Highlights of the Pierre Auger Observatory

after ≈ 10 years of operation (and ≈ 20 years from the conception)

Piera L. Ghia *(LPNHE, Paris and Univ. Paris VI and Paris VII)*

on behalf of the ***Pierre Auger Collaboration***

The Pierre Auger Collaboration

≈ 500 members, from 16 countries and 86 institutions

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Without them, the construction and the smooth operation of the Observatory,
- and the harvest of results presented here - would not have been possible

Auger science case

Based on the first Auger ICRC proceedings
M. Boratav et al, ICRC 1997, Durban

“The **Pierre Auger Observatory**...employing a giant array of particle counters and an optical fluorescence detector...aims at studying, with high statistics, cosmic rays with energies around and above the so-called Greisen-Zatsepin-Kuzmin spectral cutoff...Its main aims are:...

1. a precise reconstruction of the **energy spectrum**...

2. the **identification of primaries**, even if only statistical...Are they protons, nuclei, or perhaps something exotic? (e.g., the detection of a large amount of **gammas and neutrinos** would be an indication in favor of “exotic” theories...)...Inferences on mass composition will be drawn from the study of shower properties that might constrain **hadronic interaction models** at energies well beyond the reach of accelerator-based experiments...

3. a systematic study of the **arrival directions**, that will indicate if there is anisotropy in the distribution and/or clusters which would indicate the existence of point sources...”

Based on 28 Auger proceedings at ICRC 2015:
3 jointly with the Telescope Array Collaboration;
1 with the IceCube and TA collaborations

Outline

1. The Pierre Auger Observatory

Surface, Fluorescence, Radio, Muon and Atmospheric Detectors

2. Studies of ultra-high energy cosmic rays (and not only)

2.1 Energy spectrum and mass composition (including photons and neutrinos)

2.2 Shower properties and hadronic models

2.3 Arrival directions

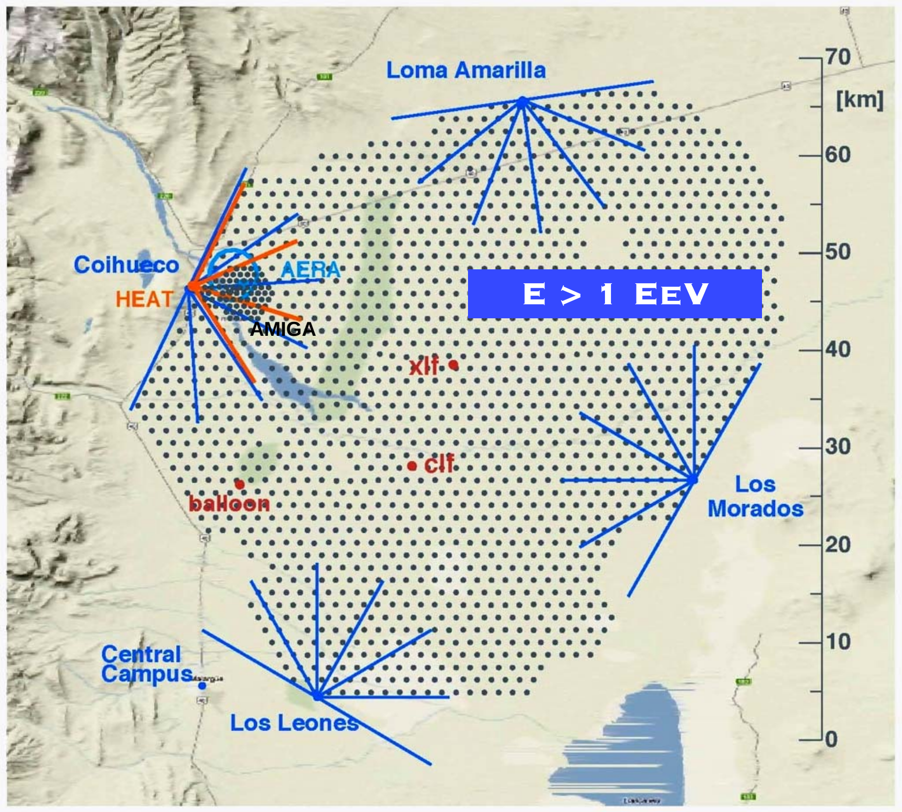
2.4 Not only cosmic rays: p-air cross-section, magnetic monopoles, solar physics

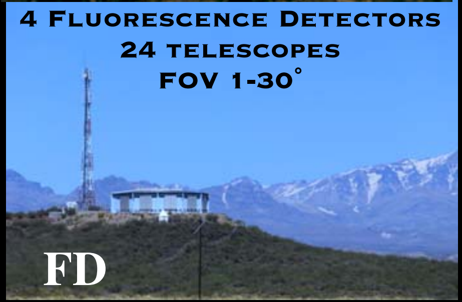
3. Conclusions: Auger(Prime) science case

1. “The **Pierre Auger Observatory**...employing a giant array of particle counters and an optical fluorescence detector...is a “hybrid” ground detector...”

