Measurement of the UHE Cosmic Ray Flux by the HiRes Experiment.

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Outline

- Physics of UHE cosmic rays.
- The High Resolution Fly’s Eye Experiment (HiRes).
- Data collection.
- Calibration issues.
- Data analysis.
- Monte Carlo development.
- HiRes monocular spectra.
- Conclusions.

HiRes Collaboration

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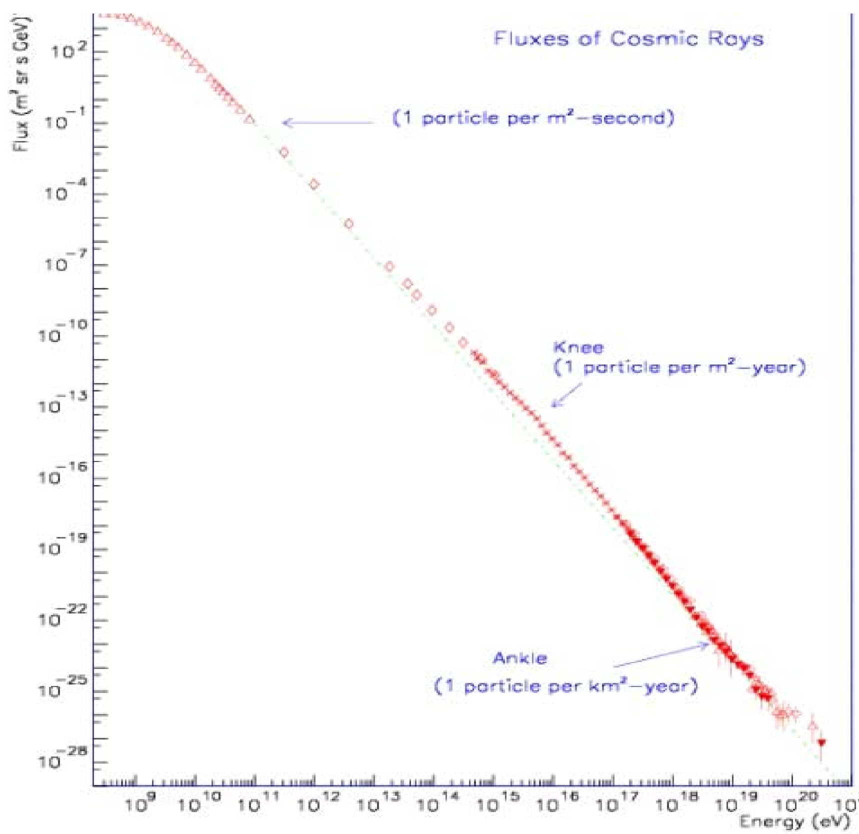
Physics of UHE Cosmic Rays: 1. Energy Spectrum.

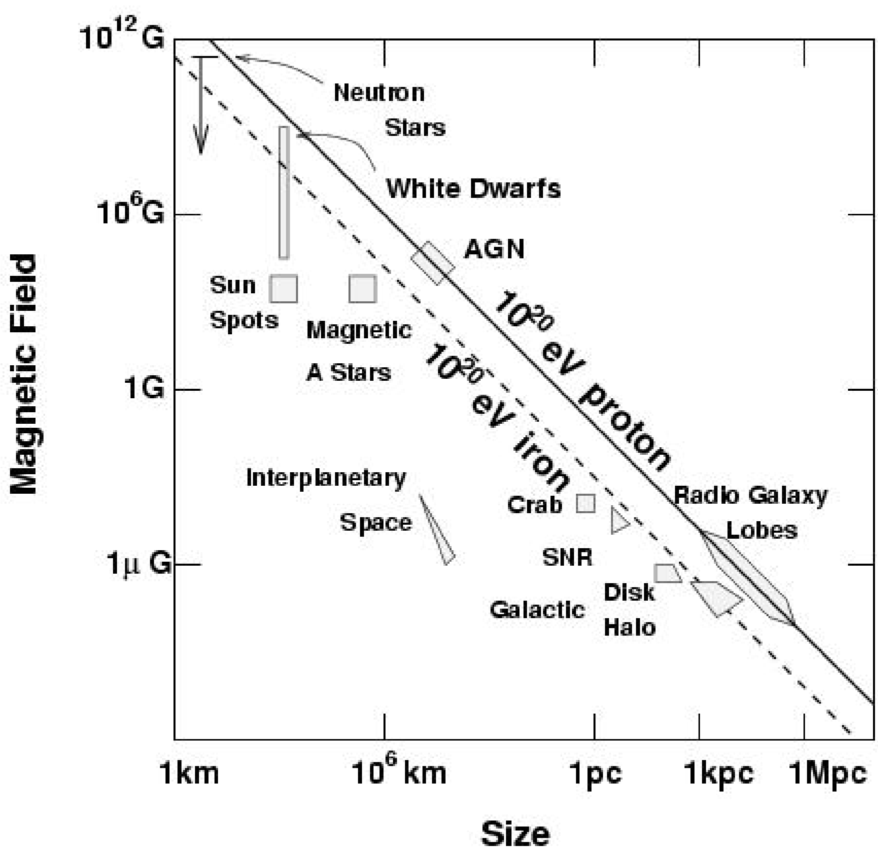
- Cosmic Rays from 10^8 eV to 10^{20} eV come from outside the solar system.



- At UHE energies the flux is low: above 10^{20} eV it is 1 event per $(\mathrm{km})^2$ per century.

Physics of UHE Cosmic Rays: 2. Acceleration.

- Acceleration in regions of expanding magnetic fields yields power law spectrum.
- AGNs can accelerate up to tens of EeV.



Physics of UHE Cosmic Rays: 3. The GZK Cutoff.

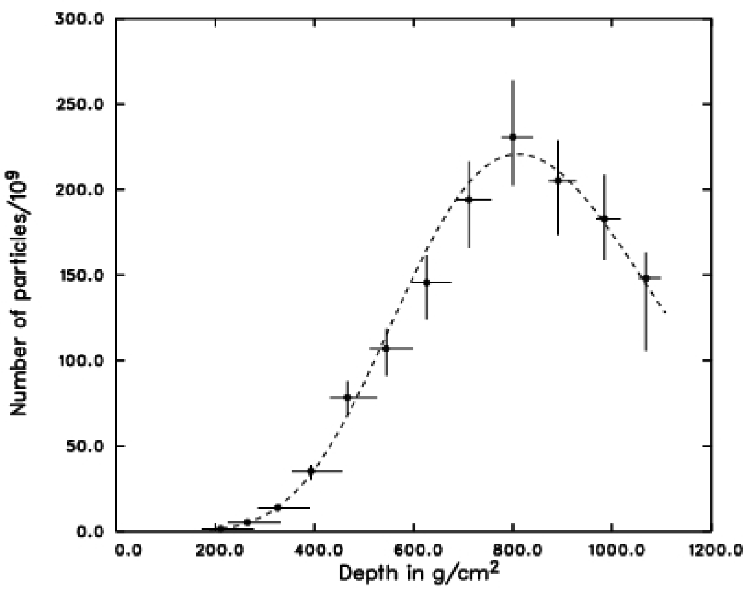
- CMBR photons interact with cosmic ray protons, 0.6 meV boosts to 100 MeV in proton CM system for $E=7\text{x}10^{19}$ eV. Excite nucleon resonances. Photopion production is a strong energy loss mechanism.
- GZK cutoff: $E < 6\text{x}10^{19}$ eV if cosmic rays travel > 50 Mpc.
- More stringent limit for nuclei, photons.
- Other energy-loss mechanisms:
  - $e^+ e^-$ pair production: threshold at $7\text{x}10^{17}$ eV
  - Expansion of the universe

Evading the GZK Cutoff: Sources must be Local.

