Ultra High Energy Cosmic Rays: Observations and Analysis

Todor Stanev
Bartol Research Institute
Dept Physics and Astronomy
University of Delaware

NOT A NEW PROBLEM, STILL UNSOLVED

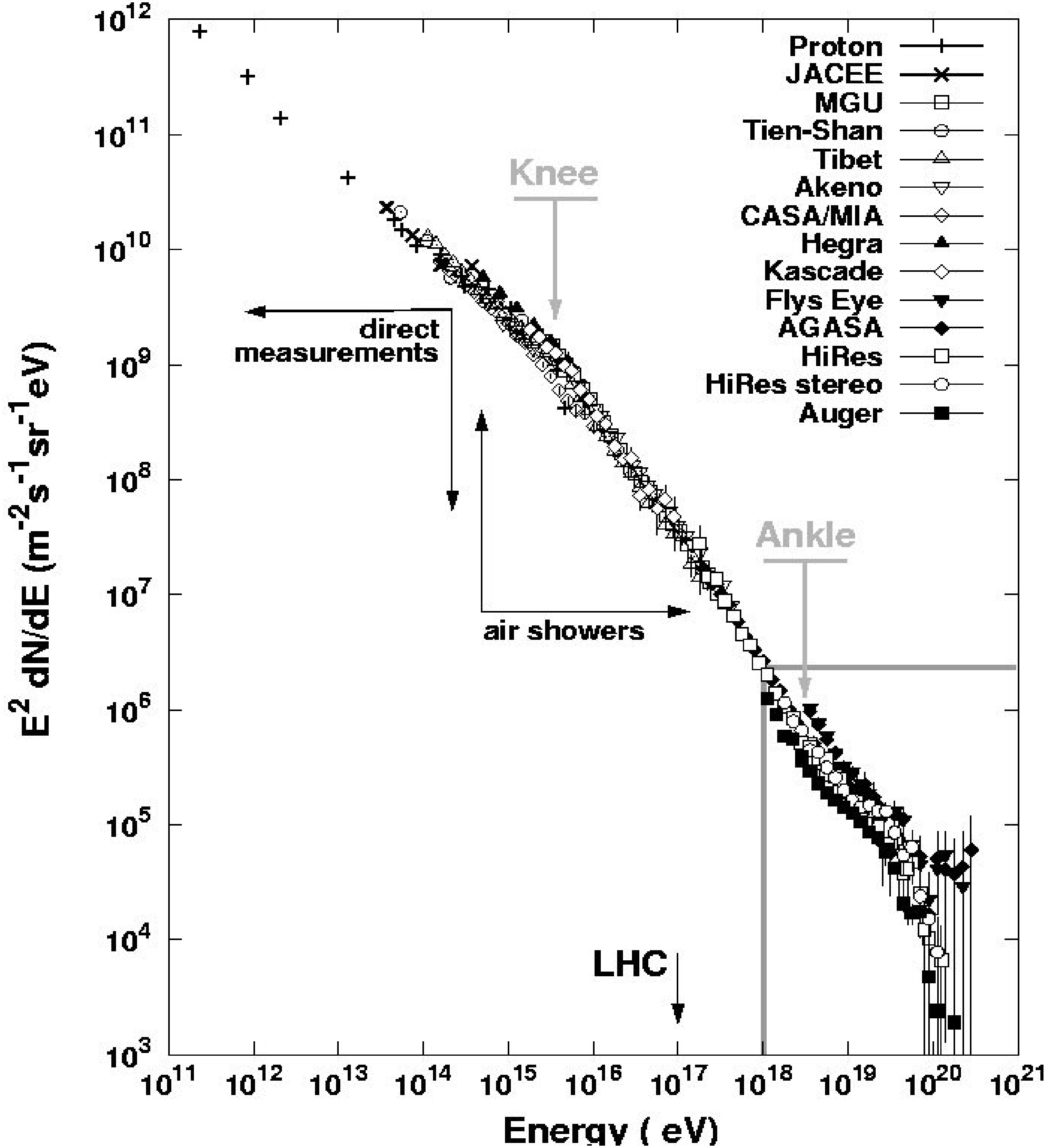
John Linsley (PRL 10 (1963) 146) reports on the detection in Vulcano Ranch of an air shower of energy above 10^{20} eV.

Problem: the microwave background radiation is *discovered* in 1965. Greisen and Zatseping&Kuzmin independently derived the absorption of UHE protons in photoproduction interactions on the 3K background.

More problems: such detections continue, the current world statistics is around 10 events

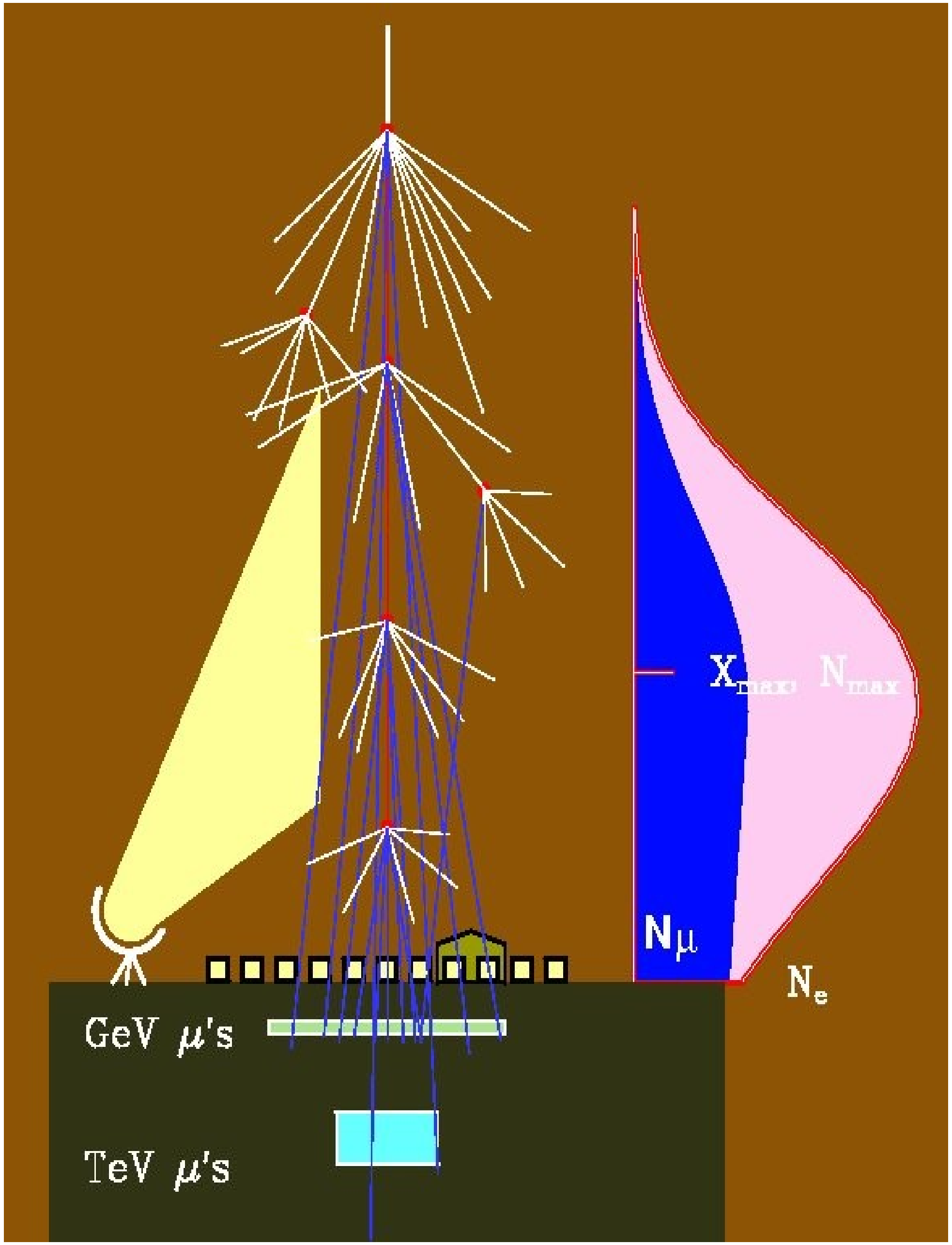
10^{20} eV =
= 2.4×10^{34} Hz
= 1.6×10^{8} erg
= 170 km/h tennis ball

