Hillas Symposium
Heidelberg: 10 December 2018

Michael Hillas
– the early days (to 1969)

Alan Watson

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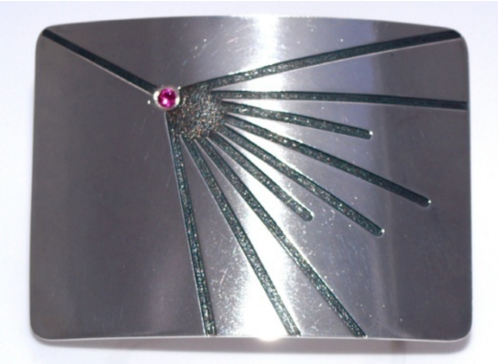
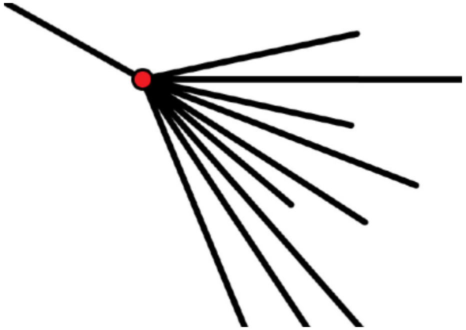




Seminal Contributions

- Cosmology
- Extensive Air Showers
  - Analysis ideas
  - Monte Carlo calculations
- Acceleration of Cosmic Rays
- Origin of Cosmic Rays
- Gamma-ray Astronomy
- Post ‘retirement’, in addition to several of above
  - Geology
  - Economics
  - Astronomy

Michael as a student ~1951

Self-portrait at 75 (?)

Early days

At school already showed signs of computational talent

- log tables

Choice of Leeds rather than Cambridge to study physics

Slide rule

- log of fundamental constants engraved on back

Seemed able to get more out of any computing device than other people

Always had an excellent idea of what more detailed computations would reveal

PhD thesis (1957) – after gaining First Class Honours Degree

'The interaction of stopped negative muons with atomic nuclei'

(i) Tests of ideas about interactions between four fermions
(ii) Interaction rate depends on nuclear structure

Private communications with Primakoff and Telegdi

123 pp with 18 pp of circuit diagrams (thermionic valves)

- **Chronotron: Nuclear Instruments and Methods 3 344 1958**

- **Results from thesis: Phil Mag 3 344 1958**

Comment by G D Rochester and J G Wilson

'Most impressive viva either of us have ever attended'

Junior fellowship at Harwell to work on shower array 'outside the wire' of Atomic Weapons Research Establishment (AWRE)

Worked with Cranshaw, Galbraith, Porter, de Beer, Jelley….

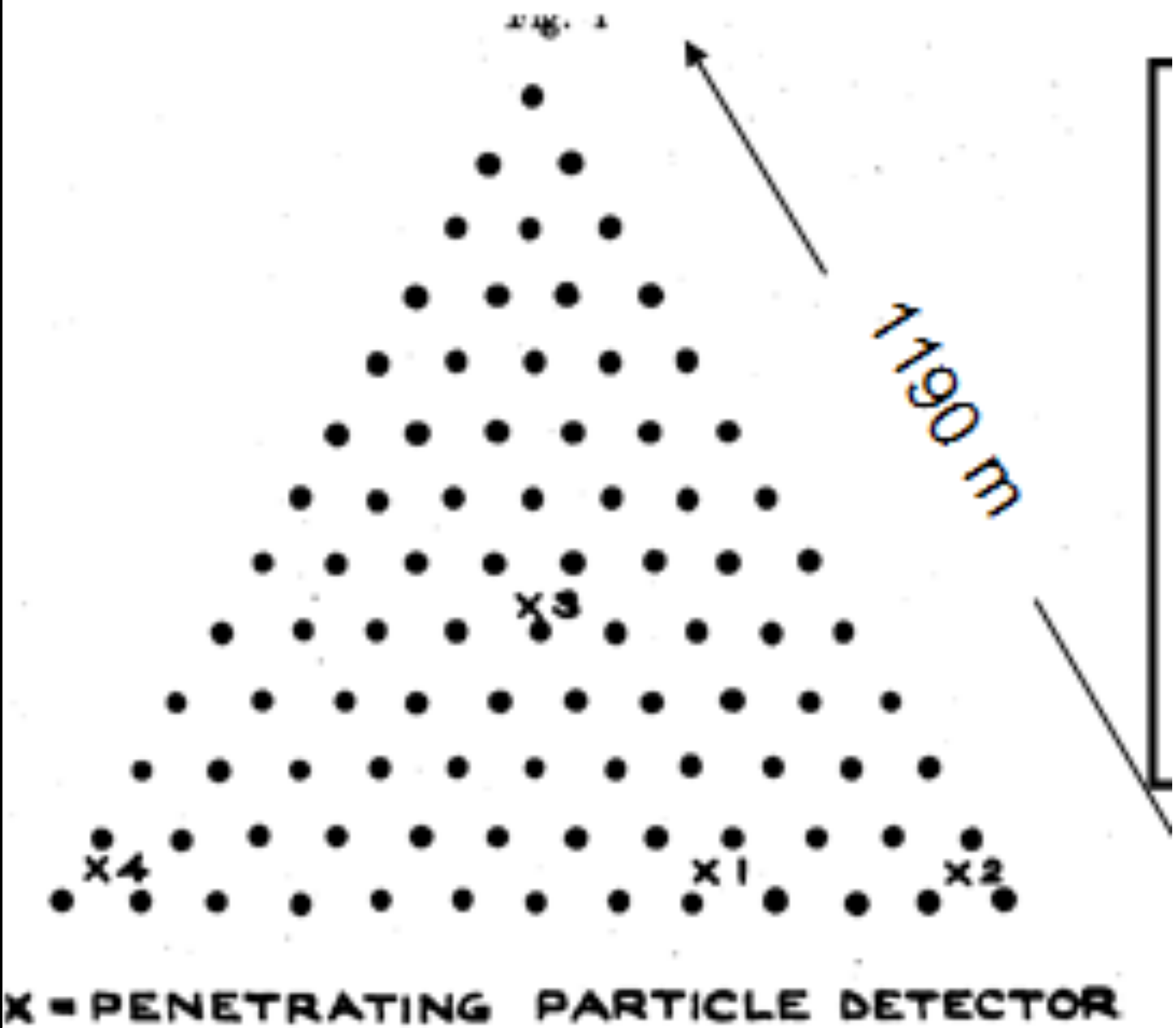
At this time there was already debate as to whether Michael was more theoretically or experimentally inclined

A reminiscence of Bill Galbraith from Harwell days:

'Hillas came later and scared the wits out of me (as Safety Officer) wading around kVs in wet enclosures housing spark counters for muons. I was relieved he later, at Leeds, took up the theory of EAS'.

Younger people lived in aircraft hangers

When rabbits bit through cables, they had to get up at night and repair equipment



Harwell (or Culham) array in mid-1950s:
91 Geiger Counter stations over 0.6 km^2

Charge difference experiment: Nature 184 892 1959

< 1 in 10^{20} difference compared with 1 in 10^{18} that is needed: Bondi and Lyttleton 1959

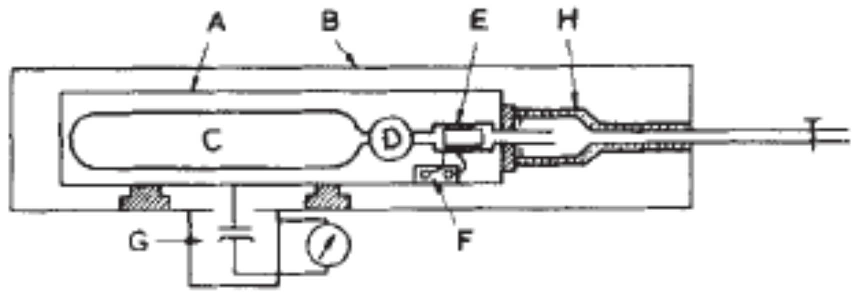


Fig. 1. *C*, Gas cylinder; *D*, reducing valve; *E*, ion trap; *F*, battery; *G*, electrometer; *H*, double-walled outlet tube containing thermal insulation; hatched areas, polystyrene insulators.

