Average shape of longitudinal shower profiles measured at the Pierre Auger Observatory

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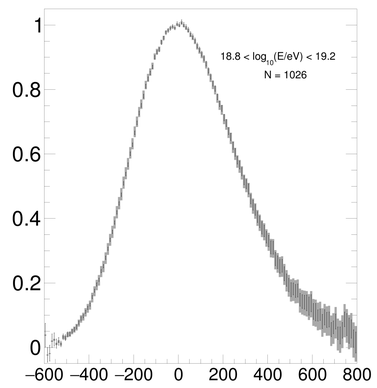
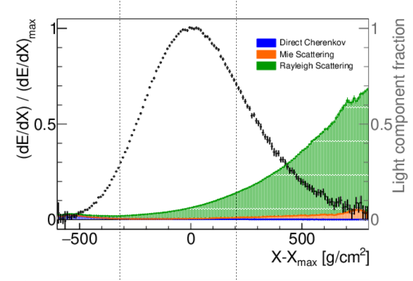
== Constructing high accuracy profiles ==



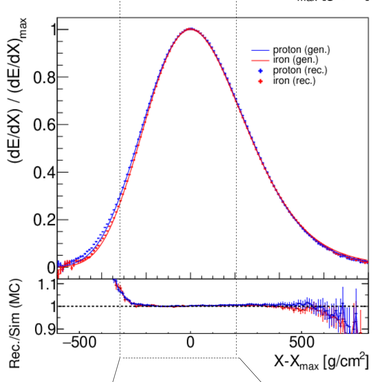
Normalized dE/dX (X-Xmax) averaged over selected events

> same data as used for unbiased analysis of Xmax distributions (excluding 1 / 24 telescopes)



Average shower profile in data, and fraction of light components

> fluorescence light is directly proportional to energy deposits



Average shower profile in MC, as generated and reconstructed

> sensitivity to different start-up of proton and iron showers

== Measuring two new observables ==

The average profiles of cosmic ray showers developing with traversed atmospheric depth are measured for the first time, with the Fluorescence Detectors at the Pierre Auger Observatory.

The profile shapes are well reproduced by the Gaisser-Hillas parametrization, at the 1% level in a 500 g/cm² interval around the shower maximum, for cosmic rays with log(E/eV) > 17.8. The results are quantified with two shape parameters, measured as a function of energy.

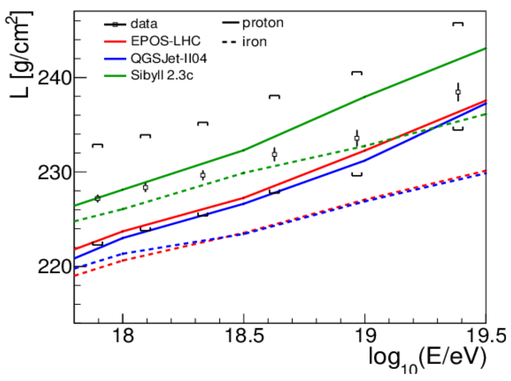
Gaisser-Hillas function re-written as

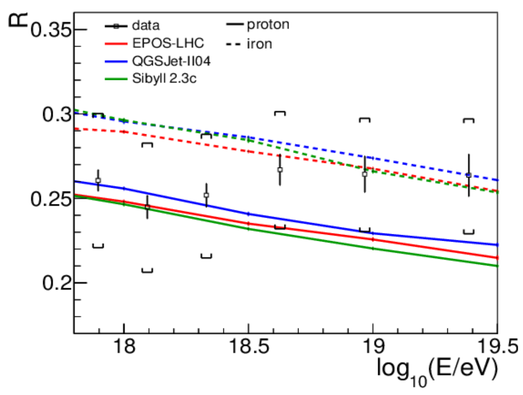
$$(\mathrm{d}E/\mathrm{d}X)' = \left(1 + R\,\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{R\,L}\right)$$

$L = \sqrt{|X_0'|\lambda}$ is a Gaussian width, can be different between models

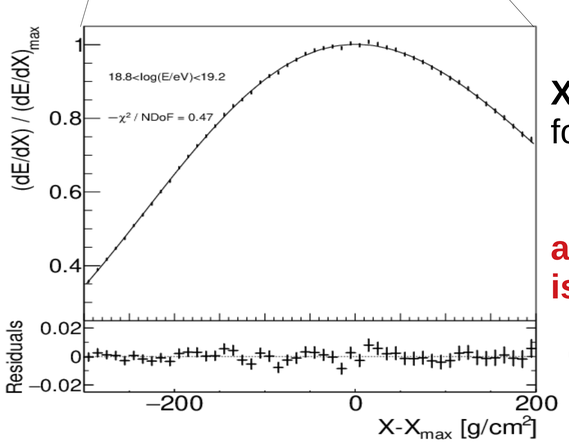
$R = \sqrt{\lambda/|X_0'|}$, is an asymmetry, similar composition dependences

model predictions for shower shapes compatible with data (within uncertainty)





