Review of the latest results from the Pierre Auger Observatory

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for the Pierre Auger Collaboration

http://www.auger.org/archive/authors_2015_06.html

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Results and open questions

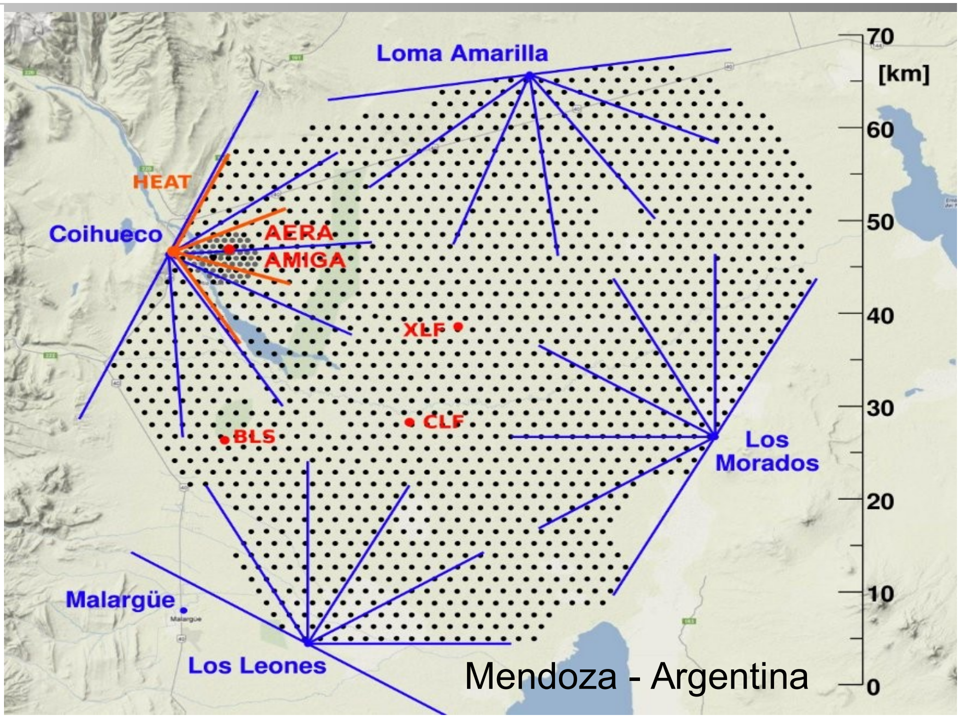
- Energy Spectrum
  - Clear upper limit (GZK). What is the origin ?
- Arrival directions
  - Isotropic or correlated with astronomic sources ?
- Nature of primary particle
  - Upper limits in the neutrino and photon flux. Probability to detect them in the near future?
  - Nuclei: light or heavy ?
- Hadronic models at the highest energies
  - Cross sections, multiplicity, inelasticity ?

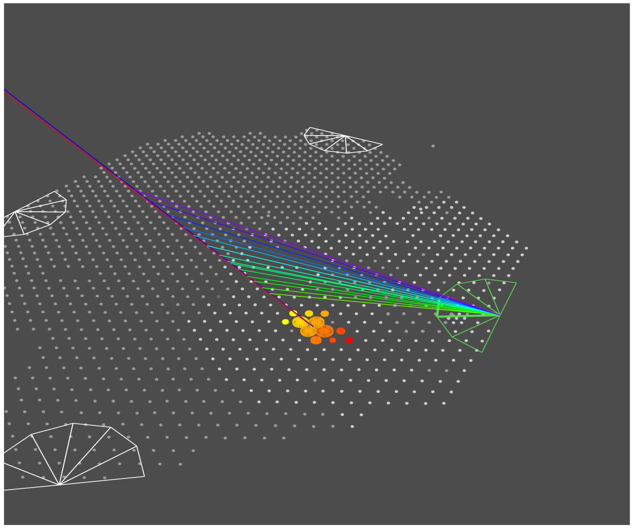
References at Pierre Auger Collaboration
. (Latest) arXiv:1509.03732
. (Complete list) http://www.auger.org/technical_info/

Pierre Auger Observatory

Base designed detectors

- Hybrid design, completed in 2008, taking data from 2004
- Surface Detector (SD): 1660 Cherenkov detectors (WCD) in a triangle array of 1.5 Km (100% duty cycle)
- 3000 Km^2 total area
- Fluorescence Detector (FD): 27 telescopes (13% duty cycle)
- Atmospheric station: Lidars, XCLF, BLS



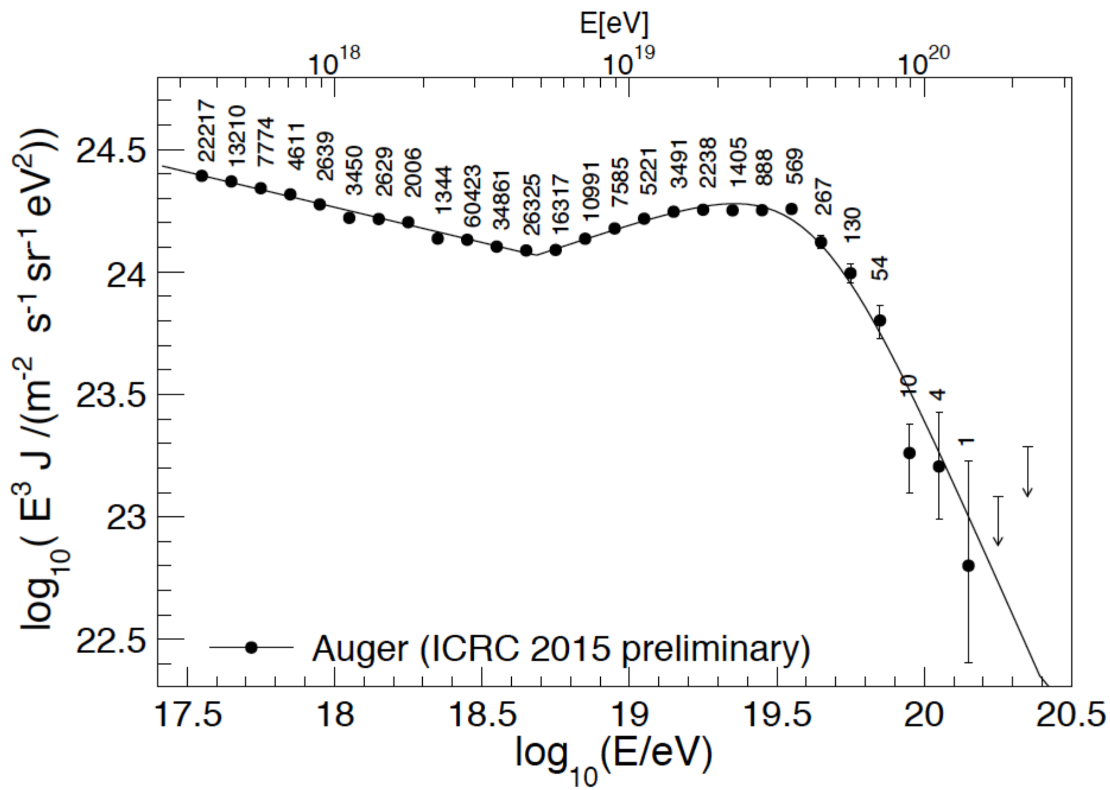


New installed detectors

- AMIGA: 61 WCD 750 m spacing: 25 km2

  + Engineering Array of 7 buried muon detectors
- HEAT: 3 High-Elevation FD: FOV 30-60°
- AERA: 153 Radio Antennas Graded 17 km^2 array

