Depth of maximum of air-shower profiles at the Pierre Auger Observatory

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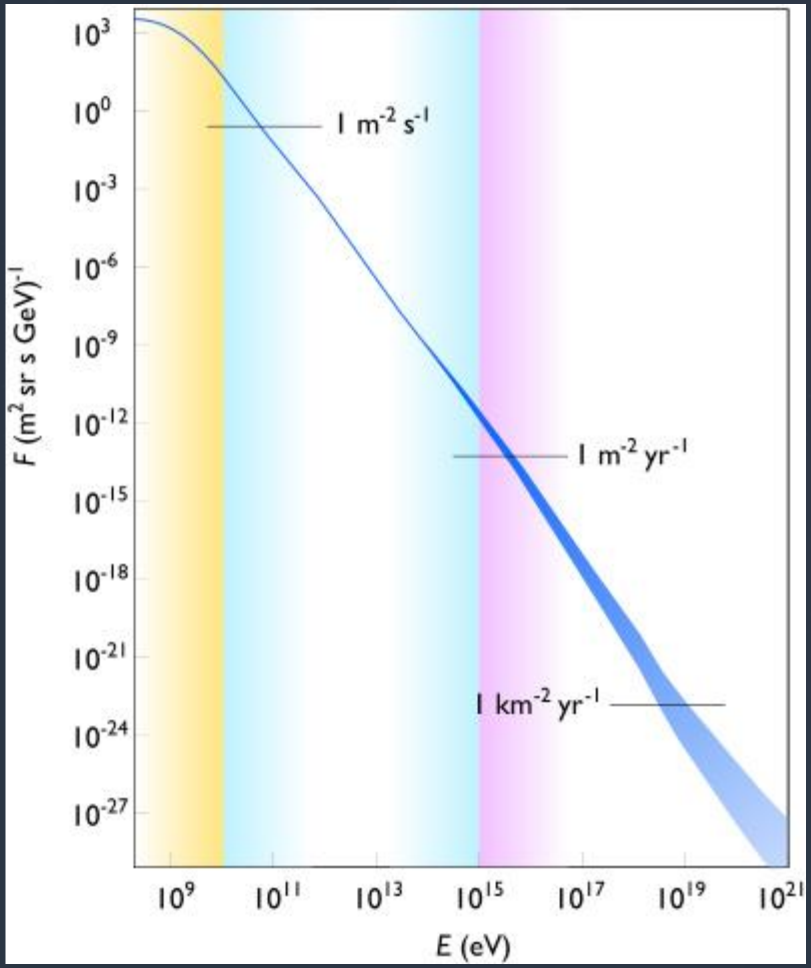
Cosmic Rays

Pros

- Energies up to $10^{21}\ eV\ \ (\sqrt{s} = 1000\ TeV)$
  Cern highest energy $\sqrt{s} = 13\ TeV$ (2015)
- Free of charge!

Cons

- Low flux at high energies
- No control over incoming direction
- No control over initial energy
- Unknown composition of incoming particle



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Low Flux and random incoming angles?
Lets built something **Really Big!!!**

Malargüe, Province of Mendoza, Argentina
Detection Area of $3000\ km^2$

Surface Detector Array (SD)
- 1600 water-Cherenkov detectors
- Triangular Grid with a $1500\ m$ spacing
- Small subgrid with a $750\ m$ spacing

Fluorescence Detector (FD)
- 24 telescopes (4 group of 6 telescopes)
- Perimetrical to overlook the entire array
- Camera covers elevation angles from 1.5^o to 30^o
  azimuth angle 30^o
- Ultraviolet light

Not so “Free of charge” after all… 50 million (Cern 4.5 billion)

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Number of incoming beam inside a medium

$$N(z) = N_o e^{-\sigma n z}$$

If the density of the medium is not constant

$$N(z) = N_o e^{-\frac{\sigma}{m} X(z)}$$

Slang depth

$$X(z) = \int_z^{\infty} \rho(z')dz'$$

But there is a special Slung depth $X_{\max}$.
It is where the shower's energy deposit is maximum.

$$X_{\max} \sim \ln A$$

Fluctuation in the first few hadronic interaction.
Statistical distribution

$$f(X_{\max}) = \sum_i p_i f_i(X_{\max})$$

More realistic

$$f_{\text{obs}}(X_{\max}^{\text{rec}}) = \int_0^{\infty} f(X_{\max})\varepsilon(X_{\max})R(X_{\max}^{\text{rec}} - X_{\max})dX_{\max}$$

In an ideal detector $\mathcal{E}$ is constant and R is close to a delta function.

