LATEST RESULTS FROM THE PIERRE AUGER OBSERVATORY

52nd Rencontres de Moriond
EW 2017
La Thuile, 24-03-2017

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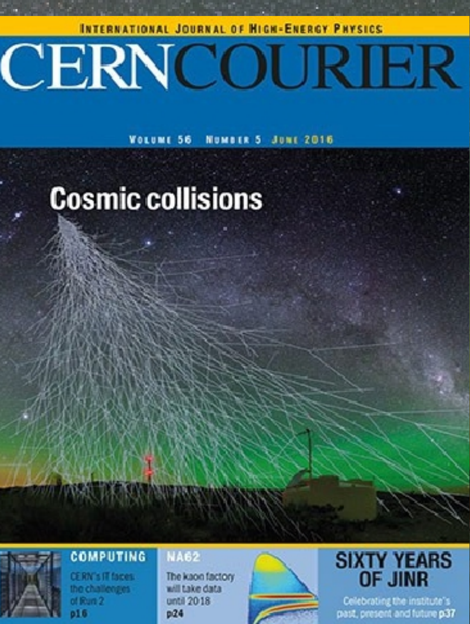
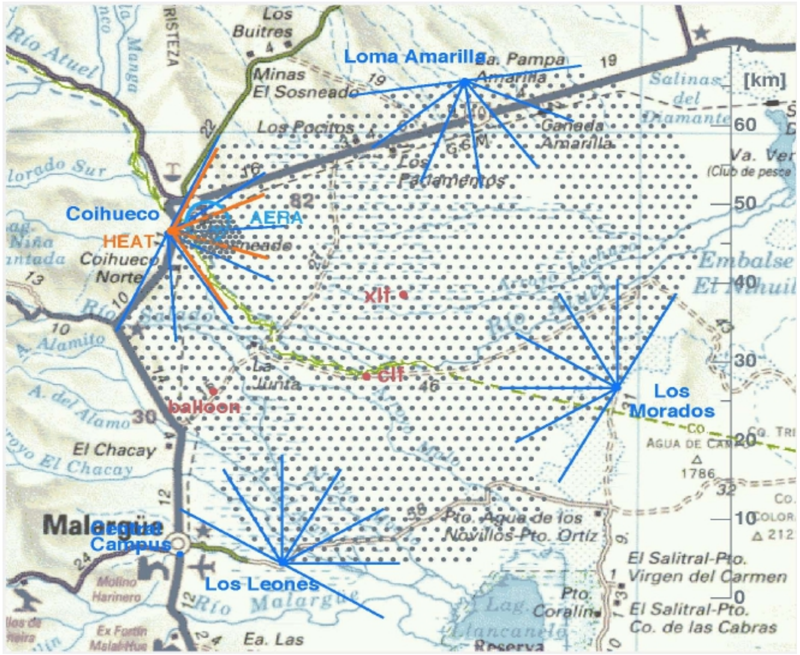


The Pierre Auger Observatory

- Largest cosmic ray detector built so far;
- Located in the southern hemisphere, near the town of Malargue, Mendoza province, Argentina;
- International collaboration of more than 450 scientists from 16 countries.

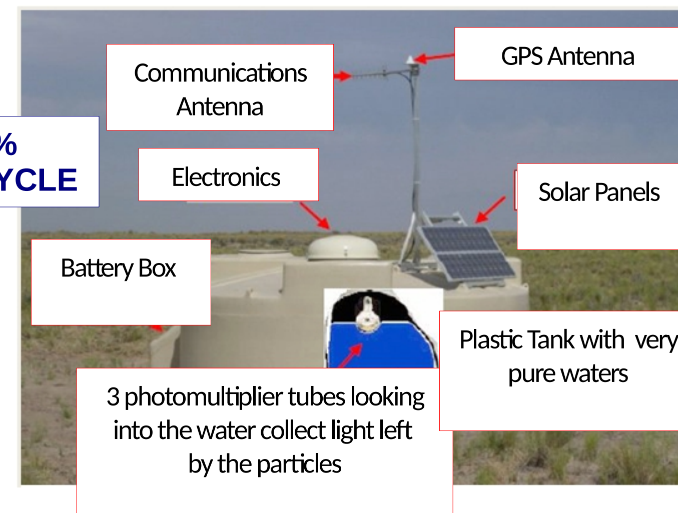
The Pierre Auger Observatory



Goals of the Experiment:

- Energy Spectrum
- Mass Composition
- Arrival Directions - Anisotropy

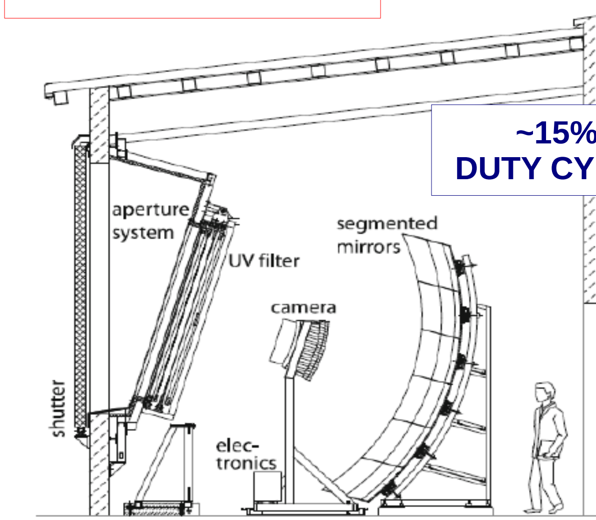
100% DUTY CYCLE



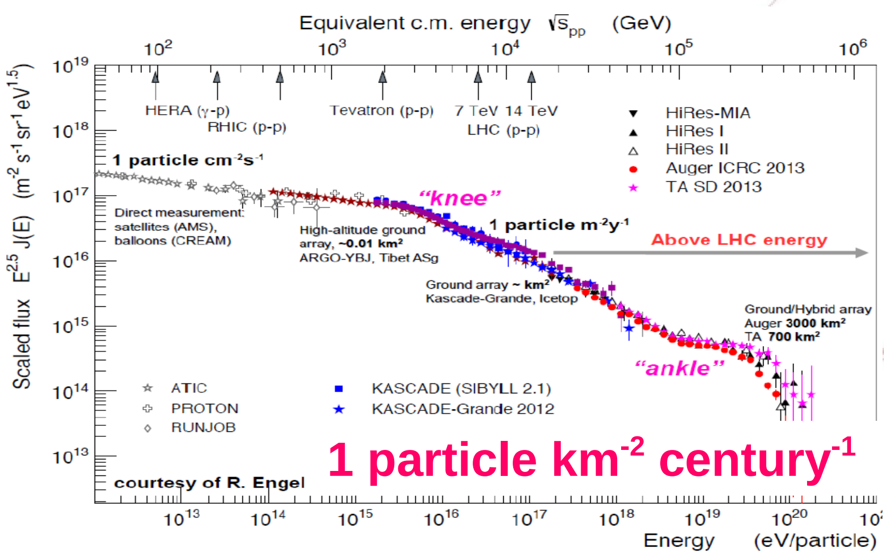
<u>SD detector:</u> 1660 Water Cherenkov detectors, covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.
<u>FD detector:</u> 24 telescopes, 6 for each sites, arranged to overlook the area covered by the SD.
The site is located in the Argentinian pampa, at ~ 1400 m above sea level (875 g/cm^2).

- **Large Aperture**
  (about 7000 km^2 sr)
- **Hybrid Detection Technique**

~15% DUTY CYCLE

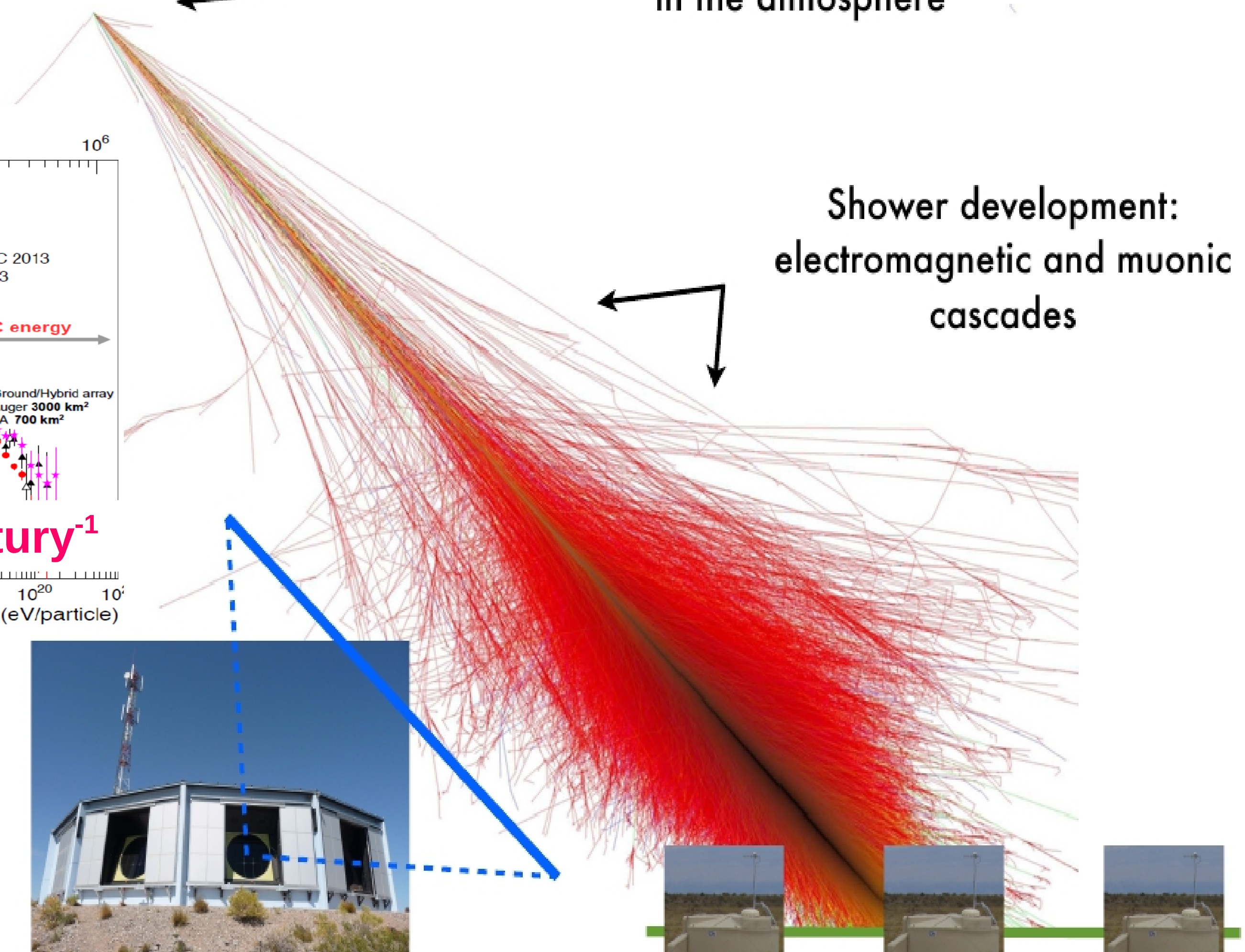


Indirect Measurements with Auger



Cosmic ray 1st interaction high in the atmosphere

Shower development: electromagnetic and muonic cascades

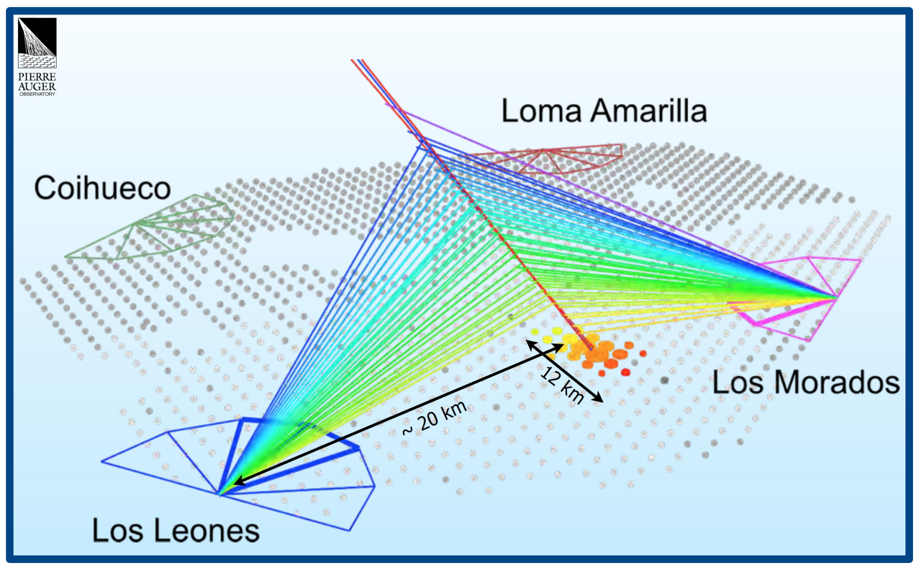


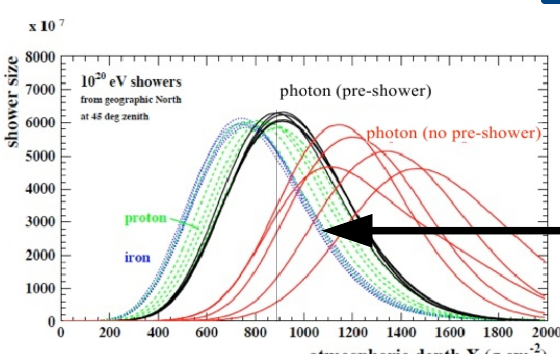
FD - longitudinal profile

SD - lateral profile

An Auger Event

- **SD:** lateral distribution of shower particles at ground;
  large statistics, fully efficient at 3 EeV.
- **FD:** longitudinal development of the shower; E >= 10^{18} eV,
  calorimetric measurement of the energy, duty cycle ~ 15%.
- **Energy resolution** → ~ 15%.
- **Angular resolution** → 1°-2°(SD) - < 1° (hybrid).

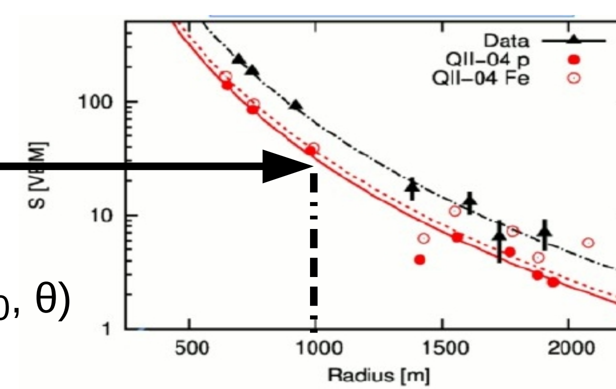




X_{max}

$E_{cal} = \int dE/dX \, dX$

S_{1000}

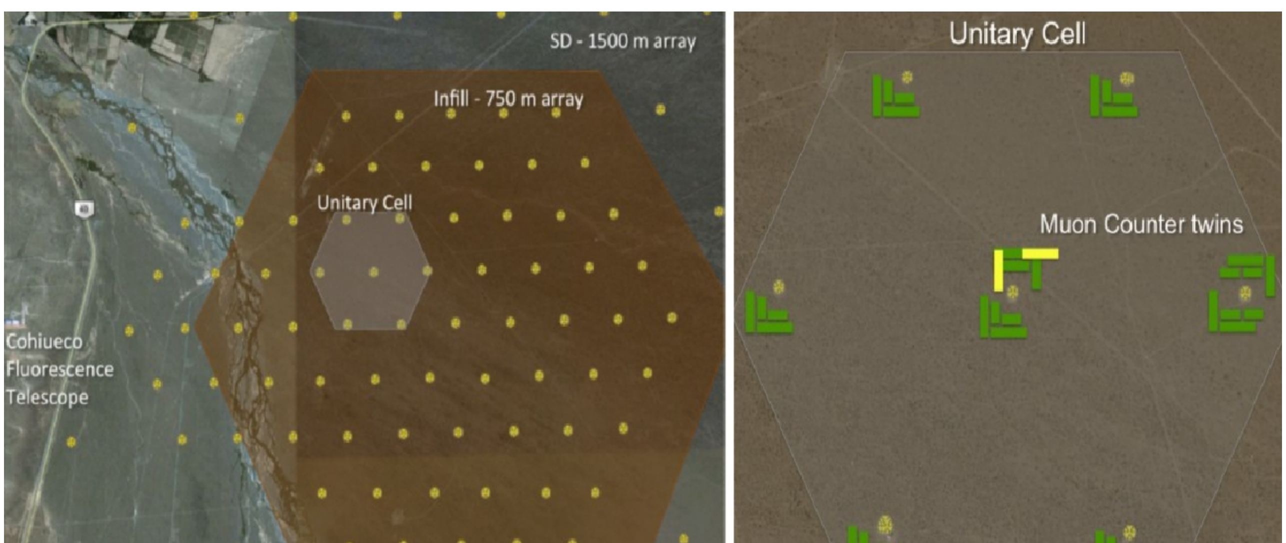


$E_{surface} = f(S_{1000}, \theta)$

Auger Enhancements

- Three additional telescopes at Coihueco site;
- Pointing above FOV of the standard SD (FOV 30°-60°);
- Lowering the energy threshold to 10^{17} eV.

