Pierre Auger Observatory
studying the universe's highest energy particles

Results from the Pierre Auger Observatory

L. Cazon, for the Pierre Auger Collaboration
LIP, Portugal

UHECRs

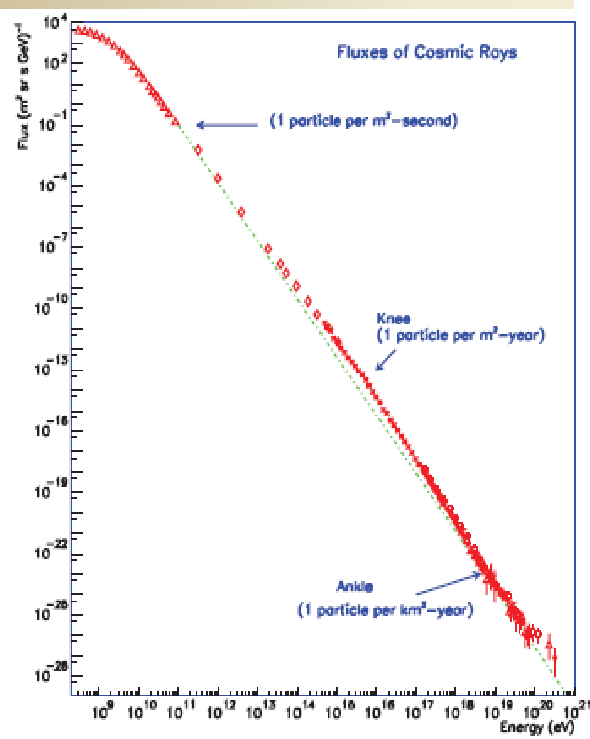
UHECRs : those with energies greater than 10^{18} eV

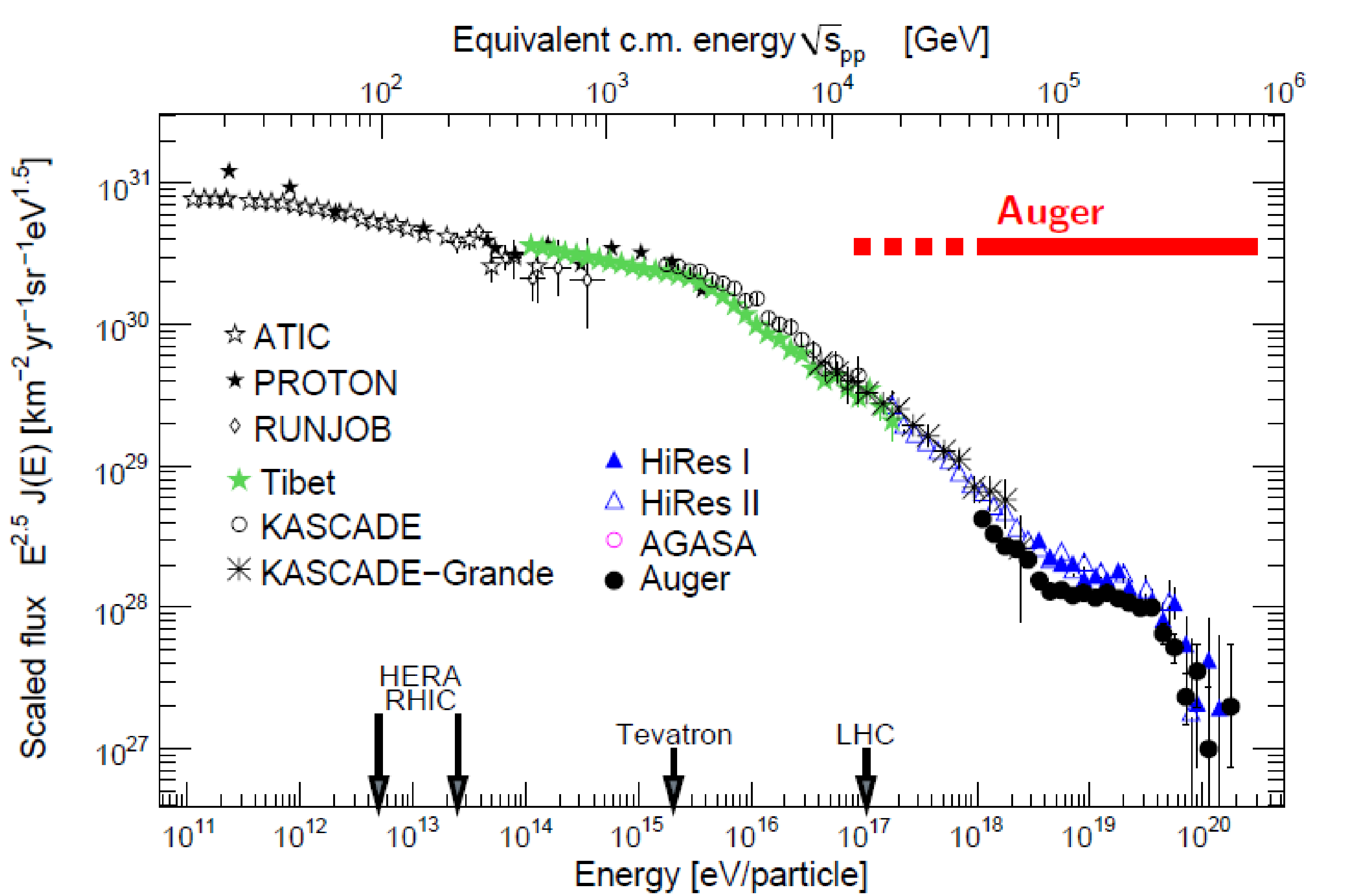
1 particle/km^2/year

How/where are they produced?

What is their composition?

How do they interact?



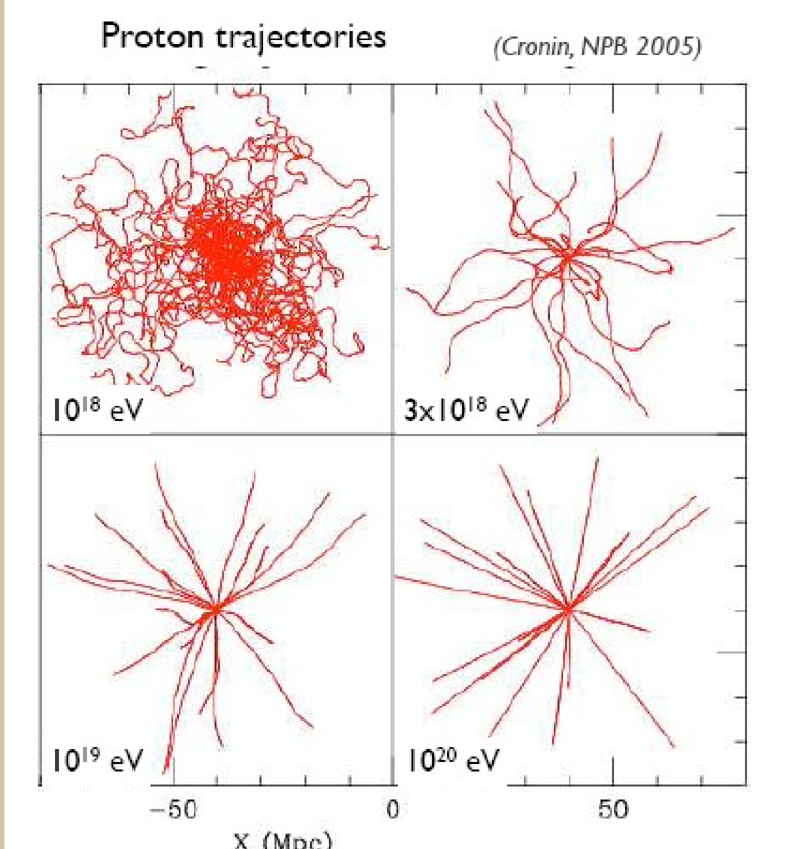


L. Cazón

Very Interesting region

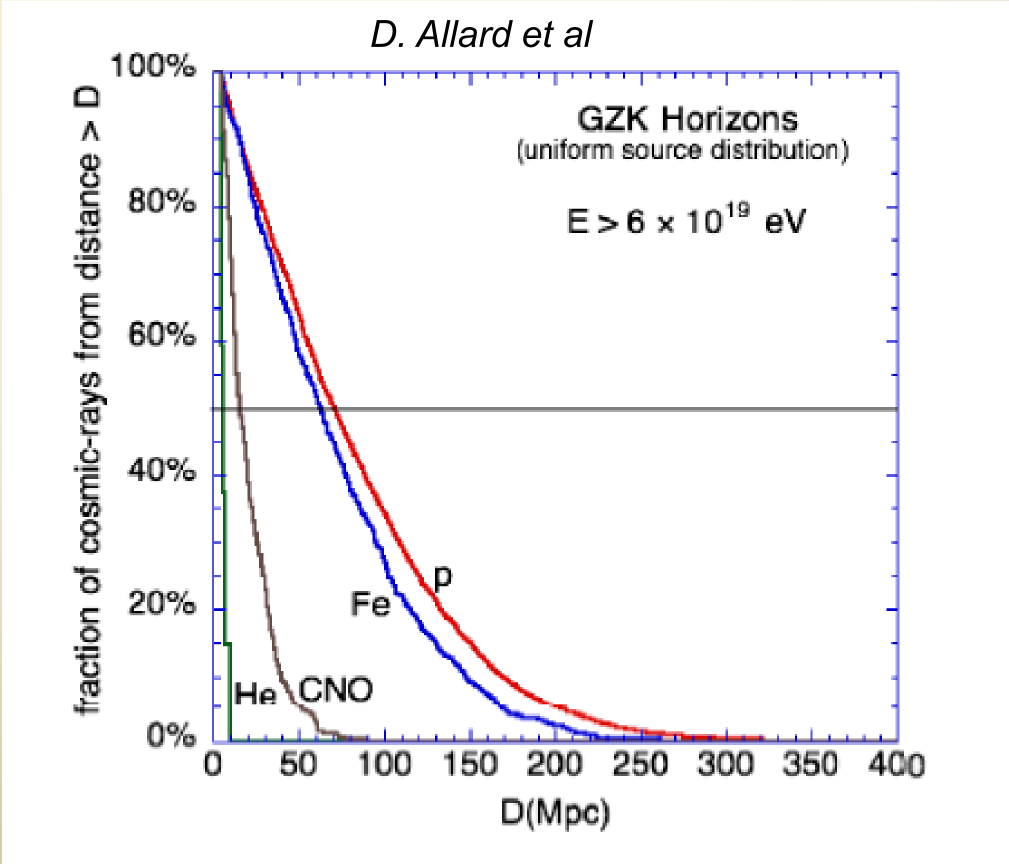
Galactic and extragalactig B fields bend the CR trajectories.

At the highest energies, UHECR point back to the sources.



Simple model for extragalactic B. B=1 nG, Lcoh=1 MPc

GZK Horizons: Only sources within 100 Mpc will reach us. Anisotropies are expected.



