CR–EX 796 (PoS 335)

PIERRE AUGER OBSERVATORY

Composition at the "ankle" measured by the Pierre Auger Observatory: pure or mixed?

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http://www.auger.org/archive/authors_2015_06.html

ICRC
The Astroparticle Physics Conference
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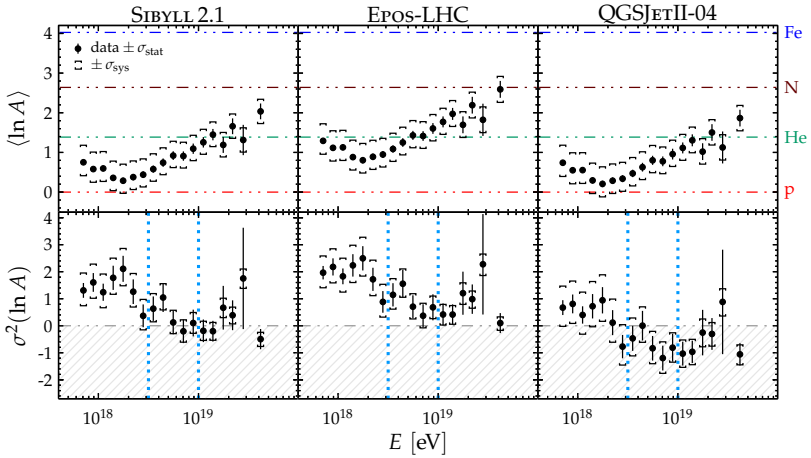
Mass composition around the "ankle" ($\lg(E/\mathrm{eV}) \approx 18.7$)

Mean and variance of $\ln A$ from the first two moments of $X_{\max}$ distributions

[The Pierre Auger Collaboration, PRD 90, 122005 (2014)]



Less model-dependent estimate of $\sigma(\ln A)$ near the "ankle"?

The Pierre Auger Observatory

Location:

Mendoza province, Argentina

Fluorescence detector (FD):

[longitudinal profile]

$24 + 3$ fluorescence telescopes at 4 locations

duty cycle $15\,\%$

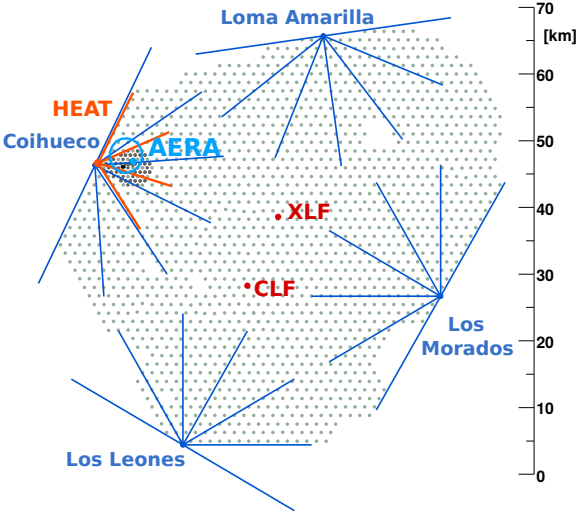
Surface detector (SD):

[lateral distribution]

area of 3000 km^2

1660 water Cherenkov detectors at 1500 m spacing

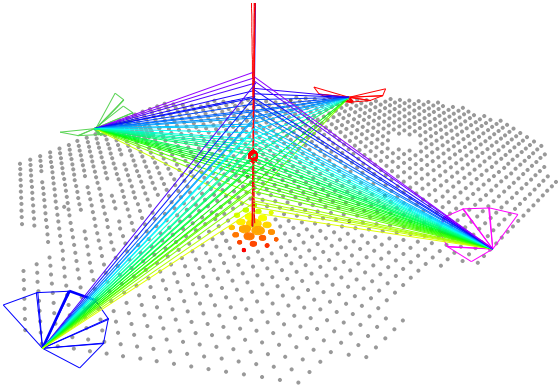
duty cycle $100\,\%$



Data

Hybrid (FD and SD)

- 8 years $12/2004 - 12/2012$
- $\lg(E/\mathrm{eV}) = 18.5 - 19.0$
- zenith angles $0° - 65°$
- 1376 high-quality events



