Pierre Auger Observatory

studying the universe's highest energy particles

Ultrahigh Cosmic Rays: The highest energy frontier

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for the Pierre Auger Collaboration

XIII Mexican Worshop on Particle and Fields, León, Gto, 2011

SCIENTIFIC OBJETIVES:

Spectrum: CR flux for $E > 10^{18}$ eV

Arrival directions: search for anisotropies (identify the sources)

Composition: light or heavy nuclei, photons, neutrinos, others?

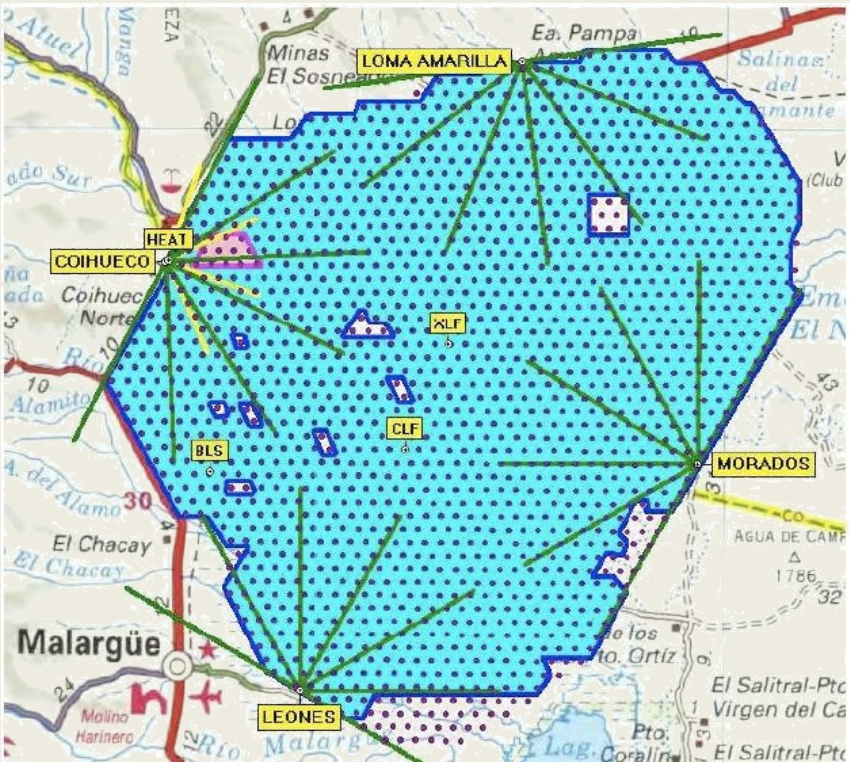
Study of interactions at energies unreachable at accelerators

Auger

The Auger Observatory in the Southern Hemisphere

Hybrid shower measurements

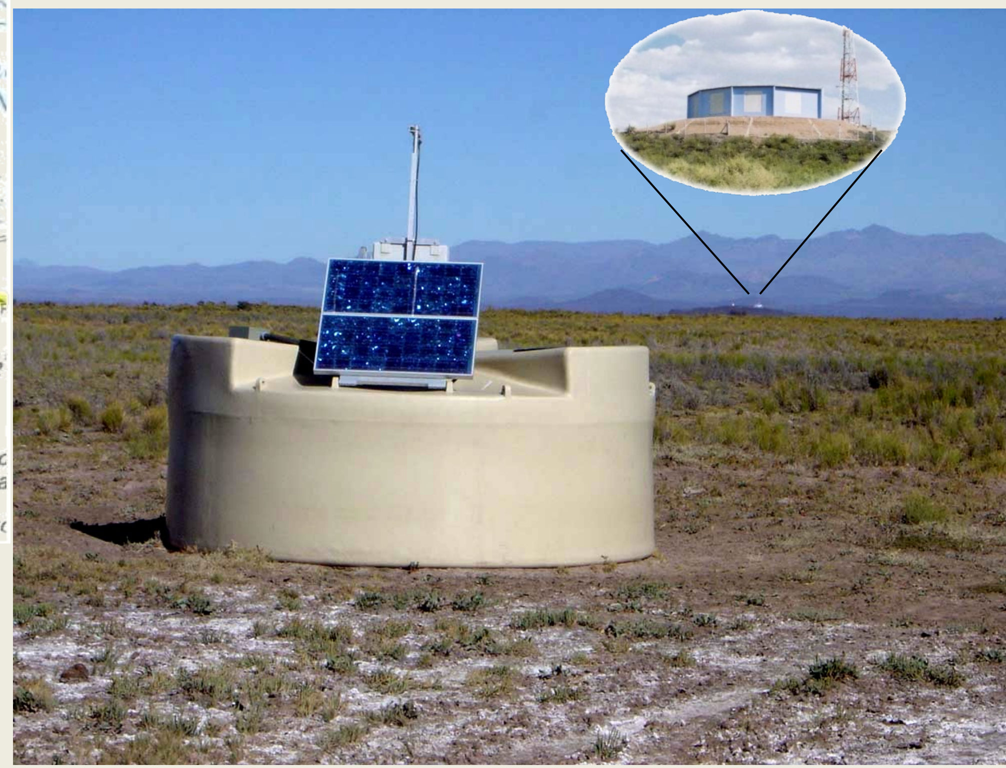
Fully deployed in Argentina since June 2008



60 km

1600 water Cherenkov stations

24 fluorescence telescopes (30°x30°)

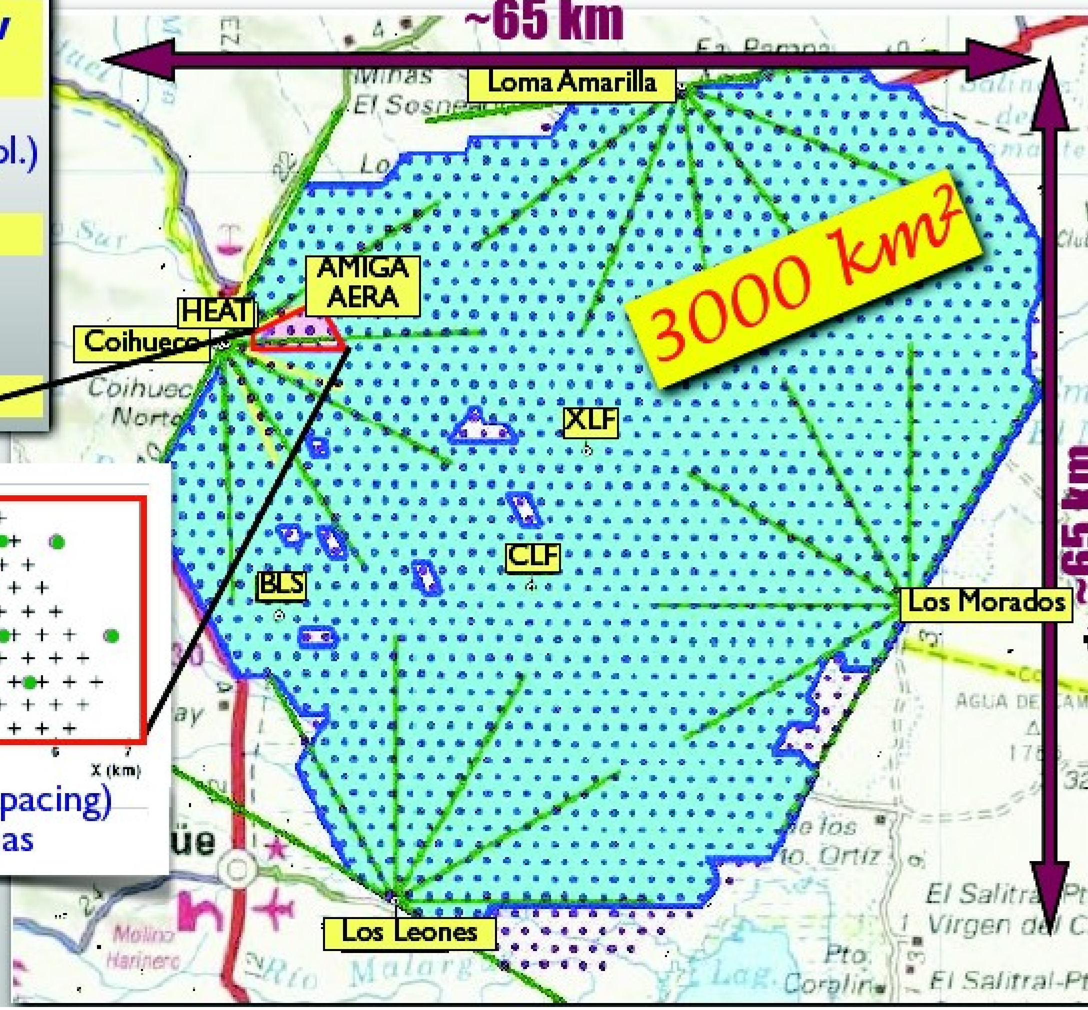


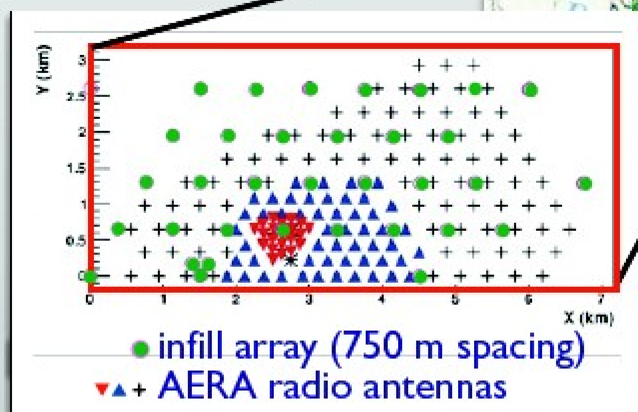
Pierre Auger Observatory in Argentina

1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

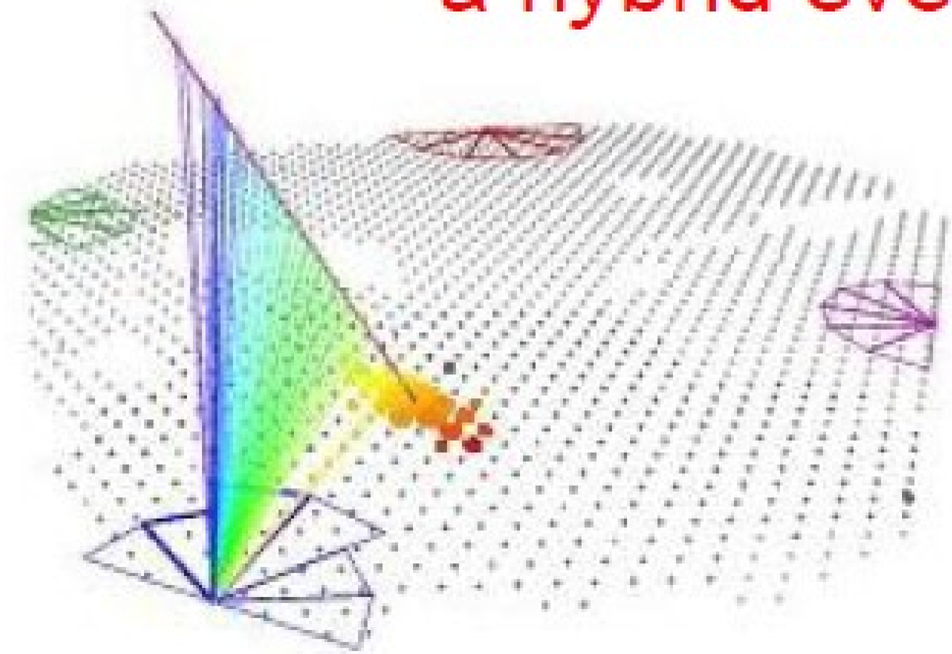
27 telescopes
in 4+1 buildings at the periphery

