EXPLORING COSMIC RAYS AT THE HIGHEST-ENERGY FRONTIER WITH THE PIERRE AUGER OBSERVATORY

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The Pierre Auger Observatory

The main goals: to study cosmic-ray particles at energies above 10^{18} eV, look for possible sources, find out primary composition.

Main results: ankle and cut-off in spectrum clearly measured, anisotropy studied in large and small scales, composition in primary nuclei studied, search for neutrinos, photons, and neutrons performed.

Auger challenges for beyond 2015:

Origin of the cut-off: GZK or exhaustion of sources,
Proton fraction at highest energies,
Constrain hadronic interaction models/new physics,
Improve knowledge of composition with upgraded detector.

The Pierre Auger Observatory

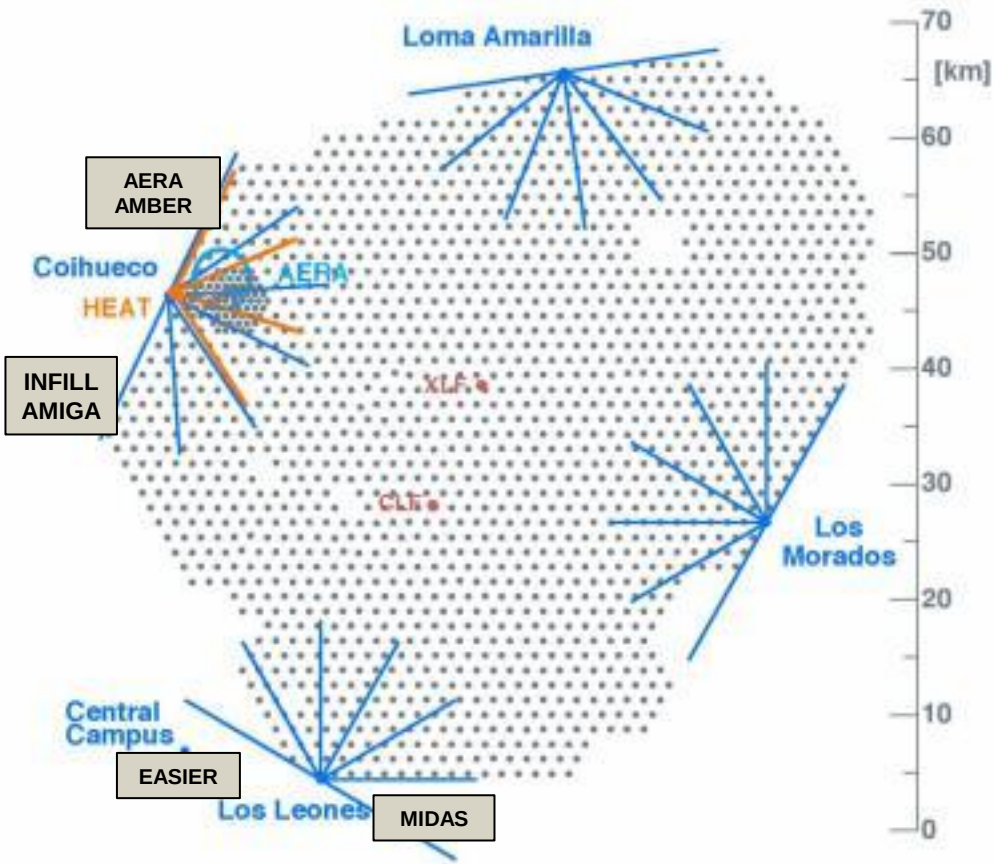
Location:
Malargüe, Mendoza, Argentina

Surface Detector (SD):
Total area 3000 km^2
1660 water Cherenkov detectors @ 1500 m
71 water Cherenkov detectors @ 750 m spacing (Infill) (~30 km^2)

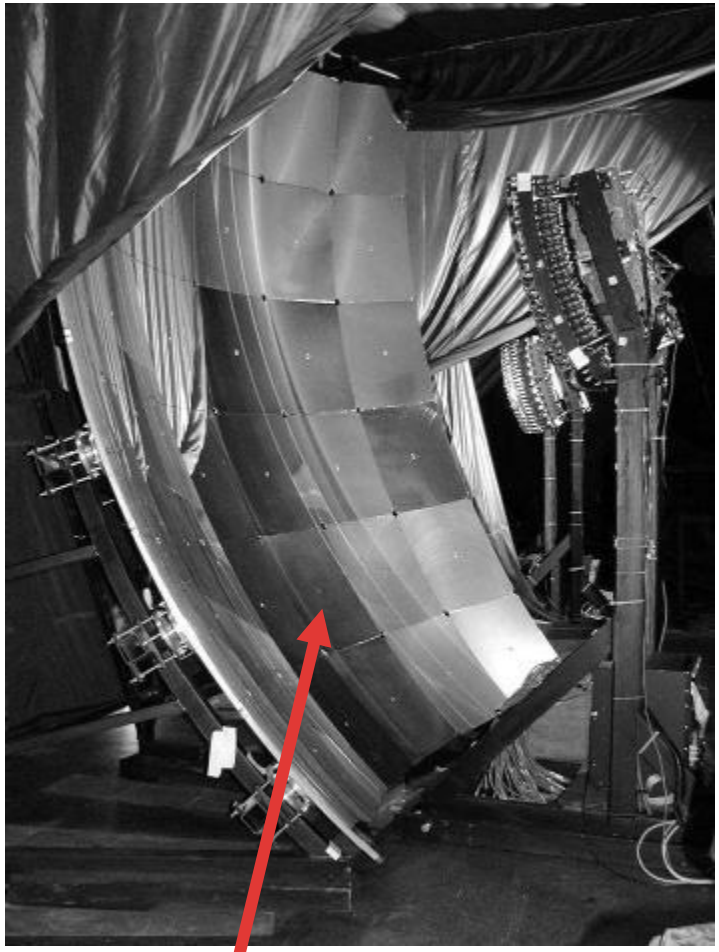
Fluorescence Detector (FD)
24+3 fluorescence telescopes at four locations

Muon Detectors
61 detectors along the Infill

AERA radio antennas (MHz)
124 in the Infill area
R&S GHz antennas
AMBER/MIDAS/EASIER

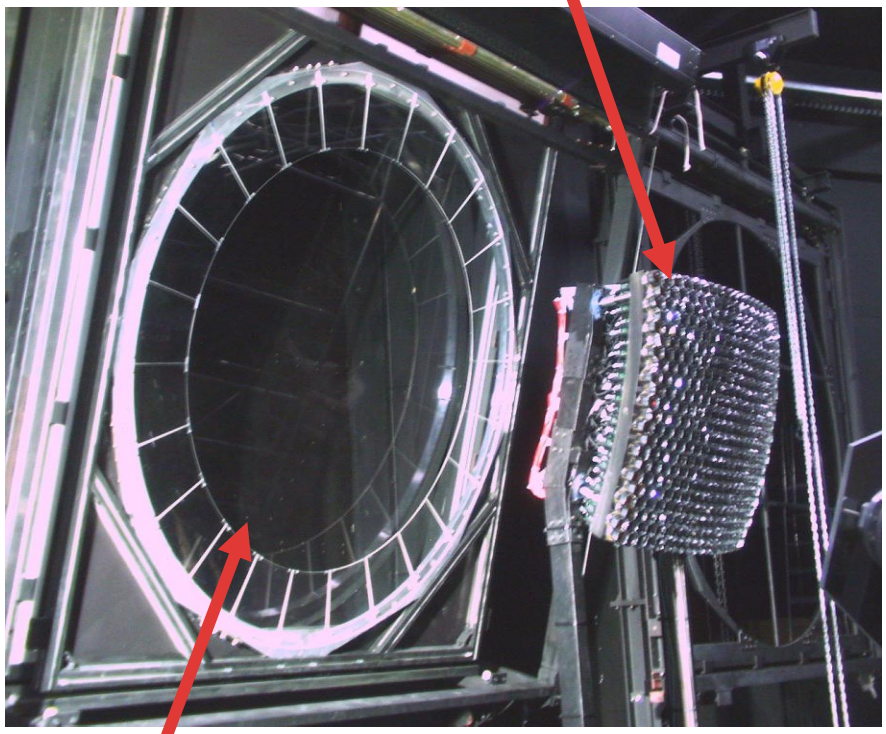


One of the fluorescence telescopes (FD)