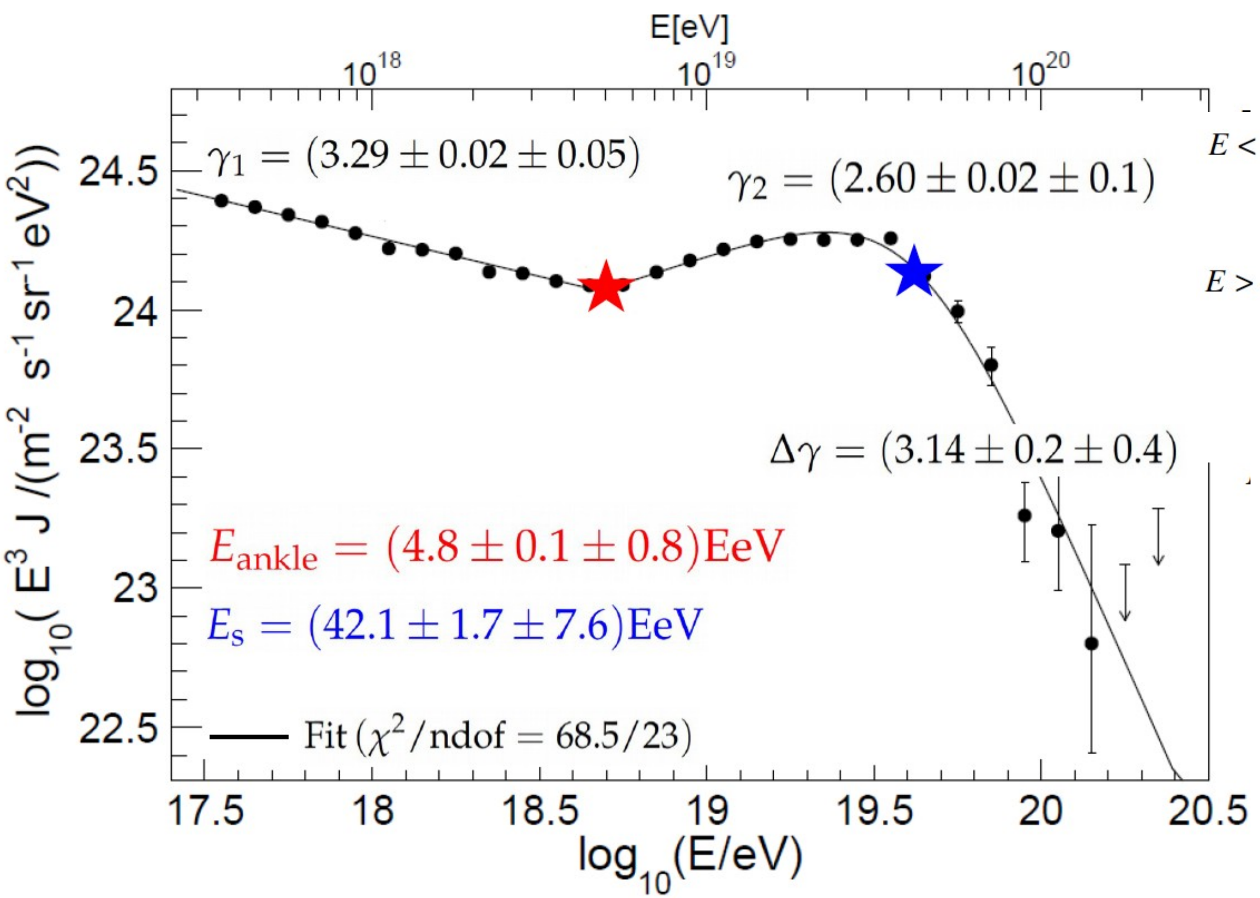
Energy spectrum



J_0 [$eV^{-1}km^{-2}sr^{-1}yr^{-1}$]	E_{ankle} [EeV]	E_s [EeV]	γ_1	γ_2	$\Delta\gamma$
$(3.30 \pm 0.15 \pm 0.20) \times 10^{-19}$	$4.82 \pm 0.07 \pm 0.8$	$42.09 \pm 1.7 \pm 7.61$	$3.29 \pm 0.02 \pm 0.05$	$2.60 \pm 0.02 \pm 0.1$	$3.14 \pm 0.2 \pm 0.4$

The energy spectrum above 3×10^{17} eV has been measured with unprecedented precision and statistics. The systematic uncertainty on the energy scale is 14%

Energy spectrum



$E < E_{\mathrm{ankle}}$:

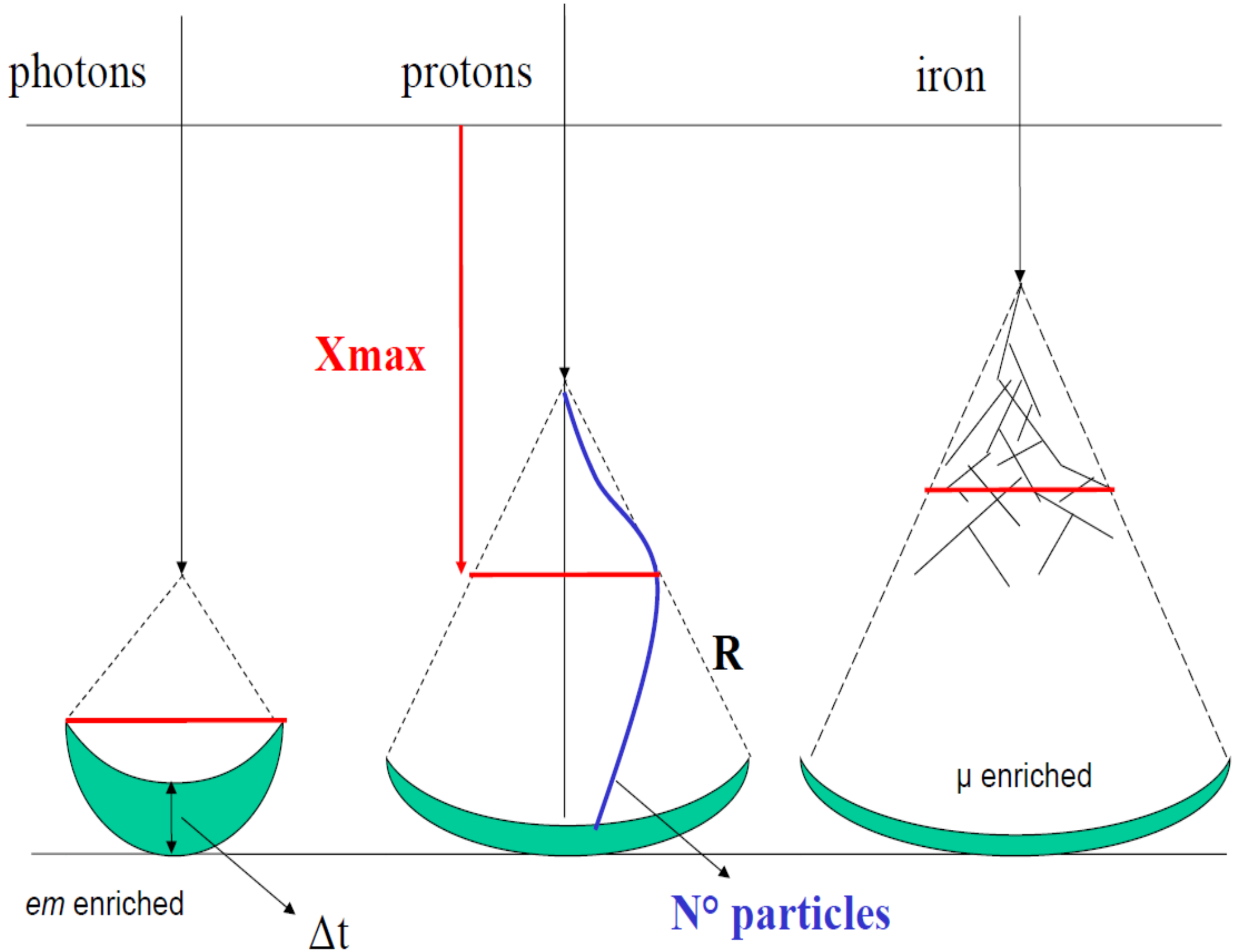
$$J(E) \propto E^{-\gamma_1}$$

$E > E_{\mathrm{ankle}}$:

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

Spectral features have been established : the hardening in the spectrum at about 5.10^{18} eV (the ankle), and a strong suppression of the flux at the highest energies

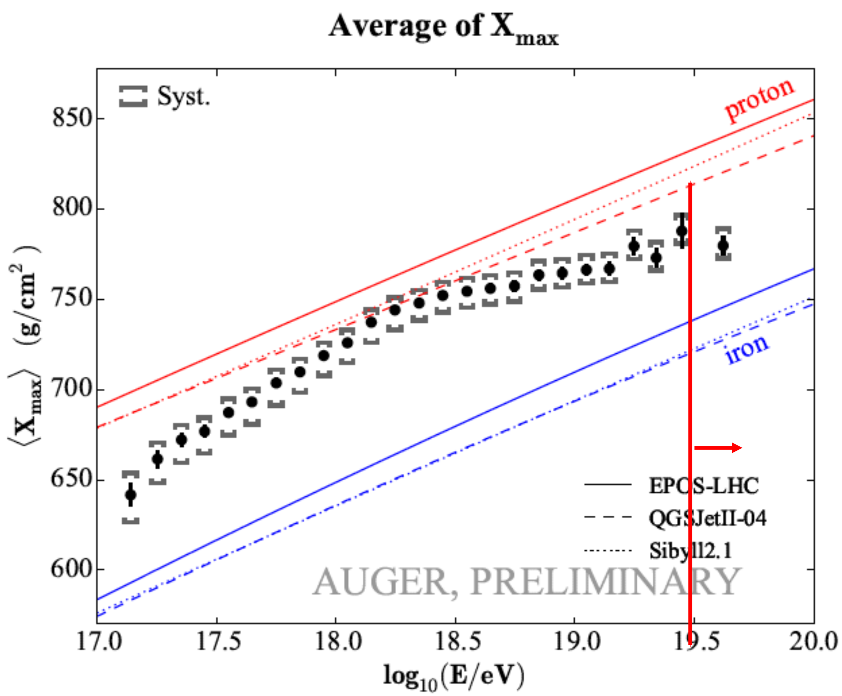
Shower development

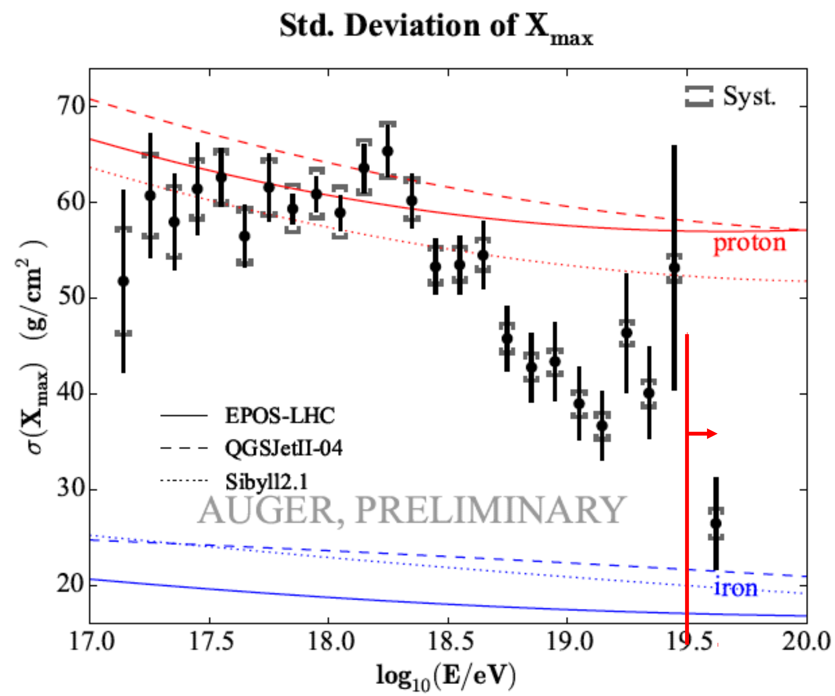


Showers from heavy nuclei will develop higher, faster, with less shower to shower fluctuations and with higher muon content than lighter nuclei showers.

