# The Pierre Auger Observatory

**Rodrigo Pelayo**
**for the Pierre Auger Collaboration**
BUAP

September 10th, 2012

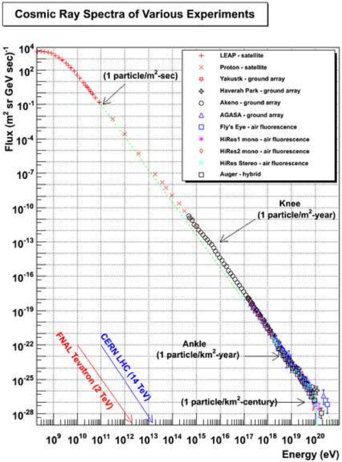
## Objective

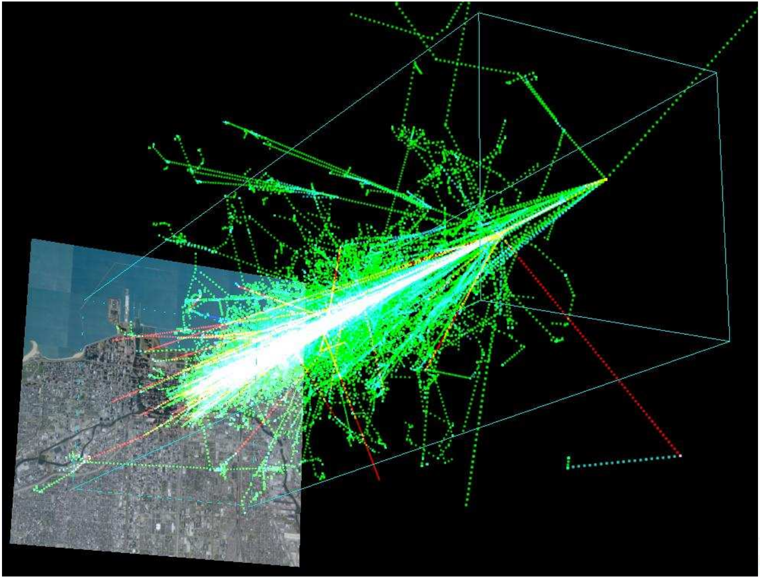
To give a general view of the Pierre Auger Observatory

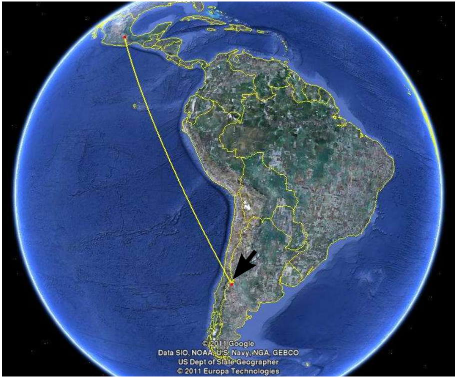
## Summary

- The Pierre Auger
- Air shower reconstruction
- Cosmic rays flux
- Particle physics results

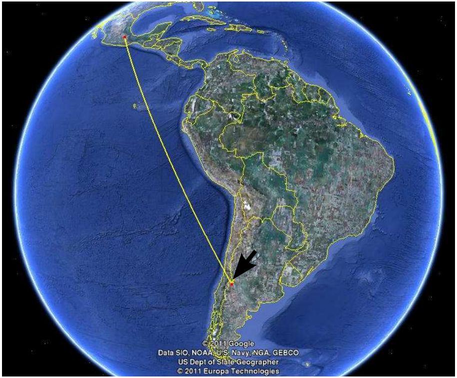
- **Spectrum:** Cosmic ray flux for $E > 10^{18}$ eV.
- **Arrival directions:** Search for anisotropies (identify the sources)
- **Composition:** Light or heavy nuclei, protons, neutrinos, etc?
- **Interactions:** Study interactions at energies unreachable for accelerators.








| | |
|---|---|
| Location: | 35°28′28″S, 69°34′60″ O |
| Elevation: | 1.416 m |
| Surface: | 41.317 km$^2$ |
| Settled: | November 16th, 1850 |
| Population: | 23,020 hab. |
| Demonym: | malargüina/o |
| Typical dish: | Chivito. |

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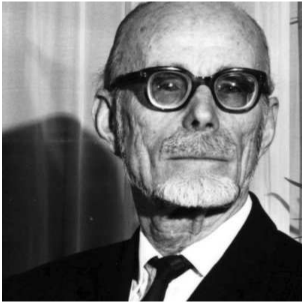
Distance from Puebla to Malargüe : 6,744 km ($\sim$ 60.59°).

# The Pierre Auger Collaboration

### $\sim$ 450 members of 91 instiutions in 18 countries

| | | |
|---|---|---|
| Argentina | Germany | Romania |
| Australia | Italy | Slovenia |
| Brazil | Mexico | Spain |
| Croatia | Netherlands | United Kingdom |
| Czech Republic | Poland | USA |
| France | Portugal | Vietnam |

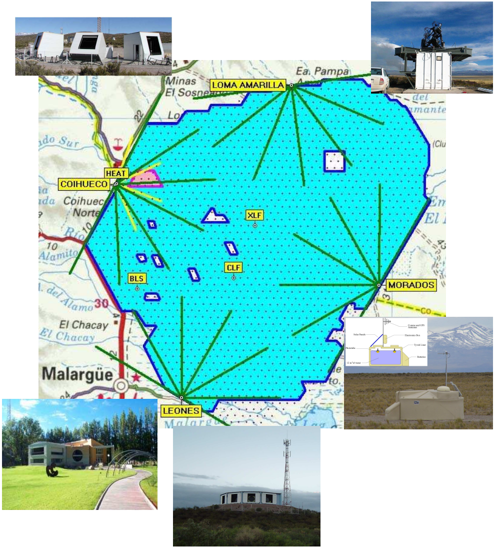


Pierre Auger (1899-1993)

