Understanding the Atmosphere as a Calorimeter for UHE Cosmic Rays

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This contribution discusses the methods to measure the energies of cosmic rays at the extreme upper end of the spectrum. After a short introduction to calorimetry in high energy physics the most important features of extensive air showers (EASs) are described. An EAS is the phenomenon which develops when a high energy particle enters the atmosphere of the Earth. The two methods of determining the energy in the range where ground based detectors have to be used are then described. The contribution ends with listing some of the unsolved problems in the field.

1. Introduction

The observational evidence for ultra high energy cosmic rays and possible ways for accelerating them have been discussed extensively by T. Stanev [1] and R. Blanford [2], respectively. It is the purpose of this contribution to describe and critically review the methods for determining the energy of cosmic ray particles in the energy range where direct detection from high flying balloons or satellites is no more possible and ground-based detector systems have to be used.

Any particle entering the atmosphere of the Earth from space is characterized by the following 8 parameters

position, direction, time,
energy, particle kind

The last item is a discrete parameter determining mass and charge of the incident particle. When these parameters have been measured we know everything we can ever hope to know about it. The 6 observables in the first line can be measured with reasonable accuracy and do not present any serious problem. It is the determination of energy and particle kind which make cosmic ray experiments so complicated and expensive. I will concentrate here on energy although this cannot be completely decoupled from the even more difficult question of determining mass and/or charge of the primary cosmic ray particle.

2. Calorimeters in High Energy Physics

The word 'calorimeter' means different things in different fields of physics and its use in high energy physics is somewhat figurative since no measurement of heat or temperature is involved. Rather than describe the design of high energy calorimeters in general terms I would like to show an example. A compehensive review of calorimetry in particle physics has recently been given in ref. [3]. The calorimeter [4] I want to describe is the one incorporated in the KASCADE [5] cosmic ray experiment and one of the largest ever built if not the largest. It is shown in Figs. 1 and 2 in the centre of the array of detector stations. Its dimensions are about 20 x 16 x 2 m^3 and it consists of roughly 3600 t of iron and another 500 t of concrete. It is subdivided into 8 horizontal plates 12 to 72 cm thick with layers of ionization chambers in between and below. These chambers have a horizontal resolution of 25 x 25 cm^2 (cf. the cross section in Fig. 3). The only purpose of the large mass of material is to force incident hadrons to interact and to do so several times since the total thickness is 11 nuclear interaction lengths, approximately the same thickness as the atmosphere. A high energy hadron will therefore interact somewhere in the calorimeter with effectively 100 % probability and produce a large number of secondary particles which go on to interact again etc. In this way the

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Figure 1: View of the KASCADE cosmic ray experiment [5]. The small huts house detectors for electrons and muons. The calorimeter is the larger building in the background.

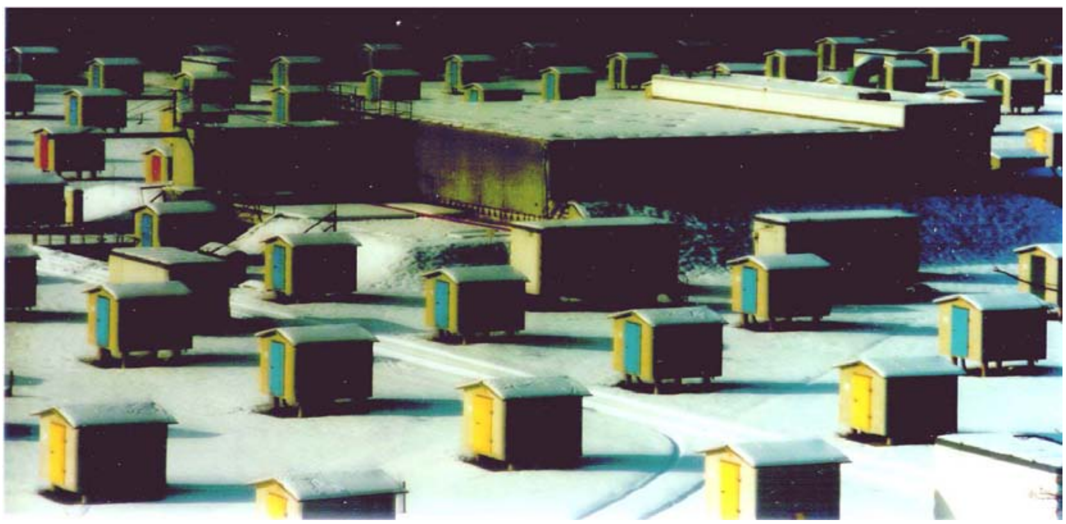

Figure 2: Closer view of the KASCADE calorimeter.

energy of the primary is fragmented into many particles. This process is called a 'shower' and I will discuss it in some more detail when considering the atmosphere. The ionization chambers measure the local energy loss of all these particles. The spatial distribution and the size of their signals is then compared to simulation calculations to deduce the energy of the primary. Fig. 4 shows as an example the response of the calorimeter to a particle whose energy was determined to 67 TeV.

The highest beam energy available from accelerators in the laboratory at present is 1 TeV, at the Fermilab. This will increase to 7 TeV in a few years time when the LHC at CERN will become operational. This will then still be roughly an order of magnitude below the energy derived for the event shown in the figure. Thus there is no chance whatsoever to calibrate such a detector by experiment, rather one has to rely on Monte Carlo calculations. I will come back to this problem later in my talk. It is also obvious that this procedure of measuring energy is rather indirect.