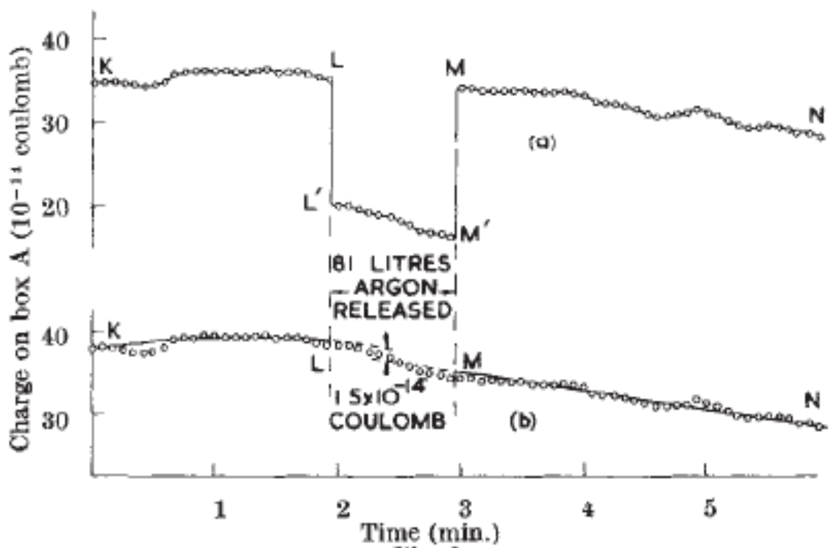


Fig. 2.

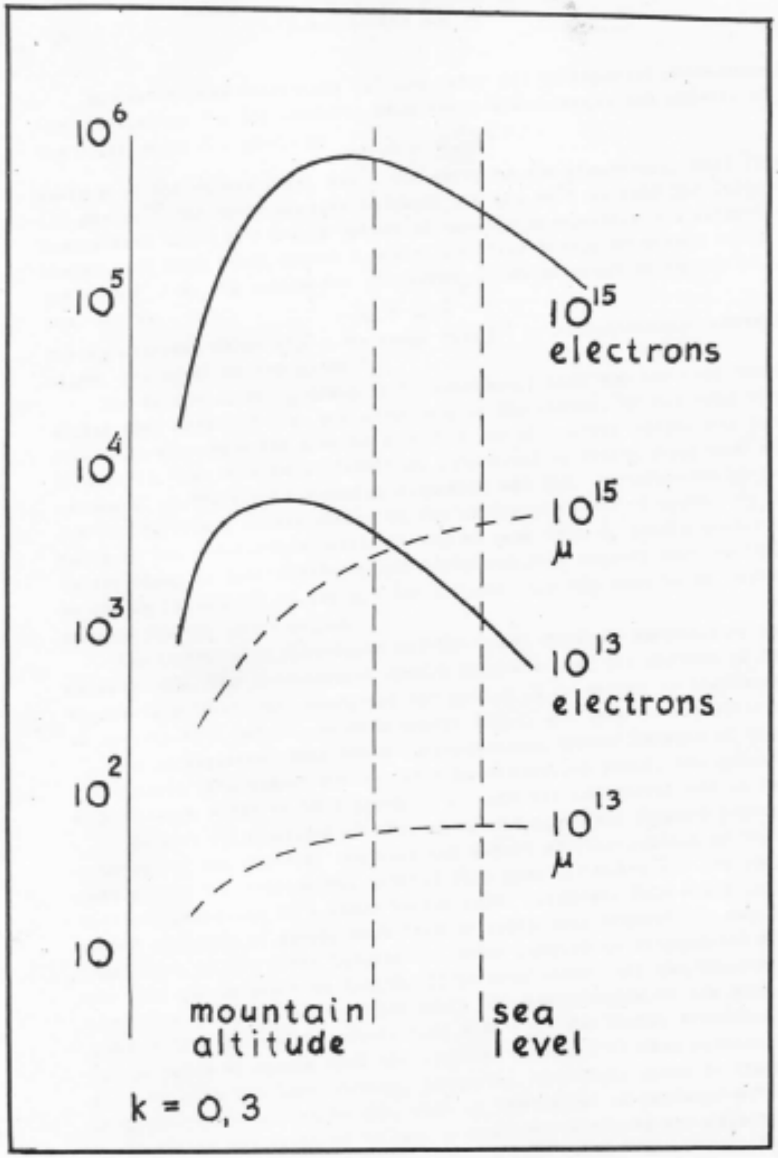


Fig 1

Key work on Shower Fluctuations

Implications:

Short cascades occur in showers so that at these energies one sees very largely the results from one interaction

At the same meeting Zatsepin proposed the same idea, describing the shower as being like 'an inverted Christmas tree'

Cranshaw and Hillas ICRC Moscow 1959

In Cranshaw and Hillas paper

"If the primary particle is an α-particle, the shower will usually be produced by one nucleon undergoing few collisions, as described for the proton primary. The other three nucleons will make collisions at mean intervals of 75 g cm^{-2} and contribute almost nothing to the photon-electron cascade as sea level"

This, of course, refers to relatively low energies. At higher energies the 'single cascade' effect becomes less and less evident, if at all

Returned to Leeds to a lectureship in 1959

Very strong reference from E C Stoner

‘Promise of outstanding contributions from him’

But ….‘may not add to the superficial gaiety of the University’

In fact Michael had a fine sense of humour – if a little dry

In his application, he wrote:

‘When AWRE decided that cosmic rays did not show the way immediately to a new energy source, this work was transferred to the universities’

He sent me this note in late 2013 when he was beginning to have difficulties with his rather ancient computer

"Further to my computer's bouts of very slow running, I currently attribute this to GCHQ's difficulty in following my typing using their analysis system. But why should they bug me? They must be alerted by frequent appearances of the name of a foreigner they are unable to clear of suspicion. I suspect it will continue until they get from me Cherenkov's email address."

Michael made it clear that he did NOT want to be involved with Haverah Park project – perhaps thought sheep behaved like rabbits

Worked on plans for large cloud chamber project

His early work in Leeds was done on KDF9 Mainframe with 64k of memory: brought into service at Leeds ~1964

By 1967 there were 9 available in UK universities: several £M

Algol 60 complier was available in Leeds with paper tape input

*** In these early days there were no graphing facilities**

Up to four programs could be run at once

In Leeds, Eldon 2 operating system (Eldon was name of a converted chapel and local pub)

Weighed about 5 tonnes

Analysis of arrival direction and core position of shower with 4 stations (first stage of Haverah Park) took several minutes

*** You had to THINK before you did anything: time was rationed!**

KDF9 Leeds University ~1967

- **Michael was still thinking deeply about showers and was one of the early people to realise the importance of pion interactions**

- **Student (Jim Hough) measuring bubble chamber pictures (1964)**

- **20 GeV/c π^- on hydrogen in Saclay 81 cm bubble chamber**

- **Established that**

$$\langle p_t \rangle = 0.34 \pm 0.01 \text{ GeV/c}$$

Average fraction of energy taken by fastest pion = 0.47

ρ^0 production = (22+/- 9)%

- **Never written-up!**

From J Hough: PhD thesis

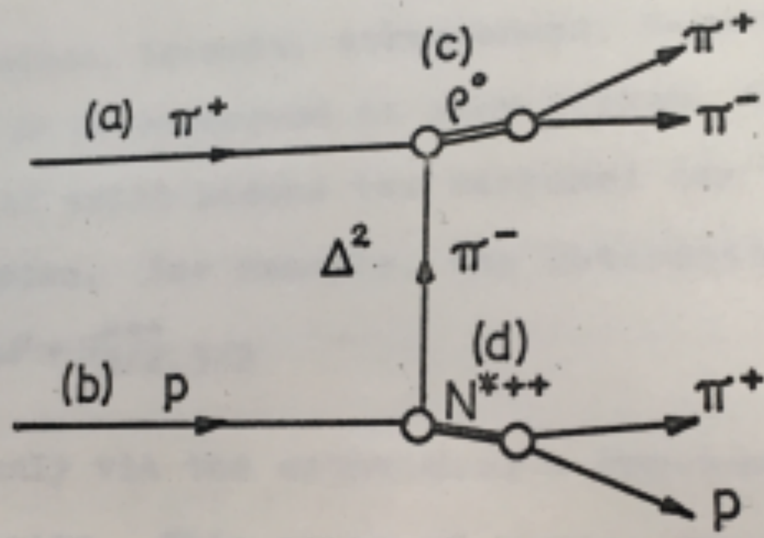


FIG. 5.1 FEYNMAN DIAGRAM FOR THE REACTION

$\pi^+ + p \rightarrow N^{*++} + \rho^\circ \quad (a + b \rightarrow c + d)$

$\rightarrow p + \pi^+ \pi^+ + \pi^-$.