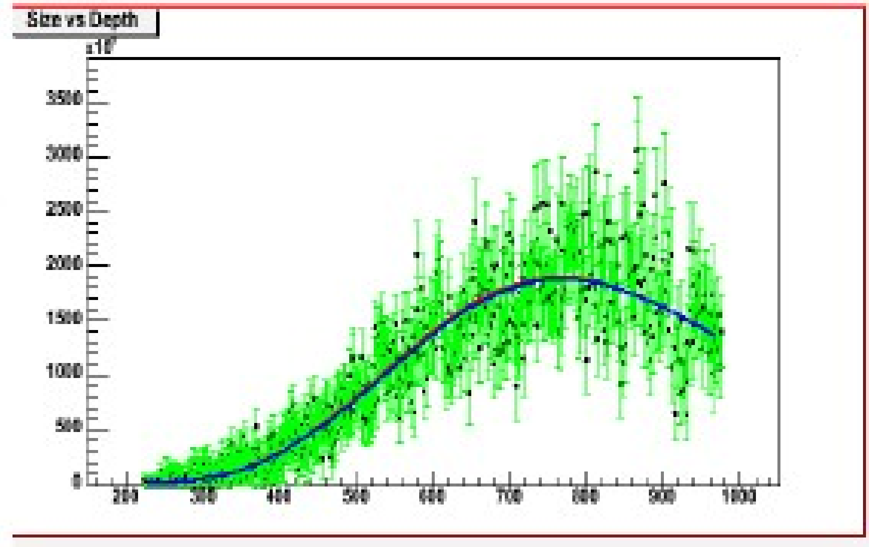
3000 km² area

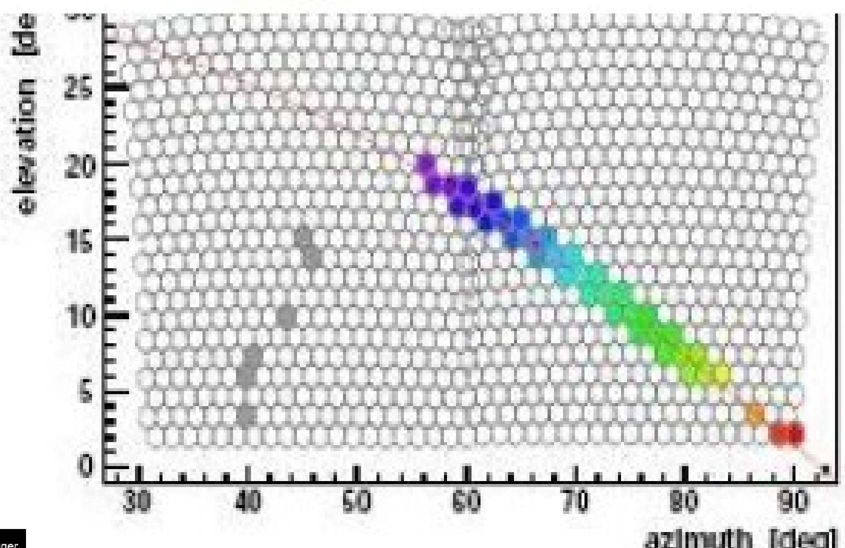




a hybrid event





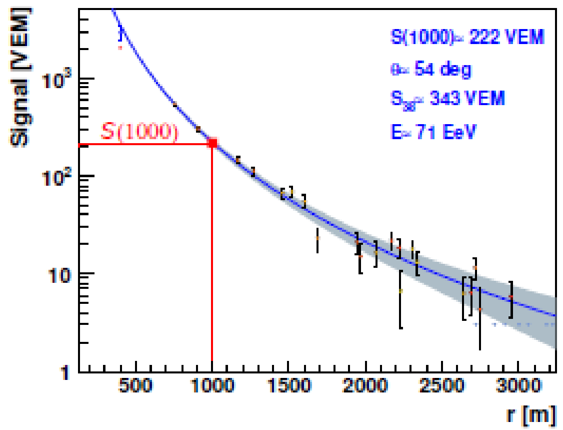


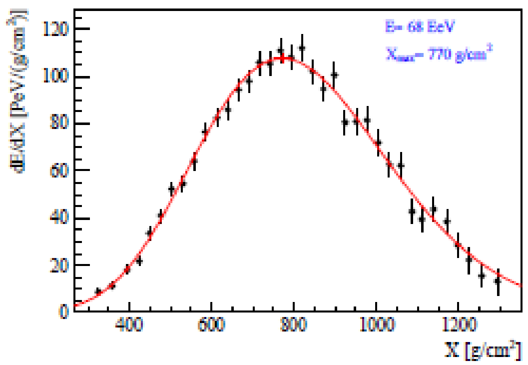
Measure Xmax
Energy calibration
angular resolution studies ...

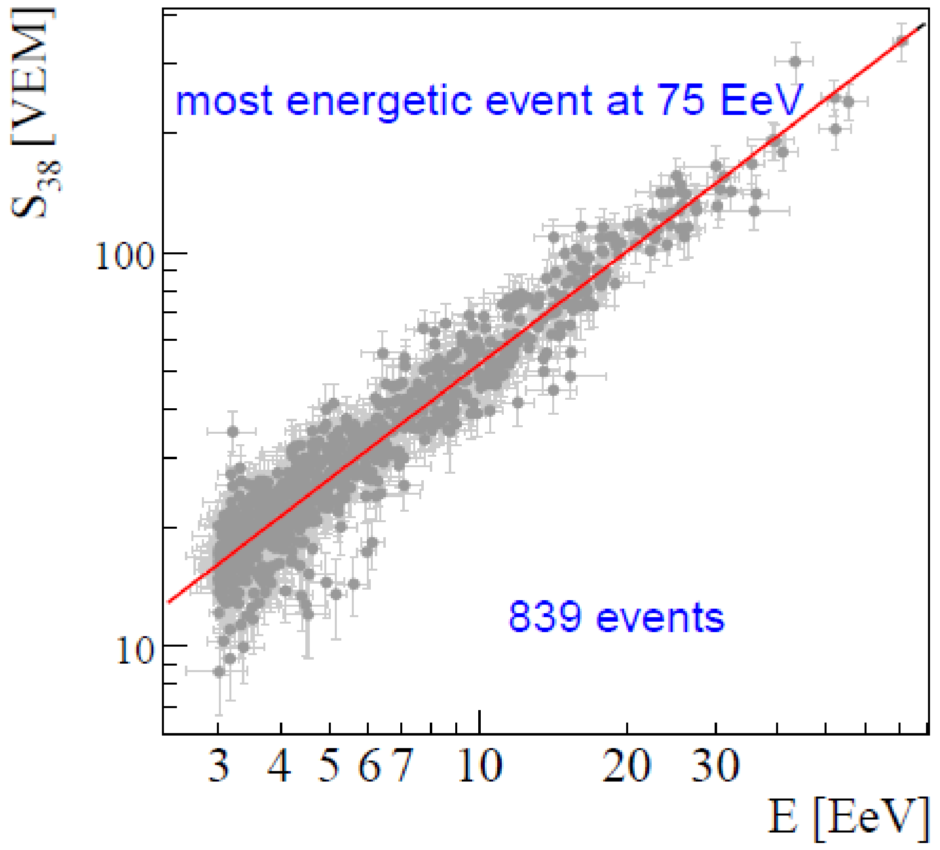
(but duty cycle ~15%)

SD energy calibration with FD

Calibration made using events with independent SD and Hybrid trigger and reconstruction

