Pierre Auger Observatory

studying the universe's highest energy particles

PIERRE AUGER OBSERVATORY

Results from the Pierre Auger Observatory:

neutrinos and other highlights

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NOW 2012

Neutrino Oscillation Workshop

Conca Specchiulla (Otranto, Lecce, Italy) September 9-16, 2012

Primary objective of the Pierre Auger Observatory …

"Measure the properties of Ultra High Energy Cosmic Rays (E > 10^{18} eV) with unprecedented statistics and accuracy"

Energy

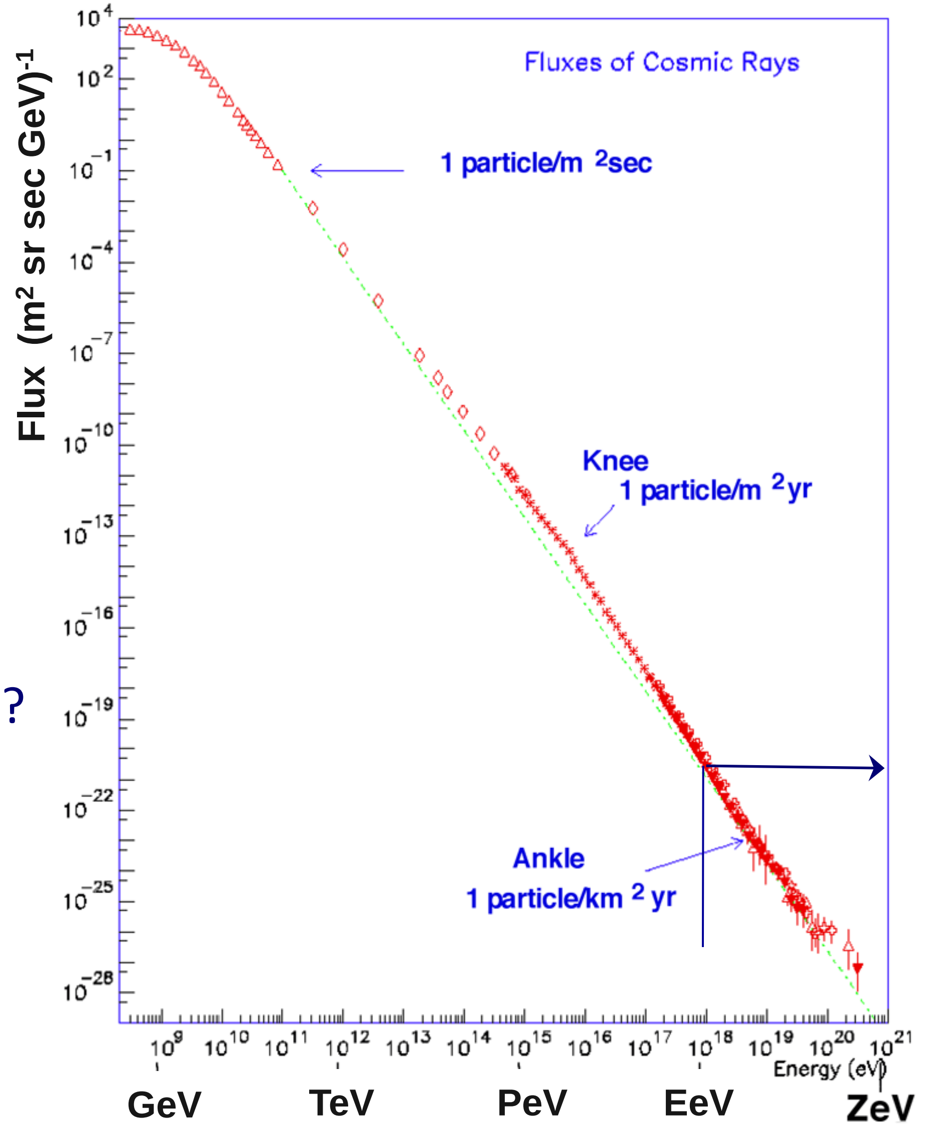
- Cutoff at the highest energies? Ankle?

Direction

- Is the UHECR flux isotropic ?
- Which are the UHECRs sources?

Mass composition

- Is the UHECR flux proton/iron-dominated?



Primary objective of the Pierre Auger Observatory …

Energy

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→ Phys. Lett. B 685 (2010) 239-246
Phys. Rev. Lett 101 (2008) 061101

Direction

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- Which are the UHECRs sources?

→ JCAP 04 (2012) 040
Astroparticle Physics 35 (2012) 354
JCAP06 (2011) 022
Astropart. Phys. 34 (2010) 314-326

Mass composition

- Is the UHECR flux proton/iron-dominated?

→ Phys. Rev. Lett 104 (2010) 091101

Tests of hadronic interaction models

- measurement of p-air cross-section

→ Phys. Rev. Lett. 109 (2012) 062002

UHE neutral primary detection

- As a bonus, the Observatory has the capability to detect UHE neutrinos, gammas and neutrons

→ Astrophysical Journal Letters, 755 (2012) L4
Physical Review D 84, 122005 (2011)
Astropart. Phys. 31 (2009) 399-406

Phys. Rev. D 79 (2009) 102001

The Pierre Auger Observatory

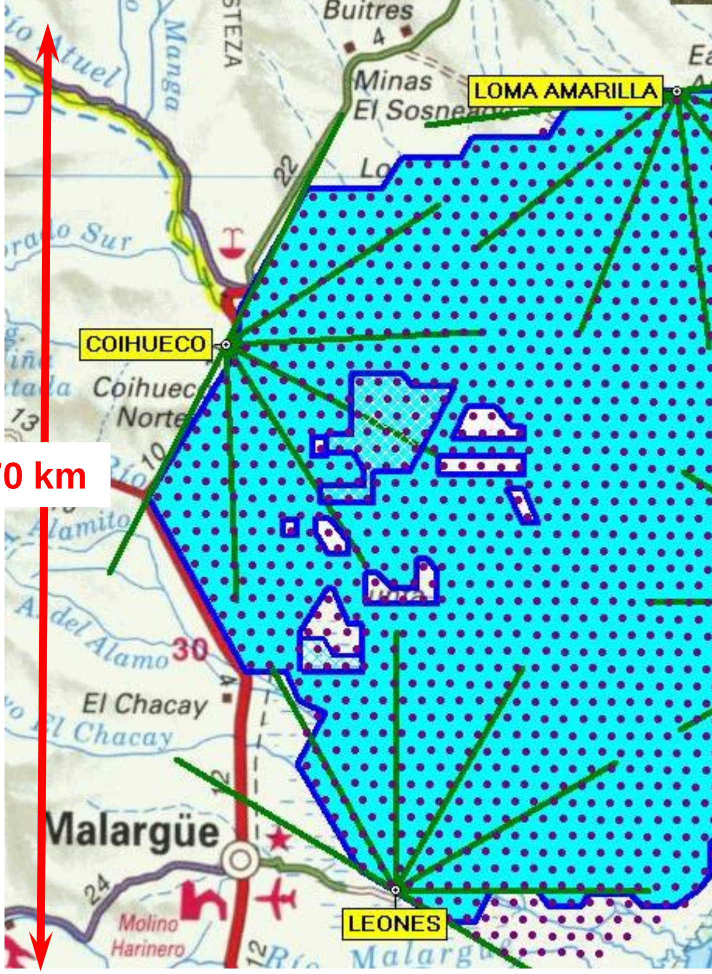
(Located in the province of Mendoza, Argentina)

