Cosmic Rays and Extensive Air Showers

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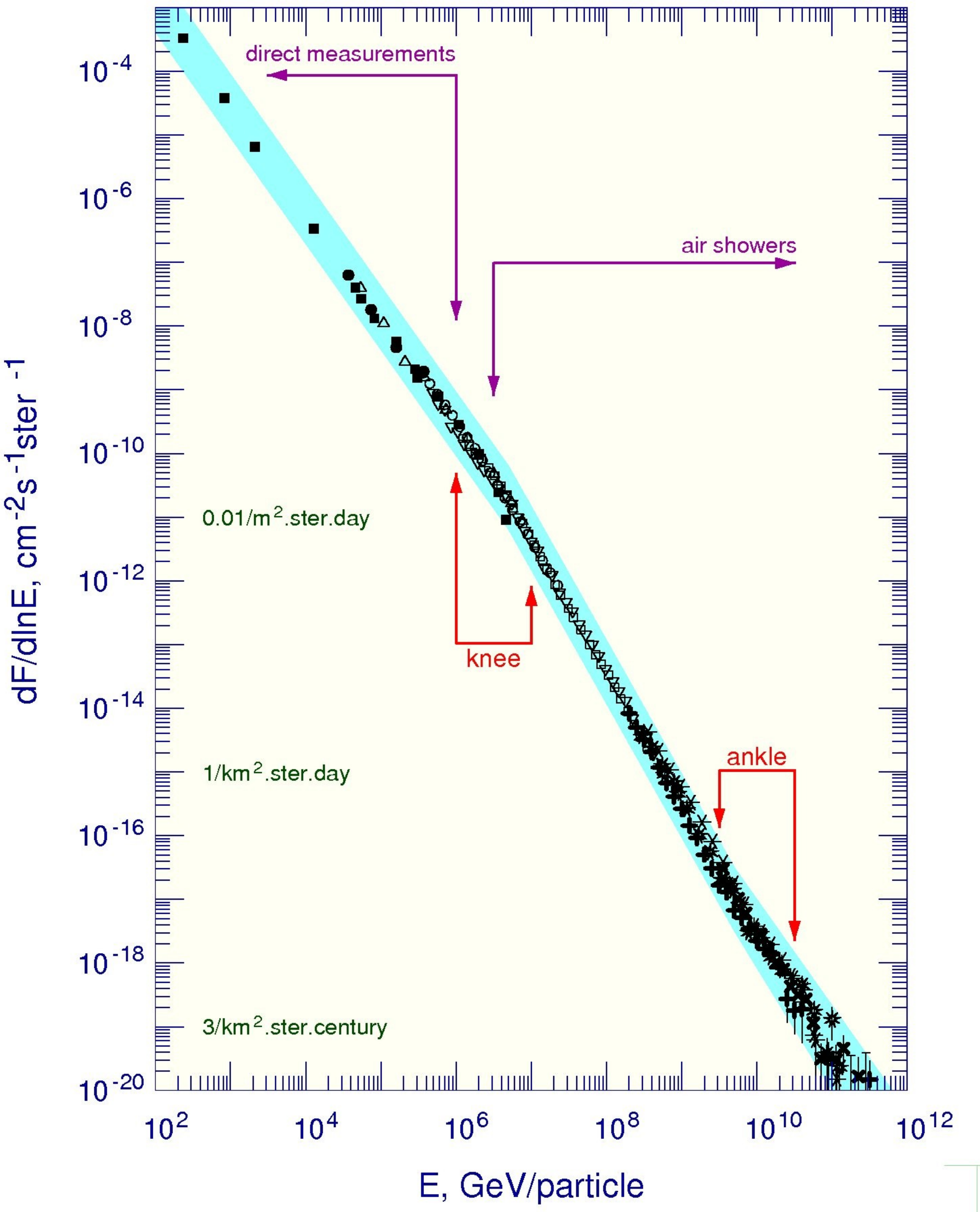
Cosmic rays are charged nuclei accelerated outside the solar system. At energies above 1 GeV most of the cosmic rays are accelerated in our Galaxy. In this energy range the cosmic ray flux is dominated by H nuclei, i.e. protons.

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 such as AMS 1. 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.

EDS'09, CERN, July 2009



The equivalent Lab energy of the LHC is 2.10^8 GeV.
The interpretation of the highest energy cosmic rays events thus requires a long range extension of the hadronic interaction models.

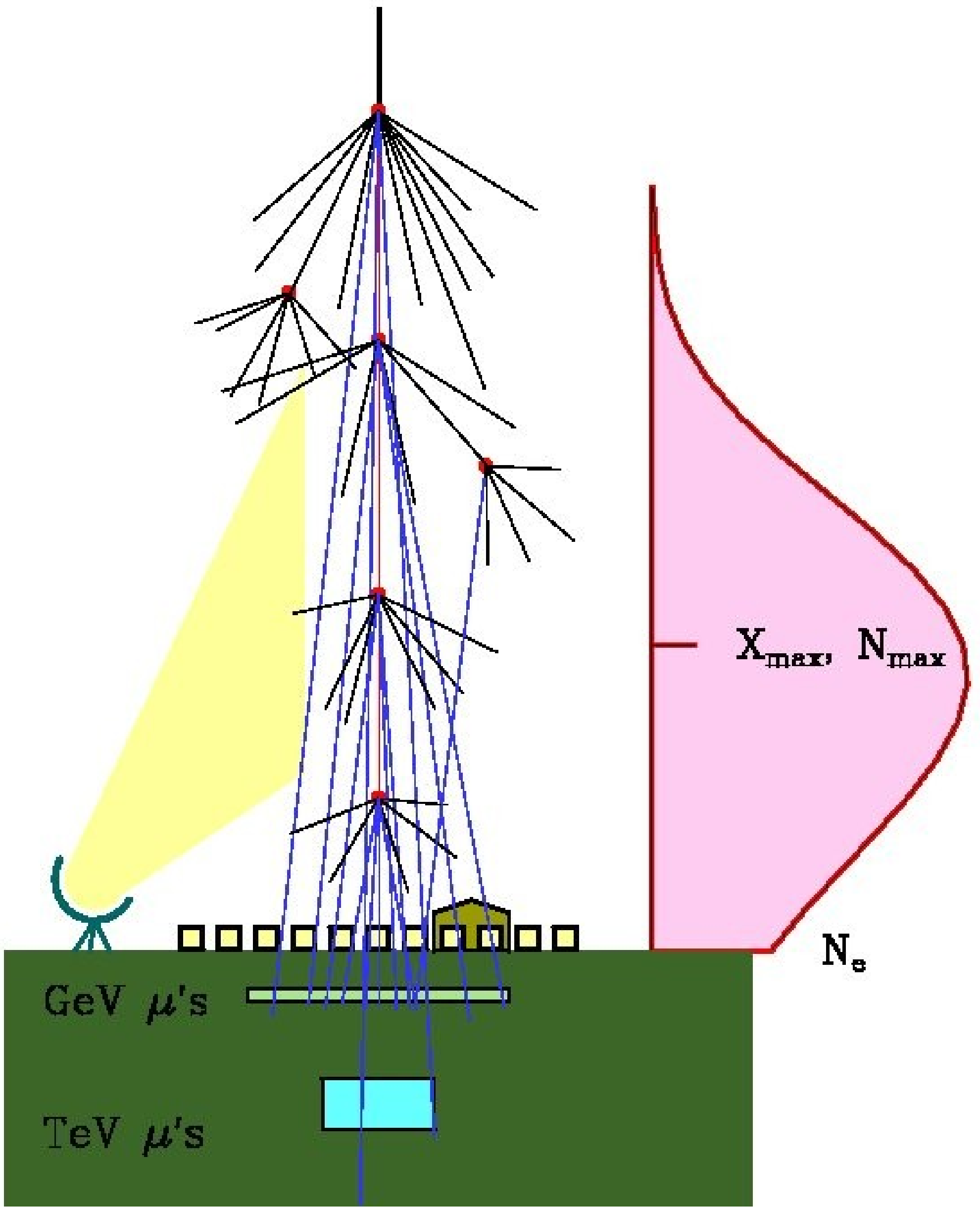
Air shower detection

Three main methods:

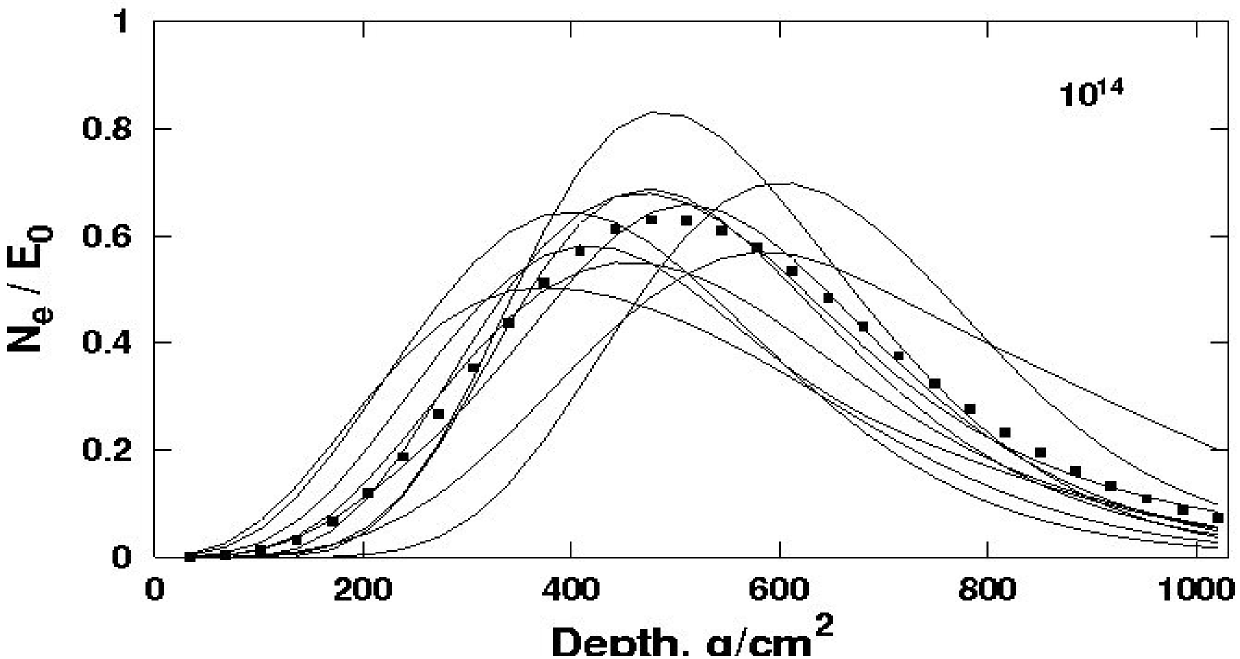
1) air shower arrays observe shower structure on a single observation level.

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.

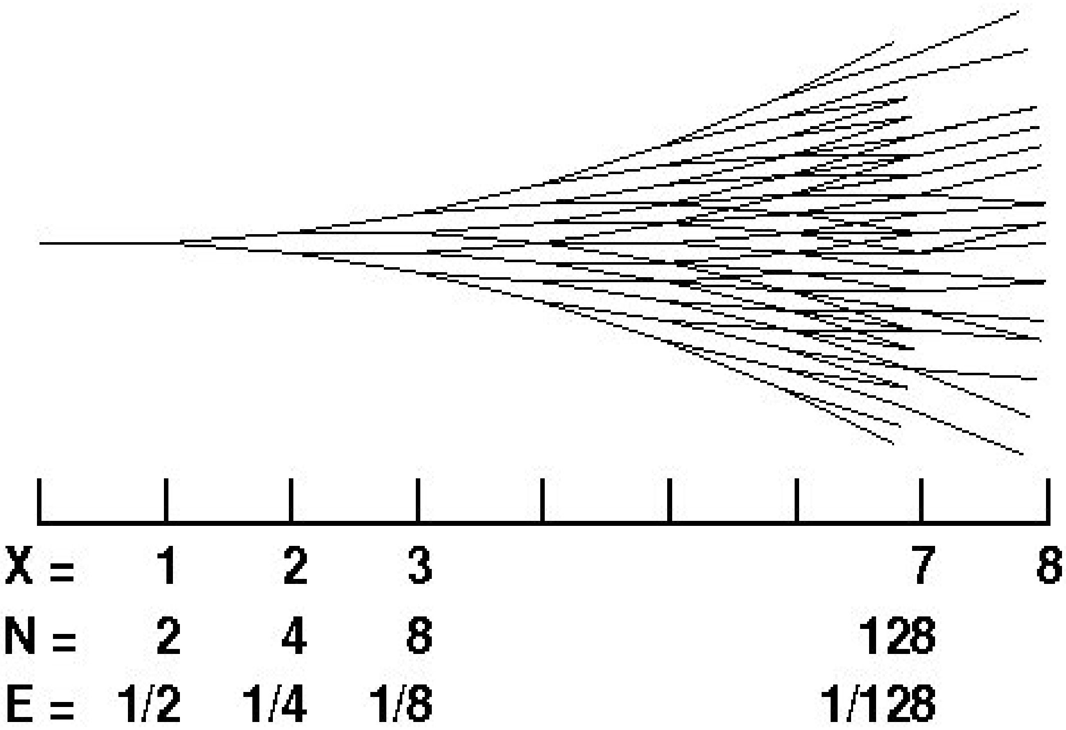


It is important at this point to emphasize the fact that cosmic rays experiments are actually **observations.** When we analyze these observations we have no idea what the beam is, neither in energy or in the type of the cosmic ray nucleus – it could be either a proton or a Fe nucleus. Using the cascade 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 1941, 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

