6th International Conference on New Frontiers in Phisycs
Kolymbary, August 24 -2017

The Pierre Auger Observatory: latest results and future perspectives

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Outline

Who are you?

- The Pierre Auger Observatory

What do you do?

- Ultra High Energy Cosmic Rays

What have you done so far?

- Scientific results

Where are you going?

- AugerPrime

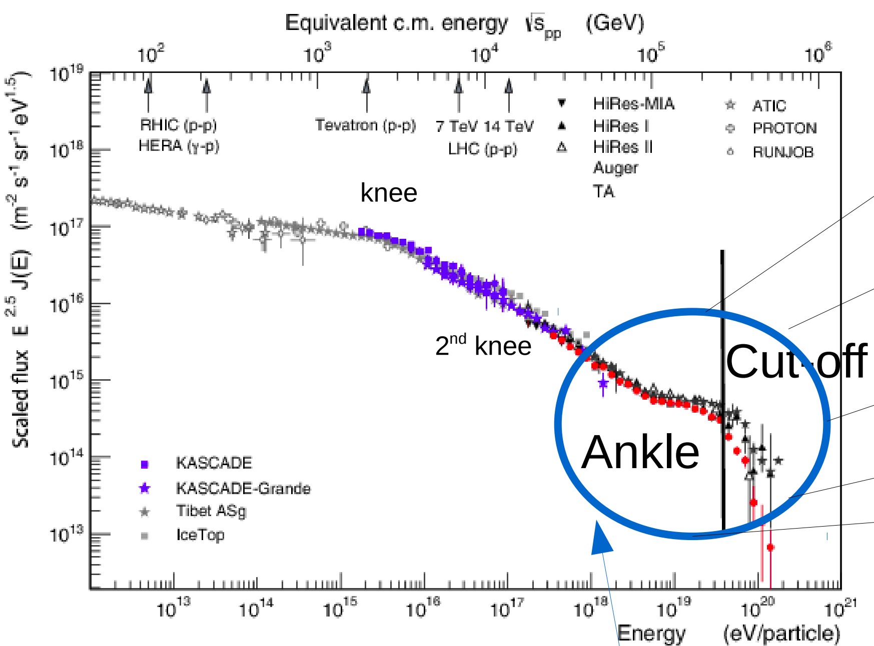
The Pierre Auger Observatory:
Studying the highest energy particles of the Universe

- The largest cosmic rays observatory in the world

- Placed near the town of Malargüe
  in the south-west of Argentina

- It covers an area of about **3000 km²**

- Data taking since 2004



Energy spectrum

Mass Composition

Arrival Direction

Photons and Neutrinos

Hadronic physics

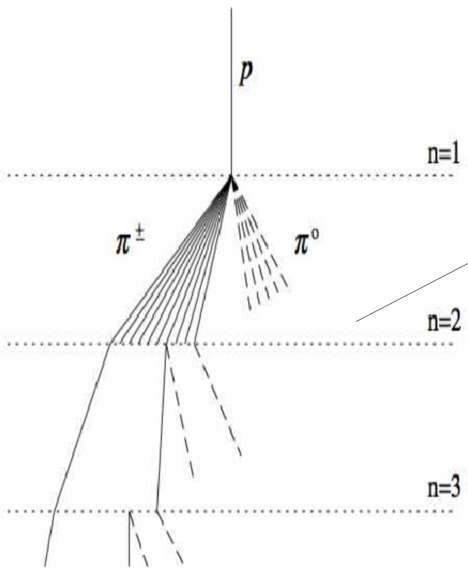
Flux: $\frac{dN}{dE} \propto E^{-\gamma}$

1 particle/km²/year

Ultra High Energy Cosmic Rays (UHECRs)

How to detect UHECRs?

Hadronic Shower



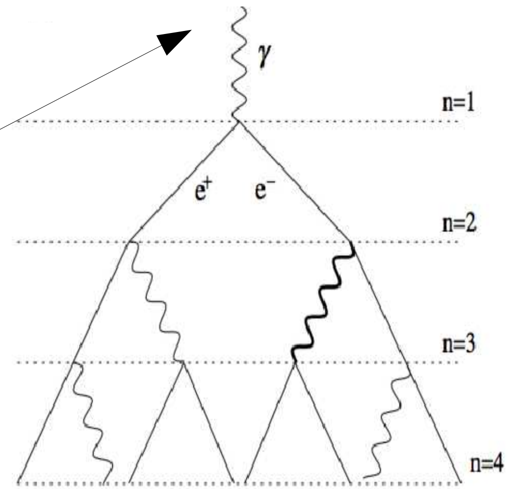
$$E_0 = (N_e + k N_\mu)$$

$$N_\mu \propto E_0^{0.85} \propto A (E_0 / A)^{0.85}$$

$$\downarrow$$

$$N_\mu \propto A^{0.15}$$

Electromagnetic shower

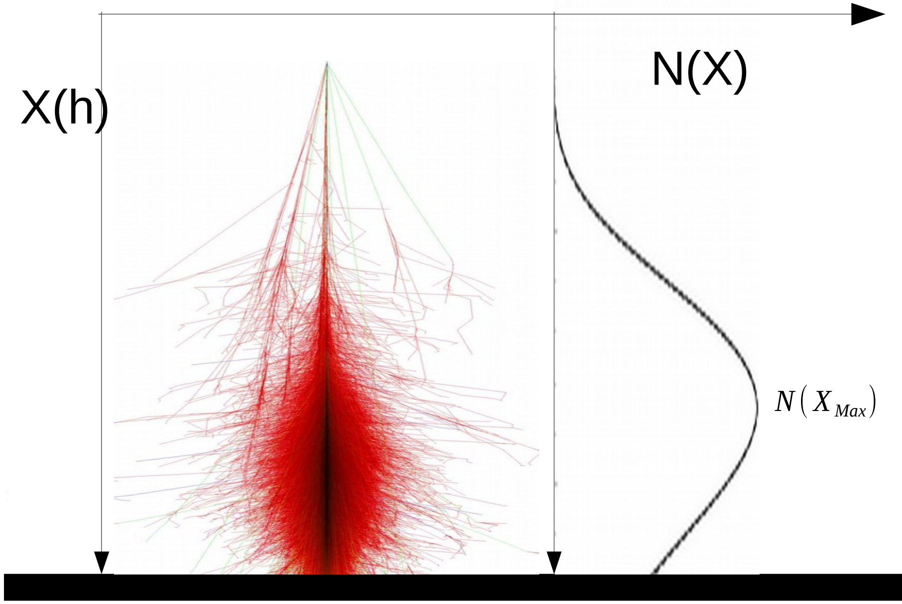


Heitler toy-model

$$N(X_{Max}) = \frac{E_0}{E_C}$$

$$X_{Max} = \ln\left(\frac{E_0}{E_C}\right) \frac{X_0}{\ln 2}$$

Extensive Air-Shower (EAS)

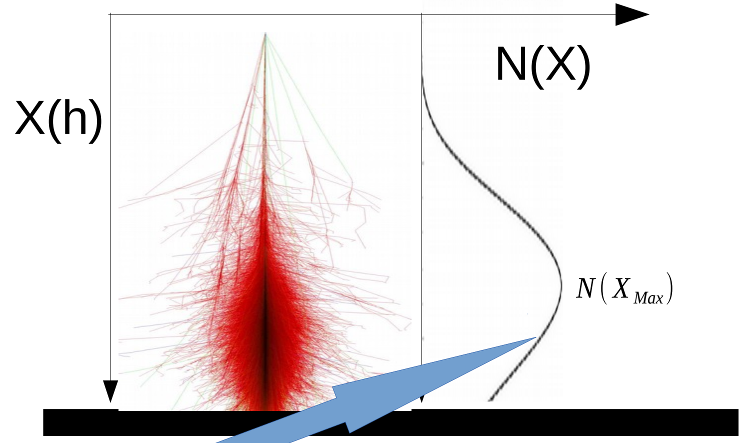


Ground level

Atmospheric depth :

$$X(h_0) = \int_{h_0}^{\infty} \rho_{air}(h)\, dh$$

Ultra High Energy Cosmic Rays (UHECRs)



How to study UHECRs?