- Observe the distribution and draw conclusions for hadronic interactions.
  p-p cross section at $\sqrt{s} = 53\ TeV$
- Hypothetical models for hadronic interactions calculate $X_{\max}$.
  Corsika program

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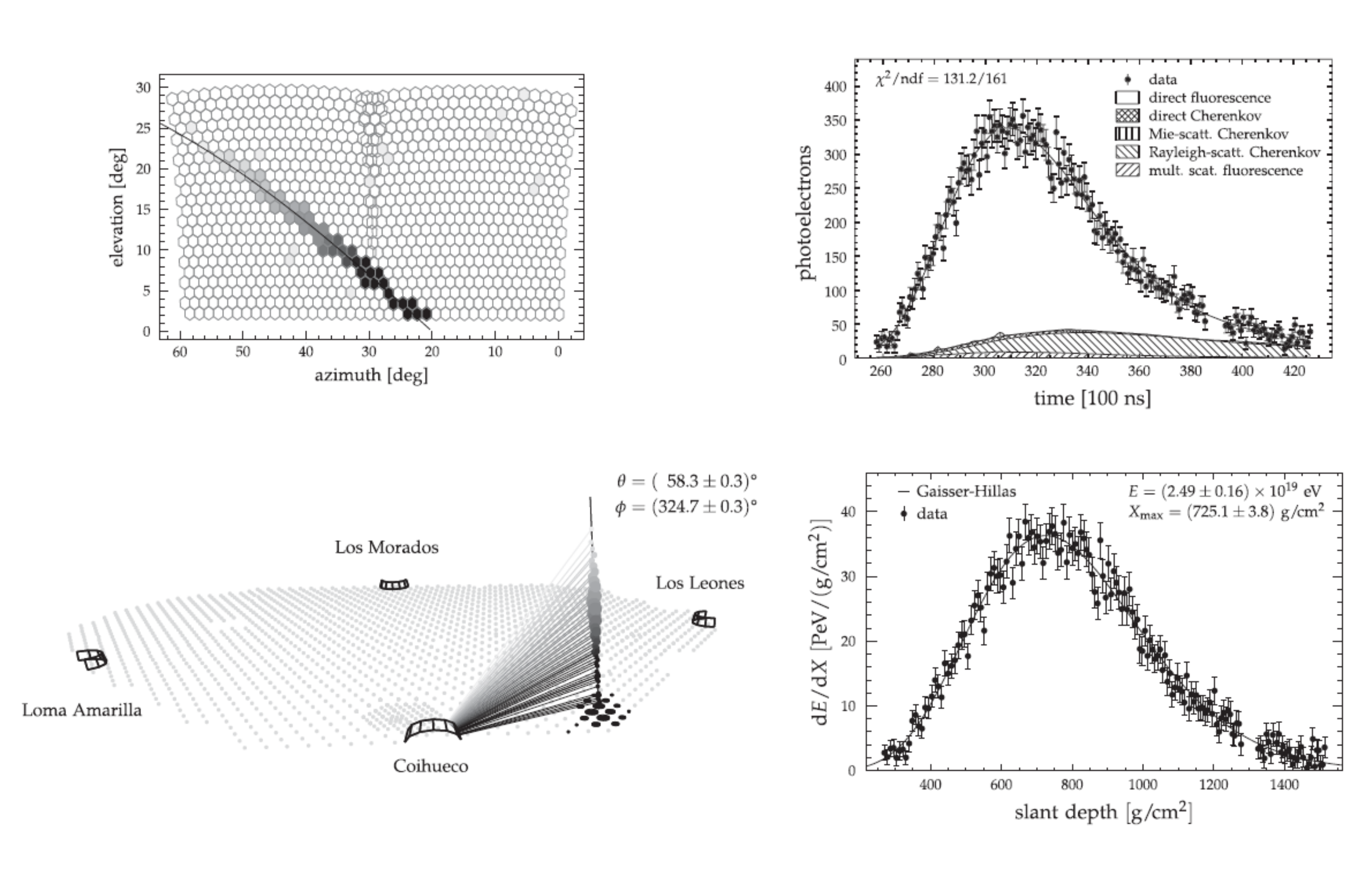
- FD detects light from an event.
- A Three dimensional reconstruction of the shower.
- Time, path length, height and slang depth Data.
- Light data corrections due to Rayleigh and Mie Scattering.
- Fluorescence photons - energy deposit.
- Cherenkov photons - charged particles.
- Energy is obtained by integration +(10-15)% neutrinos
- $X_{\max}$ from Gaisser - Hillas function.



