TAUP 2017, Sudbury, July 24-28 2017

Results from the Pierre Auger Observatory

Image: S.Saffi

Lorenzo Perrone for the Pierre Auger Collaboration

Università del Salento and INFN Lecce (Italy)

The physics case at the highest energies

Ankle

Transition galactic to extra-galactic cosmic rays

"GZK"

End of the spectrum

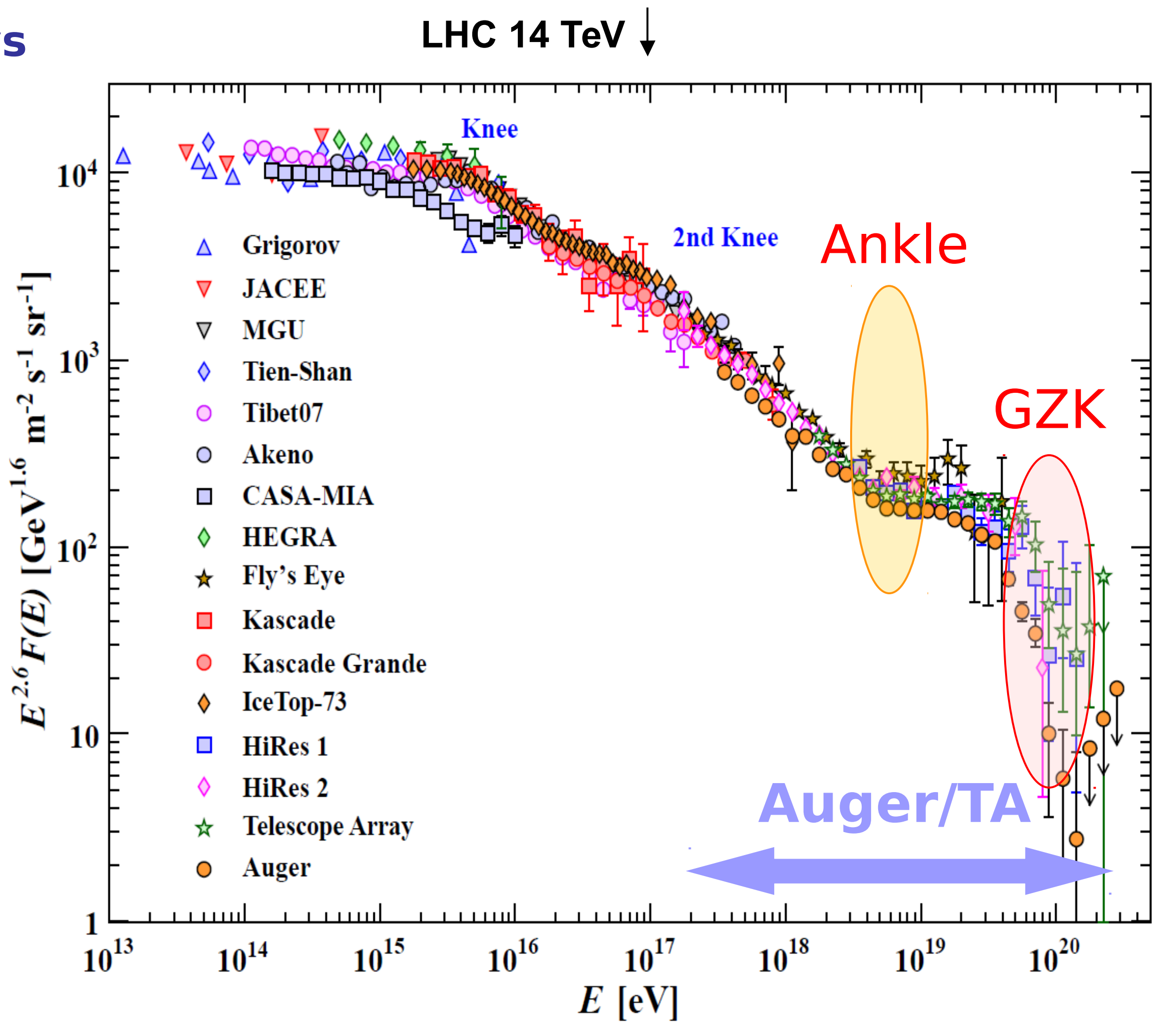
Energy spectrum

Arrival directions

Composition

Search for photon and neutrinos as primary cosmic rays

Hadronic physics



Particle Data Group

The Pierre Auger Observatory

500 members, 17 countries

Surface detector

an array of 1660 Cherenkov stations on a 1.5 km hexagonal grid (~ 3000 km²)

Fluorescence detector

4+1 buildings overlooking the array (24+3 telescopes)

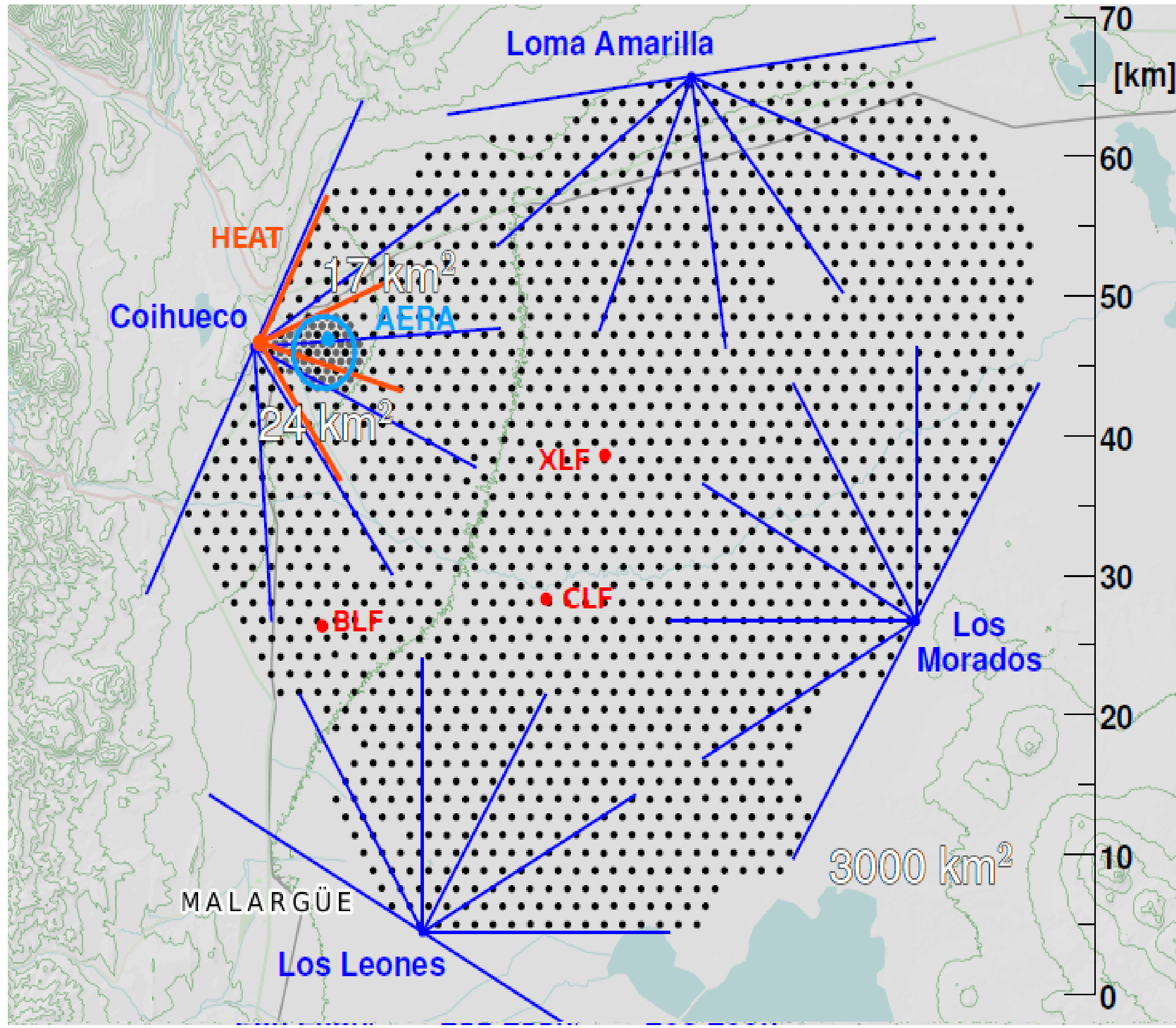
Radio detector

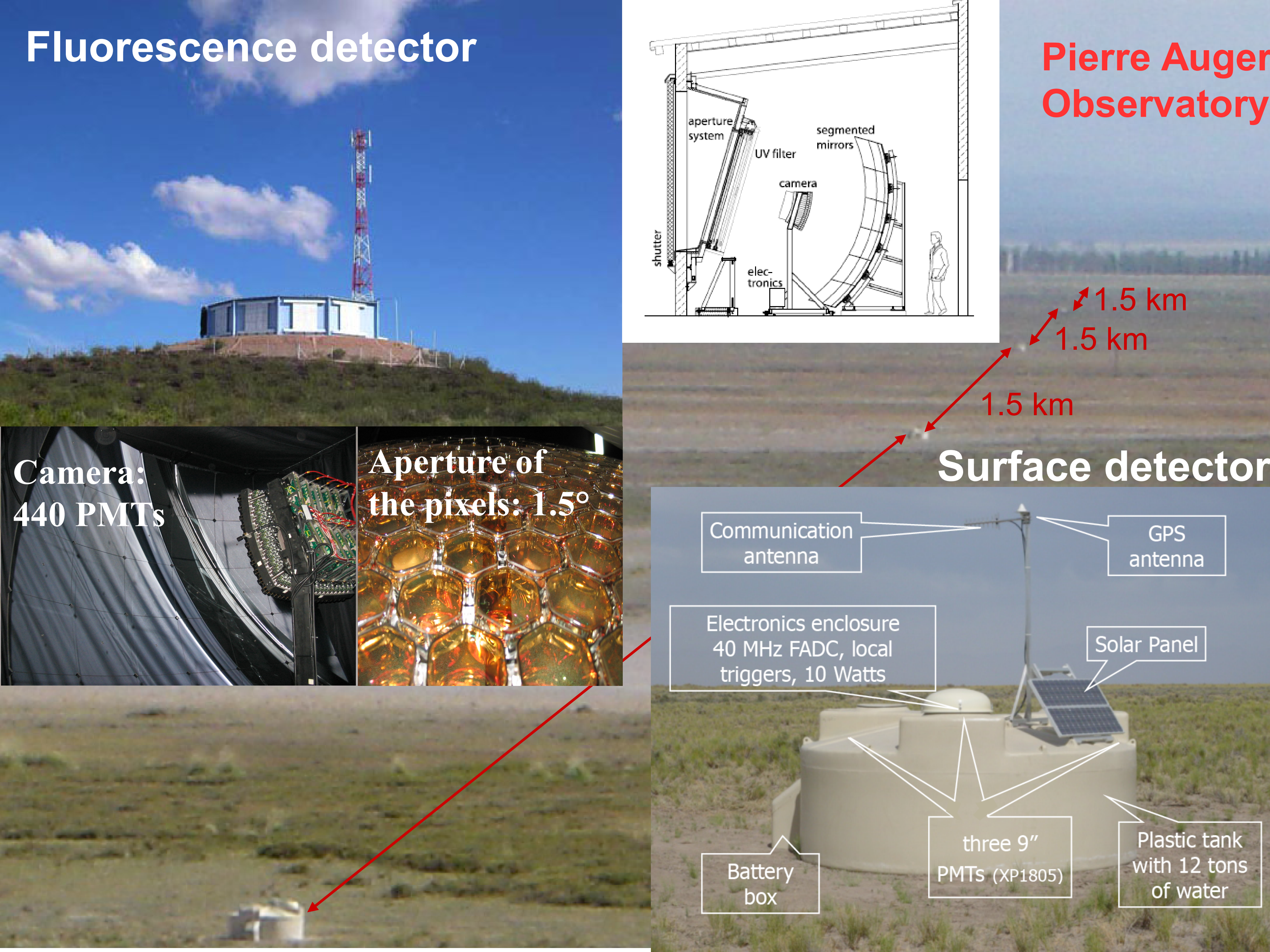
153 Radio Antenna → AERA

Low energy extensions

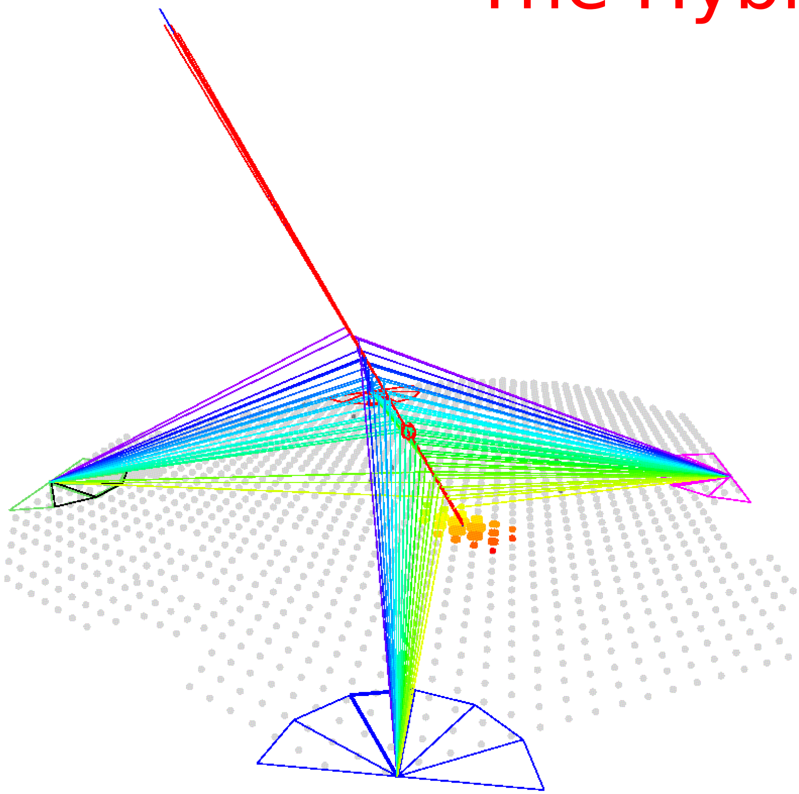
- Dense array (24km²) plus muon detectors → AMIGA
- 3 further high elevation FD telescopes → HEAT