Longitudinal development

Detection of the fluorescence light emitted by de-excitacion of atmospheric N_2 after interactions with the secondary particles of the shower

Amount of fluorescence light is proportional to the energy that the shower dissipates in the atmosphere

↓

Calorimetric measurement of the primary particle energy

X_{max} depends on primary particle mass

Lateral Distribution

Measurement of the particle density at ground level (e, γ, μ)

The distribution of particles at ground level depends on the energy and mass of the primary particle

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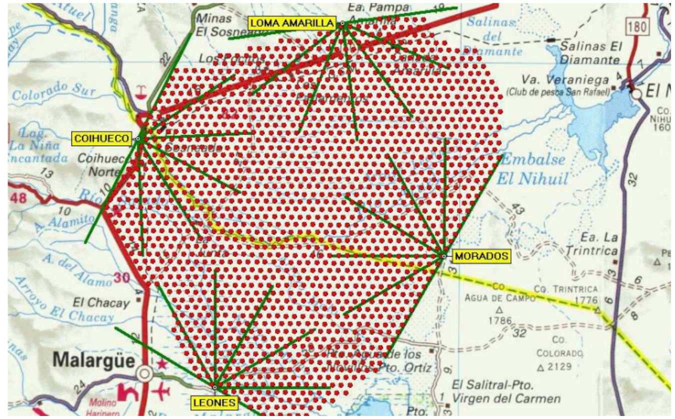
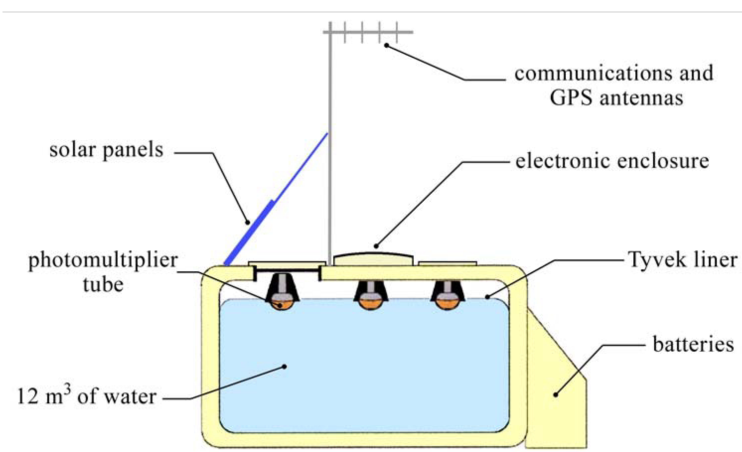
The Pierre Auger Observatory:
Hybrid detector



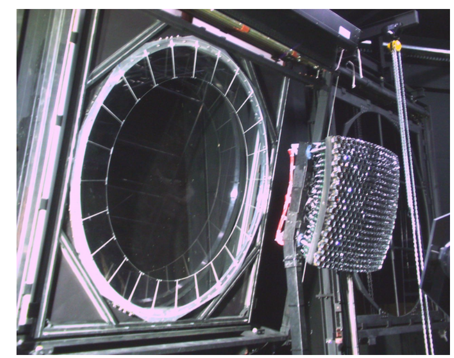
Surface Detector

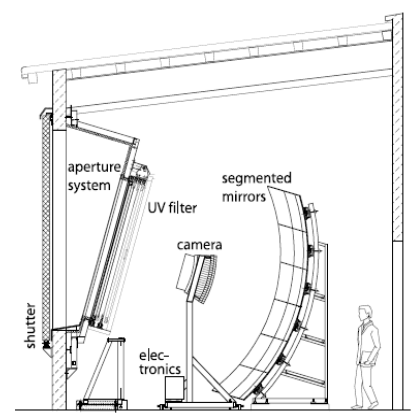
1660
Water Cherenkov Detectors
1.5 km spaced
covering an area
of about 3000 km²



Fluorescence Detector

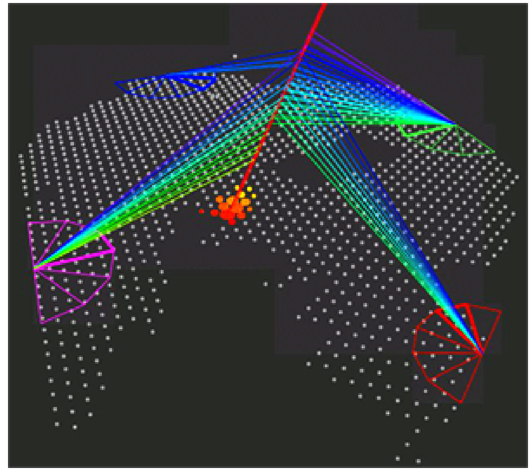
24 telescope placed in 4 sites
20x22 = 440 PMT/camera
Telescope FOV of 30° X 30°
in azimuth and elevation





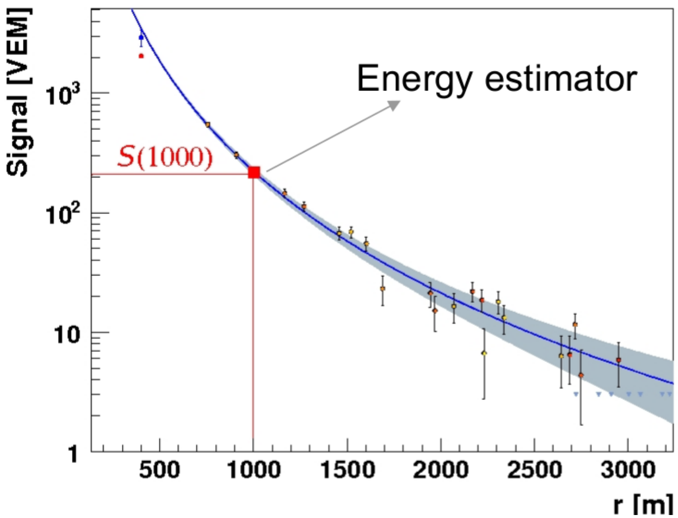
The Pierre Auger Observatory:

Hybrid detector



Surface Detector

Density of particles at the ground



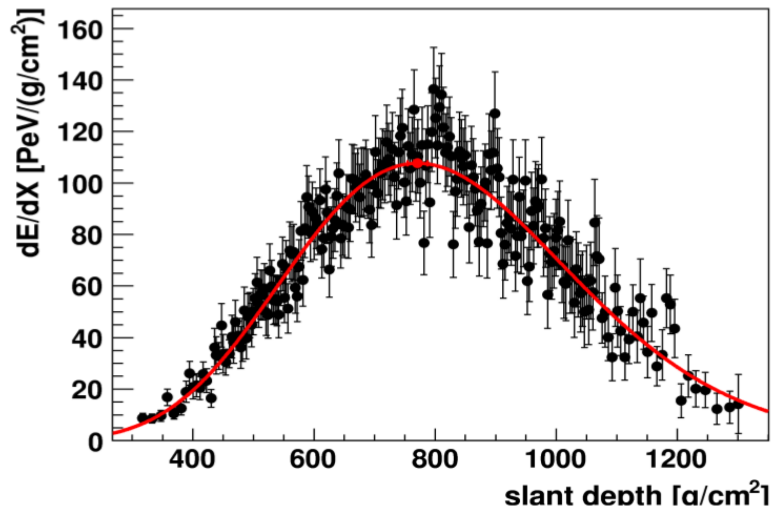
Duty cycle 100%

"Indirect" measurement of energy
Calibration SD/FD

Low sensibility to mass composition

Fluorescence Detector

Longitudinal profile



Duty cycle 15%

Direct measurement of the energy

Mass composition from X_{max} measurements

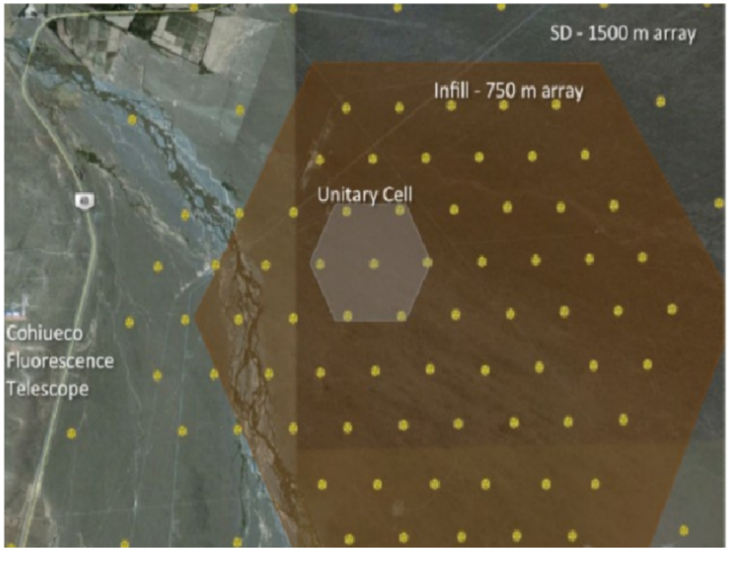
Energy scale provided by FD is used to calibrate the entire SD data sample

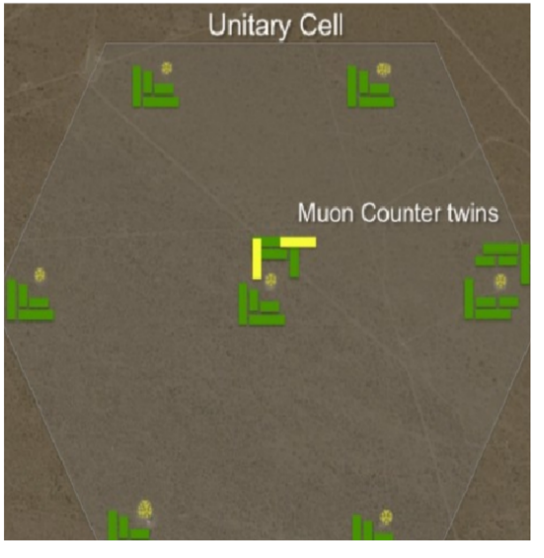
The Pierre Auger Observatory:
Enhancements

HEAT
High **E**levation **A**uger **T**elescope

Three additional telescopes at Coihueco site;
FOV 30°- 60° → above standard FD
Lowering the energy threshold to 10^{17} eV.