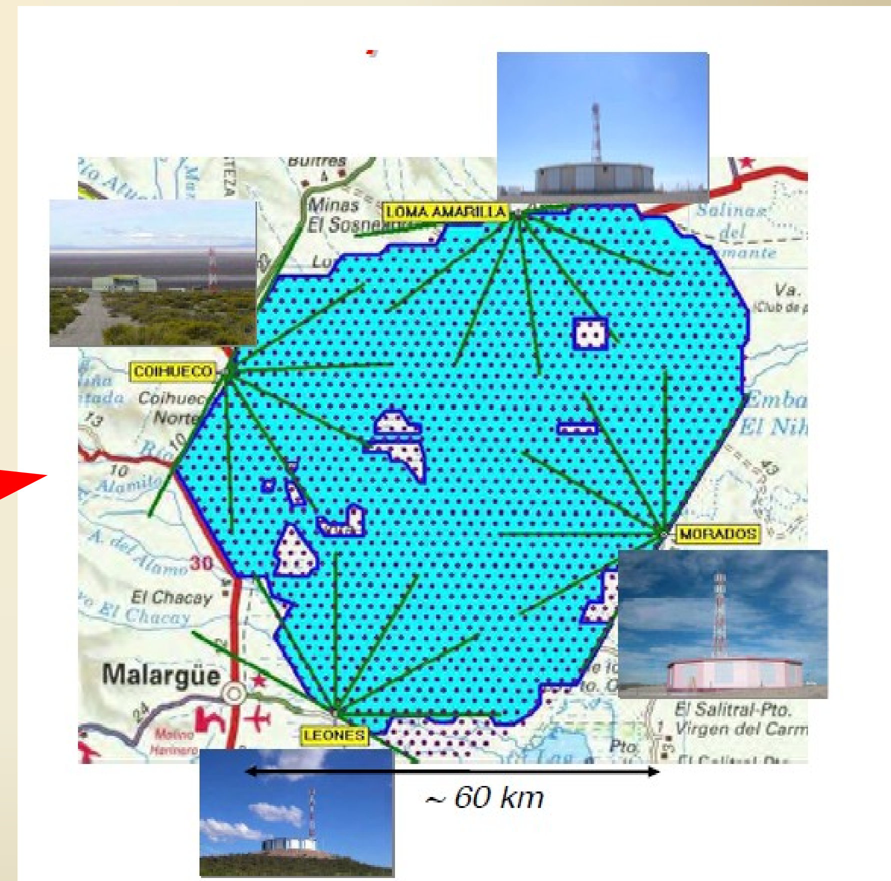
The Pierre Auger Observatory

Latitude 35 S – Longitude 69 W

1400m a.s.l. X=870 g cm^2

Data taking since 2004

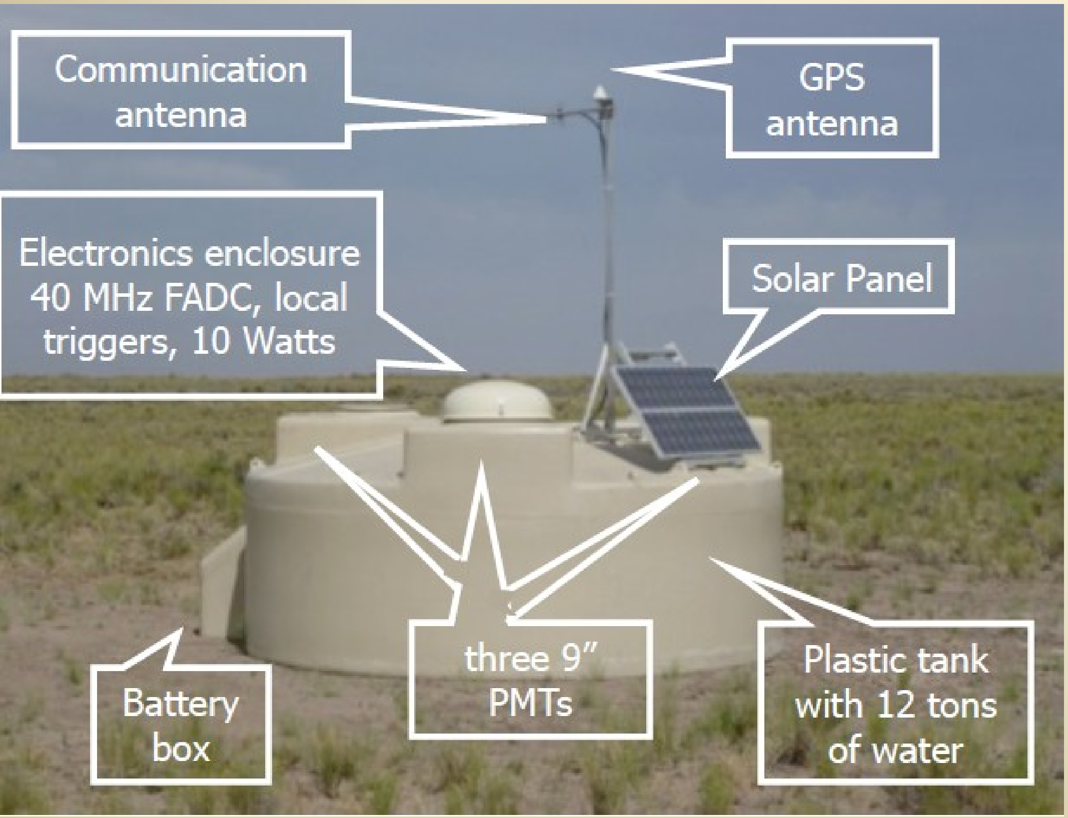
Installation completed in 2008



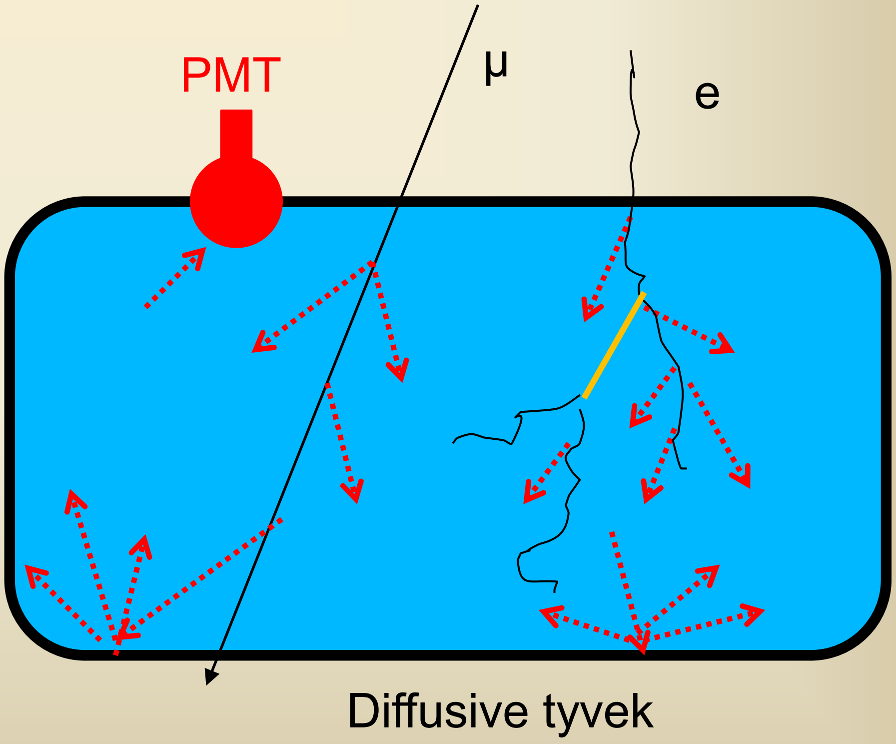
Surface detectors
1600 Cherenkov stations spaced 1.5 km
Area of 3000 km^2
100% duty cycle
Provides Large Statistics

Fluorescence detectors
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30 deg
~10% duty cycle
Provides High Accuracy

SD detectors

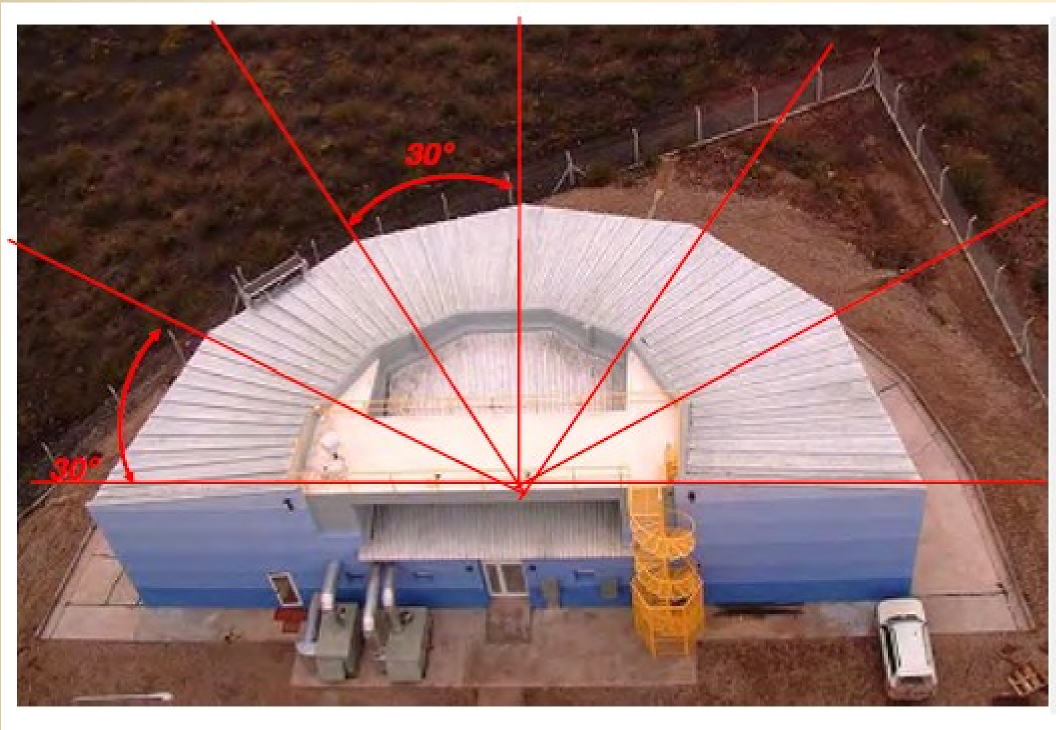


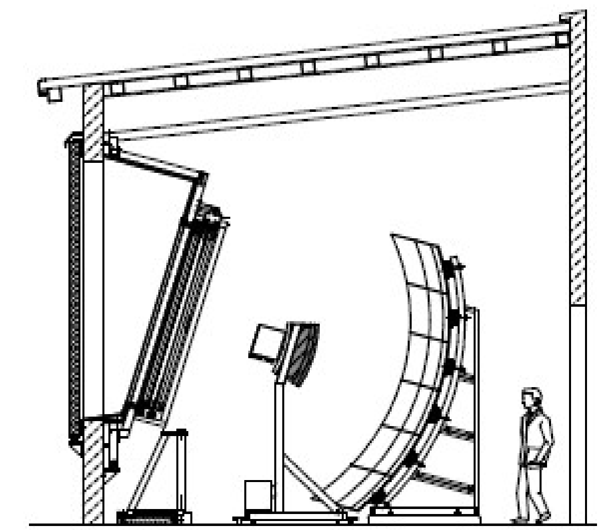
Water Cerenkov Detectors give signal proportional to their track lengh in water
Difficult to separate different particle types.
Some indirect methods

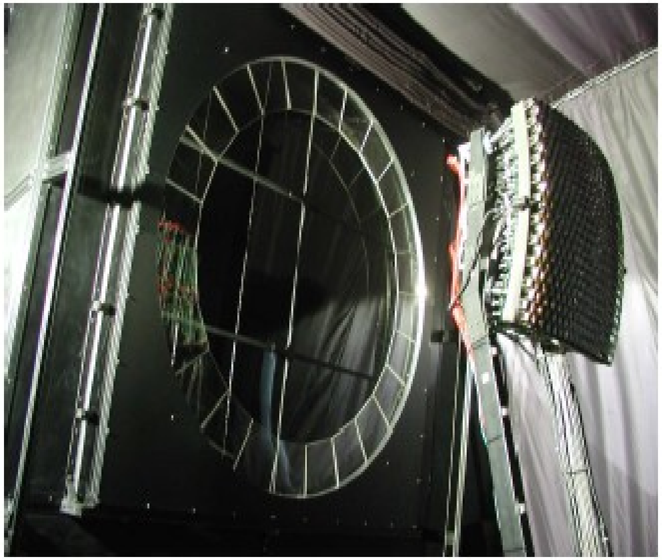


FD detectors

shutters
filters + corrector ring
camera
electronics crate



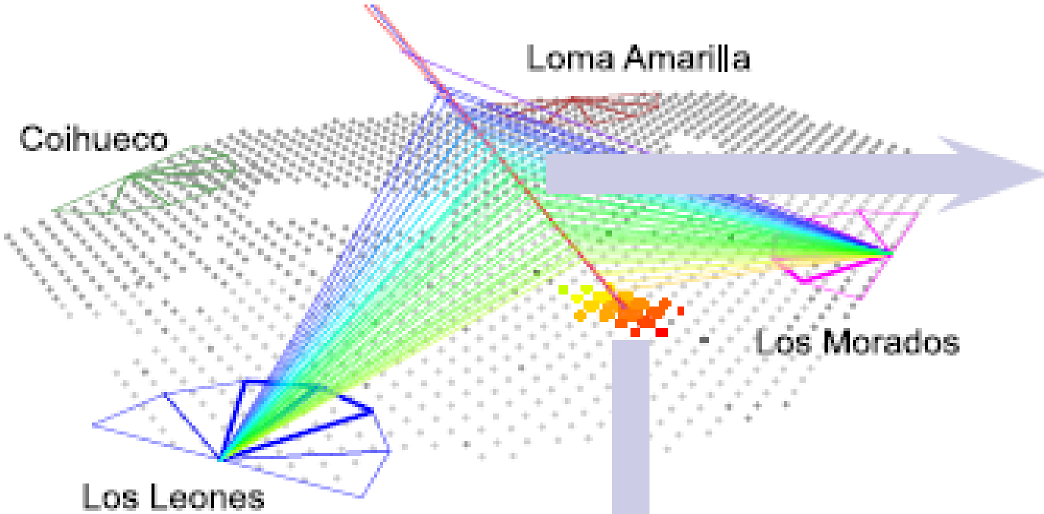


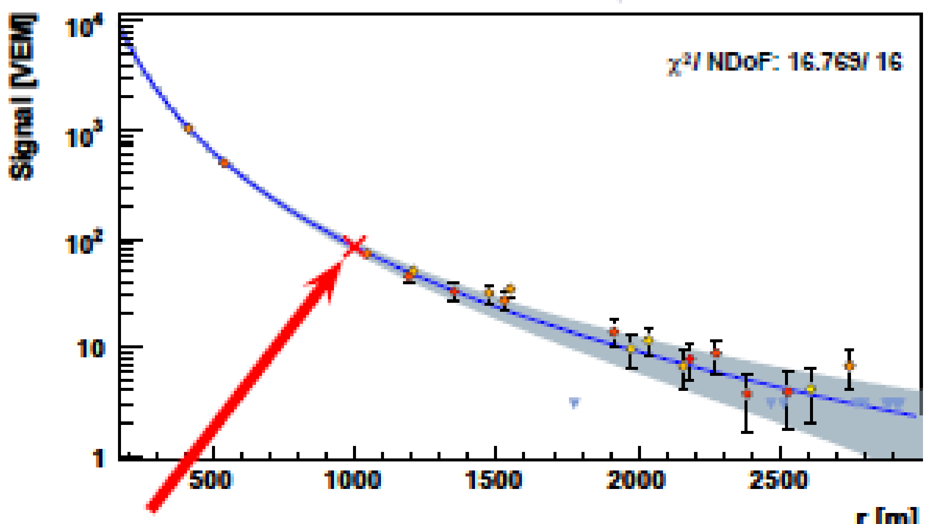


20 x 22 pixels
440 Photonis XP3062
Pixel f.o.v. = 1.5 x 1.5 deg

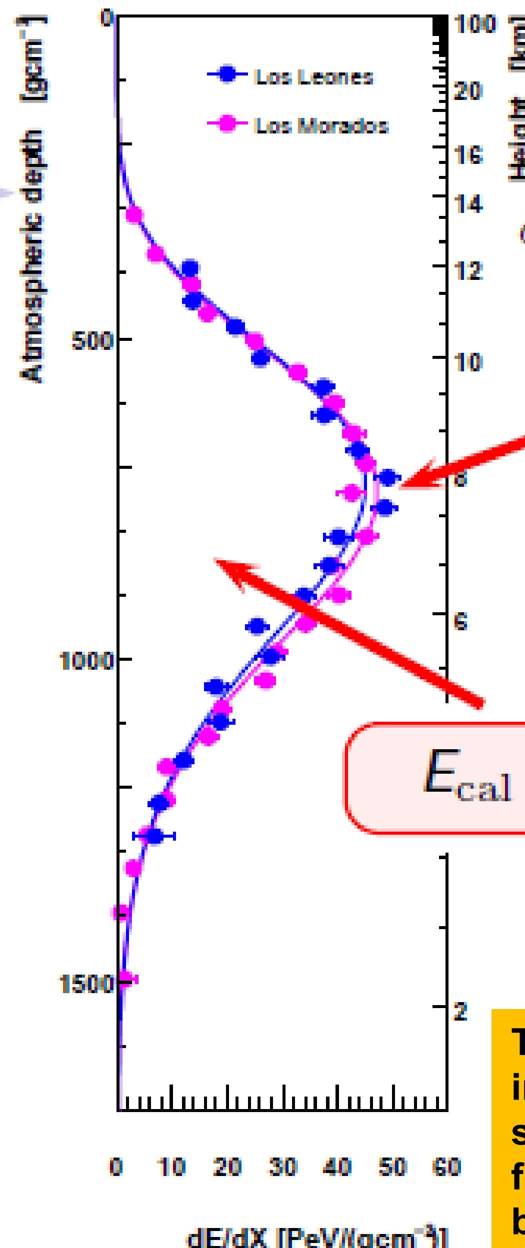
Collect Fluorescence light emited by the shower. Mainly the central region of the EM cascade.