When one wants to measure the energy of a primary cosmic ray particle the atmosphere of the Earth takes the role of the iron and concrete in the calorimeter just described. The cascade of particles which develops there is called

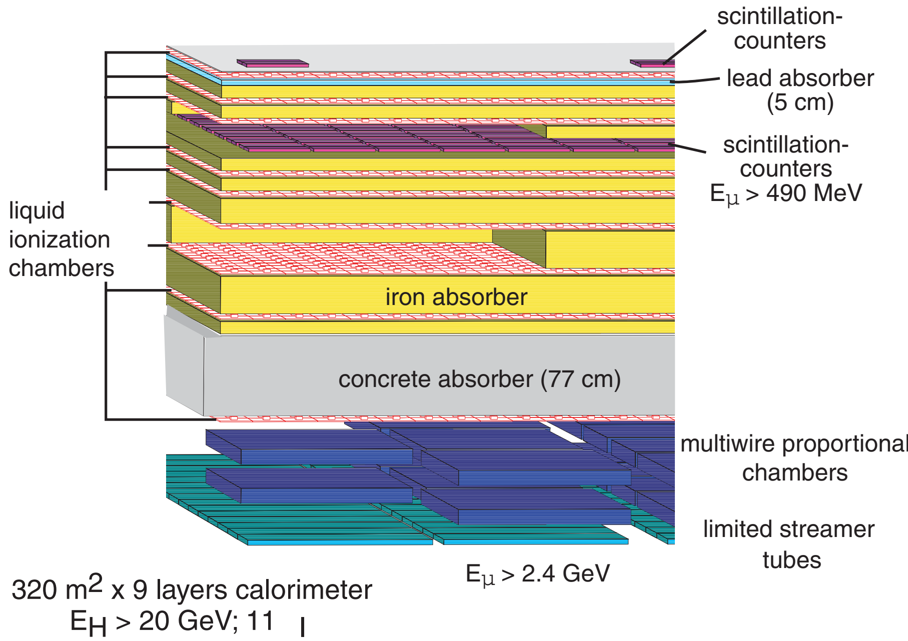

Figure 3: Schematic cross section of the KASCADE calorimeter [4]. The iron plates are marked yellow and the concrete foundation which is part of the calorimeter grey. The ionisaton chambers in between the horizontal layers are marked white and red.

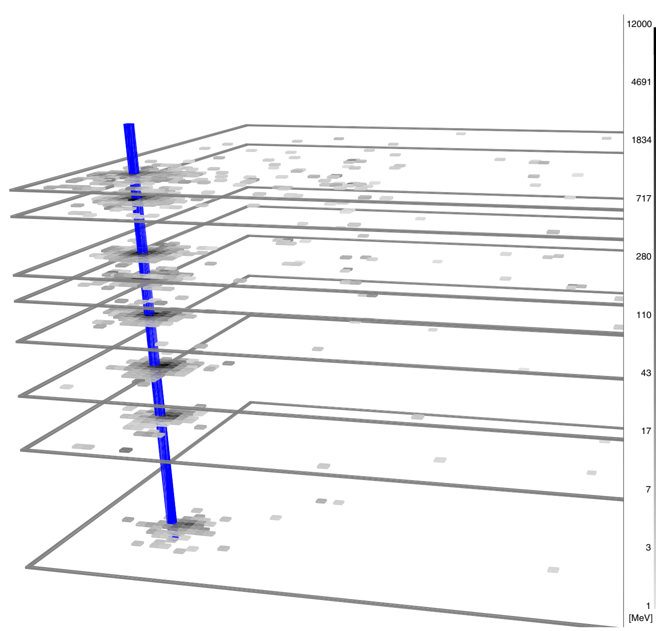

Figure 4: Display of the calorimeter response to a single hadron. Each speck represents one pad of the ionization chambers of size $25 \times 25\ cm^2$. The energy of the event is determined to 67 TeV.

an *extensive air shower* (EAS). We now have to look into this phenomenon in some more detail.

3. A Brief Course on Extensive Air Showers

For a high energy proton the thickness of the atmosphere amounts to about a dozen interaction lengths. So the chance of the proton reaching the surface of the earth undisturbed is completely negligible. Sooner or later it will interact with a nucleus of the air. For primary gamma rays or electrons the interaction length is even smaller by a factor of about 2. At the high energies of interest here a large number of secondary particles will be produced in the interaction.

$$p \; + \; \mathrm{N} \; \rightarrow \; \text{many } \pi\text{'s}, \; \text{K's}, \; \text{nucleons ...}$$

Here N stands for an air nucleus (not necessarily nitrogen). The secondary particles produced in such an interaction will include all sorts of elementary particles among them, if they exist, Higgs bosons and SUSY particles. But the majority will be pions due to their small rest mass. Neutral pions will decay immediately into two gammas which then go on producing electron positron pairs

$$\begin{aligned} \pi^0 \; &\rightarrow \; \gamma + \gamma \\ \gamma \; + \; \mathrm{N} \; &\rightarrow \; e^- \; + \; e^+ + \mathrm{N} \\ e^\pm \; + \; \mathrm{N} \; &\rightarrow \; e^\pm + \mathrm{N} + \gamma \end{aligned}$$

The latter two reactions occur again and again and so the number of electromagnetic particles increases steeply during the initial phase of the EAS. Since about a third of all pions are neutral and pions represent the majority of secondary particles on average almost a third of the primary energy is converted into electromagnetic particles following each interaction of a hadron. Since the cross section of hadron production by a photon is very small hardly any of this energy flows back into hadrons, so the EAS will predominantly consist of γs, electrons and positrons after a few generations of interactions.