AMIGA
Auger **M**uon and **I**nfill for the **G**round **A**rray



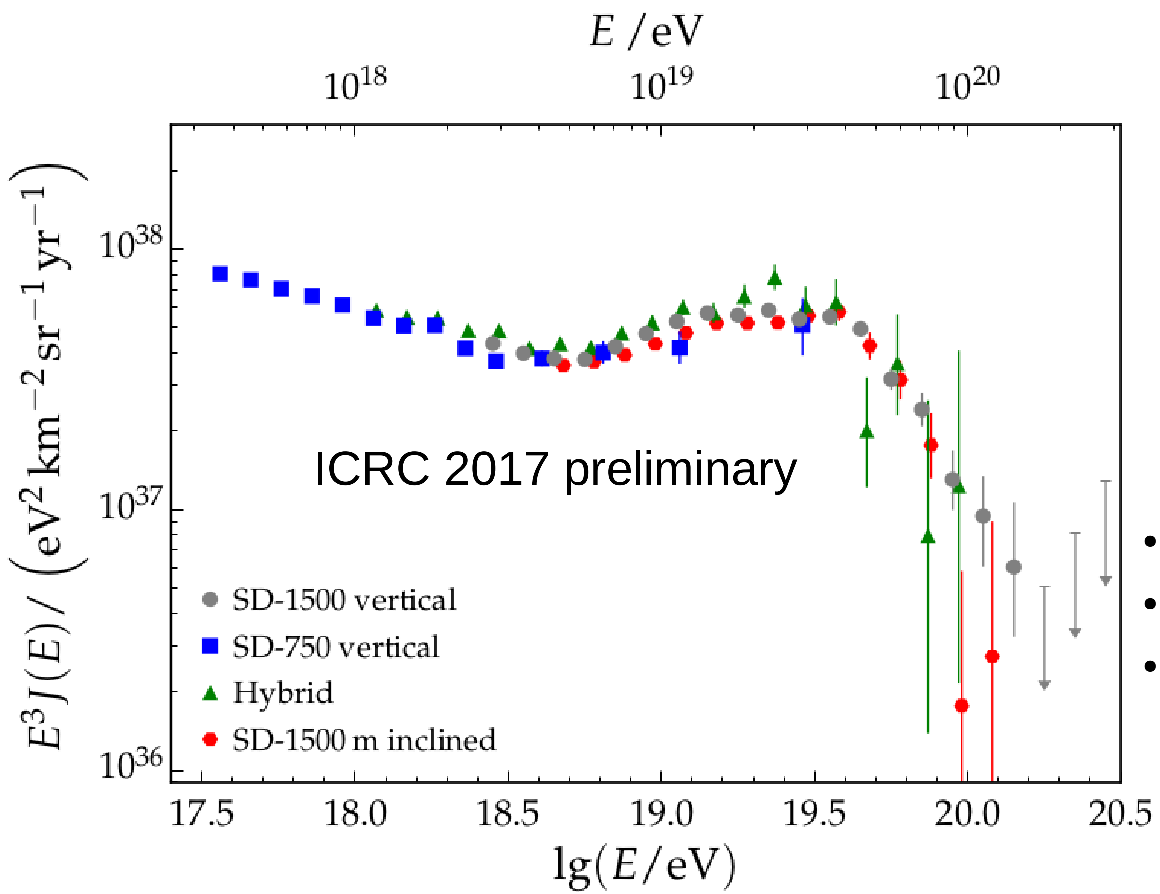


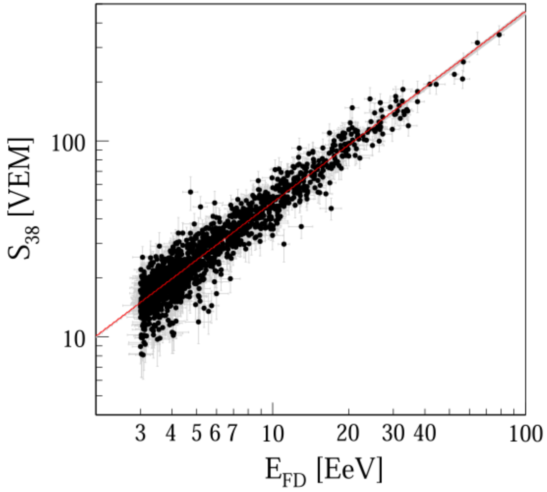
INFILL:
61 WCD in half distance (750 m);
Covering 23.5 km^2 ;
Extends energy range of SD to $3x10^{17}$ Ev

UNDERGROUND MUON COUNTERS:
30 m^2 scintillator,
64 channel multianode PMT;
Buried 2.25 m under ground level

Energy Spectrum

Exposure: 6.7×10^4 km^2 sr yr





Correlations between the SD energy estimators and the FD energy

- Hybrid;
- Infill array;
- Full array with the standard 1.5 km spacing:
  - Vertical showers ($\theta < 60°$)
  - Very inclined showers ($60° < \theta < 80°$)

Systematic uncertainties:
Energy scale → 14%
Flux → 5 - 10%

FD Xmax resolution ~ 20 g cm $^{-2}$

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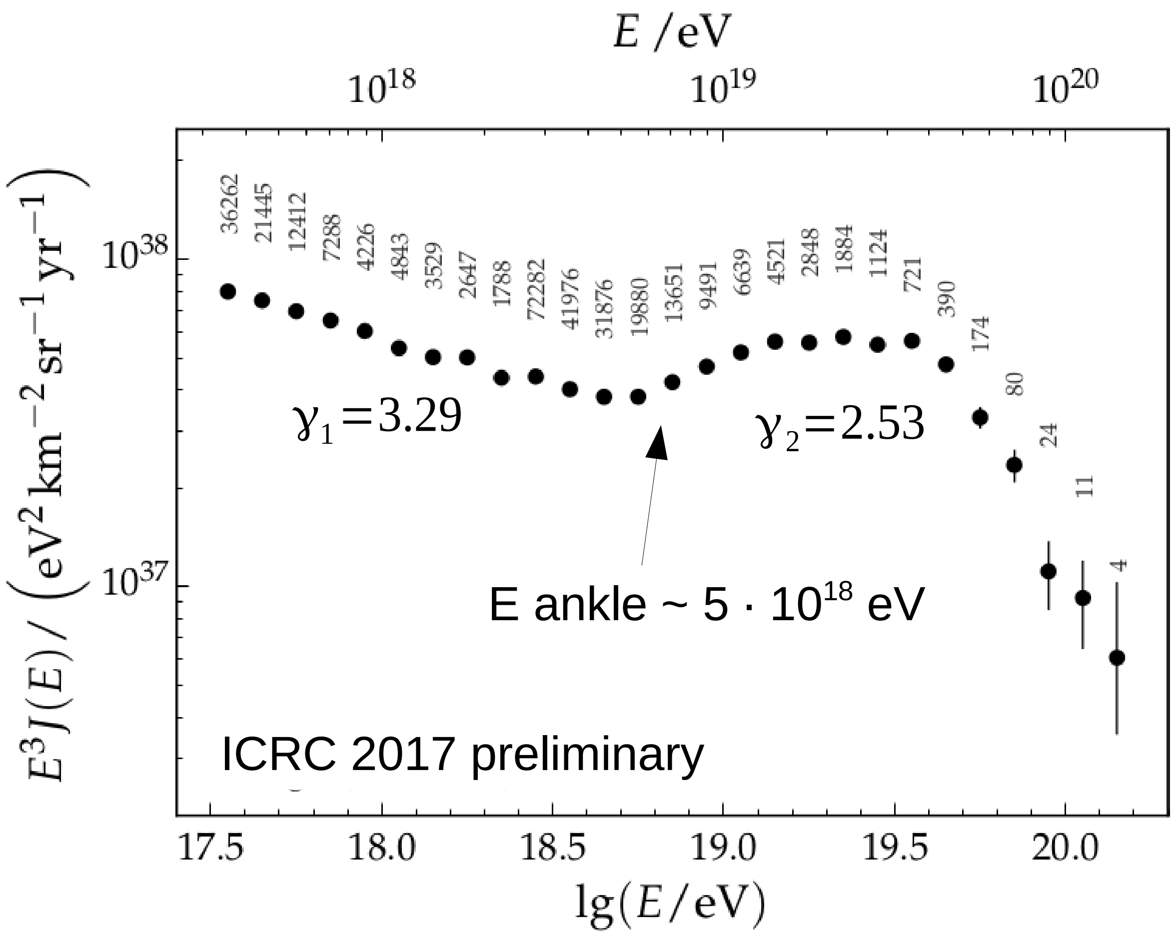
Combined Energy Spectrum