Hybrid Detector: Large and accurate





S_{1000} $E_{\mathrm{surface}} = f\,(S_{1000},\,\theta)$



$\sigma_{X_{\mathrm{max}}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

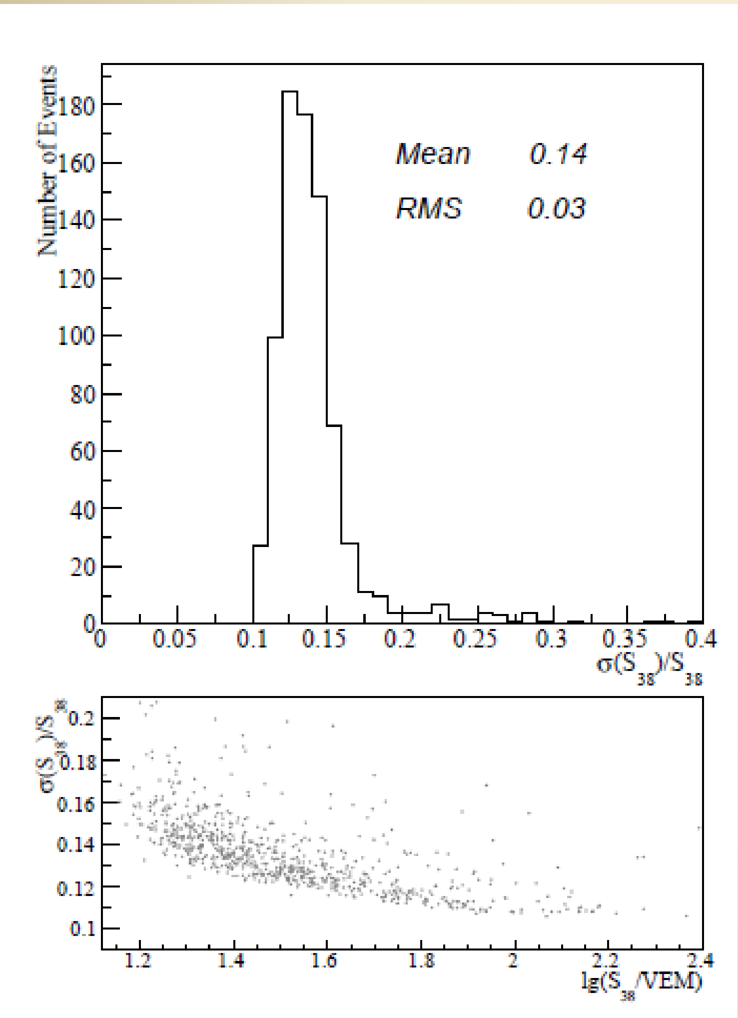
X_{max}

$E_{\mathrm{cal}} = \int \mathrm{d}X\,\frac{\mathrm{d}E}{\mathrm{d}X}$

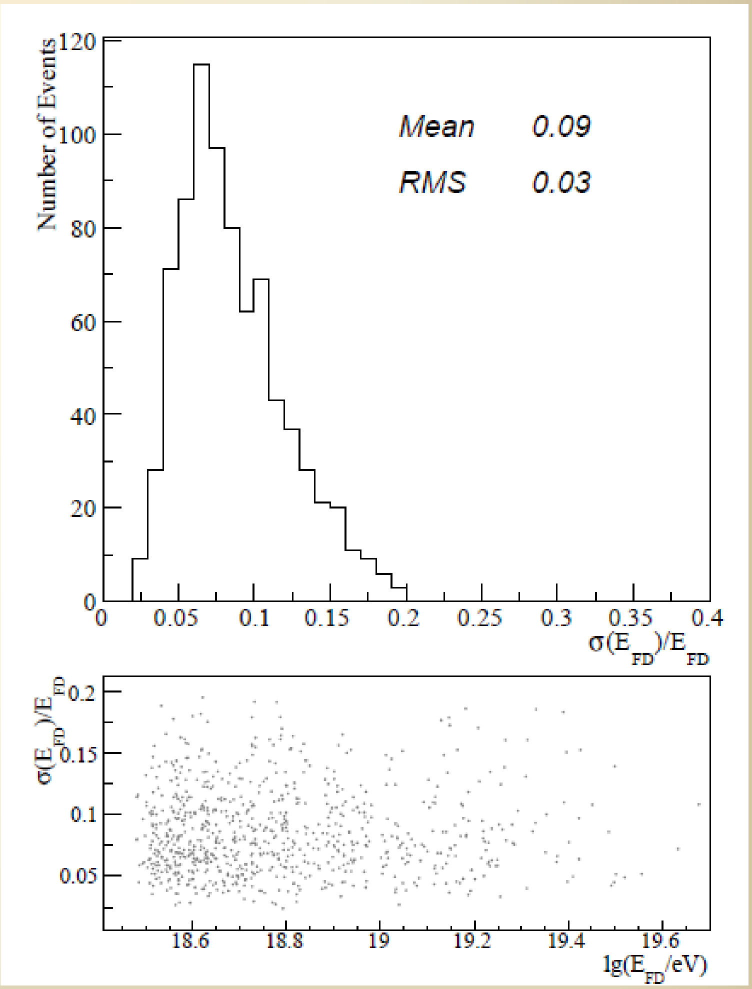
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

The energy is independent of simulations except for the energy carried by neutrinos and muons.

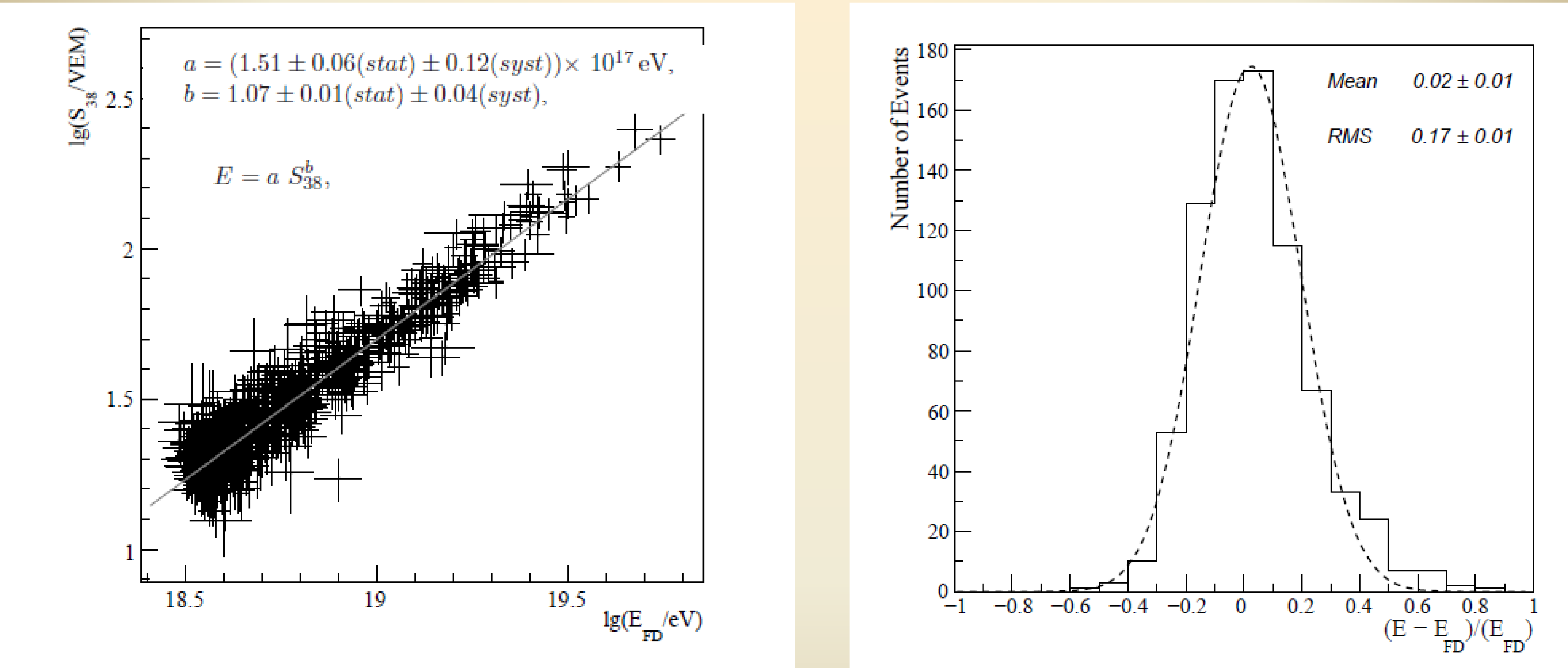
Resolution SD & FD



The systematic uncertainties on the energy scale E_{FD} sum up to 22%.The largest uncertainties are given by the **absolute fluorescence yield** (14%), the **absolute calibration** of the fluorescence telescopes (9%)and the **uncertainty due to the reconstruction** method of the longitudinal shower profile (10%).



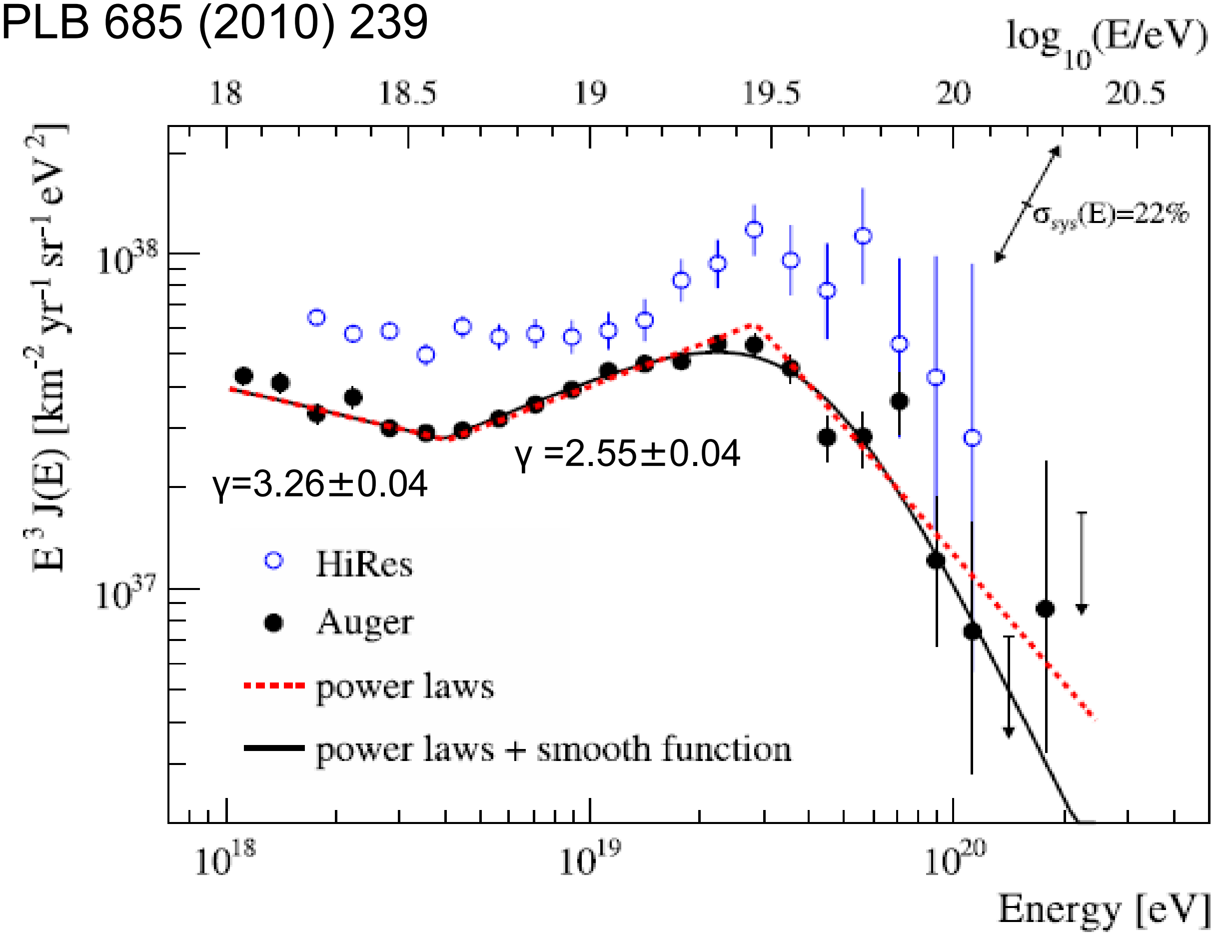
Energy Calibration of SD with FD



Calibration does not depend on hadronic interaction models
Systematical error 22%
energy resolution 17%

Energy Spectrum

PLB 685 (2010) 239



Auger data shows a flux supression at the highest energies

Cutoff significant with >20 sigma

This feature is compatible with:

GZK

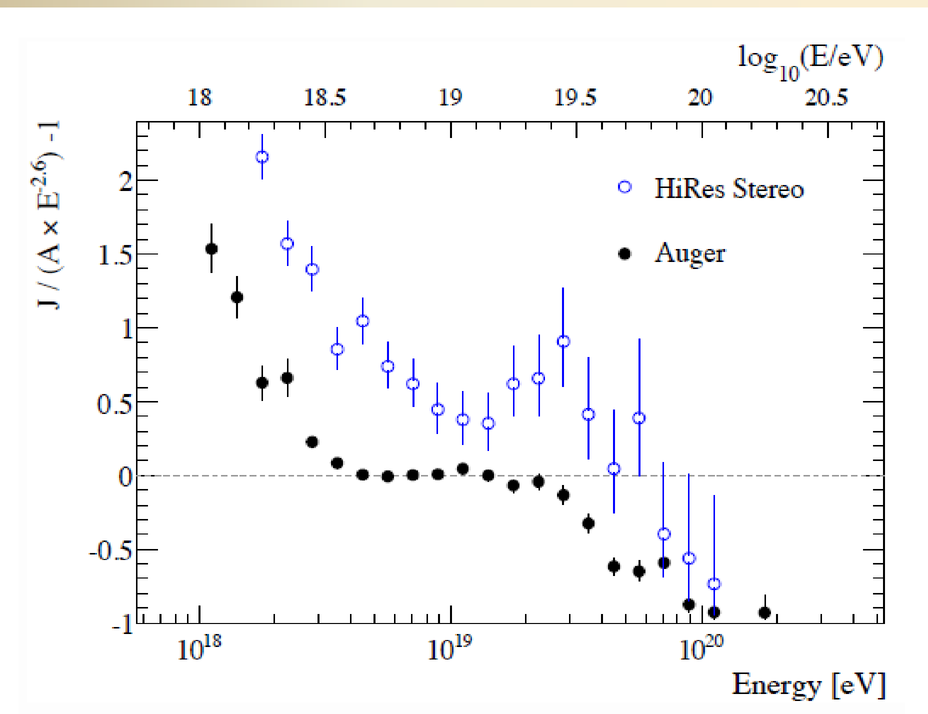
Sources running out of power

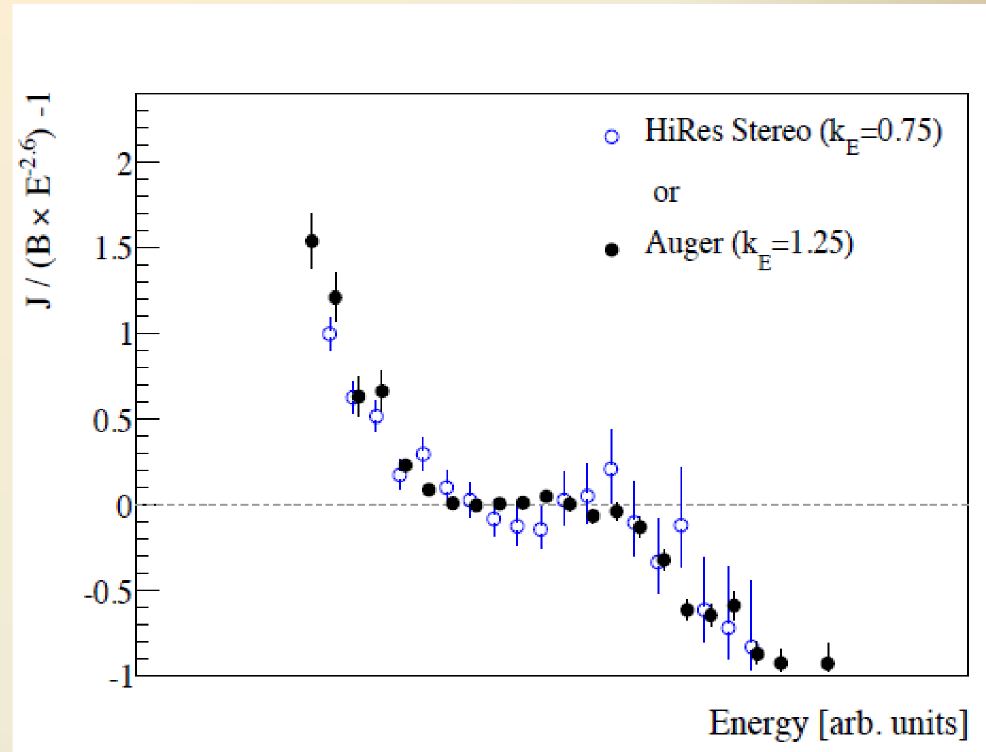
$\log_{10}(E_{ankle}/eV)=18.60 \pm 0.01$

$\log_{10}(E_{1/2}/eV)=19.61 \pm 0.03$

It combines FD and SD spectrum.