The charged pions can either go on to interact with another air nucleus or they can decay

$$\begin{aligned} \pi^\pm \; + \; \mathrm{N} \; &\rightarrow \; \text{many } \pi\text{'s}, \; \text{K's}, \; \text{nucleons ...} \\ \pi^\pm \; &\rightarrow \; \mu^\pm \; + \; \nu_\mu \\ \mu^\pm \; &\rightarrow \; \mathrm{e}^\pm \; + \; \nu_e \; + \; \nu_\mu \end{aligned}$$

The balance between interaction and decay depends on the energy of the pion, which extends their life time due to the relativistic time dilatation, and the local density, with which the probability of interaction increases. Some of the muons may decay into $\mathrm{e}^\pm$ thereby feeding the electromagnetic part of the EAS furthermore. Others will reach the surface of the Earth where they can be detected but their residual energy will be buried underground and escape undetected. Also the energy imparted to neutrinos will be lost.

If all cross sections of the reactions mentioned (and the many more involving kaons, other strange particles etc.) and the relevant decay rates are known it is possible to calculate the development of EAS. This requires Monte Carlo techniques since the final states of such reactions are subject to substantial fluctuations. This has been attempted with increasing sophistication over the last 50 years and I want now first describe the result of such calculations before turning to the question of measurement.

The number of electrons and positrons in an EAS is the quantity measured most frequently, and it is usually referred to as *shower size* N_e. Fig. 5 shows the longitudinal development of this quantity for 50 simulated showers initiated by protons of 1 PeV entering the atmosphere vertically. The general shape of the curves is similar: The shower size first increases steeply, passes through a maximum and then starts to decrease approximately according to an exponential.

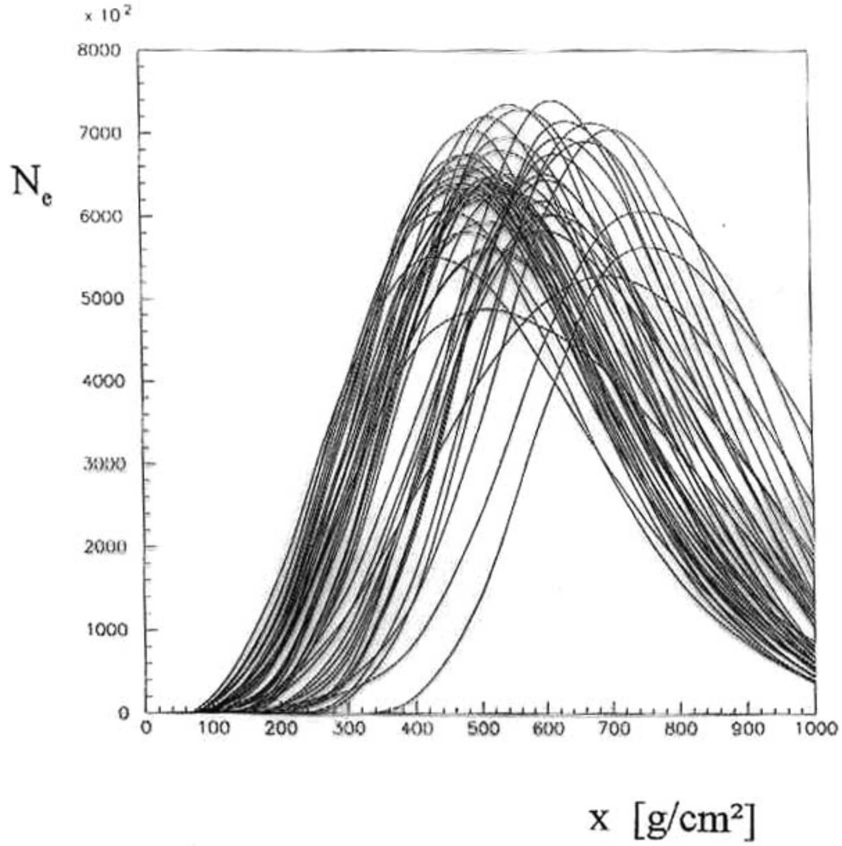

Figure 5: Longitudinal development of 50 simulated EASs. Displayed are the shower sizes N_e for events initiated by 1 PeV protons with vertical incidence versus atmospheric depth. The latter is measured in mass rather than length units.

The decrease is due to the fact that below a critical energy of about 80 MeV ionization becomes more important than bremsstrahlung and electrons and positrons lose their residual energy fast and fall below detection threshold. But there are considerable fluctuations. For the same starting conditions the shower size at sea level scatters by at least a factor of 5. In fact, there are even larger deviations from mean shower development as demonstrated in the Fig. 6. It shows the 5 smallest and the 9 largest showers at sea level out of a sample of 500 simulated ones. The small ones all develop somewhat earlier than the mean but their shape is in no way exceptionate. Six of the large showers by chance start very deep in the atmosphere and therefore attain the maximum near sea level (one of them in fact below). The remaining 3 exhibit a very funny shape. They do not start exceedingly deep but their longitudinal shape is double humped and their maxima are also close to or even below sea level. These are rare but perfectly reasonable events. Their first interaction is diffrative and the primary proton looses only a small fraction of its energy. The leading (i. e. highest energy secondary) particle emerging from this collision then by chance makes a big step before interacting a second time and the main part of the shower only starts very deep in the atmosphere.

One may ask whether such exceptionate showers at the level of 1 or 2 % really do matter. For the large showers the answer is clearly: yes, they do. This is due to the spectrum of primary cosmic rays which decreases steeply with energy. Showers which appear much larger in shower size than the average of all showers of the same primary energy will be attributed a higher primary energy and then they show up in a part of the spectrum where the primary intensity is much smaller. A small fraction of low energy events leaking to higher shower size may then fake a sizable part of events at higher energy.

