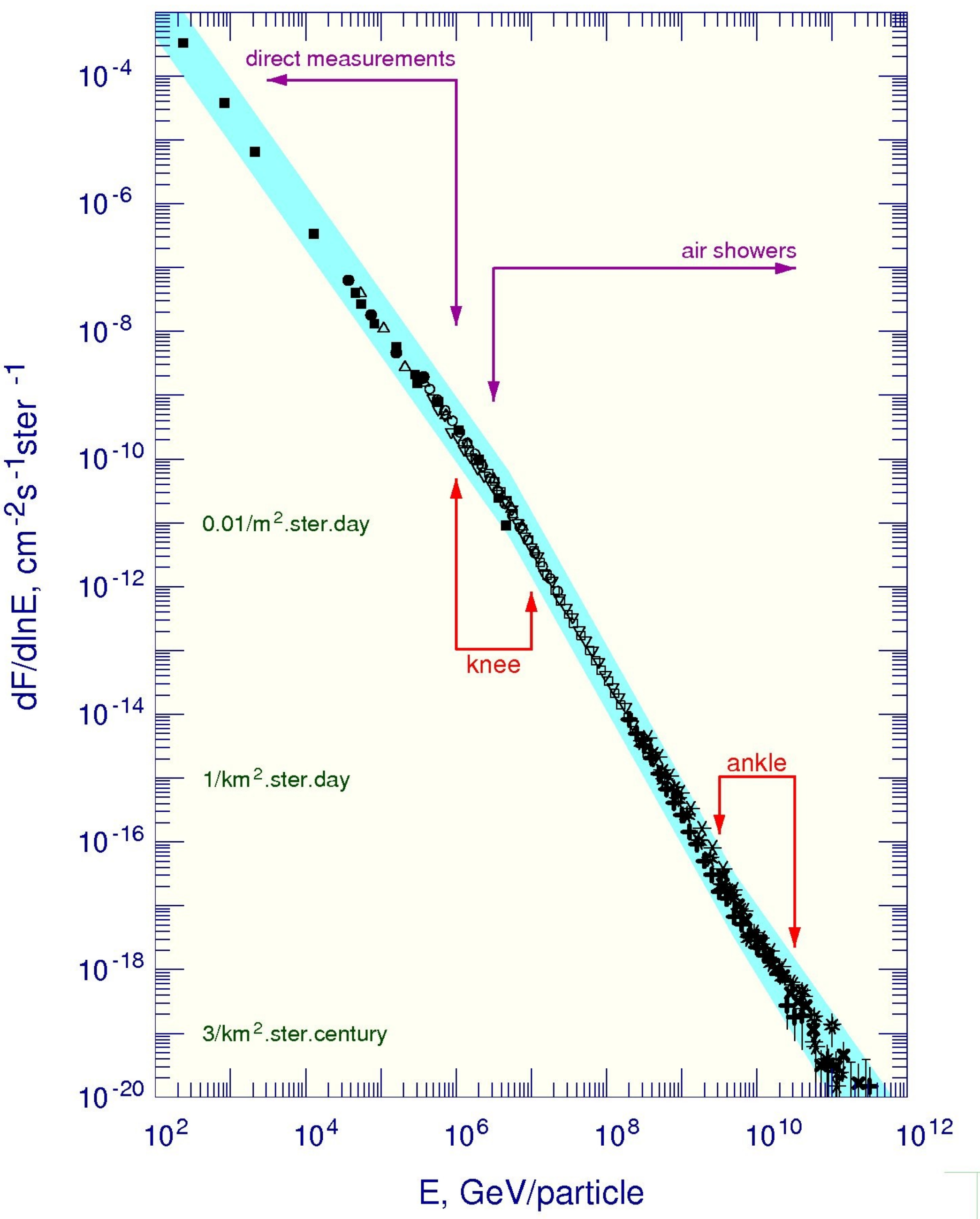
Studies of the Cosmic Ray Composition with Air Shower Data

Todor Stanev
Bartol research Institute
Department of Physics & Astronomy
University of Delaware

Cosmic rays are charged nuclei accelerated outside the solar system. At energies above 1 GeV most of the cosmic rays are accelerated in our Galaxy. In this energy range the cosmic ray flux is dominated by H nuclei, i.e. protons.

The best way to study cosmic rays is to detect them outside the atmosphere and this is done in satellite and high energy balloon experiments. This is not, however, always possible since the flux of cosmic rays is proportional to $E^{-2.7}$. At energies above 100 TeV their flux is is so small that we have to study the cascades they generate in the atmosphere – the extensive air showers.



The equivalent Lab energy of the LHC is 10^8 GeV.
The interpretation of the highest energy cosmic rays events thus requires a long range extension of the hadronic interaction models.

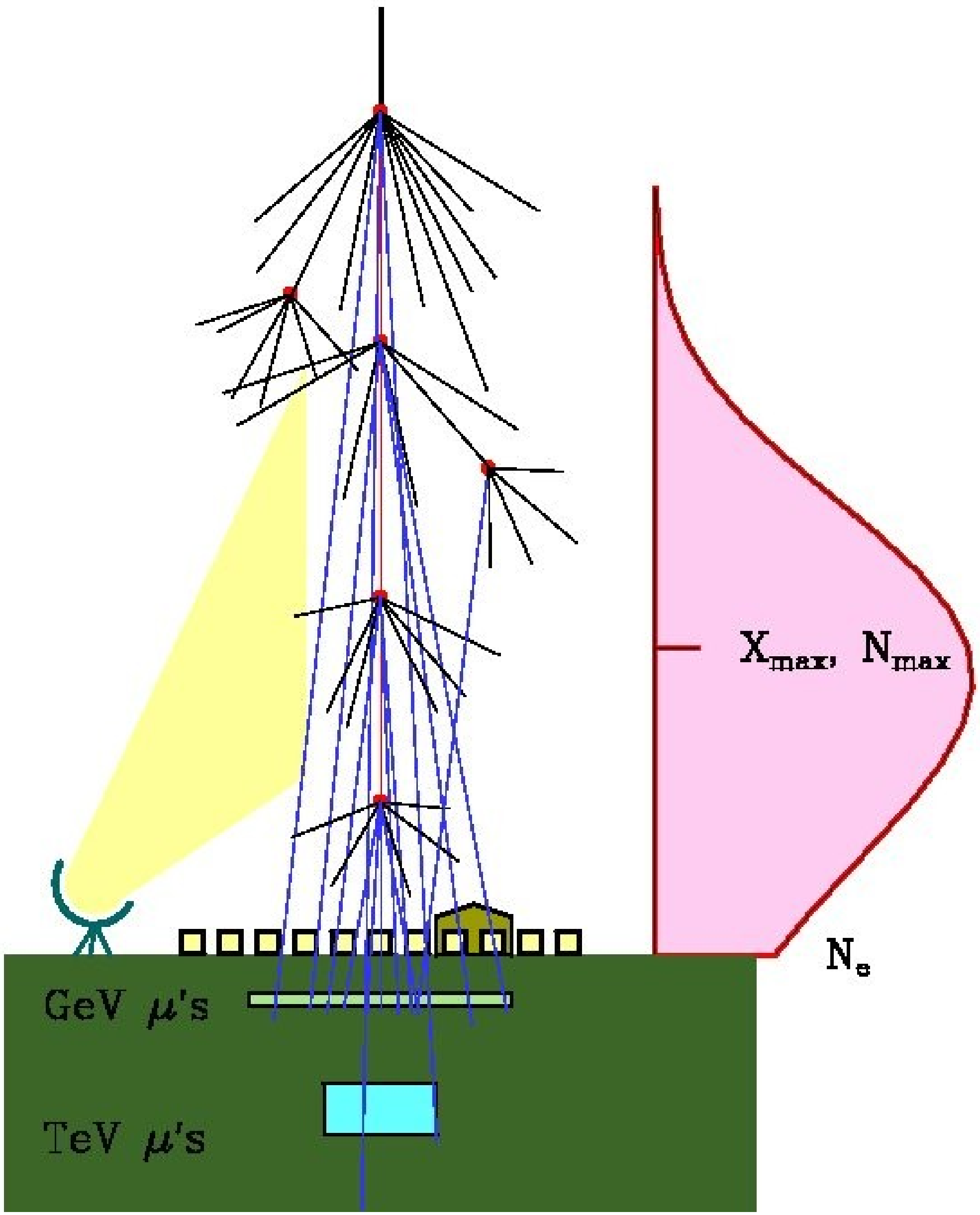
Air shower detection

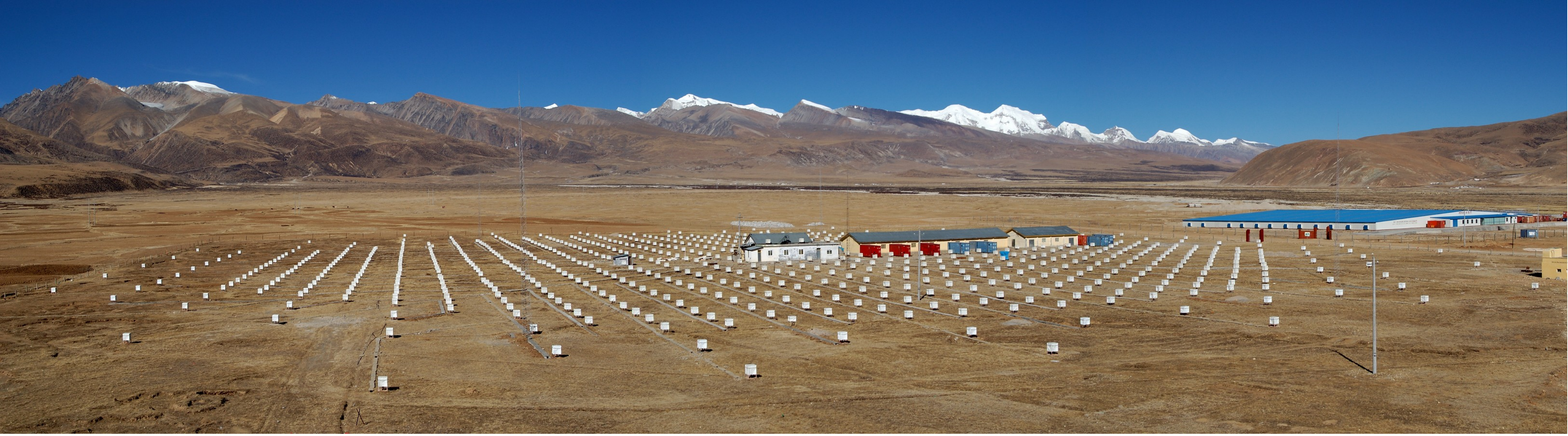
Three main methods:

1) air shower arrays observe shower structure on a single observation level.

2) Cherenkov light detectors: 1.5 degree cone around the particle track.