Water Cherenkov stations (SD)

- 1600 in 1.5 km spaced array
- 61 in 750 m grid ("infill" low energies)
- $\varnothing$3.6 m $\times$ h1.2 m (12 ton water)
- 100% duty cycle

27 fluorescence telescopes (FD)

- 4 fluorescence sites + 1 HEAT (low energies)
- 6 telescopes per site (3 for HEAT)
- $\approx$ 14% duty cycle
- field of view: $30^o \times 30^o$



Atmospheric monitoring

- LIDAR
- CLF

Low energy extensions

- AMIGA (dense array + muon detectors)
- HEAT (high elevation FD telescopes)

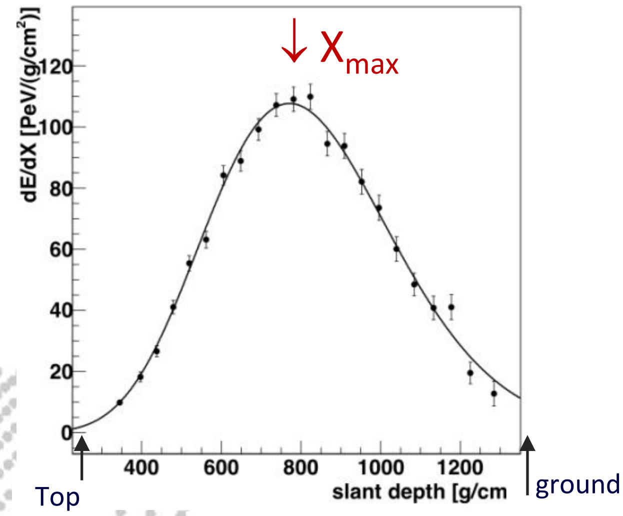
3000 km^2

1400 m altitude , 875 – 1740 g cm^{-2} (60^o)

The hybrid concept

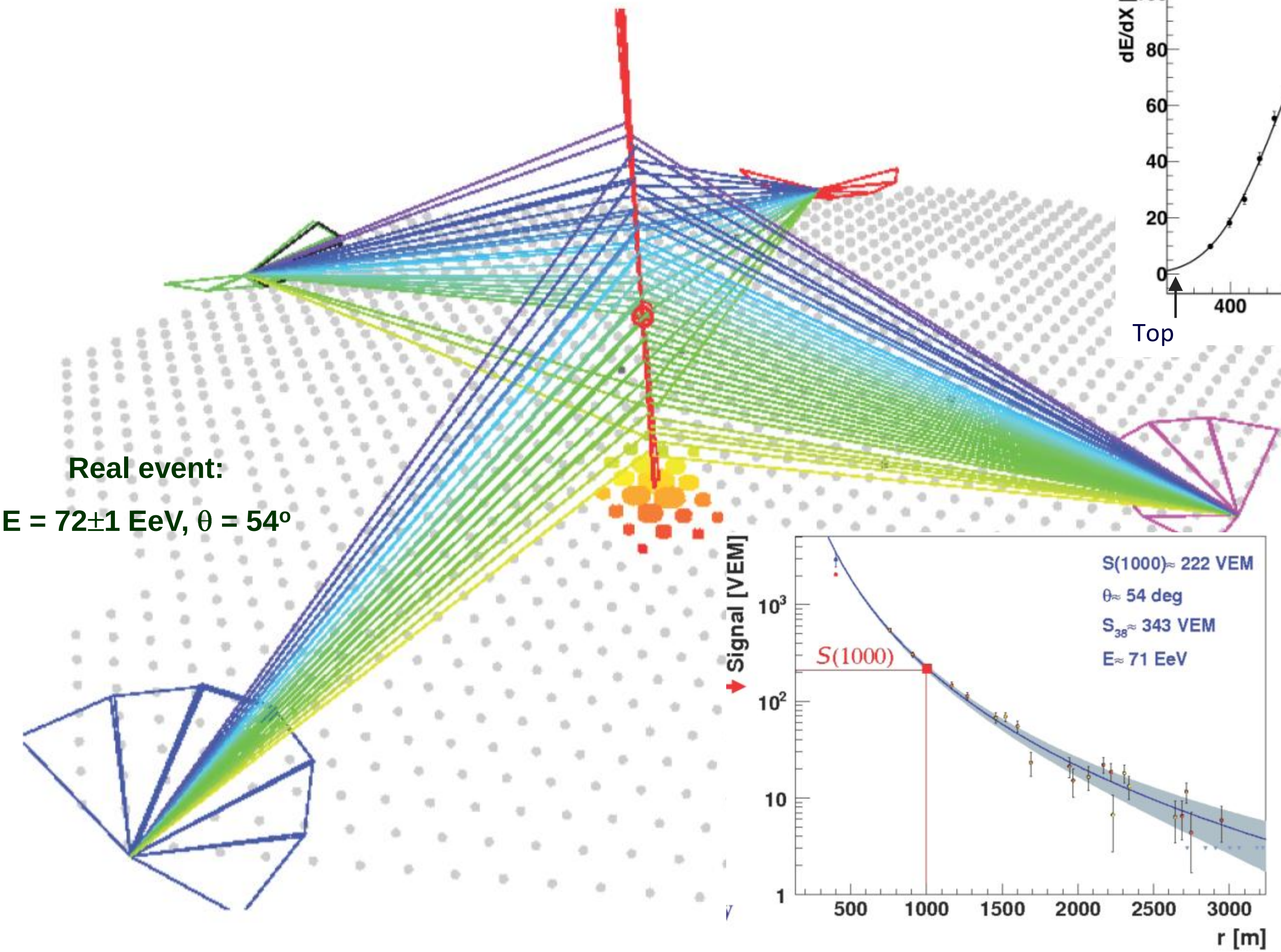
- SD only
- Hybrid: FD + at least 1 SD tank
  (→ lower energy threshold)
- Golden Hybrid: independent FD & SD reconstructions
  (→ SD calibration)

FD: measures the shower longitudinal profile.
Calorimetric measurement of energy.
Determination of shower maximum X_{max}
(primary mass and $\sigma_{p\text{-}air}$ analyses).