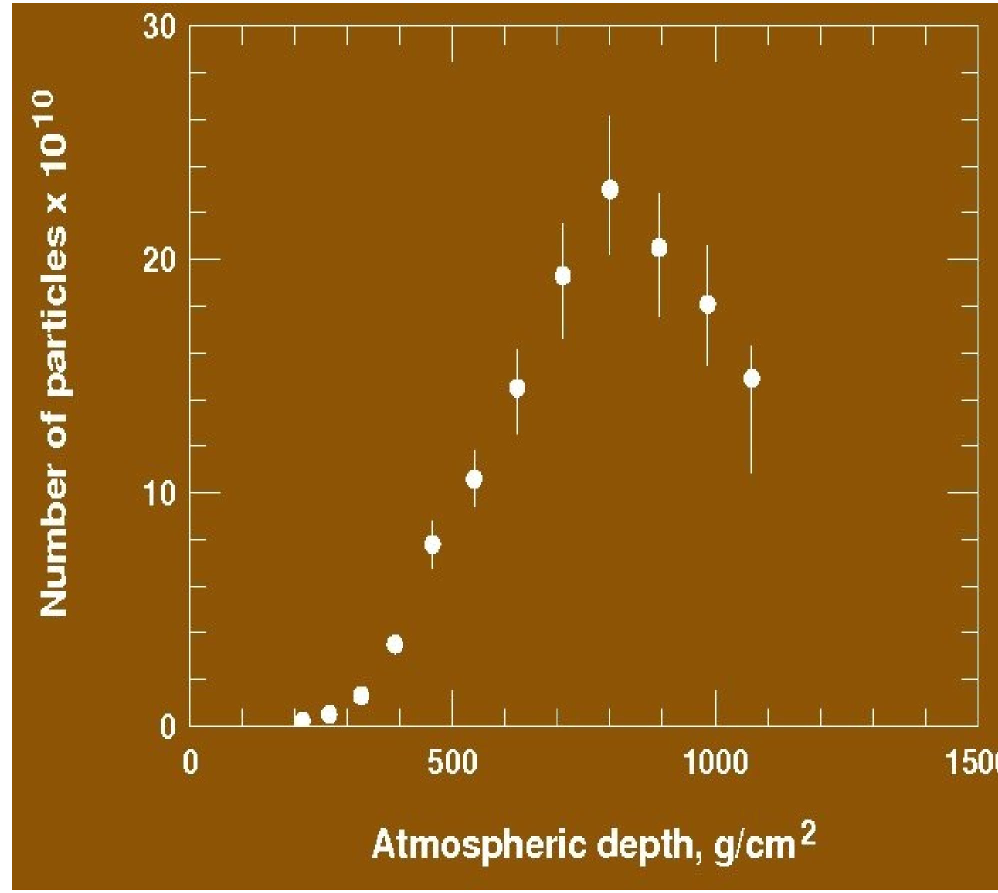
$\sqrt{s}$ equivalent is 430 TeV



The cosmic ray energy spectrum covers many orders of magnitude. Different experiments measure from kinetic energy in MeV to above 10^{11} GeV, i.e. sqrt(s) = 433 TeV.

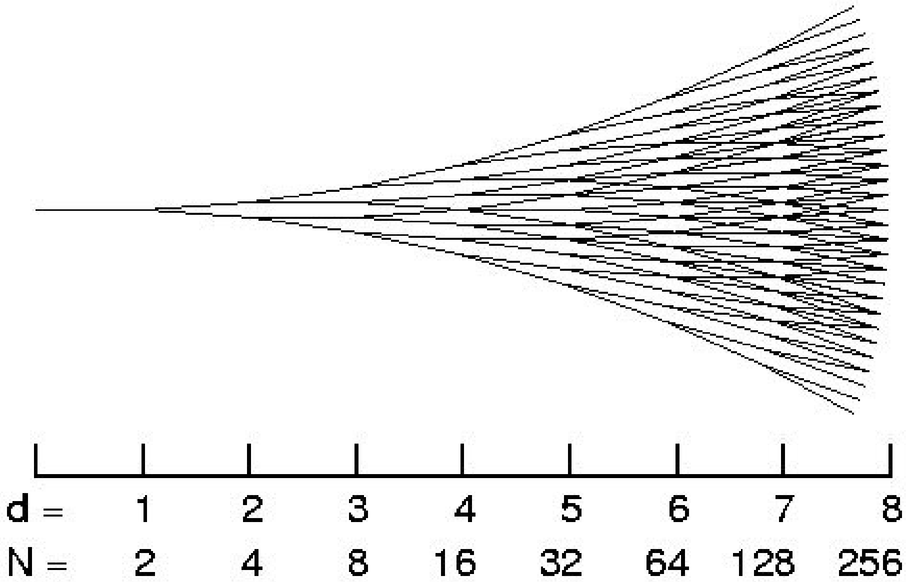
We have to extend the hadronic interaction to a factor of 50 over LHC to be able to analyze these events.





Shower profile of the highest energy shower detected by the Fly's Eye experiment. Energy estimate is 3.10^{20} eV.

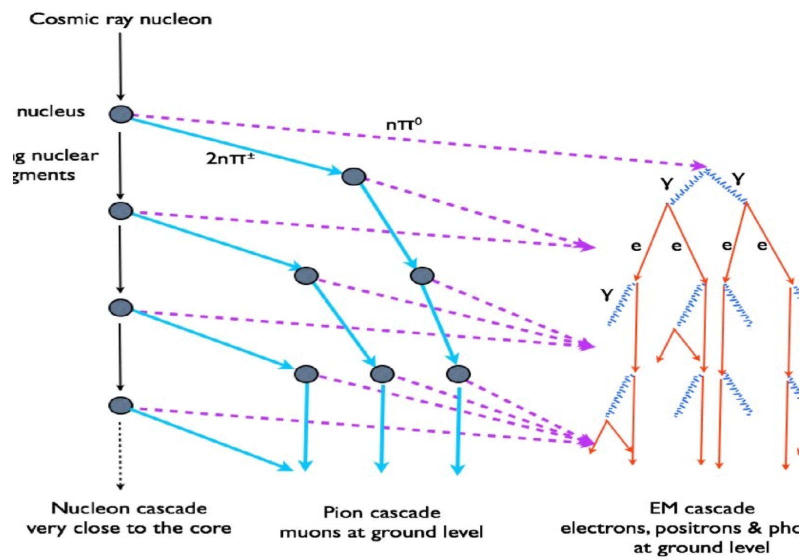
Shower detection techniques: air shower array, Cherenkov radiation, air fluorescence technique.



The simple `toy shower' model was developed by Heitler for electromagnetic cascades. Every interaction generates e identical particles. The number of particles is 2^d , i.e. we have 256 particles after 8 interactions and the particle energy is $E_0/256$.

After reaching some critical energy the number of particles starts to decline.

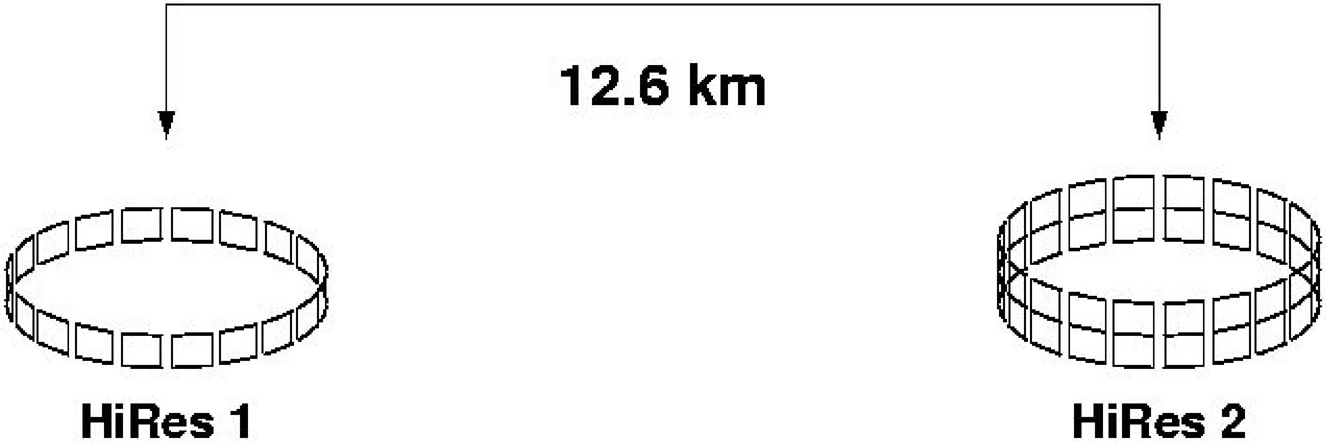
Hadronic showers are much more complicated but their development is similar. We have multiplicities much higher than two but the cross section is smaller. Shower maximum (the depth where there are maximum number of particles is proportional to log(E).



The first detector that saw a particle with energy of 10^{20} eV is the Volcano Ranch air shower array in New Mexico, USA. The array was started by the MIT group that involved B. Rossi, L. Scarsi and J. Linsley. In 1863 Linsley published a Phys. Rev. Lett. about an event with this energy. Nobody was excited after this publication – people believed that cosmic ray energy spectrum continues for ever with smaller and smaller fluxes.

The excitement came three years later, when Greisen in USA and Zatsepin and Kuzmin in the Soviet Union simultaneously published articles about the interactions of UHE cosmic rays in the microwave background and predicted that the cosmic ray spectrum will start declining after 5.10^{19} eV. This is now called GZK cutoff.