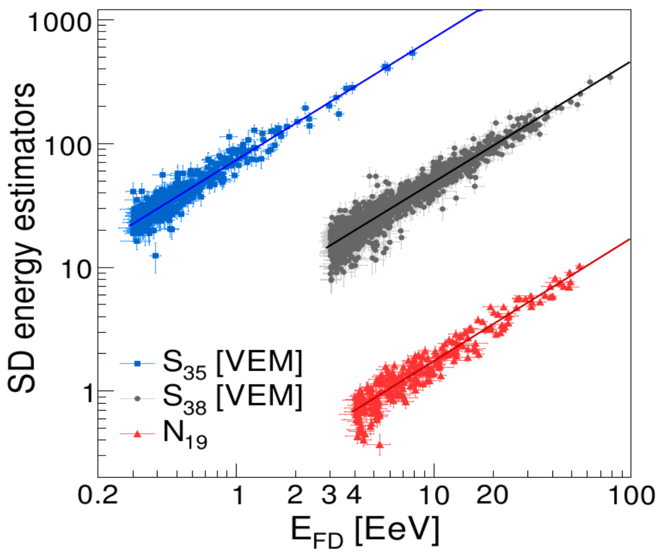
AMIGA (**A**uger **M**uon and **I**nfill for the **G**round **A**rray)



INFILL:
61 WCD in half distance (750 m);
Covering 23.5 km^2;
Extends energy range of SD to 3×10^{17} Ev.

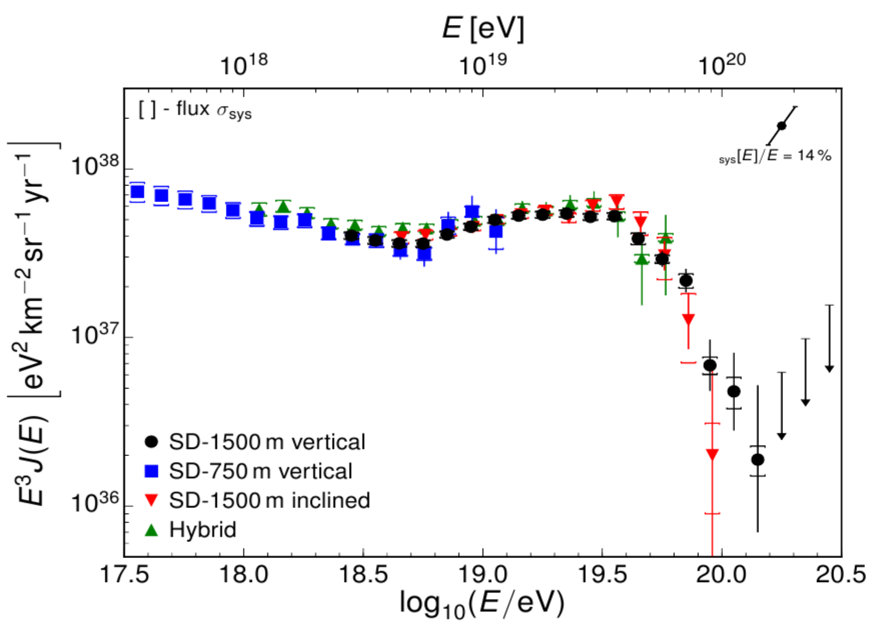
UNDERGROUND MUON COUNTERS:
30 m^2 scintillator, 64 channel multianode PMT;
Buried 2.25 m under ground level.

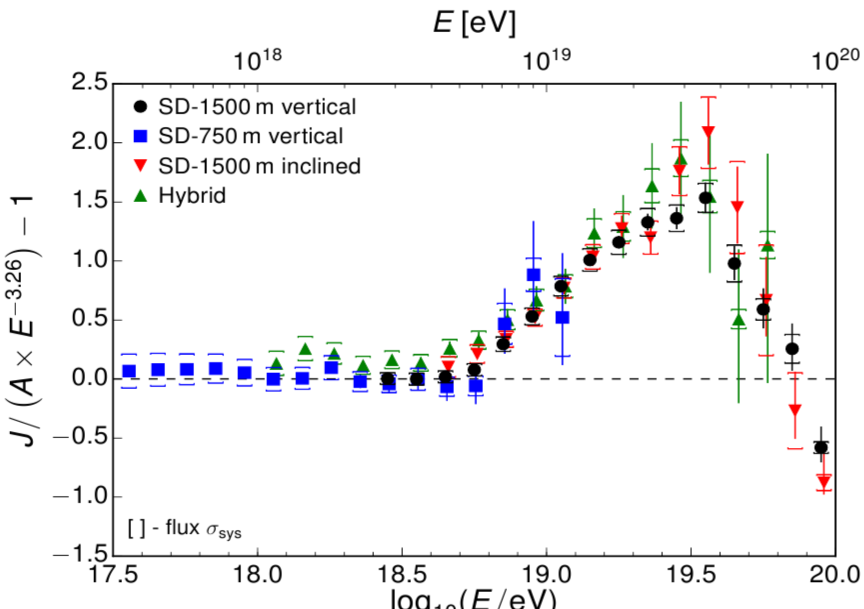
Auger Energy Spectrum



Correlations between the SD energy estimators and the FD energy:

- Infill array;
- Full array with the standard 1.5 km spacing;
- Very inclined showers (60°-80°).

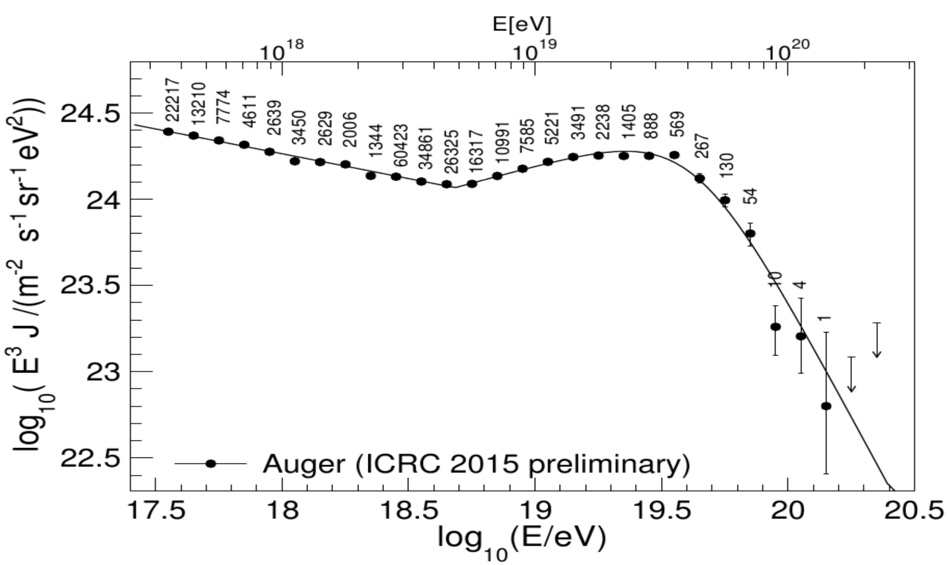




Fractional difference between the Auger spectra and a reference spectrum with an index of 3.26.

Auger Energy Spectrum

	SD-1500 m		SD-750 m	Hybrid
	vertical	inclined		
Data-taking period	01/2004–12/2014	01/2004–12/2013	08/2008–12/2014	11/2005–12/2013
Exposure [km^2 sr yr]	42500±1300	10900±300	150±5	1500±20 at 10^{19} eV
Zenith angle [deg]	0-60	60-80	0-55	0-60
Threshold energy	3×10^{18} eV	4×10^{18} eV	3×10^{17} eV	10^{18} eV
Number of events	102901	15614	61130	9346
Number of hybrid events	1731	255	469	
Energy scale (A)	(0.1871 ± 0.004) EeV	(5.71±0.09) EeV	(12.87± 0.63) PeV	
Energy scale (B)	1.023 ±0.006	1.01±0.02	1.013±0.013	
Energy resolution [%]	15.3±0.4	19±1	13±1	



Combined Spectrum

$$J(E) = J_0 \left(\frac{E}{E_{\rm ankle}}\right)^{-\gamma_1} \quad E < E_{\rm ankle}$$

$$J(E) = J_0 \left(\frac{E}{E_{\rm ankle}}\right)^{-\gamma_2} \left[1 + \left(\frac{E_{\rm ankle}}{E_{\rm s}}\right)^{\Delta\gamma}\right] \left[1 + \left(\frac{E}{E_{\rm s}}\right)^{\Delta\gamma}\right]^{-1}$$

J_0 [$eV^{-1}km^{-2}sr^{-1}yr^{-1}$]	$E_{\rm ankle}$ [EeV]	$E_{\rm s}$ [EeV]	γ_1	γ_2	$\Delta\gamma$
$(3.30\pm0.15\pm0.20)\times10^{-19}$	$4.82\pm0.07\pm0.8$	$42.09\pm1.7\pm7.61$	$3.29\pm0.02\pm0.05$	$2.60\pm0.02\pm0.1$	$3.14\pm0.2\pm0.4$

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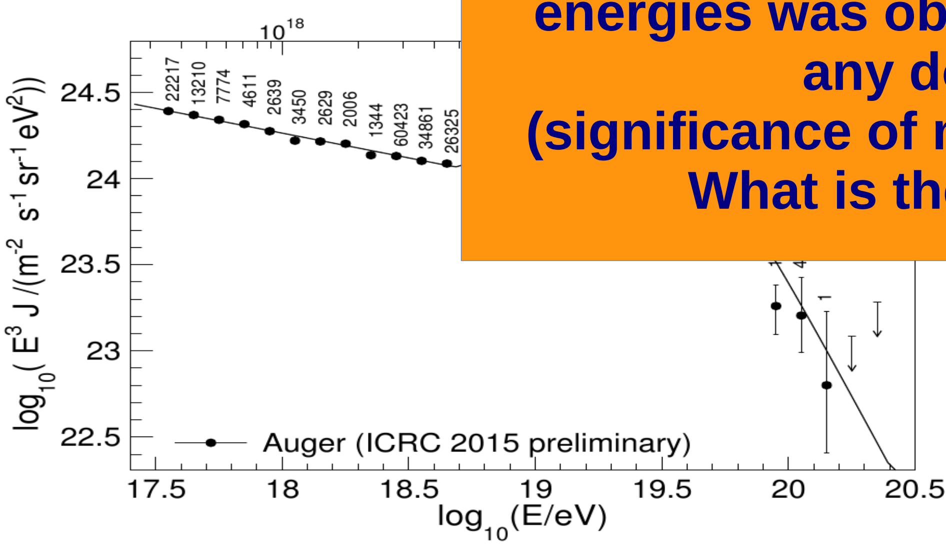
Energy resolution [%]	15.3 [illegible]	[illegible]	[illegible]	



The suppression at the highest energies was observed without any doubt (significance of more than 20 σ) What is the cause?

Spectrum

$$J(E) = J_0 \left(\frac{E}{E_{\rm ankle}}\right)^{-\gamma_1} \quad E < E_{\rm ankle}$$

$$J(E) = J_0 \left(\frac{E}{E_{\rm ankle}}\right)^{-\gamma_2} \left[1 + \left(\frac{E_{\rm ankle}}{E_{\rm s}}\right)^{\Delta\gamma}\right] \left[1 + \left(\frac{E}{E_{\rm s}}\right)^{\Delta\gamma}\right]^{-1}$$

J_0 [eV^{-1}km^{-2}sr^{-1}yr^{-1}]	$E_{\rm ankle}$ [EeV]	$E_{\rm s}$ [EeV]	γ_1	γ_2	$\Delta\gamma$
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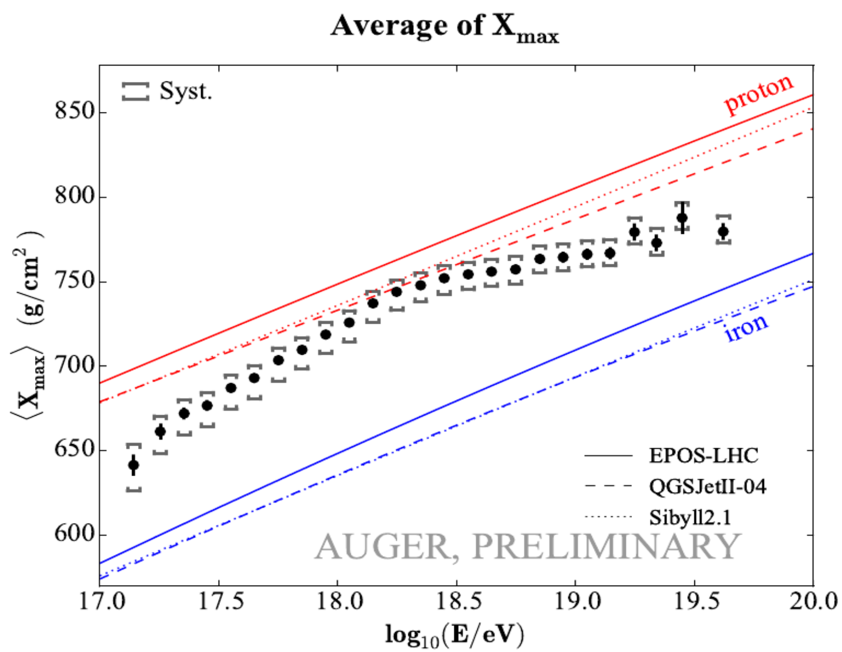
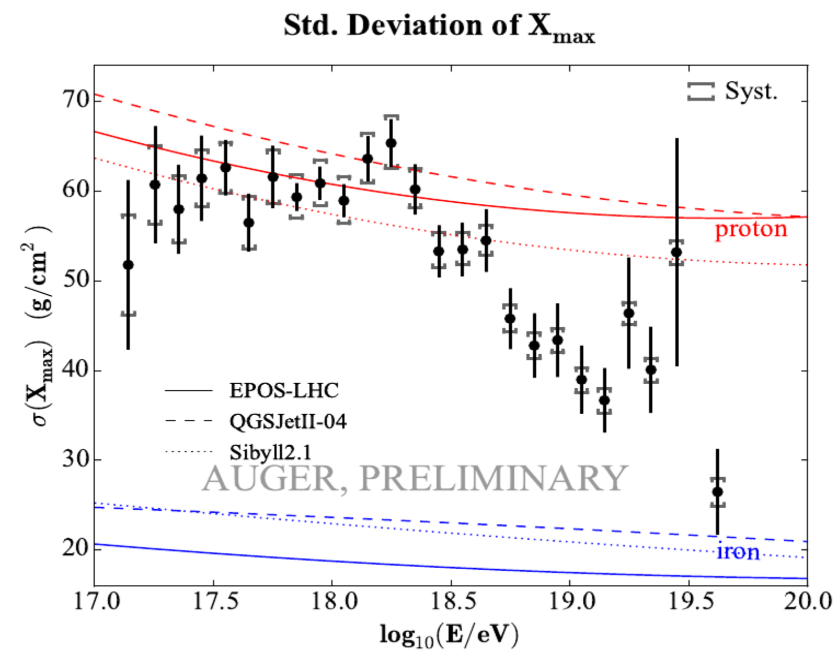
Mass Composition