Proc. Int. Conf. Cosmic Rays 1965

Studies of the cores of extensive air showers*

A. D. BRAY, D. F. CRAWFORD, D. L. JAUNCEY, C. B. A. McCUSKER, D. MELLEY, D. NELSON, P. C. POOLE, M. H. RATHGEBER, S. H. SEET, J. ULRICHS, R. H. WAND and M. M. WINN

Cornell-Sydney University Astronomy Centre, University of Sydney, Sydney, New South Wales, Australia

At Sydney there was an 8 x 8 scintillator array triggered by Geiger counters

Showers with one core: proton. With two cores: deuterium

(iii) The rate of deuterium in the primary beam above 1.1×10^6 GeV is

$$(9.6 \pm 4.6) \times 10^{-7}\ \mathrm{m^{-2}\ sec^{-1}\ sterad^{-1}}$$

giving an H/D ratio in the energy range 1.1×10^6 to 2.9×10^6 total energy of 0.087 ± 0.042. This corresponds to an amount of matter traversed by the primary beam of

$$5.6 \pm 2.4\ \mathrm{g\ cm^{-2}}.$$

Also talk in Leeds before the ICRC

From discussion in 1965 Conference Proceedings after McCusker's presentation

A M Hillas: I wish to comment on the identification of two-core showers with deuteron primaries. If an alpha particle, for instance, dissociates into four nucleons of equal energy at the top of the atmosphere, these will generally have very different energies half-way down, where they probably generate the detected cascades or at sea level, because of Poisson fluctuations in the number of collisions they have suffered. A simple Monte Carlo calculation, assuming your value of elasticity, shows that even on average the third most energetic nucleon will have only 6% of the total energy, and it quite likely that only 1 or 2 nucleons would be noticeable, either at sea level or halfway down where most of the detected soft component is originated. So many alphas would look like deuterons on this basis.

C B A McCusker: The identification of deuteron primaries is admittedly difficult. For this reason, we rejected 17 out of 20 'good' two core showers. The showers we selected had to have approximately equal electromagnetic cores, with core density of the correct value and one or two well-separated nuclear active particles close to the electromagnetic cores. Selection of two nucleons of equal energy as specifically deuterons is requiring a statistical miracle.

Calculations on the propagation of mesons in extensive air showers

A. M. HILLAS
Physics Department, U

Essentially based on CKP model for collisions

<p$_t$> = 0.32 GeV/c

and

πp collisions treated as pp collisions

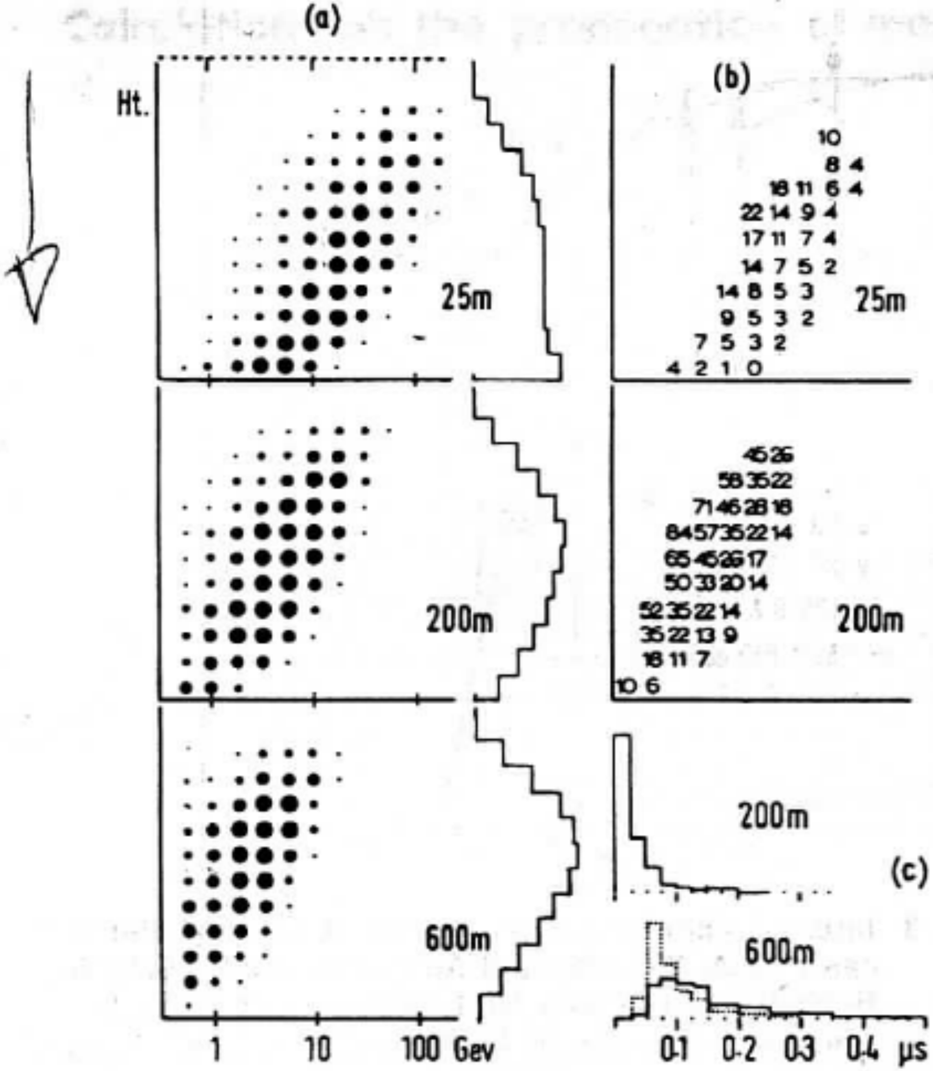


Fig. 4 (a) Distribution in energy and height of production for muons observed at stated axial distances; (b) r.m.s. Coulomb deflections (metres) against energy and production height; (c) muon arrival time delays.

Cosmic Rays in an Evolving Universe 1967

Volume 24A, number 12 PHYSICS LETTERS 5 June 1967

THE ENERGY SPECTRUM OF COSMIC RAYS IN AN EVOLVING UNIVERSE

A. M. HILLAS
Physics Department, University of Leeds, England

Received 20 April 1967

If the most energetic cosmic-ray protons originated in powerfull radio-galaxies, they were probably produced much more abundantly in the past. Their subsequent interactions with the cosmic microwaves could have produced a steepening in the energy spectrum as observed.

Cosmic rays in an evolving universe[1]

ICRC Calgary 1967

A. M. HILLAS
Physics Department, University of Leeds, Leeds, England

Received June 21, 1967

If the most energetic cosmic rays that have been detected are of extragalactic origin, and their sources were strong radio emitters, the radio-astronomical evidence suggests that the output from such sources must have been very much greater in the past than at present, varying roughly as t^{-3} over a long period. In this case, the importance of interactions between the universal flux of microwaves and intergalactic cosmic-ray protons and nuclei above 10^{15} eV is greatly increased, because of "red shifts" in the energies of the nuclei and the microwaves, and changes in density. The probable result is shown to be a steepening in the proton energy spectrum from a slope of -1.5 to -2.2 over the range 10^{16} to 10^{18} eV, as is observed, if the energy spectrum at production is always simply $E^{-1.5}$.