Basic observables

FD: depth of shower maximum, $X_{\max}$, scaled to 10 EeV

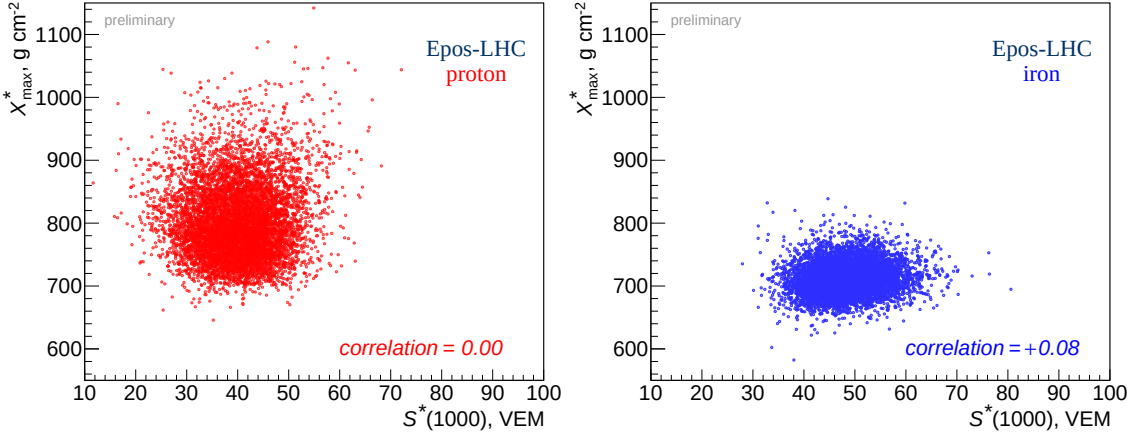
SD: signal at 1000 m from the core, $S(1000)$, scaled to 10 EeV, $38°$

The scaled observables are used, they are marked with an asterisk

$$X^*_{\max},\ S^*(1000)$$

The key idea

correlation between X^*_{max} and $S^*(1000)$ depends on the purity of the primary beam



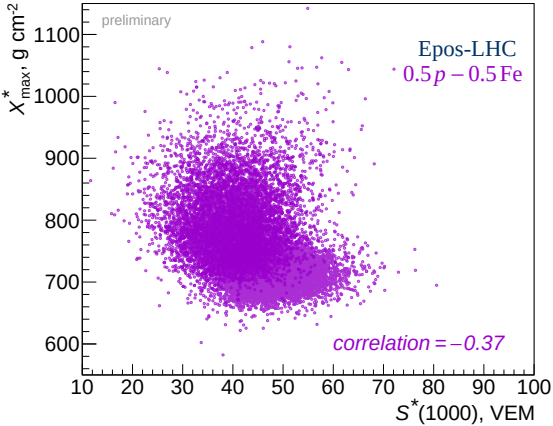
Pure compositions $\Rightarrow$ correlation $\gtrsim 0$

P. Younk, M. Risse, ApP 35 (2012) 807

The key idea

heavier nuclei produce shallower showers with larger signal (more muons)

general characteristics of air showers / minor model dependence



More negative correlation ⇒ more mixed composition

P. Younk, M. Risse, ApP 35 (2012) 807

Correlation between X^*_{max} and $S^*(1000)$

Ranking coefficient r_{G} [R. Gideon, R. Hollister, JASA 82 (1987) 656]

1. rank events in X^*_{max} and $S^*(1000)$
2. replace measured values by ranks:

   $X^*_{\mathrm{max}}(1), \ldots, X^*_{\mathrm{max}}(N) \implies 1, 2, \ldots, N$

   $S^*(1000)(1), \ldots, S^*(1000)(N) \implies 1, 2, \ldots, N$
3. count events with ranks deviating from the expectations for perfect (anti-)correlation; all events contribute 0 or 1 $\Rightarrow$ robustness against outliers