The Pierre Auger Observatory, Argentina

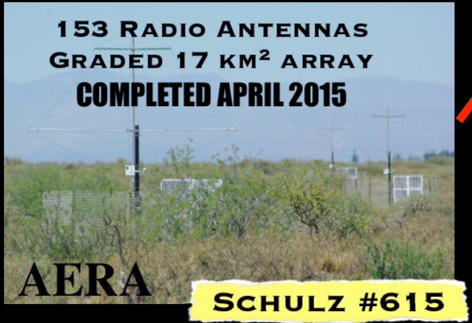
THE INITIAL DETECTORS

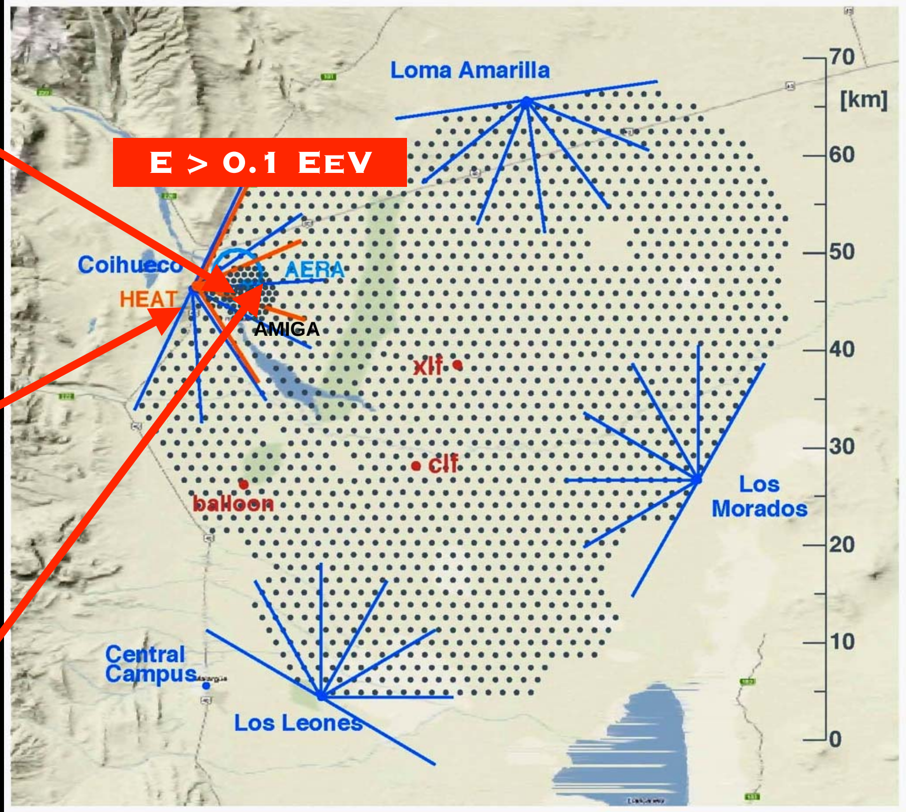




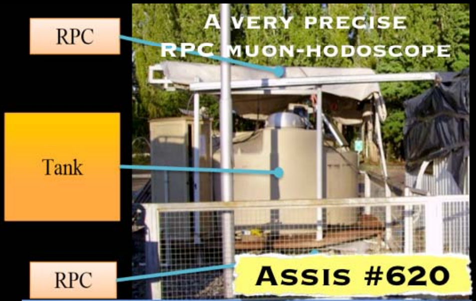
The Pierre Auger Observatory, Argentina

THE NEW DETECTORS

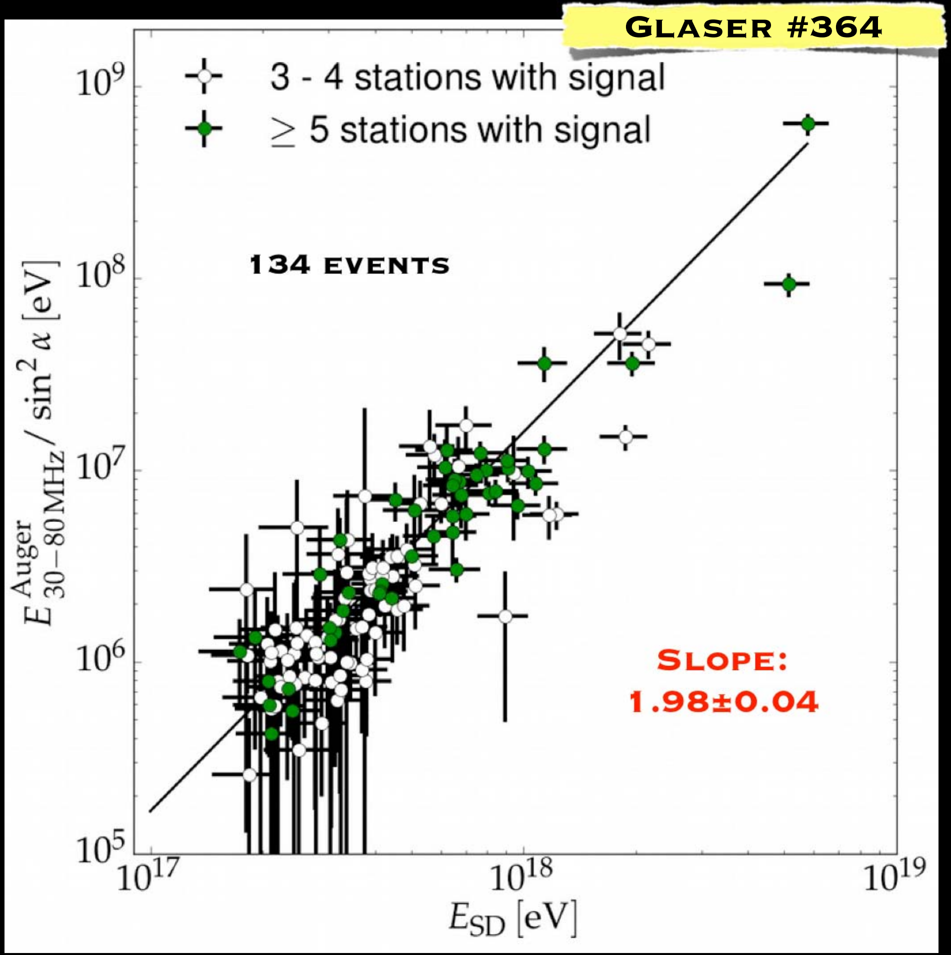




THE INITIAL DETECTORS



The energy in the radio signal of extensive air showers



The showers radio-signals scale quadratically with the cosmic ray energy

Radio energy resolution ≈ 17%

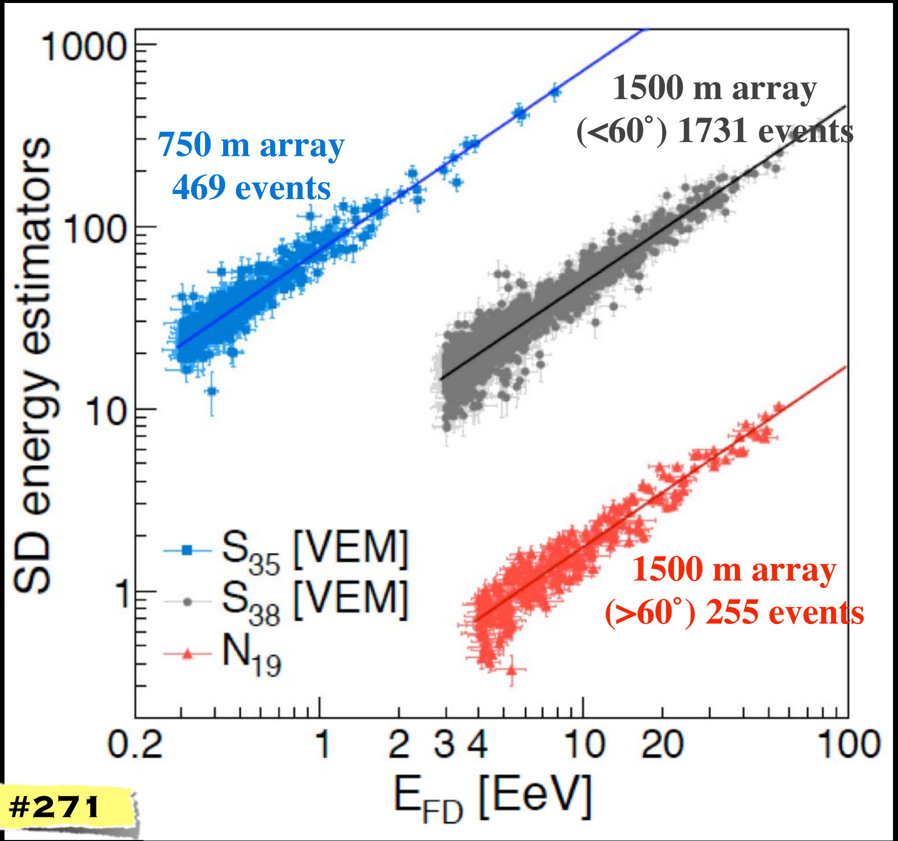
Measurement of the radiated energy (in the 30-80 MHz band):

16 MeV for a 1 EeV cosmic-ray

Independent determination of the energy scale of a cosmic-ray observatory

The data sets

Detector	E_{th} [10^{18} eV]	N($E>E_{th}$)	N($E>4\times10^{19}$ eV)
Hybrid (HEAT&SD)	**0.1**	**≈ 6000**	**-**
SD 750 m	**0.3**	**≈ 60000**	**-**
Hybrid (FD&SD)	**1**	**≈ 10000**	**≈ 15**
SD 1500 m (0˚-60˚)	**3**	**≈ 100000**	**≈ 350**
SD 1500 m (60˚-80˚)	**4**	**≈ 15000**	**≈ 100**



VALIÑO #271

The fluorescence detector sets the energy scale of all data sets
Systematic uncertainty: 14%

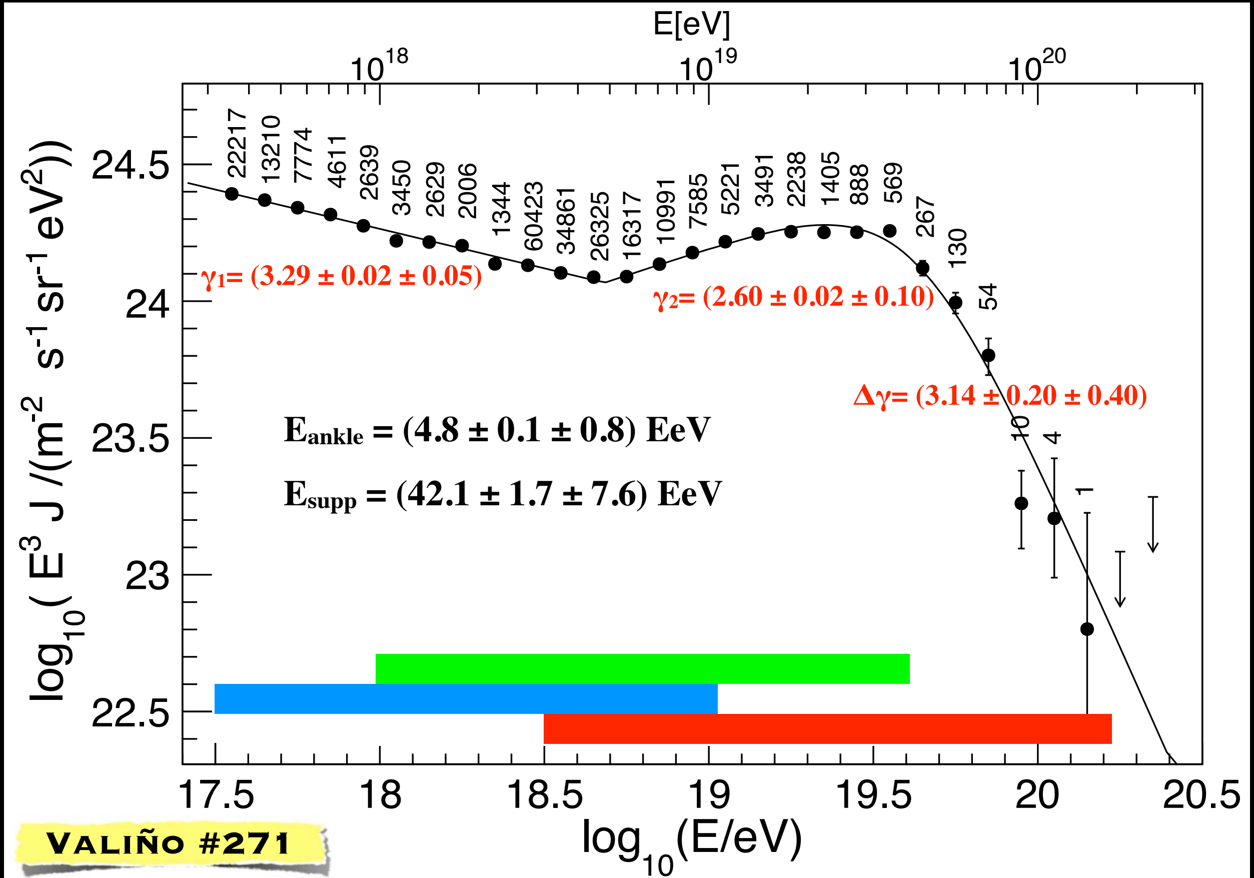
2.1 "...A precise reconstruction of the **energy spectrum**..."