X_{max} and variance

Models recently tuned based on LHC data (EPOS and QGSJETII)

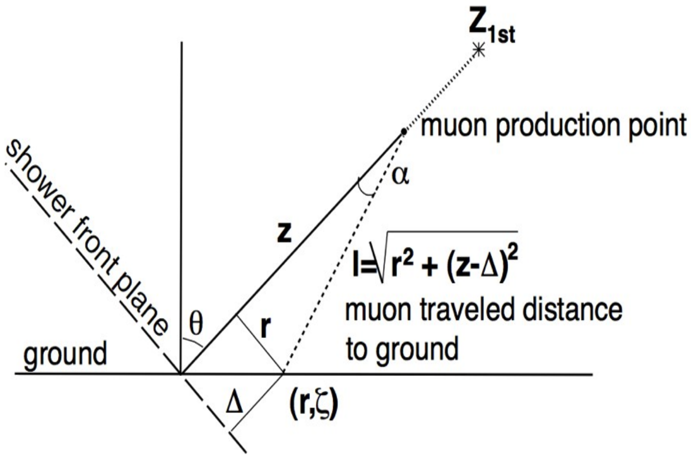


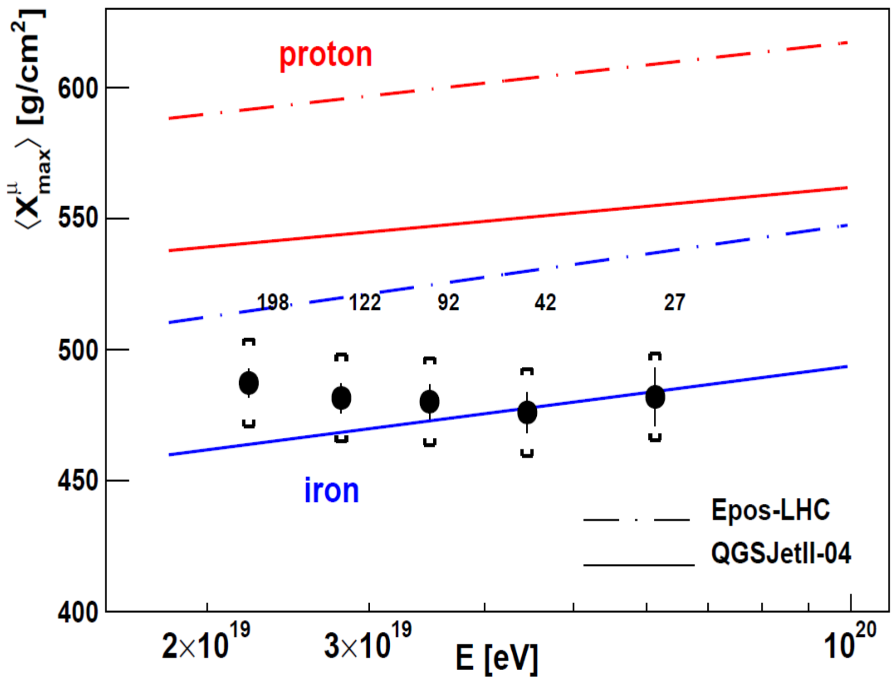


- Heavy nuclei or protons interacting or protons different than expected (interpretation depends on models)
- Still more data is needed in the GZK region

Muon Production Depth (MPD)

- Determine MPD from FADC traces from SD
- Showers at ~ 60º and stations far from the core (r > 1700m) to avoid em contamination and reduce time uncertainties

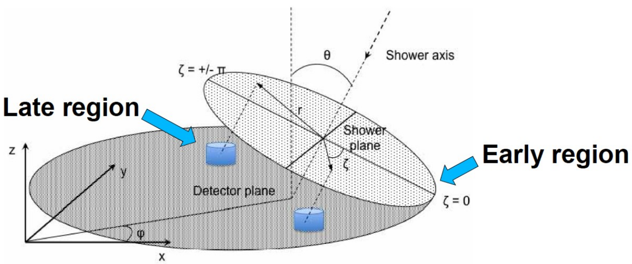




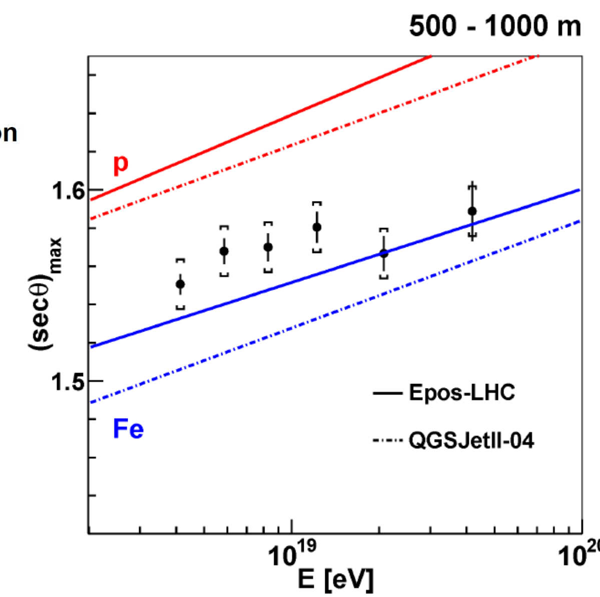
- Evolution of $<X^{\mu}_{max}>$ with Energy for data is flatter than pure p/Fe in both models
- Data bracketed by QGSJETII-04

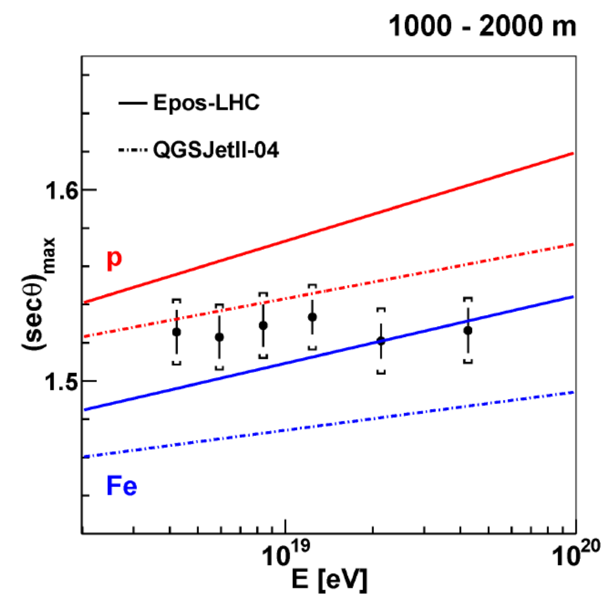
Signal Time Asymmetry

Azimuthal asymmetry in the risetime of the signals registered by the Surface Detector