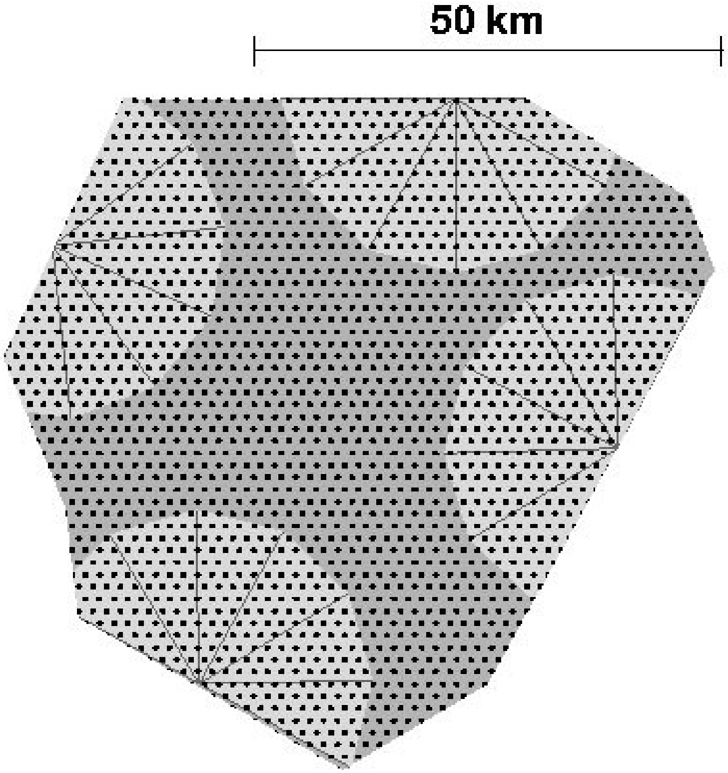
The most recent experiments cover thousands of square kilometers to detect these extremely high energy particles that come less than a few (2?) per 100 sq. km. per century.

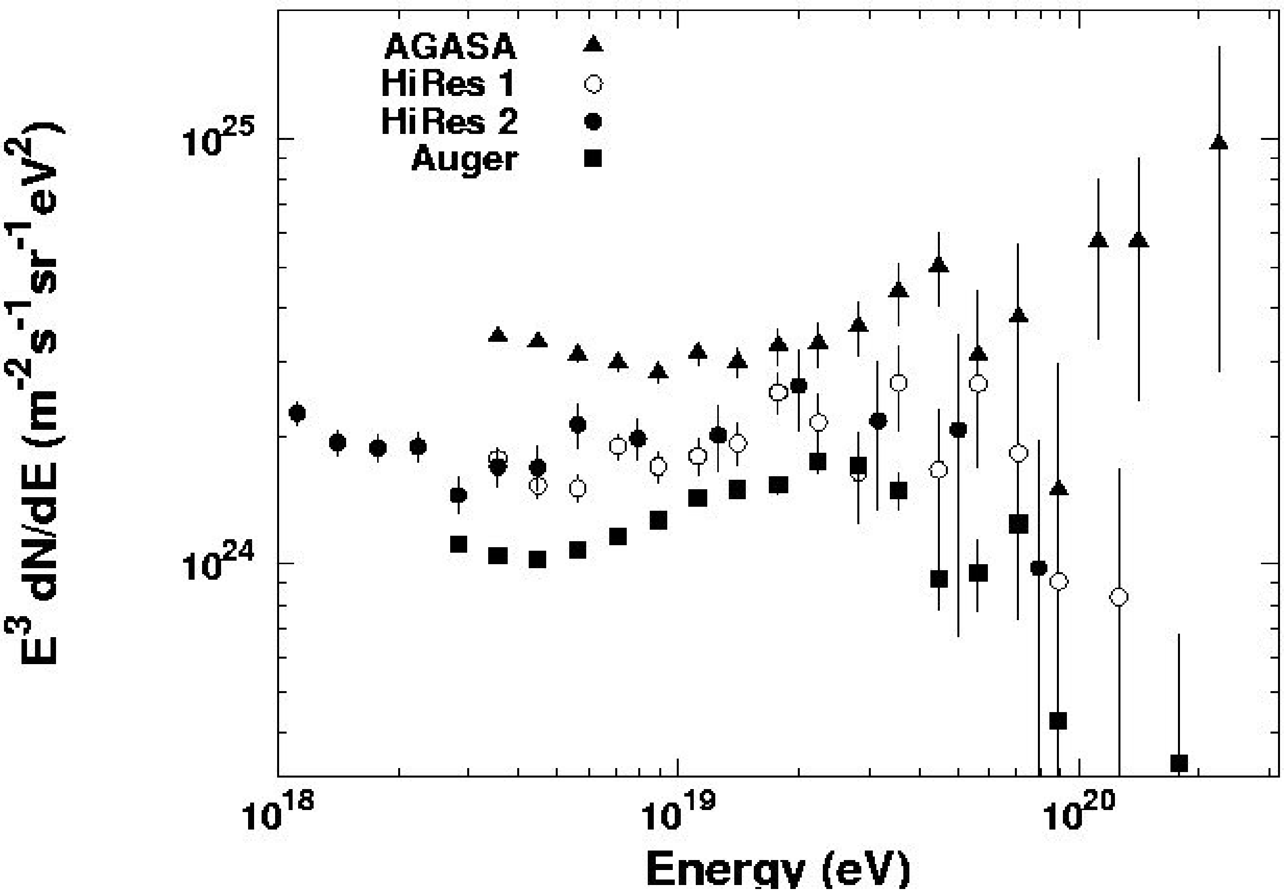


HiRes consists of two fluorescent detectors that often work in stereo mode. They can see the highest energy showers from distance of 40 km.

Here are the two detectors we will deal with today:

Auger is a hybrid detector that consists of an air shower array of area 3,000 sq.km and four fluorescent detectors. The surface detectors are at distance of 1.5 km from each other and are fully sensitive to cosmic rays of energy above 3 EeV (3.10^{18} eV). In hybrid mode it is sensitive to lower energy.





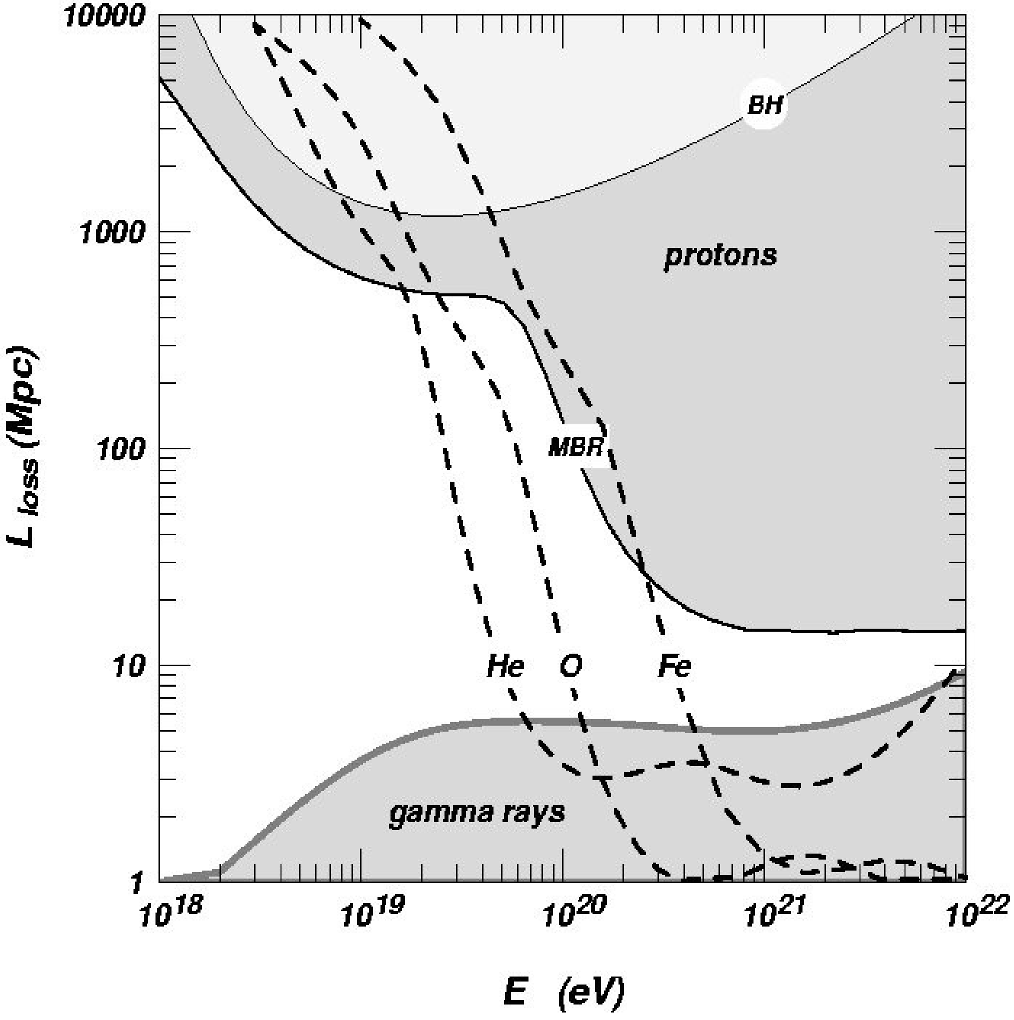
The AGASA energy spectrum continues well above the GZK cut-off. This inspired exotic *top-down* models for the generation of UHECR (decays of very heavy long lived remnants of the Big Bang).