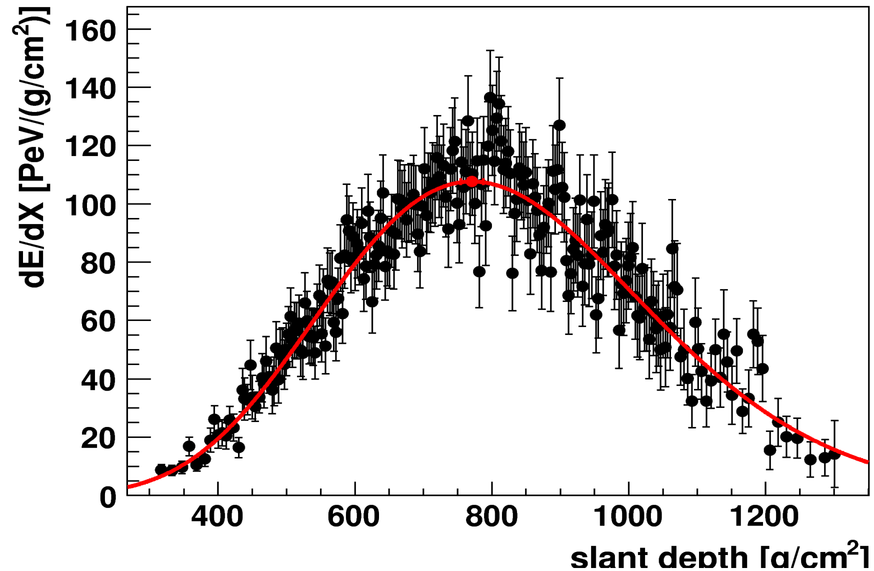
3000 km²

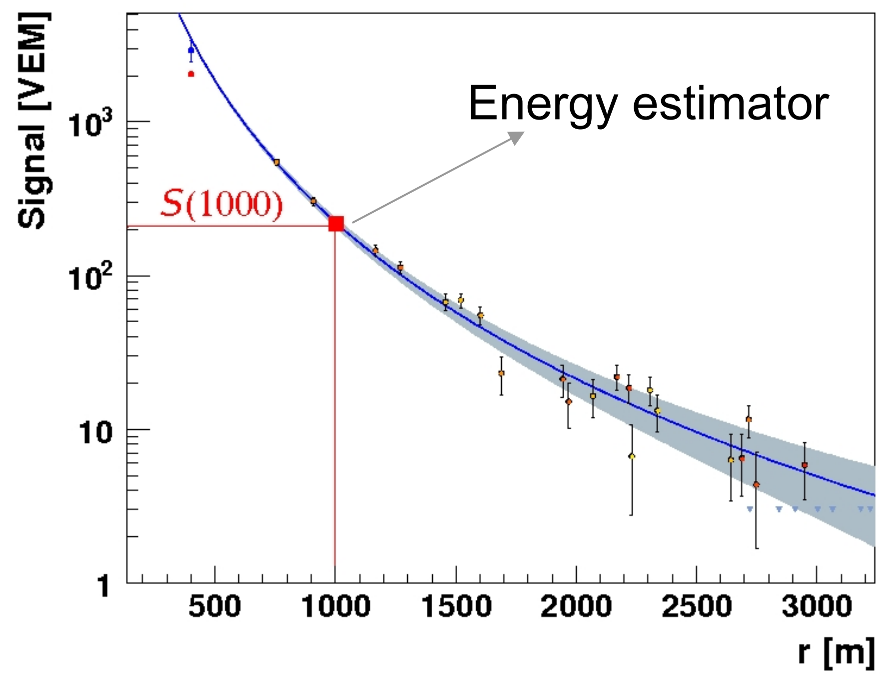



Fluorescence detector
aperture system
UV filter
segmented mirrors
camera
shutter
elec-
tronics
Pierre Auger
Observatory
1.5 km
1.5 km
1.5 km
Camera:
440 PMTs
Aperture of
the pixels: 1.5°
Surface detector
Communication
antenna
GPS
antenna
Electronics enclosure
40 MHz FADC, local
triggers, 10 Watts
Solar Panel
Battery
box
three 9”
PMTs (XP1805)
Plastic tank
with 12 tons
of water

The Hybrid paradigm







Longitudinal profile

FD - calorimetric measurement

- duty cycle 15%

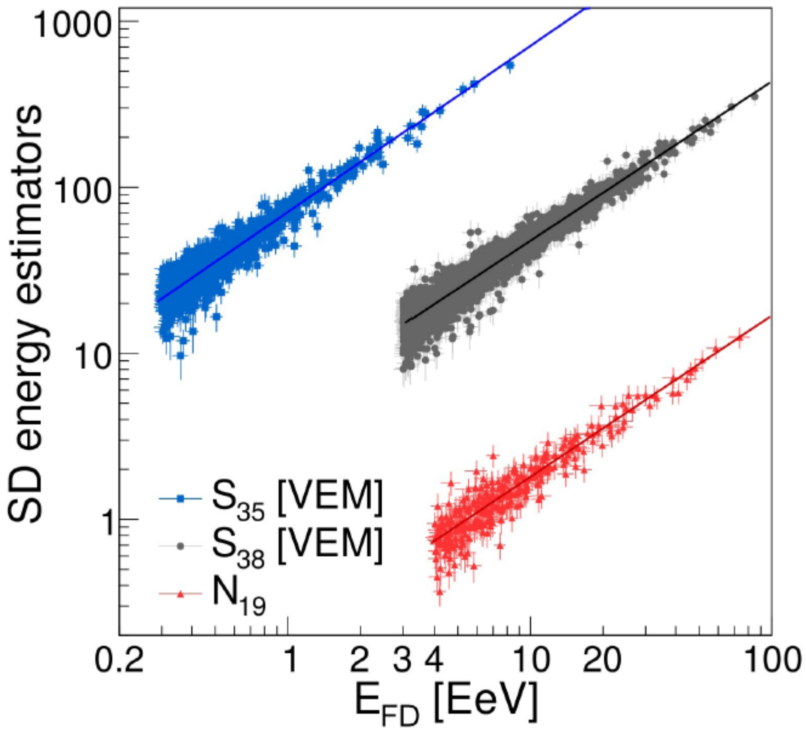
Density of particles at the ground

SD - duty cycle ~ 100%

Use the energy scale provided by FD to calibrate the entire SD data sample

Auger Collaboration @ **ICRC 2017**

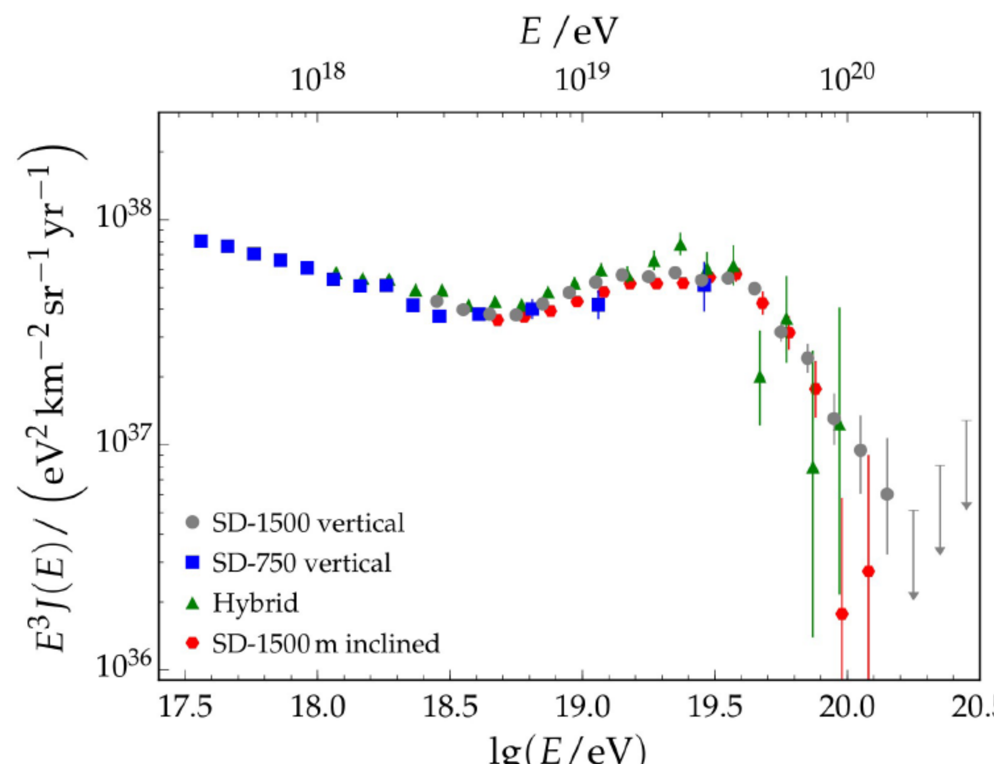
Calibration with the FD energy scale



14% Energy scale uncertainty

Energy resolution

13% SD dense array
15% SD vertical (< 60°)
19% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

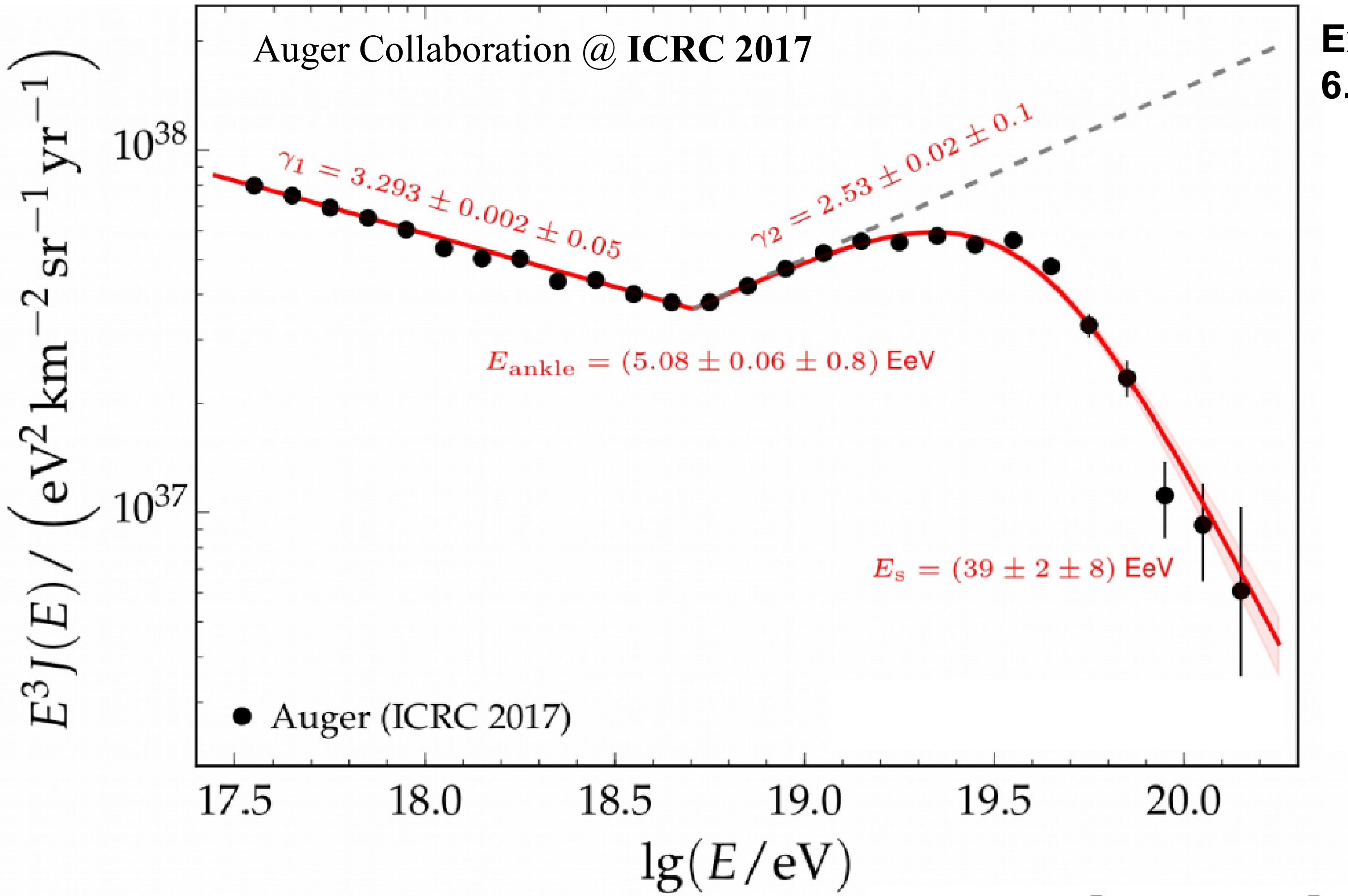


Four independent measurements

Flux uncertainties

7-14% SD dense array
6% SD vertical (< 60°)
5% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

