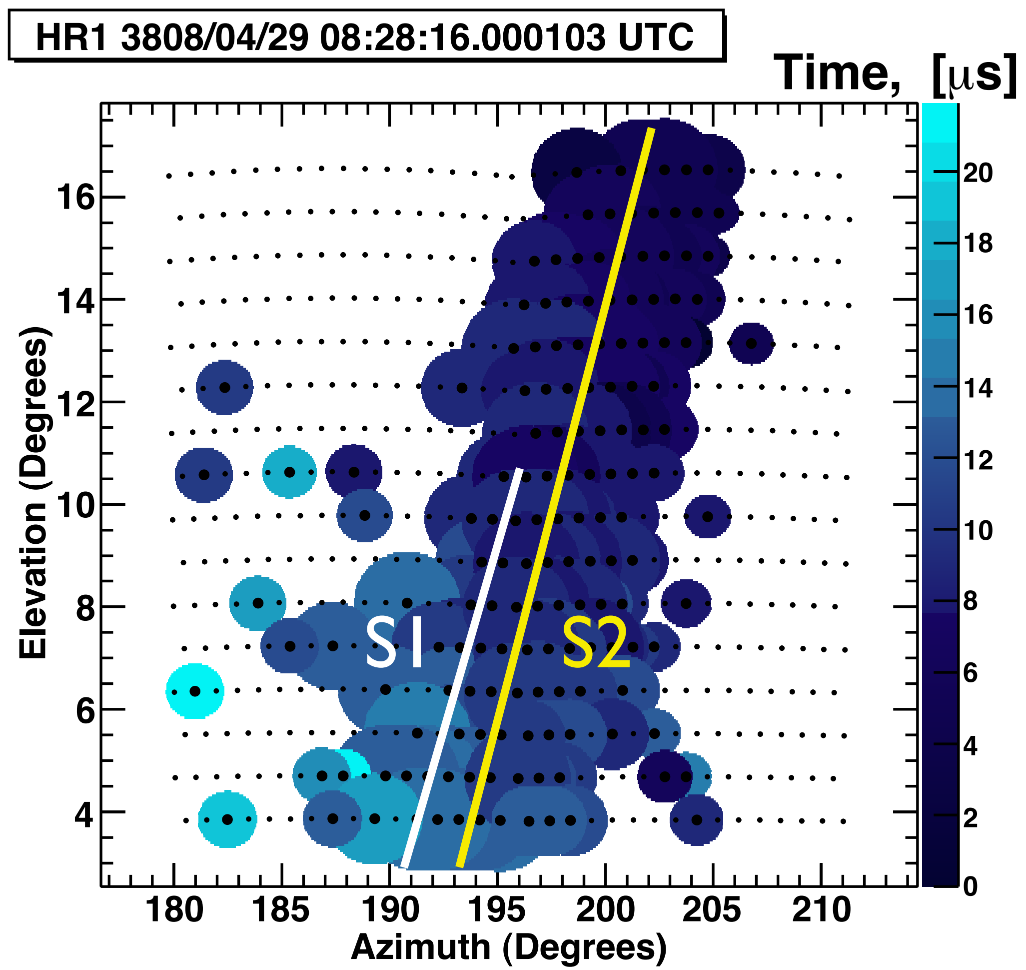


2.4σ