### The Mexican Collaboration

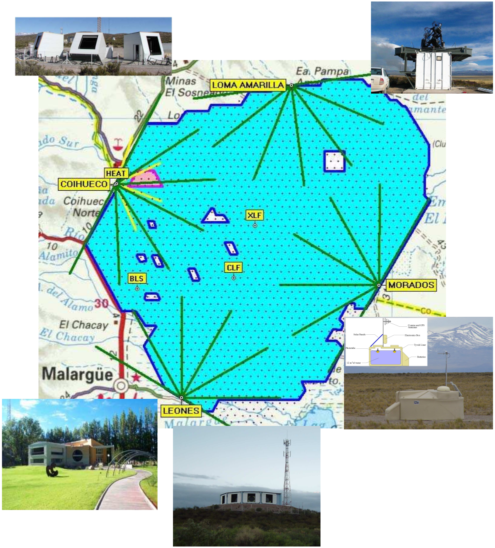
- *Benemérita Universidad Autónoma de Puebla (BUAP)*,
  R. López, O. Martínez Bravo, R. Pelayo, H. Salazar, E. Varela
- *Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV)*,
  H. Martínez, A. Zepeda
- *Universidad Michoacana de San Nicolas de Hidalgo (UMSNH)*,
  H.R. Márquez Falcon, L. Villaseñor
- *Universidad Nacional Autonoma de Mexico (UNAM)*,
  J. Alvarez Castillo, C. De Donato, J.C. D′Olivo, G. Medina-Tanco, B. Morales, L. Nellen, H.H. Silva Lopez, J.F. Valdés Galicia, B. Vargas Cárdenas

# The Pierre Auger Observatory




- 1655 Cherenkov surface detectors completed (1664 deployed), separated to 1.5 km. Working 100 % of the time.
  - 69 with separation of 750 m (INFILL & HEATLET).
- 4 Fluorescence detectors (eyes) with 6 luminescence cameras each with field of view of $30^{\circ} \times 30^{\circ}$. Working $\sim$13 % of time
- 1 mobile fluorescence detector with 3 cameras (HEAT).

# The Pierre Auger Observatory

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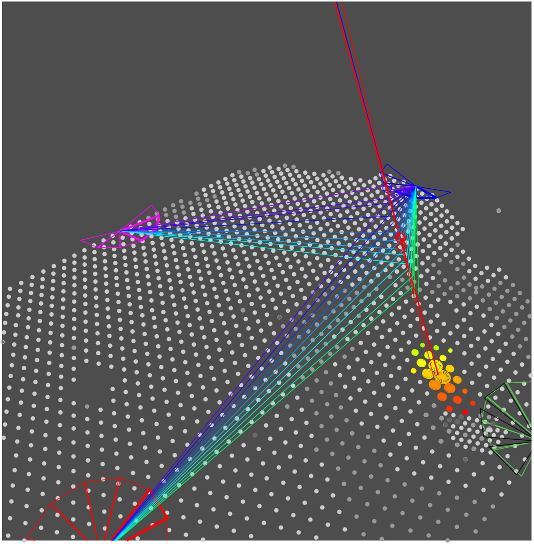
Extensions to extend the lower energy range (AMIGA)

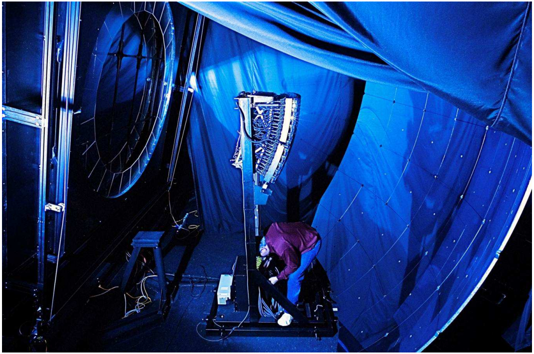
# How big is the Pierre Auger Observatory?

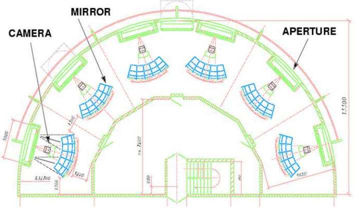
El Observatorio Pierre Auger tiene una extensión de 3,000 $km^2$.


SD centered at the FCFM-BUAP.

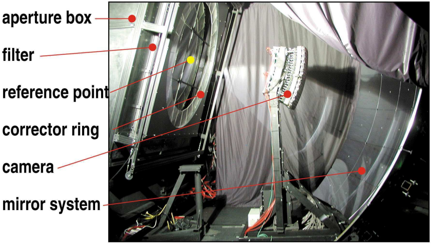
(Google-maps) http://auger.colostate.edu/ED/index.php?map=1

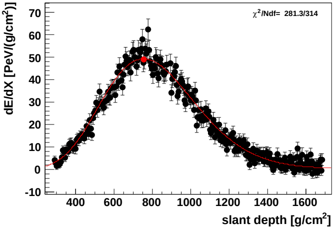




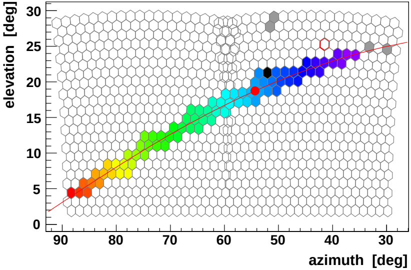



- UV-filter 300-400 nm
- 2.2 m diameter aperture stop with a Schmidt corrector ring.
- 3.8 m $\times$3.8 m mirror.
- camera with 440 PMTs.