The combined Auger spectrum



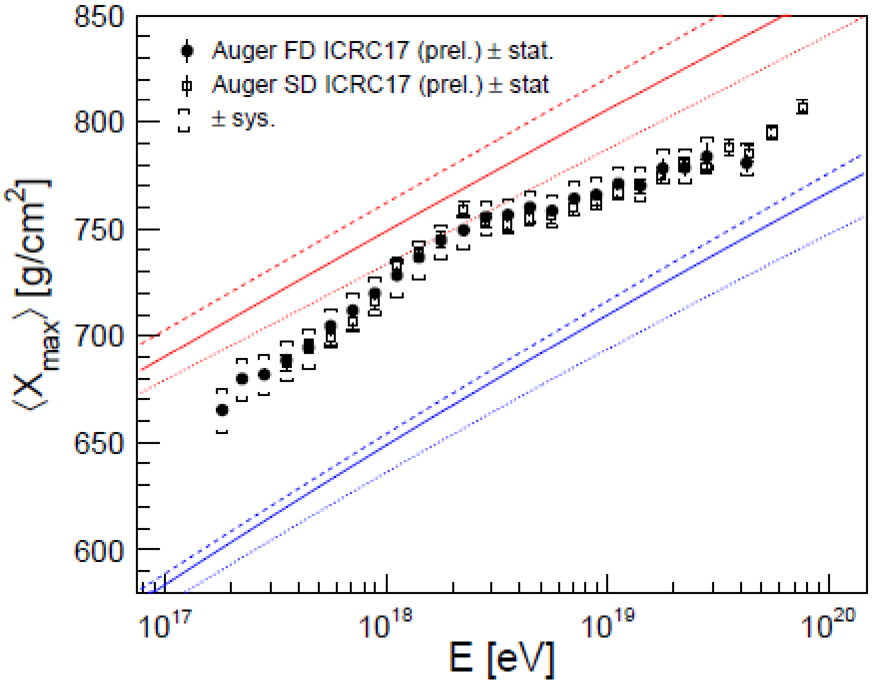
Exposure
6.7 10^4 km^2 sr y

E < E_{ankle} $J(E) \propto E^{-\gamma_1}$

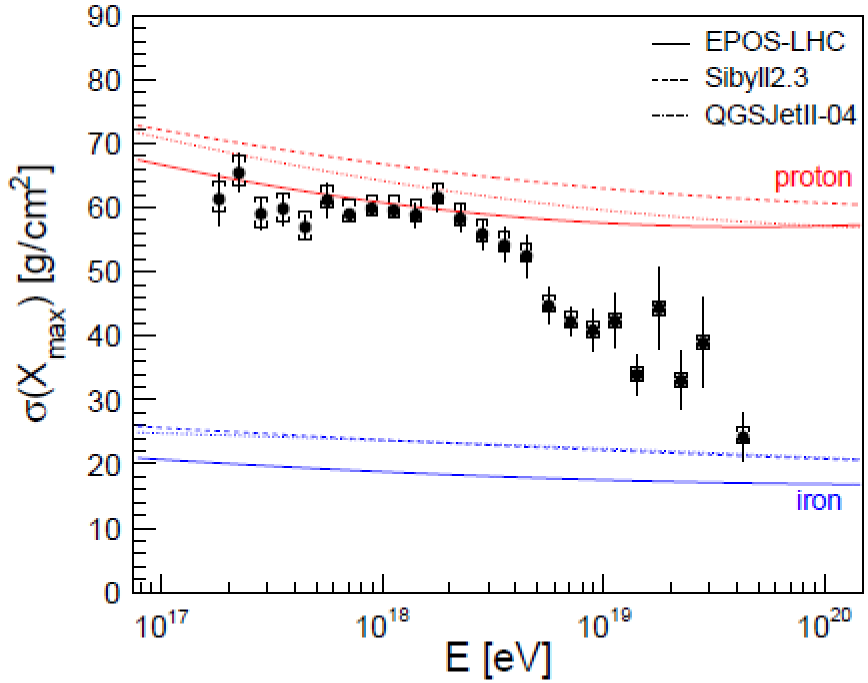
E > E_{ankle} $J(E) \propto E^{-\gamma_2} \left[1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1}$

No indication of dependence on declination

average of X_{max}



std. deviation of X_{max}



FD Syst uncertainty ~ 10 g cm^{-2} (20 g cm^{-2} at the lowest energies)

FD Xmax resolution ~ 20 g cm^{-2} (30 g cm^{-2} at the lowest energies)

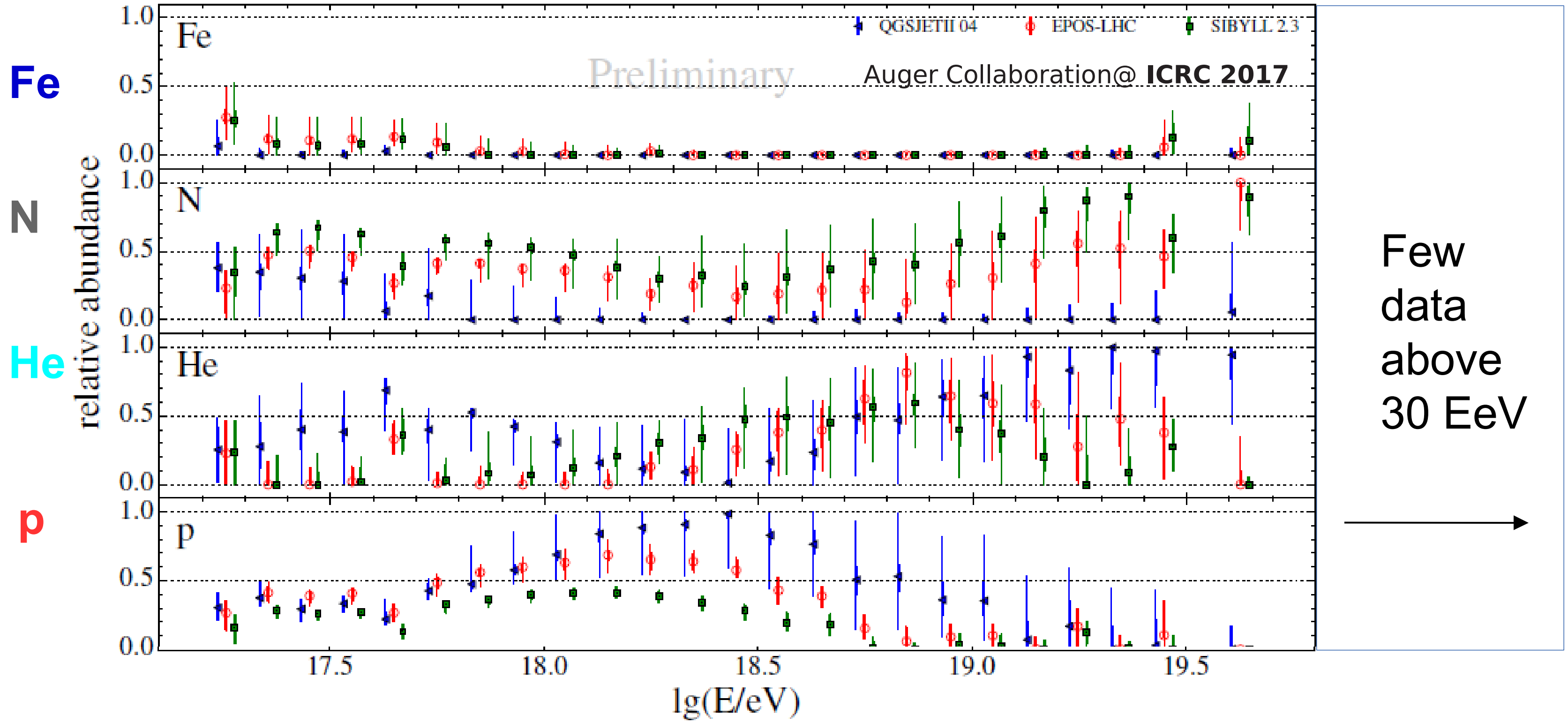
→ non constant composition

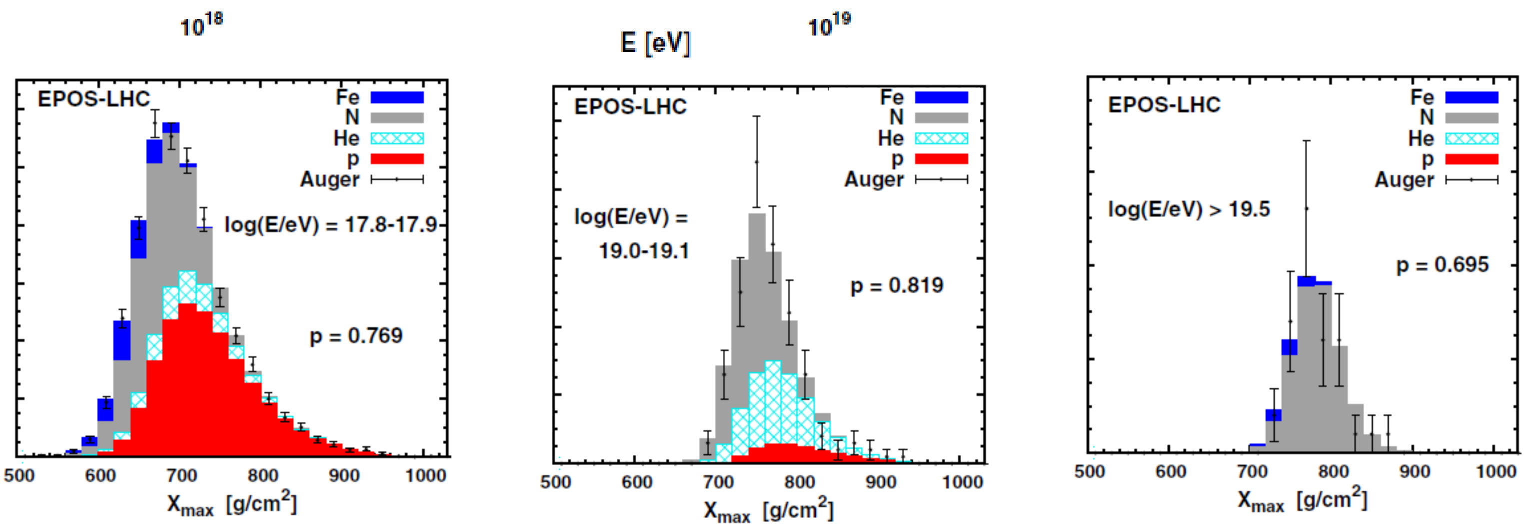
large proton fraction at the ankle

increase of the mean mass above and below ~ 2 EeV

→ interpretation depends on hadronic interaction models

Heavier components take over with energy → exhaustion of sources

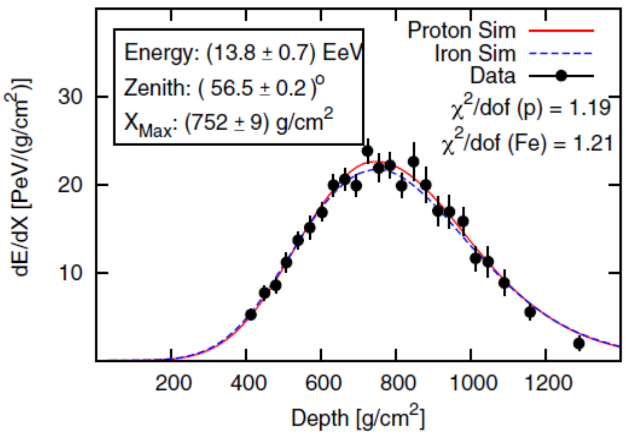




How well hadronic models match data?