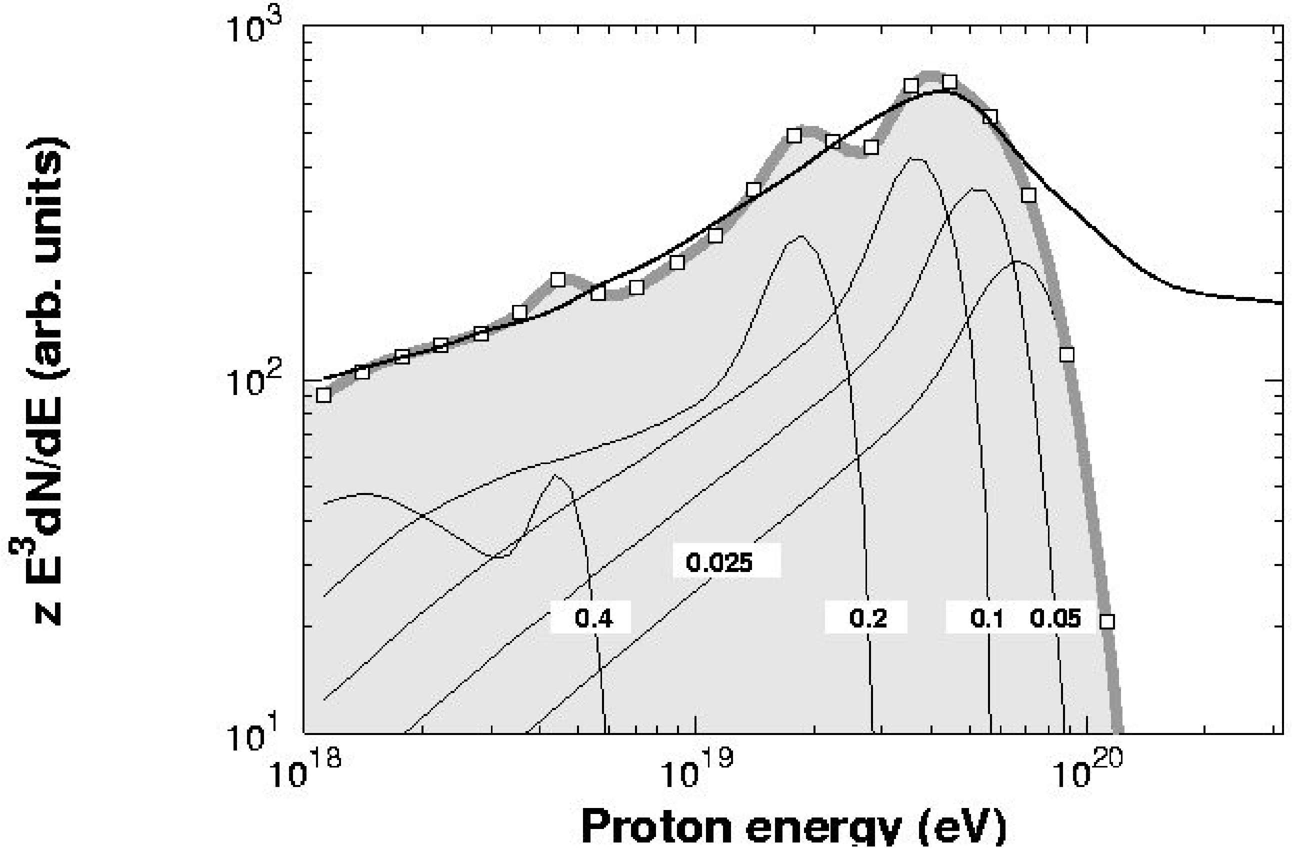
This was the situation with the measurements of the cosmic ray energy spectrum in the beginning of the 21st century. The AGASA experiment measured 11 events of energy above 10^{20} eV. Other detectors saw a declining flux at these high energies.

This is why the GRZ cutoff exists.

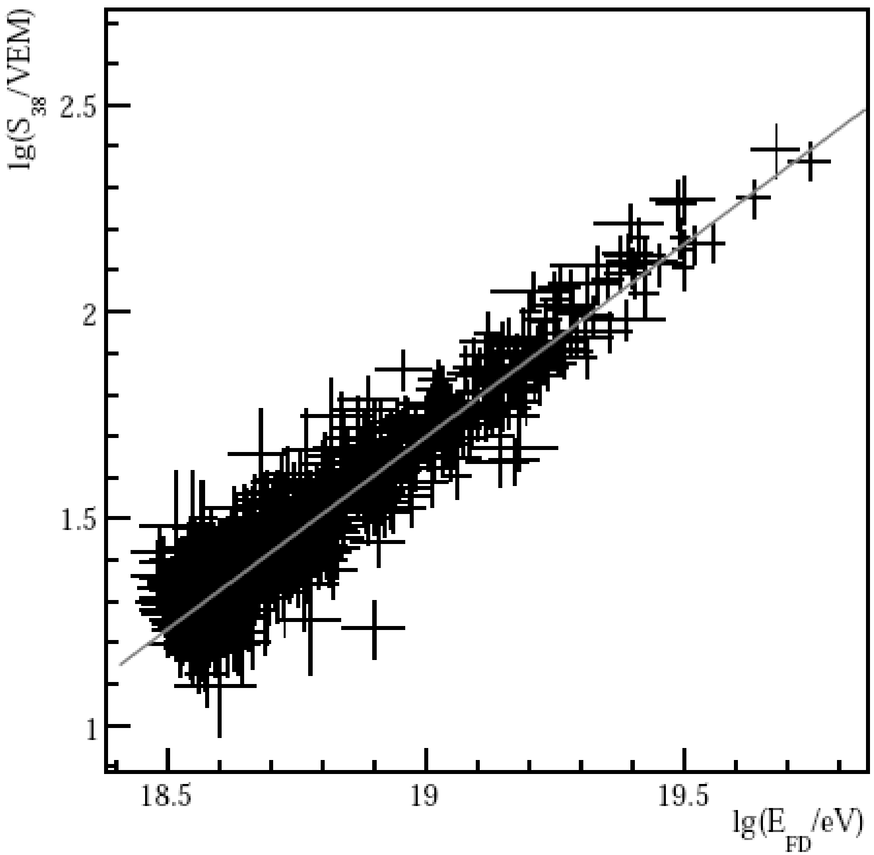
High energy particles interact with the microwave background radiation photons. Since the cm energy is low, of order of a GeV, the cross section is well known. UHECR lose energy on photoproduction interactions, pair creation, and adiabatic loss.

Nuclei lose energy in photodisintegration, losing one or two nucleons.