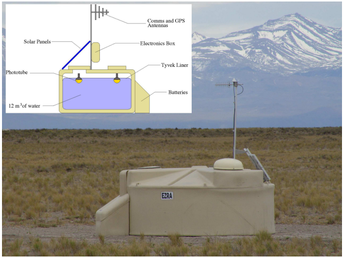

$$E_{FD} = \int dX \frac{dE}{dX}.$$

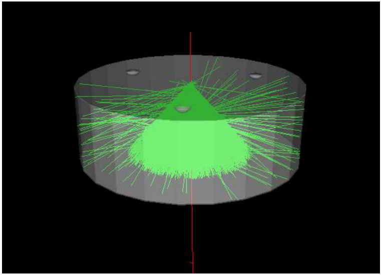



Run 2080 Event 5277
time stamp: 909387522 s 447516043 ns
Trigger: 'Physics - Int or L/R trigger', 'Shower Candidate'
hottest hybrid station: 1716 (TOT), SP = 156 m
Mie attenuation: model
LIDAR: no data ; CloudCam: no data
in Los Morados mirror 2 3 ( in DAQ: 1 2 3 4 5 6 )

E = $(3.25 \pm 0.06) \times 10^{19}$ eV
Xmax = $755 \pm 11$ g/cm$^2$
dEdXmax = $48.99 \pm 0.53$ PeV/(g/cm$^2$)
($\lambda$,X0) = ($64 \pm 4$,$-161 \pm 54$) g/cm$^2$
Cherenkov-fraction = 13%, mva=28 deg.
($\theta,\phi$)=($63.0 \pm 0.2$, $65.7 \pm 0.4$) deg
(x,y)=($44.85 \pm 0.04$, $40.66 \pm 0.09$) km
dca to Eye=$15.71 \pm 0.02$ km

# Reconstruction with the surface detector (SD)



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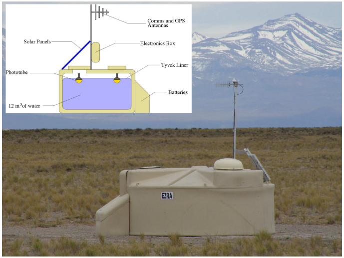
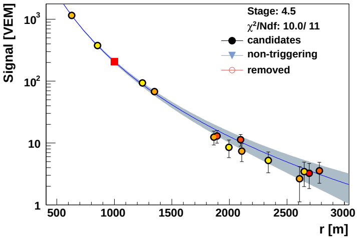
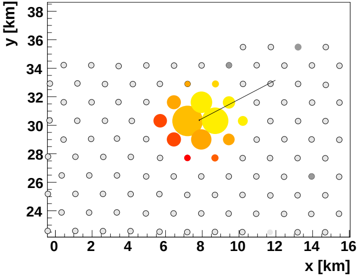
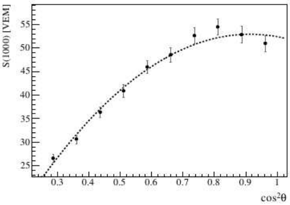


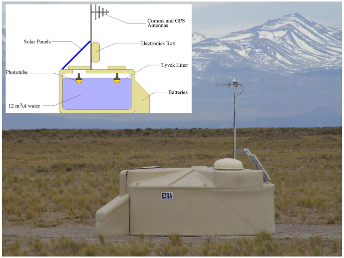



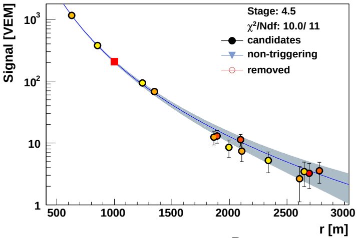



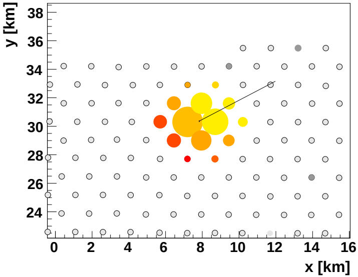

$$S_{38} = \frac{S_{1000}}{1 + ax + bx^2},$$

$$x = \cos^2\theta - \cos^2(38^\circ).$$

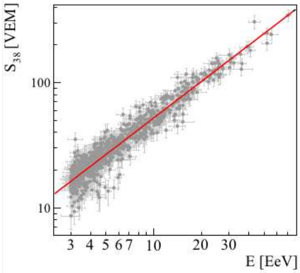



Comms and GPS Antennas
Solar Panels
Electronics Box
Phototube
Tyvek Liner
Batteries
12 m³of water
EZRA

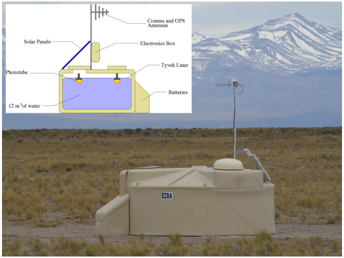

Signal [VEM]
Stage: 4.5
χ²/Ndf: 10.0/ 11
candidates
non-triggering
removed
r [m]