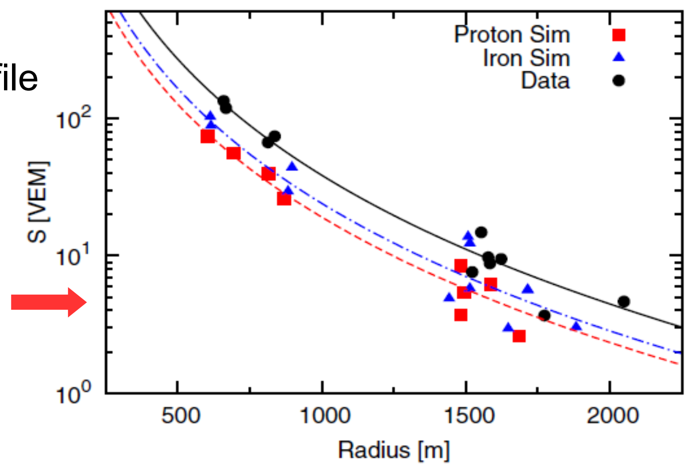
Hybrid events ~ 10^{19} eV, 0°< zenith 60°

PRL 117, 192001 (2016)



Observed longitudinal profile from FD is reproduced by simulations

Measured signal at the ground differ for data and simulations



R_{had} and R_E

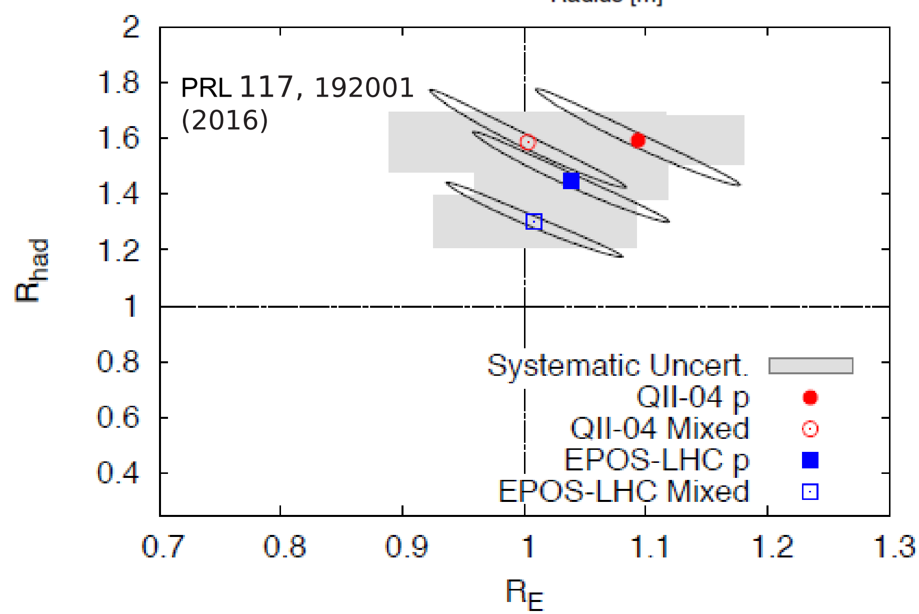
Scaling factors to match data

Evidence of muon excess

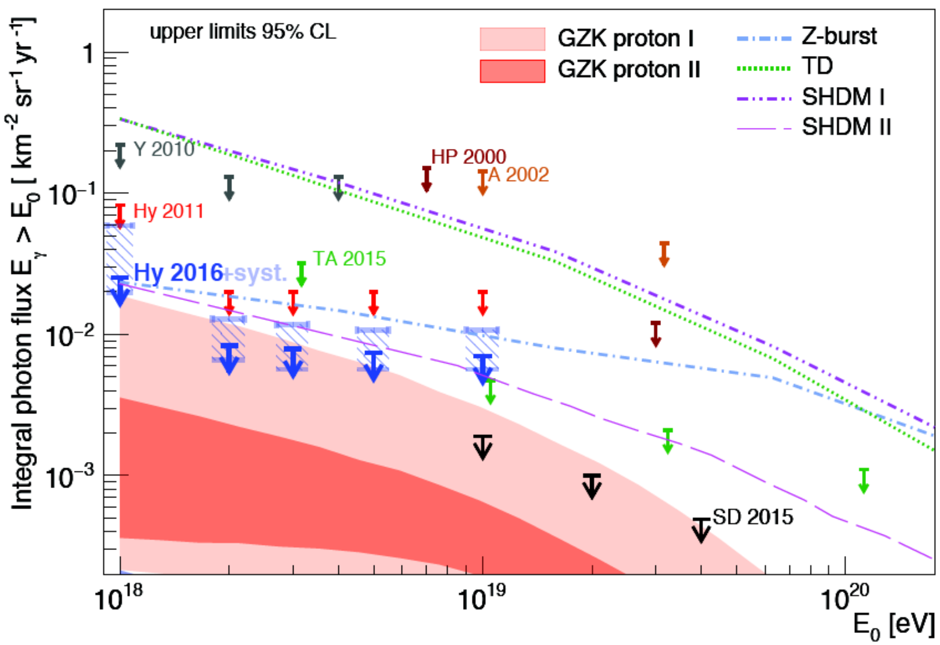
1.3< R_{had}<1.6

Insensitive to energy scale uncertainty

R_E~1



Search for photons and neutrinos



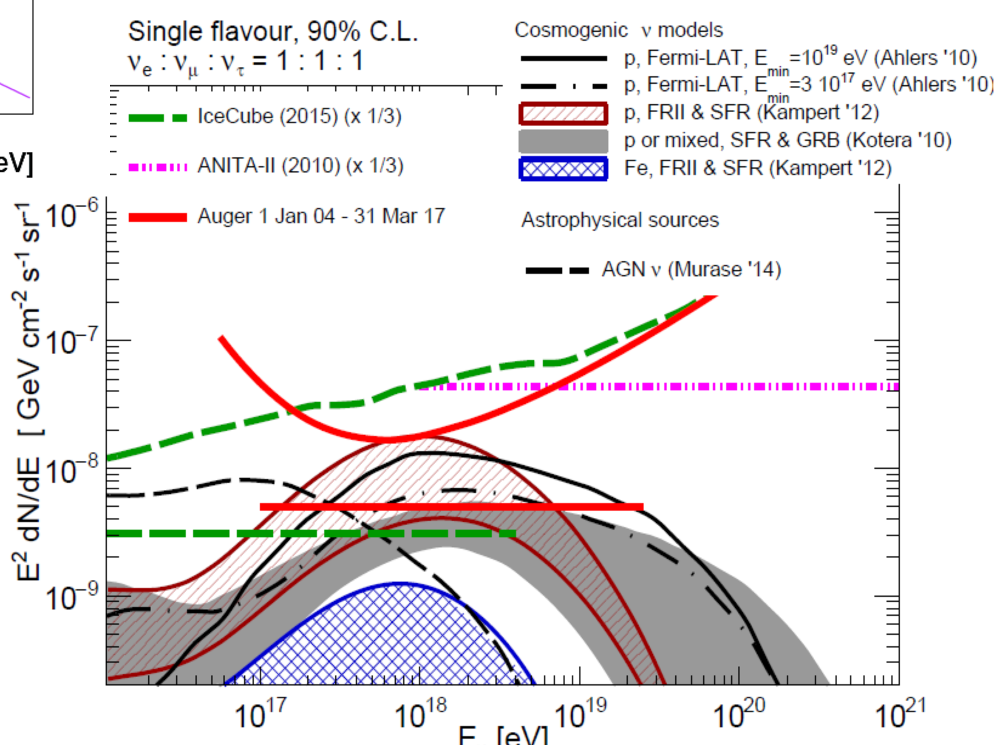
Photons

4 photons candidate above 10 EeV (SD)
3 photons candidate between 1-2 EeV (Hybrid)

Strictest limits at E> 1 EeV

- Top-down model strongly disfavored

- CR proton dominated scenario start to be disfavoured



Neutrinos

No candidates

$dN/dE = k\ E^{-2}$

→ $k \sim 5 \times 10^{-9}$ GeV $cm^{-2} s^{-1} sr^{-1}$

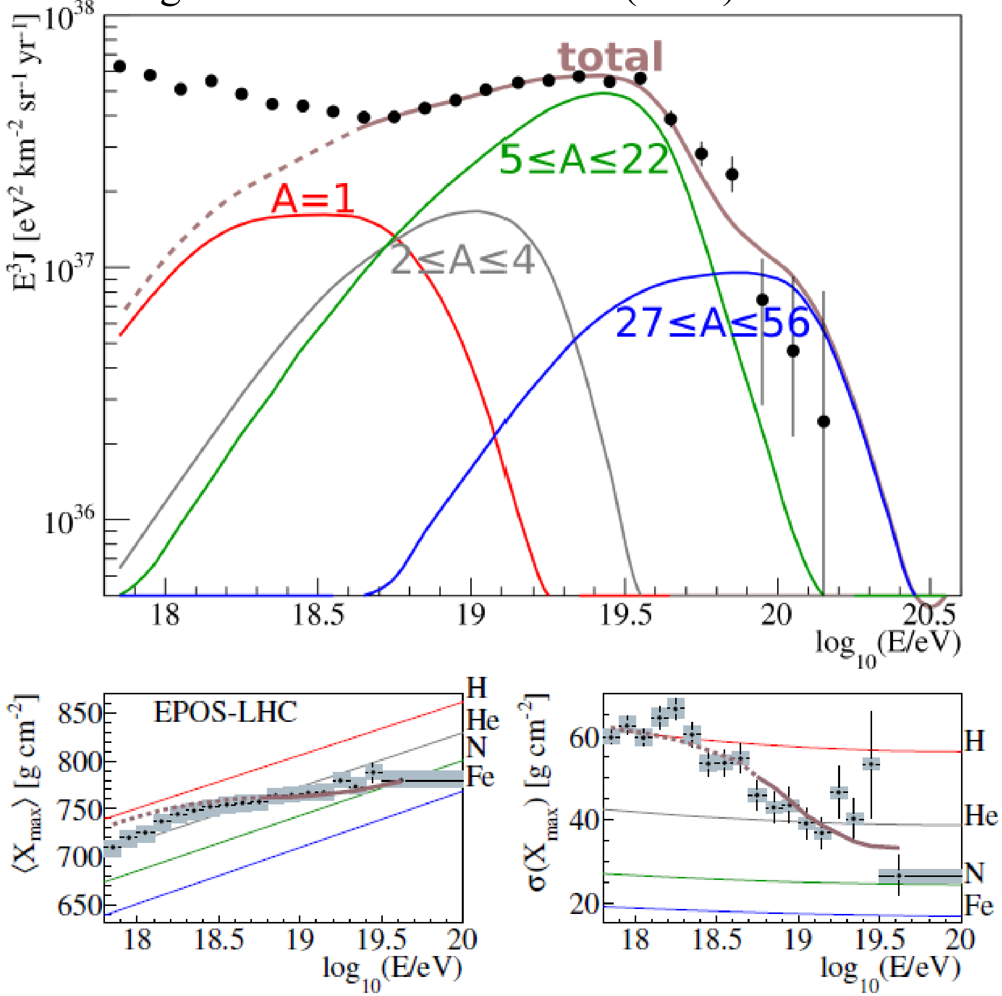
[0.1 – 25] EeV

Auger limits constrains models with pure proton primaries

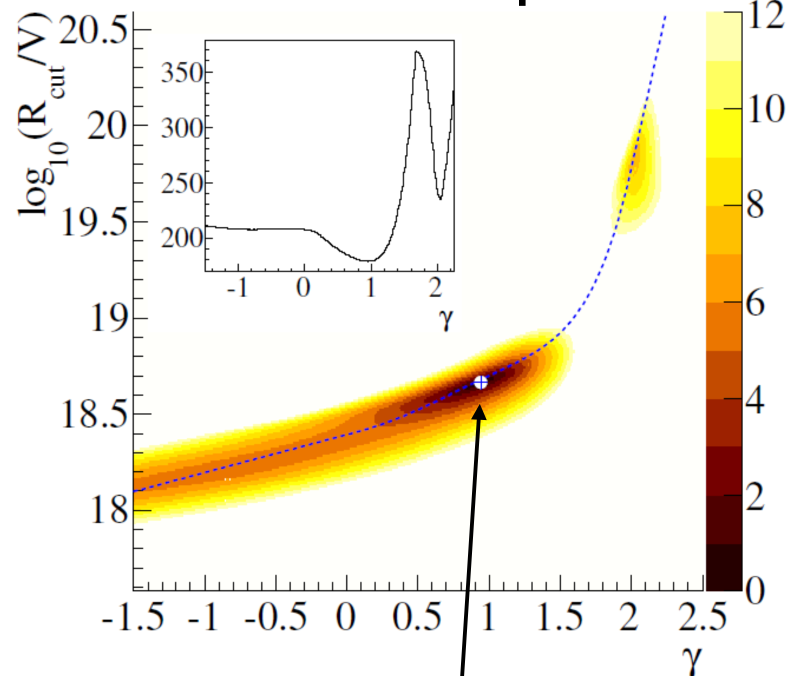
Auger data (spectrum and X_{max} simultaneously) vs astrophysical scenarios

Post-LHC models for air shower propagation through the atmosphere

Auger Collaboration JCAP04 (2017) 038



Likelihood plot



Best fit
Hard injection spectral index γ (~1)
Cutoff Energy E_{log}~ Z X 4.5 EeV
Source scenario favored