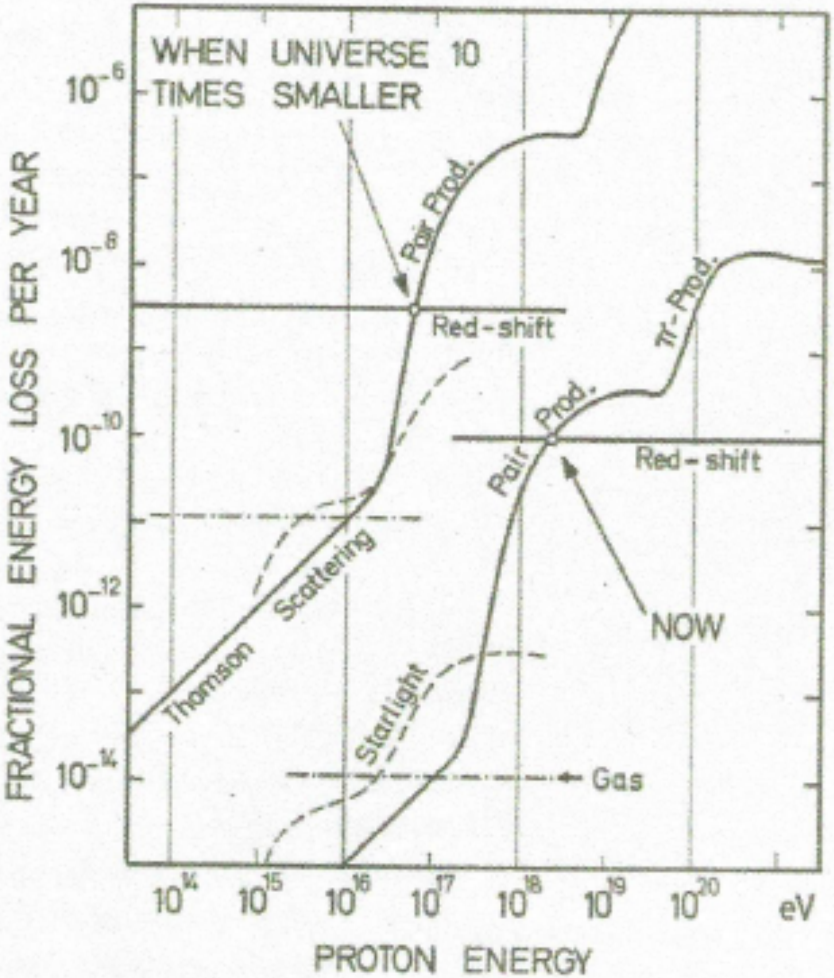


FIG. 1. Energy losses by intergalactic protons.

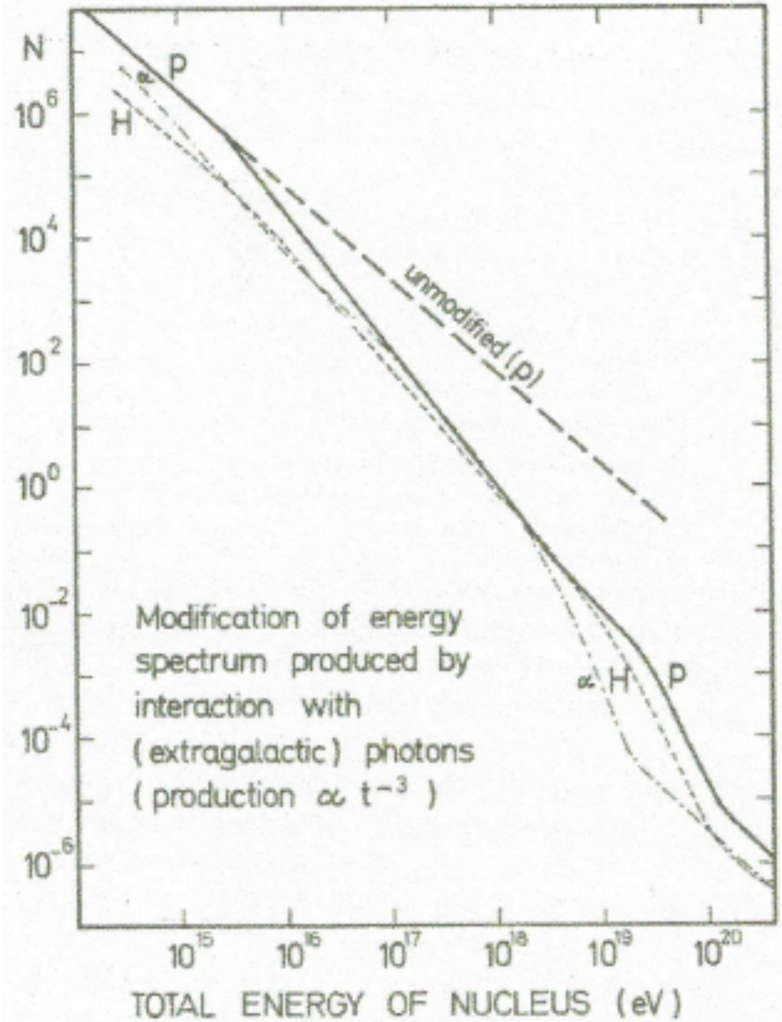


FIG. 2. Present-day spectra of protons (p), α particles, and heavy nuclei (H), predicted if production spectrum is $t^{-3}E^{-1.5}$ (starting at $t = 1.4 \times 10^8$ yr).

HILLAS: COSMIC RAYS IN

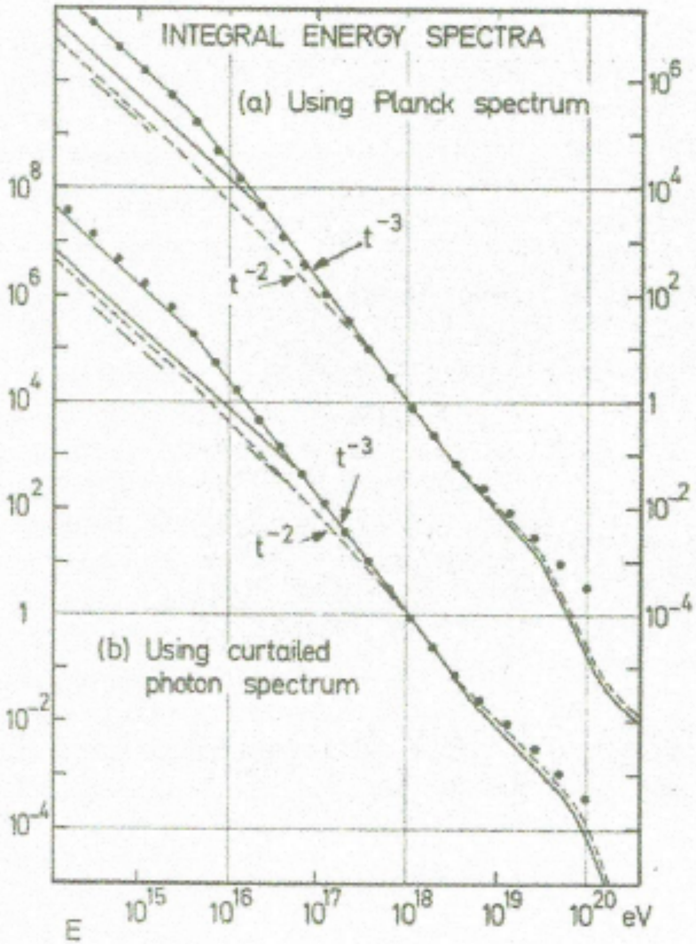


FIG. 3. Energy spectrum of intergalactic protons, if production rate $\propto t^{-2}$ or t^{-3}, starting at $t = 5 \times 10^8$ yr (lower branch of each curve) or 1.4×10^8 yr (upper branch). In case (b) the upper branch assumes production starts at 0.9×10^8 yr. (a) and

