Results of the Pierre Auger Observatory on Astroparticle Physics

Sofia Andringa, LIP
for the Pierre Auger Collaboration

Rencontres de Moriond – Electroweak 2010

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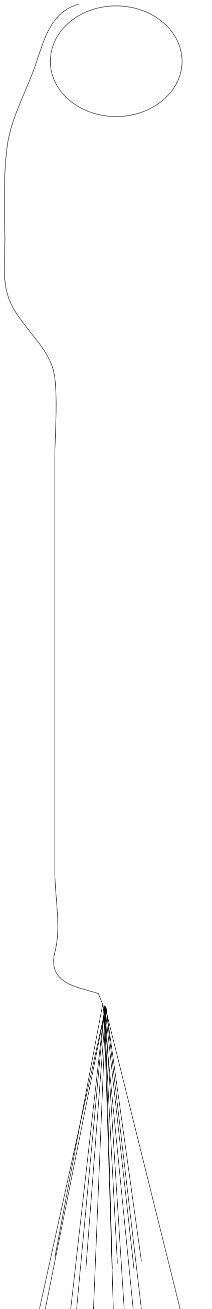

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Energy spectrum from acceleration at sources and propagation effects

Anisotropic Sky Maps: charged particle astronomy ?

Primary Particle Composition and High Energy Interactions

What particle physics can we do with high energy cosmic rays?

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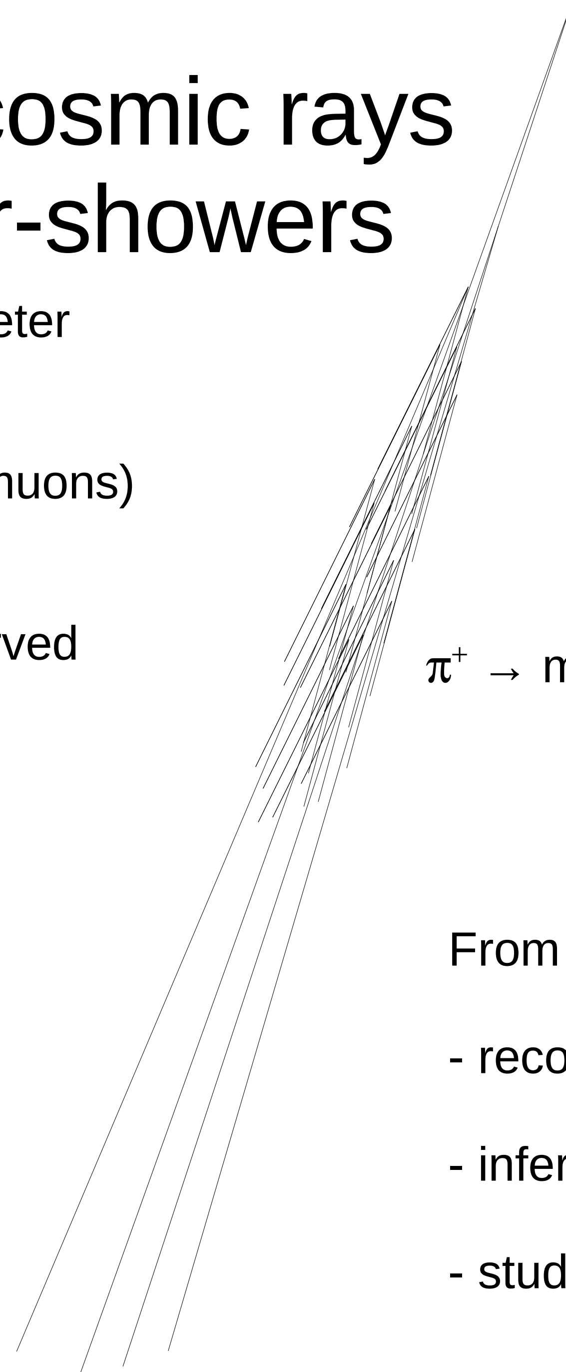
Extreme energy cosmic rays and extensive air-showers

Atmosphere is an efficient calorimeter

Many particles at ground (mostly muons)

Isotropic UV fluorescence light
and Cherenkov cone can be observed

90%-95% of the energy in
electromagnetic shower



Energy affects ground density of particles
and determines optimal sampling:
1m² / 1.5 km² for $10^{19} – 10^{20}$ eV

For charged cosmic rays:

$\pi^0 \rightarrow$ electromagnetic shower

$\pi^+ \rightarrow$ muons and invisible energy

From the two components :

- reconstruct energy and direction;

- infer primary particle identification;

- study high energy interactions;

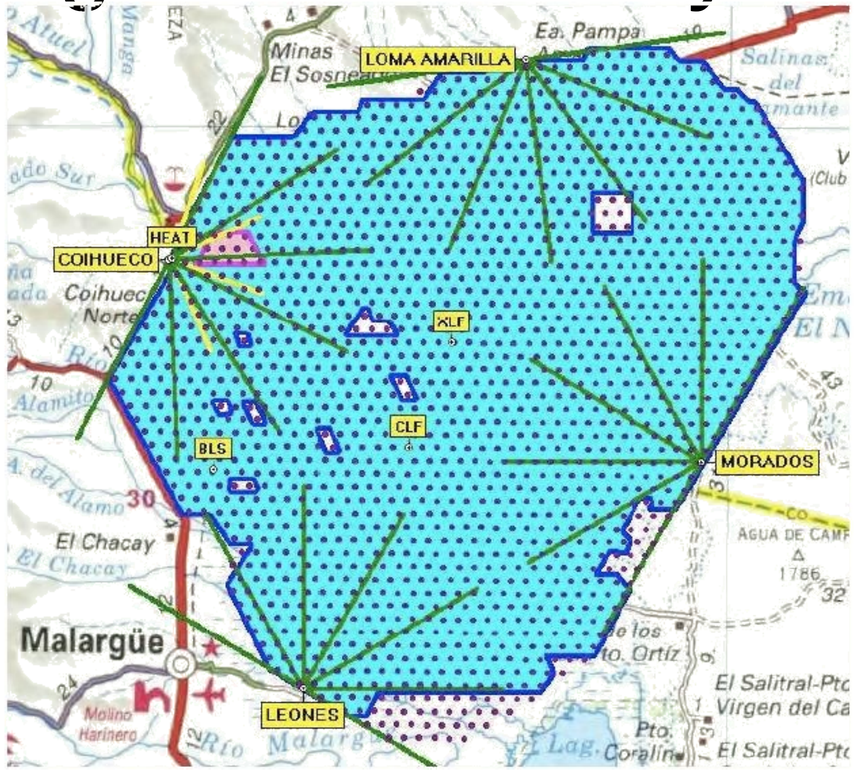
The Pierre Auger Observatory

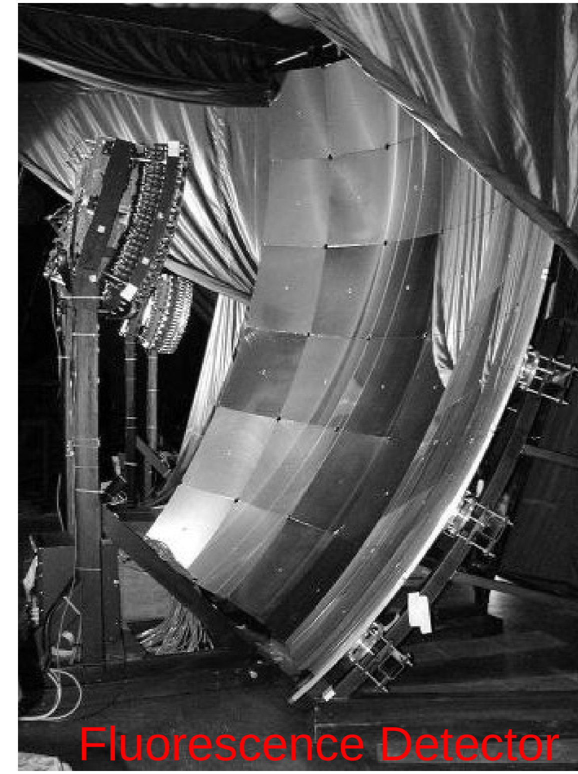
A Hybrid Observatory
with 3000 km² area
high altitude, dry climate

Ground sampling with
1600 SD tanks

Shower seen by
4x6 FD telescopes

Hybrid Reconstruction
for ~12% of events




Fluorescence Detector

Surface Detector

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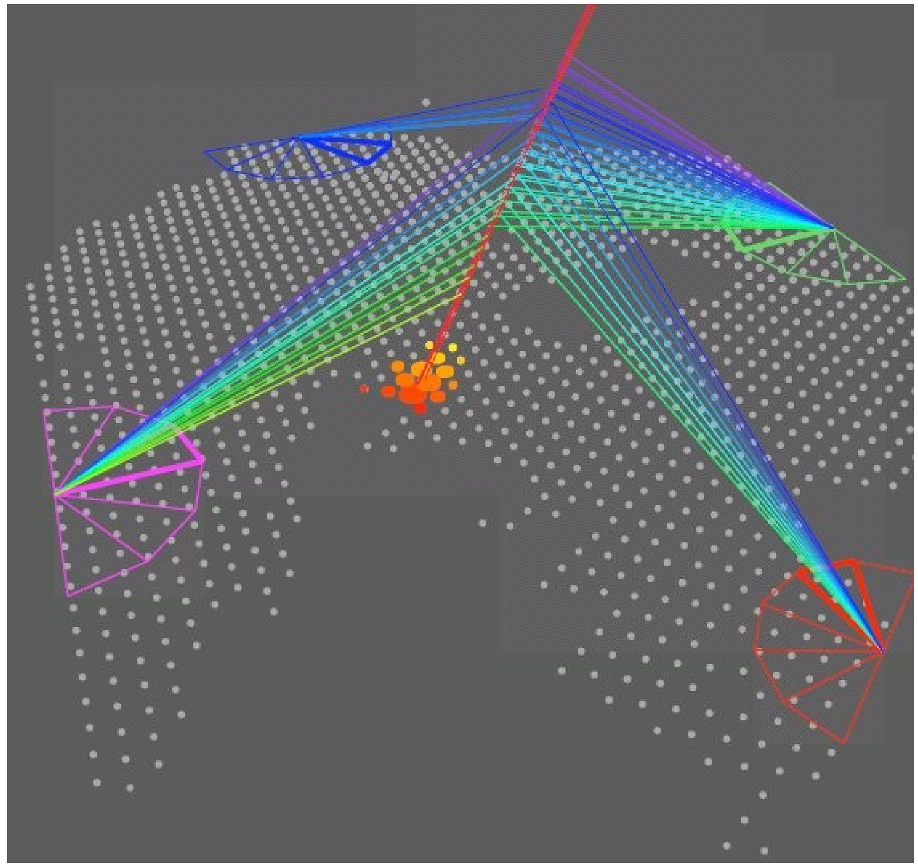
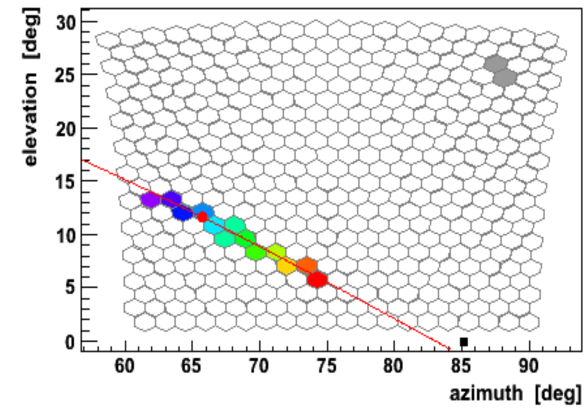
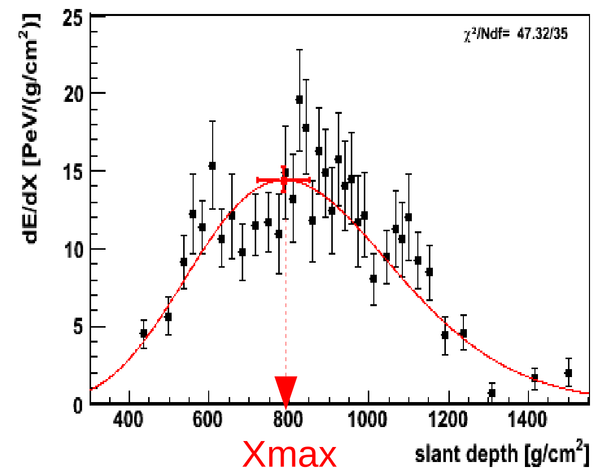
Hybrid Reconstruction
for ~12% of events

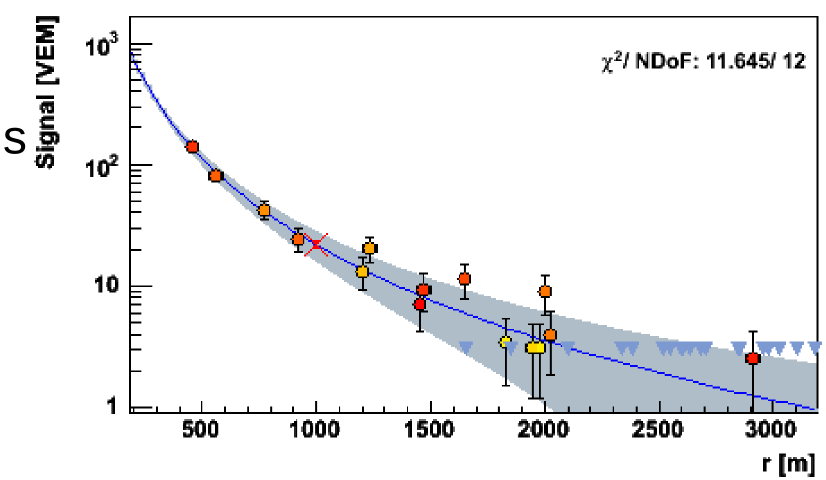
[Energy from FD
Exposure from SD]

~10 x events of previous
experiments combined!