Real event:

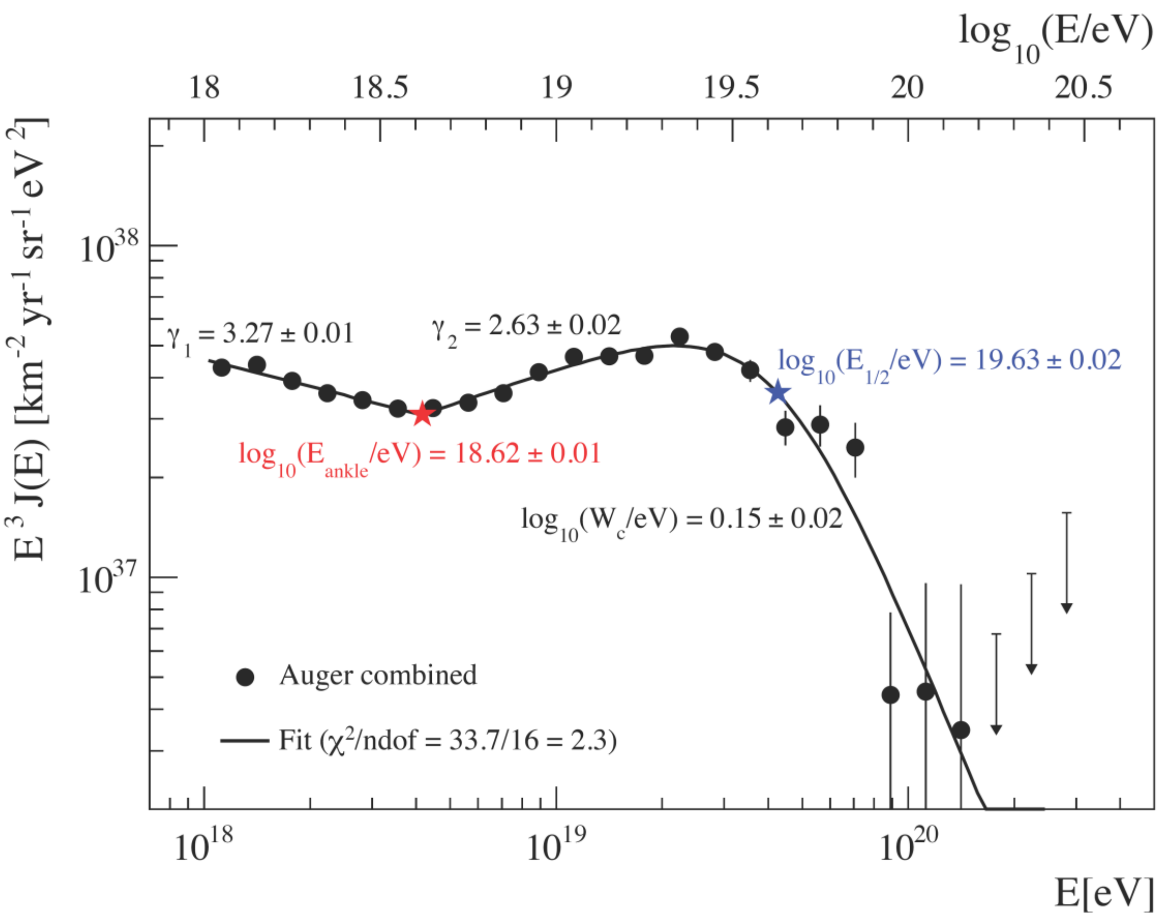
E = 72±1 EeV, θ = 54°



SD: measures the shower lateral distribution
Energy ∝ signal measured at 1 km from core

The UHECR flux

SD only + Hybrid spectra combined (agreement better than 1.5%)



Two power laws in the ankle region + smoothly changing function above

$$J(E;E>E_{\mathrm{ankle}}) \propto E^{-\gamma_2} \frac{1}{1+\exp\left(\frac{\lg E - \lg E_{\frac{1}{2}}}{\lg W_c}\right)}$$

Main systematic uncertainty

≈22% from overall energy scale

SD systematic on flux ≈ 6%

Hybrid systematic on flux ≈ 10% at 10^{18} eV (6% at 10^{19} eV)

due to **exposure** determination & E resolution

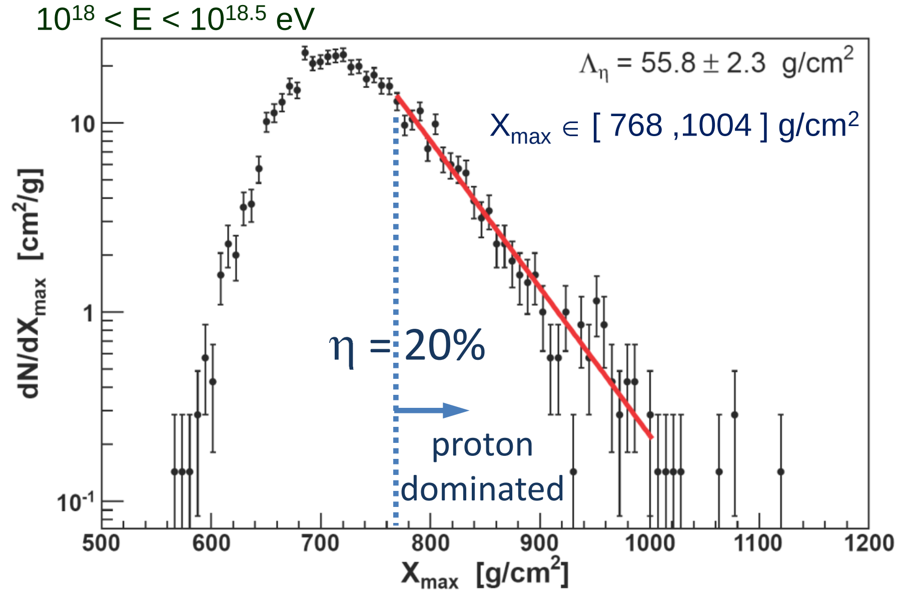
- ✓ **Ankle ★** : may indicate a change in origin of cosmic rays (Galactic to Extra Galactic origin).
- ✓ **Flux suppression ★** : found with a significance **>20σ** at higher energies.