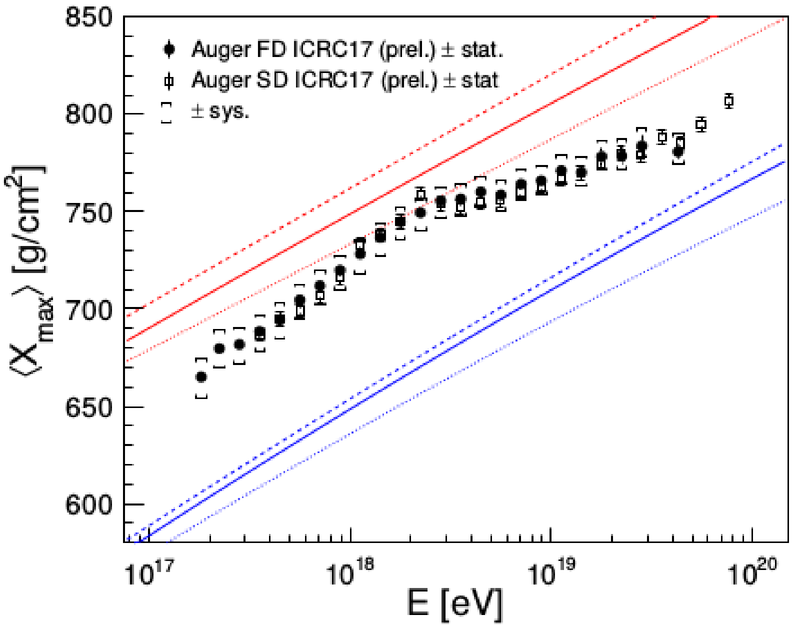
$$J_{\text{unf}}(E) = \begin{cases} J_0\left(\frac{E}{E_{\text{ankle}}}\right)^{-\gamma_1} & E < E_{\text{ankle}} \\ J_0\left(\frac{E}{E_{\text{ankle}}}\right)^{-\gamma_2}\left[1+\left(\frac{E_{\text{ankle}}}{E_s}\right)^{\Delta\gamma}\right]\left[1+\left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1} & E > E_{\text{ankle}} \end{cases}$$



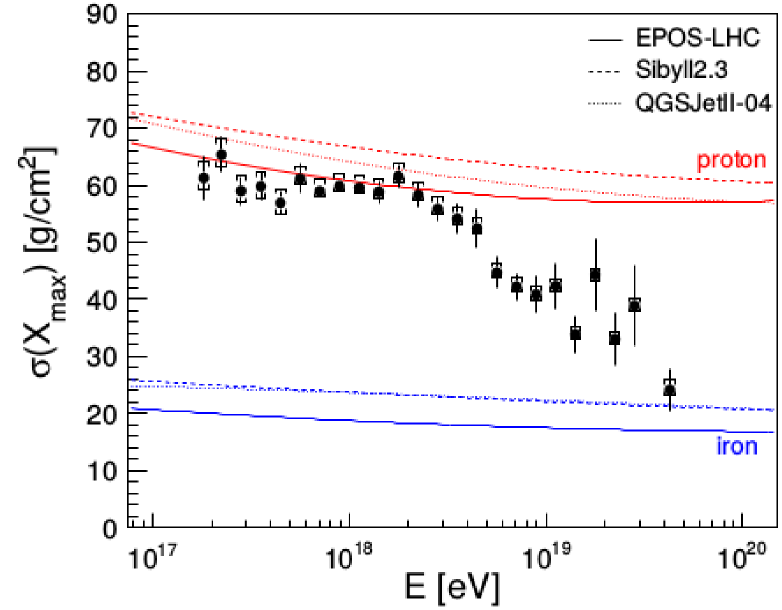
The **suppression** at the highest energies (@ about $4 \cdot 10^{19}$ eV) was observed
without any doubt
(C.L.> 20 σ)
ok but...why?

Mass Composition

Average of X_{max}



Std. Deviation of X_{max}



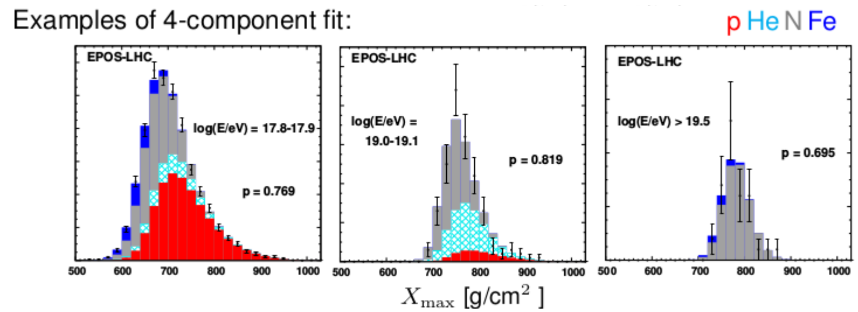
$10^{17.0}$ eV < E < $10^{18.3}$ eV → X_{max} value per decade of energy increases by about 85 g cm $^{-2}$ → lighter composition

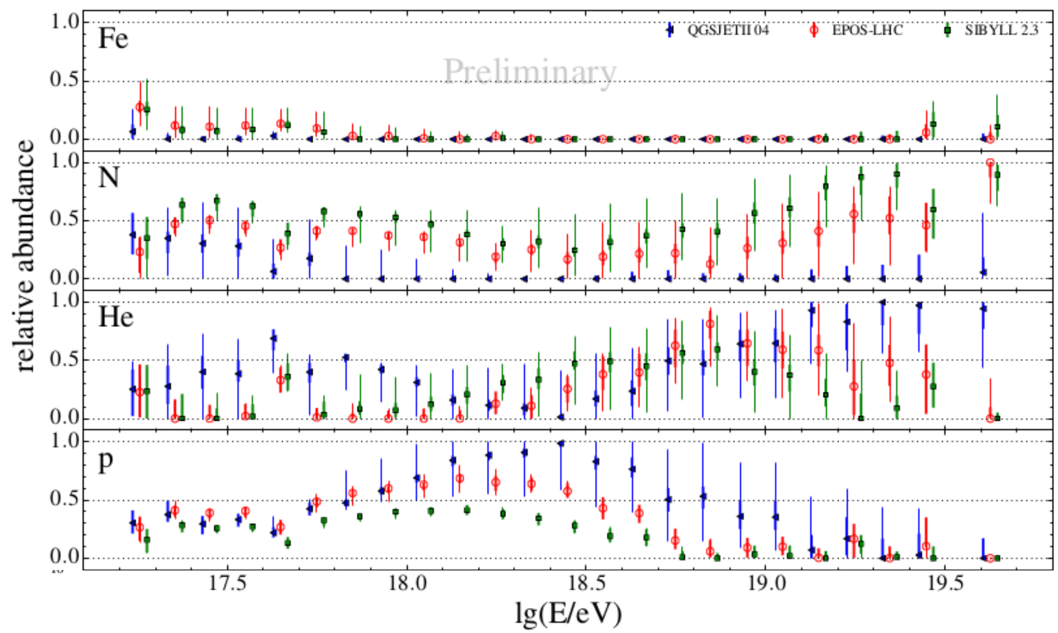
E > 18 $^{10.8}$ eV → X_{max} value per decade of energy increases by about 26 g cm $^{-2}$ → heavier composition

Mass composition is not the same at all energies
Large proton fraction at the energy of the ankle
Mean mass increases at highest energy

Mass Composition

Auger Collaboration @ICRC 2017





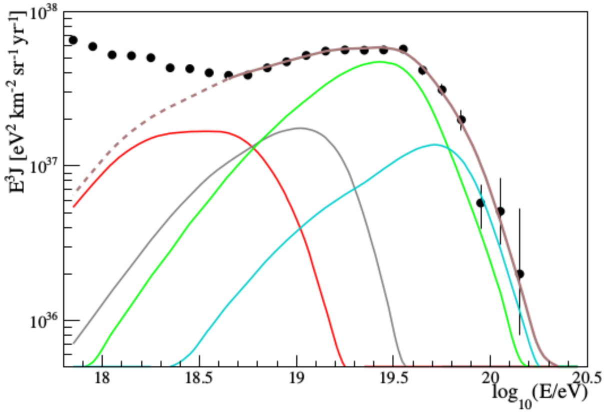
Strong indication that the mass composition of UHECRs does not consist of a pure element composition, but a rather mixture including heavy nuclei with A > 4 at the highest energies

Mass composition is not the same at all energies

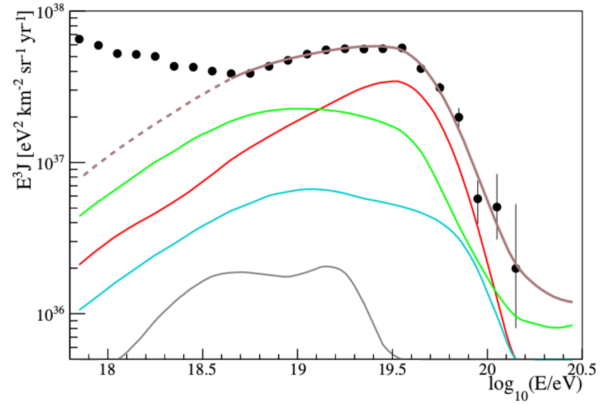
Large proton fraction at the energy of the ankle