- Bottom-Up Scenario:
  a new type of astrophysical object exists, capable of accelerating to 10^{20} eV; local hence no GZK cutoff.
- Top-Down Scenario:
  a relic particle (mass > 10^{20} eV) remains from the big bang, and the super-GZK events are its decay products.
- Discriminate by distribution on the sky:
  - Bottom-up: events point to new sources.
  - Top-down: events have the distribution of the galactic halo.

The Super-GZK Events.

- 1991: Fly's Eye experiment observed an event of 3.2 x 10^{20} eV.



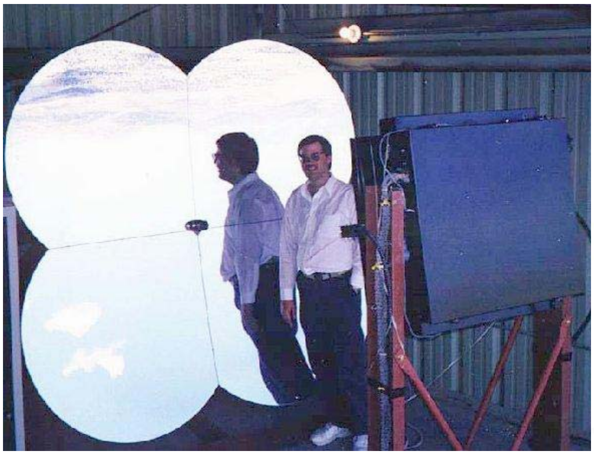
- Volcano Ranch, Haverah Park, Yakutsk saw one event each.
- Resolution problem?
- AGASA (much higher exposure) saw 8 events, but flux is higher than other experiments.
- Experiments inconsistent.
- HiRes has high exposure.

HiRes Method.

- Use atmospheric fluorescence: N_2 emits 5 UV photons /mip/meter; observe development of shower.
- Pulse height - photoelectrons - photons - shower geometry - particles in the shower - energy of primary.
- Make two measurements using two detectors observing in stereo.
- 10x improvement in geometrical resolution.
- Measure energy resolution.
- Study UHE cosmic rays with good resolution, good control of systematic uncertainties.

Mirrors and Phototubes

- 5.1 square meter mirror
- 16 x 16 array of phototubes.



The Two HiRes Detectors.

- U.S. Army Dugway Proving Ground.
- HiRes1: atop Five Mile Hill.
- 21 mirrors, 1 ring (3<altitude<17 degrees).
- Sample-and-hold electronics (pulse height and trigger time).

The HiRes2 Detector

- Atop Camel’s Back Ridge, 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings (3<altitude<31 degrees).
- FADC electronics (100 ns period).

Data Collection

- Run on nights if the moon is down for 3 hours or more:

  12% on time.
- Laser tracking of ADC, TDC channel calibrations.
- Weather observations: by eye and IR camera.
- Atmospheric observations: use laser shots from one site, observed by other detector.

Calibration Issues:

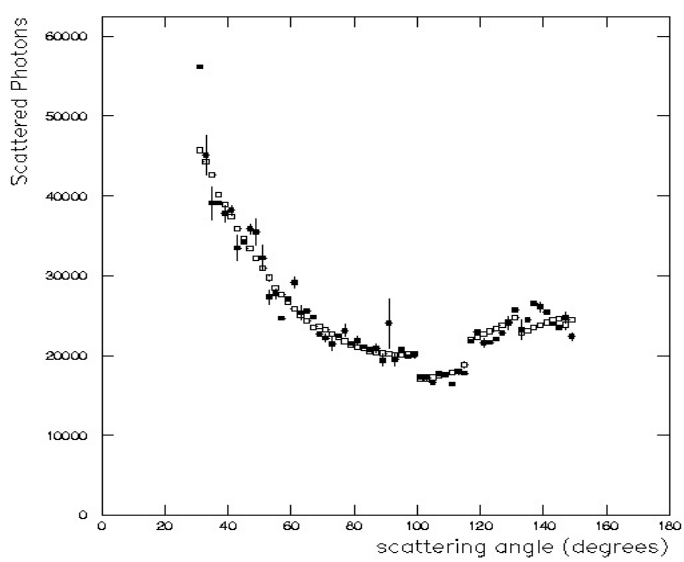
1. Absolute light calibration.

- Absolute light level is measured using a Xenon flash lamp carried to each phototube cluster: ~2% stability.
- Xenon lamp calibration by photoelectron statistics, HPD measurement (new), previous measurements: agree to ~5%.
- Ultimately we depend on NIST calibrations quoted at 10%.
- We estimate 10-15% overall calibration accuracy.

Calibration Issues:

2. Atmospheric monitoring

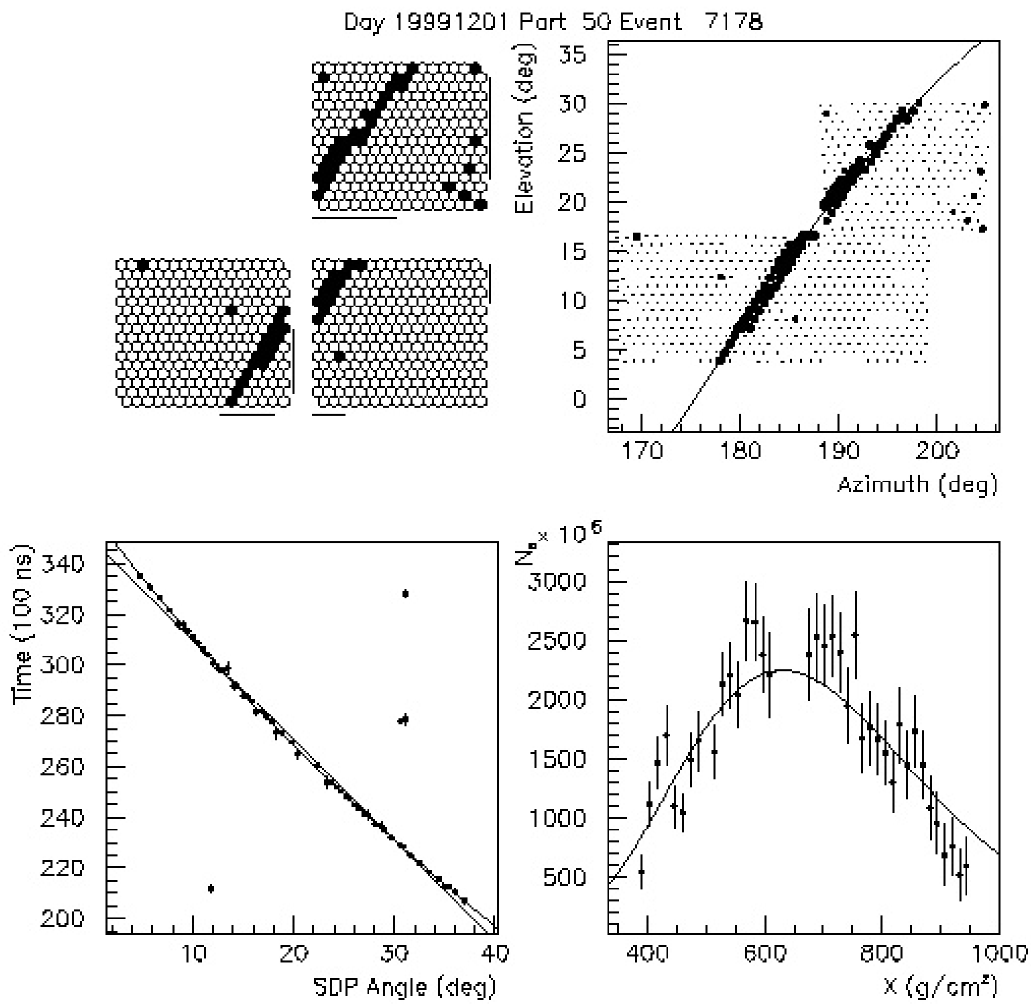
- HiRes2 steerable laser, observed by HiRes1 detector, and vice versa; pattern of shots every hour:
  - Horizontal shots determine extinction length and phase function of aerosols.