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

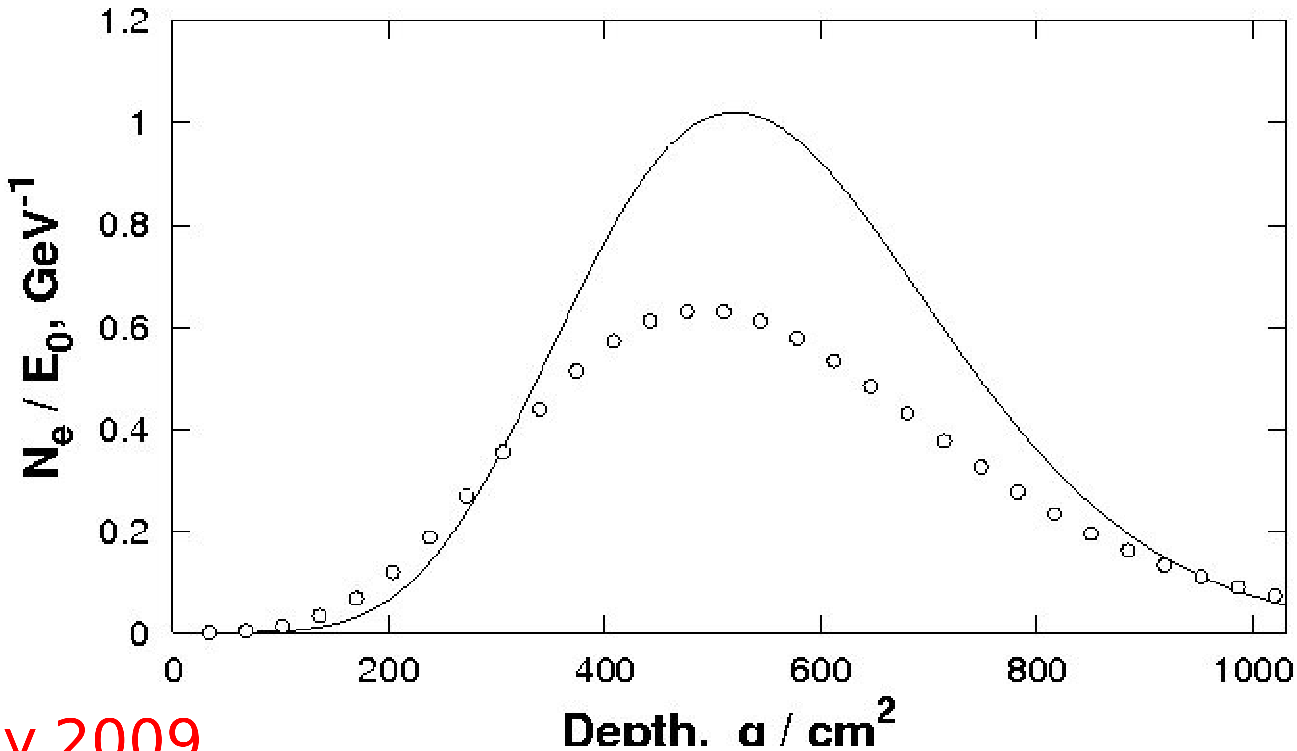
particles of energy lower than E_c do not interact.

Heitler's *toy model* can be also used to describe the main features of hadronic showers.

Hadronic showers develop after the primary nucleus interacts in the medium – will talk about the atmosphere today. 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.



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

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

and the number of muons is higher

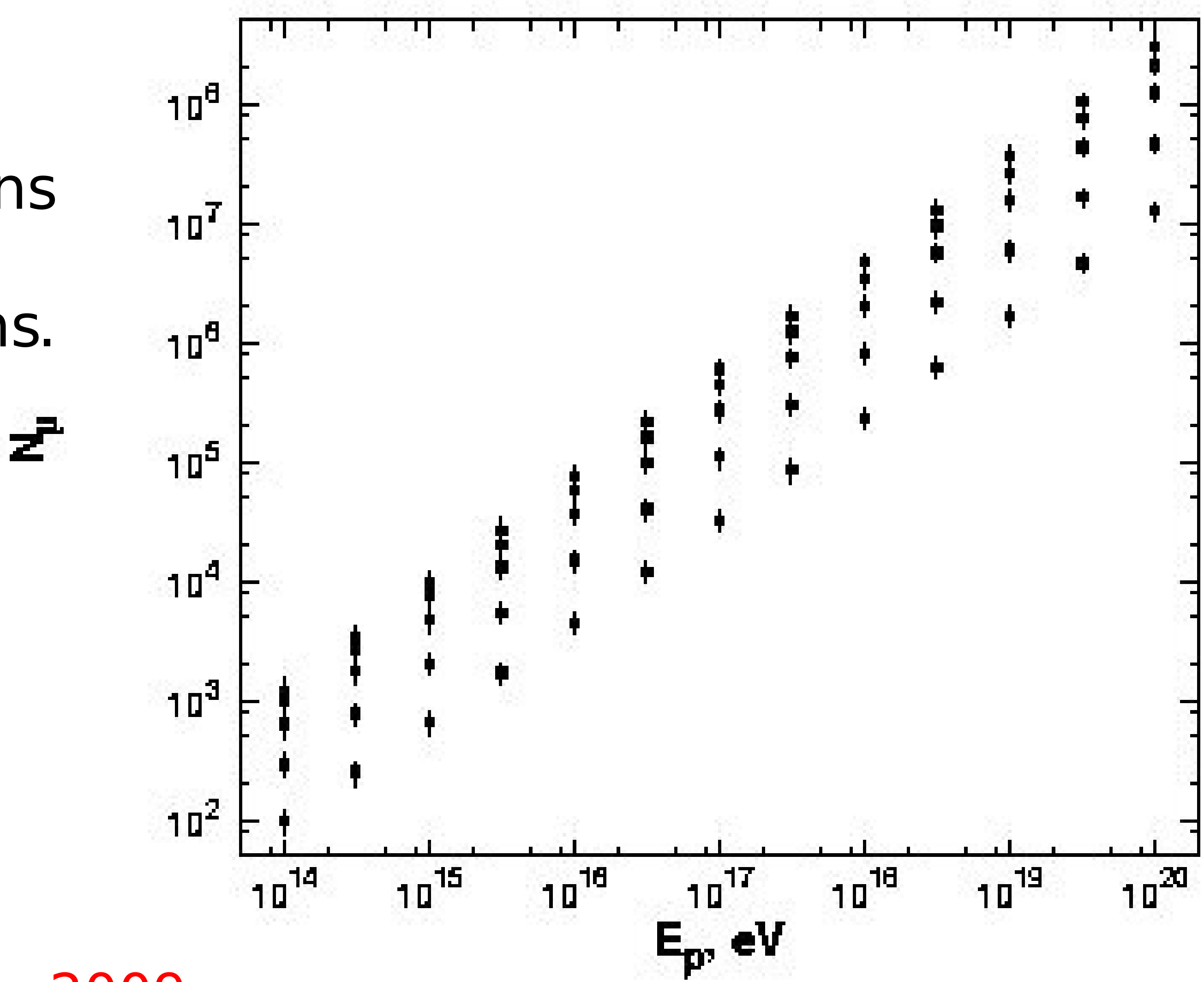
$$N^A_\mu = A\left[(E_0/A)/\varepsilon_\pi\right]^\beta = A^{1-\beta} N^p_\mu$$