Mean mass increases at highest energy

Astrophysical sources



p
He
N
Fe

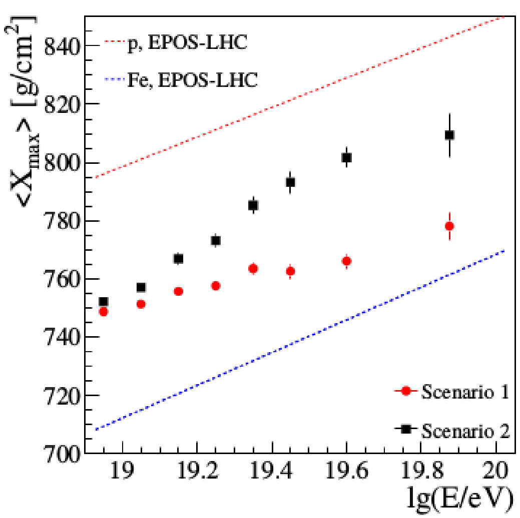


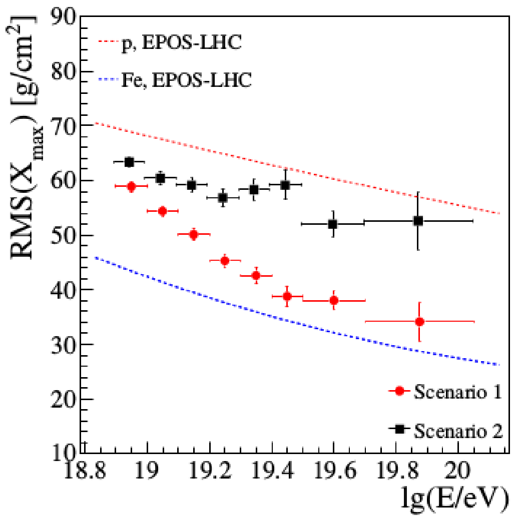
Scenario 1
Maximum rigidity: $E < ZE^{p}_{maz}$

Scenario 2
Photo-disintegration

The Pierre Auger Collaboration, JCAP 04 (2017) 038

Models predict significantly different extrapolations into the suppression region and the two scenarios can be distinguished with high significance and statistics





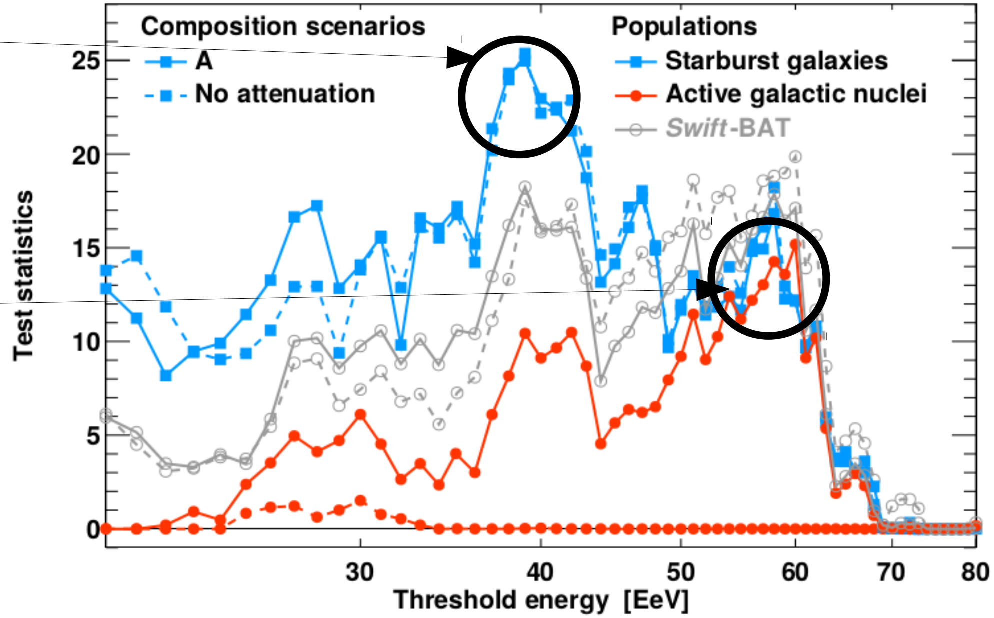
Arrival directions of the UHECRs

New study motivated by Fermi-LAT observations of high-energy gamma rays

Correlation of UHECRs with the brightest AGNs of the Swift-BAT catalog under the assumption that all the selected sources contribute equally to the UHECR flux.

Starburst Galaxies
23 bright objects within 250 Mpc.

AGN from 2FHL catalog.
17 bright objects within 250 Mpc.

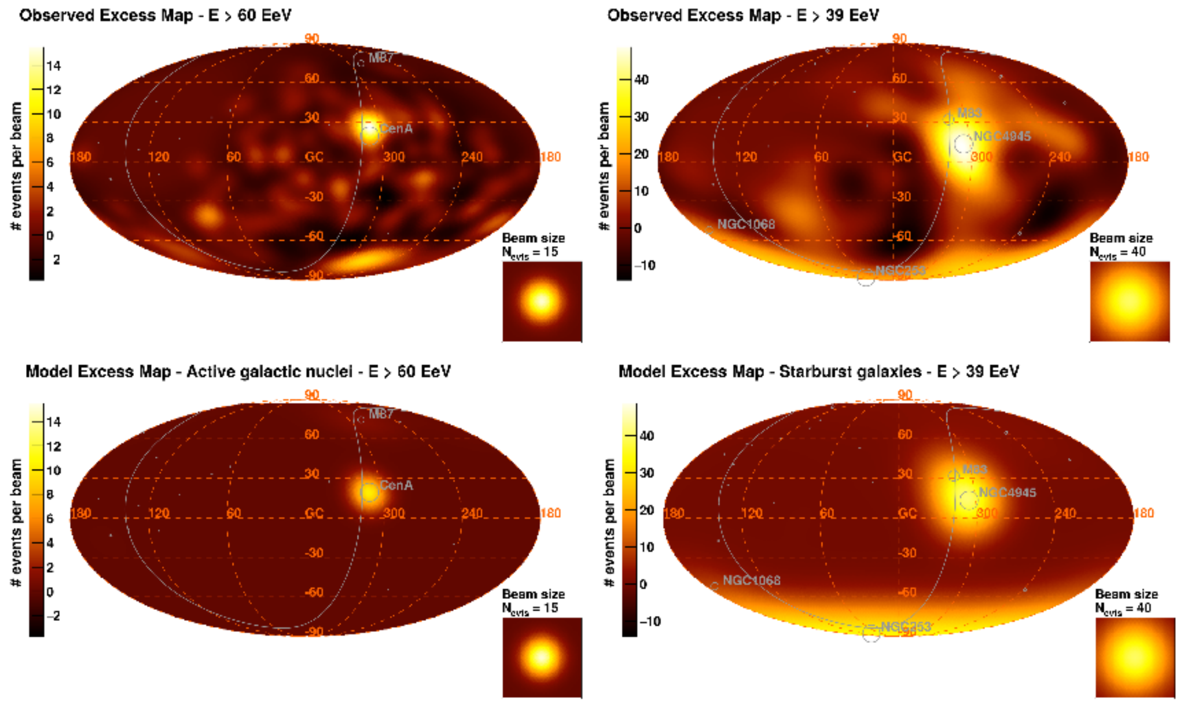


Method:
sky model as the sum of an isotropic fraction plus the anisotropic component from selected sources.
The model predictions are compared to the data using the maximum likelihood ratio method.

4396 vertical events and 1118 inclined ones @ E>20EeV

Auger Collaboration @ICRC 2017

Arrival directions of the UHECRs



Departures from isotropy:

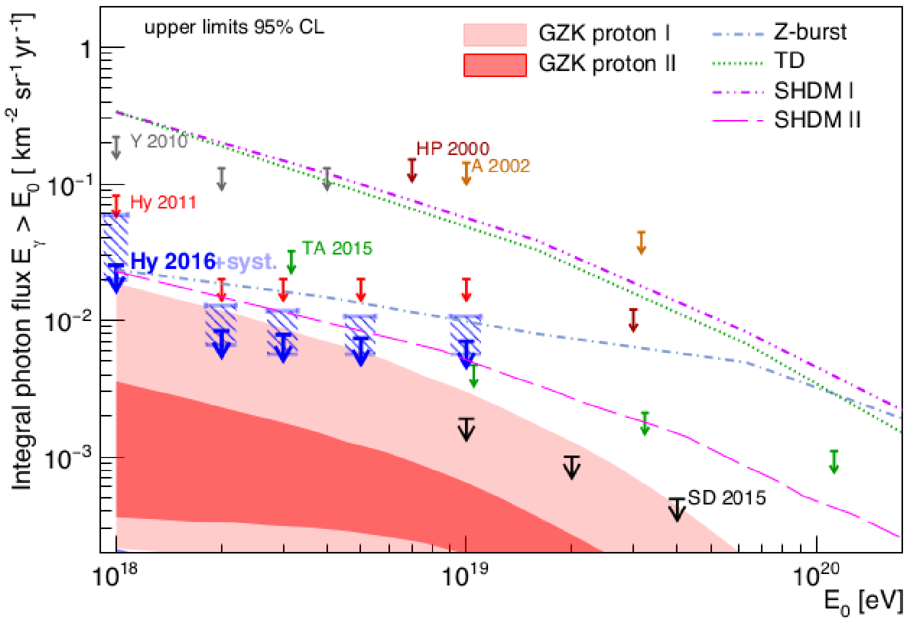
~3σ C.L. region of Centaurus A (19 observed events vs ~ 6.0 expected on average from an isotropic flux)