  - Vertical shots determine scale height of aerosols.
  - Inclined shots at various azimuthal angles test uniformity of atmosphere.
- Measure atmospheric absorption to 10-20% accuracy.

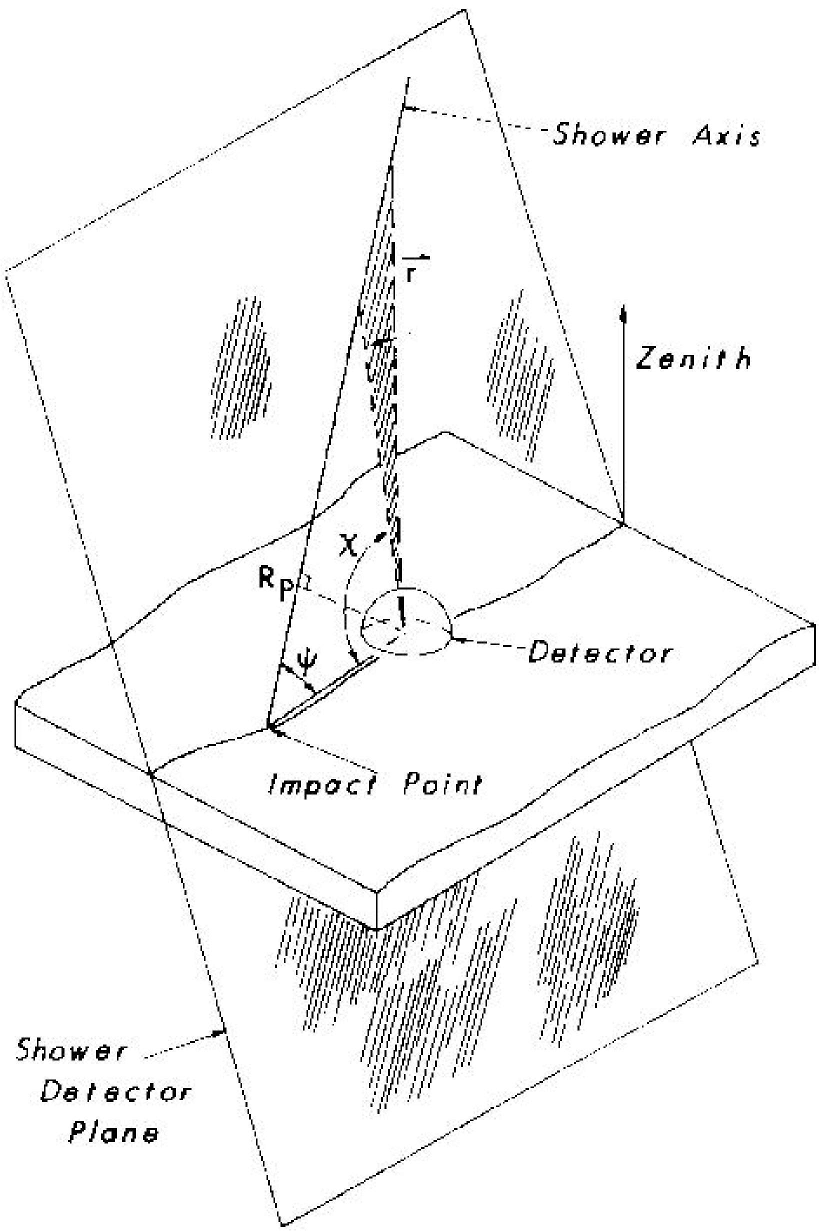
Data Analysis

- Pattern recognition.
- Time fit.
- Profile plot.
- Gaisser-Hillas fit.



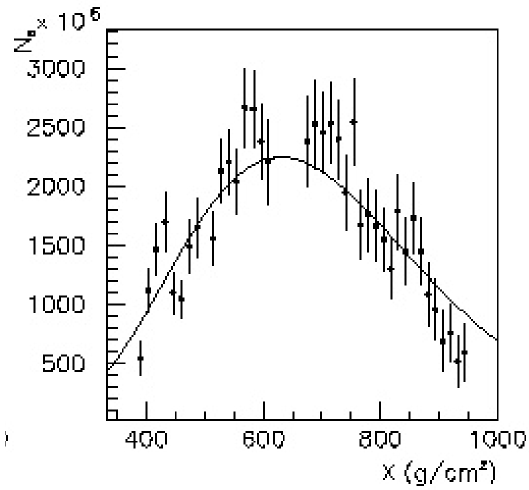
$$N(x) = \mathrm{Nmax}\left(\frac{x - x0}{xmax - x0}\right)^{\frac{x\max - x0}{\lambda}} \exp\left(\frac{x\max - x}{\lambda}\right)$$

Shower-Detector Plane Geometry



$$t_i = t_0 + \frac{R_p}{c}\tan\left(\frac{\pi - \psi - \chi_i(t_i)}{2}\right)$$

BOE Calculation



$$E = area \times \frac{dE}{dx}$$

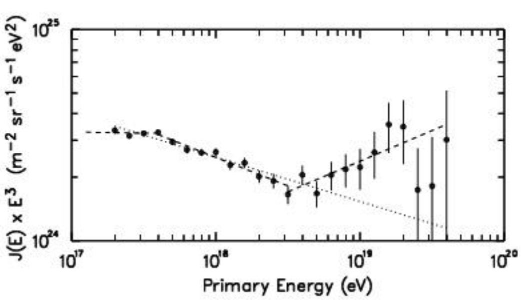
$$E = \frac{1}{2} N_{max} \times 1000 \; g / cm^2 \times 2 \frac{MeV}{g / cm^2}$$

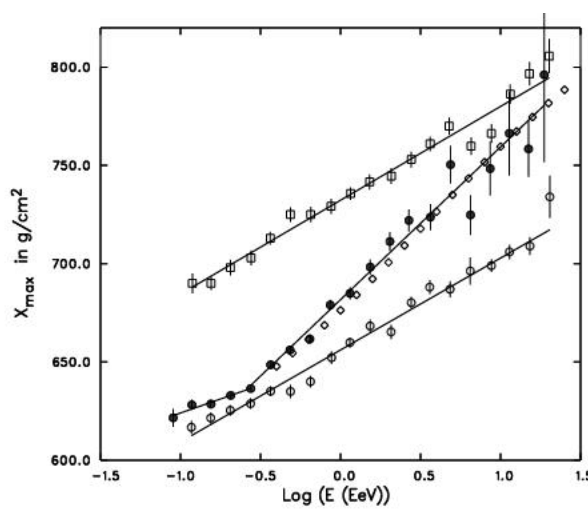
$$E = 1 \times 10^9 N_{max} \quad \text{(actually } 1.3 \times 10^9 \text{)}$$

- Energy determination is robust.
- Based on center of shower, not tails.
- Easy to Monte Carlo.

