Extensive Air Showers and Particle Physics

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Extensive air showers are the cascades that develop in the atmosphere after interactions of the cosmic rays. In vertical direction ($\cos\theta=1$) the atmosphere has more than 12 interaction lengths. High energy cosmic rays can be studied only by the detection and interpretation of the EAS. We need very good knowledge of the minimum bias physics for interpretation of the EAS results.

We shall concentrate on the highest energy cosmic rays.
Their analysis requires knowledge of the particle interactions at energies significantly higher than LHC. This is not a new problem. This is how it developed:

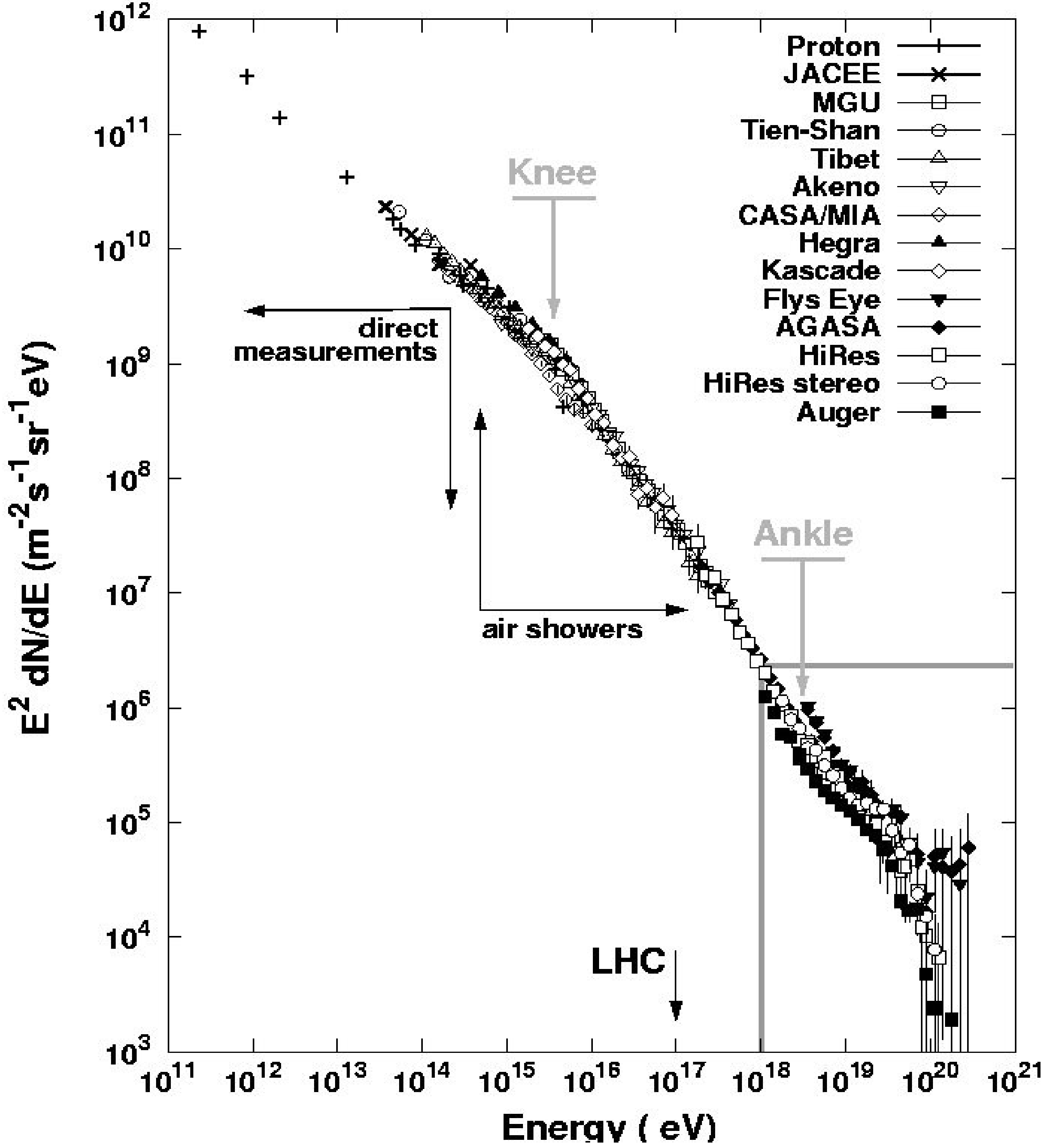
John Linsley (PRL 10 (1963) 146) reports on the detection in Vulcano Ranch of an air shower of energy above 10^{20} eV.

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

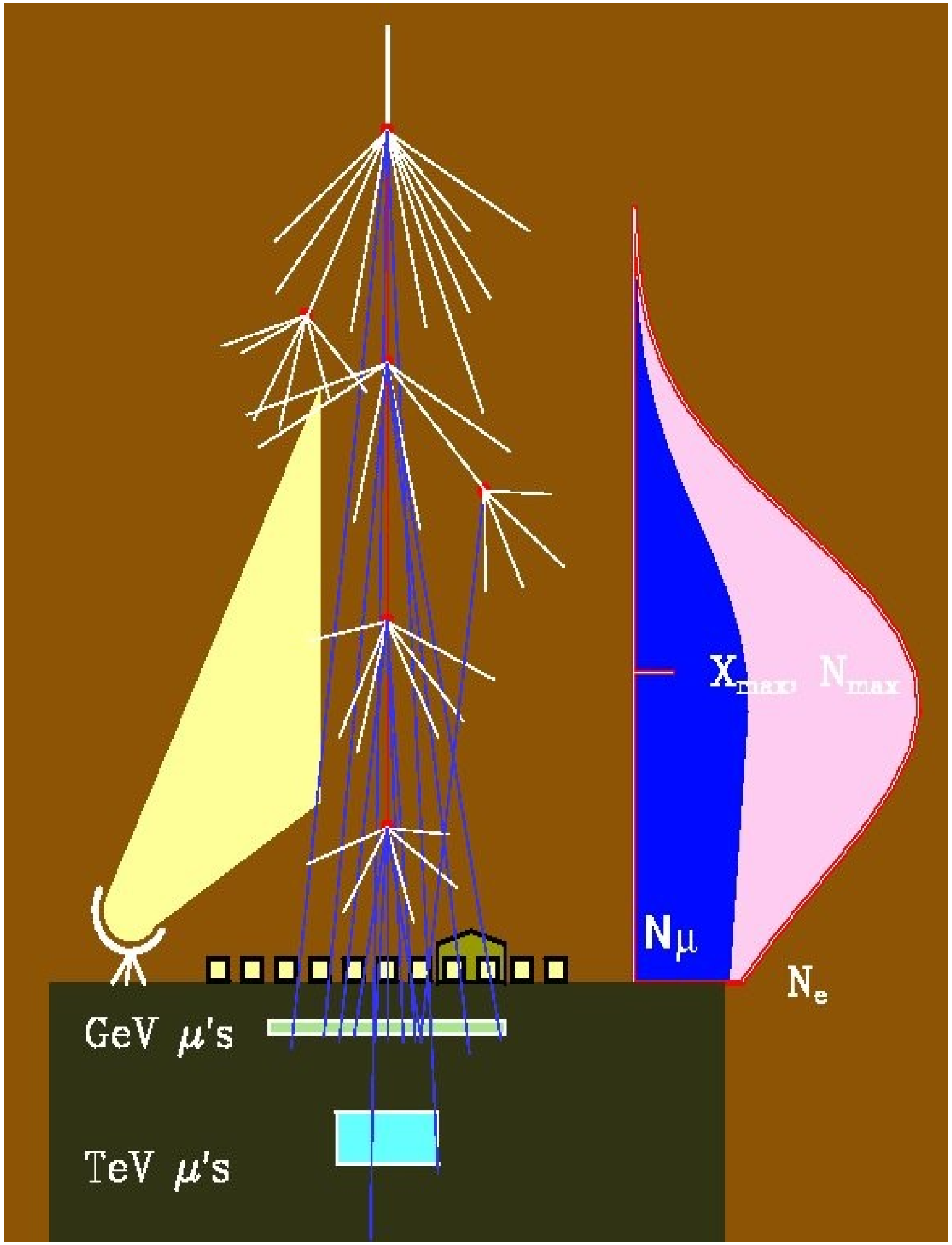
10^{20} eV =
= 2.4×10^{34} Hz
= 1.6×10^{8} erg
= 170 km/h tennis ball