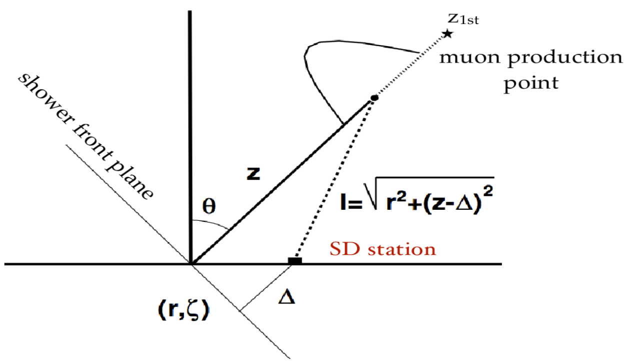


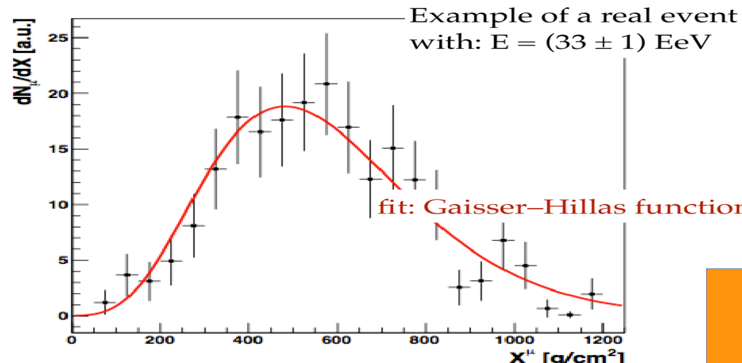
$$\boxed{\begin{aligned} \langle X_{\max} \rangle &= \langle X_{\max} \rangle_p + f_E \langle \ln A \rangle \\ \sigma^2(X_{\max}) &= \langle \sigma_{sh}^2 \rangle + f_E^2\, \sigma^2(\ln A) \end{aligned}}$$

The first two moments of the Xmax distribution (Xmax and σ (Xmax)) are related to the first two moments of the distribution of the logarithm of masses of primary particles (ln A and σ (ln A)).

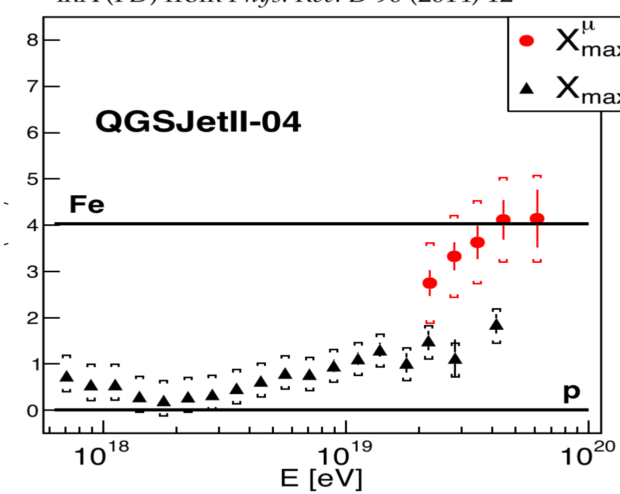
Mass Composition: extension to the highest energies

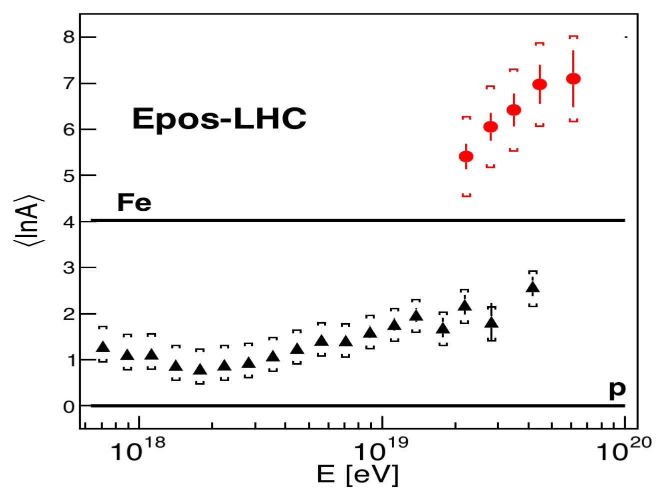
Muon Production Depth **(MPD)** obtained **from SD**





lnA (FD) from *Phys. Rev.* D 90 (2014) 12



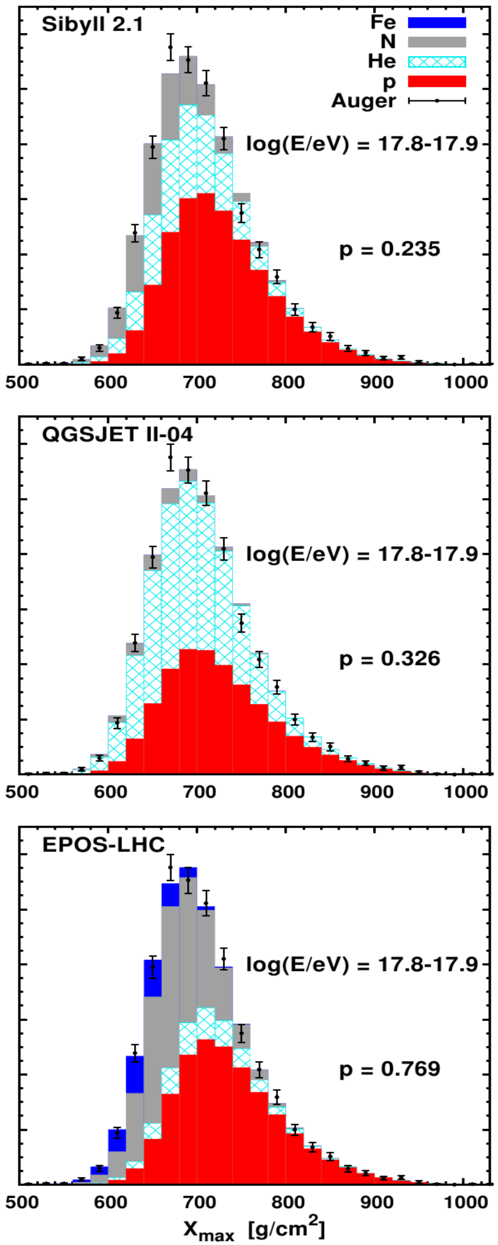


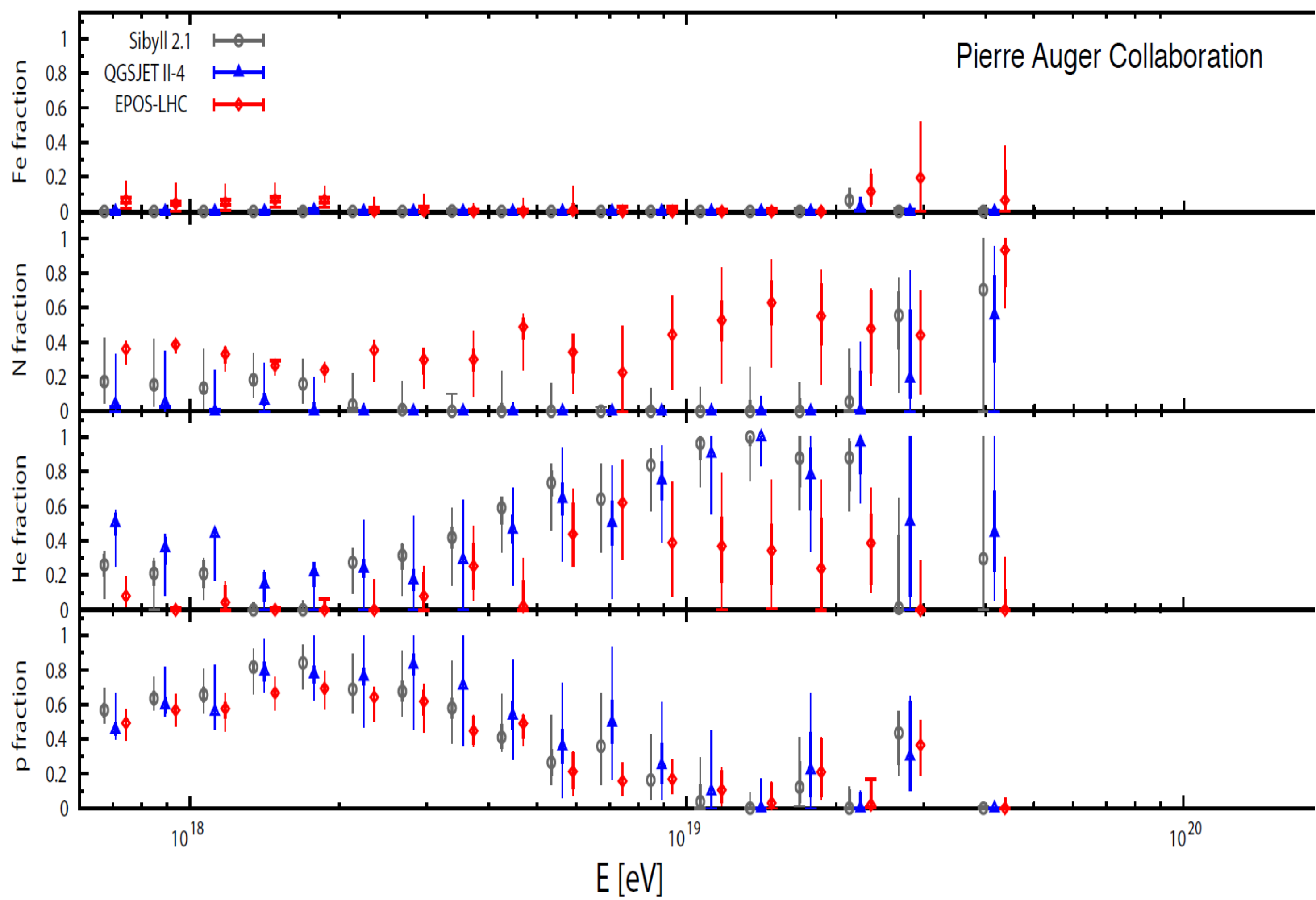
Result strongly dependent from hadronic interaction models.
We need to constrain models.

QGSJETII.04:
compatible values within 1.5 σ.

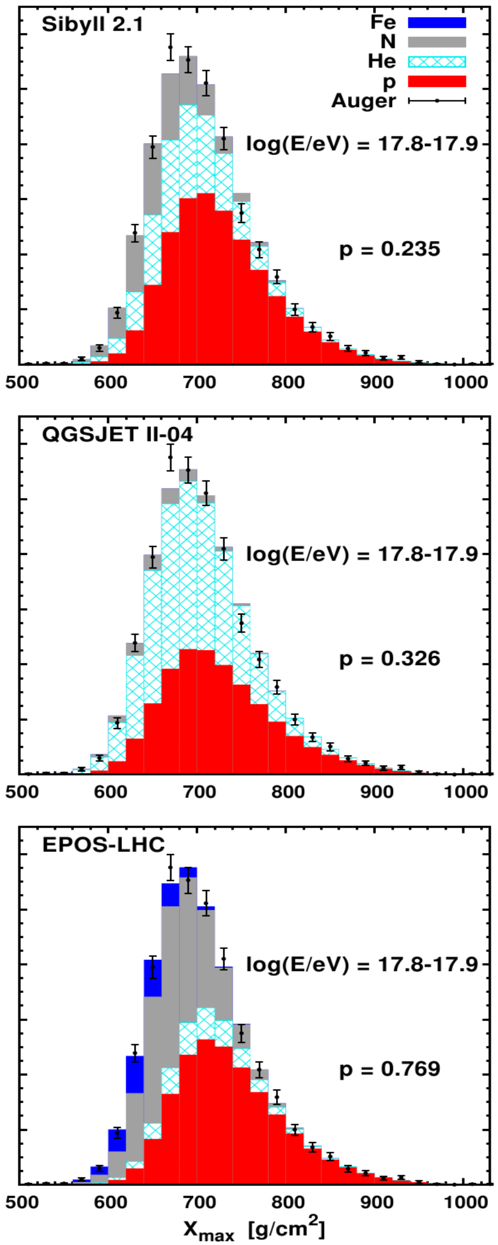
EPOS-LHC:
incompatibility at a level of at least 6 σ.

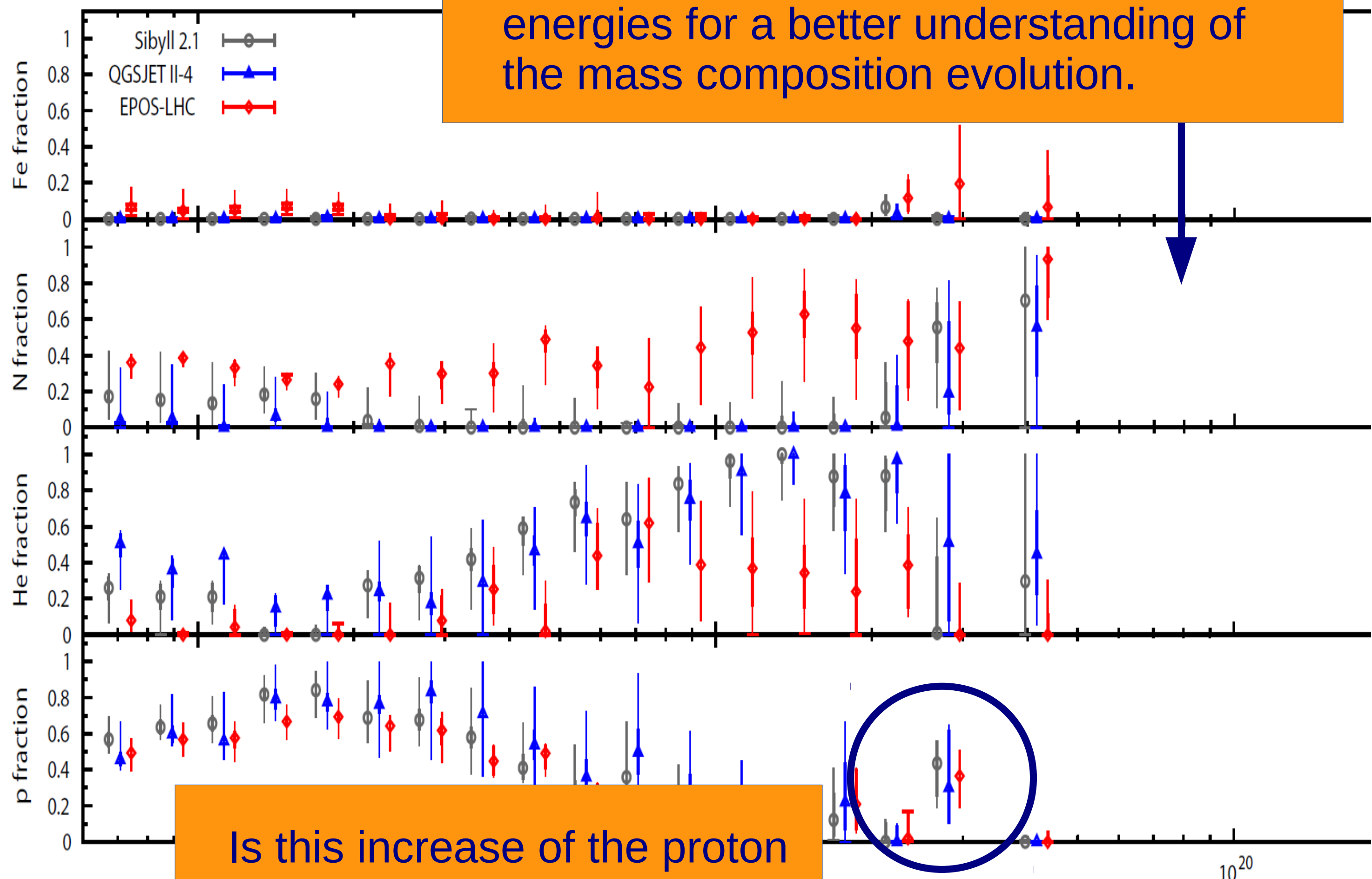
Mass Composition (Xmax Shape)





