Recent results of the Pierre Auger Observatory

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for the Pierre Auger Collaboration

University of Nova Gorica

Outline

- The Pierre Auger Observatory
- Spectrum of ultra-high energy cosmic rays
- Mass composition and hadronic interaction
- Arrival directions

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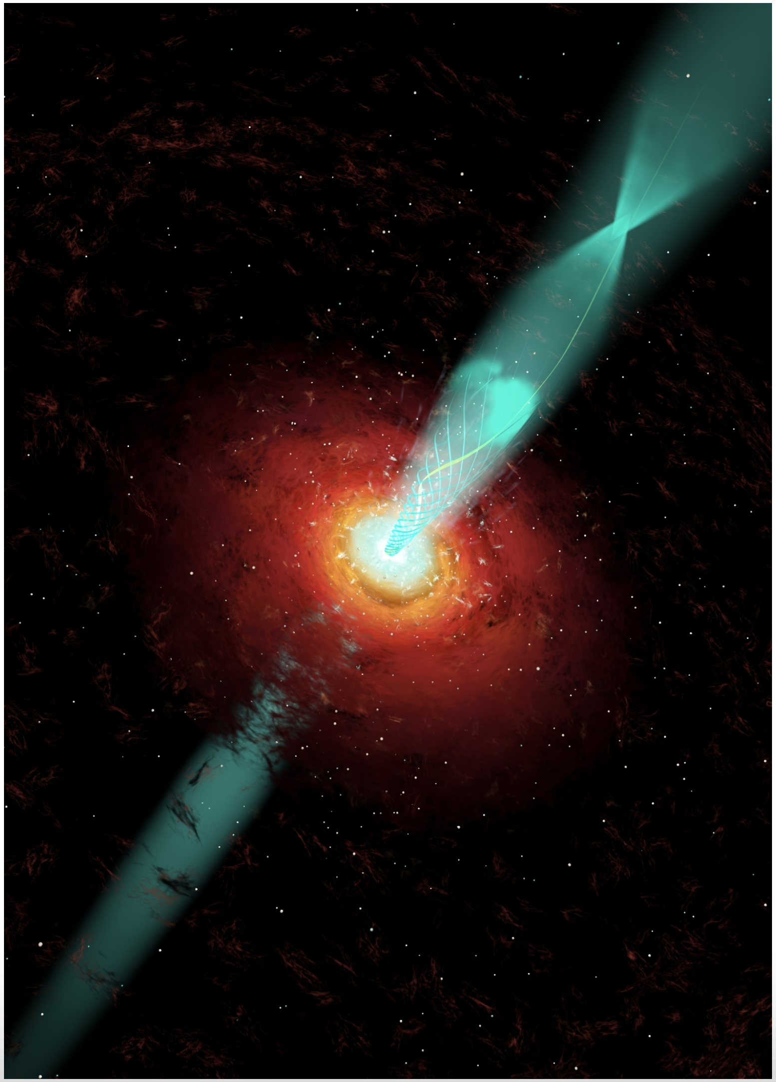
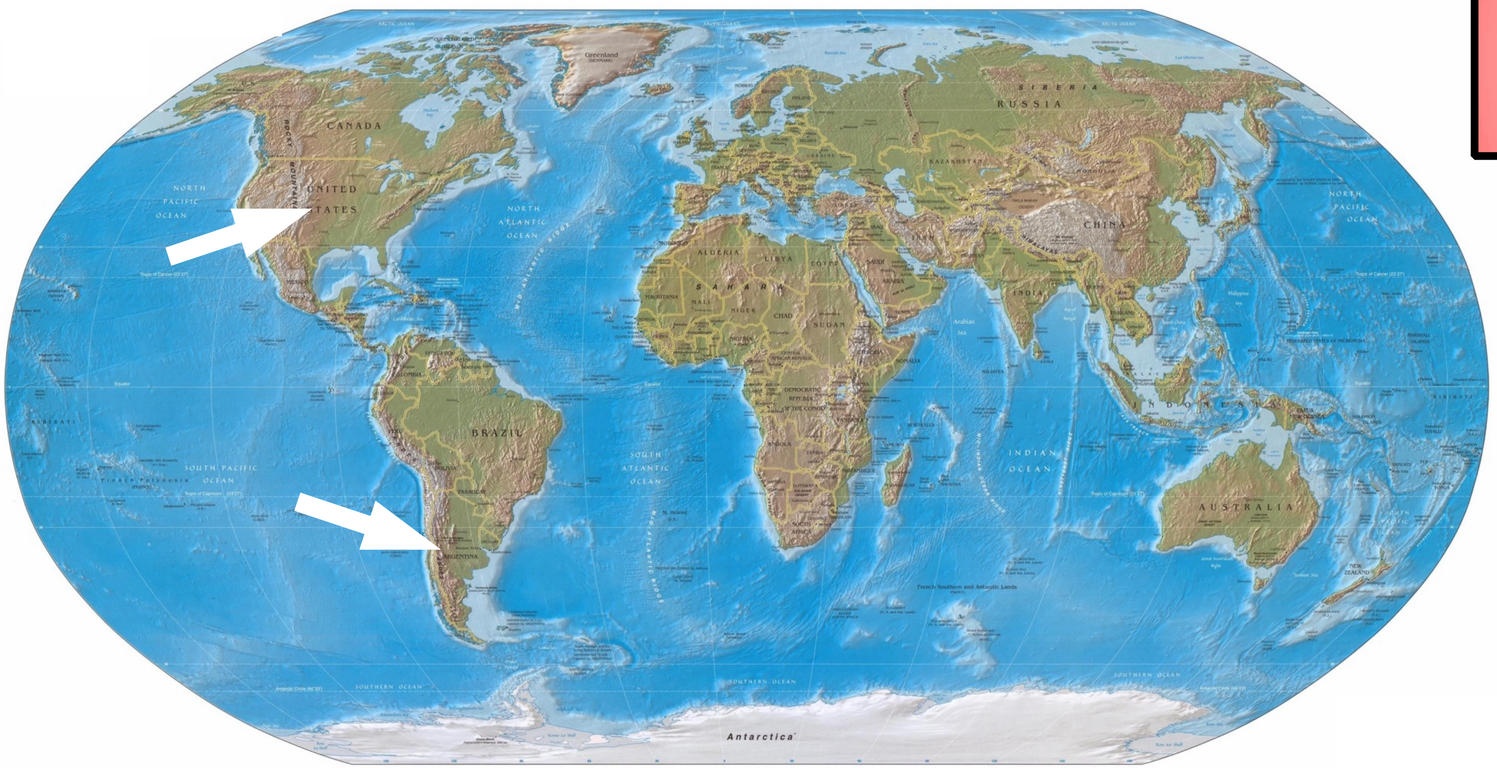
Scientific case

Study of the ultra-high energy cosmic rays (UHECR)

- determine the characteristics (flux, nature, energy)
- identify the sources (cosmic ray astronomy)
- understand the acceleration mechanisms



The Pierre Auger Observatory

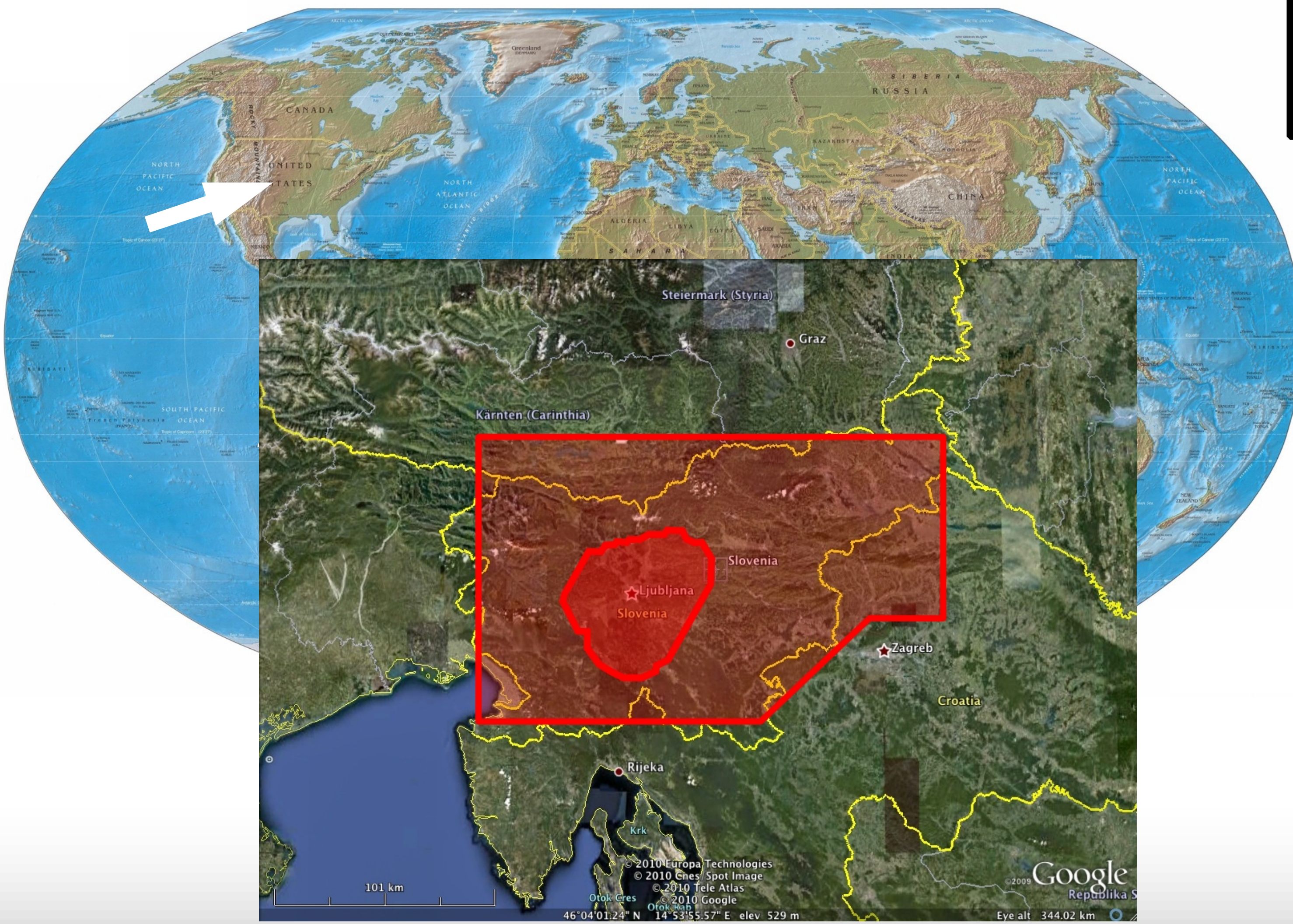


Two sites:
- Malargue (Argentina)
- Lamar (USA)