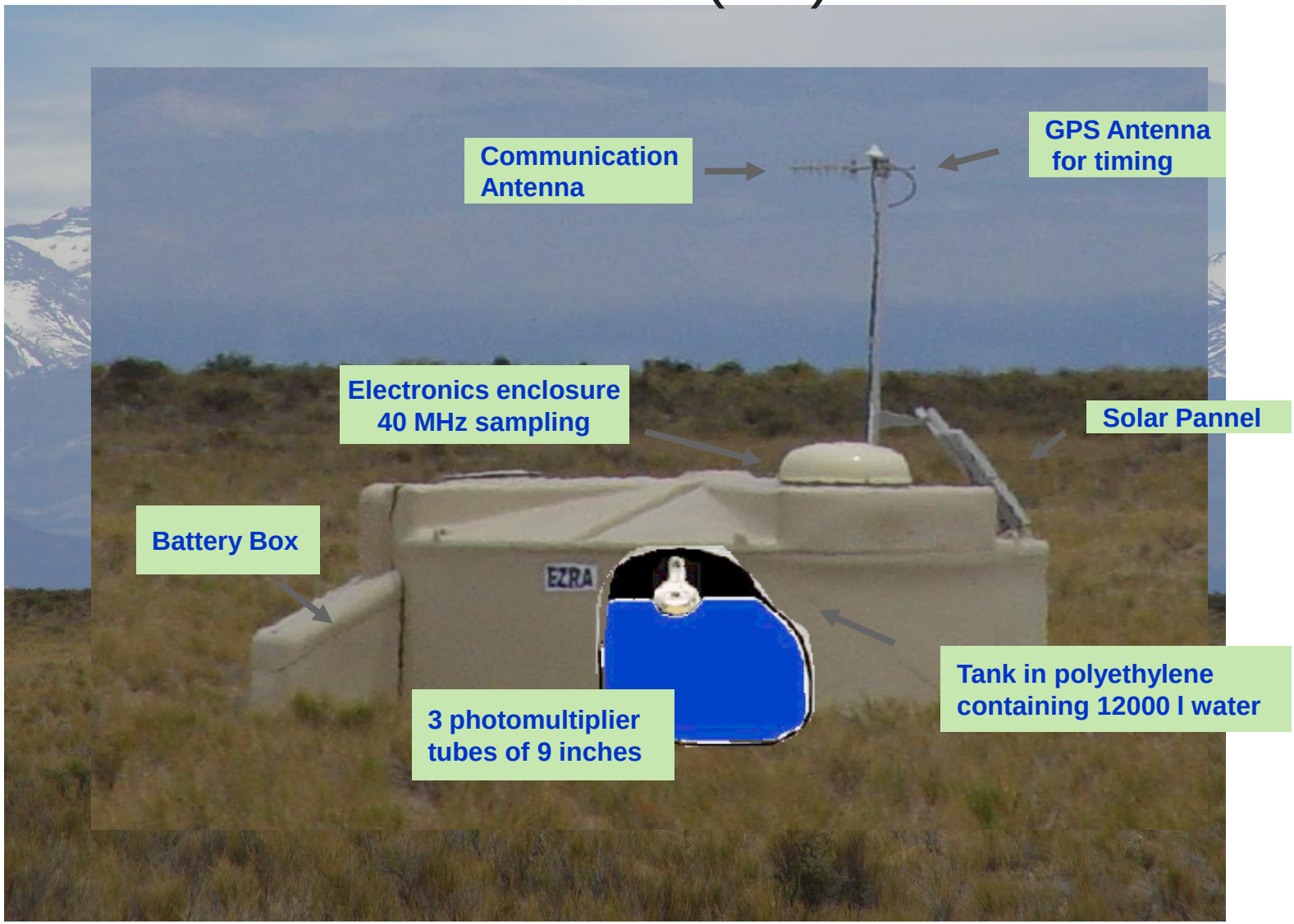
mirror 3 m^2

440 pixel camera
10 MHz sampling

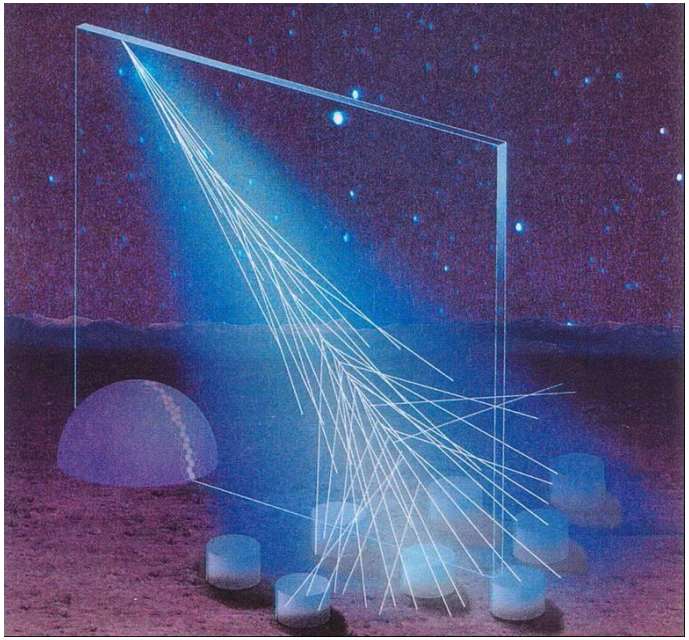


aperture, corrector ring and filter

One of the surface detectors (SD)



Hybrid detection:



Fluorescence Detector:

- **Almost calorimetric energy measurement**
- **13 % duty cycle**
- **Complex acceptance calculation**

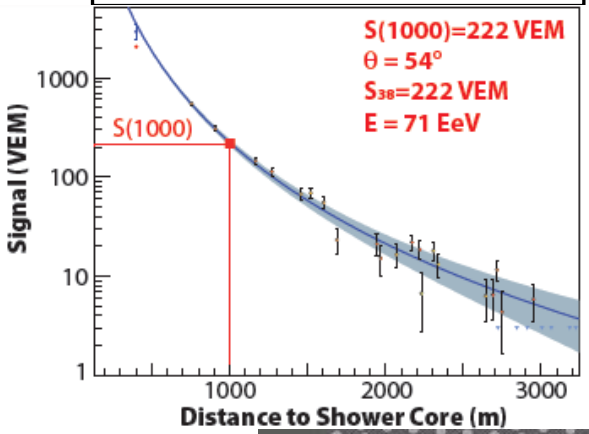
Surface Detector Array:

- **~100% duty cycle**
- **Simple geometrical acceptance**
- **Extracting primary mass depends on models**

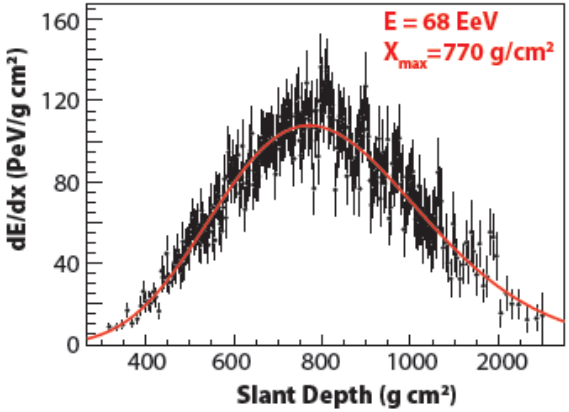
Combining both techniques allows:

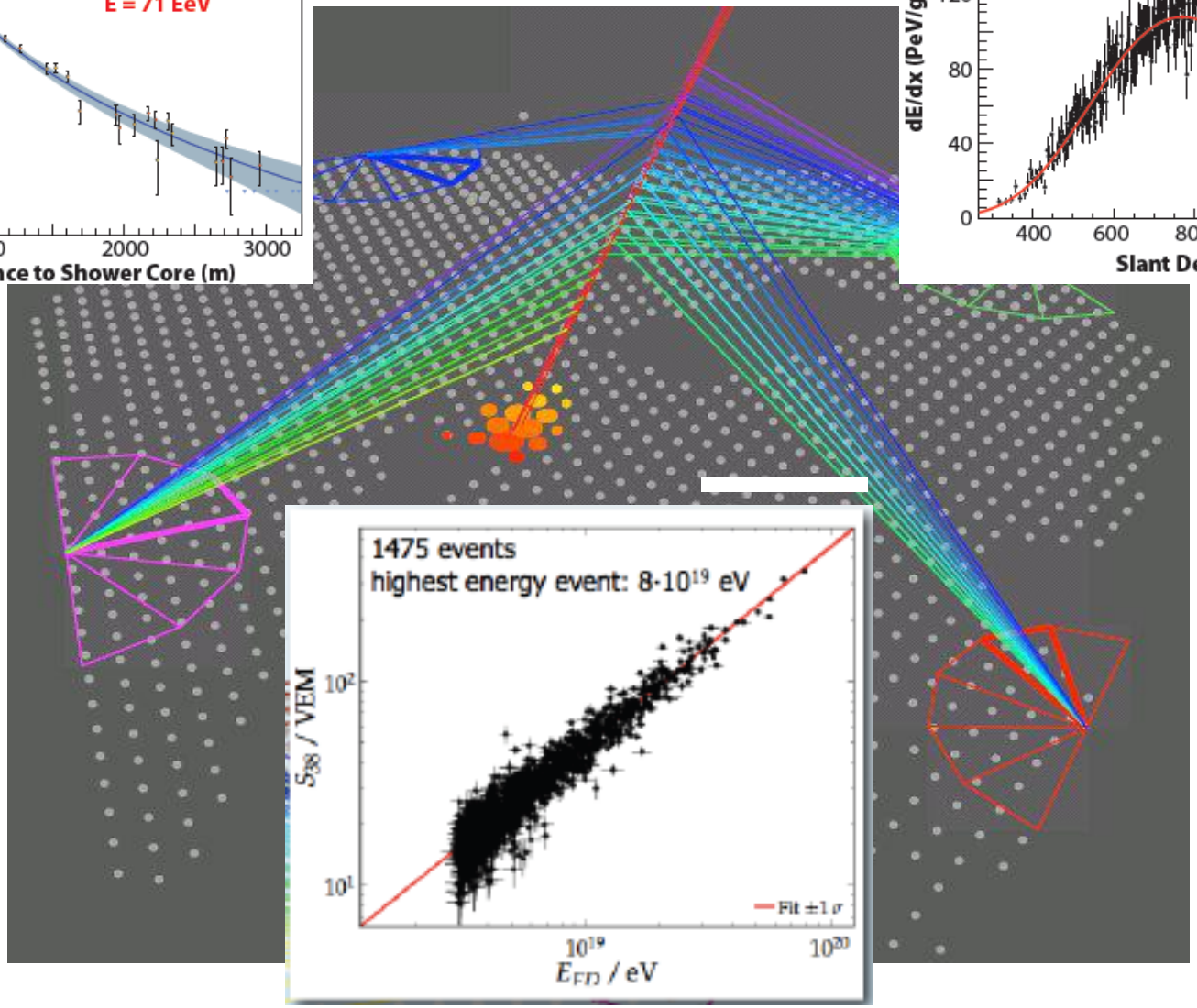
- **cross calibration in energy**
- **better angular resolution**