Spectrum comparison

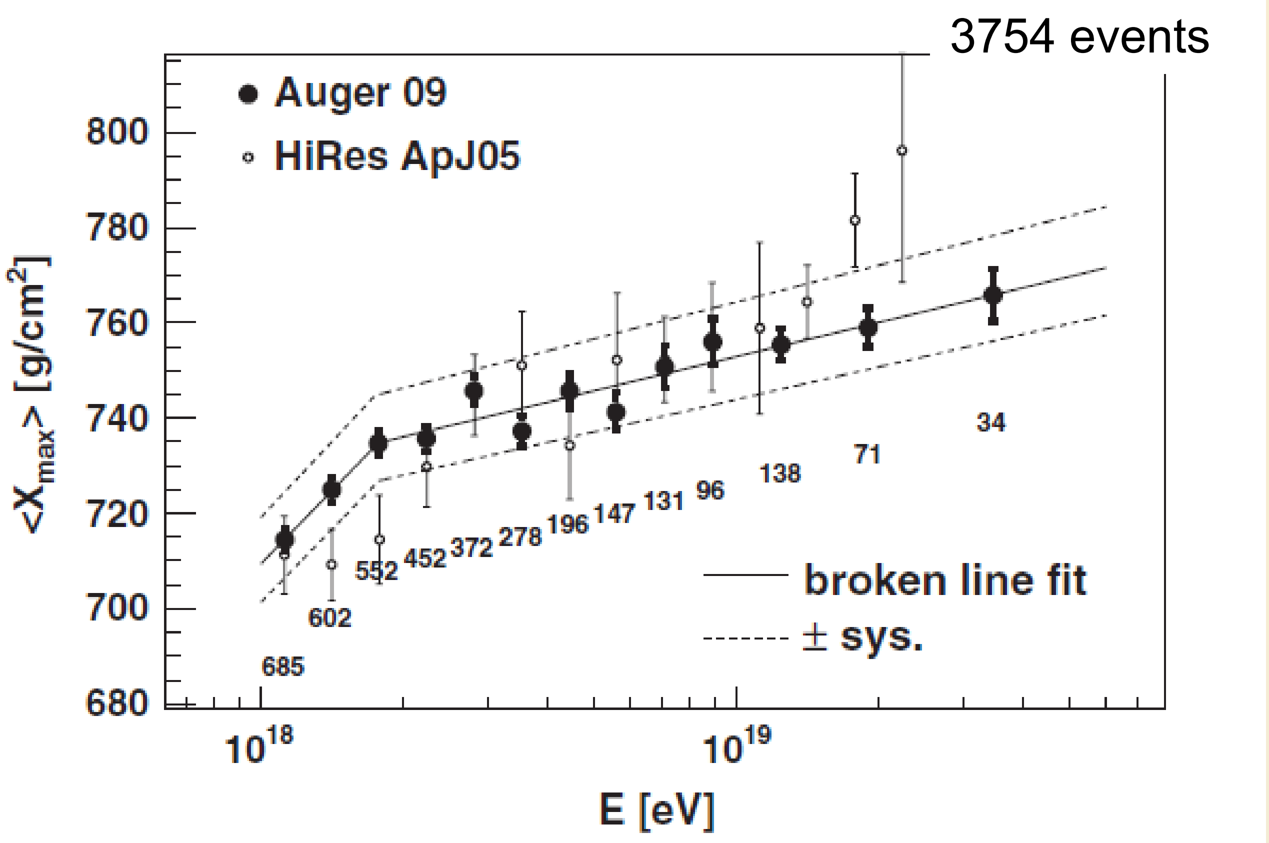




PLB 685 (2010) 239

In agreement with energy scale systematics

Xmax analysis



PRL 104 (2010) 091101

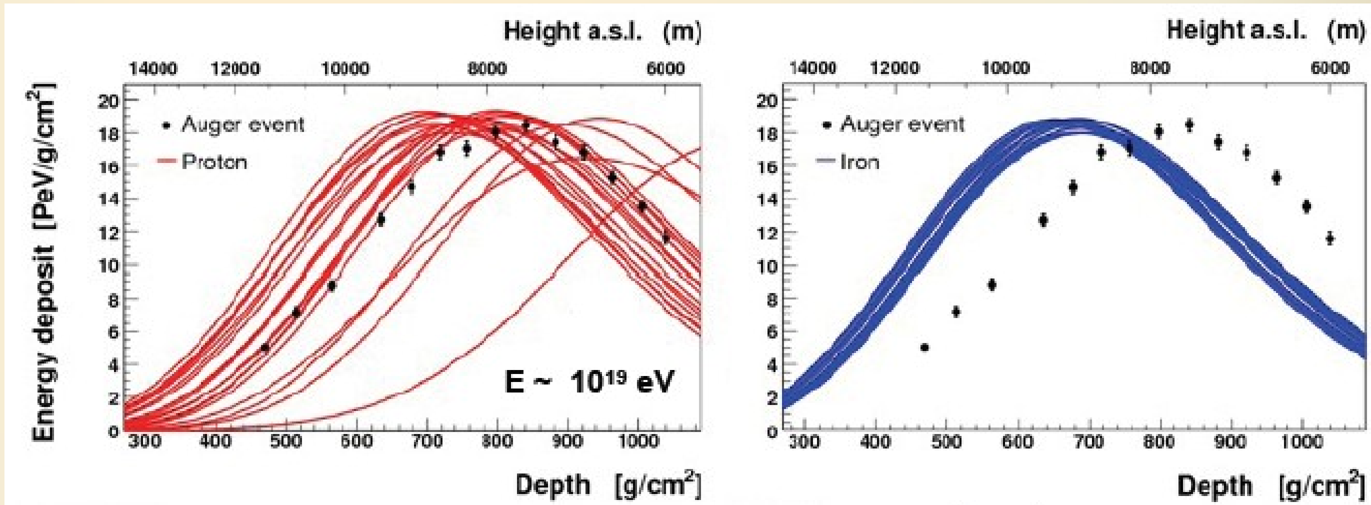
Single: $D_{10}=33 \pm 2$ g/cm^2/decade
χ^2/ndf = 35/11

Broken: $D_{10}=105^{+35}_{-21}$ g/cm^2/decade
$\log_{10}(E_{break}/\mathrm{eV}) = 18.24 \pm 0.05$
$D_{10}=24 \pm 3$ g/cm^2/decade
χ^2/ndf = 9.7/9

$$D_{10} = \frac{d\langle X_{max}\rangle}{d\lg E} \sim \alpha\left(1 - \frac{d\langle\ln A\rangle}{d\ln E}\right)\ln(10)$$

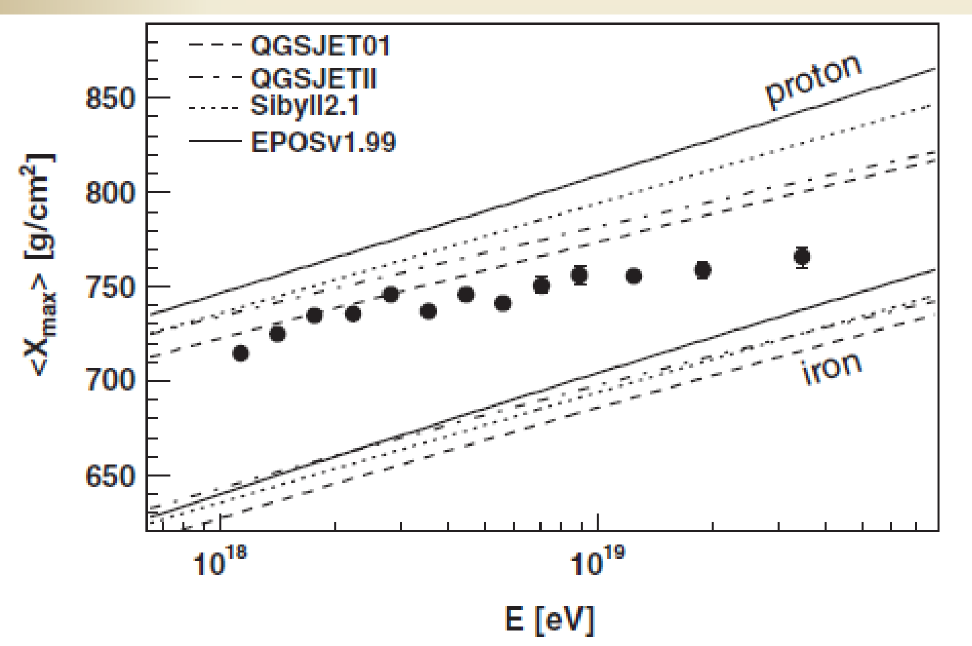
If hadronic interactions do no change much over less than 2 decades, this change on D_{10} would imply a **change on composition around the ankle**.

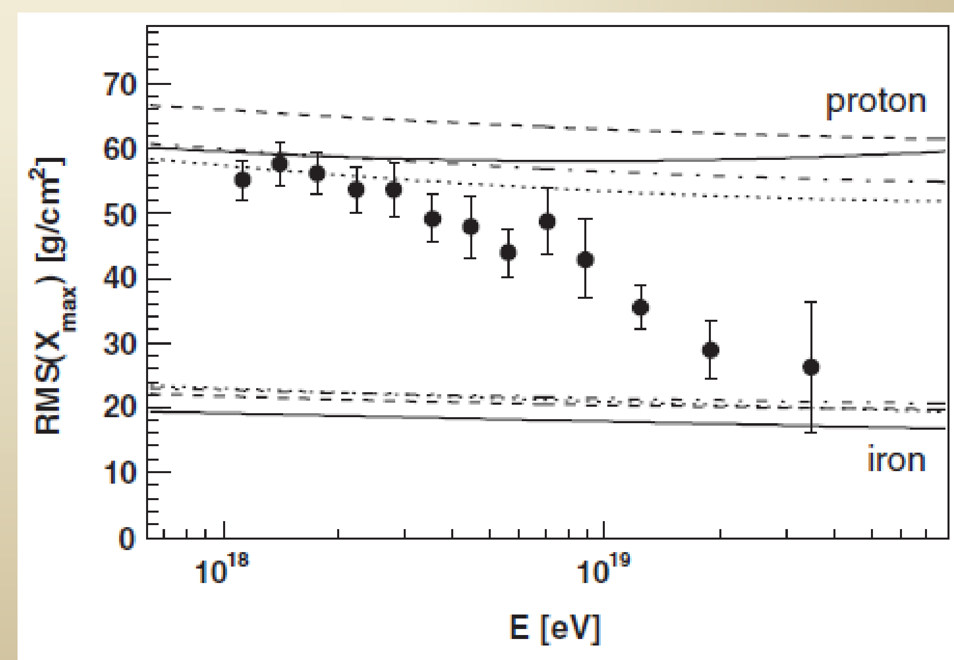
Comparison with MC



Data show either a change on composition towards heavier nucei or a change in the hadronic models

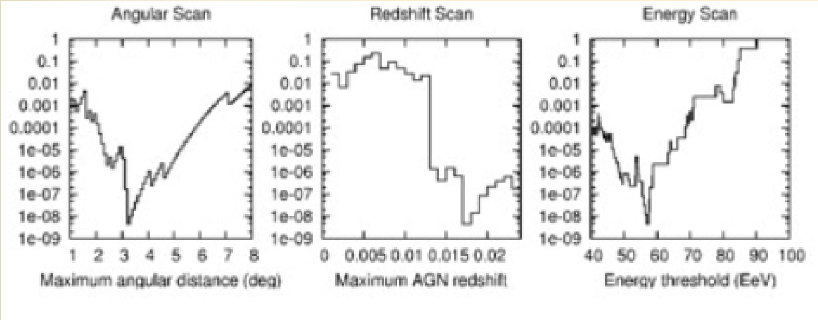
PRL 104 (2010) 091101





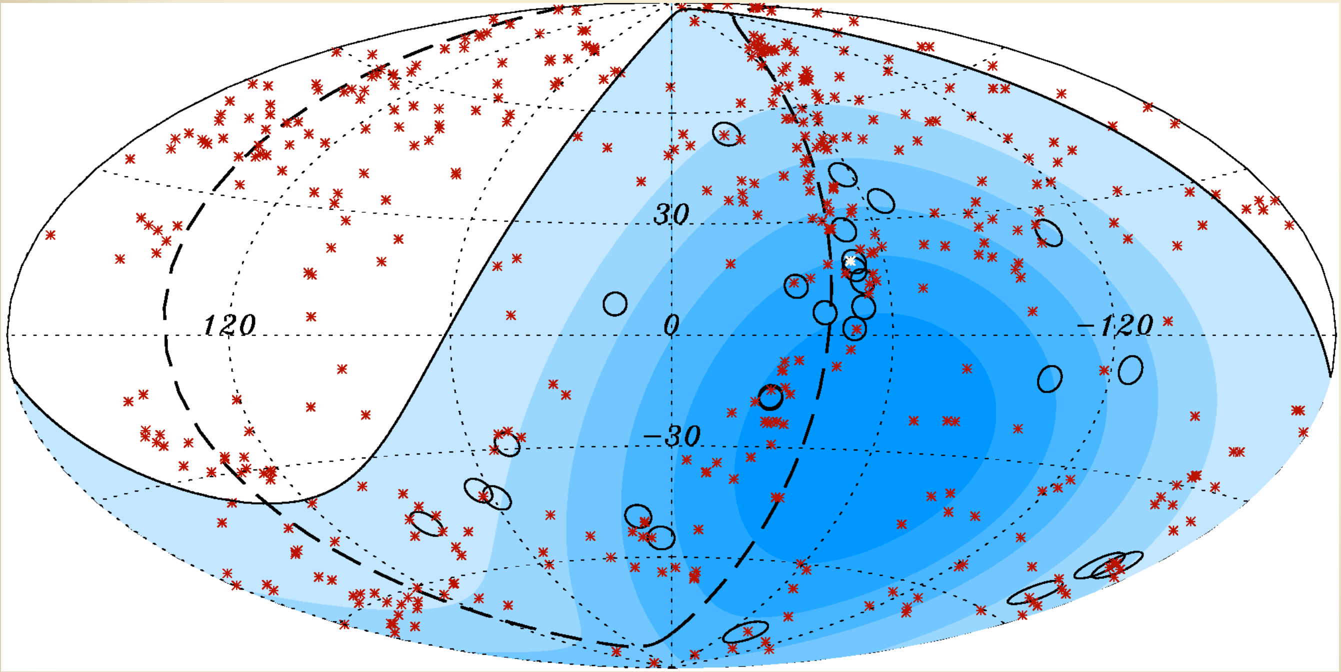
Correlation with AGN

Science **318:**938-943,2007



(z<0.018, alpha=3.1 deg, E>57 EeV)

12/15 events correlated in the exploratory scan, 3.2 expected. P<1E-8
Difficult to estimate real probability, thus confirmation required with an **independent data set.**



VCV catalogue is not *complete*: over/undersampled across the sky

A correlation with the AGNs does not necessarily mean that AGNs are the sources!!! AGNs act as tracers of the regions where the sources are.