Monte Carlo Development (for HiRes2 Monocular Spectrum).

- Inputs:
  - Library of Corsika/QGSJet showers (protons, Fe). QGSJet is tested at $2x10^{15}$ eV for protons, $1x10^{17}$ eV for Fe.
  - Fly's Eye spectrum, composition.

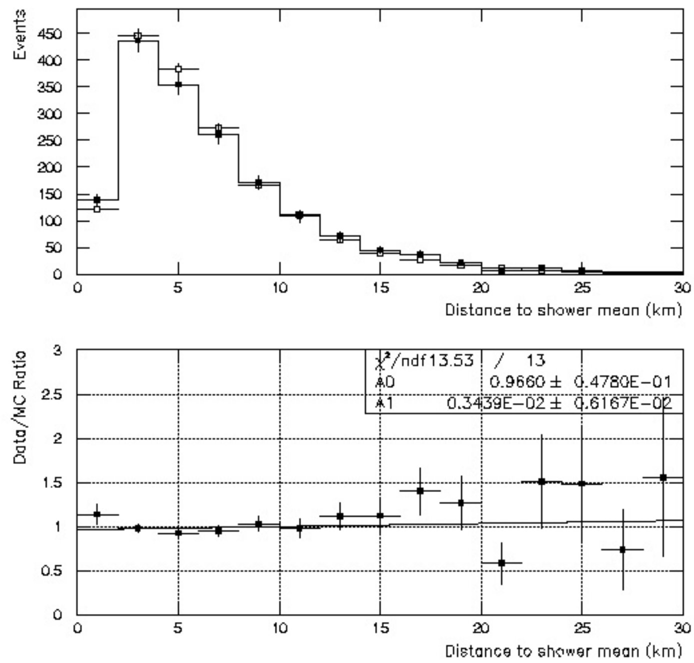




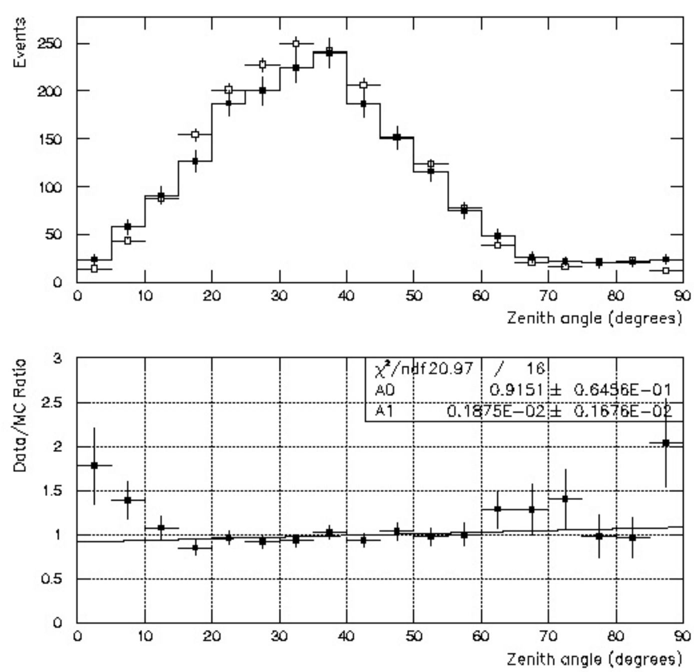
  - Atmospheric effects.
  - Electronics, trigger, and DAQ.
- Day-by-day adjustment of:
  - Live time, working mirrors, trigger gains and threshholds.
- Output in same format as data; analyze using same programs.

Comparisons between Data and Monte Carlo Events

- Distance to mean of shower.

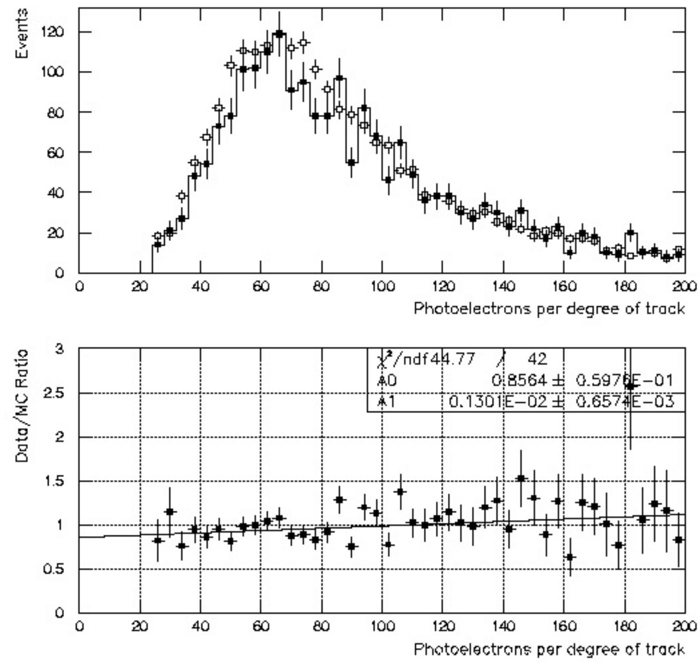


- Zenith angle.

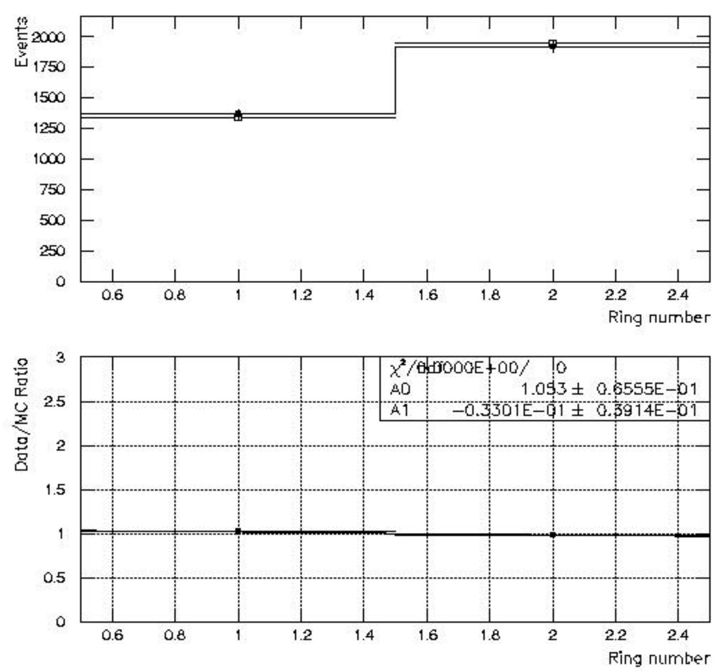


Data – MC Comparisons

- Photoelectrons per degree of track.