Mass Composition (Xmax Shape)



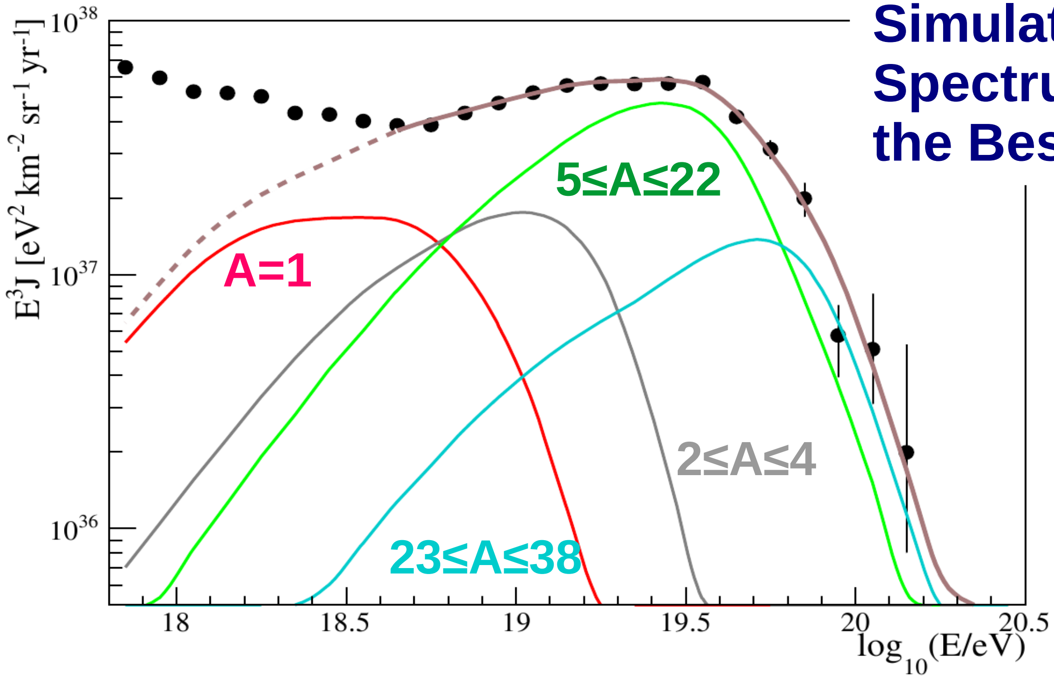


We need more statistics at the highest energies for a better understanding of the mass composition evolution.

Is this increase of the proton fraction real, or related to statistical fluctuations?

Combined Fit: Spectrum and Composition

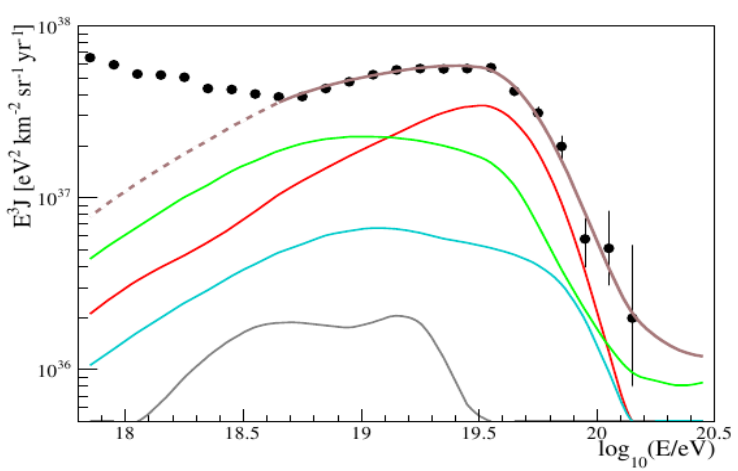
Attempt to fit Pierre Auger data on spectrum and composition to a simple astrophysical scenario: seven free parameters → J_0, γ, R_{cut}, p_H, p_{He}, p_N, p_{Si} → $p_{Fe} = 1 - \sum p_i$



Simulated Energy Spectrum obtained with the Best Fit Parameters

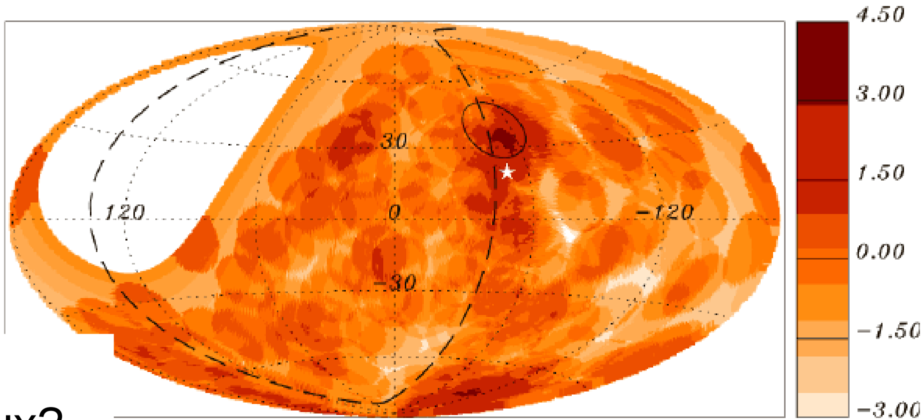
Errors on the elemental fractions are very large
→ different combinations of elemental spectra can give rise to similar observed spectra

IMPORTANT to constrain mass composition



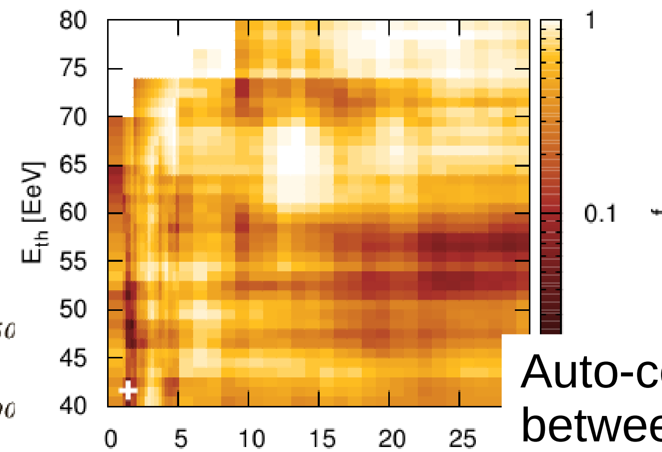
Arrival Directions: Small Scale Anisotropy

Blind search



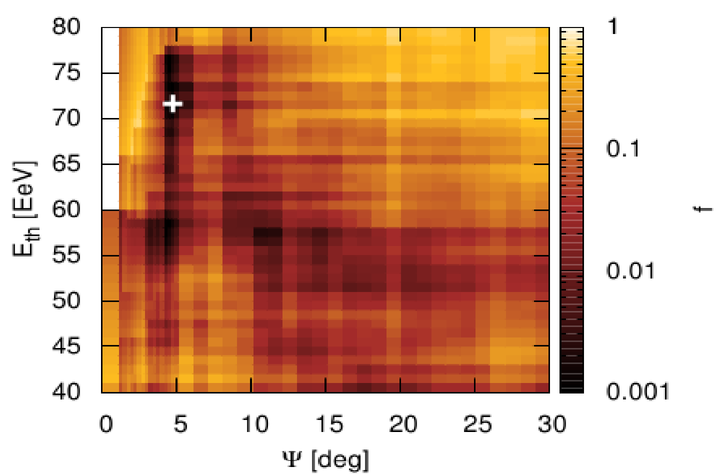
Localized excess flux?

Auto-correlation

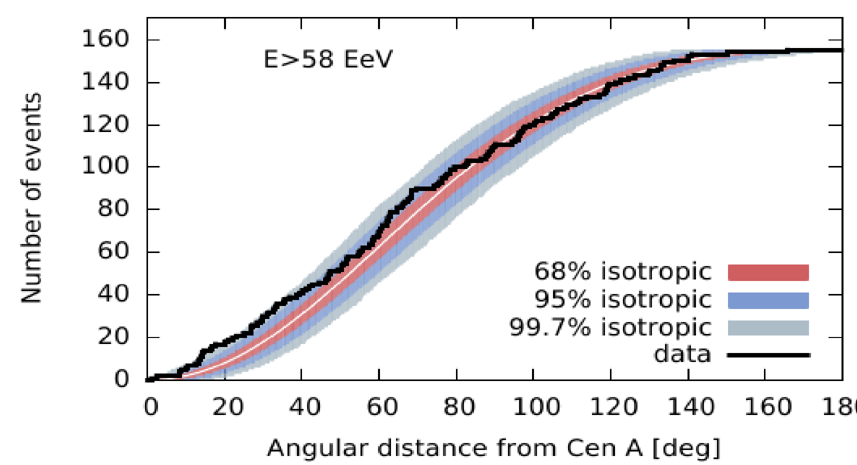


Auto-correlation between events?

Radio galaxies with jets

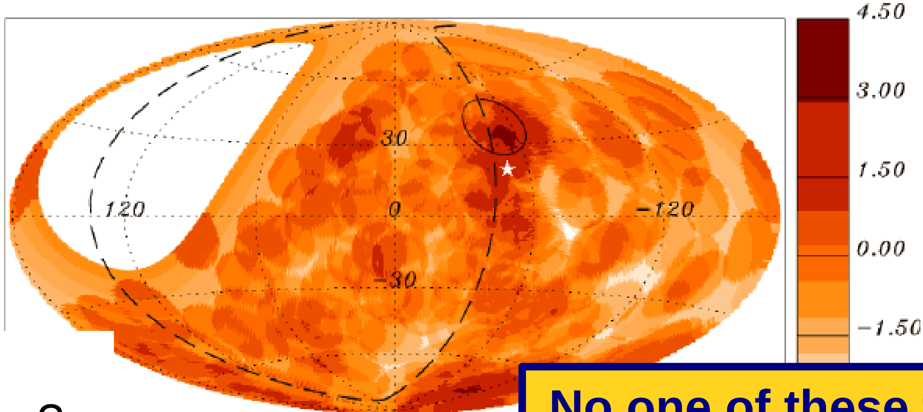


Cen A region

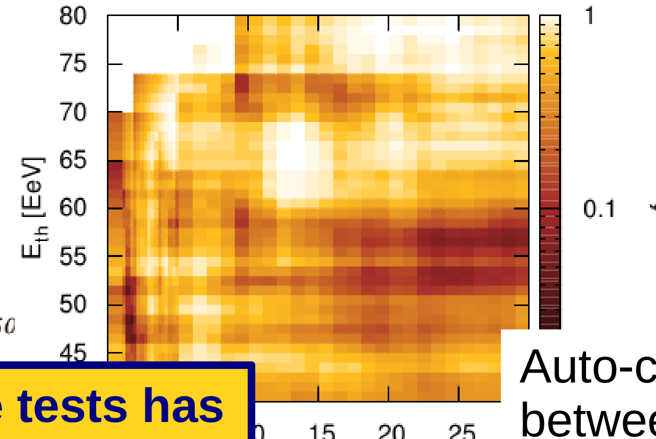


Arrival Directions: Small Scale Anisotropy

Blind search



Auto-correlation

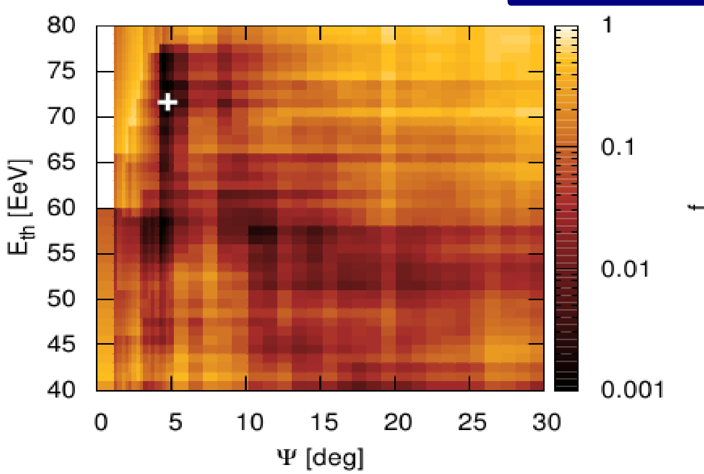


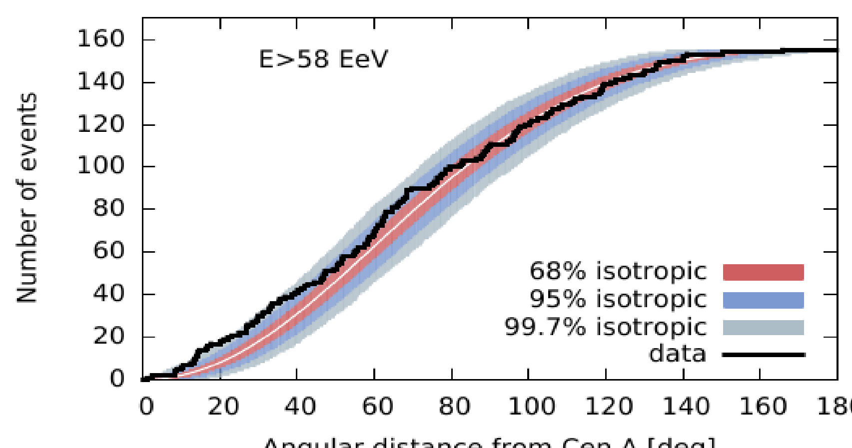
Localized excess flux?

Auto-correlation between events?

