Recent results from the Pierre Auger Observatory on ultra high energy cosmic rays

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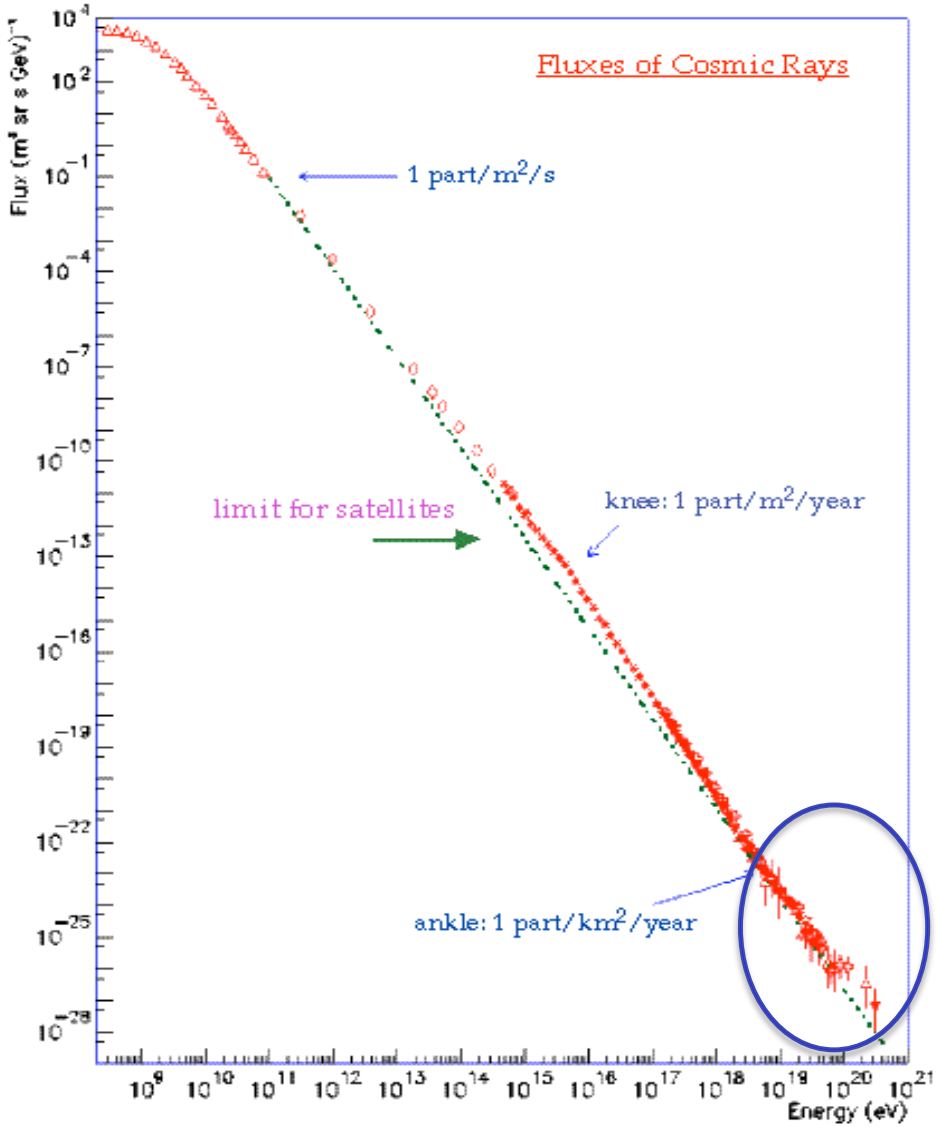
ICGAC10 - Quy Nhon – December 2011

Ultra High Energy Cosmic Rays (UHECR)



UHECR ($E>10^{18}$ eV):

- Extragalactic
- most likely protons or iron nuclei (other nuclei break up)
- Photoproduction threshold on CMB: GZK cut-off (GZK horizon ~75 Mpc)

Main topics:

- Accurate measurement of the high end of the energy spectrum
- Nature of the primaries
- Identification of possible sources
- Acceleration mechanism

UHECRs observed from the extensive air showers (EAS)

Methods:

- sampling the particle density on ground (*surface detector*)
- detecting the fluorescence light (*fluorescence detector*)

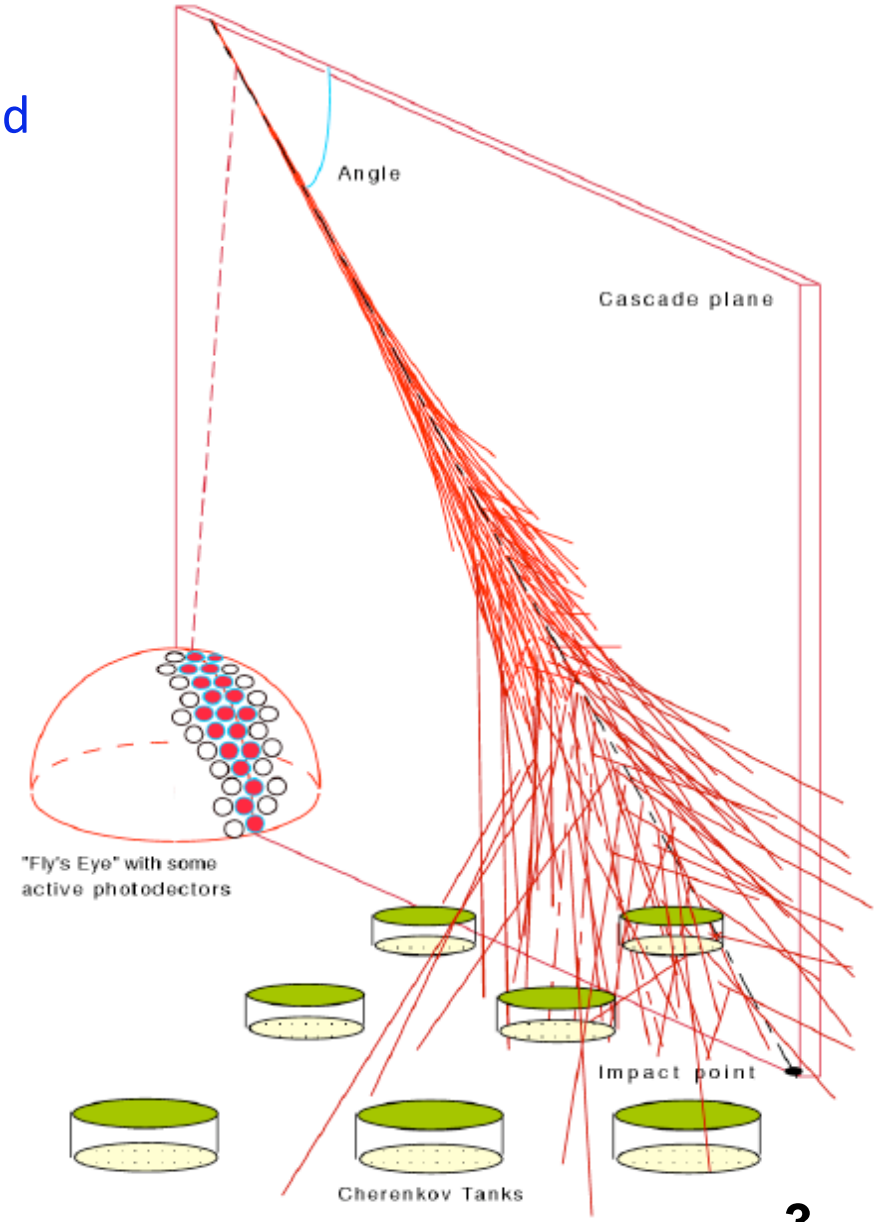
In both cases: timing gives the direction and intensity gives the energy; complementarity, very different systematic errors.

The **Pierre Auger Observatory** is the first large hybrid detector: it combines the strengths of

Surface Detector Array

&

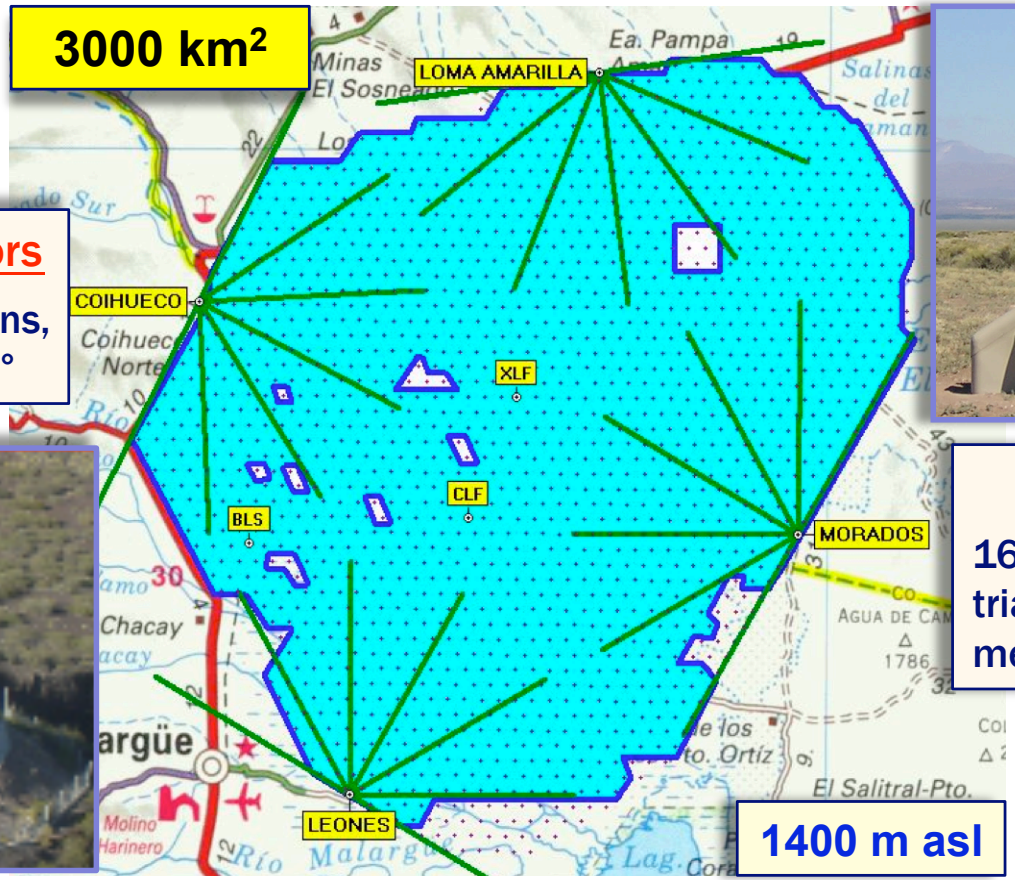
Fluorescence Detectors



Pierre Auger Observatory (PAO)