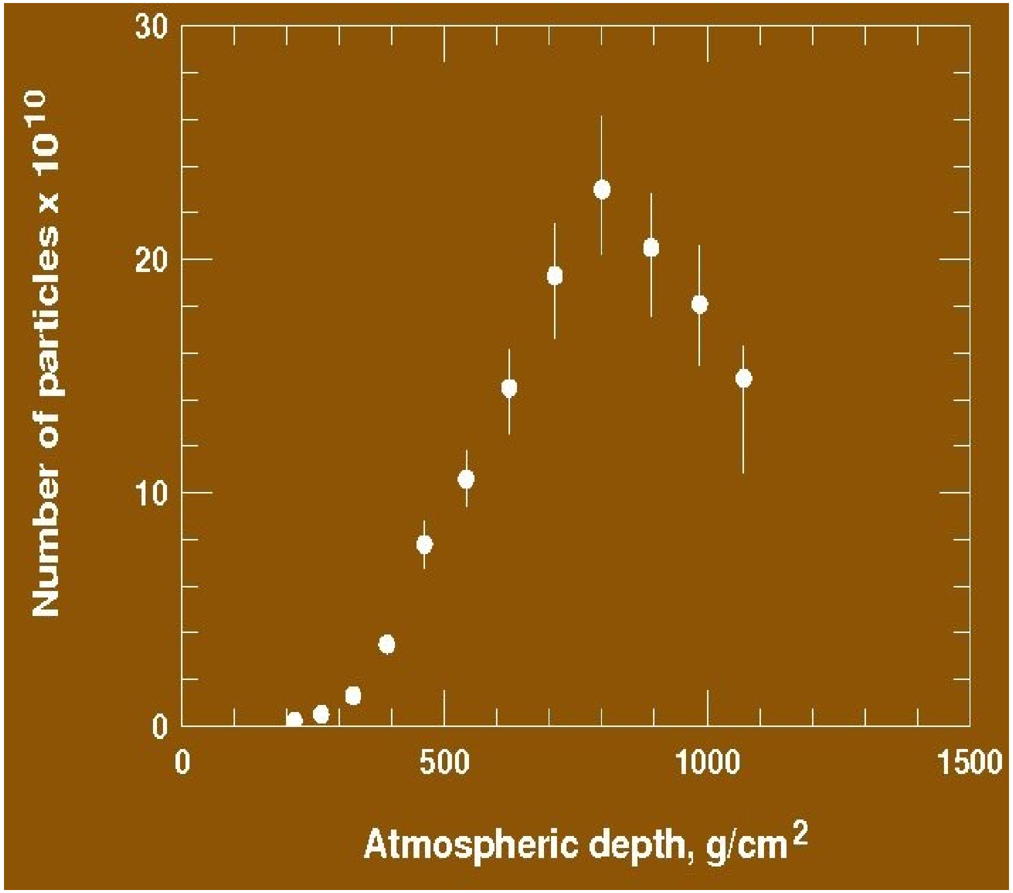
$\sqrt{s}$ equivalent is 430 TeV



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.

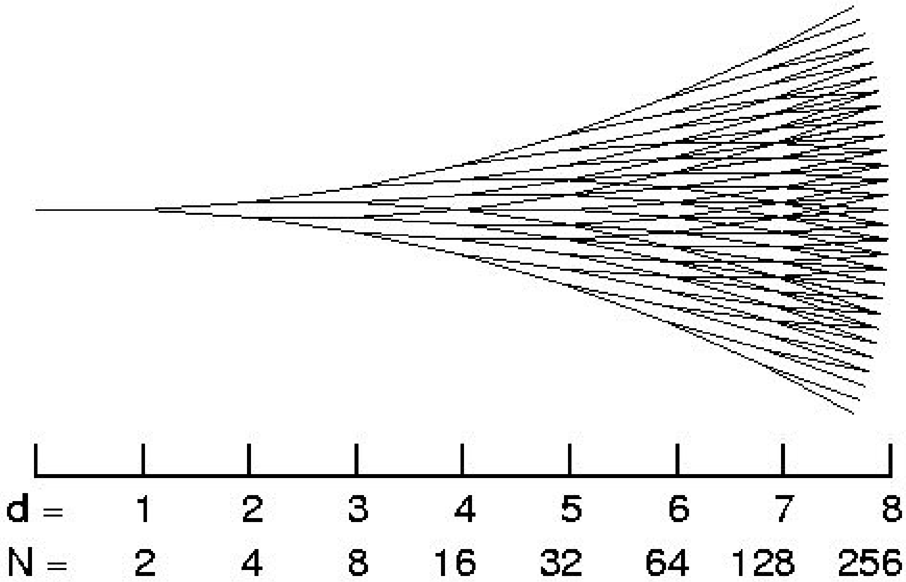
We have to extend the hadronic interaction models to a factor of 50 over LHC to be able to analyze these events.





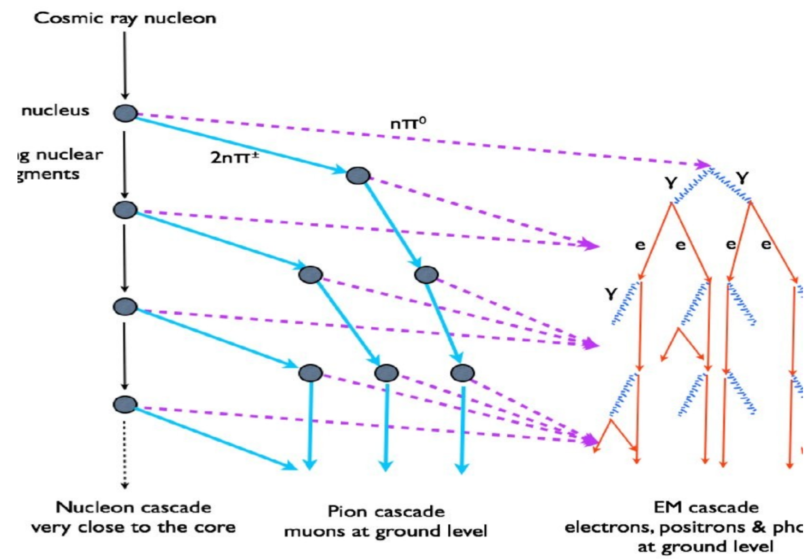
Shower profile of the highest energy shower detected by the Fly's Eye experiment. Energy estimate is 3.10^{20} eV.

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.

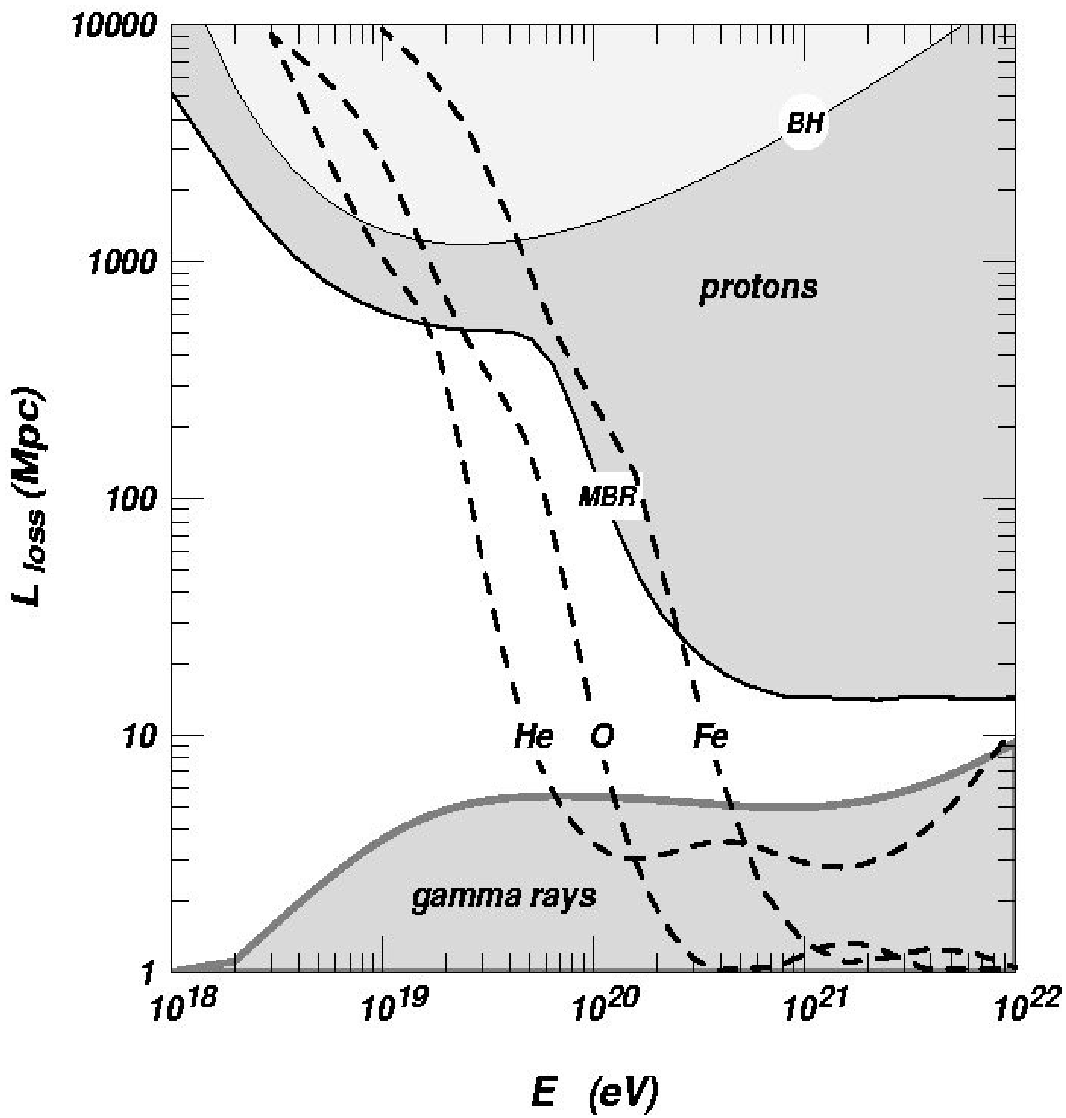
The excitement came three years later, when Greisen in USA and Zatsepin and Kuzmin in the Soviet Union simultaneously published articles about the interactions of UHE cosmic rays in the microwave background and predicted that the cosmic ray spectrum will start declining after 5.10^{19} eV. This is now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