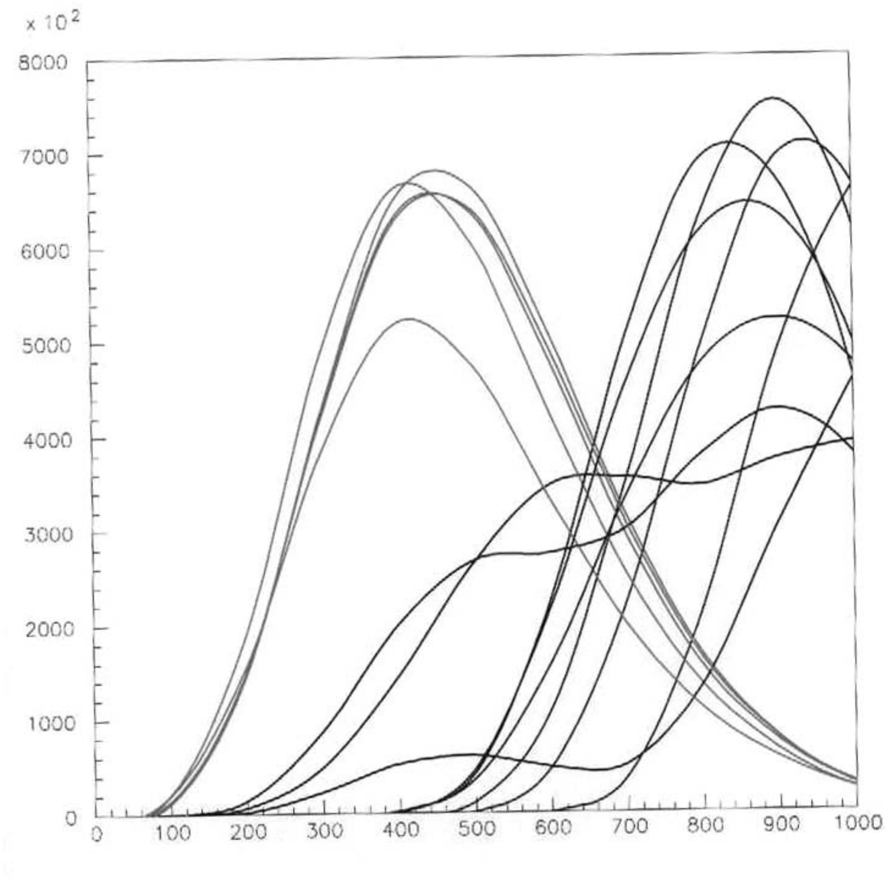

Figure 6: Longitudinal development of the 5 smallest and 9 largest EASs (at sea level) from a sample of 500 simulated ones. Displayed is the shower size N_e versus atmospheric depth in g/cm^2.

It should be mentioned that these large fluctuations are characteristics of EASs initiated by protons. Fig. 7 shows the longitudinal development of 50 showers induced by Fe nuclei. Here the fluctuations are markedly reduced. This is an effect of averaging. The total binding energy of an iron nucleus, approximately 0.5 GeV, is very small compared to the c.m.s. energy of the collision and can therefore, to first approximation, be neglected. Then an iron induced EAS can be considered as the superposition of 56 EASs initiated by nucleons with an energy smaller by a factor of 56. Therefore a considerable part of the fluctuations are averaged out.

To summarize, the main characteristics of an EAS are

- Complete fragmentation of primary energy
- Energy flows from hadrons to electromagnetic particles.
- Some energy is lost due to neutrinos and muons.
- Huge fluctuations

4. How to observe EASs

In the calorimeter described above particle detectors can be placed at arbitrary positions. This is obviously impossible in the atmosphere. There are two ways to sample an EAS:

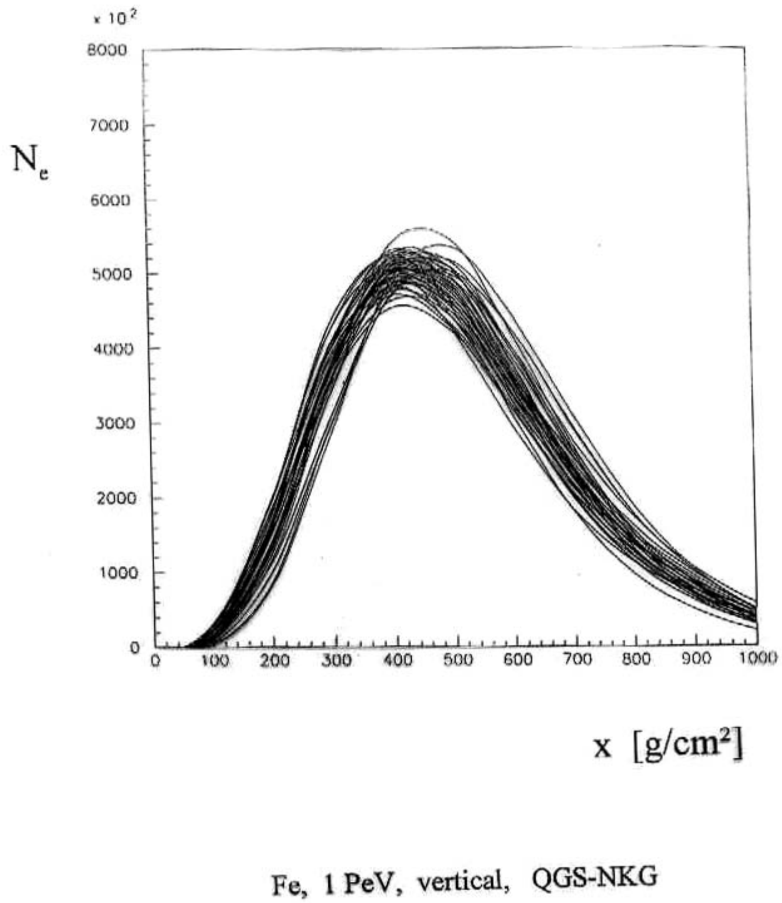

Figure 7: Longitudinal development of 50 simulated EASs. Displayed are the shower sizes N_e for events initiated by 1 PeV iron nuclei with vertical incidence versus atmospheric depth. The term QGS-NKG refers to the interaction models employed for simulating hadronic and electromagnetic interactions, respectively.