Located in Mendoza, Argentina

PAO collaboration: 19 countries; VATLY/Vietnam is an associate member



Fluorescence Detectors

24 telescopes in 4 stations, each covering 30°×28°

Surface detectors

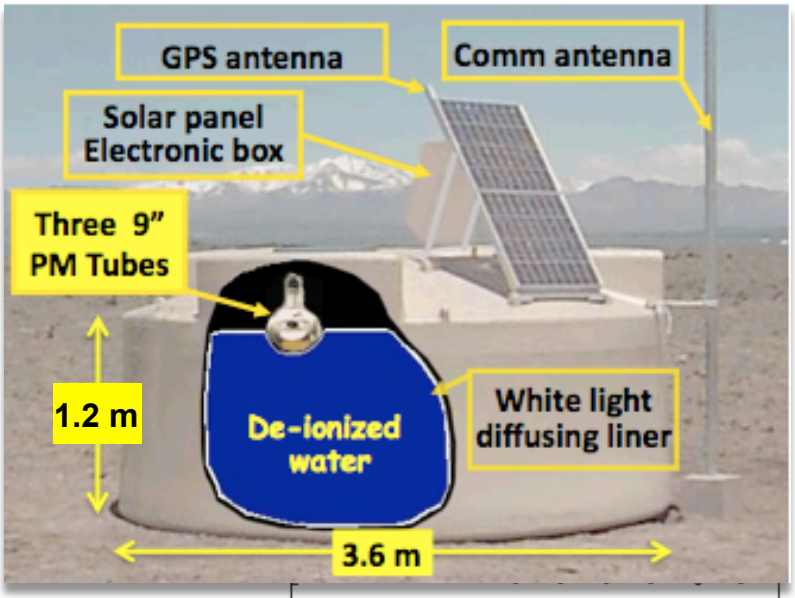
1660 Cherenkov tanks, triangular grid of 1.5 km mesh size.

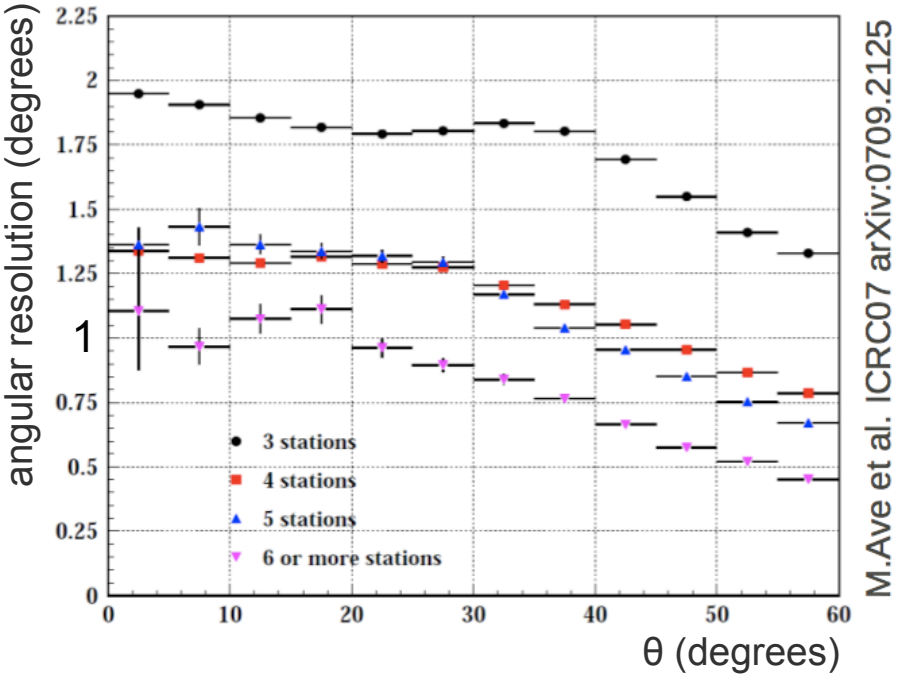
The construction was completed in 2008; progressive data taking since 2004.

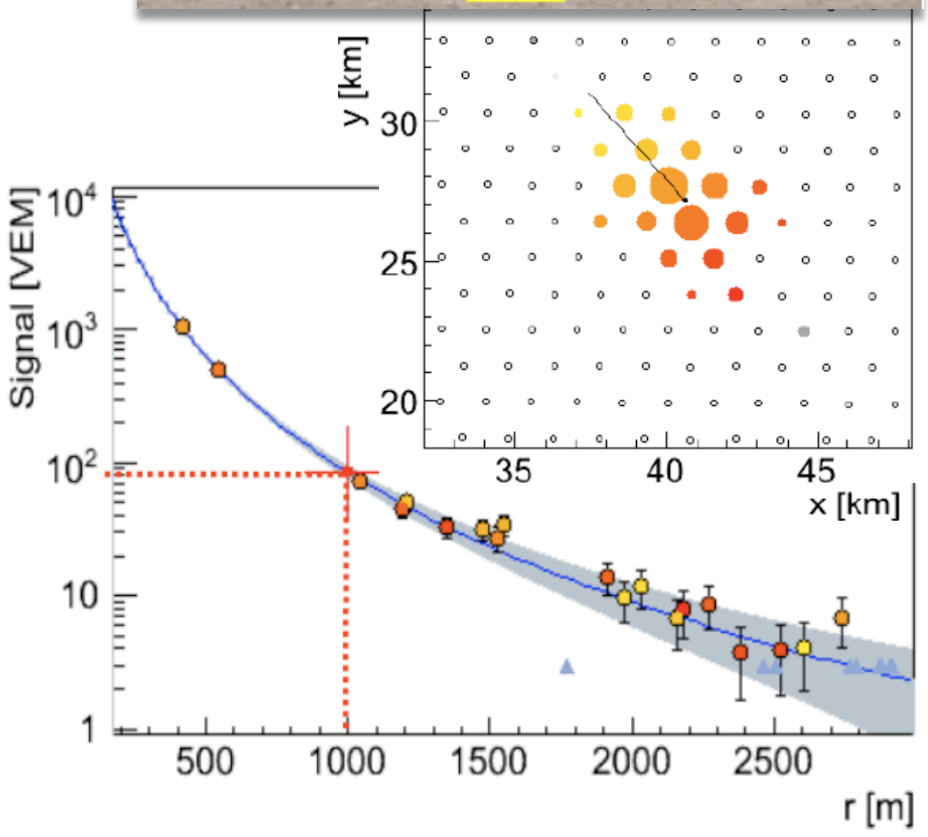
-> accumulated the largest data set with the highest precision

Surface Detectors (SD)

- Huge aperture (easily calculated)
  100% duty cycle
- Direction from tank hit times;
  good angular resolution (~1°)
- Energy measured to ~15% resolution,
  referred to the signal at 1000m
  from the shower core S(1000)