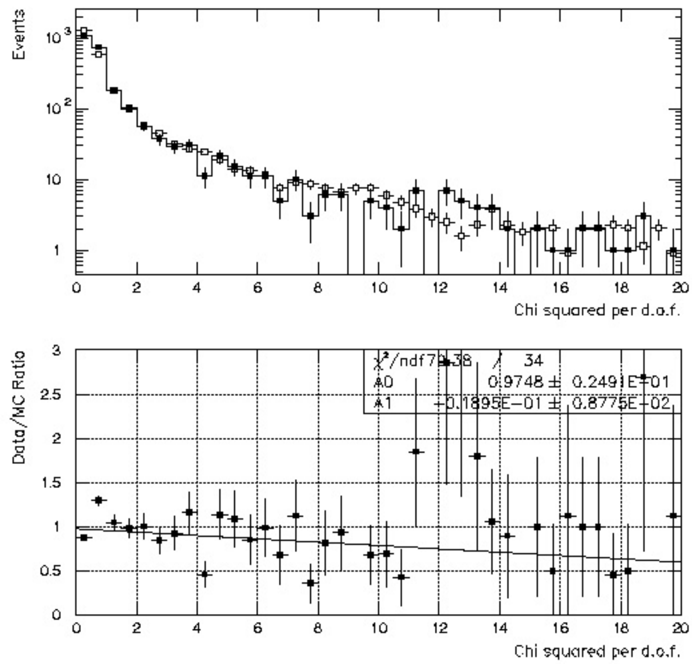


- Ring number.

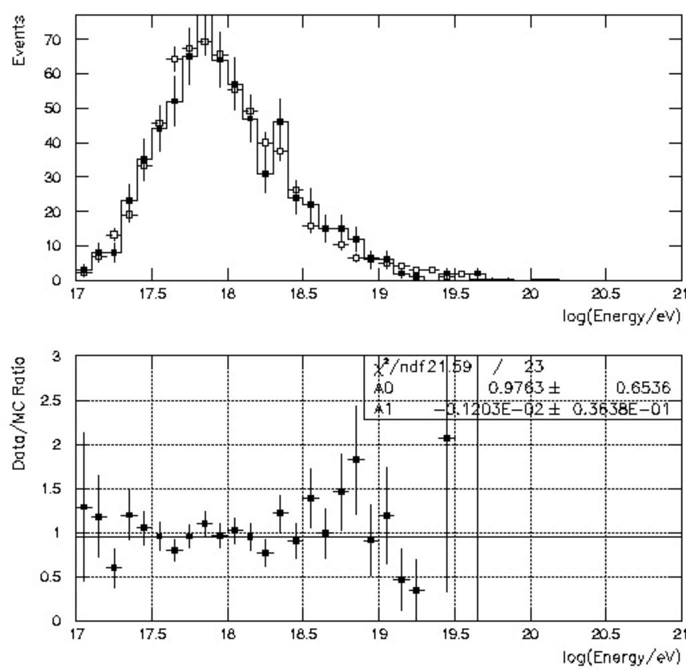


Data – MC Comparisons

- Chisquared of time fit.



- Energy.



HiRes2 Monocular Spectrum

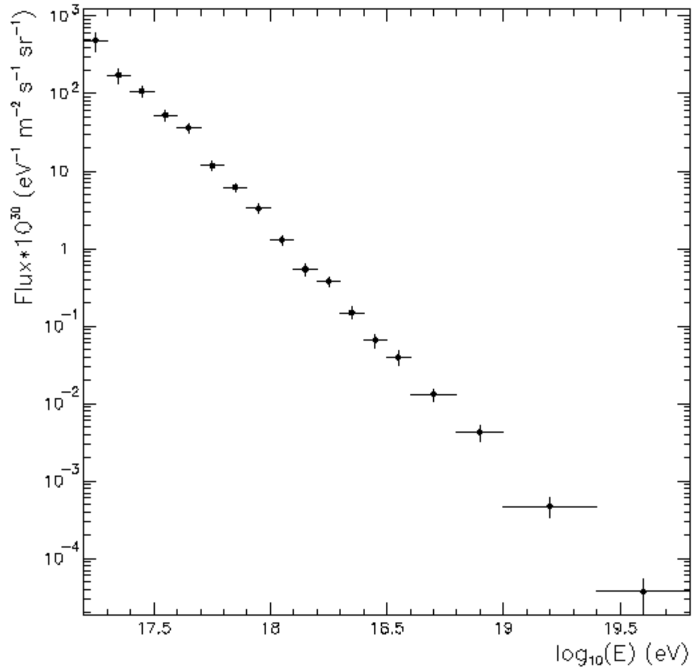
- Dec., 1999 – May, 2000 (first stable HiRes2 running).
- Consistent trigger (big change after May).
- Cuts:
  - Clear weather.
  - Downward going track.
  - Track length > 7 degrees
  - Linear fit chisquared/tube < 20
  - Pseudodistance > 1.5 km
  - .85 < tubes/degree < 3.
  - Photoelectrons/degree > 25
  - Zenith angle < 60 degrees
  - Shower max in view

Spectrum Results

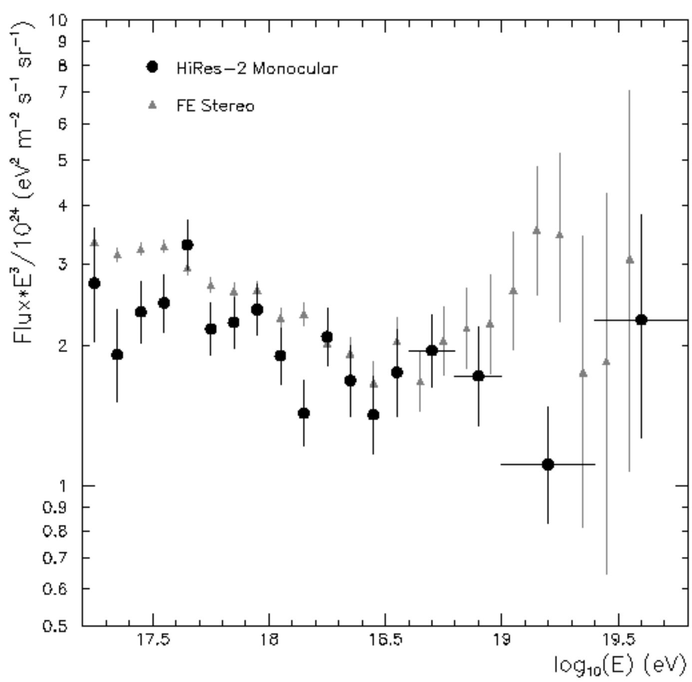
- J(E)

$$= \frac{N_D}{N_A} \times \frac{N_T}{A\Omega T\Delta E}$$

(correct for resolution)



- E^3 J(E)