Lateral distribution



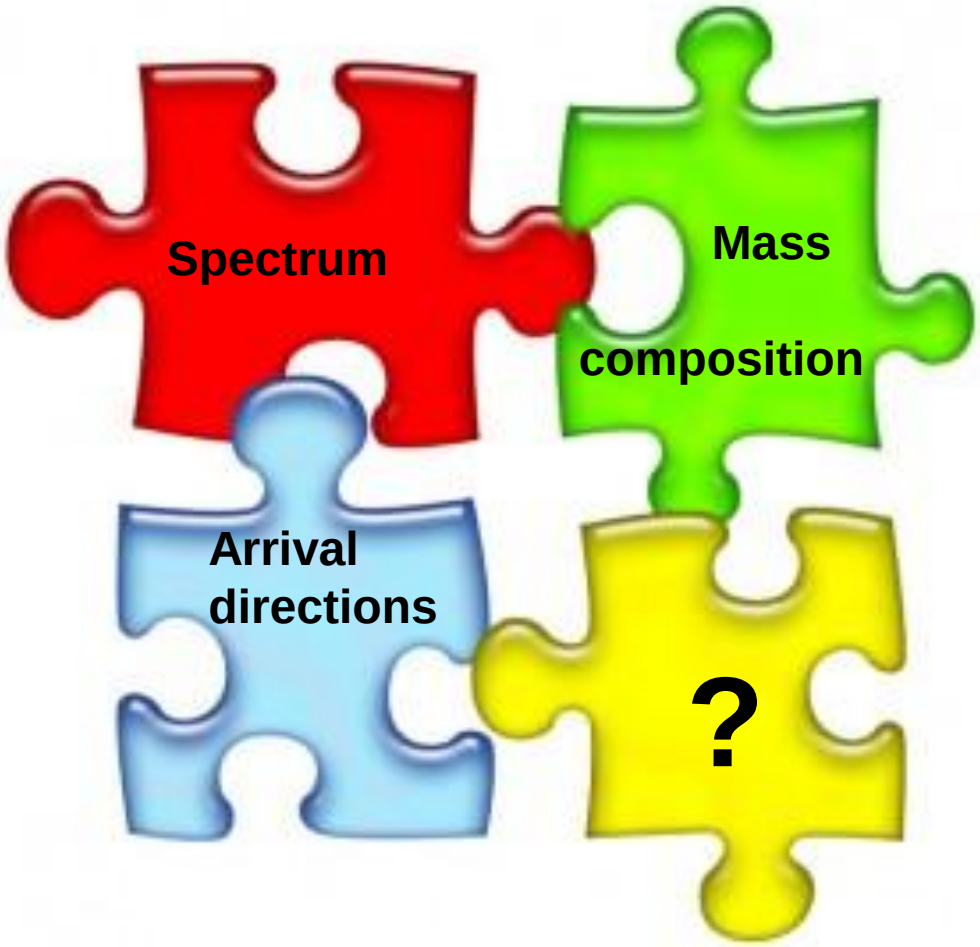
Longitudinal distribution



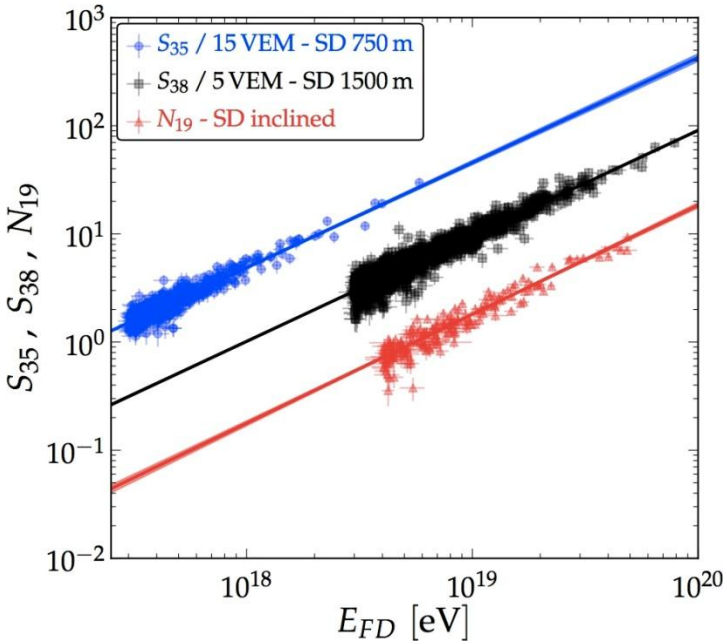


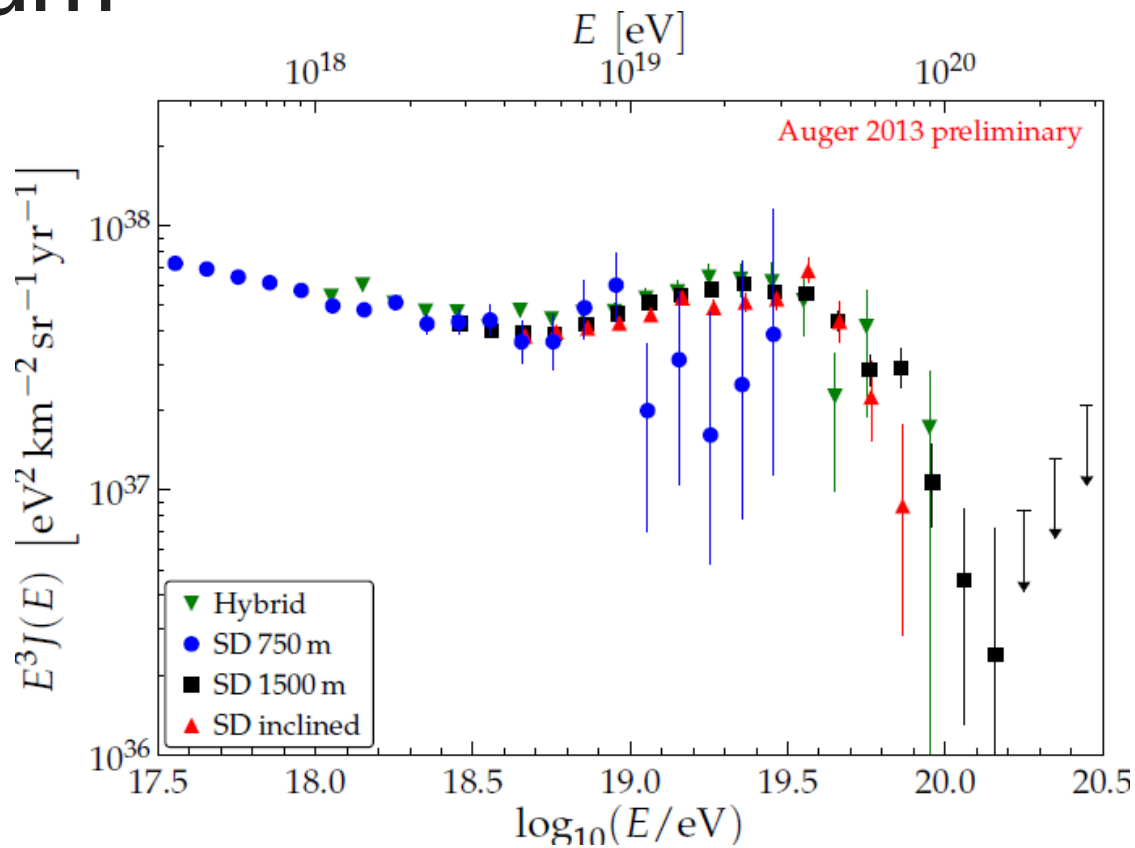
Energy Calibration

What do we have? A puzzle...



Energy Spectrum



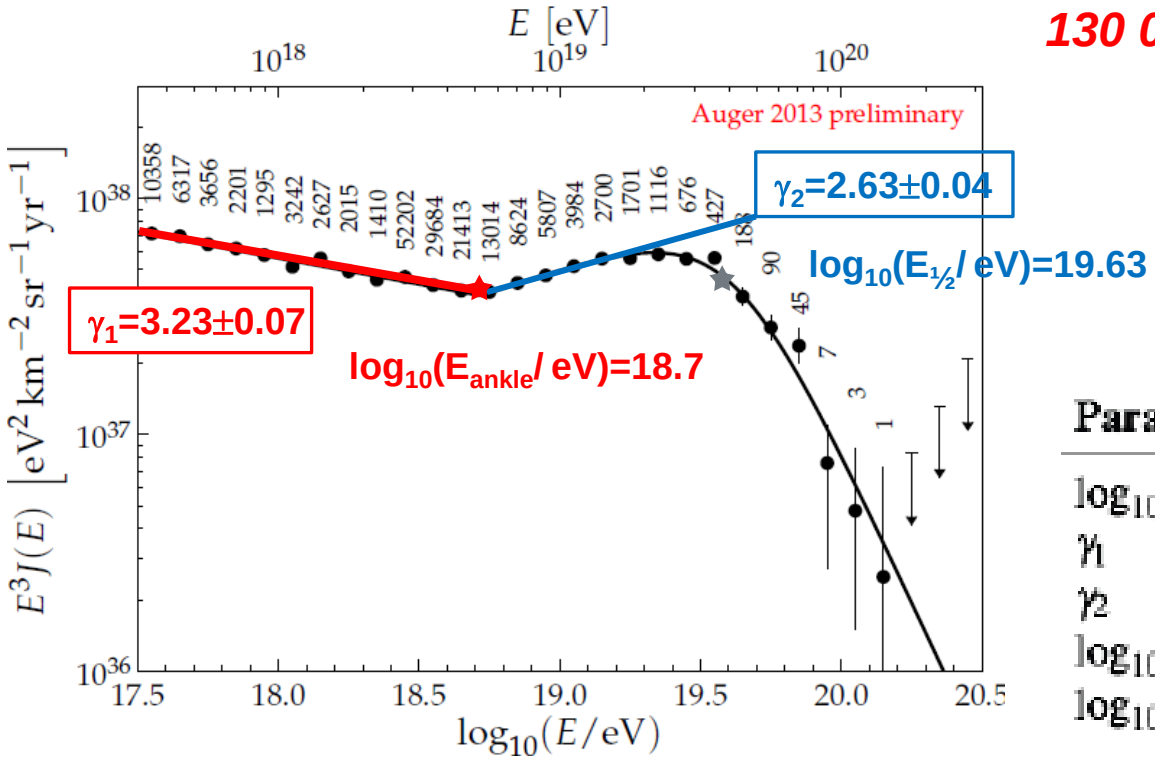


- Data from the SD / FD provide **four independent measurements;**
- The **four spectra agree** within statistical and systematic uncertainties .