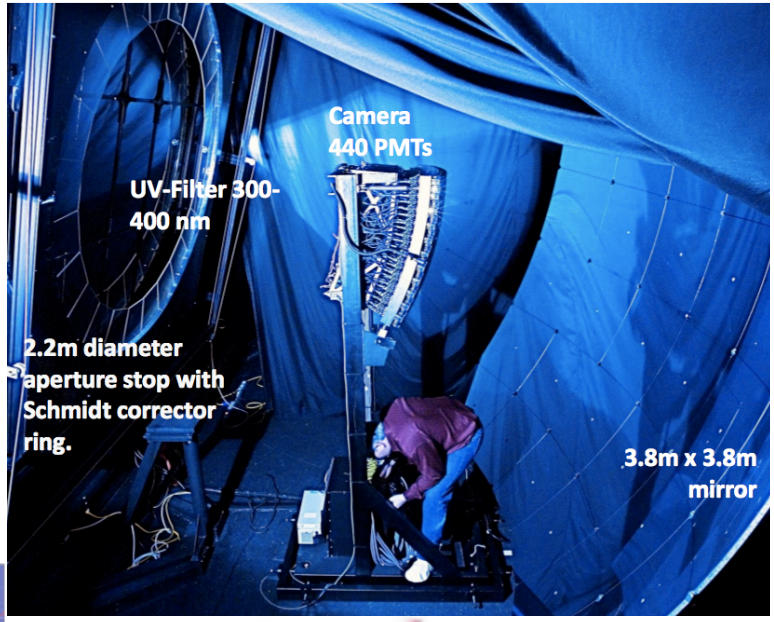


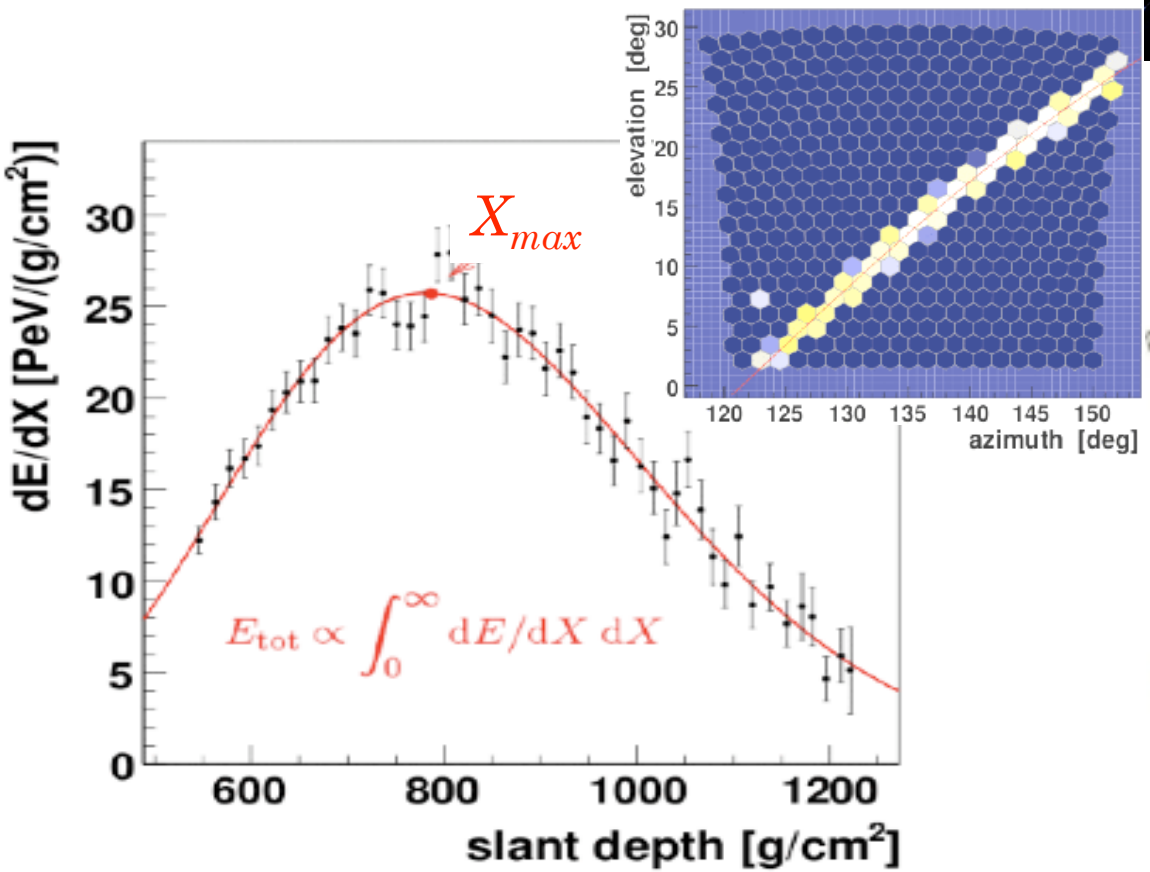


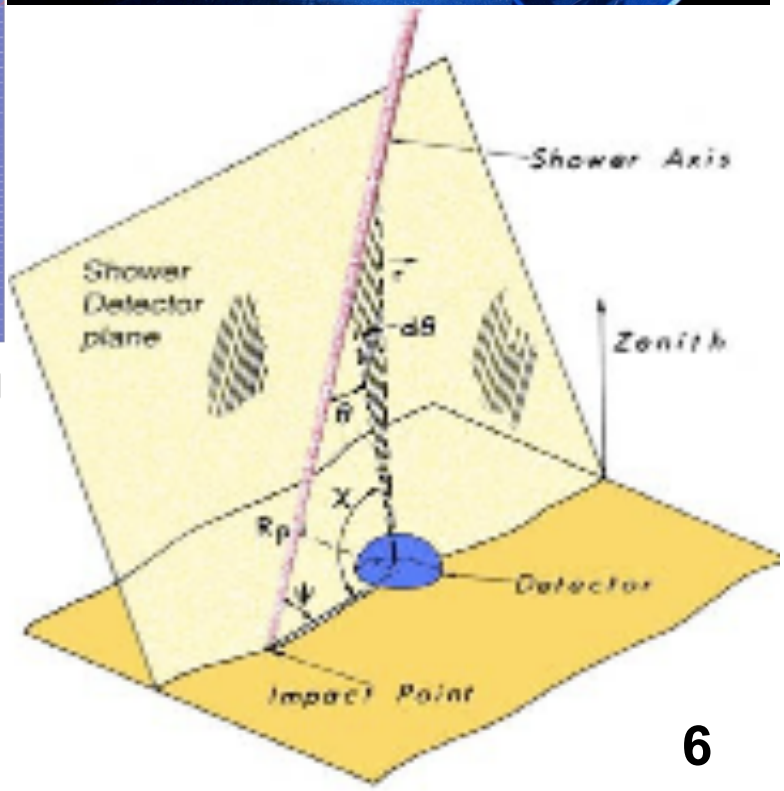


Fluorescence Detectors (FD)

- clear moonless nights: ~13% duty cycle
- precise directions (stereos or hybrids)
- a direct view of shower maximum
- near calorimetric energy measurements from integrated longitudinal profile.



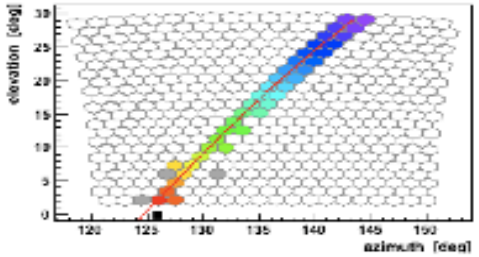


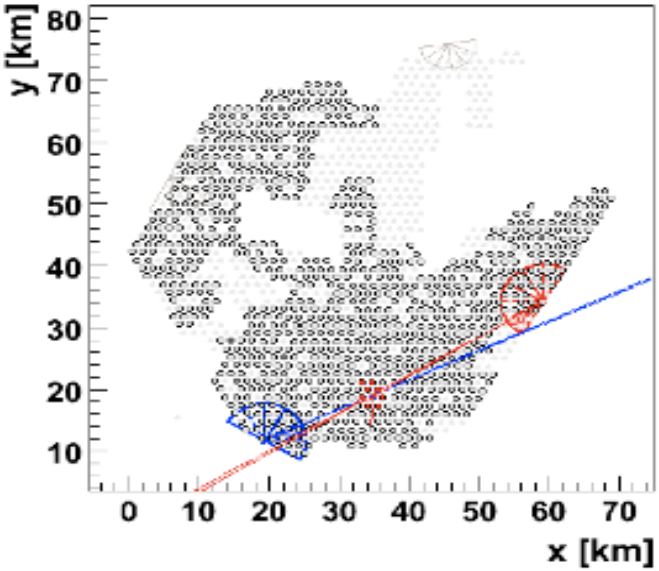


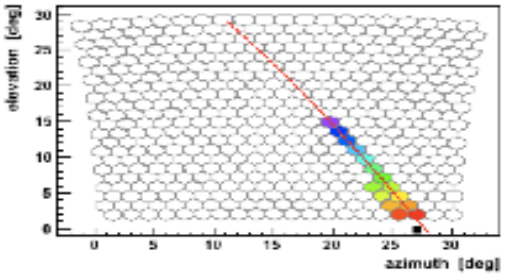
Hybrid events

essential for energy calibration and X_{max} measurement

E=(1.88±0.14) x 10^{19} eV





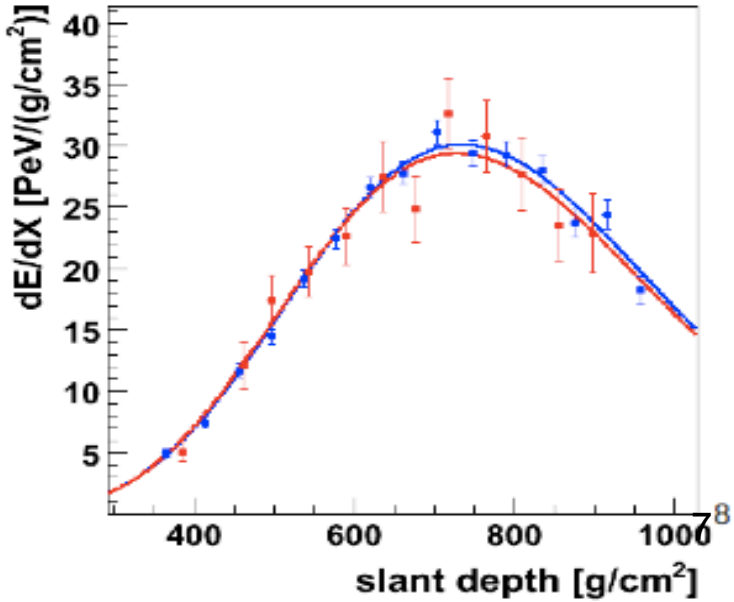


E=(1.85±0.19) x 10^{19} eV

(Statistical error, including contributions from geometry, atmosphere)