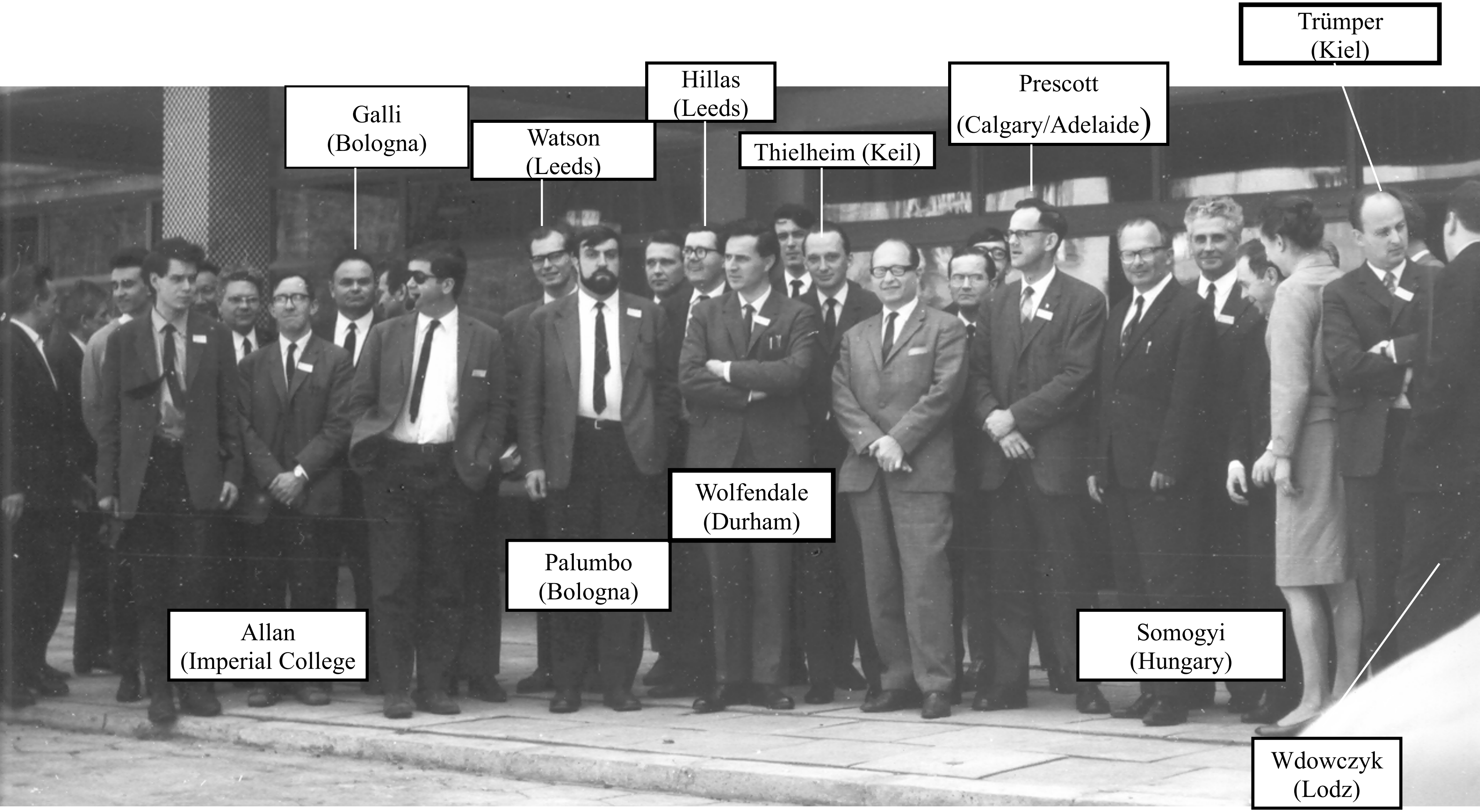
1. Energy taken out of proton spectrum by microwaves should appear in another form

Electrons and positrons of ~10^{15} eV and then through inverse Compton to give γ-rays of 10^{11} eV

First discussion of this?

2. Several times expressed to me that the dip in the spectrum due to pair production was never credited to him.

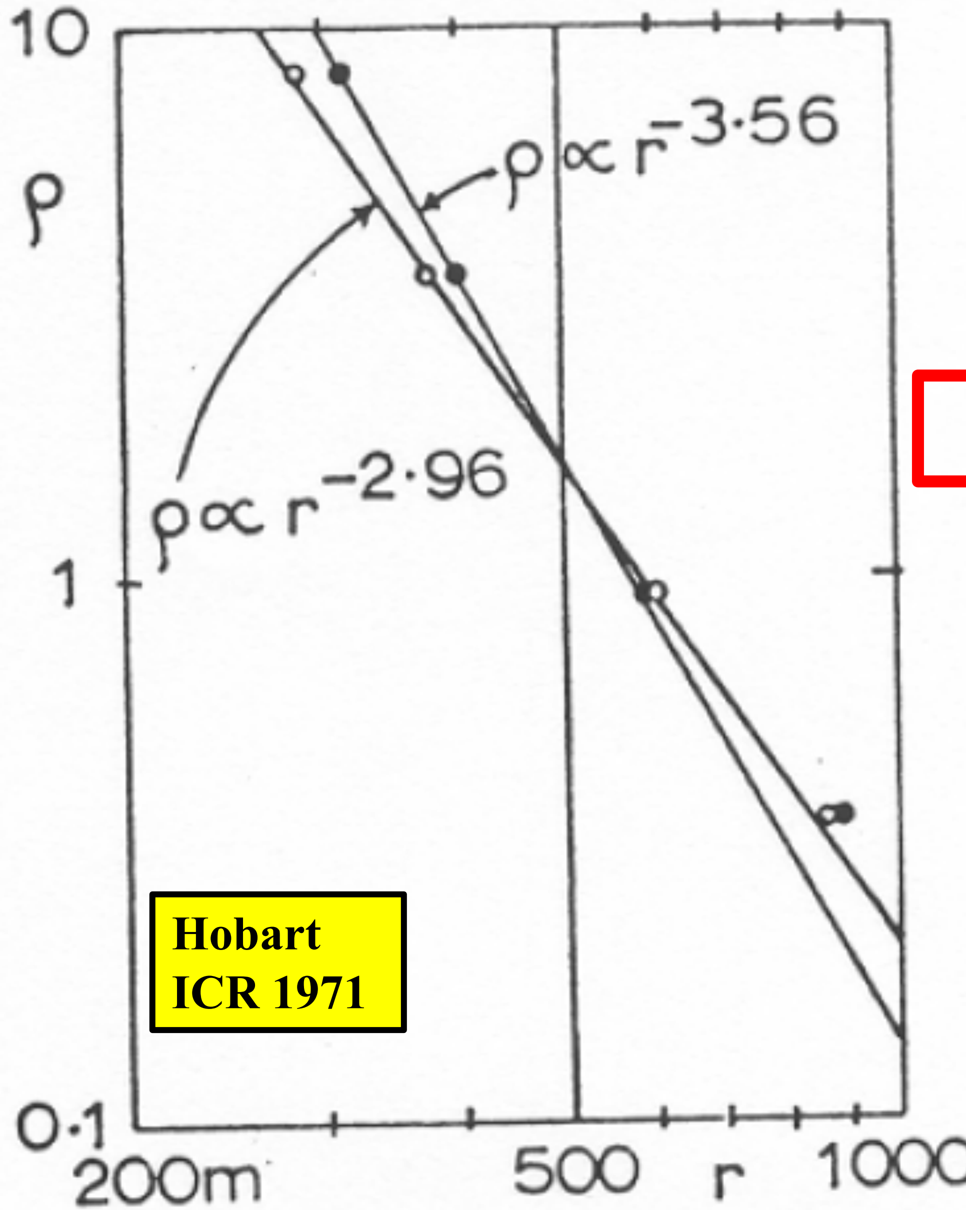
In fact, Hill and Schramm who developed this idea further (Phys Rev D31 564 1985), do give full recognition – but this seems to have been lost subsequently



First European Symposium on High Energy Interactions and Extensive Air Shower: Lodz, Poland April 1968

Proc. 11th Int. Conf. on Cosmic Rays, Budapest 1969

DERIVATION OF THE EAS SPECTRUM



ing the primary … r distribution
First, sta… … of the axis.
has to be assu… sumed $\sim r^{-n}$
In the Haveral… to be deter-
(200 m < r < … Park will
mined empiric… E_{100}, the total
serve as an exa… covering
energy depositi… three outer
the area from … of observed
detectors spac… slightly different
particle densiti… of 50 observed
best-fit core po… differing by 0.6
showers it was … n is probably
typically gave … n were chosen
known to an …

to give an exact … lues of n would
fluctuate much m… , the alternative
fits to the data c… ound usually to
give the same an… the sample exa-
mined ρ_{500} was u… tions. A similar
effect will arise i… h the density is
well-determined depending on the detector spacing.

Haverah Park: $\rho(500)$ and $\rho(600)$ for 500 and 1800 m spacing (empirical)