- full sky coverage
- high statistic

Above 2×10^{19} eV
- south ~ 25 evt/year
- north ~ 200 evt/year

The Pierre Auger Observatory



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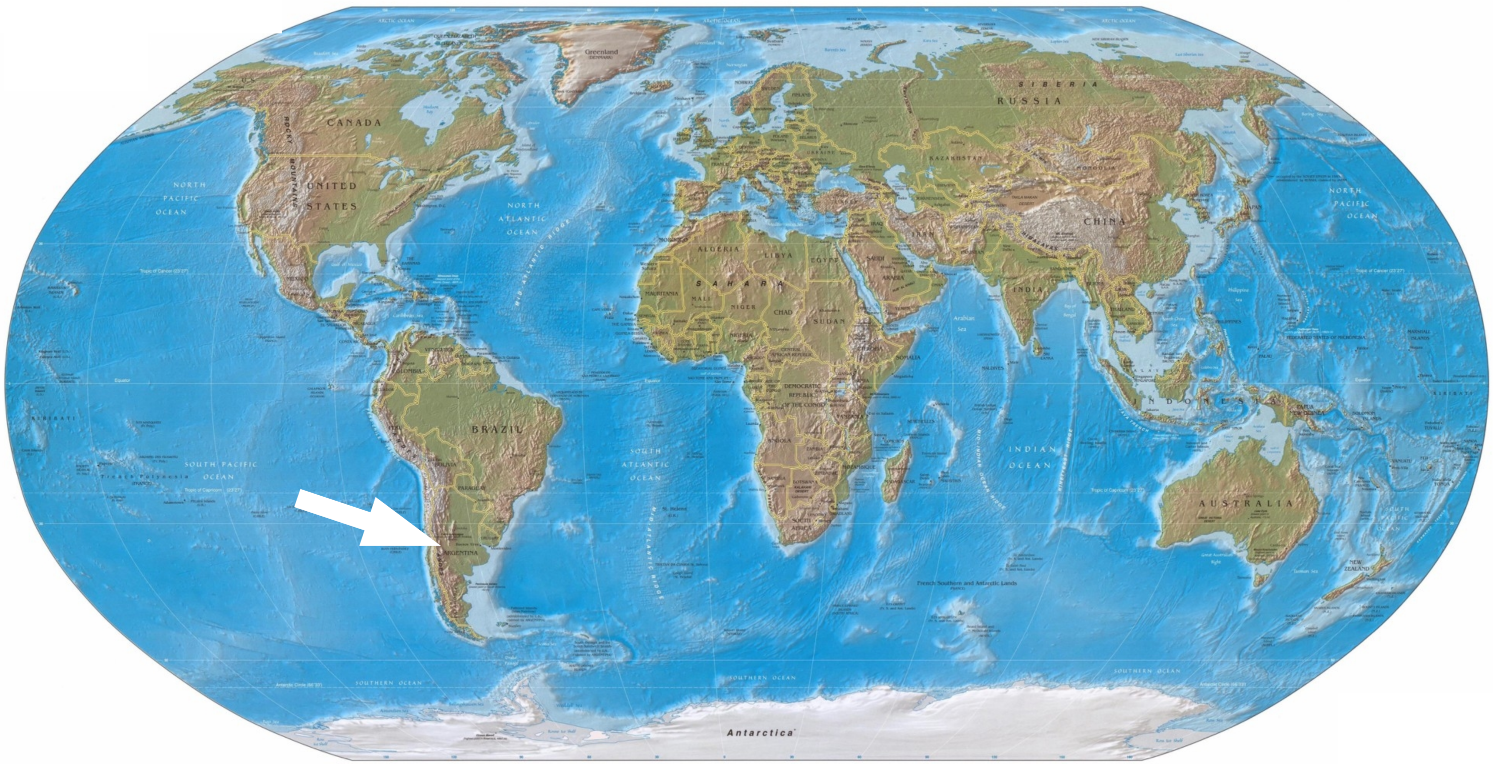
The southern site



Malargue (Argentina)

2004 => data
2008 => completion

The southern site

Malargue (Argentina)

2004 => data
2008 => completion

Hybrid detection

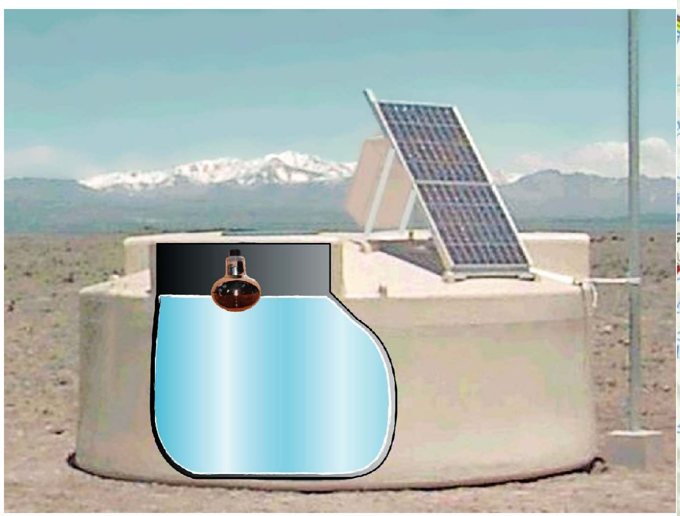
Detection of the extensive air shower (EAS) induced by UHECR with two methods

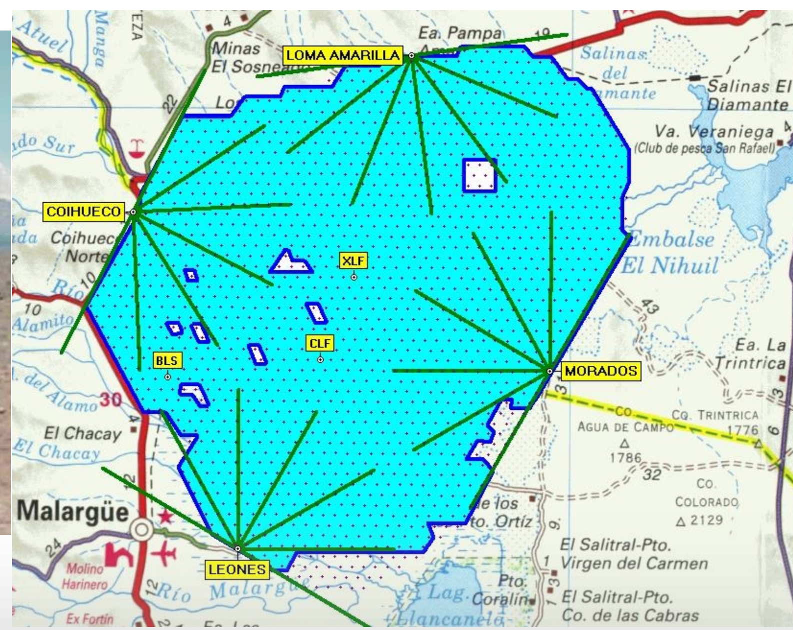
sampling at the ground level of the shower particles

Array of 1660 Cherenkov Detectors (SD)

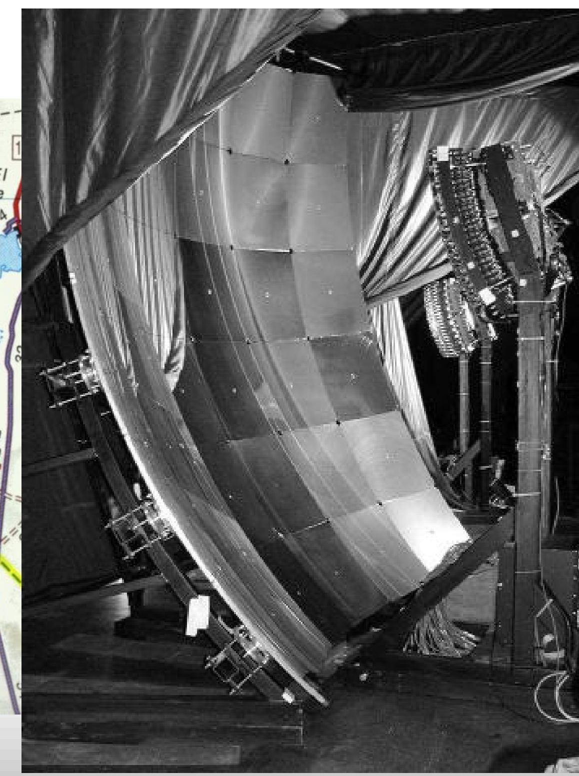
detection of the fluorescence light emitted by the air molecules after the shower crossing

24 fluorescence telescopes in 4 sites (FD)