A. Schulz for Auger Collaboration, Proc. 33rd ICRC 2013,arXiv: 1307.5059

Energy Spectrum

130 000 events

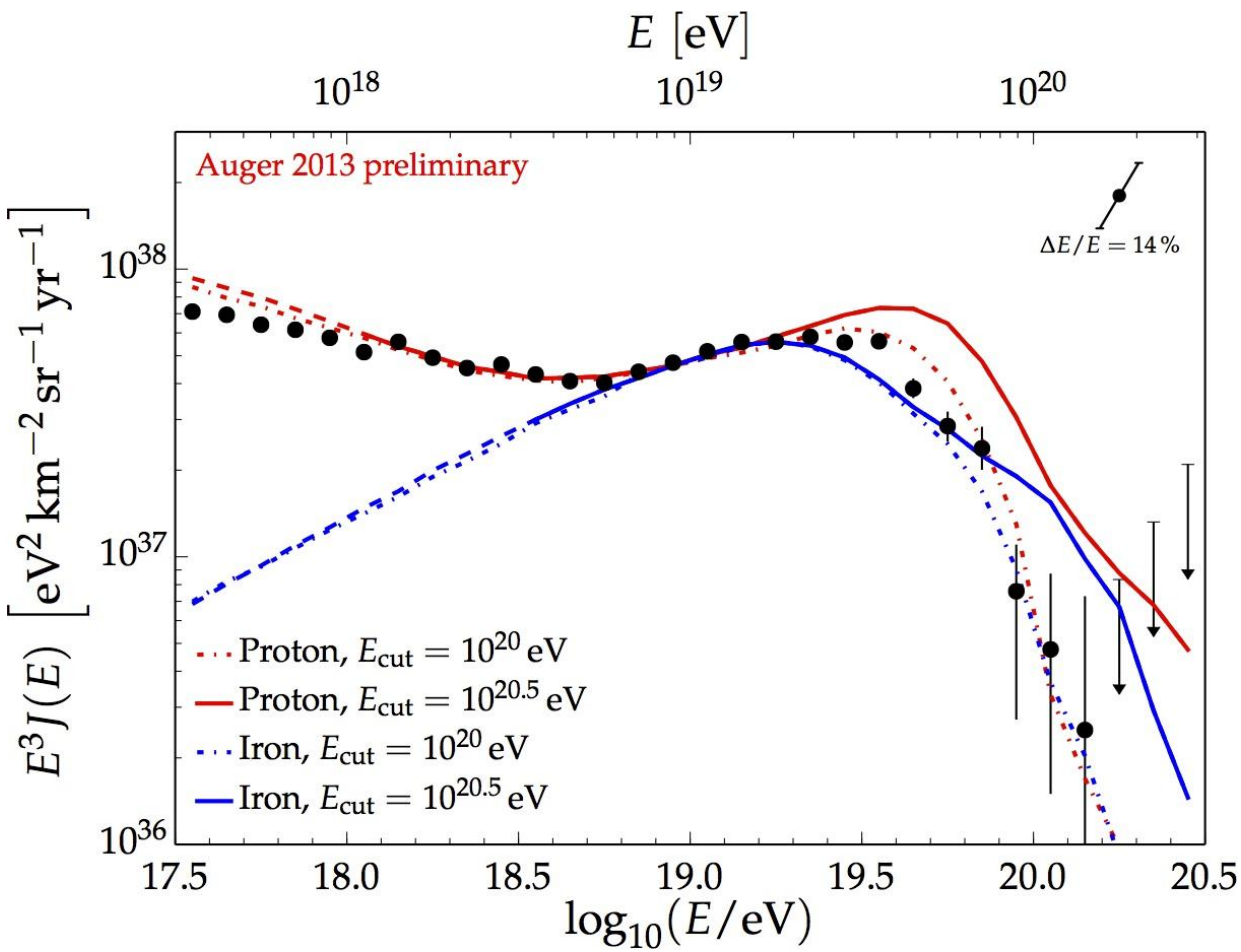


Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
$\log_{10}(E_a/\mathrm{eV})$	$18.72 \pm 0.01 \pm 0.02$
γ_1	$3.23 \pm 0.01 \pm 0.07$
γ_2	$2.63 \pm 0.02 \pm 0.04$
$\log_{10}(E_{1/2}/\mathrm{eV})$	$19.63 \pm 0.01 \pm 0.01$
$\log_{10} W_c$	$0.15 \pm 0.01 \pm 0.02$

$$J(E; E > E_a) \propto E^{-\gamma_2} \left[1 + \exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c}\right)\right]^{-1}$$

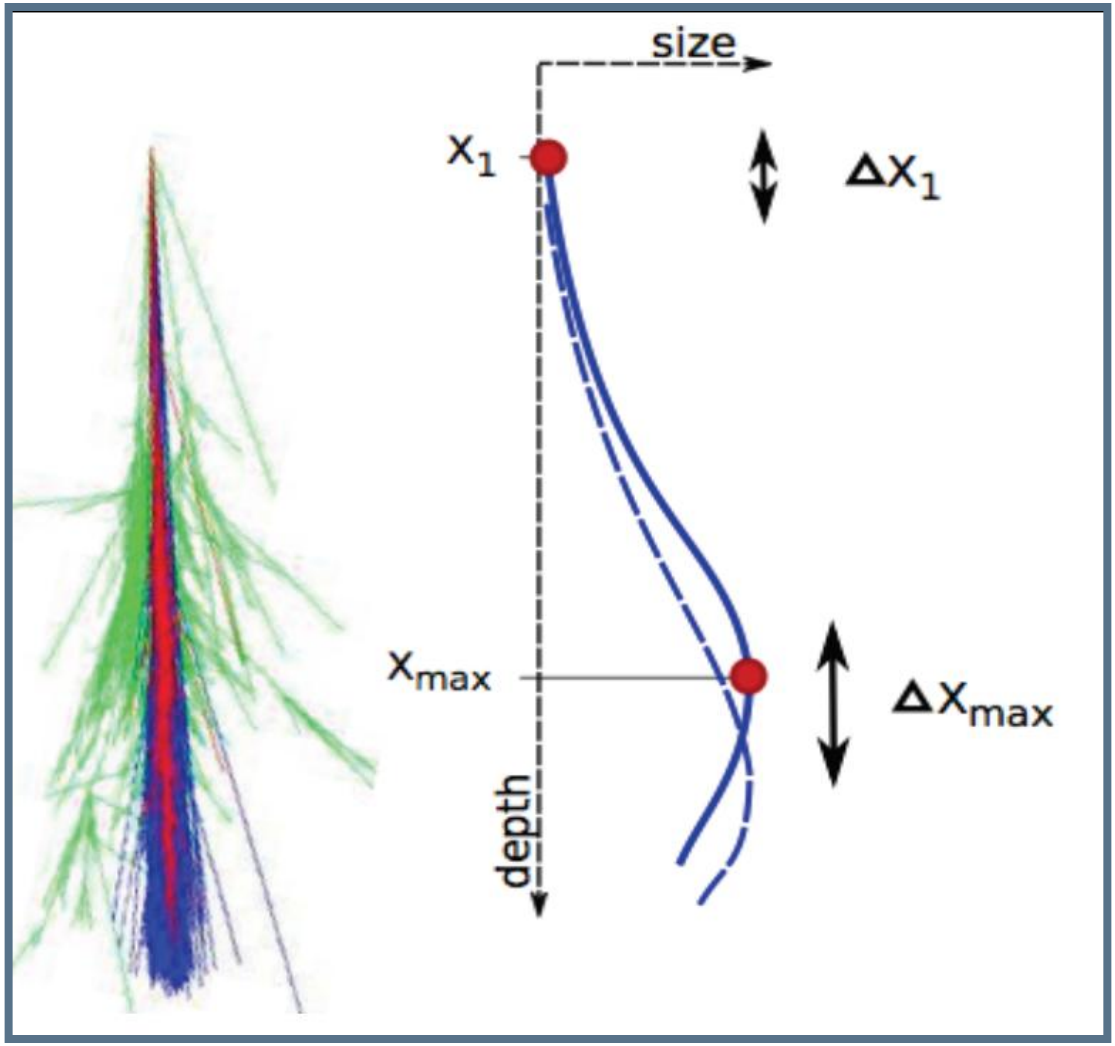
A. Schulz for Auger Collaboration, Proc. 33rd ICRC 2013,arXiv: 1307.5059

Energy spectrum and models

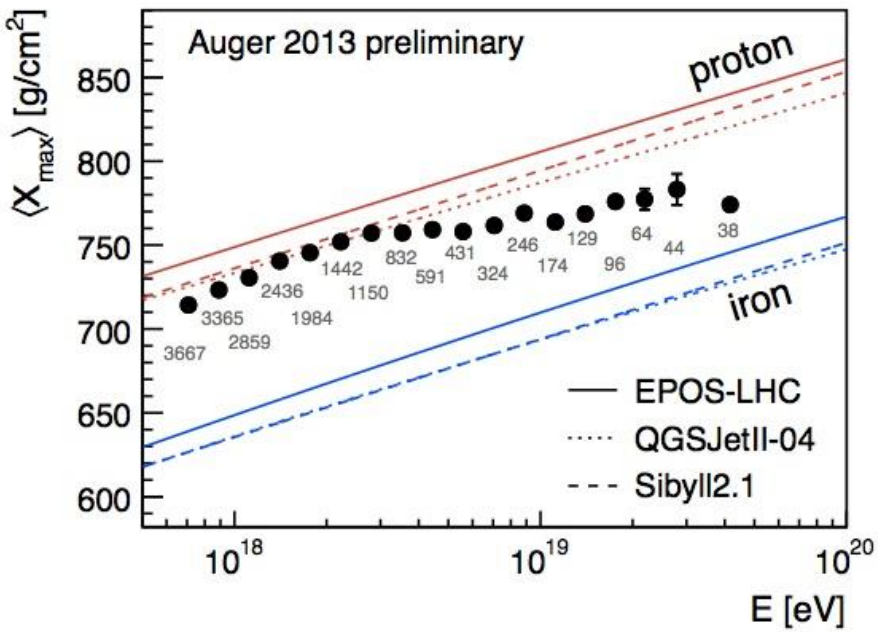


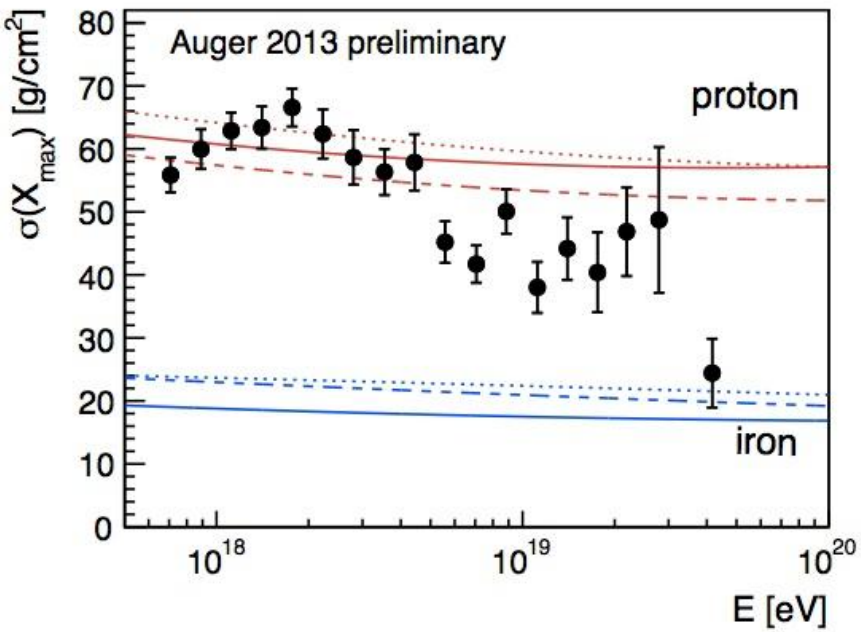
A. Schulz for Auger Collaboration, Proc. 33rd ICRC 2013,arXiv: 1307.5059

Mass composition measurements (FD)



