Measurement of the average electromagnetic longitudinal shower profiles at the Pierre Auger Observatory

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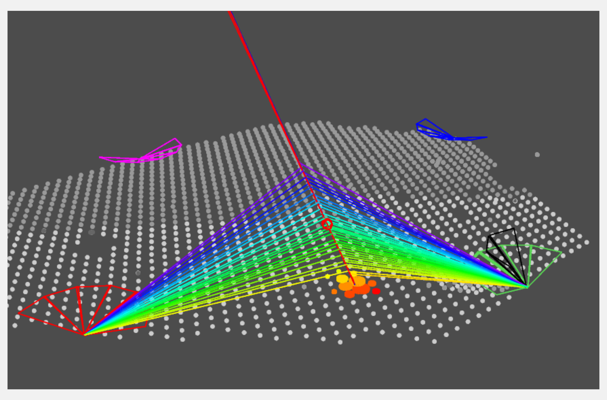
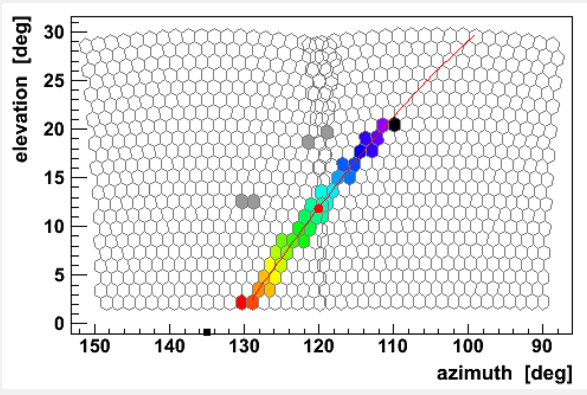
In addition to the standard X_{max} and energy, the longitudinal profiles of extensive air showers also contain interesting information. For energies above $10^{17.8}$ eV, we present the average profiles as a function of depth measured for the first time at the Pierre Auger Observatory. The profile shapes for different energy ranges are all well reproduced by a Gaisser-Hillas function. A detailed analysis of the systematic uncertainties is done using data and a full detector simulation, and the results are compared with predictions of hadronic interaction models for different primaries.

Hybrid event reconstruction in Auger

The Pierre Auger Observatory consists of:

- 3000 km² Surface Detector array
- 1660 stations taking data in coincidence
- 4 x 6 Fluorescence Detector telescopes spanning 1.5º to 30º in elevation (3 extra telescopes observe higher elevations, not used in this analysis)
- Several autonomous atmospheric Mmnitoring tools





Event reconstruction is done in sequence:

- geometry from pixel pointing directions + timing (including 1 SD station)
- light emission, taking into account atmospheric attenuation
- profile fit including all light components (fluorescence and Cherenkov)
- the fit, with some shape constraints, returns the shower maxima $(dE/dX)_{max}$ and X_{max}

The construction of the average electromagnetic longitudinal profile

The maxima of the shower ($(dE/dX)_{max}$, X_{max}) change with energy and composition.
The shape is almost universal but still has information on shower development properties

- it can be described by a Gaisser-Hillas function

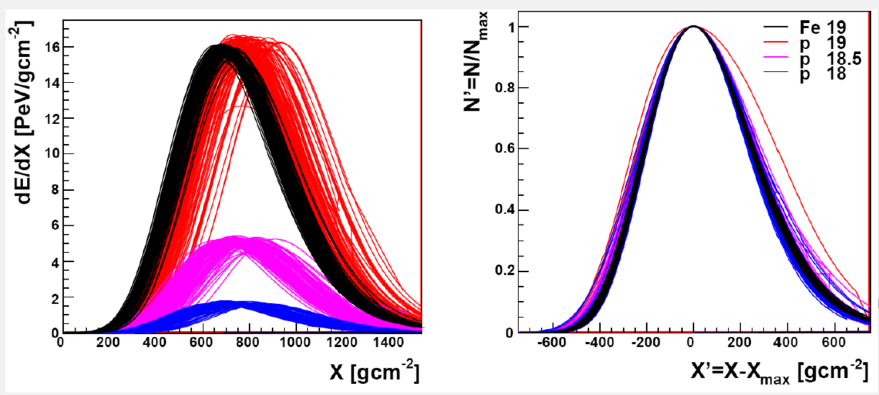
$$\left(\frac{dE}{dX}\right)' = exp\left(-\frac{1}{2}\left(\frac{X'}{L}\right)^2\right)\prod_{n=3}^{\infty} exp\left(-\frac{R^{n-2}}{n}\left(-\frac{X'}{L}\right)^n\right)$$

$$= \left(1+R\cdot\frac{X'}{L}\right)^{R^{-2}} exp\left(-\frac{X'}{R\cdot L}\right)$$