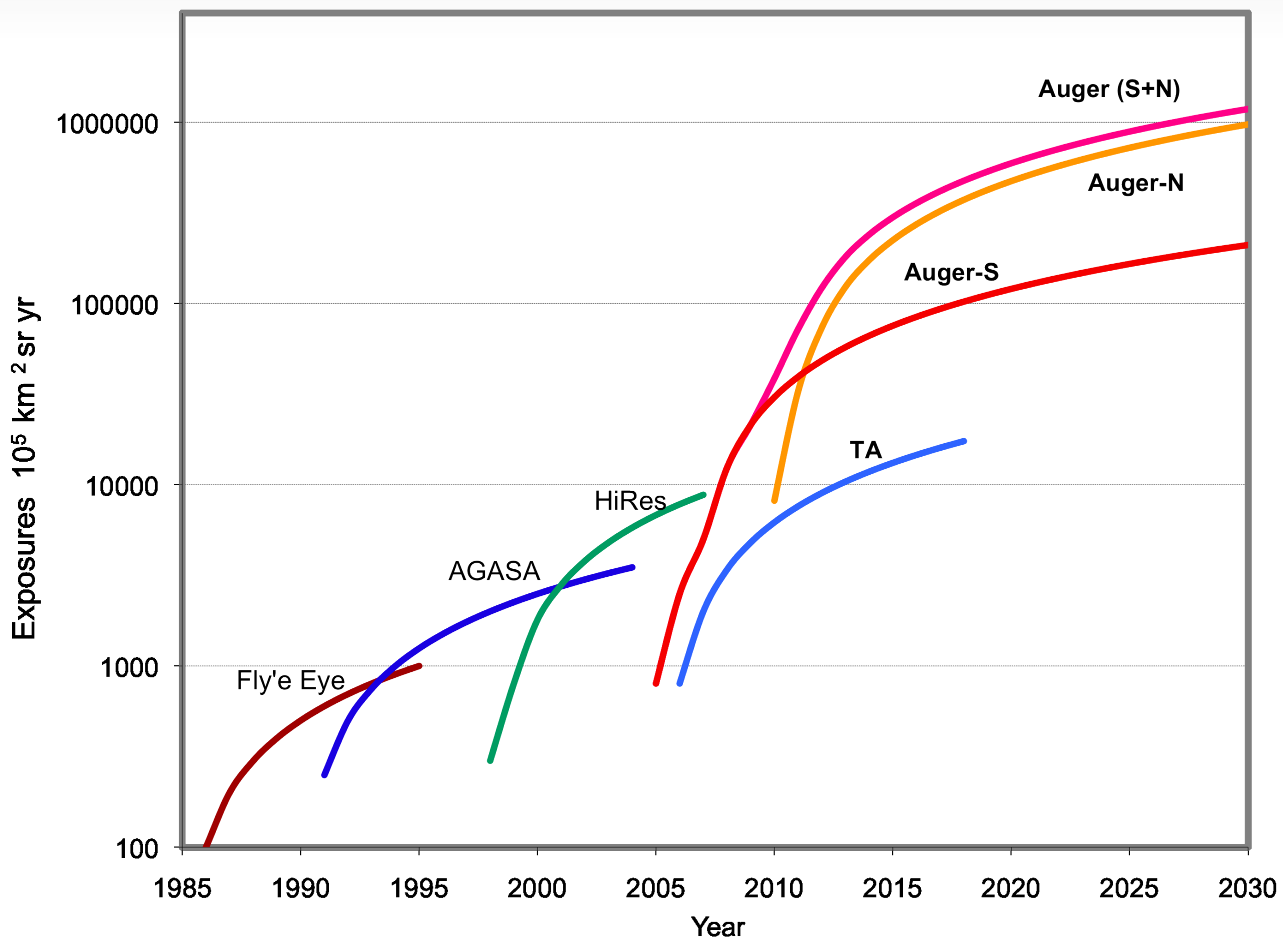




3000 km^2

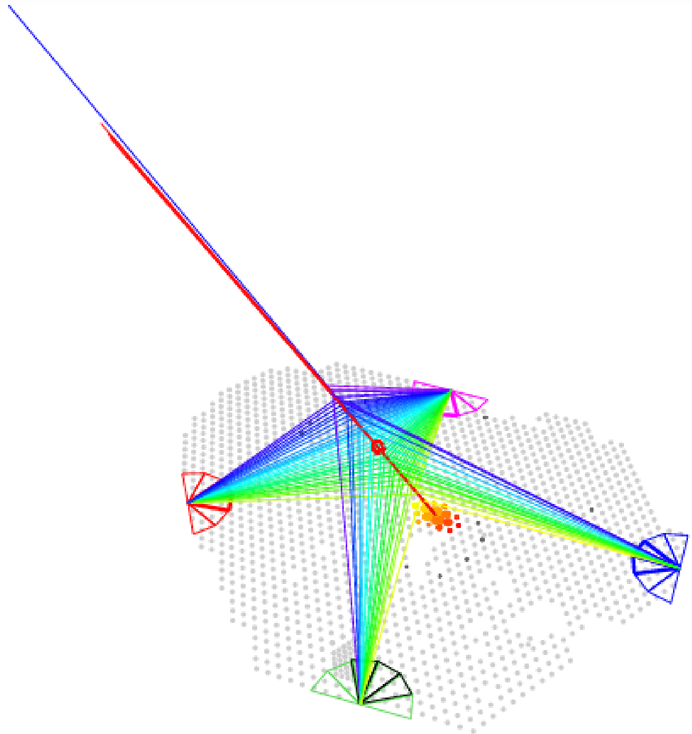


Exposure



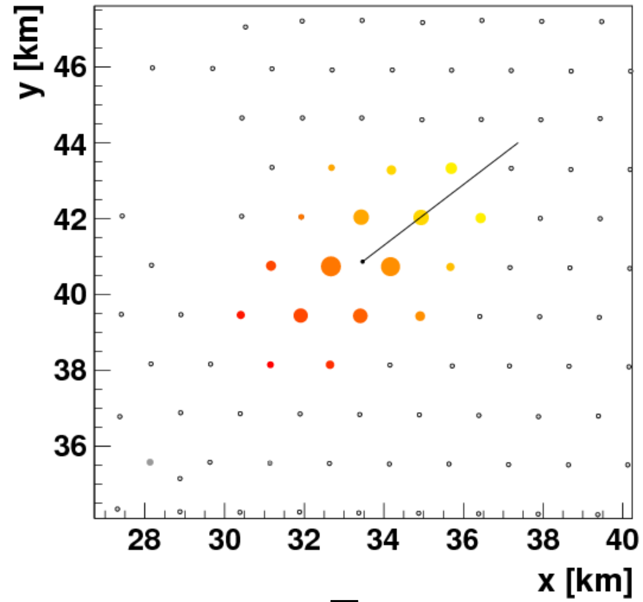
2000 trans-GZK cosmic rays in 10 years

Hybrid detector

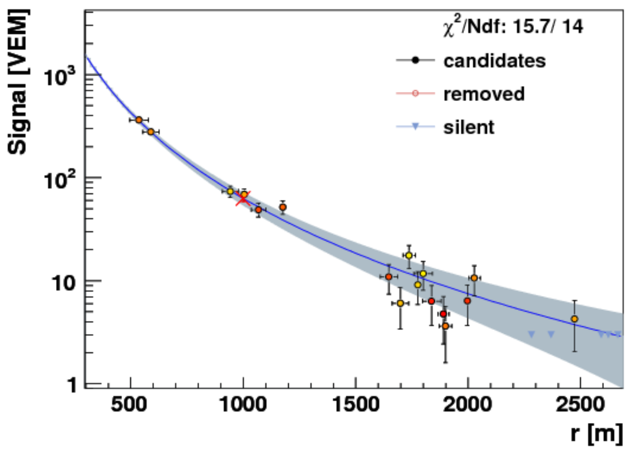


One example

Measurement of the shower front

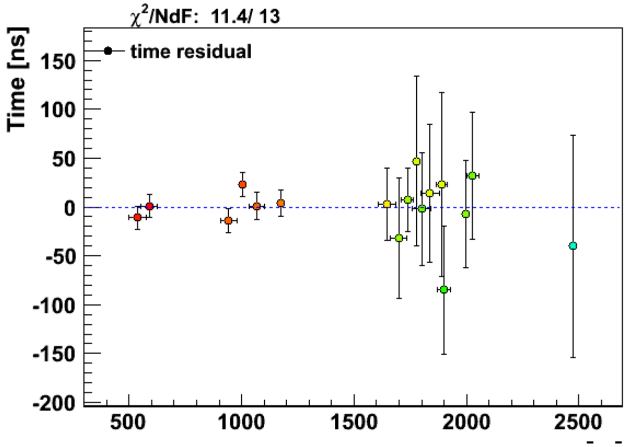


E ~ 2.70×10^{19} eV

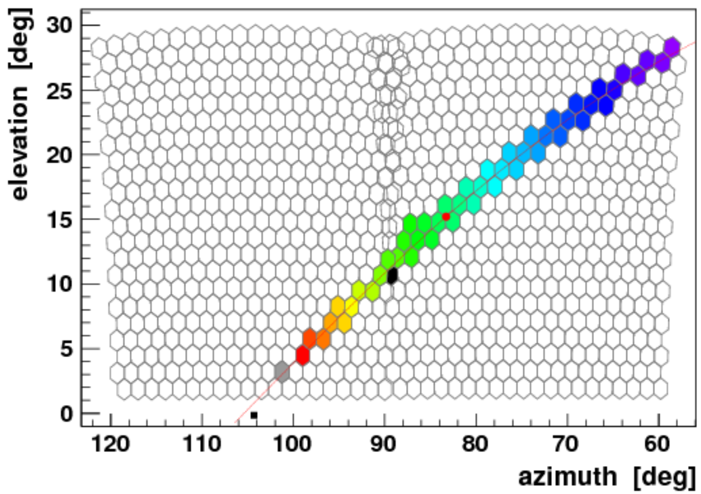


Lateral Distribution Function (LDF)

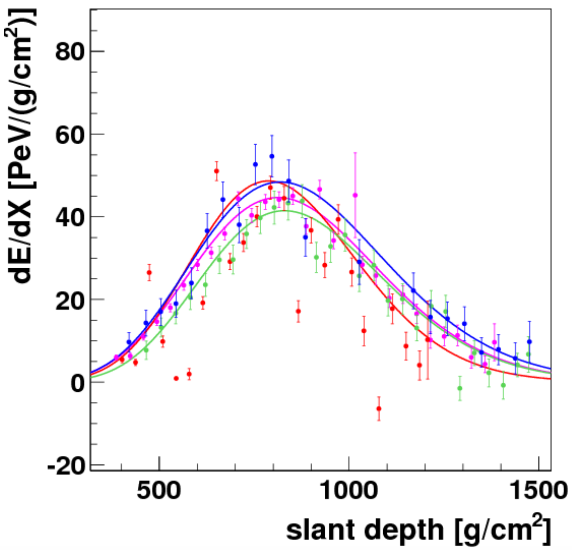
θ ~ 59.8° Φ ~ 38.8°



Measurement of the longitudinal profil of the shower

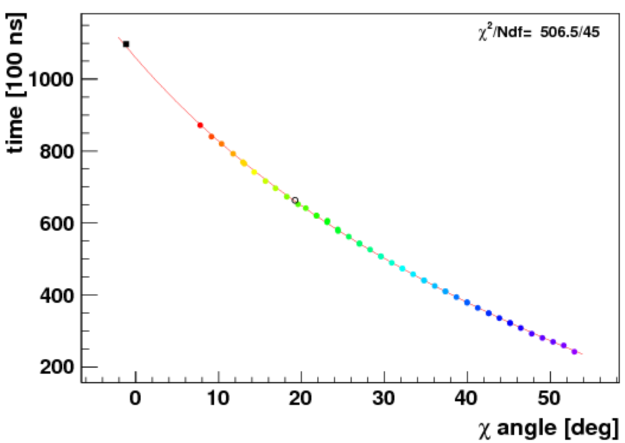


E ~ 3.02×10^{19} eV

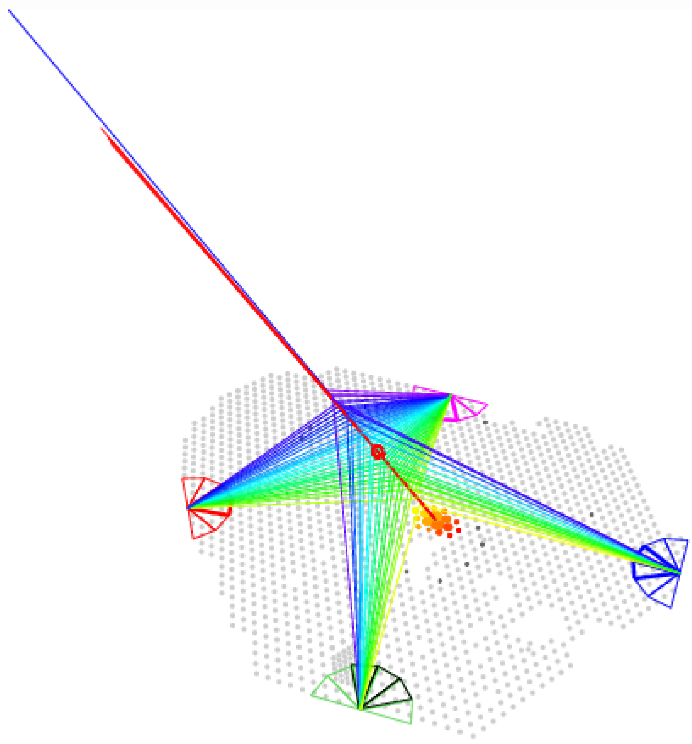


Gaisser-Hillas Function

θ ~ 59.6° Φ ~ 39.8°



Hybrid detector



Surface array:

- 100% duty cycle
- angular resolution < 1°
- exposure

Fluorescence telescopes:

- 13% duty cycle
- angular resolution < 0.6°
- energy estimation (calorimeter)

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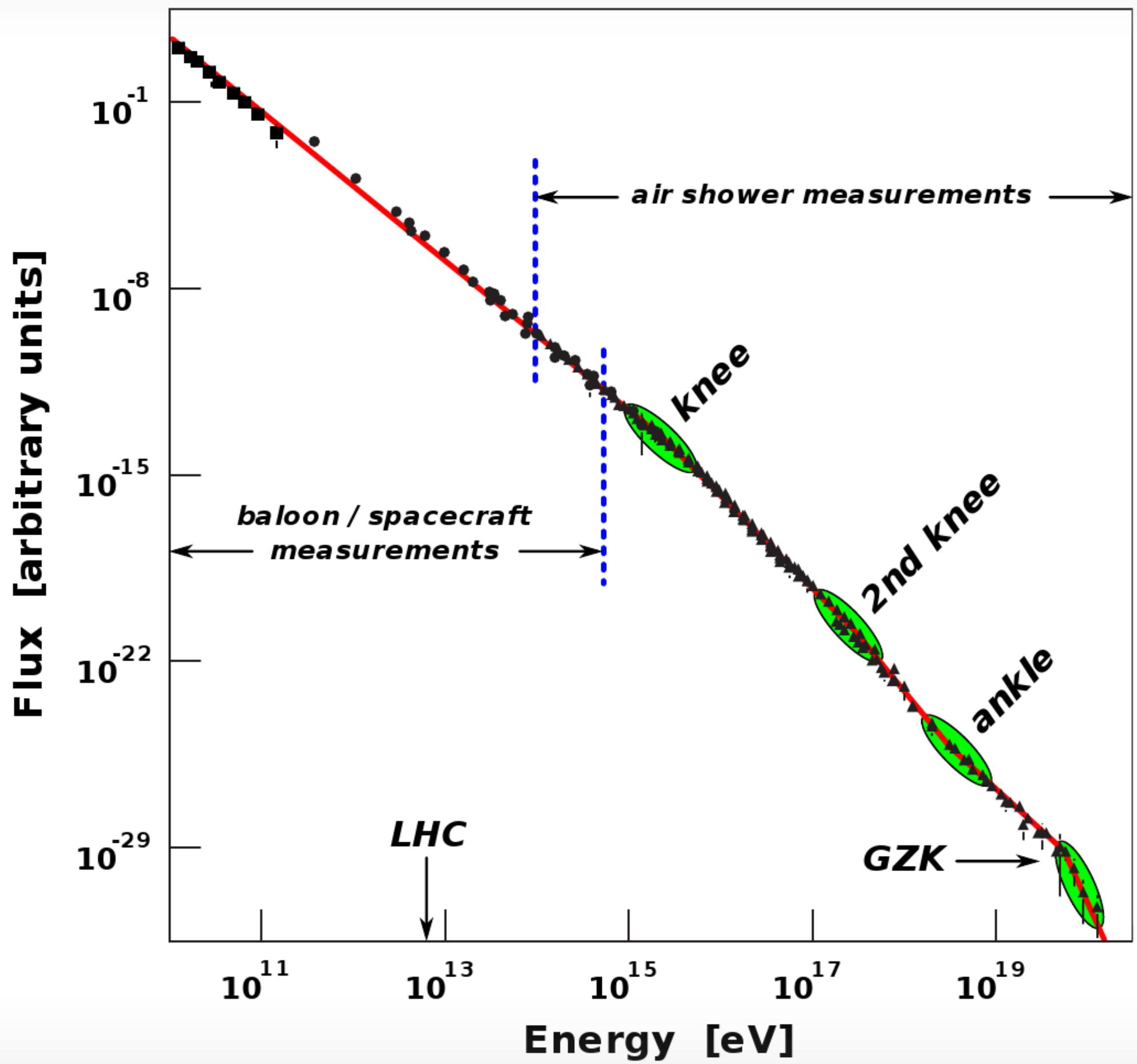
Energy spectrum