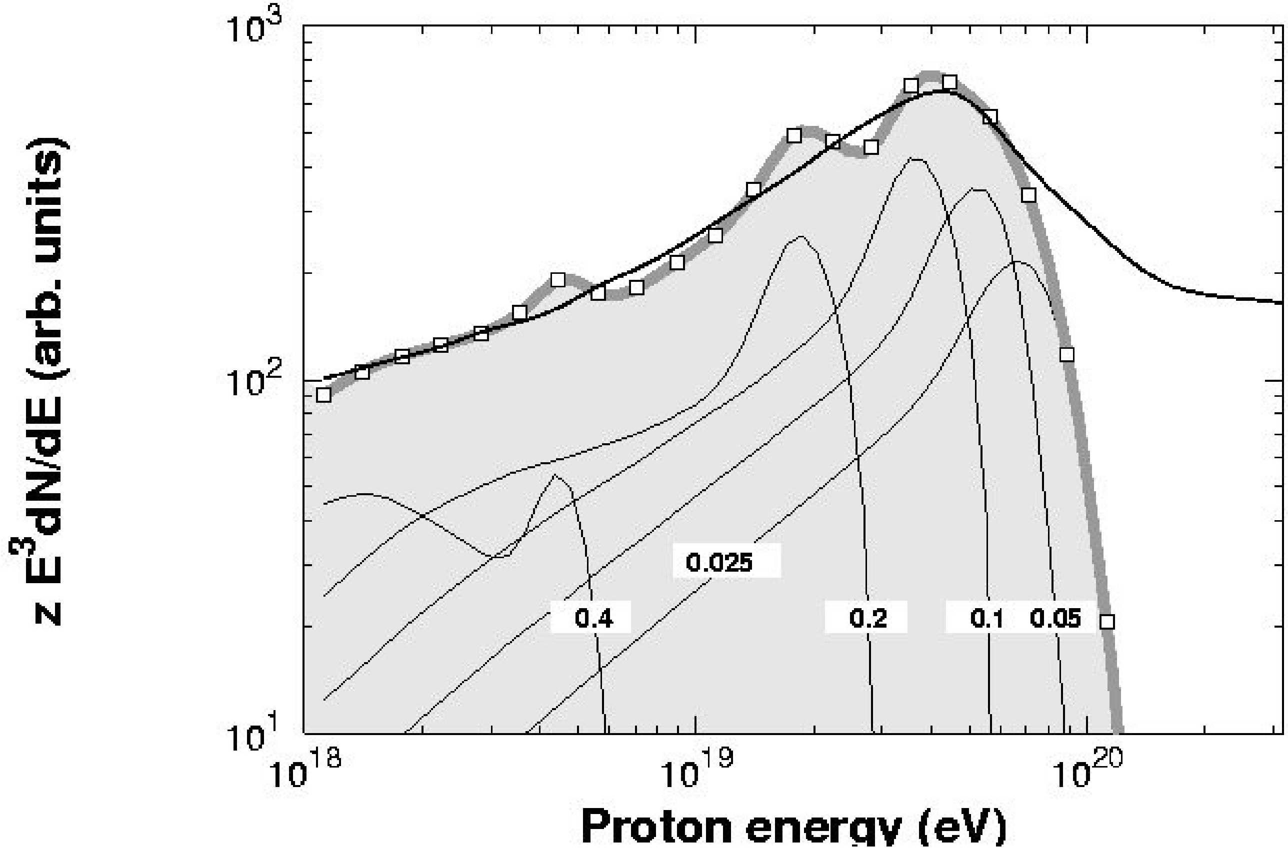
The most recent experiments cover thousands of square kilometers to detect these extremely high energy particles that come less than a few (2?) per 100 sq. km. per century.

This is why the GZK effect exists.

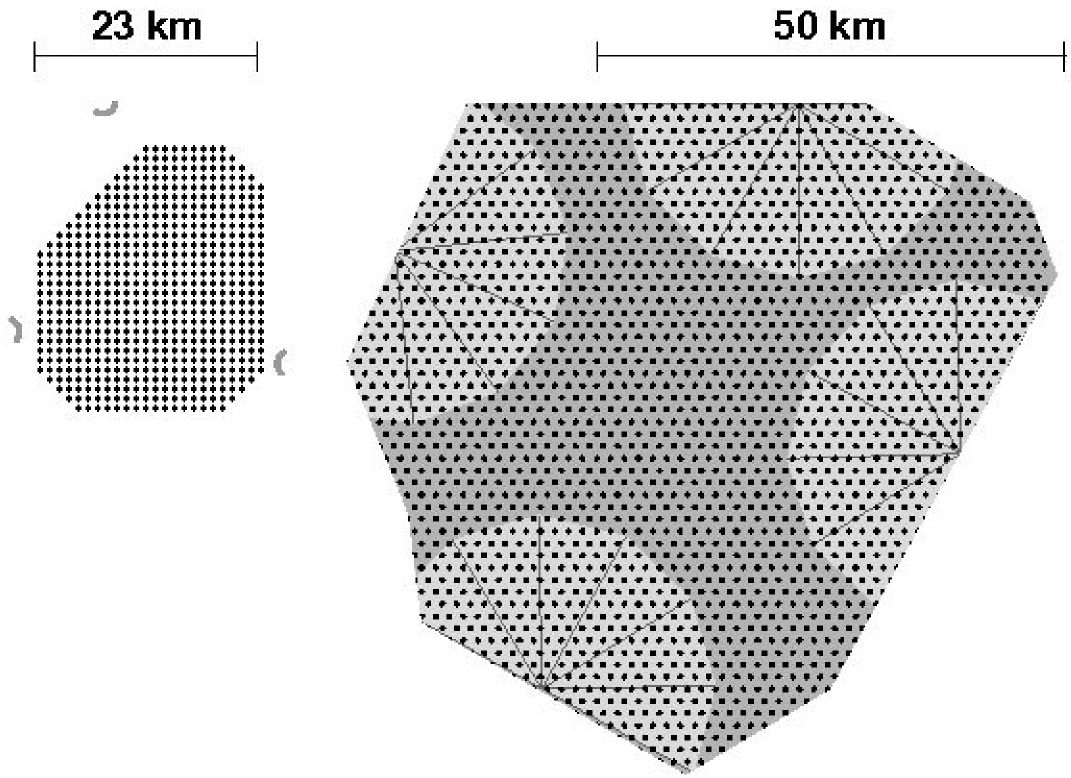
High energy particles interact with the microwave background radiation photons. Since the cm energy is low, of order of a GeV, the cross section is well known. UHECR lose energy on photoproduction interactions, pair creation, and adiabatic loss.

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.

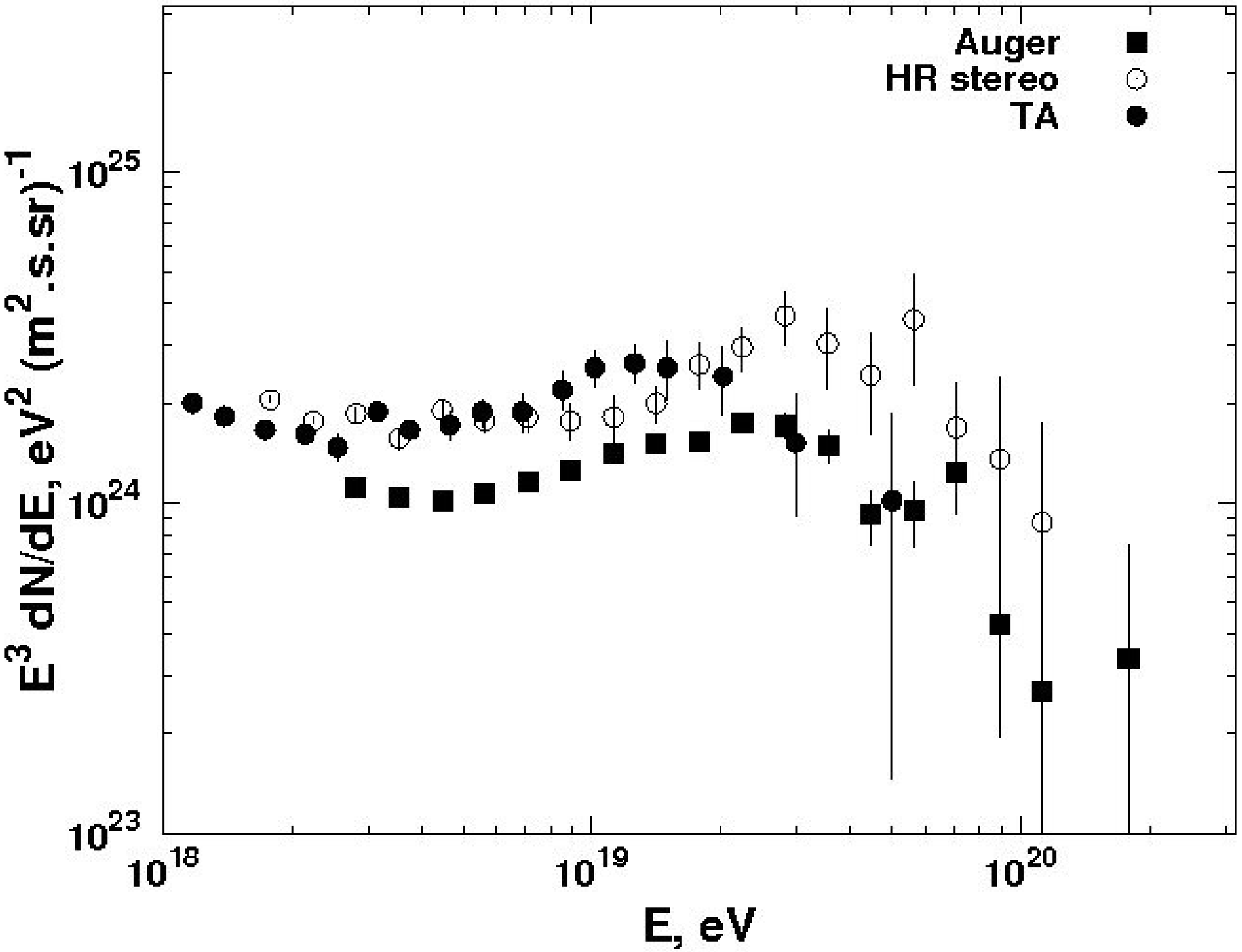


There are currently two detectors that study the ultrahigh energy cosmic rays:

- The Auger observatory in Argentina
- The Telescope Array in Utah, USA

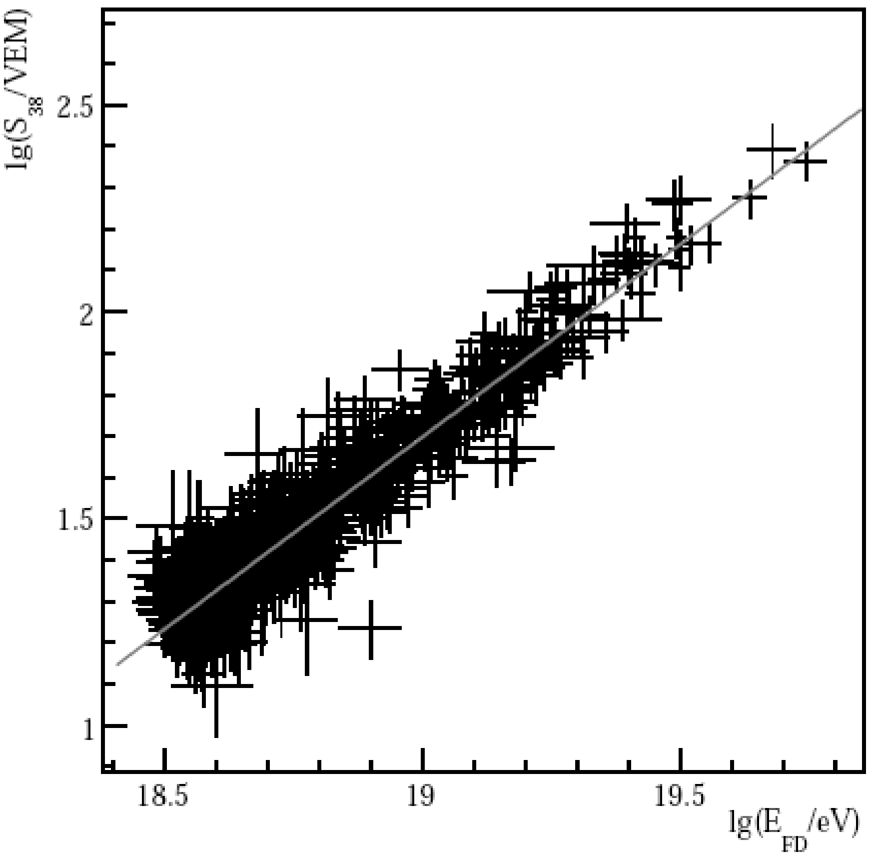
Auger is a hybrid detector that consists of an air shower array of area 3,000 sq.km and four fluorescent detectors sites. The surface detectors are at distance of 1.5 km from each other and are fully sensitive to cosmic rays of energy above 3 EeV (3.10^{18} eV). In hybrid mode it is sensitive to lower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

The Telescope Array is a smaller hybrid detector using scintillator Counters and three fluorescent detectors, one of which uses the Remnants of the High Resolution FlysEye (HiRes).

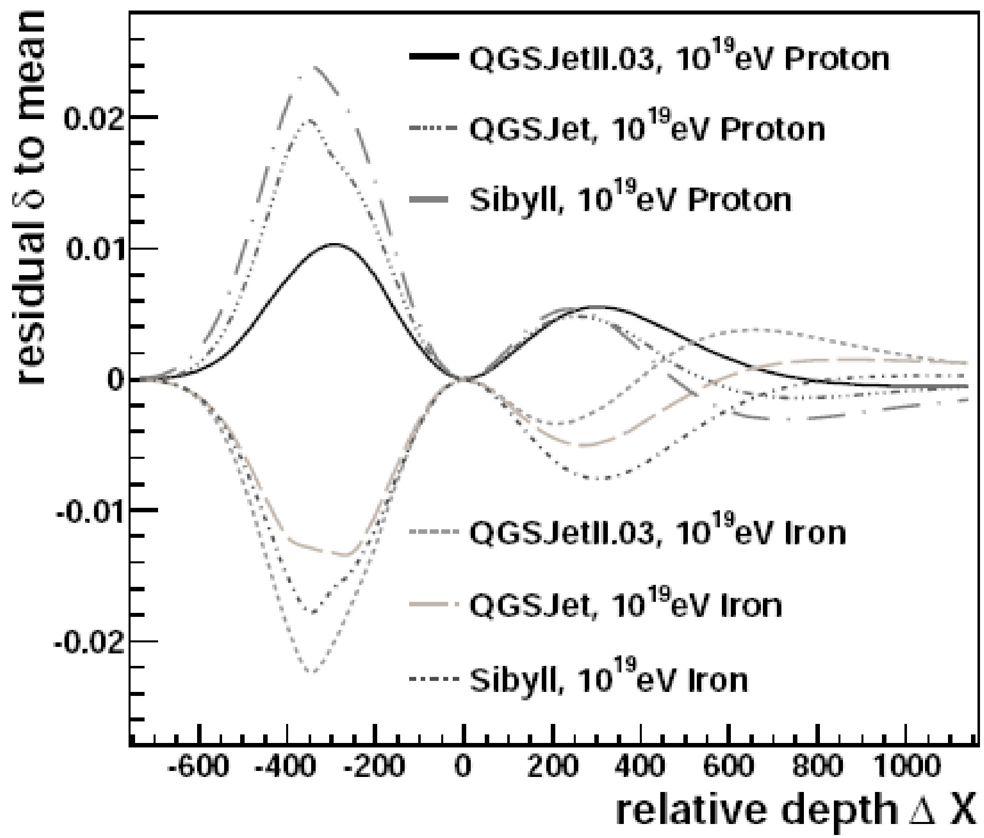


The energy spectra measured by Auger and TA are different by about 20% from each other, but all of them see the decrease of the flux predicted by the GZK calculation.

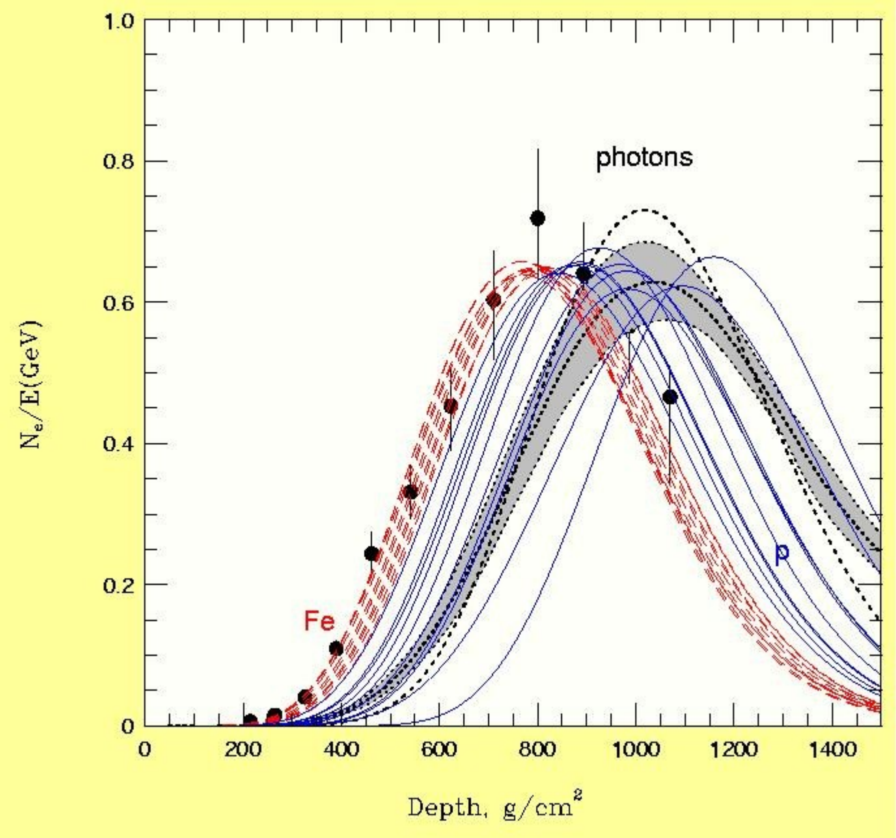
This is very different from the previous measurement of the AGASA detector that saw 11 events above 10^{20} eV. One of the possible reasons was that AGASA did not use any of the contemporary hadronic interaction models. This is how important is the use of correct models for the estimate of the cosmic ray energy.



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. After normalization S_{1000} is used to measure UHECR energy spectrum.