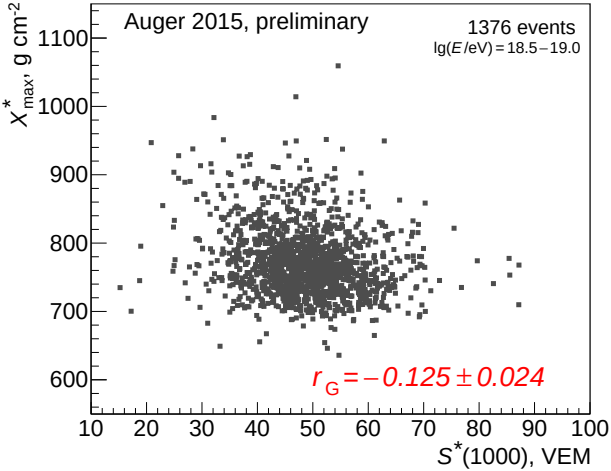
r_{G} is invariant to any transformations leaving ranks unchanged

e.g. to systematics in X^*_{max} and $S^*(1000)$

various coefficients applied (incl. Pearson, Spearman), conclusions unchanged

Correlation $r_{\mathrm{G}}(X^*_{\mathrm{max}},\, S^*(1000))$ in data

correlation is significantly negative

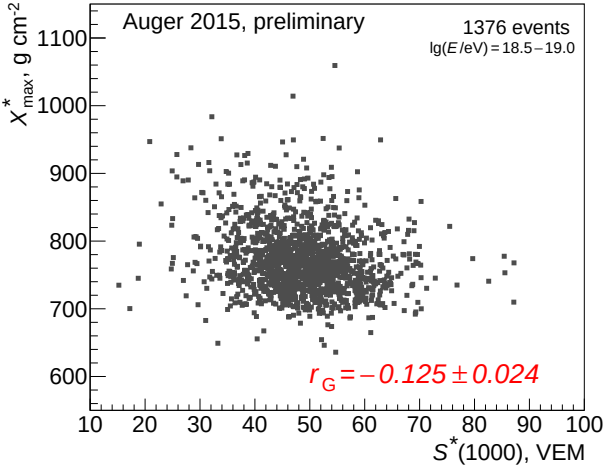


unique plot of hybrid experiment

systematics plays only a minor role $\sigma_{\mathrm{syst}}(r_{\mathrm{G}}) \lesssim 0.01$

due to invariance of r_{G} to additive and multiplicative scale transformations

Data vs pure beams



$r_G(X^*_{max}, S^*(1000))$ for protons

Epos-LHC	QGSJetII-04	Sibyll 2.1
0.00	$+0.08$	$+0.07$

difference to data

$\approx 5\sigma$	$\approx 8\sigma$	$\approx 7.5\sigma$

difference is larger for other pure beams

primary composition is mixed

Dispersion of masses in the primary beam

Correlation is more negative for more mixed compositions

$$\Downarrow$$

Use $\boldsymbol{r_{\mathrm{G}}(X^*_{\mathrm{max}},\ S^*(1000))}$ to estimate the dispersion $\boldsymbol{\sigma(\ln A)}$ of primary masses

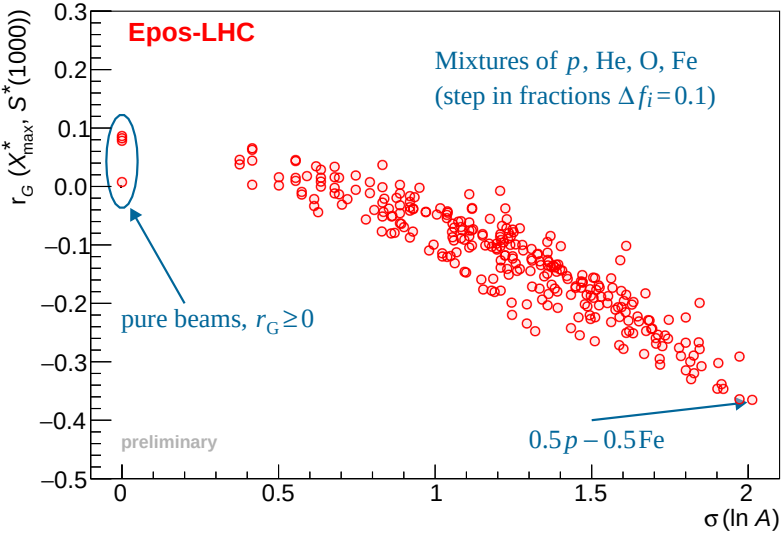
$$\sigma(\ln A) = \sqrt{\langle \ln^2 A \rangle - \langle \ln A \rangle^2}$$

$$\langle \ln A \rangle = \sum_i f_i \ln A_i, \quad \langle \ln^2 A \rangle = \sum_i f_i \ln^2 A_i$$