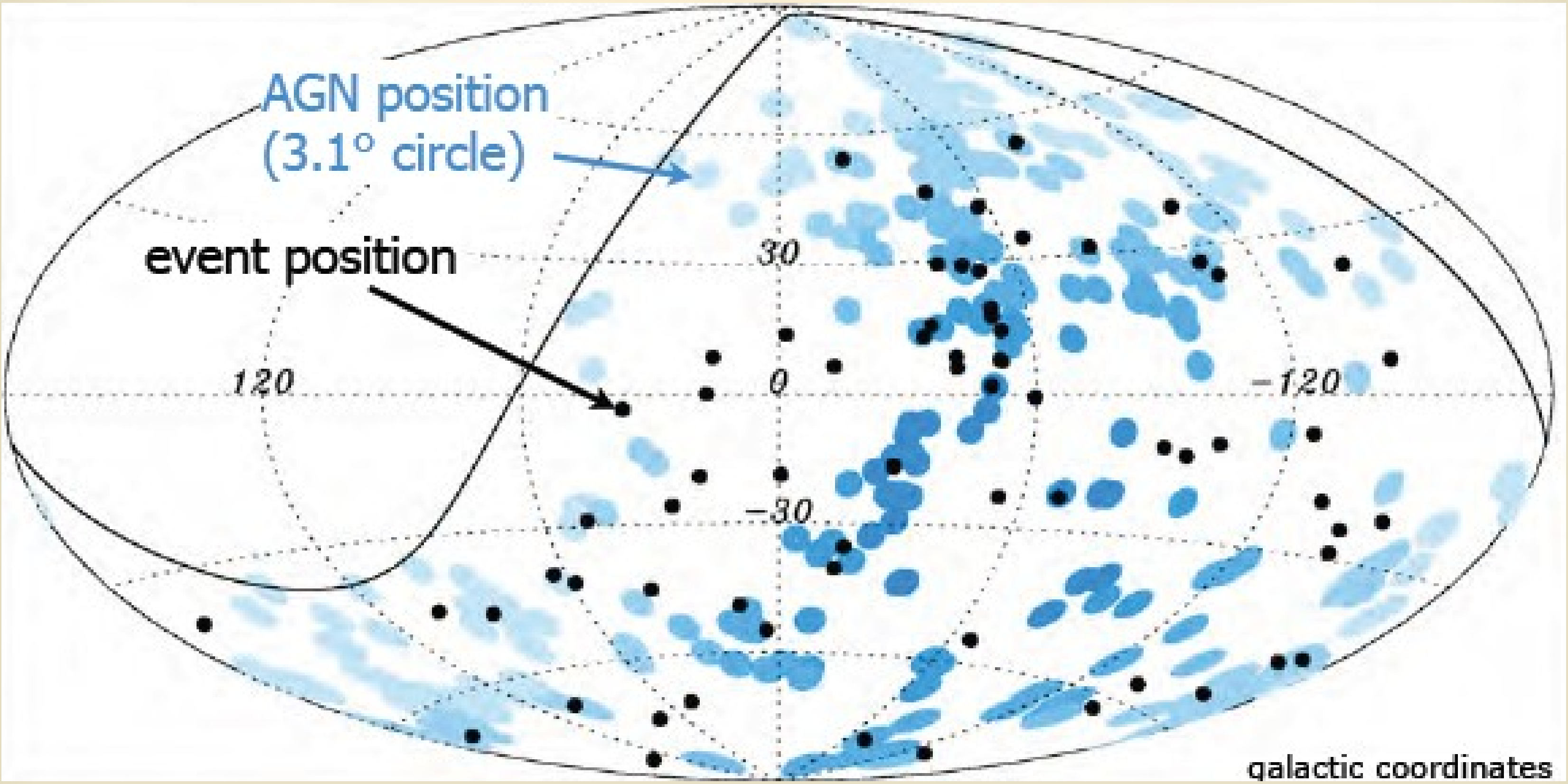
Prescription was set.
8/13 events found to correlate.

- Null hypothesis (Isotropy of UHECR) rejected at 99% CL
- Large correlation (~70%) with extragalactic matter (traced by AGN)

Angular resolution ~1 deg

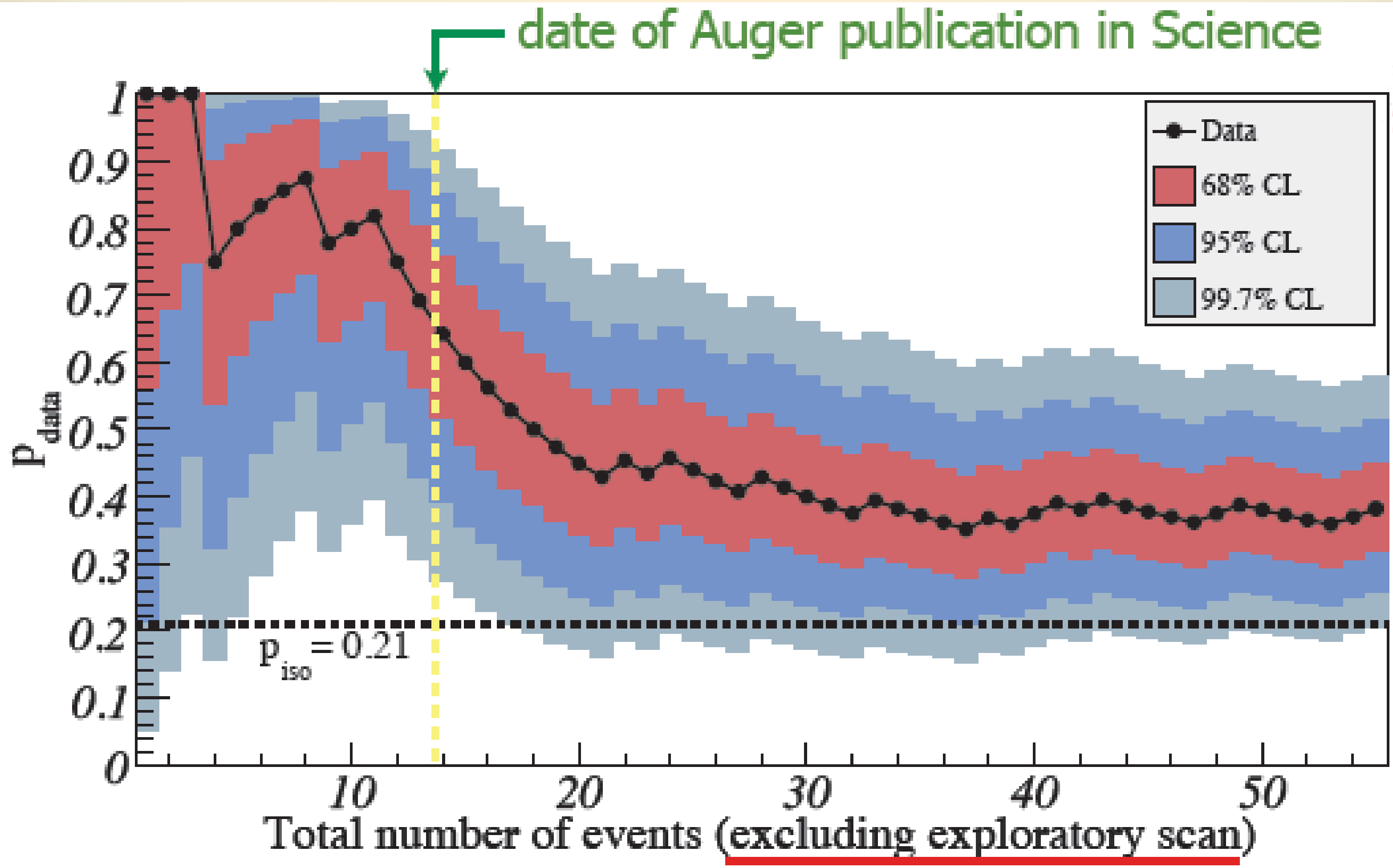
Update

Astroparticle Physics 34 (2010) 314–326



69 events observed (up to 31.12.2009; 20370 km^2 sr y)
14.5 correlations expected if isotropy. 29 observed.

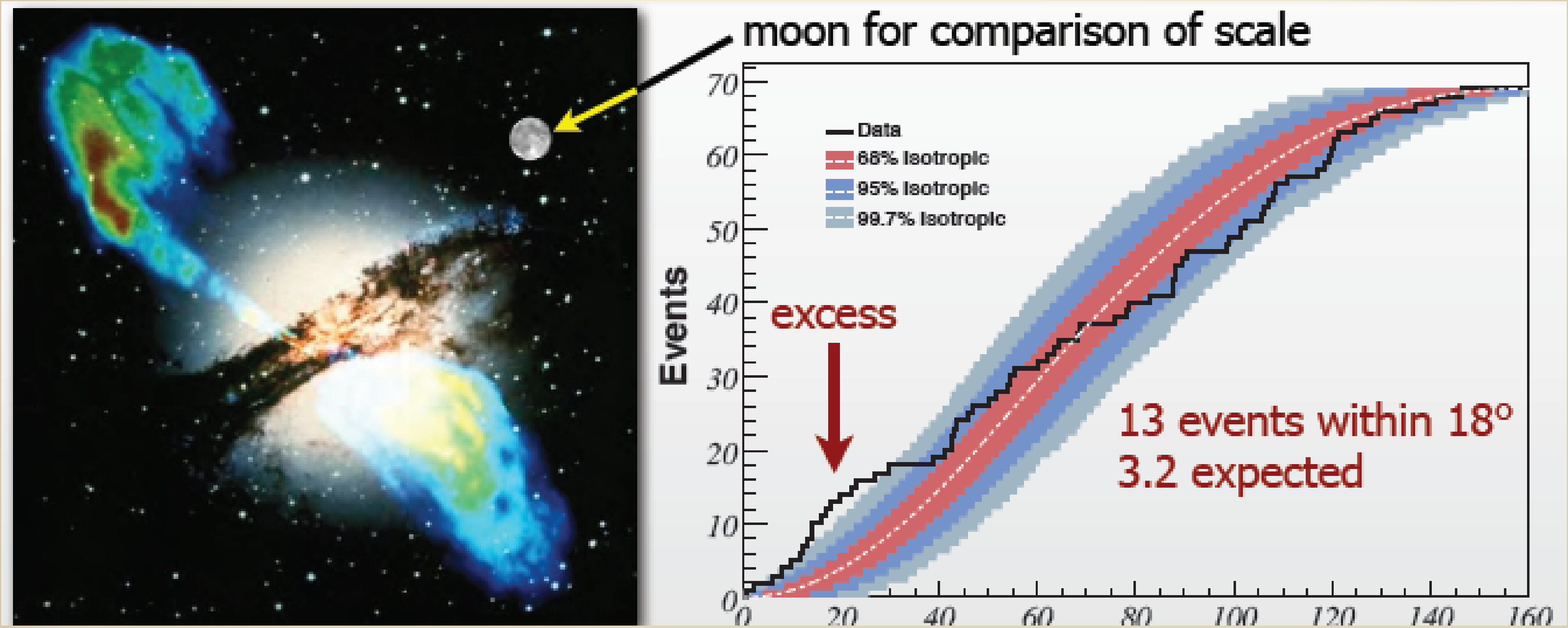
Astroparticle Physics 34 (2010) 314–326



After publication in 11/2007, correlation degree dropped from 69^{+11}_{-13} % (9/13) to 38^{+7}_{-6} % (21/55)

Hot spot

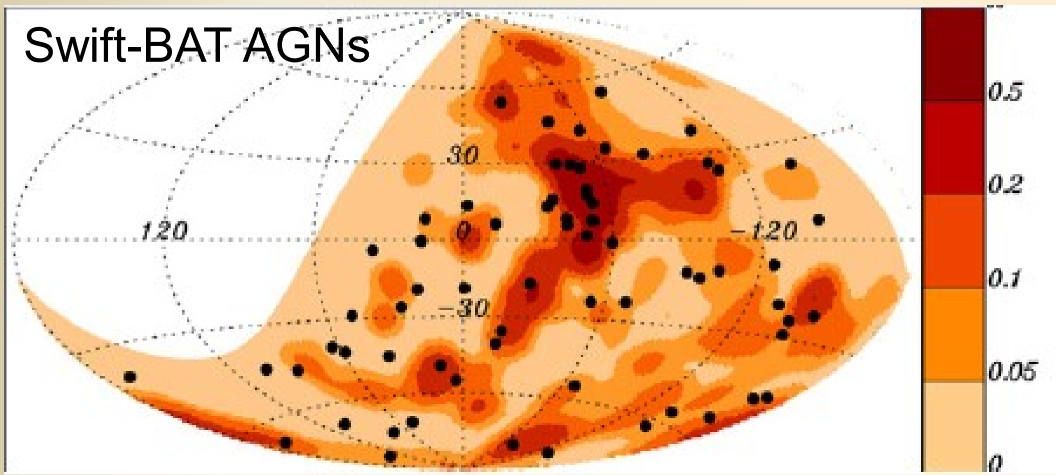
At 3.8 Mpc distance, Cen A is the closest AGN.
Obvious source candidate.