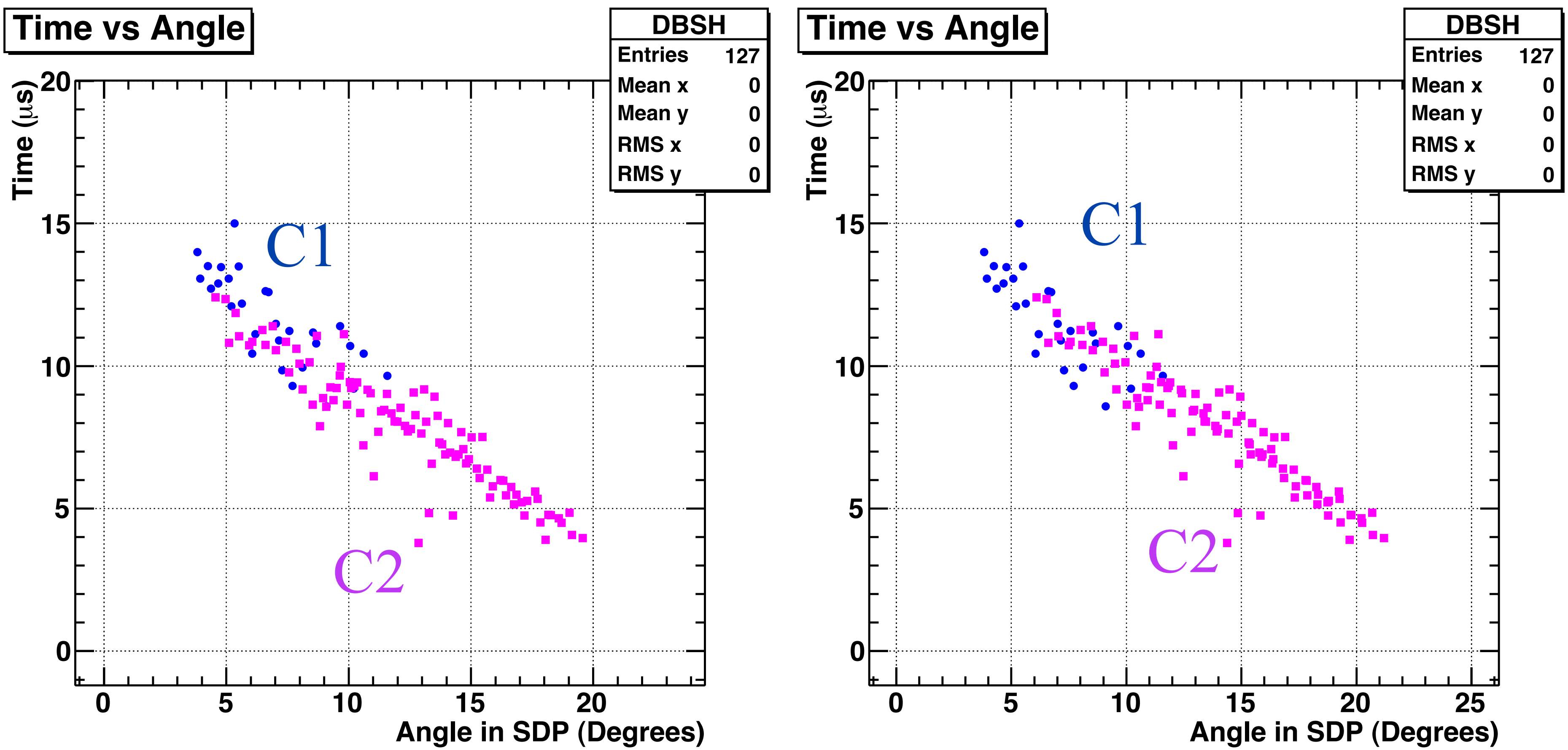
Overlapping Showers

Double-shower
Monte Carlo