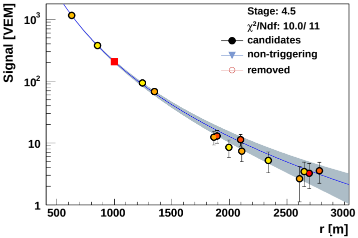

y [km]
x [km]

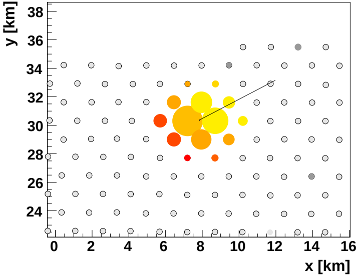
$$E = A\,(S_{38})^B$$


S38 [VEM]
E [EeV]

# Reconstruction with the surface detector (SD)




**Event 9015693 :-)**

**Time 947575892 s 155004000 ns**

**FD & 3TOT & 4C1; 6T5**

**Candidates: 14 (Acc: 7, Bad: 26)**

**$E = (3.94 \pm 0.09) \times 10^{19}$ eV**

**$(\theta, \phi) = (11.9 \pm 0.2, 34.0 \pm 1.0)$ deg**

**$S1000 = 206.6 \pm 4.5 (\pm 8.5)$ VEM**

**$(x,y) = (7.83 \pm 0.00, 30.36 \pm 0.02)$ km**

**$\beta$ (fixed) = -2.49 ( $\pm$ 0.17 )**

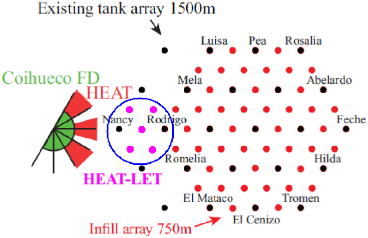
**$\gamma$ (fixed) = 0.20**

**$R = 8.94 \pm 0.43$ km**

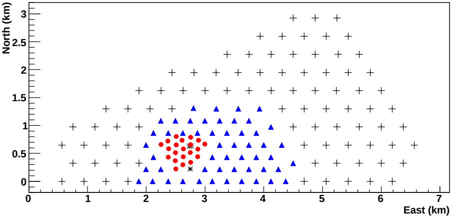
**$r_{opt}$ = 855.50 m**

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

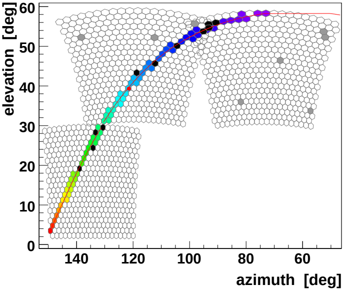
**Amiga:** Auger Muon and Infill Ground Array.



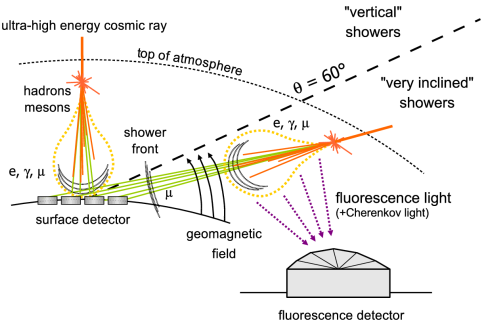

**AERA:** Auger Engineering Radio Array:

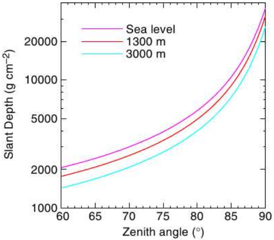


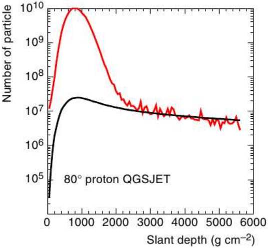

**HEAT:** High Elevation Auger Telescopes.



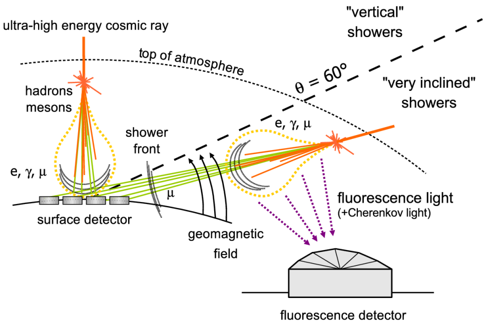
# Inclined (horizontal) air showers [HAS]

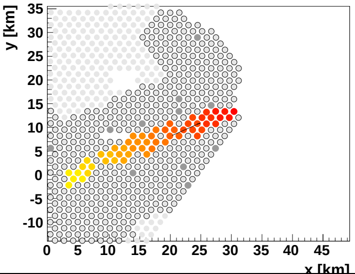


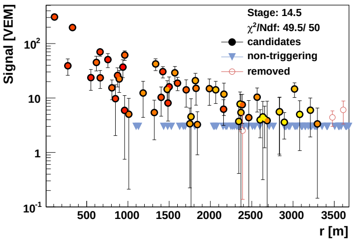



# Inclined (horizontal) air showers [HAS]

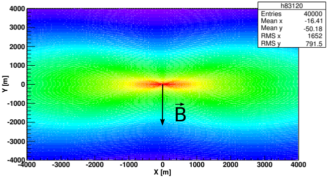


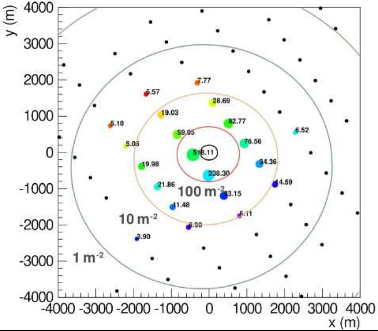



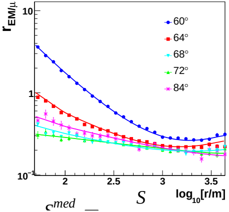
The objective is to estimate the muon number in the tanks:

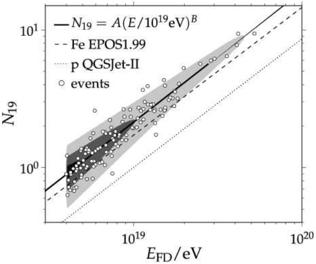
$$N_\mu = N_{19}\rho(x - x_c, y - x_c, \theta, \phi)A_\perp(\theta).$$




83°

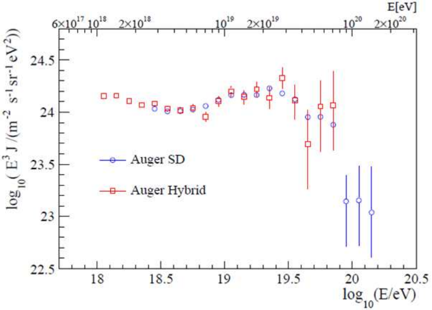


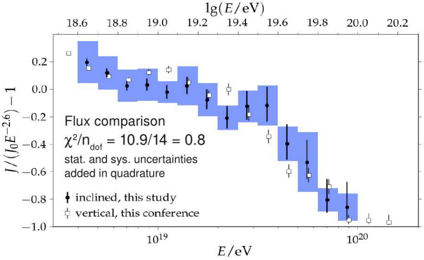

H.Dembinski, T. Hebber, T. Schmidt, GAP 2009-168

G.Rodríguez, et al, ICRC-2011




SD and Hybrid spectrums.

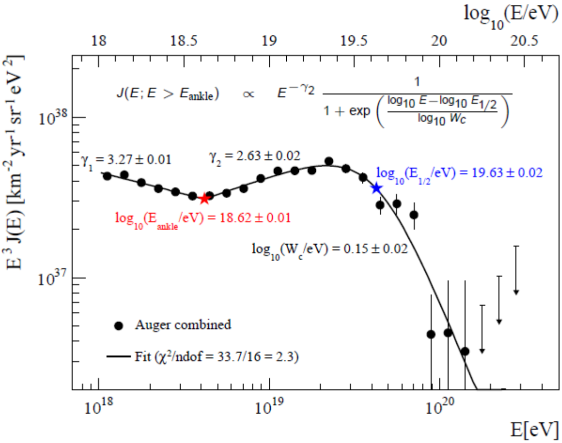
F. Salamida, ICRC 2011




HAS and vertical spectrums.

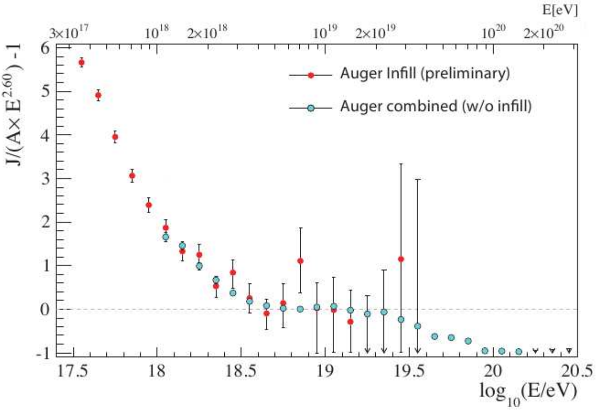
H.Dembinski, ICRC 2011

# Fitting the combined spectrum II - smooth cut-off

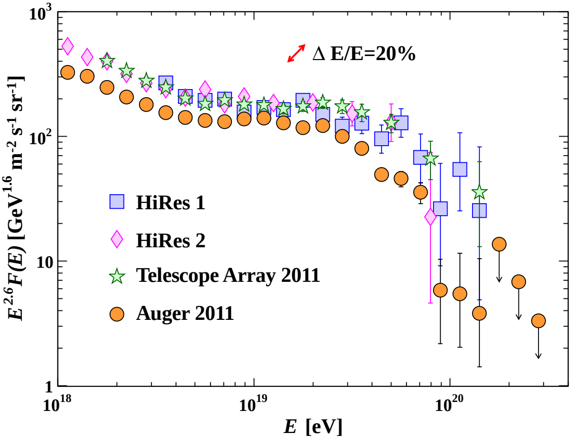



- precise measurement of spectral features
- results compatible with PLB publication

ICRC 2011 By I. C. Maris



# Spectrum compared

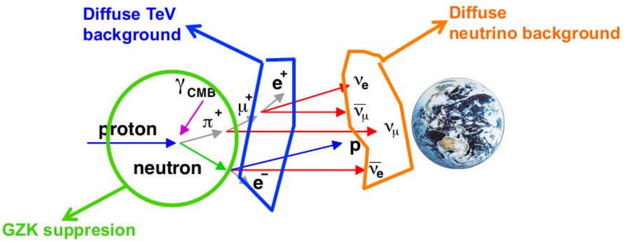



There is a shift of 25 % in the energy respect to Auger.