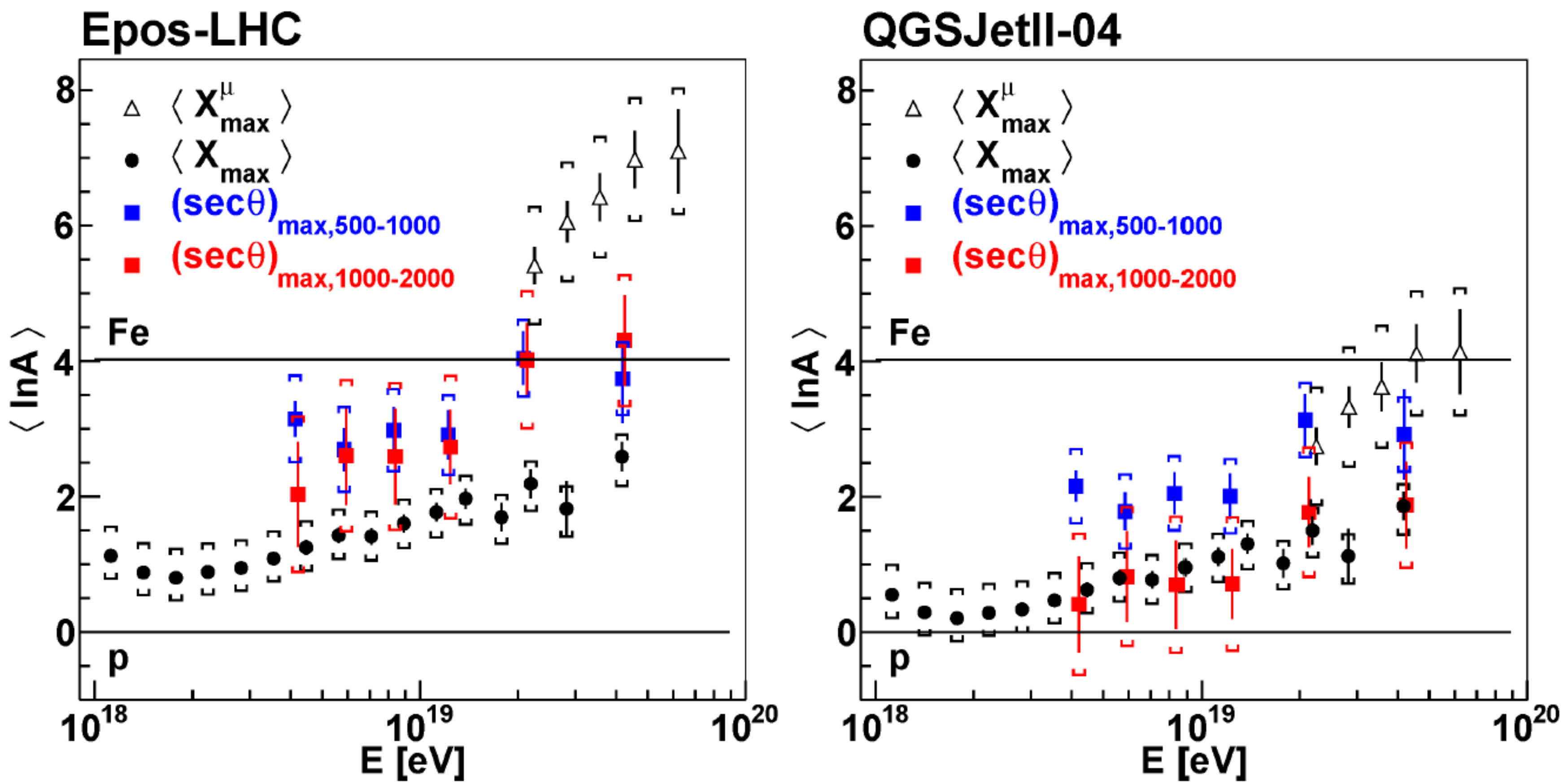
In inclined showers, particles reaching the detectors later have traversed longer atmospheric paths





Model-dependent discrepancies between data and MC have been found

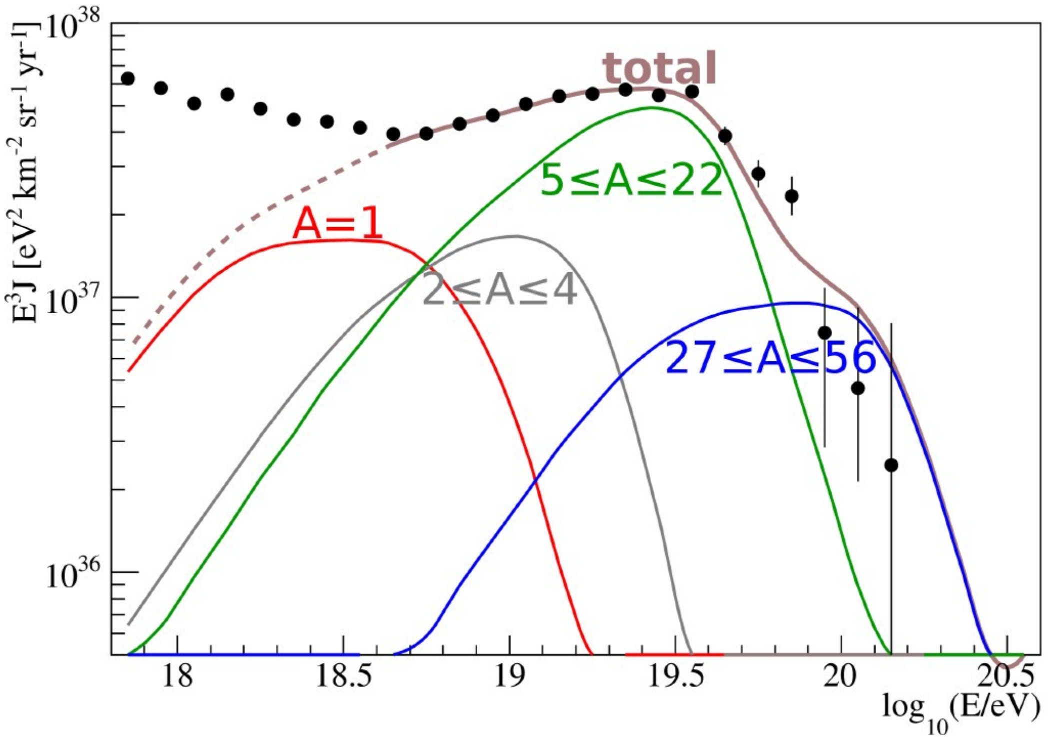
Comparison of FD and SD parameters

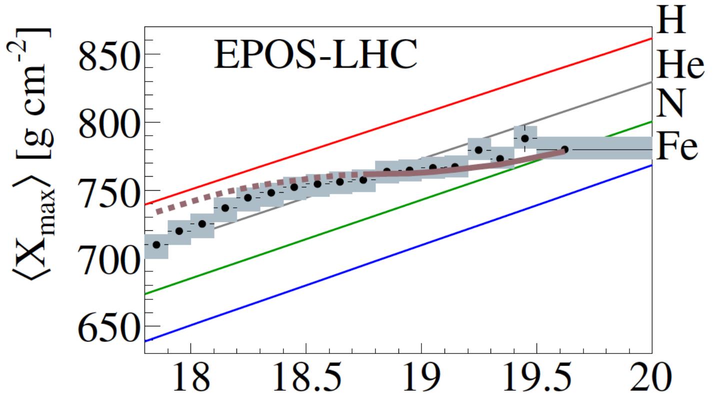


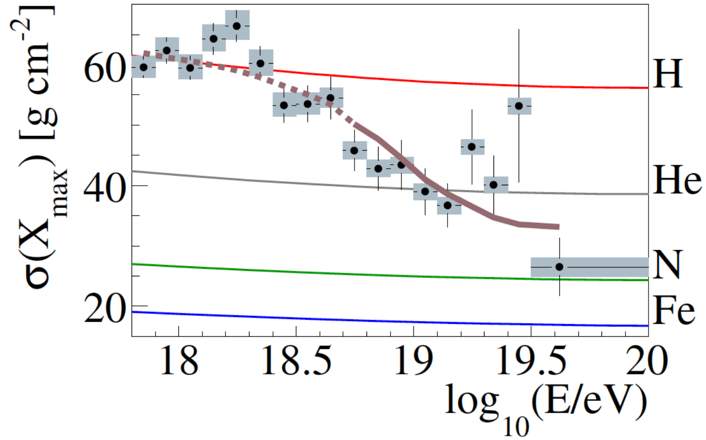
Comparison with lnA from X_{max} data: values compatible within 1.5 σ for QGSJETII-04 incompatible at > 6 σ for EPOS-LHC (MPD)

Spectrum and Composition

- Simple Model of UHECR (source, propagation and interaction in the atmosphere) to reproduce the Auger spectrum and X_{max} distributions at the same time
- Fit parameters: injection flux normalization and spectral index, cutoff rigidity, p-He-N-Fe fractions