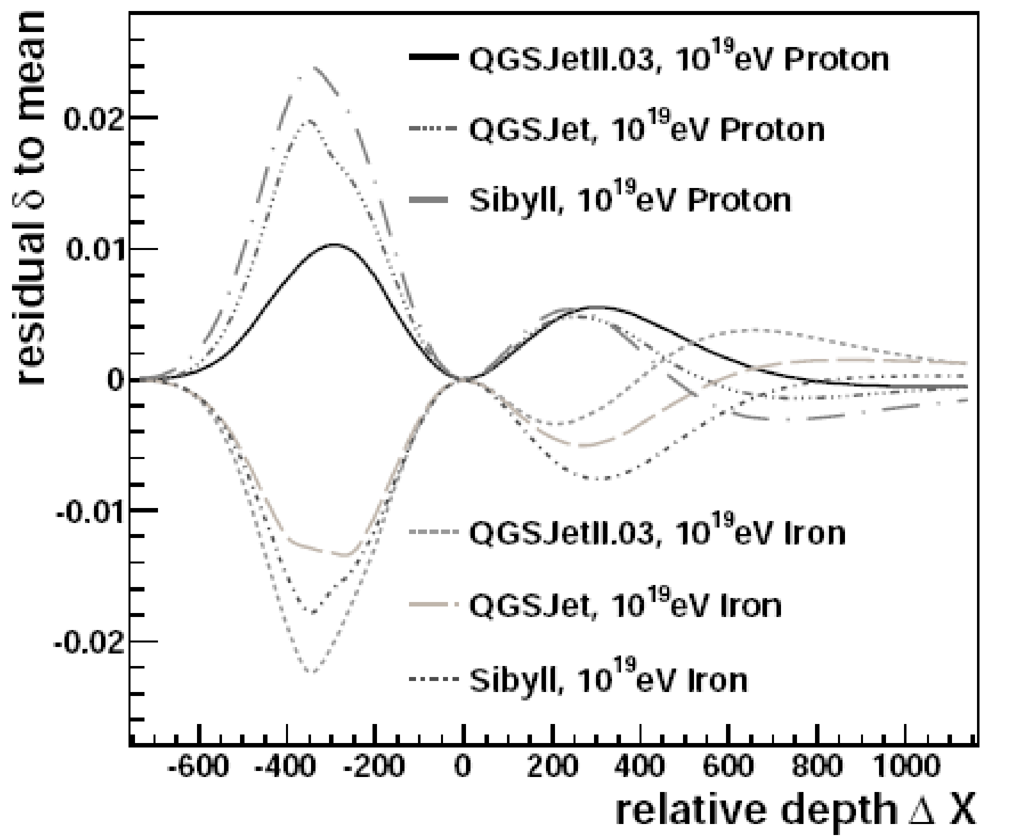




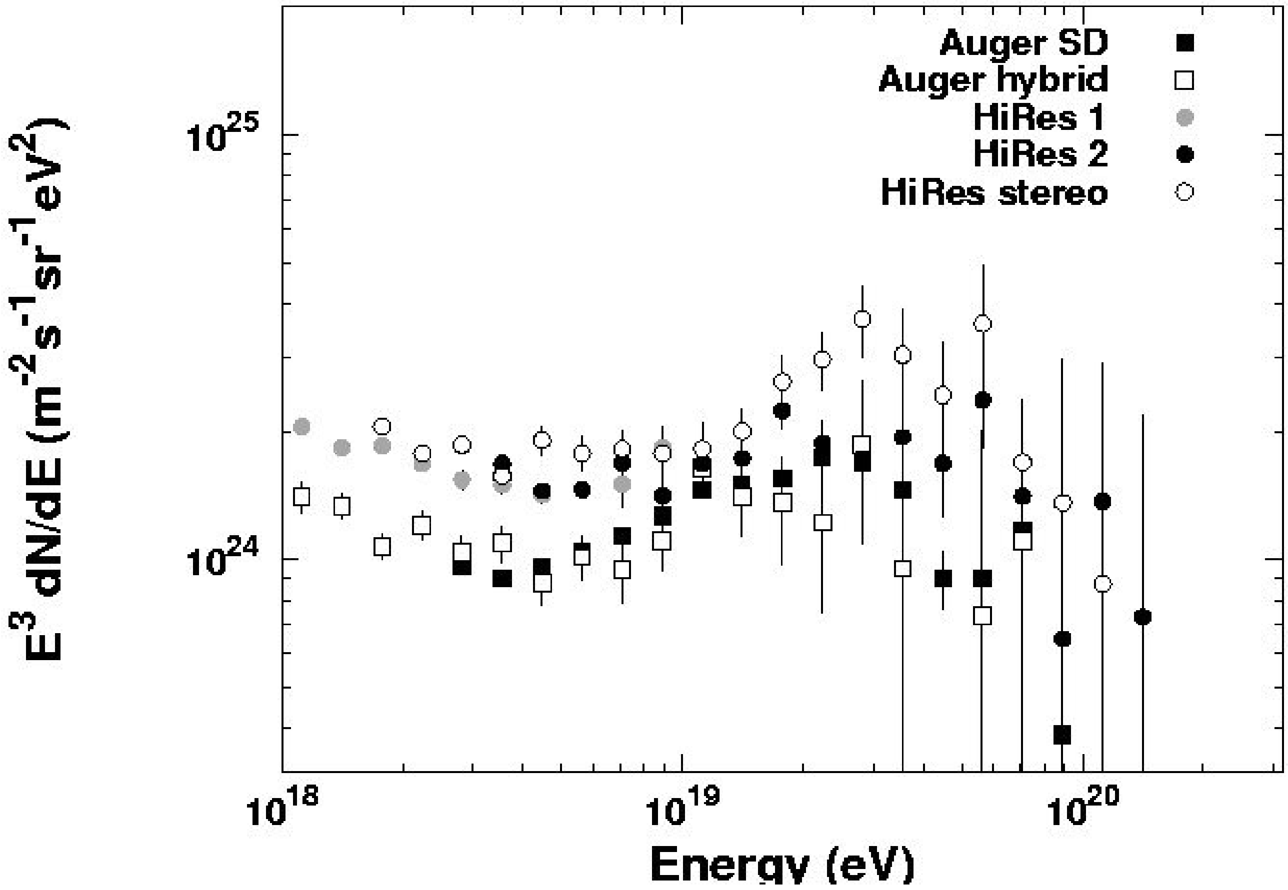
Formation of the proton energy spectrum in propagation through the microwave background. The injection (acceleration) energy spectrum is E^{-2} with an exponential cutoff . The highest energy protons interact and lose energy. A flattening of the spectrum Is formed above 10^{19} eV.



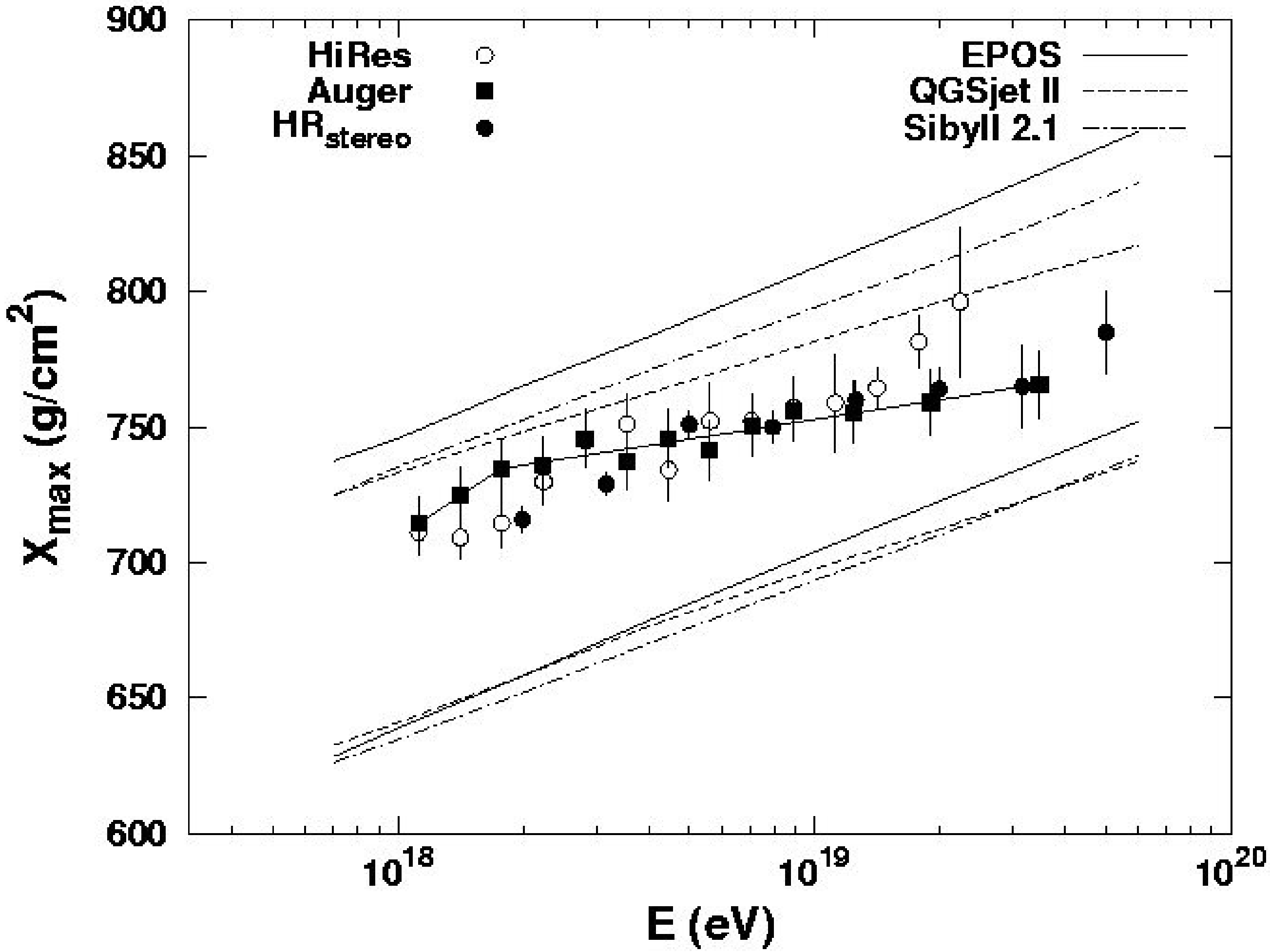
Auger uses the signal at 1 km from the air shower core. They correlate it to the shower fluorescence profile which is less model dependent. S_{1000} is used to measure UHECR energy spectrum.