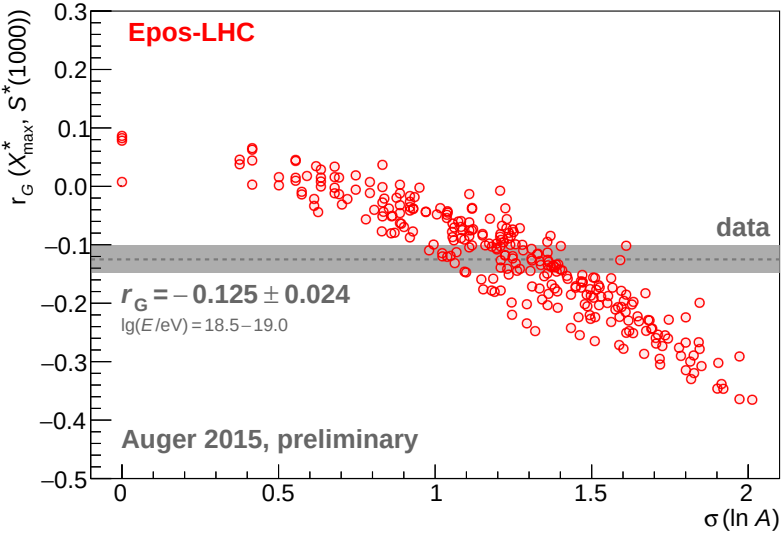
f_i — relative fractions of masses $A_i = 1, \ldots, 56$

P. Younk, M. Risse, ApP 35 (2012) 807

$r_G(X^*_{max}, S^*(1000))$ vs dispersion of masses $\sigma(\ln A)$



Dispersion of masses: data vs simulations



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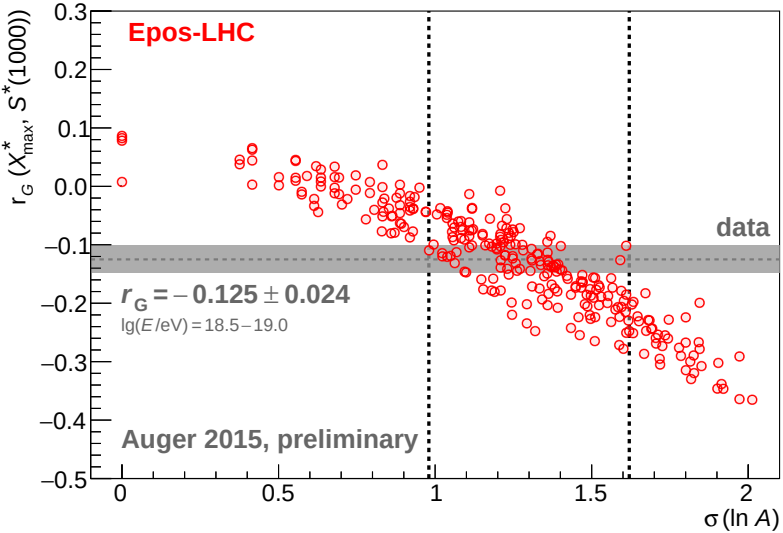
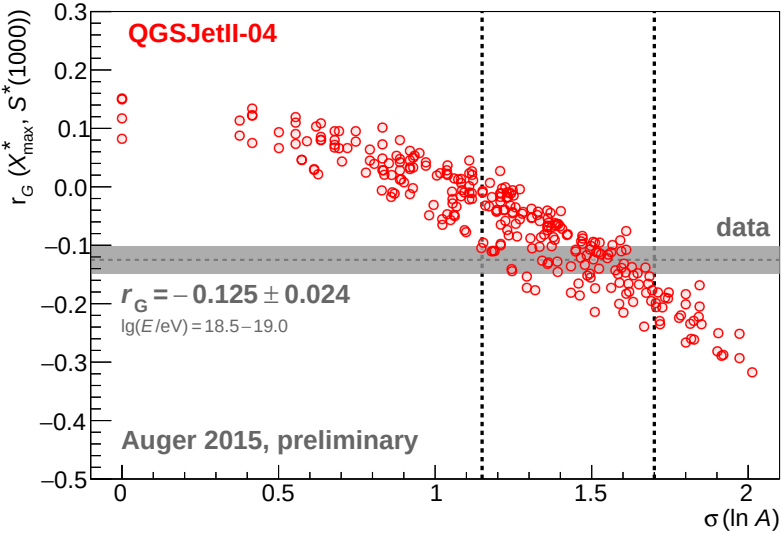