Combined spectrum (SD + hybrid)

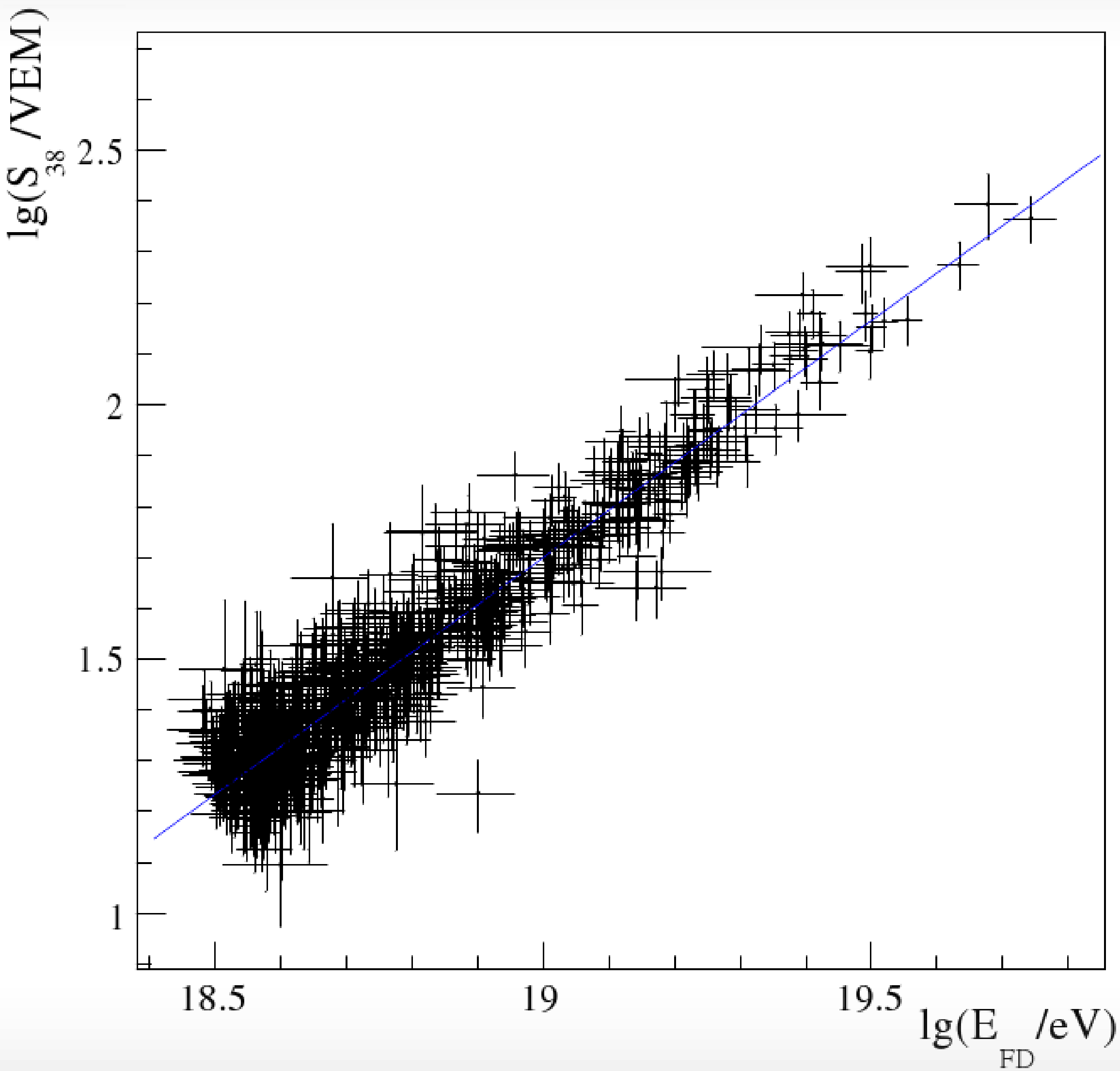
- exposure for both modes
- increase of the energy range

  SD above $10^{18.5}$ eV

  FD above 10^{18} eV

- calibration of the SD with hybrids

Energy spectrum



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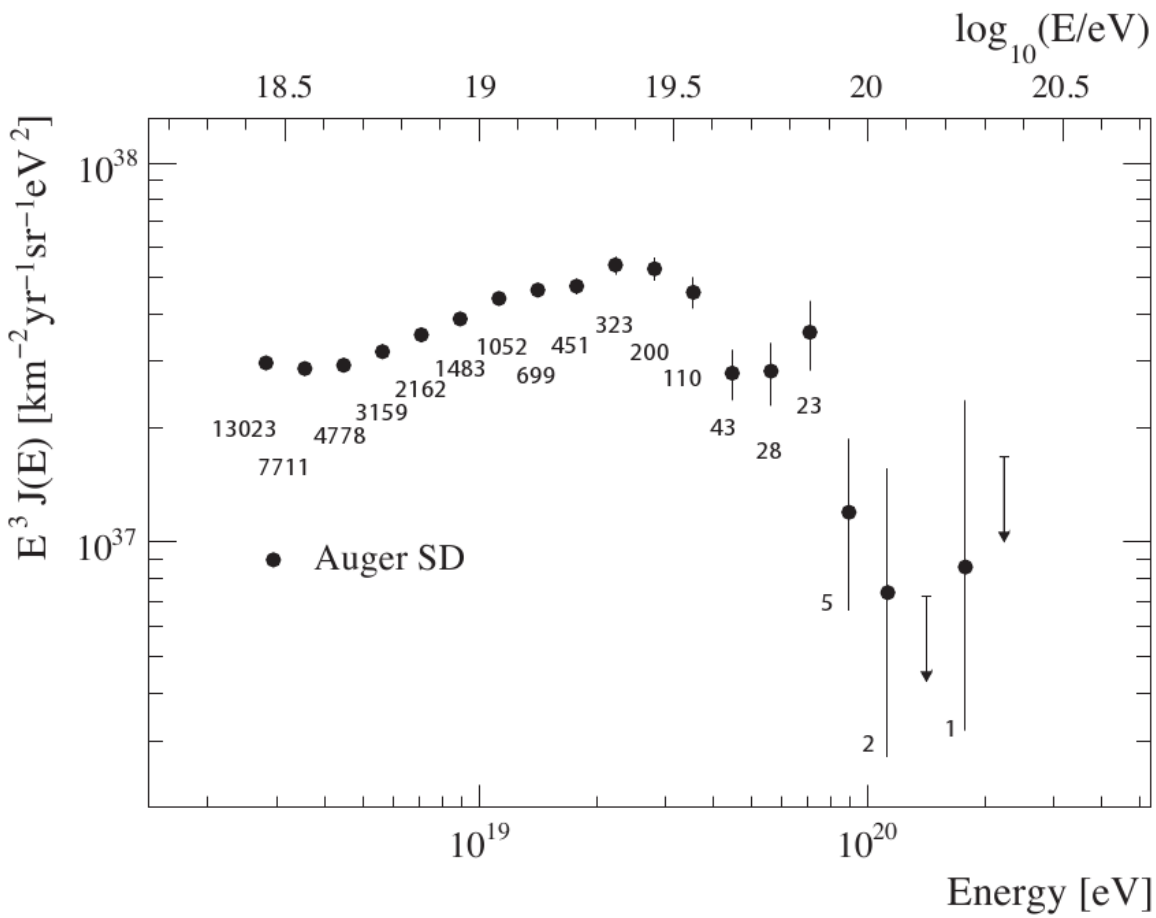
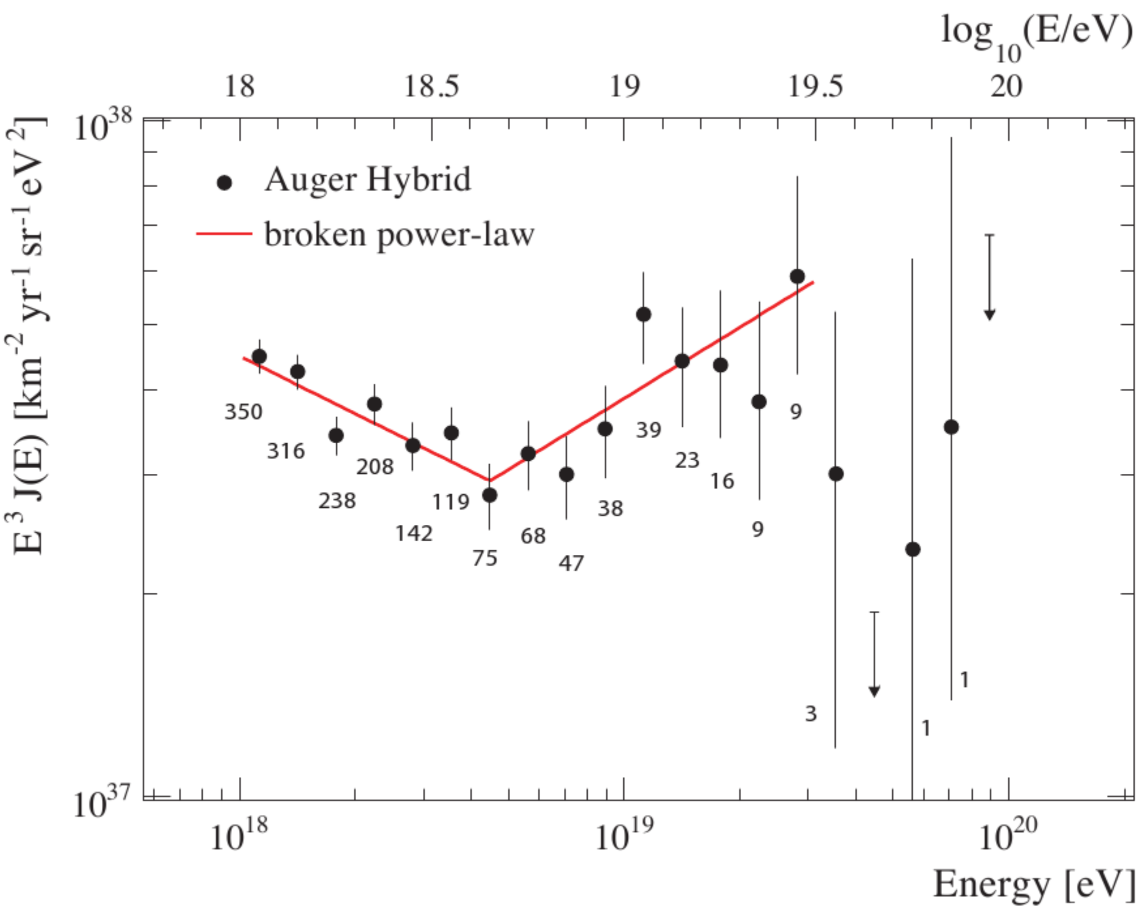
SD energy spectrum