CAVEAT: Dependence on the propagation models

i.e cross sections for photo-disintegration and for background light spectrum

Large Scale anisotropy at the highest energies

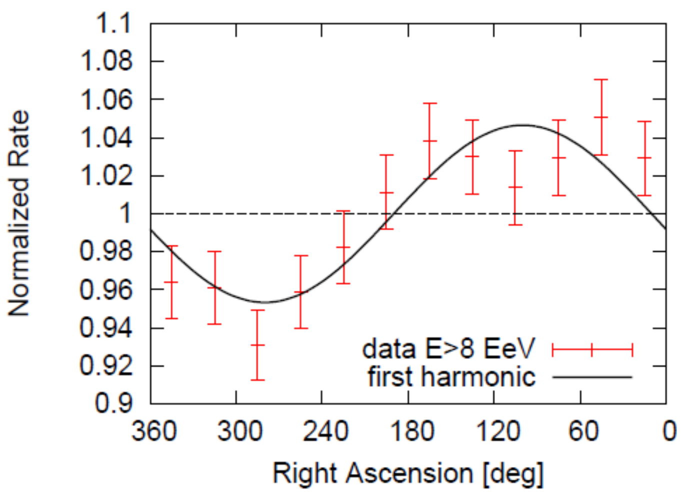
Auger Collaborations @ **ICRC 2017**

E > 8 EeV
Exposure=76800 km²sr y

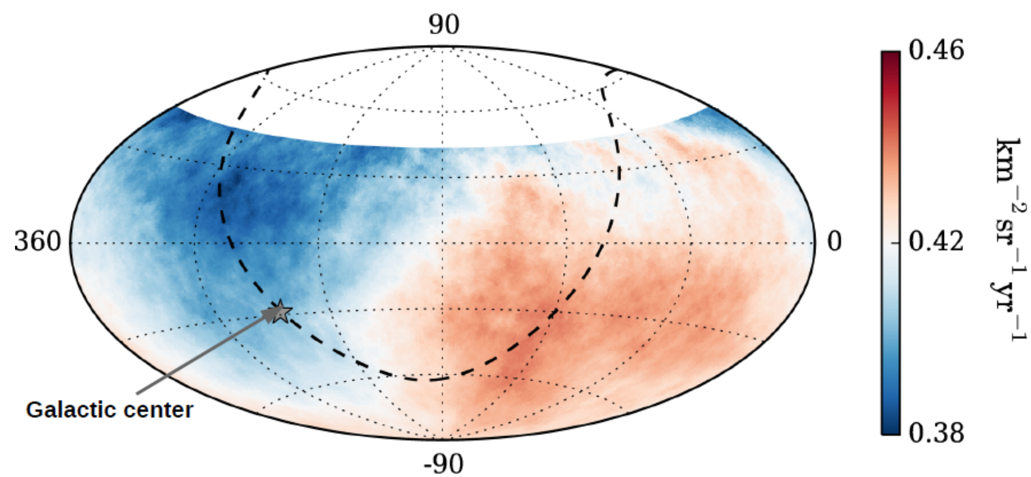
Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
>8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)



Equatorial coordinates



3D dipole $\rightarrow (6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$

dipole direction ~ 125° from GC → **disfavors galactic origin**

Interpretation →

Inhomogeneus large scale distribution of sources
Diffusion in extra-galactic magnetic field by nearby sources

Indication of anisotropy at intermediate scale

Auger @ ICRC2017

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

AGN from 2FHL catalog.
17 bright objects within 250 Mpc.
Flux >50GeV as proxy for UHECR

Starburst Galaxies 23 bright objects within 250 Mpc. Radio Flux > 1.4 GHZ as proxy for UHECR

Method: sky model as the sum of an isotropic fraction plus the anisotropic component from selected sources f_{ani}

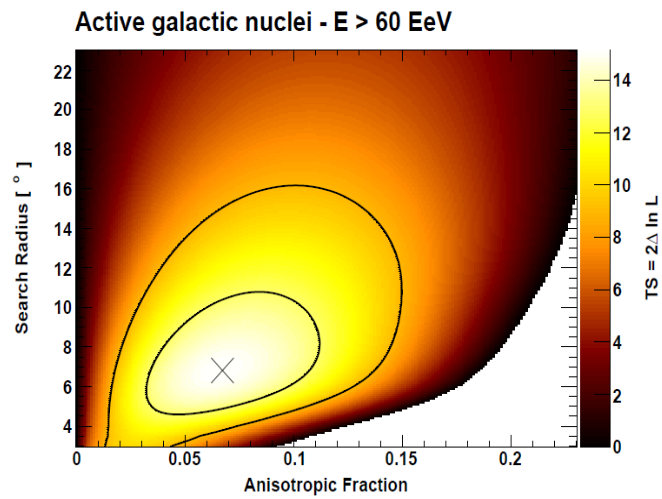
Test statistics (TS): likelihood ratio

$$TS=2\log[L(\Psi,f_{ani})/L(f_{ani}=0)]$$

f_{ani} and Ψ (search radius) free parameters

Directional exposure and relative weight of sources taken into account.

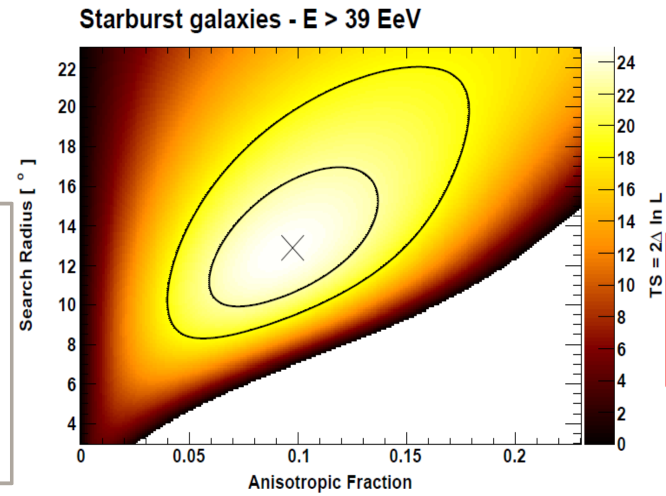
PRELIMINARY!



TS = 15.2 E_{th}> 60 EeV

f_{ani} ~ 7% Ψ = 7°

post-trial probability
3×10^{-3} (~ 2.7 σ)

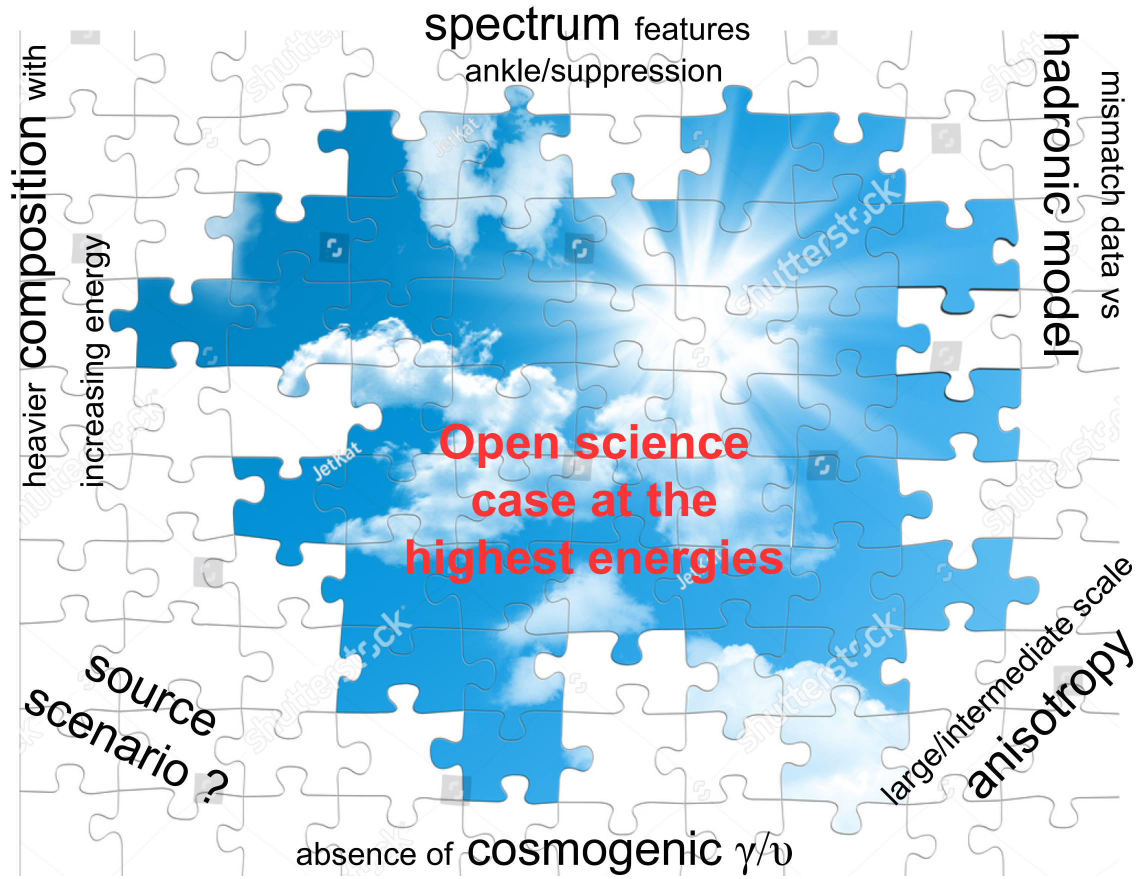


TS = 24.9 E_{th}> 39 EeV

f_{ani} ~ 10% Ψ = 13°

post-trial probability
4×10^{-5} (~ 4.9 σ)

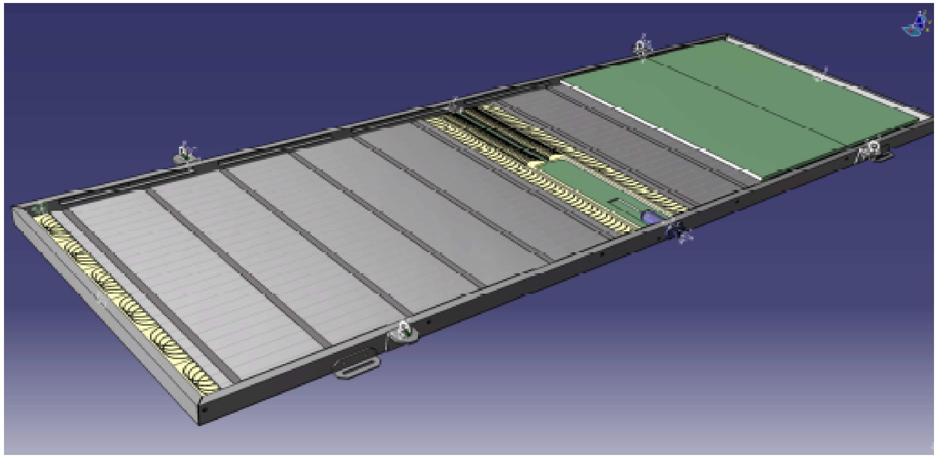
Attenuation according to JCAP04 (2017) 38.
Negligible for nearby objects (starburst)



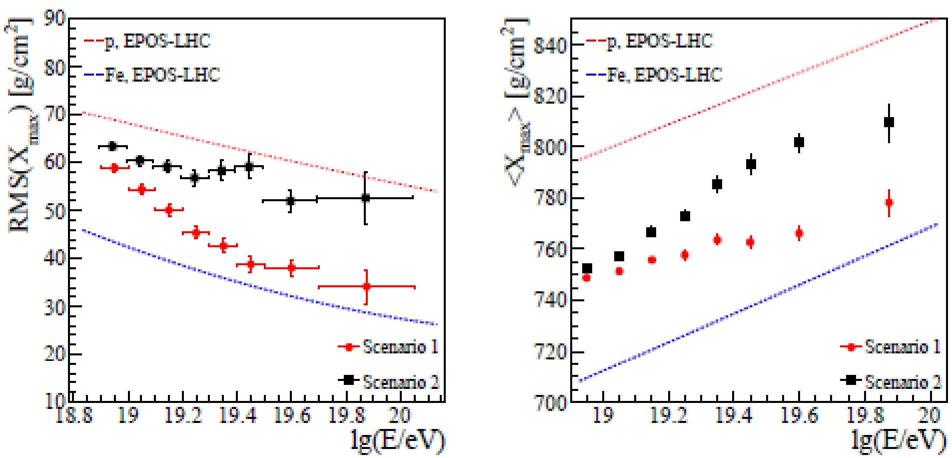
- need composition data E> 40 EeV to understand the nature of the suppression
- better understanding of hadronic interaction models
- isolate a light component pointing back to astrophysical sources