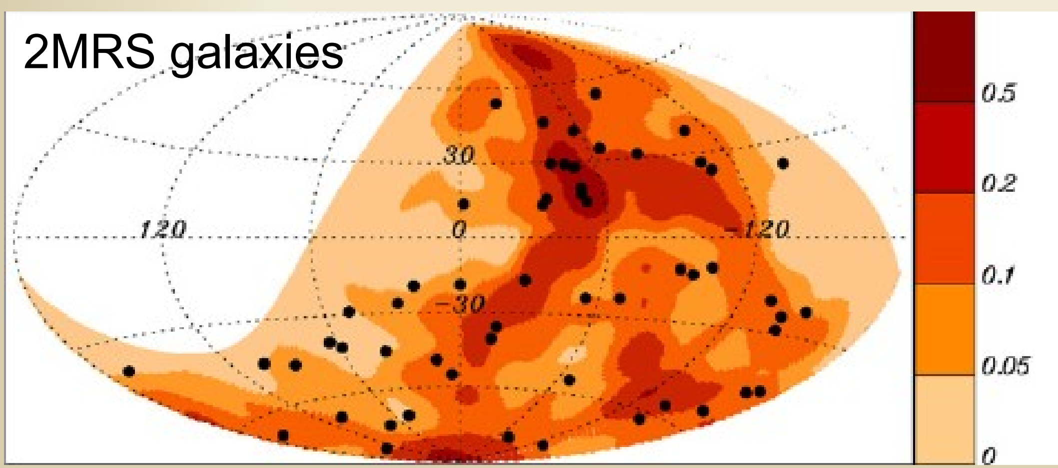
Separation angle (deg)

Astroparticle Physics 34 (2010) 314–326

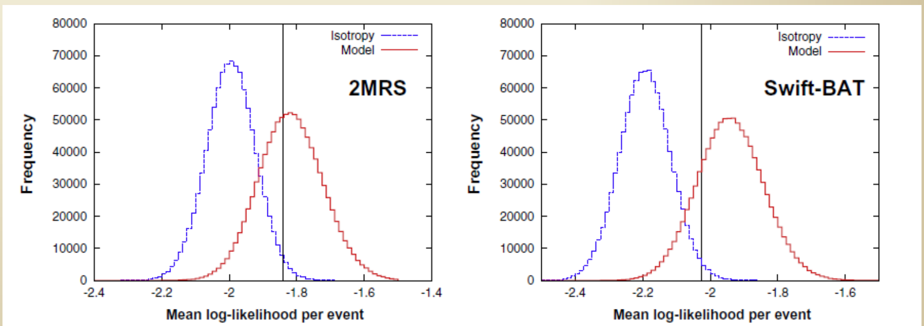
Other catalogs



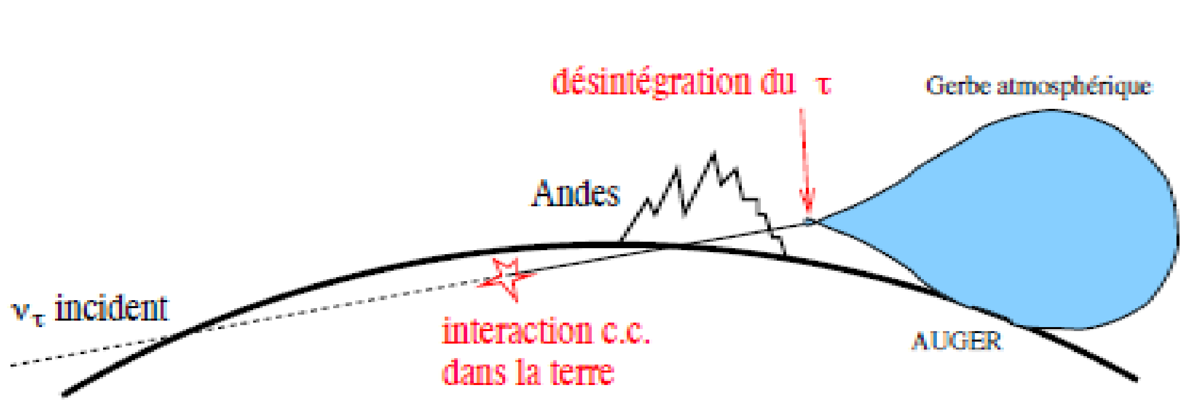
Smoothed maps

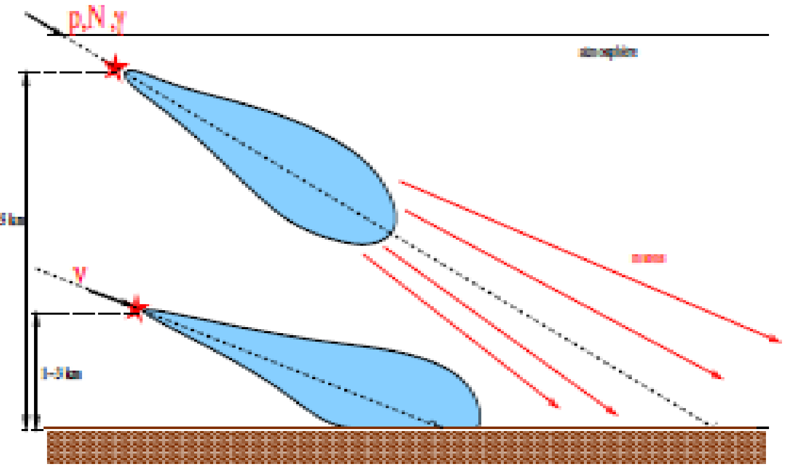


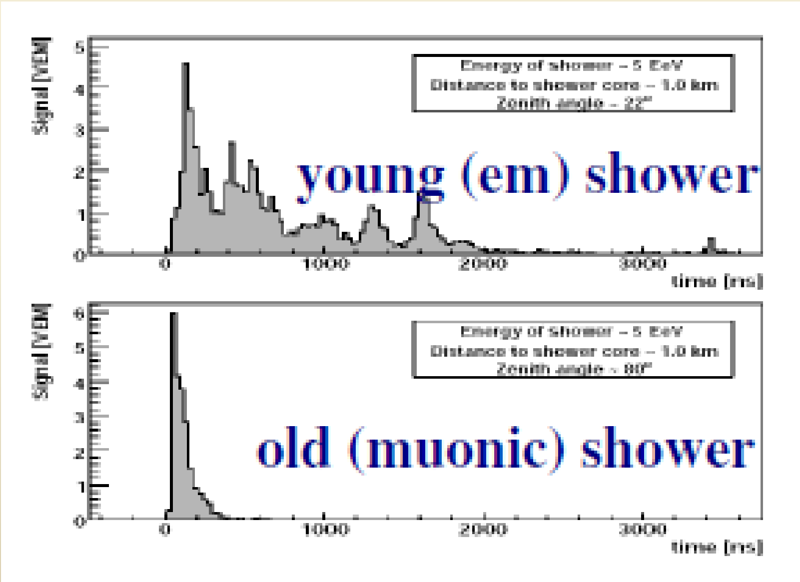
Comparisons with flux limited (unbiased) catalogs show that there **are multiple astrophysical models** of anisotropy arising from the distribution of matter in the nearby universe which are **fully consistent** with the observed distribution of arrival directions.



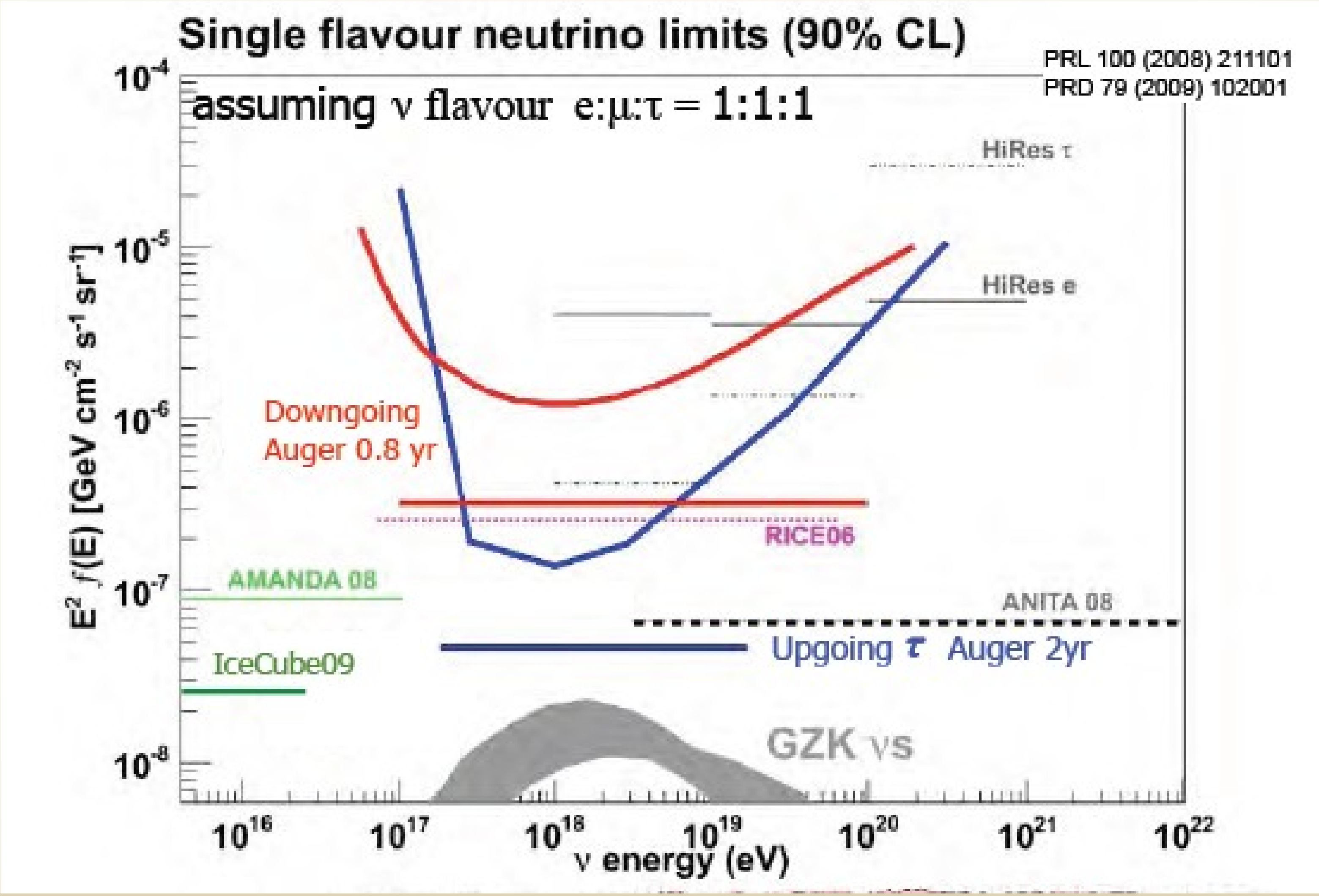
Neutrinos


désintégration du τ
Gerbe atmosphérique
Andes
ν_τ incident
interaction c.c.
dans la terre
AUGER


p,N,γ
γ

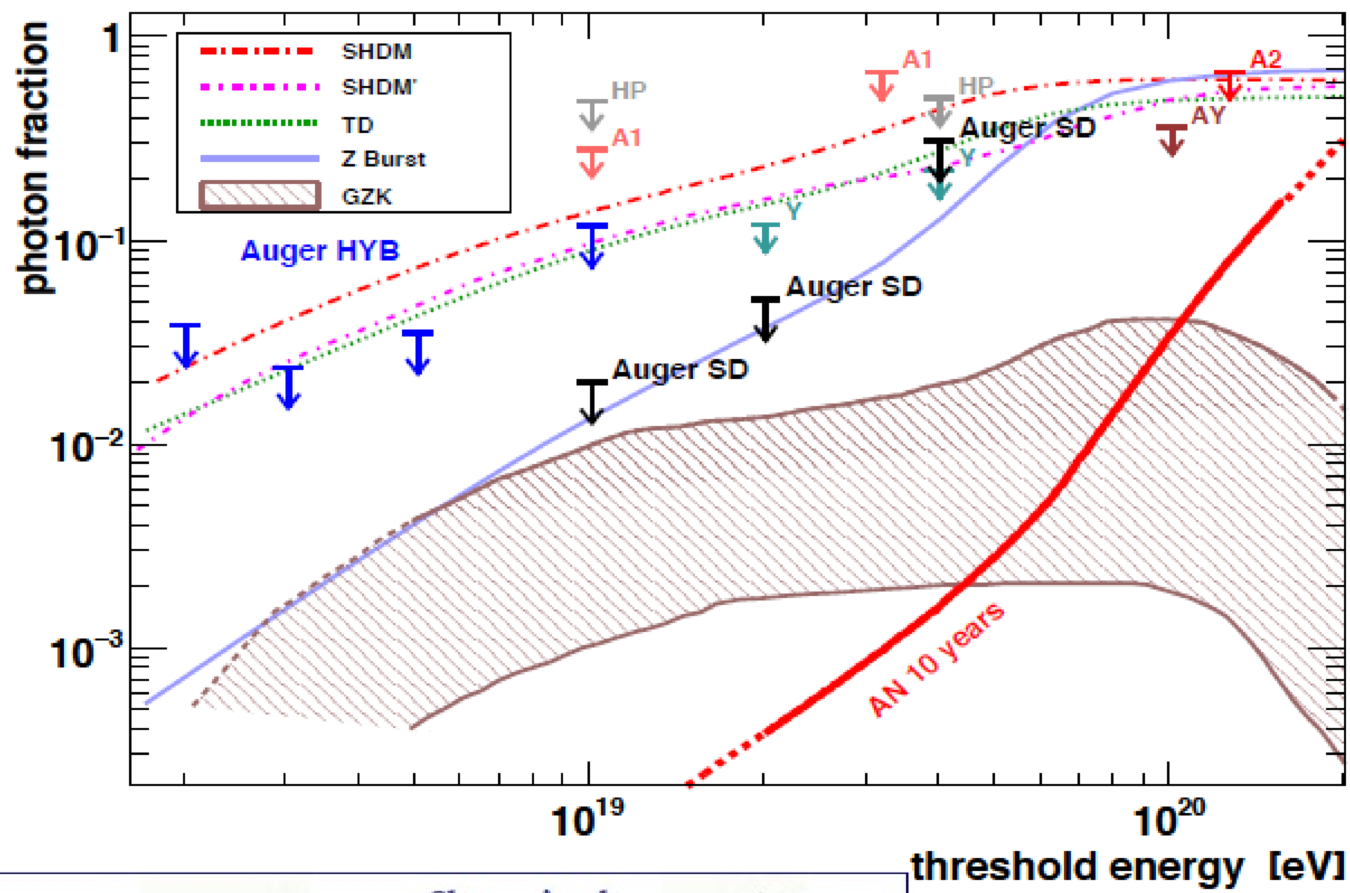

Signal [VEM]
Energy of shower ~ 5 EeV
Distance to shower core ~ 1.0 km
Zenith angle ~ 22°
young (em) shower
time [ns]
Signal [VEM]
Energy of shower ~ 5 EeV
Distance to shower core ~ 1.0 km
Zenith angle ~ 80°
old (muonic) shower
time [ns]

