Studies of the UHECR Mass Composition and Hadronic Interactions with the FD and SD of the Pierre Auger Observatory

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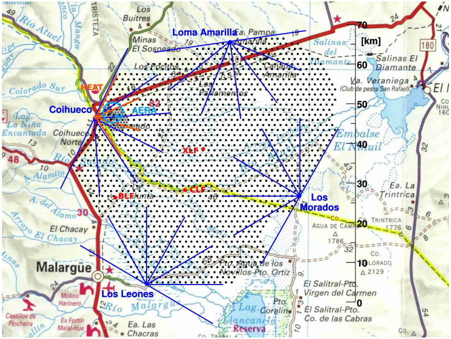
RICAP 18

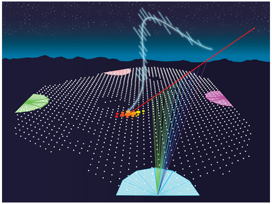
The Pierre Auger Observatory

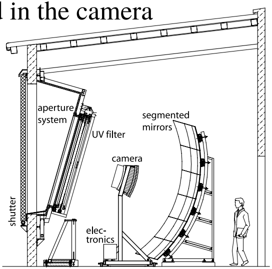
- **Hybrid detector**
- It's the largest detector of cosmic rays built so far
- It has more than 1660 surface detectors located in a triangular array covering a total area of 3000 km^2.
- The array is overlooked by 24 fluorescence telescopes
- It is located near Malargüe, in the province of Mendoza in Argentina.

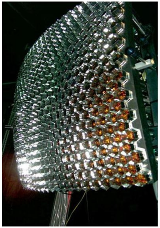


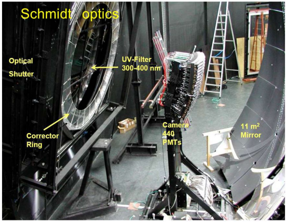
The Fluorescence Detector (FD)

- The FD measures the nitrogen fluorescence caused by the interaction between charged particles in the shower with atmospheric nitrogen.
- Duty cycle: $\sim 15\%$ (clear, moonless nights)
- Light is collected in mirrors then focused in the camera



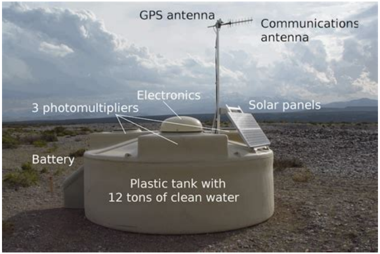


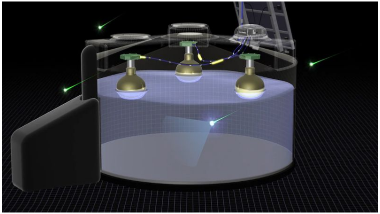




The Surface Detector (SD)

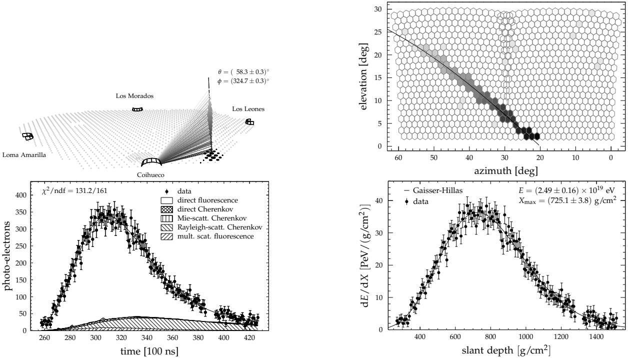
- Measures the arrival time of secondary particles of the shower at the ground
- These particles emit Cherenkov radiation in water that can be measured by the photomultiplier tubes
- Duty cycle $\sim 100\%$