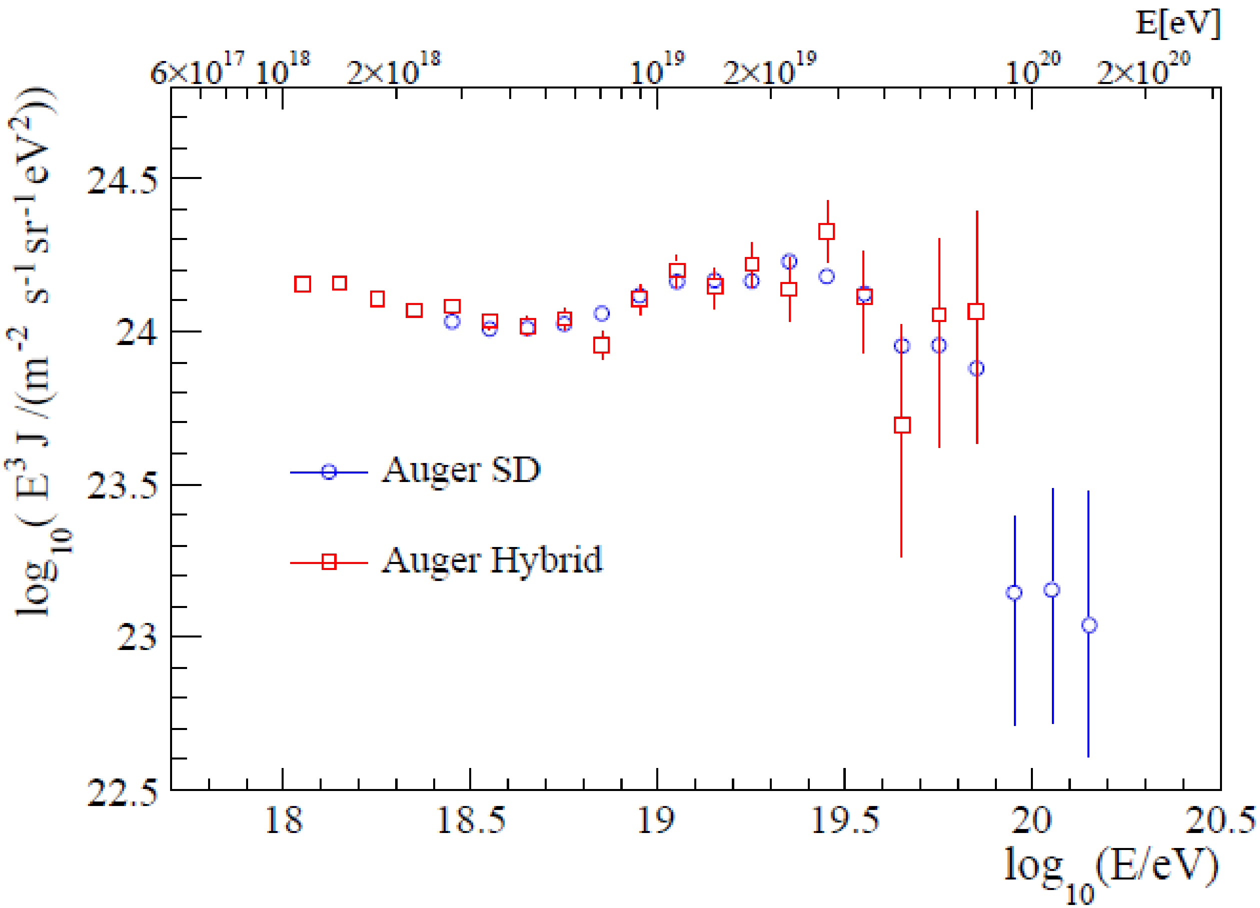




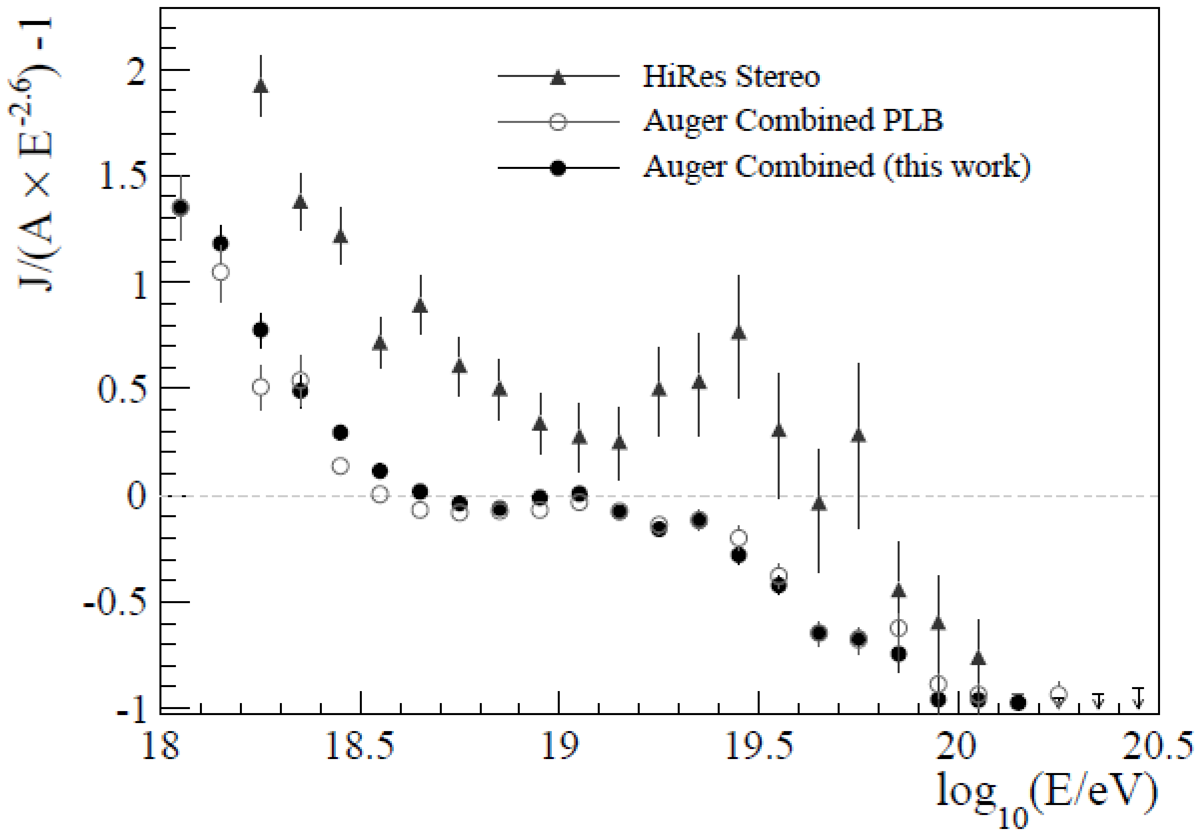


Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

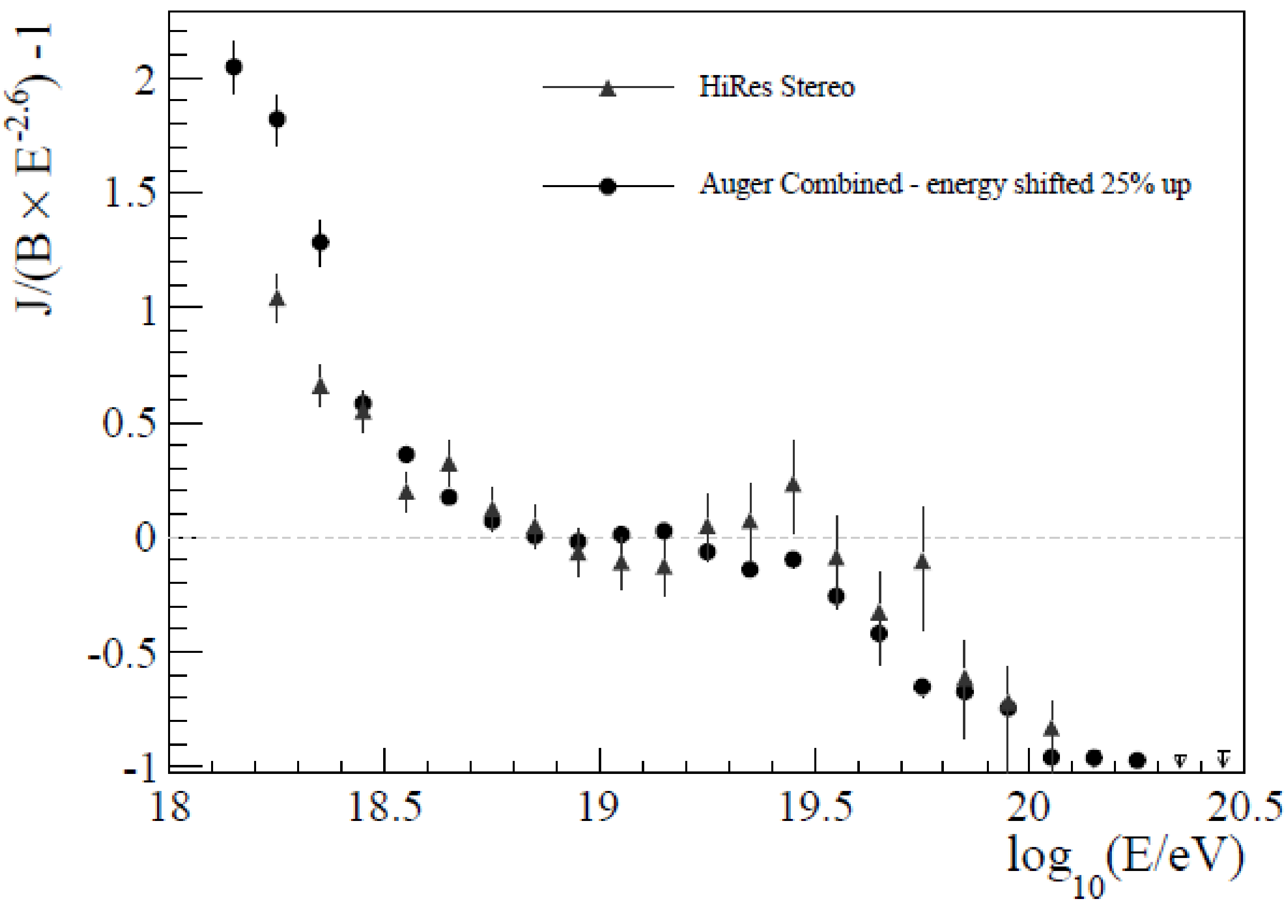
Hybrid energy spectrum



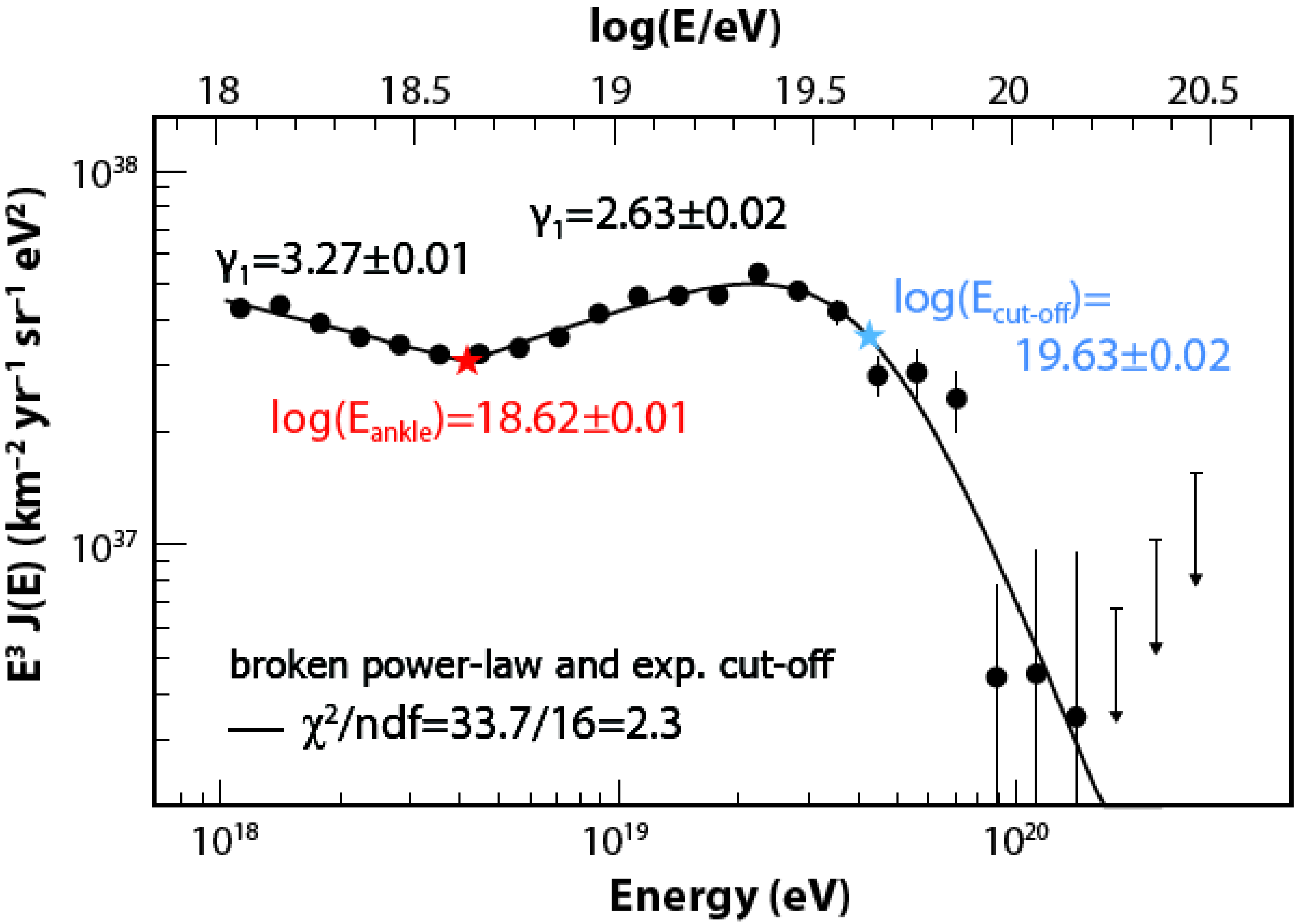
- very good agreement with SD
- difference in flux with old publication less than 2%



- difference w.r.t PLB due to changes in calibration curve
- very high statistics, spectral features very well defined