Stereo events: X_{max} *independently measured by each station*

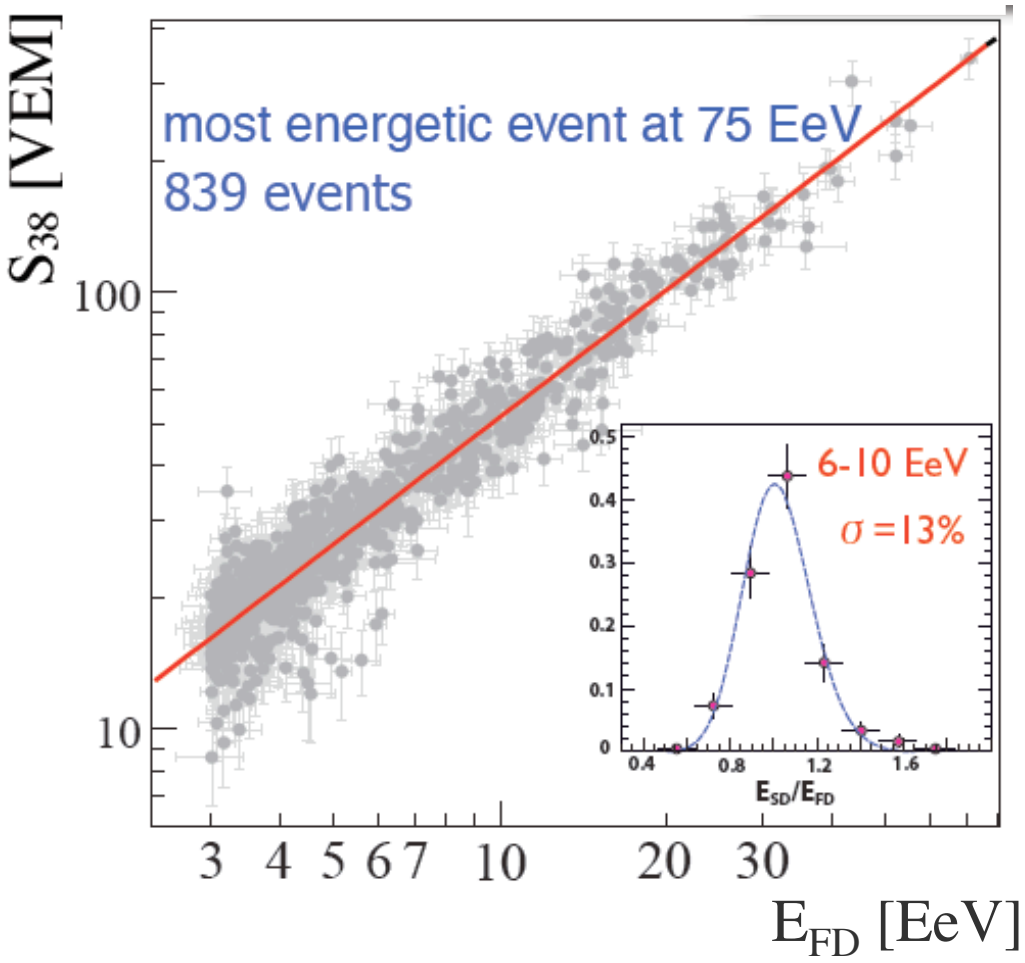
-> Comparing X_{max} values: typical resolution ~20g/cm^2 (at 10^{19} eV)



Event 2412881 30 June 2006

Energy calibration of the array

Uses a **subset of high quality hybrid events** ($\chi^2 < 2.5$ for the longitudinal profile fit, depth of maximum in the field of view, etc....) and the SD energy estimator S(1000) referred to 38° zenith angle, S_{38}.



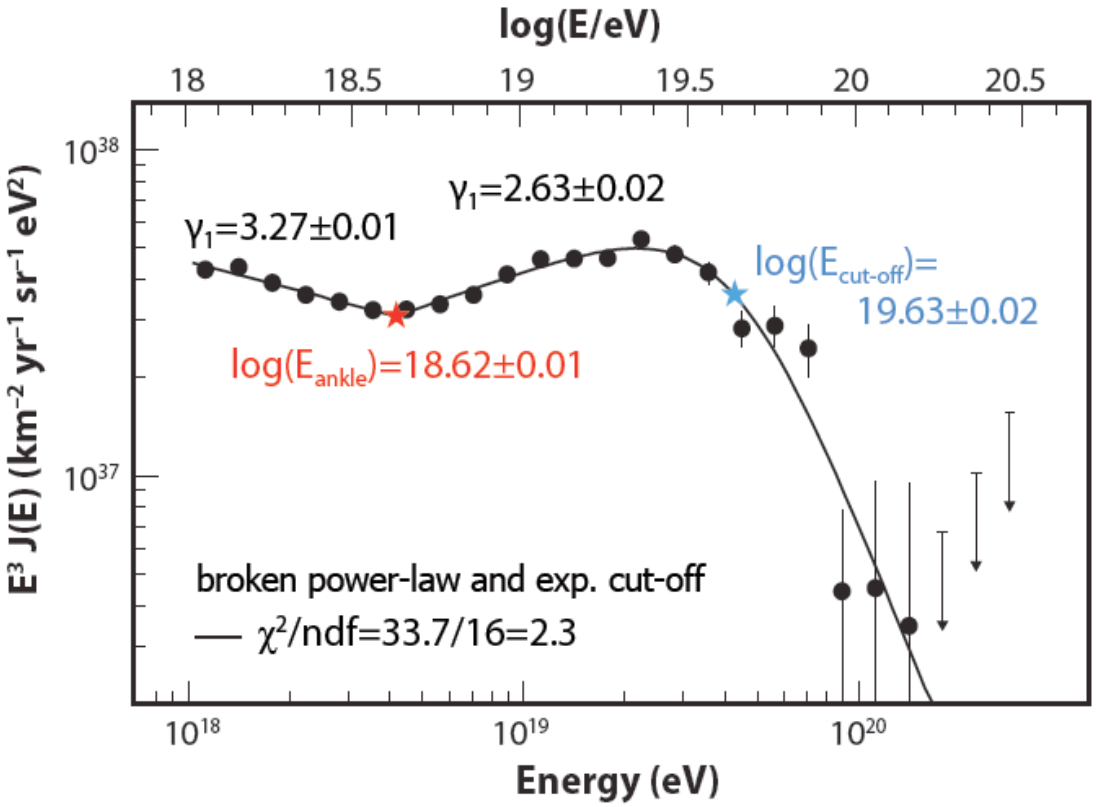
$$E_{FD} = a\, S_{38}^{b}$$

$$a = 1.49 \pm 0.06(stat) \pm 0.12(syst)$$

$$b = 1.08 \pm 0.01(stat) \pm 0.04(syst)$$

Total *E* uncertainty: 22%

Energy spectrum



Spectrum includes full statistics available

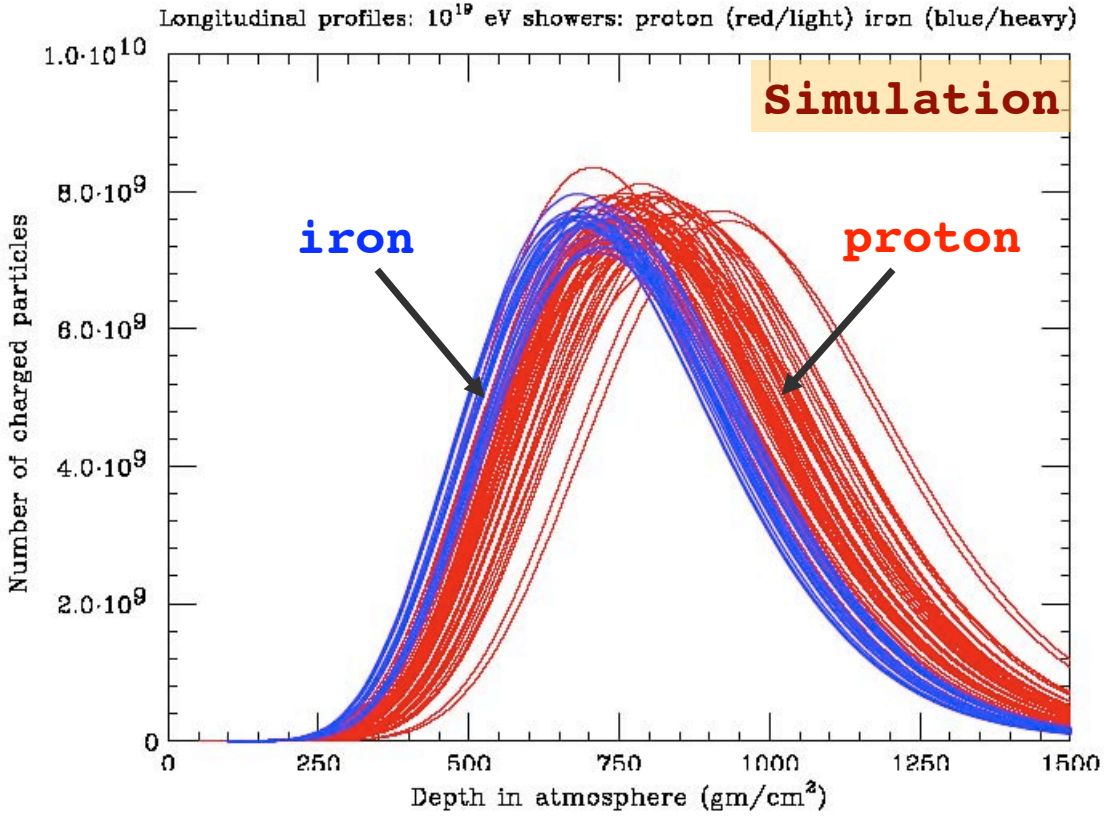
- A clear suppression is observed at E > 4 10^{19} eV, consistent with GZK cut-off
- Iron and proton hypotheses predict very similar cut-offs
- Hypothesis of a single power law is rejected to better than 6 sd
- Sudden change of slope at 4 10^{18} eV (ankle) usually associated with the galactic to extragalactic transition