$X_{\mathbf{max}}$: Definition

$$X(z) = \int_z^\infty \rho(r(z'))\, z',$$

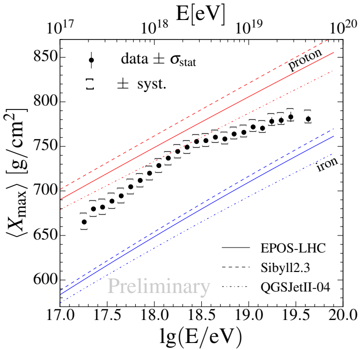


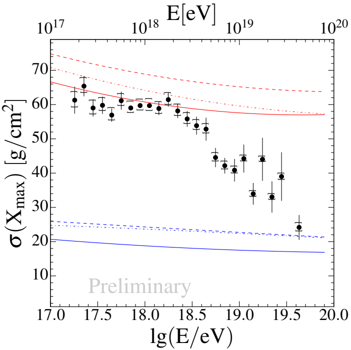
- The longitudinal profile is fitted with a Gaisser-Hillas function:

$$f_{\mathrm{GH}} = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\max} \left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\lambda}} e^{\frac{X_{\max} - X}{\lambda}}$$

- $X_{\max}$ is obtained from this fit

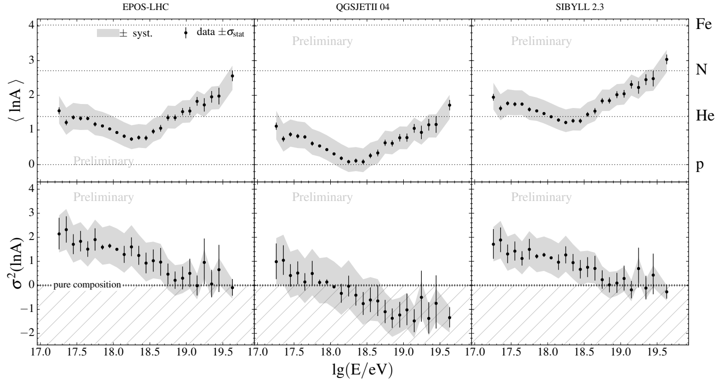
X_{max}: First two moments





- For a constant composition $D_{10} = \dfrac{\mathrm{d}\,X_{max}}{\mathrm{d}\,\lg(E/\mathrm{eV})} = 60\ \mathrm{g/cm^2/decade}$
- $D_{10} = 79 \pm 1\ \mathrm{g/cm^2/decade}$ between $10^{17.2}$ and $10^{18.33}$ eV
- $D_{10} = 26 \pm 2\ \mathrm{g/cm^2/decade}$ from $10^{18.33}$ eV onwards.

$X_{\max}$: First two moments $\rightarrow \langle \ln A \rangle$



- Values $\sigma^2 < 0$ are due to models predicting larger $\sigma(X_{\max})$ than the observed

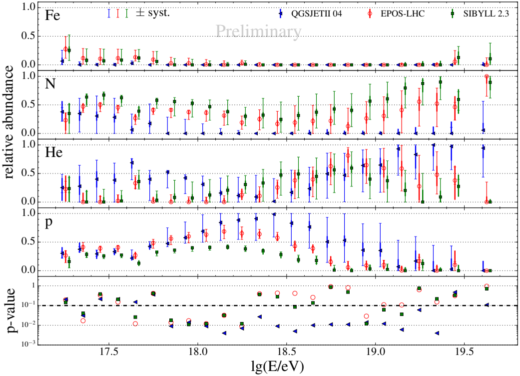
J. Bellido for the Pierre Auger Collaboration
Proc. 35th ICRC (2017)

Conclusions

- Similar trend for all the models: ligther mass up to $10^{18.33}$ eV and then heavier mass.
- Results depend on the hadronic interaction model

$X_{\max}$: Composition Implications

- Composition that best matches the distribution of $X_{\max}$ in data:



- Fewer p-values were expected below the 0.1 line (bad fits).

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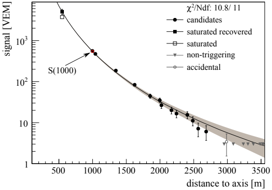
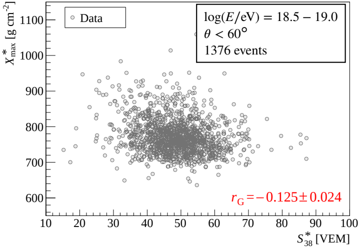
Conclusions

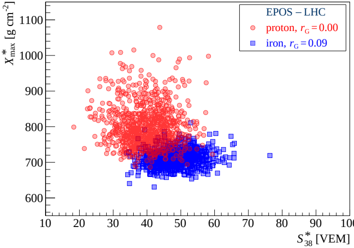
- Models can not find a combination of fractions that can reproduce the details of the distributions of $X_{\max}$.