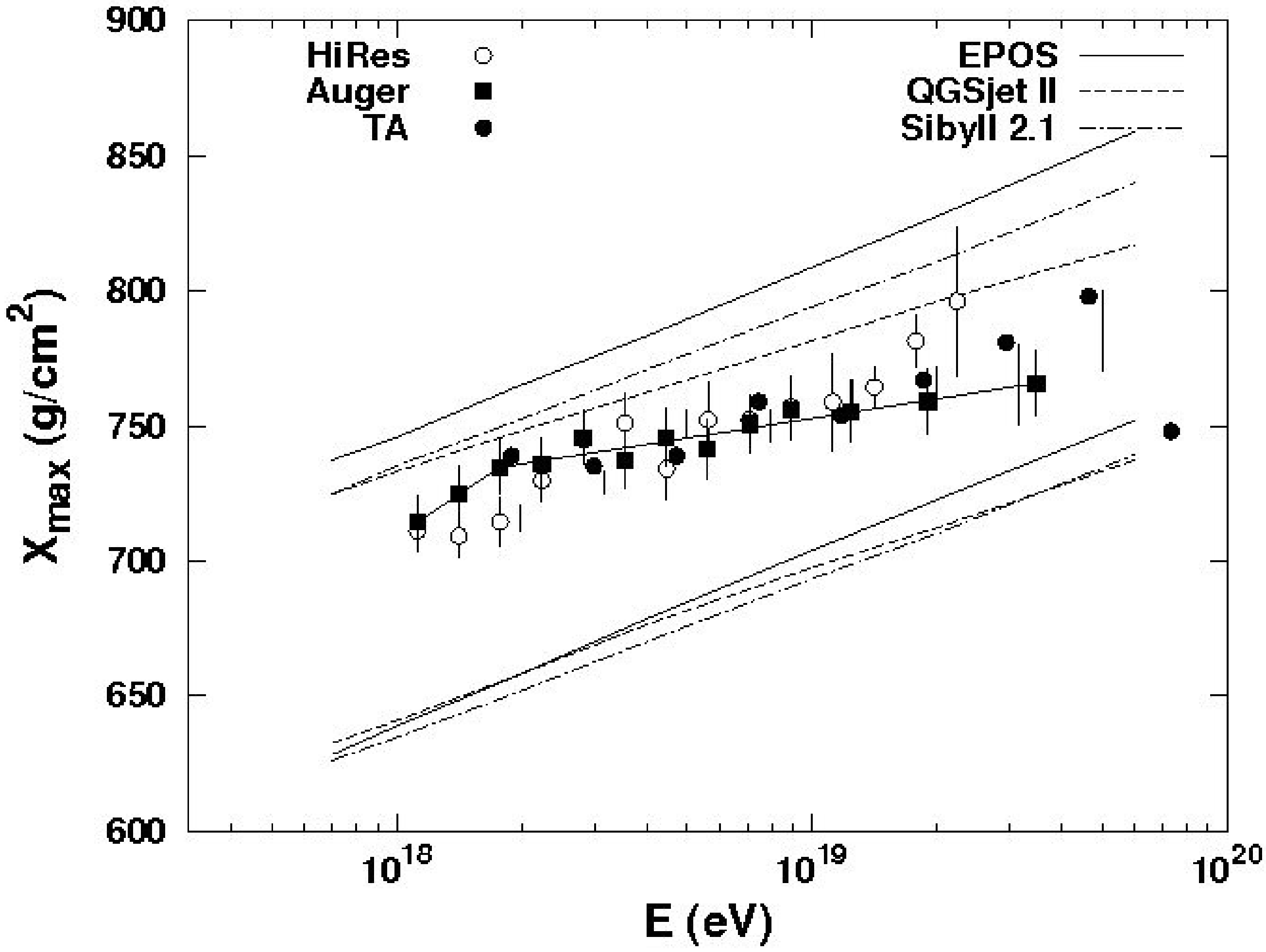


The errors in energy estimate are relatively small in all hadronic interaction models.



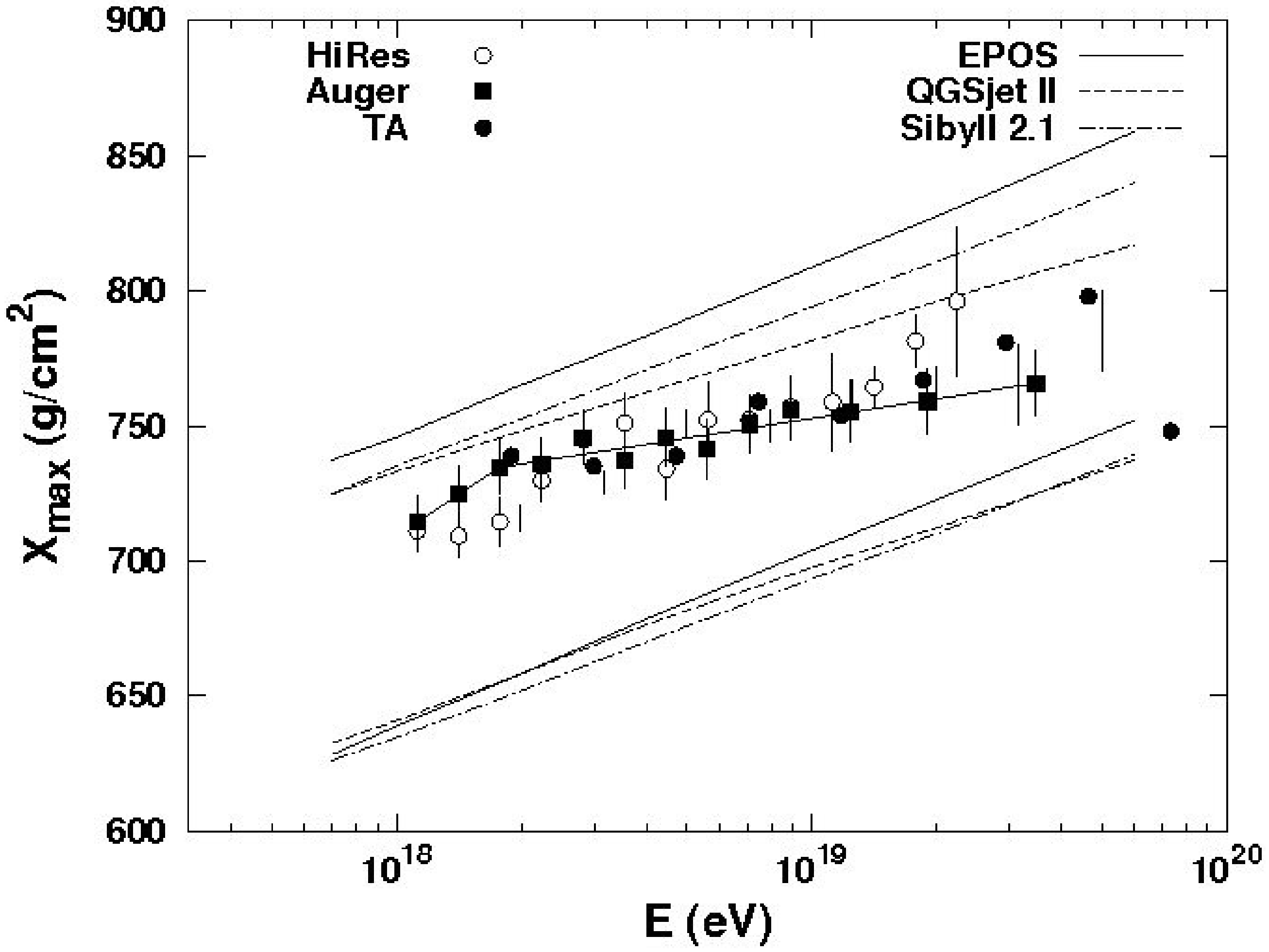
To study the chemical composition of UHECR the experiments observe the depth of maximum of the air showers. Heavy nuclei have significantly higher depth of maximum.

The graph above shows the shower profiles of iron, proton and gamma ray induced showers.



The depth of the shower maximum depends on the mass of the primary cosmic ray. Heavy nuclei EAS develop faster and generate higher X_{max}.

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). TA and HiRes measures light composition at all energies.