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Dec 2004 – Dec 2012

Pre-selection Cuts

- Uncertain relative times FD – SD, misaligned telescopes
- Aerosol measurement within one hour
- Full shower reconstruction (Thunders)
- Shower trajectory far away or close enough
- Trajectory passing though clouds
- Energy lower than 10^17.8 eV

Quality Cuts

- At least one SD trigger
- $X_{\max}$ observed in field of view
- $X_{\max}$ with large errors from Gaisser – Hillas
- Fiducial Field of view
- Gaps in the profile

TABLE I. Event selection criteria, number of events after each cut and selection efficiency with respect to the previous cut.

Cut	Events	ε [%]
Pre-selection:		
Air-shower candidates	2573713	...
Hardware status	1920584	74.6
Aerosols	1569645	81.7
Hybrid geometry	564324	35.9
Profile reconstruction	539960	95.6
Clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
Quality and fiducial selection:		
P(hybrid)	105749	95.1
$X_{\max}$ observed	73361	69.4
Quality cuts	58305	79.5
Fiducial field of view	21125	36.2
Profile cuts	19947	94.4

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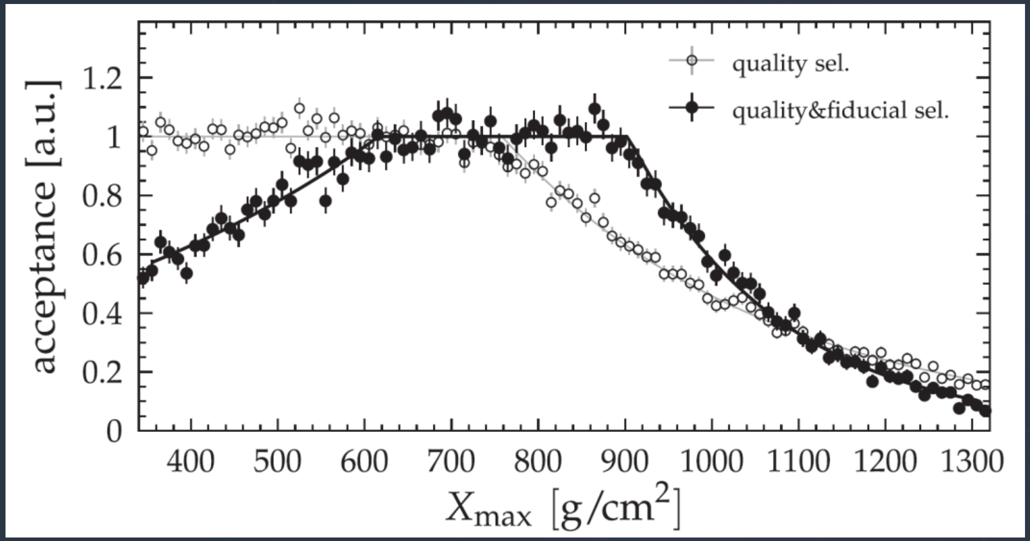
Time dependent Simulations for the atmosphere, the FD and the SD detectors.

$$\text{efficiency} = \frac{\text{Selected events}}{\text{Generated events}}$$

"The shape of the longitudinal energy-deposit profiles of the air showers at ultrahigh energies is, to a good approximation, universal, i.e., does not depend on the primary particle type or details of the first interaction".

Thus the acceptance depends only on the and the energy and $X_{\max}$.