Correlations between $X^*_{\max}$ and S^*_{38}

- The idea is to exploit the correlation between $X_{\max}$ and the number of muons N_μ.
- Muons contribute 40 to 90 % of $S(1000)$.
- First, to avoid a dependence on the energy or the zenith angle $X_{\max}$ and $S(1000)$ are scaled to $X^*_{\max}$ and S^*_{38} (10 EeV and 38°)
- The correlation coefficient is $r_G(X^*_{\max}, S^*_{38})$ [R. Gideon, R. Hollister, JASA 82 (1987) 656]. It is robust against outliers





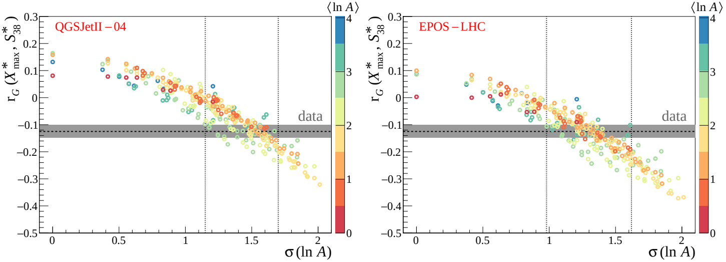


- For a **pure** composition $r_G \gtrsim 0$ while for a **mixed** composition $r_G < 0$

Correlations between $X^*_{\max}$ and S^*_{38}

Values of $r_G(X^*_{\max}, S^*_{38})$ for data and different compositions

data	-0.125 ± 0.024 (stat)		
	EPOS-LHC	QGSJetII-04	Sibyll 2.1
p	0.00	0.08	0.06
He	0.10	0.16	0.14
O	0.09	0.16	0.17
Fe	0.09	0.13	0.12
$0.5\,p$ – $0.5\,$Fe	-0.37	-0.32	-0.31
$0.8\,p$ – $0.2\,$He	0.00	0.07	0.05



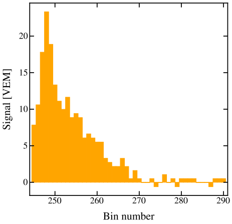
Conclusions

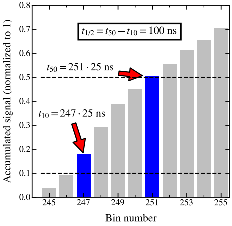
Mixed composition needed with nuclei heavier than He ($\sigma(\ln A) \simeq 1.35 \pm 0.35$)

Phys.Lett. B762 (2016) 288-295

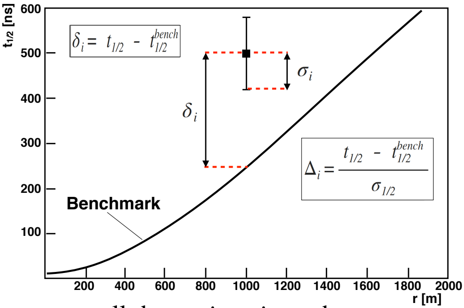
Delta Method: Definition

- Based on the risetime $t_{1/2}$, time for the signal measured by the SD to raise between a 10% and a 50% of the total signal.





- Benchmark: Parameterization of the risetime as a function of the distance to the core



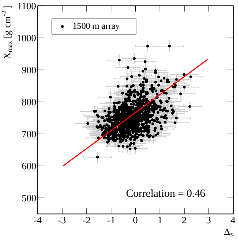
- The final observable is the average over all the stations in each event:

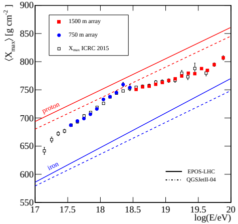
$$\Delta_s = \frac{1}{n} \sum_{i=1}^{n} \Delta_i$$

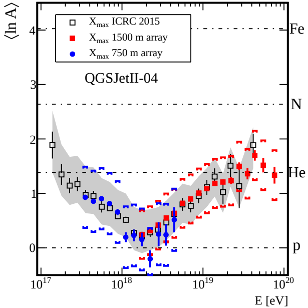
Delta Method: Calibration with $X_{\max}$