Angular resolution ~ 0.6º
Energy calibration ~20%

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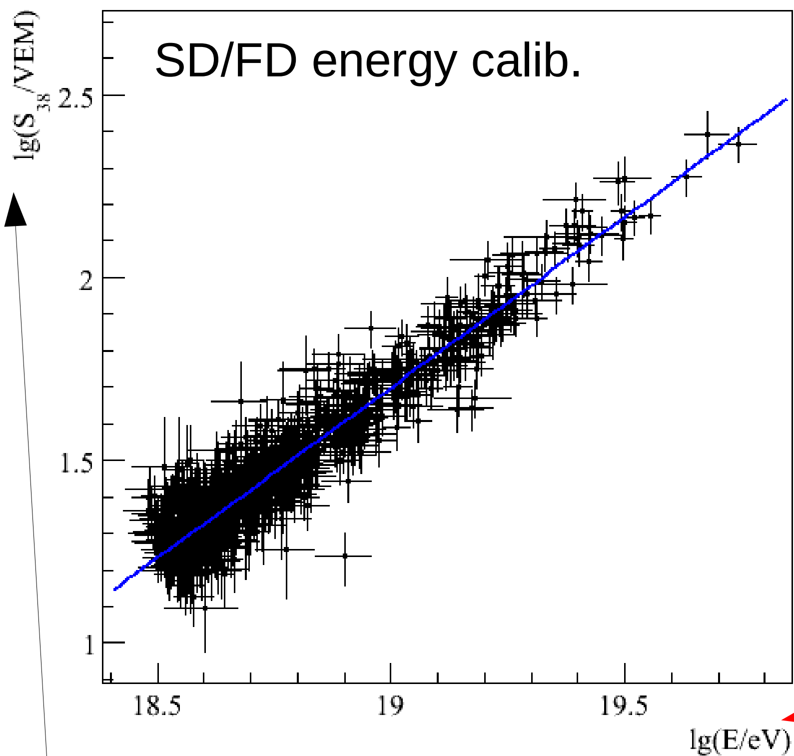
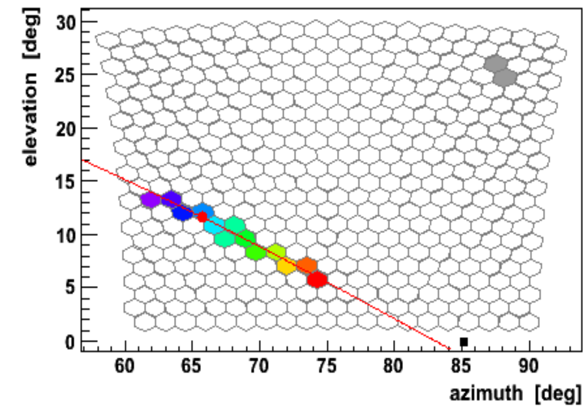
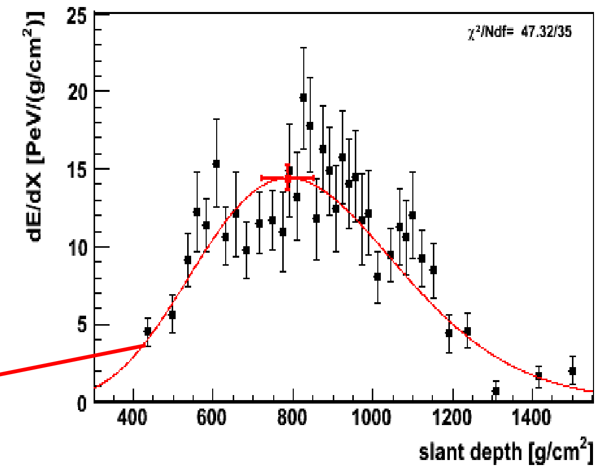
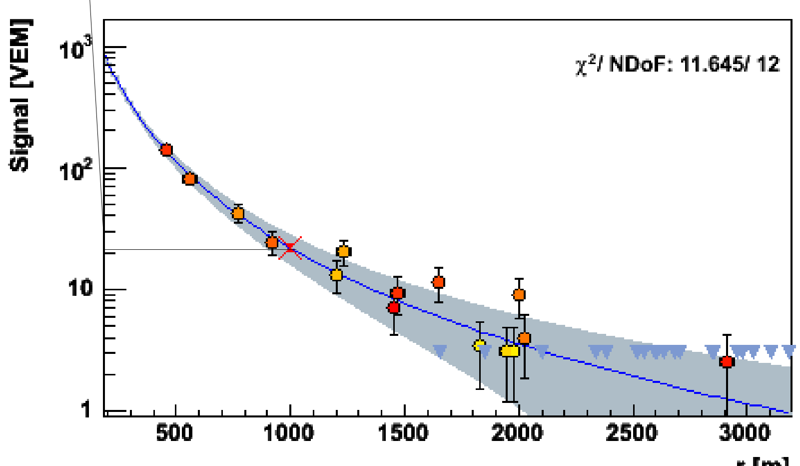