The number of muons then becomes

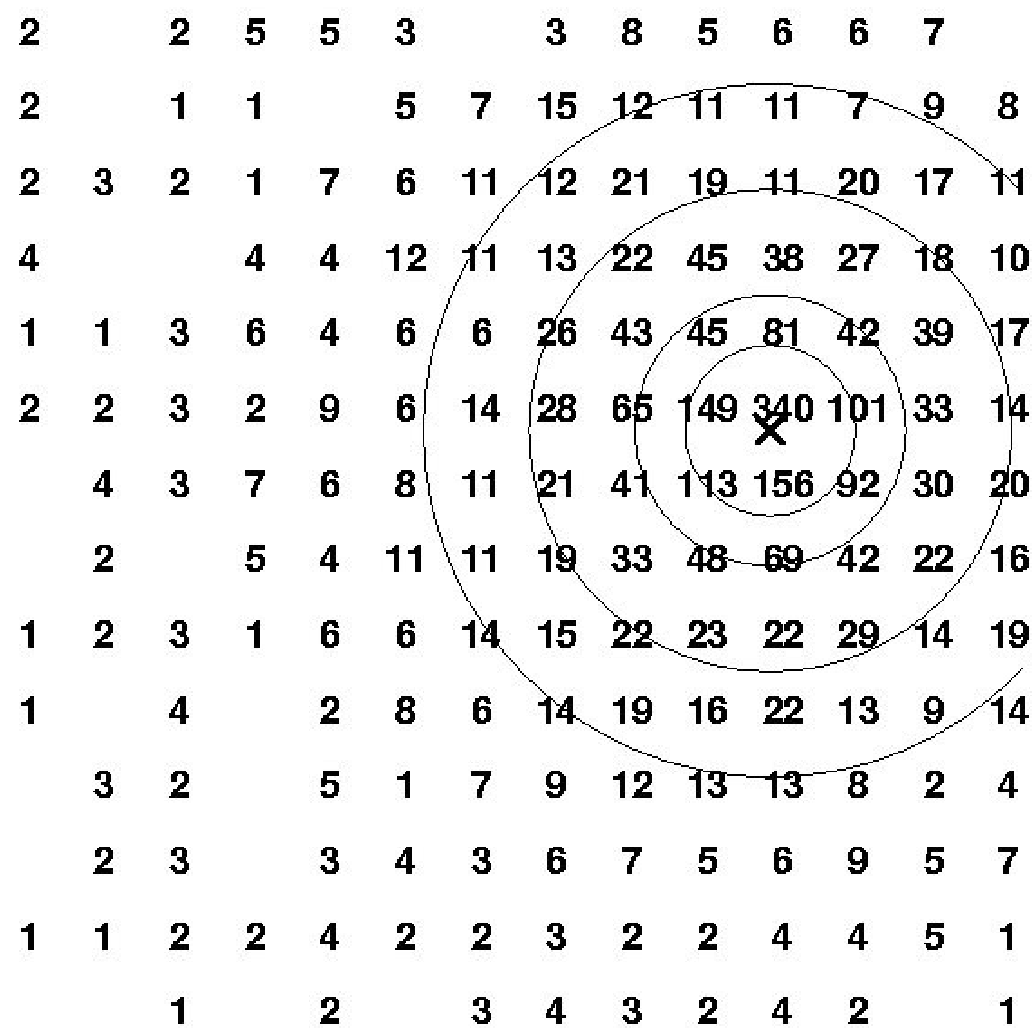
p 1.00
He 1.23
O 1.52
Fe 1.83 , which is correct in order of magnitude.

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.

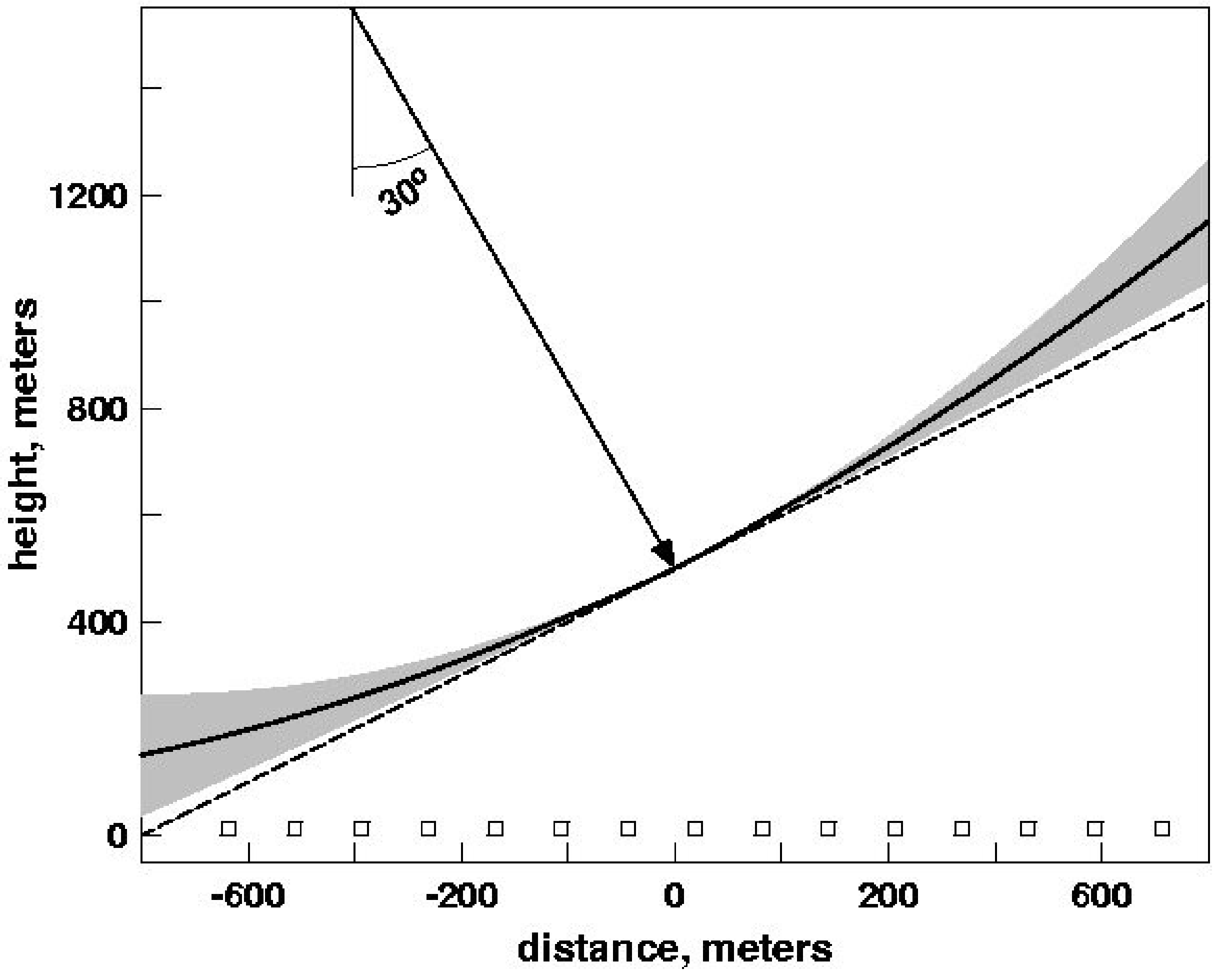
β is 0.90 for 0.3 GeV muons and 0.86 for 30 GeV muons.