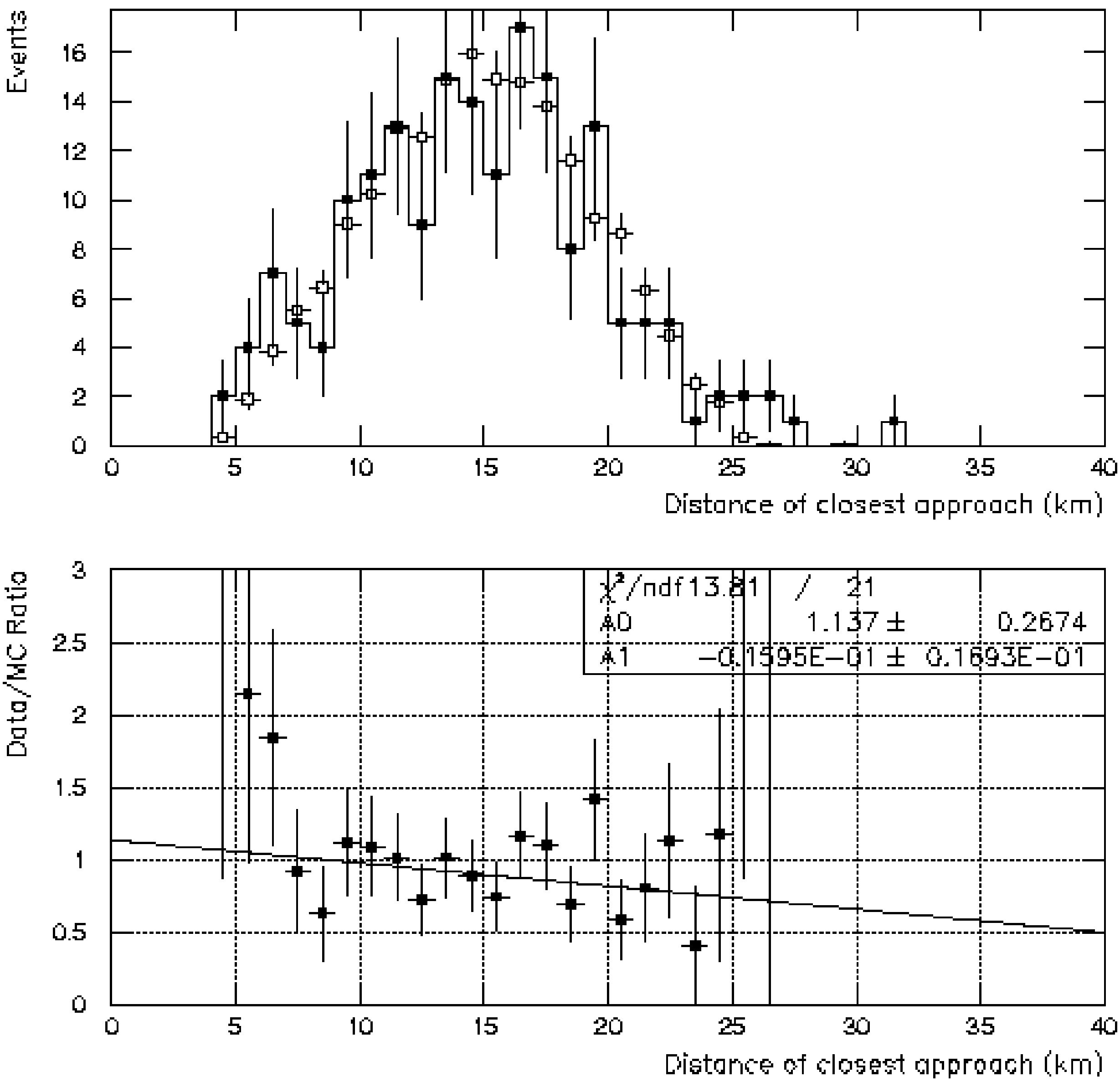


HiRes1 Monocular Spectrum

- Period: June, 1997 – May, 2001
- 50915 mirror hours.
- Cuts:
  - Clear weather.
  - Downward going track.
  - Track length > 7.9 degrees
  - Pseudodistance > 5 km
  - .85 < tubes/degree < 4.
  - Photoelectrons/degree > 25
  - Constrained fit converges.
  - Shower max in view
- Minimum energy is 3×10^{18} eV due to shorter tracks.