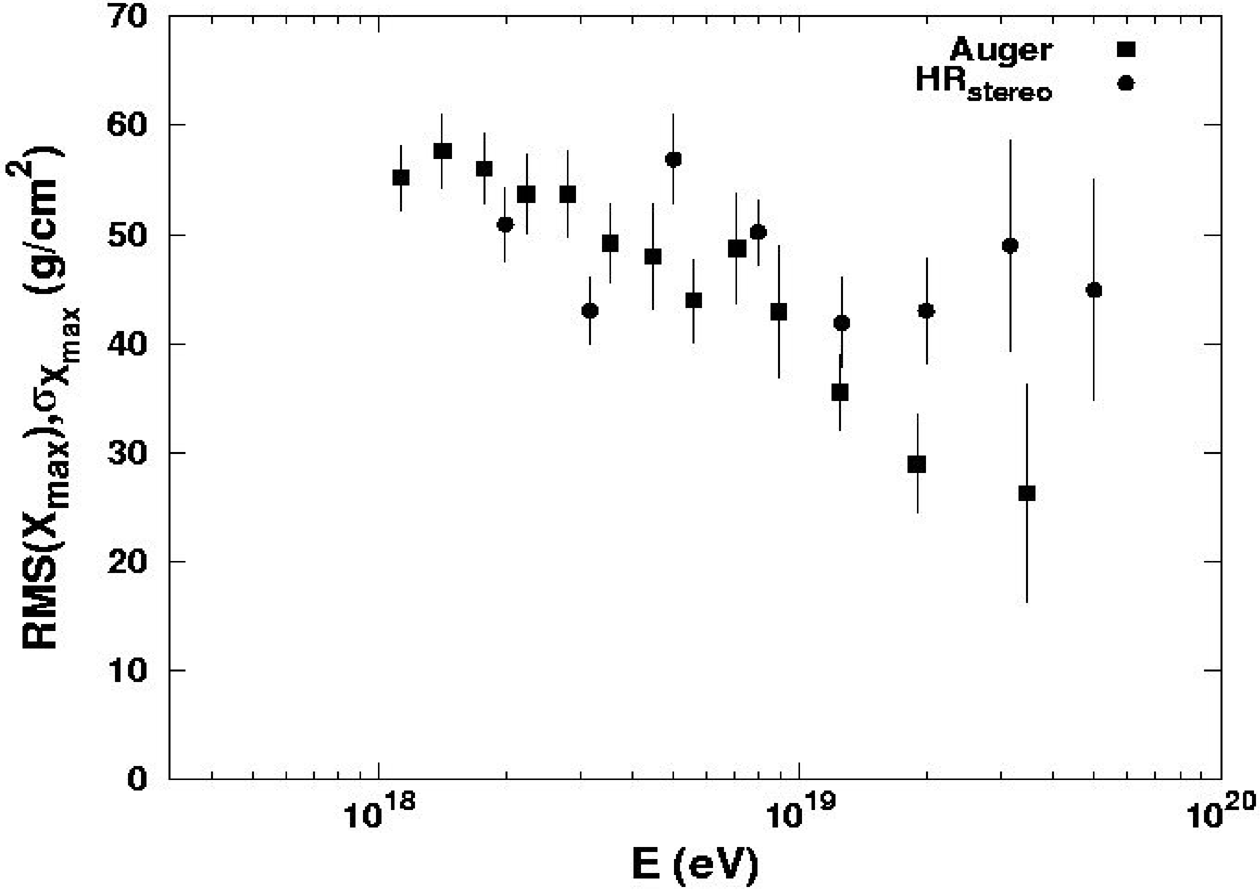
The errors in energy estimate are relatively small in all hadronic interaction models.



The UHECR energy spectrum measured by HiRes and Auger. Apart from the about 20% difference in the energy assignment Both spectra show the expected flattening at 3.10^{19} eV and a cutoff after that. Both spectra are consistent with the GZK effect.



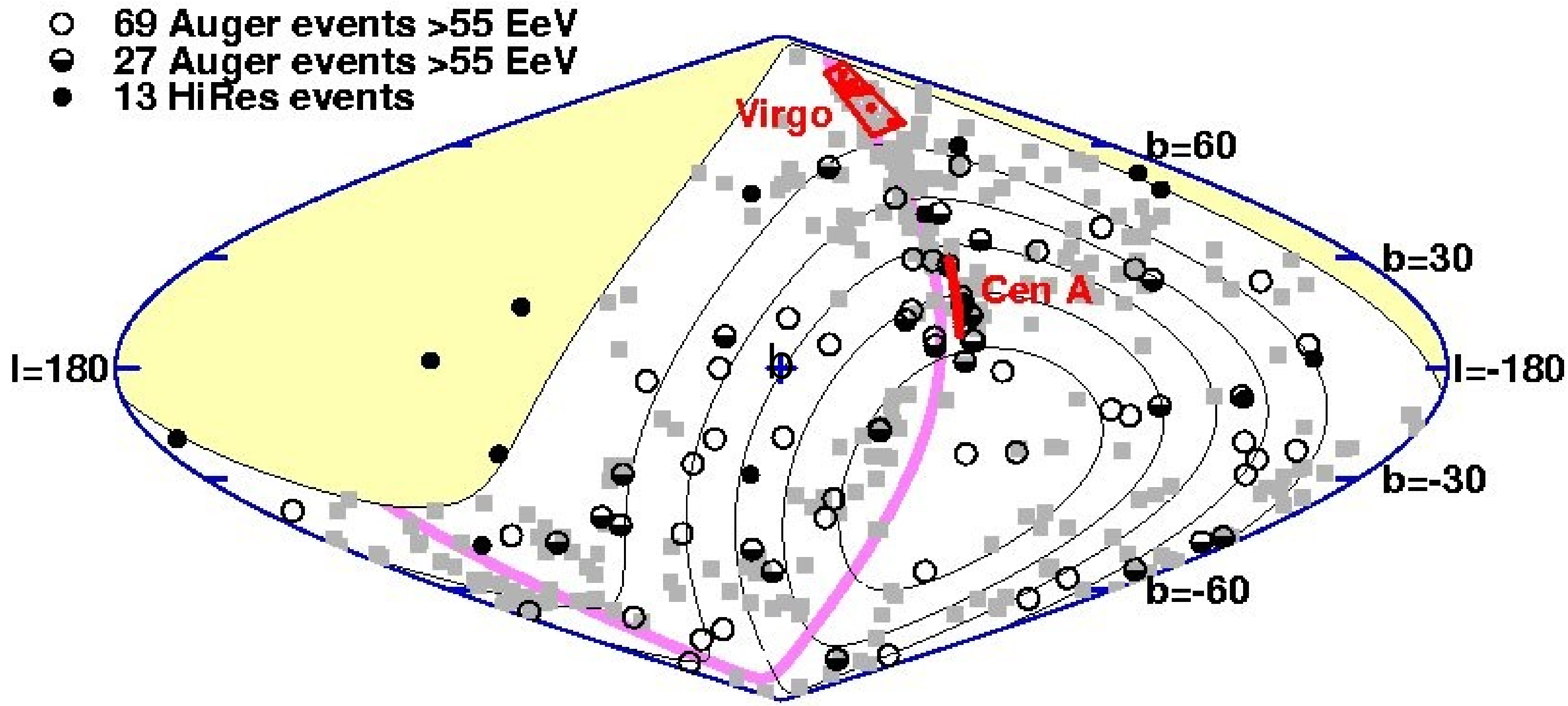
A much bigger difference is in the measurement of the UHECR chemical composition, which is related to the measured depth of maximum. Auger derives a composition that is light (H) and then becomes heavier (almost Fe). HiRes measures light composition at all energies.



Another composition related measurement is the fluctuations of X_{max} as a function of energy. Showers of heavy primary particles show Smaller fluctuations.

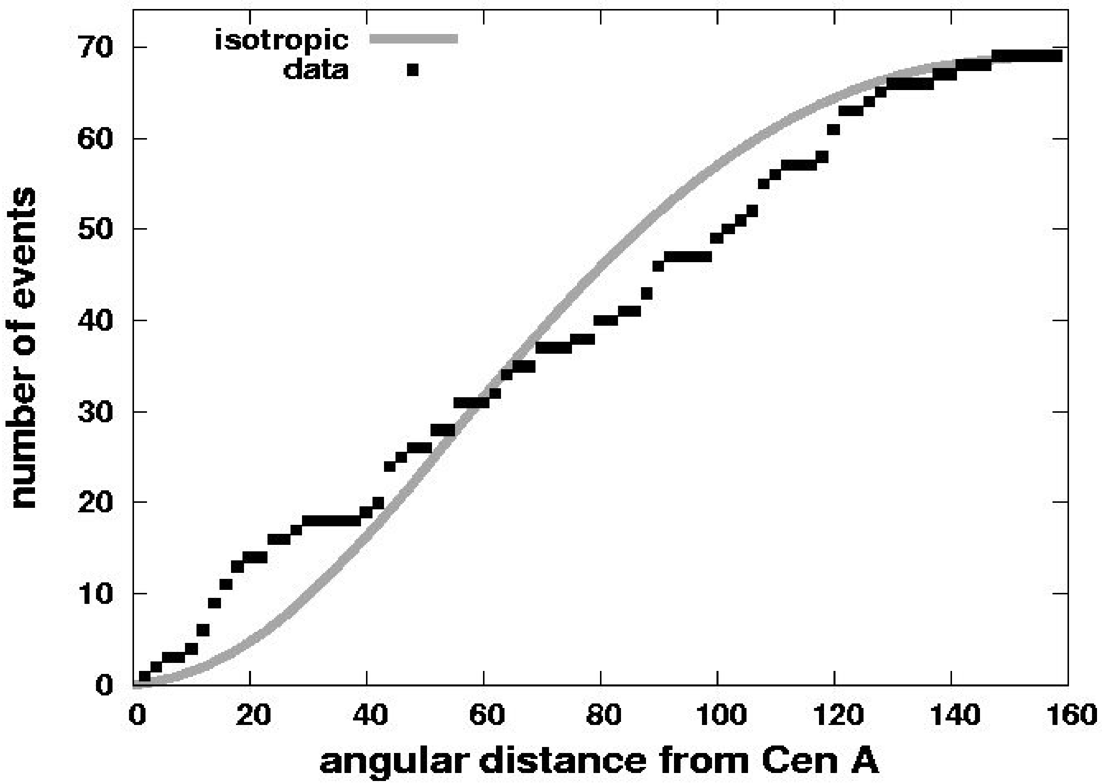
The heavy composition measured by Auger suggest another possibility: the cutoff is not caused by the GZK type energy loss but by reaching the maximum energy of the cosmic ray accelerators *(`Disappointing model')* by Berezinsky et al.