PDG 2011

# Greisen-Zatsepin-Kuzmin (GZK) limit

**p + CMBR: Photo-pion production & GZK feature**




$$p + \gamma_{CMB} = \begin{cases} \rightarrow n + \pi^+ \\ \rightarrow p + \pi^0 \\ \rightarrow p + e^+ + e^- \end{cases}$$

$\lambda \approx 6$ Mpc / $E_{th}$ ~$10^{19.6}$ eV
$\Delta$E~20% per interaction

$\lambda \approx 1$ Mpc / $E_{th}$ ~$10^{18}$ eV
$\Delta$E~0.1% per interaction

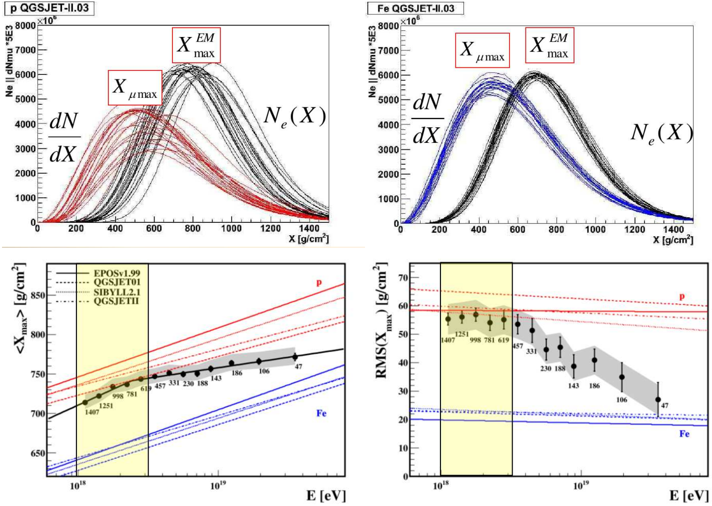
ankle

G. Medina Tanco - ICN/UNAM

# Cross section proton-Air and proton-proton in Auger

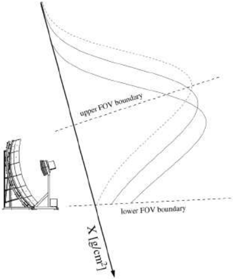
PRL 109, 062002 (2012) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2012

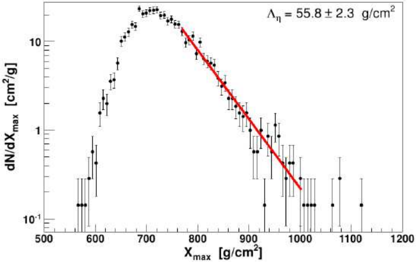
**Measurement of the Proton-Air Cross Section at $\sqrt{s} = 57$ TeV with the Pierre Auger Observatory**

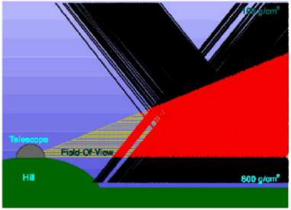



According to composition studies, primaries tend to be mainly protons in the range $10^{18} - 10^{18,5}$ eV.

P.Facal, ICRC 2011



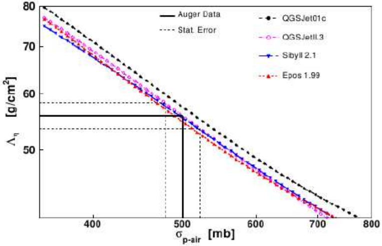




R. Ellsworth et al., Phys. Rev. D 26, 336 (1982).

in a model dependent approach, the tail of the $X_{max}$ distribution is related to the mean free path.

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

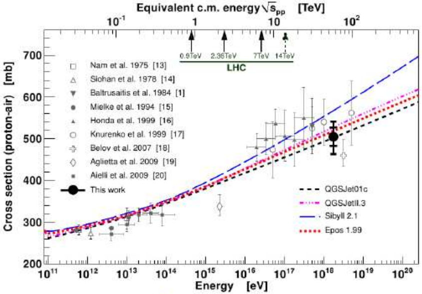
$$\Lambda_\eta = [55.8 \pm 2.3({\rm stat}) \pm 1.6({\rm sys})]\ \ {\rm gcm}^{-2}$$




| Description | Impact on $\sigma_{\text{p-air}}$ |
|---|---|
| $\Lambda_\eta$ systematics | $\pm 15$ mb |
| Hadronic interaction models | $^{+19}_{-8}$ mb |
| Energy scale | $\pm 7$ mb |
| Conversion of $\Lambda_\eta$ to $\sigma^{\text{prod}}_{p\text{-air}}$ | $\pm 7$ 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 |

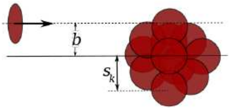
This correlation is obtained after doing a correction at "low energies" with tevatron data using the correction factor:

$$f(E,f_{19}) = 1 + (f_{19} - 1)\frac{\log(E/10^{15}\text{eV})}{\log(10^{19}\text{eV}/10^{15}\text{eV})}$$




$$\sigma^{\text{prod}}_{\text{p-air}} = \left[505 \pm 22(\text{stat}) \; {}^{+28}_{-36} \; (\text{sys})\right] \text{ mb}$$