HiRes1 Data-MC Comparison

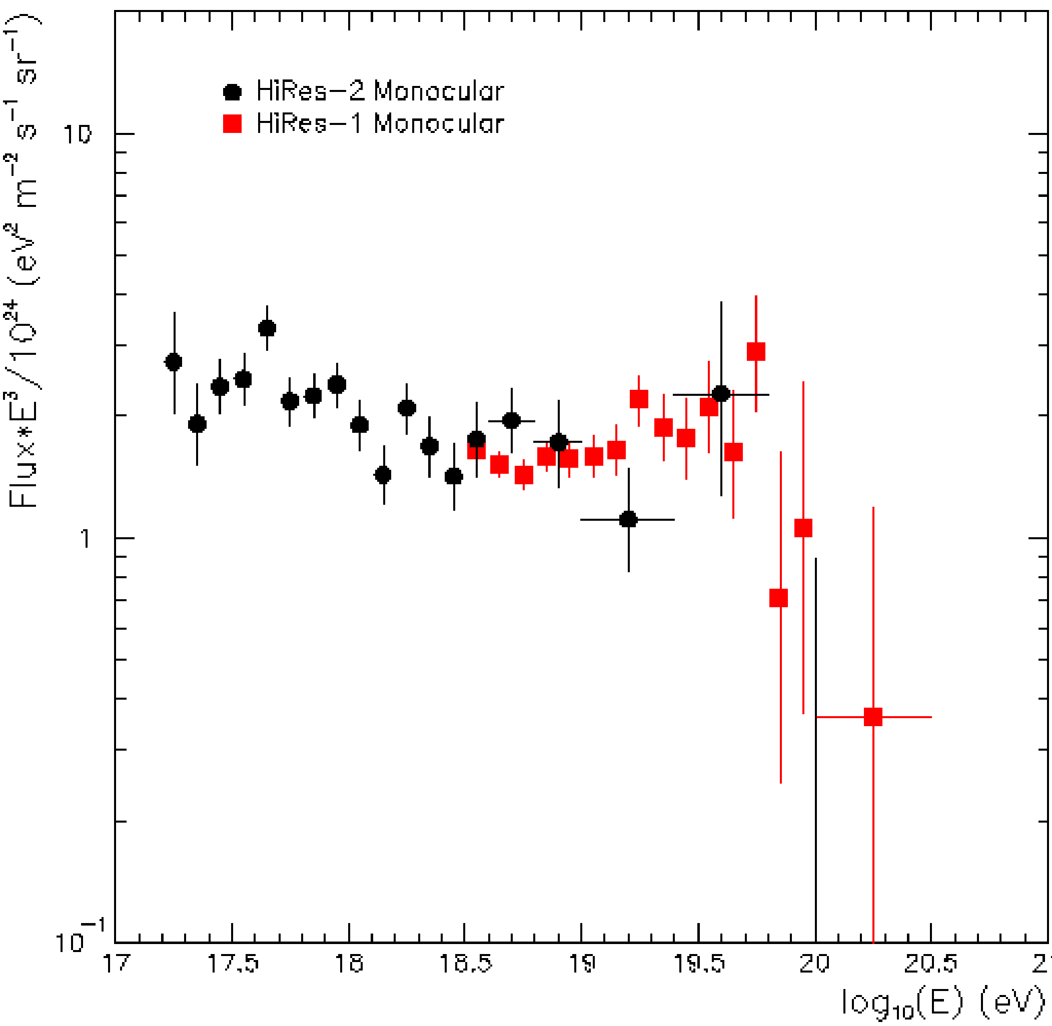
R_p, 18.4<log(E/eV)<18.6



Systematic Uncertainties

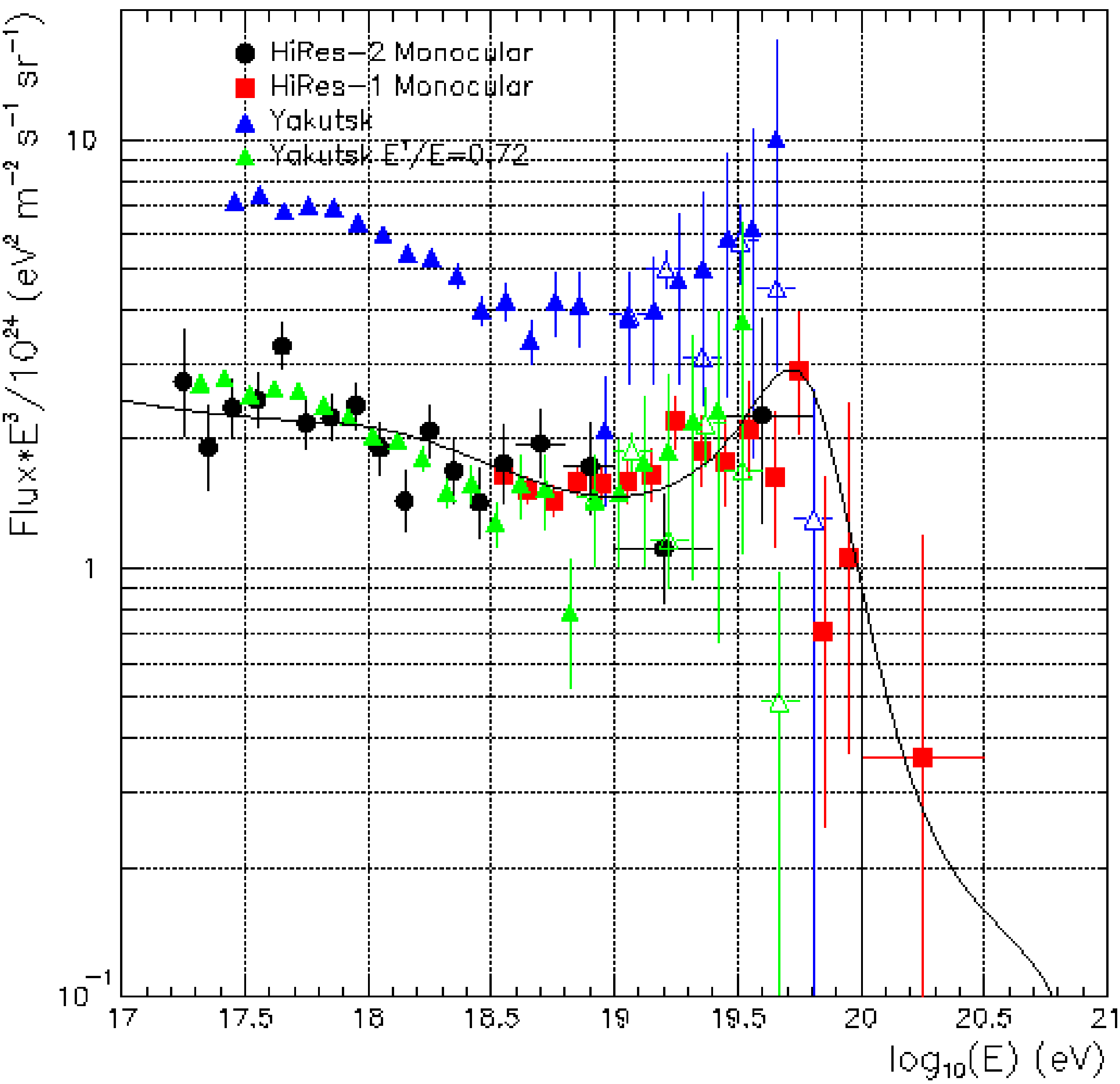
- PMT calibration: 10%
- Fluorescence yield: 10%
- Unobserved energy: 5%
- Atmospheric absorption:
  most sensitive to vertical aerosol optical depth (VAOD)
  - Mean VAOD = 0.04
  - VAOD RMS = 0.02
  - VAOD systematic is smaller.
  - Modify MC and analysis programs to use VAOD = 0.02 and 0.06, reanalyze.
  - J(E) changes by 15%
- Total systematic uncertainty = 21%

HiRes Mono Spectra

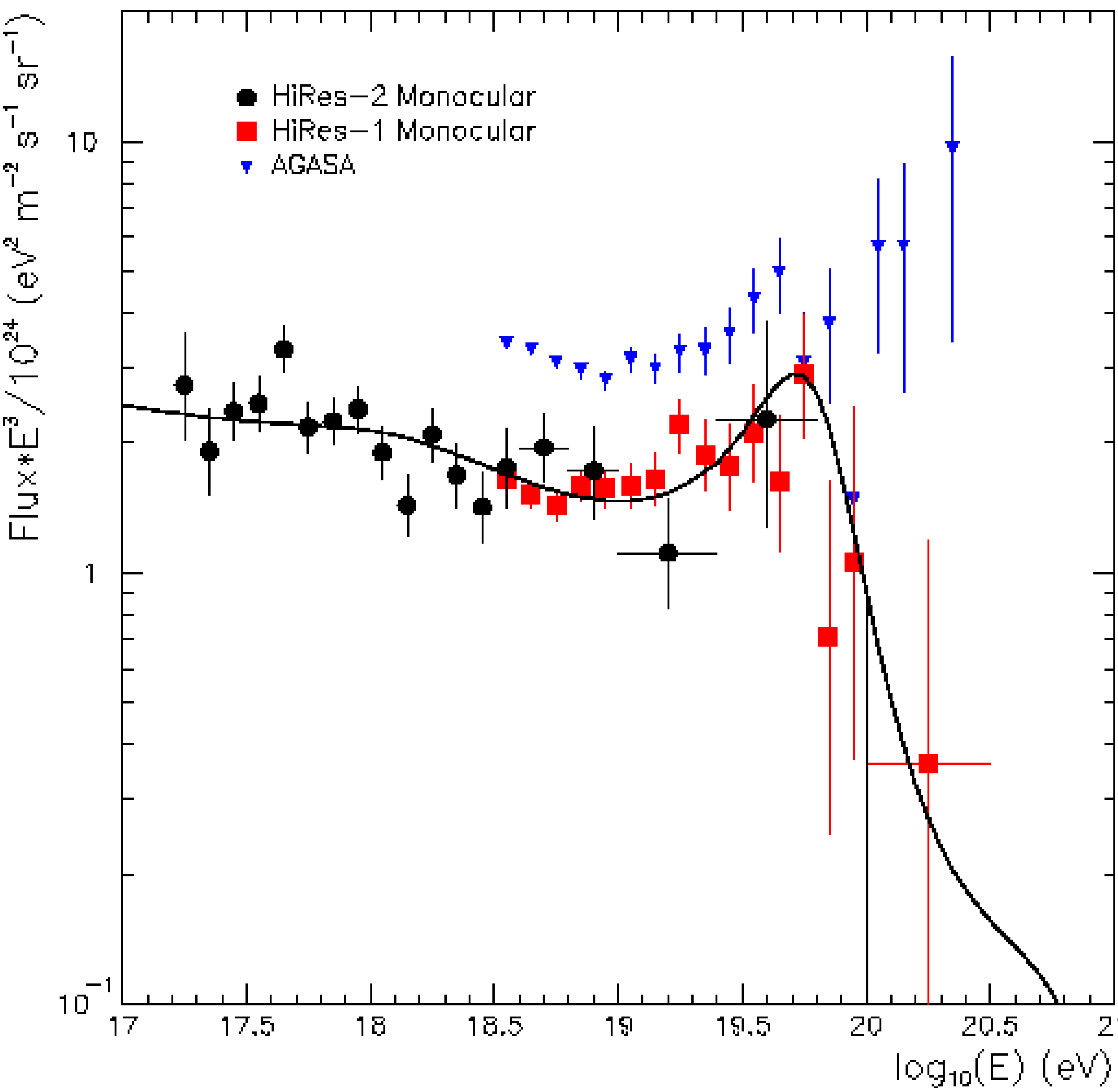


- $E^{-2.8}$ from 18.7 to 19.8; Predicts 19.1 events, logE>19.8; See 5. Probability = 1.4×10^{-4}