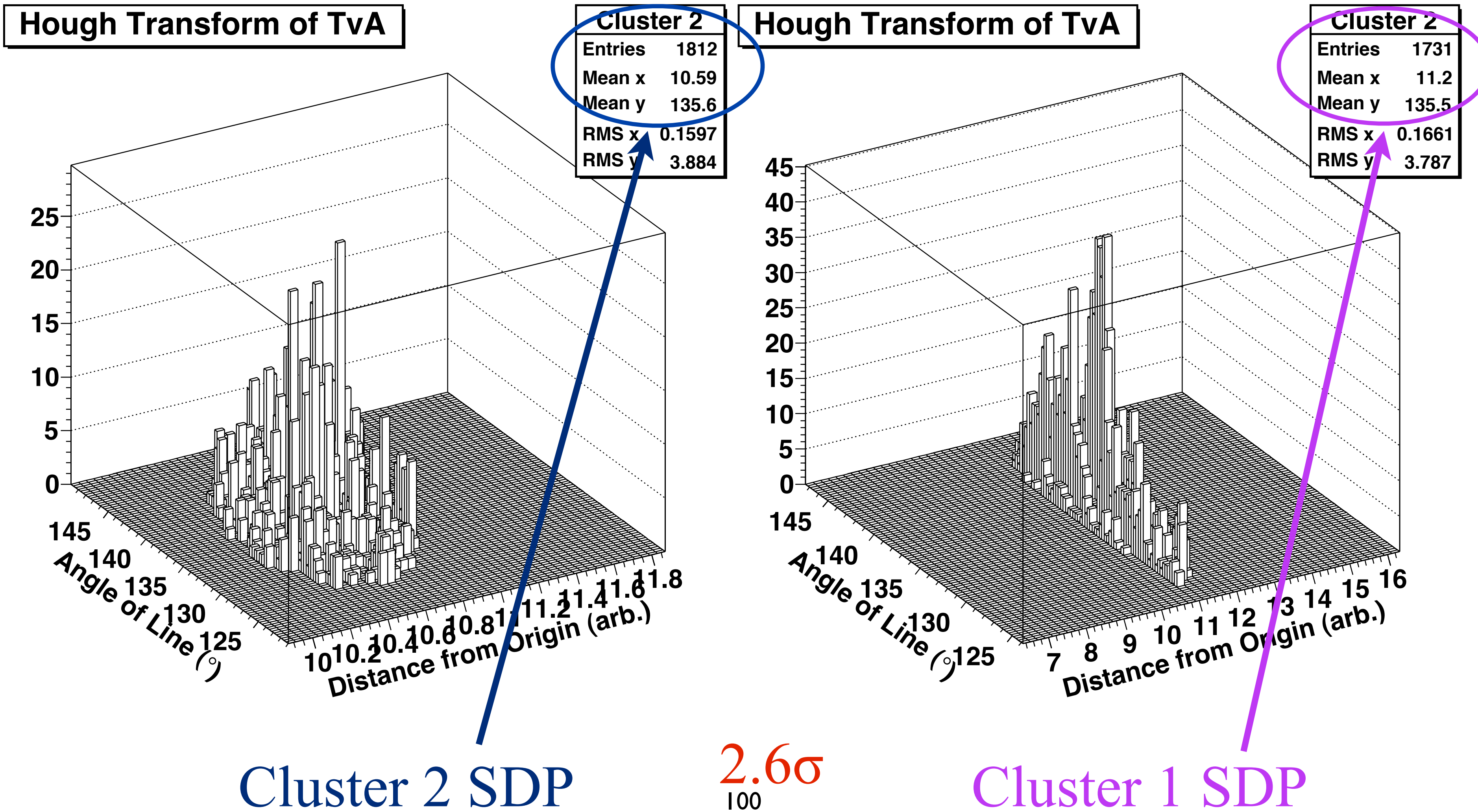
Can we distinguish these?