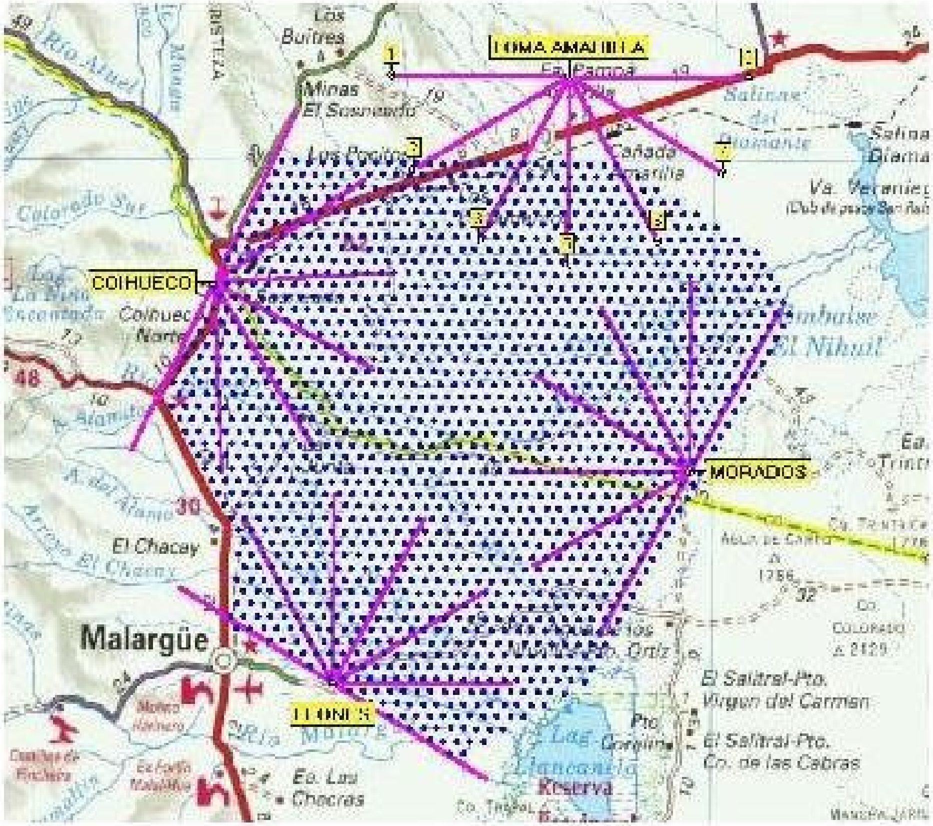
3) fluorescent light detectors: isotropic emission of about 4 photons per meter track at sea level.



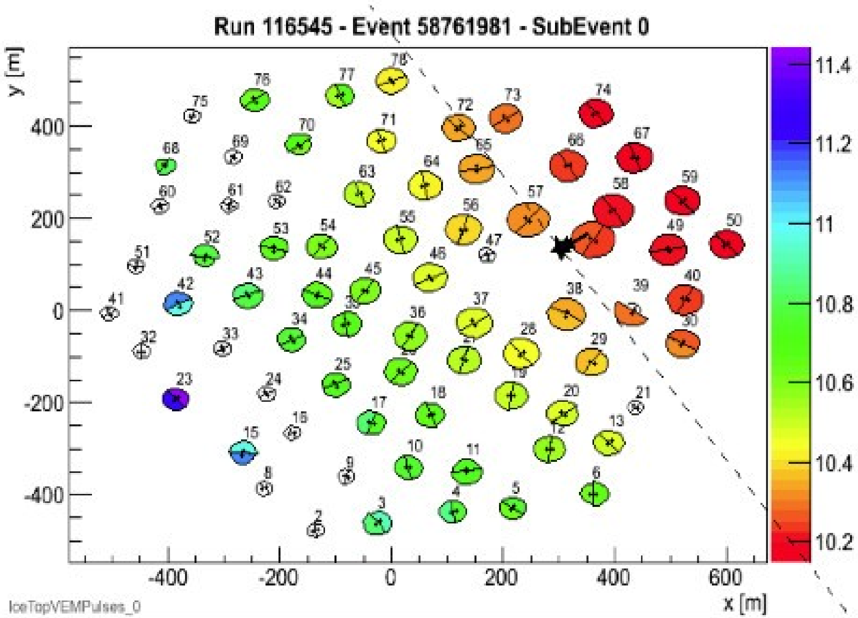


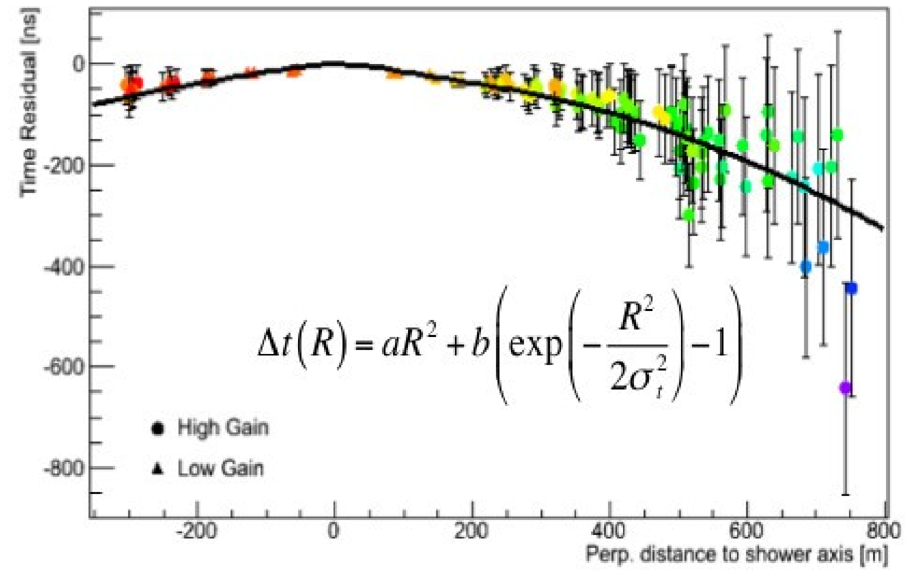
Top: the Tibet III air shower array at an altitude of 4,300 m above sea level.

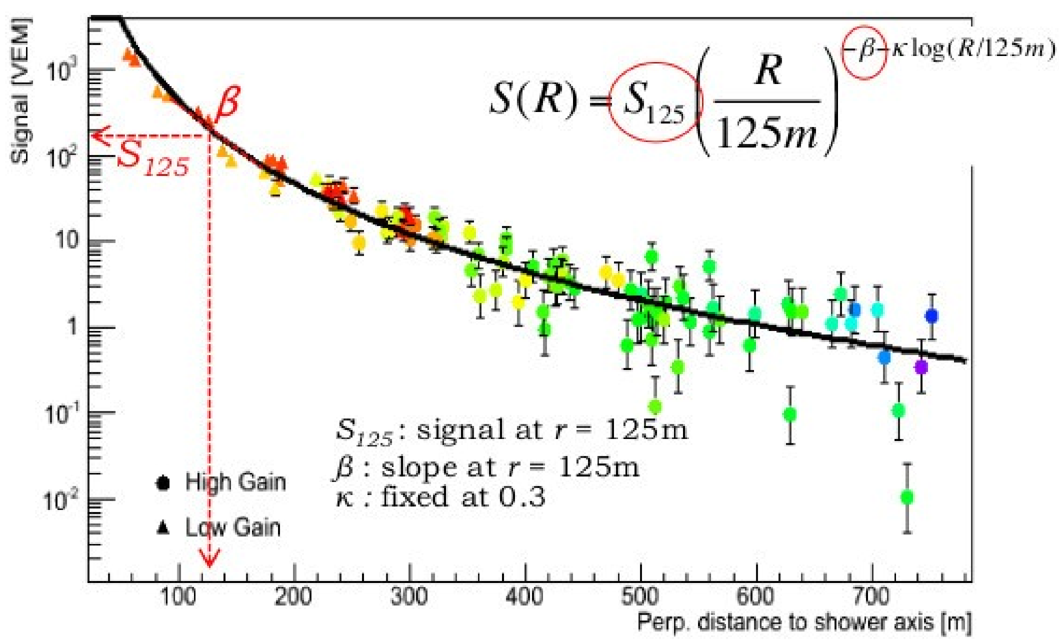
Right: map of the Auger Southern Observatory in Argentina. The enclosed are of the experiment is 3,000 sq.km.