Arrival directions of UHECR



The arrival directions of the highest energy events of the Auger observatory are not isotropic. Among the first 27 events above 55 EeV 70% were correlated with AGN from VCV catalog at redshift < 0.02. Now with 69 events this correlation has decreased To 40% but still exists. This creates controversy with the heavy UHECR composition. Fe nuclei would scatter a lot in the galactic and extragalactic magnetic fields and would appear totally isotropis at arrival to Earth. Most of the anisotropy seems to be related to the direction of the radio galaxy Cen A.

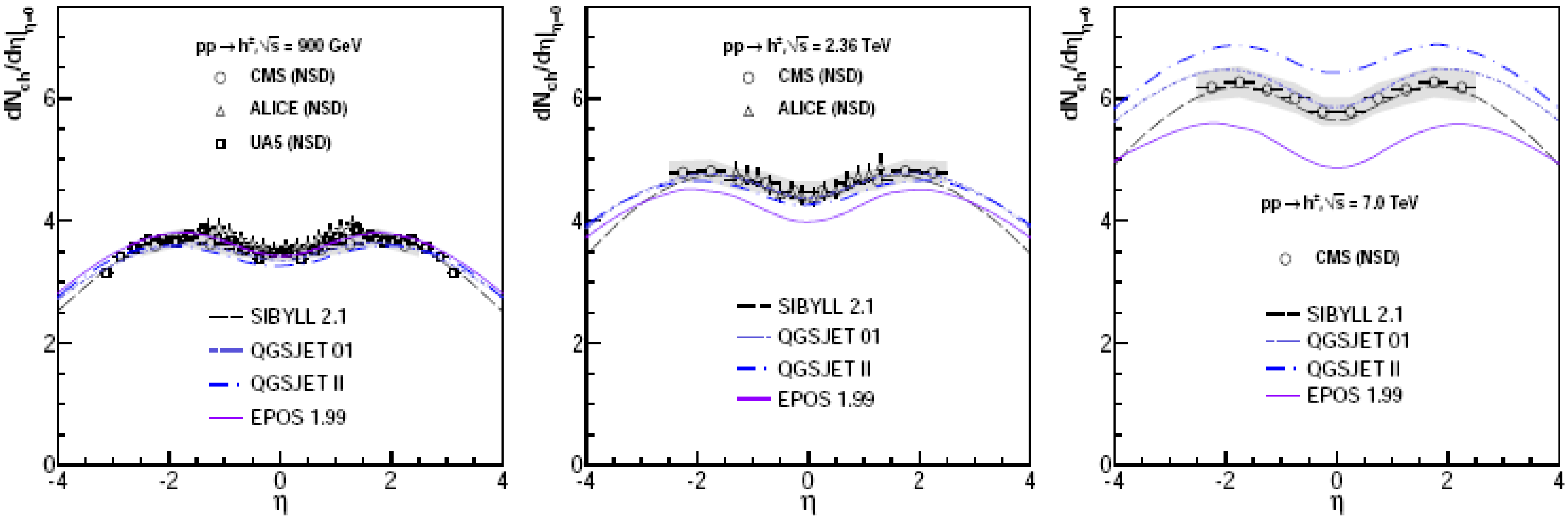
Is Centaurus A the only source of UHECR that we see?



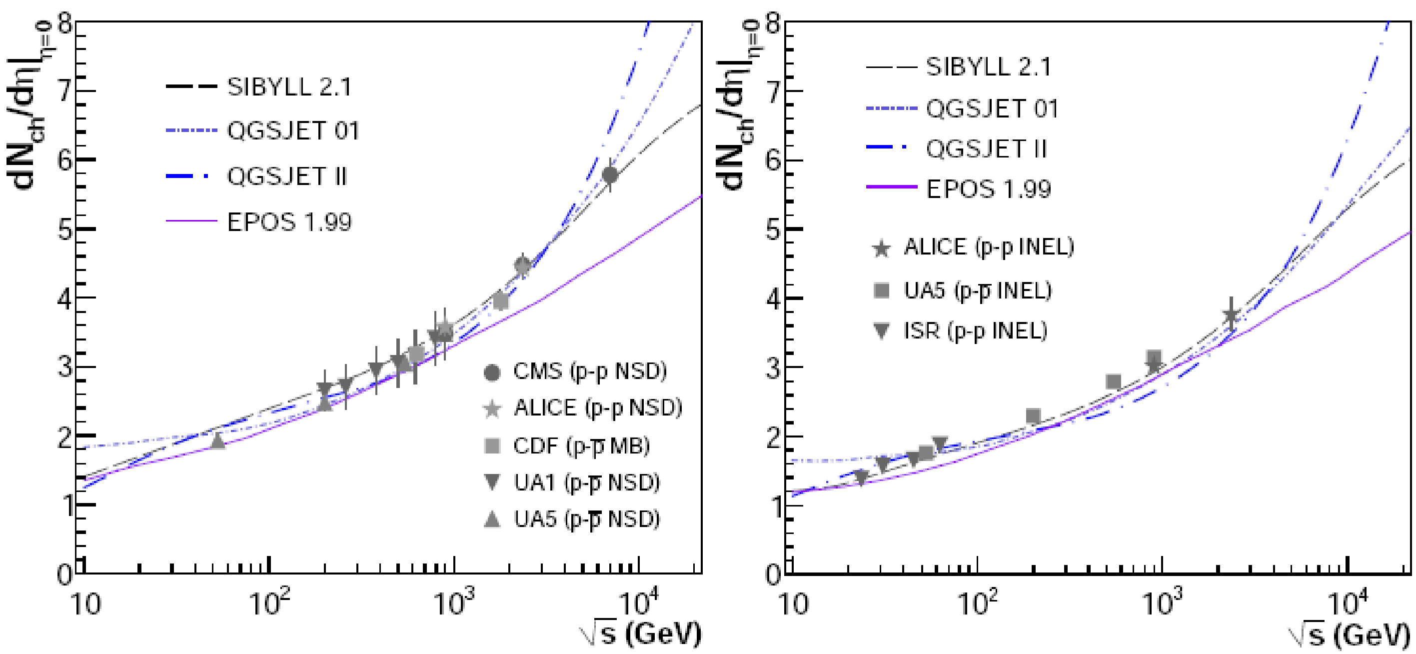
There are 13 events within 18 degrees of Cen A. There are no events within 18 deg. of M87 and the Virgo cluster of galaxies.

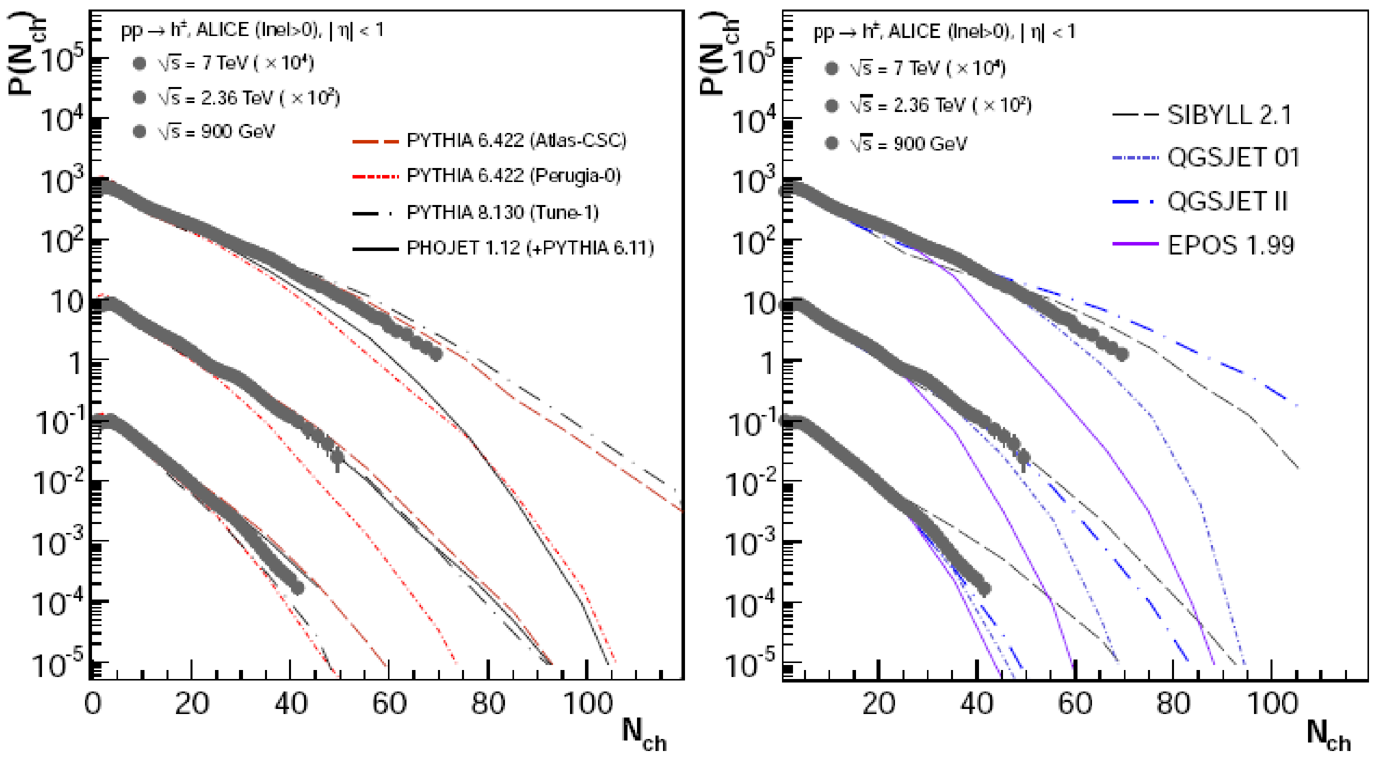
Cen A is only 3.8 (3.4?) Mpc away. It is the most powerful radio source that we observe. Its current AGN is not however powerful. The magnetic field in the giant lobes (500 kpc) of Cen A is μGauss. It is in front of the Centaurus cluster of galaxies.

