Pierre Auger Project Note: GAP-97-019

Notes on the Biggest Showers

John A.J. Matthews
New Mexico Center for Particle Physics
University of New Mexico
Albuquerque, NM 87131

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Abstract

Several cosmic rays showers have been reported with energies $\geq 10^{20}$ eV. These *notes* provide both background references and a commentary on the two largest showers.

This note reviews the following:

1. Detection of Extensive Air Showers
2. Fluorescence Technique and Uncertainties
3. Ground Array Technique and Uncertainties
4. Spectra from Akeno, Fly's Eye, Haverah Park and Yakutsk
5. Two events are well above 1×10^{20}eV

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1. Detection of Extensive Air Showers

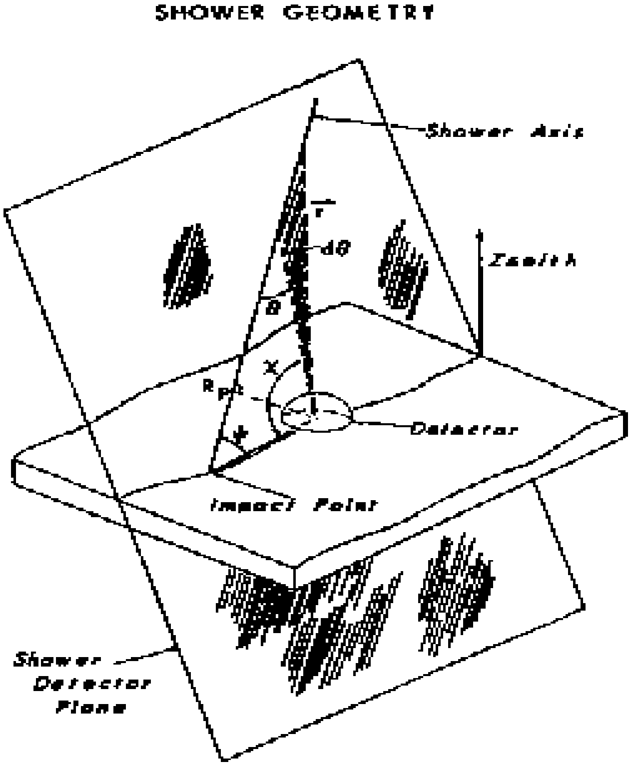


FIGURE 4.4 Reconstruction geometry. Once the shower detector plane is determined, the remaining variables to be determined are R_p and Ψ. The shaded area $d\Omega$ represents the field of view of a tube.

- Use *air fluorescence* to track and measure the shower = Fly's Eye:
    1. (+) measures shower longitudinal development and depth of shower maximum (X_{max})
    2. (+) laboratory calibration of fluorescence yield (per deposited energy)
    3. (−) atmosphere must be carefully monitored over a hugh area
- Fig. Ref.: R. M. Baltrusaitis, et al, NIM **A240**, 410 (1985)

1. Detection of Extensive Air Showers *(con't)*

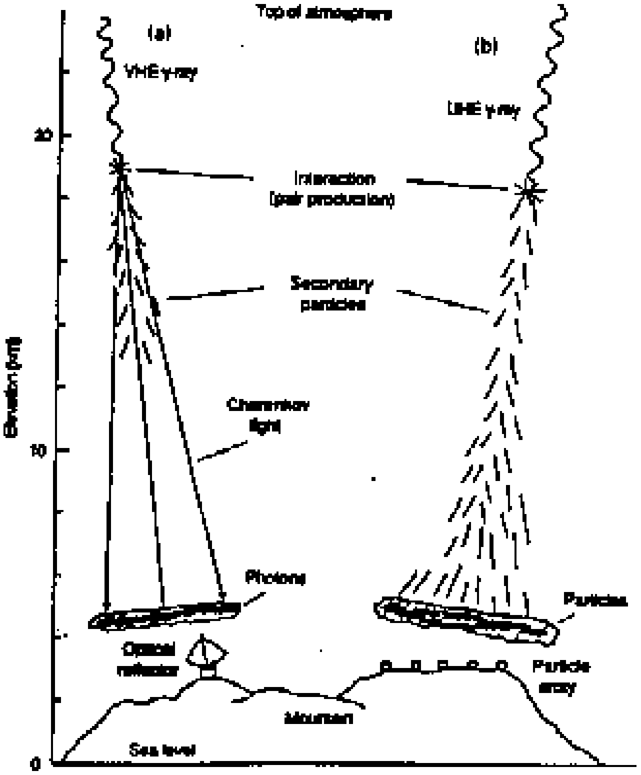


Figure 14.1: Schematic representation of air showers in two energy regions and the corresponding detectors: (*a*), $E \sim 1$ TeV, air Cherenkov telescope; (*b*) $E \sim 1$ PeV, air shower array. (From Lamb & Weekes 1987. © 1987 by AAAS.)

- Use *ground arrays* to determine shower direction and characterize shower near shower maximum = Akeno, Haverah Park, Volcano Ranch and Yakutsk:
    1. (+) details of shower composition and lateral distribution are studied
    2. (+) 100% duty factor
    3. (−) absolute energy calibration depends on Monte Carlo simulation or cross calibration (*eg Yakutsk also measures air Cherenkov signal*)
- Fig. Ref.: T. K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge Univ. Press (1990)

2. Fluorescence Technique

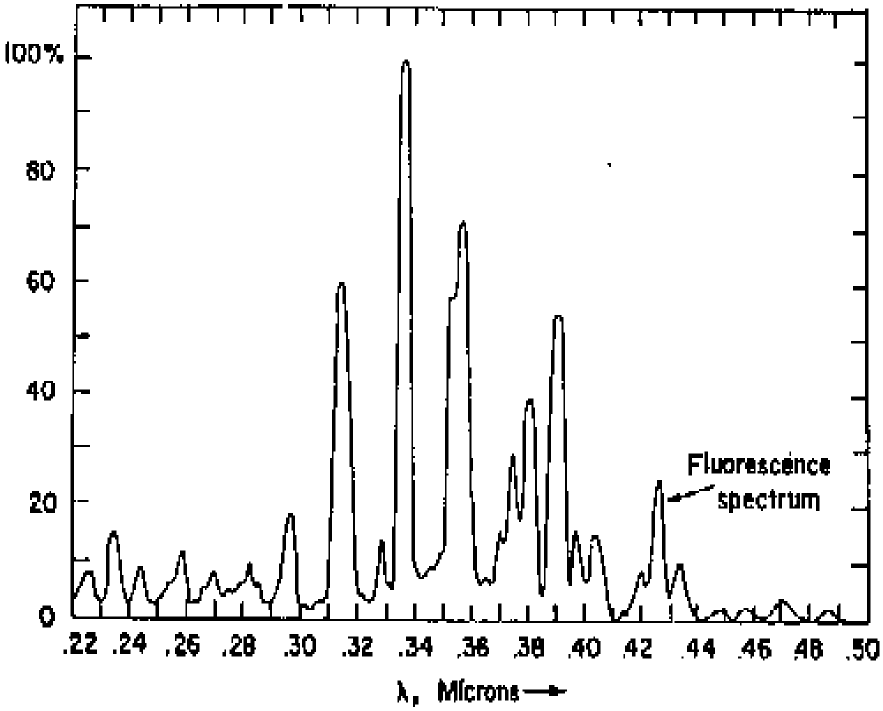


FIGURE 6.1 Spectrum of nitrogen fluorescence in the near ultraviolet.

(View 300~400nm in Fly's Eye)

- $\sim 0.5\%$ of collisional dE/dx in air appears in *air fluorescence*:
    1. 50 keV electrons – G. Davidson and R.O'Neil, J. Chem. Phys. **41**, 3946 (1964)
    2. 4 MeV α's – A.N. Bunner, Ph.D. Thesis, Cornell U. (1964)
    3. 1.4 to 1000 MeV electrons – F. Kakimoto, et al, N.I.M. **A372**, 527 (1996)
- Fig. Ref.: P. Sokolsky, *Introduction to Ultrahigh Energy Cosmic Ray Physics*, Addison-Wesley (1989)

2. Fluorescence Technique *(con't)*

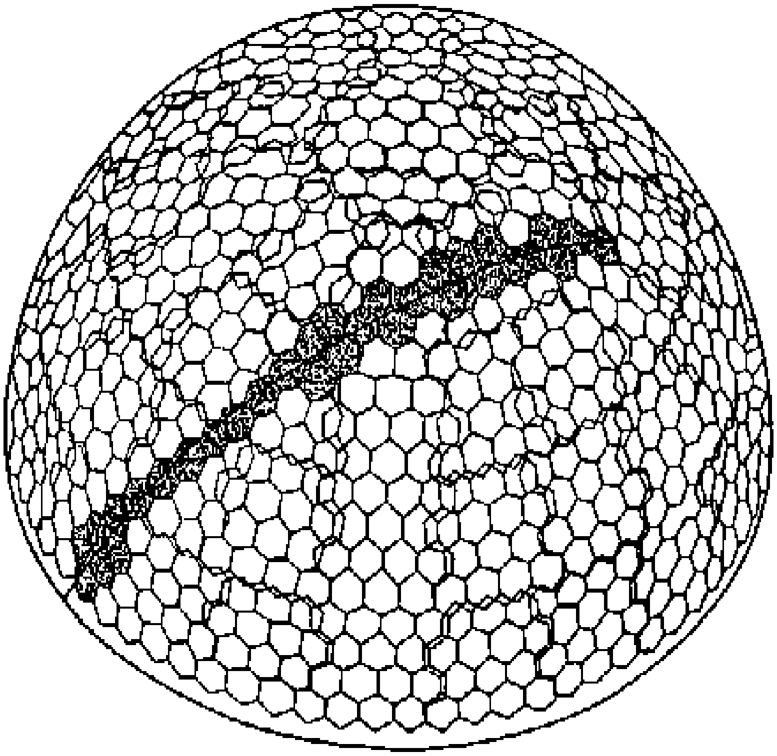


FIGURE 6.3 "Fly's Eye" phototube apertures. Shaded region represents light from EAS striking the detector. The solid line indicates the EAS trajectory across the sky.