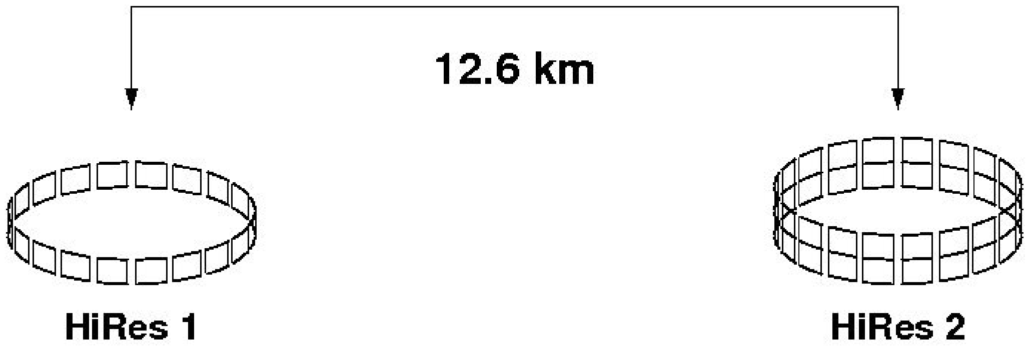


The IceTop air shower array on top of IceCube





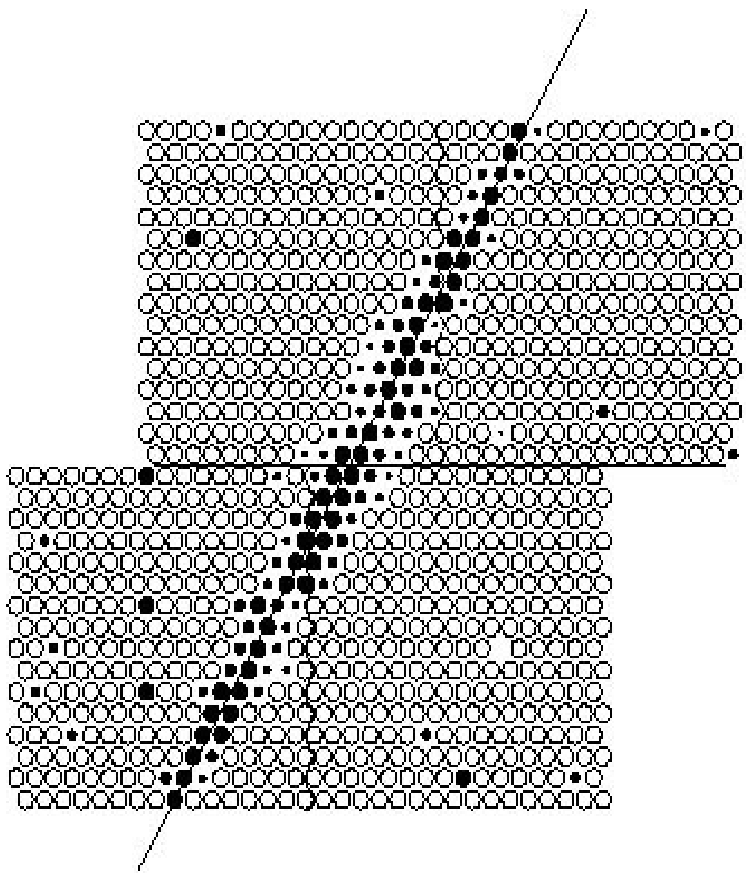


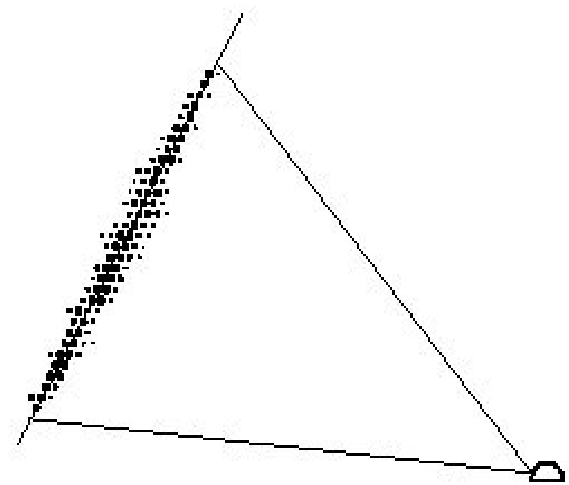


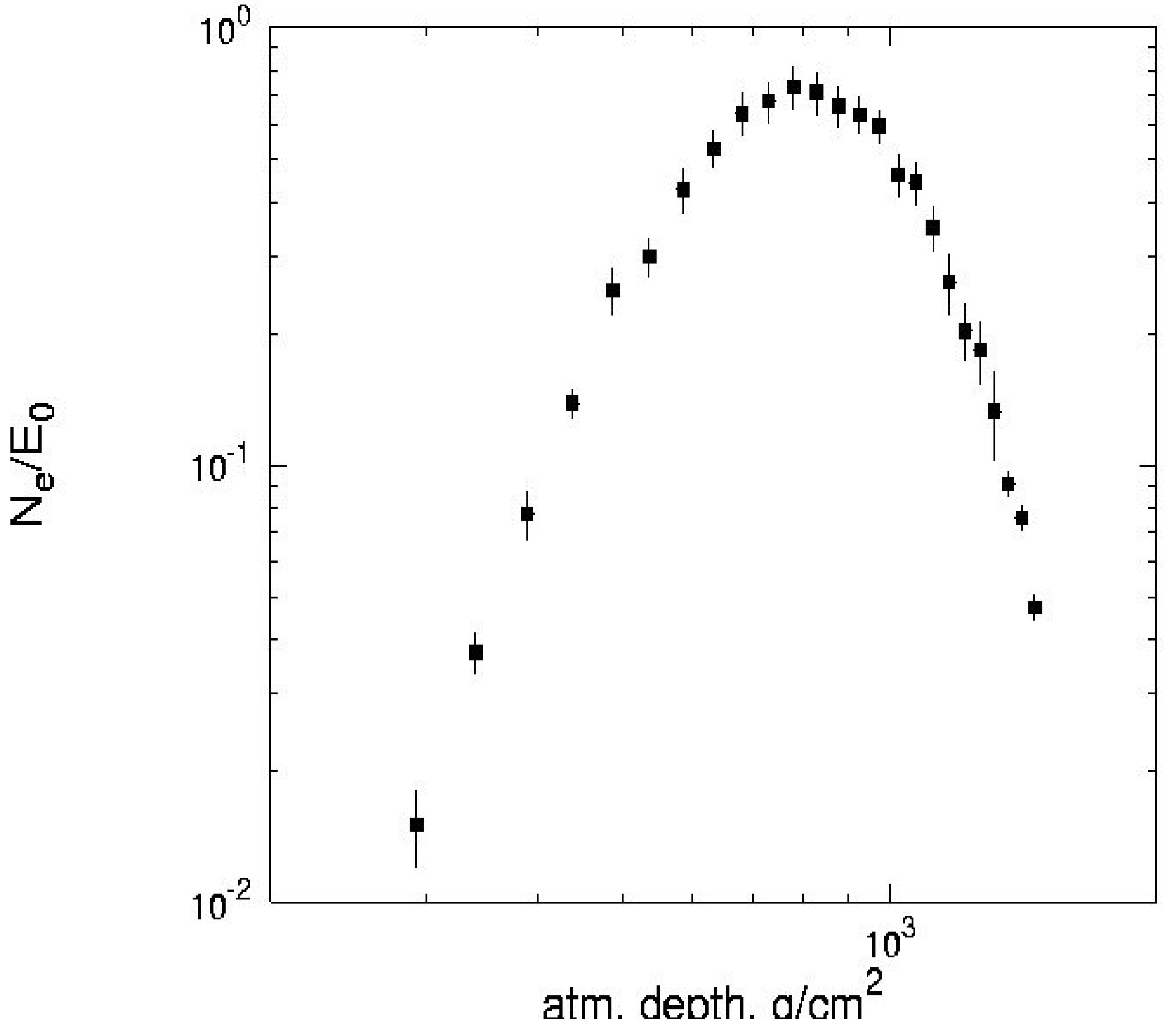
The HiRes fluorescent detector in Utah consisted of two telescopes with slightly different field of view. One of them looks at elevations of 3 to 17 degrees and the other one from 3 to 31 degrees. They can also work in coincidence.

Shower fluorescence telescopes

The fluorescent light is emitted by N atoms excited by the ionization of the charged shower particles, mostly electrons. The light emission is isotropic and the highest energy showers can be detected from distances exceeding 30 km



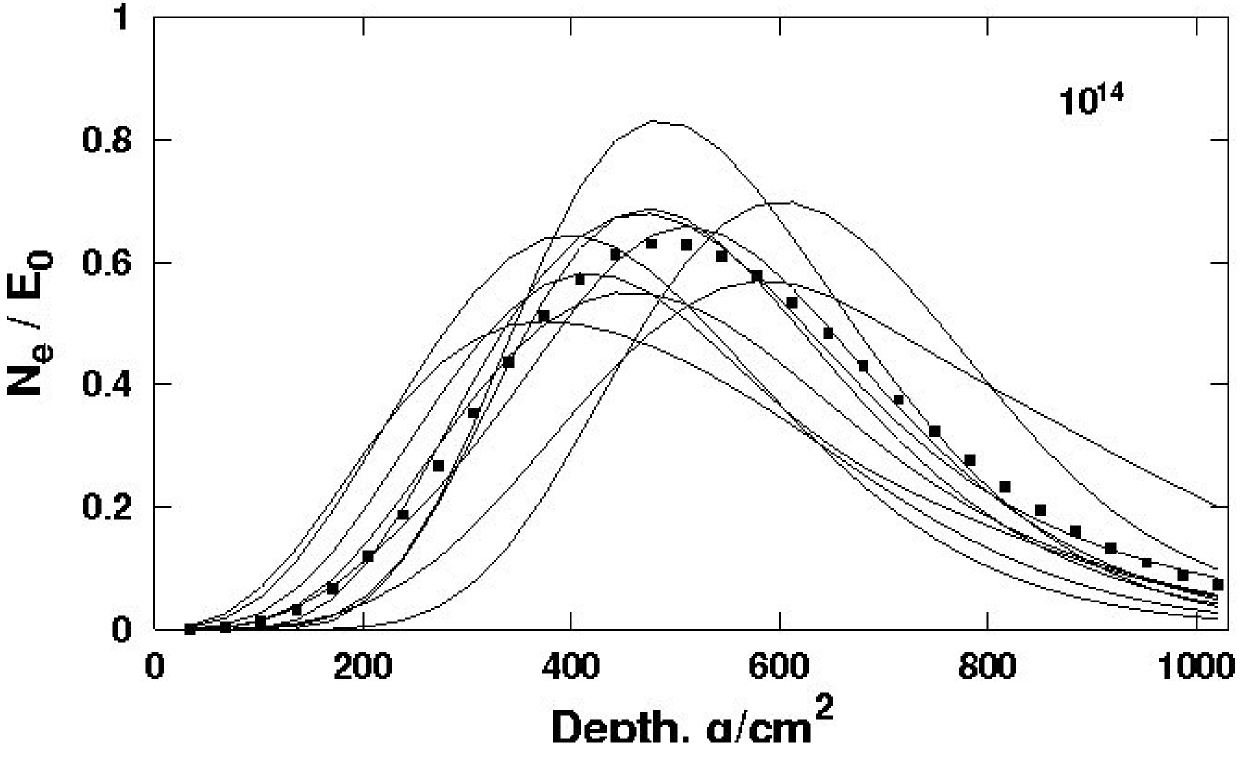




Primary energy determined from an integral over the shower longitudinal profile with an account for the missing energy (in high energy muons and neutrinos). One can also see the depth of shower maximum at around 800 g/cm^2.