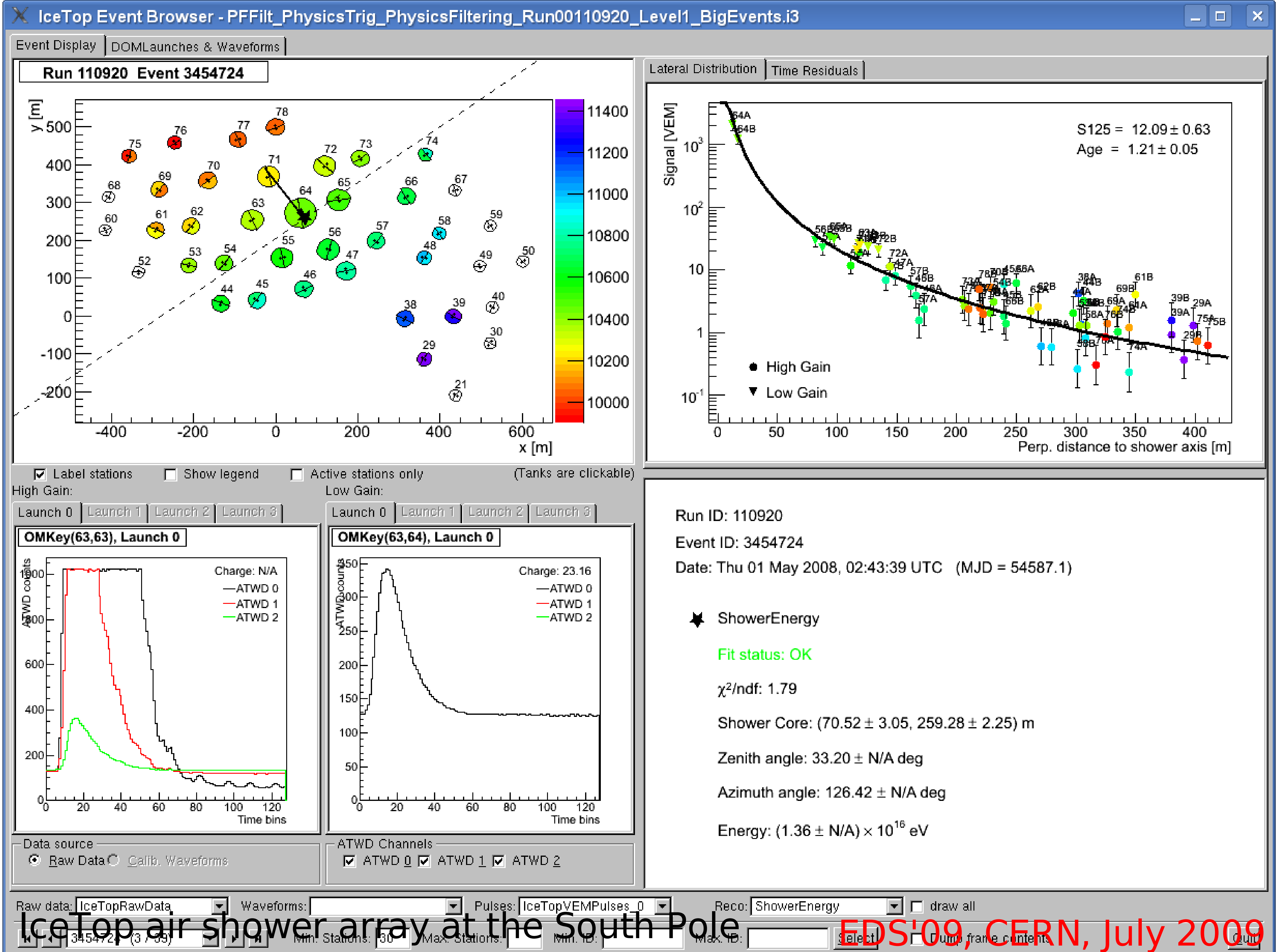


Air shower reconstruction: shower core in air shower array – 196 counters on a 15 m grid. Densities calculated with the Greisen's formulae. Simulated fluctuations proportional to sq. root of density.



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





IceTop air shower array at the South Pole

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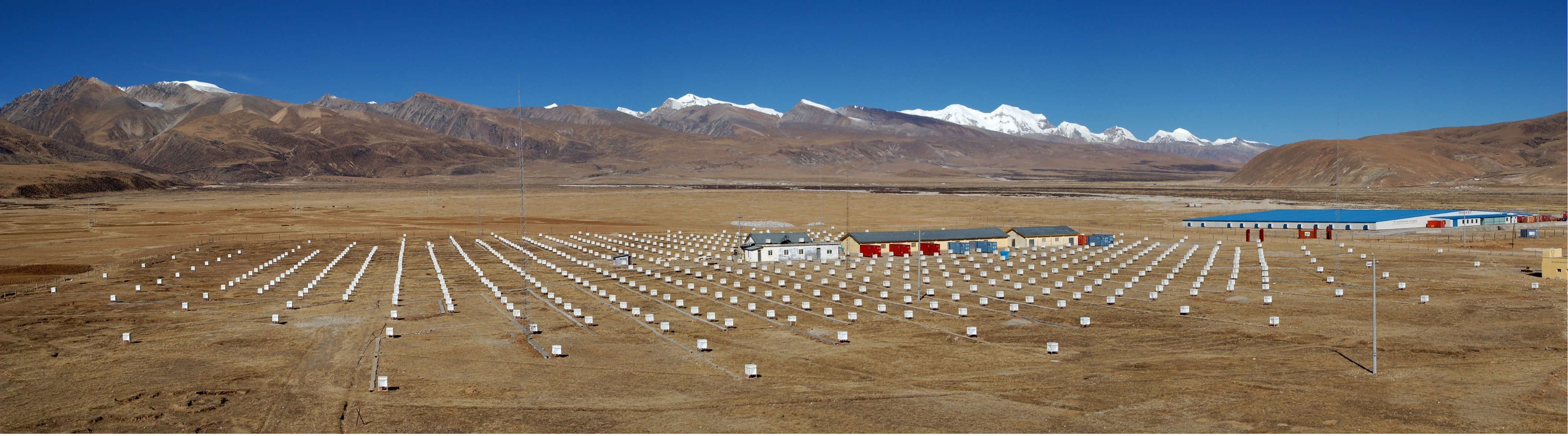
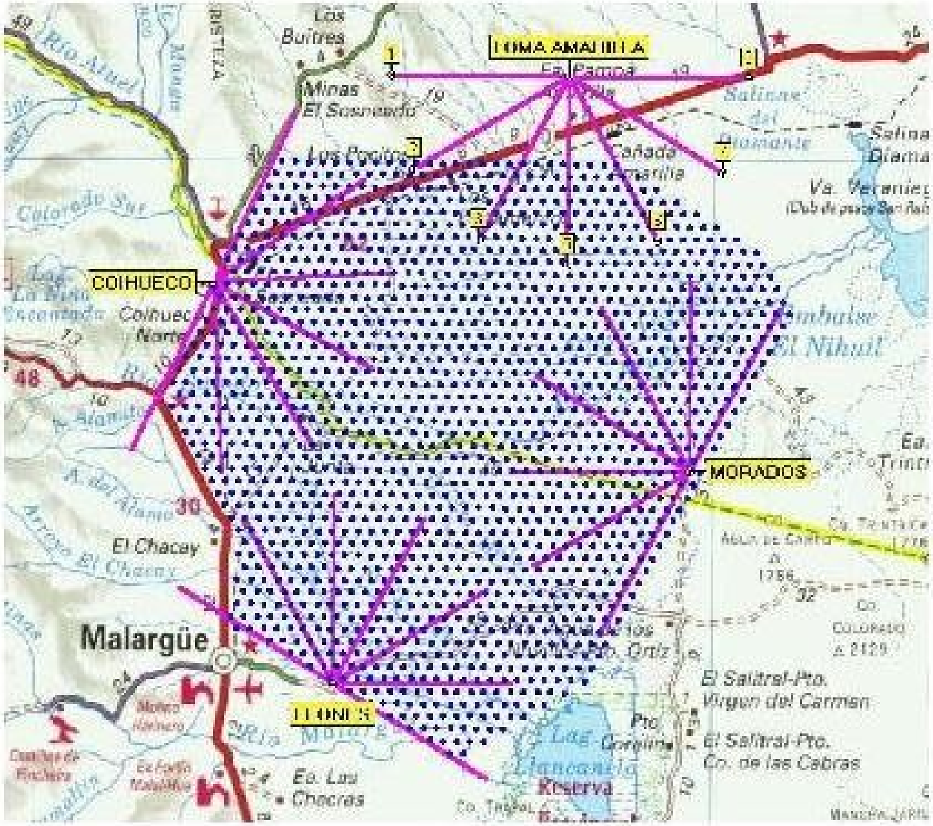


Top: the Tibet III air shower array at an altitude of 4,300 m above sea level.