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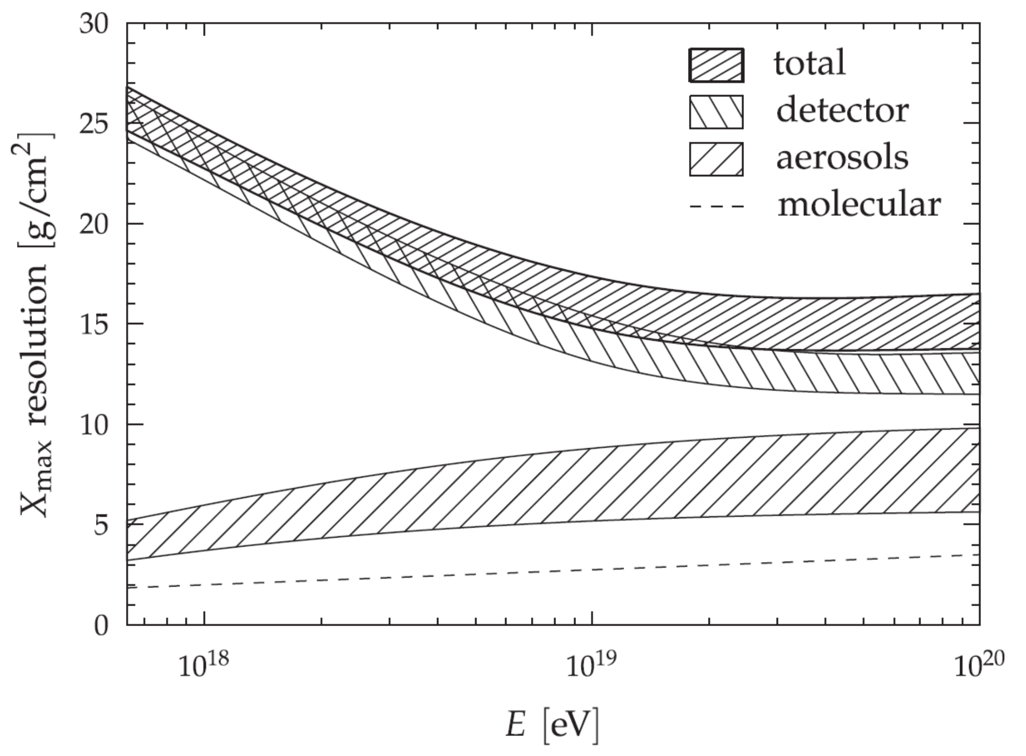
Broadening of the original distribution by statistical fluctuations of $\langle X_{\max}^{\mathrm{rec}} \rangle$ around $\langle X_{\max} \rangle$.

- Detectors
  1. Number of photoelectrons and GH fit
  2. Alignments of the telescopes
  3. time of arrival between FD and SD detectors
- Aerosols measurements
- Molecular Atmosphere

$$R(X_{\max}^{\mathrm{rec}} - X_{\max}) = fG(\sigma_1) + (1-f)G(\sigma_2)$$



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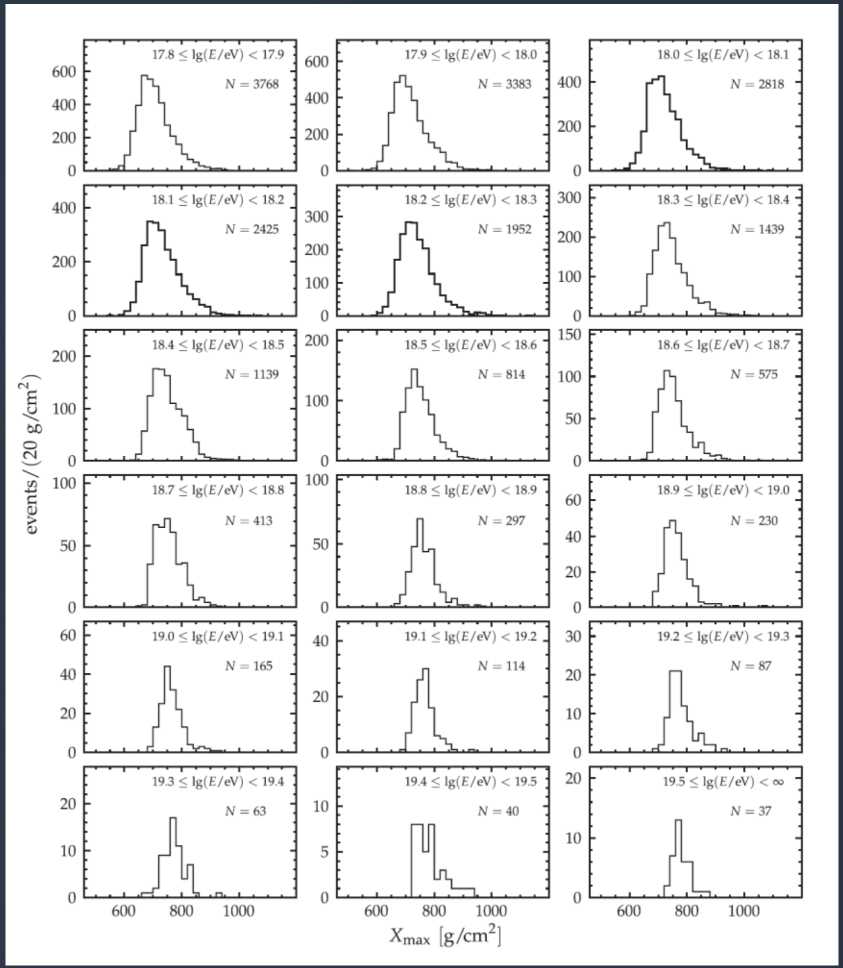