It is important at this point to emphasize the fact that cosmic ray experiments are actually **observations.**

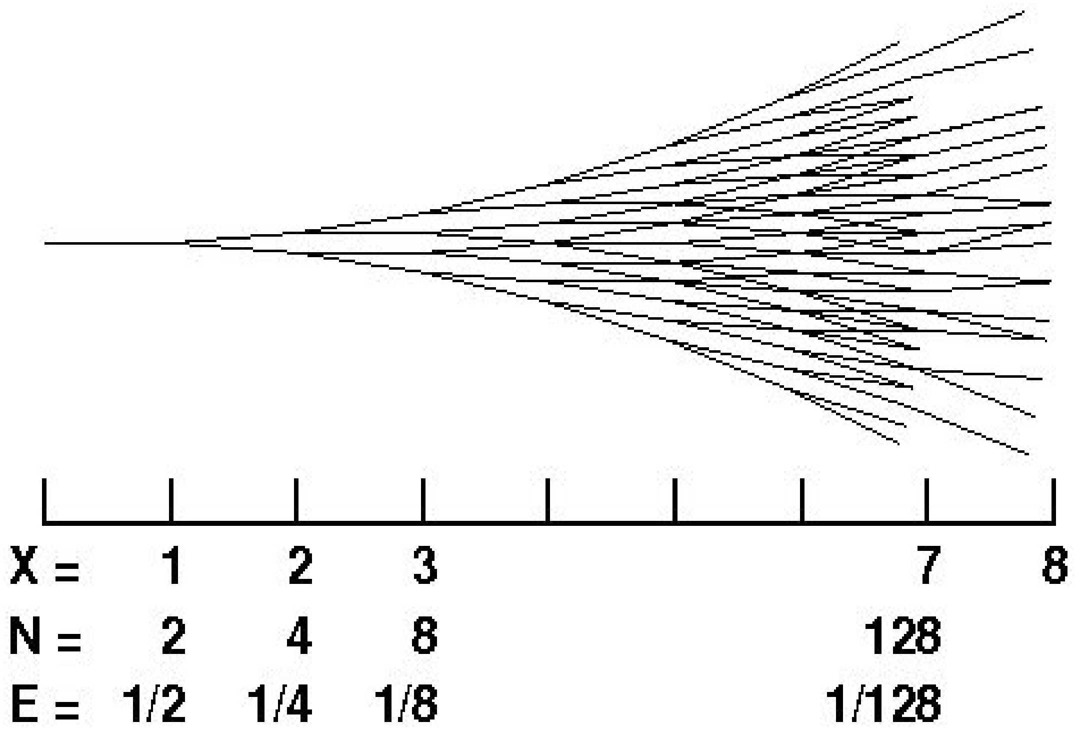
When we observe an air shower we know neither its energy or the type of the cosmic ray nucleus – it could be either a proton or a Fe nucleus. Using the cascade information we have to determine the type of nucleus that initiated the cascade and its energy. This is not possible in individual events because of the fluctuations in shower development and all results are obtained from statistical analysis of groups of events.



Shower theory was developed in 1930's when quantum electrodynamics (QED) was the most fashionable field of physics. Experimentally cascades were observed since the 1920's.

All famous physicists of that time, from Bhabha to Landau and Oppenheimer, wrote and solved cascade equations their own way. Toward the end of that period, in 1954,

Heitler explained with his *toy cascade* model the main features of the shower development.



Heitler's *toy model* only describes shower development before the shower maximum

There is only one type of particles in Heitler's cascade. They have fixed interaction length. Every time when these particles interact they generate two particles that share their energy. This way the number of particles increases and their energy declines. This is simply energy conservation.

$N = 2^n$, $E = 1/2^n$, where n is # of interactions

$X_{max} = \lambda \log_2(E_0/E_c)$

particles of energy lower than E_c do not interact.

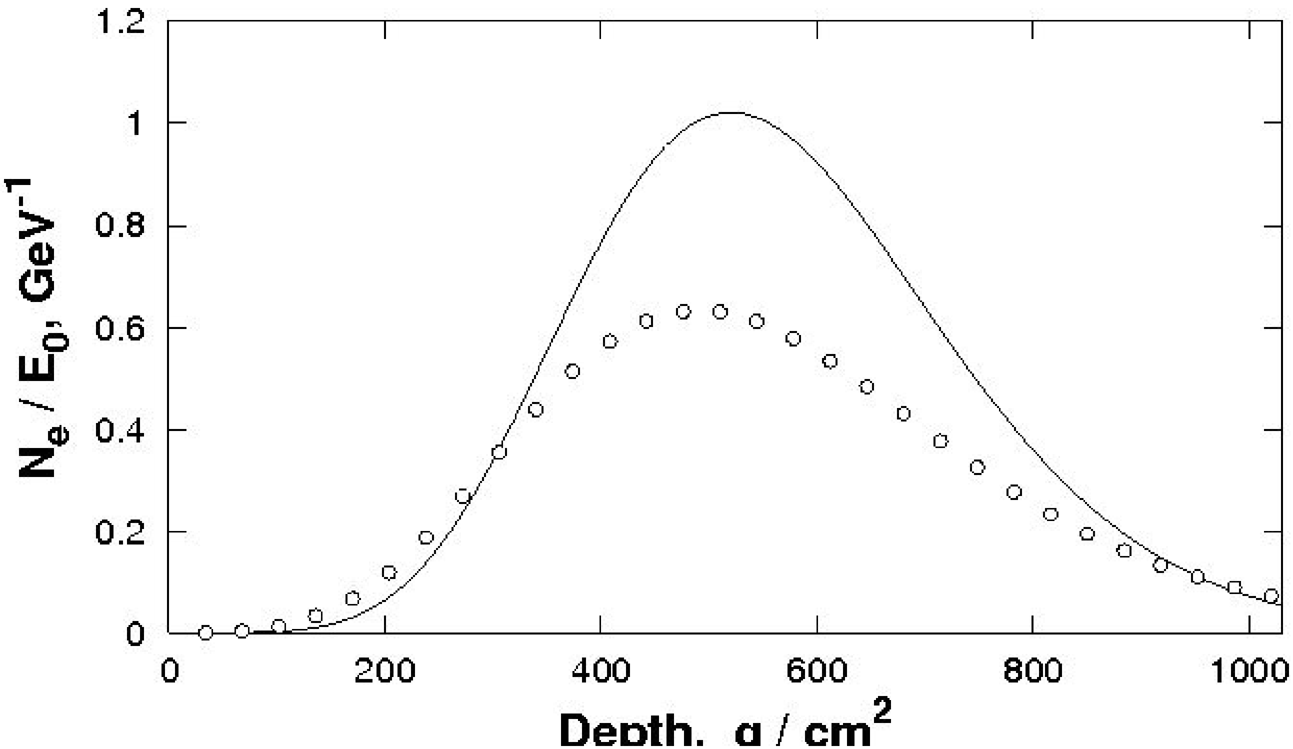
Heitler's *toy model* can be also used to describe the main features of hadronic showers, see Matthews (2005)

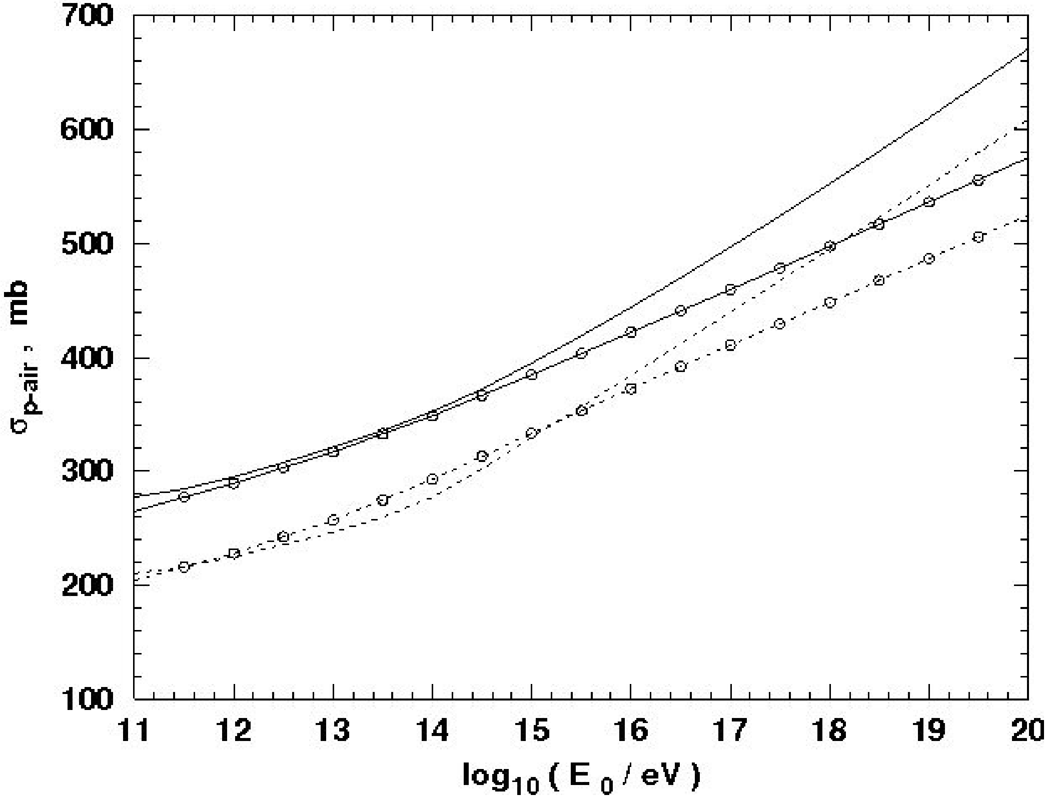
Hadronic showers develop after the primary nucleus interacts in the medium – we have to know about the structure of the atmosphere.

The neutral pions produced in the interaction (1/3 of all pions) decay to two gamma rays that start electromagnetic showers. Other neutral mesons also contribute to the start of electromagnetic showers.

Charged pions, that carry 2/3 of the energy lost by the nucleus, either decay or interact. In further interactions charged pions again carry 2/3 of the parent energy and 1/3 goes into electromagnetic cascade.

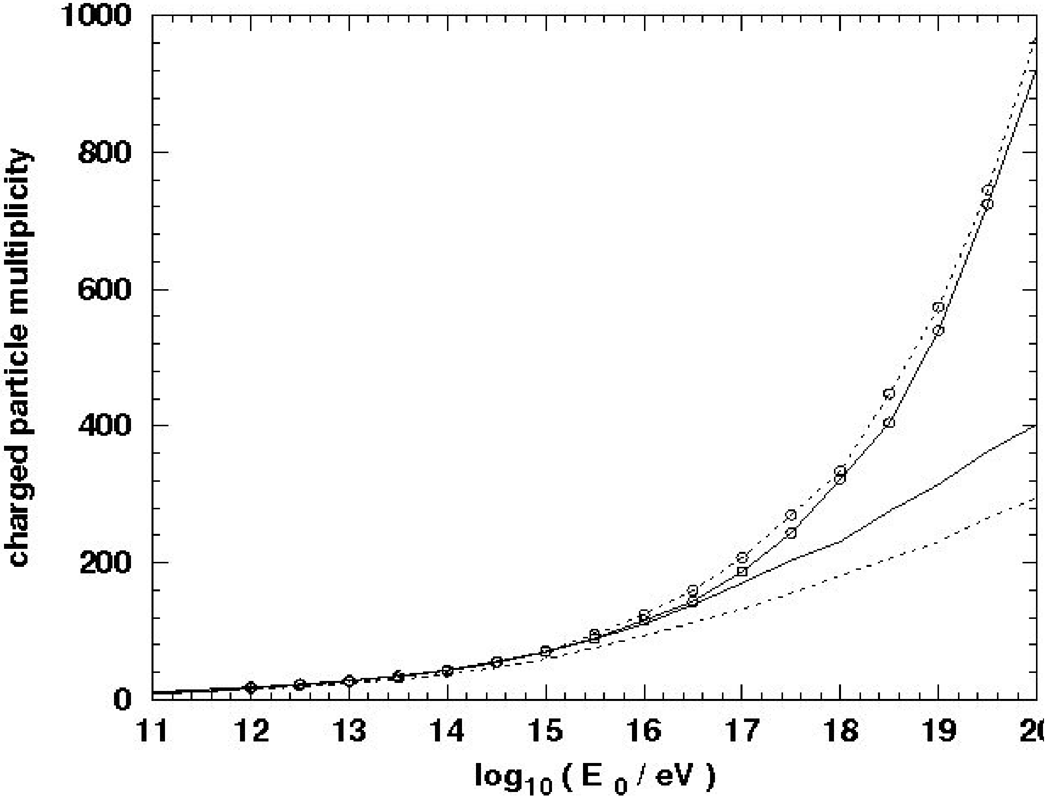
For this reason hadronic showers have somewhat different shape than electromagnetic ones. For the same primary energy they have smaller # electrons than electromagnetic showers. Hadronic showers start developing faster because of the higher multiplicity and they last longer in air because the hadronic cross section is smaller – pion interaction length is 120 g/sq.cm.