"...The **identification of primaries**...protons? nuclei? ...gammas and neutrinos?"

Precise reconstruction of the all-particle spectrum over 3 decades in energy

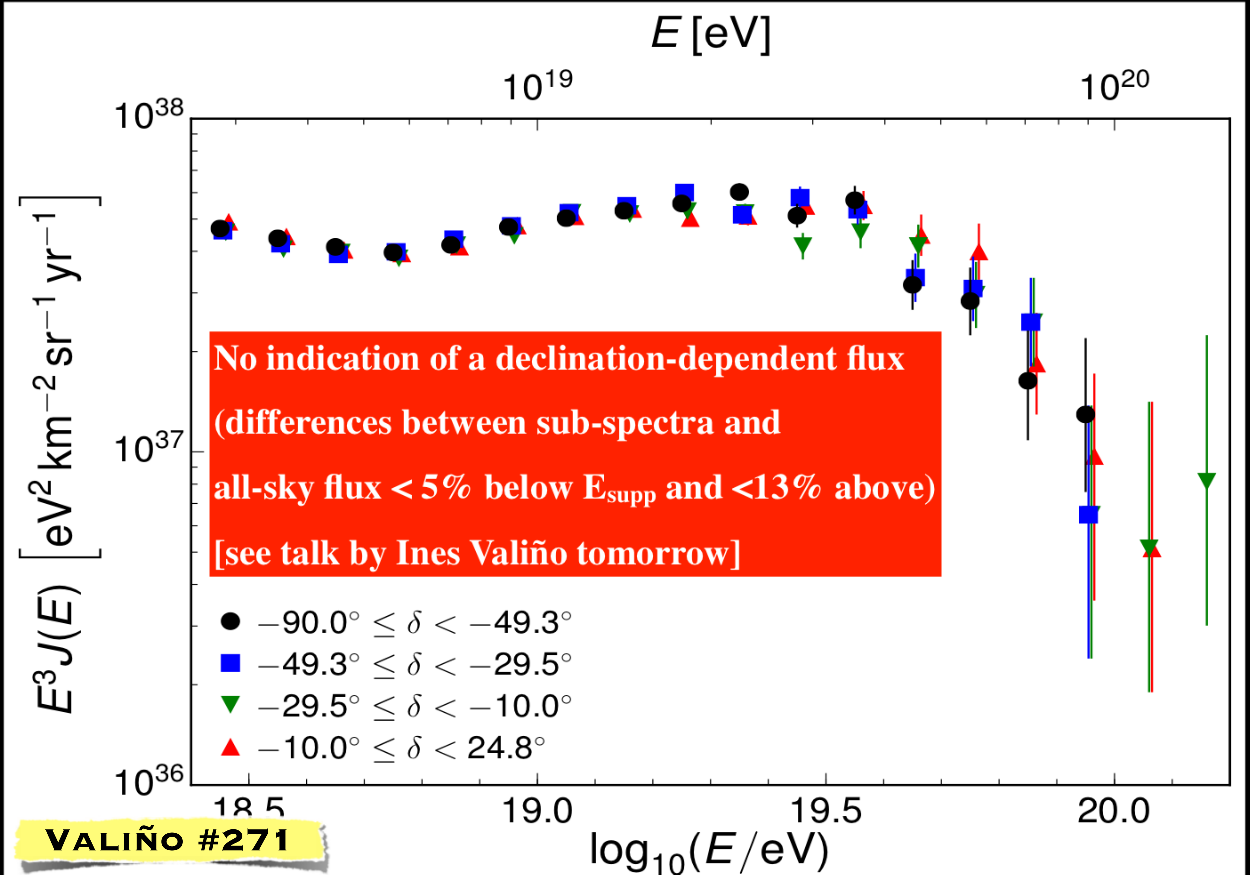
4 data sets combined: **SD 750 m**, **FD (hybrid)**, **SD 1500 m (0-60˚)**, **SD 1500 m (60-80˚)**

≈ 200 000 events, ≈ 50000 km² sr yr exposure, FOV: -90˚, +25 in δ



All-particle spectrum in different declination bands

The large number of events and wide FOV allow for the study of the flux vs declination



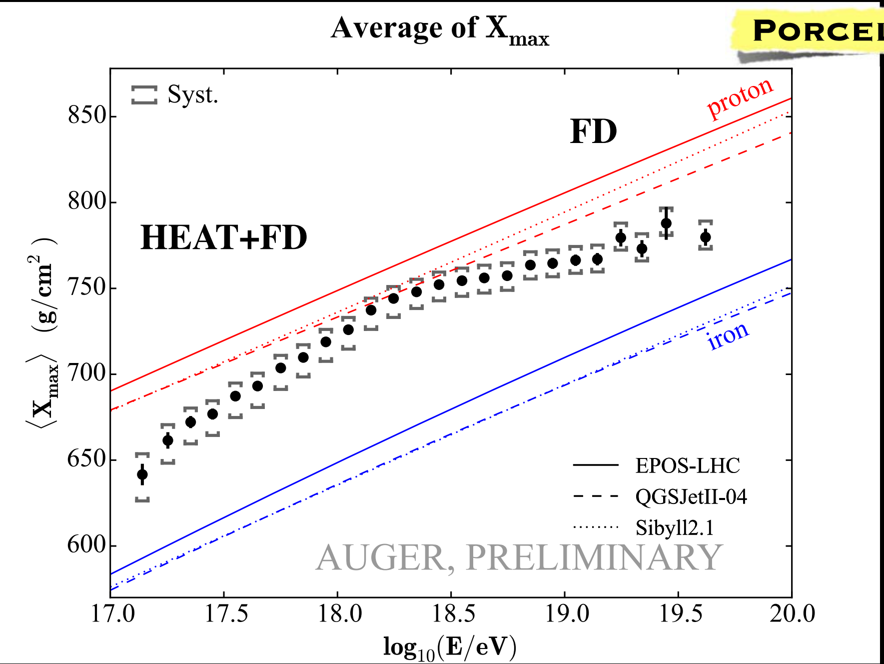
First measurement of the depth of shower maximum over 3 decades in energy