Mass Composition

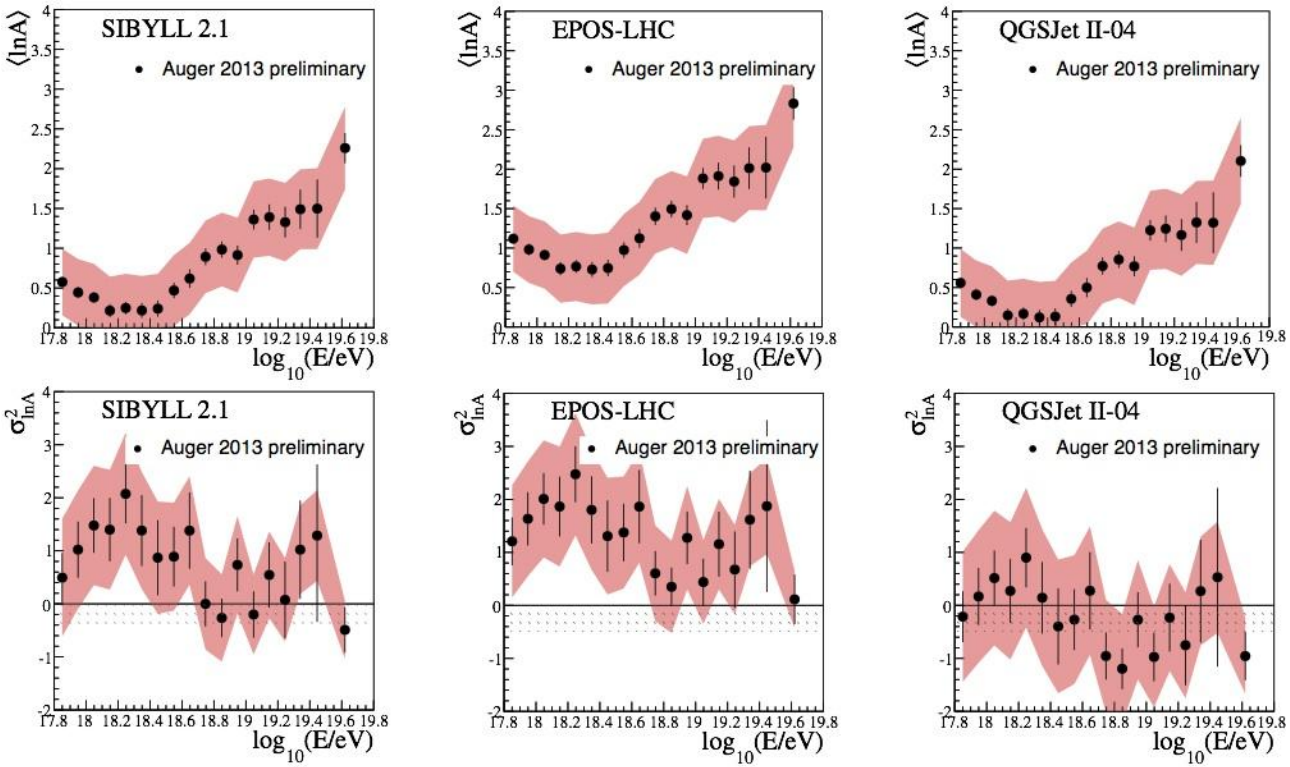




High-quality hybrid data: anti-bias cuts for a direct data-model composition.

Letessier-Selvon, for Auger Collaboration, Proc.33rd ICRC 2013,arXiv: 1310.4620

Average mass composition: X_{max} and <*lnA*>



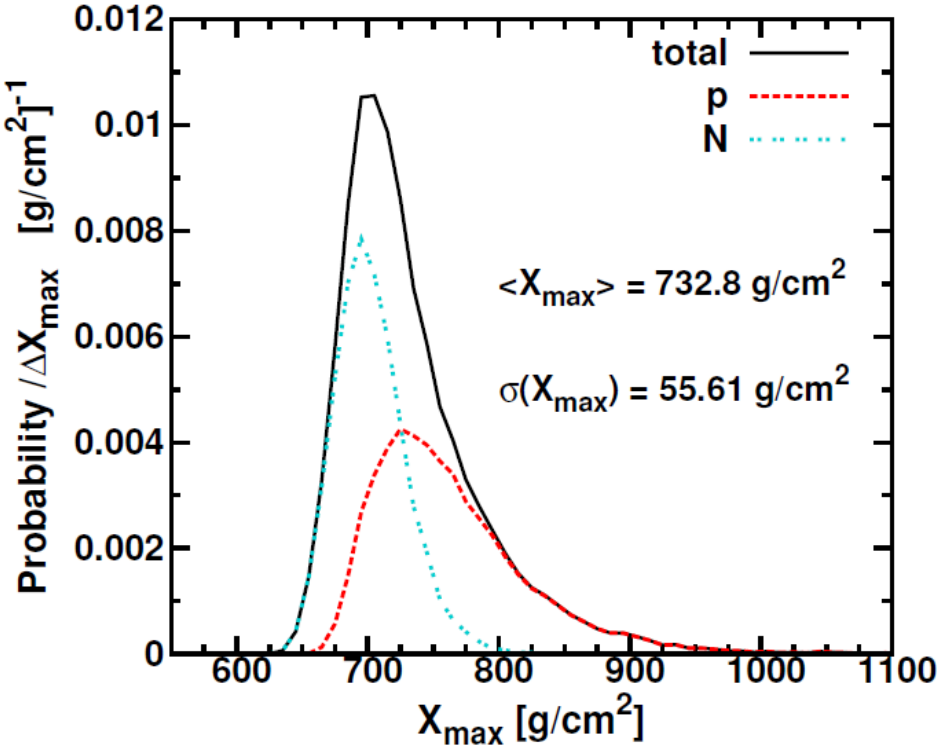
- All models show a trend to <*lnA*> increasing from light to medium with *E;*
- The mix is between light/medium-mass nuclei (not only *p*-Fe);
- Dispersion: spread reflects mixture at sources and propagation effects.

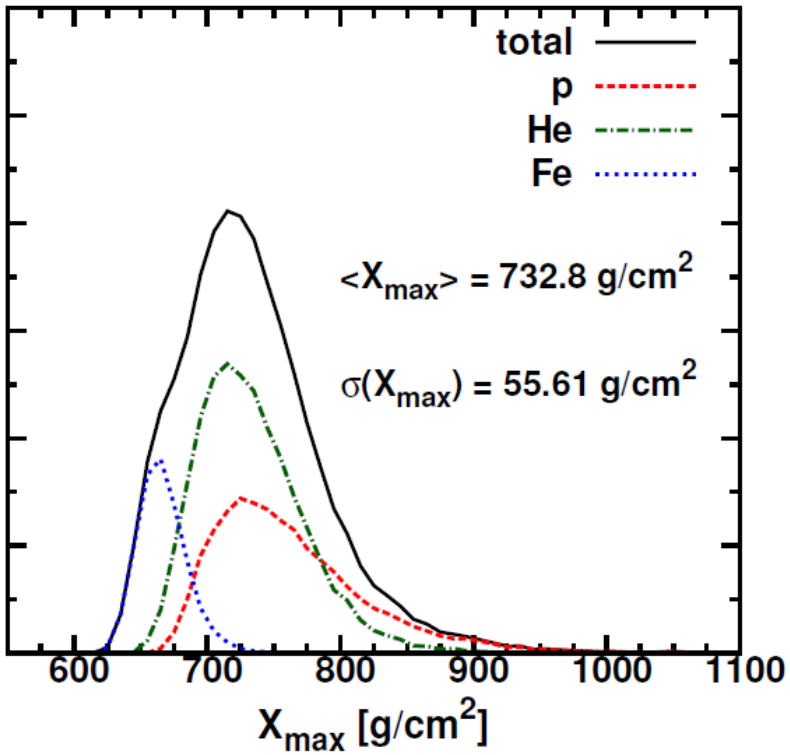
The Pierre Auger Collaboration, JCAP 02 (2013) 026

Update on X_{max} measurements: coming soon

- data from 12/2004 –12/2012
- energies > $10^{17.8}$ eV
- 19947 high-quality FD events
- resolution: 26 g/cm^2 @ $10^{17.8}$ eV,15 g/cm^2 @ $10^{19.3}$ eV.
- **new X_{max} distributions will be released soon....**

Composition implications: what is also being studied



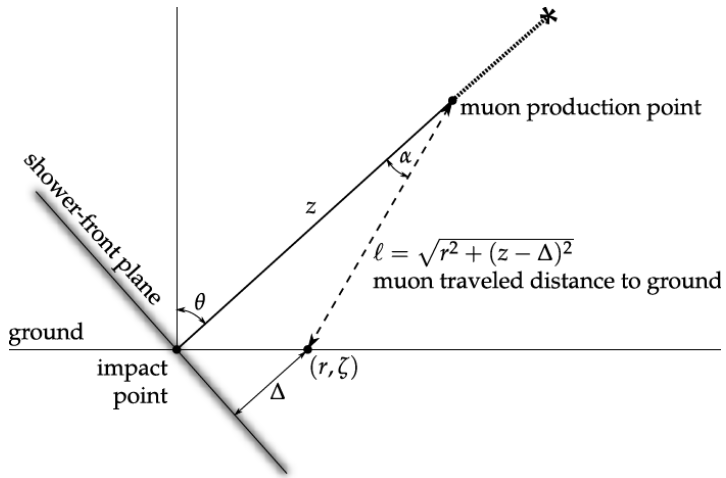


- Simulated X_{max} distributions with same mean/dispersion and different compositions.
- In this example, EPOS-LHC used to generate 10^4 events.

Preliminary results:

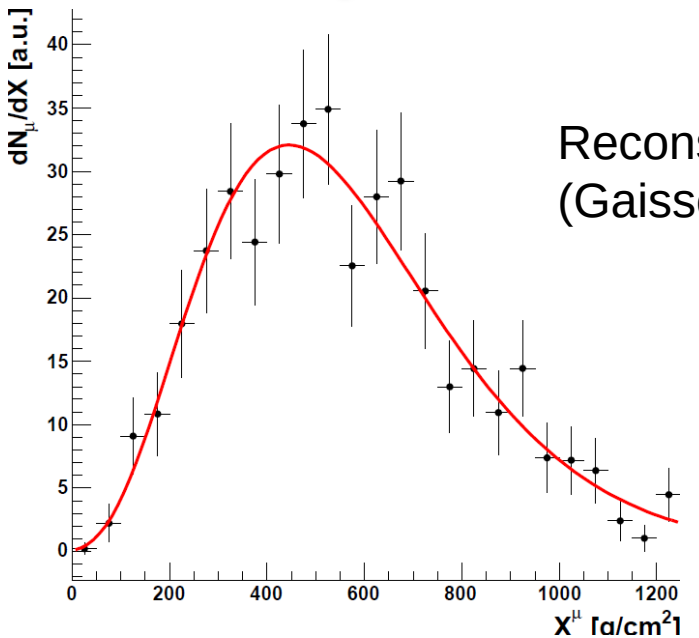
- A mixture of simply protons and iron nuclei does not describe the data over the whole energy range;
- All models give similar predictions of protons and iron fractions;
- Data are better fit when intermediate masses are included;
- Strong energy dependence of resulting proton fractions, decreasing at higher energies;
- None of the models predicts a significant iron contribution.