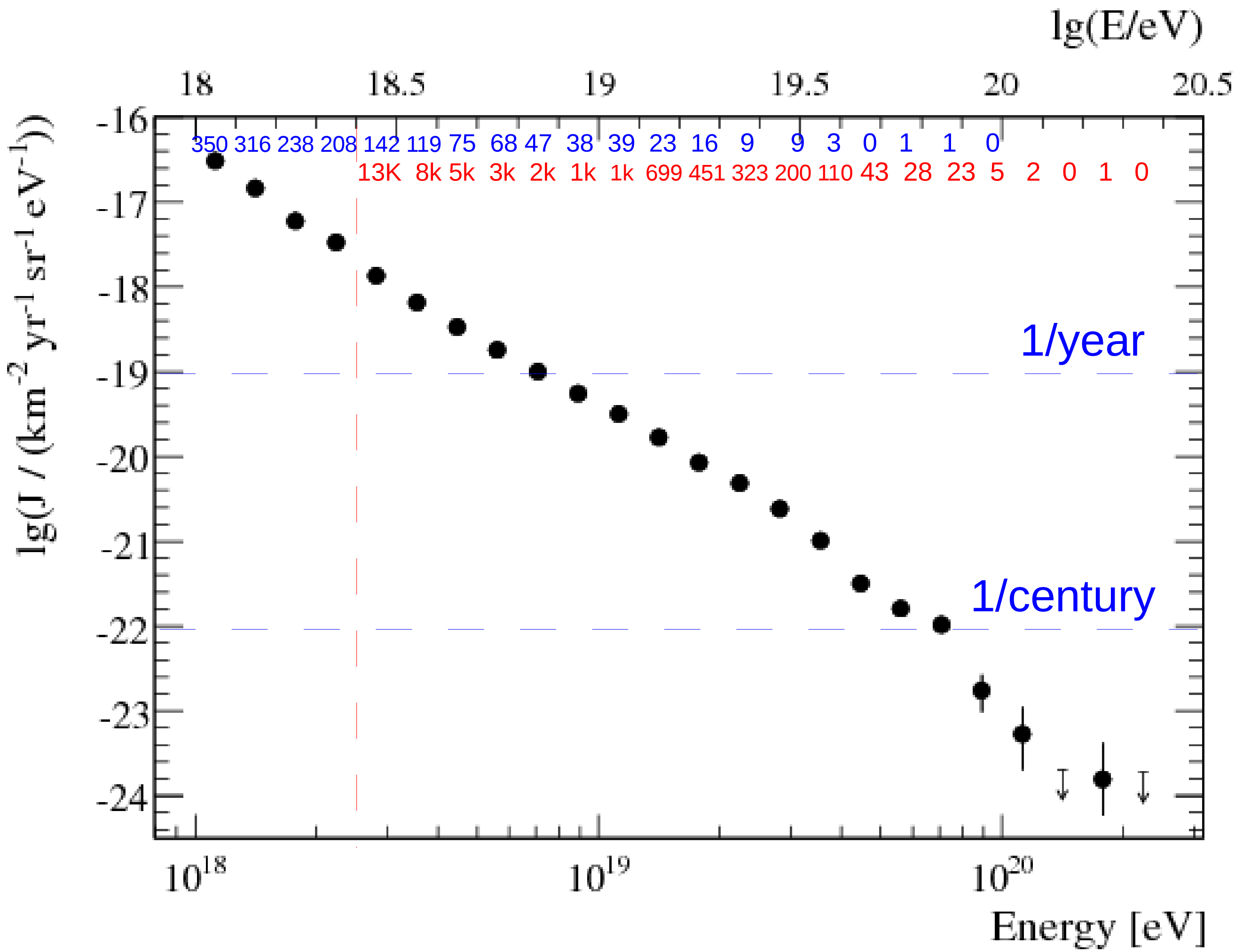






Angular resolution ~ 0.6º
Energy calibration ~20%

Flux and energy spectrum:
cosmic ray origin and propagation



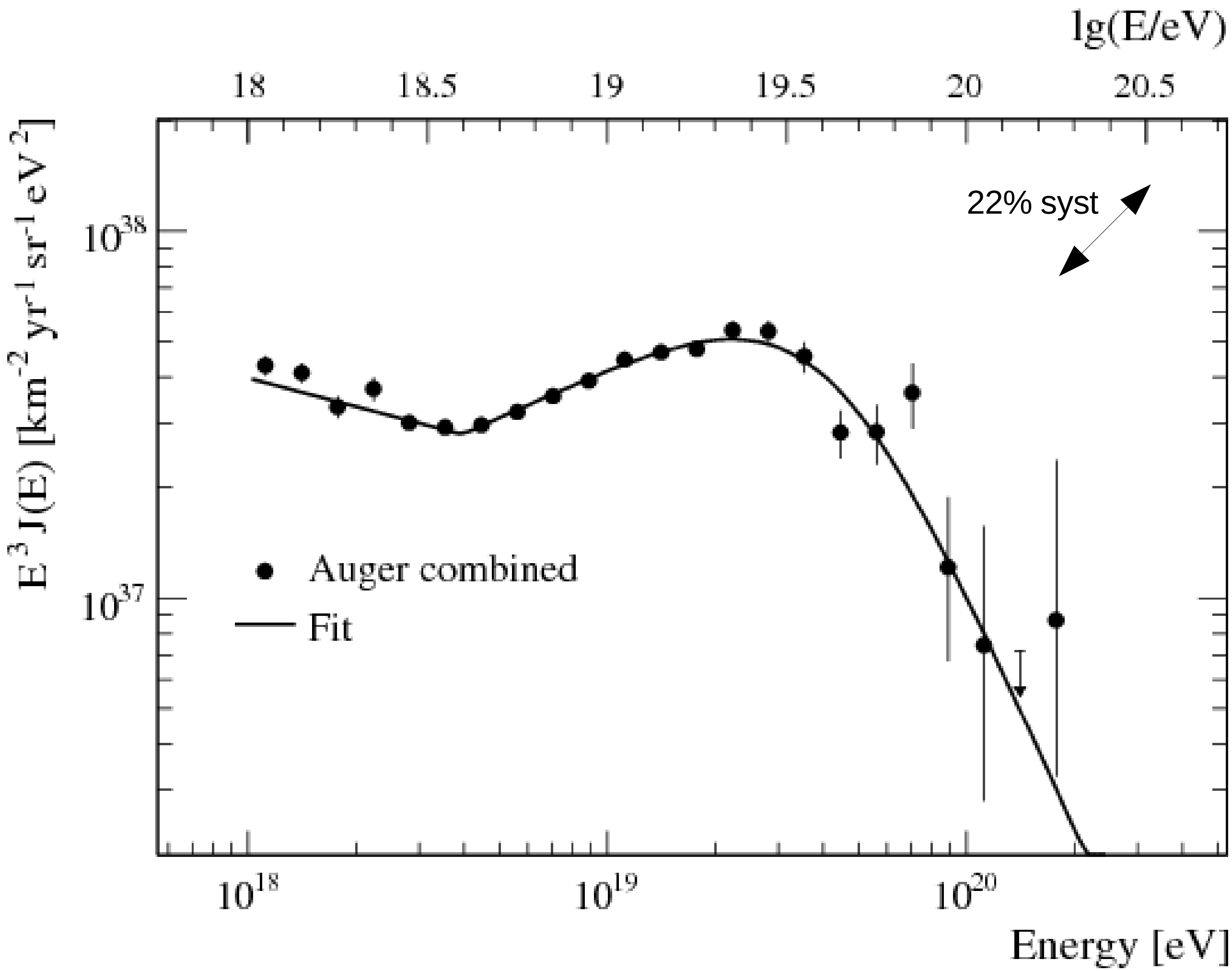
22% systematic error
will decrease in future:

Fluorescence yield
(dedicated measurements)
FD reconstruction
and absolute calibration
Atmospheric attenuation
(already monitored by
redundant techniques)

FD ----> SD statistics dominate, confirmed by FD

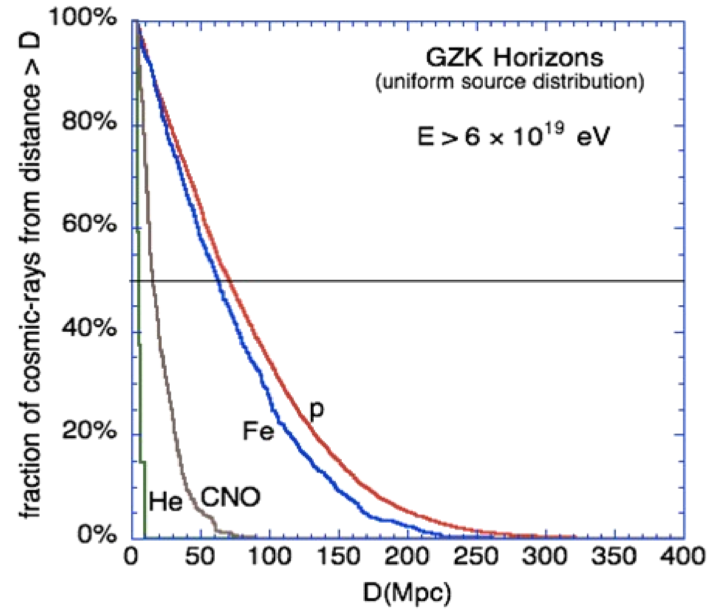
Exposure of 13000 km² sr yr ~ 2 years of full Auger

Flux and energy spectrum: cosmic ray origin and propagation

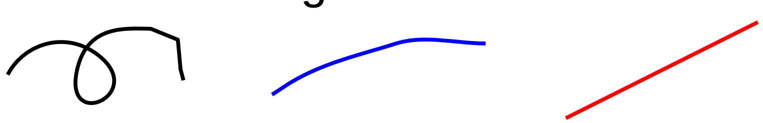


Interaction with CMB limits observable distance (GZK)

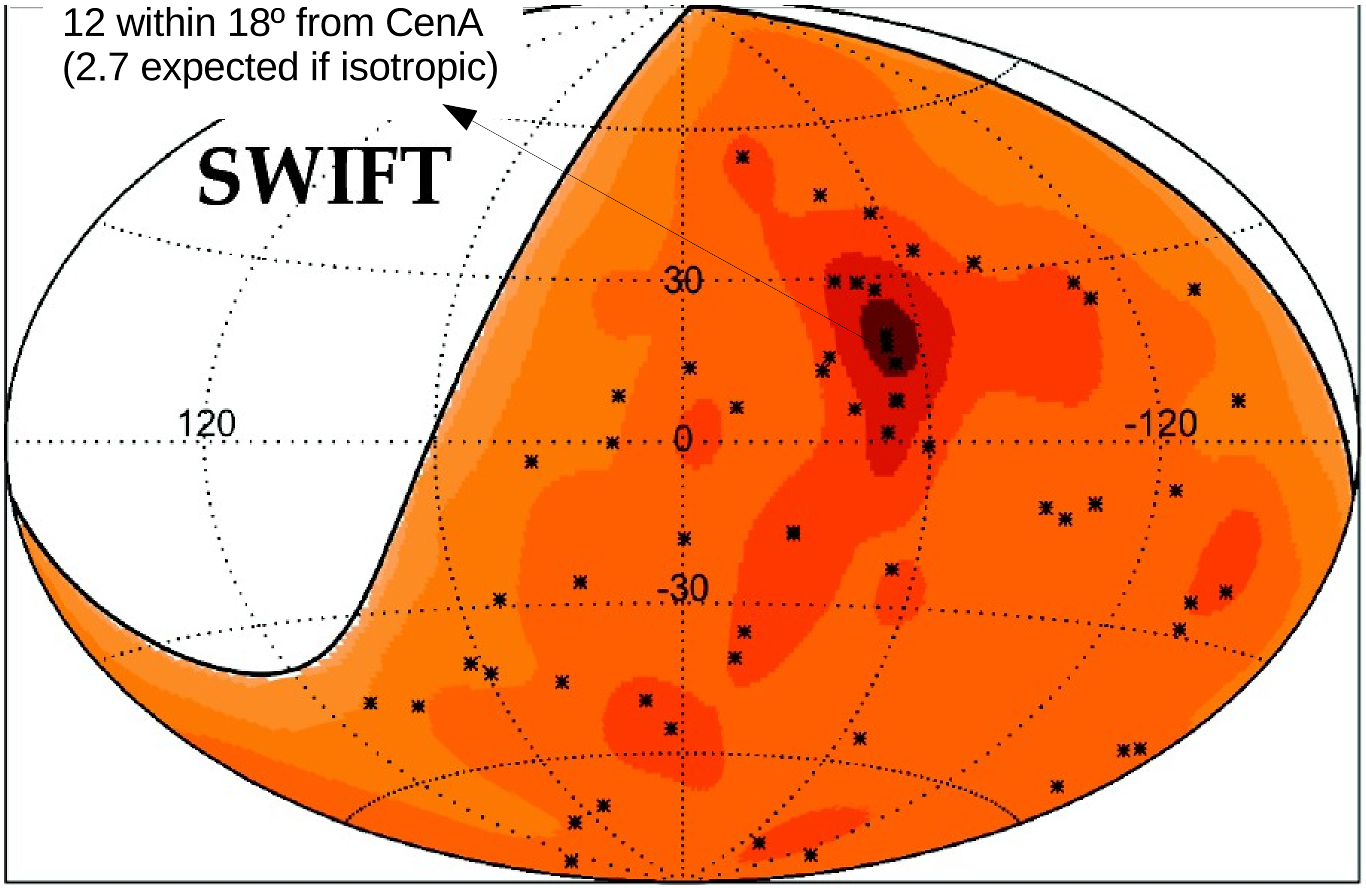
nuclear photo disintegration and $p\gamma \rightarrow \Delta \rightarrow p\pi\ (\nu),\ n\pi\ (\gamma)$



galactic to extra-galactic transition
limits of magnetic confinement



Anisotropic arrival directions: towards charged particle astronomy? high energy sources astrophysics?



58 events with Swift-BAT AGN density x exposure map

The highest energy (E>55 EeV) events are compatible with AGN source catalog with D<150 Mpc (from GZK) within small deflection (α<3º)

GZK limit:
Δ resonance from p or Fe photo-disintegration? (other nuclei do disintegrate)

Magnetic deflection:
favors protons (Q=1) against iron nuclei (Q=26) or neutral particles

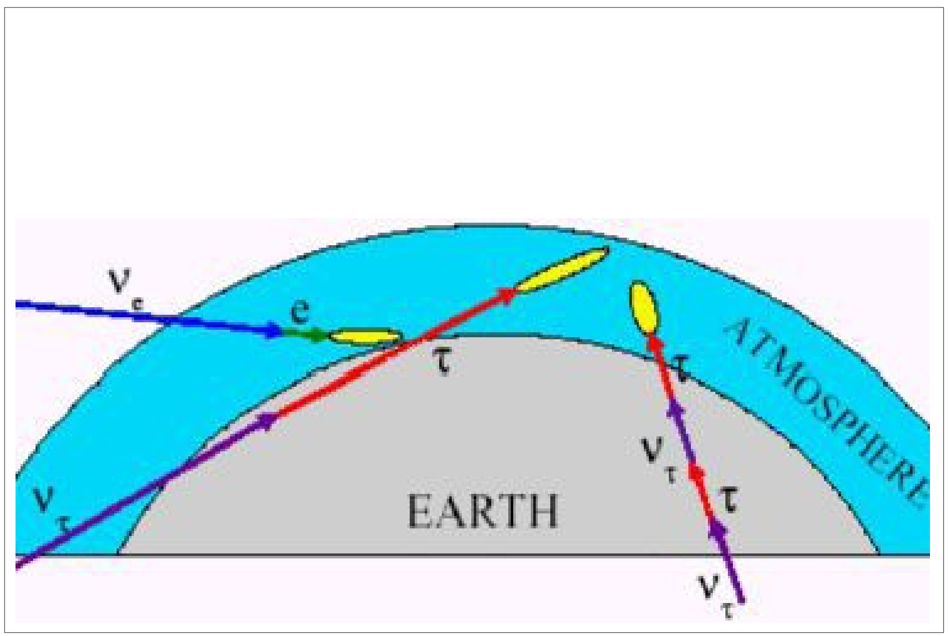
Auger data favors extra-galactic sources located in close-by high density matter regions (AGN catalogs provide traces for these regions, and not necessarily the actual sources)

Neutral cosmic-rays: searches for neutrinos and photons

Would be perfect for astronomy.
Even if not directly accelerated in sources.

Could signal new particle decays.
Have not been seen before at these energies.

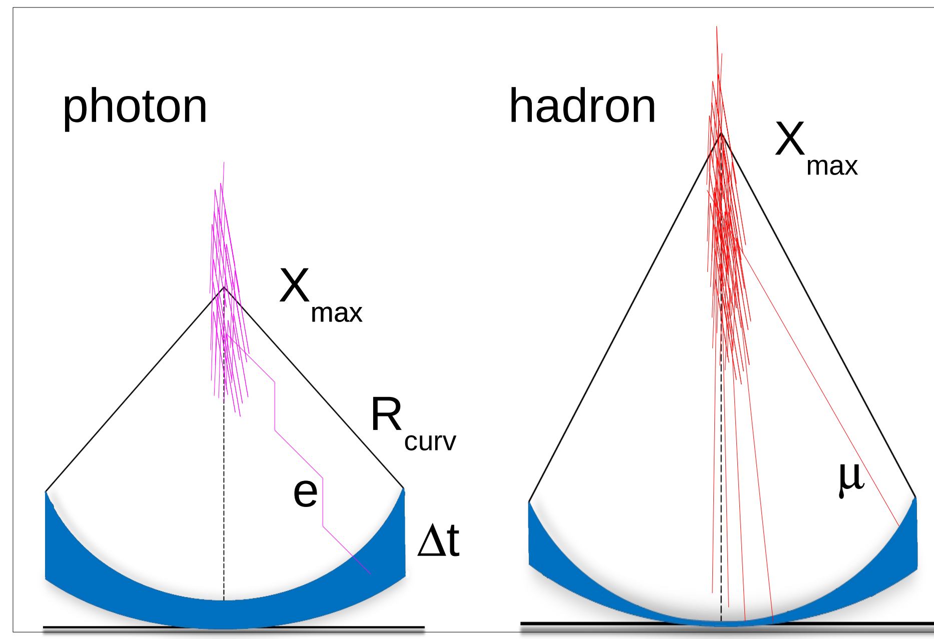
Lower cross-sections imply very clear signatures!