The high multiplicity of the old QGSjet98 model compensa-tes for the larger cross section of Sibyll 2.1. The interaction length in air is approximately 24,000/σ g/cm^2.

Cross sections for protons and pions (above) and average charge multiplicity in Sibyll 2.1 (lines) and QGSjet98 (points). Contempo-rary interaction models agree with each other up to the energy where there are accelerator measurements.



One can use Heitler's *toy model* to roughly describe hadronic showers assuming that only the first interaction contributes to the shower size:

$$X_{max} = X_0 \ln\left[\frac{2(1-K_{el})E_0}{(\langle m\rangle/3)\varepsilon_0}\right] + \lambda_N(E_0)$$

The number of electrons in the maximum then is

$$N_e^{max} = \frac{1}{2}\frac{\langle m\rangle}{3}\frac{(1-K_{el})E_0}{\varepsilon_0}$$

The factor of 1/3 comes from the fraction of neutral pions and ½ comes from the splitting of the neutral pion energy in two gamma rays. The depth of maximum and number of electrons are not very far from a real calculation.

Air shower development depends mostly on the forward part of the interactions.

With a simple substitution of E_0 with E_0 / A one can extend the estimate to showers initiated by nuclei heavier than protons. The depth of maximum becomes shallower

$$X_{max}^{A} = X_0 \ln\left[\frac{2(1-K_{el})E_0}{(\langle m\rangle/3)\varepsilon_0 A}\right] + \lambda_N(E_0) = X_{max}^{p} - X_0 \ln A$$

and the number of muons is higher

$$N_\mu^A = A\left[(E_0/A)/\varepsilon_\pi\right]^\beta = A^{1-\beta} N_\mu^p$$

The number of muons then becomes

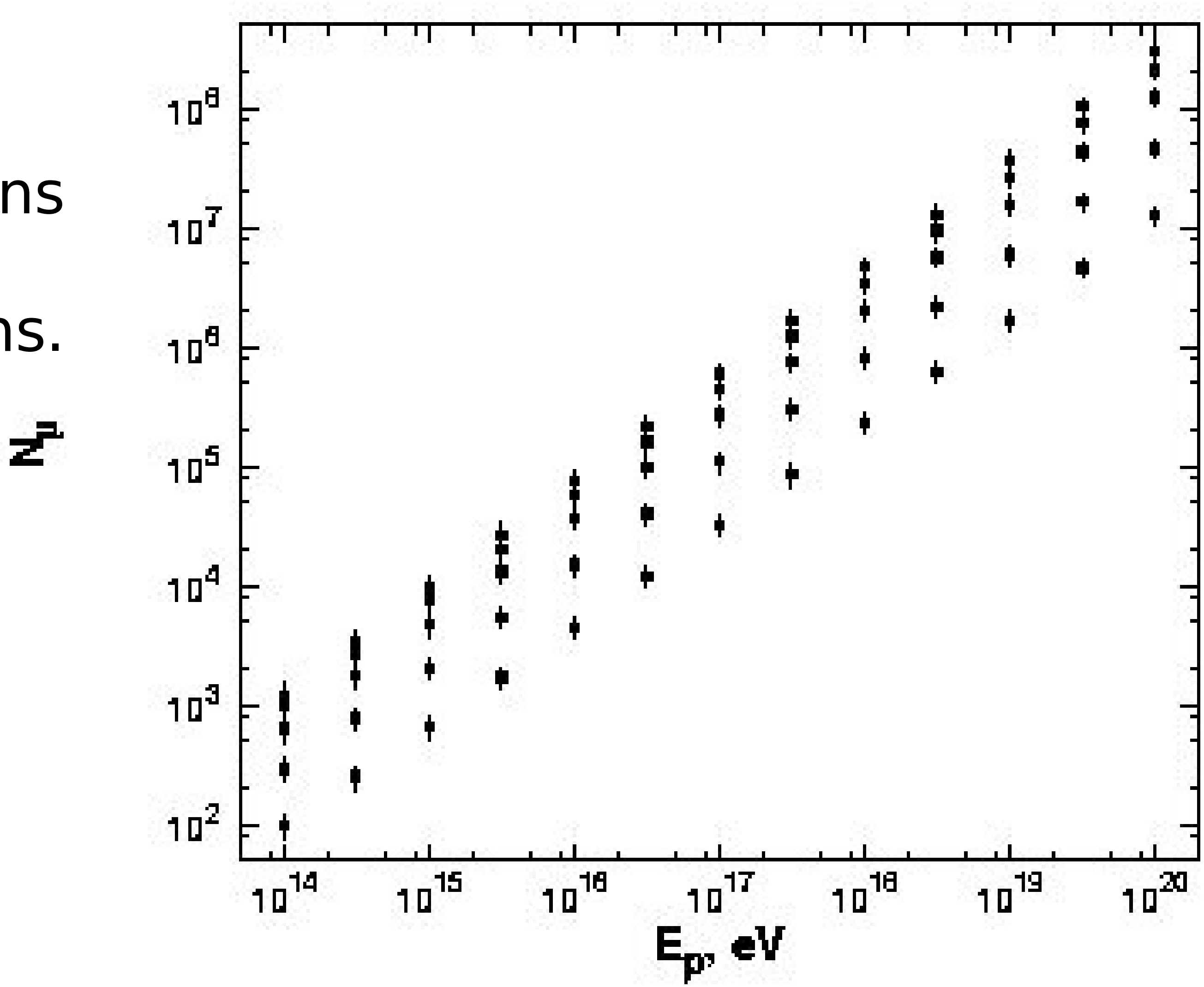
p	1.00
He	1.23
O	1.52
Fe	1.83 , which is correct in order of magnitude.

The ratio of the number of muons in the shower to the number of electrons in the shower becomes very useful for studies of the cosmic ray composition. The higher this ratio is the heavier is the primary nucleus. Contemporary experiments often use the density ratio at certain distance from the shower core. One obviously needs muon counters to do such measurements.

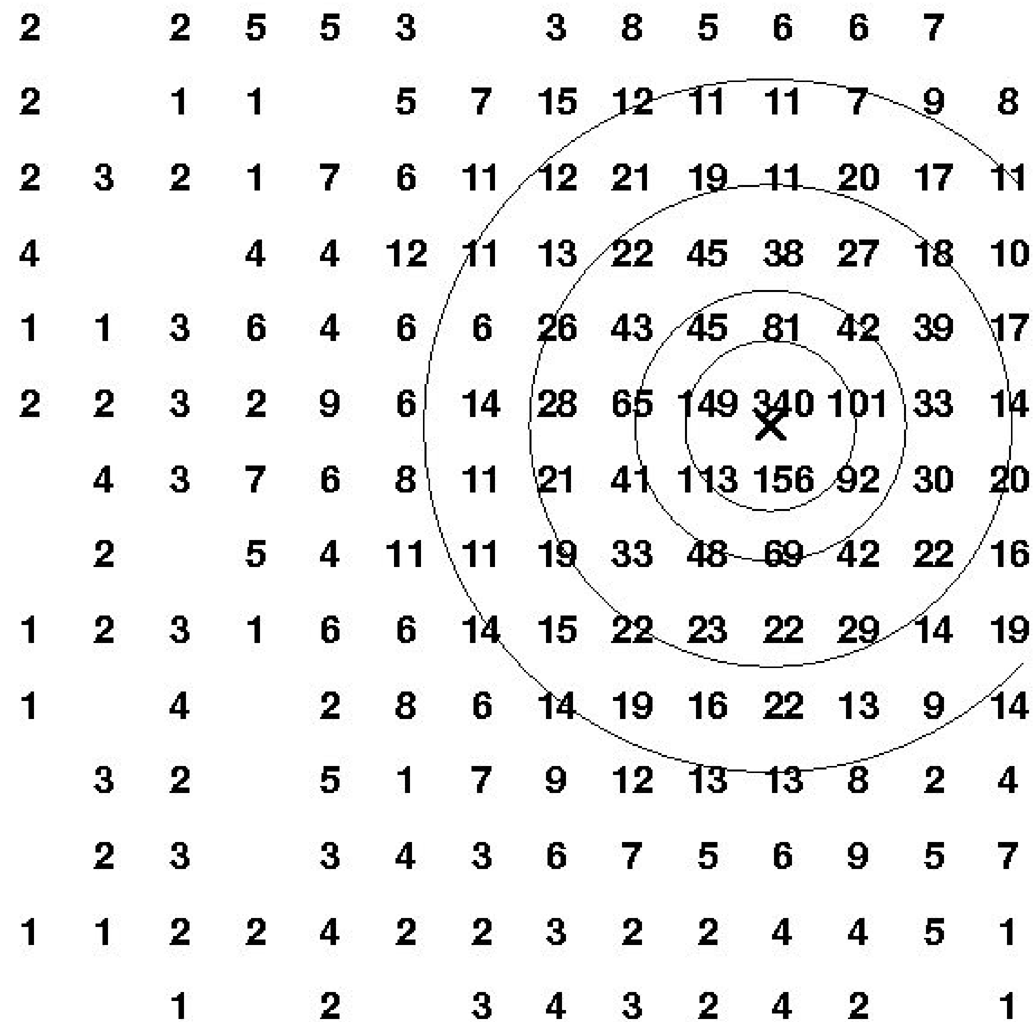
The other important parameter for composition studies is the depth of shower maximum X_{max}. It can be studied using the shower Cherenkov or fluorescent light, i.e. needs optical detectors. At relatively low energy (10^{15} eV) the Cherenkov light is very useful, while the fluorescent light is used above 10^{17} eV. Such showers generate enough light to be observed from large distances.

This is the result of a real calculation (Sibyll 2.1) of the muon number in vertical proton showers for muons above 0.3, 1, 3, 10, and 30 GeV.