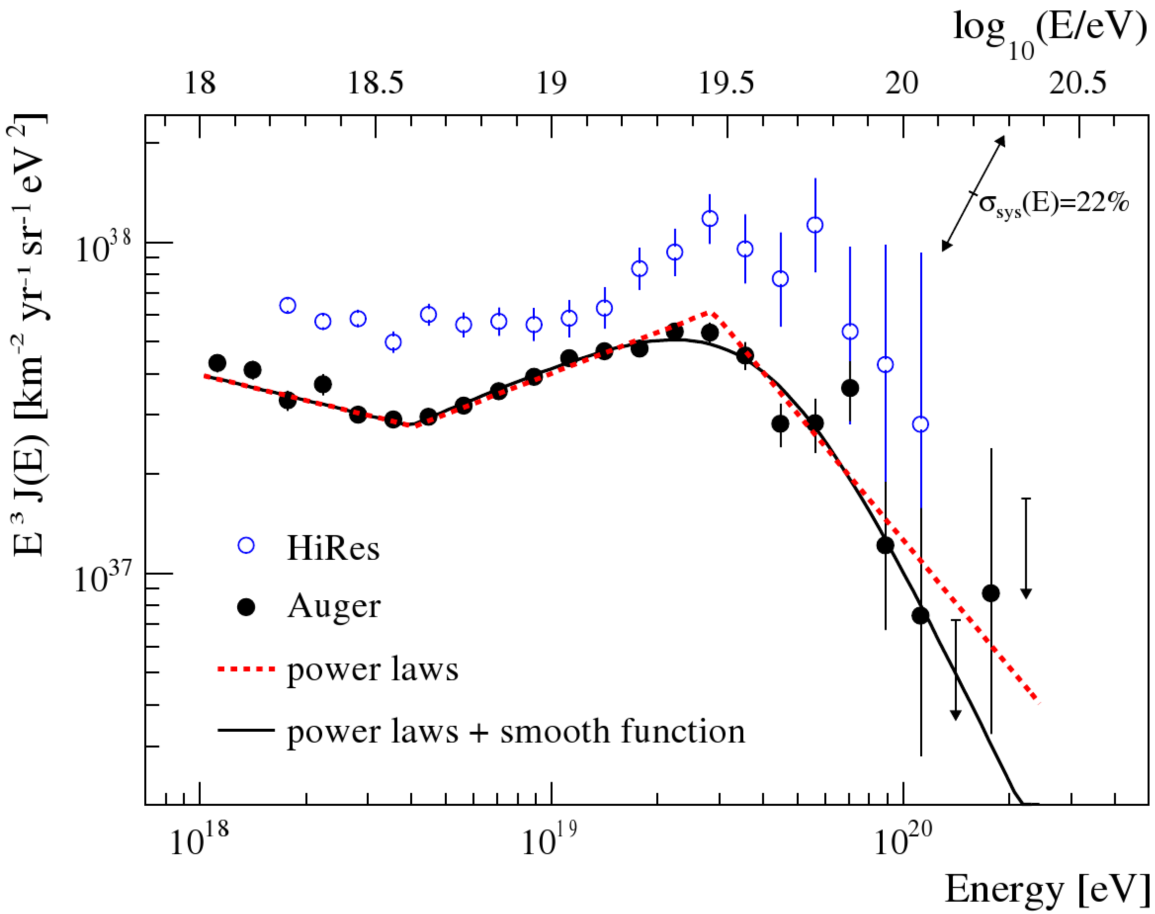
- Uncertainties
  flux ~ 5.8%
  energy resolution ~ 20%

Hybrid energy spectrum



- Uncertainties
  flux ~ 10% at 10^{18} eV
  flux ~ 6% above 10^{19} eV
  energy resolution < 6%

Combined energy spectrum



- lg(E_{ANKLE} / eV) ~ 18.6
- power law:
  below ~ 3.3
  above ~ 2.6
- lg($E_{1/2}$ / eV) ~ 19.6
- Uncertainties
  flux < 4%
  energy resolution ~ 22%

GZK suppression significant at 20 σ

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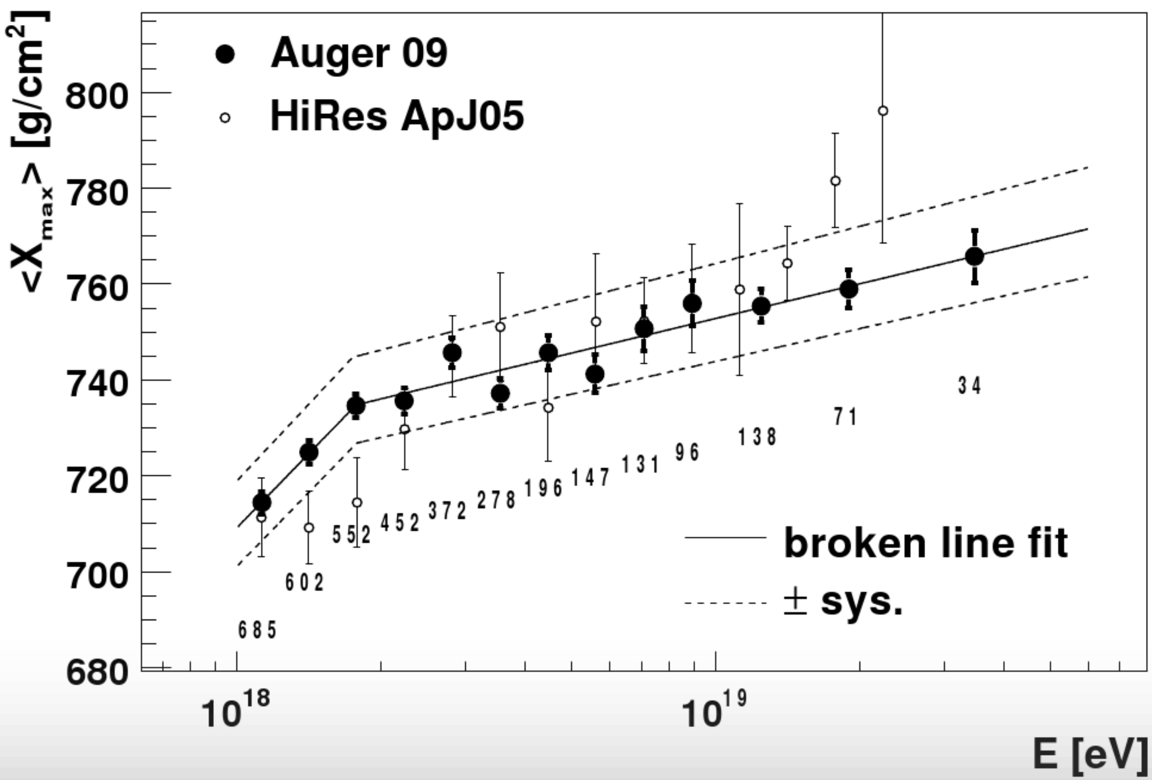
Mass composition with hybrids

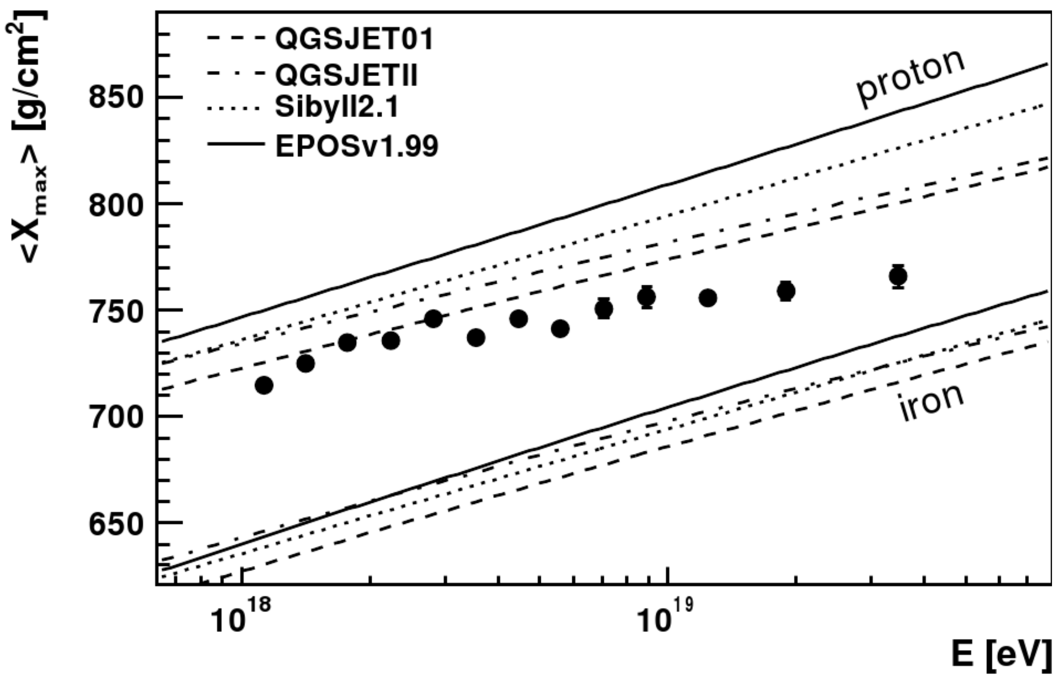
- One observable: the depth of maximum of the shower development (X_{max})

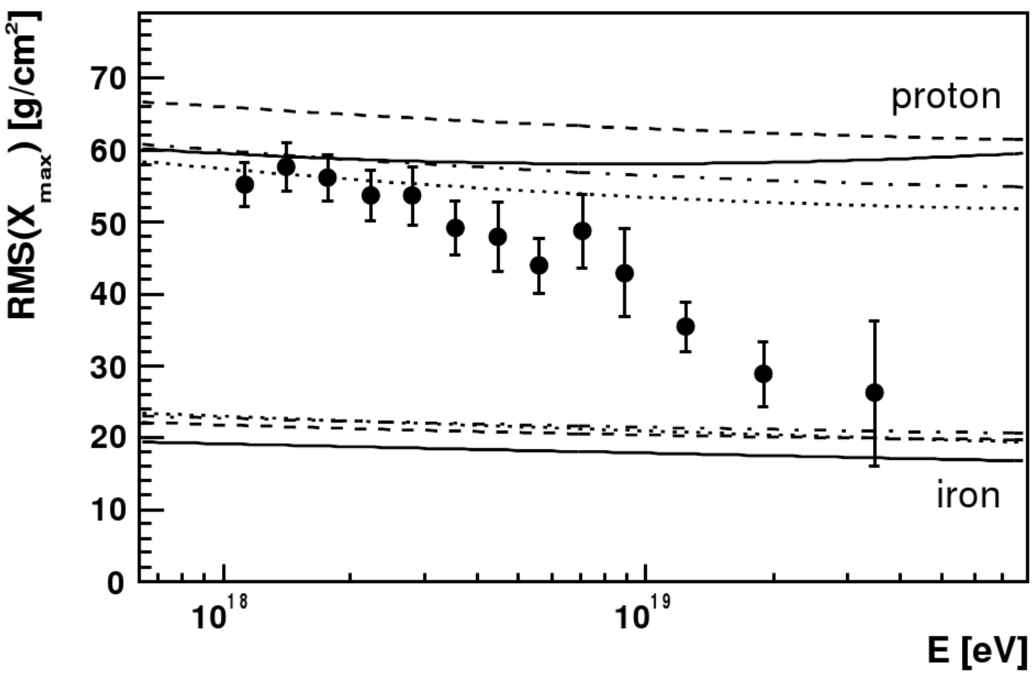
X_{max} is in the view field => direct measurement

- RMS(X_{max}) sensitive to $n_{nucleons}$ and to the interaction length
- $d(X_{max})/dlgE$ (elongation rate) sensitive to a change in the composition