Neutrinos cross most atmosphere

+ young horizontal showers
(still with electromagnetic signals)

+ taus from neutrino interactions
in the Earth/Andes



Photons interact deeper than hadrons

+ deeper profiles in FD measurements

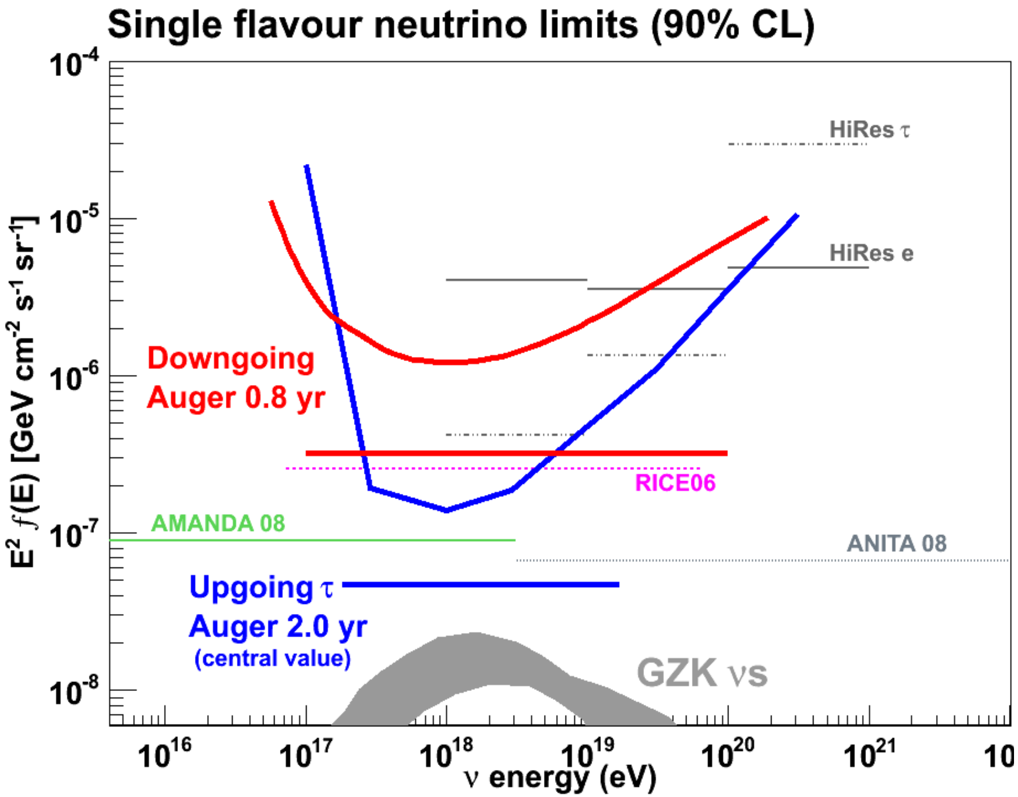
+ also in SD: curved shower fronts

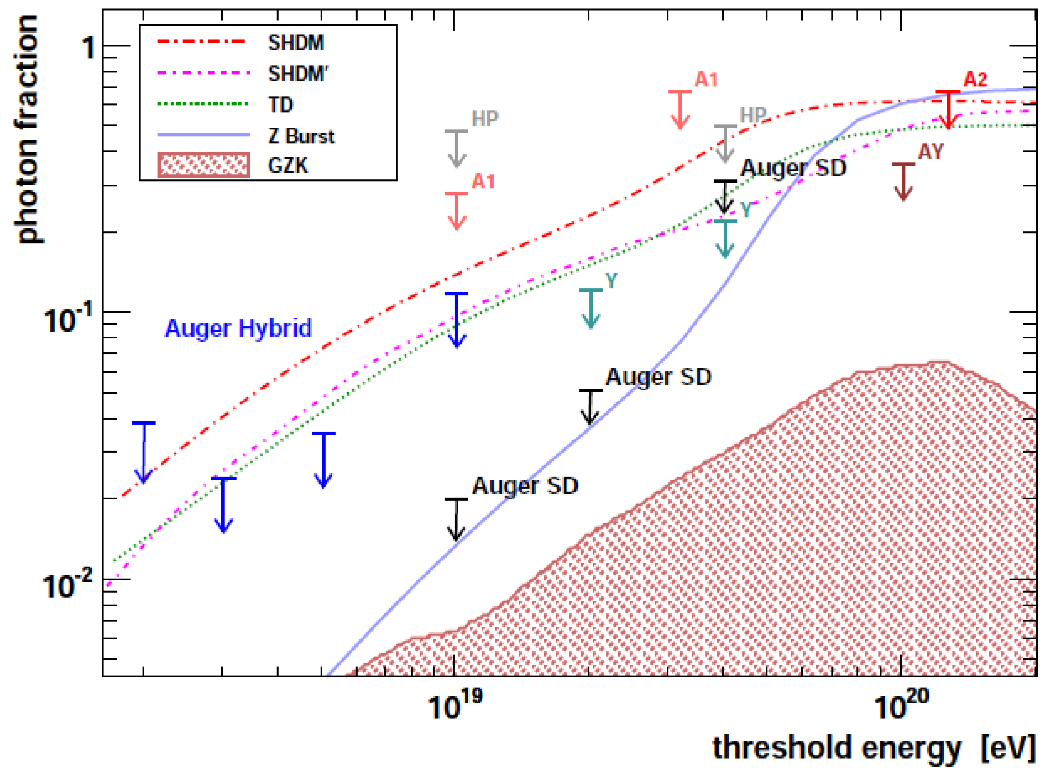
+ wide time signals (also no muons)

Neutral cosmic-rays: Limits on neutrinos and photons

Auger data already excludes most of the "top-down" models, with exotic particle decays

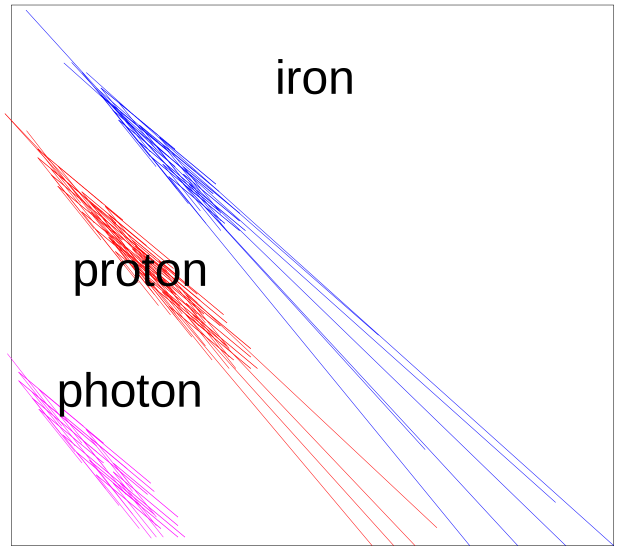
(horizontal shower spectrum and photon limit are also important for energy calibration)

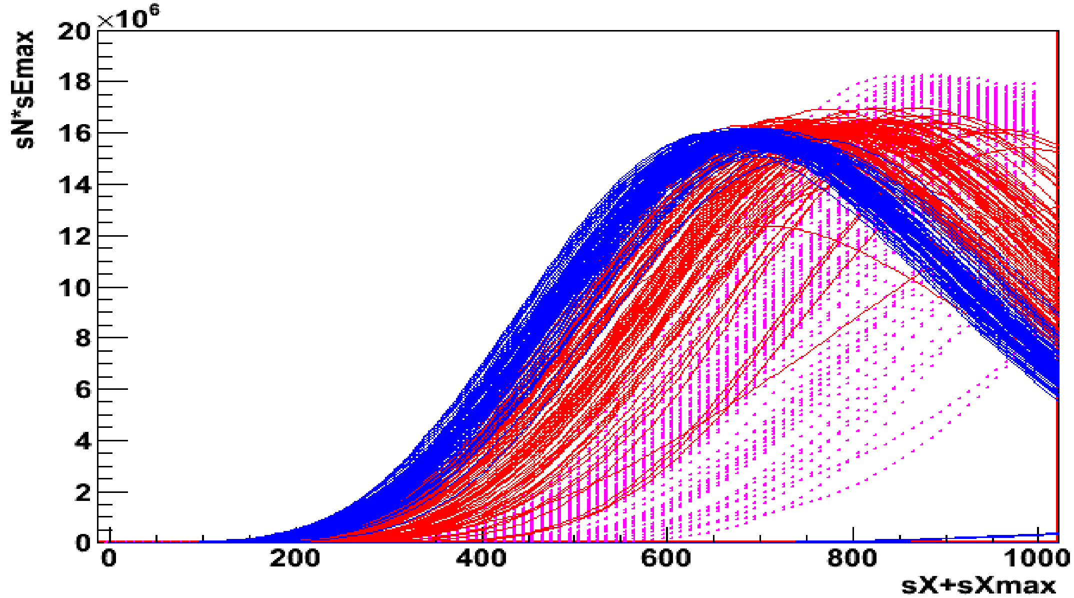




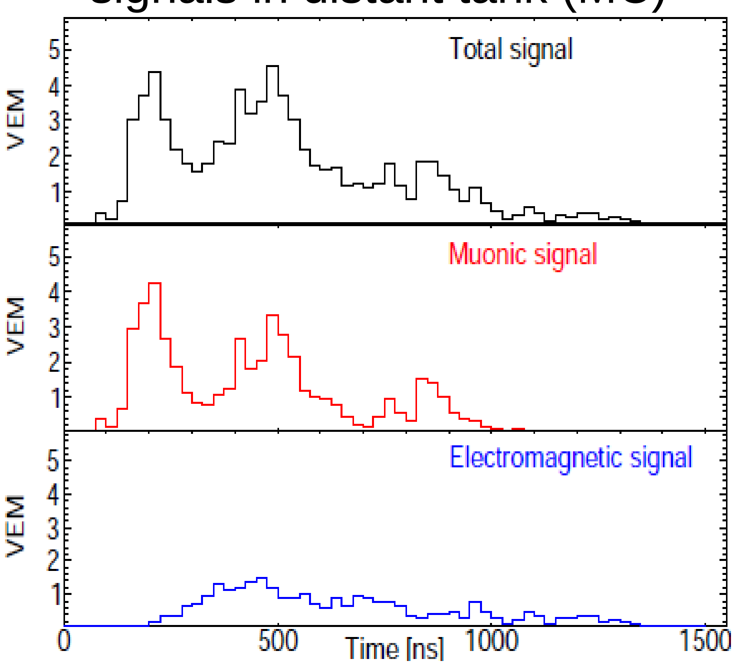
with more statistics, the GZK neutrino/photon signatures for protons will be probed

Charged cosmic-rays identification





signals in distant tank (MC)