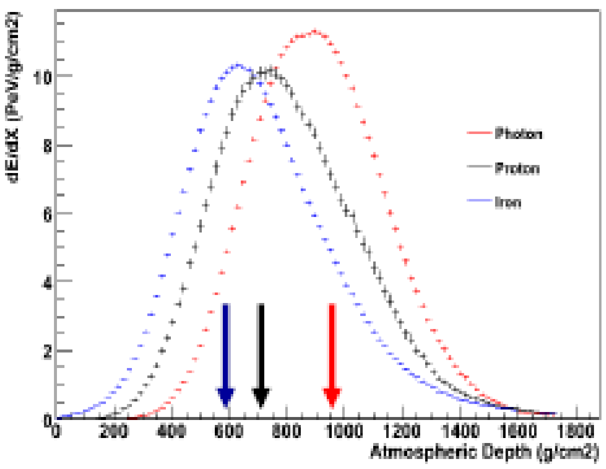
Neutrino Limits

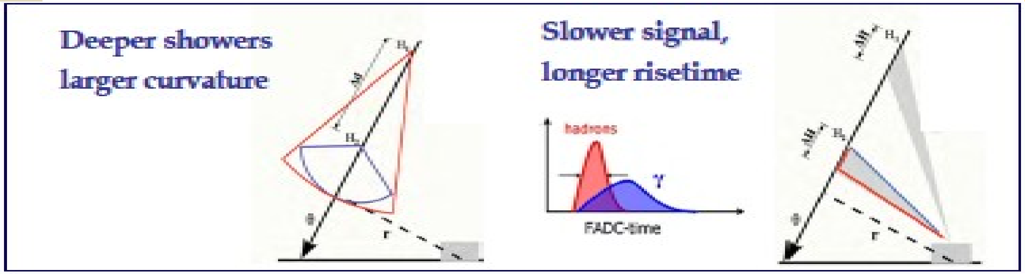


Photon limits

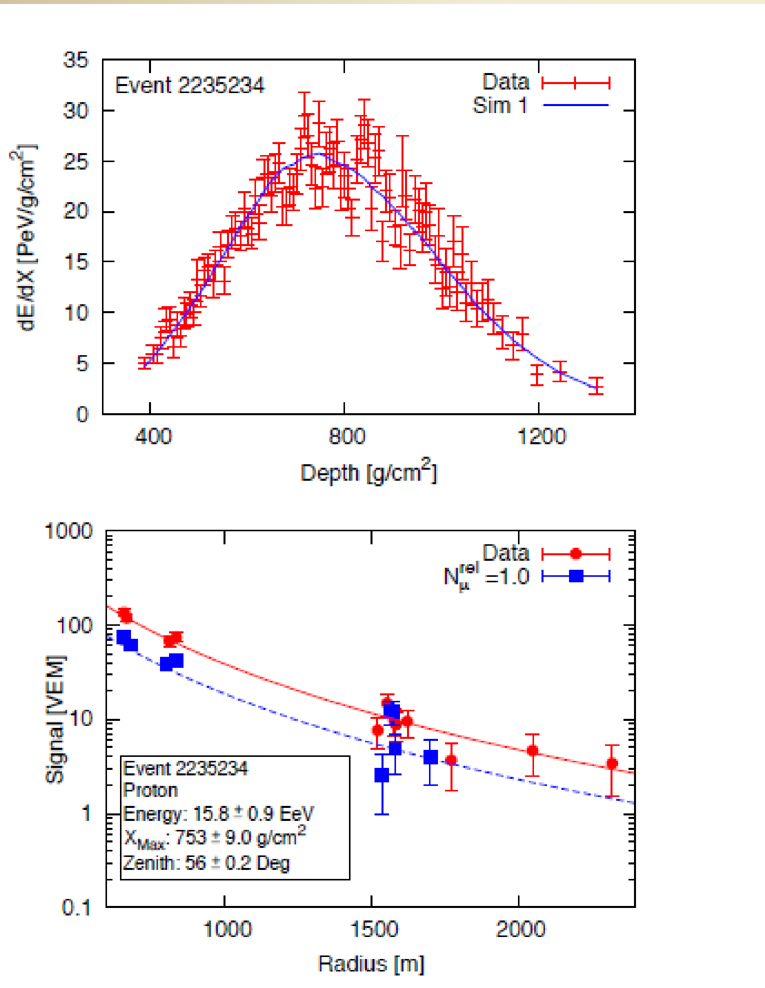
Astropart. Phys. 31 (2009) 399





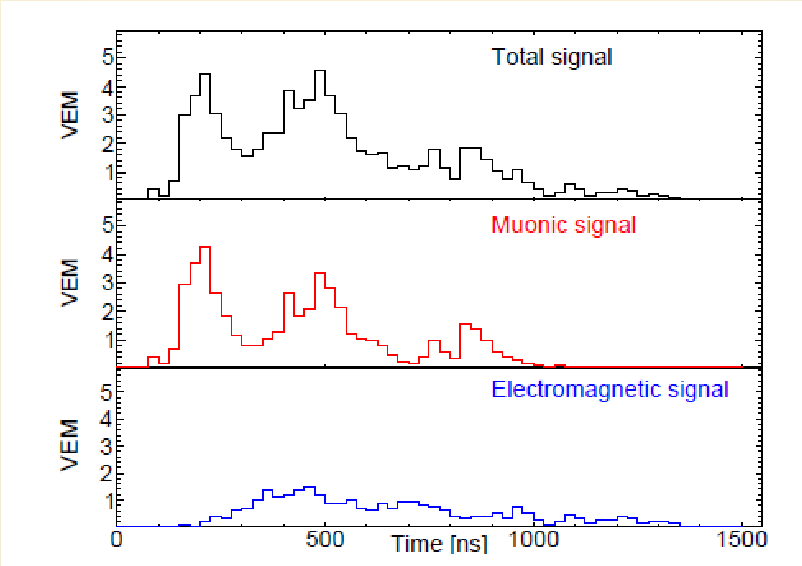


Number of muons



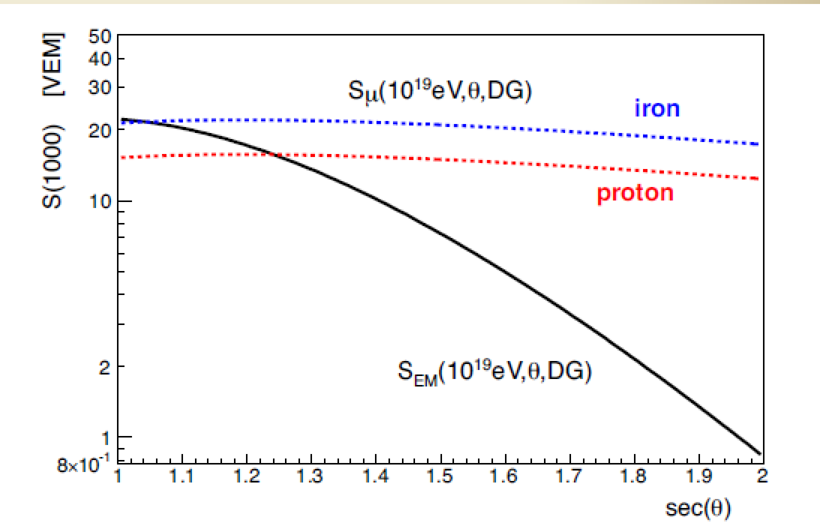
Hybrids

Muon jump



Smoothing

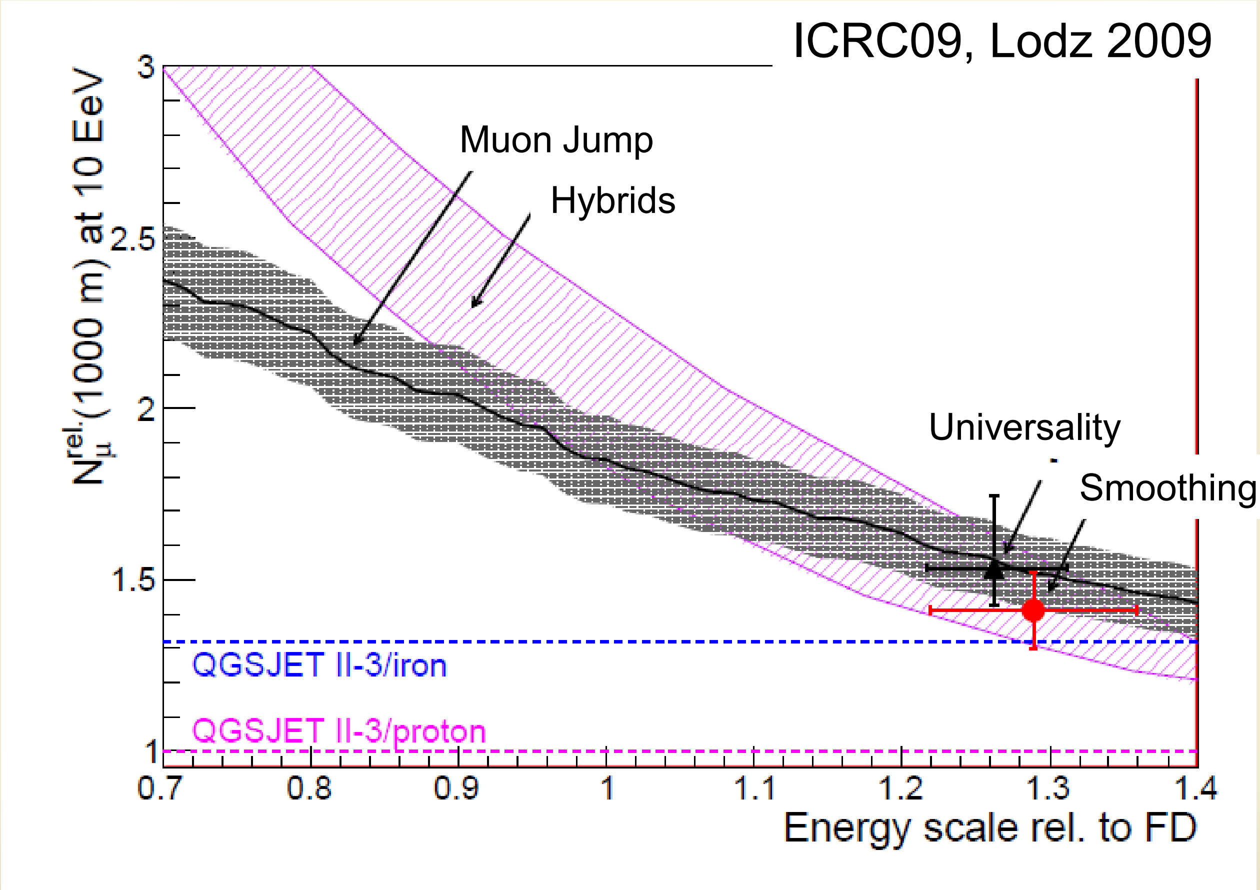
Universality



$$S_{\mathrm{MC}}(E,\theta,<X_{\max}>) = S_{\mathrm{EM}}(E,\theta,DX) + N_\mu^{\mathrm{rel}} S_\mu^{\mathrm{QGSII,p}}(10^{19}\,\mathrm{eV},\theta,DX)$$

L. Cazón

Number of muons



It also implies an energy scaling (different from FD)

$$N_\mu^{\rm rel}(10\ {\rm EeV}) = 1.53^{+0.09}_{-0.07}\,({\rm stat.})^{+0.21}_{-0.11}\,({\rm syst.}).$$

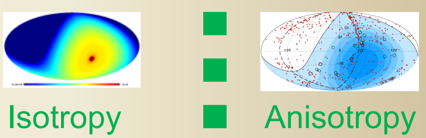
(Universality)

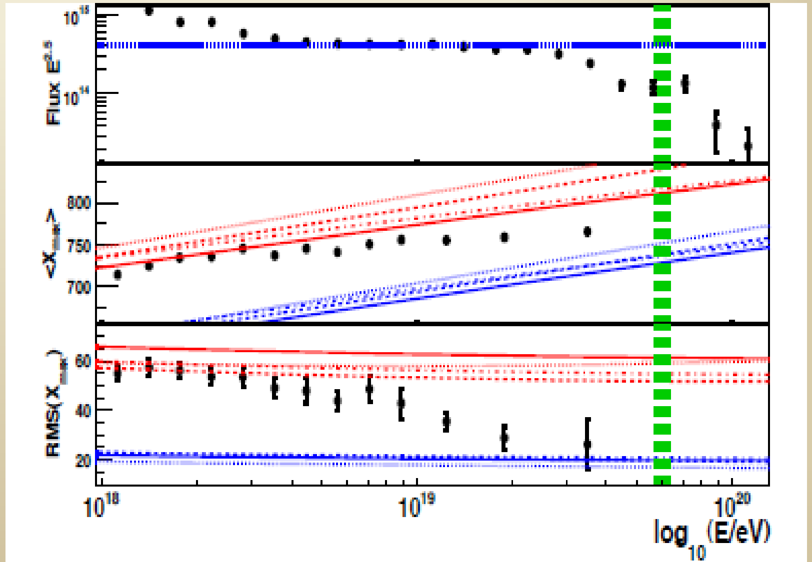
$$E' = 1.26^{+0.05}_{-0.04}({\rm syst.}) \times E_{FD}$$

Conclusions

- Flux suppression of UHECR unequivocally established
  - GZK? Sources running out of power?
- UHECR anisotropy at 99% CL
  - Light primaries? Heavy primaries with weak B? Sources closeby?
- Composition: intriguing results
  - Heavier? Failing models? Cross sections?
- Top down models