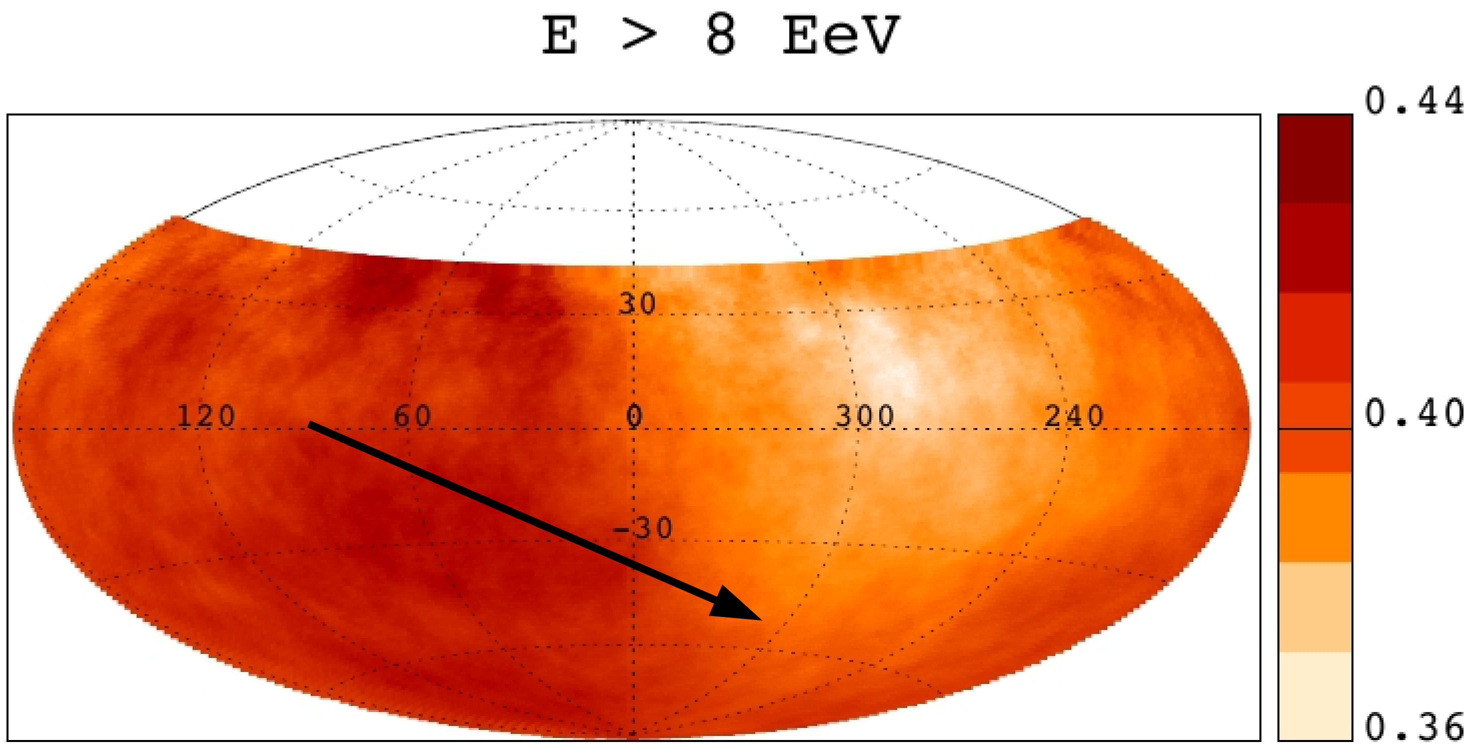
No one of these tests has shown a significative excess

Radio galaxies with … region





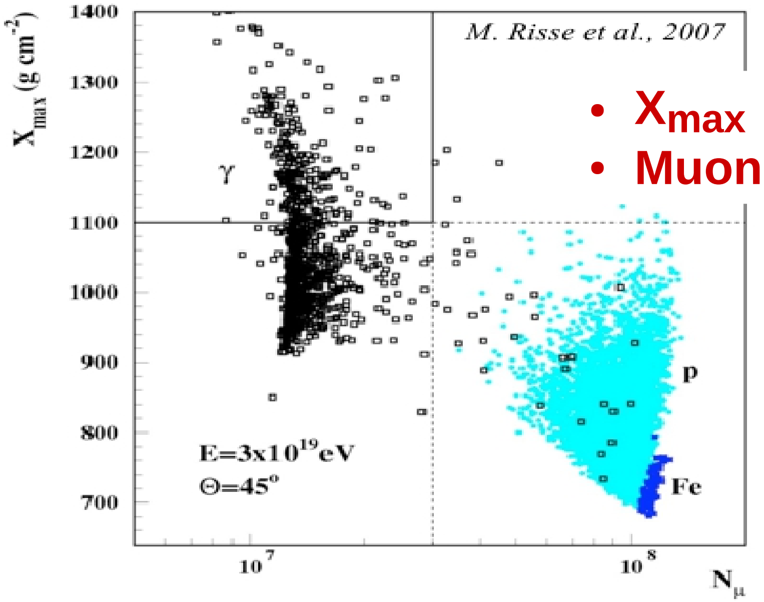
Large Scale Anisotropy



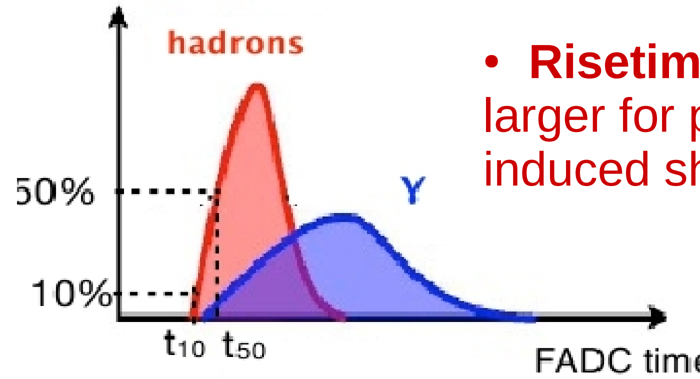
Dipole Searches:
Sky map in equatorial coordinates of flux, in $km^{-2} yr^{-1} sr^{-1}$ units, smoothed in angular windows of 45° radius, for observed events with energies E >8 EeV.

A largest departure from isotropy with a (4 +- 1)% amplitude in the first harmonic in RA was observed.
The total dipole amplitude for the higher energy bin is 0.073 ± 0.015 pointing to $(\alpha, \delta) = (95° \pm 13°, -39° \pm 13°)$.

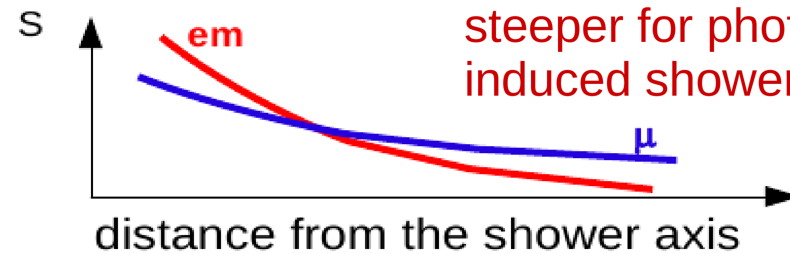
Photon Search



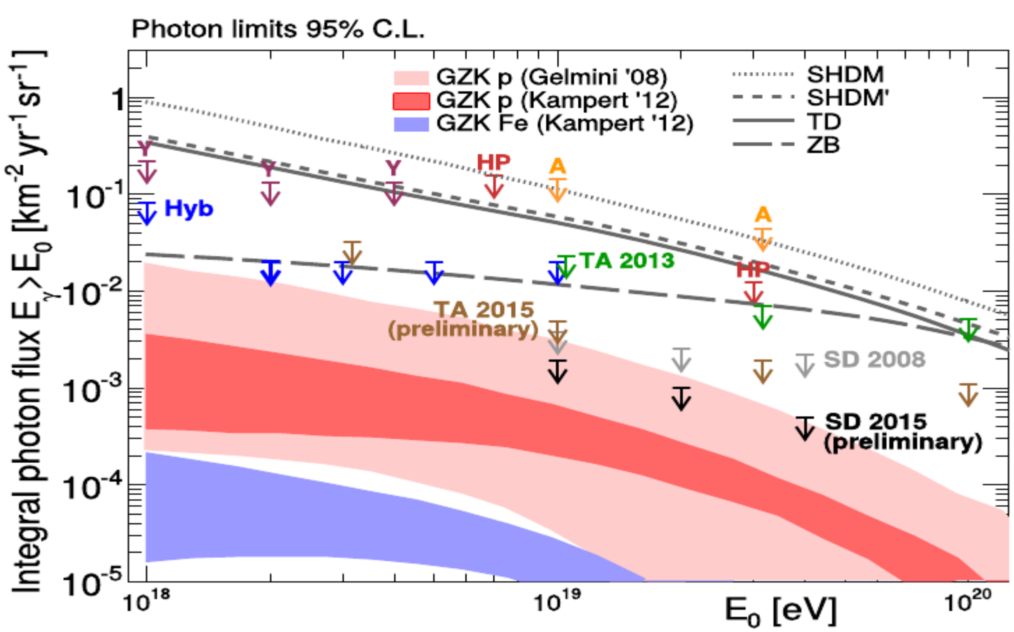
- X_{max}
- **Muon Content**



- **Risetime:** t50-t10, larger for photon-induced showers

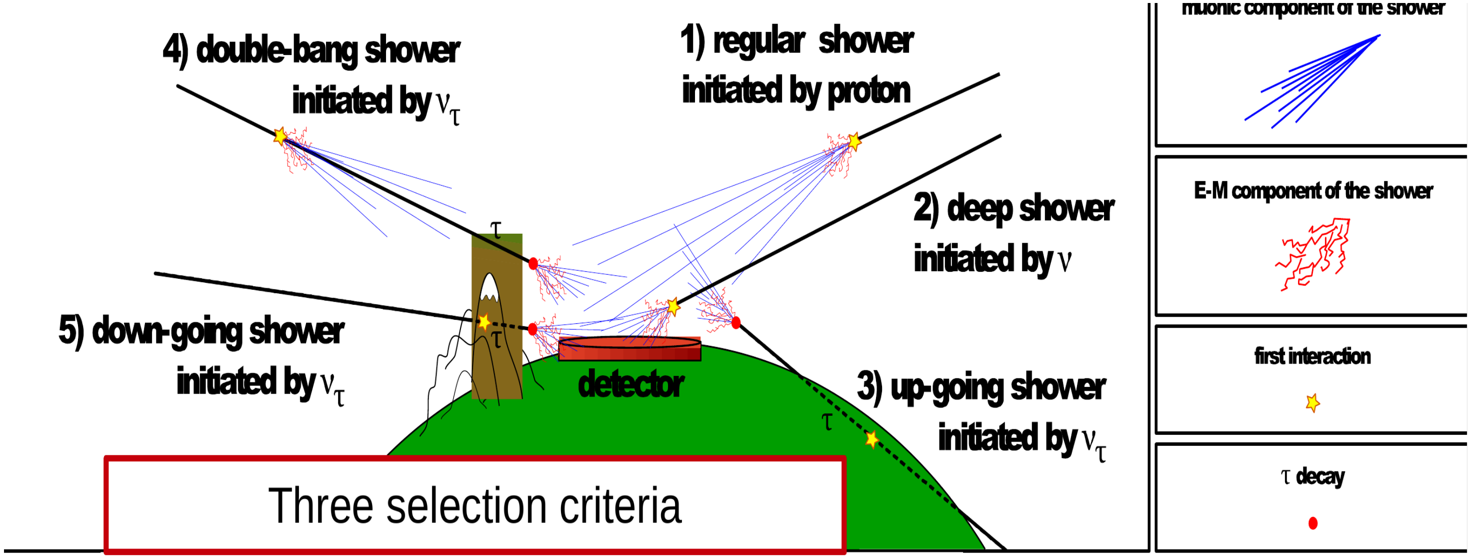


- **LDF of total signal:** steeper for photon-induced showers



- No photon events observed;
- "Top down" models strongly disfavoured.

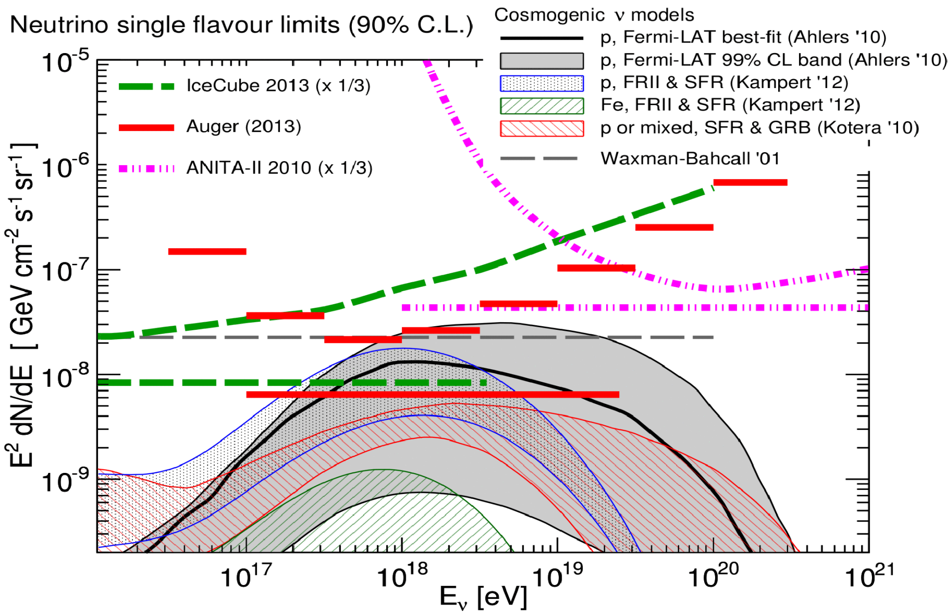
Neutrino Search



Dow-going low angle:
(2, 4) - DGL (60°-75°)

Dow-going high angle:
(2, 4, 5) - DGH (75°-90°

Earth-Skimming:
(3) – ES (90°-95°)



NO EVENTS OBSERVED

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

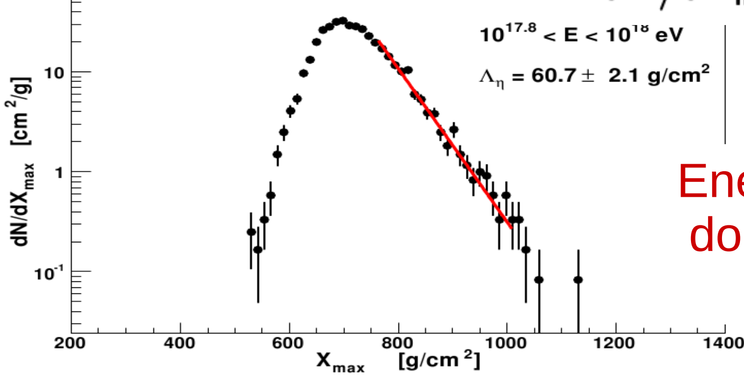
90% CL in the energy range 0.1-25 EeV

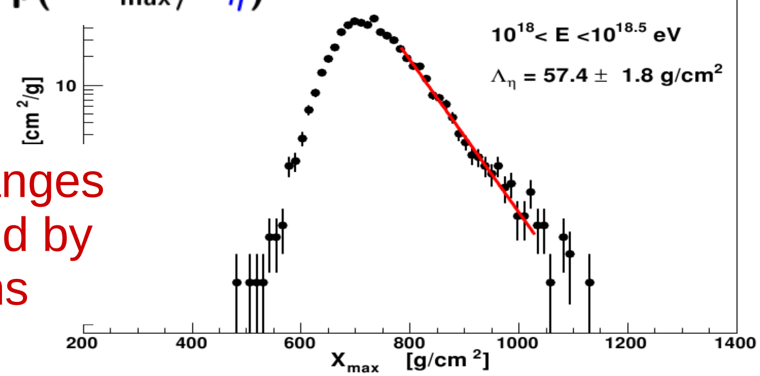
Auger limit constrains models that assume a pure primary proton composition injected at the sources and strong evolution of the sources.

Proton-Air Cross Section

The tail of the deepest shower Xmax distributions is related to the first interaction points, and consequently to the proton-air cross section.