Auger Observatory: S(1000) for 1500 m array
S(450) for 750 m

Telescope Array: S(800) for 1200 m spacing

IceTop: S(125) for 125 m spacing

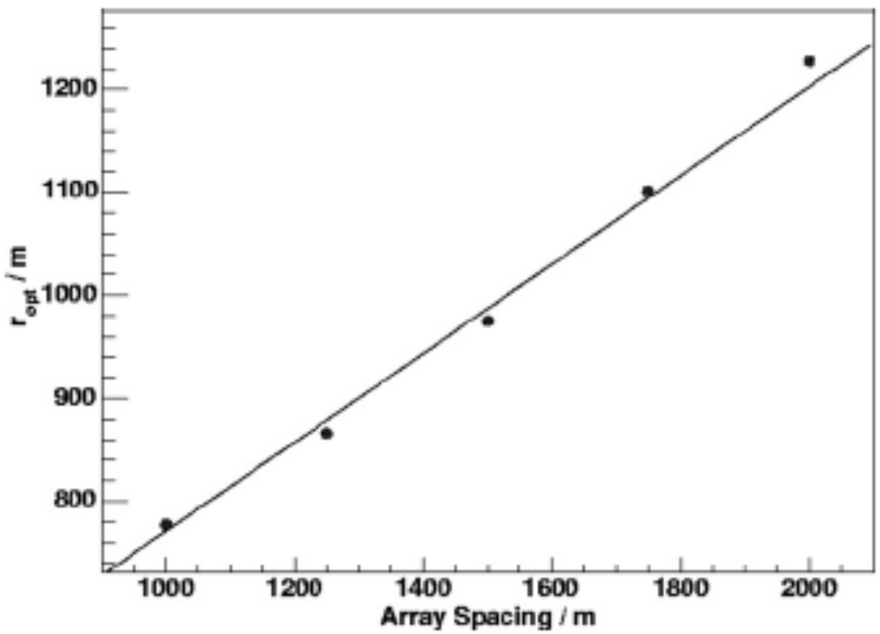


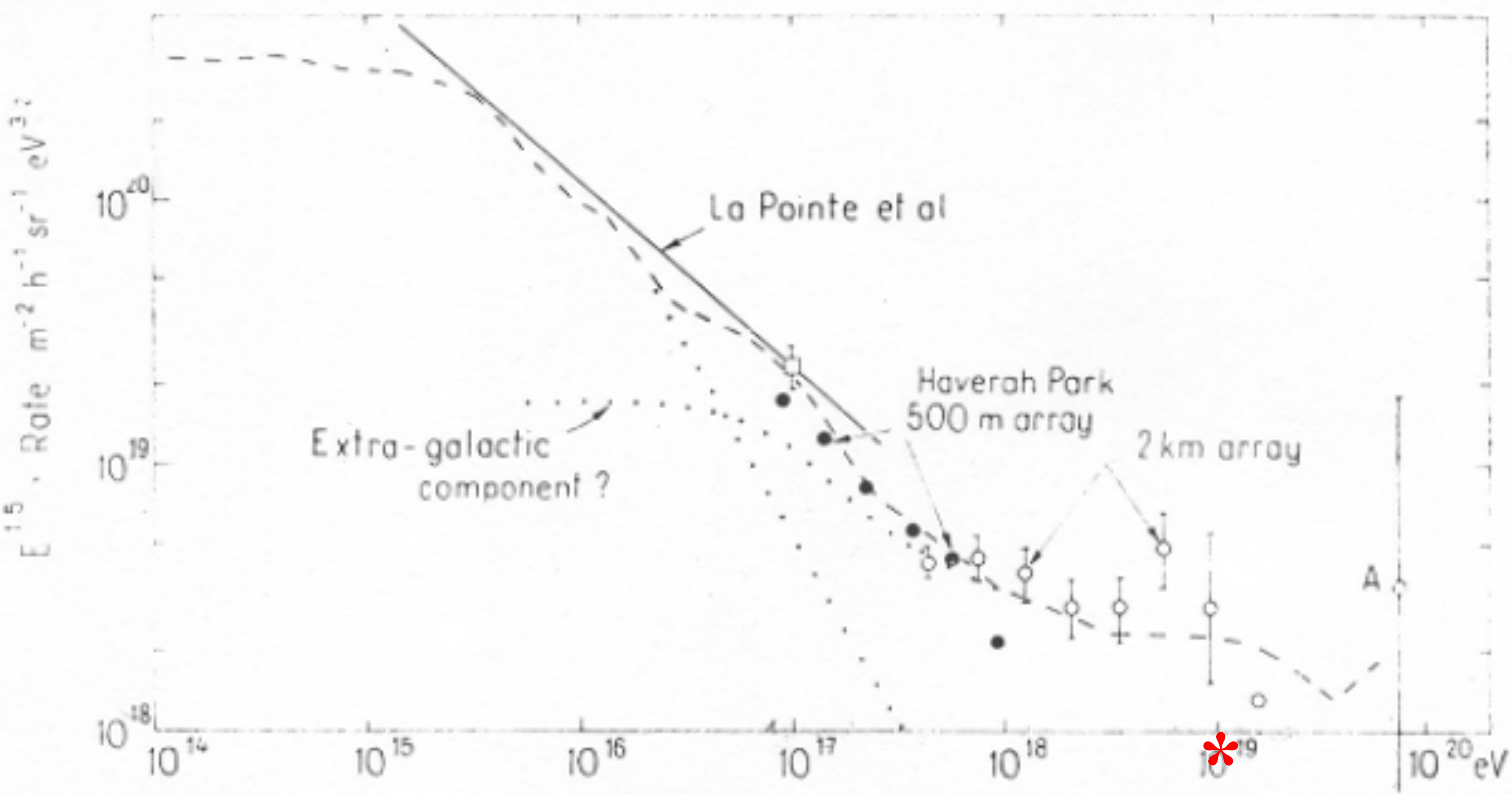
Fig. 6. r_{opt} as a function of the surface array spacing. The uncertainties in r_{opt} are smaller than the points.

r_{opt} from Newton, Knapp and Watson 2007

Table 1

Energy content of showers of two selected sizes

Size N at shower maximum	3.9×10^{6}	7.8×10^{7}
Size N at sea level	6.3×10^{5}	2.0×10^{7}
Ionization above sea level	4.4×10^{15} eV	8.8×10^{16} eV
Energy of soft component at sea level	0.14×10^{15} eV	0.4×10^{16} eV
Energy of hadrons at sea level	0.08×10^{15} eV	0.2 ?
Energy of muons at sea level	0.64×10^{15} eV	1.3×10^{16} eV
Energy of neutrinos (estimated)	0.33×10^{15} eV	0.6×10^{16} eV
Total energy E_p	5.6×10^{15} eV	11.3×10^{16} eV



e primary integral energy spectrum $R(E)$ plotted as $E^{1.5}R$. The dashed line i

Later treatment (1971) of Volcano Ranch data not appreciated by John Linsley!

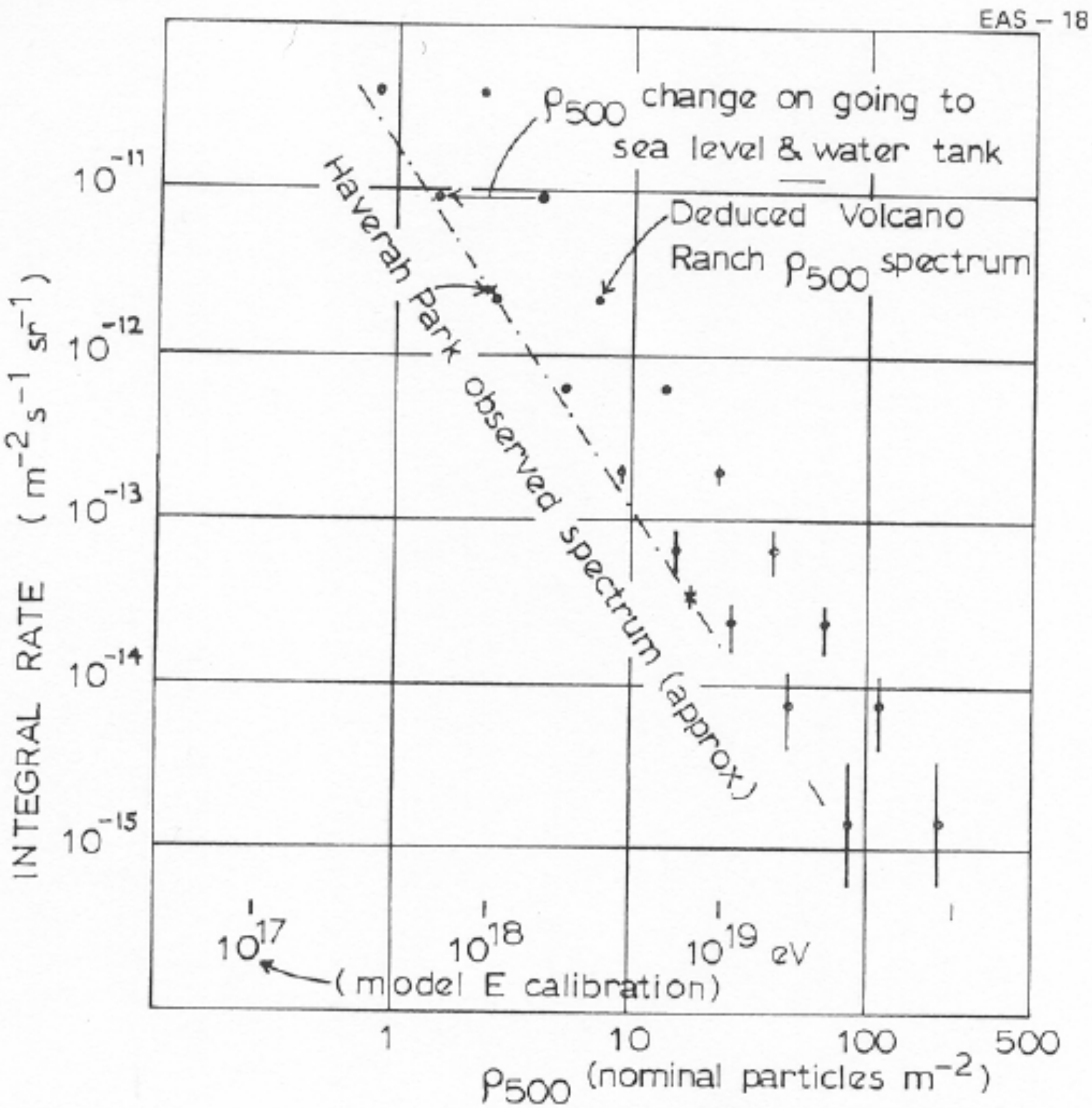


Fig. 3:

Comparison of (adjusted) Volcano Ranch shower size spectrum with Haverah Park shower size spectrum.