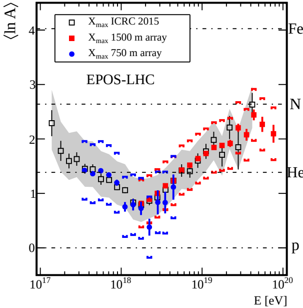
- Δ_s can be calibrated with hybrid events that have $X_{\max}$:

$$X_{\max} = a + b\Delta_s + c\log(E/\mathrm{eV})$$







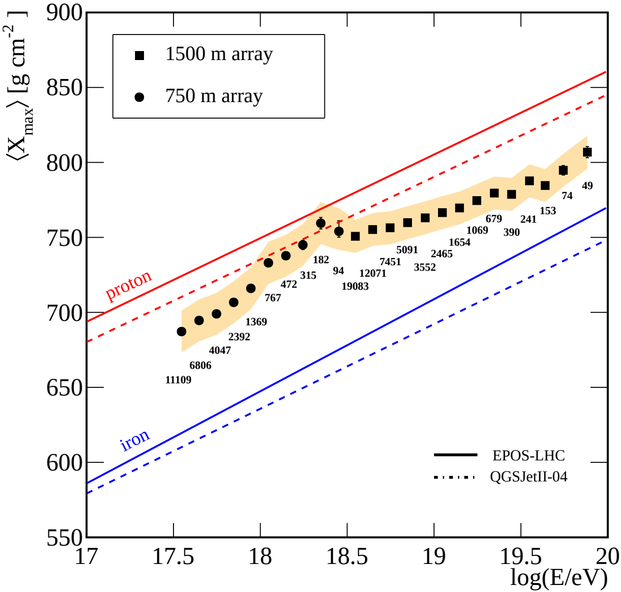


Conclusions

- $X_{\max}$ can be measured with the SD up to 100 EeV
- Mass is getting smaller until ~ 2 EeV then rises possibly stopping at the highest energies

Phys. Rev. D96 (2016) no.12, 122003

Delta Method: Calibration with X_{max}

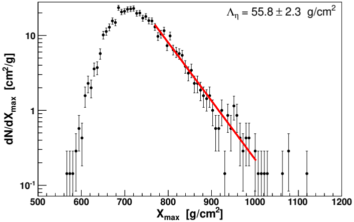


Proton-Air Cross-Section

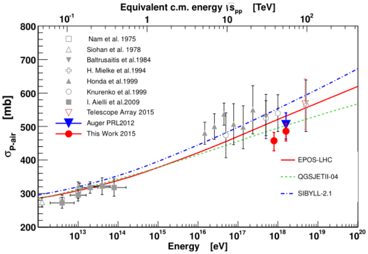
- At the tail of the X_{max} distribution:

$$\frac{\mathrm{d}N}{\mathrm{d}X_{\text{max}}} \propto e^{\frac{-X_{\text{max}}}{\Lambda_\eta}}$$

- η is the fraction of most deeply penetrating showers used ($\eta = 0.2$)



$$\Lambda_\eta = \left[55.8 \ \pm 2.3(\text{stat}) \ \pm 1.6(\text{sys})\right] \ \text{g/cm}^2$$



- Cross-sections are modified in simulations to match Λ_η with the following factor

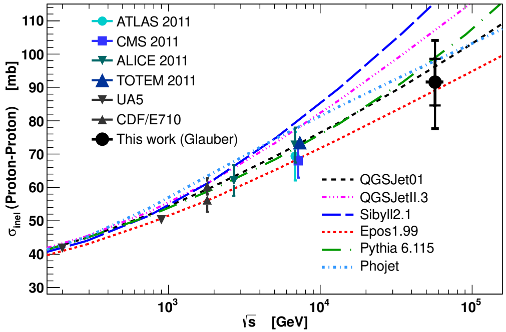
$$F(E, f_{19}) = 1 + (f_{19} - 1)\ \frac{\log\left(E/E_{\text{thr}}\right)}{\log\left(10^{19}\ \text{eV}/E_{\text{thr}}\right)}$$

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

R. Ulrich for the Pierre Auger Collaboration
Proc. 34th ICRC (2015)

Proton-Proton Cross-Section

- Inelastic and total cross-sections are computed using the Glauber model at $\sqrt{s} = 57$ TeV.