Depth of Shower Maximum X_{max}

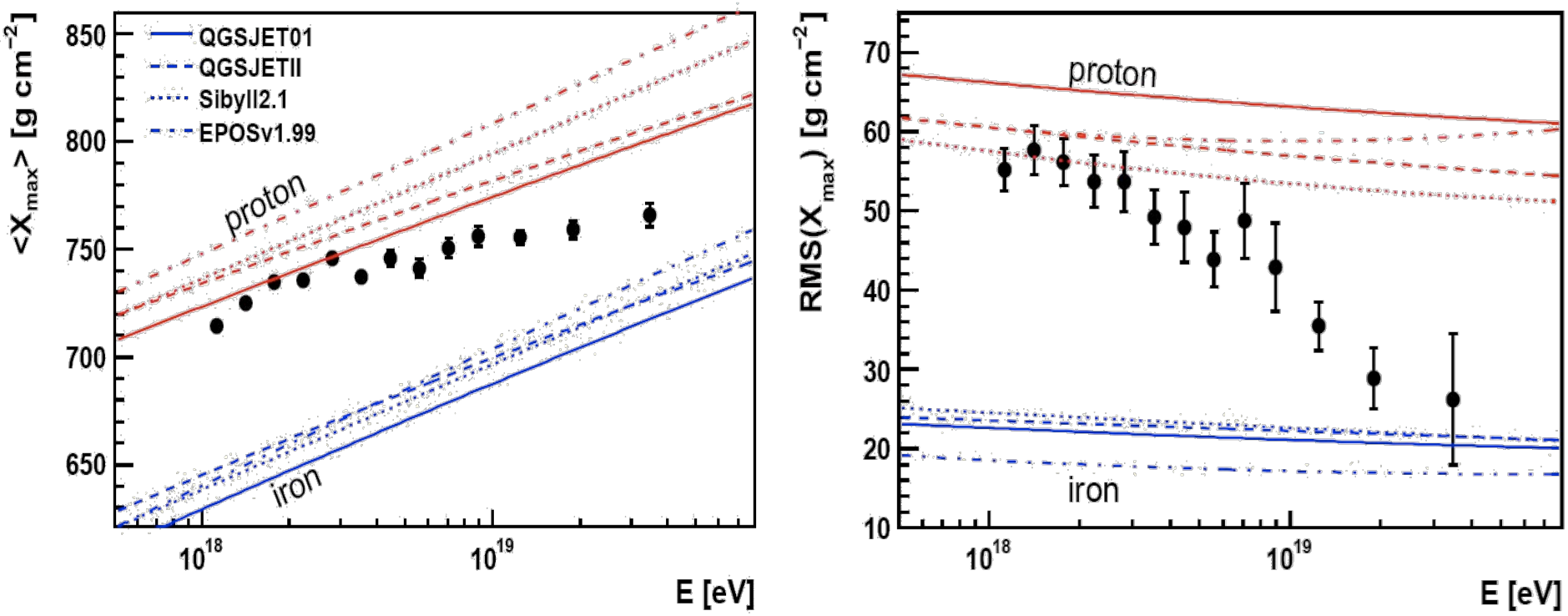
Uses high quality hybrid events: E> 10^{18} eV, light emission angle towards the FD < 20°, X_{max} in the field of view, good fit to the longitudinal profile, etc...

After all cuts: 6744 events are selected for the X_{max} analysis

Main interest is to distinguish between proton and iron primaries



X_{max} measurement



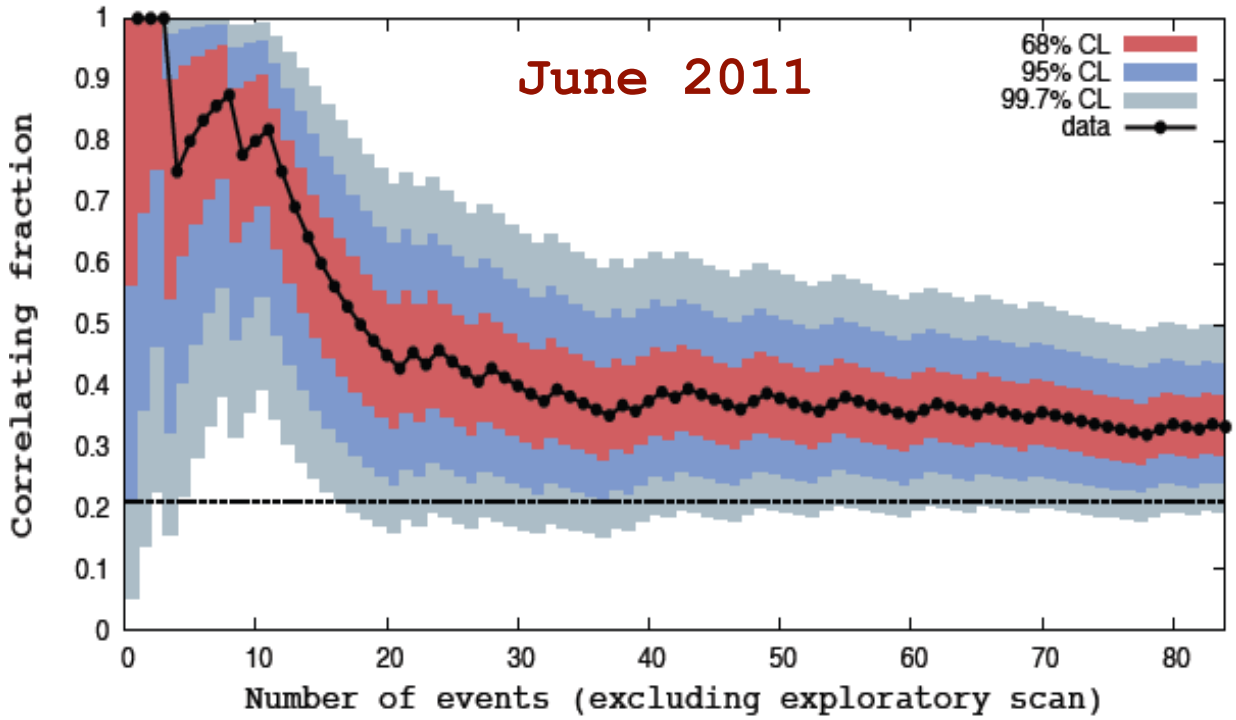
Clear trend to higher primary masses when energy increases

Interpretation in terms of a simple p-Fe mixture currently inconclusive

Anisotropy

Select UHECRs having $E > 55$ EeV and pointing back within 3.1° to a VCV catalogue nearby galaxy (<75 Mpc, GZK horizon):

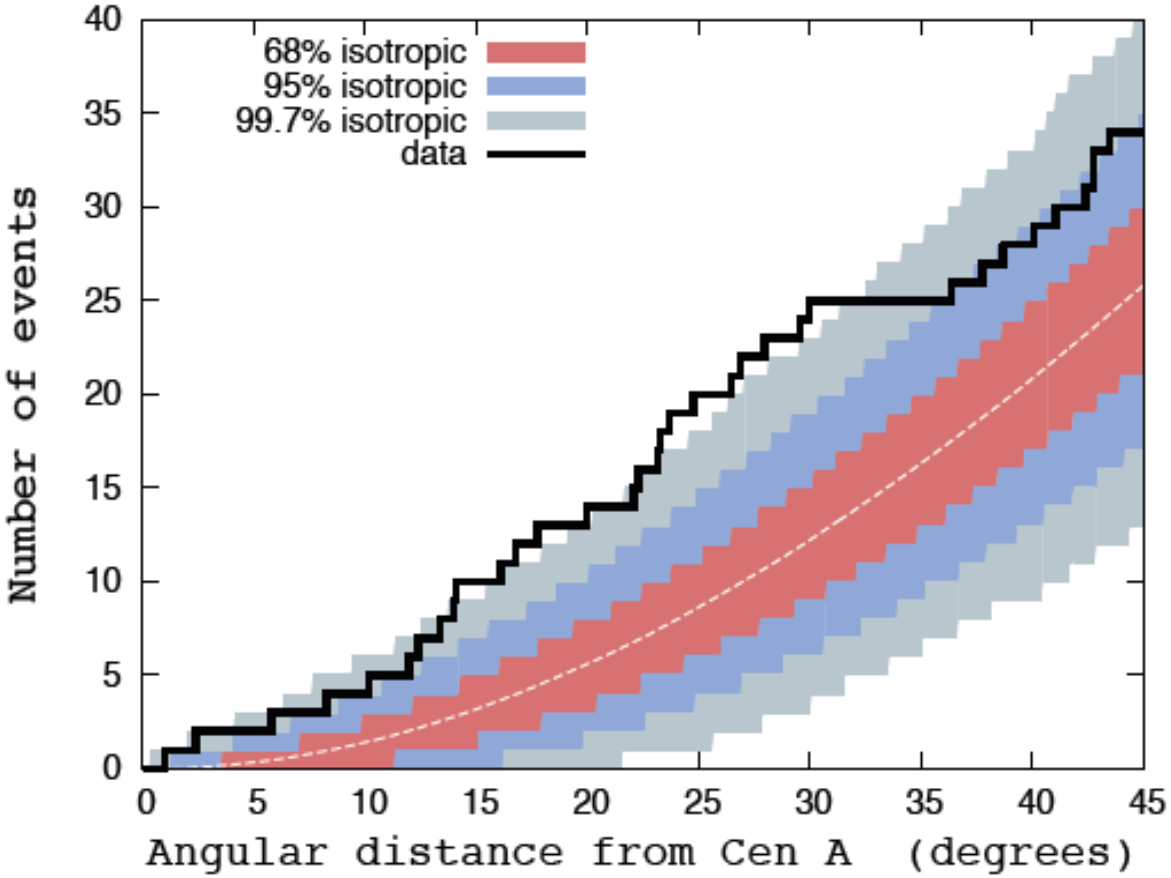
28 correlating events out of 84, 33 ± 5%