Overlapping Clusters



Overlapping Clusters



Cut Parameter

Shift in mean of cluster 2

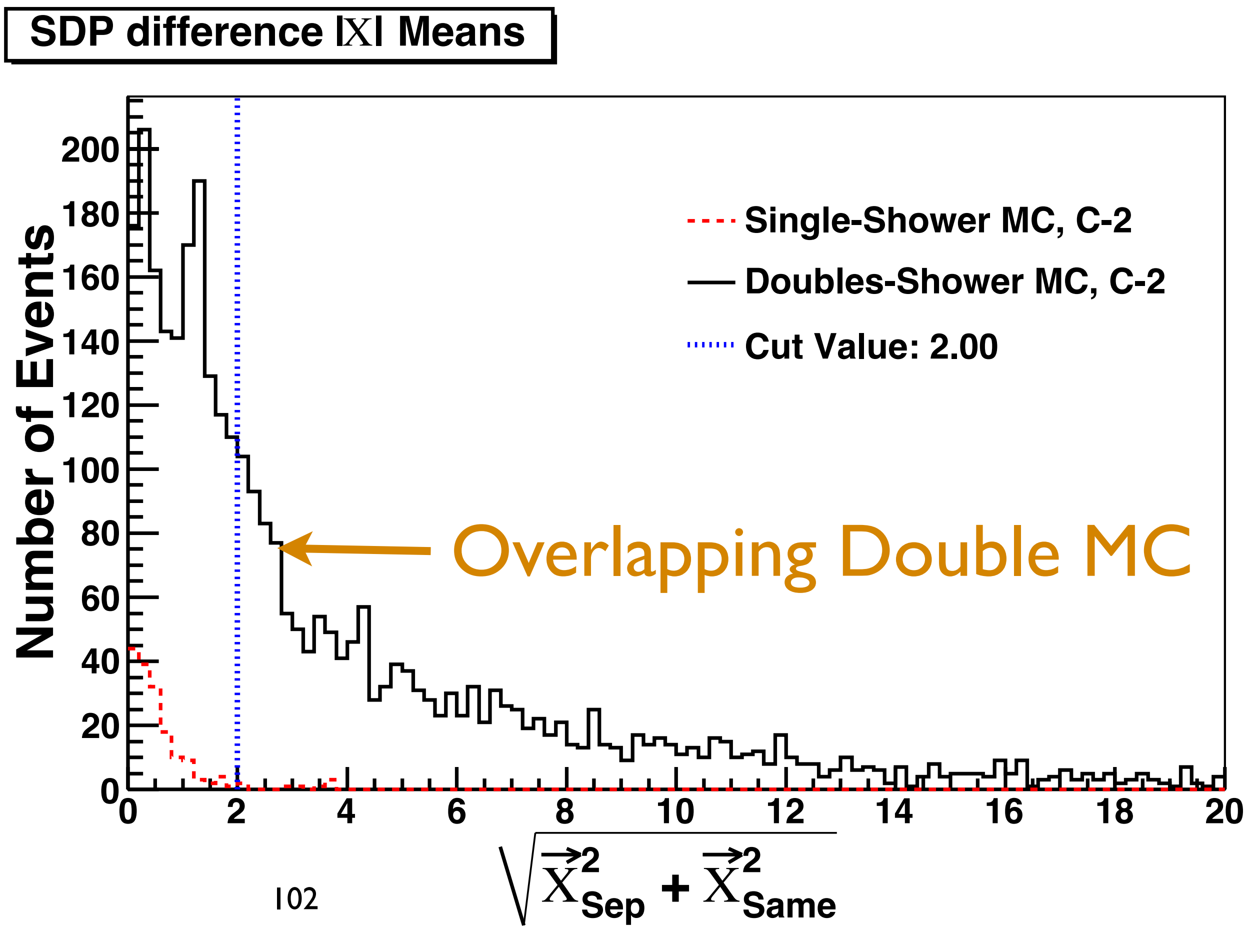
normalized to the RMS error