$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

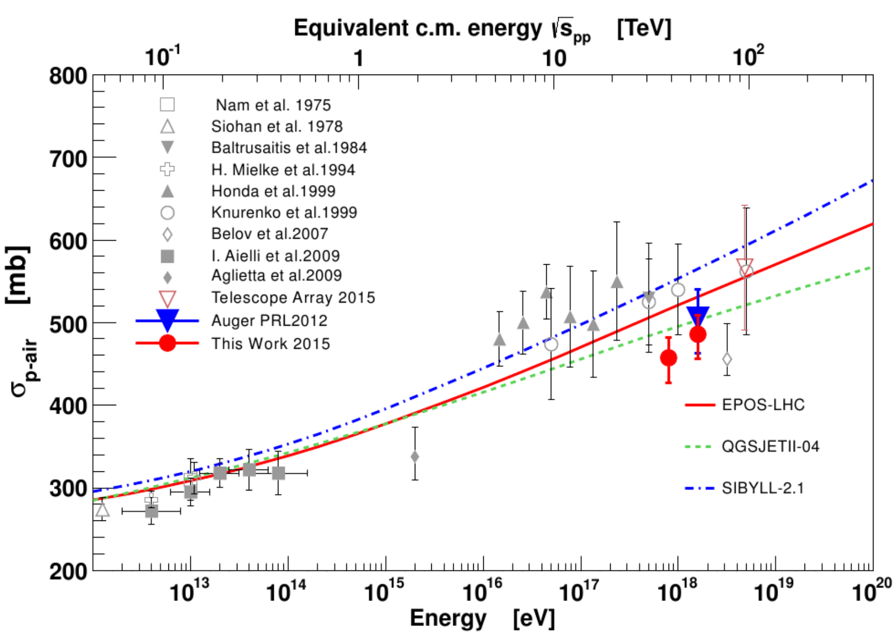


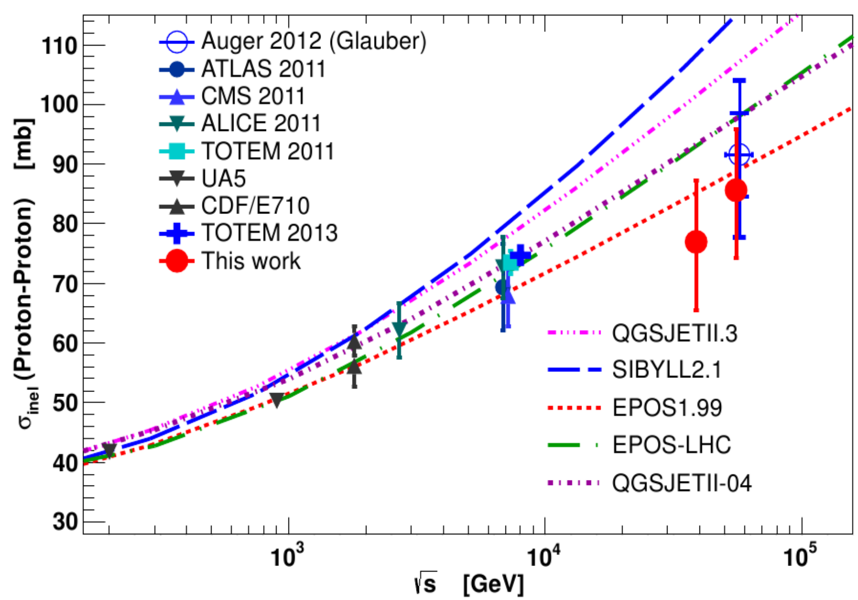


Energy ranges dominated by protons

$10^{17.8}$ – 10^{18} eV

10^{18} – $10^{18.5}$ eV

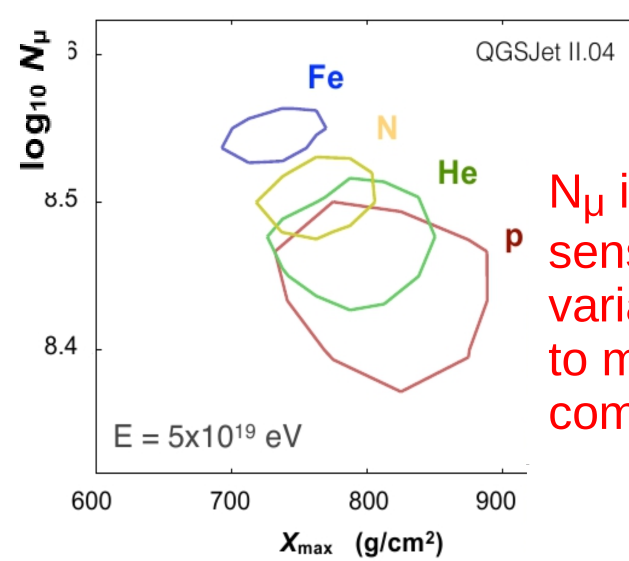




AugerPrime (up to 2025): Motivations

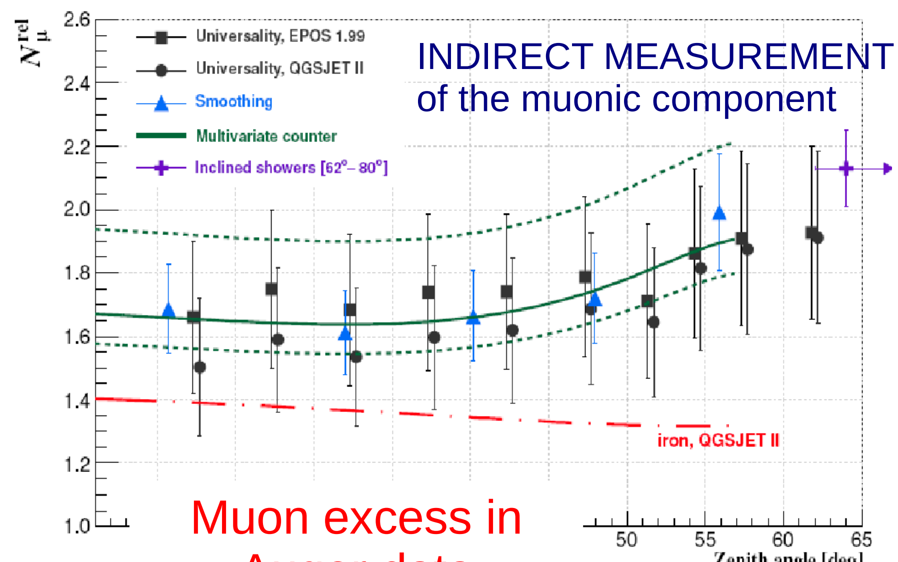
1) The mass composition and the origin of flux suppression at the highest energies;

2) Proton contribution in the flux suppression region (E> 5x 10^{19} eV);



N_μ is a very sensible variable to mass composition

3) Fundamental particle physics at energies beyond reach of man-made accelerators.

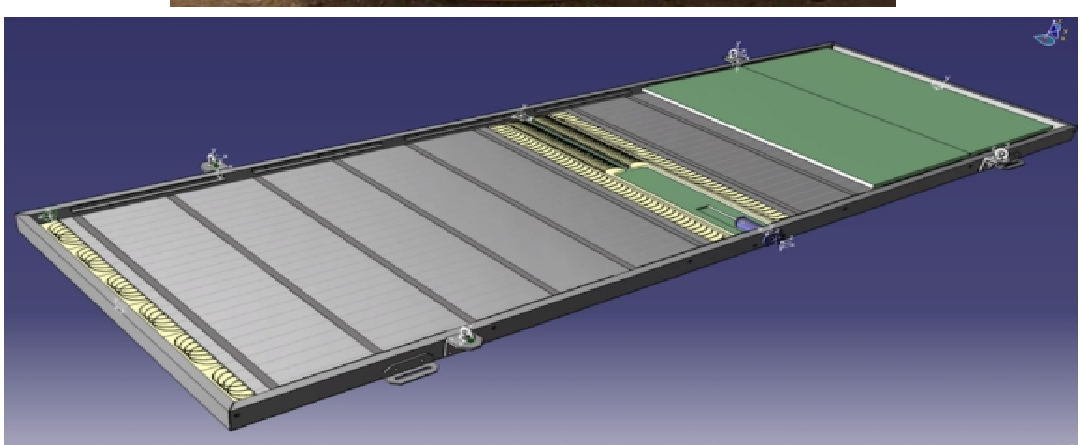


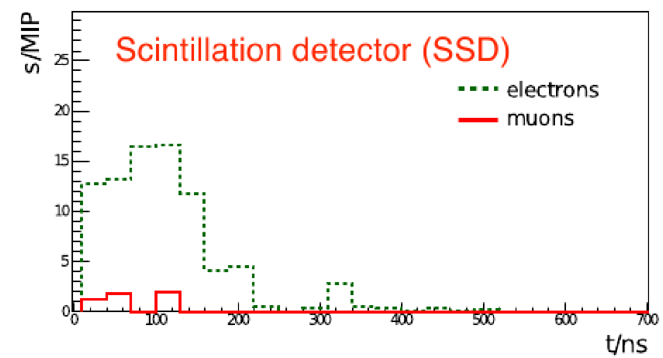
INDIRECT MEASUREMENT of the muonic component

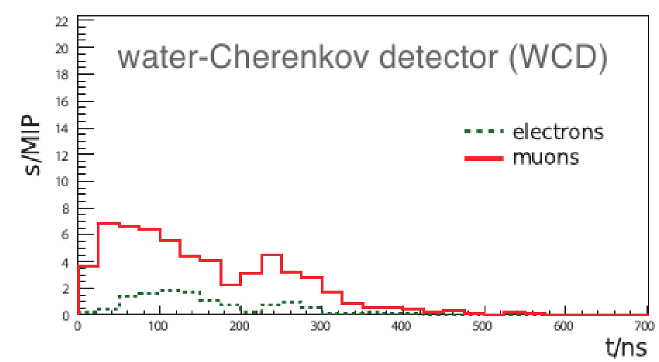
Muon excess in Auger data

AugerPrime: Strategy

- Faster and more powerful electronics, small PMT in the tank to increase the dynamic range;
- Scintillator (SSD) above the WCD to measure the mass composition with 100% duty cycle;
- Underground Muon Detector with AMIGA to have a direct muon measurement;
- Extended FD operation to periods with higher night sky background to have more statistics.







$$\boxed{S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}}$$

Conclusions

- Clear observation of spectral features;
- No clear picture about mass composition above ~ 40 EeV;
- Strong photon and neutrino limits;
- p-air and p-p cross section at $\sqrt{s}$ = 57 TeV;
- No significative excess observed in studies of small scale anistropy;
- Large scale dipole.

AugerPrime will allow a study of mass composition above 5 x 10^{19} eV and address:

- Origin of the flux suppression (GZK energy loss Vs maximum energy of sources);
- Proton contribution of more than 10% above 5 x 1019 eV?
- particle astronomy, GZK γ and ν fluxes;
- New particle physics beyond the reach of LHC?

First SSD Prototypes Installed

Thank you for your attention

BackUp

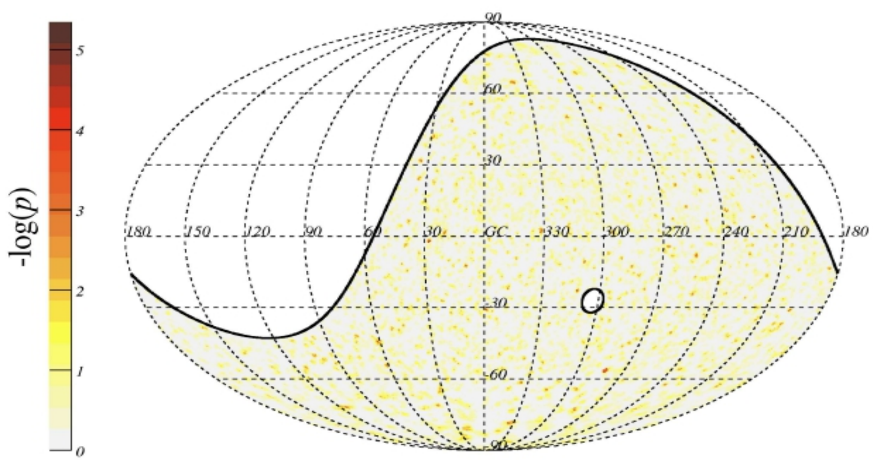
Energy Scale

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total Fluorescence yield	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total Atmosphere	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total FD calibration	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total FD profile rec.	**6.5% ÷5.6%**
Invisible energy	**3%÷1.5%**
Stat. error of the SD calib. fit	**0.7%÷1.8%**
Stability of the energy scale	**5%**
Total	**14%**

Search for Point Sources of EeV Photons

The present study targets **all exposed celestial directions**. It is a "blind" search to see if there might be an indication of a photon flux from any direction.

Celestial Map of -log(p)