Phys. Rev. Lett. 109, 062002 (2012)

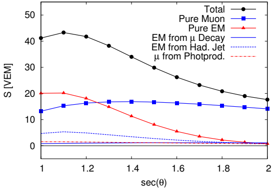
Conclusions

$$\sigma_{pp}^{\mathrm{inel}} = \left[92 \ \pm 7(\mathrm{stat})\ {}^{+9}_{-11}(\mathrm{sys}) \ \pm 7(\mathrm{Glauber})\right] \ \mathrm{mb}$$

$$\sigma_{pp}^{\mathrm{tot}} = \left[133 \ \pm 13(\mathrm{stat})\ {}^{+17}_{-20}(\mathrm{sys}) \ \pm 16(\mathrm{Glauber})\right] \ \mathrm{mb}$$

Muons in Inclined Events

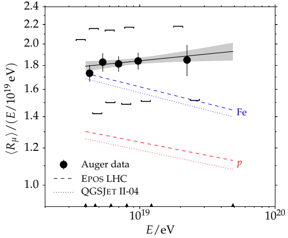
- Muons dominate the signal in inclined events

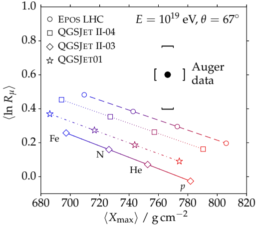


- The muon density ρ_μ is modeled at the ground point $\vec{r}$ as:

$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi),$$

- N_{19} is studied and simulation and corrected by its bias $\rightarrow R_\mu$





$62° < \theta < 80°$
174 events accepted
$4 \cdot 10^{18}$ eV $< E < 5 \cdot 10^{19}$ eV

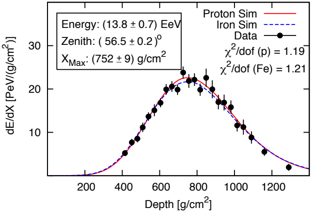
Conclusions

- Number of muons 30%-80% higher than what models predict

Phys. Rev. D 91, 059901 (2015)

Testing Hadronic Interactions

- Simulations that match the longitudinal profile of data are produced

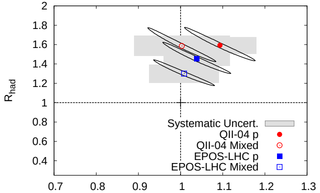


$0° < \theta < 60°$
411 events accepted
6 EeV $< E < 16$ EeV

- The signal is rescaled to match the signal at the ground in data:

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had},i,j}$$

Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

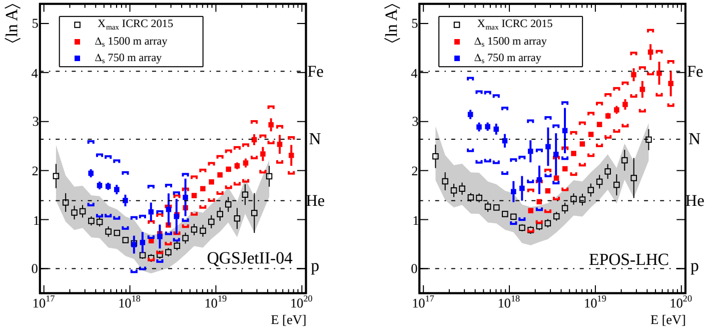


Conclusions

- No energy rescaling is needed
- Hadronic signal is significantly larger for data than that predicted by models

Phys. Rev. Lett. 117, 192001 (2016)

The Delta Method Again



- In the risetime (and therefore Δ) there is a mixture of electromagnetic and muonic component
- The values of Δ can not reproduce $X_{\max}$, coming from the electromagnetic cascade

Summary

- Average mass decreases until $10^{18.3}$ eV and then increases
- Caveat: Interpretation of the results on mass composition depend on the hadronic interaction models.
- Simulations can not reproduce certain observations. There seems to be a problem in the modeling of hadronic interactions, particularly in the number of muons.