Mass composition with hybrids





if the extrapolations of the hadronic models are correct

the mean mass increases with energy

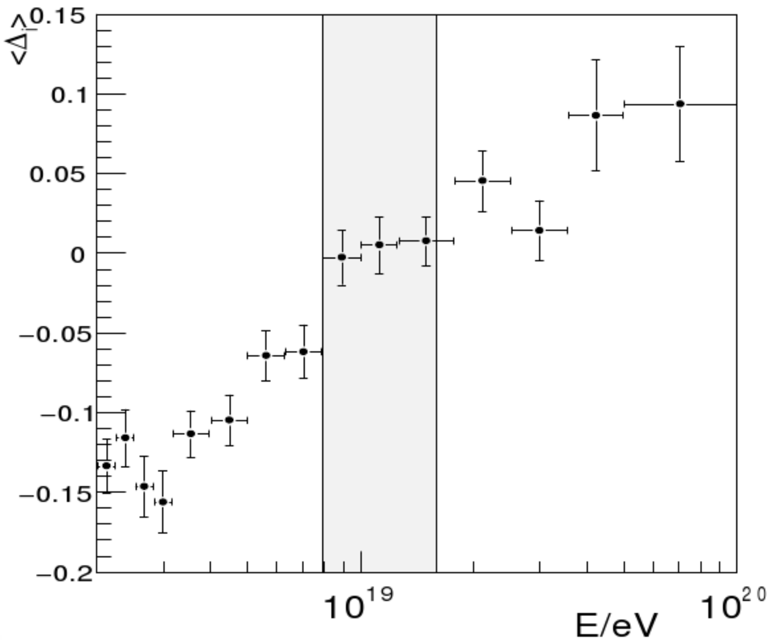
Mass composition with SD

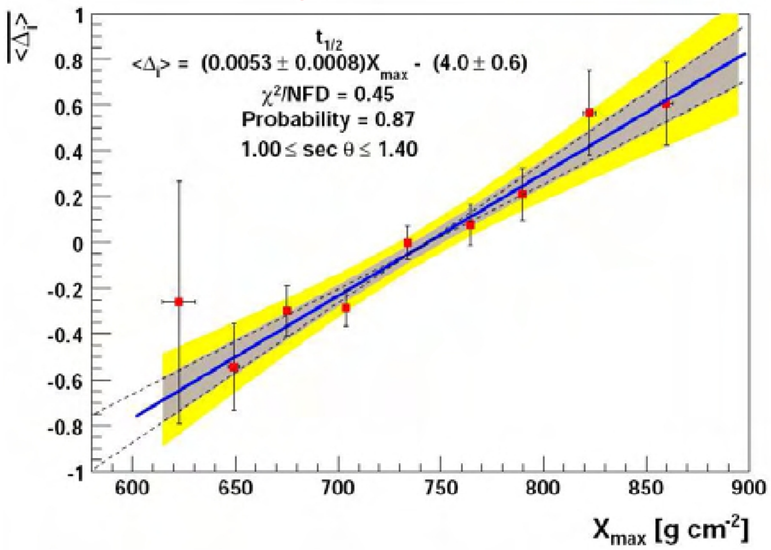
- Method: use of the shower front

  $t_{1/2}$ => discriminate between muonic and electronic components
  N_μ/N_{em} => age of the shower (and X_{max})
  X_{max} => primary mass composition

$$< \Delta_i >= \frac{1}{N} \sum_{i=1}^{N} \frac{t_{1/2}^i - t_{1/2}(r, \theta, E_{ref})}{\sigma_{1/2}^i(\theta, r, S)}$$

signal rise time



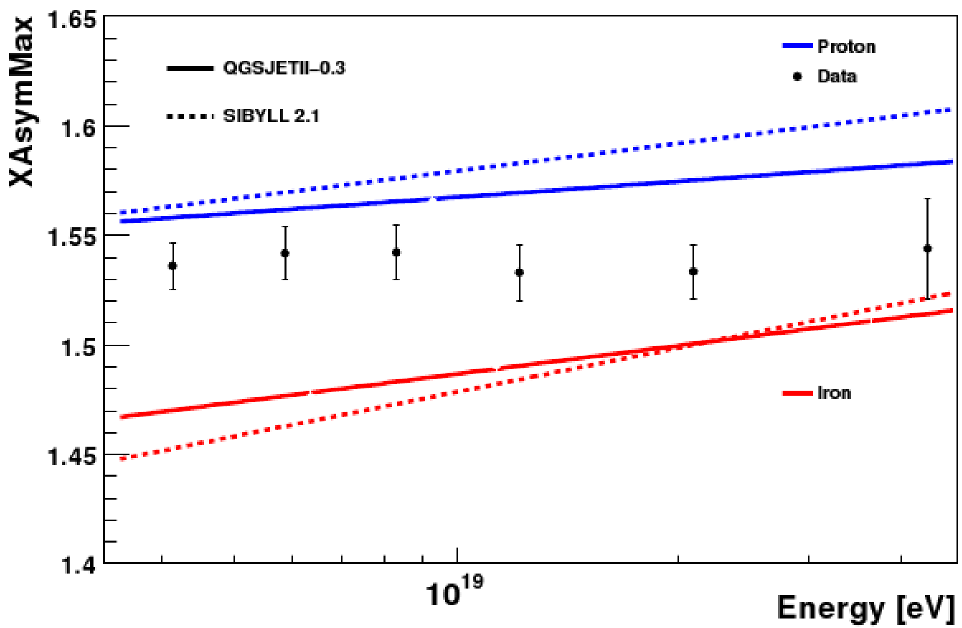


Mass composition with SD

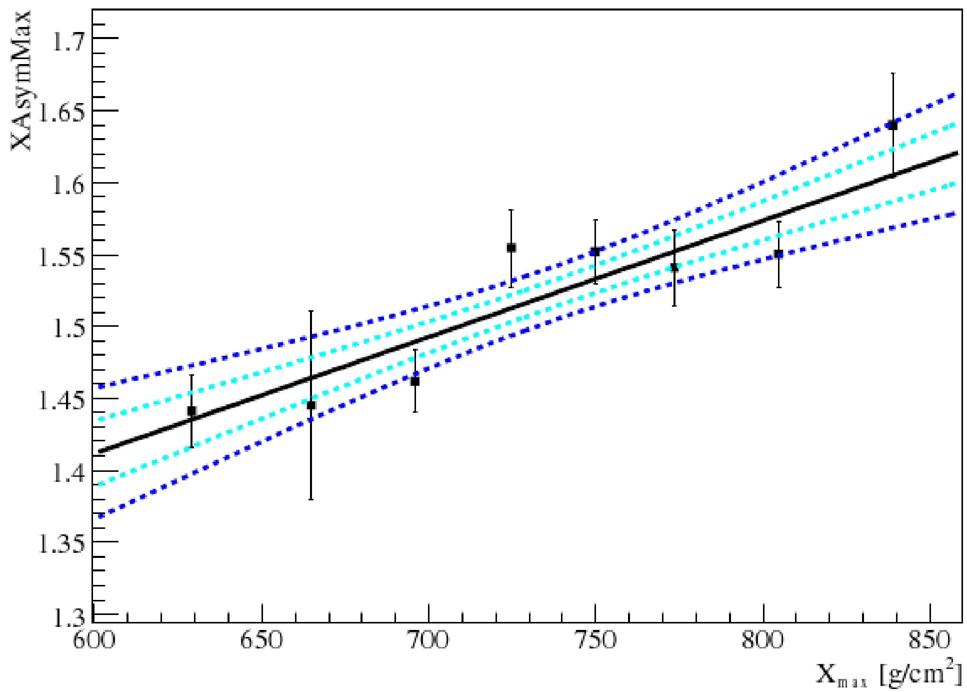
- method: asymmetry in $t_{1/2}$ between upstream and downstream stations (non-vertical showers)

$$< t_{1/2}/r >= a + b \cos\zeta$$

r: distance to the core
ζ: azimuth in the shower plane

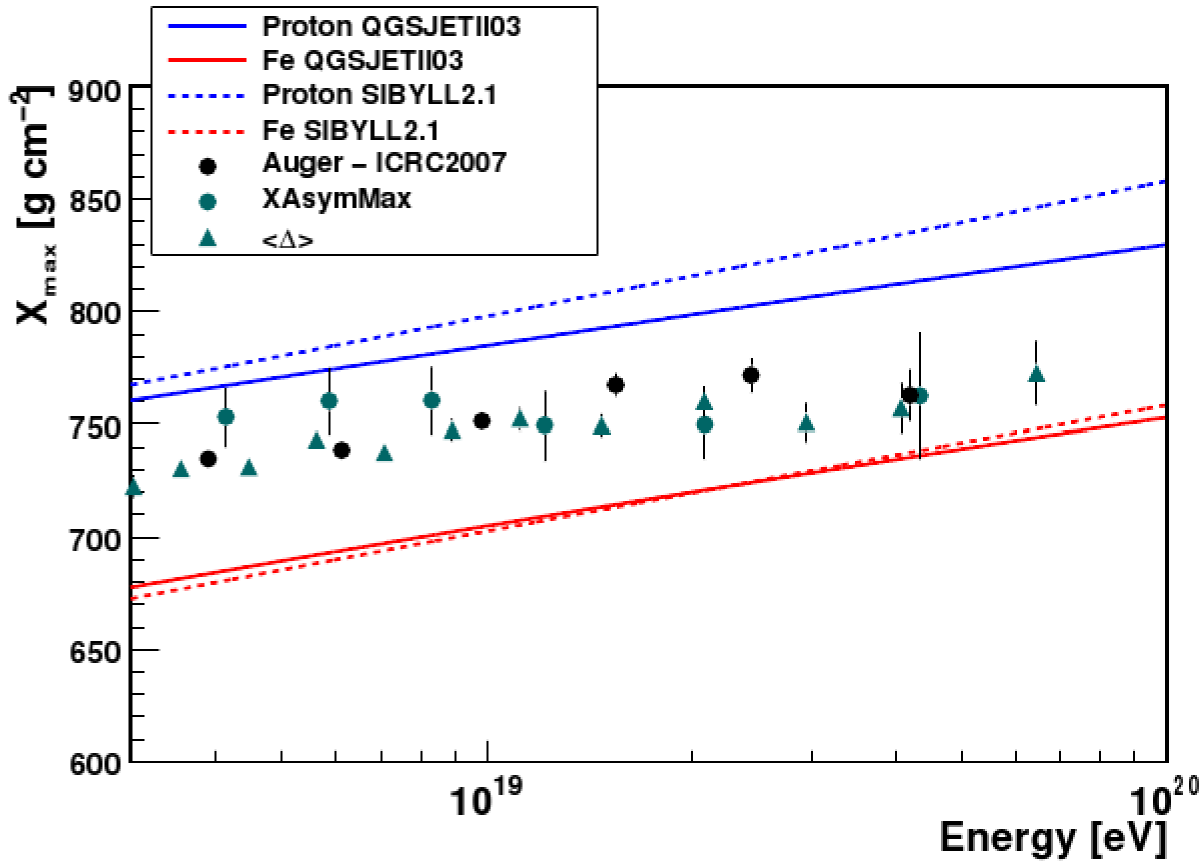


almost independent of N_μ



calibration with X_{max}

Mass composition with SD



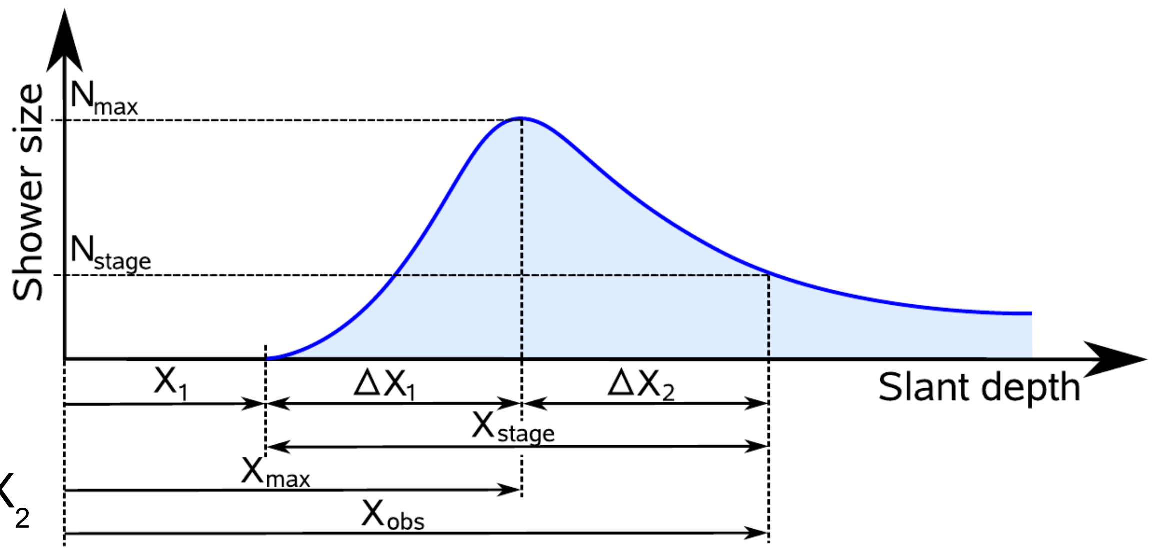
mean mass seems to increase with energy

Proton-air cross section

Method
- fixed energy and stage of development
- use the shower characteristics to estimate the frequency of the 1st interaction as a function of the shower zenith (penetration in atmosphere)
- assuming an exponential decay, estimate the interaction length and cross section
- compare to models