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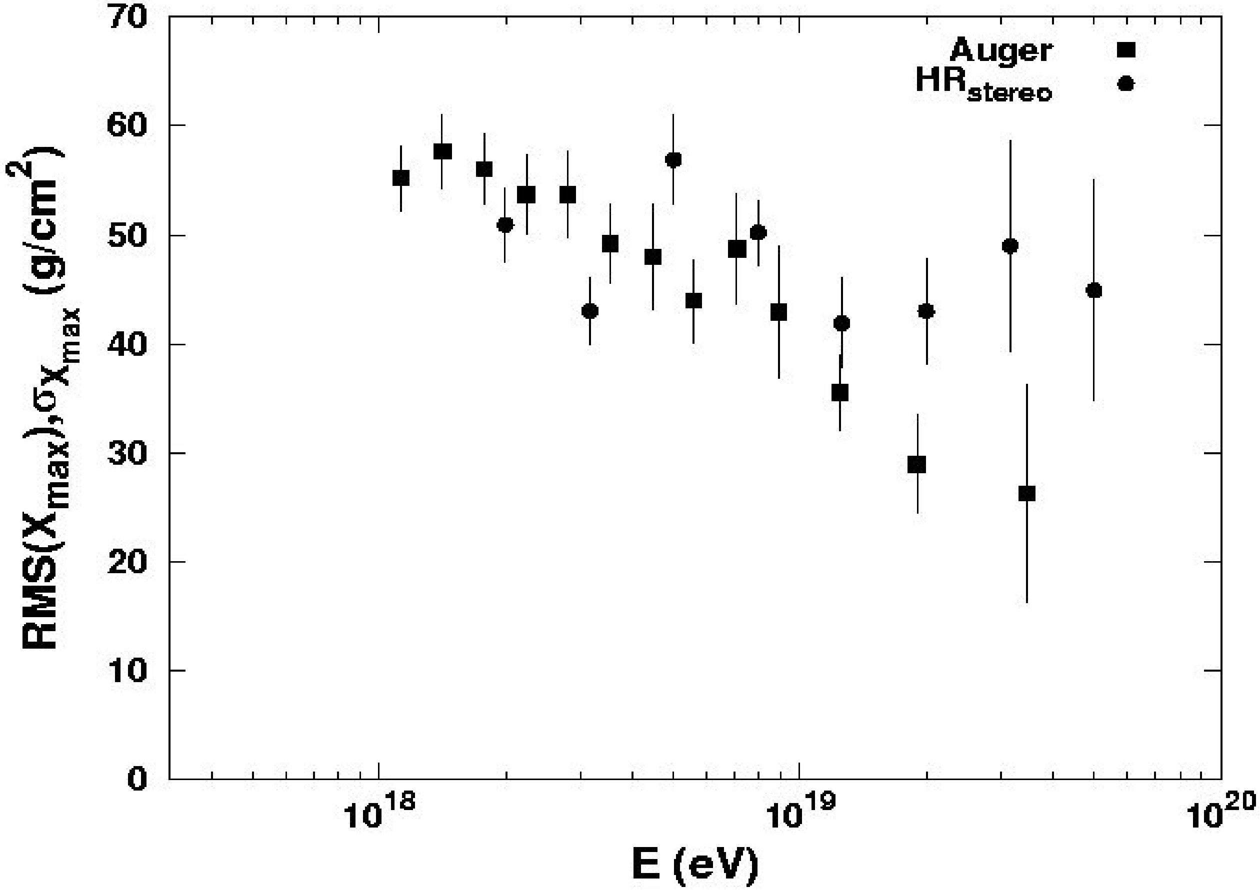
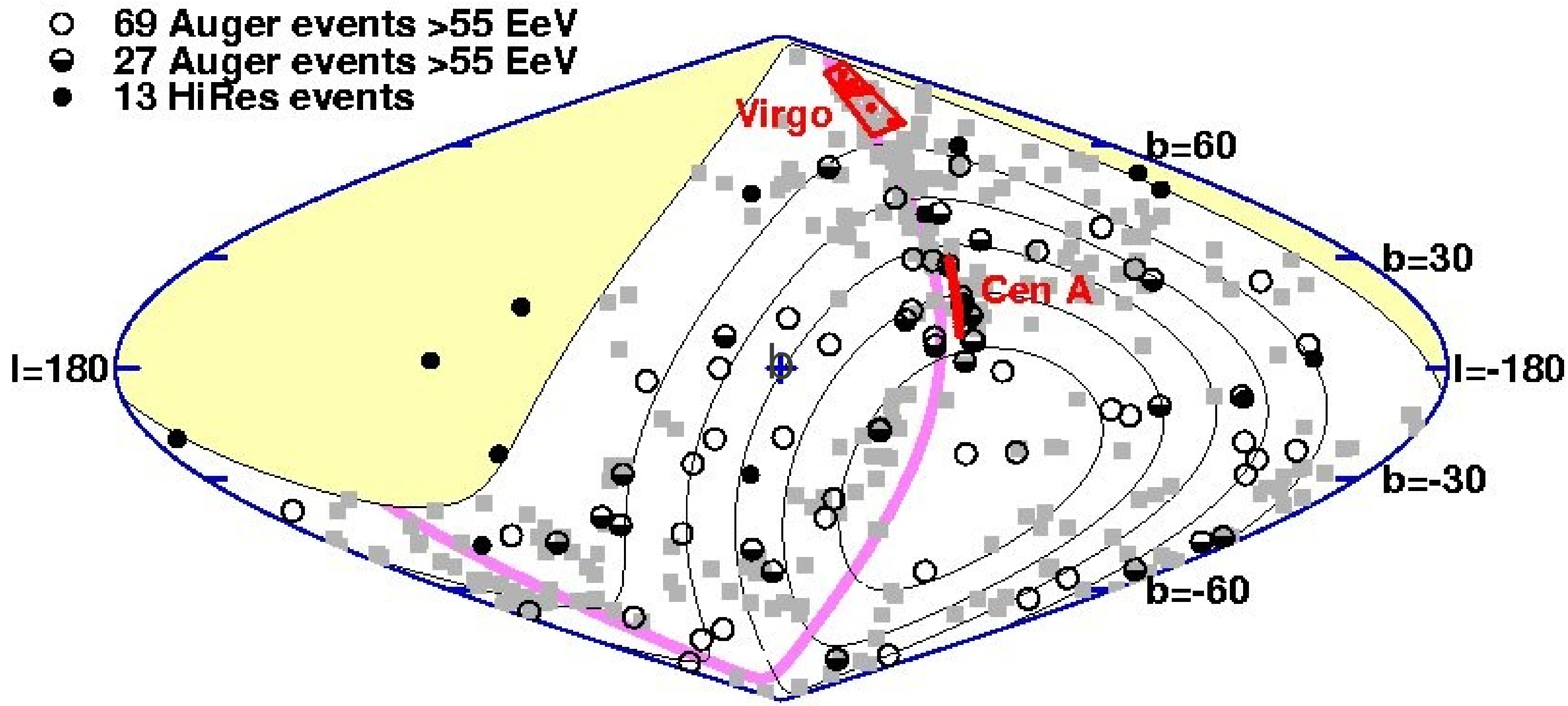


Another composition related measurement is the fluctuations of X_{max} as a function of energy. Showers of heavy primary nuclei show smaller fluctuations.

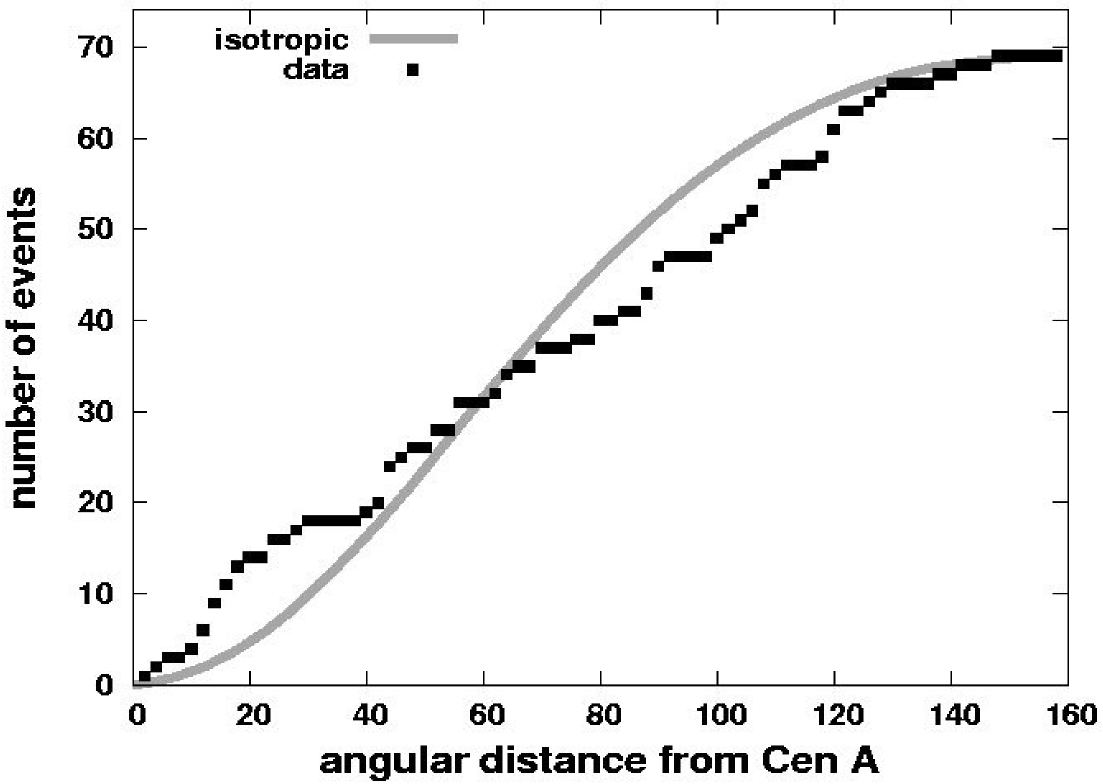
The heavy composition measured by Auger suggest another possibility: the cutoff is not caused by the GZK type energy loss but by reaching the maximum energy of the cosmic ray accelerators *(`Disappointing model')* by Berezinsky et al.
The uncertainty in the composition of UHECR makes the search of their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

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?