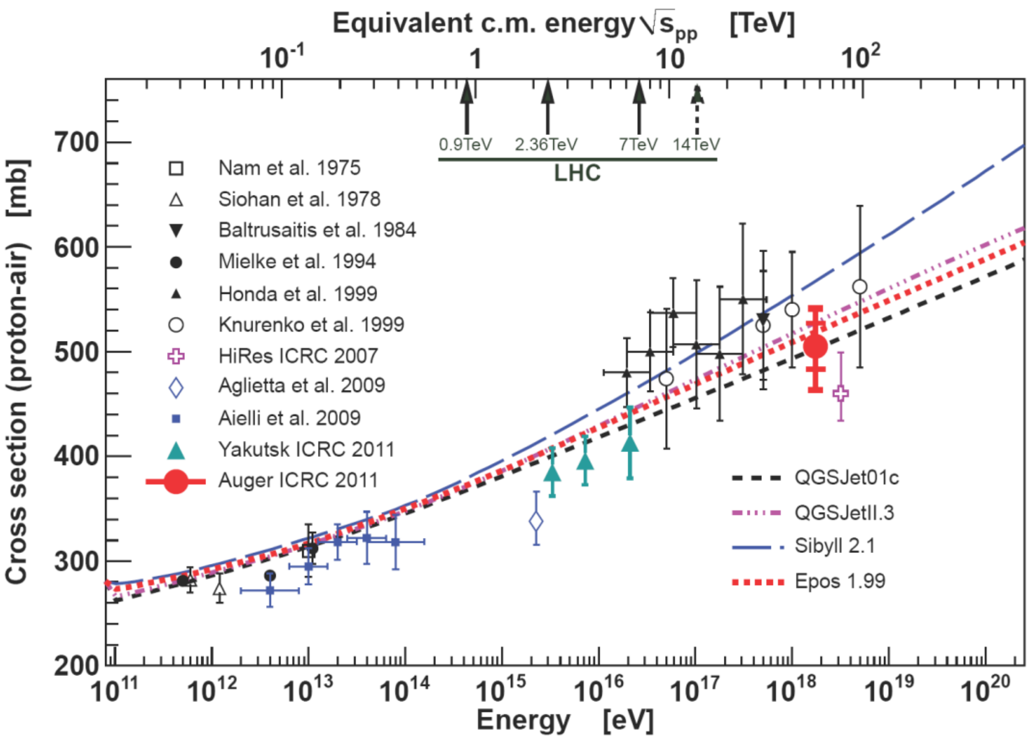
p-air cross section at $\sqrt{s}$ = 57 TeV (<E>≈1.7 EeV)

Tail of the X_{max} distribution sensitive to cross-section

$$\frac{dN}{dX_{max}} \propto \exp - \left(\frac{X_{max}}{\Lambda_\eta} \right) \qquad \sigma_{p-air} = \frac{\langle m_{air} \rangle}{\Lambda_\eta}$$

- ✓ Define Λ_η as primary observable via exponential shape
- ✓ Select a proton enriched data sample (η=20%)
- ✓ Use simulations to correlate Λ_η^{MC} with cross-section
- ✓ Λ_η^{MC} adjusted to reproduce the measured Λ_η





σ_{p-air} = (505 ± 22 stat $\pm^{28}_{36}$ sys) mb

Phys. Rev. Lett. 109 (2012) 062002

Systematic uncertainties:

- Hadronic models
- energy scale
- simulations … total +20 mb −15 mb
- photon and helium fraction:
  - photon fraction 0.5% +10 mb
  - He fraction 25% −30 mb

Test of hadronic interaction models

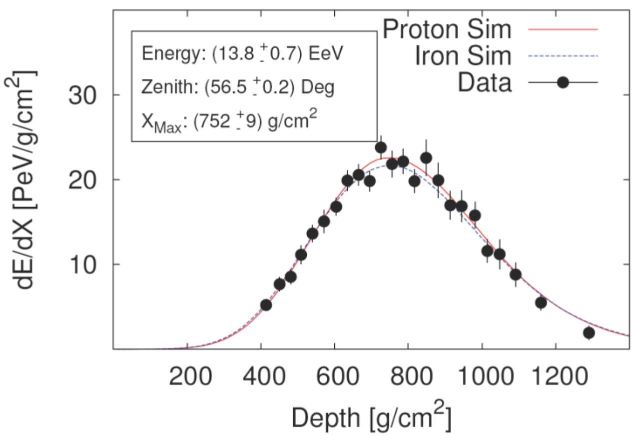
The information on the nature of the EAS primary particle and cross-section depends on models used in MC simulations ⇒

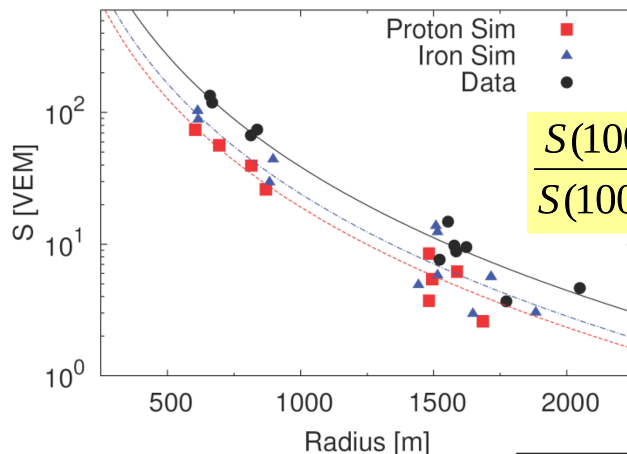
It is crucial to validate hadronic models!

Ground signals comparison in an event-by-event basis

$18.8 < \log(E/eV) < 19.2$ → 227 golden hybrid events (library of MC events matching data LP)

Ground signal systematically lower than observed





$$\frac{S(1000)_{data}}{S(1000)_{Simul}}$$

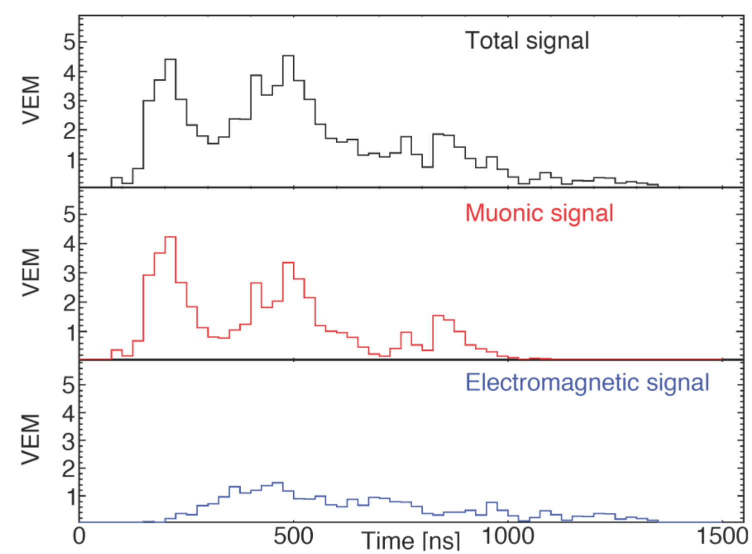
≈ 1.5 vertical showers

≈ 2 horizontal showers

4 independent methods to check the muon content relative to models → $S_{tot} \approx S_{em} + S_{\mu}$