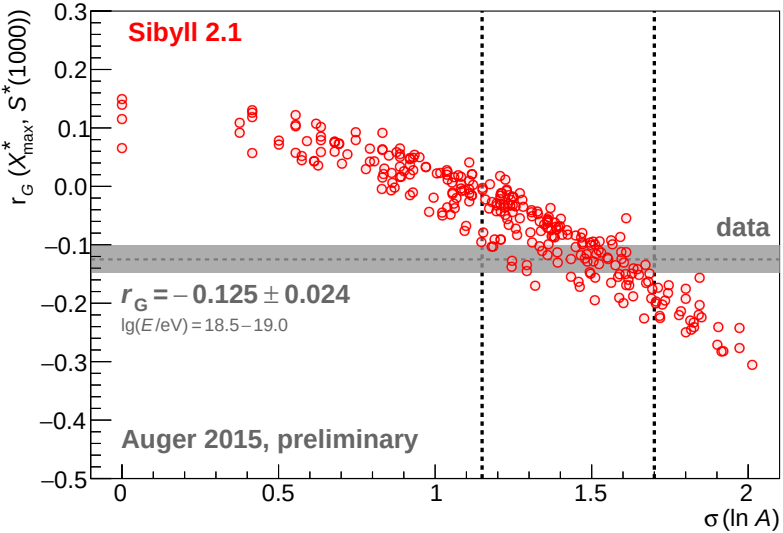
data are compatible with dispersion of masses $\sigma(\ln A) \gtrsim 1$

Dispersion of masses: data vs simulations



data are compatible with dispersion of masses $\sigma(\ln A) \gtrsim 1.1$

Dispersion of masses: data vs simulations



data are compatible with dispersion of masses $\sigma(\ln A) \gtrsim 1.1$

Uncertainties in hadronic models

Can one get $r_{\mathrm{G}}(X^*_{\mathrm{max}}, S^*(1000)) < 0$ for pure protons?

Change proton-air interactions (study with CONEX 3D)

[T. Bergmann et al., ApP 26 (2007) 420, R. Ulrich et al., PRD 83 (2011) 054026]

The modification factor ($f_{19} = 1.5$: increase up to factor 1.5 at 10 EeV)

$$f(E) = 1 + (f_{19} - 1)\frac{\lg(E/1\ \mathrm{PeV})}{\lg(10\ \mathrm{EeV}/1\ \mathrm{PeV})}$$

Modified parameters (for Epos-LHC)

- cross-section
- pion charge ratio
- elasticity
- multiplicity

r_{G} changes by $\lesssim 0.03$

Possible under-production of muons by hadronic models?

[G. Farrar for the Pierre Auger Collaboration (2013) arXiv:1307.5059, A. Aab et al., PRD 91 (2015) 032003]

re-weighting of muons at ground by factor 1.3: r_{G} decreases by $\lesssim 0.03$

changes are small compared to difference between data and protons

Summary

- significantly negative correlation between $X^*_{\max}$ and $S^*(1000)$ is found in data:

$$\boldsymbol{r_{\mathrm{G}}(X^*_{\max},\, S^*(1000)) = -0.125 \pm 0.024} \; (\lg(E/\mathrm{eV}) = 18.5 - 19.0)$$

- difference to pure beams is $\gtrsim \boldsymbol{5\sigma}$:

the primary composition around the "ankle" is mixed

- dispersion of masses in the primary beam compatible with data:

$$\boldsymbol{1.0 \lesssim \sigma(\ln \mathrm{A}) \lesssim 1.7} \; \text{(within the interaction models used)}$$

results are robust against experimental uncertainties on $X^*_{\max}$ and $S^*(1000)$

results are robust against moderate modifications of hadronic interactions

Uncertainties

Some of the checks for $r_{\mathrm{G}}(X^*_{\mathrm{max}}, S^*(1000))$

- different FD telescopes
- different time periods
- smaller angular ranges
- smaller energy ranges
- variations in event selection
- changes of energy, X_{max}, $S(1000)$ scales
- ad hoc energy and zenith angle dependent biases in X_{max} (up 10 $\mathrm{g/cm^2}$) and $S(1000)$ (up to 10%)

systematic error on r_{G} estimated to be 0.01

statistical uncertainty $\sigma_{\mathrm{stat}}(r_{\mathrm{G}}) \approx 0.9/\sqrt{N}$ (sample of N events)
(obtained using dedicated MC studies)

for data $\boldsymbol{\sigma_{\mathrm{stat}}(r_{\mathrm{G}}) \approx 0.9/\sqrt{1376} \approx 0.024}$