Electromagnetic shower

exact parameterization
from e → eγ & γ → ee;
with Xmax, Nmax

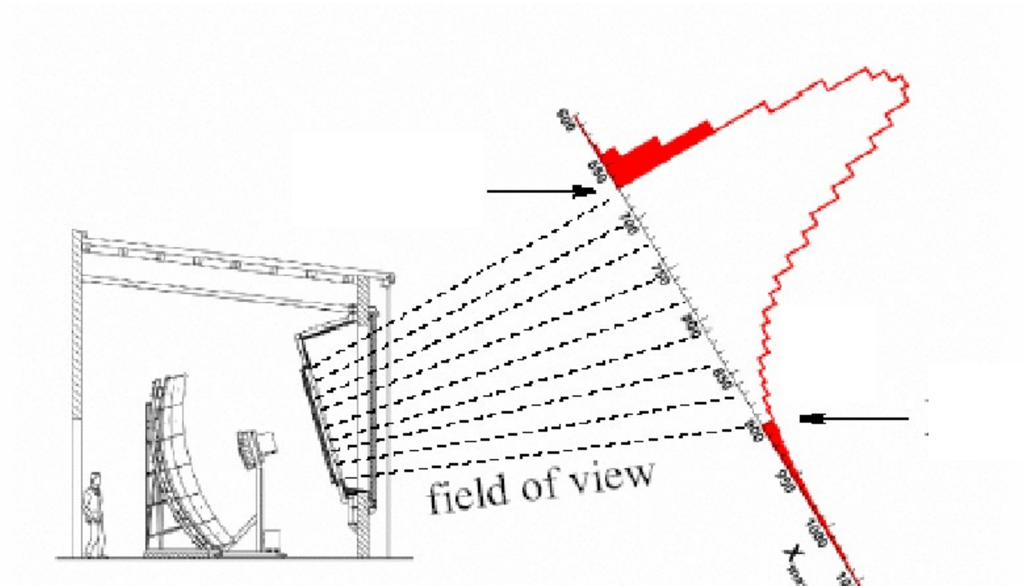
p-air interaction
[several for heavy nuclei]

fed by π → γγ
from hadronic shower
[faster and less fluctuations]

empirically modified with X1, λ

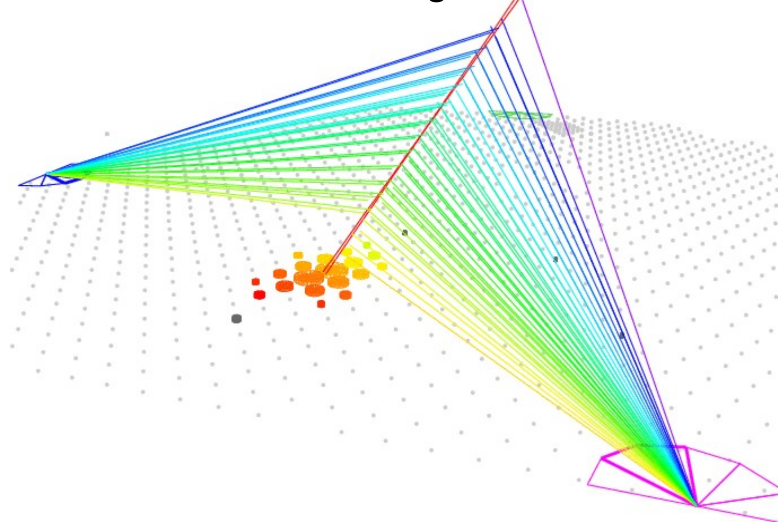
π–>μν imply muons at ground
and invisible energy in FD
[more muons in heavy nuclei]

FD profile analysis and Xmax determination

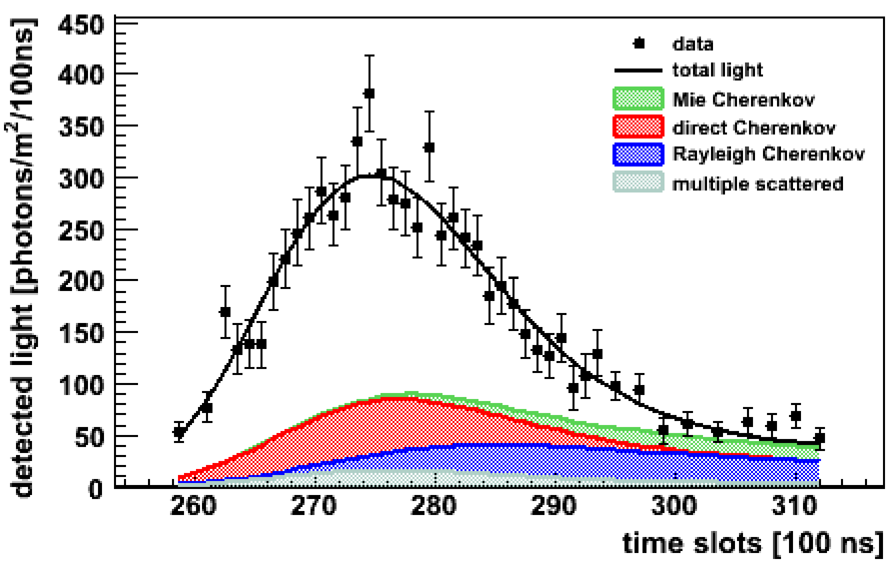


evaluate attenuation and
scattering in atmosphere

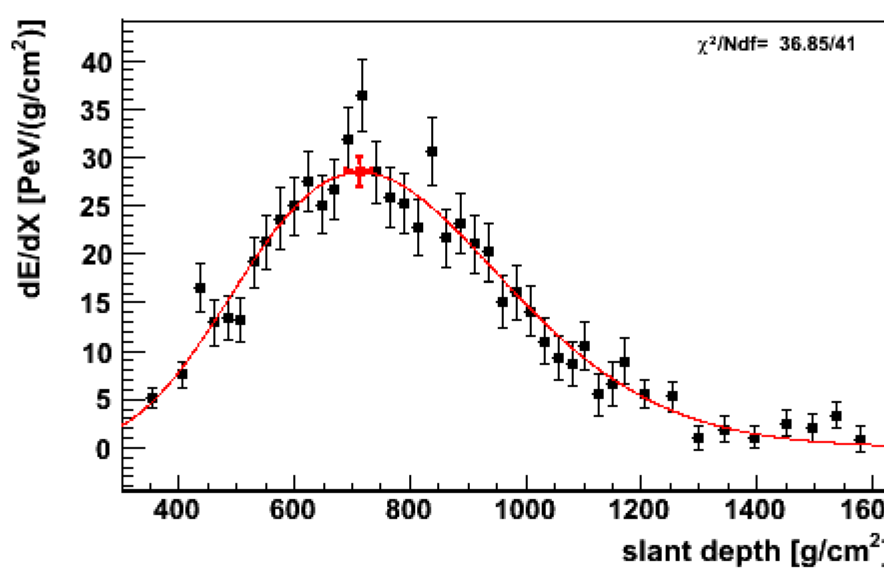
checks in stereo events
Xmax resol. ~20 gcm^{-2}



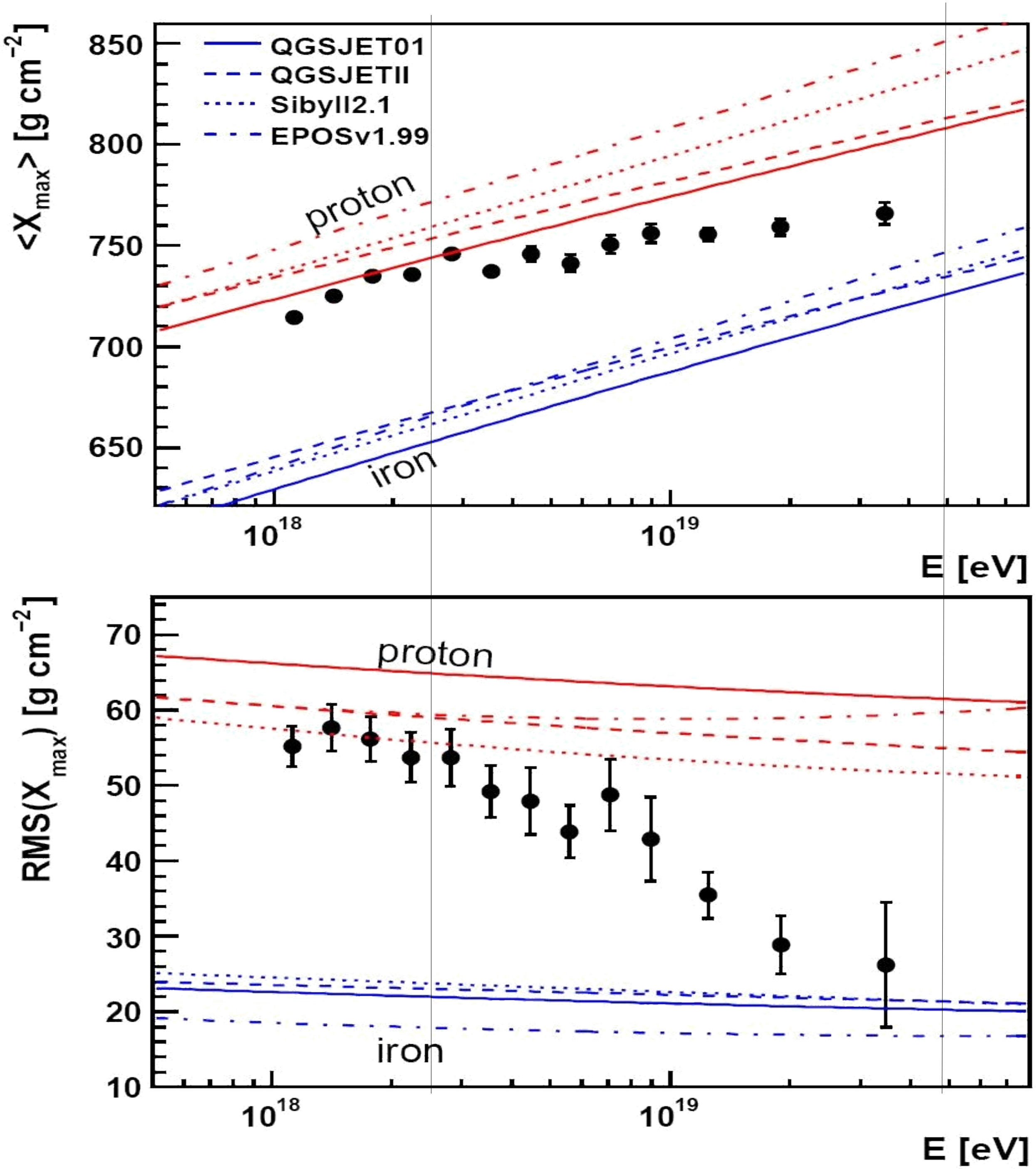
Fluorescence + Cherenkov photons



extract Xmax, shape and energy



Charged cosmic-rays mass composition



FD results compared with hadronic model predictions

$Xmax = X_1 + D_{development}$
both deeper for protons

[cross-section plus interaction details]