This function can be written as a Gaussian of width L, with a distortion term governed by R. This becomes apparent when the profiles are translated to X_{max} and scaled by $(dE/dX)_{max}$, i.e:

- $X' = X - X_{max}$
- $(dE/dX)' = (dE/dX) / ((dE/dX)_{max}$

This plot shows simulation of different primaries and energies (left) and the same profiles after each being translated by its own X_{max} and $dEdX_{max}$



In this work we want to:

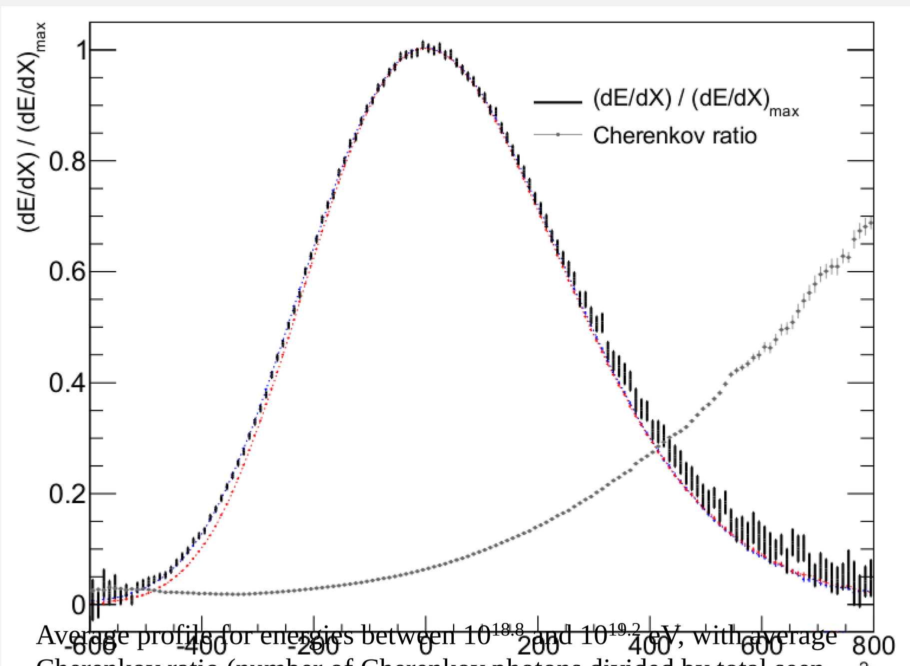
- Verify the shape is as expected (and used in Auger for light component separation), at least around the maximum, where it has enough light and fluorescence still dominates.
- Cross-check the shape is consistent for different measurement conditions

Event selection

The data selection is based on the one done in the latest Auger X_{max} paper.
The used events are selected with:

- good hybrid geometry
- long showers (> 300g/cm²) with expected X_{max} resolution < 40 g/cm²
- low Cherenkov contribution (shower axis to telescope angle >20º)
- good atmosphere (aerosol measurement and no clouds)
- less than 25% of pixels incompatible with the geometry time fit
- one telescope excluded due to alignment problems

In total 15782 events were selected. Data is divided in 6 energy bins, and each profile in 10 g/cm² bin in distance to X_{max}, where we average the normalized deposited energy, weighted by its squared error.

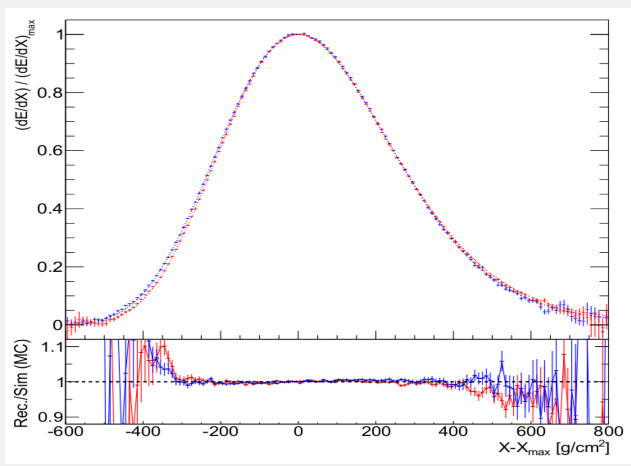


Average profile for energies between $10^{18.8}$ and $10^{19.2}$ eV, with average Cherenkov ratio (number of Cherenkov photons divided by total seen photons) superimposed

Monte Carlo Validation

Shower simulations were performed:

- using Corsika,
- QGSJetII03 as high energy hadronic interaction model
- from 10^{17} to 10^{20} eV,
- following data taking conditions.



These showers are then propagated through a full detector simulation:

- Reconstructed showers follow simulated ones in a large range around the center.