Comparison to composition from fits of $X_{\max}$ distributions

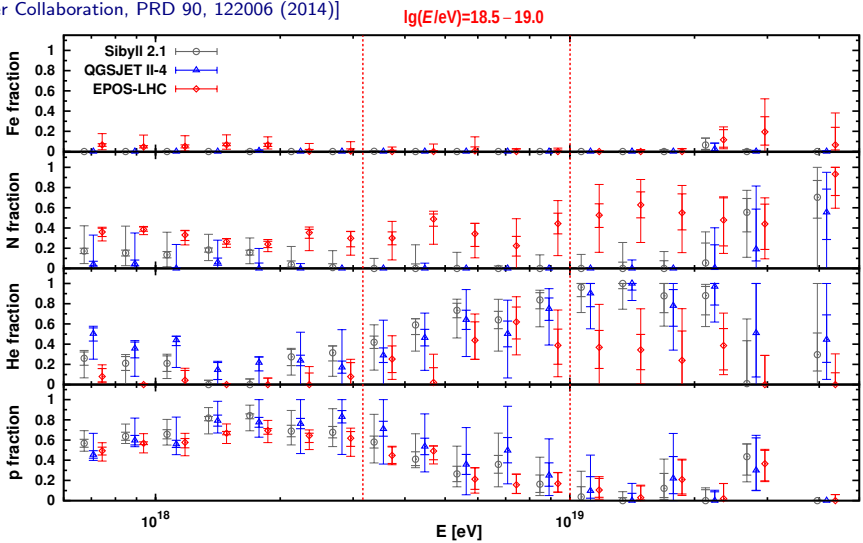
Model	composition from fits of $X_{\max}$ distributions [The Pierre Auger Collaboration, PRD 90, 122006 (2014)] $\sigma(\ln A)$	$r_{\mathrm{G}}(X^*_{\max},\, S^*(1000))$	correlation between $X^*_{\max}$ and $S^*(1000)$ $\boldsymbol{r_{\mathrm{G}} = -0.125 \pm 0.024}$
	$(\approx 0.5\,p - 0.5\,\mathrm{He})$		
QGSJetII-04	≈ 0.69	$\approx +0.08$	$1.15 \lesssim \sigma(\ln A) \lesssim 1.7$
Sibyll 2.1	≈ 0.69	$\approx +0.08$	$1.15 \lesssim \sigma(\ln A) \lesssim 1.7$
	$(\approx 0.35\,p - 0.30\,\mathrm{He} - 0.35\,\mathrm{O})$		
Epos-LHC	≈ 1.17	≈ -0.08	$1.0 \lesssim \sigma(\ln A) \lesssim 1.6$

Inconsistent results on $r_{\mathrm{G}}(X^*_{\max},\, S^*(1000))$ for QGSJetII-04 and Sibyll 2.1;

for Epos-LHC results are within 2σ from each other

Composition from fits of $X_{\max}$ distributions

[The Pierre Auger Collaboration, PRD 90, 122006 (2014)]



QGSJetII-04, Sibyll 2.1: $\approx 0.5\,p - 0.5\,\mathrm{He}$; Epos-LHC: $\approx 0.35\,p - 0.30\,\mathrm{He} - 0.35\,\mathrm{O}$

Event selection

Related to $X_{\max}$

same as in [The Pierre Auger Collaboration, PRD 90, 122005 (2014)]

Pre-selection

- hardware status
- aerosols
- hybrid geometry
- profile reconstruction
- clouds

Quality and fiducial selection

- $P(\text{hybrid})$
- $X_{\max}$ observed
- quality cuts
- fiducial field of view
- profile cuts

Related to $S(1000)$

- at least 5 working stations around the station with the highest signal
- exclusion of events with stations having saturated signal traces