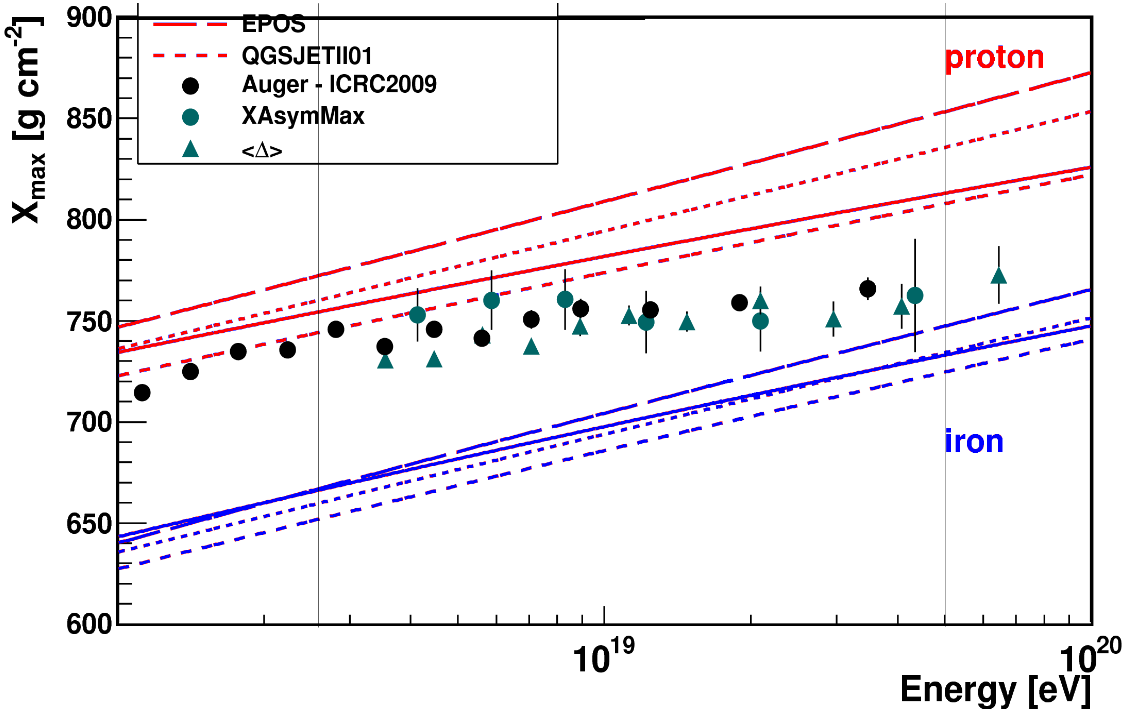
Very small fluctuations

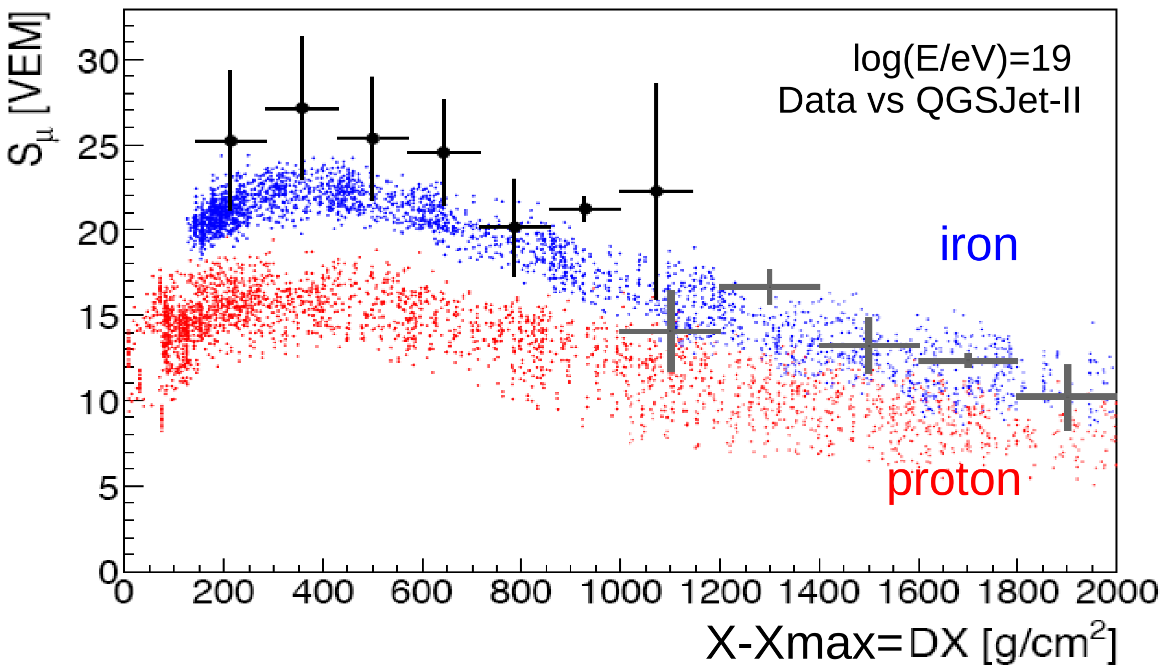
→ high cross-section

→ high multiplicity

new particle physics?

SD analysis for mass composition





<Xmax> derived from SD
(no systematic errors yet)

- indirect parameters,
like in photon analysis

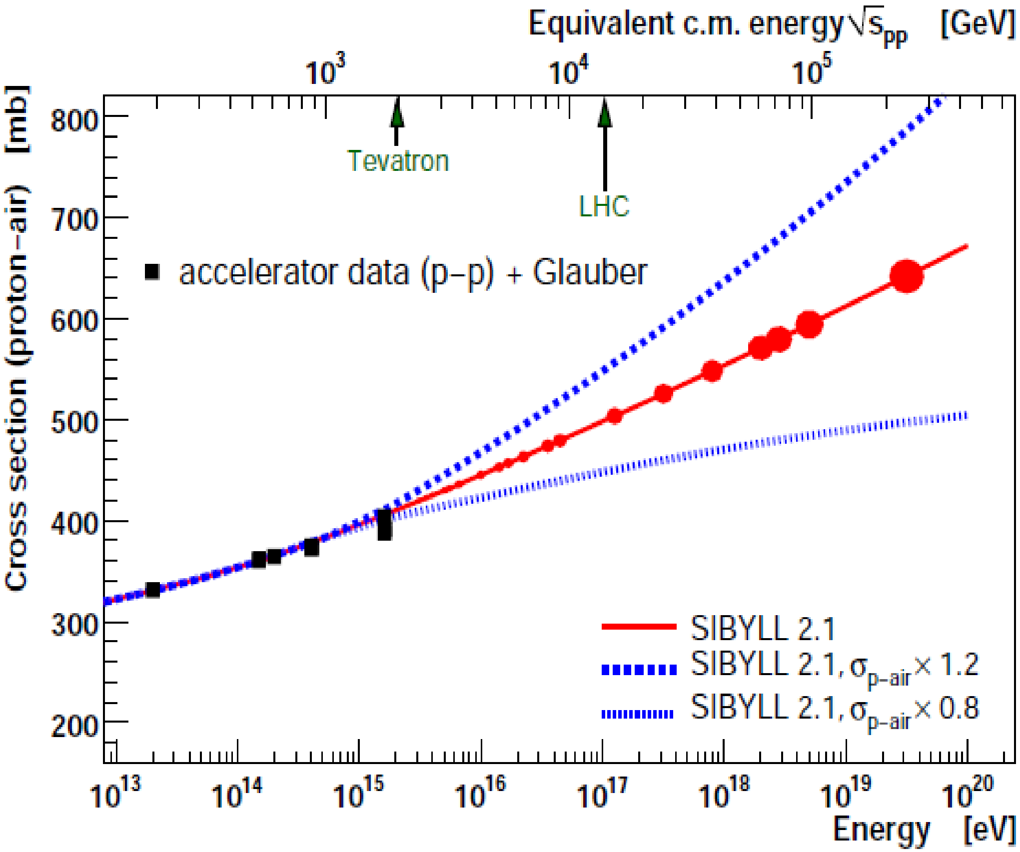
confirm high energy trend towards iron primaries or very high cross-sections

(in conflict with anisotropy?)

excess of muons at ground (confirmed by several independent analysis)

favoring iron primaries also or questioning hadronic models?

Testing high energy hadronic models



Cross-sections, multiplicity, inelasticity

all extrapolated from low energy!

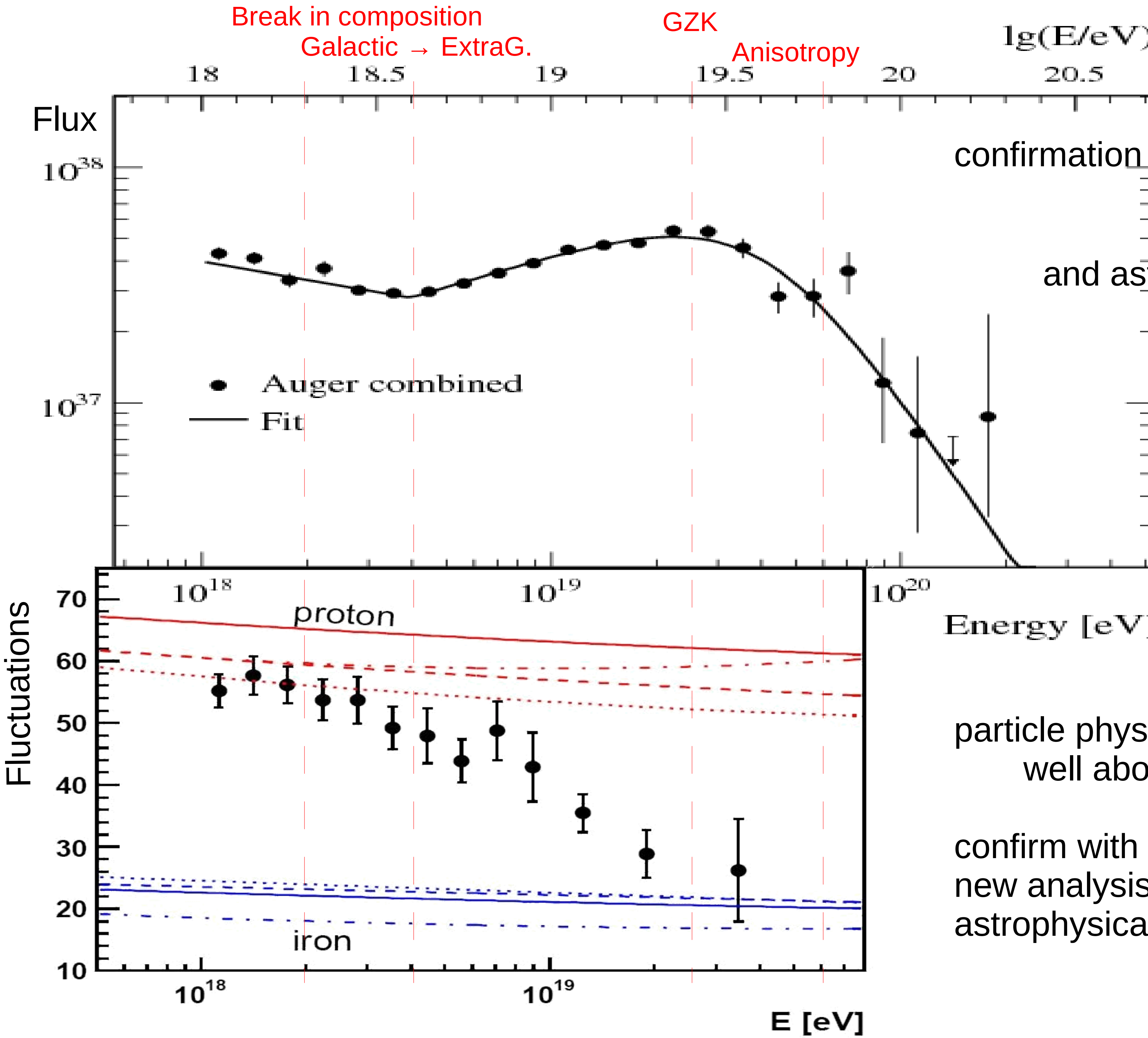
for first but also subsequent interactions

can change shower development,
and muon densities at ground

LHC and dedicated experiments will
help to constrain the energy evolution

combined results from all the analysis
and information from new measurements
will help to pin-down “new” particle physics