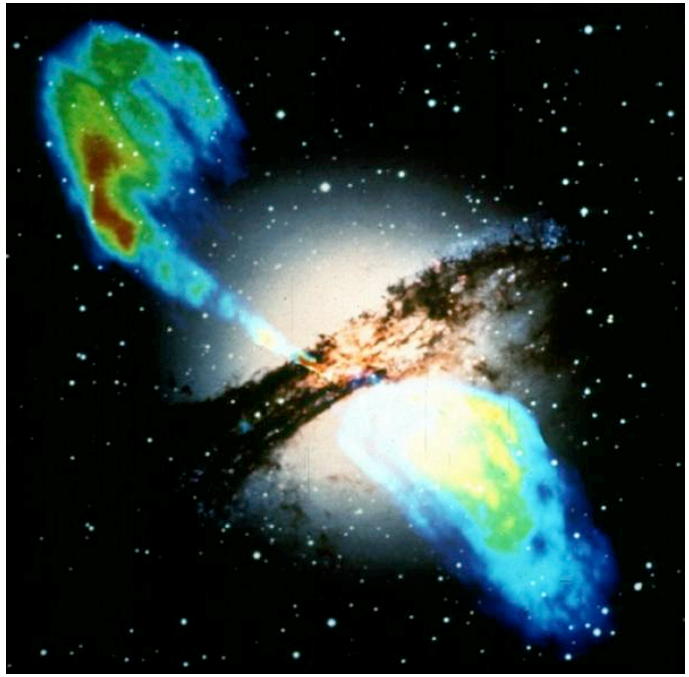


In 2007, there were 18 correlating events out of 27. Present data indicate that only 9 should have been expected.

Possible systematic effects have been searched for without success, implying an important statistical fluctuation.

Possible excess of events toward Centaurus A





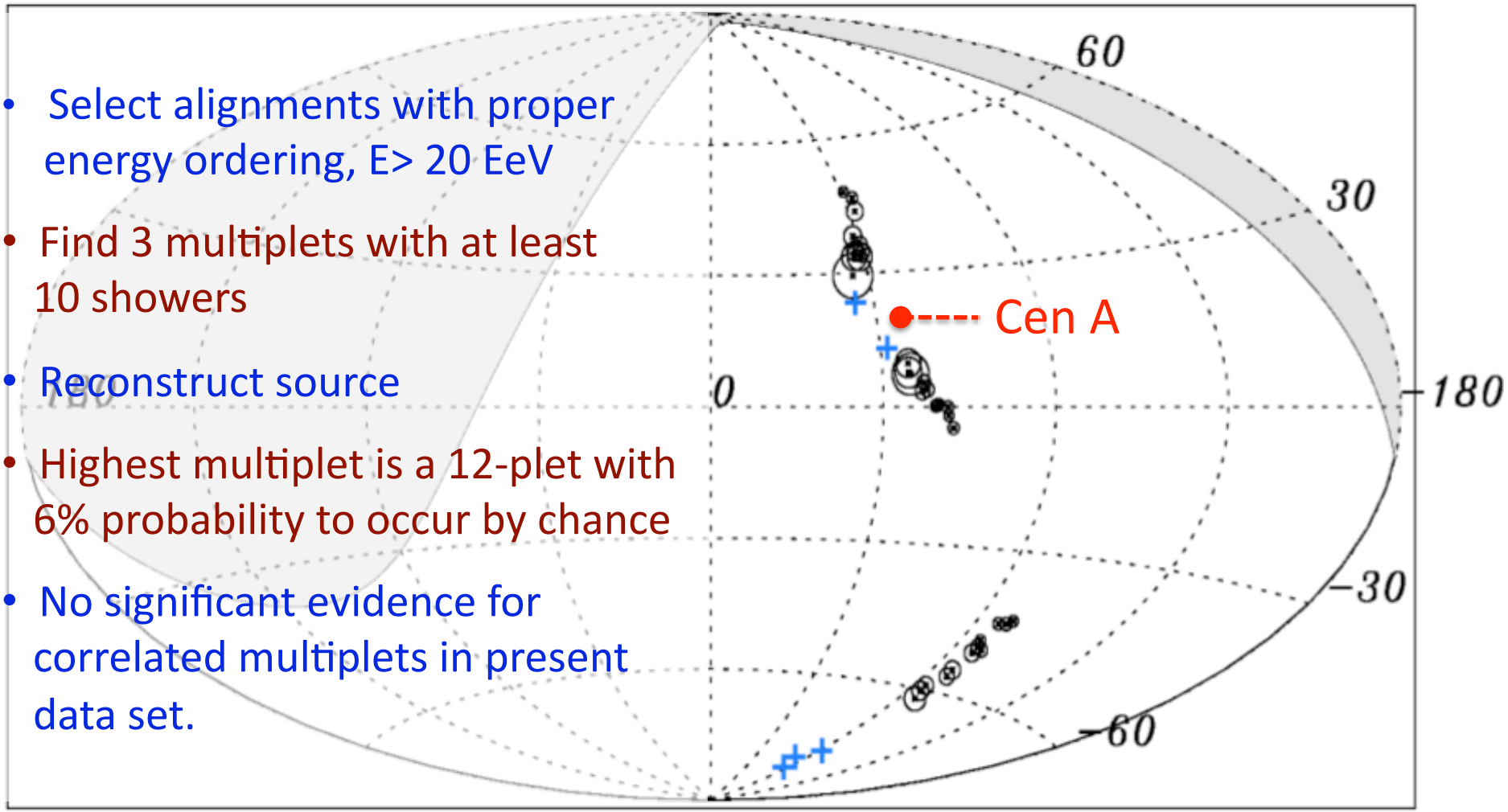
Cen A, colliding elliptic and spiral galaxies, contains in its centre the nearest AGN to Earth

Largest departure now at 24^{o} : 19 observed/ 7.6 expected

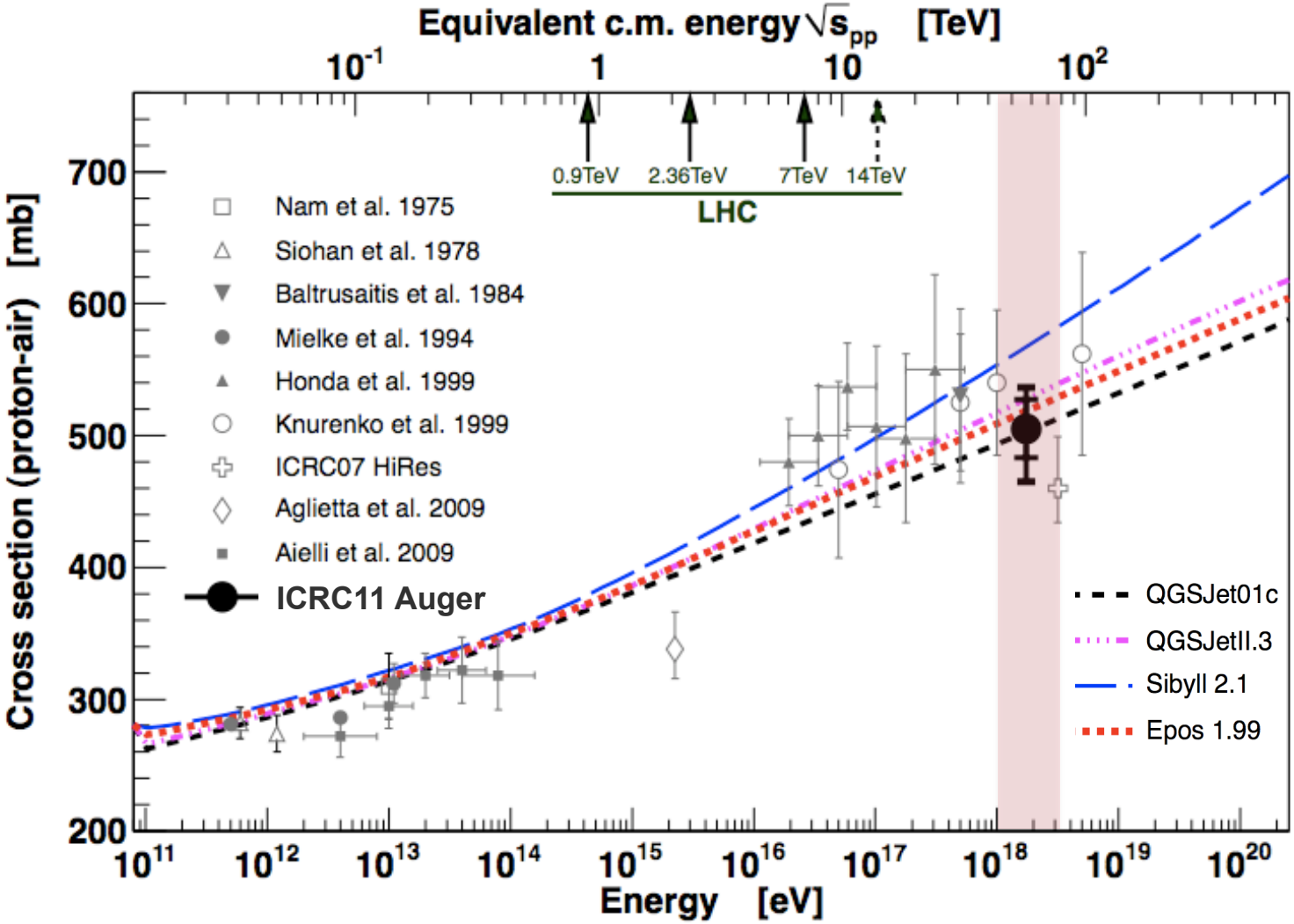
Search for multiplets

motivated by possible deflection in magnetic fields

- Select alignments with proper energy ordering, E> 20 EeV
- Find 3 multiplets with at least 10 showers
- Reconstruct source
- Highest multiplet is a 12-plet with 6% probability to occur by chance
- No significant evidence for correlated multiplets in present data set.