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



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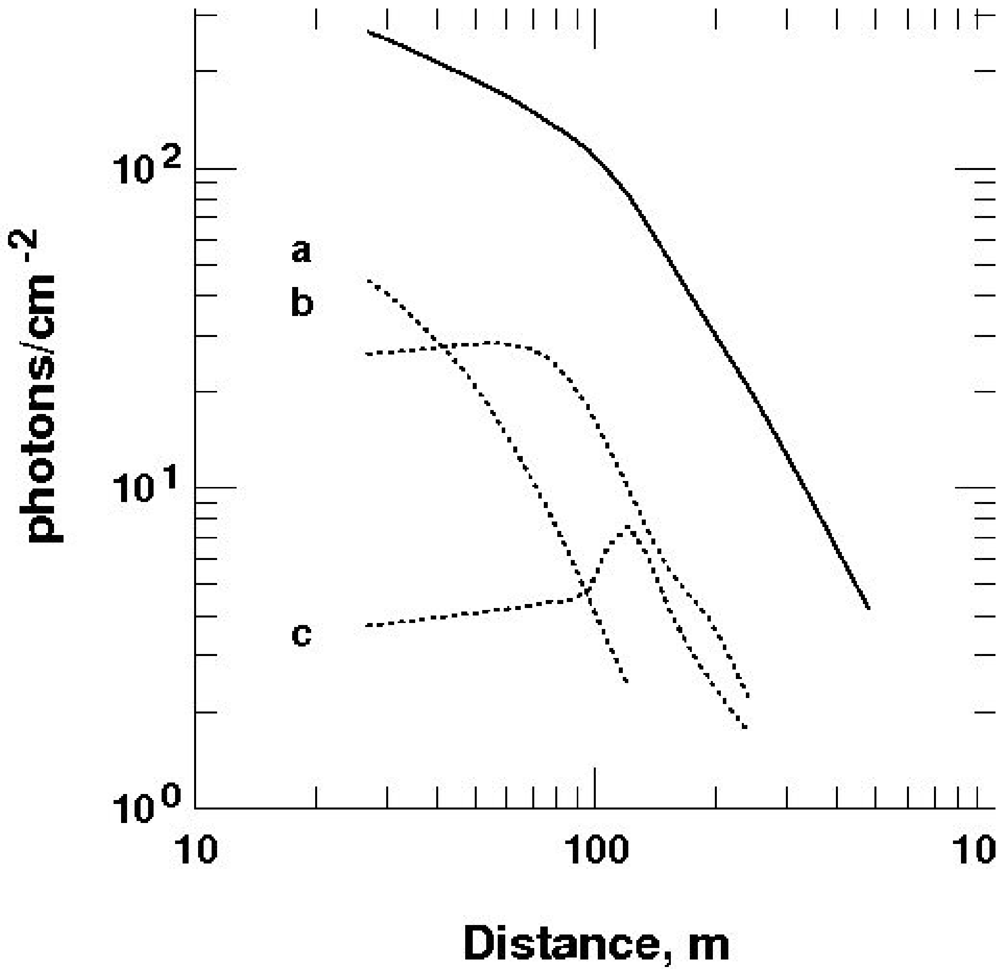
Shower Cherenkov light

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



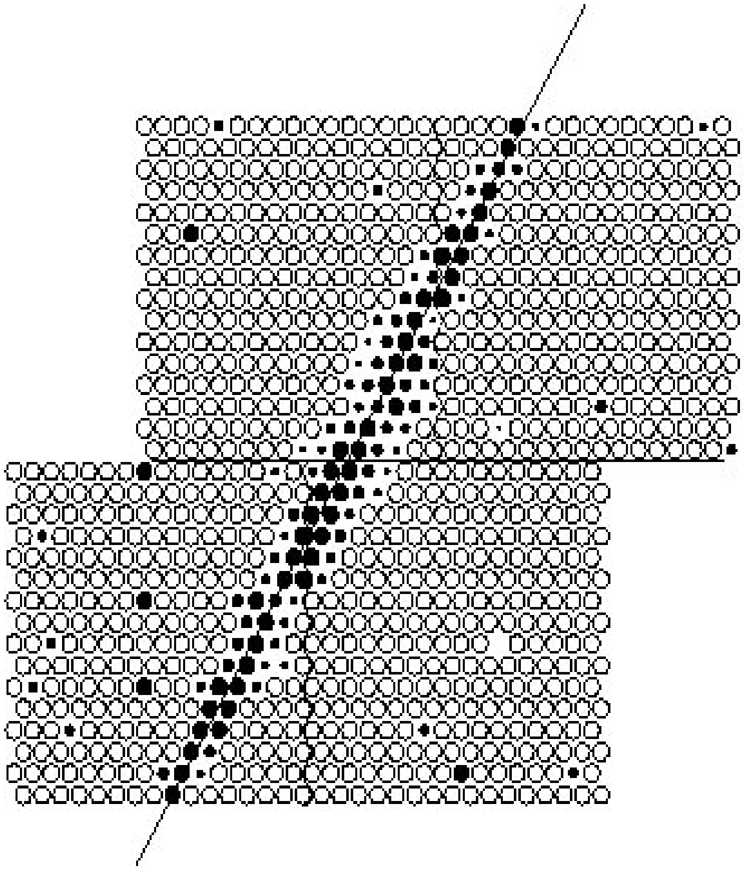
Lateral distribution
a) close by em shower
b) shower at X_{max}
c) early em shower

Density at 100 m related to shower primary energy.

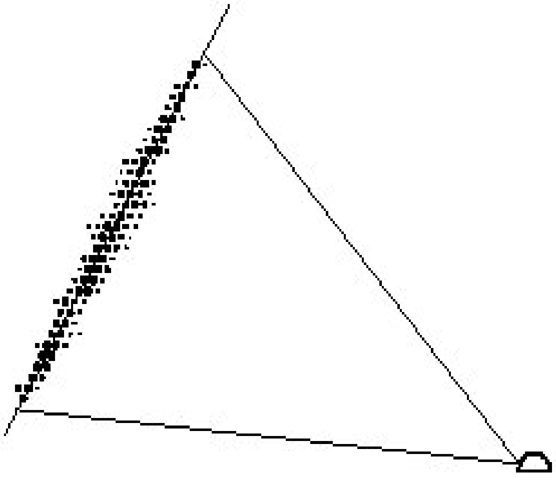
Density ratio at 40m/(>100 m) used to find shower maximum with accuracy of 20-40 g/sq.cm