Overview of present results



confirmation with γ/ν

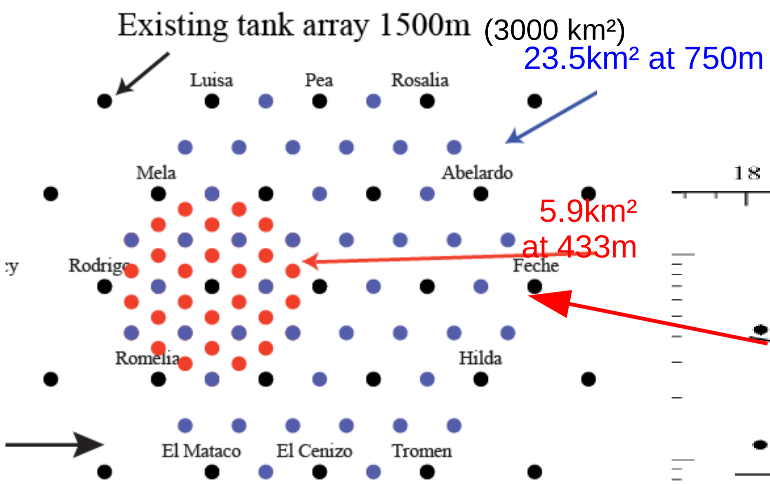
and astronomy

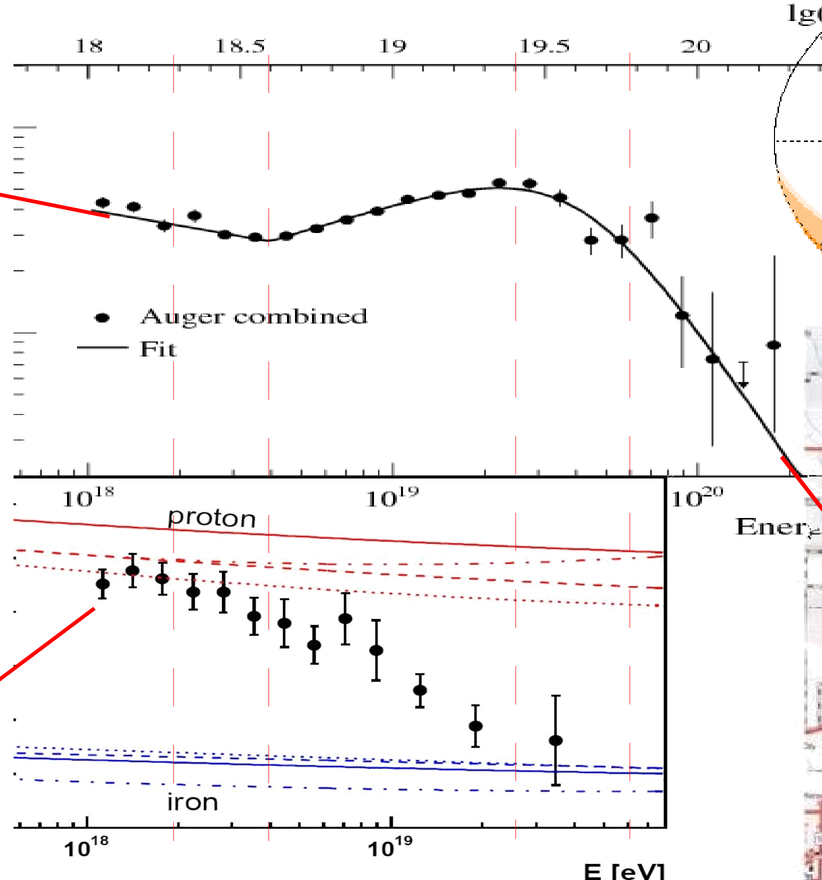
particle physics
well above the LHC

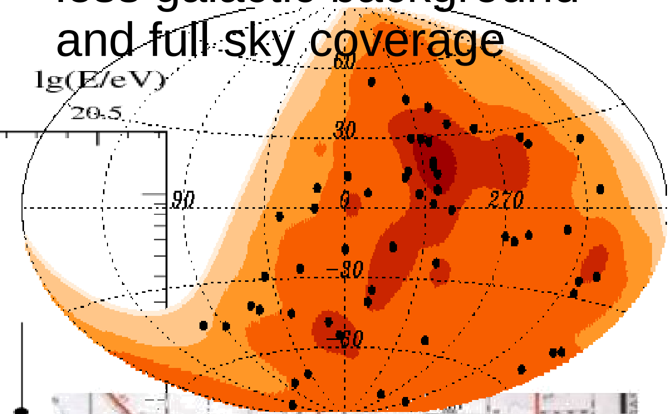
confirm with more data,
new analysis and
astrophysical sources?

The future Auger observatory

Auger North with 20000 km²
high energy measurements
less galactic background
and full sky coverage

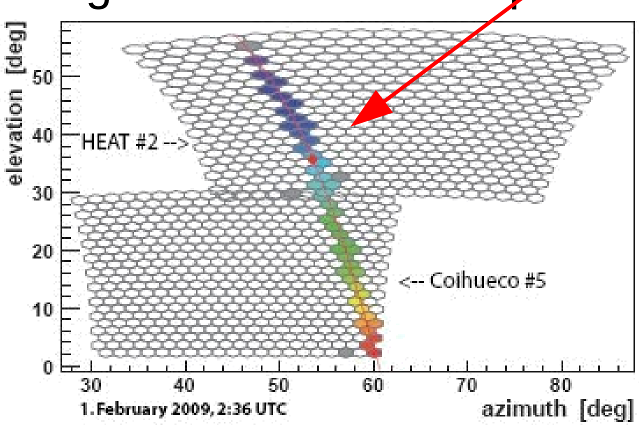






SD low energy infill
+ muon component in
underground stations

FD shower start-up in
high elevation telescopes



Conclusions and Outlook

The Pierre Auger Observatory has high quality data with unprecedented statistics

- limits on neutrino and photon fluxes
  excluding most “top-down” models

- high precision charged particle energy spectrum
  implying a galactic/extra-galactic transition and
  a GZK-like suppression probably due to CMB interactions

- anisotropy of the highest energy cosmic-rays,
  opening the road for charged particle astronomy and
  the study of acceleration mechanisms at sources

- shower analysis for mass composition and hadronic interaction studies
  both muon abundance and shower maximum distributions
  favor heavy nuclei dominance or unexpectedly high cross-sections
  in contradiction with present hadronic model expectations

New detectors will provide even more data, and new analysis are being prepared

An Observatory for Astrophysics but also very high energy Particle Physics

Back-up: Auger publications

"Measurement of the energy spectrum of cosmic rays above 1018 eV using thePierre Auger Observatory", to appear in Phys. Lett. B (2010) (arXiv:1002.1975v1 [astro-ph.HE]).

"Measurement of the Depth of Maximum of Extensive Air Showers above 1018 eV", Phys. Rev. Lett. 104, 091101 (2010) (arXiv:1002.0699v1 [astro-ph.HE]).

"Limit on the diffuse flux of ultrahigh energy tau neutrinos with the surface detector of the Pierre Auger Observatory", Phys. Rev. D79 (2009), 102001.

"Upper limit on the cosmic-ray photon fraction at EeV energies from the Pierre Auger Observatory", Astrop. Phys. 31 (2009), 399.

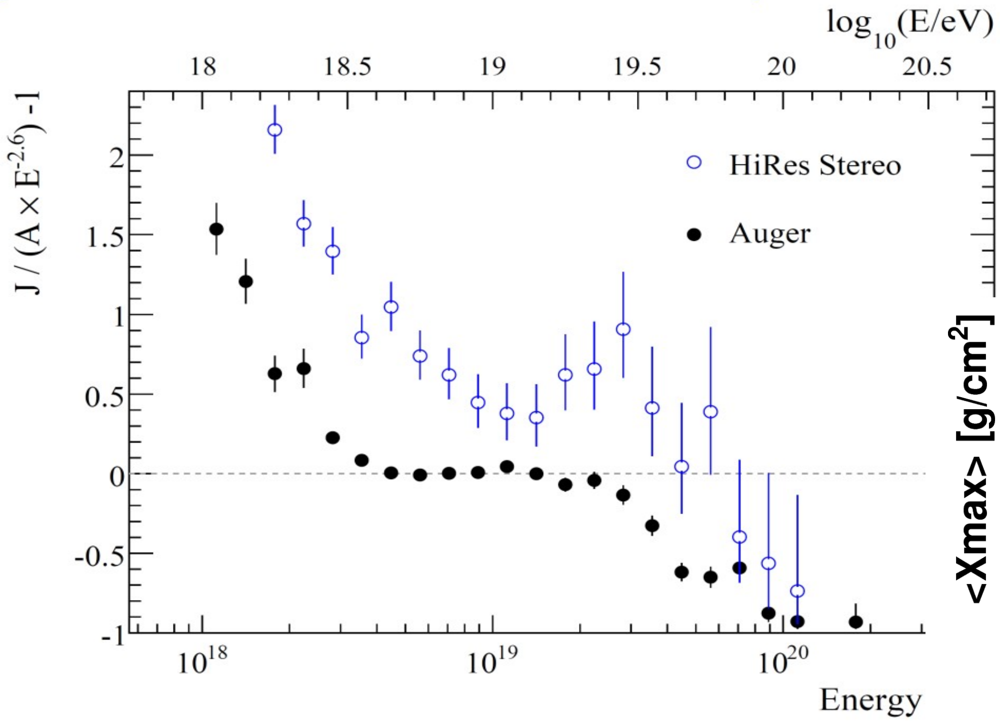
"Upper Limit on the Cosmic-Ray Photon Flux Above 1019 eV Using the Surface Detector of the Pierre Auger Observatory", Astrop. Phys. 29 (2008), 243.

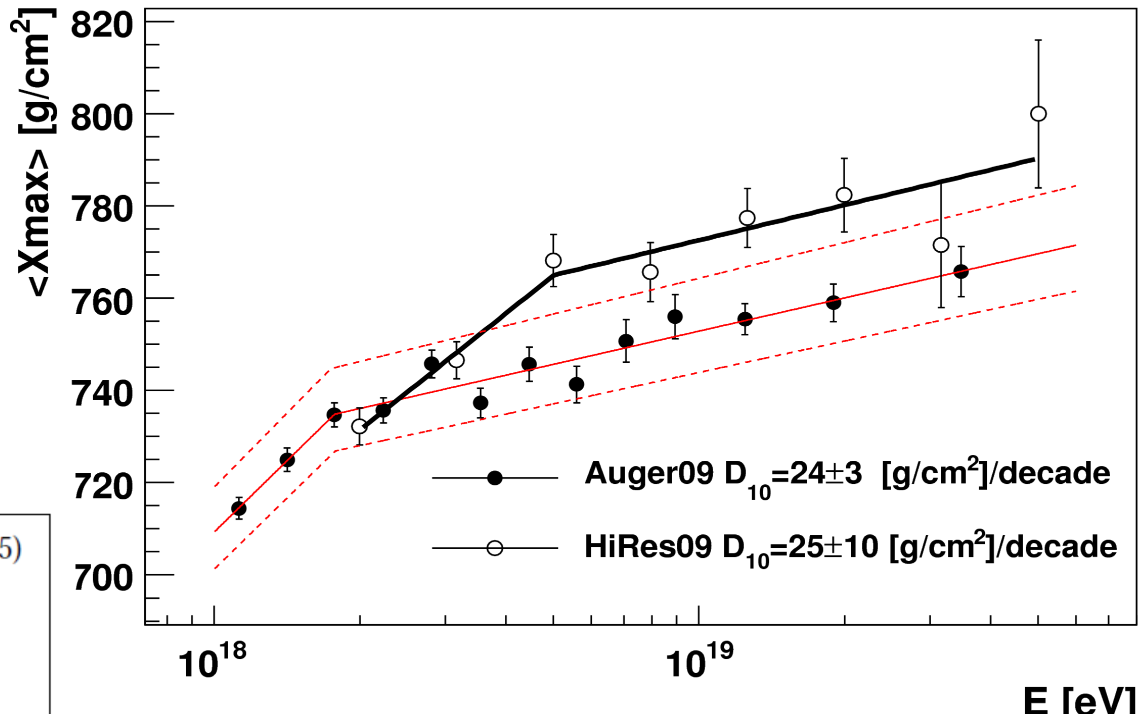
"Correlation of the highest energy cosmic rays with nearby extragalactic objects", Science 318 (2007), 939.

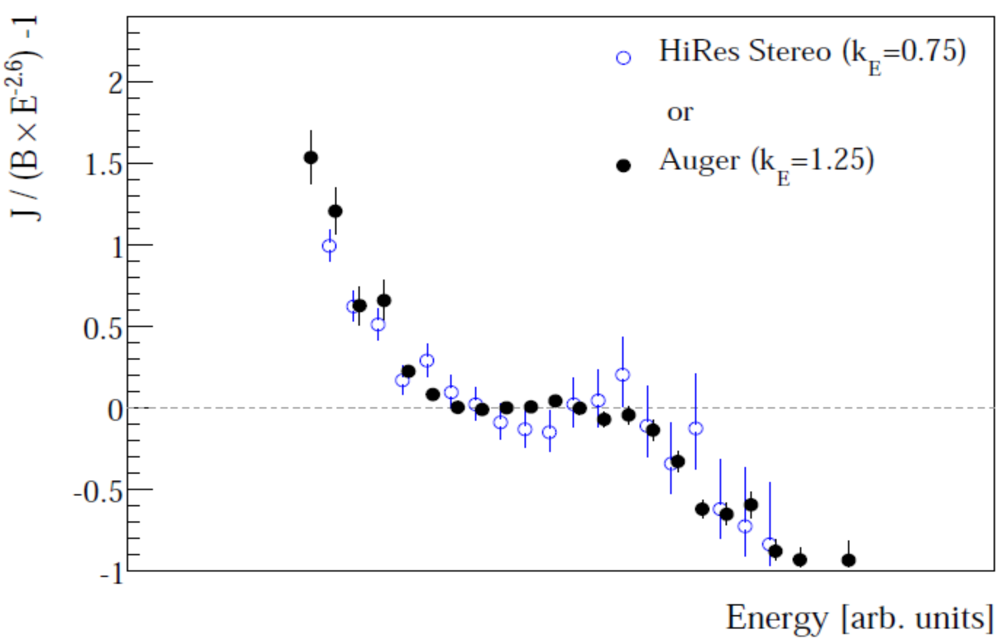
"Anisotropy studies around the galactic centre at EeV energies with the Auger Observatory", Astrop. Phys. 27 (2007), 244.