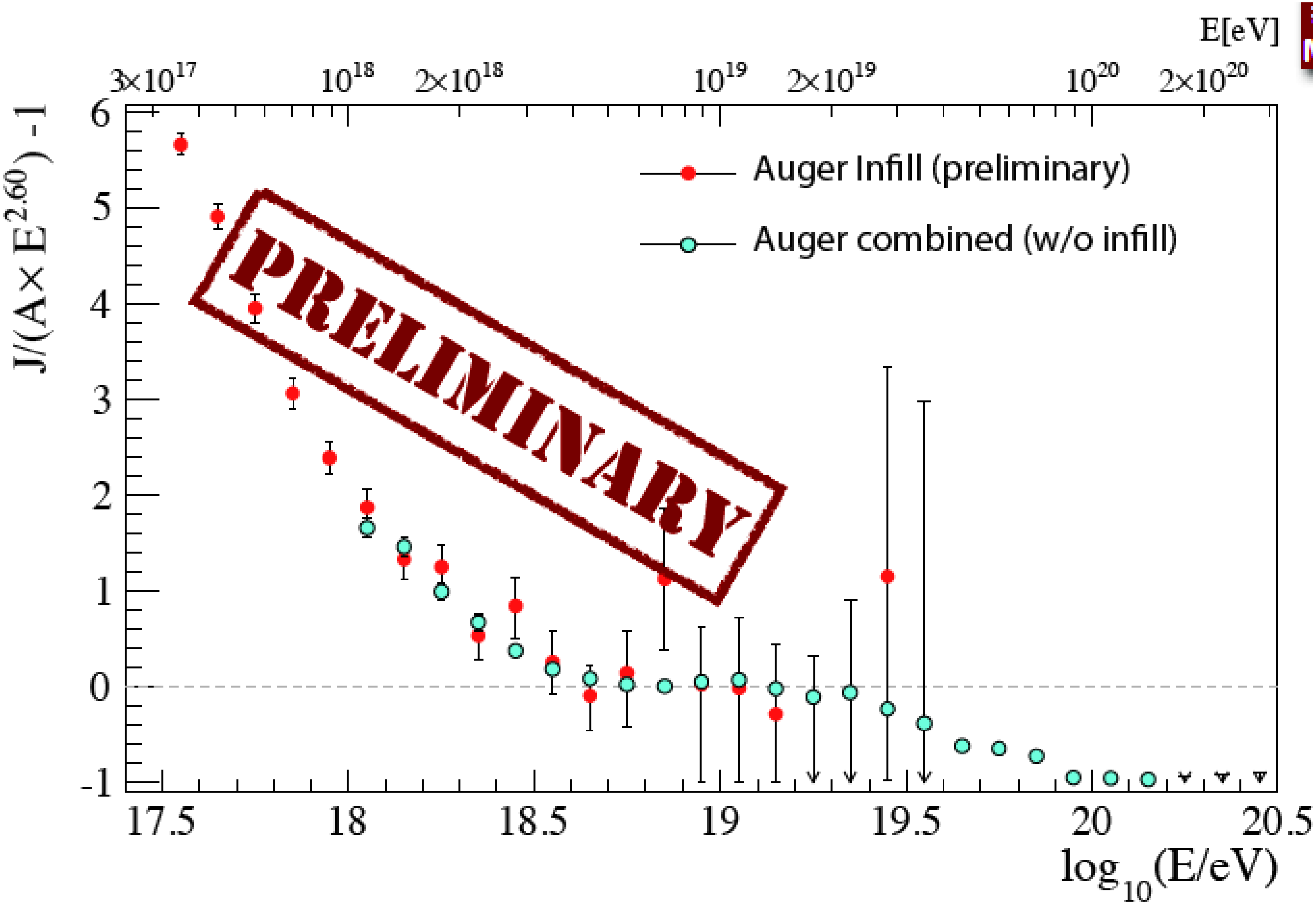


- Energy shift of 25% applied to Auger combined spectrum



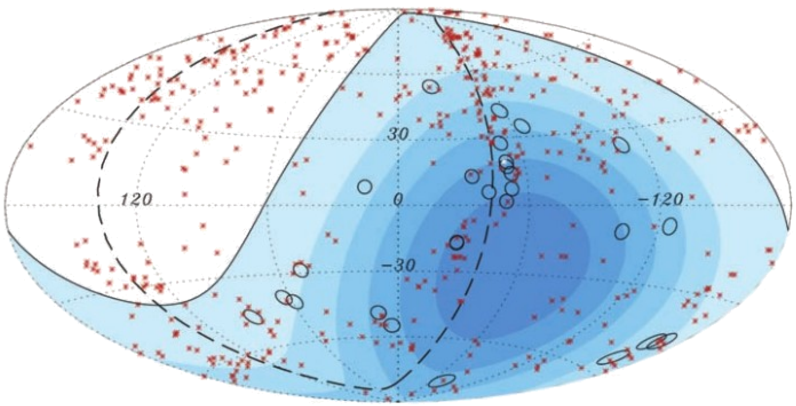
Exposure = 20 905 km^2 sr yr (60% increase over PLB 685 (2010))

Inclined showers add another 5300 km^2 sr yr (→ #724)

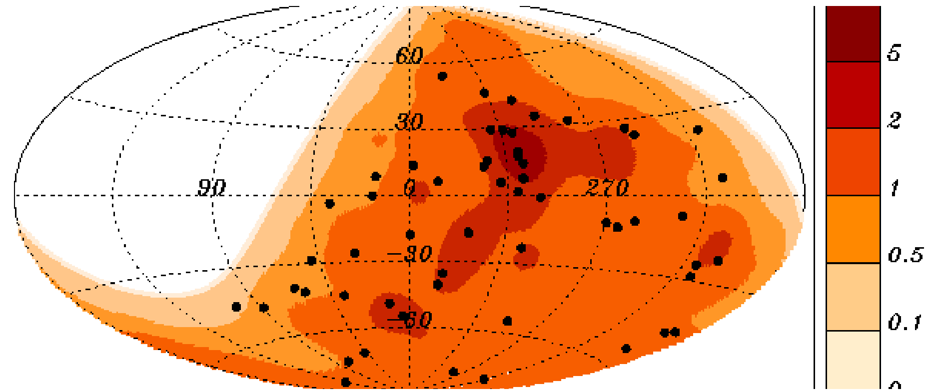


Exposure of infill array: (26.4±1.3) km² sr yr

The Auger Sky above 60 EeV

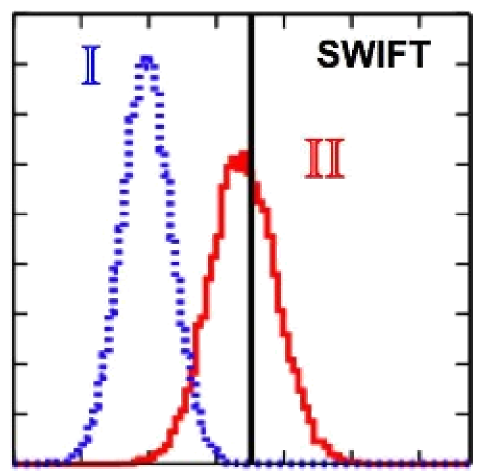


27 events as of November 2007



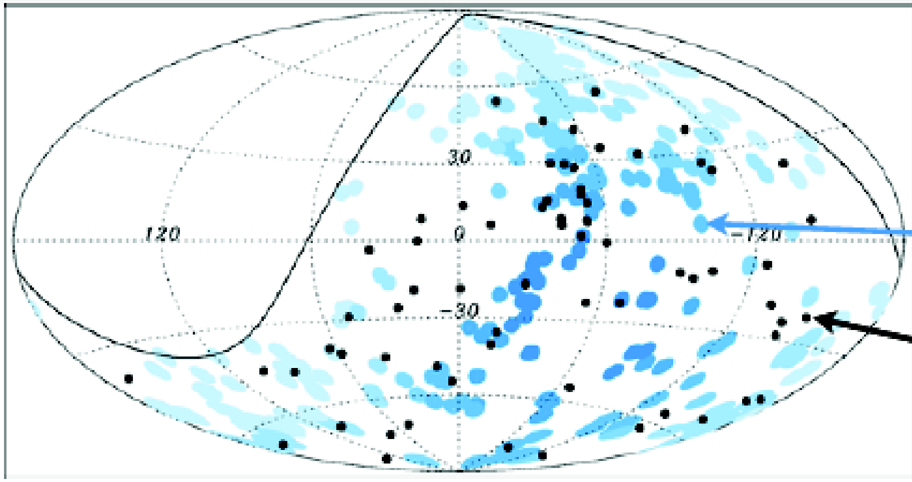
58 events, 2010 (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).



Log(Likelihood)

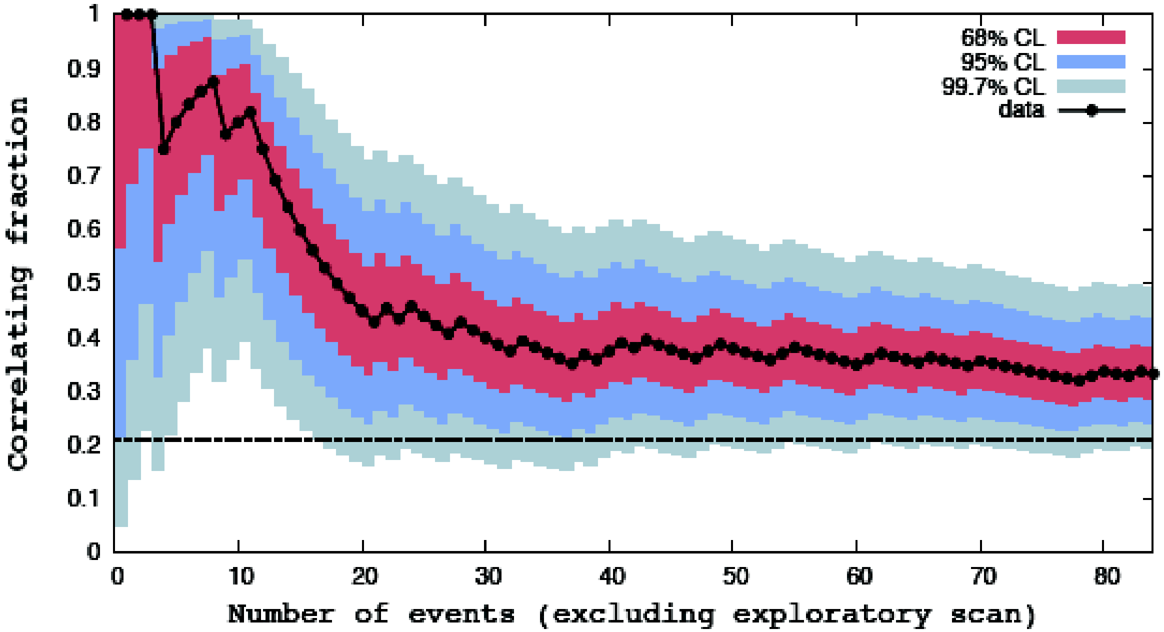
Update of Correlation with VCV-AGN



Astropart. Phys. 34 (2010) 314

AGN position
(3.1° circle)