The detectors registering the secondary particles can either be placed on the surface of the Earth, usually in a regular pattern. This **ground array** method is the traditional way exemplified by the KASCADE experiment shown above. Each of the small houses seen in Fig. 1 contains a detector for electrons. From their signals the horizontal electron distribution can derived and integrated to give the total electron number.

But, as we have seen above, this is not related to energy in an unambiguous way. One has therefore to look for additional information to distinguish the various types of showers shown in Figs. 5 and 6. The shower observables most suitable for this purposes are the shape of the electron lateral distribution and the number of muons. The first one of these can be derived from the various detector signal of the array and so requires no additional detectors. The lateral distribution is very steep for showers in their early stage of development and gets flatter near maximum and beyond[1]. The longitudinal development of the total muon number is shown in Fig. 8 for the same showers as

[1]This behaviour has led to the habit to call the numerical parameter describing the steepness of the lateral electron distribution the *shower age.*

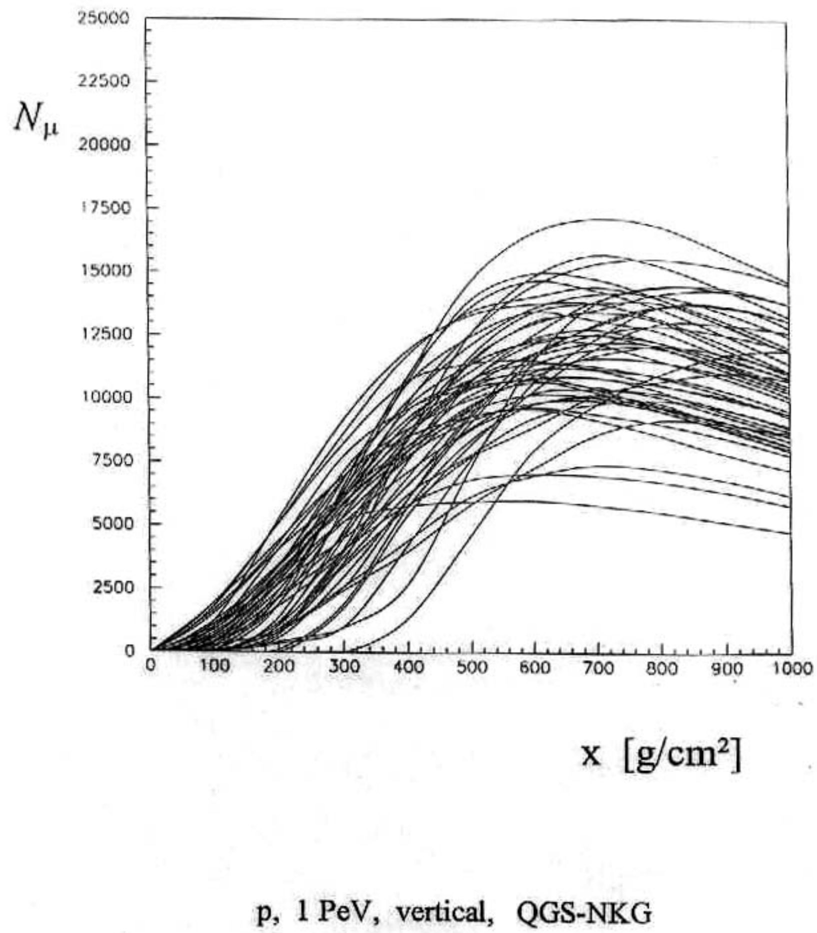

Figure 8: Longitudinal development of 50 simulated EASs. Displayed are the muon numbers for events initiated by 1 PeV protons with vertical incidence versus atmospheric depth. Please note the difference in shape as compared to the electron numbers displayed in Fig. 5.

displayed in Fig. 5. The muon number reaches its maximum a bit deeper in the atmosphere and then decreases slower. So the electron to muon ratio decreases during the late phase of shower development. Unfortunately both these additional observables also depend on the character of the primary particle. If it is a nucleus, as expected, both depend on its mass. Therefore the analysis becomes more complicated and depends on more details of the simulations.