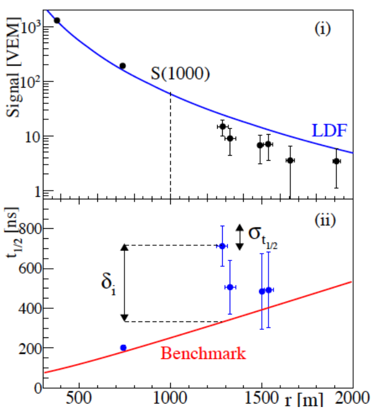


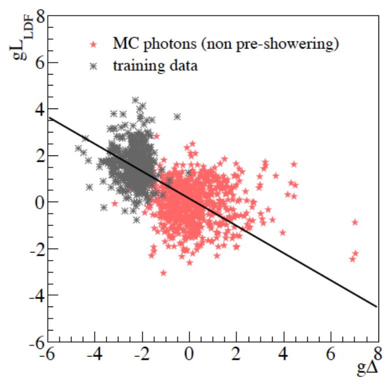
Hard metal-rich injection

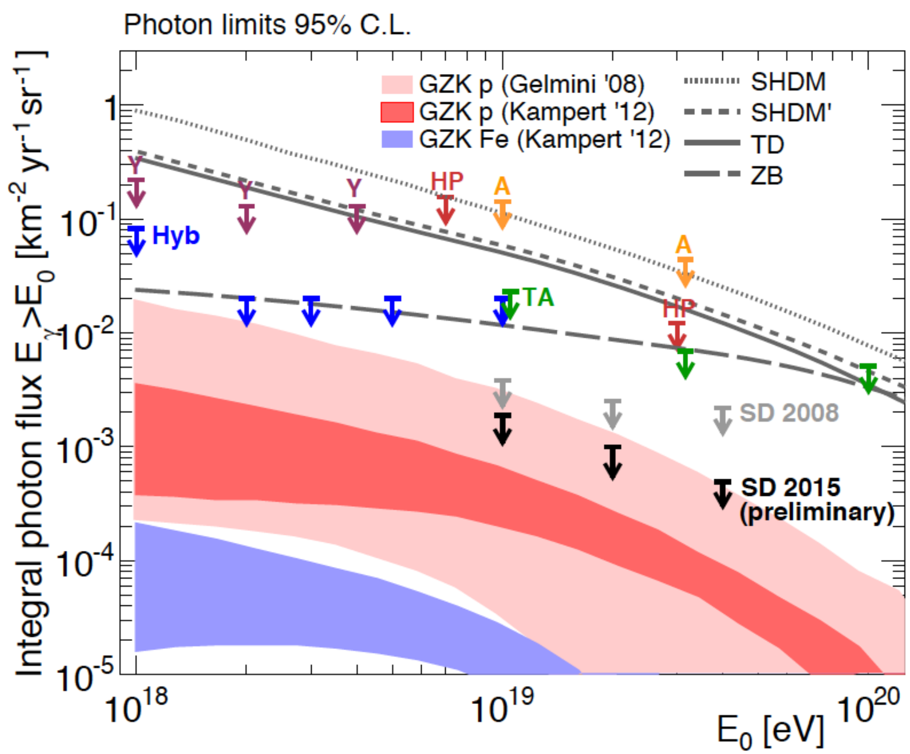
Photon limits

Photons develop deeper in the atmosphere and present higher fluctuations than p y Fe

Shape of the LDF and time structure of signals in showers with 30° < θ < 60°





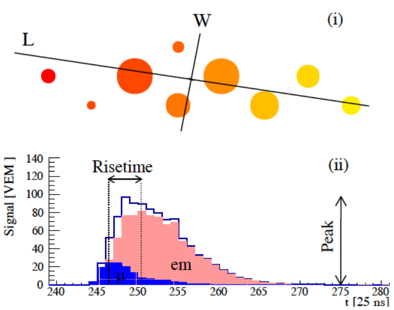


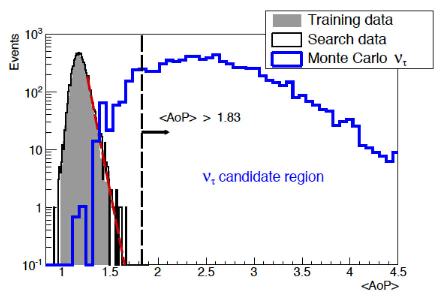
- top-down model strongly disfavoured
- preliminary U.L. above 10 EeV start constraining the most optimistic models of cosmogenic photons with p primaries injected at the source ($p + \gamma_{CMB} \rightarrow p + \pi^0\ (\gamma\gamma)$)

Neutrino limits

- Small cross-section but at large zenith angles (θ>60) the thickness of the atmosphere is large enough to allow interactions.
- Showers initiated by neutrinos are deep in the atmosphere (“young” showers).

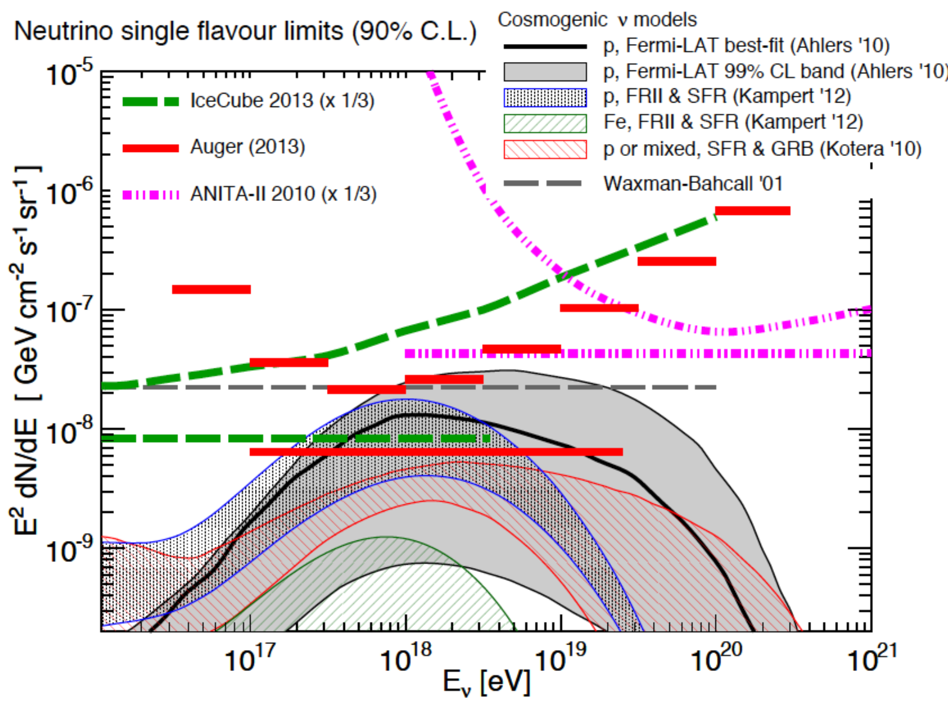
Elongated shape of the footprint and time structure of signals in very inclined showers (θ>60°)





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

→ k ~ 6.4 x 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

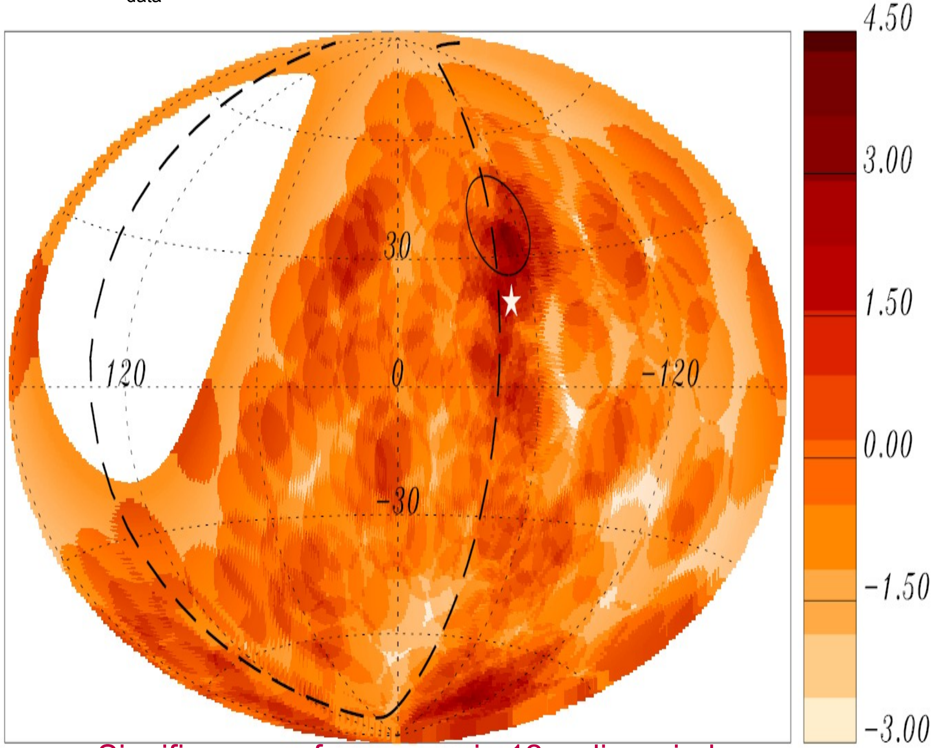


- top-down (exotic) models strongly constrained
- start constraining cosmogenic model with pure p composition at the source (cosmogenic neutrinos $p + \gamma_{CMB} \rightarrow n + \pi^+ (\mu^+ \nu_\mu)$)

Search for anisotropies

Blind searches

Angular auto-correlation function: count the number of pairs n_{data} of CR events within angular radius Ψ.