distinguishes double- and single-showers

Final Cuts

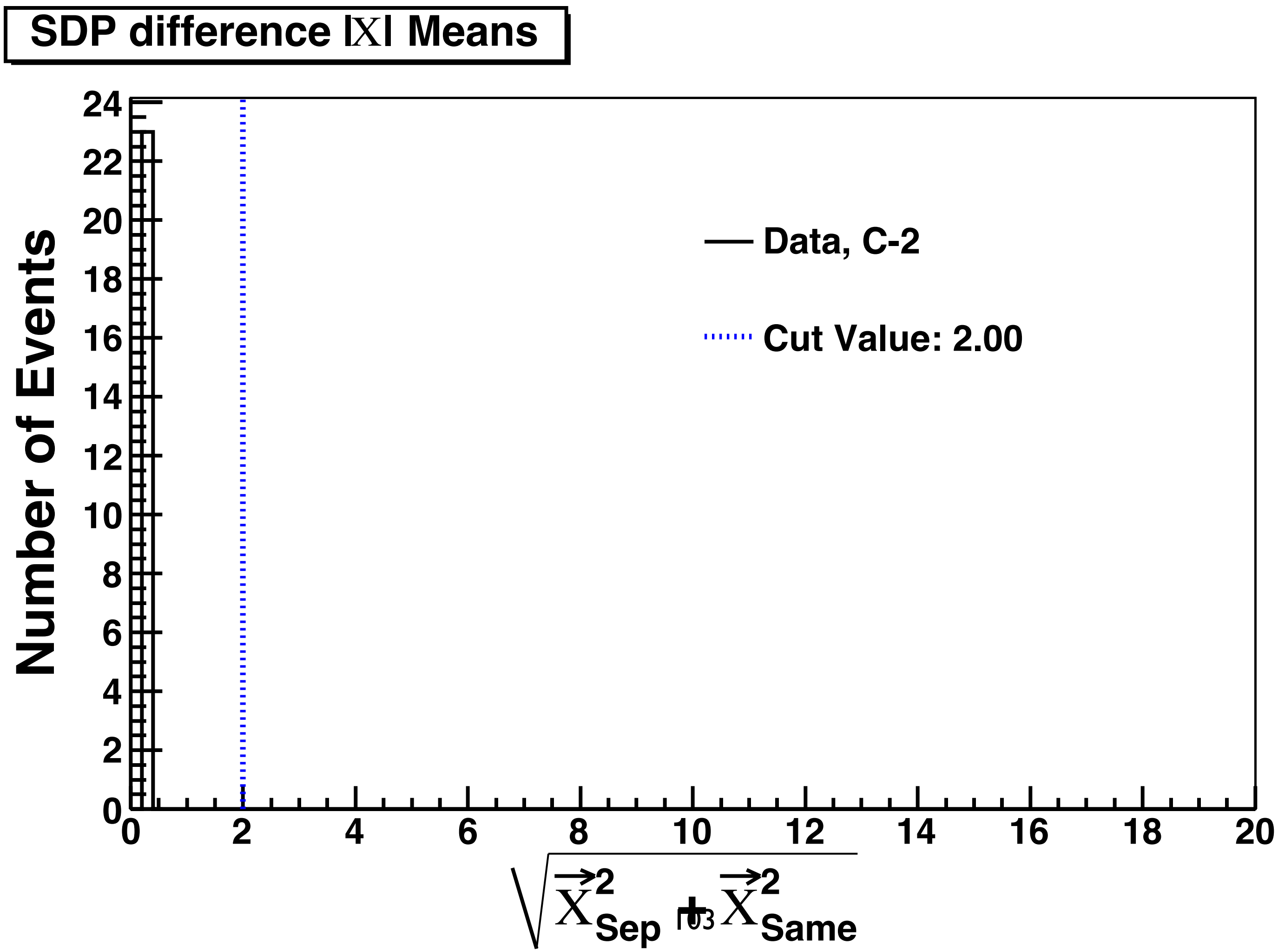
- Single-shower MC (5×data)
- Same processing/analysis