Backup

$X_{\mathbf{max}}$ Measurement: Event Reconstruction

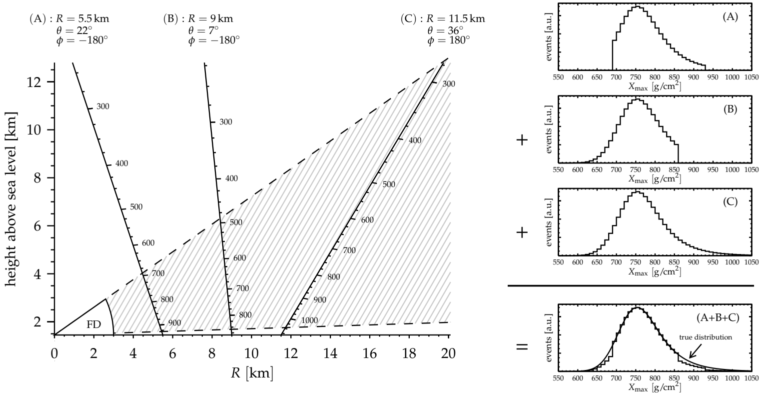
- Plane shower-telescope from light arrival times and viewing angle
- Three dimensional reconstruction with the time of arrival of the shower front at ground level (SD)
- 0.6° resolution
- Signals in the PMTs are converted to time-trace of light thanks to the calibration
- Time bins are projected to pieces of path length $\Delta\ell_i$ centered at height h_i and with slant depth X_i

X_{max} Measurement: Data Selection

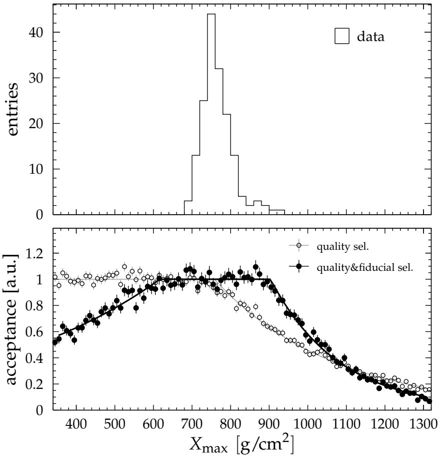
cut	events	ε [%]
pre-selection:		
air-shower candidates	2573713	-
hardware status	1920584	74.6
aerosols	1569645	81.7
hybrid geometry	564324	35.9
profile reconstruction	539960	95.6
clouds	432312	80.1
$E > 10^{17.8}$ eV	111194	25.7
quality and fiducial selection:		
P(hybrid)	105749	95.1
X_{max} observed	73361	69.4
quality cuts	58305	79.5
fiducial field of view	21125	36.2
profile cuts	19947	94.4