Shower characteristics
- SD =>N_e, N_μ
- FD =>X_{max}

Influential parameters
- flux of cosmic rays
- mass composition
- shower to shower fluctuations (ΔX_1)
- frequency of shower with N_e after ΔX_2
- energy of the shower (N_μ or X_{max})
- detector resolution



Hadronic interaction

Model dependence

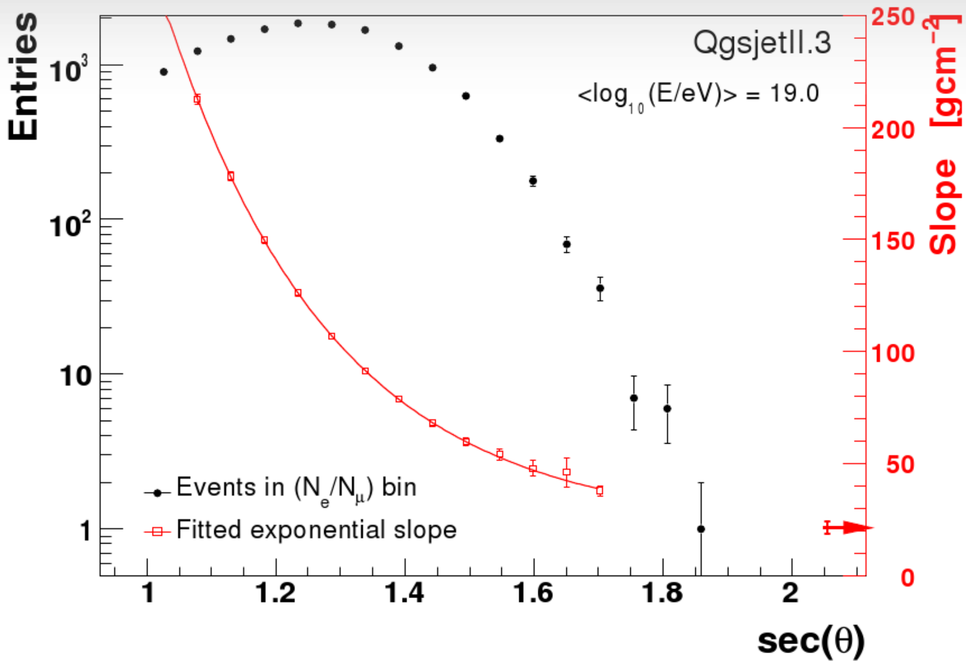
Exponential decay (k factor)

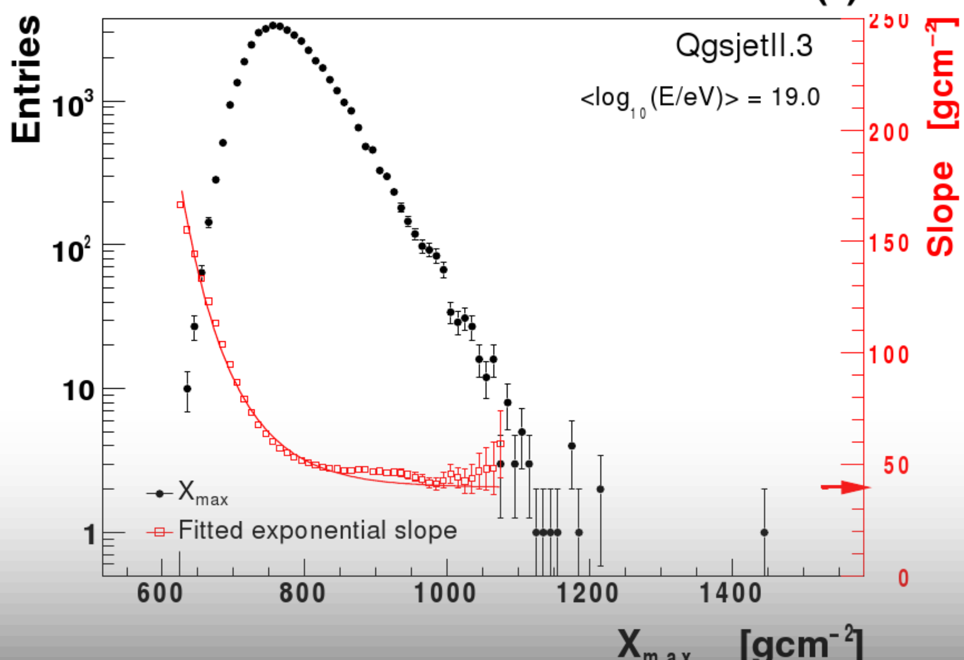
- $\Lambda = k \times \lambda_{int}$
- large uncertainty on the asymptotic
- k depends on the hadronic model
- FD => 7%
- SD => 28%

Unfolding X_{max} distribution

- better accuracy (no ΔX_2)
- less model dependent

(R.Ulrich et al., arXiv:0906.0418)





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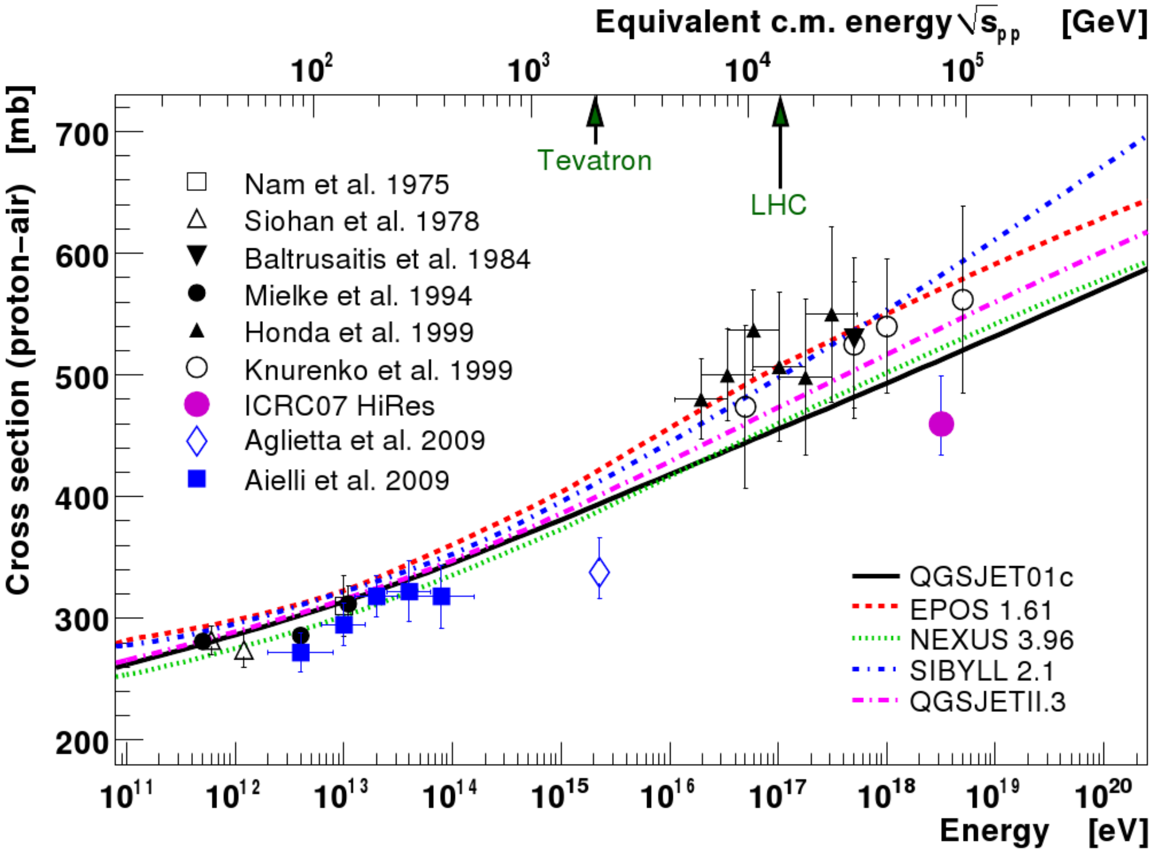

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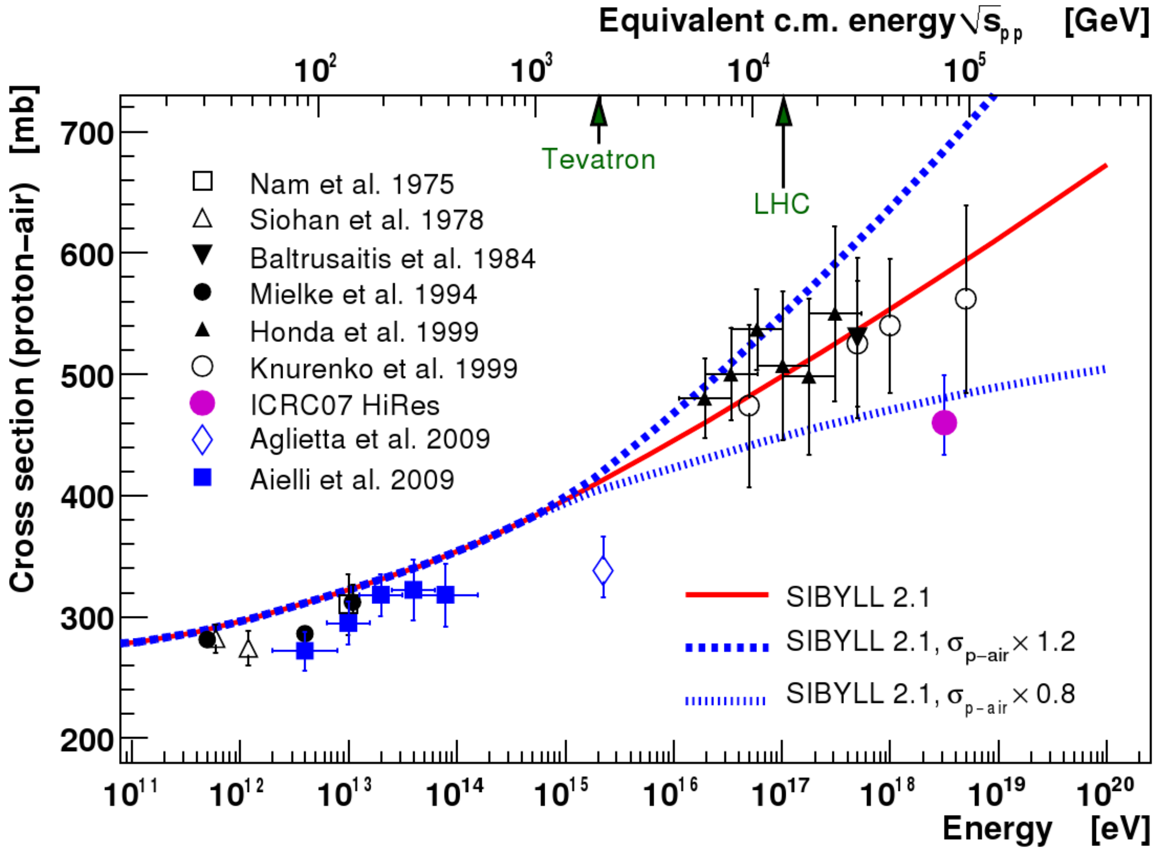

SD: k = 0.40 × model (± 0.11)
FD: k = 0.97 × model (± 0.07)