1. Smoothing of FADC traces
2. Multivariate muon counter
3. Shower universality
4. Inclined showers

- Far from the core muons produce spikes.
- S_{μ} determination: systematic < 8% resolution ≈20%



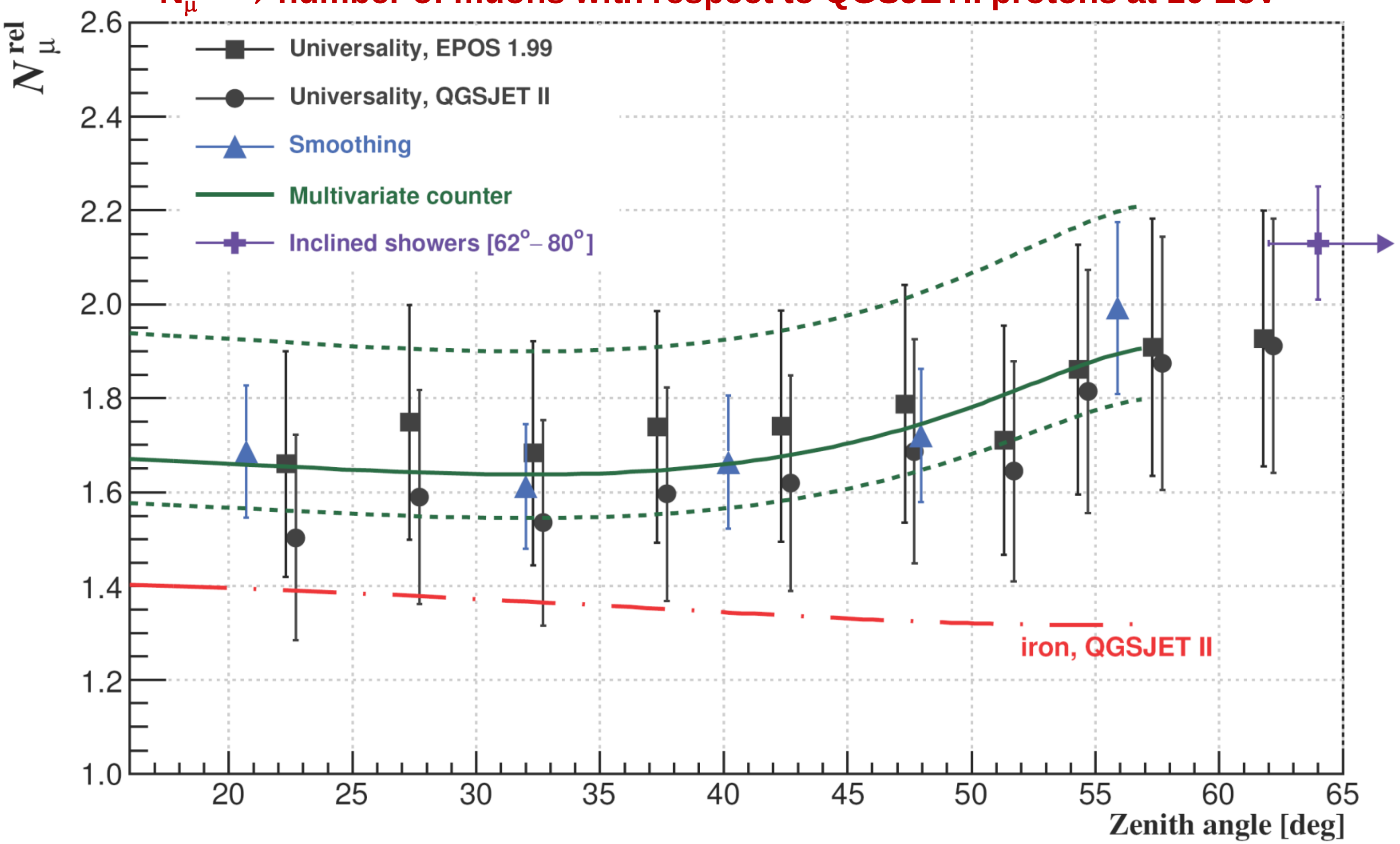
Test of hadronic interaction models

All five different methods show that the hadronic interaction models UNDERESTIMATE the number of muons by a factor 25% – 100% (depending on the model and primary).

$$N_\mu^{rel} \approx 1.5 - 2 \quad \text{(for proton-induced showers)}$$

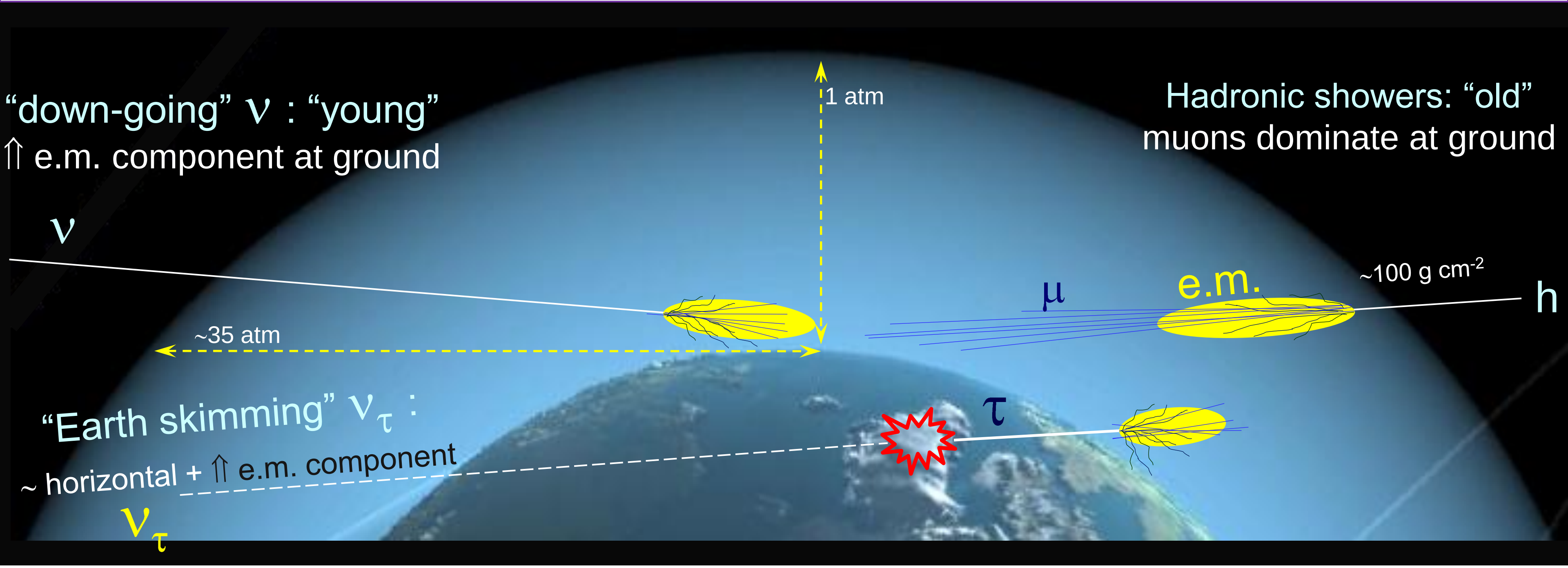
The discrepancy can not be explained by the composition alone.