p-Air Cross-Section at $\sqrt{s}$ = 57 TeV



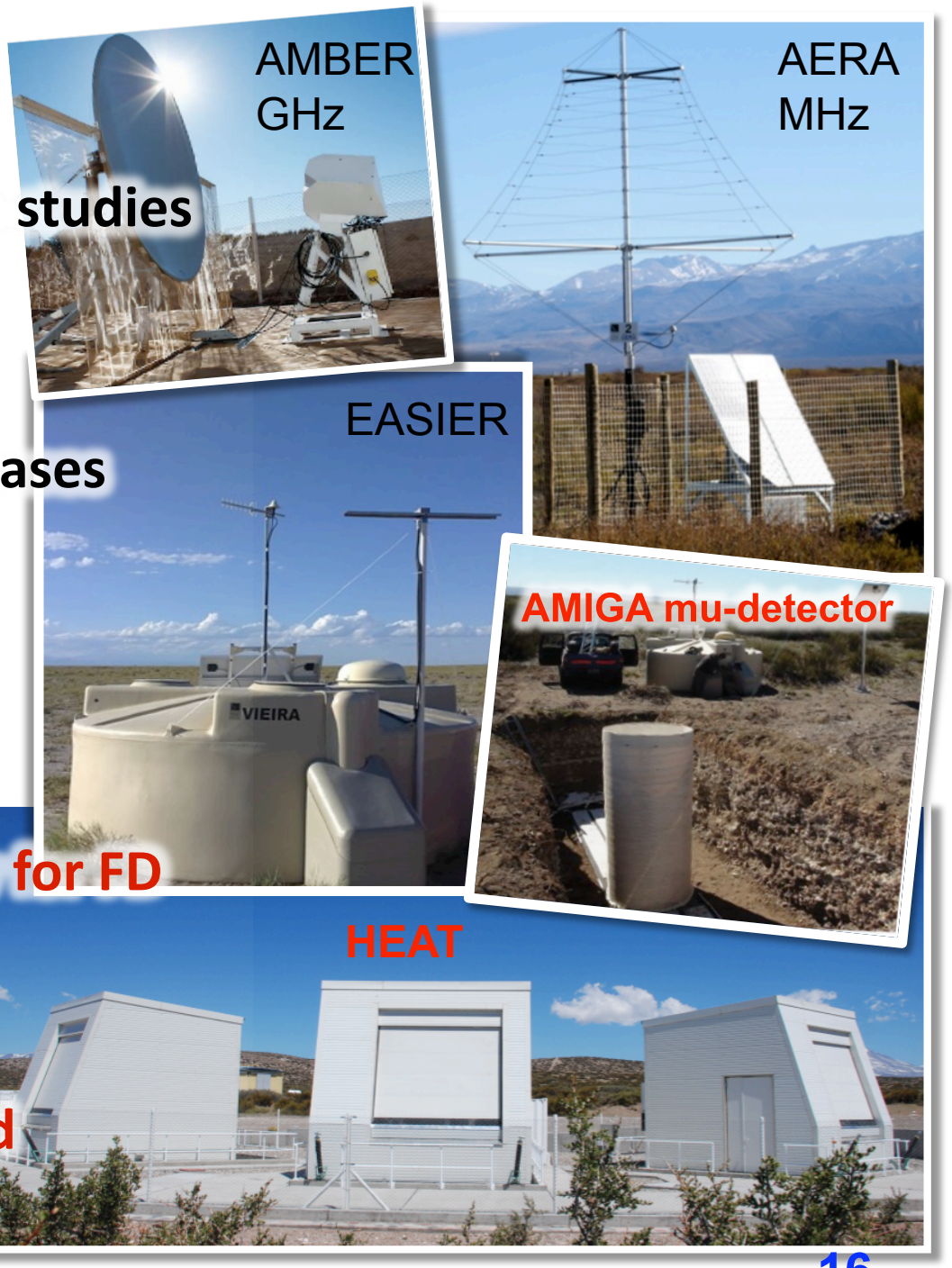
$$\sigma_{p\text{-air}} = \left(505 \pm 22_{\text{stat}} \left(^{+26}_{-34}\right)_{\text{sys}}\right) \text{ mb}$$

Other results

- SD related mass composition studies
- photon and neutrino limits
- first harmonic modulation
- Solar Physics: Forbush decreases
- Atmospheric Phenomena:
  Observation of Elves

New additions

- enlargement of field of view for FD
- radio detection of showers
- Infill array
- muon detectors underground



Summary

Selected results obtained by the PAO have been presented:

- Energy spectrum is measured with highest statistics ever, confirming the suppression of the flux above 4 10^{19} eV, consistent with the GZK cut-off
- Clear trend to higher primary masses when energy increases from $\langle X_{max} \rangle$ and $\mathrm{Rms}(X_{max})$
- Arrival directions correlate with matter/AGN within GZK horizon above 55 EeV; possible excess towards Centaurus A
- p-Air cross section has been measured at $\sqrt{s} = 57$ TeV well beyond LHC energy

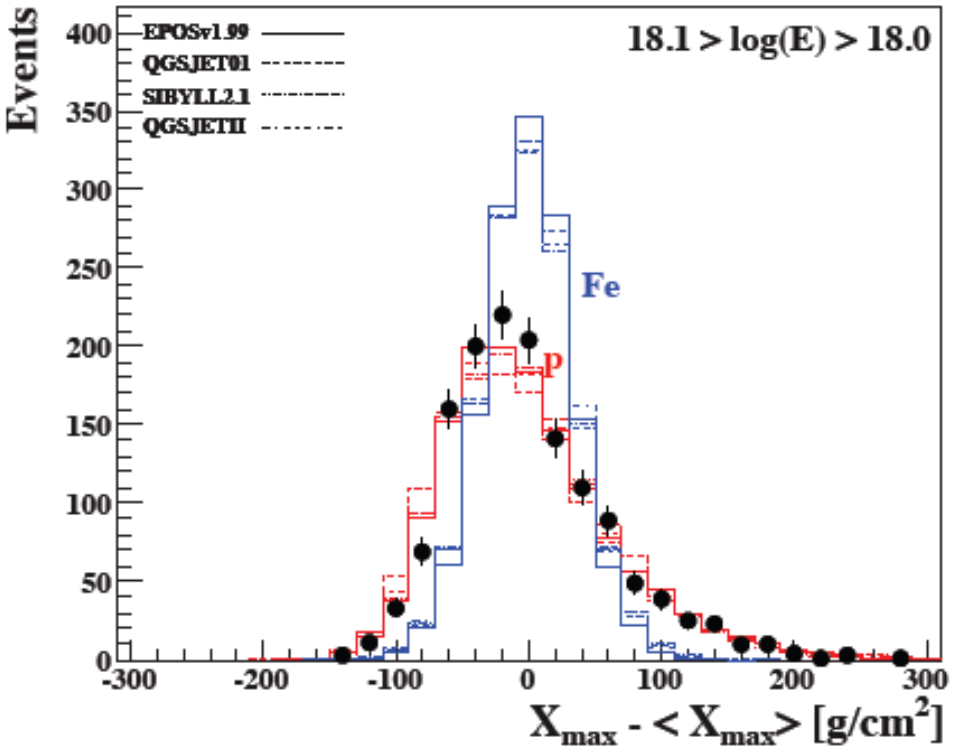
And many more …

Thank you for your attention!