Auger upgrade program: Auger Prime

3.8 m^2 (1 cm thick) scintillators on each of the main array station



Scintillators sensitive to the electromagnetic content of the shower



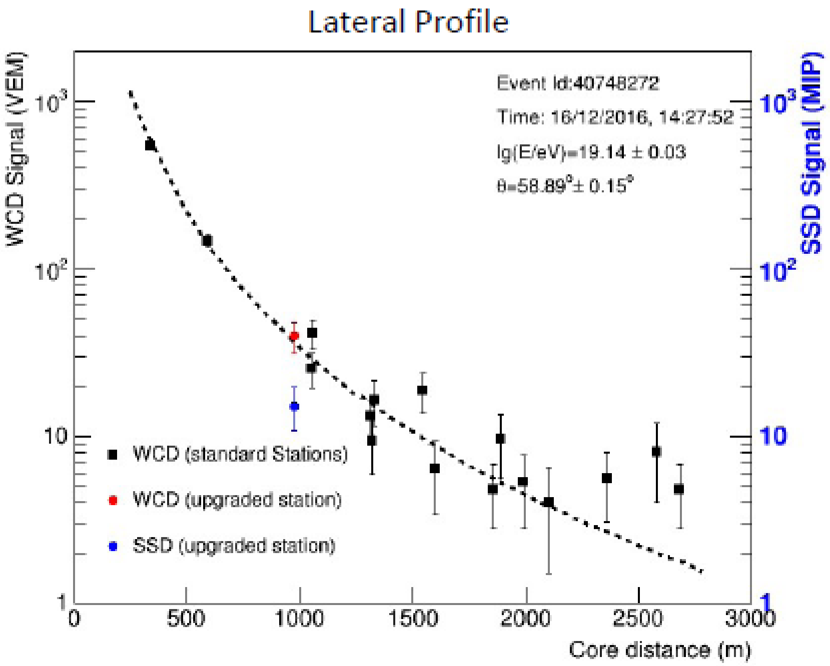
Scenario 1 : maximum rigidity

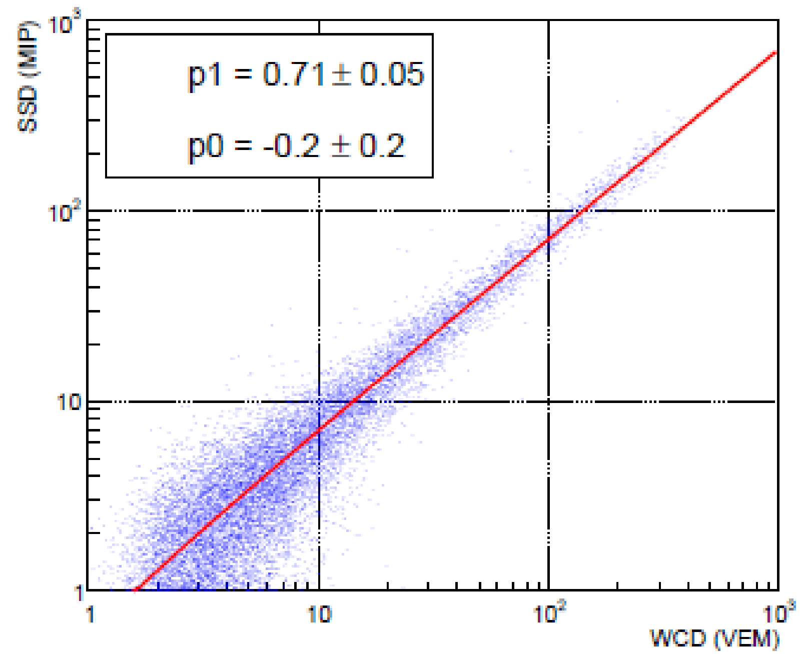
Scenario 2: photo-disintegration

Moreover

- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

The Engineering array (12 upgrgaded station) in operation since October 2016



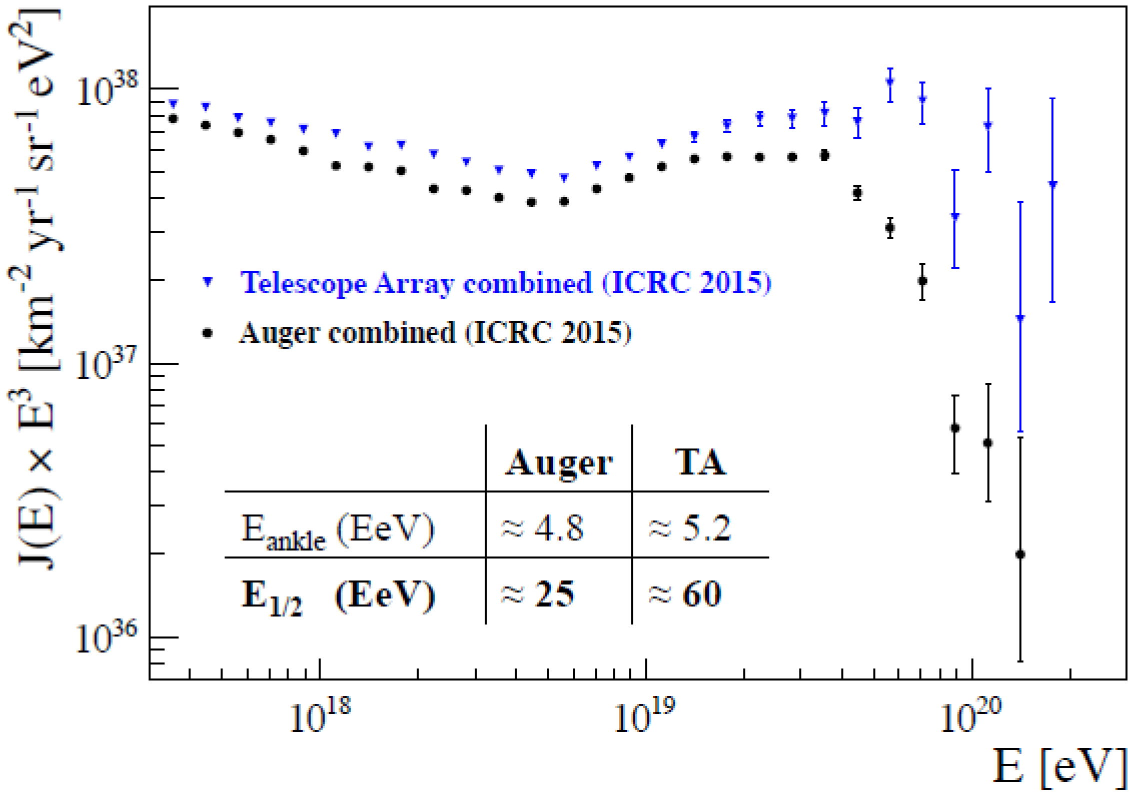


Time Schedule

- Designed finalized and tested
- 180 SSD modules to be shipped by the end of 2017
- finish construction by 2019
- data taking up to 2025

BACKUP SLIDES

AUGER vs Telescope Array



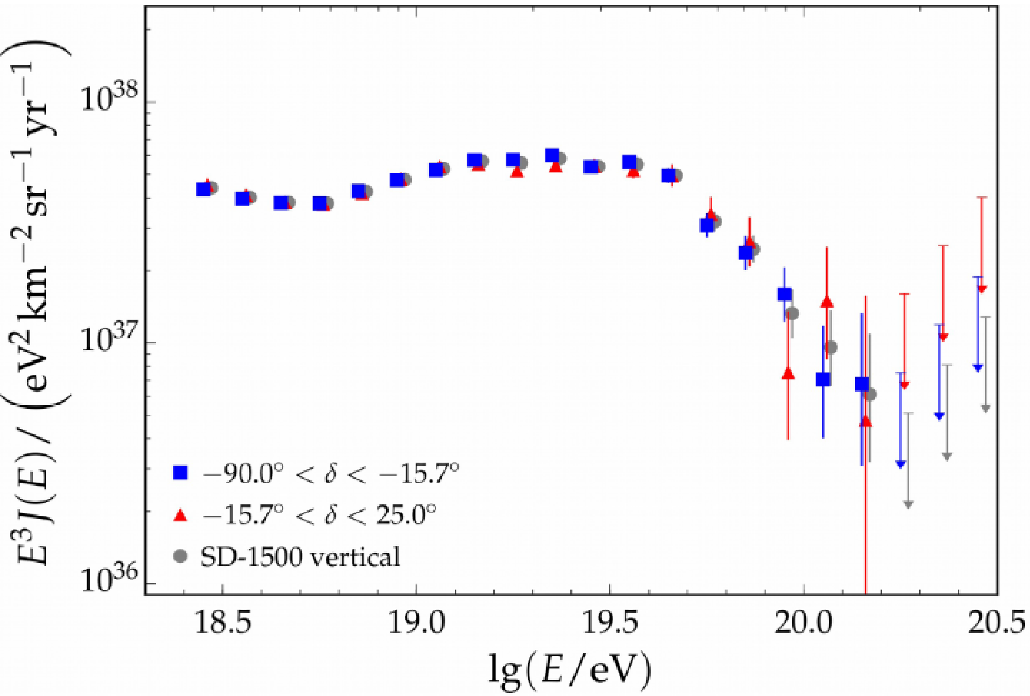
	Auger	TA
E_{ankle} (EeV)	≈ 4.8	≈ 5.2
$E_{1/2}$ (EeV)	**≈ 25**	**≈ 60**

Marginally consistent at the highest energies

Position and steepness of the suppression quite different

We are observing the sky from different Hemispheres
Does the point of view matters?

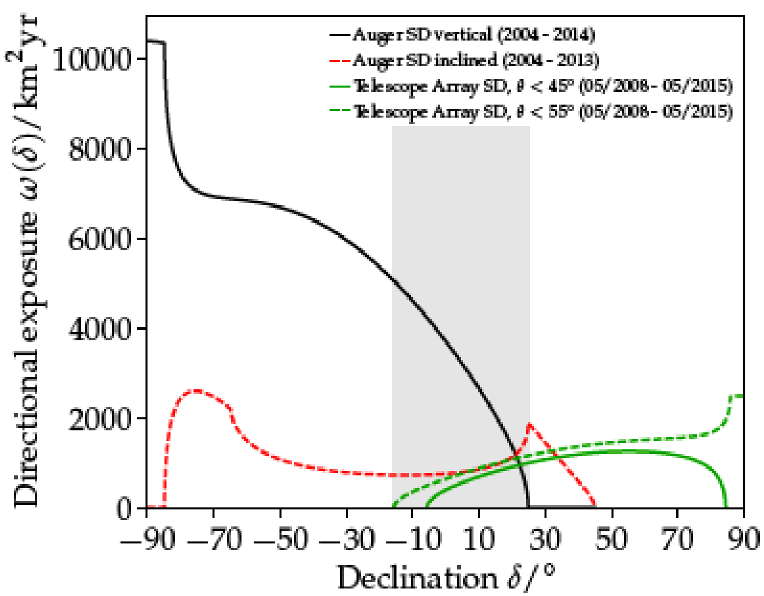
AUGER vs Telescope Array



Auger Collaboration @ICRC 2017

No indication of dependence on declination

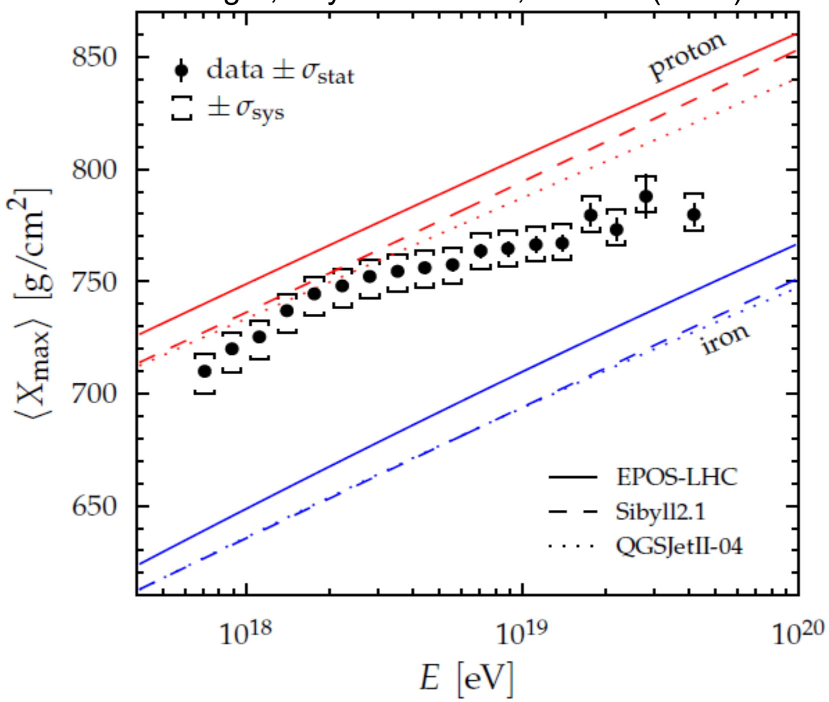
Compatible with the dipole anisotropy observed at E > 8 EeV