The energy estimate of the cosmic ray showers is based on simulations with the hadronic interaction models. Recent LHC results give us an option to check how these models perform at 7 TeV in cms.



Source: d'Enterria et al, 2010

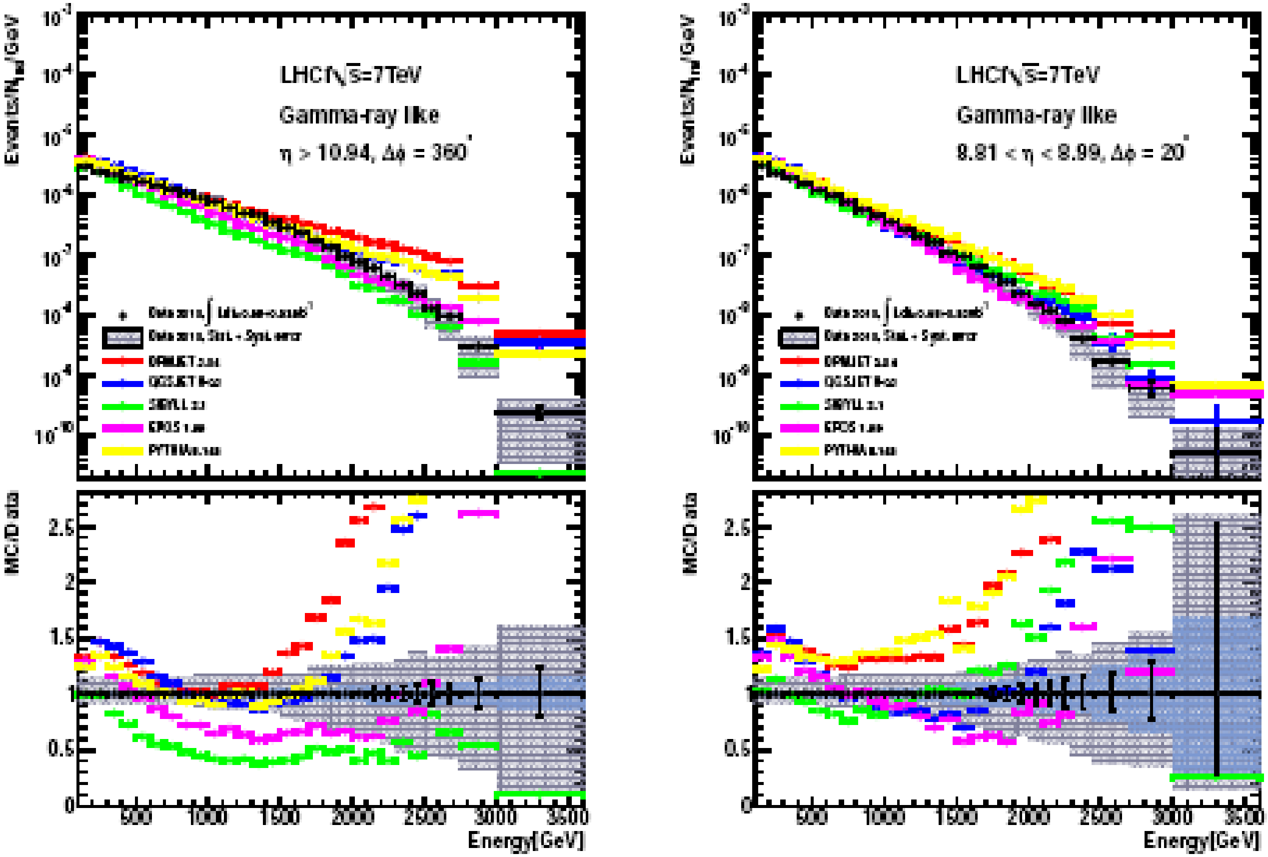




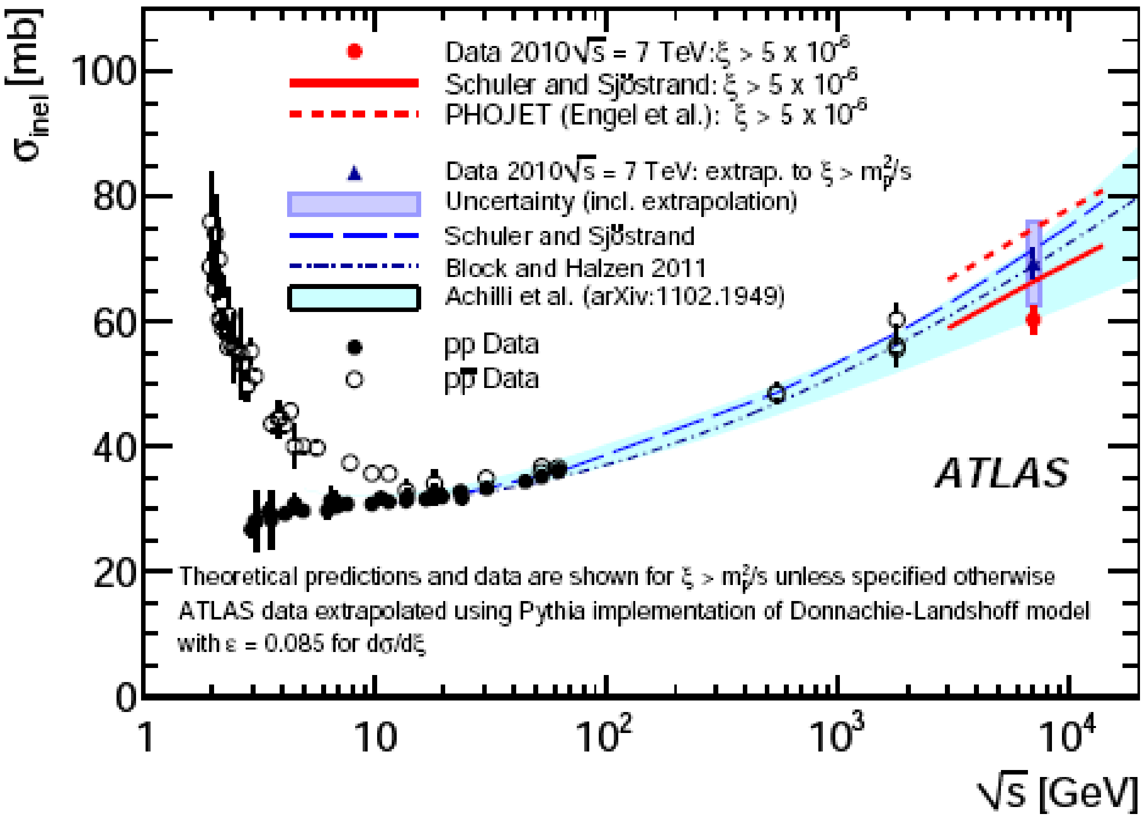
Source: d'Enterria et al

The conclusion of the paper is that the models used for UHECR analysis perform not worse then the typical PYTHIA versions at 7 TeV in cms.

Not everything, however, is that good.



The models do not describe well the very forward region (η>8) measured by LHCf. Sibyll 2.1 seems to fit not too bad this small region of the phase space.



The inelastic cross section measured by ATLAS is 69.4 +/- 2.4 +/- 6.9 mb

Sibyll: 80 mb
QGSjet01: 65 mb

Summary

The UHECR spectrum does not extend to nergies above 10^{11} GeV as the AGASA spectrum from 10 years ago seemed to indicate. Both HiRes and Auger agree that there are very few events above that energy.

The measurements of these two detectors do not agree on the cosmic rays chemical composition. Auger has also set strict limits on the the fraction of γ-rays. Thus the top-down models of UHECR acceleration may only apply to the very high energy region.

The arrival direction of the events above 55 EeV is not isotropic. A large fraction of the events comes from direction close to Cen A.

The models used for the analysis of these events mostly agree with the measurements of the LHC at 7 TeV in cms. There are some problems with LHCf and mostly with the ATLAS cross section measurements. To adjust the hadronic interaction models we need to wait for a couple of years to study better the whole phase space and reach 14 TeV in cms.