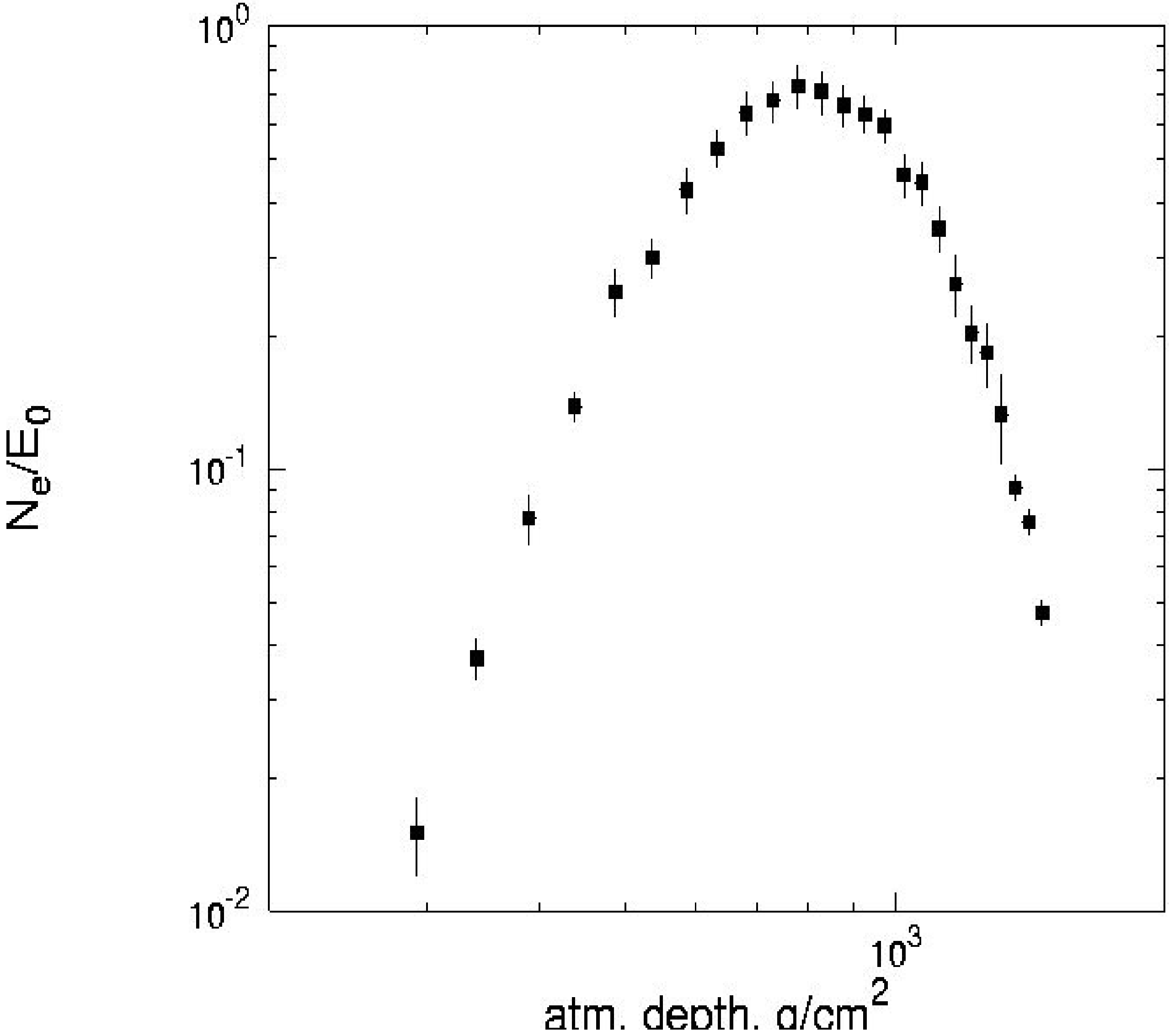
Shower fluorescent light – fluorescent telescopes

Emission by N atoms excited by the particle ionization.
Isotropic, about 4 photons per electron per meter.
Showers above 10^{17} eV can be detected, large ones from impact parameter > 30 km.