In the figure to the left are shown simulated (thin lines) and reconstructed (thick lines) for proton (blue) and iron (red) initiated showers

Gaisser-Hillas fit

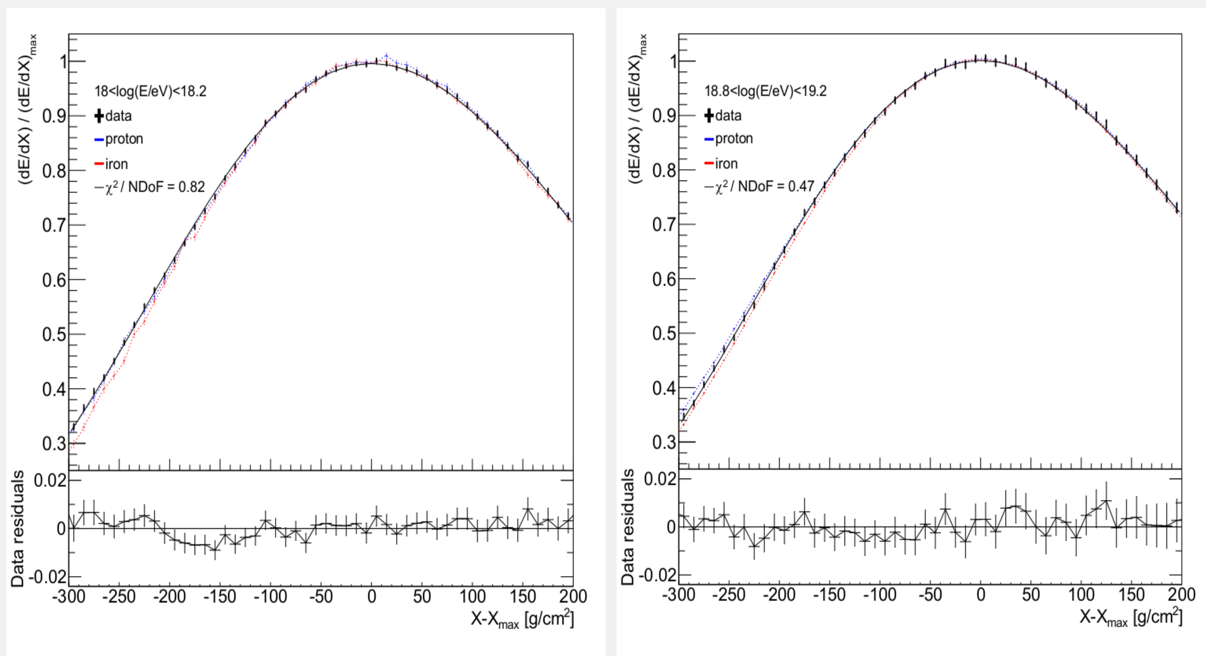
Data is compared with the simulation for the central profile, X' in [-300, 200] g/cm²

The fits were done with four parameters:

- R
- L
- free maximum in depth and normalization to account for experimental resolution.

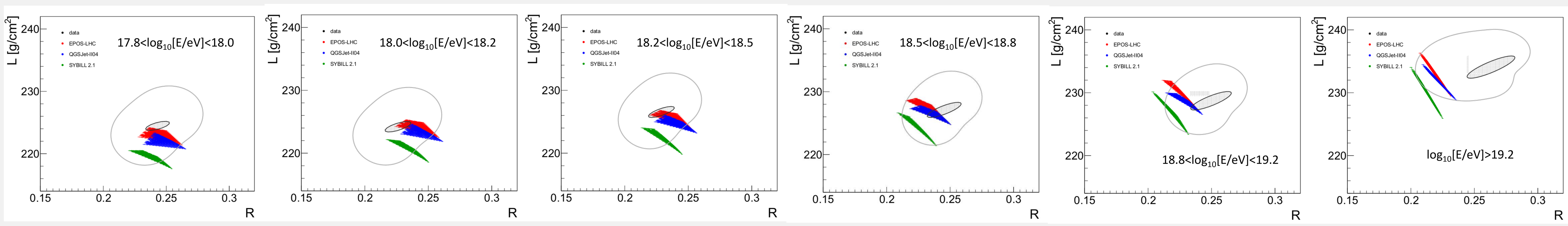
The data are fully compatible with a Gaisser-Hillas longitudinal profile within the defined range and the shape parameters can be retrieved with very high statistical precision.

The residulals of the data fit in each bin are shown in the lower plots.