Another approach to estimate mass composition: muon production depth (SD)



$$z \approx \frac{1}{2}\left(\frac{r^2}{c(t - \langle t_\varepsilon \rangle)} - c(t - \langle t_\varepsilon \rangle)\right) + \Delta - \langle z_\pi \rangle$$

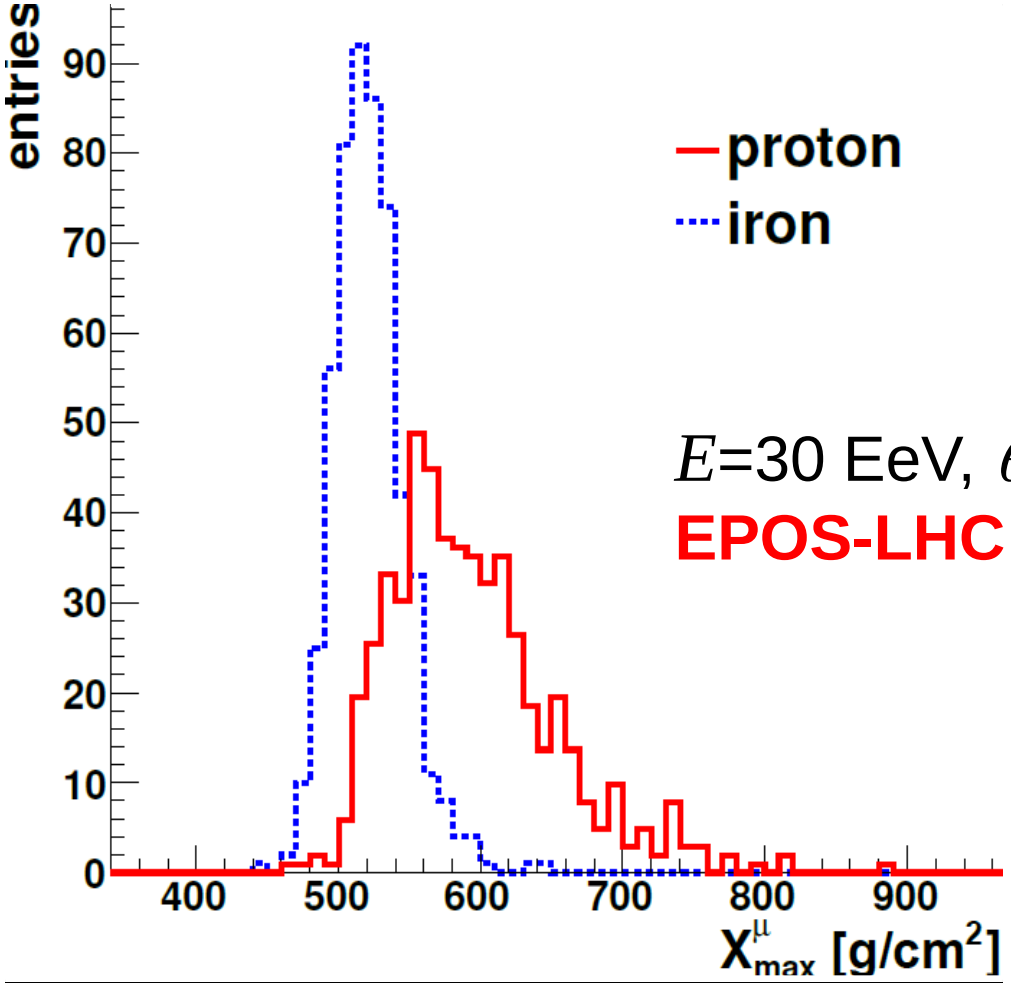
$$X^\mu = \int_z^\infty \rho(z')dz'$$



Reconstruction of X^μ of an event with E=(95±3) EeV, θ=59° (Gaisser-Hillas fit)

The Pierre Auger Coll., Physical Review D 90 (2014) 012012

X^{μ}_{max} distributions for proton and iron showers @ 30 EeV



The Pierre Auger Coll., Physical Review D 90 (2014) 012012

MPD analysis:

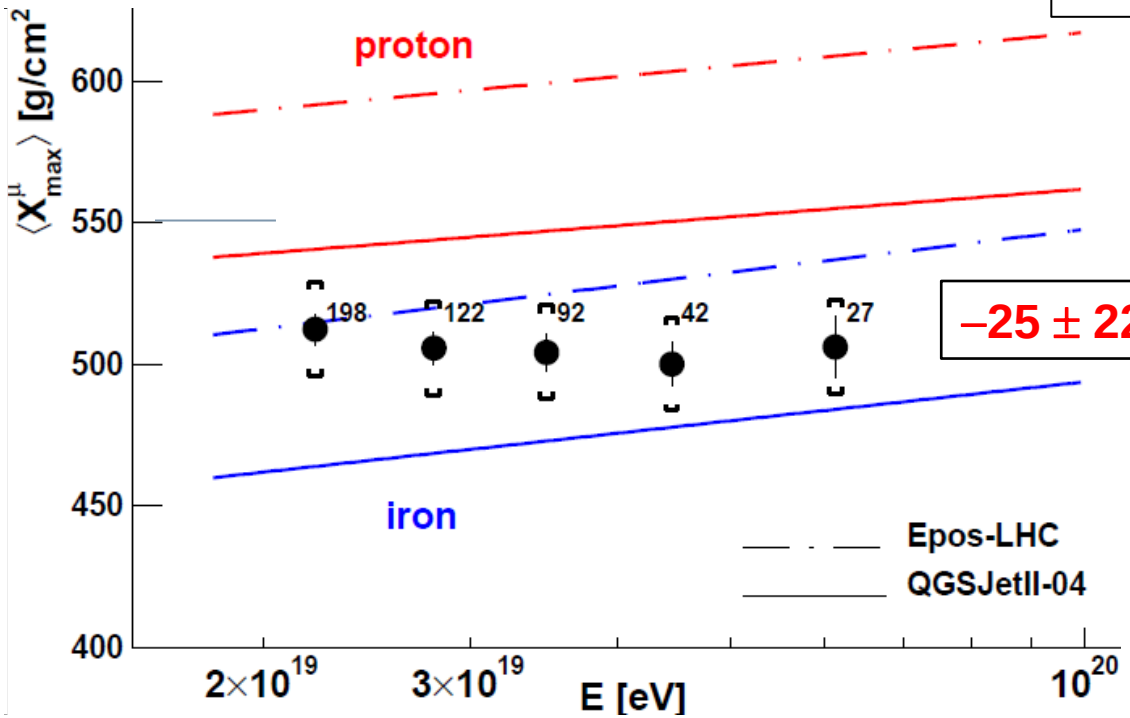
- Data from 01/2004 – 12/2013
- Energies > 20 EeV
- Zenith angles [55°,65°]
- Distances from the core [1700, 4000] m
- 481 events selected
- Systematic uncertainty 17 g/cm^2
- Resolution 100 (80) g/cm^2 @ $10^{19.3}$ eV for p (Fe)
  50 g/cm^2 @ 10^{20} eV

The Pierre Auger Coll., Physical Review D 90 (2014) 012012

Mean reconstructed MPD

Muonic elongation rate : $D_{10}^{\mu} = d\left\langle X_{\max}^{\mu} \right\rangle / d\,lg\,E \left[\mathrm{g/cm^2/decade}\right]$

Predictions:
35.9±1.2 (proton)
48.0 ± 1.2 (iron)



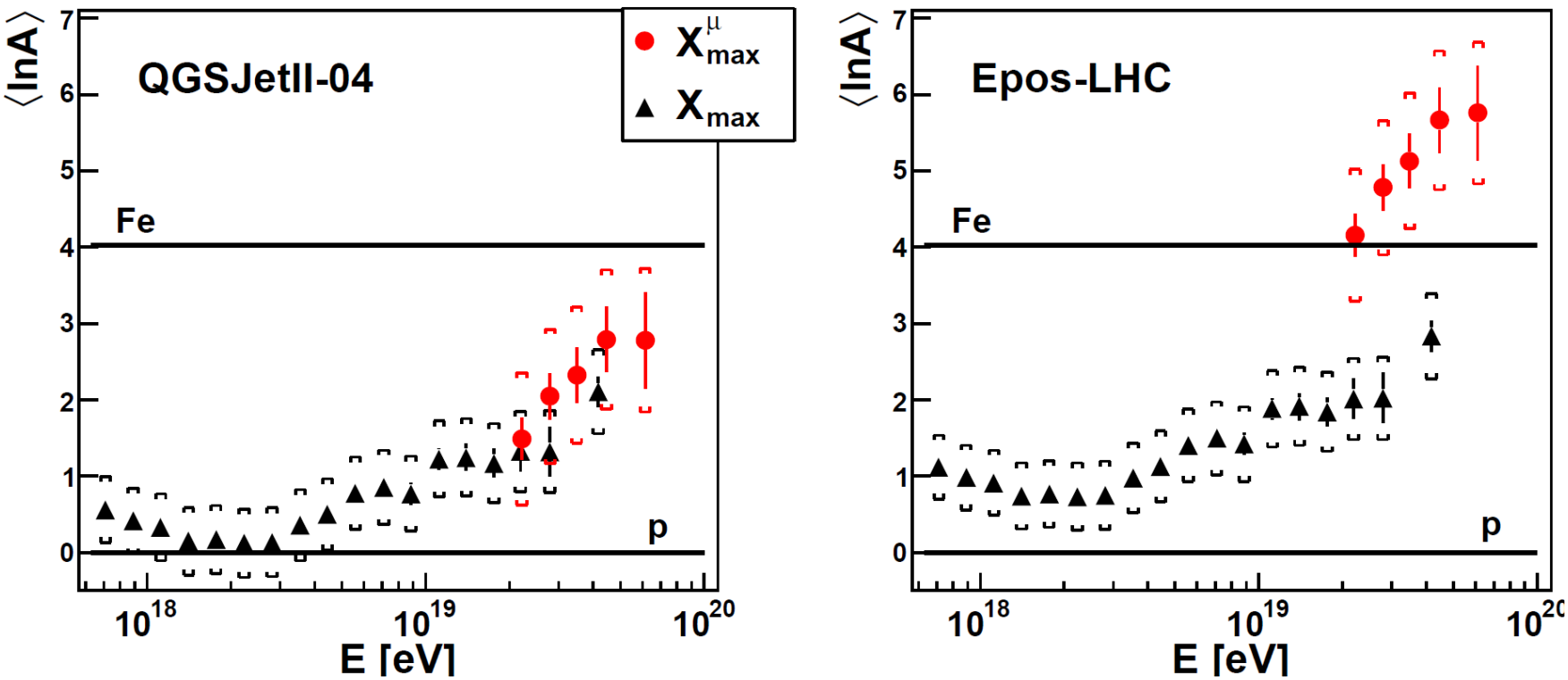
–25 ± 22(stat)±21(syst)

- Data are bracketed by QGSJetII-04 and fall below EPOS-LHC predictions;
- Data show a flatter trend than predicted for pure p or Fe showers.