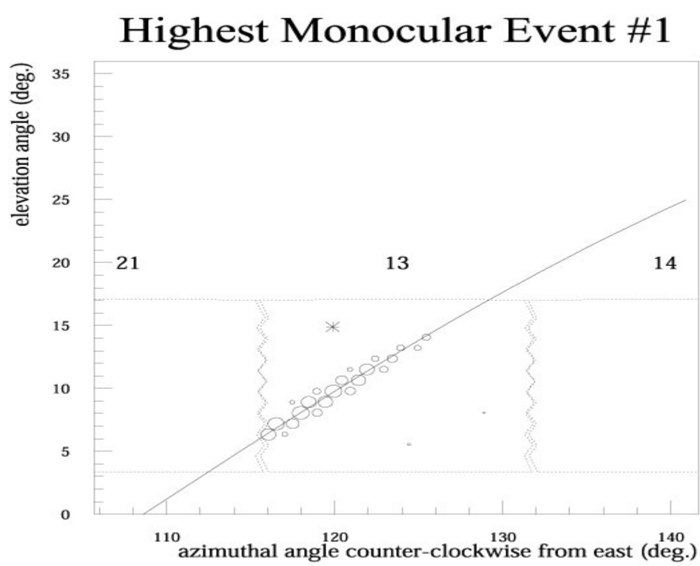
HiRes and Yakutsk

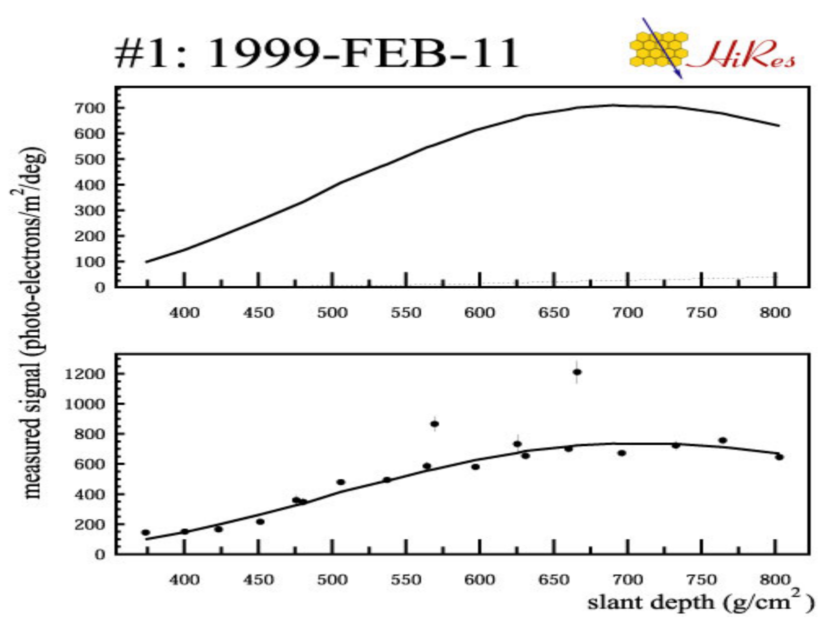


HiRes and AGASA; Fit to galactic+extragalactic model

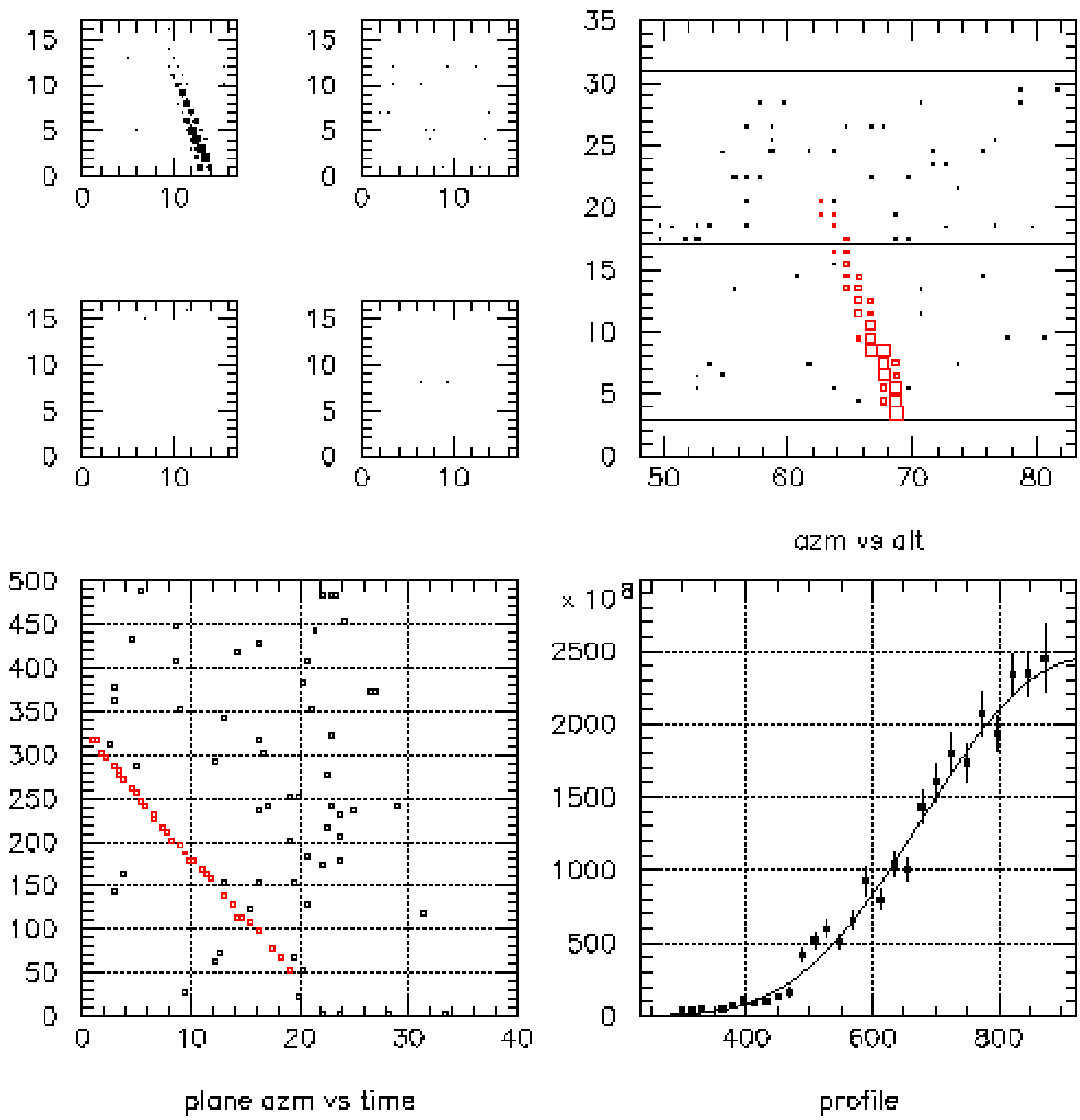


Highest Energy Event in HiRes1 Mono Spectrum





Highest Energy Stereo Event (as seen from HiRes2)



Conclusions

- The two HiRes detectors are collecting data smoothly.
- Calibration is under control.
- Measured flux agrees with Fly’s Eye experiment:
- The GZK pileup seems to exist.
- One model accounts for four spectral features of the data.
- We are seeing “interesting” events.
- Need more statistics:
  – Build a third detector!
  – Run for 5 years!