Significances of excesses in 12-radius windows for the events with E 54 EeV

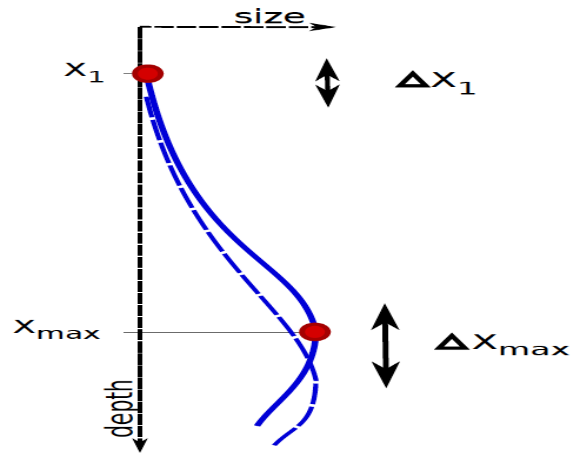
Correlation with astrophysical sources

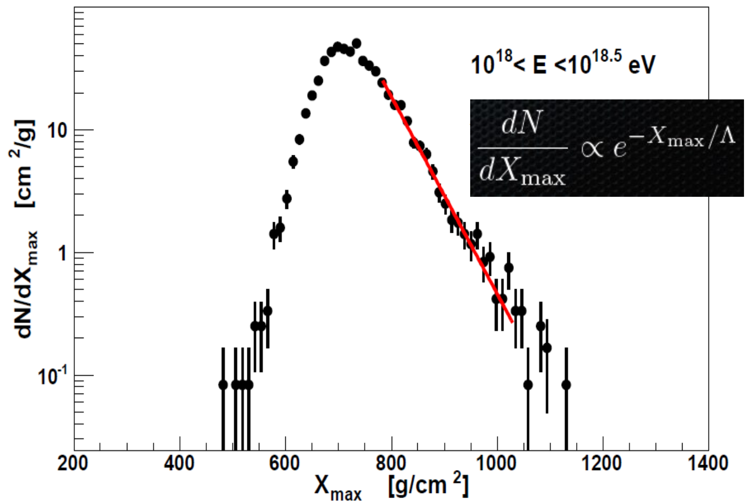
Catalogues search: for each value of E, Ψ and D, compute the fraction f of isotropic simulations having an equal or higher number of pairs than the data, and search for its minimum f_{min}

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	1.5×10^{-3}	24%
Swift AGNs	58	1	80	6×10^{-5}	6%
Radio galaxies	72	4.75	90	2×10^{-4}	8%

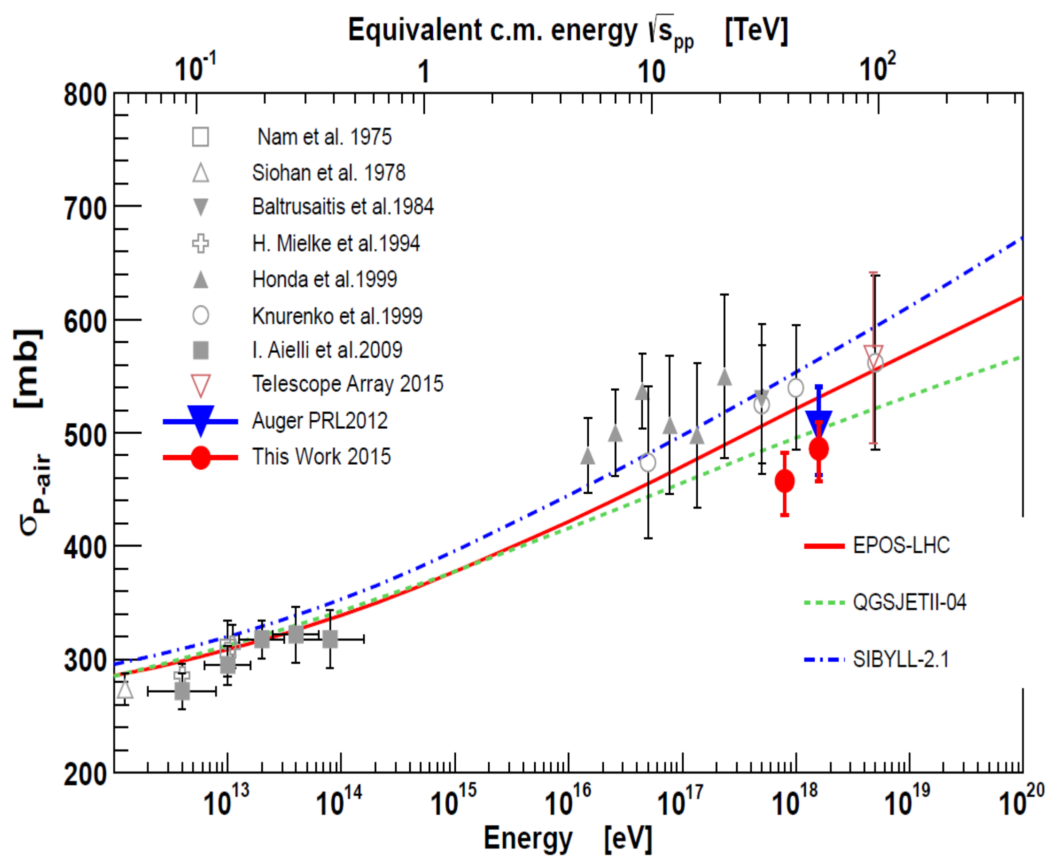
No statistically significant deviation from isotropy for the different test performed

p-air cross section





10^{18} eV – $10^{18.5}$ eV → X_{max} proton dominated region



Measurements compatible with models

Conclusions

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

- **T**rend towards a heavier composition at the highest energies (from X_{max} data, very few data above 40 EeV). Spectrum and Xmax data together favours the scenario.
  - Need still more mass composition data in the suppression region accessed by the SD.

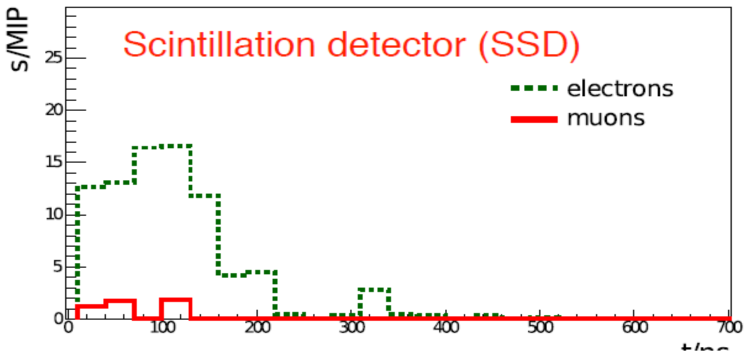
- Mass-related shower observables from fluorescence and surface detector (accessing different shower components) provide tighter constraints to hadronic models than either technique alone.
  - Need for more detailed mass related data form the SD.

  - Stringent photon limits strongly disfavour exotic sources: astrophysical sources expected. But a high degree of (small-scale) isotropy observed, challenging the original expectation of particular sources and light primaries.

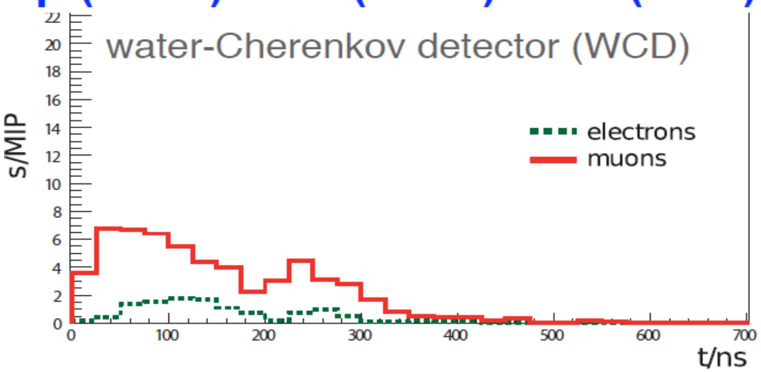
  - Need to select light primaries for doing more accurate Cosmic-Ray Astronomy.

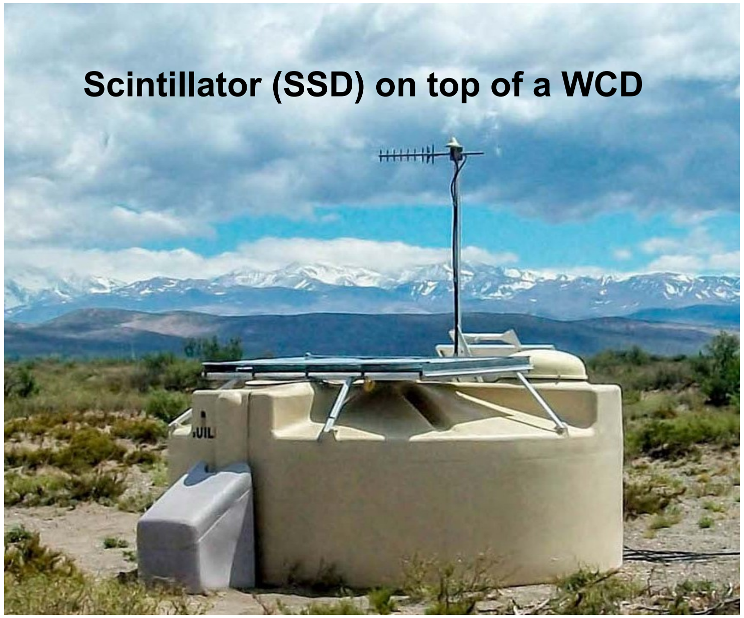
AugerPrime: Future challenge

- Understand the origin of the flux suppression
- Mass composition measurements at the highest energies (up to a 10% of proton content)
- Event by event composition determination for charge based astronomy
- Improve understanding of hadronic interaction over the LHC energy sclae



Sμ (WCD) = a S(WCD) + b S(SSD)





Complementarity of response to EAS em and μ components

Backup slides

The source model

We try to fit Pierre Auger Observatory data on UHECR spectrum and composition to a simple astrophysical scenario:

- Identical sources homogeneously distributed in a comoving volume
- Injection consisting only of ^{1}H, ^{4}He, ^{14}N and ^{56}Fe nuclei (approximately equally spaced in $\ln A$)
- Power-law spectrum with rigidity-dependent broken exponential cutoff

$$\frac{\mathrm{d}N_{\mathrm{inj},i}}{\mathrm{d}E} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