The Pierre Auger Coll., Physical Review D 90 (2014) 012012

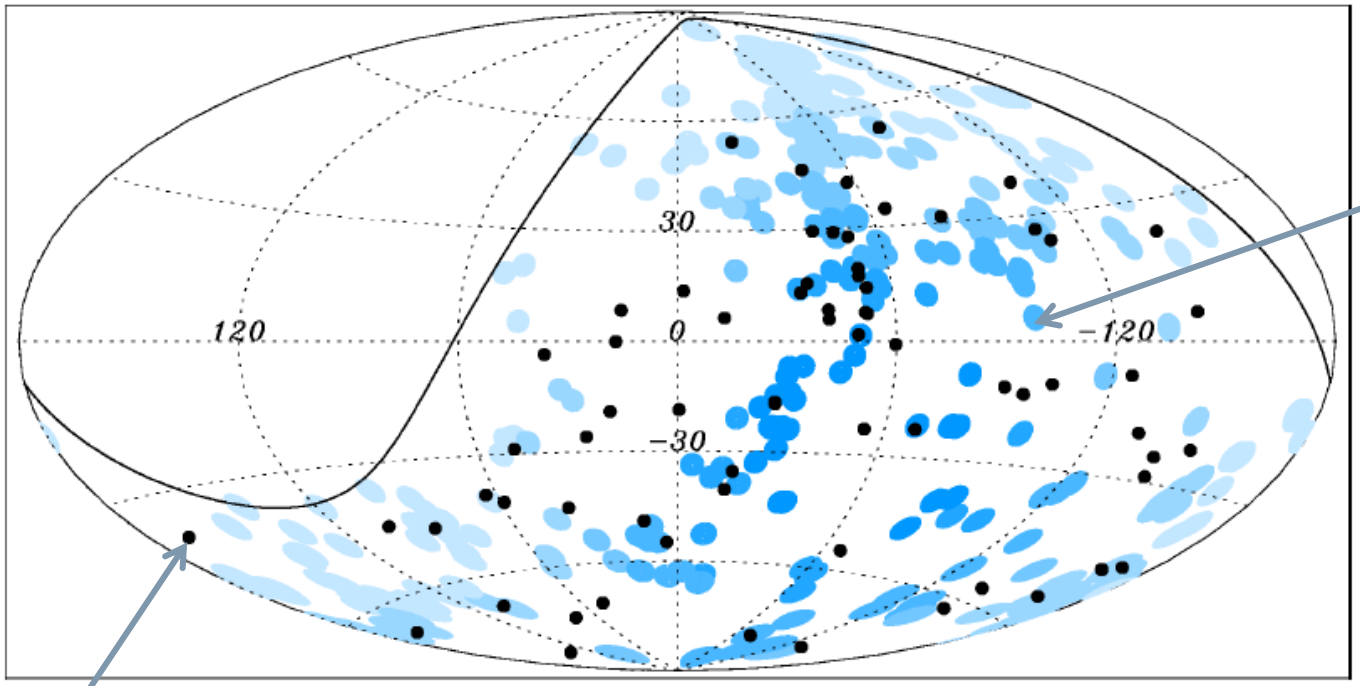
Mean logarithmic mass from MPD and X_{max}

$<lnA>$ from X_{max} and MPD for EPOS LHC



Consistency of the two X_{max} allows one to **constrain hadronic interaction models**.

Correlation of the highest energy cosmic rays with nearby extragalactic matter



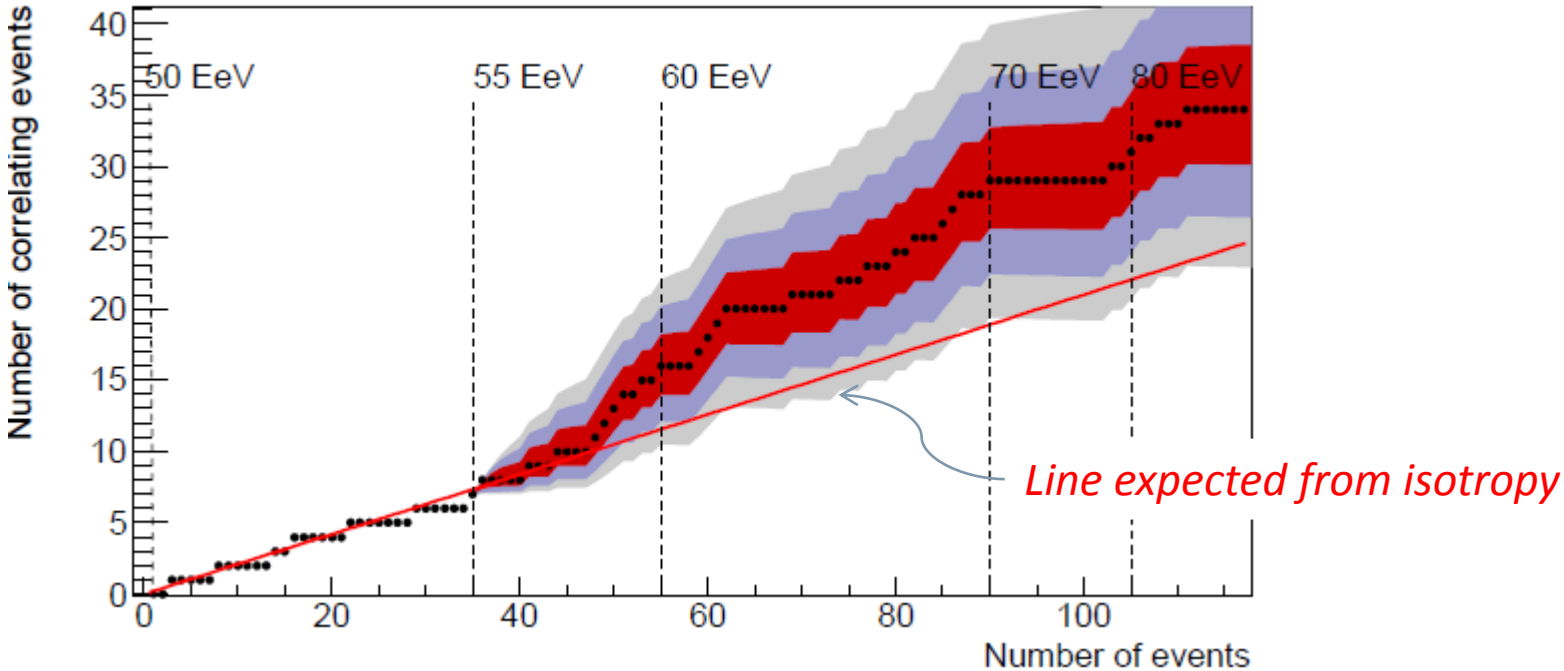
AGN

Cosmic Ray

VCV: 21/55 events correlating (11.6 expected)
Probability=0.3%

The Auger Collaboration, Astropart. Phys. 34 (2010) 314

Latest update on the correlation of the highest energy cosmic rays with nearby extragalactic matter



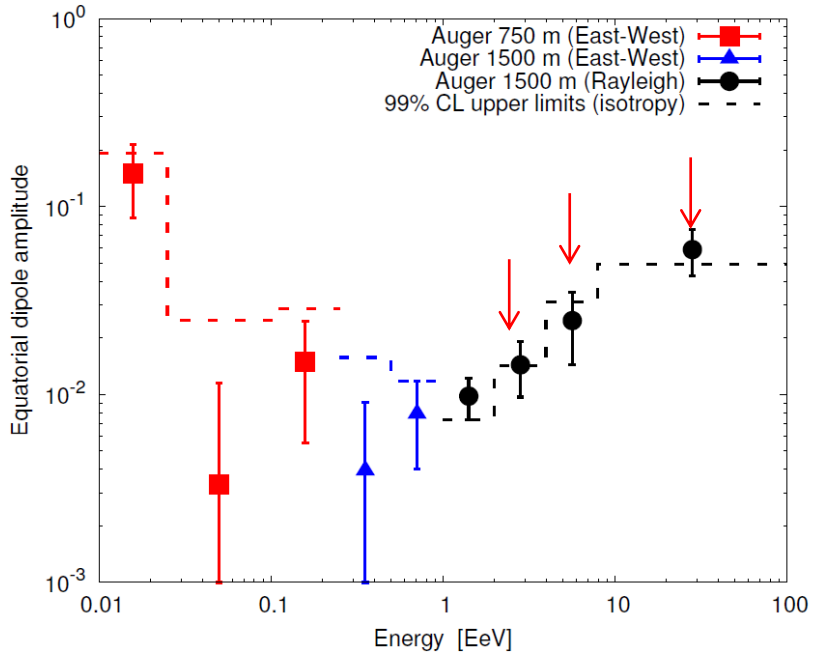
- Isotropy rejected with a 99% C.L.;
- Signal 2σ above the expected for isotropy: (33±5)% (28/82) instead 21%;
- The proton fraction is small: consistent with $Xmax$ results.

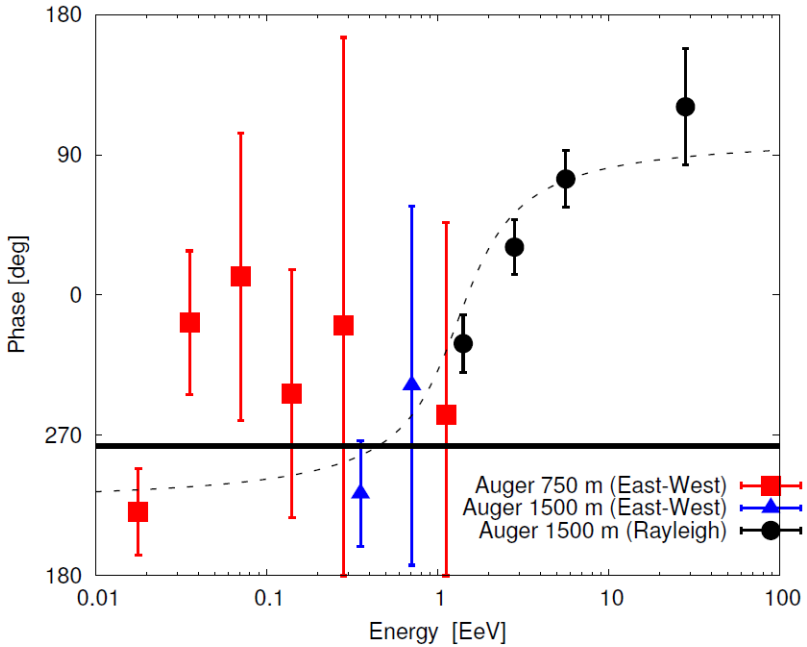
Letessier-Selvon, for the Auger Collaboration, Proc. 33rd ICRC 2013, arXiv: 1310.4620

Large-scale anisotropy: Equatorial dipole amplitude and phase

no clear evidence of anisotropy..

interesting....