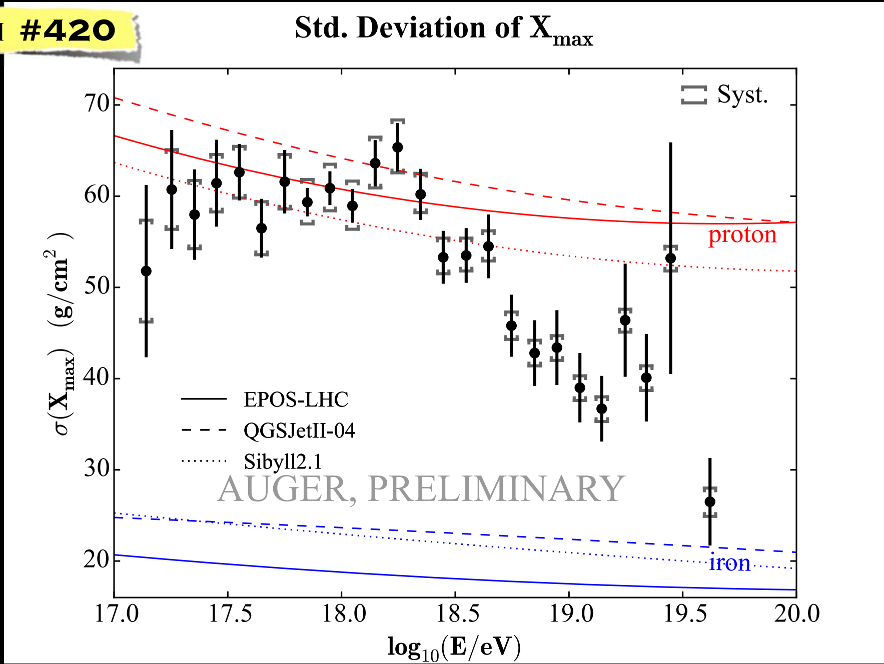
Depth of shower maximum premiere observable for mass composition studies

HEAT data extends the FOV of the fluorescence detector up to 60°

Extension of the depth of shower maximum measurements down to 10^{17} eV

Porcelli #420



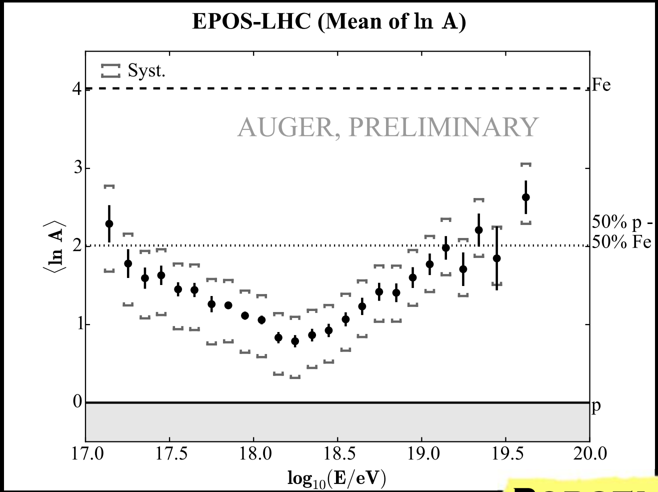


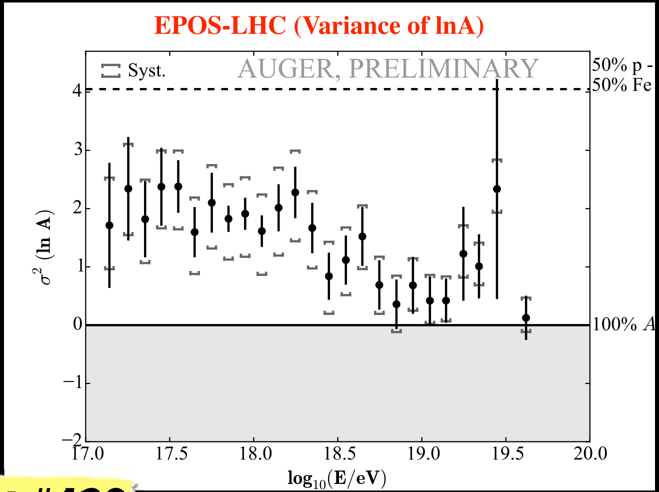
Compared to expectations from proton and iron

EPOS-LHC, QGSJETII-04, Sybill2.1 as hadronic interactions models

From the depth of shower maximum to primary mass (lnA)

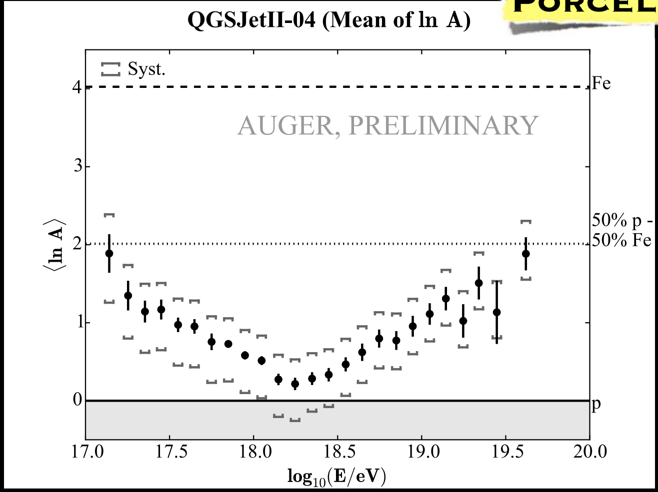
Epos-LHC

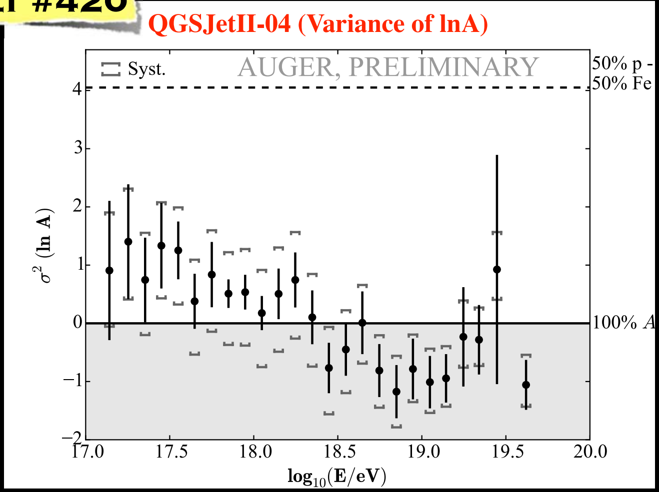




Porcelli #420

QGSJetII-04





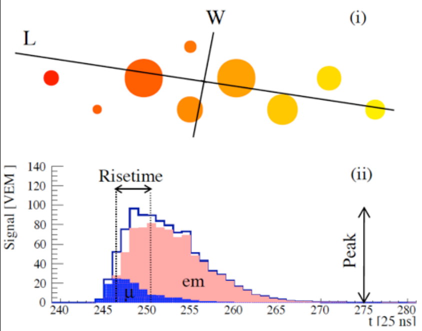
Similar trend for both models: heavier composition at low energies (largest mass dispersion), lightest one at ≈ 2x10^{18} eV, getting heavier again towards higher energies (smaller mass dispersion)

[N.B: very few data above ≈ 40 EeV)

Not only inferences on mass but test of models too

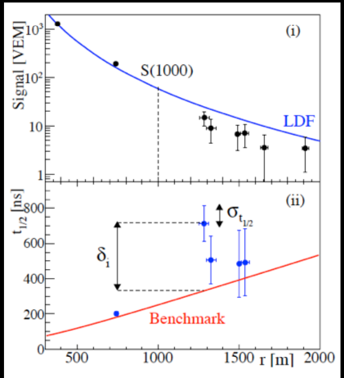
The conversion to σ^2(lnA) through QGSJETII-04 yields unphysical results

Stringent neutrino- and photon-flux limits at EeV energies

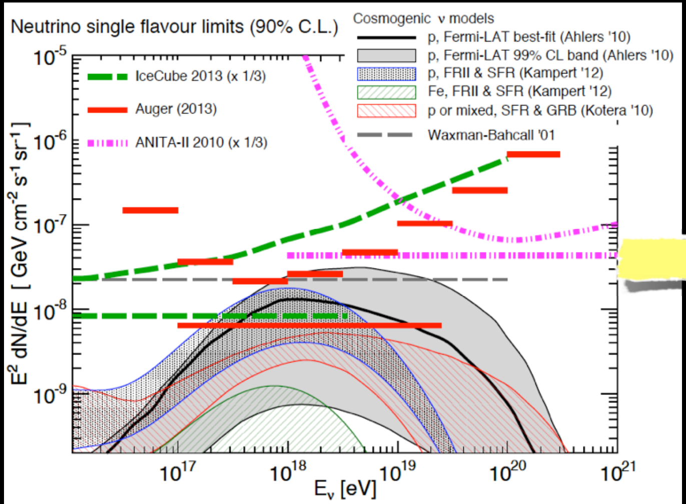


Observables to select **neutrinos:** shape of the footprint and time structure of signals in very inclined showers (θ>60°)