- Air fluorescence signal is collected by an array of (fixed) mirrors that measure shower brightness, timing and direction:
  1. Fly's Eye – R.M. Baltrusaitis, et al, N.I.M. **A240**, 410 (1985)
  2. HiRes – D.J. Bird, et al, 24th I.C.R.C. **3**, p500, p504, and p548 (1995)
- Fig. Ref.: P. Sokolsky, *Introduction to Ultrahigh Energy Cosmic Ray Physics*, Addison-Wesley (1989)

2. Fluorescence Uncertainties

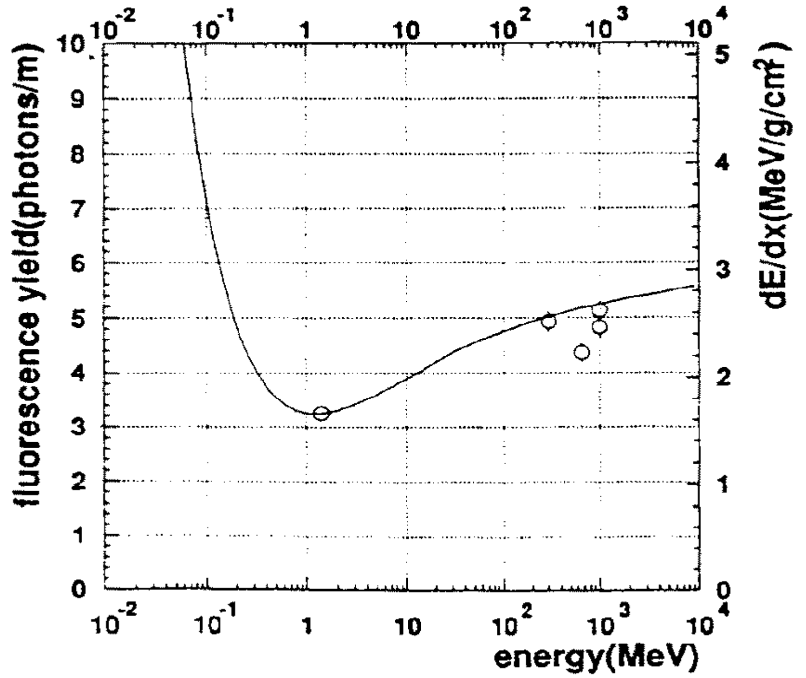


Fig. 7. Energy dependence of nitrogen fluorescence between 300 and 400 nm in dry air at a pressure of 760 mm Hg. The dE/dx curve is shown as a solid line. The scale of the fluorescence yield is adjusted so that the 1.4 MeV point lies on the dE/dx curve.

- *air fluorescence* yield:
  1. Fly's Eye quoted ±20% systematic uncertainty in fluorescence yield
  2. Latest laboratory calibration [F. Kakimoto, et al, NIM **A372**, 527 (1996) – fig. above]:
     - includes a range of electron energies and air pressures
     - includes *Fly's Eye* broad band filter
     - statistical errors of 3% and systematic errors of 10%
  3. New fluorescence yield changes $E_{shower}^{Fly'sEye} < 2\%$
     – E.C. Loh and H.Y. Dai, Tokyo I.C.R.C. (1996)

2. Fluorescence Uncertainties *(con't)*

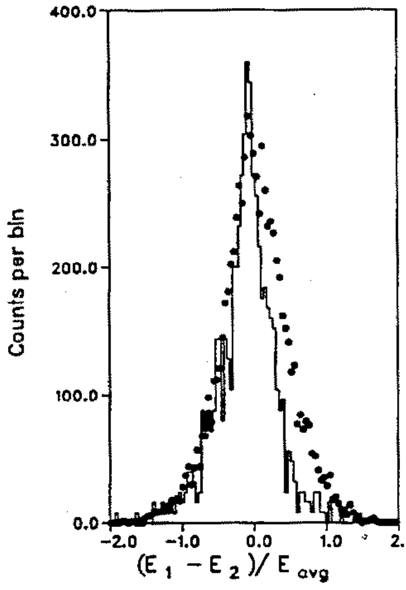


Figure 3: Relative fluctuations between energy reconstructed by FEI and FEII. Dots: events below 2×10^{18}eV. Solid line: events above 2×10^{18}eV (the counts are scaled by a factor of 8 for comparison).

- Fly's Eye I *versus* II measurements of resolution:
  1. **Monocular measurements of binocular events provide a measurement of many statistical and systematic errors**
  2. Above 2×10^{18}eV, Fly's Eye $\underline{\delta E/E = 27\%}$ (solid line in fig. above) – D.J. Bird, et al, Astrophys. J. **424**, 491 (1994)
  3. But ... misses some common systematics:
     - atmospheric corrections for *distant* lines of sight: F.E. I - II monitored errors for showers at modest separation ≤ 5 km *versus* shower distances ≤ 20 km
     - $\sim 10 \pm 10\%$ correction for unseen energy (ν's, μ's, n's, ...) – J. Linsley, 18th I.C.R.C. **12**, 135 (1983)

3. Ground Array Technique

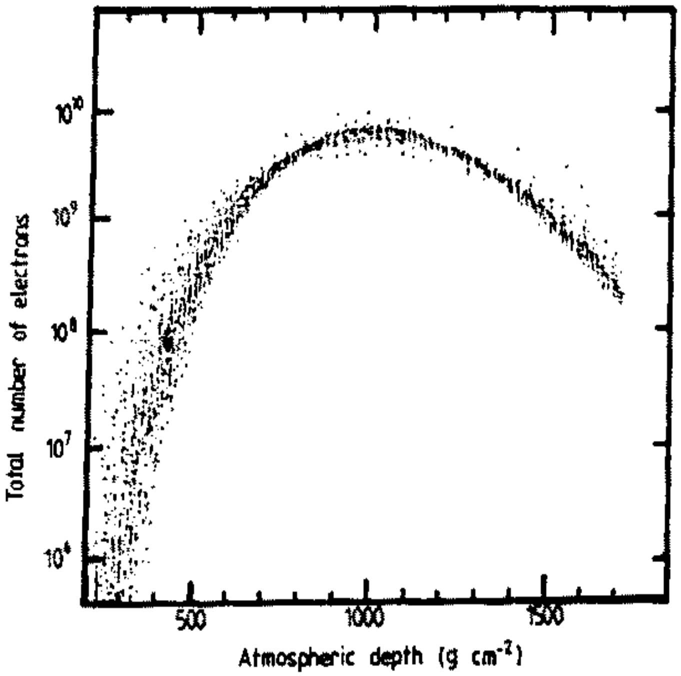


Figure 3. Longitudinal development curves for 10^{19} eV protons (the depth of the centre of gravity of the transition curve of each shower is adjusted to be the same).

- Characterize shower by measurement near shower maximum:
  1. Near shower maximum measurements are relatively insensitive to differences between shower X_{max} and measurement depth $X_{atmos} \cdot sec(\theta)$
  2. High energy showers result in large charged particle densities even at large distances; *E.g.* $\geq 1/\mathrm{m}^2$ at ~ 1.4 km from 1×10^{19} eV shower. Thus:
     - large arrays (and detector spacings)
     - large range in signal amplitudes and arrival times
- Fig. Ref.: H. Y. Dai, et al, J. Phys. G **14**, 793 (1988)

3. Ground Array Technique *(con't)*

- A variety of ground arrays:
  1. Akeno/AGASA, depth 920 gm/cm^2 – S. Yoshida, et al, Astropart. Phys. **3**, 105 (1995):
     - plastic scintillators, 2.2 m^2 area, 1 km spacing
     - reconstruct electron density $S(600) \equiv \#$ M.I.P./m^2 at 600m from shower core

     - (some) shielded proportional counters ($\mu_{th} \approx 0.5$ GeV)
     - reconstruct penetrating muon density $\rho_\mu(600) \equiv \#$ muons/m^2 at 600m from shower core

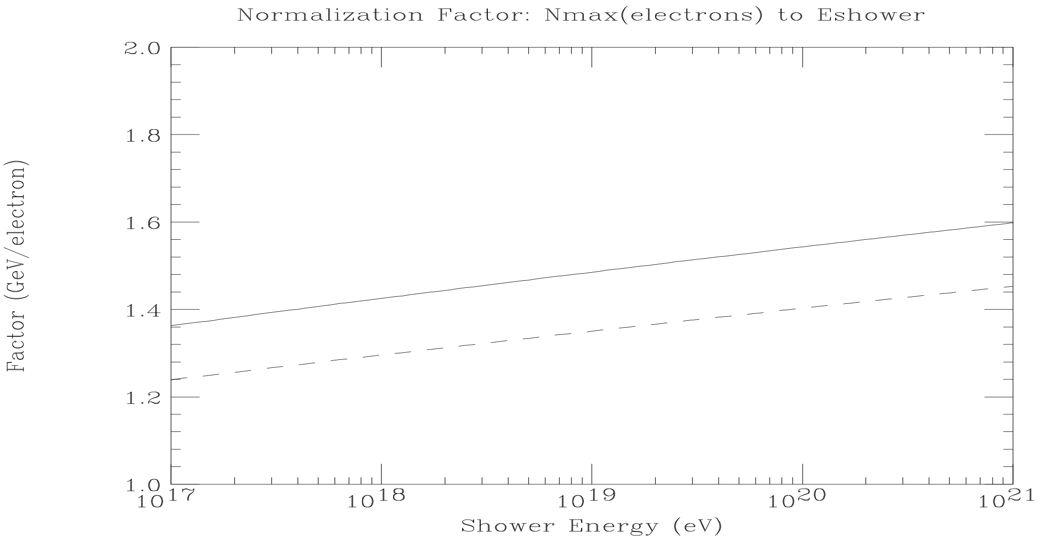
  2. Haverah Park, depth 1010 gm/cm^2 – M.A. Lawrence, et al, J. Phys. G, **17**, 733 (1991):
     - variety of water Cherenkov tanks, majority 2.3 m^2 area and 1.2 m deep, typically in local clusters, large scale spacing $\sim$ 1 km
     - reconstruct electromagnetic energy plus *weighted* muon density $\rho(600) \equiv \#$ Vertical Equivalent Muons /m^2 at 600m from shower core

3. Volcano Ranch, depth 820 $\mathrm{gm/cm^2}$ – J. Linsley, P.R.L. **10**, 146 (1963); 15th I.C.R.C. **12**, 89 (1977):
    - mostly plastic scintillators, 3.26 $\mathrm{m^2}$ area, various spacings to $\sim$ 800 m
    - reconstruct shower size, N, in M.I.P.s (electrons) at ground level