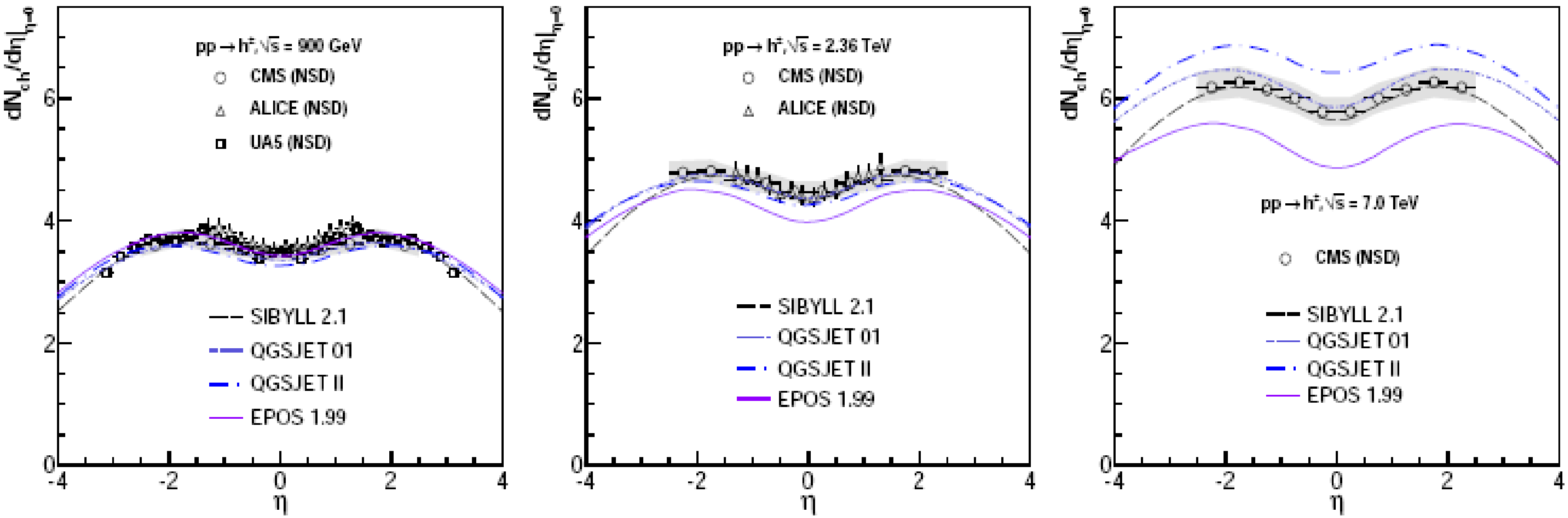
There are 13 events within 18 degrees of Cen A. There are no events within 18 deg. of M87 and the Virgo cluster of galaxies.

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.

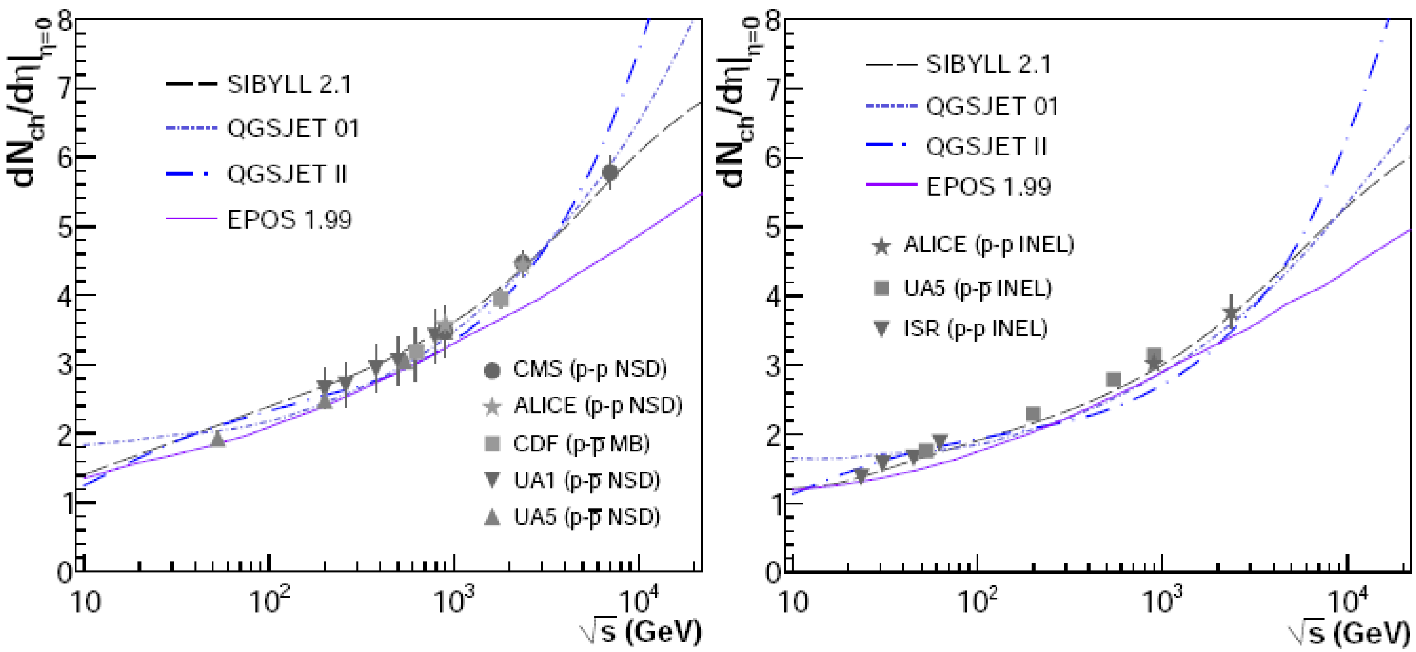
The energy estimate of the cosmic ray showers is based on simulations with the hadronic interaction models. Recent LHC results give us an option to check how these models perform at 7 TeV in cms.

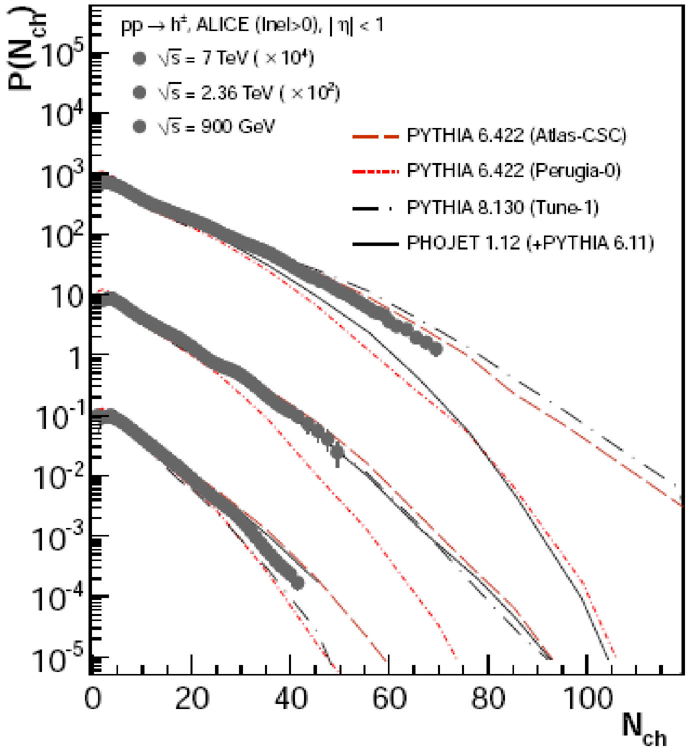
There is a big difference, though, between interaction models used in accelerator physics and those used in air shower analysis. We have to follow the whole shower development. i.e. be correct in reproducing the minimum bias events in a very wide energy range. Contemporary models work from Laboratory energy of 80 GeV to 10^{11} GeV. Models like Fluka are used at lower energy.

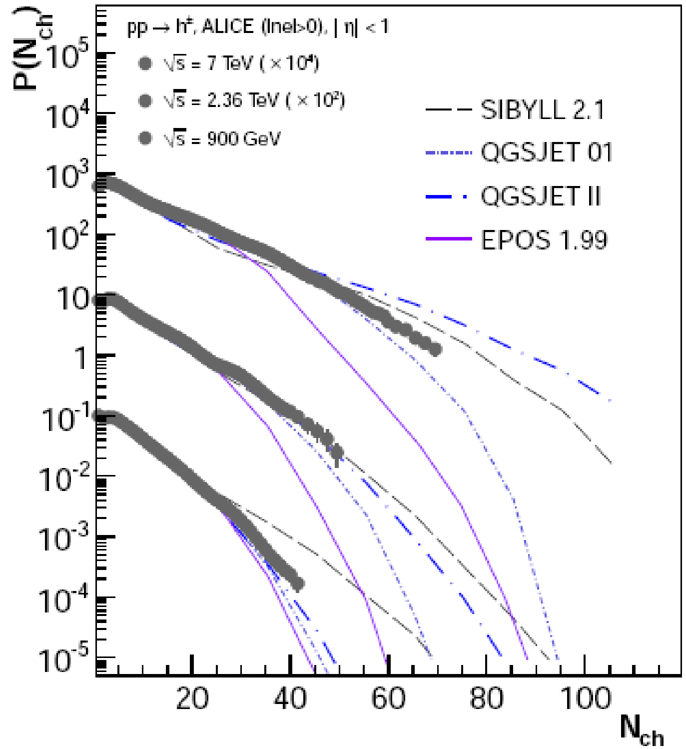
Here is how hadronic interaction models widely used for air Shower analysis reproduced the first LHC data sets.