To determine double-shower tracks: compare shift in Hough Means of cluster-2



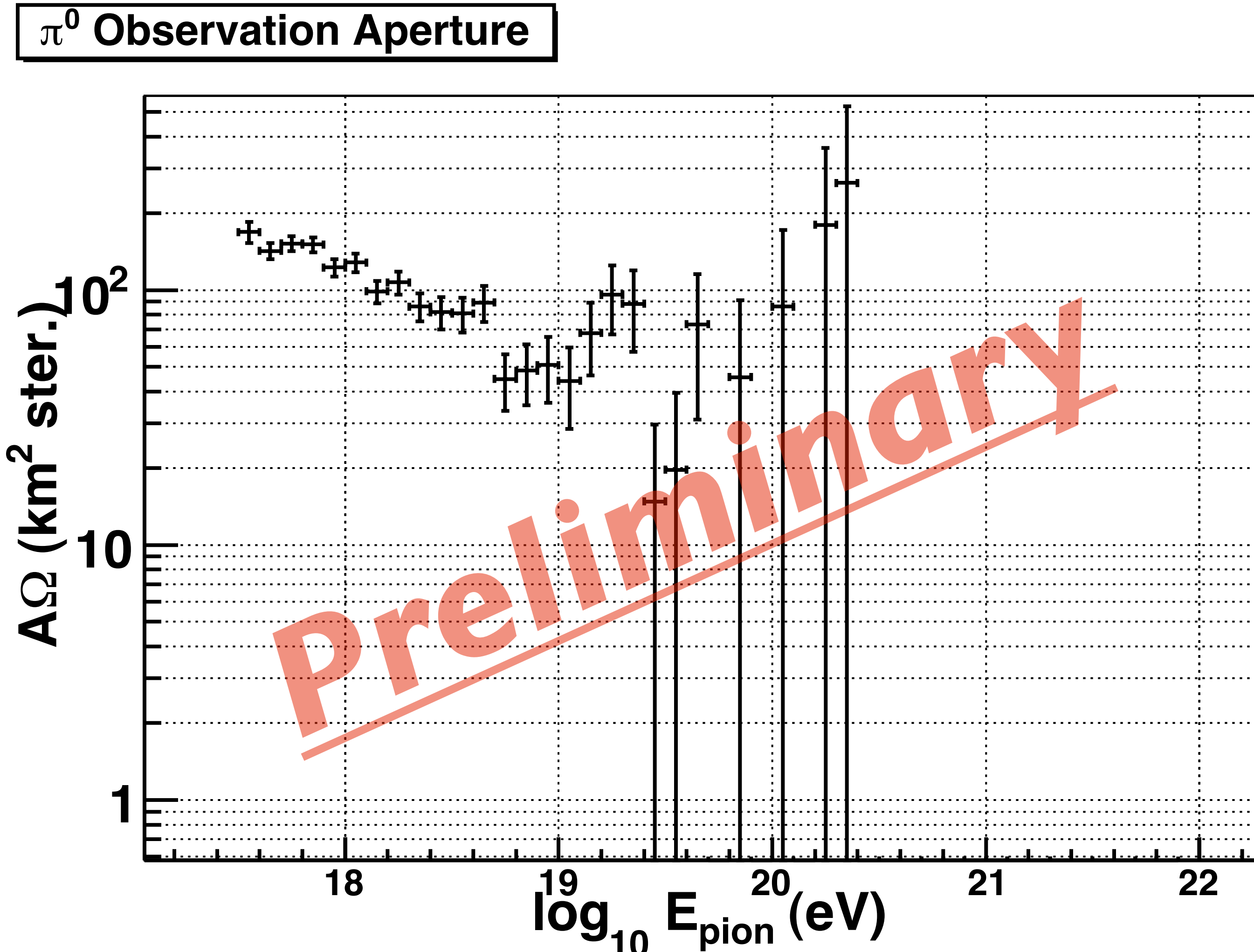
1590 (57%) Double-shower MC events kept

Final Double-Showers in the Data



Double-Shower Aperture

Spherical volume in which HiRes-1 can observe double-showers from pion decays



Summary

- Physics shows very unlikely scenario for cosmic-rays to interact heliosphere
- If they were to occur and both showers were able to reach Earth, HiRes-1 could have seen them
- We saw no double-shower candidates
- Further refinement will result in upper-limit publication