$\gamma \approx 2.15.$

Proc. 11th Int. Conf. on Cosmic Rays, Budapest 1969

CALCULATIONS ON THE PARTICLE AND ENERGY-LOSS DENSITIES IN EXTENSIVE AIR SHOWERS AT LARGE AXIAL DISTANCES

A. M. HILLAS, J. D. HOLLOWS, H. W. HUNTER, D. J. MARSDEN

Department of Physics, University of Leeds, Leeds, U.K.

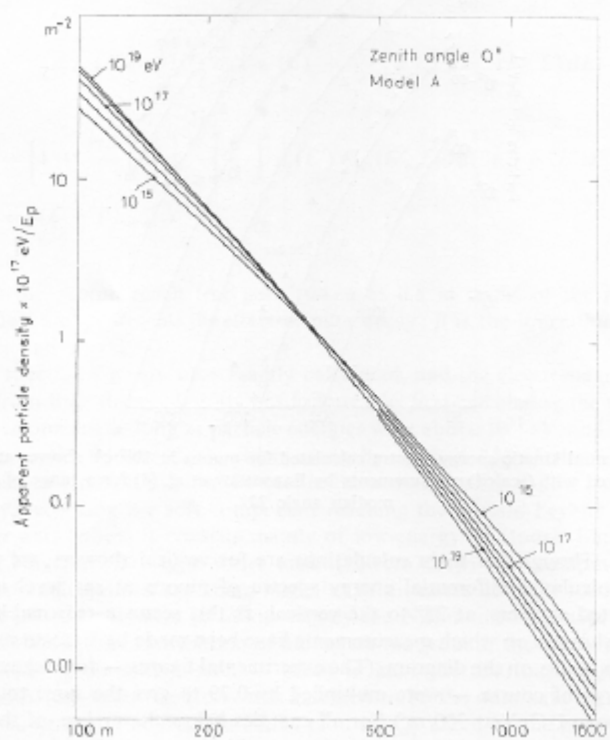


Fig. 2. Lateral structure function calculated for 120 cm water detectors for vertical showers of $E_p = 10^{15}$—10^{20} eV/nucleon. Multiply the density scale by $E_p/10^{17}$ eV

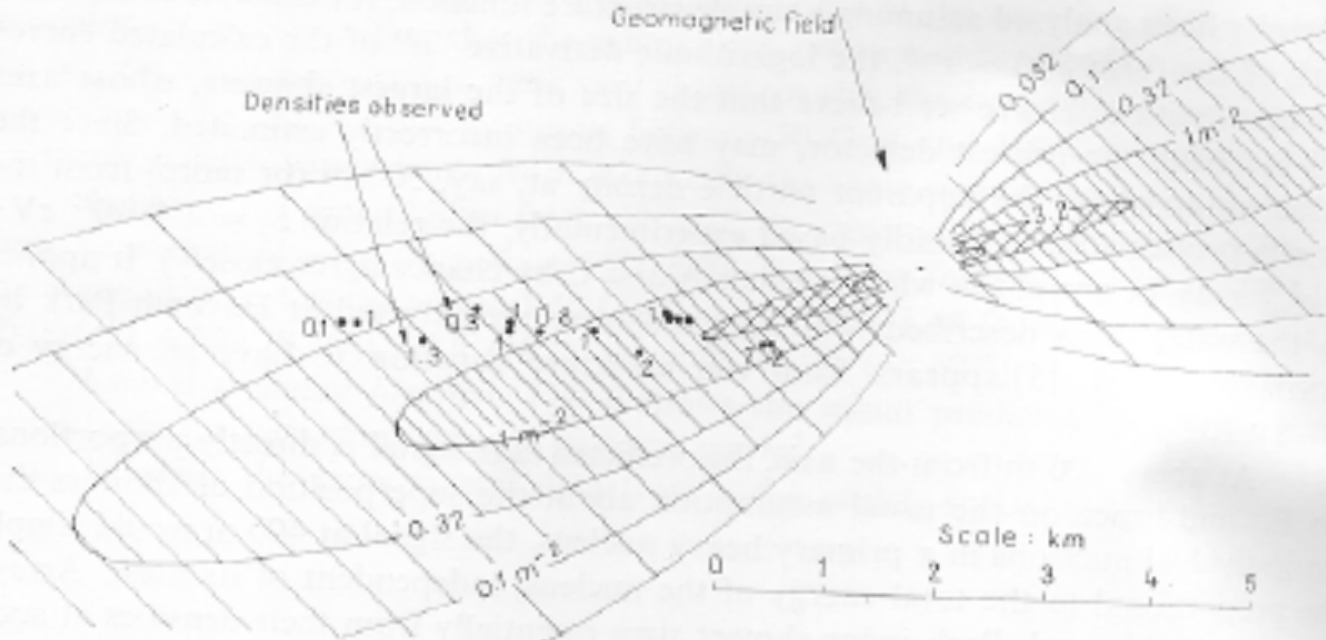


Fig. 3. Muon densities in the plane normal to the axis of a 10^{20} eV shower incident at 85° to the vertical, assuming a geomagnetic field component of 0.466 gauss in this plane. The Haverah Park array is superimposed

$\theta = 85^o$ Nearly uniform densities over 4 km Factor of 2 of 10^{20} eV

New Constraints from Haverah Park Data on the Photon and Iron Fluxes of Ultrahigh-Energy Cosmic Rays

M. Ave,[1] J. A. Hinton,[2] R. A. Vázquez,[1] A. A. Watson,[2] and E. Zas[1]

[1]*Departamento de Física de Partículas, Universidad de Santiago, 15706 Santiago de Compostela, Spain*

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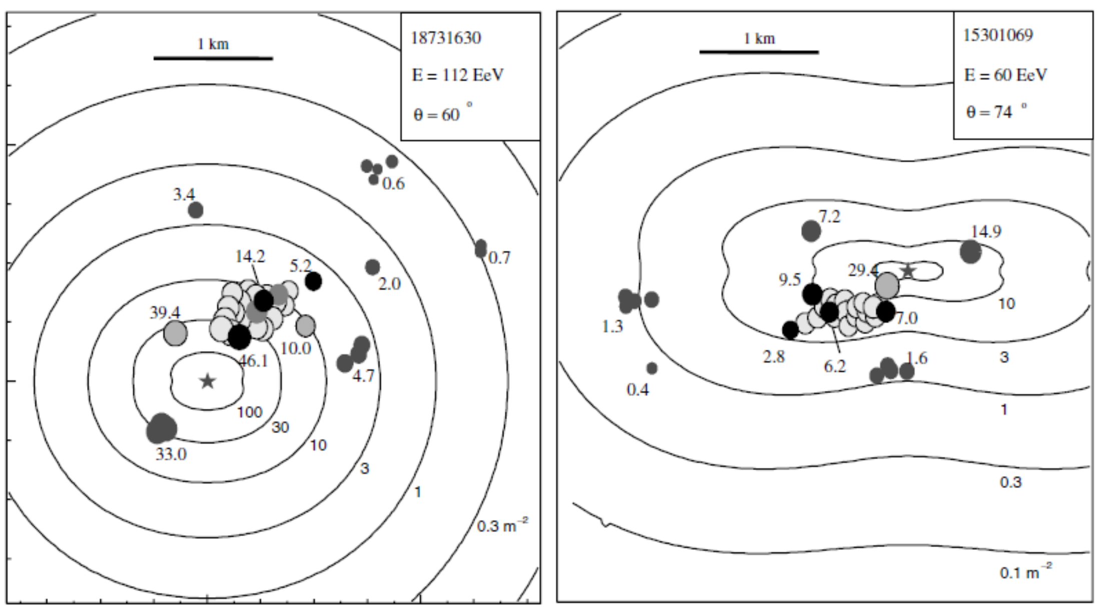
(Received 16 March 2000; revised manuscript received 8 August 2000)

Using data from inclined events ($60° < \theta < 80°$) recorded by the Haverah Park shower detector, we show that above 10^{19} eV less than 41% (54%) of the primary cosmic rays can be photons (iron nuclei) at the 95% confidence level. Above 4×10^{19} eV less than 65% of the cosmic rays can be photonic at the same confidence level. These limits place important constraints on some models of the origin of ultrahigh-energy cosmic rays. Details of two new events above 10^{20} eV are reported.