4. Yakutsk, depth $\sim$ 1000 $\mathrm{gm/cm^2}$ – G.B. Khristiansen, 19th I.C.R.C. **9**, 487 (1985):
    - plastic scintillators of 3.26 $\mathrm{m^2}$ area, spacing = 0.5 and 1 km; some muon detectors also
    - reconstruct electron density $S(600) \equiv \#$ M.I.P./$\mathrm{m^2}$ at 600m from shower core

    - air Cherenkov detectors; spacing 0.5 and 1 km; provide absolute energy calibration for primary scintillator $S(600)$ measurement

3. Ground Array Technique/Uncertainties



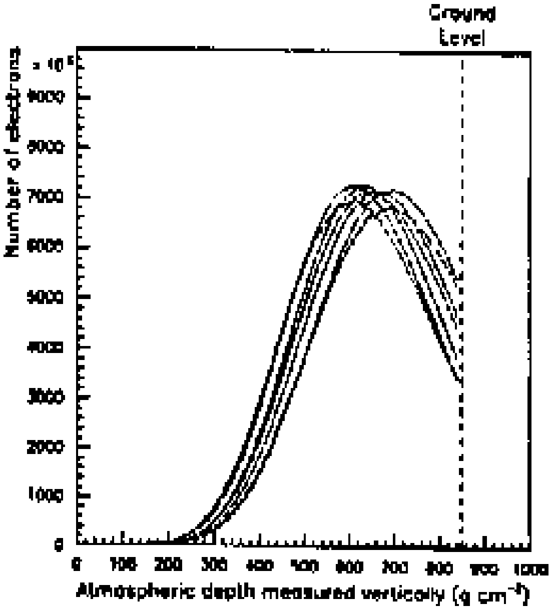
J. Linsley, 18th CRC, Vol 12, page 135 (1983)

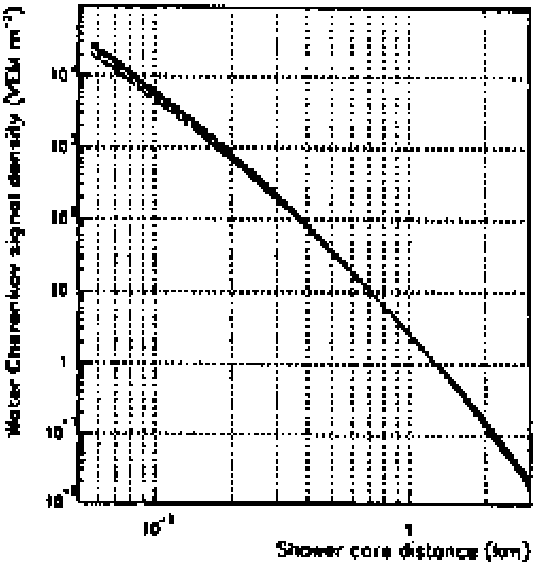
dE/dx = 2.34 MeV/(gm/cm^2)

dashed: Nmax to Eshower(EM), solid = dashed x 1.1

- Use shower *size* (N_{max}) and *width* (σ_{shower}) to measure shower energy – J. Linsley, 18th I.C.R.C. **12**, 135 (1983):
  1. Large showers are approximately Gaussian
  2. Thus:
  $$E_{shower} \approx N_{max} \cdot \sqrt{2\pi} \cdot \sigma_{shower} \cdot < dE/dx >$$
  where $\sigma_{shower} \approx 230$ gm/cm^2 and $< dE/dx > \approx 2.34$ MeV/(gm/cm^2) = $e^{\pm}$ dE/dx in air at $E_{critical}$.
  3. Prone to shower fluctuations – thus no longer used – see J. A. J. Matthews, GAP-97-018
  4. ... but $N_{max} \rightarrow E_{shower}$ simple check of Fly's Eye measurement. *(try it yourself!!)*

3. Ground Array Technique/Uncertainties *(con't)*





- Use particle density (ρ, S) some distance from shower core to measure shower energy:
  $\rho(500) \propto E_{shower}$ **and has** ***small*** **fluctuations – A.M. Hillas, et al, 12th I.C.R.C. 3, 1001 (1971)**
  1. Extensive shower simulations found that $\delta\rho/\rho$ is minimized at at radii $\geq$ 500 m from the shower core:
     - $\rho(500)$ was insensitive to depth of initial interaction
     - $\rho(500)$ was insensitive to initial composition
     - $\rho(500)$ had modest sensitivity to zenith angle of shower.
  2. Thus use $\underline{\rho(500) \text{ to characterize the shower (energy)}}$ and other event features (X_{max} or ρ_μ or ...) to discriminate on composition.
- Fig. Ref.: Pierre Auger Project FAQ's, C. Prkye, et al (1997)

3. Ground Array Technique/Uncertainties *(con't)*

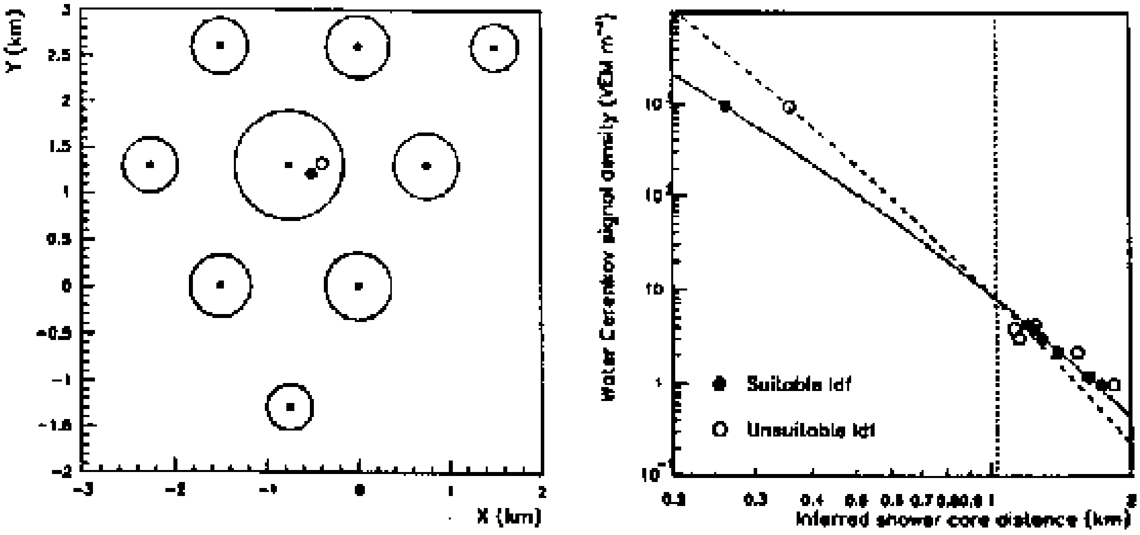
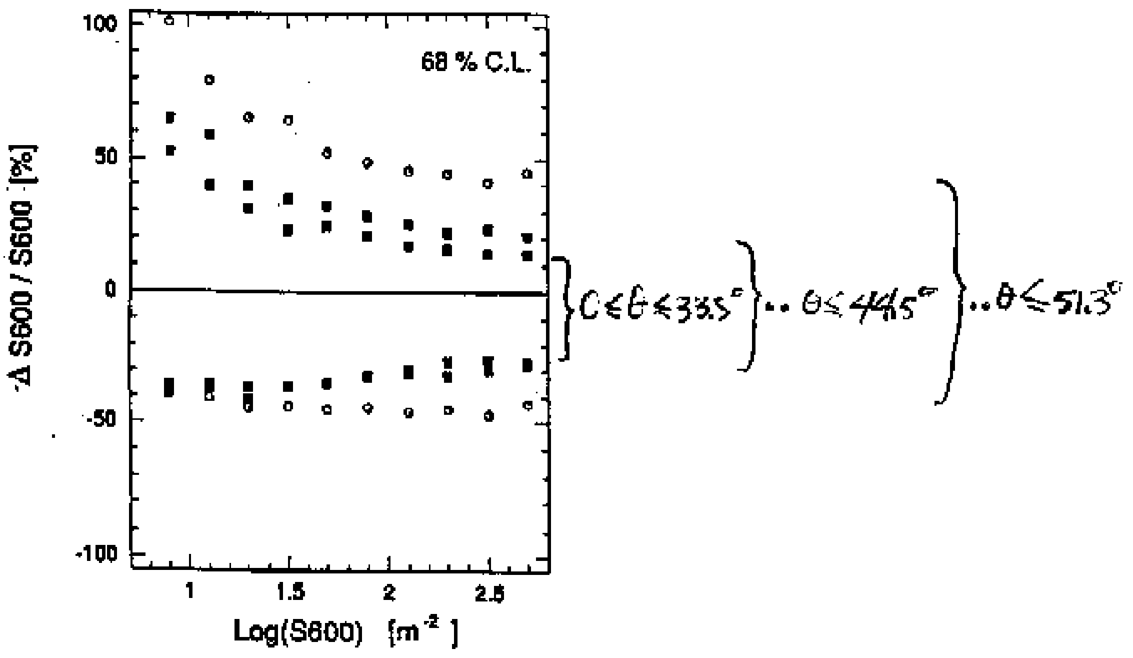


Figure 4: Reconstruction of a simulated ground array event using two lateral distribution functions. The left frame shows an array map; the small squares are the detector units, the circles surrounding them having radius proportional to the log of the signal size. The right frame shows the signal sizes plotted against the inferred distances to the shower core. Two lateral distribution functions have been used; the first is a good match to the data (filled points and solid line); the second is far too steep (open points and dashed line). In the left frame the reconstructed core positions on the basis of the two ldfs are also indicated.