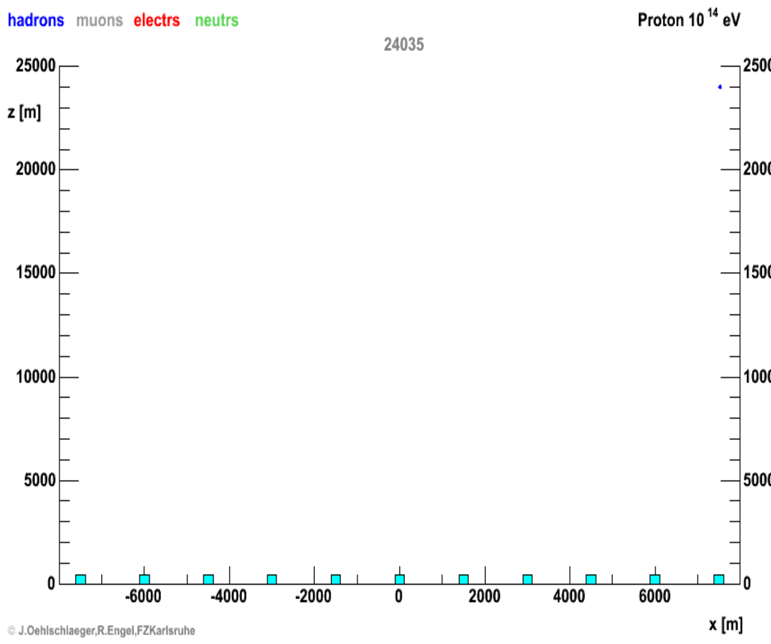
β is 0.90 for 0.3 GeV muons and 0.86 for 30 GeV muons.

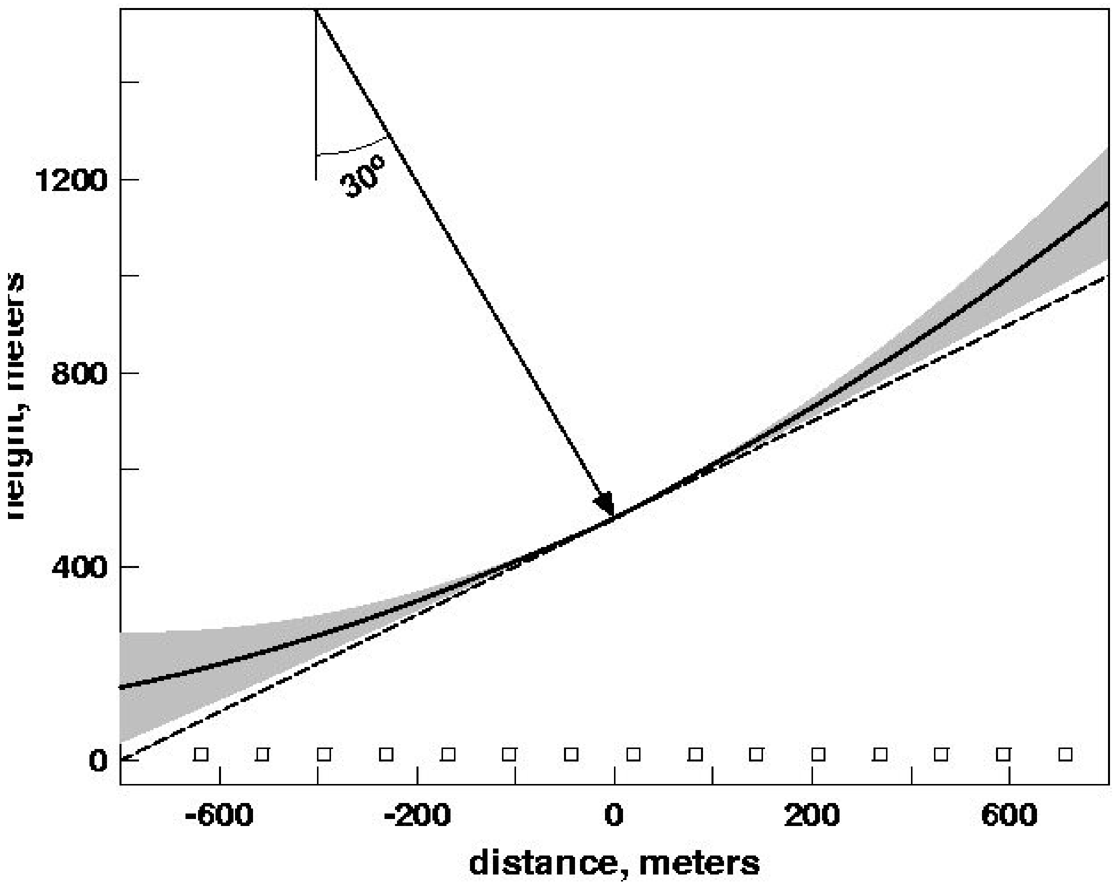


Air shower reconstruction: shower core in air shower array – 196 counters on a 15 m grid. Densities calculated with the Greisen's formulae. Simulated fluctuations proportional to sq. root of density.



Shower arrival direction from timing. One should account for the curvature of the shower front.





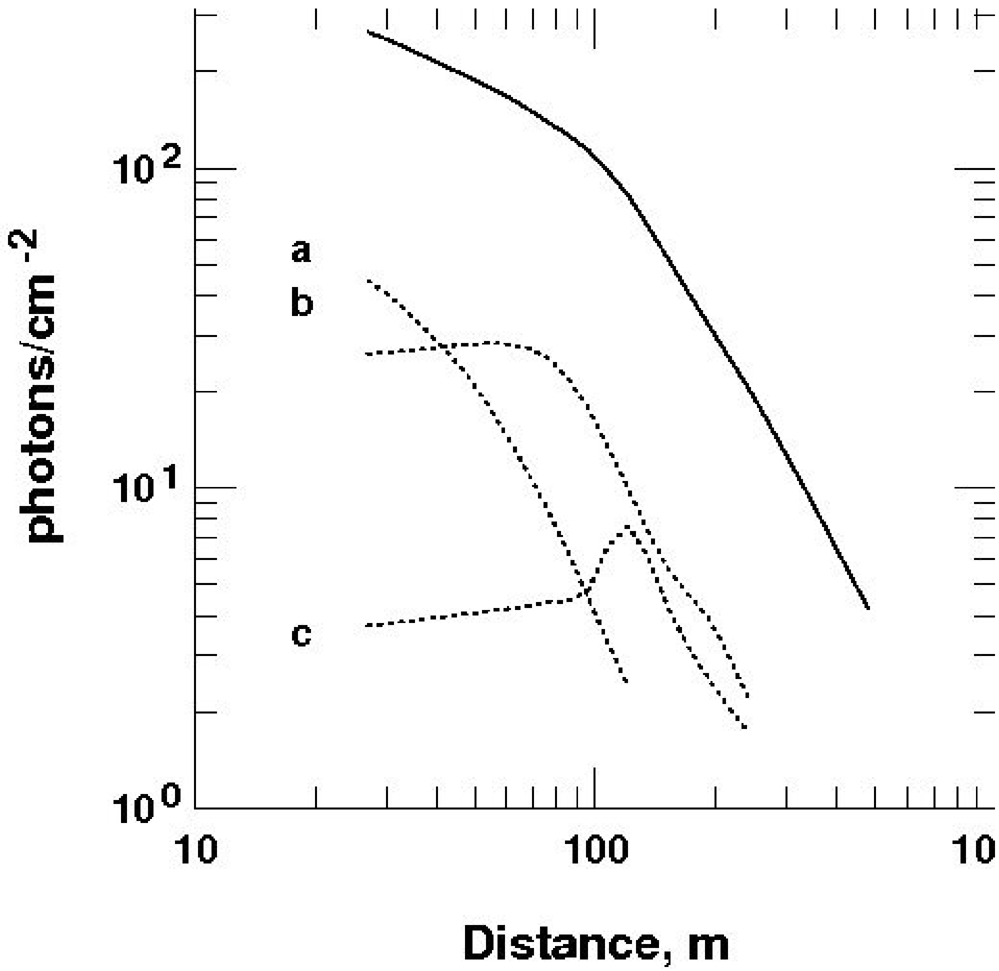
Shower Cherenkov light

Electron threshold at sea level is 21 MeV. It is higher at higher altitude.
Emission angle 1.5 deg.

Lateral distribution
- a) close by em shower
- b) shower at X_{max}
- c) early em shower

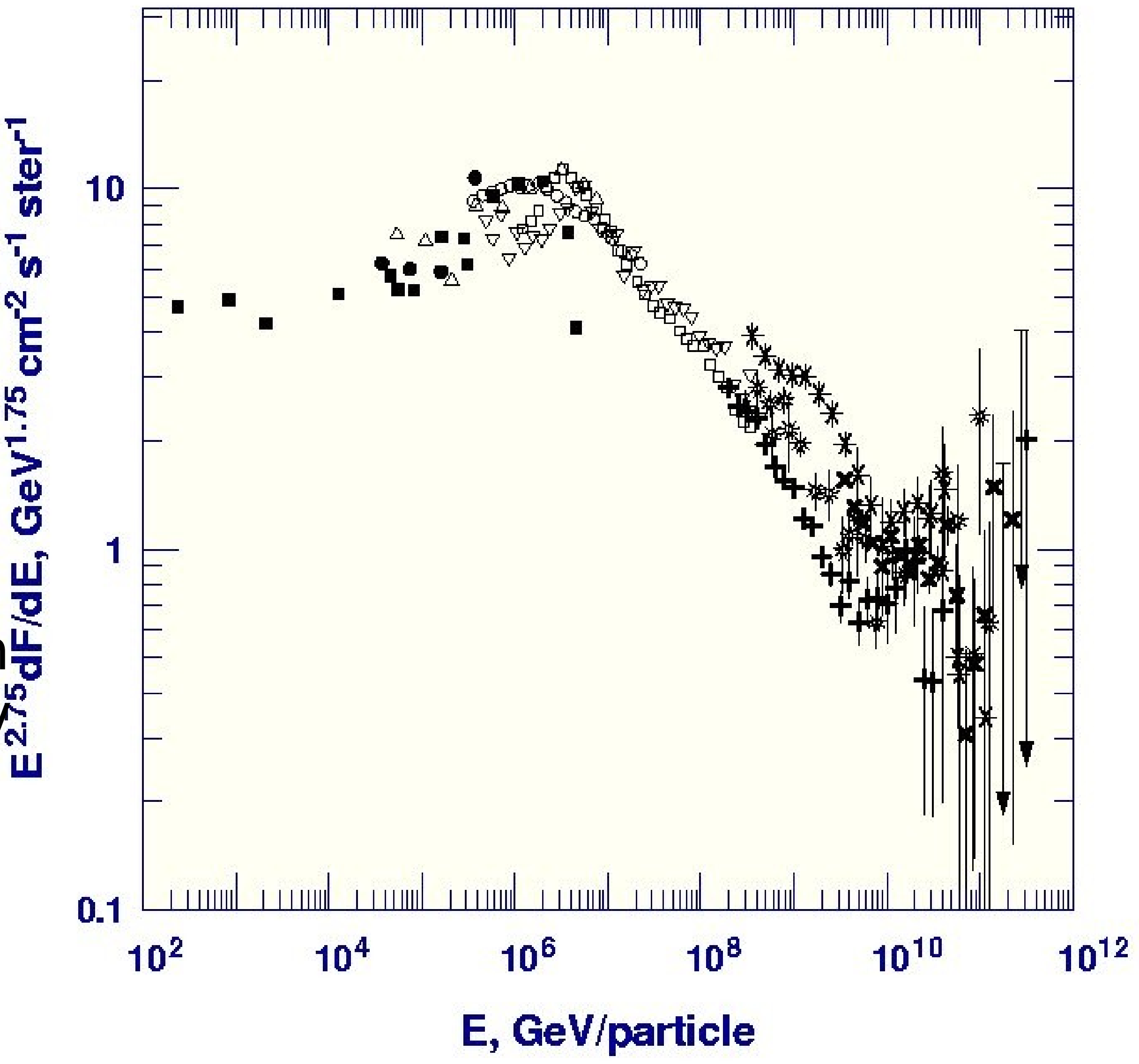
Density at 100 m related to shower primary energy.