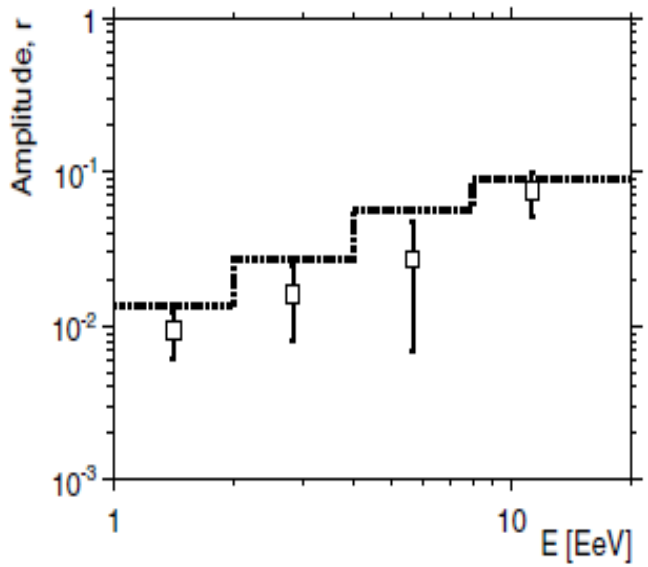




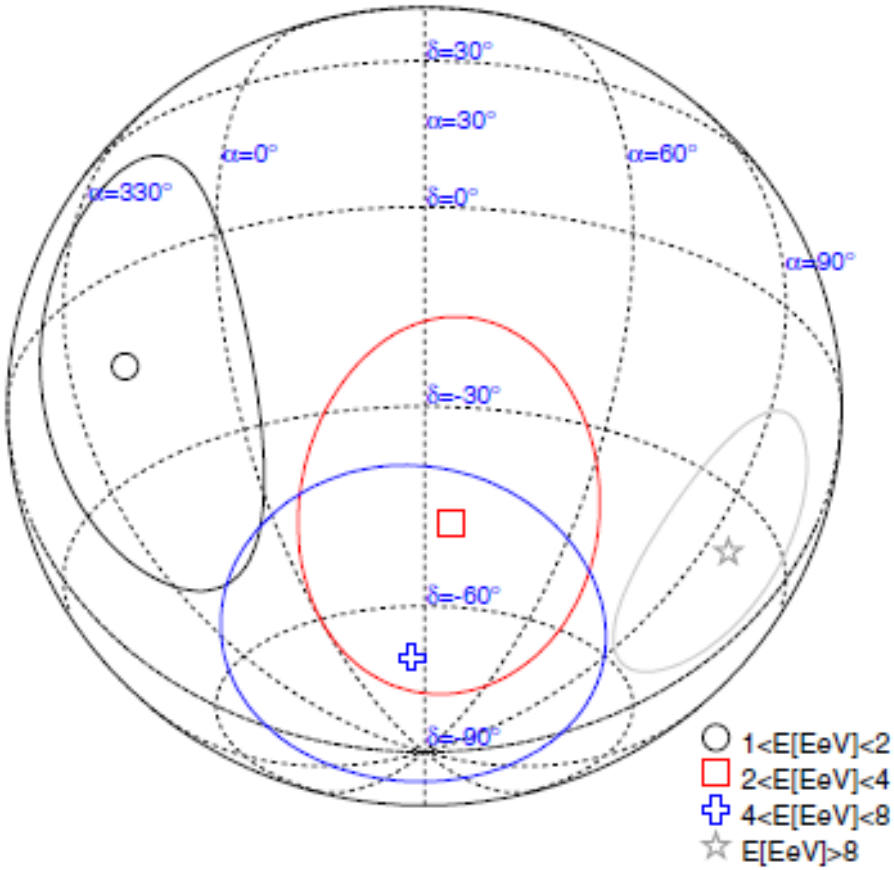
prescription still running....

I. Sidelnik for Auger Collaboration, Proc. 33rd ICRC 2013, arXiv: 1307.5059

Large-scale anisotropy search



Reconstructed amplitude of the dipole



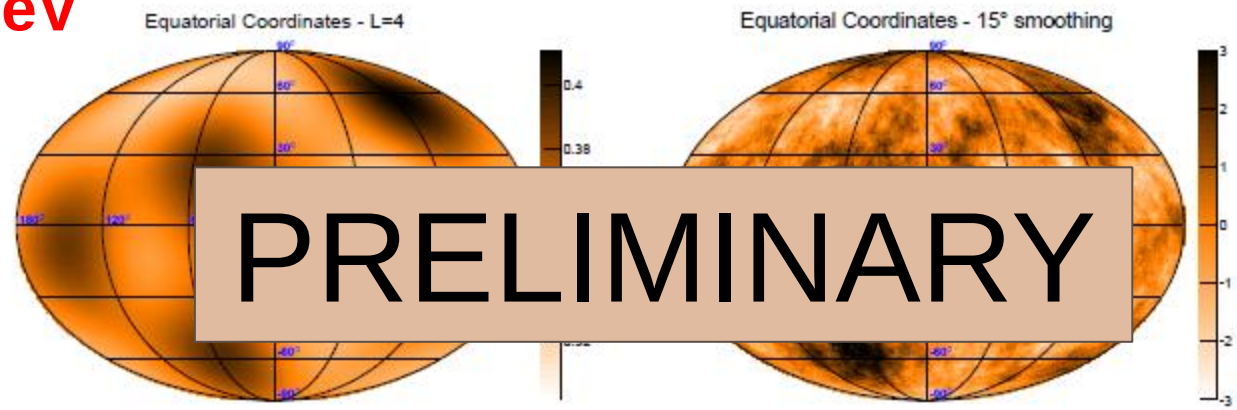
Reconstructed declination and right ascension of the dipole

The Pierre Auger Collaboration, ApJL, 762 (2013) L13

Joint Auger and Telescope Array analysis: full-sky coverage

Auger: 8259 events
TA: 2130 events

$E > 10^{19}$ eV



Flux sky map in $km^{-2} yr^{-1} sr^{-1}$ using a multipolar expansion up to $\ell = 4$.
Significance sky map smoothed out at a 15° angular scale.

The Auger Collaboration, to appear in Astrophysical Journal (2014)

Looking for photons, neutrinos, neutrons....

Photons:

- *The Pierre Auger Collaboration, ApJ, 789 (2014) 160*

Neutrons from our Galaxy:

- *The Pierre Auger Collaboration, ApJ, 789 (2014) L34*
- *The Pierre Auger Collaboration, ApJ, 760 (2012) 148*

Neutrinos:

- *The Pierre Auger Collaboration, Advances in High Energy Physics, (2013) 708680*
- *The Pierre Auger Collaboration, Astrophysical Journal Letters, 755 (2012) L4*

Summary of the discussion

- The ankle in the spectrum and the change in composition just about a few 10^{18} eV; hints of anisotropy on large scale;
- A suppression of the flux above 5×10^{19} eV; three events above 10^{20} eV; no data for Xmax; point source anisotropy at 2σ.
- EeV photons, galactic neutrons, neutrinos still not detected.
- Constrains on hadronic interaction models: cross section and muon content in showers.

Open questions...

- Is there a (small) proton component at UHE?
- Does the lack of Galactic neutrons indicate that there are no protons at energies around the ankle? No proton sources in our Galaxy?
- Does the suppression reflect the GZK effect ($E_{1/2}$ lower than expected) or otherwise the exhaustion of the sources? composition studies indicate increasing primary masses; no photons and neutrinos as indirect evidence.

Possible scenarios:

photodisintegration

sources accelerate nuclei up to a E_{max}
light elements are fragments of heavier nuclei
- cut-off would be due to energy loss of nuclei in photodisintegration
- light elements appear at E shifted by the ratio $M_{daughter}/M_{parent}$
- N-Si nuclei at the sources, no protons

maximum energy

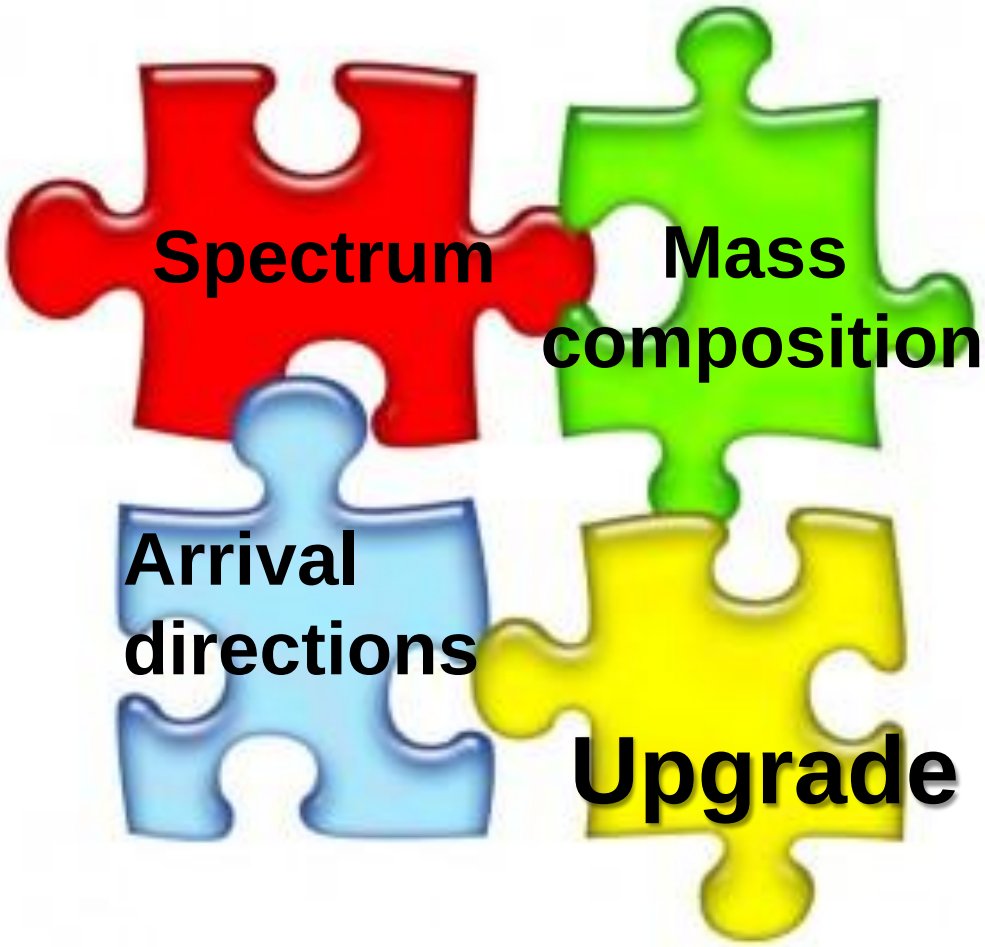
sources accelerate nuclei up to a $E_{max} \propto Z$
Composition in the source similar to the Galactic one
- cut-off: E_{max} would be reached in the source
- Composition getting heavier for increasing energy
- Protons at the ankle are of extragalactic origin, no GZK γ or ν

proton dominance

the all particle flux consists of extragalactic protons
the source has a cut-off energy
- cut-off : energy loss processes for protons is pion-photoproduction
- Ankle due to pair production of protons on CMB photons
- New physics to explain heavier composition at UHE

Special thanks to A. Castellina, Vulcano Workshop 2014

Coming back to the beginning of this talk...



Plan for the future:

Motivation: find out origin of the cut-off and composition:

- GZK or E_{max} of sources?
- Proton fraction at UHE?
- Help to constrain hadronic interaction models.

Continue operation up to 2023 with upgraded detectors, improving:

- electronics,
- discrimination of muonic/electromagnetic components.

Conclusion

- Rich harvest of data;
- Broad Science Program;
- Stable operation + Enhancements;
- Experimental Breakthroughs;
- First $\sigma_{\text{p-air}}$ & σ_{pp} well above LHC energies;
- Anisotropies stabilizing;
- Photons and neutrinos nearing GZK regime.

ACKNOWLEDGEMENTS

FAPESP

THANKS FOR YOUR ATTENTION!