- For sparse arrays there is a *natural* distance where $\rho(500)$ is measured (instrumentally) with the least uncertainty:
    1. Studied by Akeno group – H.Y. Dai, et al, J. Phys. G, **14**, 793 (1988)
    2. Natural size related to detector geometry and spacings
    3. Thus $\rho(500)$ may change to $\rho(600)$ or ... to minimize $\delta\rho/\rho$ in a given experiment.
- Fig. Ref.: Pierre Auger Project FAQ's, C. Prkye, et al (1997)

3. Ground Array Technique/Uncertainties *(con't)*



$0 \leq \theta \leq 33.5^\circ$ .. $\theta \leq 44.5^\circ$ .. $\theta \leq 51.3^\circ$

- Overall statistical and systematic error in ($\rho(600), S(600)$) measurement:

  1. From simulations the Akeno group estimates $\delta S(600)/S(600) \sim 10\%$ for vertical showers. This degrades to $\sim 40\%$ at zenith angles of 45°; see fig. above – S. Yoshida, et al, Astropart. Phys., **3**, 105 (1995)
  2. The Haverah Park group estimate that the uncertainty in $\delta\rho_\theta(600)/\rho_\theta(600) \leq 20\%$. The additional uncertainty from the *attenuation length* correction to $\delta\rho_0(600)/\rho_0(600)$ is $< 25\%$ where $\rho_0(600)$ is the corrected particle density to $\theta = 0$. – M.A. Lawrence, et al, J. Phys. G, **17**, 733 (1991); A. Watson, GAP Workshop, March 11-12 (1994).

3. Ground Array Technique/Uncertainties *(con't)*

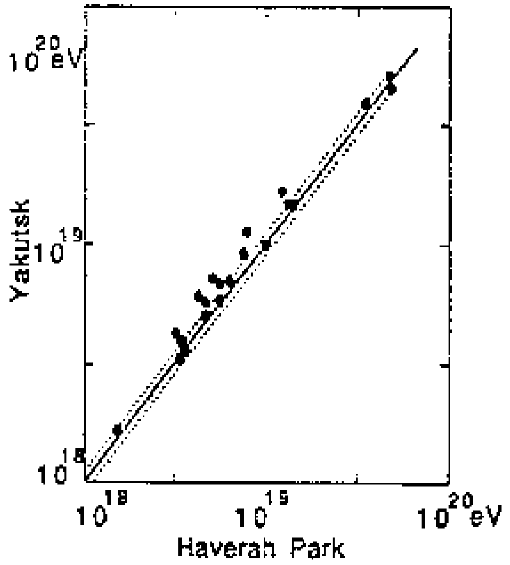


Figure 6. A comparison of the energy assignments made to events recorded at Haverah Park using (vertical axis) the Yakutsk $S(600)$/energy conversion and (horizontal axis) the Haverah Park $\rho(600)$/energy relation. The point at 2×10^{18} eV is an average of 20 events; the other 20 points are for individual events.

- To correlate (ρ, S) and E_{shower} vary physics in Monte Carlo simulations to find the *best* match with $(\rho(600), S(600))$ data:

  1. Akeno/AGASA (H.Y. Dai, et al, J. Phys. G, **14**, 793 (1988)):

     $$E_{shower} = (\ 2.03 \pm 0.10 \times 10^{17} eV/(\#/m^2)\ ) \cdot S^{1.02 \pm 0.02}(600)$$

  2. Haverah Park (M.A. Lawrence, et al, J. Phys. G, **17**, 733 (1991)):

     $$E_{shower} = (\ 7.04 \pm 20\% \times 10^{17} eV/(\#/m^2)\ )\ \cdot\ \rho^{1.018 \pm 3\%}(600)$$

  3. Haverah Park simultaneous measurement of showers in water Cherenkov and scintillators allowed a comparison of $\rho(600)$/energy relation and Yakutsk $S(600)$/energy relation. *Agreement is within* ±20% *on an event by event basis.*

- Fig. Ref.: M.A. Lawrence, et al, J. Phys. G, **17**, 733 (1991)

4. Spectra from Akeno, Fly's Eye, Haverah Park and Yakutsk

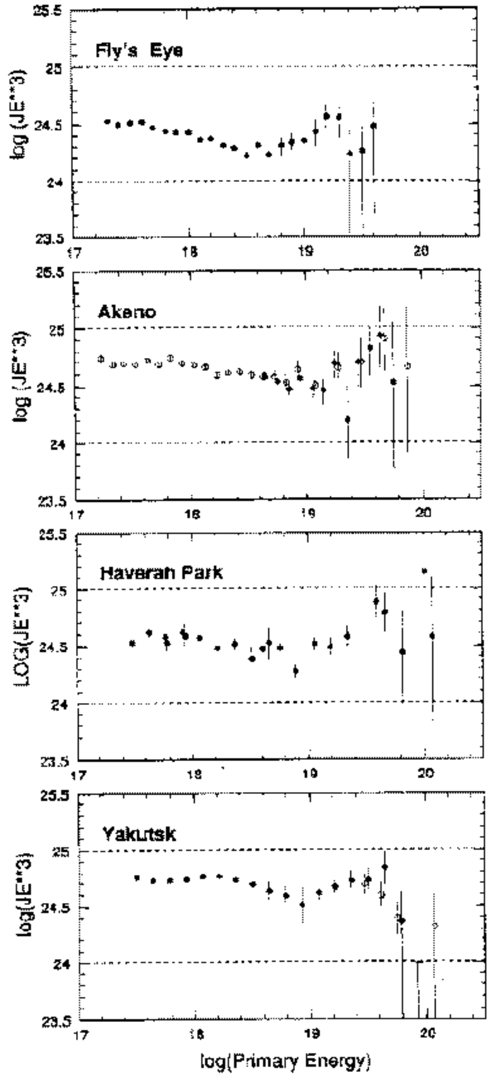


Figure 4: (a) Fly's Eye stereo energy spectrum (Bird *et al.* 1993a), (b) Akeno (Chiba *et al.* 1993a), (c) Haverah Park (Lawrence *et al.* 1991) and (d) Yakutsk (Efimov *et al.* 1990).

- All experiments have good qualitative agreement, *e.g.* all show a *dip* near 1 × 10^{19}eV – this is called the *ankle*
- Fig. Ref.: M. Teshima, Proceedings of 23rd I.C.R.C., 257, World Scientific (1993)

4. Spectra from Akeno, Fly's Eye, Haverah Park and Yakutsk

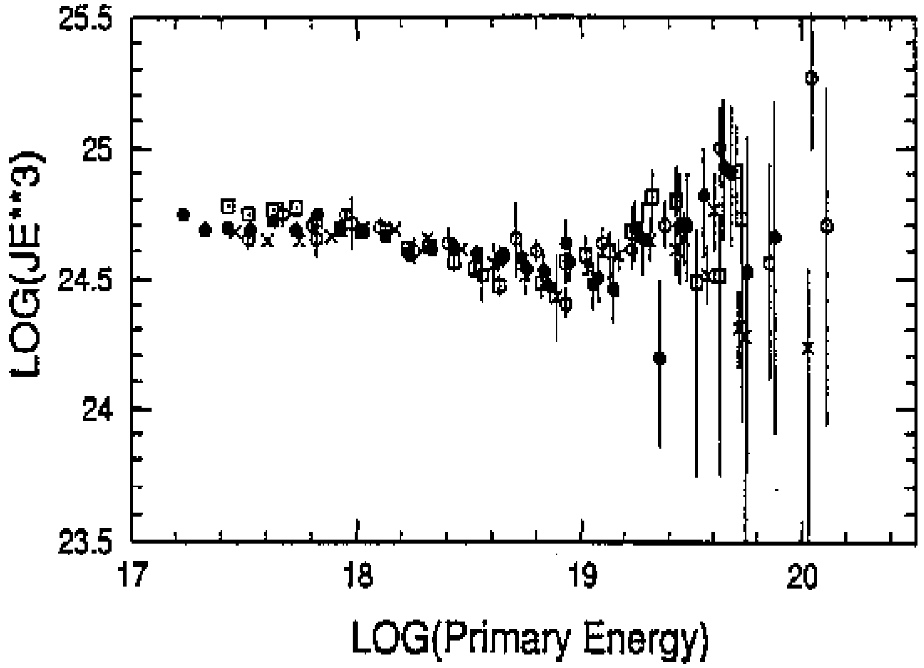
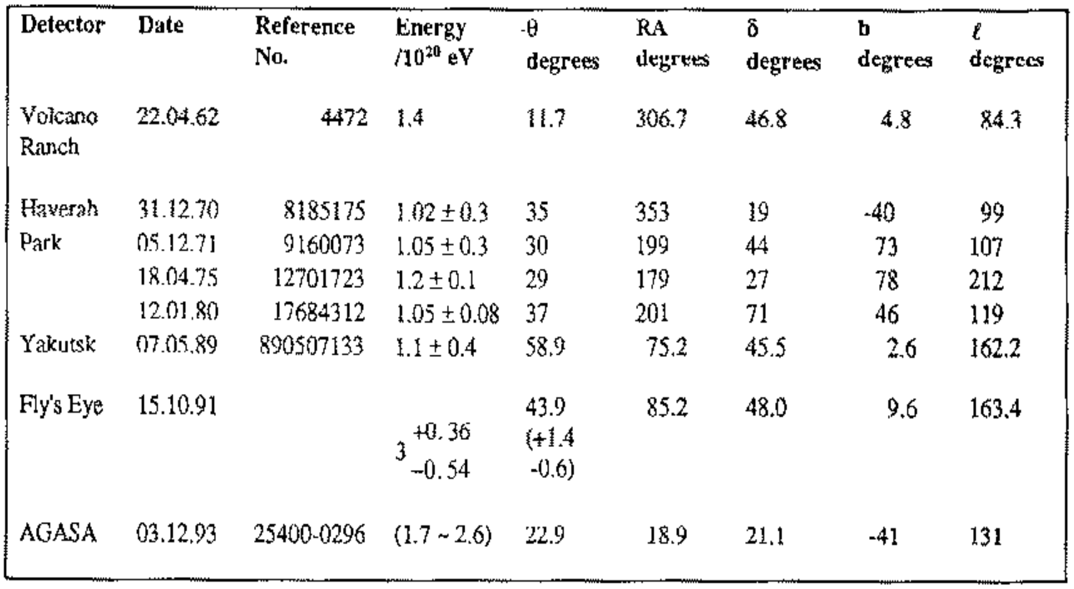


Figure 6: Grand Unified energy spectrum. The energy scales are shifted to follow AGASA result.