N_μ^{rel} → number of muons with respect to QGSJETII protons at 10 EeV



Search for UHE neutrino primaries

$\nu \equiv$ very inclined & "young" (deep) shower



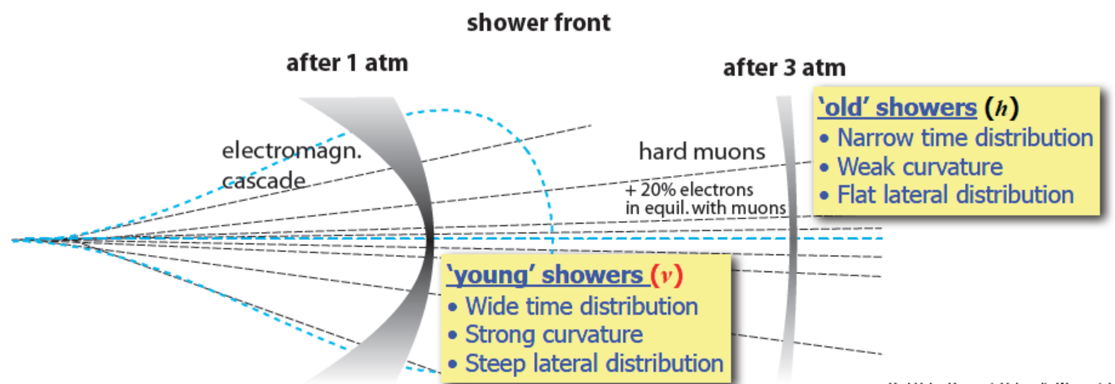
✓ **Why *very inclined* ?**

Due to the low neutrino cross-section → large amount of matter for interaction
→**inclined** neutrinos are likely to induce EAS close to ground

Atmosphere @Auger site Vertical ≈880 g/cm^2 Horizontal ≈32000 g /cm^2

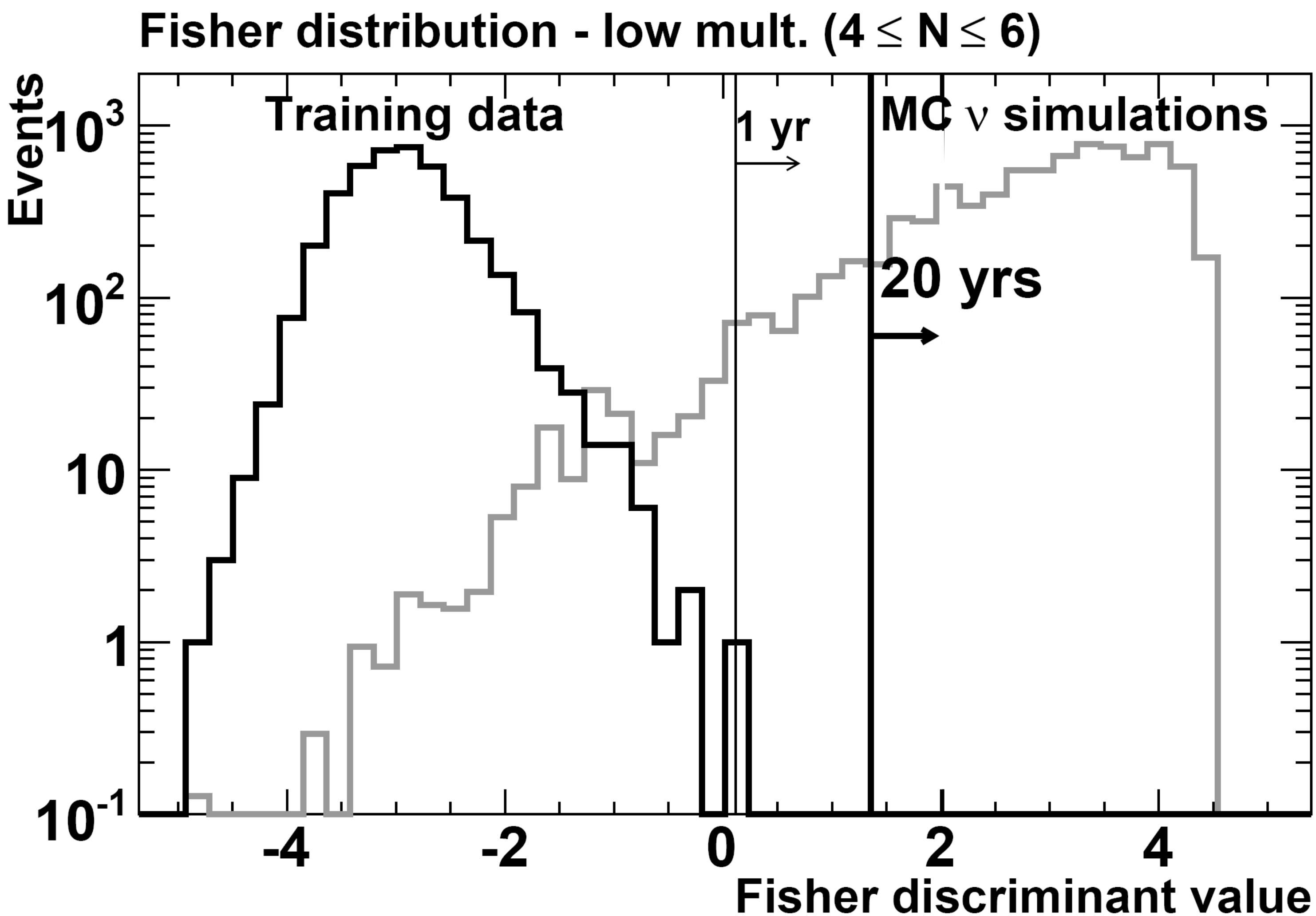
✓ **Why *young* ?**

→ ν interact deep in the atmosphere
→ look for **young** showers
→ **high e.m. component in early stations**



Fisher discriminant method

- “safe” cut on *Fisher* value such that expected background **< 1 event / 20 years** of Auger data



UHE ν search results

Physical Review D 84, 122005 (2011)
Astrophys. J. Lett., 755 (2012) L4

After un-blinding … **0 candidates** survive the cuts for the search period:
Down-going : Nov 07 to May 10
Earth-skimming: Jan 04 to May 10