Profiles for low energy (10^{18} to $10^{18.2}$ eV, left) and high energy ($10^{18.8}$ to $10^{19.2}$ eV, right)

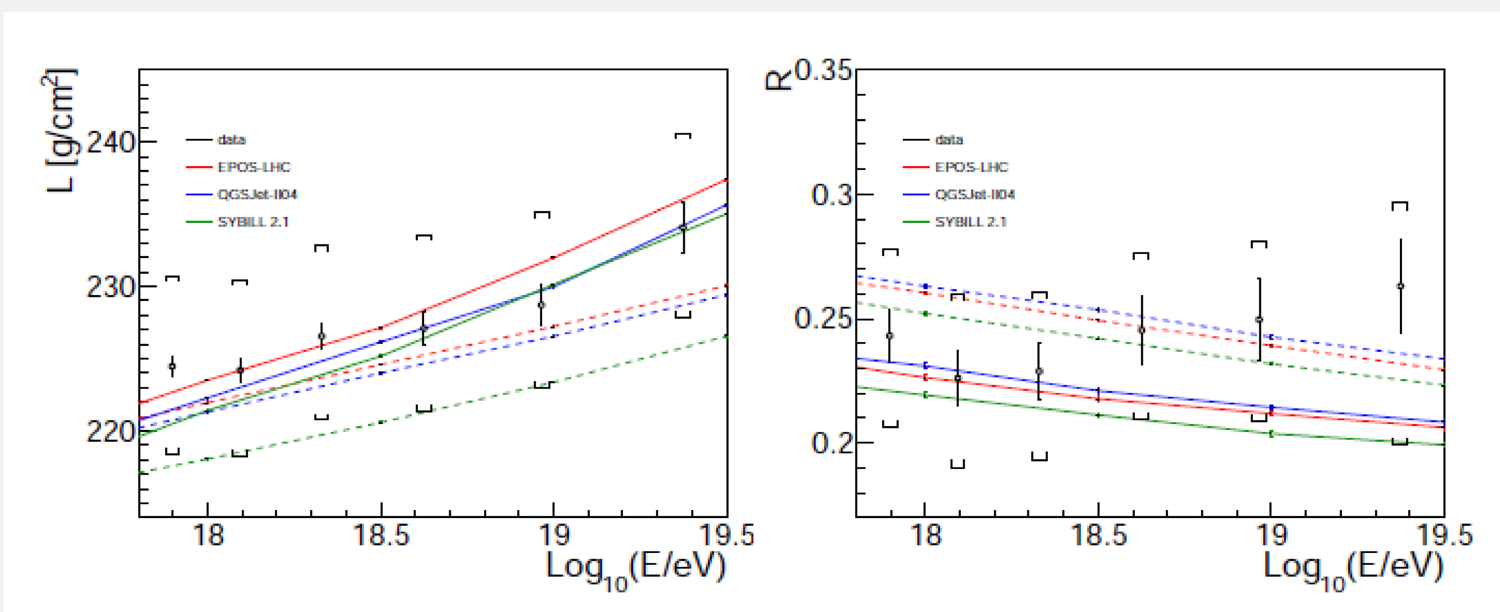
Results and systematic uncertainties



Atmospheric conditions (clouds, aerosol distribution, season of the year) change mainly the asymmetry, R.
Light component separation (emission yields, multiple scattering, and final fluorescence percentage) change mostly the width, L.
There are also telescope-to-telescope differences not fully explained by simulations.
Sources of uncertainties include also selections in geometry or the uncertainties from proton/iron reconstruction bias and of the energy scale of 14%.

	R	L [g/cm^2]
Atmosphere	0.053	3.6
Light components & fit	0.011	4.0
Telescope	0.023	3.2
Geometry	0.018	2.0
Bias corr. & Energy	0.007	0.6
Total	**0.063**	**6.3**
Statistical	0.019	1.8

The energy evolution of L and R in data is compared with proton and iron expectations from the different models (plot below). Black lines represent statistical errors while brackets represent the systematic uncertainty. L increases as predicted; R also increases, which is not expected, but is within systematic uncertainties.
The correlation between the two variables can be exploited by showing, for fixed energy, one variable as a function of the other (upper plots). In these plots also all possible compositions (combination of proton, helium, nitrogen and iron) are shown for all hadronic interaction models.



Conclusions

In this work, the average longitudinal profile shape of the air showers in the Pierre Auger Observatory was measured.
We first validated the method in a full detector simulation of proton and iron primaries, which showed that reconstructed and simulated profiles are in very good agreement for all energies above $10^{17.8}$ eV.
We have shown that average profiles on data are well described by a Gaisser-Hillas function through the entire fitting range chosen.
We estimated the systematic uncertainties contributing to our measurement, and concluded that the atmospheric description and he Cherenkov contribution are the main factors that affect the asymmetry and the width of the profile, respectively.
The two shape parameters, R and L, resulting from this fit were compared with model predictions, being fully compatible with them.