+ Poceedings of the 31st Internacional Cosmic Ray Conference, Lodz, Poland, 2009

Back-up: comparison with other experiments





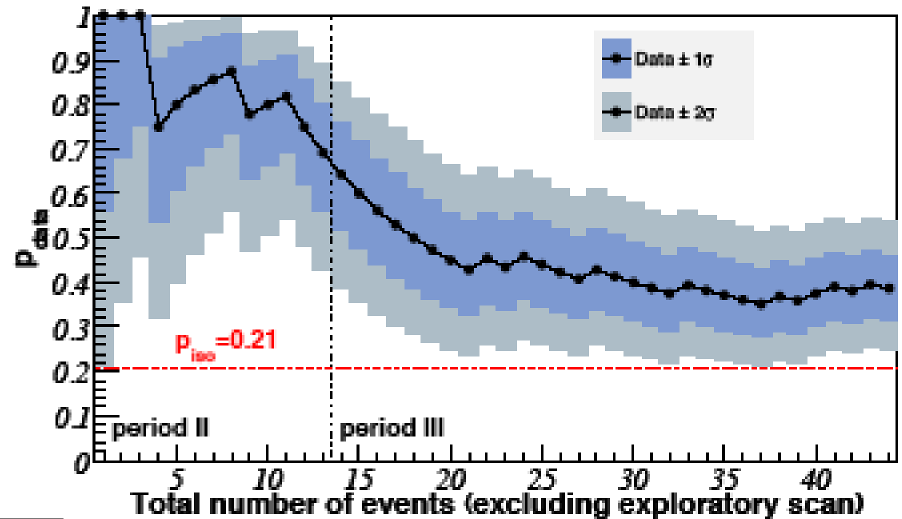


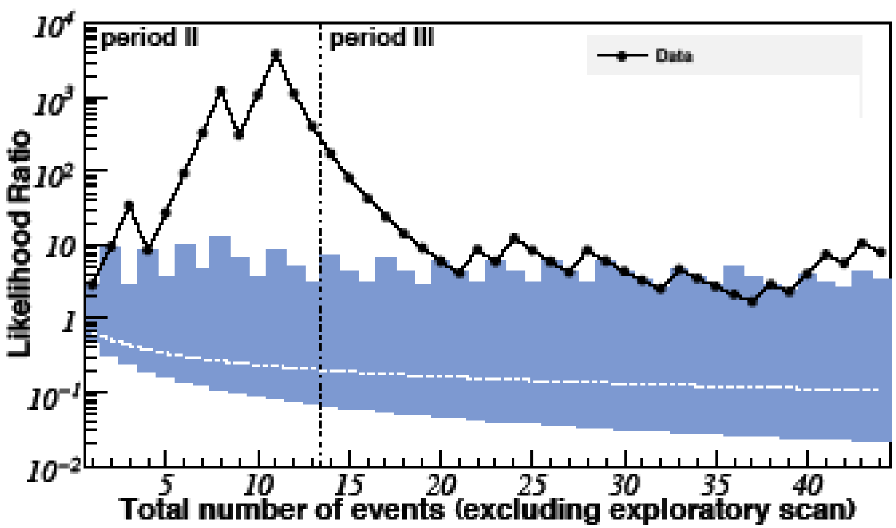
Status of the Prescribed Anisotropy Test

(correlation with VCV catalog of AGNs)

39% correlate (post exploration)

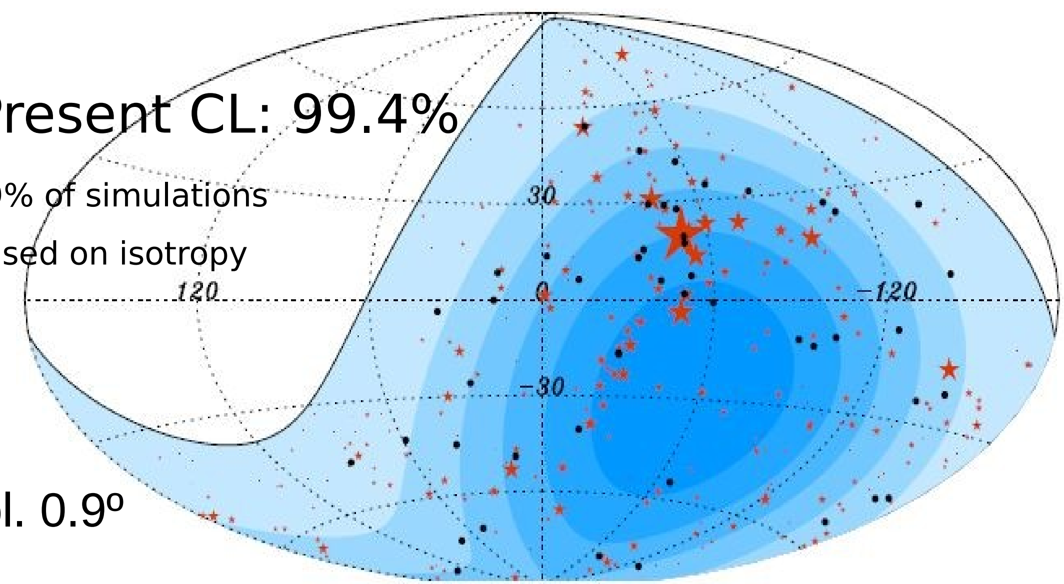
(21% expected for isotropy)





Present CL: 99.4%

99% of simulations based on isotropy



Events with θ<60º, angular resol. 0.9º

Swift-BAT 39-month Catalog of AGNs

E_{th}	N	ψ	z_{max}	k	k_{iso}	P
58 EeV	48 events	$6.2°$	0.057	44	26.1	2×10^{-8}
		$4.1°$	0.05	32	14.1	1×10^{-7}
		$4.0°$	0.018	20	6.3	9×10^{-7}

Table 1: Summary of parameters for the minimum of the isotropic cumulative binomial probability P and for illustrative examples of other local minima. k is the number of correlating events and k_{iso} the average chance correlations expected for an isotropic flux.

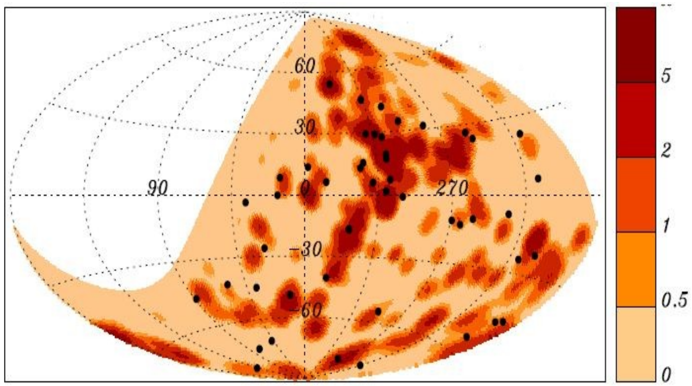
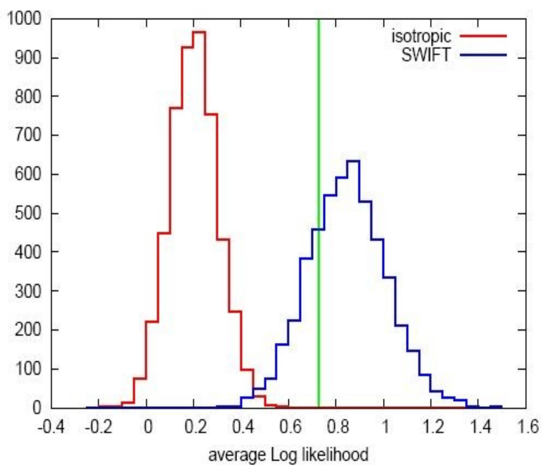
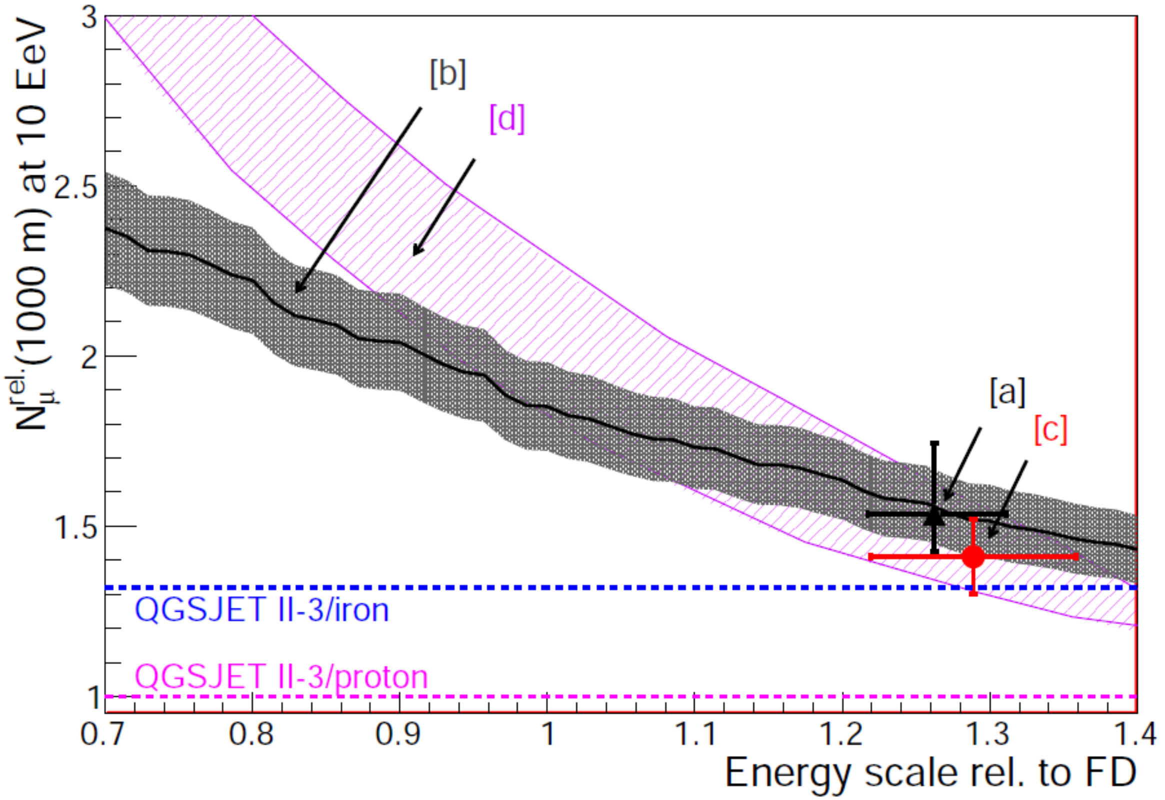


Figure 3: Top: Skymap in galactic coordinates with the AGN in the 39-months Palermo SWIFT-BAT catalog plotted as red stars with size proportional to the assigned weight (relative exposure, X-ray flux and GZK attenuation factor). Bottom: density map based on the map on top, smoothed with an angular scale $\sigma = 3°$. The black dots are the arrival directions of the 48 cosmic rays with energy larger than 58 EeV. The object with largest weight in the map on top is Cen A, and there are several other objects with relatively large weight within 20° or so. From the density map one expects on average 9 times more events in a circle of 20° radius centered in Cen A than in a similar circle around the direction towards the Virgo cluster.



igure 4: Distributions of mean log-likelihood per event for isotropic realizations of 48 events (red) nd for realizations of the model based upon the Palermo SWIFT-BAT 39-months catalog of fig. , smoothed over an angular scale of 3° and with an isotropic fraction of 50% (blue). The mean g-likelihood per event for the arrival directions of the 48 CRs with energy larger than 58 EeV is ndicated by a green vertical line.

Back-up: Testing hadronic models (muons/E)



SD energy derived from S1000, stability independent of models

check FD energy vs. MC energy vs. muon to electromagnetic content by:
- shower universality [a]
- re-simulation of hybrid showers [d]
- muon jumps [b]
- electromgantic smoothing [c]