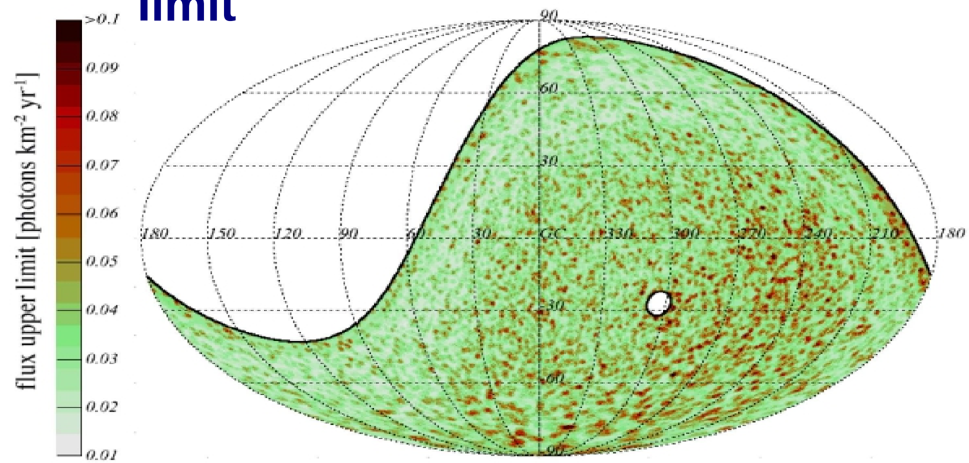


p = Poisson probability of having a number of observed events ≥ expected bkg

$p_{min} = 4.5 \times 10^{-6} \rightarrow p_{chance} = 36\%$

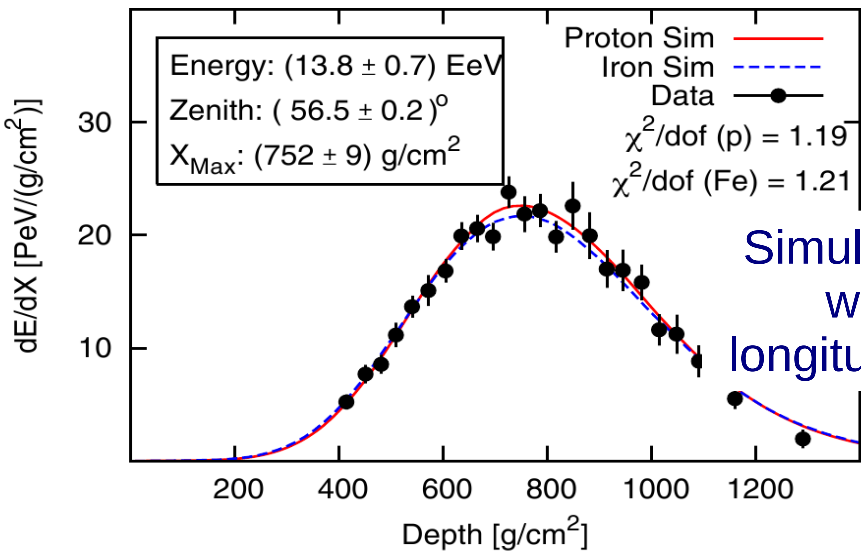
NO SIGNIFICATIVE EXCESS

Celestial Map of photon flux upper limit

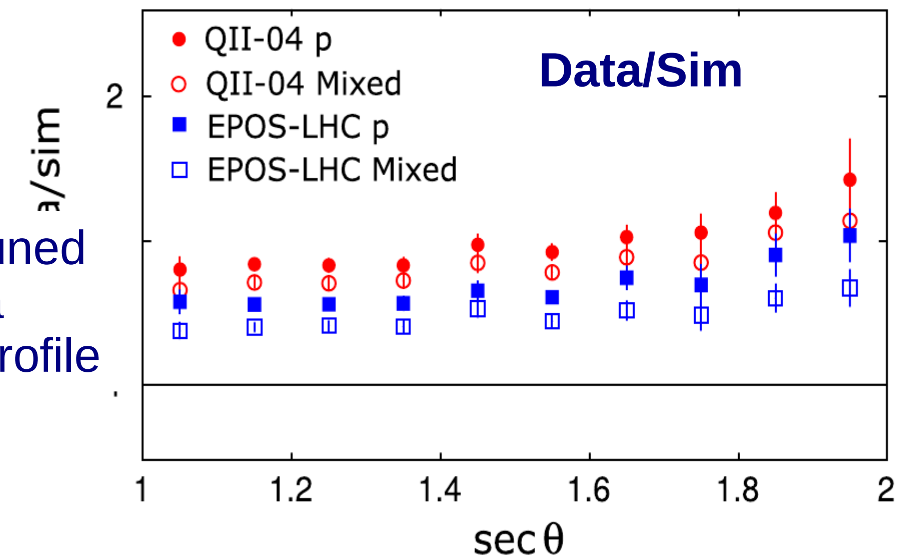


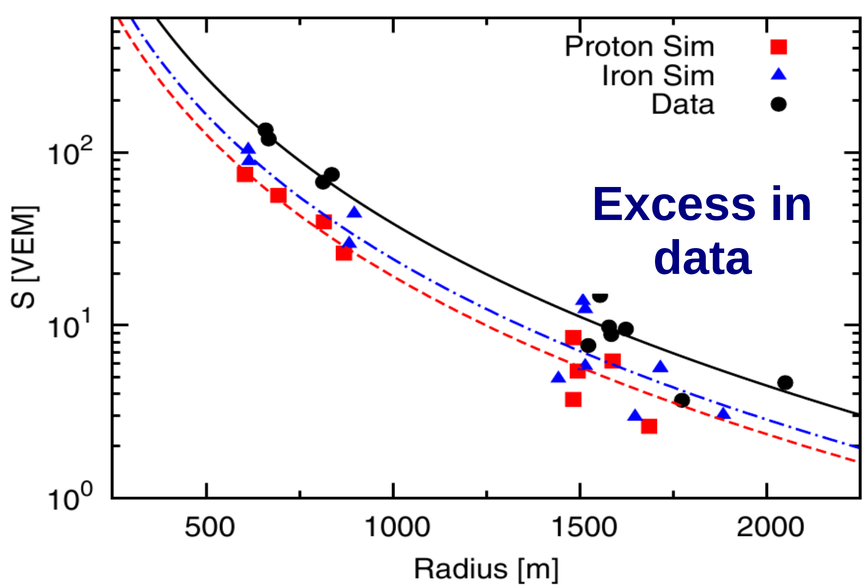
mean value = 0.035 photons km^{-2} yr^{-1}
(0.14 photons km^{-2} yr^{-1})
energy flux = 0.06 eV cm^{-2} s^{-1}
(0.25 eV cm^{-2} s^{-1})

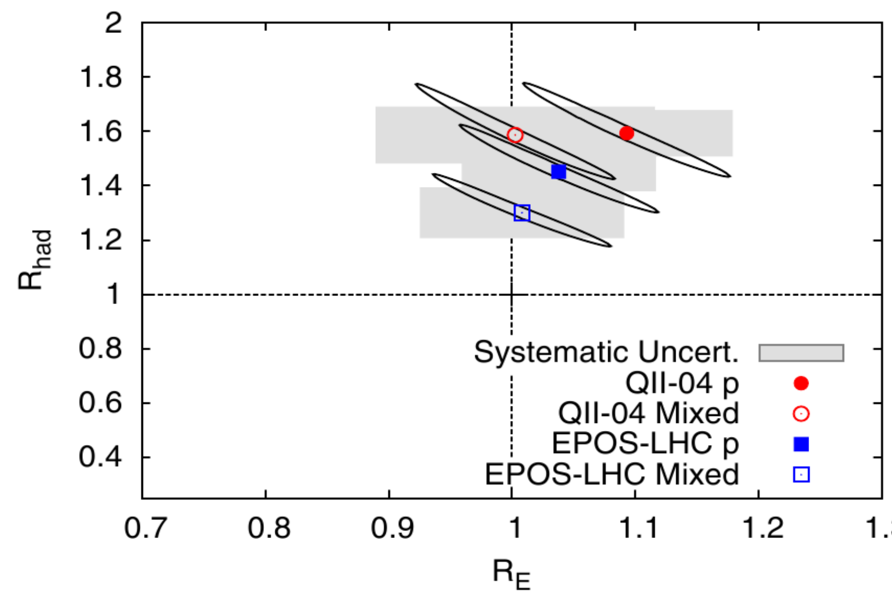
Muon Excess in Auger Data



Simulation tuned with data longitudinal profile

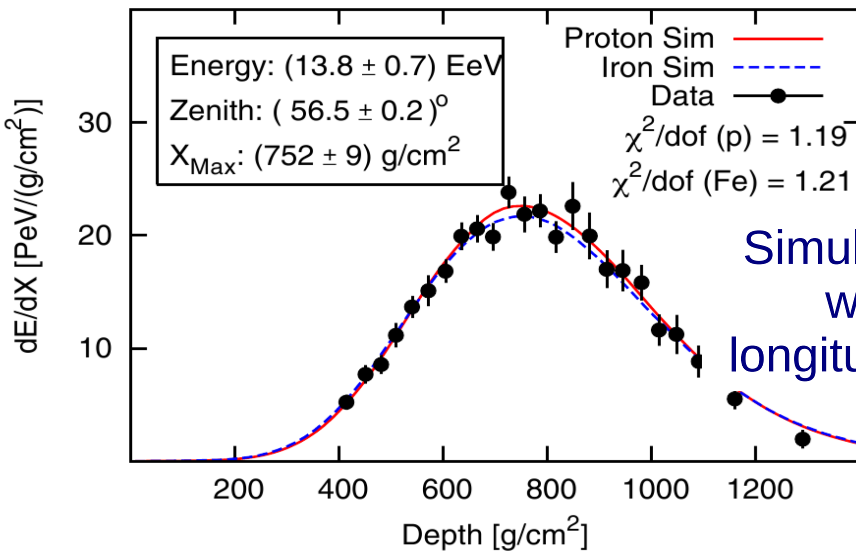




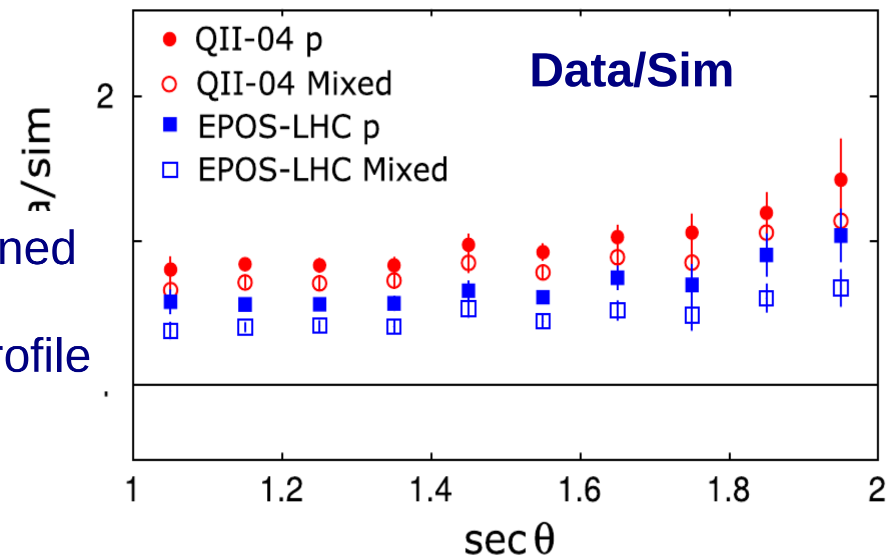


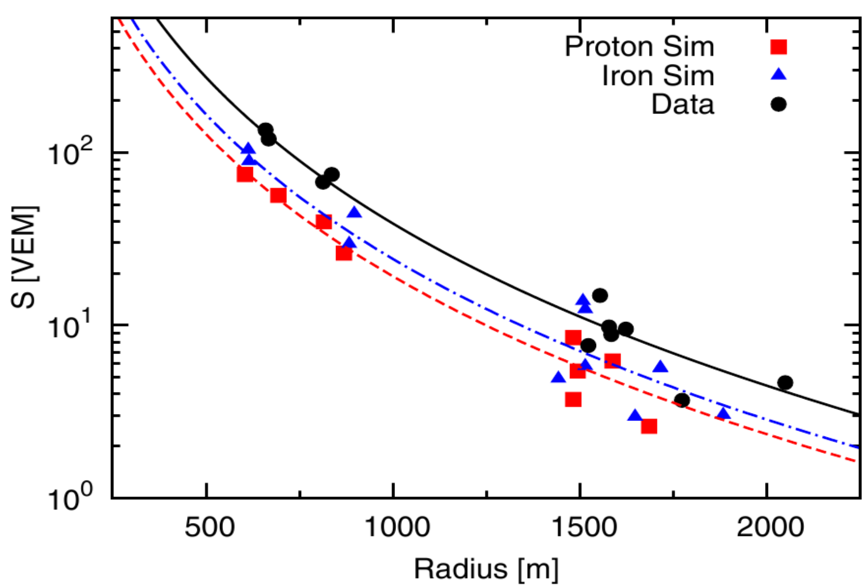
$$S_{\mathrm{resc}}(R_E, R_{\mathrm{had}})_{i,j} \equiv R_E S_{\mathrm{EM},i,j} + R_{\mathrm{had}} R_E^{\alpha} S_{\mathrm{had},i,j}$$

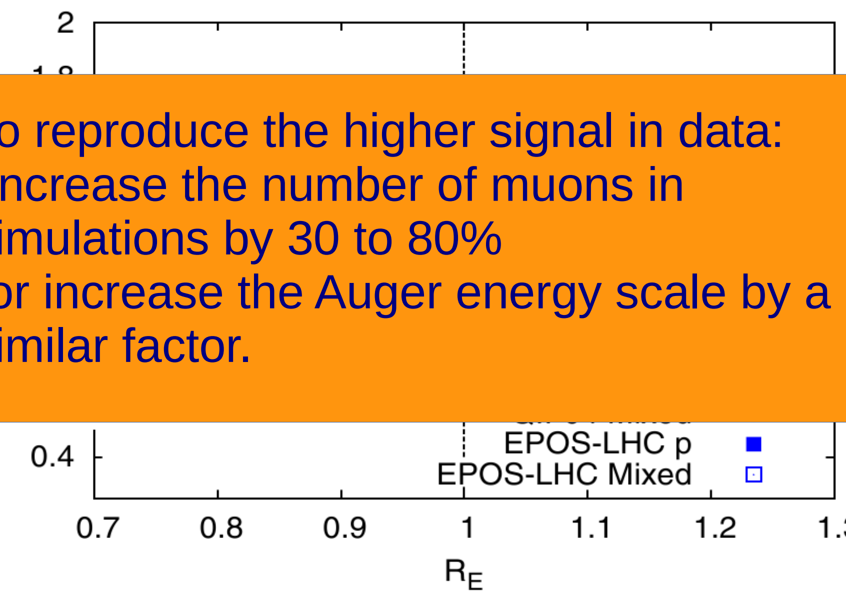
Muon Excess in Auger Data



Simulation tuned with data longitudinal profile



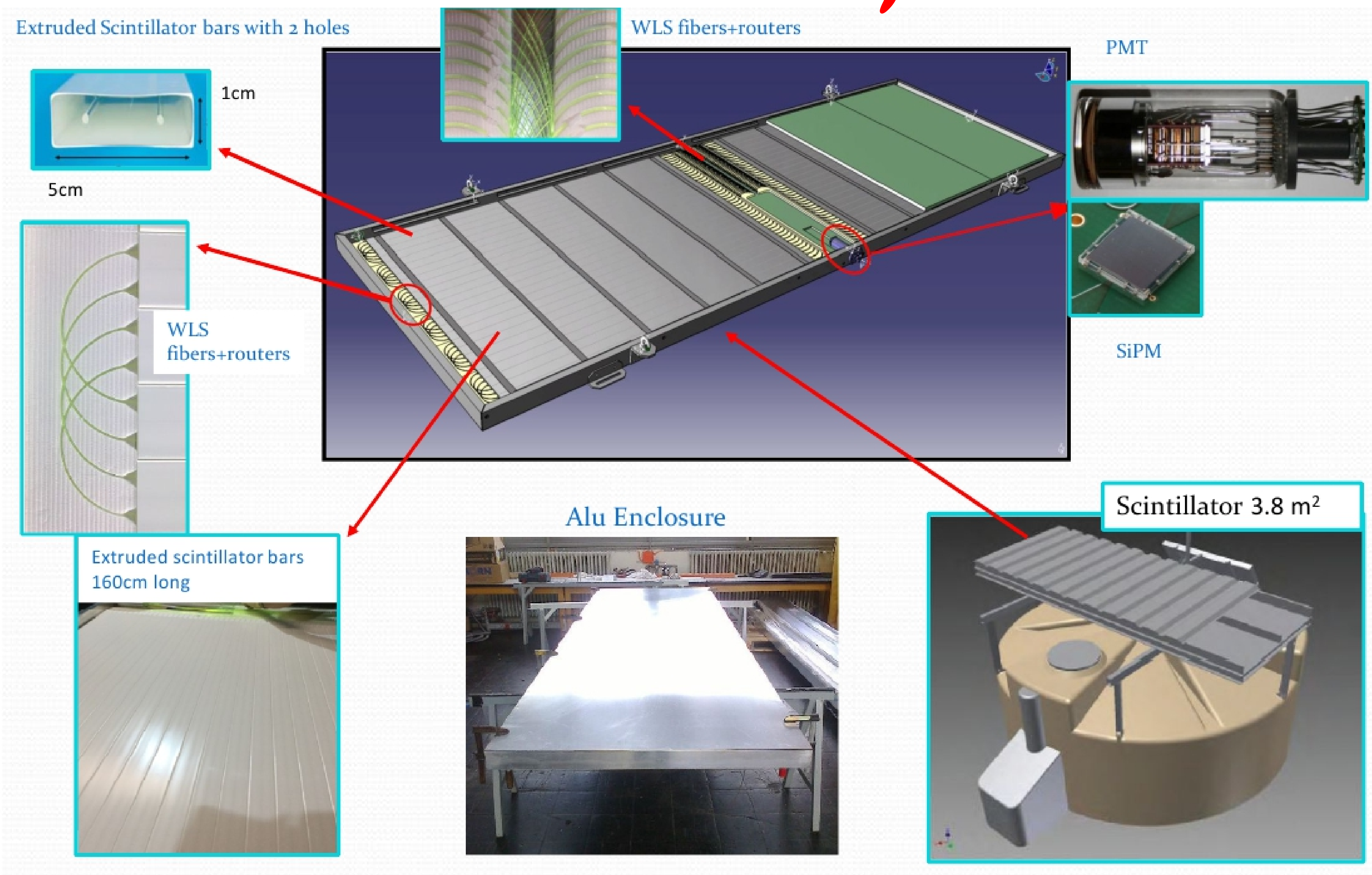




To reproduce the higher signal in data:
- increase the number of muons in simulations by 30 to 80%
- or increase the Auger energy scale by a similar factor.