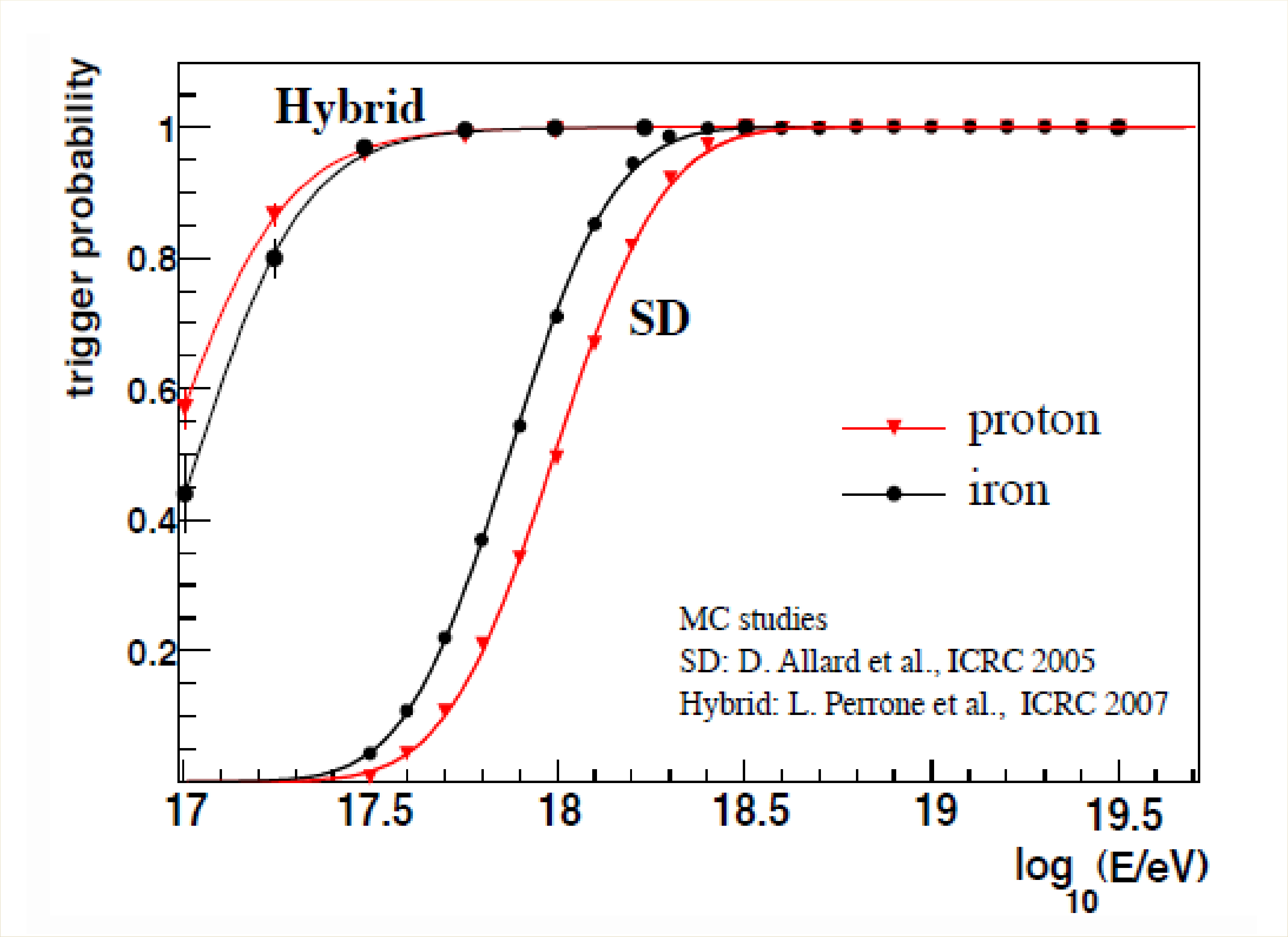
  disfavored



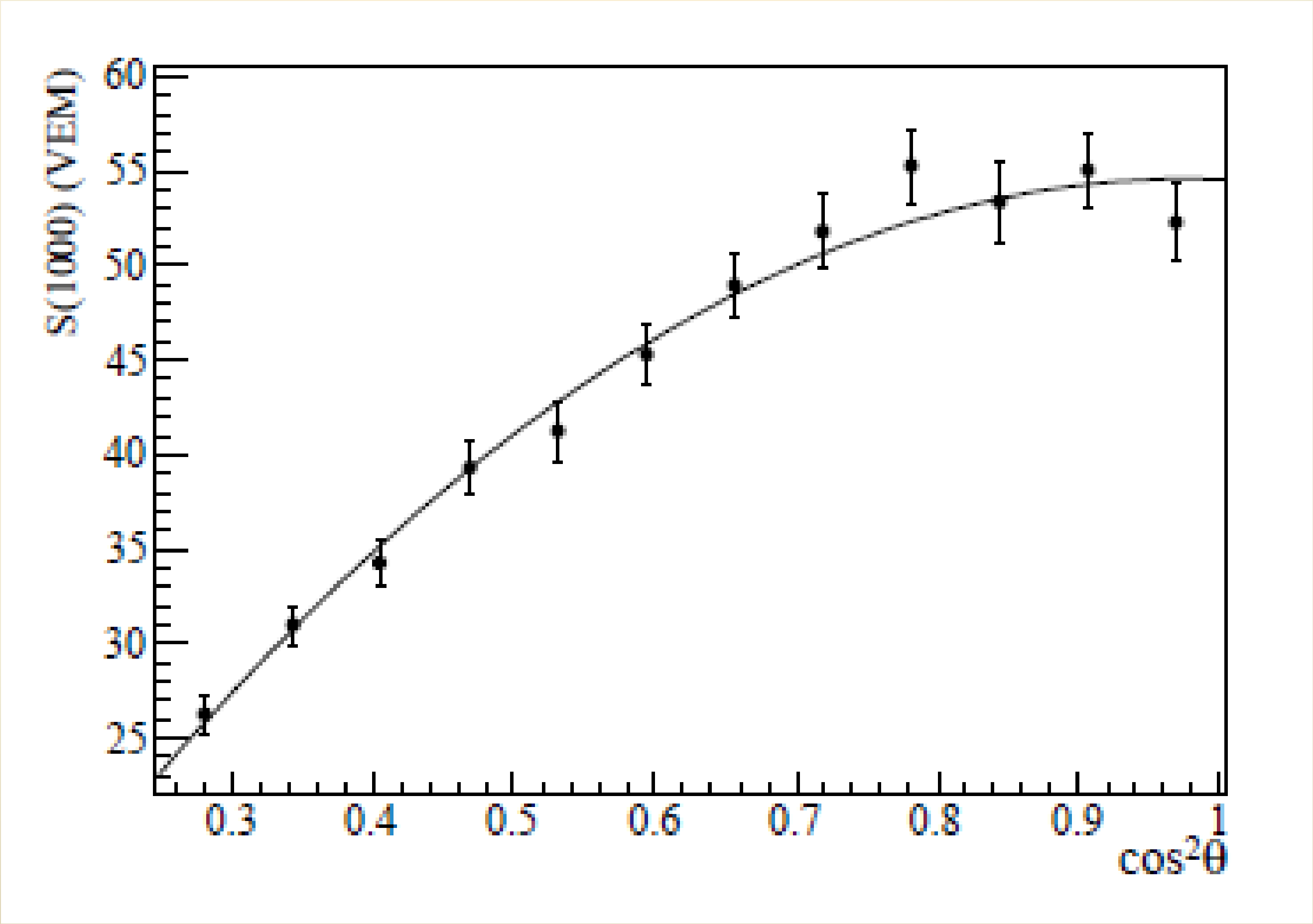


Back up slides

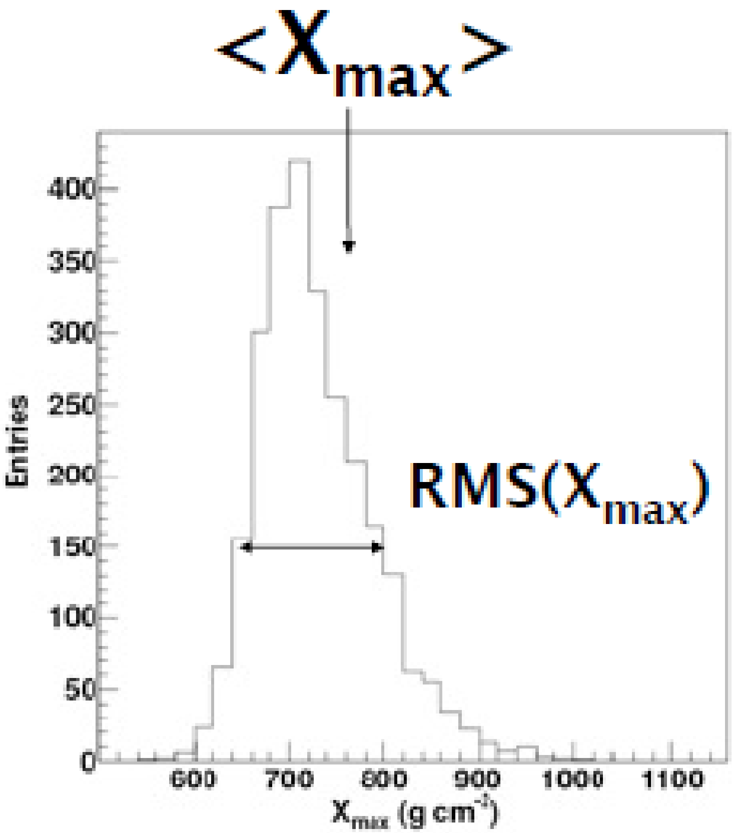
Acceptance

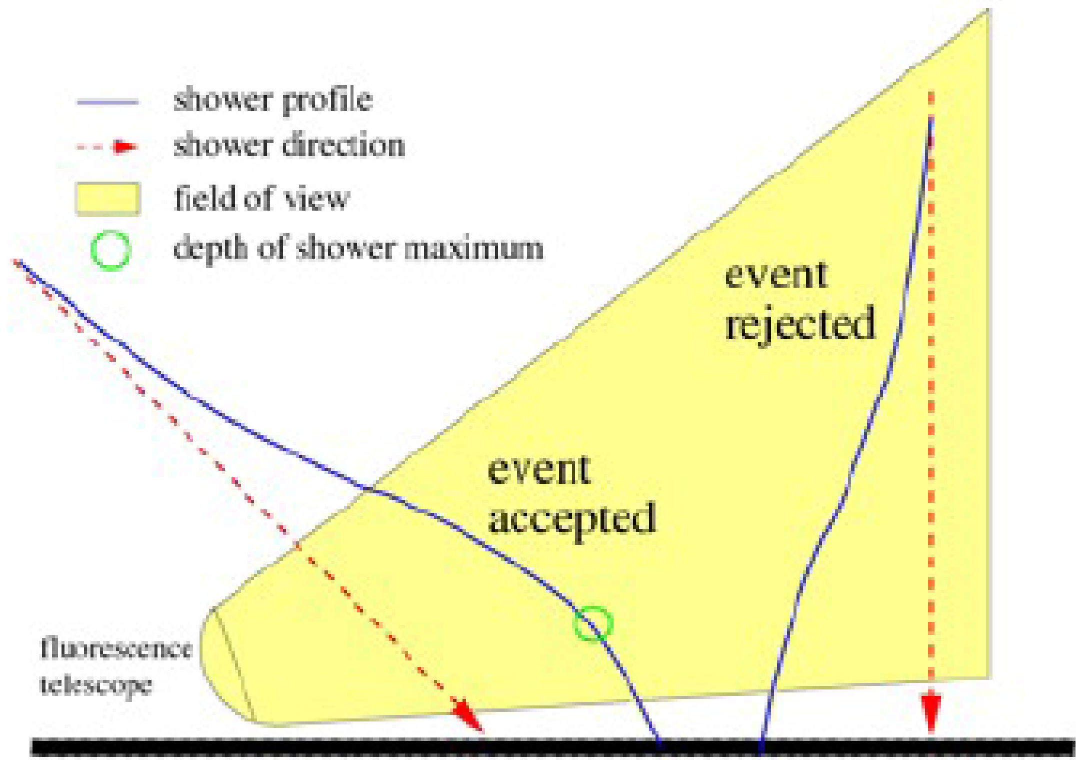

trigger probability
1
0.8
0.6
0.4
0.2
Hybrid
SD
proton
iron
MC studies
SD: D. Allard et al., ICRC 2005
Hybrid: L. Perrone et al., ICRC 2007
17
17.5
18
18.5
19
19.5
log10 (E/eV)

CIC Method



Unbiased reconstruction of X_{max}



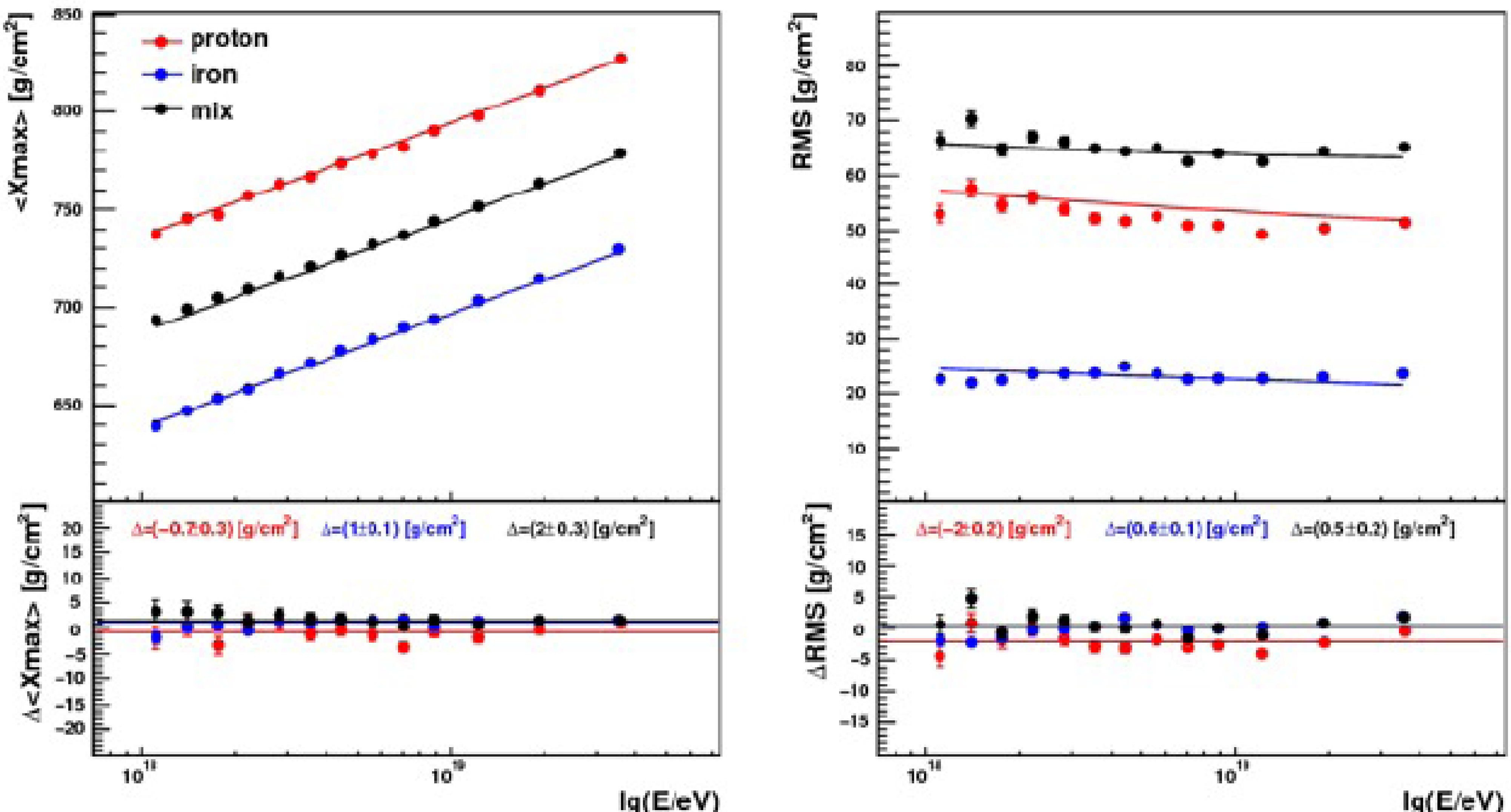


- Ex: X_{max} must be in the field of view to be reconstructed. This could introduce a bias, for ex. by selecting deeper showers close to detector

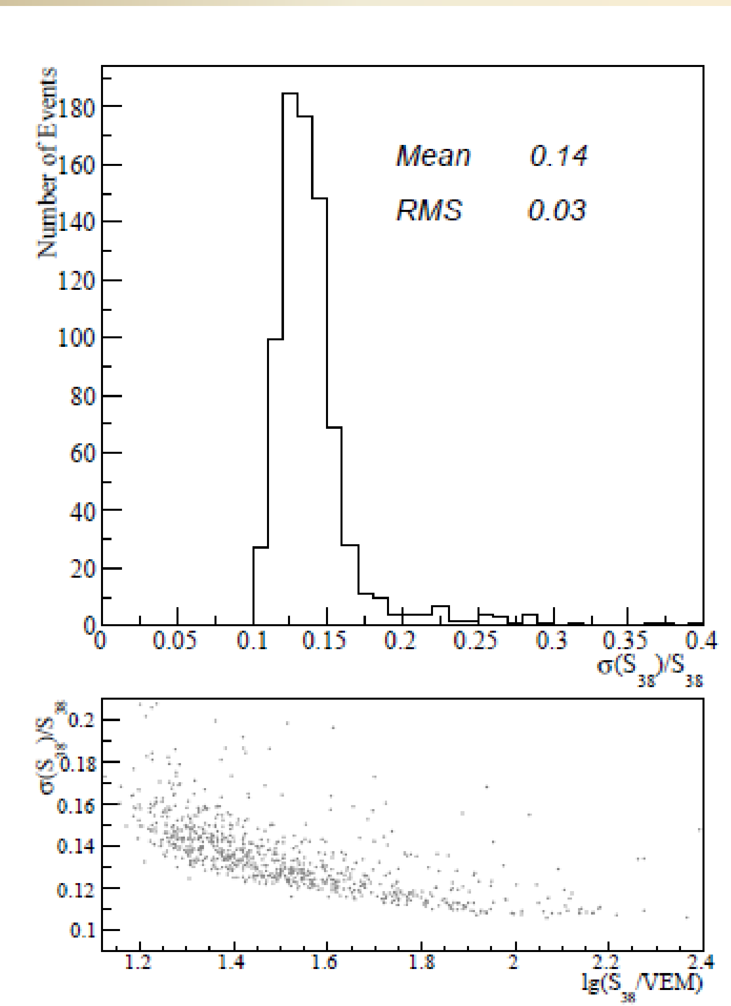
- Auger approach: devise selection criteria which produce an unbiased X_{max} distribution

Monte Carlo Check

Lines corresponds to simulation input to the full detector MC: reconstructed MC data provide unbiased estimate of <X_{max}> and RMS(X_{max})



Resolution SD & FD



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