The second method, pioneered by the Fly's Eye group in Utah, observes the EAS optically and registers the **fluorescense light** emitted when the cloud of particles traverses the atmosphere. The many charged particles in the EAS excite nitrogen molecules which then deexcite by emitting photons mainly in the near ultraviolet. An EAS therefore represents a kind of dim shooting star which can be observed optically. The technique of measurement is illustrated in Fig. 9 which shows the famous FLY'S EYE experiment [7], the first one of this kind. The sky is observed by a large number of fixed spherical mirrors each with an array of photomultipliers in the focal plane. Each multiplier observes a certain spot on the sky and the amount of light and its arrival time are registered. Here one observes the longitudinal development and hence is able to integrate the emitted light along the shower path. The relation between light intensity and local energy loss of the shower particles is subject of intense study at present mainly by groups associated with the AUGER experiment [9]. All results obtained so far appear to indicate that

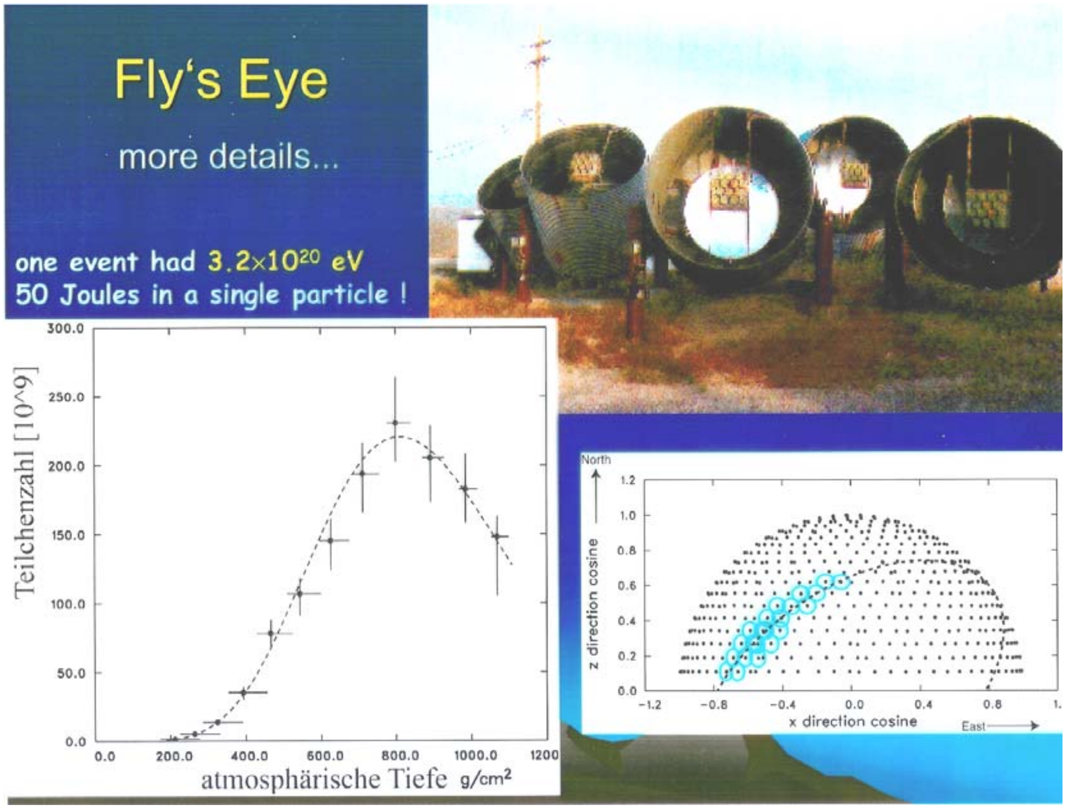

Figure 9: Principle of the FLY'S EYE experiment to observe EASs via fluorescence light [7]. The upper right panel shows some of the imaging mirrors with their photomultiplier arrays in the focal planes. The lower right panel illustrates the principal of the measurement. Each dot represents the center of a field observed by one of the photomultipliers and the blue curves indicate the signals obtained from an individual shower. In the lower left the observed longitudinal development of the highest energy event ever registered is displayed [8].

both quantities are proportionate to each other. Then the total energy deposited by the shower can be determined. This number fluctuates considerably less than the electron number at a fixed atmospheric depth (though it still does). But the integrated light in any case renders a firm lower limit to the primary energy and this is independent of simulations and on the kind of primary particle.

Nevertheless a few potential problems of this way of observing EASs should be mentioned. First, the light signal is rather weak therefore only events of very high energy can be observed. Second, observations are only possible in dark nights and with a clear sky, therefore the duty cycle of observation is hardly larger than 10 % even at the most suitable observation sites. It is also important to measure the distance between shower and telescopes reliably since the fluorescence light is emitted isotropically. If this distance is overestimated so is the primary energy. All fluorescence light detectors now in operation or under construction therefore consist of two or more stations as illustrated in Fig. 10 in order to improve the accuracy of distance determination.

It should be mentioned that there is another kind of light emitted by the EASs, Cherenkov radiation. This is produced by electrons moving faster than the speed of light in air and is concentrated in a cone in the shower direction. It will therefore only be registered if the shower points towards the telescopes which will not frequently be the case. Cherenkov light is very useful for measuring cosmic γ rays in the GeV to TeV range [13]. For the observation of EASs via fluorescence light it is more of a nuisance because it can be scattered towards the detectors and this has to be corrected for to avoid an overestimation of the primary energy.

It is worthwhile to discuss how the anomalous EASs displayed in Fig. 6 appear when seen by a fluorescence detector. The small showers cannot be distinguished from showers initiated by primaries of lower energy. This will