Density ratio at 40m/(>100 m) used to find shower maximum with accuracy of 20-40 g/sq.cm



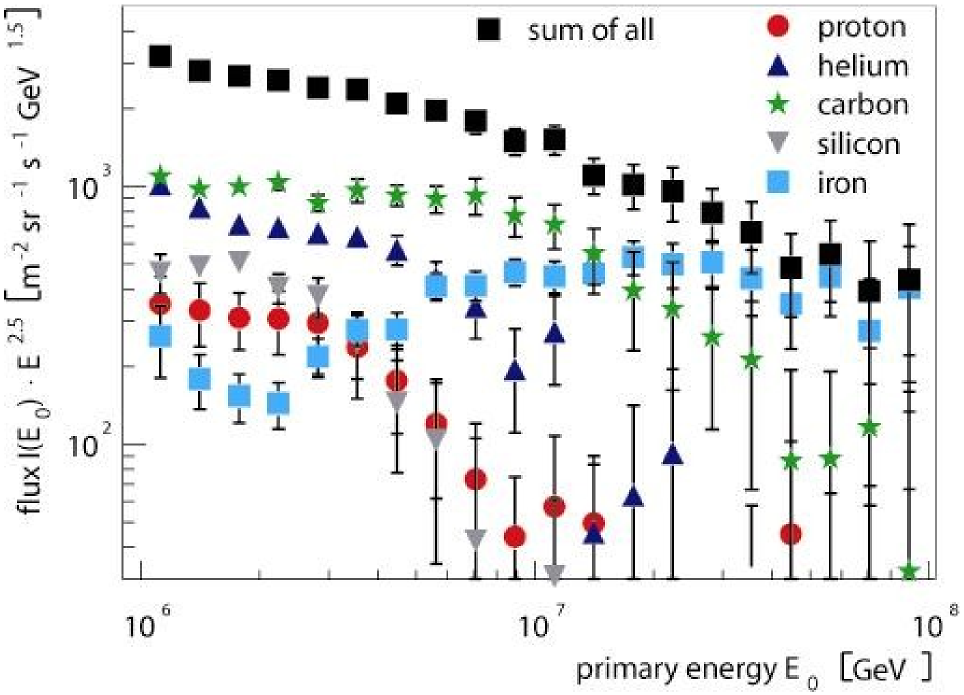
Cosmic ray spectrum

Differences between various experiments are emphasized by the multiplication of the flux by $E^{2.75}$. This is done to show the main features in the cosmic ray spectrum: the *knee* and the *ankle*. In the region of the knee the composition is derived from the muon/electron ratio or from Cherenkov radiation. At the ankle the composition is extracted from the depth of maxumum.



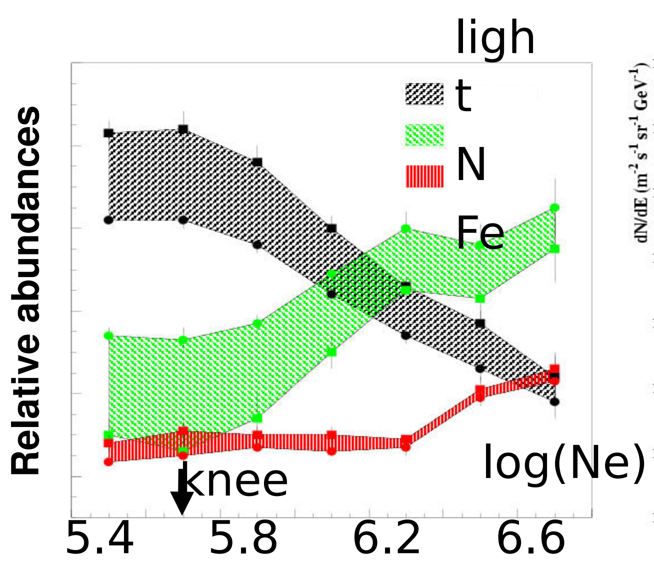
There are multiple data sets for the region of the knee. To avoid confusion I will only show two of them that mostly agree with each other. Both of them show that the cosmic ray composition becomes heavier, i.e. there are more and more heavy nuclei with increasing energy. Most people are convinced that this is a rigidity effect which shows that cosmic ray accelerators (SNR?) reach the maximum acceleration energy first for protons, then for He, CNO, etc. until they are only capable of acceleration Fe nuclei.

The Kascade collaboration has attempted to derive the spectra of the different groups of nuclei.

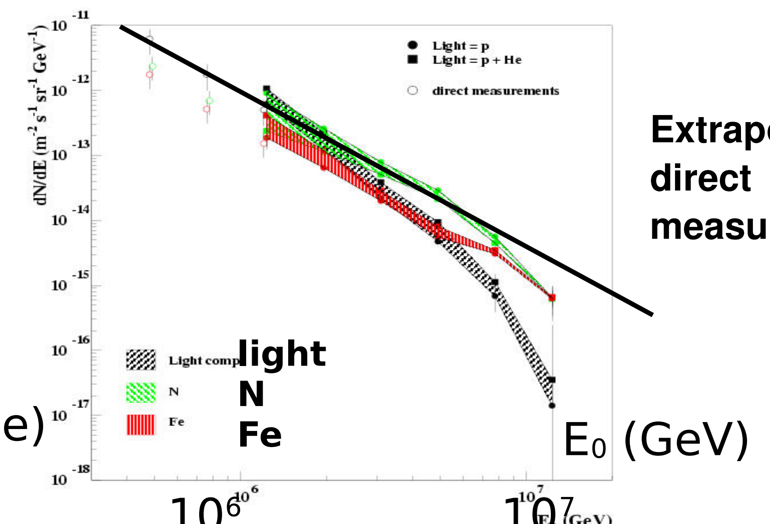


Kascade data: fluxes of different nuclei

EAS-Top data



Heavier above knee



Extrapolation direct measurements

Light comp. breaks off first

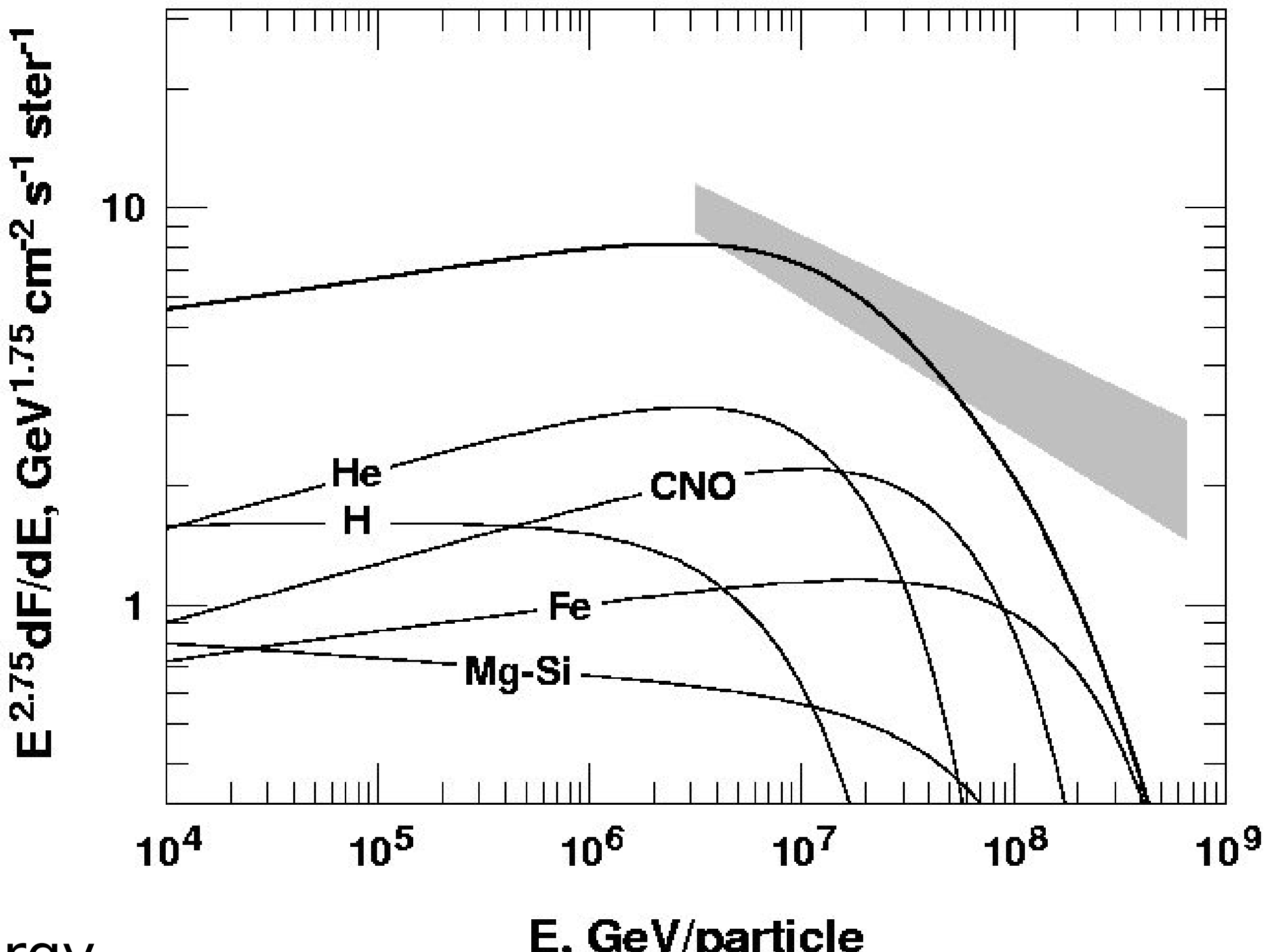
The results from the previous page are obtained with the use of a specific hadronic interaction model – QGSjet. When a different model is used (Sibyll 2.1 in the case of Kascade) the result is different, although the trend is the same – the composition becomes heavier with increasing energy.