# Cross section proton-proton



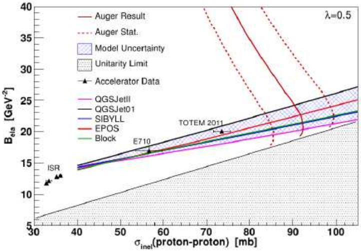

$$\sigma_{\rm tot} = \sigma_{\rm prod} + \sigma_{\rm el} + \sigma_{\rm qe}$$

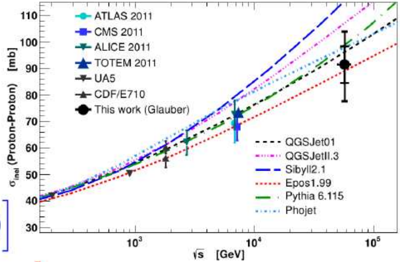
Using the Glauber-Gribov theory for collisions ptoton-nucleus

$$\sigma^{\rm tot}_{hA} = 2\Re e \int d^2\vec{b} \left\{ 1 - \prod_{k=1}^{A} \left[ 1 - \int \rho(\vec{r}_k) a_k(\vec{b} - \vec{s}_k) d^3 r_k \right] \right\}$$

$$\sigma^{\rm el}_{hA} + \sigma^{\rm qel}_{hA} = \int d^2\vec{b} \left\{ 1 - \prod_{k=1}^{A} \left[ 1 - a_k(\vec{b} - \vec{s}_k) \right] \right\} \prod_{k=1}^{A} \left( \rho(\vec{r}_k) d^3 r_k \right)$$

$$a_k(s, \vec{b}_k) = (1 - i\rho) \frac{\sigma^{\rm tot}_{hN}}{4\pi B^{\rm el}_{nN}(s)} \exp\left( -\frac{b^2}{2B^{\rm el}_{hN}(s)} \right)$$



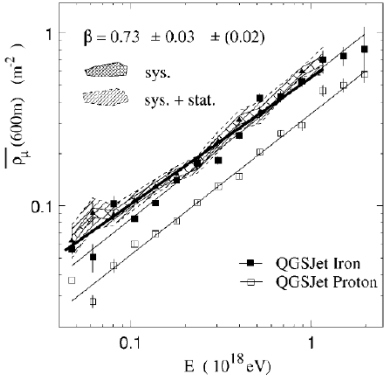




$$\sigma^{\rm inel}_{pp} = \left[ 92 \pm 7({\rm stat}) \begin{array}{c} +9 \\ -11 \end{array} ({\rm sys}) \pm 5({\rm Glauber}) \right]$$

$$\sigma^{\rm tot}_{pp} = \left[ 133 \pm 13({\rm stat}) \begin{array}{c} +17 \\ -20 \end{array} ({\rm sys}) \pm 15({\rm Glauber}) \right]$$

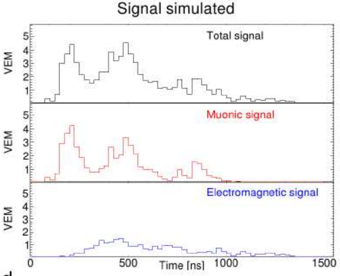
$$\sqrt{s} = \sqrt{2 m_p E_{\rm lab}} = 57 \pm 0.3({\rm stat})\ \text{TeV}$$

The first inconsistency between predicted and measured muon number were found by HiRes-MIA [PRL **84**, 4276(2000)] and confirmed by KASCADE-Gande [Czech J. Phys **56**, A241(2006)].



The Pierre Auger Observatory does not have a muon detector and, it is not possible to separate the muonic component from the signal of the surface detector stations. For this reason there has been developed several methods for muon counting.

$$S_{tot} = S_\mu + S_{em}$$




- **Smoothing:** Iterative method averaging the FADC signal in Nbins and countind de positive differences bin by bin. This difference is correlated to the muon number. This method has an uncertainty of 8 %.

- **Multivariate:** Complex method that uses multivariate analysis and artificial neural networks to predict the number of muons. Uncertainty of 6 %.

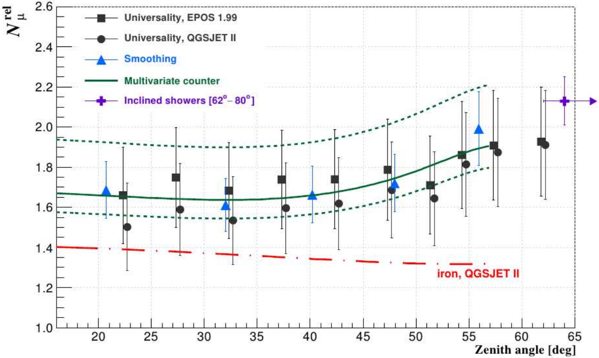
- For **inclined showers** (zenith angle > 60°) the muon number is infered using a library of MC muon maps at $10^{19}$ eV related to energy through calibration constants A, B. Uncertaity of 15 %.