~2.7σ C.L. excess has been found in the directions of the active galaxies from Fermi-LAT

~4σ C. L. starburst galaxies in direction of Cen. A and in the South Galactic pole (NGC 4945, NGC 1068 NGC 253 and M83)

Cosmogenic photons search

UHE photons are tracers of the Greisen-Zatsepin-Kuzmin (GZK) process.
If these predicted GZK photons were observed, it would be an indicator for the GZK process being the reason for the observed suppression in the energy spectrum of UHE cosmic rays



$$p + \gamma_{CMB} \rightarrow p + \pi_0 \downarrow \gamma\gamma$$

Search for photons
E > 1EeV

Photons vs Hadrons showers

- Higher value of the Xmax
- Lower average number of muons
- Steeper LDF and consequently a smaller footprint on ground

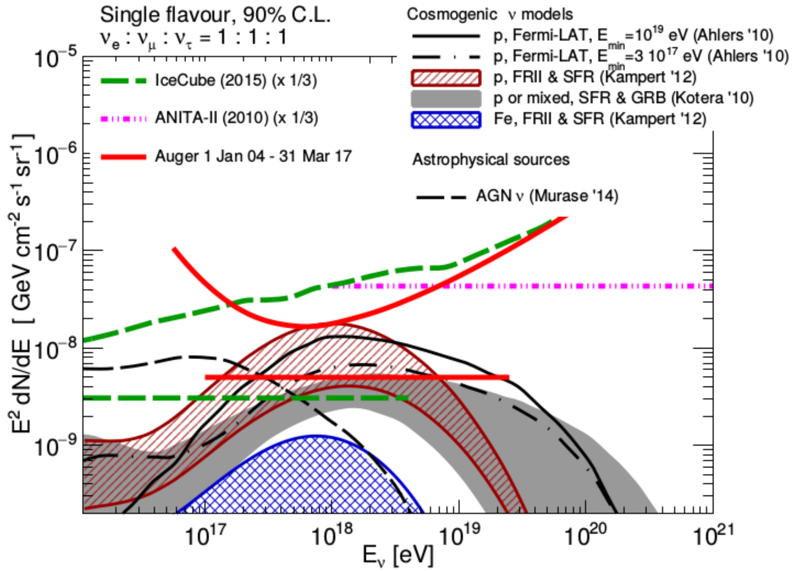
4 photons candidate above 10 EeV (SD)
3 photons candidate between 1-2 EeV (Hybrid)
The current upper limits impose tight constraints on current top-down scenarios proposed to explain the origin of UHE cosmic rays

Cosmogenic neutrinos search

Neutrinos of ~ 10^{18} eV are expected from interactions of UHECR in the sources or during propagation through the Universe.

$$p+\gamma_{CMB} \rightarrow n+\pi^{+}$$
$$\downarrow$$
$$e^{+}+\nu$$

E > 100 PeV



Down-going (all flavors) neutrinos that develop deep in the atmosphere generating inclined showers and triggering the Auger surface detector can be identified provided their zenith angles exceed 60 degrees.

Tau neutrinos entering the Earth with a zenith angle close to 90 degrees can interact and produce a tau lepton that decays in the atmosphere inducing an “upward-going” shower that triggers the surface detector.

$dN/dE = k\ E^{-2}$
→ k ~ 6.4 x 10 -9 GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

No neutrino events observed
Different models for cosmogenic neutrinos that attempt to explain the origin of cosmic rays are excluded at the 90% C.L particularly those that assume proton primaries

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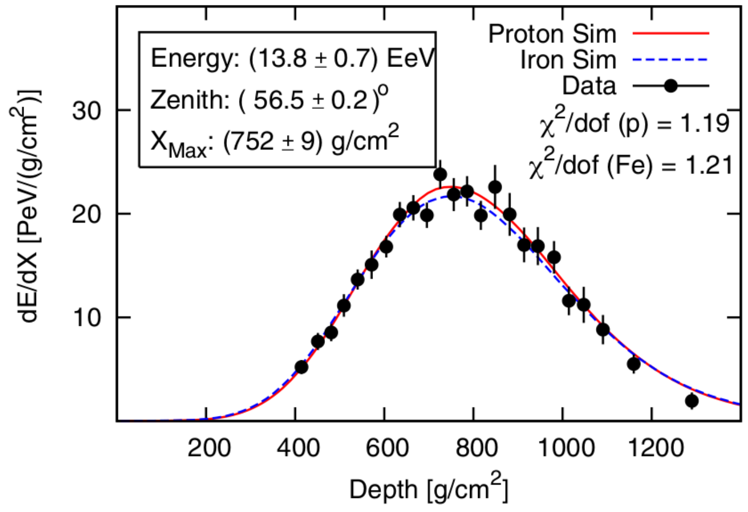
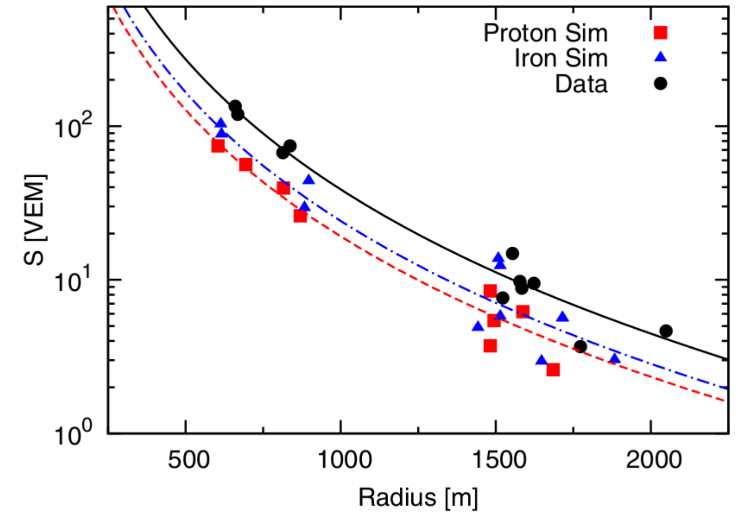
Hadronic physics

PRL 117, 192001 (2016)

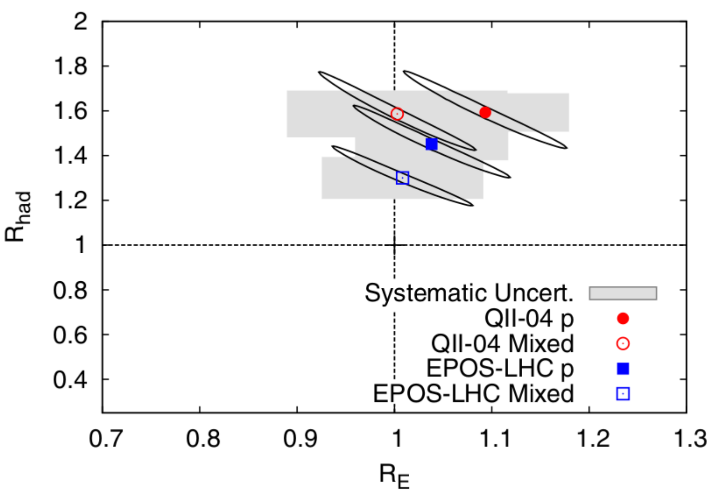
Data set:
411 vertical hybrid events with $10^{18.8} < E < 10^{19.2}$ eV
1 January 2004 and 31 December 2012



The measured longitudinal profile with its matching simulated showers, using QGSJet-II-04 for proton and iron primaries



The observed and simulated ground signals for the same event.



excess of muons in UHECR air showers compared to predictions of hadronic interaction models

$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E S_{\mathrm{EM},i,j} + R_{\mathrm{had}} R_E^{\alpha} S_{\mathrm{had},i,j}.$$

R_E energy rescaling parameter to allow for a possible shift in the FD energy calibration,

R_{had} multiplicative rescaling of the hadronic component of the shower

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AugerPrime – Motivations

Why keep studying UHECRs?

- Mass composition at highest energies
- Origin of "Cut-off": GZK vs Maximum energy of the sources
- Proton contribution to the flux → Proton Astronomy?
- Muon excess → "New" hadronic interaction physics?