event position



Update including June 2011

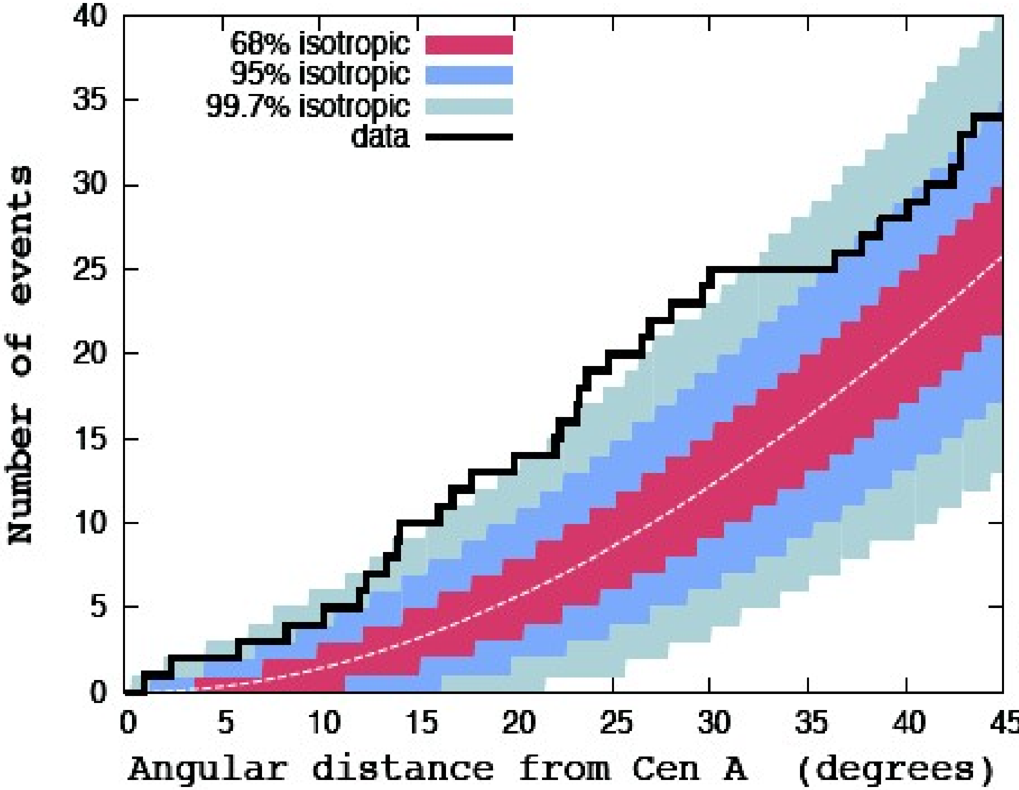
33±5%

Total: 28/84

P=0.006

Telescope Array:
8/20 = 40%
with iso-bkg = 24%

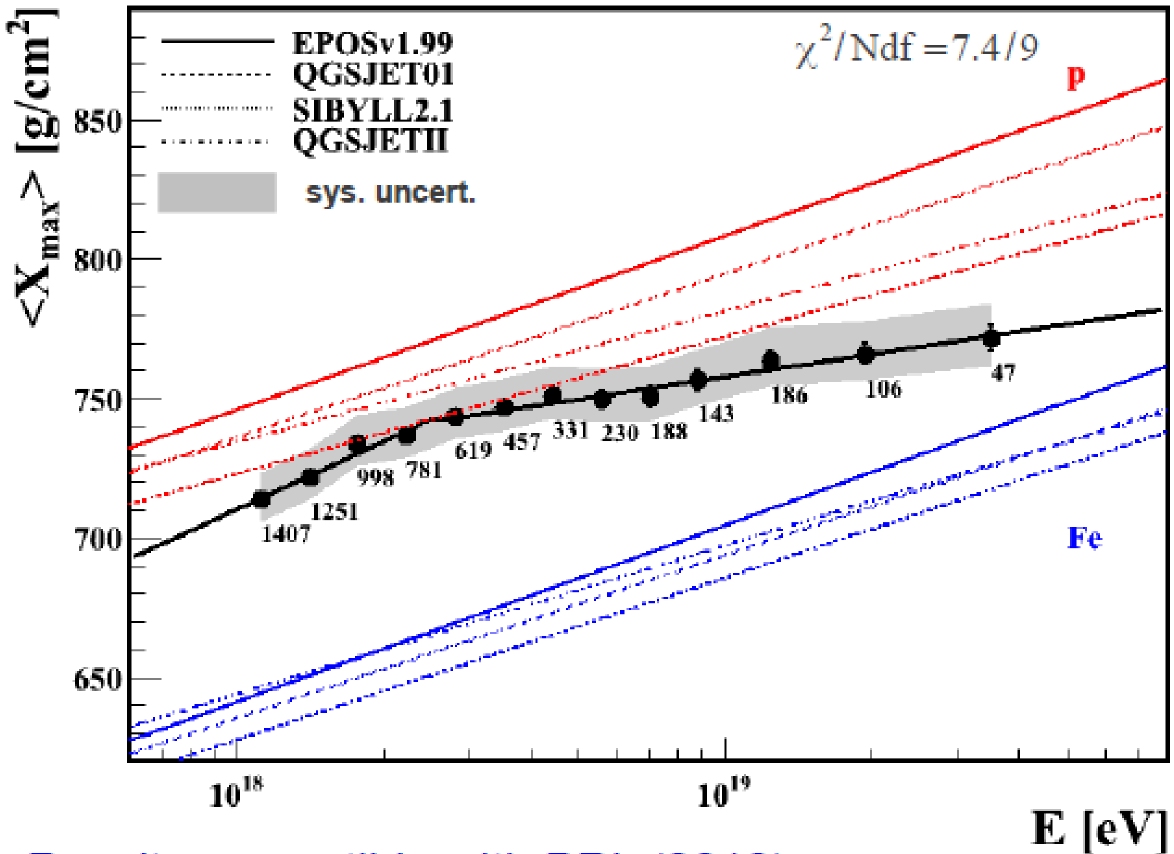
Update on Cen A



Update including June 2011

KS test yields 4% isotropic probability
Largest departure now at 24°: 19 observed / 7.6 expected

$\langle X_{max} \rangle$ vs. Energy



Low Energy

$D_{10} = 82^{+48}_{-8}\ \mathrm{g/cm^2/decade}$

High Energy

$D_{10} = 27^{+3}_{-8}\ \mathrm{g/cm^2/decade}$

Energy break

$\log(E_{break}/\mathrm{eV}) = 18.38^{+0.07}_{-0.17}$

Below E_{break} the small lever arm of the fit results in higher statical uncertainties in D_{10}

- Results compatible with PRL (2010)
- Data are best described with two slopes; break is near the same energy as the ankle feature of the spectrum
- At high energy $\langle X_{max} \rangle$ increases *slowly* with energy.

Shower Depths of Maximum X_{max}

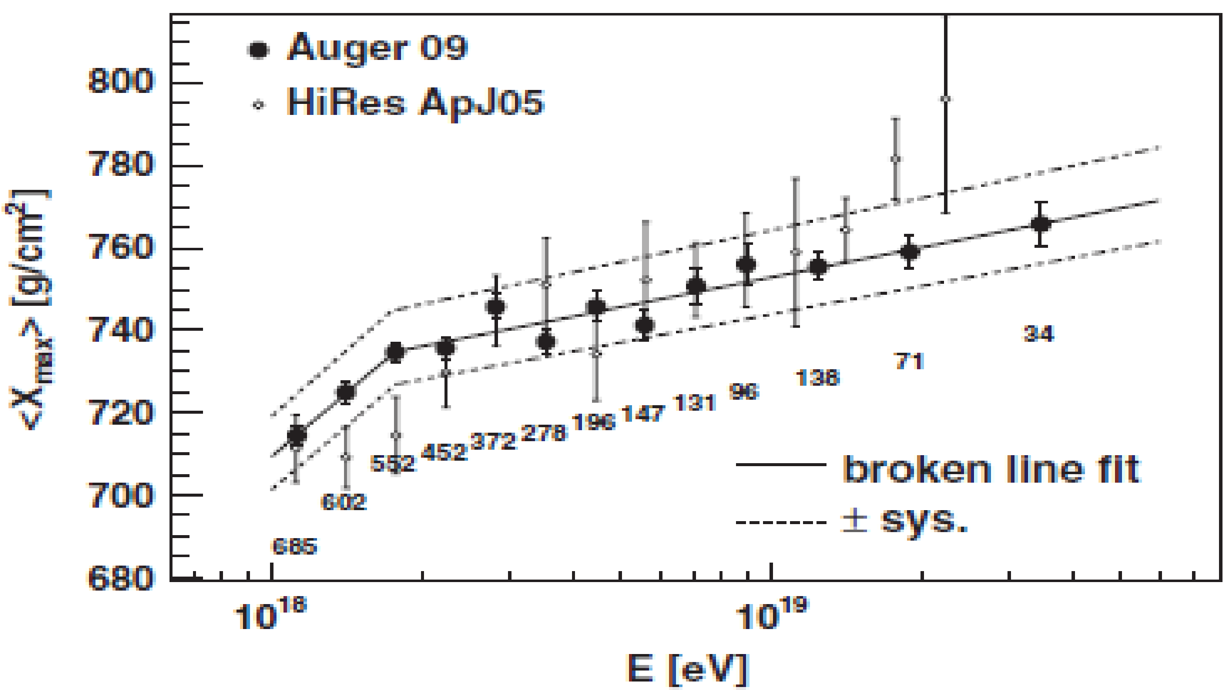
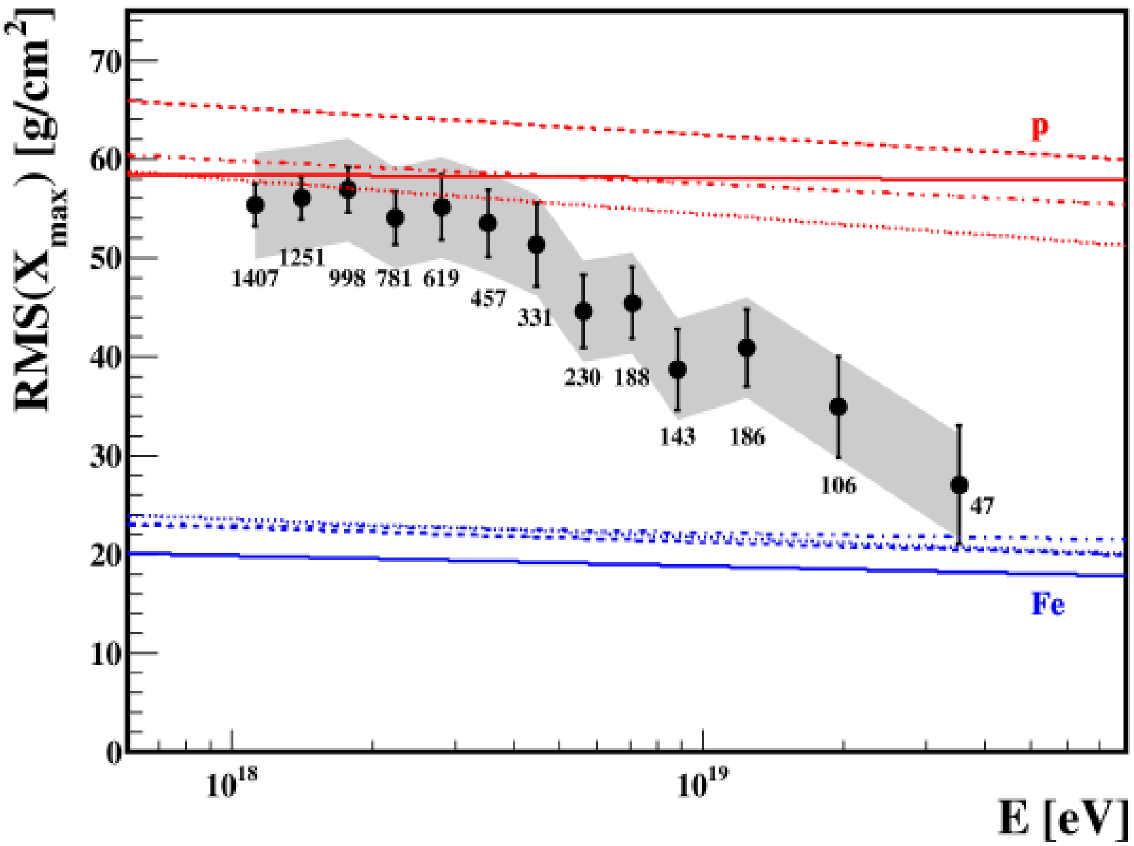


FIG. 2. $\langle X_{max} \rangle$ as a function of energy. Lines denote a fit with a broken line in $\lg E$. The systematic uncertainties of $\langle X_{max} \rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.