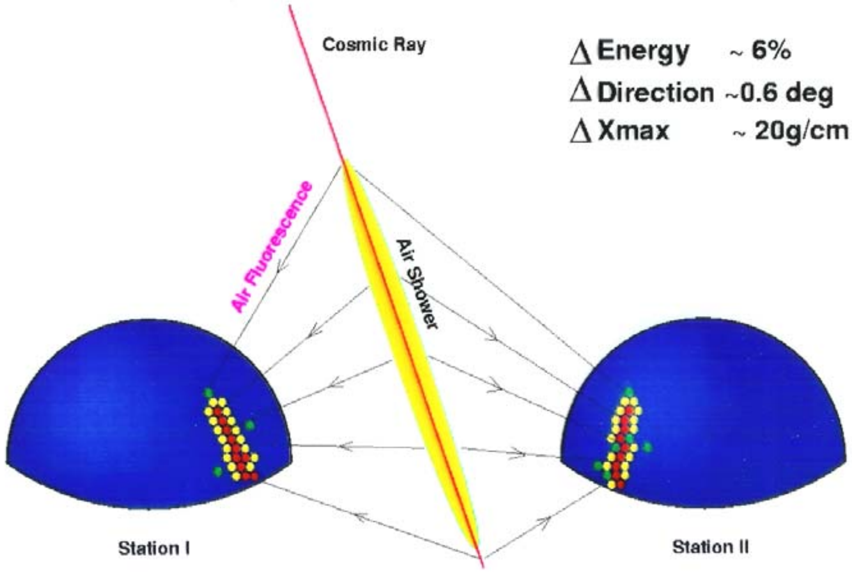

Figure 10: Principle of the stereo observation of the fluorescence light emitted by an EAS.

lead to a distortion of the derived spectrum which can only be corrected for by taking recourse to simulations. The showers developing late would also appear too small but observation would indicate that they dip into ground and one would therefore be warned. The double humped showers are very interesting because they could, if observed, give information on the diffractive cross section at energies much larger than available at accelerators.

The two largest experiments which have yielded the bulk of high energy cosmic ray data, AGASA [6] in Japan and FLY'S EYE [7] in Utah (including its improved successor HIRES FLY'S EYE [10]), represent these two types of experiments. The energy spectra which the two groups derive are in good agreement for most of the energy range (though not quite as good at the extreme upper end of the spectrum) if the relative energy scales are readjusted by about 25 %. This is a remarkable achievement in view of the completely different experimental approaches (and hence also gives credence to the simulations used in their analysis). The AUGER [11] experiment in Argentina which is just beginning to take data, and the TELESCOPE ARRAY [12] under construction in Utah by a Japanese-American collaboration will contain both types of detectors and therefore allow a direct comparison of the two techniques for the first time.

Both types of measurement face a number of different technical problems which are beyond the scope of this talk, though.

The method of determining the energy of a cosmic ray particle by observations from the ground can be summarized by

- The measurement is very indirect. What is measured is not the primary particle but a (usually small) fraction of secondary particles produced in the huge number of interactions in the atmosphere of the Earth.
- It relies for calibration on the comparison of measurements with simulations of the processes occurring in the atmosphere.
- The processes are subject to huge fluctuations which makes this comparison very difficult.

The last item implies that the allocation of energy to an individual event is subject to large uncertainties. This situation prevails especially at the extreme upper end of the observed spectrum.

5. Problems remaining

Simulations of EAS can only be considered reliable if a number of input data are known to sufficient accuracy. These comprise

- Life times and branching ratios of all unstable particles. These are mostly well known and available from the Particle Data Group [14].
- Cross sections of electromagnetic processes. These can be calculated by known methods and most simulation programs make use of the EGS4 program [15] developed at SLAC. It should be born in mind, though, that an EAS of 10^{20} eV primary energy may contain γ rays of 10^{19} eV and it is by no means obvious that first order QED as employed in EGS4 is still adequate at such high energies.
- Cross sections of interactions between all kinds of high energy hadrons and air nuclei. These are obviously not well known.
- A comparison between observations and simulations also requires a detailed knowledge of the density structure of the atmosphere which can be obtained by standard meteorological methods which are not always applied, though.

The crucial item here is strong interactions between shower particles (mostly pions, nucleons and kaons) and nuclei in the air (i. e. nitrogen, oxygen and argon). The safest way to obtain these would be by measurement, of course. But the highest beam energy available in the laboratory today is 1 TeV, at the Fermilab collider. The center of mass energy of two protons of this energy colliding corresponds to a laboratory energy of about 2 PeV in a reference system where one of the colliding particles is at rest. With the operation of the LHC at CERN a few years from now this will increase to 14 TeV or 100 PeV, respectively. This is still short of what is needed for simulating the highest energy events observed by 3 orders of magnitude in laboratory energy. This gap has to be bridged by theoretical extrapolation.

In fact, the situation is even worse. Collider detectors are blind in the direct forward directions. Detecting particles very close to the primary collider beams is difficult (though not impossible). The consequences can be seen in the Fig. 11. The upper part shows the calculated distribution of particles produced in high energy collisions versus rapidity. The latter quantity can be understood as a nonlinear function of the emission angle with particles emitted perpendicular to the collision axis showing up in the center and forward and backward particles at the ends. So the functions shown are essentially angular distributions. The two shaded vertical bands indicate the acceptance of two collider detectors, UA5 at CERN and CDF at the Fermilab. As can be seen both experiments register most of the secondary particles although their fraction decreases with primary energy.

The lower part of the figure shows the energy of all secondaries per rapidity interval. Since the particles emitted in the forward directions have the highest energies the curves now peak there, well outside the detector acceptance. With but a bit of exaggeration one may therefore say that collider detectors register most of the secondary particles but hardly any energy. This situation is essentially unchanged when the transformation into a system is considered in which one of the primary particles is at rest, as is adequate for EASs. For rapidity this means the addition of a constant. Hence in the upper part of the figure the distribution is just shifted horizontally. In the lower part an additional factor has to be applied which increases exponentially with rapidity suppressing one of the peaks (corresponding to the particle at rest in the atmosphere) while the other one is boosted. So almost all of the primary energy in the EAS goes into an angular range on which we have essentially no experimental information even at existing colliders.