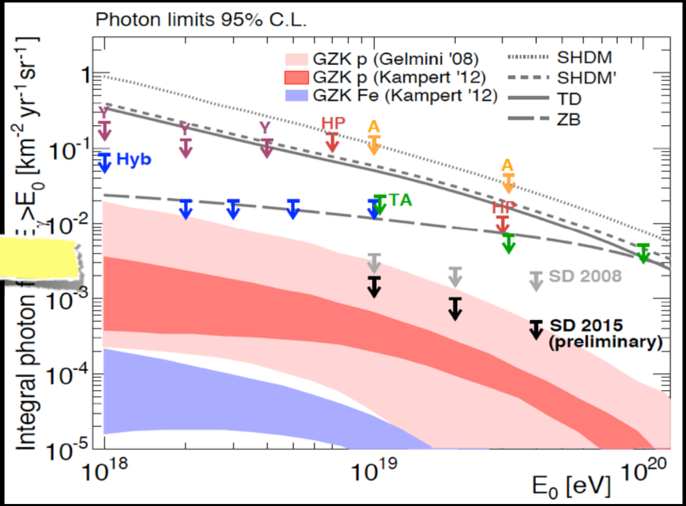
EAS observables to select **photons:** shape of the LDF and time structure of signals in showers with 30<θ<60°



NEUTRINOS



Bleve #1103



PHOTONS

First limit from an EAS array below WB bound

Top-down models strongly disfavored

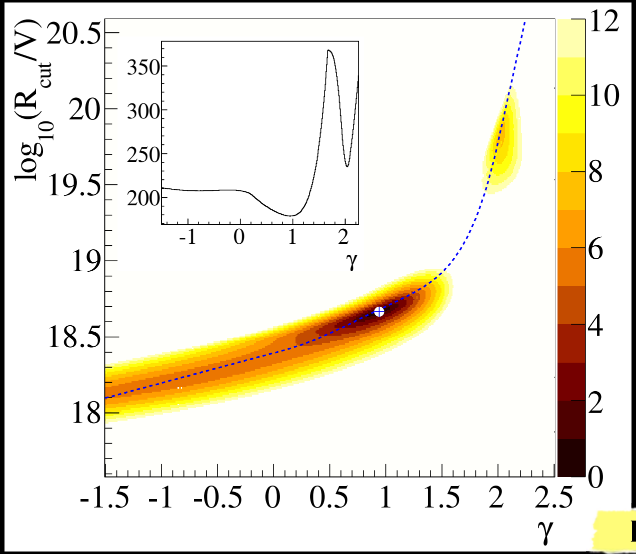
What do spectrum and composition data tell us?

(Simple) Model of UHECR to reproduce the Auger spectrum and Xmax distributions at the same time

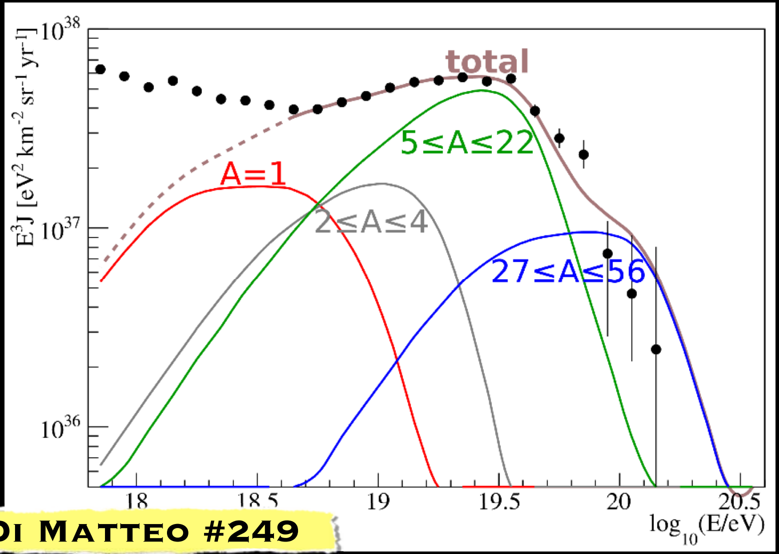
Homogeneous distribution of identical sources accelerating p, He, N and Fe nuclei.

Fit parameters: injection flux normalization and spectral index γ, cutoff rigidity R_{cut}, p-He-N-Fe fractions

R_{cut} and γ

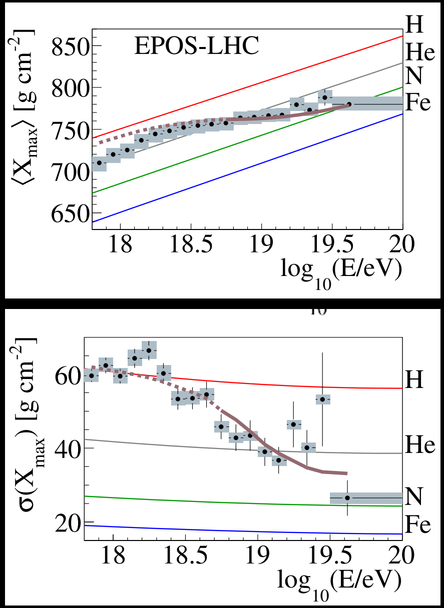


Energy spectrum and elements fractions



Di Matteo #249

<Xmax> and σ(Xmax)

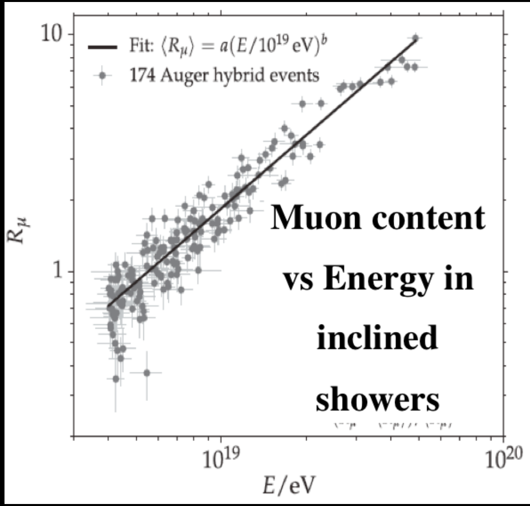


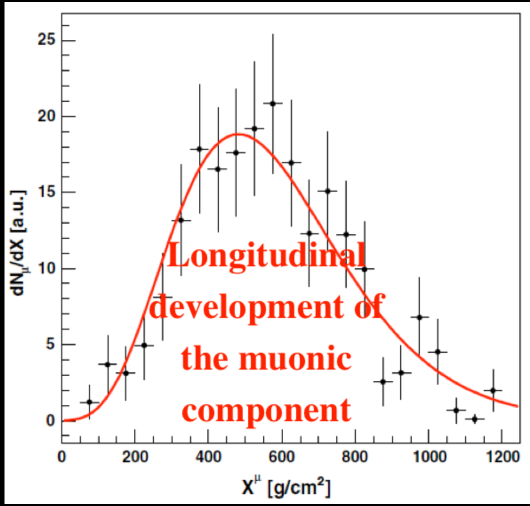
Best fit with very hard injection spectra (γ ≲ 1)

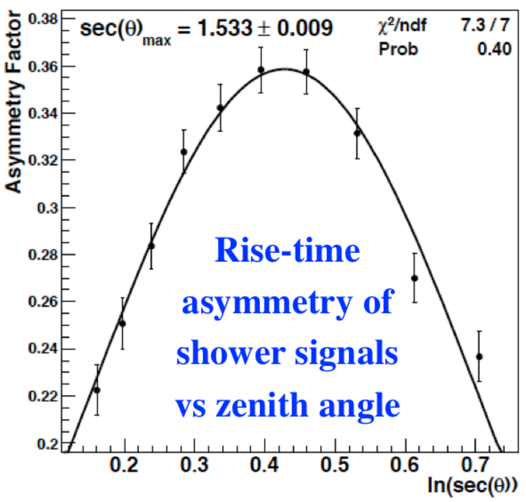
Flux limited by maximum energy at the sources (R_{cut} ≲ 10^1..7 eV

2.2 “Shower properties measurements might impose constraints on **hadronic interaction models** at energies well beyond the reach of accelerator-based experiments...”