- Six free parameters $(J_0, \gamma, R_{\mathrm{cut}}, p_{\mathrm{H}}, p_{\mathrm{He}}, p_{\mathrm{N}})$; $p_{\mathrm{Fe}} = 1 - p_{\mathrm{H}} - p_{\mathrm{He}} - p_{\mathrm{N}}$

The Propagation models

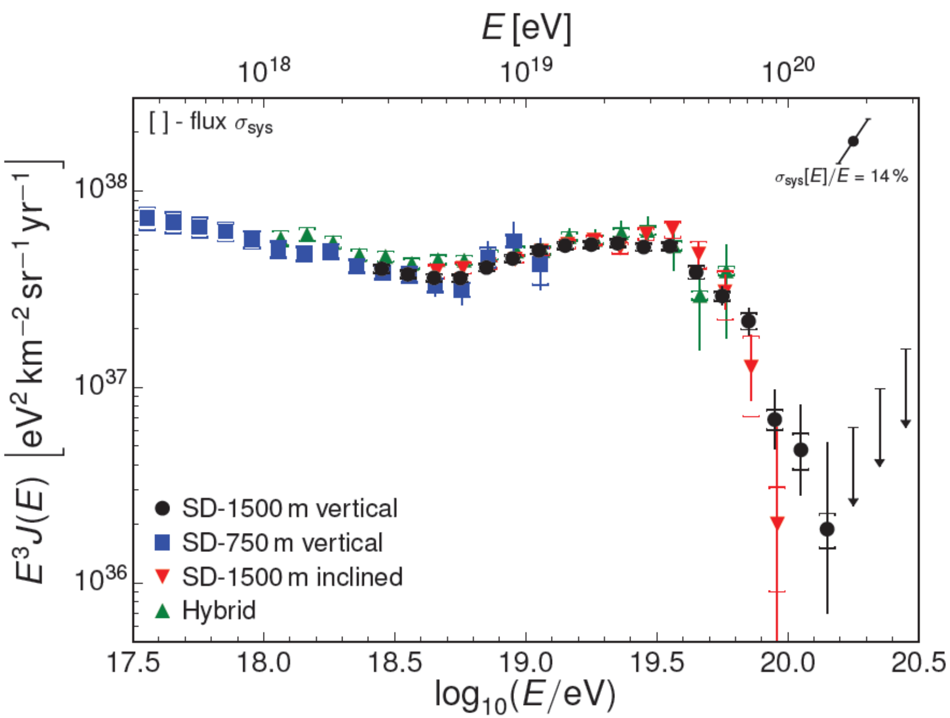
- Propagation potentially strongly sensitive to:
  - Photodisintegration cross sections (esp. into α particles)
  - Extragalactic background light spectrum (esp. in the far IR)
- We used:

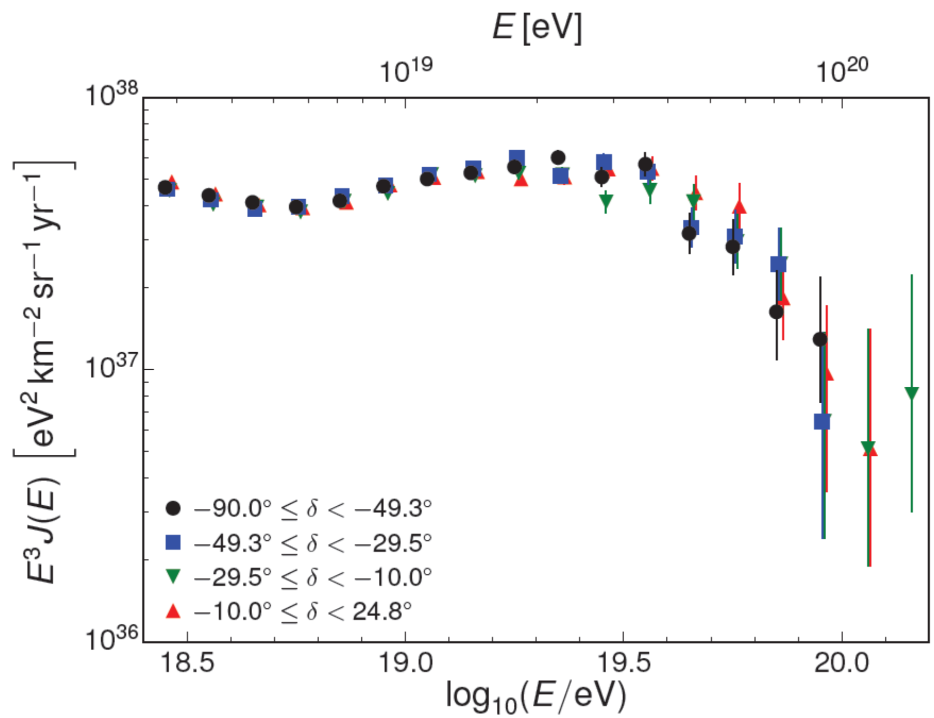
SPG *SimProp*, PSB cross sections, Gilmore 2012 EBL model
SPD *SimProp*, PSB cross sections, Domínguez 2011 EBL model
STG *SimProp*, TALYS cross sections, Gilmore 2012 EBL model
CTG CRPropa, TALYS cross sections, Gilmore 2012 EBL model
CTD CRPropa, TALYS cross sections, Domínguez 2011 EBL model
CGD CRPropa, Geant4 cross sections, Domínguez 2011 EBL model

- For details, see R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet and D. Walz, *Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp*, prepared for submission to *JCAP* (coming soon on arXiv)
- We neglect magnetic fields $\rightarrow$ 1D propagation

Energy spectrum

- 4 data sets combined: SD 750 m, FD (hybrid), SD 1500 m (0-60°), SD 1500 m (60-80°)
- The large number of events and wide FOV allow for the study of the flux vs declination





No indication of a declination-dependent flux:
differences between sub-spectra and all-sky flux < 5% below E_{supp} and <13% above

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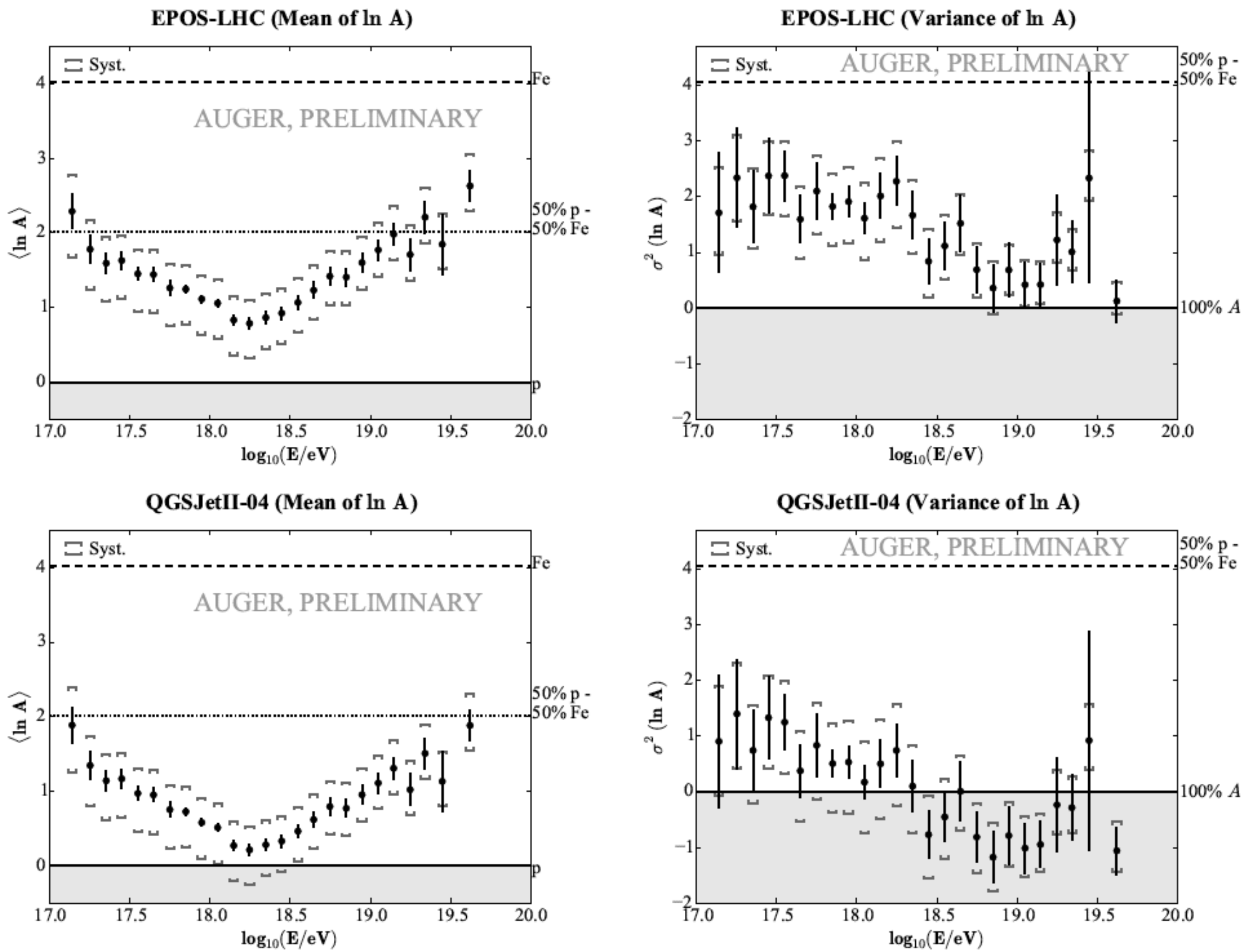
lnA and variance