Simulations of EASs have therefore to rely on theoretical cross sections and particle distributions for strong interactions at the highest energies. These cannot be calculated exactly at the present state of QCD but are rather based on models which one might be tempted to call phenomenological if this word were not used for calculations which are much closer to exact QCD than the models employed here (the term 'QCD inspired' is frequently used instead).

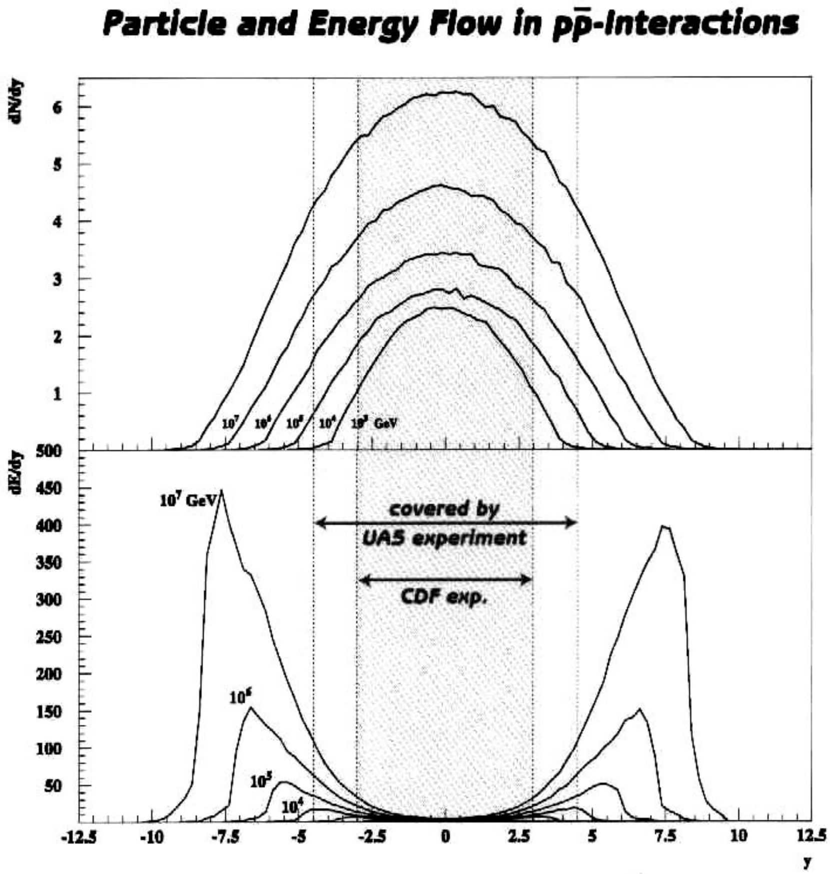

Figure 11: Rapidity distribution of the number of secondary particles (upper panel) and of their integrated energies (lower panel) in simulated high energy proton antiproton collisions.

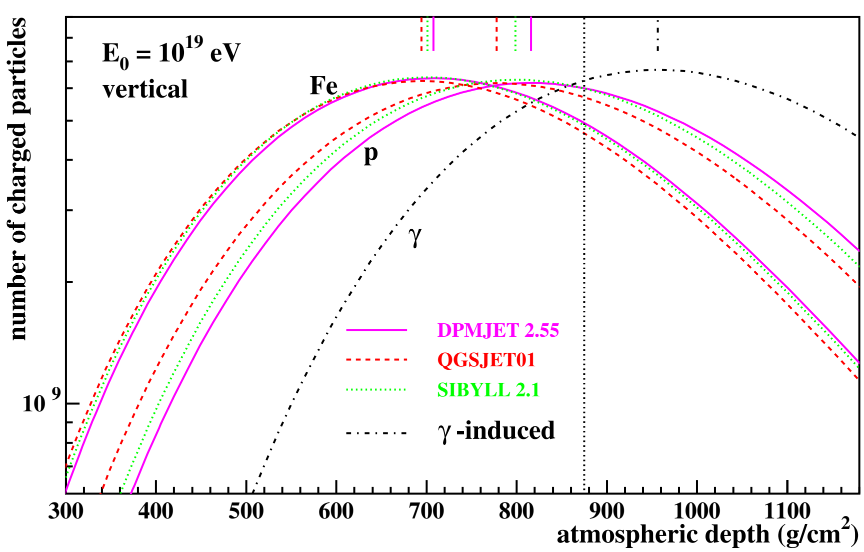

Figure 12: Longitudinal development of simulated EASs calculated with three different interaction models. The curves represent averages of 100 showers each.

Over the last 10 years a lot of effort has gone into the development of such models of which quite a number exist called SIBYLL, VENUS, QGS-JET, DPM-JET,NEXUS etc. [16]. In the same period of time the results of these different models have tended to converge. This shows that model builders have come to agree on what is the best way to perform such calculations. An example for this is demonstrated in the Fig. 12. While this is reassuring it unfortunately does not necessarily imply that they have converged towards reality. There are in fact cosmic ray observations in the PeV range which cannot be described consistently by any of the models available at present. Nevertheless using these models is the best one can do at present.

6. Conclusions

- The two different methods to measure the energy of extremely high energy cosmic ray particles yield very similar results. In view of the completely different systematic errors encountered this is a considerable achievement which gives credence to the results. This should not be underestimated in view of the intriguing differences at the extreme upper end of the spectrum.
- The analysis of ground array data is more sensitive to the systematic uncertainties of simulations although the fluorescence technique is also not immune to this problem.
- The upcoming AUGER and TELESCOPE ARRAY experiments will allow, for the first time, a cross calibration of the two methods of observation and therefore increase the credibility of the results.
- More experimental information on the forward direction from accelerator experiments is urgently needed.

Acknowledgments

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