PRL **104,** 091101 (2010) PHYSICAL REVIEW LETTERS week ending 5 MARCH 2010

Measurement of the Depth of Maximum of Extensive Air Showers above 10^{18} eV

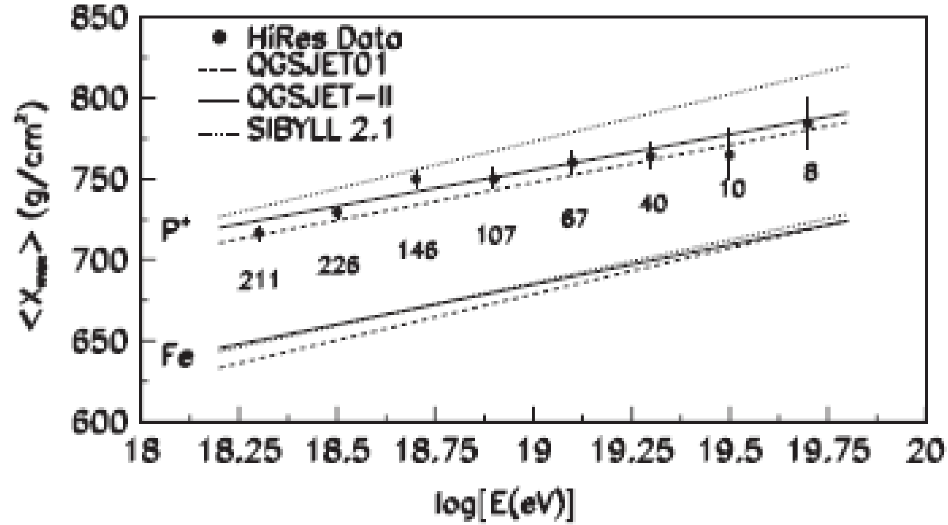
RMS(X_{max}) vs. Energy



Resolution is subtracted from data:
27 g/cm² → low energy
18 g/cm² → high energy

- Compatible with published results PRL(2010)
- There is a change in behavior around the same energy as <X_{max}>: above 2.5 10^{18} eV there is a fast decrease of RMS(X_{max}) towards the values expected for heavy primaries.

Hi-Res X_m - results favor protons

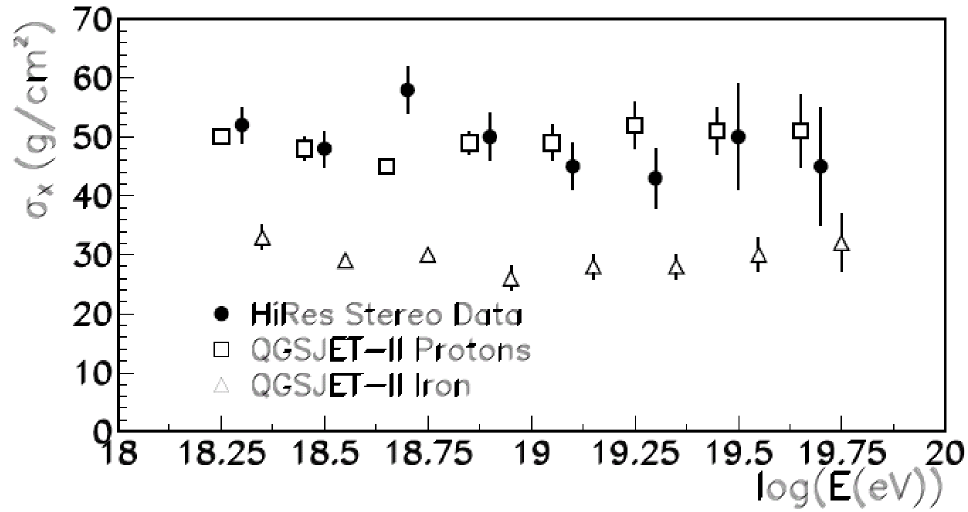


Mean depth of maximum vs energy

Evidence for proton dominated composition above 1.6 EeV

PRL 104 161101 (2010)

HiRes Collaboration arXiv:0910.4184



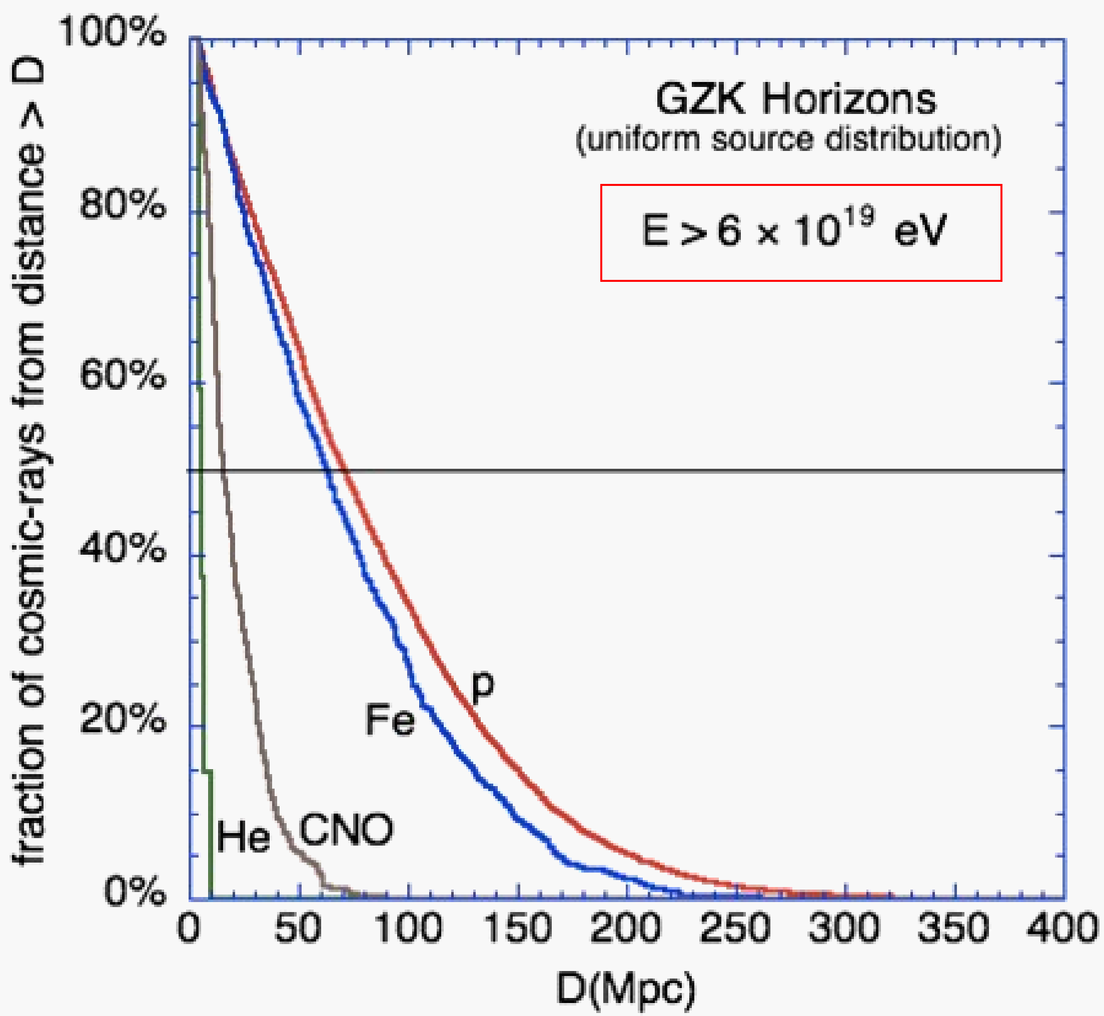
Width of distribution vs energy

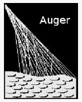
Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.