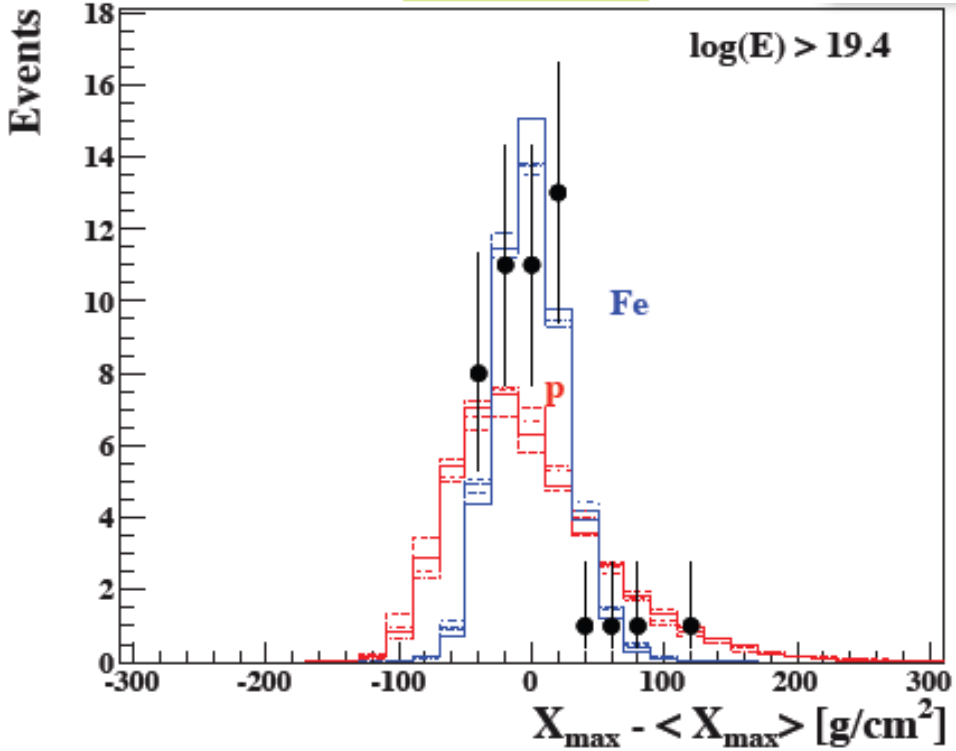
Back up …

X_{max} Distributions vs Models

10^{18} eV



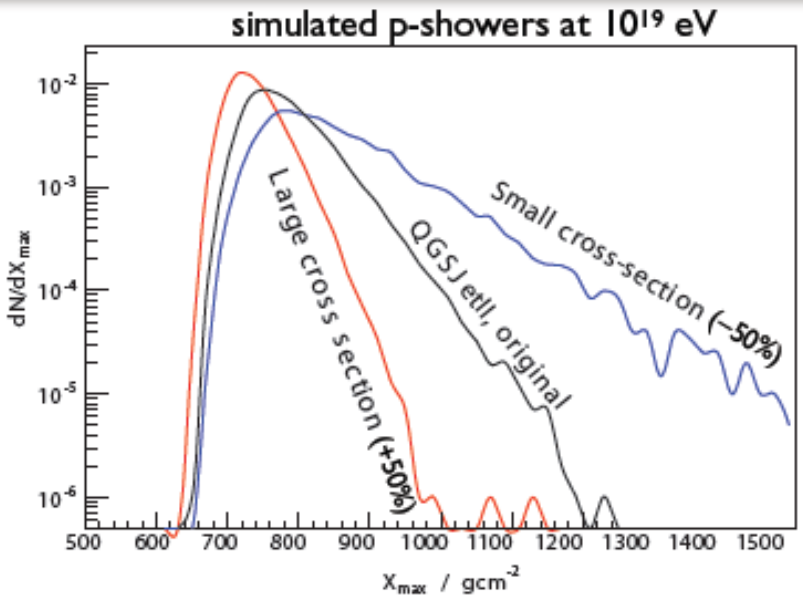
$> 10^{19.4}$ eV



- wide distribution
- well described with a substantial fraction of protons

- narrow distribution
- compatible with significant fraction of heavy nuclei

p-Air Cross-Section

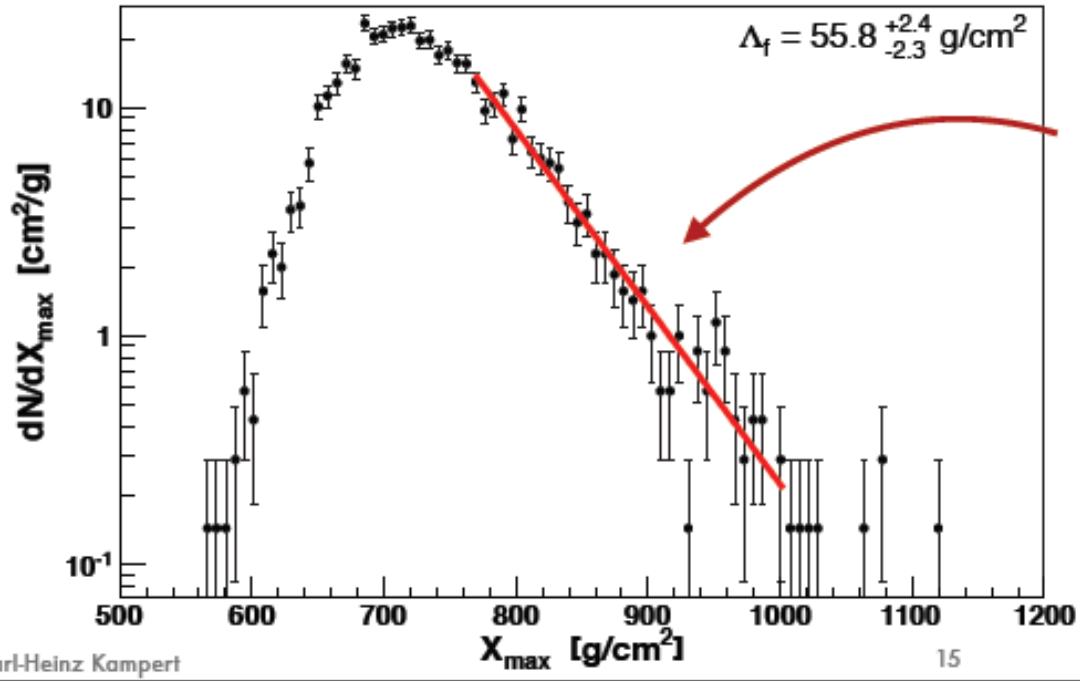


#946: Ulrich

Tail of X_{max} distribution

⇕

Inelastic cross-section



10^{18} eV < E < $10^{18.5}$ eV

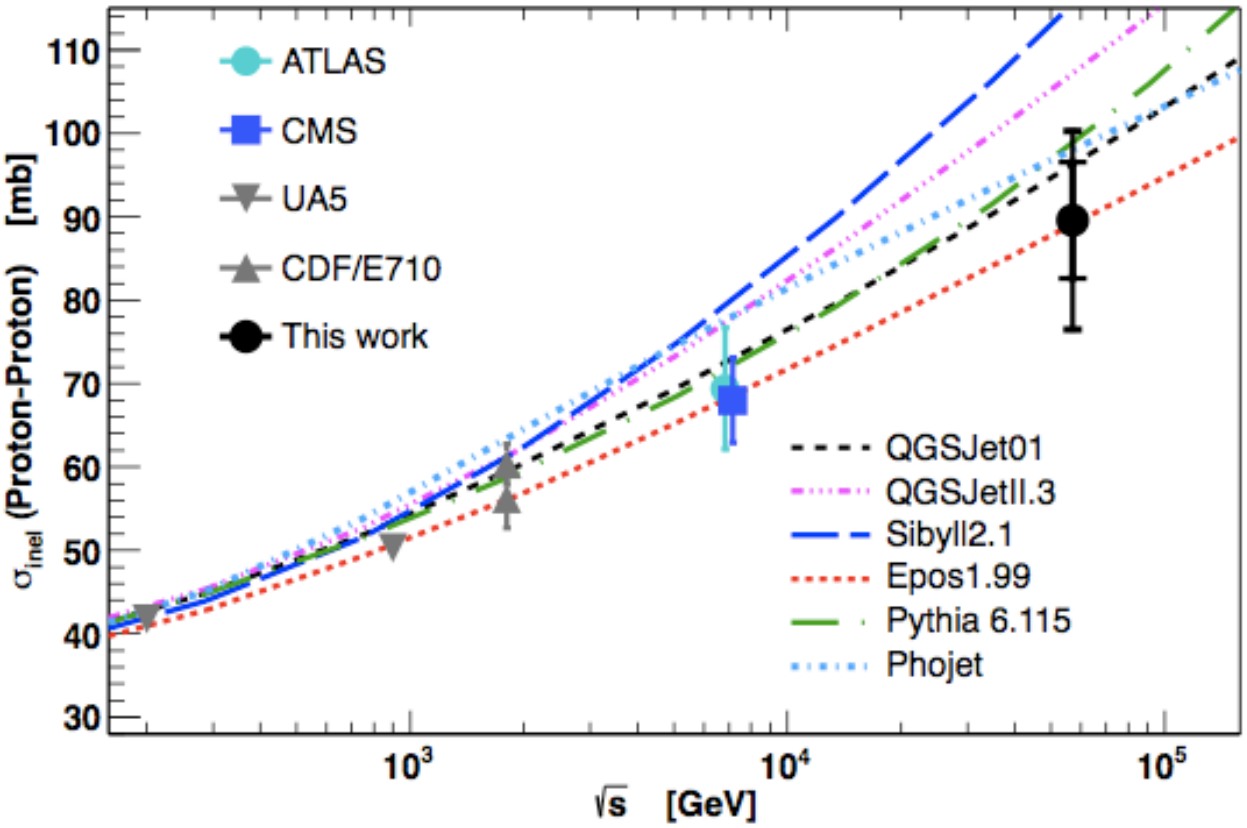
tail dominated by protons

$$dN/dX_{max} \propto \exp\left(-X_{max}/\Lambda_\eta\right)$$

$\Lambda \rightarrow \sigma_{p\text{-Air}}$
by tuning models to describe tail seen in data

Inelastic Proton-Proton Cross-Section

Glauber conversion + propagation of modeling uncertainties



$$\sigma_{pp}^{\text{inel}} = \left(90 \pm 7_{\text{stat}} \ \left(^{+8}_{-11}\right)_{\text{sys}} \pm 1.5_{\text{Glauber}}\right) \text{ mb},$$