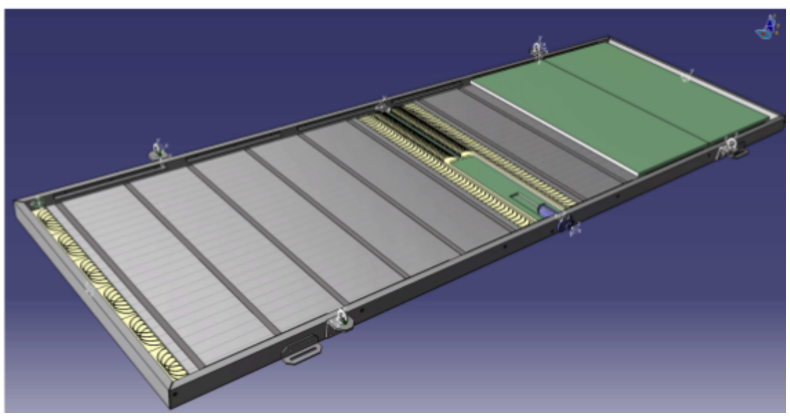
Enhancement of the capability of the Surface Detector to identify the mass of the primary particle on a shower-by-shower basis

A thin scintillation detector, which is mounted above the larger WCD, provides a robust and well-understood scheme for particle detection that is sufficiently complementary to the water-Cherenkov technique and permits a good measurement of the density of muons.

AugerPrime – The project of the upgrade

Enhancement of the capability of the Surface Detector to identify the mass of the primary particle on a shower-by-shower basis

New detectors
SSD
Surface Scintillator Detector



SSD module: 3.8 m × 1.3 m
two scintillator sub-modules, each composed of 24 bars of extruded scintillator

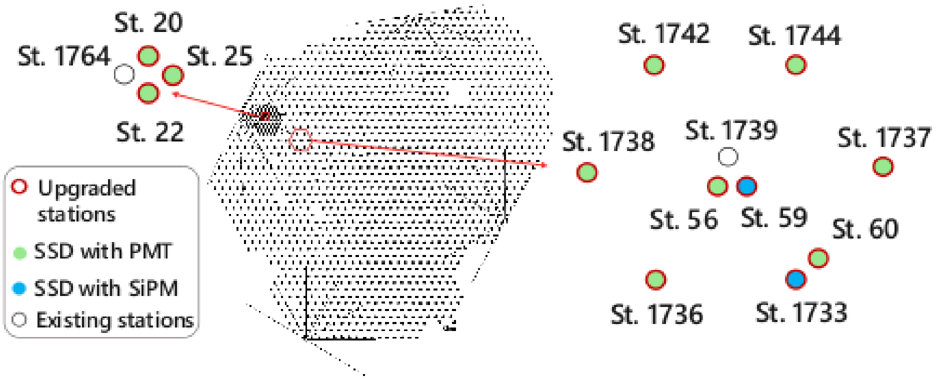
1.5'' PMT Hamamatsu R9420

Upgrade of WCDs

New electronics of the SD
It will increase the data quality thanks to better timing accuracy and a faster ADC sampling.

Extension of the dynamic range of the WCD
The dynamic range of the WCD will be enhanced by a factor 32 with an additional small (1") PMT that will be inserted in the WCD

AugerPrime – Schedule



October 2016: “Engineering array” with 12 upgraded detectors

End of 2017: 180 SSD modules to be shipped

Finish construction by 2019

Data taking up to 2025

The number of collected events will be doubled in comparison to the statistics collected up to now by the existing Pierre Auger Observatory, with the advantage that every future event will have mass information and will allow us to better address some of the most pressing questions in UHECR physics

Summary

Spectrum → strong flux suppression

Mass composition → light @ ankle
mixed @ UHE

Hadronic interactions → excess of muons

Photons and neutrinos search → constraints on p-dominated sources

Source → compatible with maximum rigidity scenario

Arrival direction → indication of anisotropy

All these hot topic will be clarified by AugerPrime

6th International Conference on New Frontiers in Phisycs
Kolymbary, August 24 -2017

The Pierre Auger Observatory: latest results and future perspectives

Thank you for your attention!

ezione di Catania

INFN
Istituto Nazionale di Fisica Nucleare

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OBSERVATORY

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Backup

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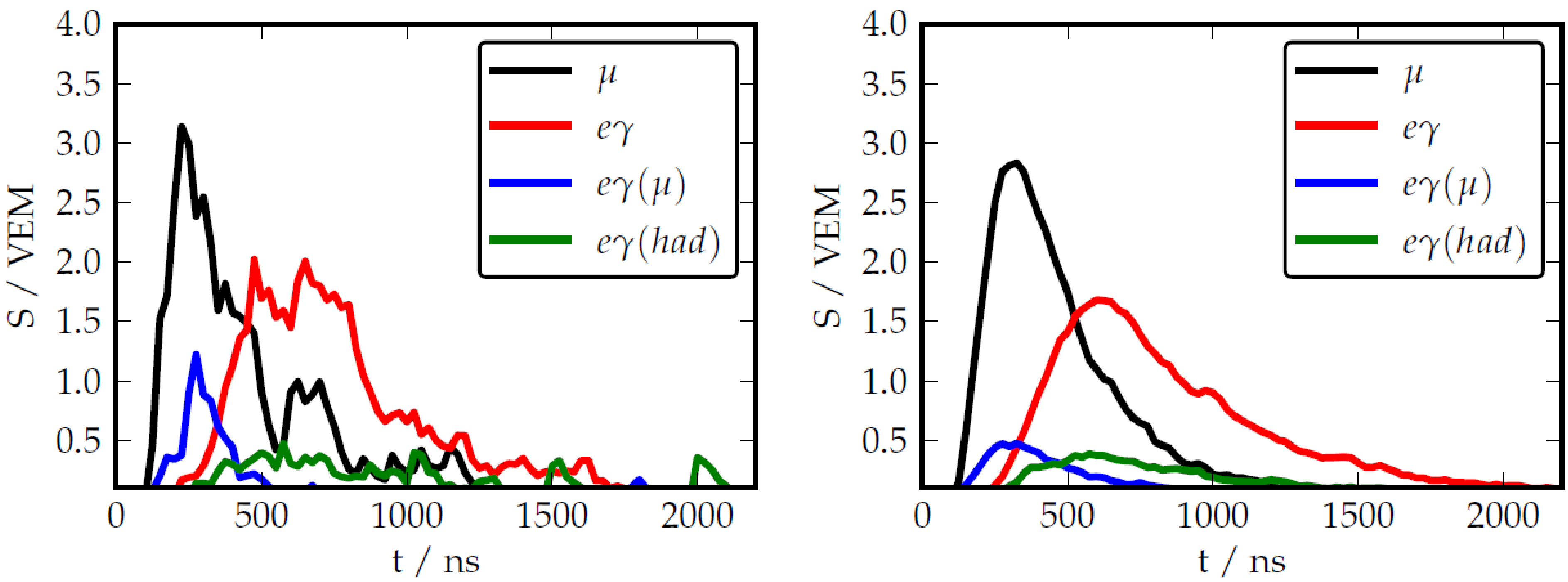
AugerPrime – Analysis Techniques

”Universality of hadronic showers”
Characteristics of showers at ground level depends only on E, Xmax e Nμ

Parameters can be evaluated from the time structure of the signal in each detector, shower by shower



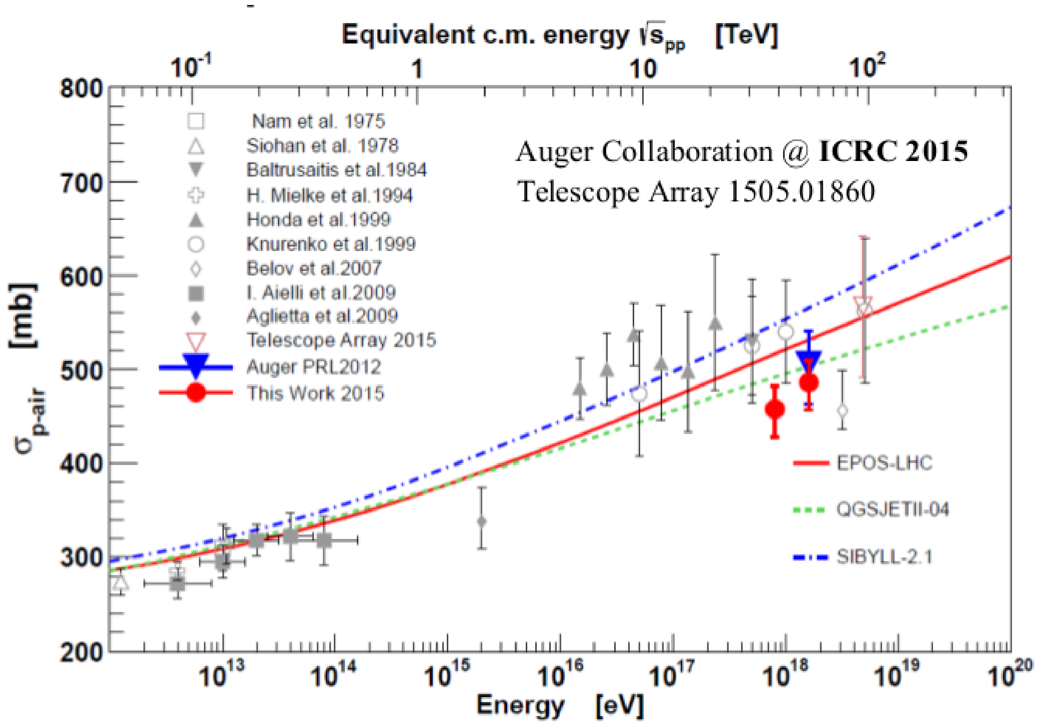
(a) Individual component traces

(b) Average traces in one DX bin

SD Dinamic Range

Range	Intent	Dynamic Range																						
bits		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
LowGain	VEM	AnodeX32																						
HighGain	Showers						Anode																	
VeryHighGain	Cores											SPMT												
Ipeak (mA)		0.0006					0.02		0.08			1.2						40						
Vpeak (mV)		0.03					1		3.9			64						2000						
Ipeak SPMT (mA)												0.02						1.25					40	
Vpeak SPMT (mV)												1						64					2000	
Npart (VEM)		0.01					0.3		1.2			10						600					20000	