Assuming

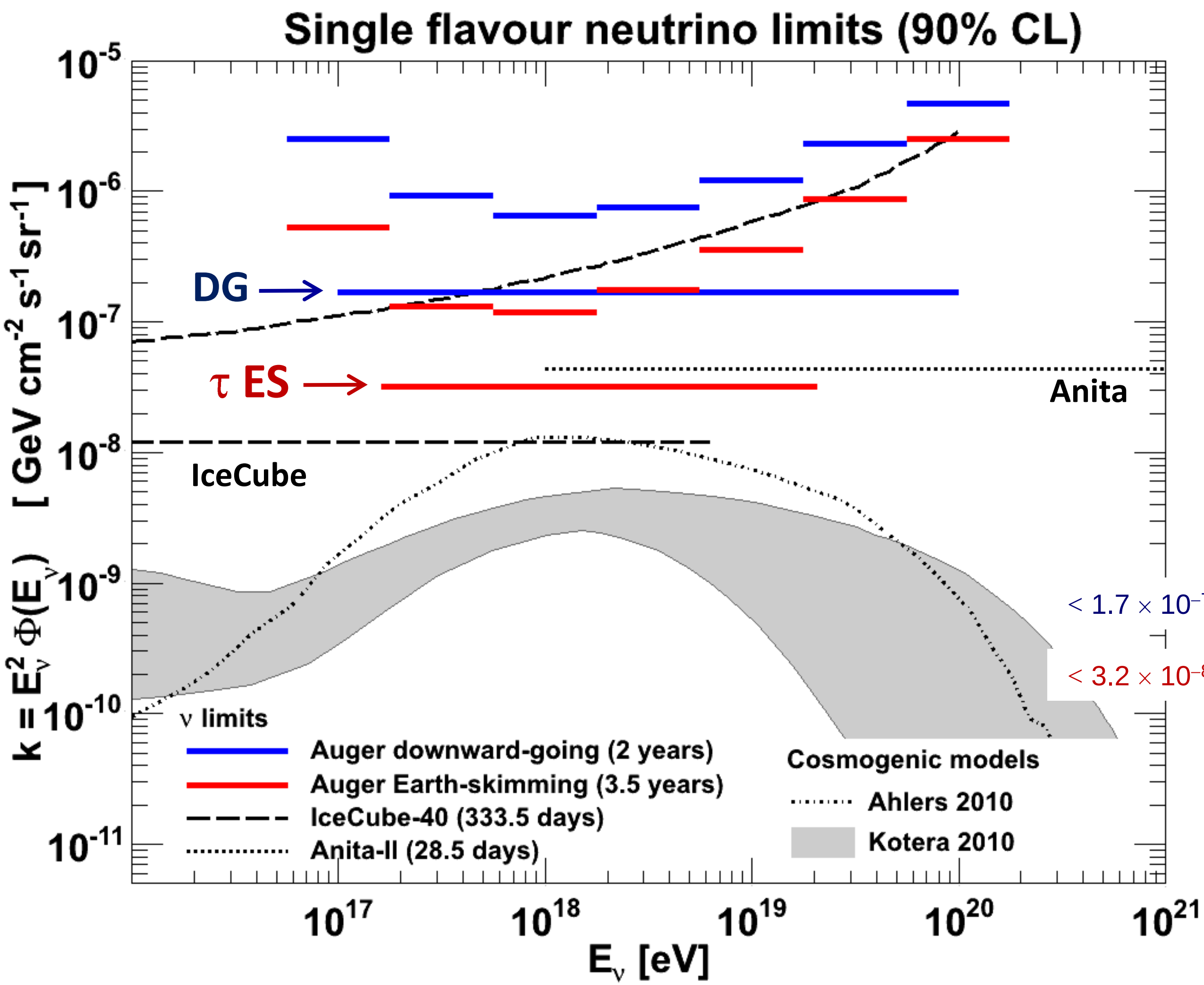
$$\frac{dN}{dE} \equiv f(E_\nu) = k \cdot E_\nu^{-2}$$

Differential limit ($\Delta \log_{10} E = 0.5$)

$$f(E_\nu)_{lim} = \frac{N_{exp}}{E_\nu \cdot \mathcal{E}(E_\nu) \cdot \Delta \ln E_\nu}$$

Integral limit

$$N_{exp} = \int f(E_\nu) \cdot \mathcal{E}(E_\nu) \cdot dE_\nu$$



$< 1.7 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} $E \in [10^{17}, 10^{20}]$ eV

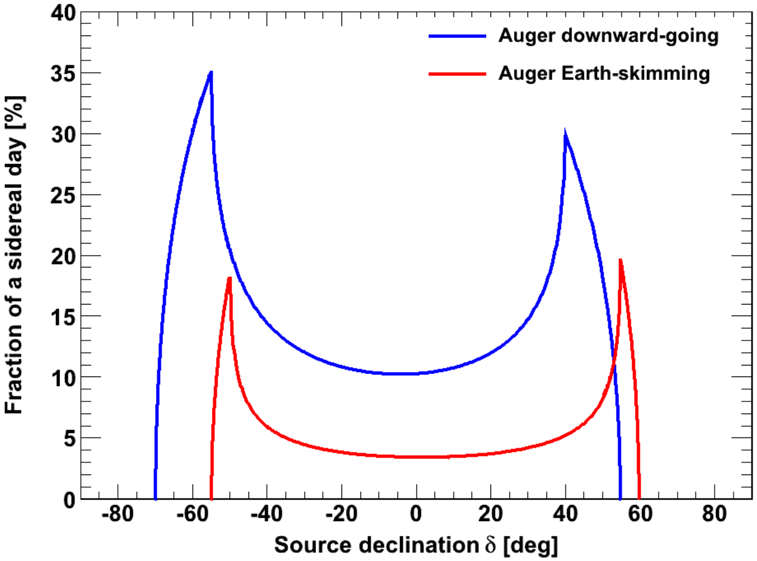
$< 3.2 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} $E \in [1.6\times10^{17}, 2\times 10^{19}]$ eV

IceCube-40: Phys. Rev. D 83 (2011) 092003
ANITA II: Phys. Rev. D 82 (2010) 022004
Ahlers : Astropart. Phys. 34 (2010) 106
Kotera: JCAP 10, 013 (2010)