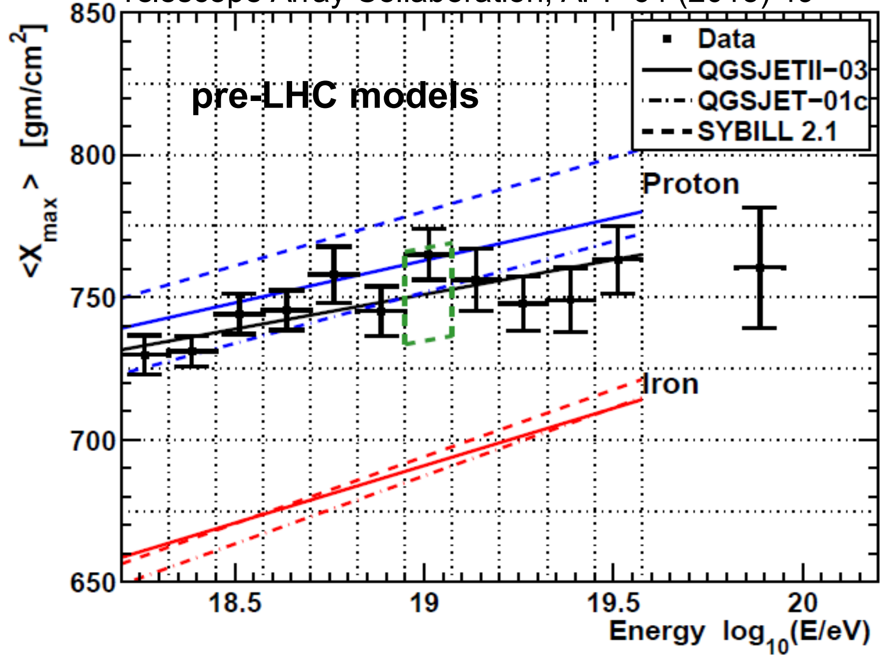
Telescope Array hot spot (δ~ - 44°) is outside the common declination band

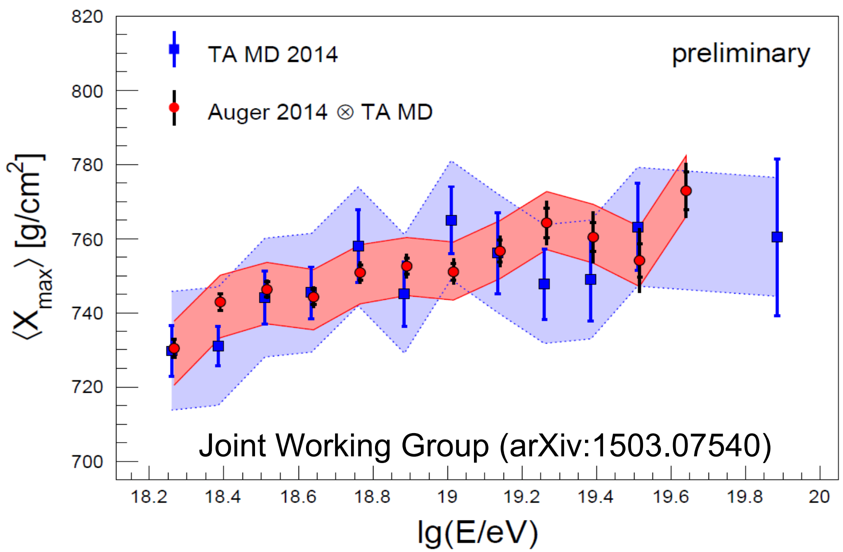
AUGER vs Telescope Array

Auger; Phys. Rev. D 90, 122005 (2014)



Telescope Array Collaboration, APP 64 (2015) 49





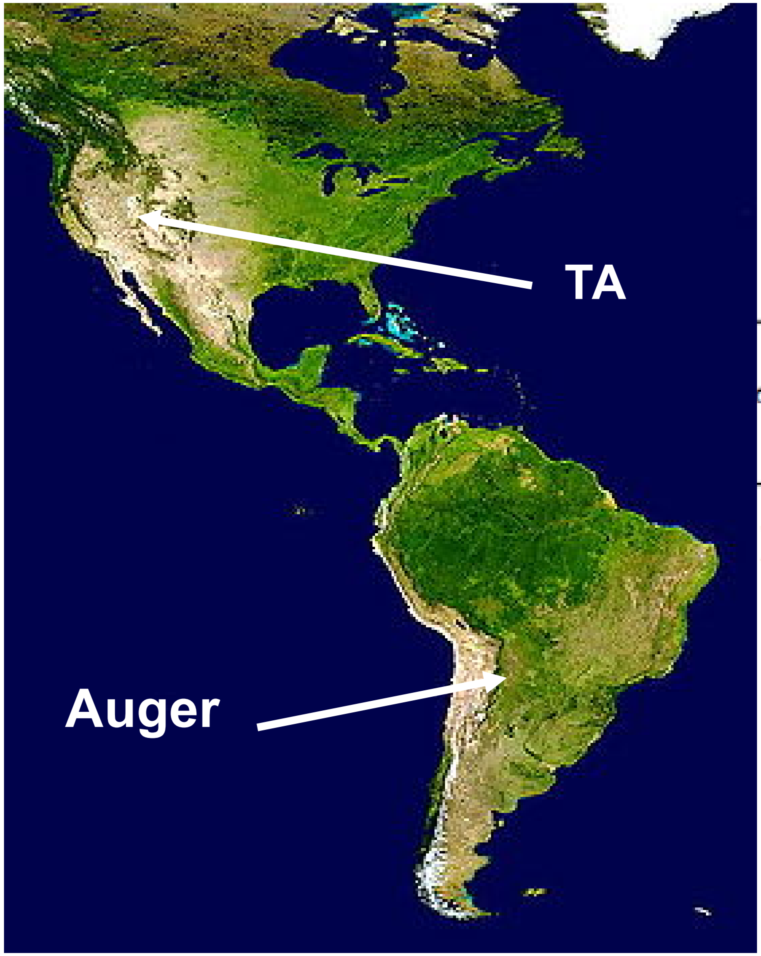
Apparently the two measurements differ

different hadronic models except for Sibyll.
different methods

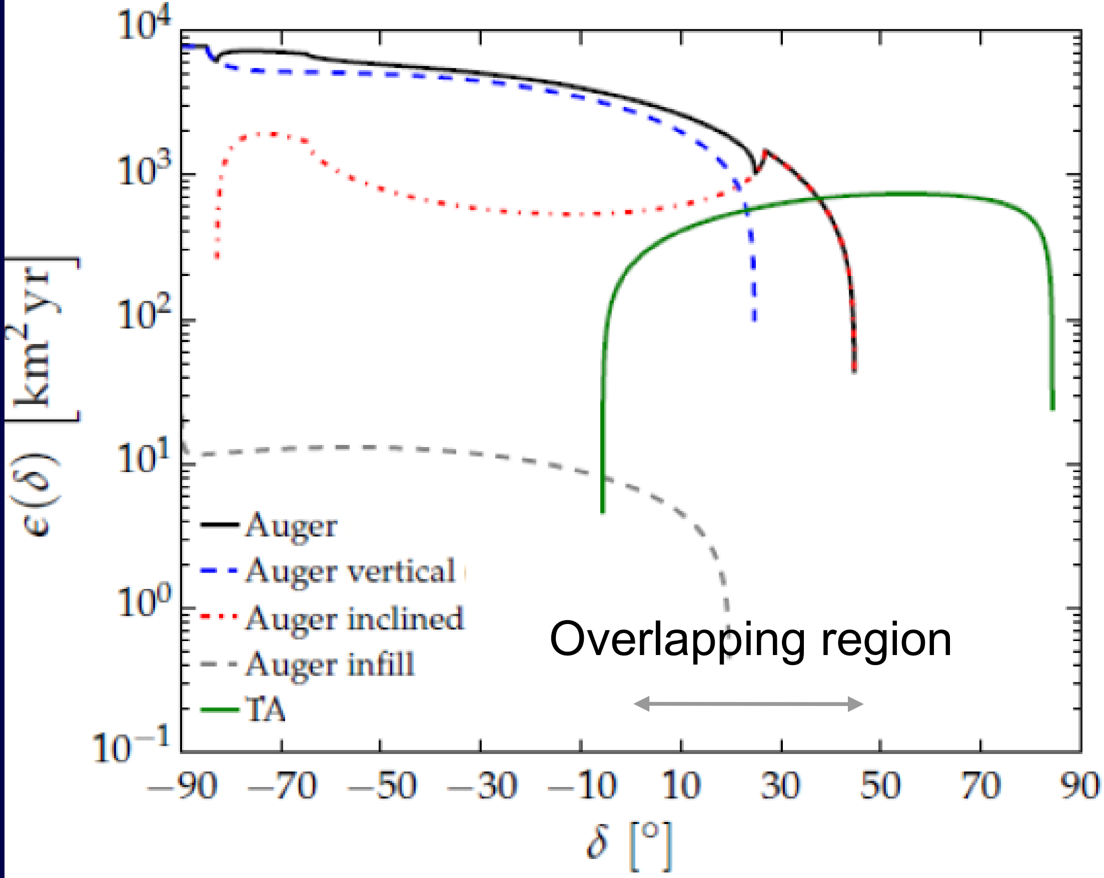
Auger data folded with TA acceptance are in perfect agreement with TA data at the level of few g/cm^2 (much less than systematic uncertainty)

Confirmed by further analysis @ ICRC2017

Auger and Telescope Array



Exposure (Time ⊗ Area)



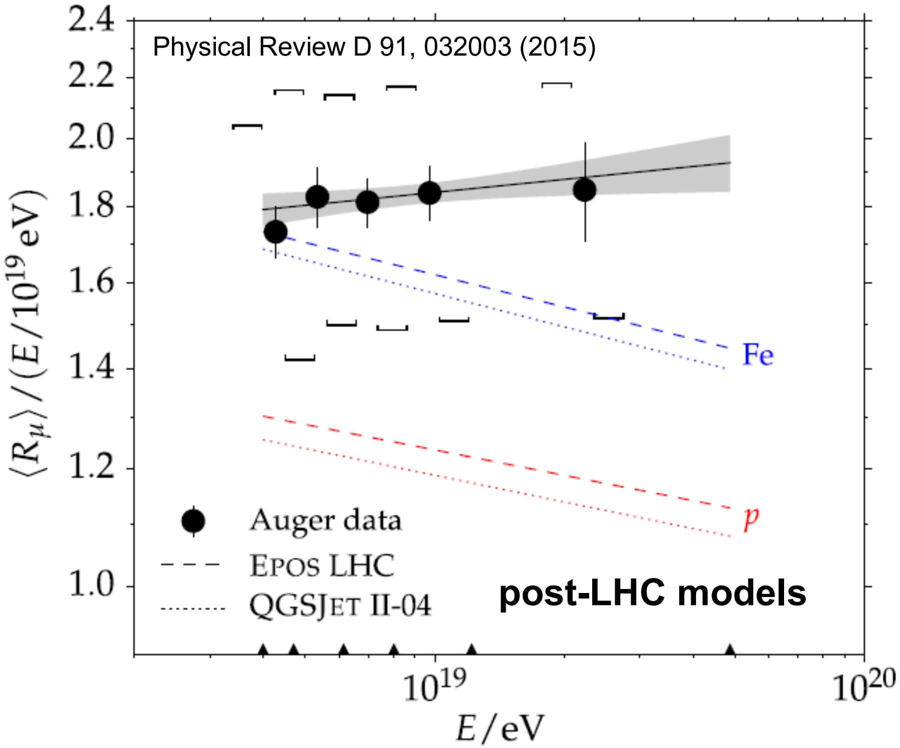
- Auger and TA are complementary

Auger ~3000 km², TA ~ 700 km²

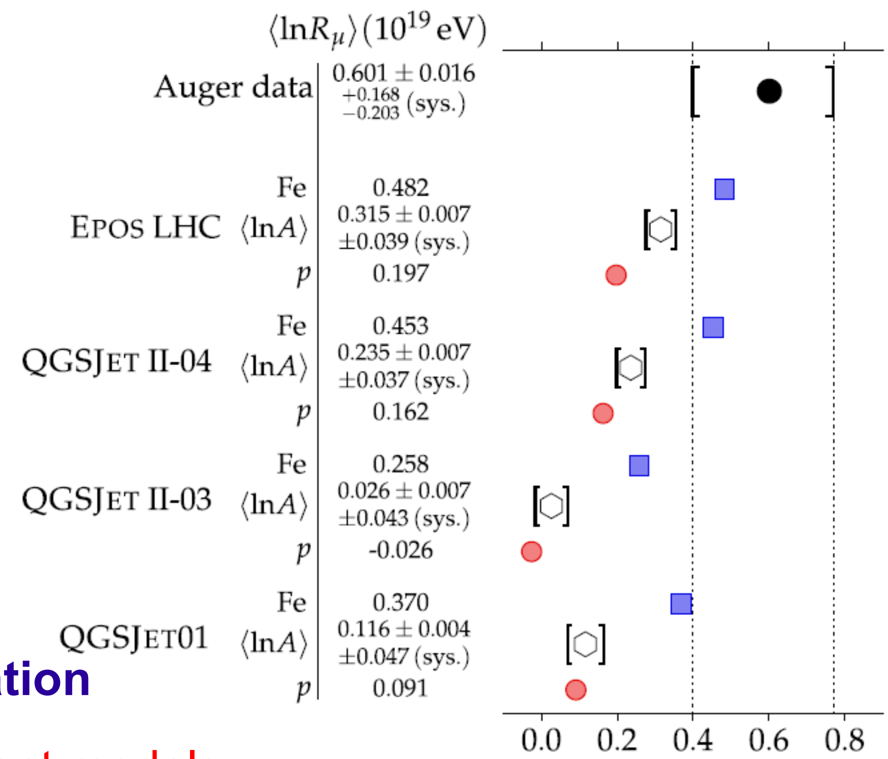
Auger exposure ~ 8 times TA

How well our hadronic models match data?