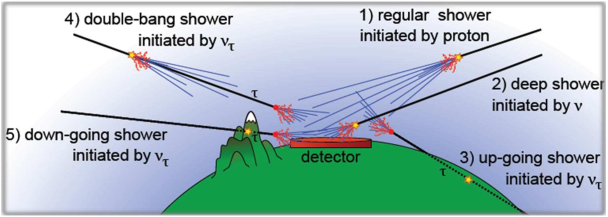
$$\frac{n_\mu^{\text{data}}}{n_\mu^{\text{MC}}} = \frac{N_{19}^{\text{data}}}{N_{19}^{\text{MC}}} = \frac{A(E_{\text{FD}}/10\ \text{EeV})^B}{A_{\text{MC}}(E_{\text{FD}}/10\ \text{EeV})^{B_{\text{MC}}}}$$

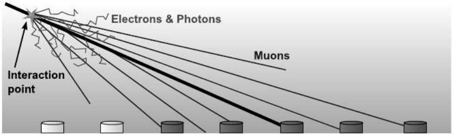
- **Universality:** It is possible to get a relation of the muon number and $X_{max}$.

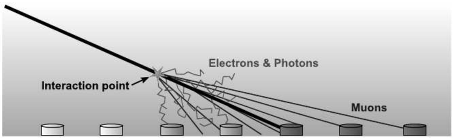
$$S_\mu^{\text{fit}} = \frac{\text{S}\,(1000)}{1 + \cos^\alpha(\theta)/\left((X_{\max}^{\text{v}}/A)^{1/b} - a\right)}$$

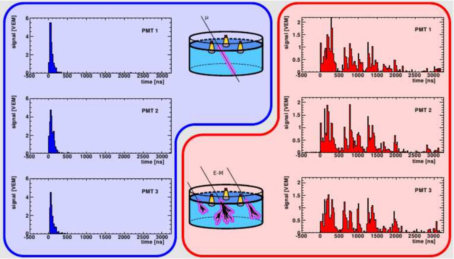
# Summary of muon deficit measured by Auger with different methods



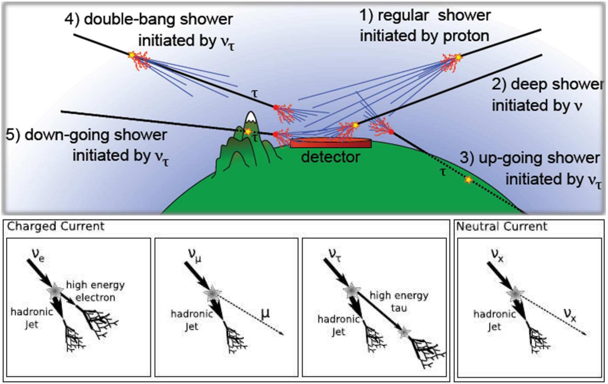

4) double-bang shower
initiated by $\nu_\tau$
1) regular shower
initiated by proton
2) deep shower
initiated by $\nu$
5) down-going shower
initiated by $\nu_\tau$
$\tau$
detector
3) up-going shower
initiated by $\nu_\tau$

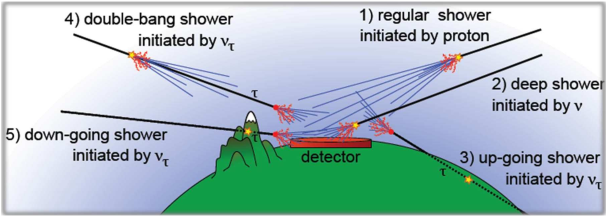

Electrons & Photons
Muons
Interaction
point

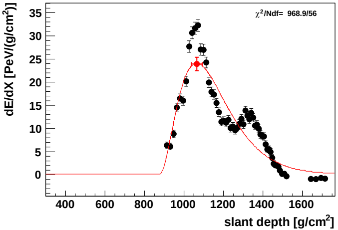

Electrons & Photons
Interaction point
Muons

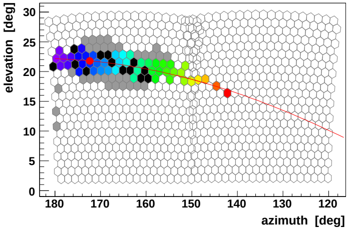

PMT 1
PMT 2
PMT 3
signal [VEM]
time [ns]
E-M

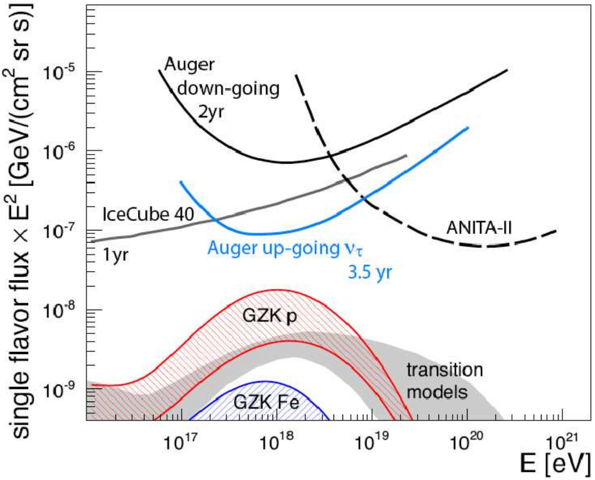
# Neutrino searches




4) double-bang shower
initiated by $\nu_\tau$
1) regular shower
initiated by proton
2) deep shower
initiated by ν
5) down-going shower
initiated by $\nu_\tau$
detector
3) up-going shower
initiated by $\nu_\tau$
τ


$\chi^2$/Ndf= 968.9/56
dE/dX [PeV/(g/cm²)]
slant depth [g/cm²]
0
5
10
15
20
25
30
35
400
600
800
1000
1200
1400
1600


elevation [deg]
azimuth [deg]
0
5
10
15
20
25
30
180
170
160
150
140
130
120




Salamida, 2012