Shower properties (mass-sensitive) measured with the surface detector







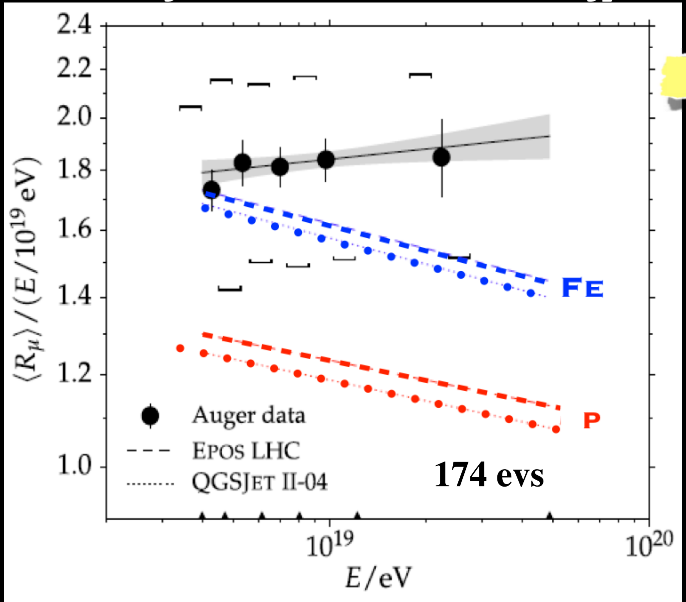
COLLICA #336

MINAYA #405

Testing hadronic models: the EAS muon content (FD and SD data)

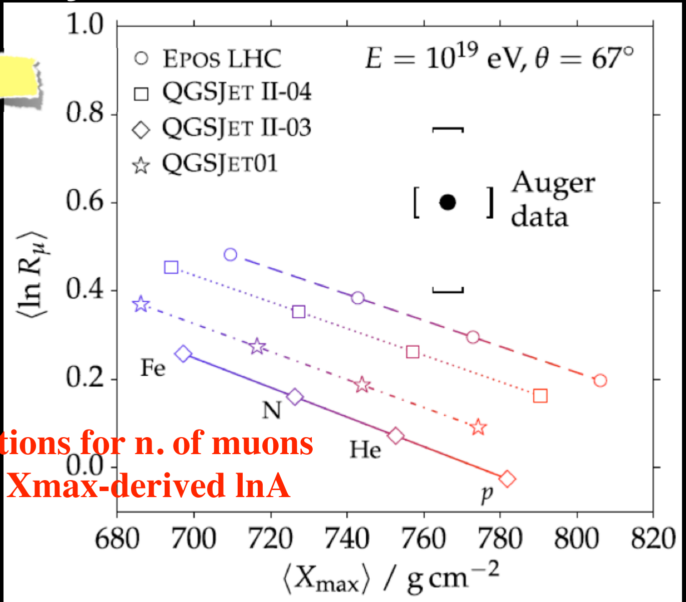
Horizontal showers (θ > 60˚) dominated by muons (em component largely absorbed)
Estimation of the number of muons vs energy from horizontal showers observed by FD and SD

Average n. of muons vs energy



COLLICA #336

Average n. of muons vs <Xmax> at 10 EeV



Predictions for n. of muons from Xmax-derived lnA

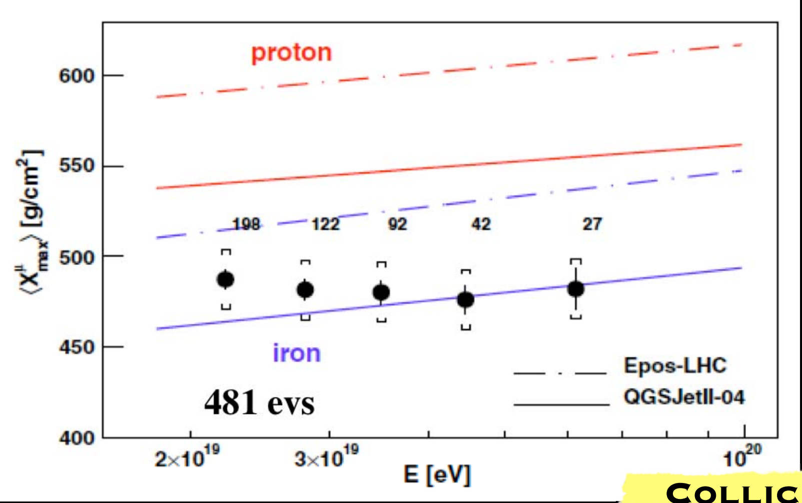
High abundance of muons in data
Systematic uncertainty inherited from energy scale

Tension between n. of muons and Xmax
Deficit of muons in simulations between 30% and 80%

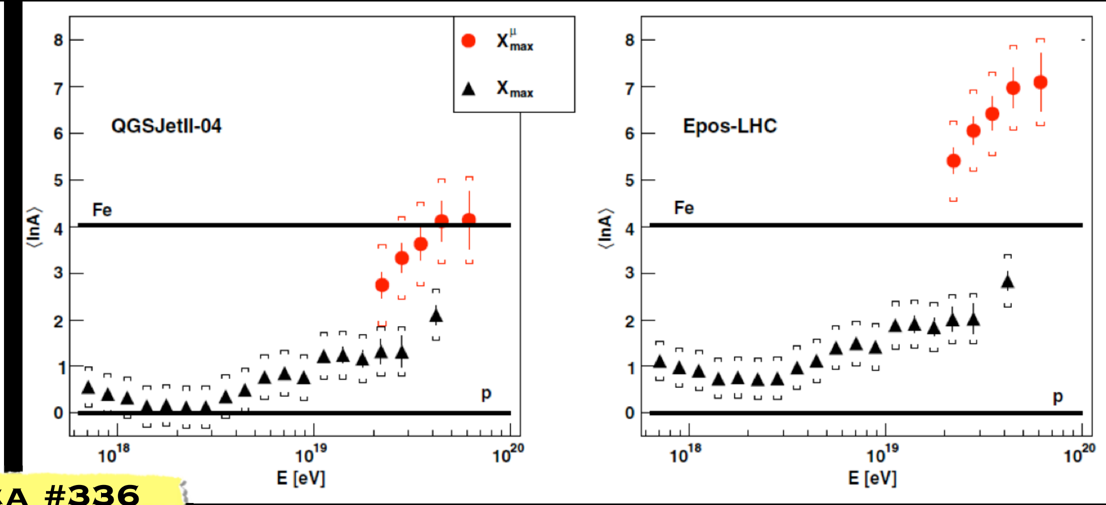
Testing hadronic models: the Muon Production Depth (SD data)

Horizontal showers (θ > 60˚) dominated by muons (em component largely absorbed)
Muon production depth can be reconstructed from the time structure of SD signals in horizontal EAS

Max of the MPD distributions vs E



Conversion of the max of the MPD distributions to lnA

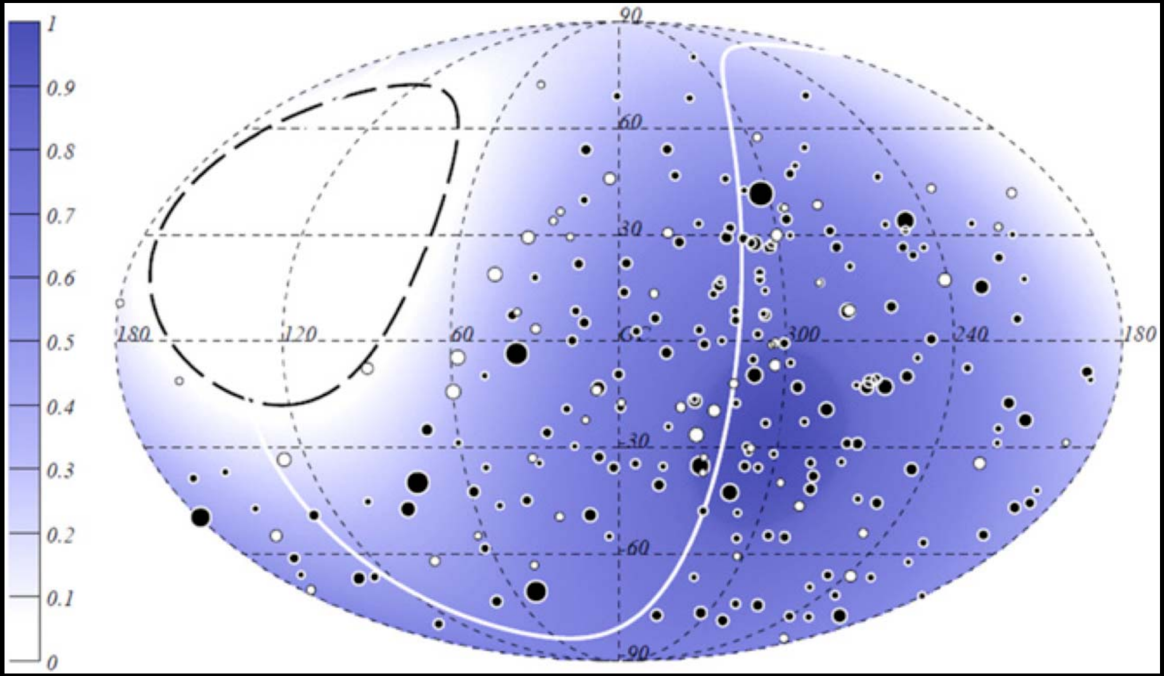


Collica #336

Evolution vs E for data flatter than pure p or Fe in both models
Data bracketed by QGSJetII-04