Similar trend for both models getting heavier towards higher energies and smaller dispersion. QGSJETII yields non-physical results

Update of the VCV correlation test

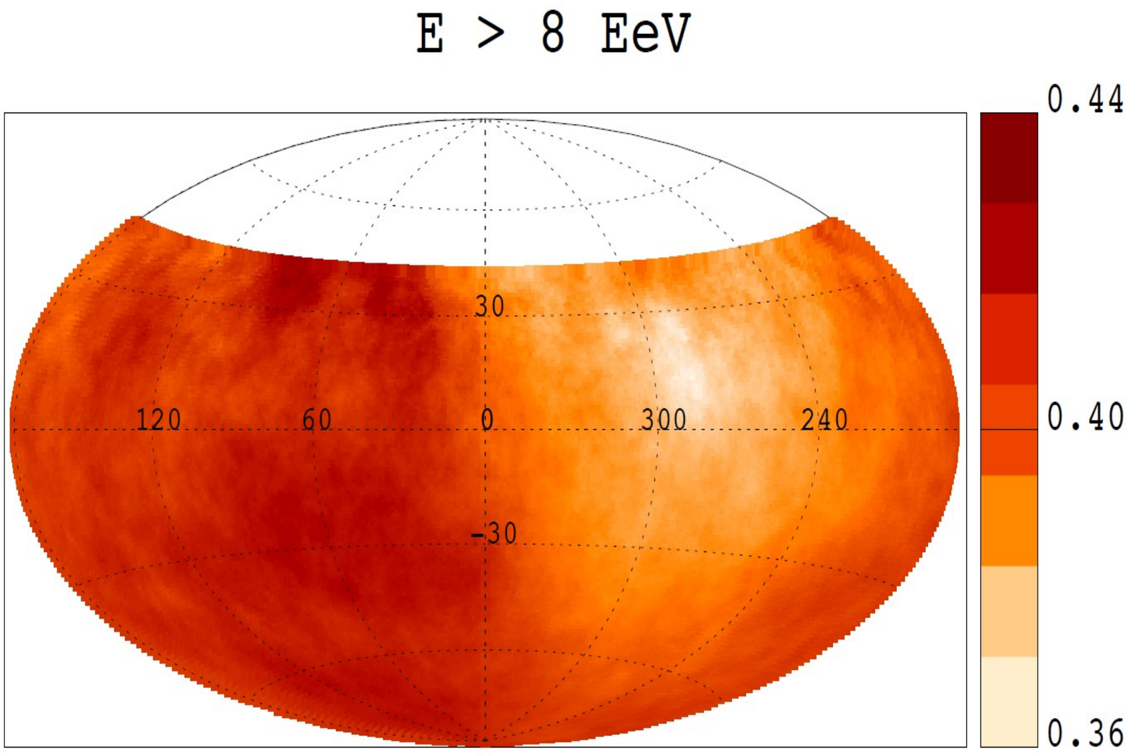
Update of the VCV correlation test

- Previous analyses:
  - Correlation with AGN from the VCV catalog with d < 75 Mpc
  - Count the fraction of events with E > 55 EeV that have $\Psi < 3.1^{o}$
  - Result with 69 events (2010): $f = 38 \pm 7$ %
  - Isotropic expectation f_{iso}=21%
- Update with the present data set: (with Eth=53 EeV with the updated energy scale)
  - Correlation fraction: $f = 28.1 \pm 3.8$ %

- The VCV test no longer provides a significant indication of anisotropy.

Large scale anisotropies

- The flux of cosmic rays can be decomposed in terms of a multipolar expansion onto the spherical harmonics $$\Phi(\mathbf{n}) = \frac{\Phi_0}{4\pi}\left(1 + r\,\mathbf{d}\cdot\mathbf{n}\right)$$



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

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Catalogs

Update of the VCV correlation test

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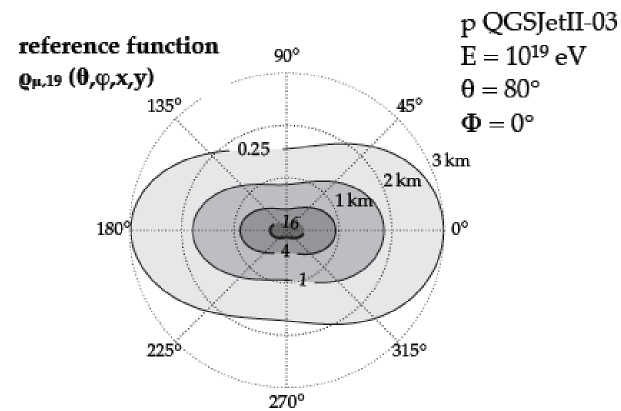
Muons in highly inclined showers

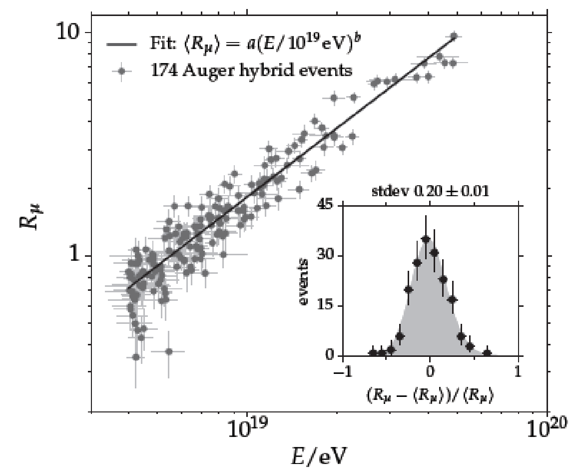
The number of muons per unit area at the ground level has a shape which is almost independent of energy, composition or hadronic model

$$\rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII03},\ p, E = 10^{19}\ eV,\ \theta)$$

The measured muon scale factor N_{19} with respect to muon reference density profiles is converted to

$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$





<u>Analysis details:</u>

- ➤ data set: 01/2004 - 12/2013
- ➤ $E > 4 \times 10^{18}$ eV (100% SD trigger)
- ➤ zenith angles [62°, 80°] (low EM contamination)
- ➤ 174 hybrid events after quality cuts

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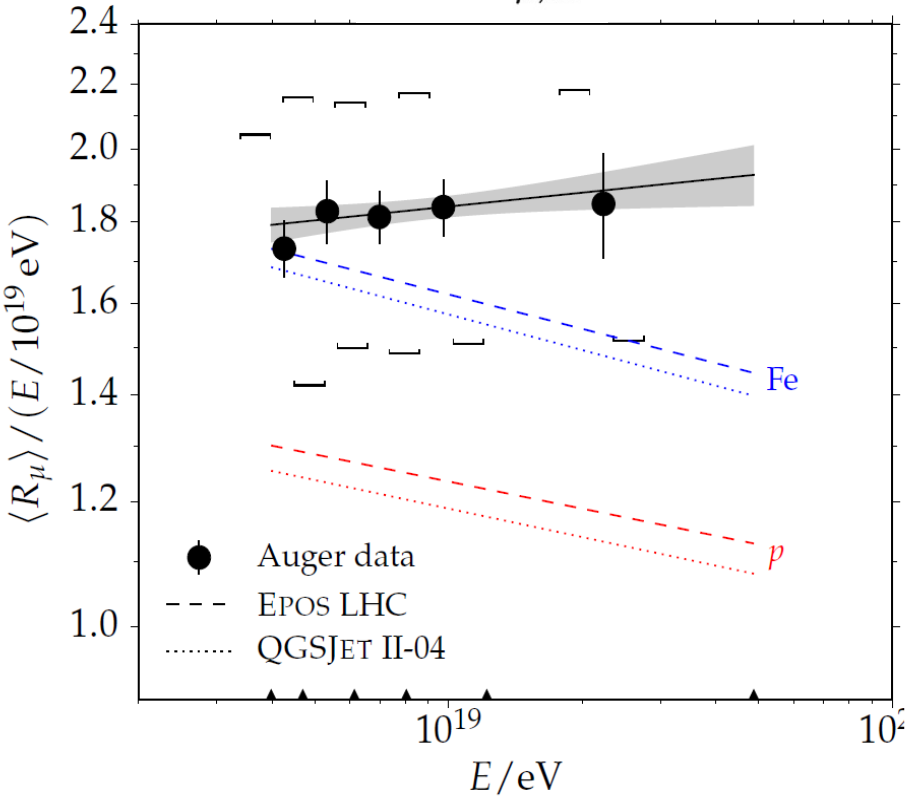
Number of muons in the EAS

- Muons are directly correlated with the primary hadronic interactions
- Detectors do not distinguish between em and μ components
- Inclined showers (θ> 60º) dominated by the muon component at ground since em one is absorbed in the atmosphere
- Direct measurement of muon component

$$R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$$



Observed a muon deficit in the models

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