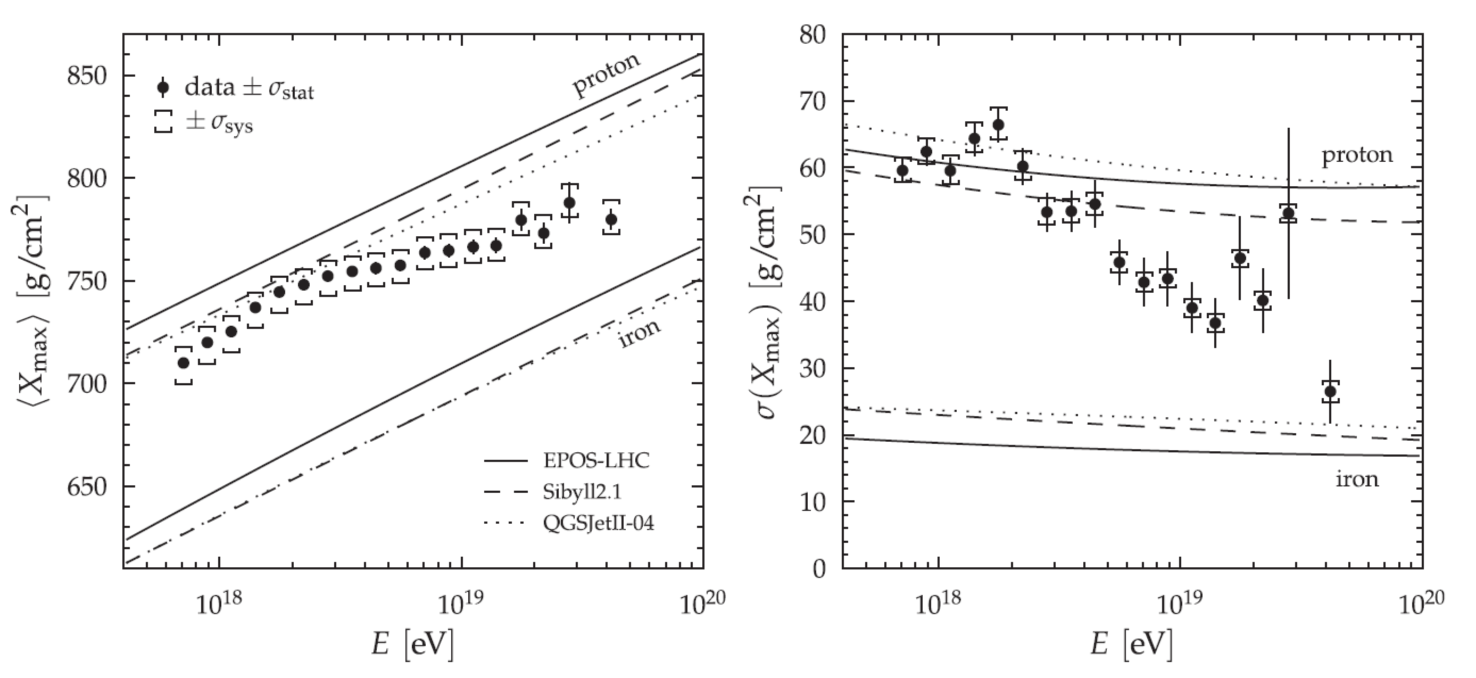

$$\langle X_{\max} \rangle = c + D \ln E$$

Thank you for your time