Comparison with lnA from Xmax data: values compatible within 1.5 σ for QGSJetII-04 incompatible at > 6 σ for Epos-LHC

2.3 "...a systematic study of the **arrival directions**, that will indicate if there is anisotropy in the distribution and/or clusters which would indicate the existence of point sources..."



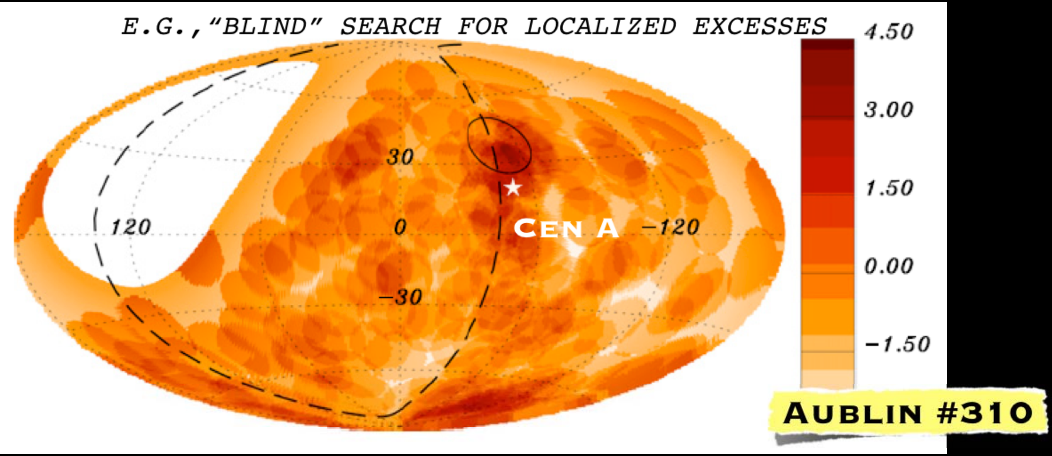
At small/intermediate scales: no evidence of anisotropy

Data set: 602 events with E > 40 EeV, $\vartheta < 80^\circ$ (66450 km^2 sr y) Covered FOV in declination: -90° - +45°

Anisotropy tests over a wide range of angles: 1° - 30°; at different energy thresholds: 40 - 80 EeV

"INTRINSIC" ANISOTROPY TESTS

Cross-correlation, blind search for excesses

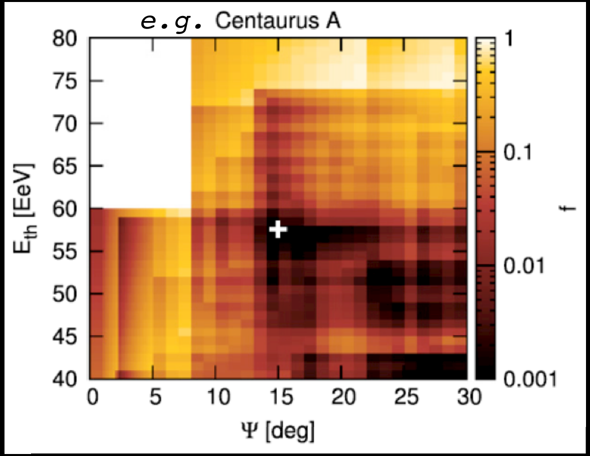


Most significant excess (18° from Cen A):

Post-trial probability: 69%

ASTROPHYSICAL CATALOGS TESTS

2MRS galaxies, Swift-BAT AGNs, radio galaxies, Cen A



Minimum at = 15° and E_{th} = 58 EeV

Post-trial probability: 1.4%

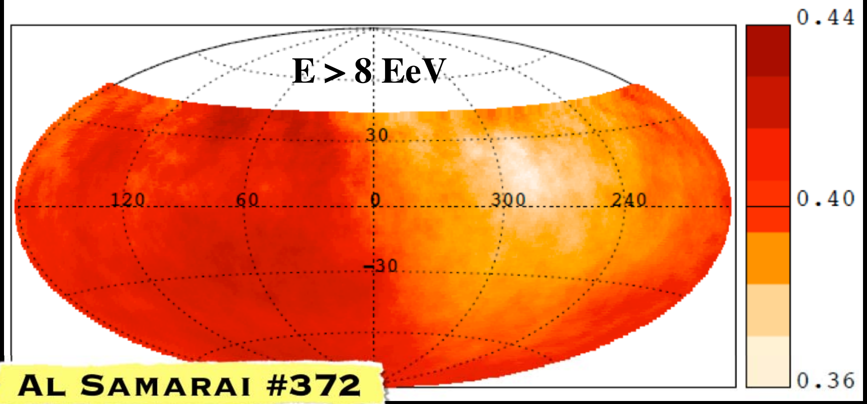
NO STATISTICALLY SIGNIFICANT DEVIATION FROM ISOTROPY IN NONE OF THE TESTS

The most significant deviations from isotropy are at intermediate scales

At large scales: indication of a dipole at E>8 EeV

AUGER: Harmonic analysis in right ascension and azimuth (declination-sensitive)
≈ 70000 events with E>4 EeV and $\vartheta < 80^\circ$
85% sky coverage. Two energy bins: 4-8 EeV and > 8 EeV

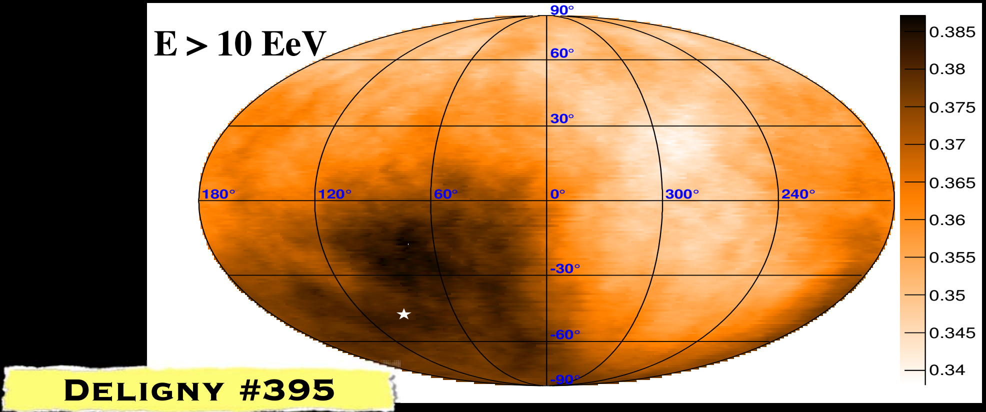
Sky map of the CR flux (45° smoothing)



Dipole Amplitude: 7.3 ± 1.5% (p=6.4x10^{-5})
Pointing to (a, d) = (95°±13°, -39°±13°)

AUGER and TA: Spherical harmonic analysis
≈ 17000 Auger events and ≈ 2500 TA events with E>10 EeV
Full sky coverage

Sky map of the CR flux (60° smoothing)



Dipole Amplitude: 6.5 ± 1.9% (p=5x10^{-3})
Pointing to (a, d) = (93°±24°, -46°±18°)