- *Grand unified spectra* obtained by normalizing to AGASA or to Fly's Eye spectra:
  - combined spectra retain features of individual spectra
  - multiplicative energy scale factors of 0.9, 0.8 and 0.8 bring Haverah Park, Yakutsk and AGASA data into agreement with Fly's Eye stereo data – S. Yoshida, et al, Astropart. Phys. **3**, 105 (1995)
- Individual experiments estimate uncertainties 20 ~ 30% consistent with *grand unification* scale factors.
- Fig. Ref.: M. Teshima, Proceedings of 23rd I.C.R.C., 257, World Scientific (1993)

5. Two events well above 1×10^{20}eV



Detector	Date	Reference No.	Energy $/10^{20}$ eV	-θ degrees	RA degrees	δ degrees	b degrees	ℓ degrees
Volcano Ranch	22.04.62	4472	1.4	11.7	306.7	46.8	4.8	84.3
Haverah Park	31.12.70	8185175	1.02 ± 0.3	35	353	19	-40	99
	05.12.71	9160073	1.05 ± 0.3	30	199	44	73	107
	18.04.75	12701723	1.2 ± 0.1	29	179	27	78	212
	12.01.80	17684312	1.05 ± 0.08	37	201	71	46	119
Yakutsk	07.05.89	890507133	1.1 ± 0.4	58.9	75.2	45.5	2.6	162.2
Fly's Eye	15.10.91		$3^{+0.36}_{-0.54}$	43.9 (+1.4 -0.6)	85.2	48.0	9.6	163.4
AGASA	03.12.93	25400-0296	(1.7 ~ 2.6)	22.9	18.9	21.1	-41	131

Table 1: Details of events for which the energy of the progenitor has been claimed to be about 10^{20} eV (from Northern Hemisphere Experiments)

- Compilation of big events – A. A. Watson, Proc. 1994 Snowmass Summer Study *Particle and Nuclear Astrophysics and Cosmology in the Next Millenium*, Eds. E.W. Kolb and R.D. Peccei, 126 (1995)

5. Two events well above 1×10^{20}eV *(con't)*

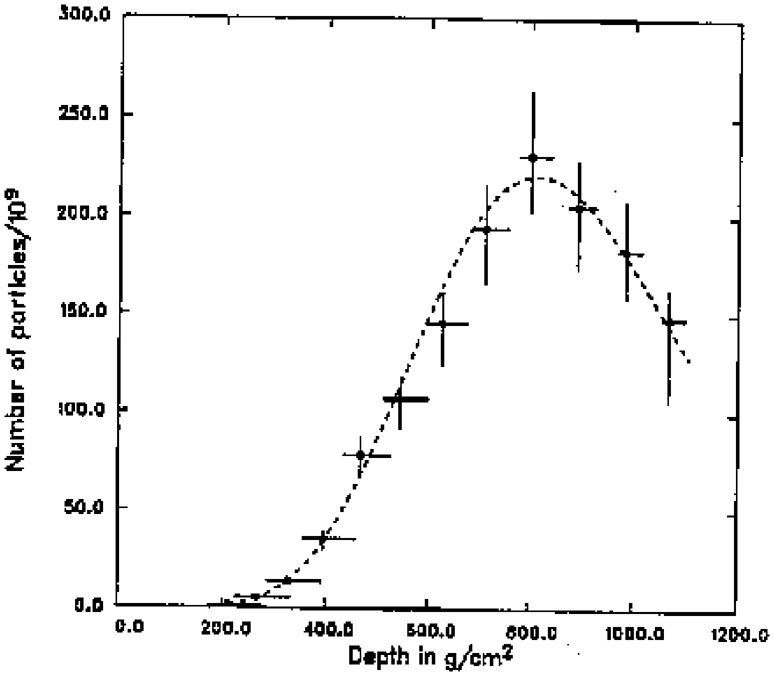
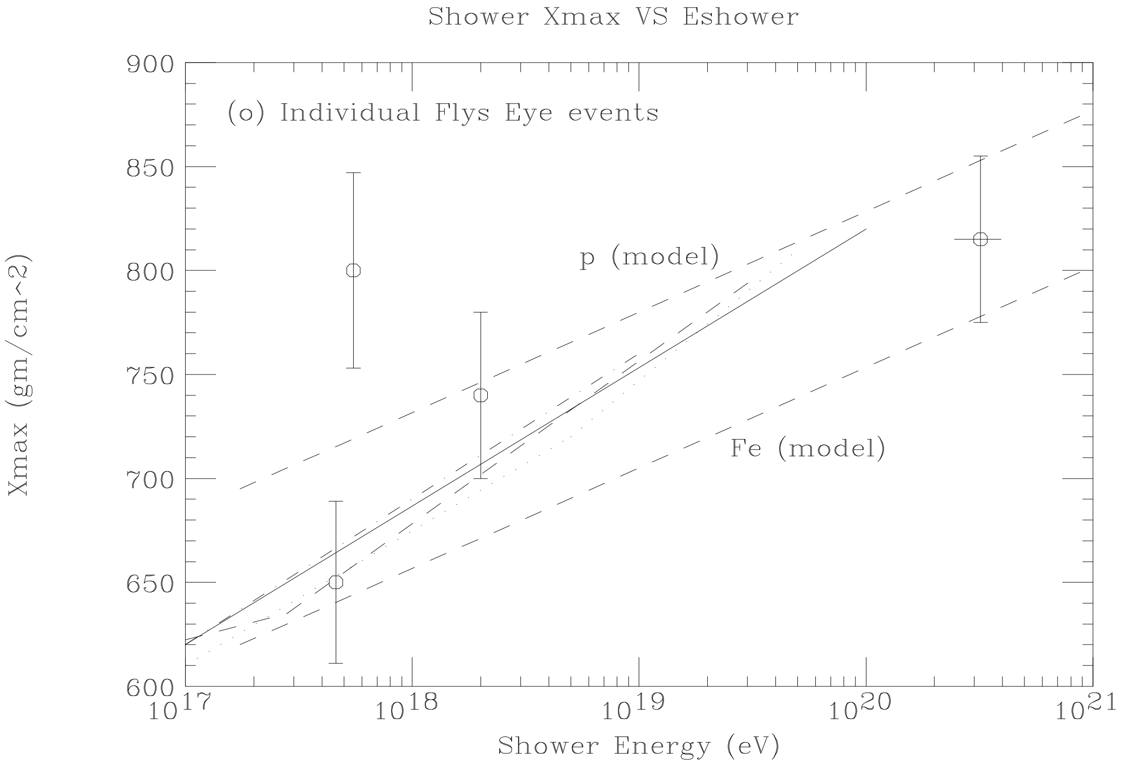


Figure 3: The 3-parameter best-fit shower profile is shown along with points obtained from the data in 5-degree intervals. The size at maximum is greater than 200 billion particles.

- Fly's Eye event:
  1. $E_{shower} = 3^{+0.36}_{-0.54} \times 10^{20}$ eV
     $X_{max} = 852^{+68}_{-100}$ g/cm^2
     – D.J. Bird, et al, Astrophys. J., **424**, 491 (1994)
  2. $E_{shower} = 3.20^{+0.92}_{-0.94} \times 10^{20}$ eV
     $X_{max} = 815^{+60}_{-53}$ g/cm^2
     – D.J. Bird, et al, Astrophys. J., **441**, 144 (1995)

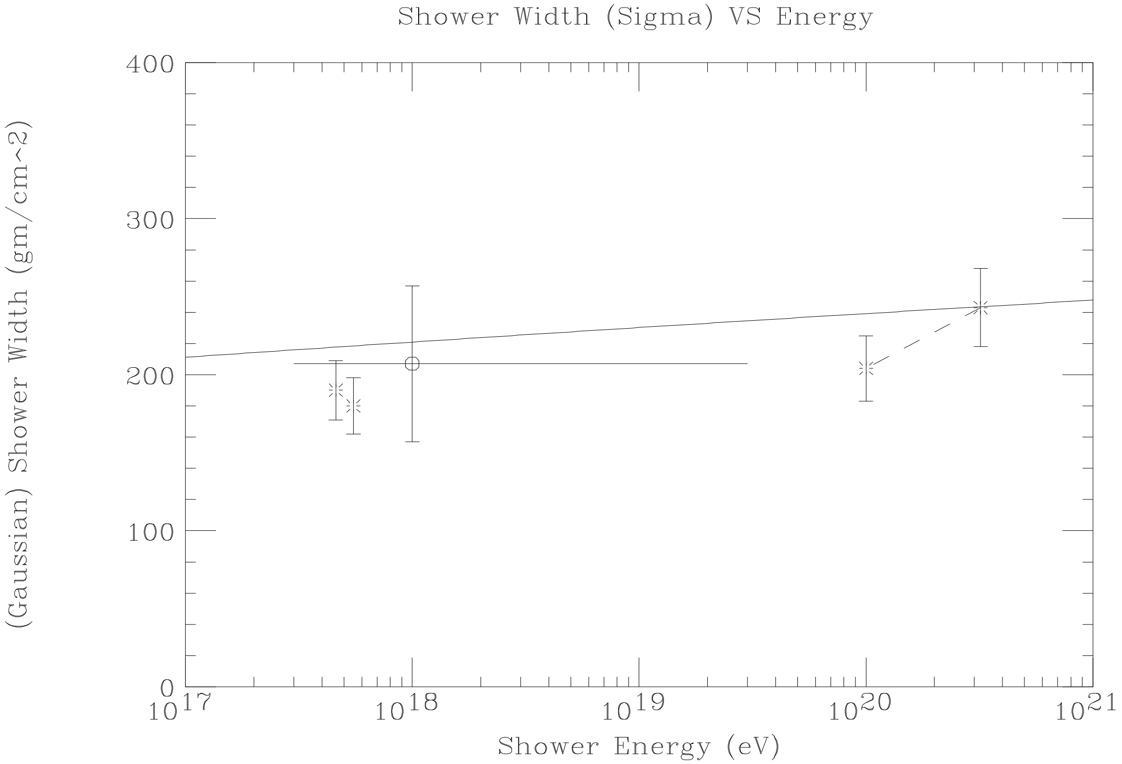
5. Two events well above 1×10^{20}eV *(con't)*



(dots) M. N. Dyakov et al, 23CRC, Vol 4, 303 (1993
(dotdash) G. L. Cassiday et al, Astrophys. J. 356, p669 (1990)
(dash) D. J. Bird et al, Astrophys. J., 424, p491 (1994)
(solid) Xmax model for simple EM shower study: GAP−97−018

- Within uncertainties $X_{max} = 815^{+60}_{-53}$ g/cm^2 consistent with other measurements.
- Fig. Ref.: J. A. J. Matthews, GAP-97-018 (1997)

5. Two events well above 1 × 10^{20}eV *(con't)*



J. Linsley, 18th CRC, Vol 12, page 135 (1983)

(∗) Flys Eye INDIVIDUAL Showers

(o) Flys Eye ALL Showers > 3x10~17eV

- Within uncertainties $\sigma_{shower} \approx 243 \pm 10\%$ gm/cm^2 consistent with other measurements.
- Forced fit to $E_{shower} = 1 \times 10^{20}$eV gives $\sigma_{shower} \approx 204 \pm 10\%$ gm/cm^2 which agrees less well with other measurements.