p-p cross section measurement



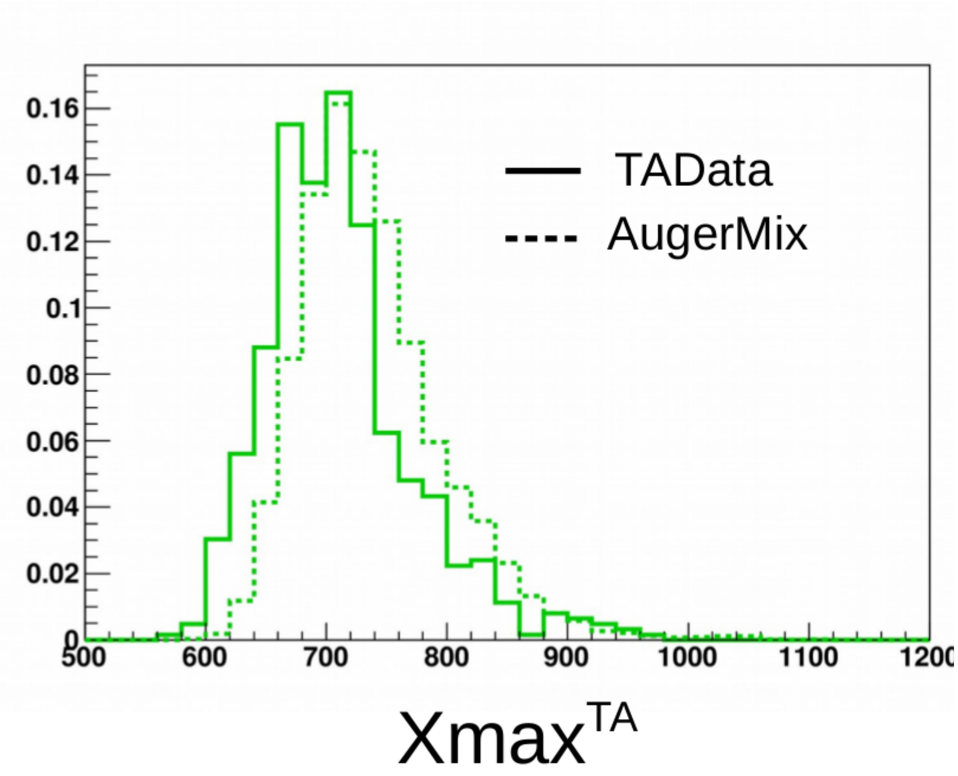
P-p cross section @57 TeV c.m.s = 486±16(stat)+19/-25(syst)] mb

Energy Spectrum

	SD 1500 $< 60^\circ$	SD 1500 $> 60^\circ$	SD 750	Hybrid
Data taking period	Jan. 2004 – Dec. 2016	Jan. 2004 – Dec. 2016	Aug. 2008 – Dec. 2016	Jan. 2007 – Dec 2015
Exposure [km^2 sr yr]	51,588	15,121	228	1946 @10^{19} eV
Number of events	183,332	19,602	87,402	11,680
Zenith angle range [deg.]	0–60	60–80	0–55	0–60
Energy threshold [eV]	3×10^{18}	4×10^{18}	3×10^{17}	10^{18}
Calibration parameters				
Number of events	2661	312	1276	
A [eV]	$(1.78 \pm 0.03) \times 10^{17}$	$(5.45 \pm 0.08) \times 10^{18}$	$(1.4 \pm 0.04) \times 10^{16}$	
B	1.042 ± 0.005	1.030 ± 0.018	1.000 ± 0.008	
Energy resolution [%]	15	17	13	

Auger vs Telescope Array: X_{max}

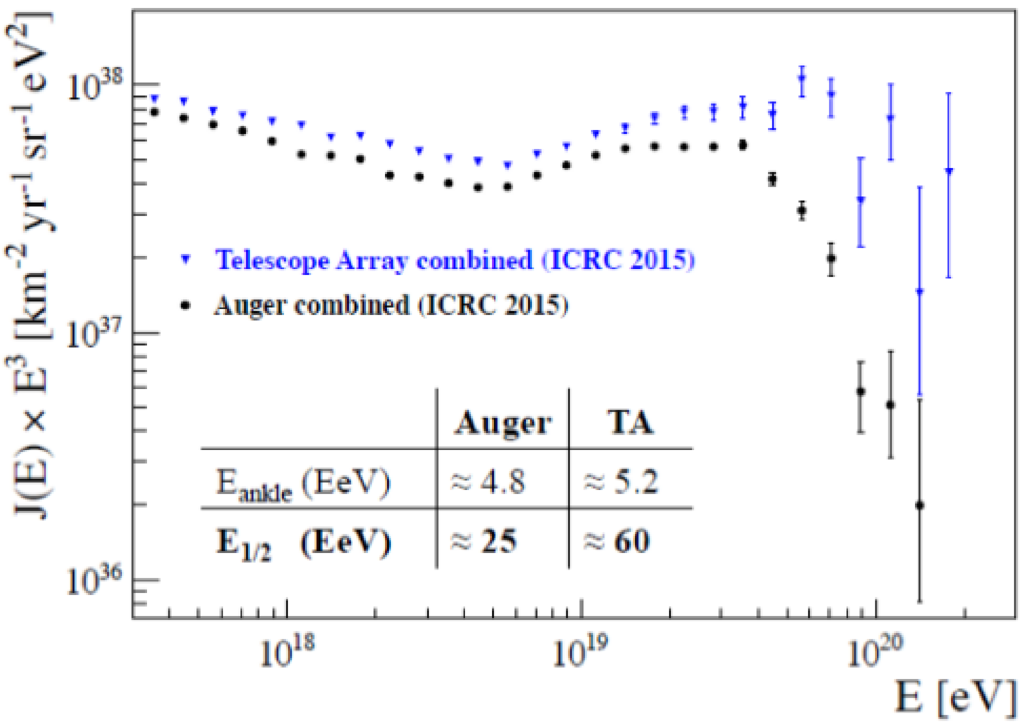
18.2 < log 10 (E/eV) < 19.0

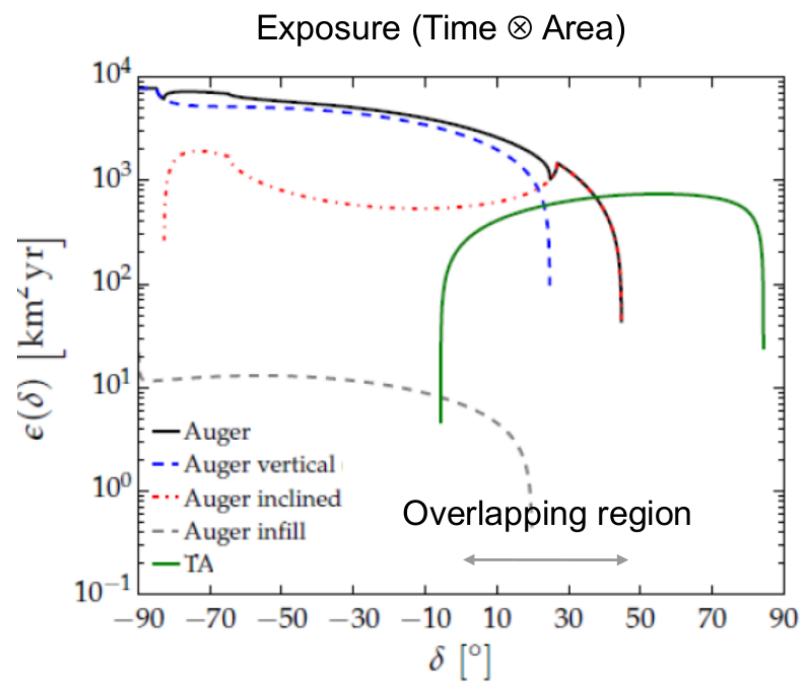


Proper comparison demands use of detector simulation and analysis chain of both experiments!

TA Xmax distributions are compatible to AugerMix Xmax distributions within the systematic uncertainties

Auger vs Telescope Array: Spectrum





Position and steepness of the suppression quite different

Different point of view?