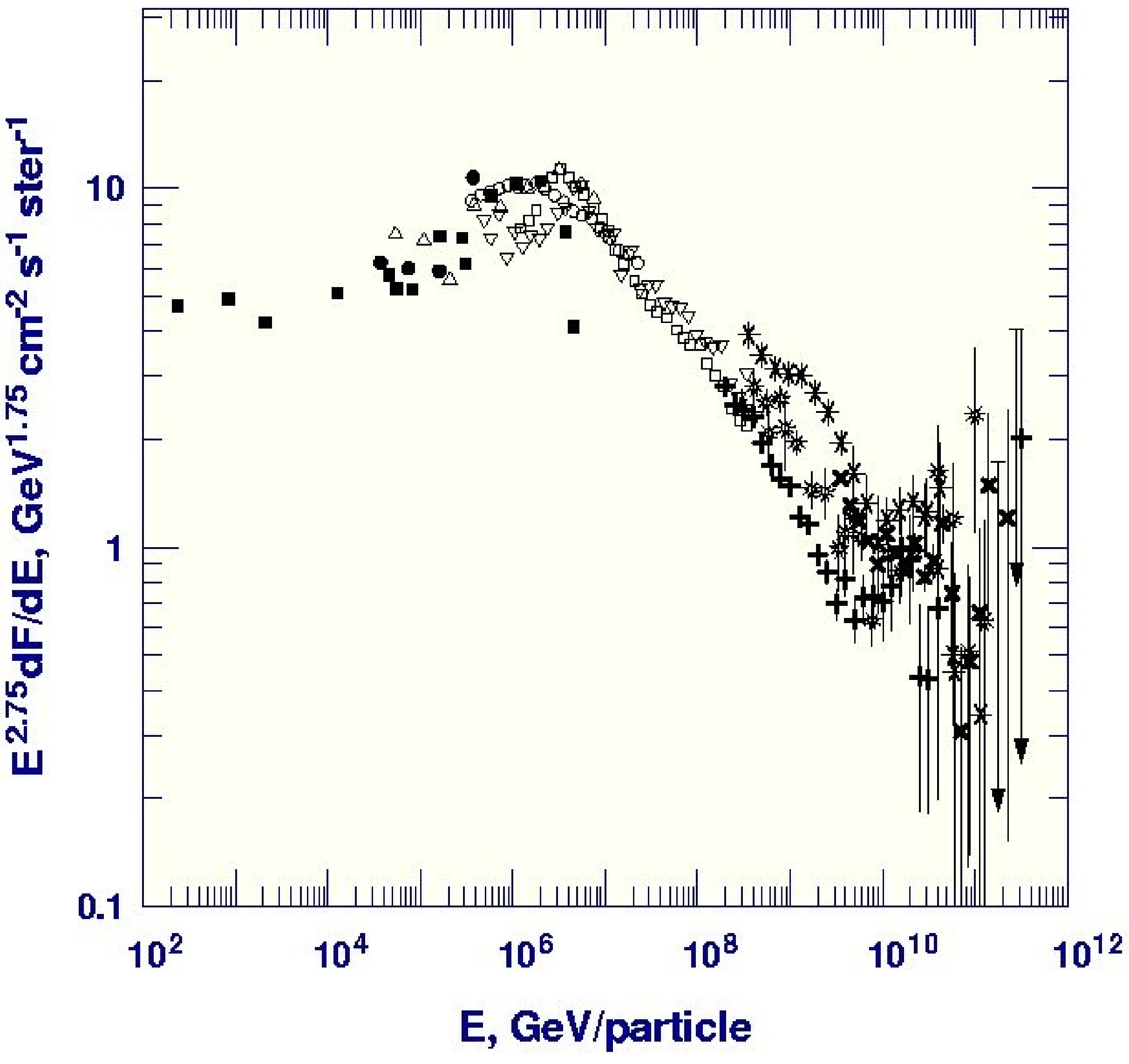
Reconstruction



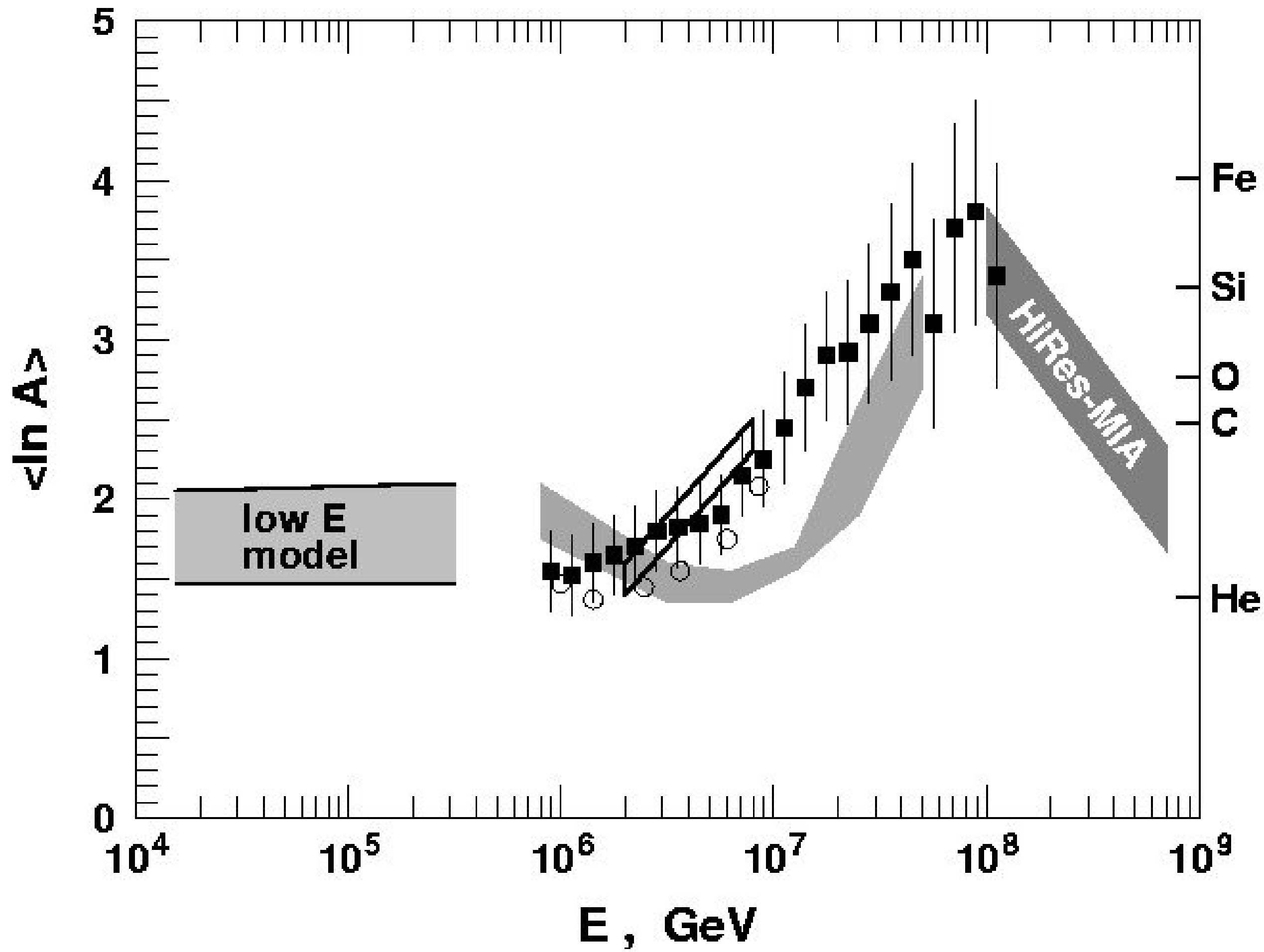


Primary energy determined from an integral over the shower longitudinal profile with an account for the missing energy (in high energy muons and neutrinos).

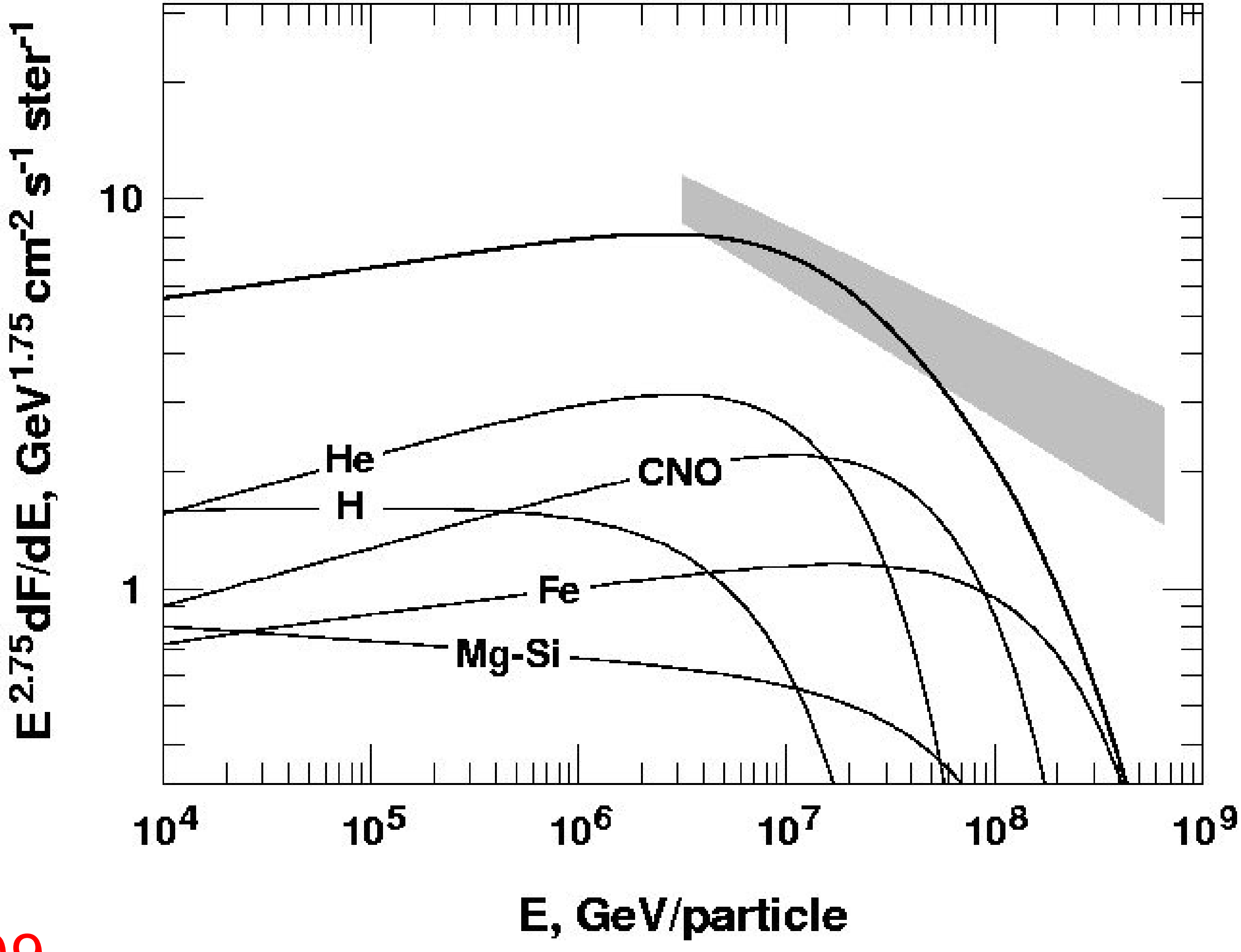
Cosmic ray spectrum



Cosmic ray composition as a function of energy: Kascade data. The lighter chemical composition at the highest energies is now challenged.



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



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.