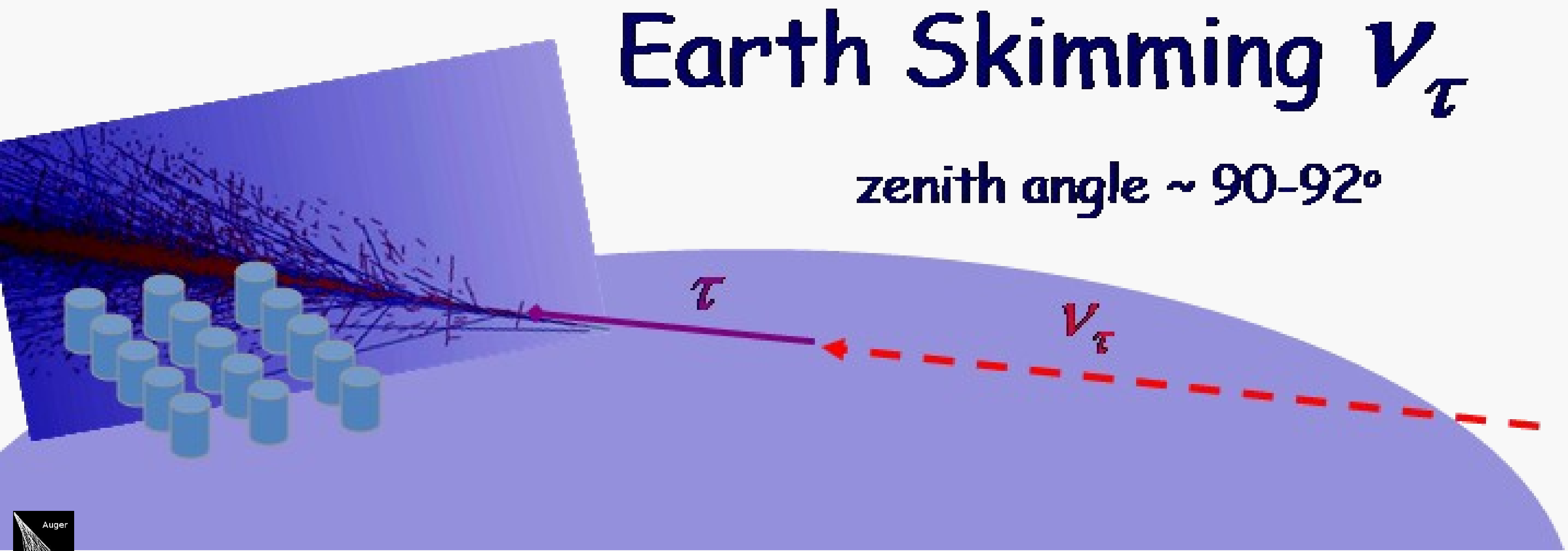




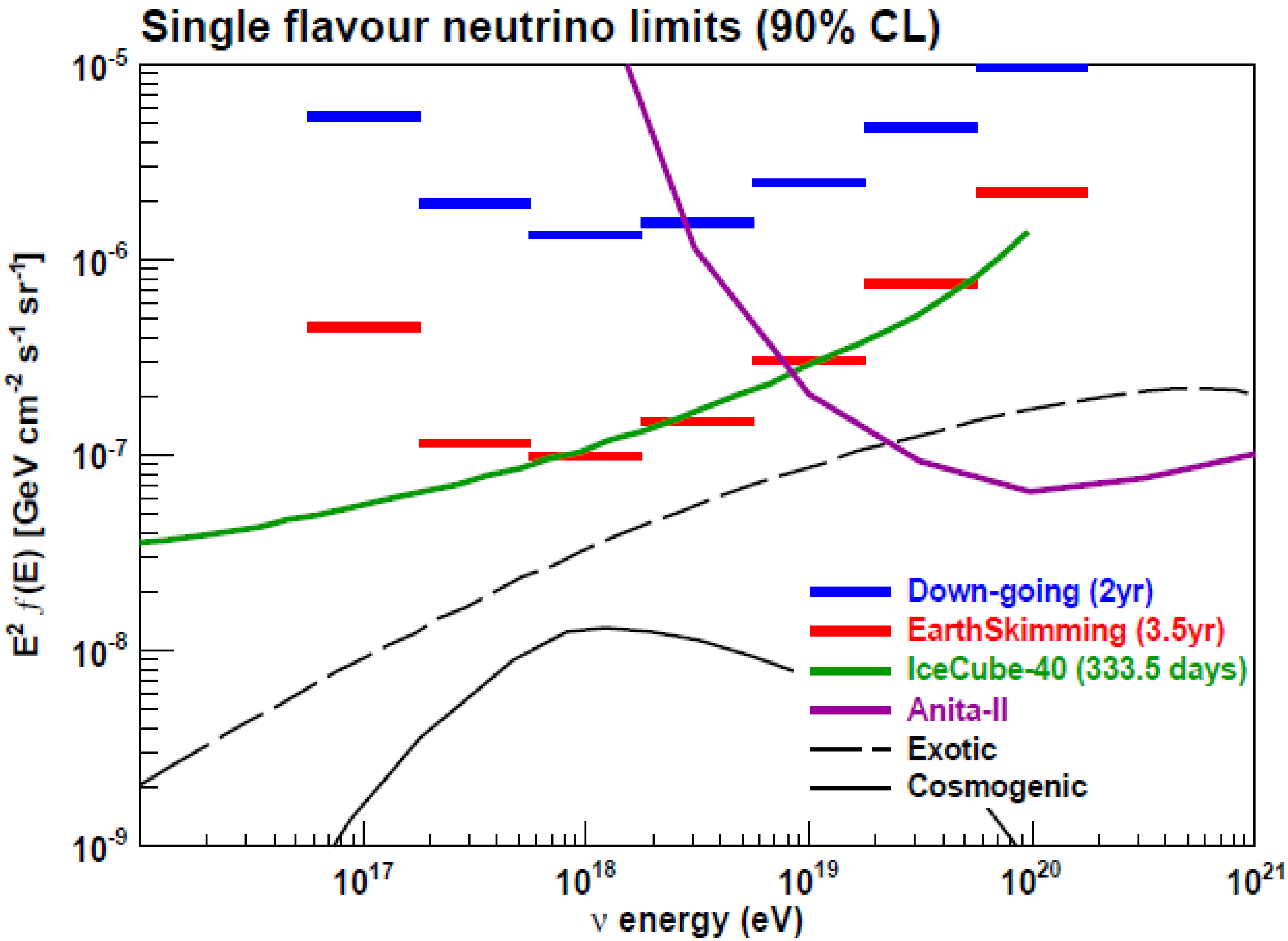
The Auger UHE Neutrino Observatory

Neutrinos can be identified as "young" showers at very great atmospheric slant depth (either upward or downward).

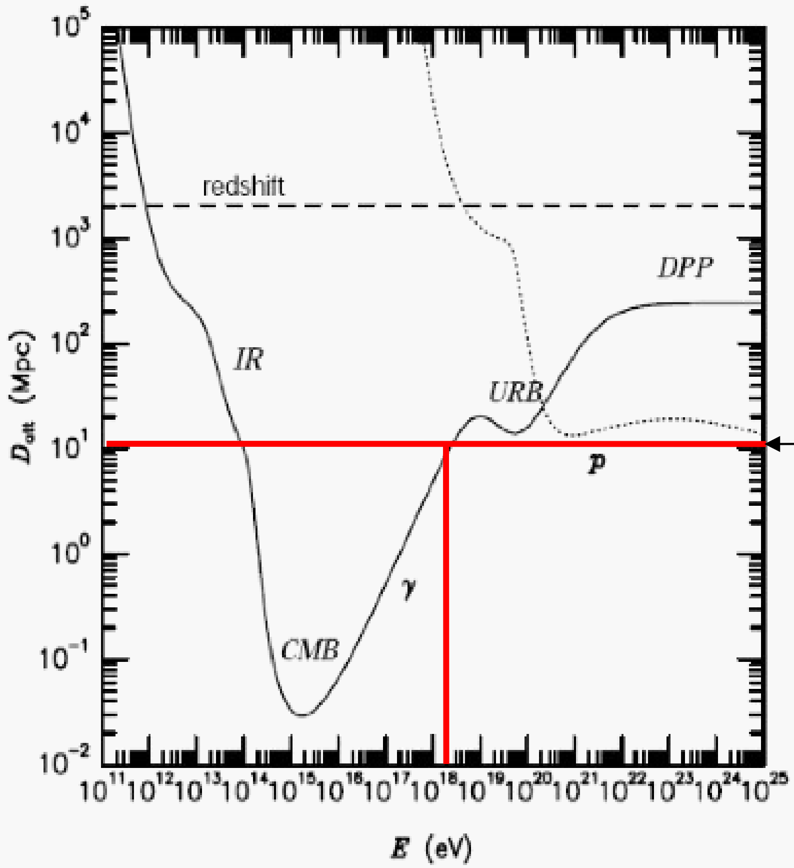
Auger exposure to tau Neutrinos



Differential limits to diffuse fluxes



The UHE Gamma Ray Astronomical Window



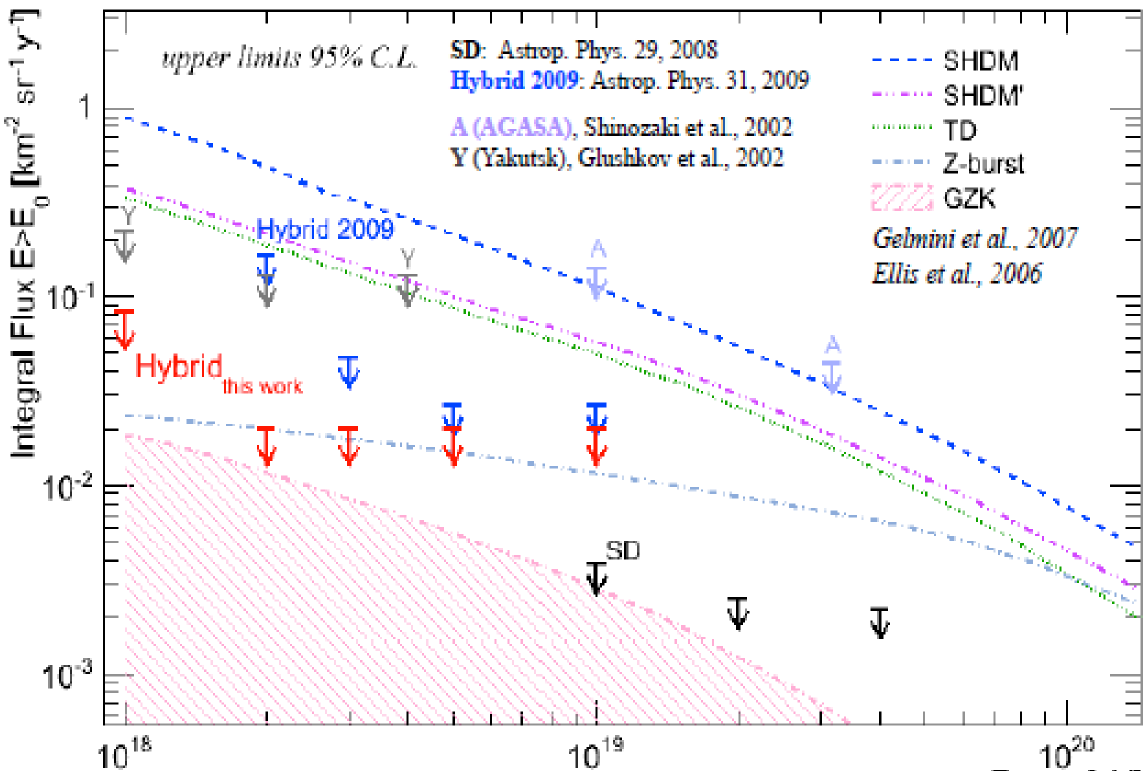
Photon attenuation length exceeds 10 Mpc for E > 2 EeV

Photon showers penetrate deeper than hadronic showers.

They can be recognized individually with hybrid measurements.

A photon component can be measured statistically by the surface array.

Upper Limits to the Integral Photon Flux



* Fraction limits **Hybrid 2009** converted to flux scaling for the Auger spectrum

E_0 [EeV]	N_γ	$\phi_\gamma^{95CL}(E_\gamma > E_0)$ $[\mathrm{km^{-2}\,sr^{-1}\,y^{-1}}]$
1	6	8.2×10^{-2}
2	0	2.0×10^{-2}
3	0	2.0×10^{-2}
5	0	2.0×10^{-2}
10	0	2.0×10^{-2}

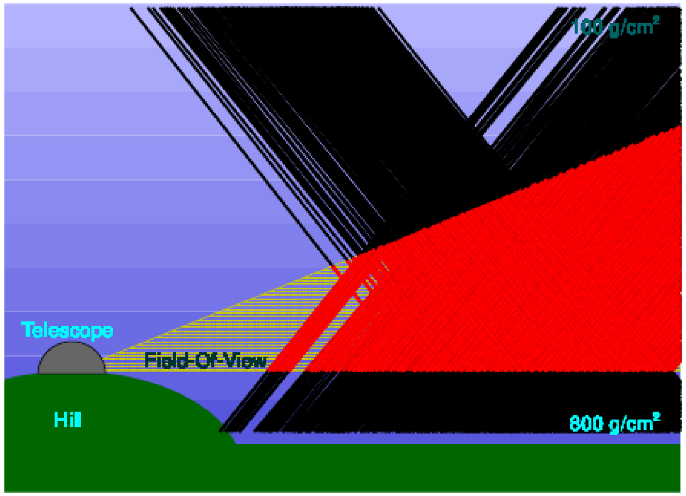
Impact of systematic uncertainties

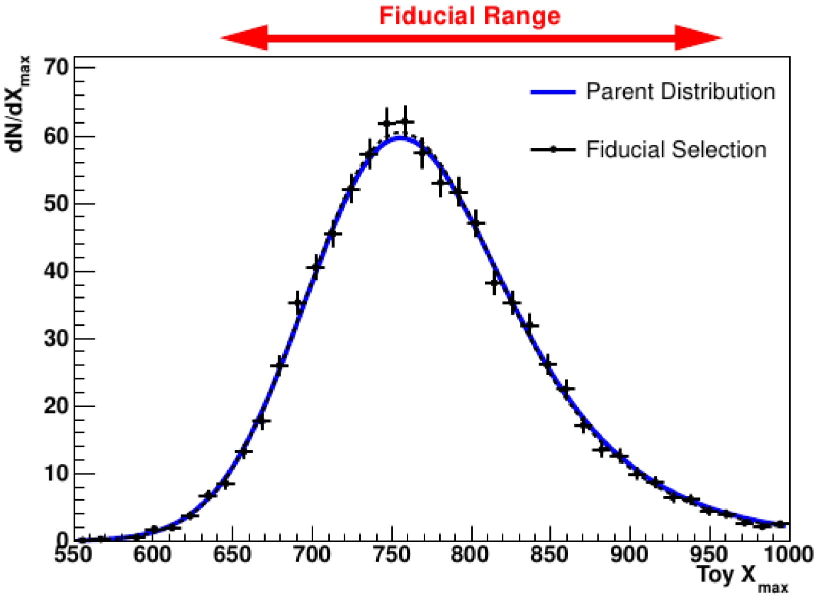
(Exposure, ΔX_{max}, ΔS_b, Energy scale, hadronic interaction model and mass composition assumptions)