5. Two events well above 1×10^{20}eV *(con't)*

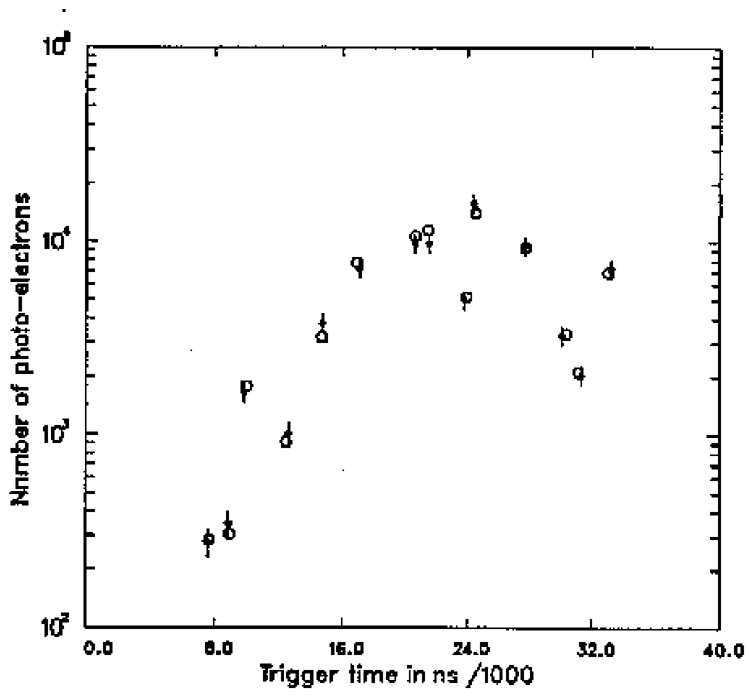


Figure 6: The data (trigger times and amplitudes for the 14 phototubes) are shown by dots with error bars in both amplitude and time (although the time error bars are smaller than the dots for some tubes). The circles denote simulated data using the best-fit shower parameters and our model of the light production, atmospheric transmission, and detector response.

- Comparison of data and event simulation (assuming parameters of fitted shower) shows no anomalies.
  Better if plot showed the estimated contribution of scattered air Cherenkov light.
- Fig. Ref.: D. J. Bird, et al, Astrophys. J. **441**, 144 (1995)

5. Two events well above 1×10^{20}eV *(con't)*

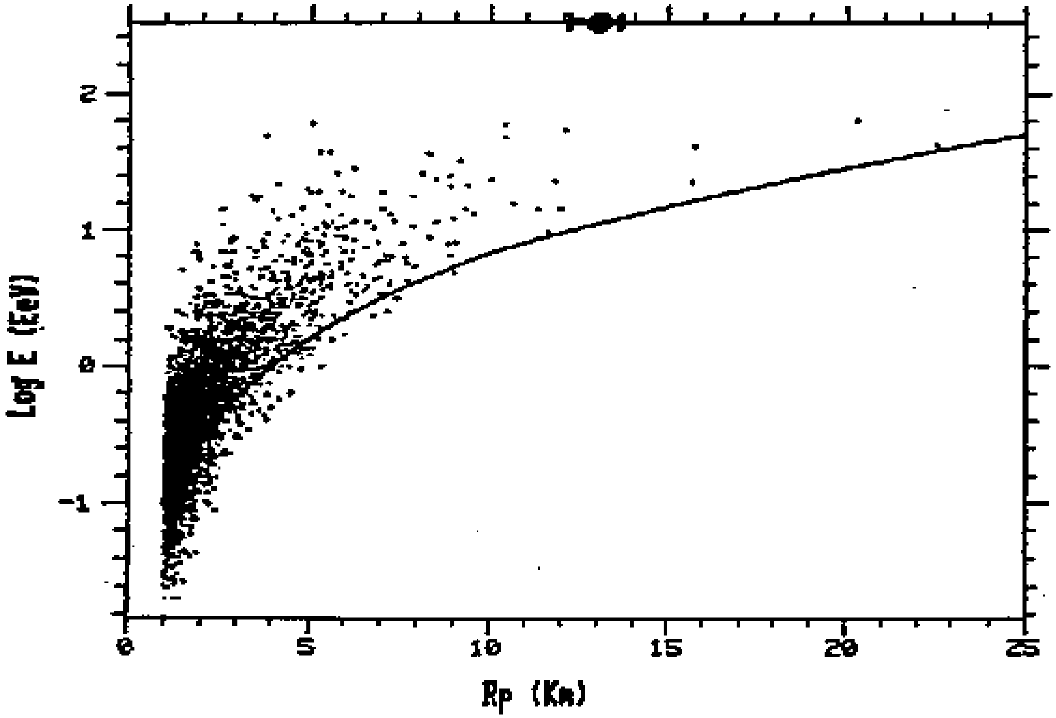


Fig. 9. Distribution of shower energy E vs impact parameter R_p for approximately 4000 events. The line represents a simple estimate of the minimum detectable energy given by: E(EeV) $= 0.1\ R_p^{1.5} e^{R_p/\lambda}$, where λ is the Rayleigh scattering length ~18 km.

- Shower fit results *versus* other Fly's Eye showers:
  $E_{shower} = 320^{+35}_{-40} \pm 85$ EeV where 1 EeV = 10^{18} eV
  $R_p = 13.0^{+0.5}_{-0.8} \pm 0.8$ km
  N.B. shower is more distant than most.
- Fig. Ref.: K. D. Green, *Atmospheric Fluorescence Technique*, GAP Workshop, March 11-12, 1994

5. Two events well above 1×10^{20}eV *(con't)*

- *Back of envelope* check of E_{shower} error estimates:

- Check I:

  1. χ^2 fit uncertainty: $(^{+35}_{-40})$ EeV
     Fit χ^2 normalized to 1/DoF ... reasonable but "fit" errors may therefore be under or over estimated.

  2. Systematic:
     Fluorescence yield: (±20% = ±64 EeV)
     Atmospheric trans./atten.: (±8% = 26 EeV) – H.Y. Dai, GAP Workshop, March 11-12 (1994)
     Atmospheric monitoring was consistent with "clear atmosphere for October" but was monitoring adequate for a shower at 13 km? N.B. most Fly's Eye showers were much closer than 13 km.
     Missing energy (ν's etc): (±10% = ±32 EeV)
     Total = ±76 EeV *VS* quoted total systematic of ±85 EeV

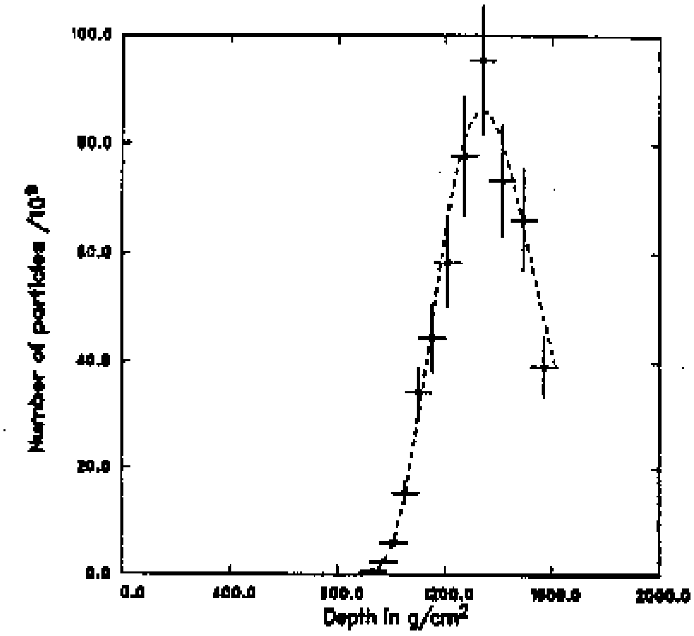
- Check II:

  1. Monocular reconstruction of binocular events provide experimental measurement (showers $> 2 \times 10^{18}$eV) of $\delta E/E = (\pm 27\% = \pm 86$ EeV$)$
     - *Possibly an overestimate by* $3.2 \times 10^{20} eV$ *... but in absence of how uncertainty varies with distance no strong motivation to decrease this estimate.*
     - *In future this uncertainty should be measured versus shower energy, distance, time of year, ...*

  2. Other systematics:
     Fluorescence yield: (±20% = ±64 EeV)
     Missing energy (ν's etc): (±10% = ±32 EeV)
     Total = ±72 EeV

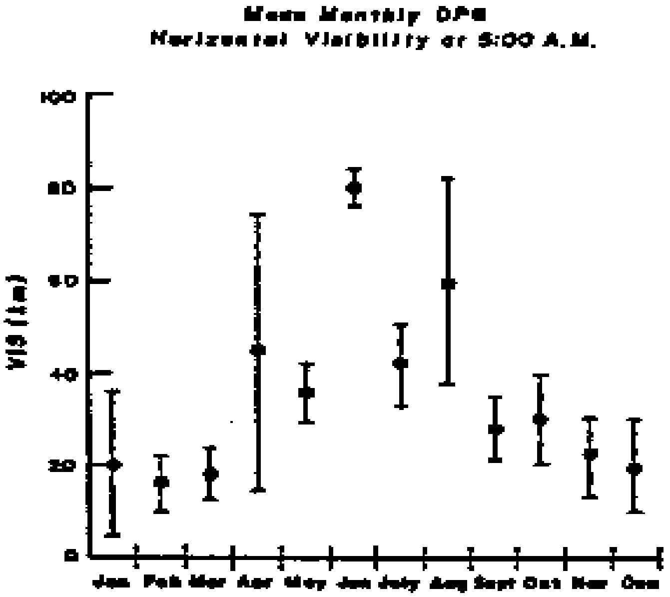
  3. Combined error:
     ±112 EeV *VS* quoted total of $^{+92}_{-94}$ EeV