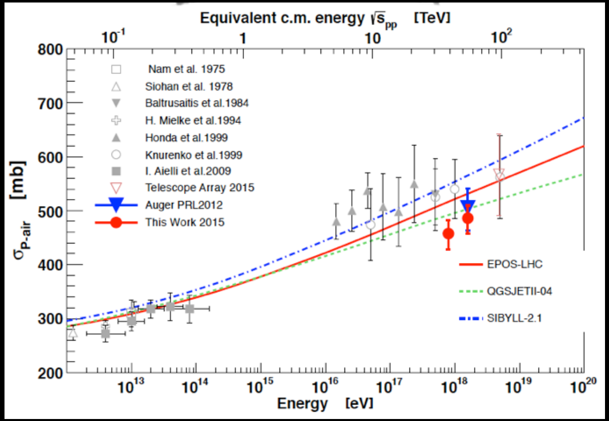
Indications of large-scale anisotropies of CRs at E > 8-10 EeV challenging the original expectations of isotropy at these energies

2.4 Not only cosmic rays

Not only ultra-high energy cosmic rays

Particle Physics

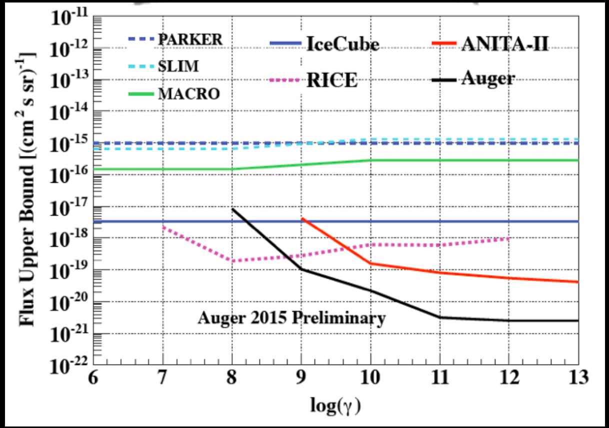
ULRICH #401



p-air cross-section measured at two energies
Data consistent with a rising cross-section with E

Fundamental Physics

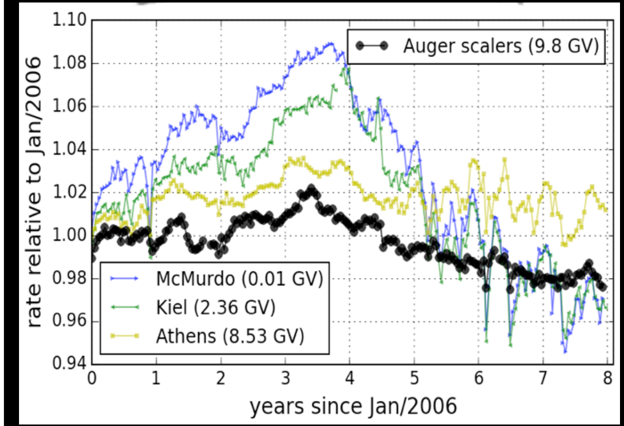
FUJII #319



Best upper limits on ultra-relativistic magnetic monopoles for $\gamma \geq 10^9$
Factor 10 improvement for $\gamma \geq 10^{10}$

Solar Physics

MASIAS-MEZA #074



8-yr period of the last solar cycle observed at higher rigidities than neutron monitors

3. Conclusions

After 10 years of operation

1. All-particle spectrum: unquestionable existence of a flux suppression above ≈ 40 EeV (GZK-reminiscent)

2. **T**rend towards a heavier composition at the highest energies (from Xmax data, very few data above 40 EeV). Spectrum and Xmax data together favors the scenario where the suppression is a source effect. **NEED FOR MASS COMPOSITION DATA IN THE SUPPRESSION REGION - ACCESSED BY THE SURFACE DETECTOR**

2bis. Mass-related shower observables from fluorescence AND surface detector (accessing different shower components) provide tighter constraints to hadronic models than either technique alone. **NEED FOR MORE MASS-RELATED DATA FROM THE SURFACE DETECTOR**

3. Stringent photon limits strongly disfavor exotic sources: astrophysical sources expected. But a high degree of (small-scale) isotropy observed, challenging the original expectation of few sources and light primaries. **NEED TO SELECT LIGHT PRIMARIES FOR DOING COSMIC-RAY ASTRONOMY**

After 10 years of operation: Auger science case

“The **Pierre Auger Observatory**...aims at studying, **with high statistics** ***and mass-discrimination capabilities*** cosmic rays at energies around and above the so-called Greisen-Zatsepin-Kuzmin spectral cutoff...Its main aims are:...

1. a precise reconstruction of the **energy spectrum** ***as a function of the primary mass***

2. the **identification of primaries**, ***on an event-by-event basis, up to the highest energies***. Inferences on mass composition will be drawn from the study of shower properties...whose measurement might impose constraints on **hadronic interaction models** at energies well beyond the reach of accelerator-based experiments...

3. a systematic study of the **arrival directions** ***of proton-enhanced data samples***, that will indicate if there is anisotropy in the distribution and/or clusters which would indicate the existence of point sources...”

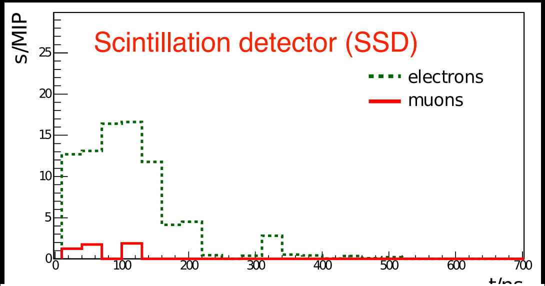
After 10 years of operation: AugerPrime science case

• Understand the origin of the flux suppression • Do composition enhanced anisotropy studies

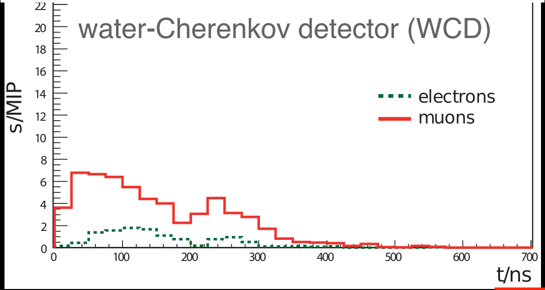
• Study UHE EAS properties and hadronic interactions

Composition measurements up to 10^{20} eV by Surface Detector array

Complementarity of response to EAS em and μ components

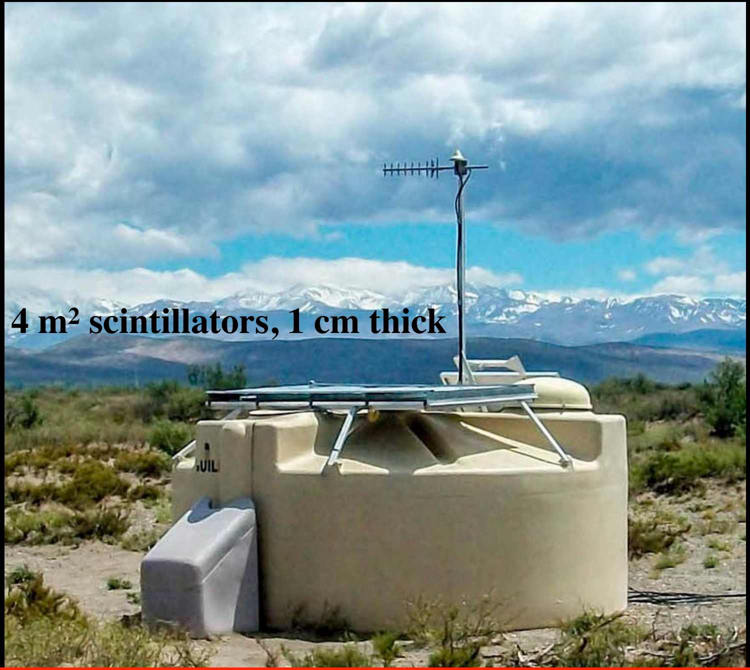


S_μ (WCD) = a S(WCD) + b S(SSD)



a and b from simulations
Weak dependence on mass and models

Scintillator (SSD) on top of a WCD



[see talk by Ralph Engel on August 5th]

ALSO

New electronics: faster sampling of ADC traces, better timing accuracy, increased dynamic range

Underground muon detectors in the 750 m array for cross-checks based on direct muon measurements

Extension of the FD duty cycle from ≈ 15% to ≈ 20%