Source: d'Enterria et al, 2010



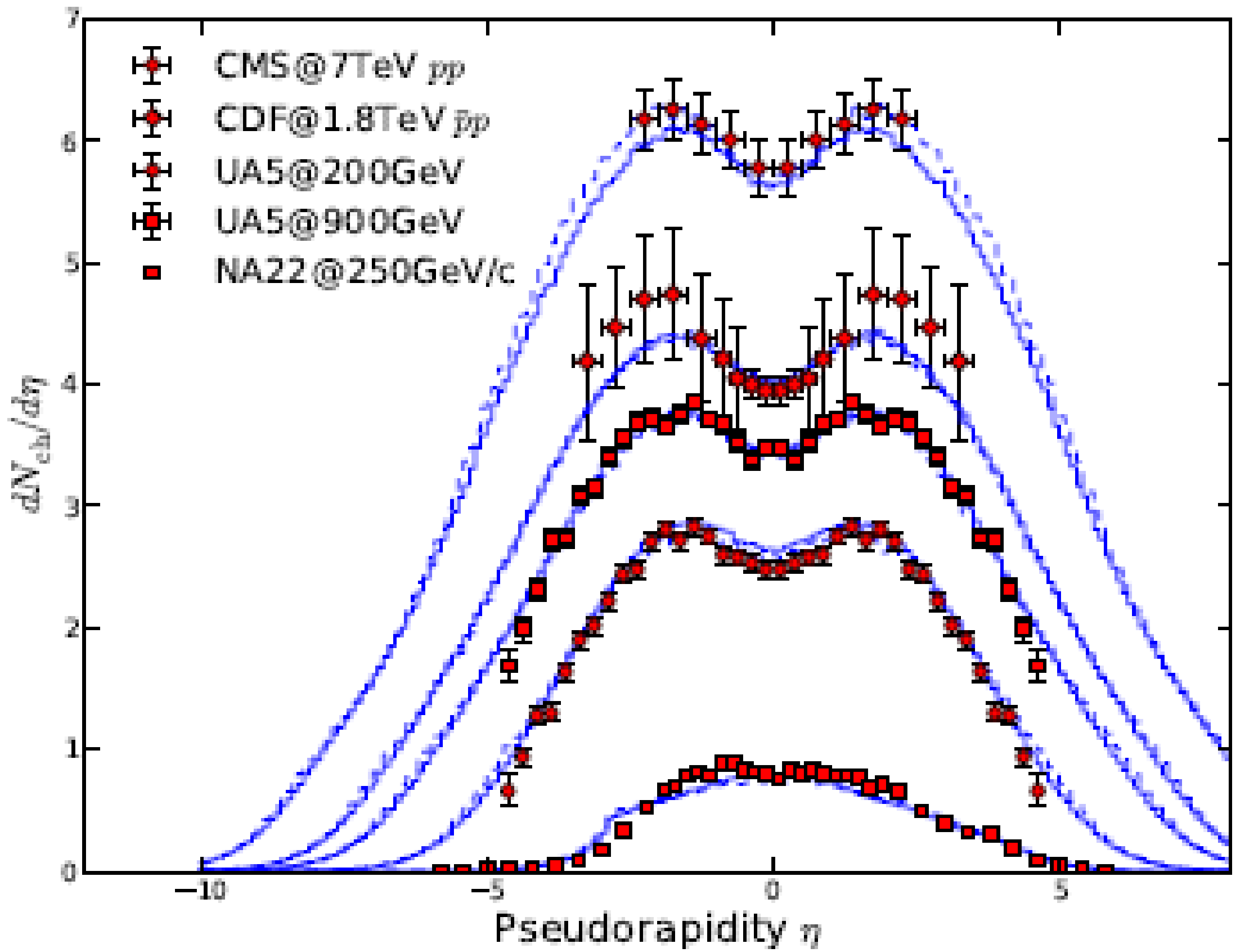




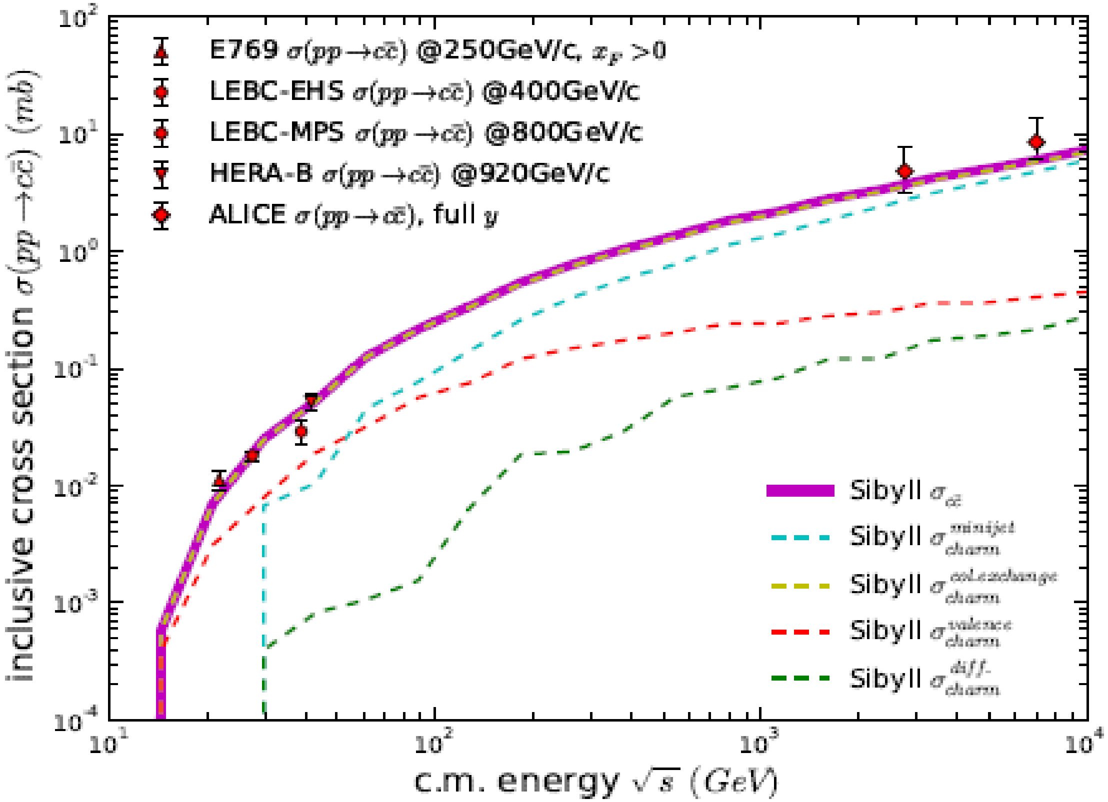
Source: d'Enterria et al

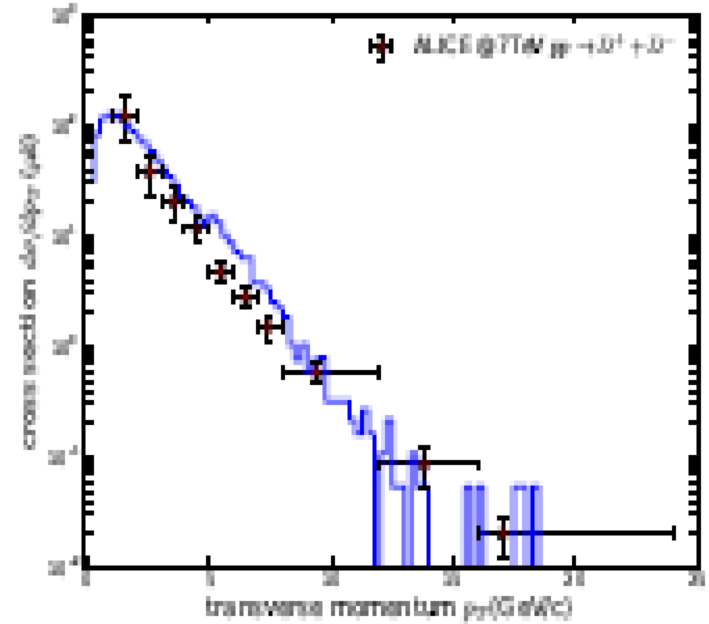
The conclusion of the paper is that the models used for UHECR analysis perform not worse then the typical PYTHIA versions at 7 TeV in cms.

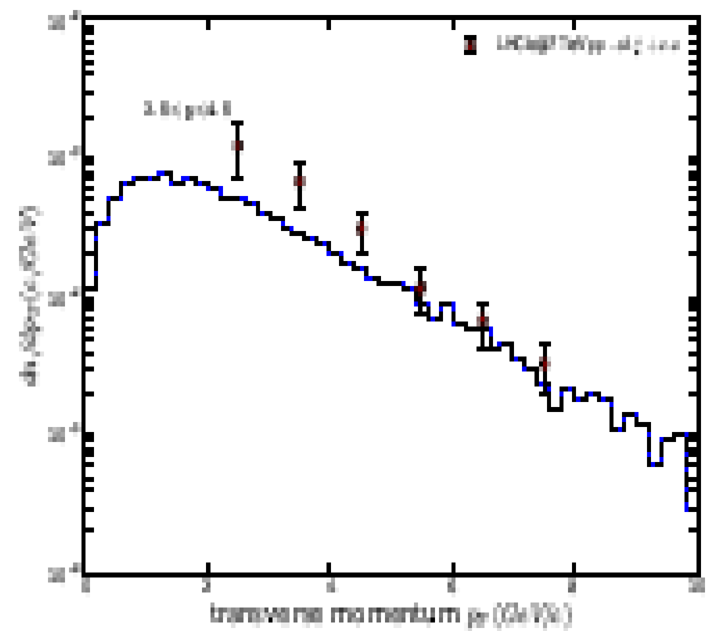
Not everything, however, is that good. All models are now Undergoing changes to fit well the LHC data. It is not very easy, though, because air shower development depends mostly on the forward gegion that is not measured in collider experiments.



Here is how the current version of Sibyll reproduces the measured rapidity distributions in a wide energy range.







LHC data were also used to implement charm production in Sibyll. On top we show the inclusive cross section for charm production. Not everything is right yet but we continue working on it.

Summary

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

The measurements of these detectors do not agree on the cosmic rays chemical composition. Auger has also set strict limits on the fraction of ultrahigh energy γ-rays and neutrinos.

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. The relatively small problems in comparison to data are being corrected now. To fully adjust the hadronic interaction models used in the cosmic Ray analysis we need to wait for a couple of more years to study better the whole phase space and reach 14 TeV in cms.