Limits on point-like sources of UHE neutrinos

Astrophys. J. Lett., 755 (2012) L4

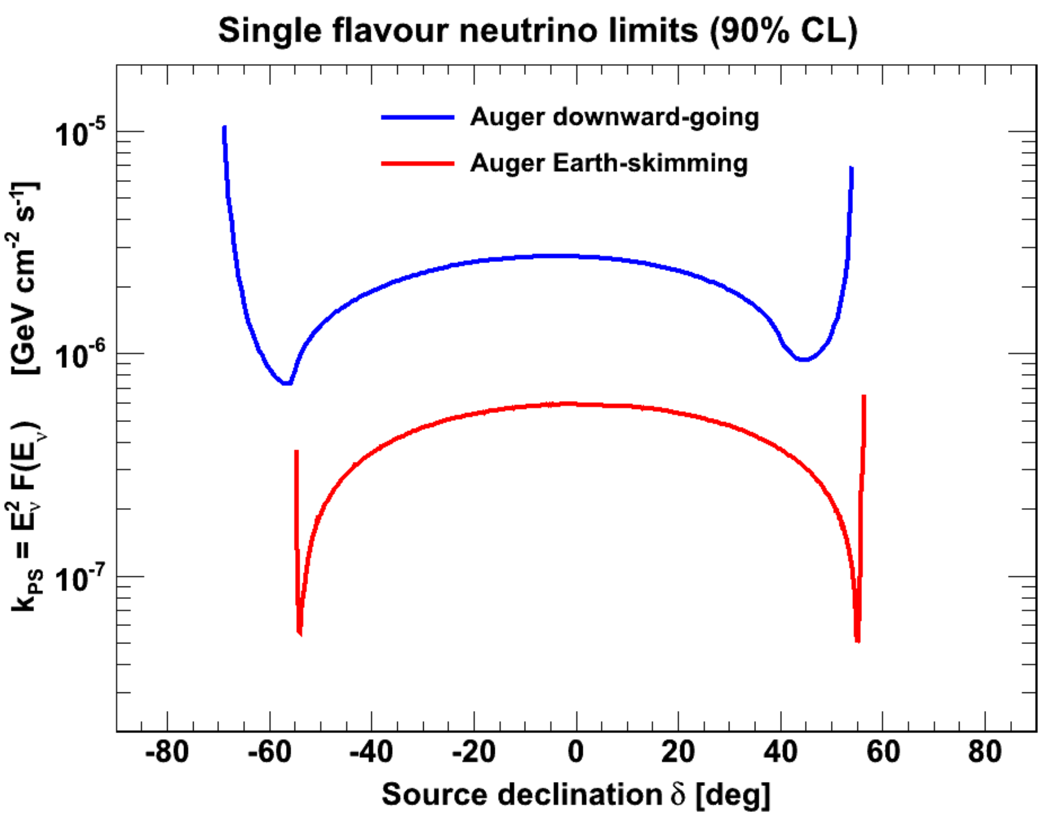
Search for point-like sources of UHEν over a broad range of declinations: [north –65° , south 55°]



$$\cos\theta(t) = \sin\lambda\ \sin\delta + \cos\lambda\ \cos\delta\ \sin(2\pi t/T - \alpha)$$

Zenith angle   declination λ = 35.2° (Auger latitude)   Right ascension

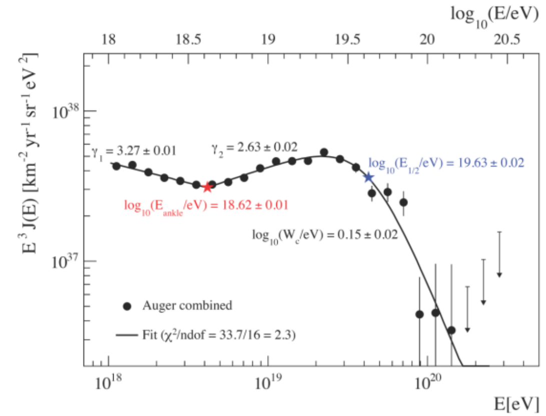
The exposure at each declination is computed based on the time a source is visible in the sky. No neutrino candidates → compute a limit as function of the declination:



Summary

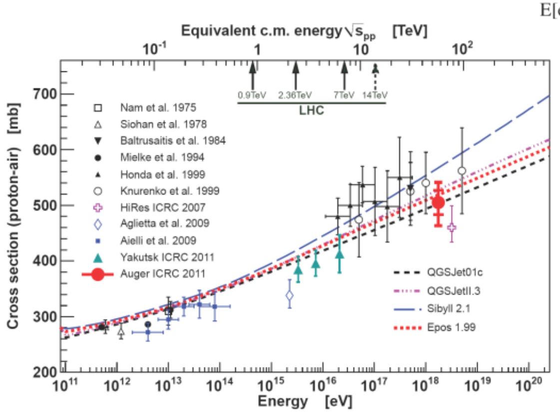
Spectrum

- Flux suppression established at $E > 4 \times 10^{19}$ eV
- Ankle observed at $\approx 4 \times 10^{18}$ eV



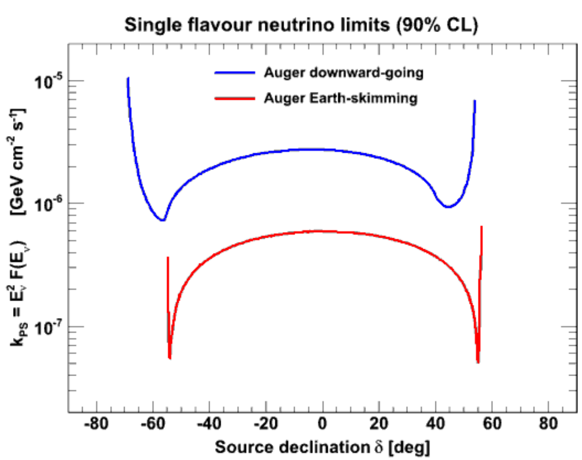
Hadronic interactions

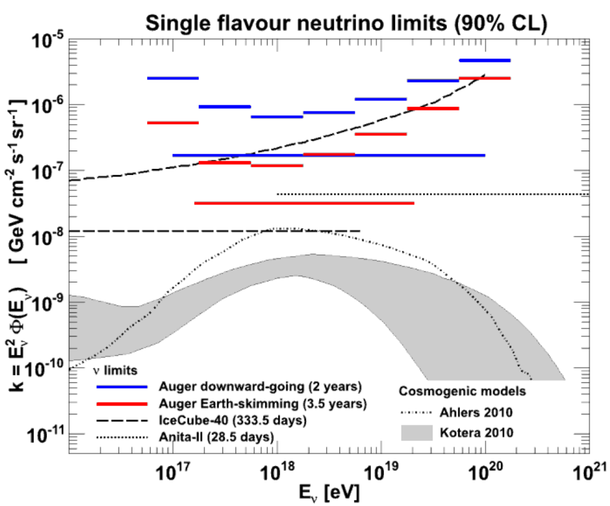
- First measure of the p-air cross section at 57 TeV
  (much beyond LHC energies)
- Models underestimate the muon number by 25 – 100%



Neutrinos

- Improved neutrino limits on the diffuse flux
- Sensitivity to point-like sources in broad δ range [–65°, 55°]





Hybrid shower detection