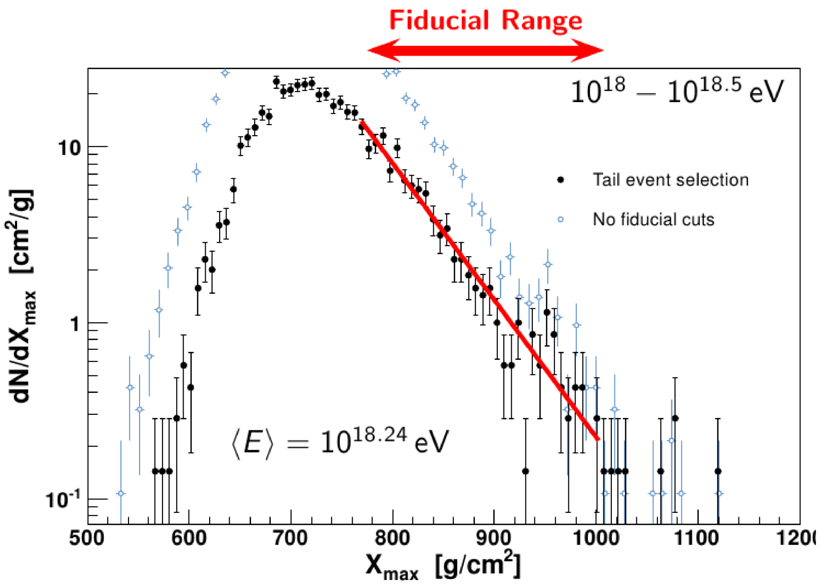
$$^{+20\%}_{-64\%} \; (E_0 = 1 \text{ EeV})$$

$$^{+15\%}_{-36\%} \; (E_0 > 1 \text{ EeV})$$

proton-air production cross section





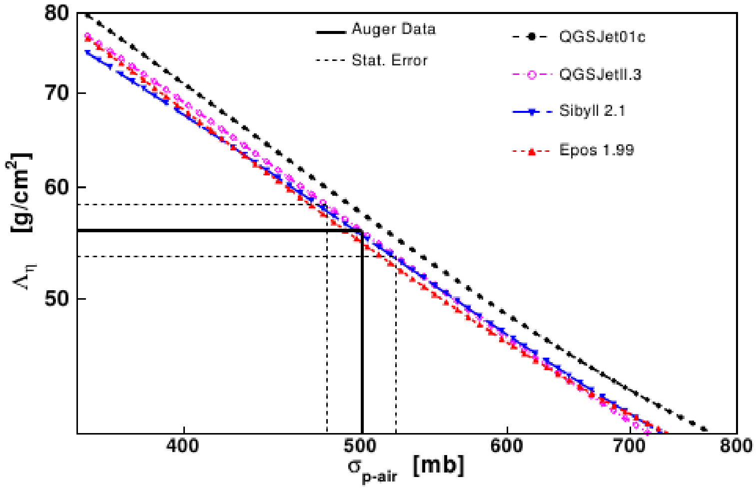


The p-air cThe p-air cross section can be deduced from the average penetration length that is related to the tail of *X*max distribution.

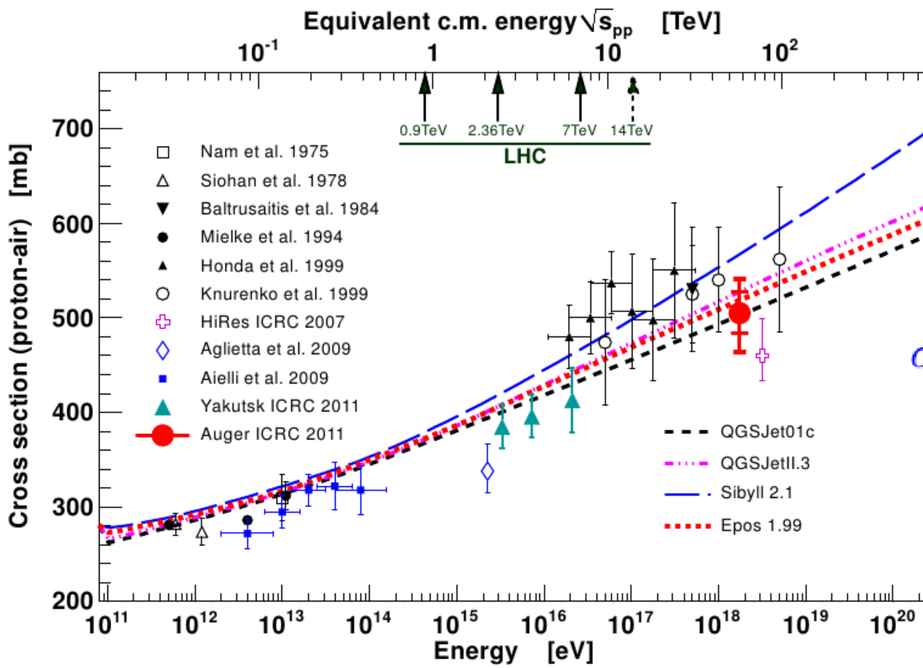
$$dN/dX_{\max} \sim \exp\left(-X_{\max}/\Lambda_\eta\right)$$

$$\Lambda_\eta = [55.8 \pm 2.3_{\rm stat} \pm 1.6_{\rm sys}]\ {\rm g/cm^2}$$

- The relation between penetration length and p-air cross section can be
- found from simulations after correcting the low energy values using
- Tevatron measurements, and Glauber theory.



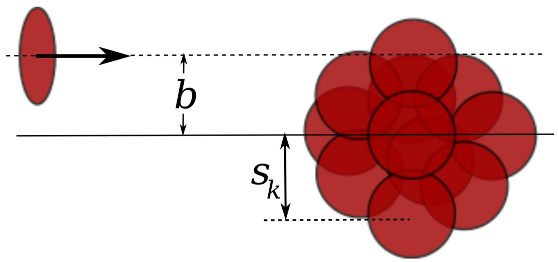
Description	Impact on $\sigma_{p\text{-air}}$
Λ_η systematics	± 15 mb
Hadronic interaction models	$^{+19}_{-8}$ mb
Energy scale	± 7 mb
Conversion of Λ_η to $\sigma^{\text{prod}}_{p\text{-air}}$	± 7 mb
Photons, <0.5 %	$< +10$ mb
Helium, 10 %	-12 mb
Helium, 25 %	-30 mb
Helium, 50 %	-80 mb
Total (25 % helium)	-36 mb, $+28$ mb



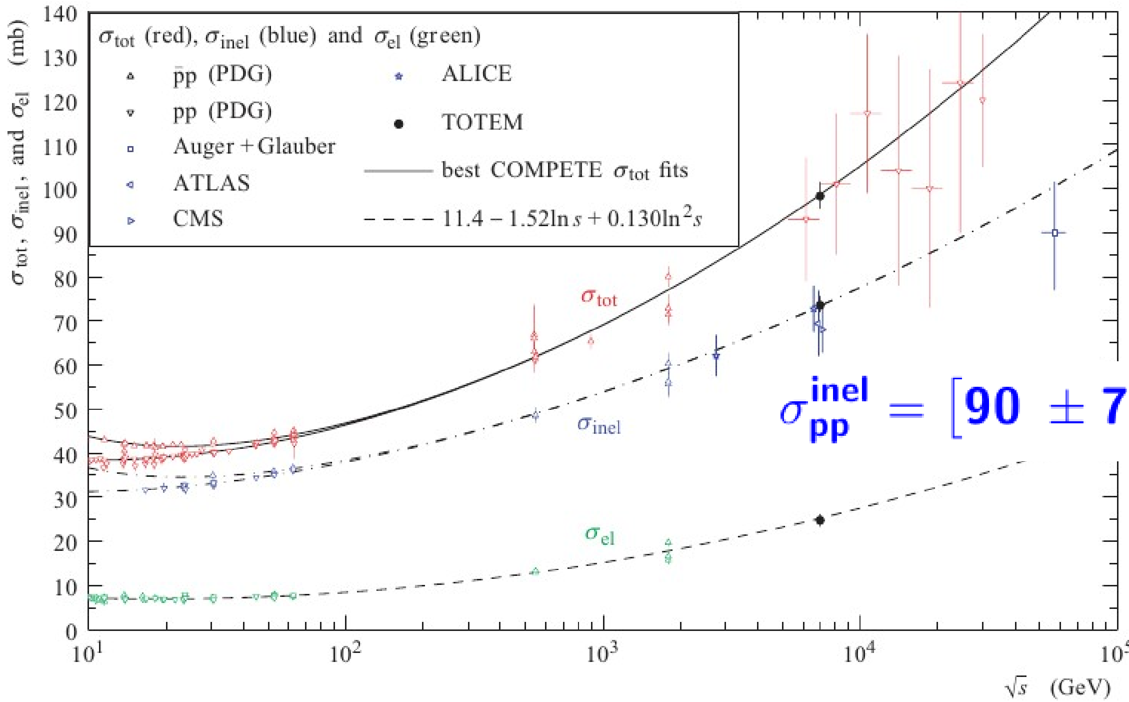
$$\sigma_{p-\text{air}} = \left[505 \pm 22_{\text{stat}} \pm \left(\begin{array}{c} +28 \\ -34 \end{array} \right)_{\text{sys}} \right] \text{mb}$$

Proton-proton cross section

Using Glauber theory is possible to estimate the proton-proton inelastic cross section.



$$\sigma_{pA}^{\rm prod} \approx \int d^2\vec{b} \left\{ 1 - \left[1 - \sigma_{pp}^{\rm inel} \frac{\rho_A(\vec{b})}{A} \right]^A \right\}$$



$$\sigma_{\rm pp}^{\rm inel} = \left[90 \pm 7_{\rm stat} \; (^{+9}_{-11})_{\rm sys} \pm 1.5_{\rm Glauber} \right] \; \rm mb$$

$$\sqrt{s_{\rm pp}} = [57 \pm 6] \; \rm TeV$$

$$(73.5 \pm 0.6^{\rm stat} \; ^{+1.8}_{-1.3} \; ^{\rm syst}) \; \rm mb$$

- CONCLUSIONS

- Far greater exposure is needed to

  - Identify the class of sources via anisotropy
  - Measure the spectra of bright sources or source regions
  - Determine the particle type(s) above 55 EeV
  - If protons, measure interaction properties above 250 TeV (CM)
  - Determine the diffuse cosmogenic intensity of neutrinos and photons
  - Detect cosmogenic neutrinos and photons

Auger

An Air Fluorescence Telescope

30° x 30°
Field of View