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

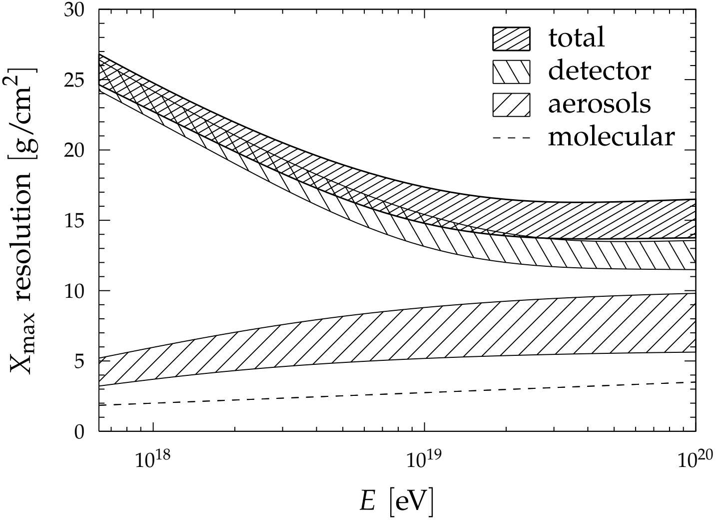
X_{max} Measurement: Field of view



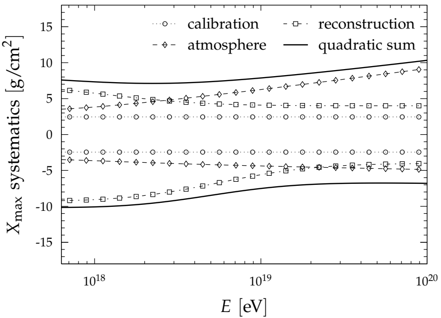
X_{max} Measurement: Acceptance



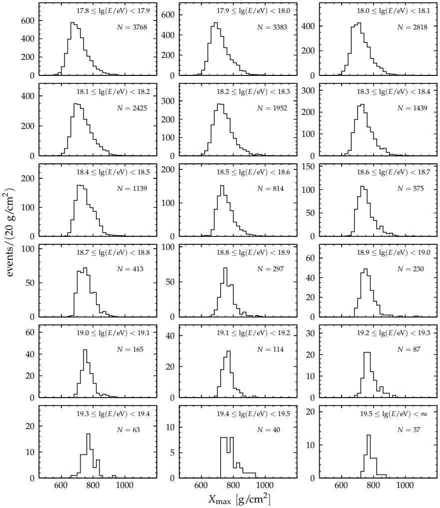
$X_{\mathbf{max}}$ Measurement: Resolution



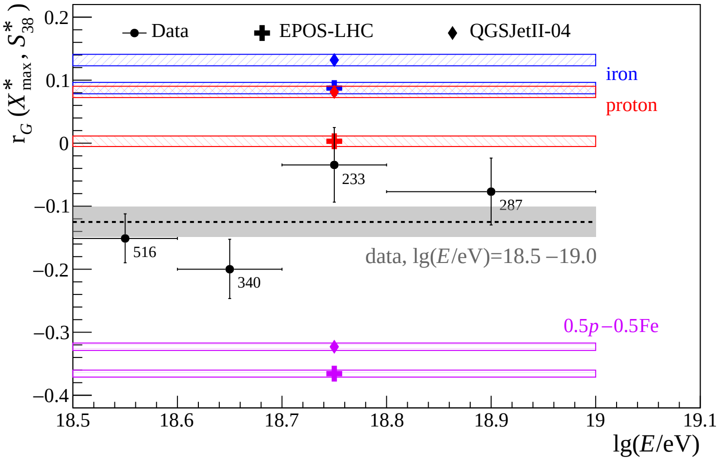
X_{max} Measurement: Systematic Uncertainties



$X_{\max}$ Measurement: Distributions



Correlations between X^*_{max} and S^*_{38}



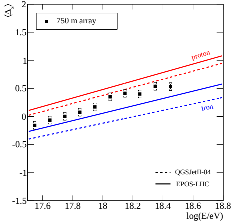
Correlations between $X^*_{\mathbf{max}}$ and S^*_{38}: Uncertainties

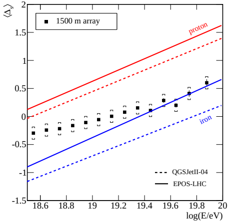
- Cross-checks:
  - Division of the data set in terms of time periods, FD telescopes or zenith angle ranges
  - Variations of the event selection criteria
  - Variations of the scaling functions when transforming to the reference zenith angle and energy
  - Adopting other methods to calculate the correlation coefficient
  - Studying the effect of possible outlier events
- Systematics:
  - Estimated 0.01 on r_G by introducing artificial biases in the values of $X^*_{\max}$ and S^*_{38}.
- Hadronic interactions:
  - The pre-LHC versions of EPOS and QGSJetII were checked
  - CONEX simulations with changed parameters (cross-section, multiplicity, elasticity and pion charge ratio)

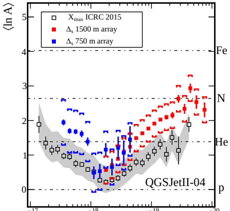
Delta Method: Evolution with Energy

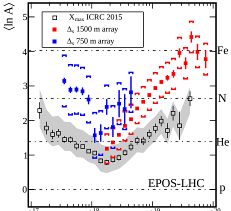
- The average value of Δ, $\langle\Delta_s\rangle$ is studied as a function of the energy and transformed to $\langle\ln A\rangle$:

$$\langle\ln A\rangle = \ln 56\,\frac{\langle\Delta_s\rangle_{\mathrm{p}} - \langle\Delta_s\rangle_{\mathrm{data}}}{\langle\Delta_s\rangle_{\mathrm{p}} - \langle\Delta_s\rangle_{\mathrm{Fe}}}$$