5. Two events well above 1×10^{20}eV *(con't)*



- *What if # 1*: There are large correlations between track angle and track distance in the reconstruction of monocular showers. The non-observation in the 2nd *eye* constrains this somewhat. The plot above shows the reconstructed shower when the distance is reduced to yield $E_{shower} = 1 \times 10^{20}$ eV.
  - $\sigma_{shower} \approx 204 \pm 10\%$ gm/cm^2 is a little low
  - the beginning point of the shower, $X_0 = 807$ g/cm^2, is inconsistent with a γ, p, light or heavy nuclei primary. A ν primary is possible but unlikely ... other events? *It is amusing that the track angle, Ψ, decreases (shower becomes more horizontal) as the track distance, R_p, decreases.*
- Fig. Ref.: D. J. Bird, et al, Astrophys. J. **441**, 144 (1995)

5. Two events well above 1×10^{20}eV *(con't)*



- What if # 2: The dominant uncertainty in the atmospheric corrections is from light scattering on aerosols which vary over the year (E.C. Loh, Nucl. Phys. Proc. Suppl. **14A**, 256 (1990) shown above) and can vary $\sim 20\%$ from day to day – P. Sokolsky, et al, Phys. Reports **217**, 225 (1992) *N.B. event at ~ midnight Oct. 14, 1991.*
- Qualitatively aerosols are *near the ground.* Aerosols both decrease the signal (increased attenuation) and increase the signal (scattering of air Cherenkov light). *As noted, better if events explicitly showed the estimated contribution of scattered air Cherenkov light.*
- When the analysis was repeated with *zero* aerosols then $E_{shower} = 2.20 \times 10^{20}$eV.
- Fig. Ref.: E. C. Loh, Nucl. Phys. B (Proc. Suppl.) **14A**, 256 (1990)

5. Two events well above 1×10^{20}eV *(con't)*

- Summary:
  1. Combined total uncertainty of $^{+92}_{-94}$ EeV is consistent with other Fly's Eye events.
  2. The new measurement of the air fluorescence yield would tend to reduce this error somewhat.
  3. Very likely that this uncertainty is non-Gaussian on the low energy side. This is a very *bright* shower, cf *What if*s, that is difficult to force to energies as low as 1×10^{20} eV.

5. Two events well above 1×10^{20}eV *(con't)*

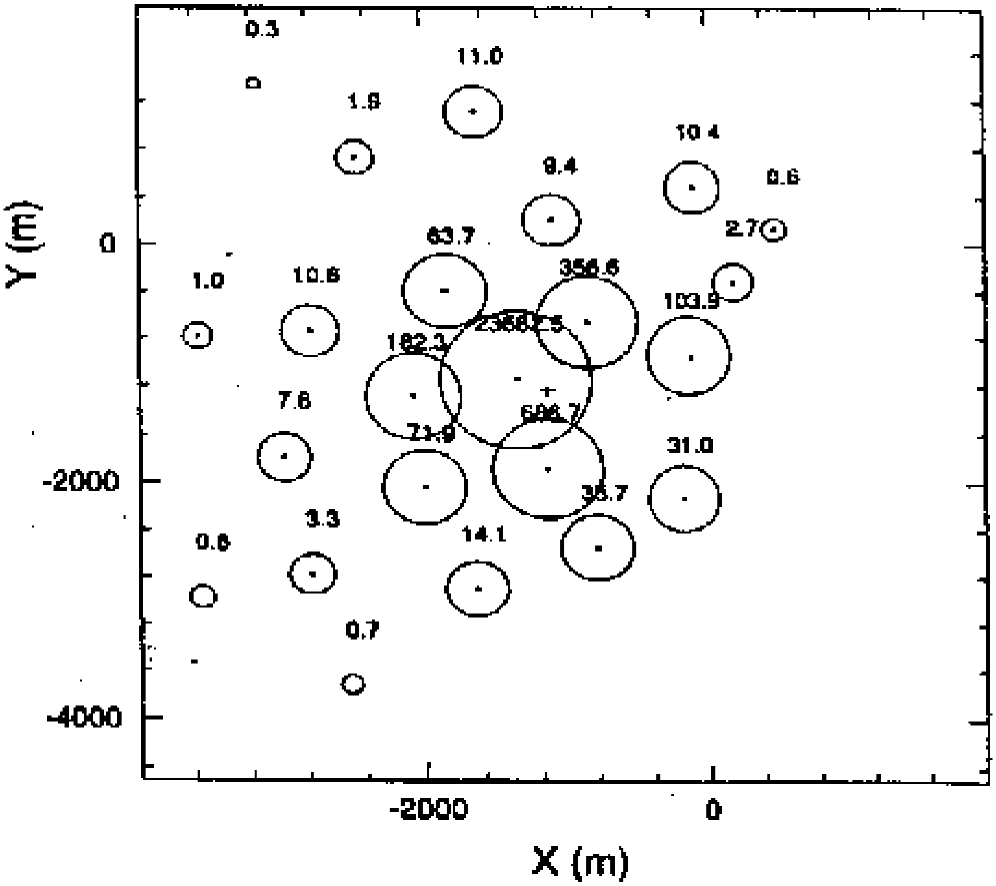


FIG. 1. Map of the density distribution of the giant EAS. The radius of each circle represents the logarithm of the density at each detector location. A cross shows the estimated position of the shower core.

- AGASA event:
  1. $E_{shower} = (1.7 - 2.6) \times 10^{20}$ eV
     - S. Yoshida, et al, Astropart. Phys. **3**, 105 (1995)
     - N. Hayashida, et al, Phys. Rev. Lett. **73**, 3491 (1994)

5. Two events well above 1 × 10^{20}eV *(con't)*

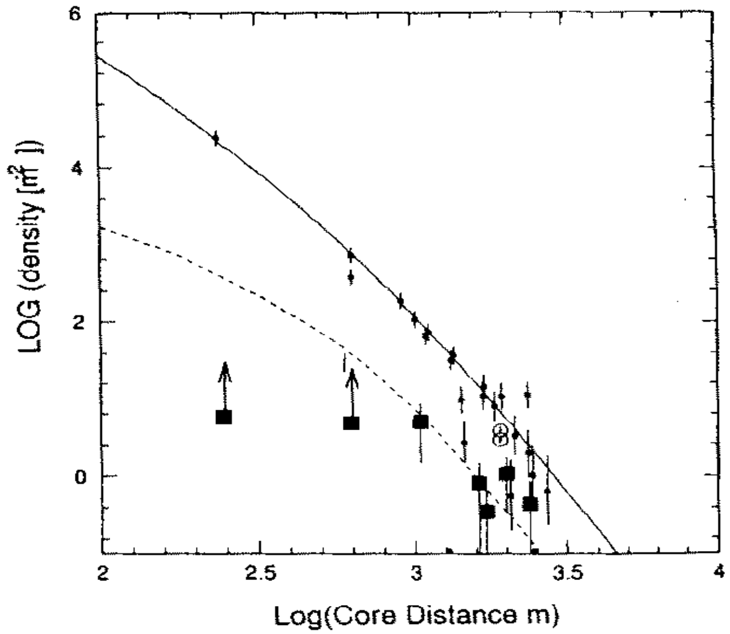


FIG. 2. The lateral distribution of charged particle (closed circles) and muons (shadowed squares). The large open circle is that measured by a detector for arrival time distribution. The expected lateral distribution of charged particles is shown by a solid line and that of muons by a dotted line.

- Radial distribution of charged particles (shown above):
  1. Particle densities measured in scintillators, $S_{23}(r)$, and shielded proportional counters, $\rho_\mu(r)$, depend on the reconstructed shower core location and are uncorrected for the 22.9° zenith angle of the shower.
  2. Functional form (not normalization) of radial distribution functions come from Akeno/AGASA data between approximately $10^{18} \sim 10^{19}$ eV – S. Yoshida, et al, J. Phys. G, **20**, 651 (1994); N. Chiba, et al, 23rd I.C.R.C. **4**, 307 (1993)
  3. Transverse shape of shower is consistent with lower energy showers.
- Fig. Ref.: N. Hayashida, et al, Phys. Rev. Lett. **73**, 3491 (1994)

5. Two events well above 1×10^{20}eV *(con't)*

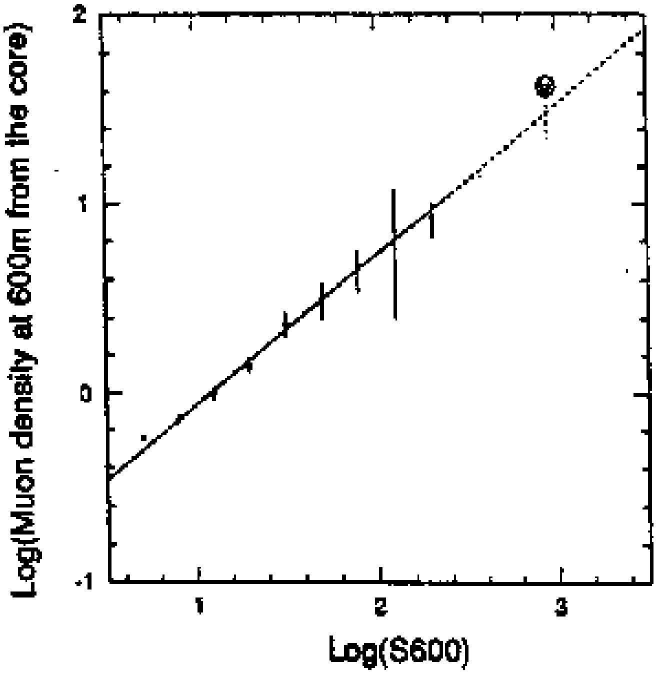


FIG. 3. $\rho_\mu(600)$ vs $S_0(600)$ relation. An open circle is the estimated value of the present event, and filled circles are average values for each bin determined by the AGASA experiment.