== Precision checks of the shower reconstruction procedures ==



X' = X-Xmax in [-300,200] g/cm² for precise quantification of shape

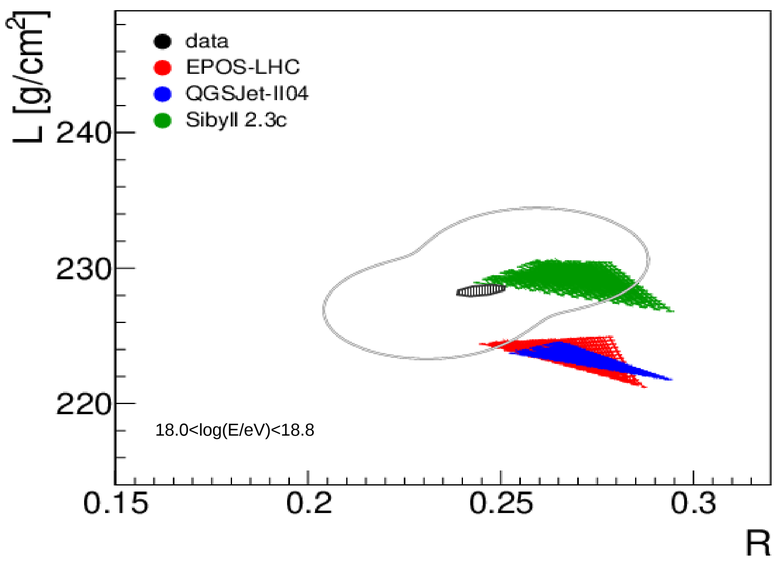
average longitudinal profile shape is a Gaisser-Hillas to 1% precision

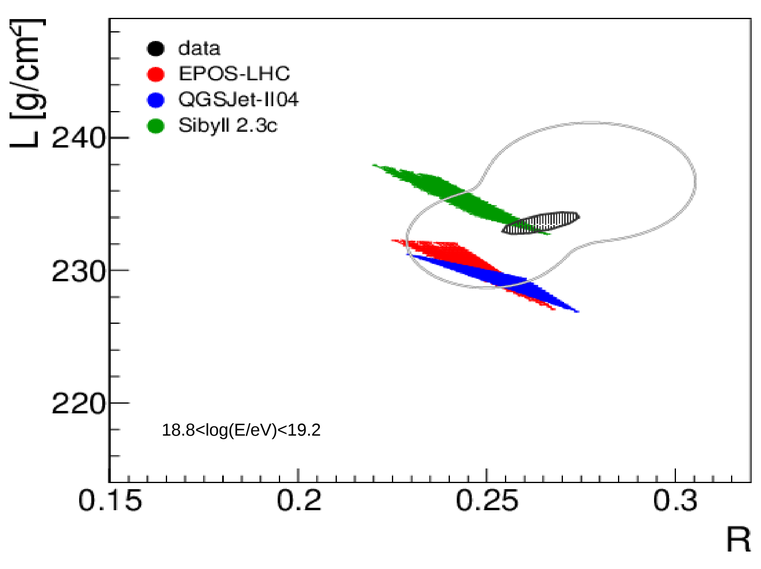
	R	L [g/cm^2]
Atmosphere	0.030	5.5
Light components & fit	0.018	3.3
Geometry	0.018	2.2
Detector	0.012	1.8
Bias corr. & Energy scale	0.010	1.0
Total	**0.040**	**7.3**
Statistical	0.012	0.9

Summary table of maximal error: errors are asymmetric and vary in energy, and are correlated

Uncertainty propagation dominated by
→ description of hourly aerosol profile
→ constraints on profile fit of single events

Systematic study of detection conditions
→ wider profile with more scattered light
→ small differences between telescopes





== More tests for shower models ==

Data constraints on primary composition
data and statistical error in dark grey ellipses
correlated systematic uncertainty in light grey

Predictions form hadronic interaction models
coloured areas for combinations of H, He, N, Fe
pure proton in upper left, pure iron in lower right

== First measurement of average shower shapes in depth ==

> a 1% level check that the shape follows a Gaisser-Hillas function

> a systematic test of the shower reconstruction procedures used

> new observables to test hadronic interaction model predictions

> indication of the main uncertainties to address in future works

== References ==

> The Pierre Auger Collaboration, A. Aab et al., NIMA 795 (2015) 127
> S. Andringa, R. Conceição, M. Pimenta, APP 34 (2011) 360

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