The reason is, of course, that the muon densities at ground level depend strongly on the features of the interactions. QGSjet generates much higher secondary multiplicity than Sibyll 2.1. The average secondary pion energy is thus lower and many more pions decay and generate muons rather than interact. Thus from the same muon/electron ratio these two models derive different compositions.

Interpretation of the cosmic ray spectrum. Derivation of the individual spectra from the Kascade data is pretty close to this picture.

This is a simple model of the cosmic ray composition with an exponential cut-off at rigidity (p/Z) of 10^7 GV.

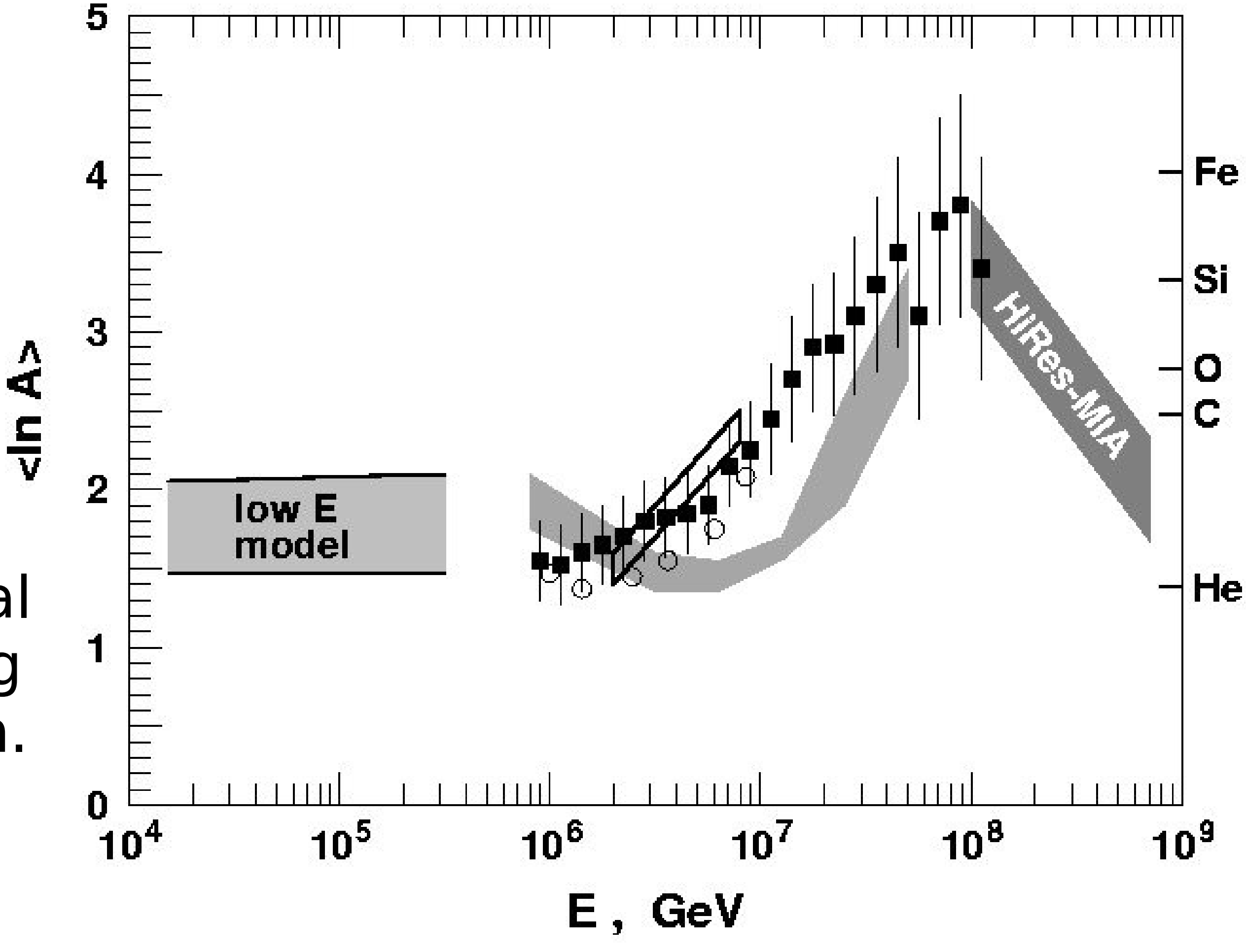
The total cosmic ray energy spectrum is OK but the spectra of individual nuclei are not fully consistent with data. The shaded area shows the CR spectrum at higher energy.



Cosmic ray composition as a function of energy: Kascade data. The lighter chemical composition derived from the HiRes-MIA data is now challenged.

Data sets are not fully consistent. We see here the results of three different analyses of the same data set.

<ln A> is a classical way of representing the CR composition.

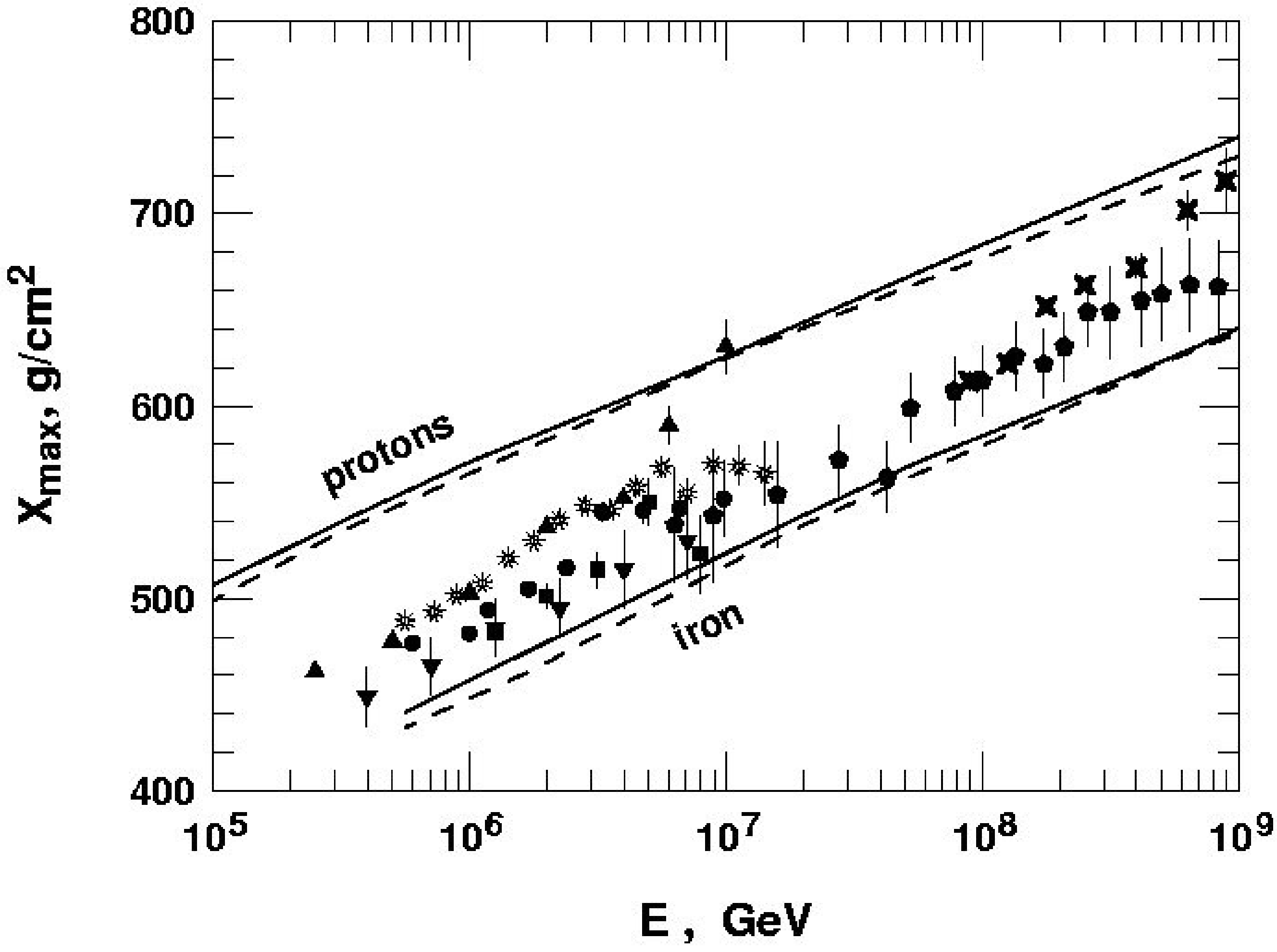


The problems are even worse when different data sets are used for derivation of the cosmic ray composition.

Muon to electron ratio was used by Kascade and EAS-Top experiments.
Cherenkov light is used by many experiments in the same energy range. At higher energy the data only comes from fluorescent detectors.

It is not obvious how the differences between hadronic Interaction models used in the analysis affects various derivations of the composition.

Measurement of the cosmic ray composition with the depth of maximum. It is not obvious now that the highest energy cosmic rays are protons and He nuclei as we expected.



The average depth of maximum as a function of the shower energy is not the only composition related parameter. The fluctuations of the depth of maximum are also very sensitive to the composition. In the superposition model the fluctuations are inversely proportional to $A^{1/2}$.
In more detailed MonteCarlo calculations the dependence is not that strong, but still the difference between H and Fe are about a factor of three. This will be discussed when the data on the composition at the highest energies is dicussed.

There are also X_{max} related parameters that can be measured by the surface air shower arrays. The arrival time distributions in function of the distance to the shower axis is very much related to the depth of maximum although it has lower accuracy.

The cosmic ray composition can be *roughly* extracted from air shower data. `*Roughly*' means that one cannot measure a single nuclear component other than H (protons). It also means that the primary cosmic ray particle atomic number cannot be measured on shower by shower basis because of The strong fluctuations in the shower development, which are mostly due to the depth of the first interaction of the primary particle.

Results on the composition are obtained in statistical manner in the presence of a large data base. Showers of similar energy are binned and then their composition related characteristics - muon to electron number or density ratios or depth of maximum development are studied.

Another problem is that all studies depend strongly on the hadronic interaction model used in the analysis. Different interaction models give wildly different muon/electron ratios or depths of shower maximum.

For this reason we were eager to learn about the LHC results at energies closer to those of air showers. We do deal with proton-nucleus and nucleus-nucleus interactions but the basic features of the interaction models can be checked towards the experimental data and the models have become better and the differences between them are smaller now.

The conclusion thus is that the extraction of the cosmic ray composition from air shower data is not very exact and has lots of uncertainties. We do not have any choice in this case and the hope is that the analysis tools will improve in the Future as they have during the last several years