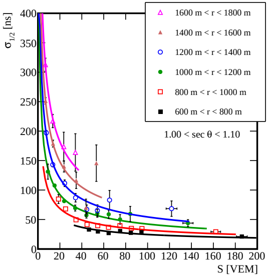


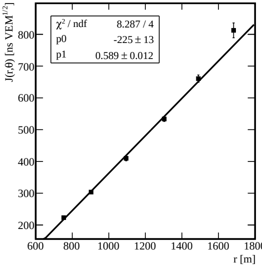






Delta Method: Risetime Uncertainty





$$\sigma_{1/2} = \sqrt{\left(\frac{J(r,\theta)}{\sqrt{S}}\right)^2 + \left(\sqrt{2}\frac{25\,\mathrm{ns}}{\sqrt{12}}\right)^2}$$

$$p_0(\theta) = \begin{cases} (-340 \pm 30) + (186 \pm 20)\ \sec\theta, & r \leq\ 650\,\mathrm{m} \\ (-447 \pm 30) + (224 \pm 20)\ \sec\theta, & r >\ 650\,\mathrm{m} \end{cases}$$

$$p_1(\theta) = \begin{cases} (0.94 \pm 0.03) + (-0.44 \pm 0.01)\ \sec\theta, & r \leq\ 650\,\mathrm{m} \\ (1.12 \pm 0.03) + (-0.51 \pm 0.02)\ \sec\theta, & r >\ 650\,\mathrm{m} \end{cases}$$

Delta Method: Data Selection

Table: Quality cuts applied to the events of the 750 m and the 1500 m arrays. ϵ stands for the overall efficiency. The explanation for the different cuts can be found in the text.

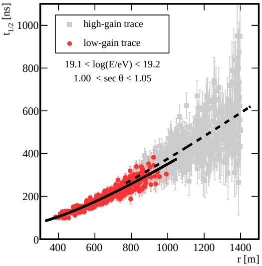
750 m array			1500 m array		
Quality cuts	Events	ϵ (%)	Quality cuts	Events	ϵ (%)
$17.5 < \log(E/\mathrm{eV}) < 18.5$	159 795	100.0	$\log(E/\mathrm{eV}) > 18.5$	217 469	100.0
$\sec\theta < 1.30$	72 907	45.6	$\sec\theta < 1.45$	97 981	45.0
6T5 trigger	29 848	18.7	6T5 trigger	67 764	31.0
Reject bad periods	28 773	18.0	Reject bad periods	63 856	29.0
≥ 3 selected stations	**27 553**	**17.2**	≥ 3 selected stations	**54 022**	**24.8**

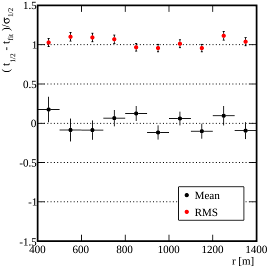
Delta Method: The Benchmark

$$t_{1/2}^{\text{low-gain trace}} = 40\,\text{ns} + \sqrt{A(\theta)^2 + B(\theta)r^2} - A(\theta)$$

$$t_{1/2}^{\text{high-gain trace}} = 40\,\text{ns} + N(\theta)\left(\sqrt{A(\theta)^2 + B(\theta)r^2} - A(\theta)\right)$$

$$A(\theta) = a_0 + a_1(\sec\theta)^{-4}$$
$$B(\theta) = b_0 + b_1(\sec\theta)^{-4}$$
$$N(\theta) = n_0 + n_1(\sec\theta)^2 + n_2 e^{\sec\theta}$$





Delta Method: Systematic Uncertainties

Table: Breakdown of the systematic uncertainties of X_{max} for the 750 m and 1500 m arrays. The systematic uncertainty obtained in the measurement of X_{max} with the FD and HEAT detectors propagates directly into the values obtained with the SD data. The rest of systematic uncertainties quoted in this table are intrinsic to the Delta method.

750 m array		1500 m array	
Source	Systematic uncertainty ($\mathrm{g\ cm^{-2}}$)	Source	Systematic uncertainty ($\mathrm{g\ cm^{-2}}$)
Uncertainty on calibration	10.0	Uncertainty on calibration	5.0
Seasonal effect	2.0	Seasonal effect	2.0
Diurnal dependence	1.0	Diurnal dependence	1.0
Ageing	3.0	Ageing	3.0
HEAT systematic uncertainty	8.5	FD systematic uncertainty	8.5
Angular dependence	<1.0	Angular dependence	1.5
Total	**14.0**	**Total**	**11.0**

Proton-Air Cross-Section: Systematics

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