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

SSD (Surface Scintillator Detector)



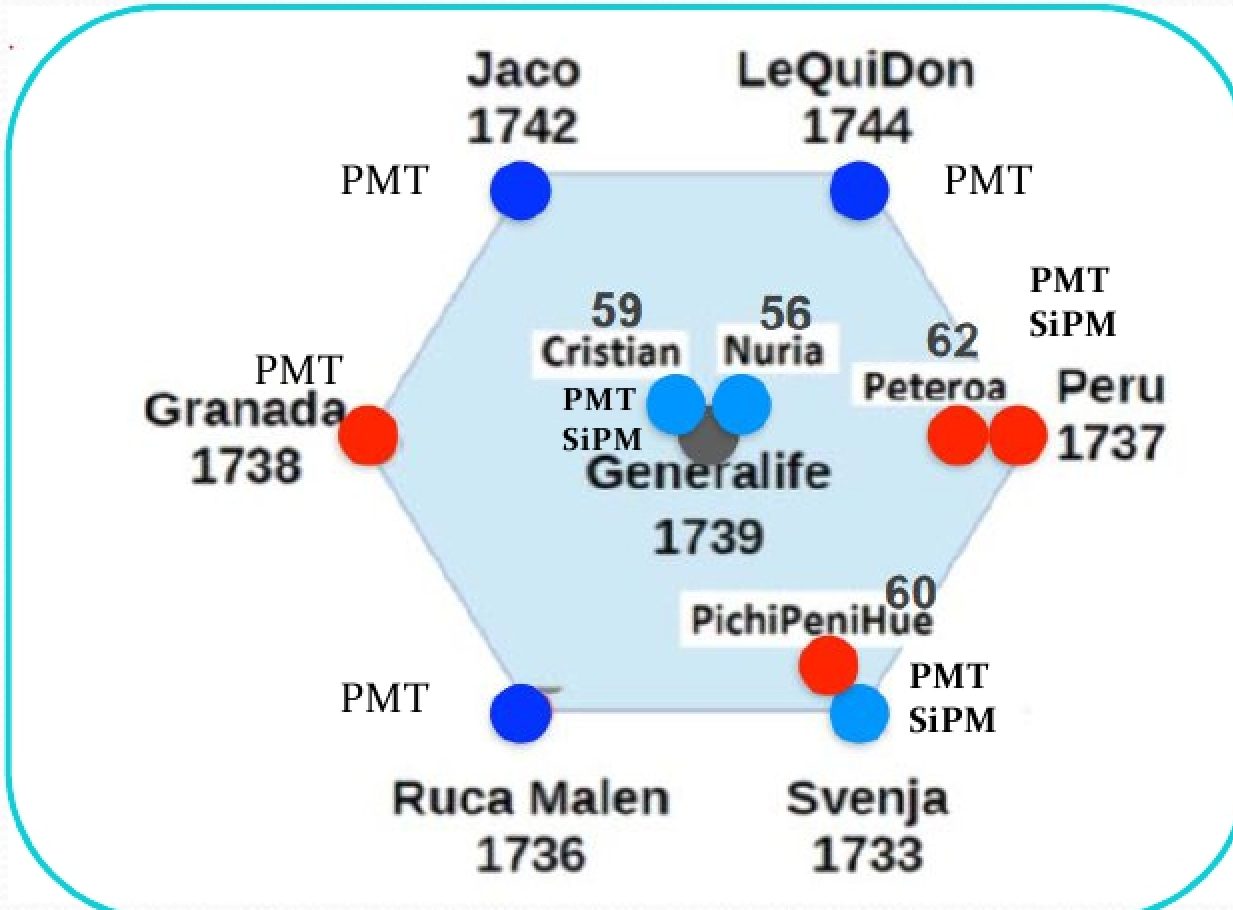
SSD: The Engineering Array

12 SSD EA Module ready!
On their way to PAO.

Located in infill array

Infill — PMT, PMT

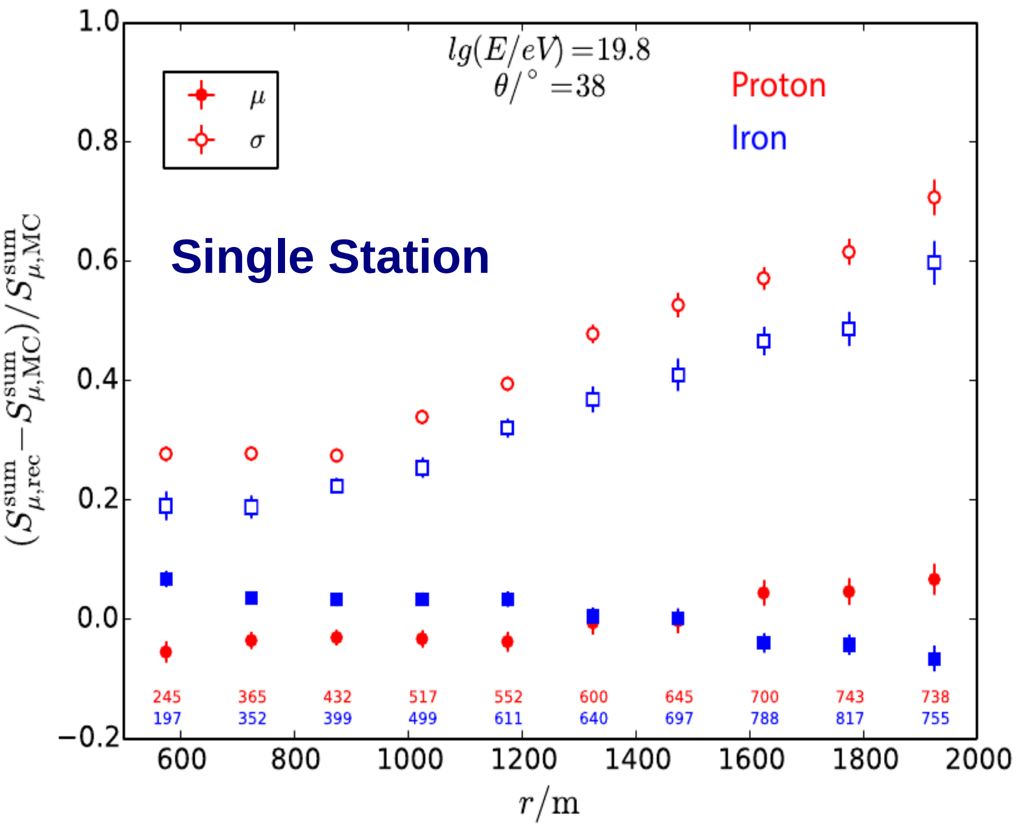
Located in standard array

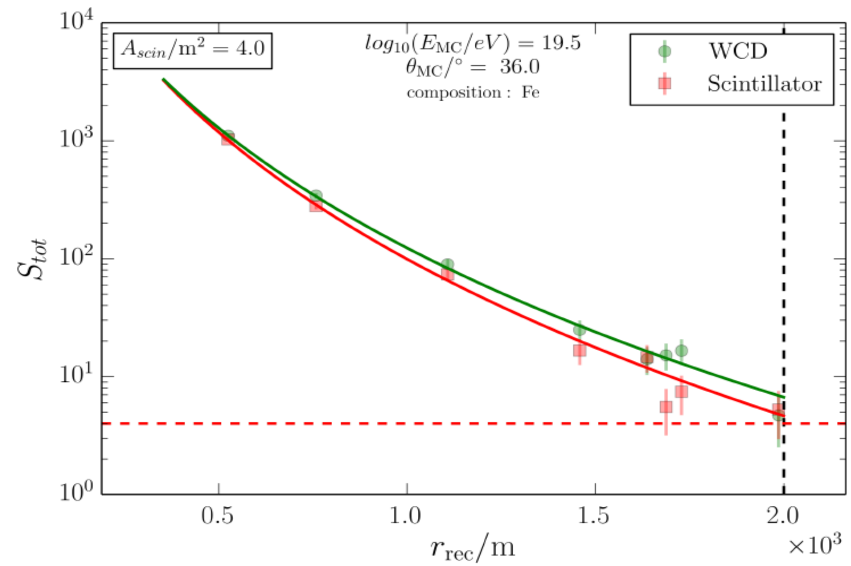


Twin stations will allow to verify particle number resolution

AugerPrime: Perspectives

$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$





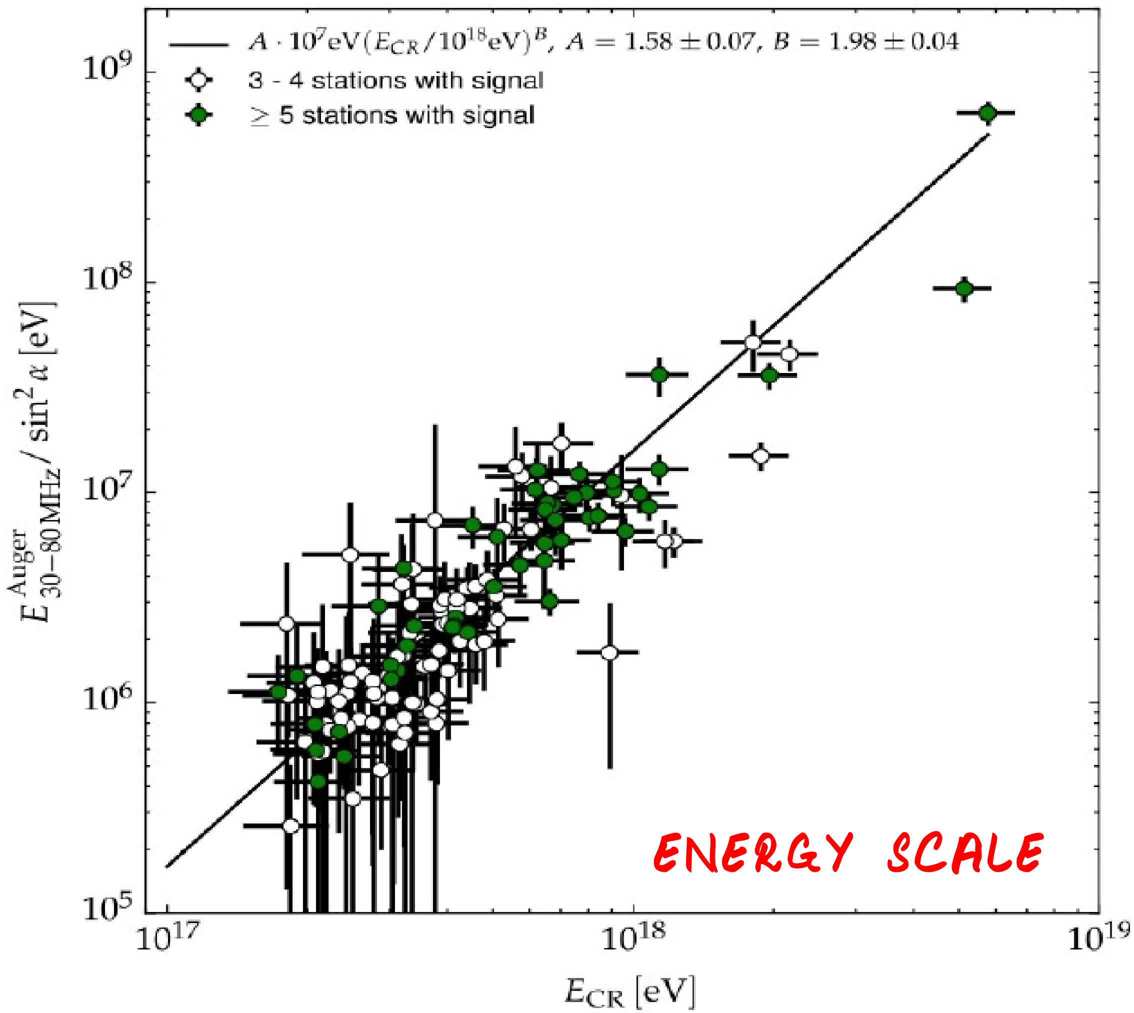
Resolution at $10^{19.8}$ eV

$$\left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\mathrm{proton}} \approx 22\% \qquad \left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\mathrm{iron}} \approx 14\%$$

$$\boxed{f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma(S_{\mathrm{Fe}})^2 + \sigma(S_{\mathrm{p}})^2}} \sim 1.5}$$

AERA

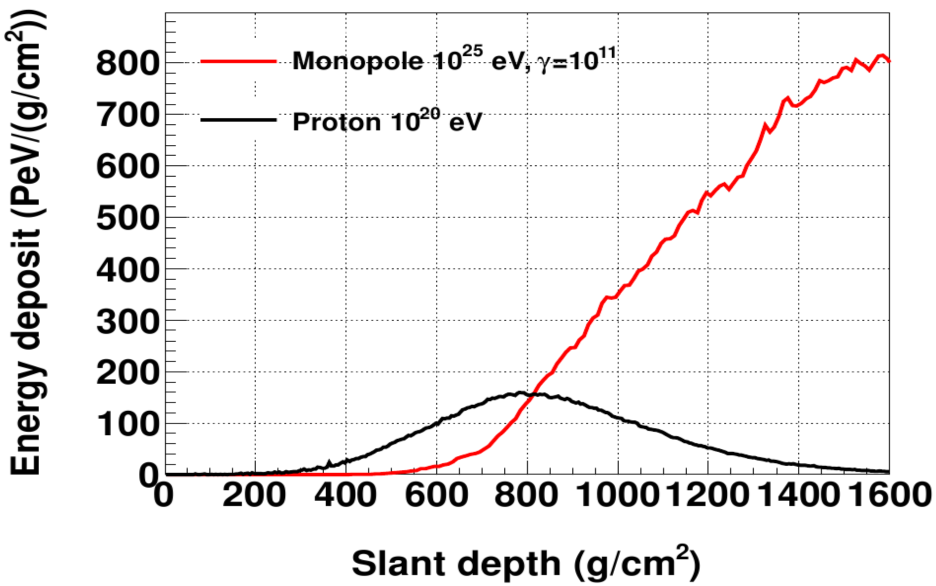
- More than 150 antennas that cover an aerea of about 17 km^2.
- They are used to detect radio emission from extensive air showers in the 30 - 80 MHz frequency band.
- Duty cycle close to 100% (problems only during thunderstorms).
- Intercalibration among AMIGA-HEAT-standard FD-AERA.



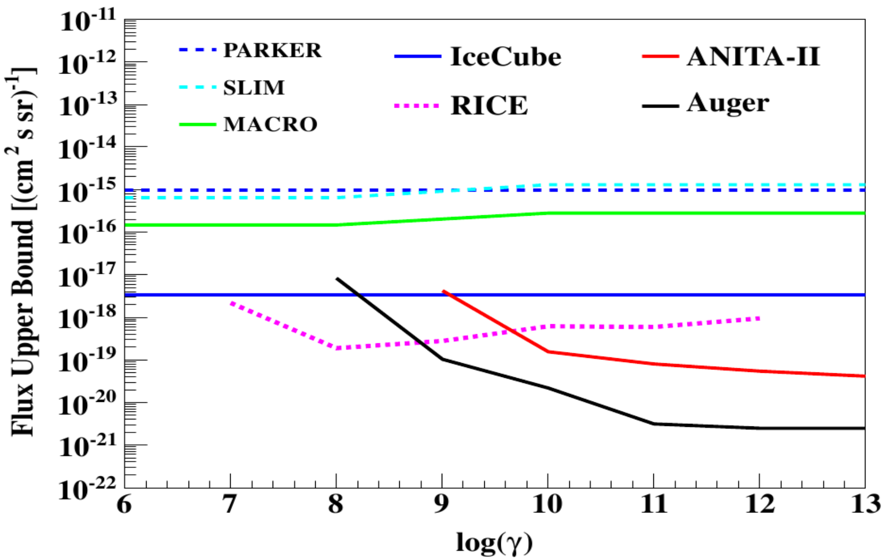
5500 showers measured in coincidence with SD (300 with FD)

MAGNETIC MONOPOLES

Intermediate-mass monopoles (IMMs, M ~ $10^{11} - 10^{20}$ eV/c^2) .



Much larger energy deposit and deeper development.



The best limit for $\gamma \geq 10^9$, with a factor of ten improvement for $\gamma \geq 10^{9.5}$.