- Comparison of $\rho_\mu(600)$ and $S_0(600)$:
  1. $\rho_\mu(600)$ and $S_0(600)$ are independent measurements with different systematics.
  2. $\rho_\mu(600)$ was obtained by *extrapolation* of data at radii $r \geq 1000$m.
  3. $S_0(600)$ was estimated to be 892 to $1065/\mathrm{m}^2$ (*i.e.* <u>no correction</u> to <u>standard correction</u> to $\theta = 0$).
  4. Comparison with lower energy showers suggests that $\rho_\mu(600)$ is larger than expected (*i.e.* a higher energy shower or different composition).
- Fig. Ref.: N. Hayashida, et al, Phys. Rev. Lett. **73**, 3491 (1994)

5. Two events well above 1×10^{20}eV *(con't)*

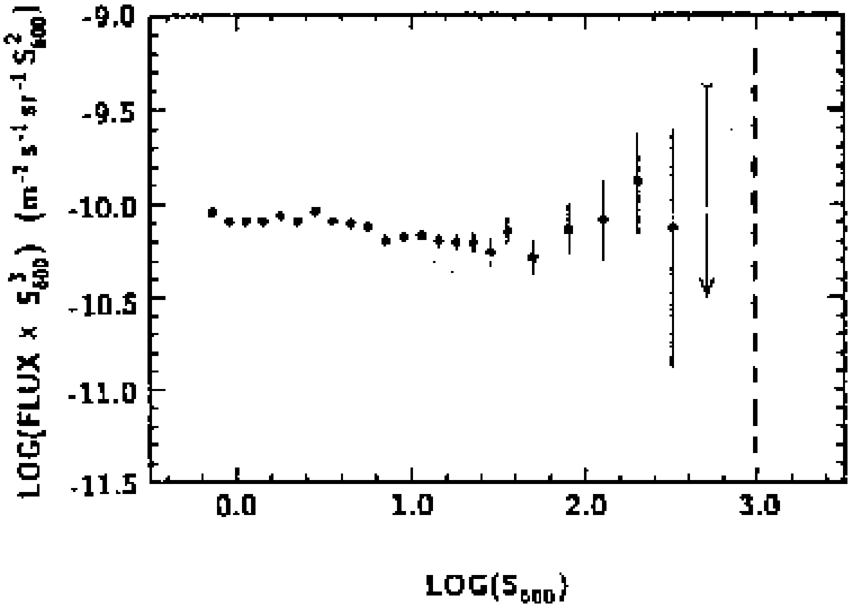
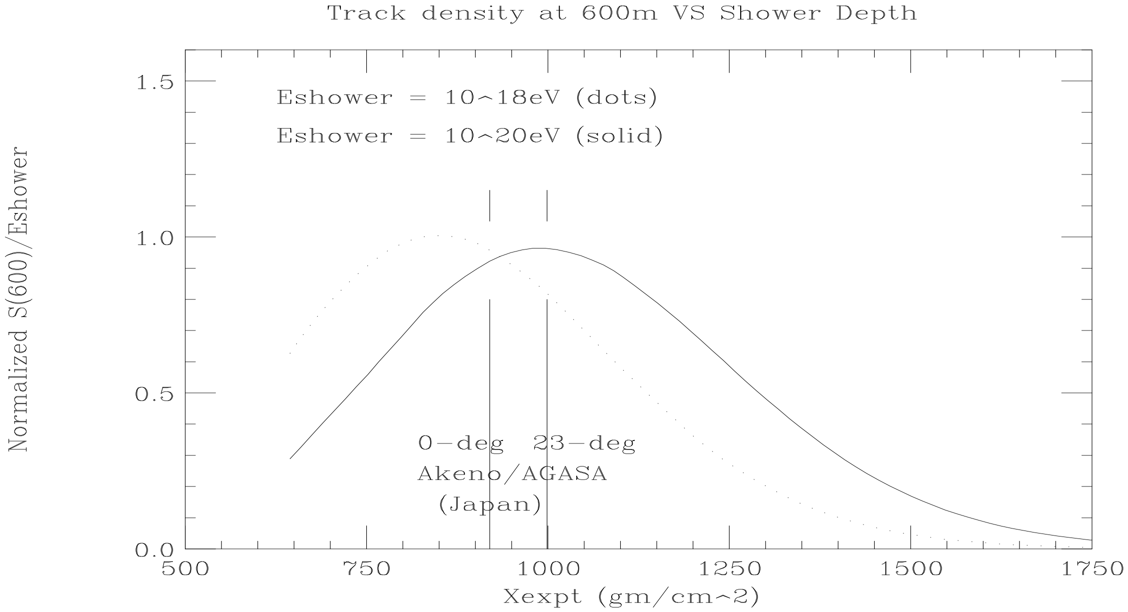


Figure 10. The differential S_{600} spectrum at 920 g cm^{-2} vertical depth. The upper limit at the highest bin is the 90% CL.

- Shower analysis gives $S_0(600) = 892$ to $1065/\mathrm{m}^2$:
  1. $S_0(600)$ is $\sim 3\times$ previous showers (see above)
     – M. Nagano, et al, J. Phys. G, **18**, 423 (1992)
  2. Simulations for $\theta < 34°$ find $\delta S_0(600)/S_0(600) \approx^{-0.27}_{+0.13}$
     – S. Yoshida, et al, Astropart. Phys., **3**, 105 (1995)
  3. At $\theta < 23°$, $\delta S_0(600)/S_0(600) \approx^{-0.21}_{+0.066}$, *i.e.* the shower energy may be systematically underestimated.
  4. Finally $\underline{E_{shower} = 2.0 \times 10^{17} \cdot S_0(600)}$ results in $\underline{E_{shower} = 1.7 - 2.6 \times 10^{20}\mathrm{eV}}$.
  5. *Using these numbers I obtain* $\underline{E_{shower} = 1.67 - 2.58 \times 10^{20} eV.}$
- Fig. Ref.: M. Nagano, et al, J. Phys. G **18**, 423 (1992)

5. Two events well above 1×10^{20}eV *(con't)*



S(600)/Eshower normalized to maximum of 1.0 at 10~18eV

Xmax model for simple EM shower study: GAP–97–018

- Check I Correction from $\theta = 22.9°$ to $0°$:
  For $E_{shower} \approx 2 \times 10^{20}$ eV then $X_{max} \approx X_{max}(Fly'sEye) \approx 815^{+60}_{-53}$gm/cm^2.
  In comparison AGASA observes showers at $X_{eff}(\theta) = 920$gm/cm^2 $\cdot$ $sec(\theta) = 999$gm/cm^2 at 22.9°. The sandard AGASA correction to $\theta = 0°$ is to scale $S_{23}(600)$ by $\underline{\sim 1.19\times}$. But the shower *elongation* from typical showers of $\sim 1\times10^{18}$eV to 1×10^{20}eV corresponds to an overall correction of $\underline{\sim 1.0\times}$ (see above). The AGASA attenuation length correction was a scale factor of $\underline{1.0 \sim 1.19\times}$.
- Fig. Ref.: J. A. J. Matthews, GAP-97-018 (1997)

5. Two events well above 1×10^{20}eV *(con't)*

- Check I' Estimate the minimum event energy:
  1. Set $S_0(600) = S_{23}(600) = 892 \pm 10\%/\mathrm{m}^2$, *i.e.* make no zenith angle (upward) correction.
  2. Adjust (down) the factor relating $S_0(600)$ to E_{shower} by $0.8\times$, *viz.* the observed energy scale discrepancy between Akeno/AGASA and the stereo Fly's Eye data.
  3. Thus $E_{shower}^{Minimum} = (892 \pm 10\%/\mathrm{m}^2) \cdot (2.0 \times 10^{17}$ $\mathrm{eV}/(\#/\mathrm{m}^2) \times 0.8) = \underline{1.43 \pm 0.14 \times 10^{20}\mathrm{eV}}$.

- Check II *Back of envelope* check of E_{shower} errors:
  1. *Arbitrarily* assign Haverah Park uncertainty from reconstructing shower zenith angle, core location plus instrumental errors of ∼ 20% to AGASA event.
  2. Assume the AGASA attenuation corrections with 50% uncertainty: *i.e.* 1.19 ± 0.10
  3. *Arbitrarily* assign Haverah Park uncertainty in absolute calibration of ±20%
  4. Thus $E_{shower} = (892 \pm 20\%/\mathrm{m}^2) \cdot (1.19 \pm 0.1) \cdot (2.0 \pm 20\% \times 10^{17}\ \mathrm{eV}/(\#/\mathrm{m}^2)) = \underline{2.13 \pm 0.64 \times 10^{20}\mathrm{eV}}$.
  5. By comparison AGASA *quotes* $\underline{2.15 \pm 0.45 \times 10^{20}\mathrm{eV}}$.

- Check II' *Back of envelope* check of E_{shower} errors:

  1. Same as 1. (above)
  2. Note that extra depth of shower measurement ($\theta = 22.9°$) is compensated by extra depth for 2×10^{20}eV shower. Use an attenuation correction of 1.0 ± 0.1.
  3. Use detailed Akeno/AGASA correction to primary energy:

     $$E_{shower} \;=\; (\,2.03{\pm}0.10{\times}10^{17} eV/(\#/m^2)\,)\cdot S_0^{1.02\pm0.02}(600)$$

  4. Thus $E_{shower} \;=\; \underline{2.07 \pm 0.57 \times 10^{20}\text{eV}}$.
  5. By comparison AGASA *quotes* $\underline{2.15 \pm 0.45 \times 10^{20}\text{eV}}$.

- Summary:

  1. AGASA total uncertainty of $1.7 \sim 2.6 \times 10^{20}$eV may be somewhat underestimated: *e.g.* $\underline{\sim 21\%}$ uncertainty versus typically $\underline{20 \sim 30\%}$ for other ground arrays.

  2. As in the Fly's Eye event:
     - the particle density $S_0(600) \approx 1000/\text{m}^2 \approx 3\times$ previous Akeno/AGASA events; *i.e.* this is a big shower.
     - it is difficult ($> 2\sigma$) to interpret this event at an energy as low as 1×10^{20} eV.

5. Two events well above 1×10^{20}eV *(con't)*

After investigation
at least 2 events are consistent
with energies substantially
$> 1 \times 10^{20}$ eV

Don't forget several events near 1×10^{20} eV. Given the $20 \sim 30\%$ uncertainties on individual events these events are all within $\sim 1\sigma$ of 1×10^{20} eV and are very interesting.