Average muon content per shower
(inclined hybrid)



Muon content vs predictions for proton and iron plus prediction for the mix that matches FD Xmax data

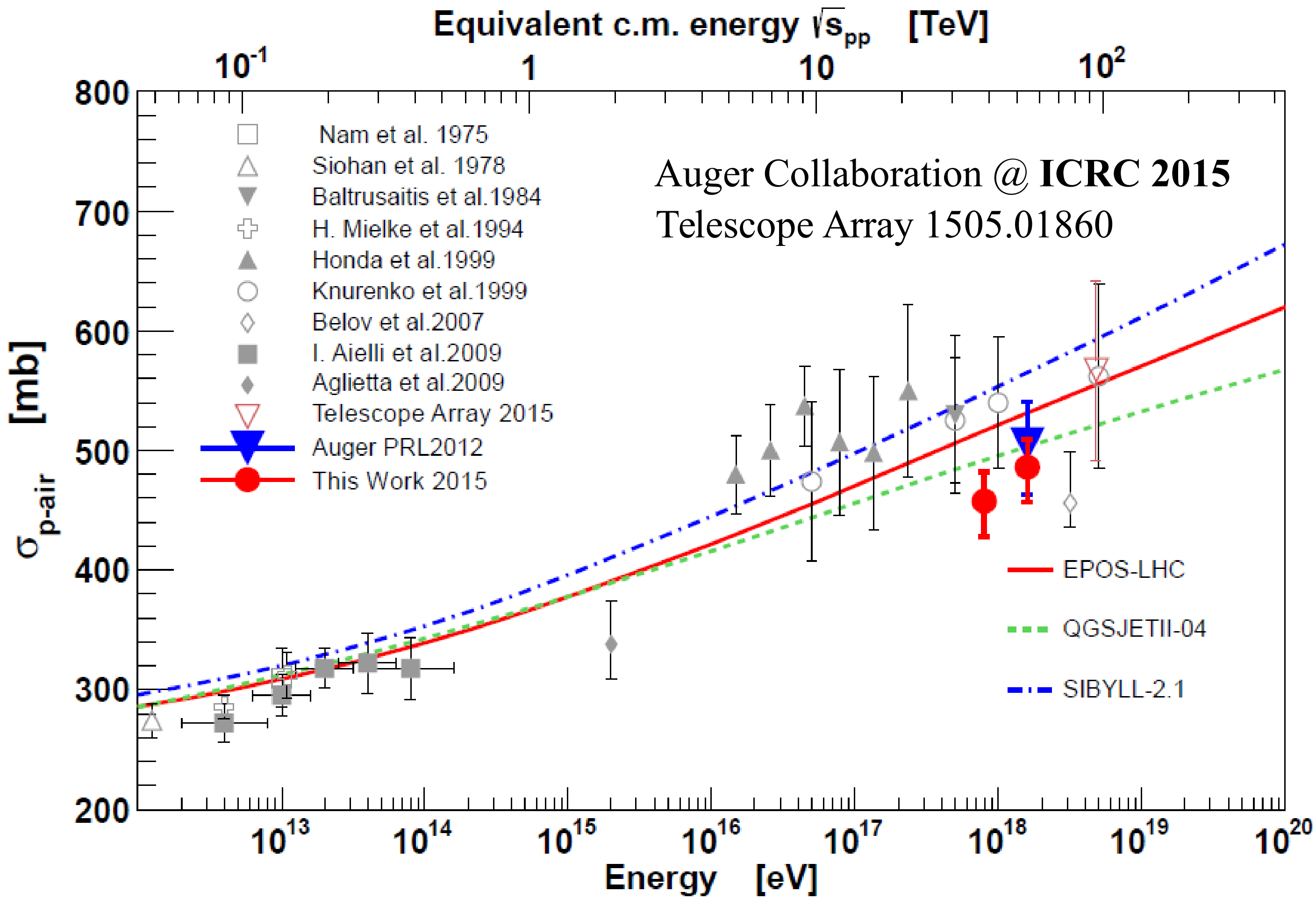


More muons in data than in simulation

Not easy to reproduce data with current models

Pion interaction major uncertainty for muon discrepancy **[R. Engel @ ICRC 2015]**

p-air cross-section

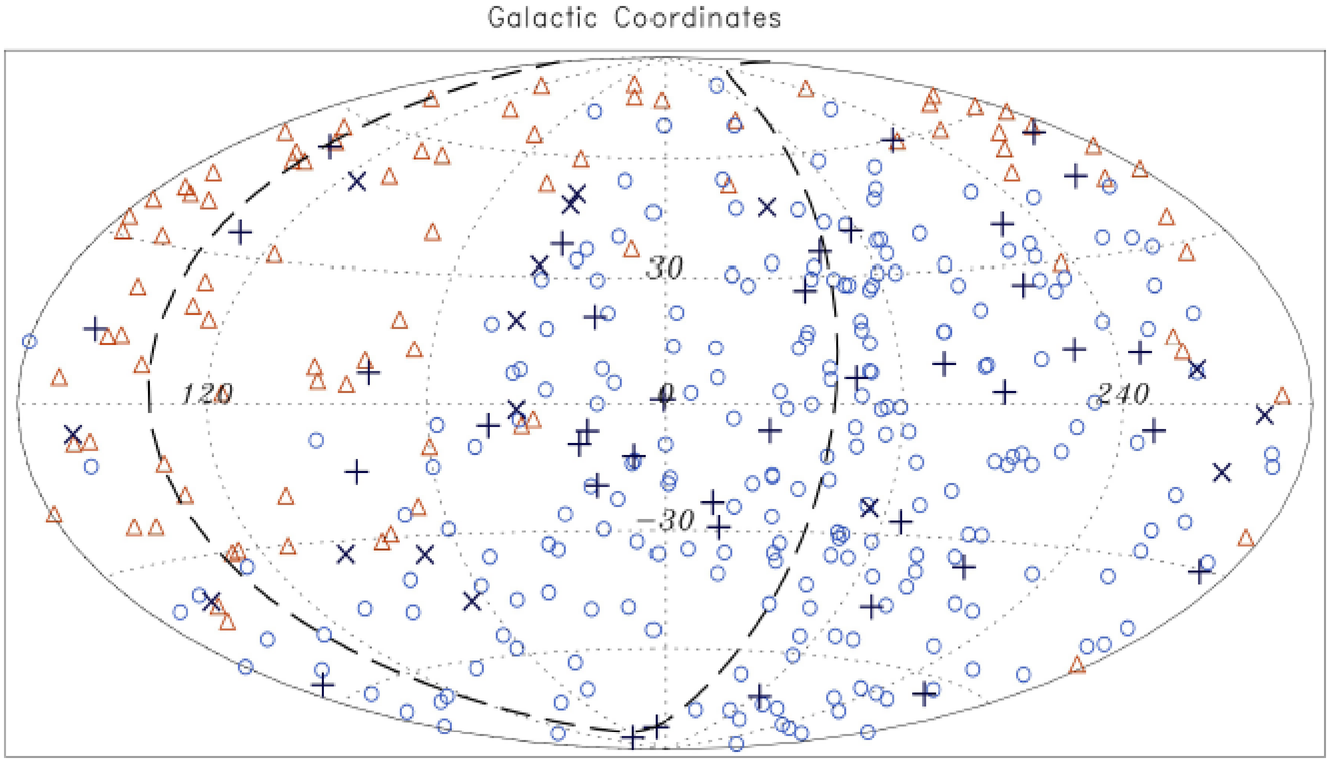


Lower energy [457±18(stat)+19/-25(syst)] mb
Higher energy [486±16(stat)+19/-25(syst)] mb

Sys uncertainty: method, models, helium contamination

Correlation with UHE neutrinos

Telescope Array, Auger, IceCube Collaborations @ **ICRC 2015**



Joint analysis of 3 Collaborations!

△TA > 57 EeV O Auger > 52 EeV + IC cascade X IC tracks

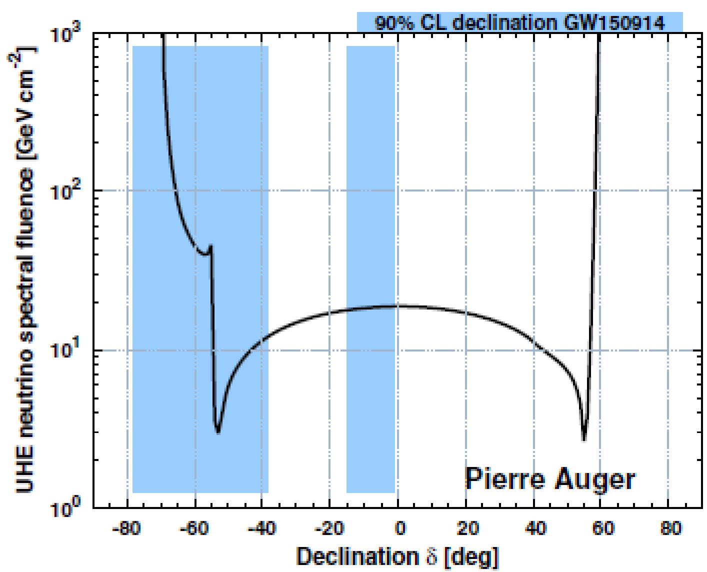
All correlations less than 3.3 sigma significance
To be monitored with larger data set
(in particular the analysis with cascades)

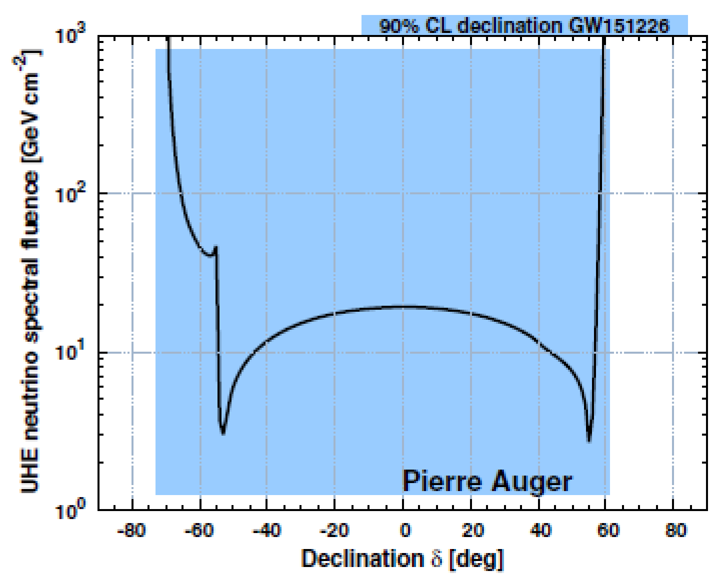
Ultra-high energy neutrino follow-up of gravitational waves events GW150914 and GW151226

The Pierre Auger Collaboration, Phys. Rev. D 94, 122007 (2016)

Search for neutrinos in time window of 500s or 1 day around the events

Sensitiviy for δ in the band -65° up to 60°



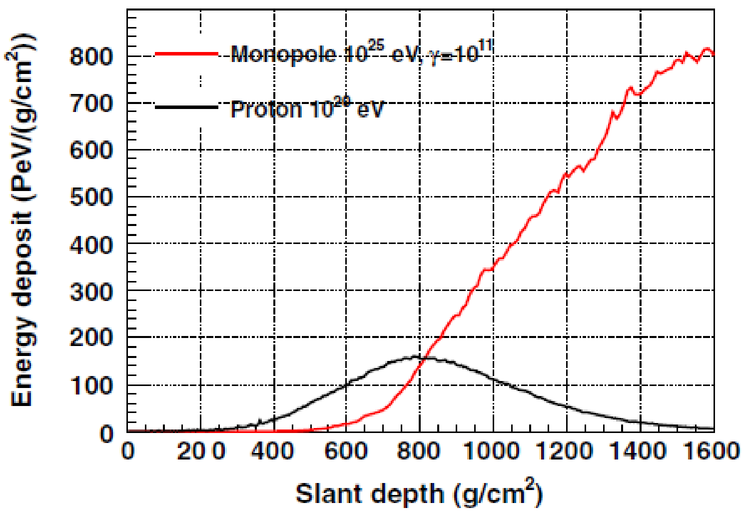


No candidates found. Fluence upper limit

Blu bands:
90% CL position of the GW event

Search for ultrarelativistic monopole

The Pierre Auger Collaboration, Phys. Rev. D 94, 082002 (2016)



Simulated longitudinal profile for a monopole

No candidate found
Upper limits set