IG. 1. Density maps of two events in the plane perpendicular to the shower axis. Recorded muon densities are shown as circles

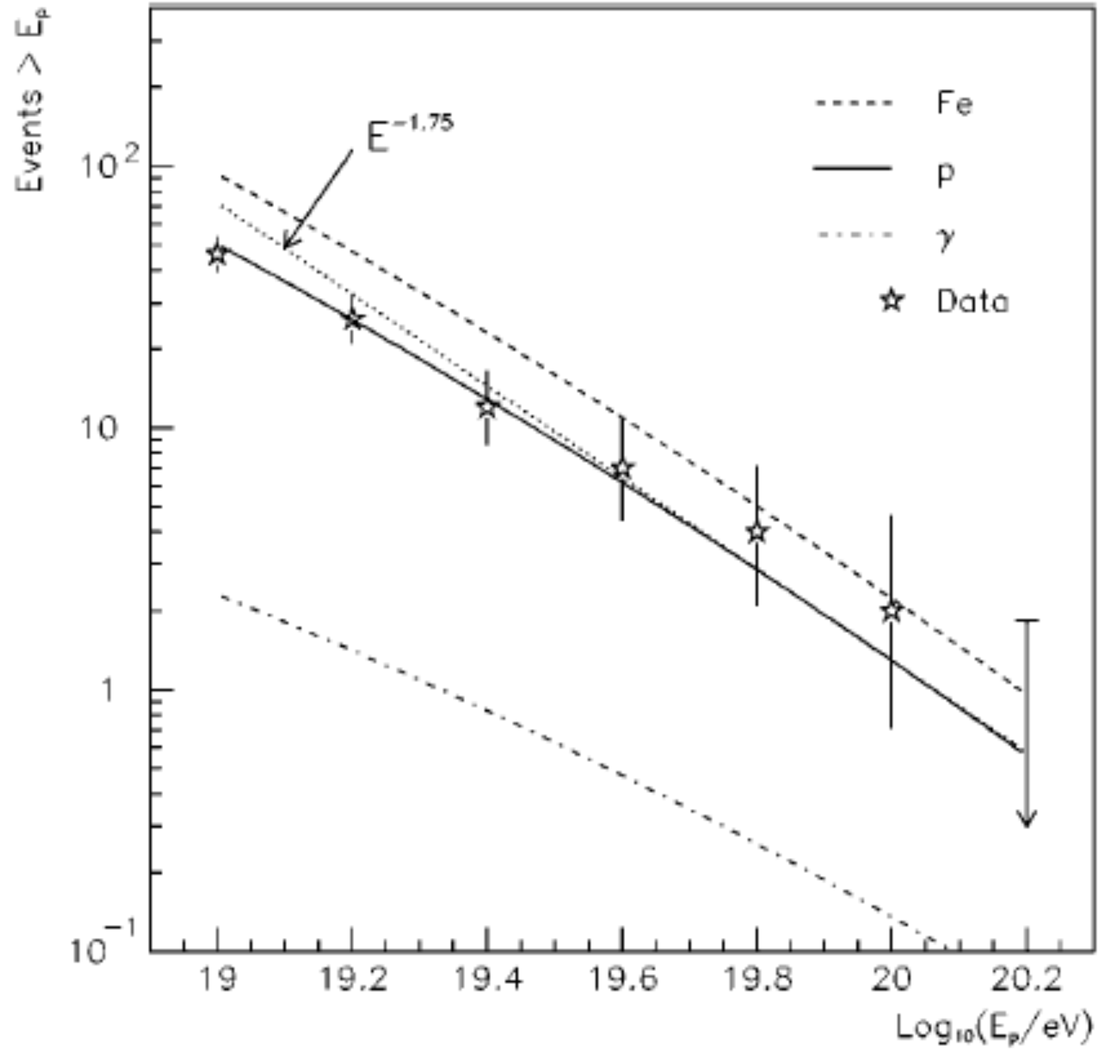
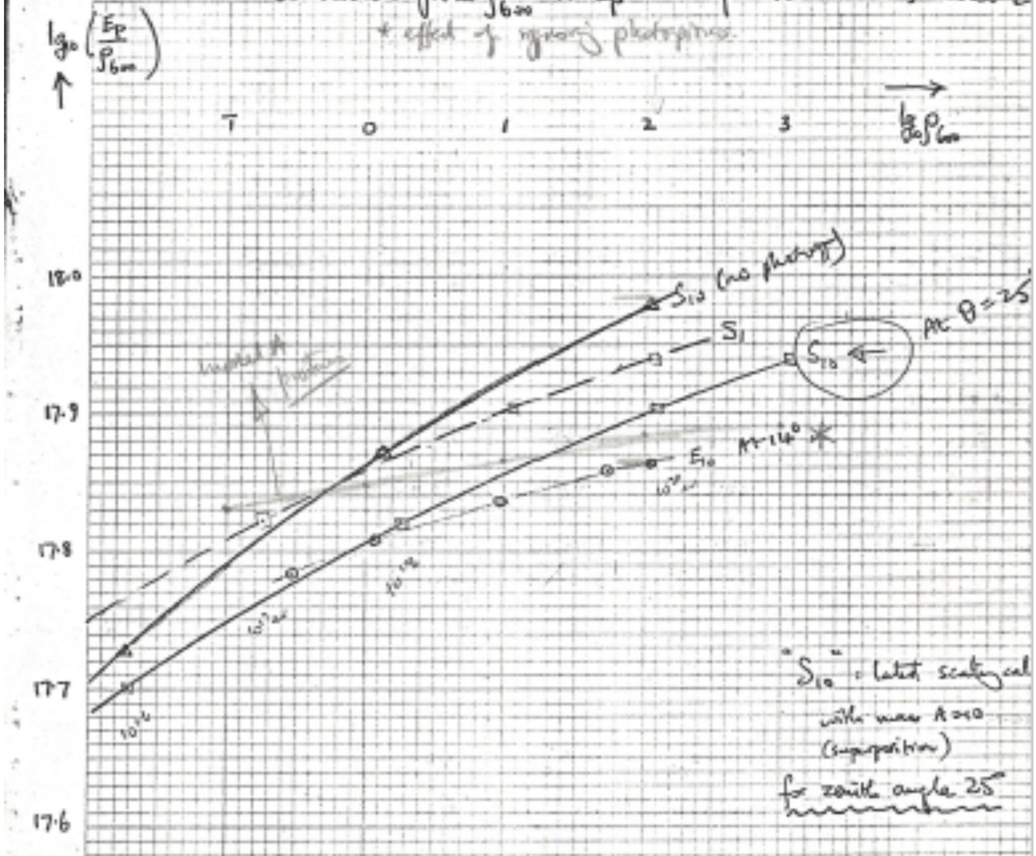


FIG. 2. Integral number of inclined events as a function of energy for the Haverah Park data set compared to the predictions for iron, protons, and photon primaries. Here the energy is calculated assuming a proton primary. The slope of the assumed

Conversion from ρ_{600} to E_p : comparison with Model E

* effect of ignoring photoprimes



In $10^{17}-10^{18}$ eV region, same E_p is required as for model E.

At 10^{20} eV, energies are higher with latest model
↖ but very marginally. (< 10%).

There is very little curvature in the $\rho_{600} \to E_p$ conversion (photons do not have this effect)

✱ (but θ not quite same)

* I must check back on whether Model E figures referred to 14° (the zenith) or 0°.

Seminal Work by 1969 – when just 36

- **Δq: Nature**
- **Fluctuations in showers: ICRC**
- **Understanding of importance of pions: unpublished**
- **Dip at 1 EeV as due to pair-production:**
  Physics Letters *and* ICRC
- **ρ(500): ICRC**
- **Analysis of inclined showers: ICRC**

Work largely reported in ICRC Proceedings: a bad habit!