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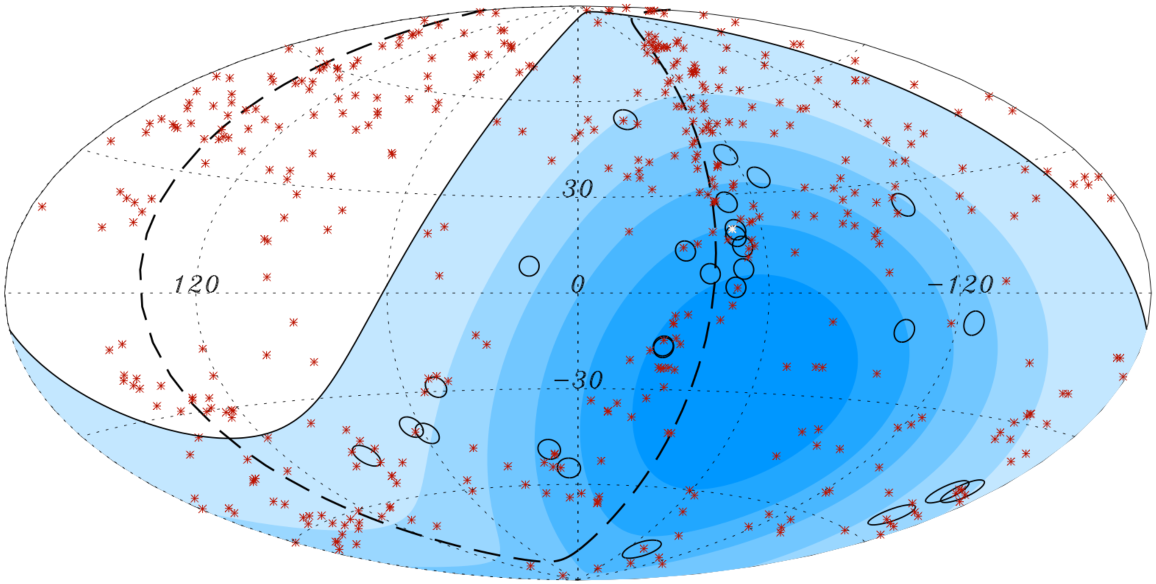
Arrival directions

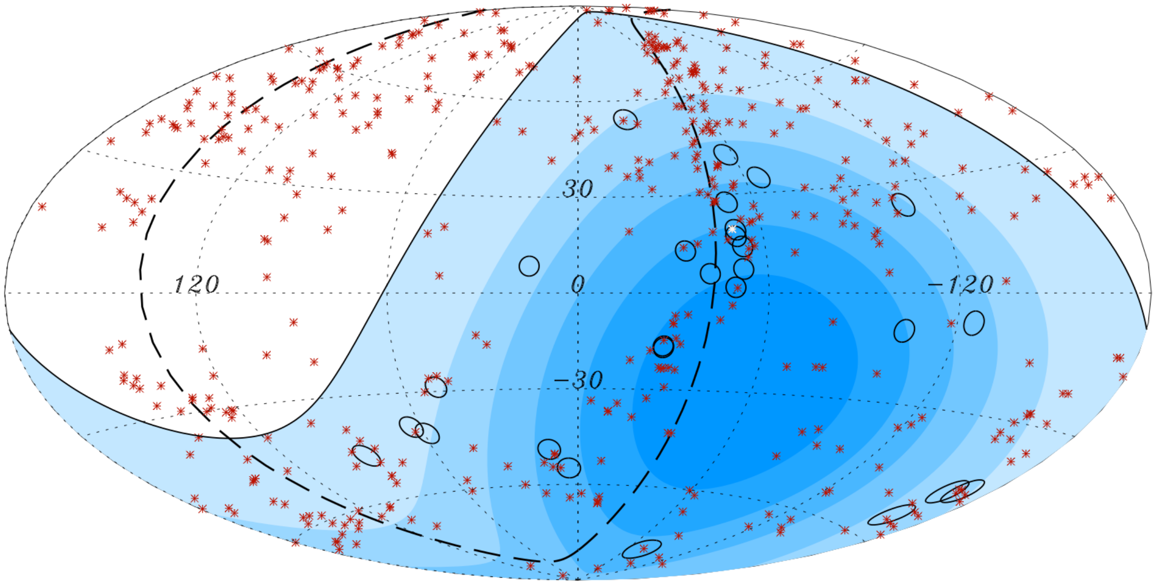
$$P = \sum_{j=k}^{N} \left(\begin{array}{c} N \\ j \end{array} \right) p^j (1-p)^{N-j}$$



Prescription

- 1^{st} January 2004 – 26^{th} May 2006
- angular distance: 3.1°
- maximal redshift: 0.018 (75 Mpc)
- minimal energy: 55 EeV (57 EeV)
- 9/14 correlating events

Arrival directions



(Auger, Science 318 (2007) 938)

Period II

- 27th May 2006 – 31st August 2007
- 9/13 correlating events
- isotropy rejection > 99%

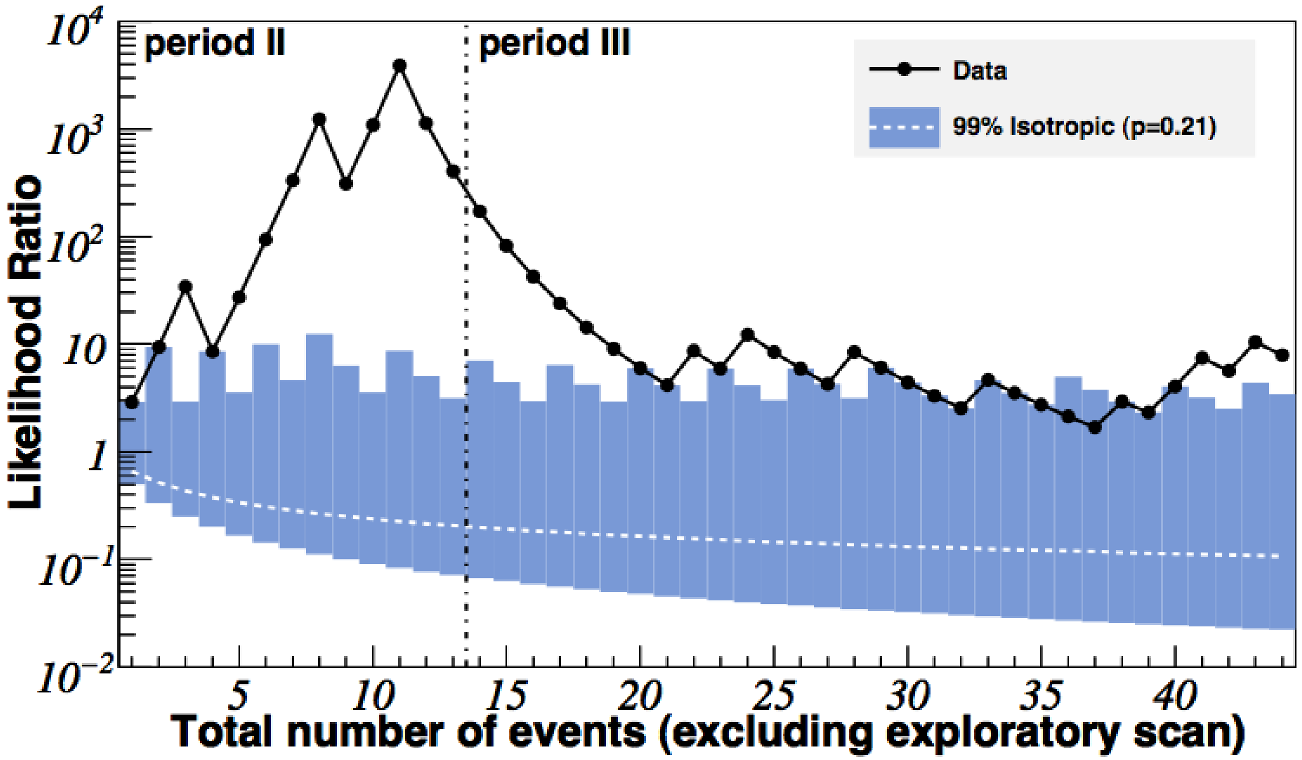
Period III

- 1st Sept. 2007 - 31st March 2009
- 8/31 correlating events
- still signal, but weaker
- isotropy rejection > 99%

Arrival directions

Likelihood ratio

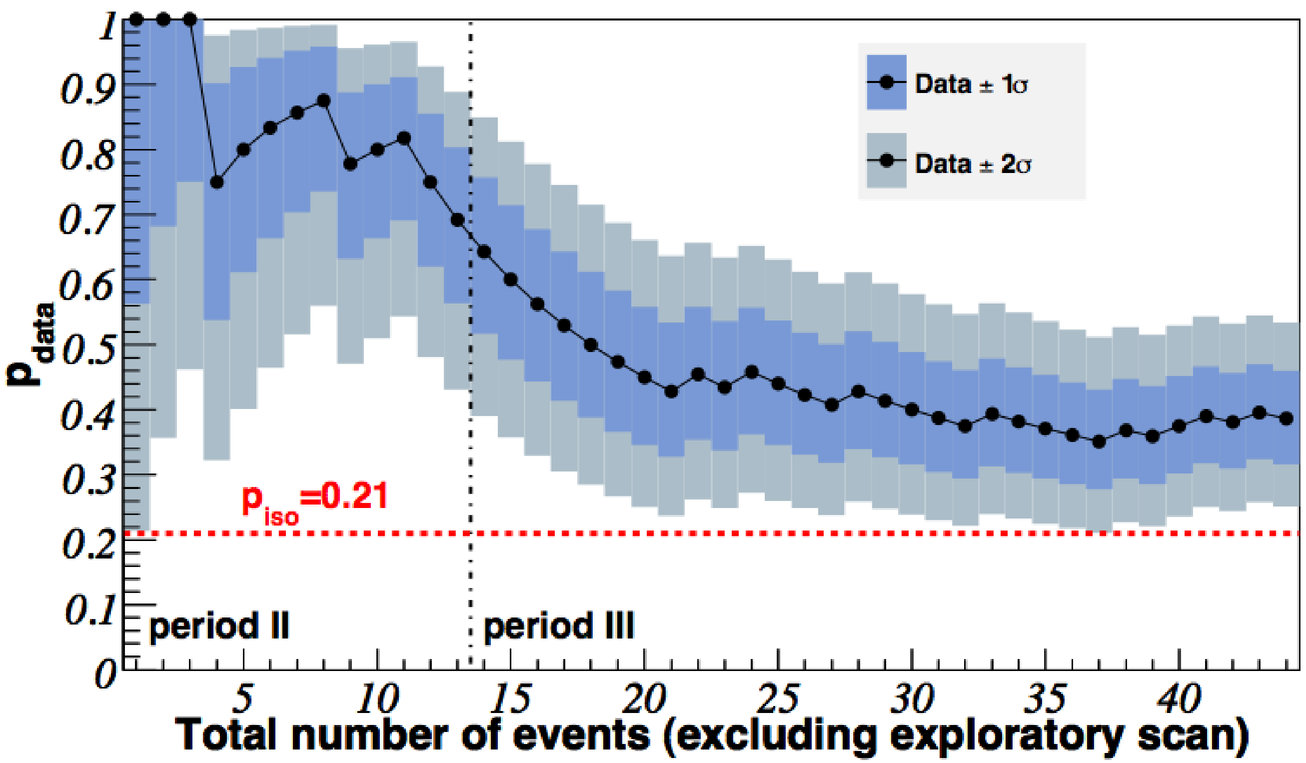
$$R = \frac{\int_p^1 p_1^k (1-p_1)^{N-k}\, dp_1}{p^k (1-p)^{N-k+1}}$$



Compatible with anisoptropy

Arrival directions

Signal monitoring



$p_{data} = 0.38 \pm 0.07$

Compatible with anisotropy

Summary and outlook

Data from 2004 up to 2009

- GZK suppression
- energy spectrum characteristics
- mean mass of the primary increasing with energy
- correlation between the arrival directions and the closest AGNs

In the near future

- Update of the data set
- cross section proton-air
- models for hadronic interaction

See other Auger presentations about radio detection, neutrinos and photons

BACK-UP SLIDES