CRI2g (PoS 482)

PIERRE AUGER OBSERVATORY

ICRC2019
Madison, WI, USA

Mass Composition of Cosmic Rays with Energies above $10^{17.2}$ eV from the Hybrid Data of the Pierre Auger Observatory

Alexey Yushkov* for the Pierre Auger Observatory†

* Institute of Physics of the Czech Academy of Sciences

† Av. San Martín Norte 304, 5613 Malargüe, Argentina

http://www.auger.org/archive/authors_icrc_2019.html

Fluorescence Detector

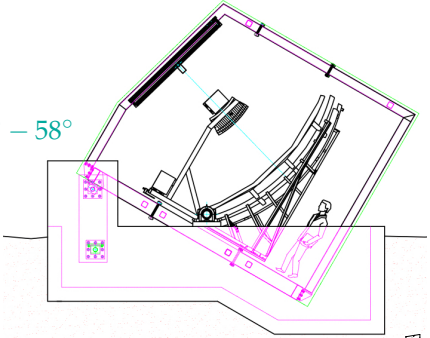
High elevation Auger telescopes

elevation $30^\circ - 58^\circ$

3 telescopes at Coihueco site

range of $X_{\max}$ analysis: $10^{17.2}$ eV $< E < 10^{18.1}$ eV

data: same to ICRC (2017) [J. Bellido, PoS(ICRC2017)506]



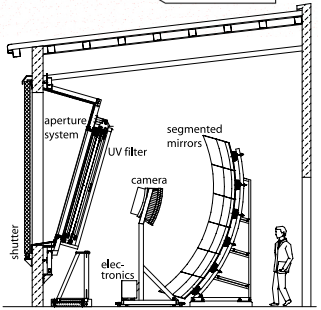
Standard telescopes

elevation $1.5^\circ - 30^\circ$

24 telescopes at 4 sites

range of $X_{\max}$ analysis: $E > 10^{17.8}$ eV

compared to ICRC (2017): update with $2016 - 2017$ (+20% of statistics)



Measurements of the depth of shower maximum $X_{\max}$

47863 high-quality events

1020 events with $E > 10$ EeV

the highest energy 104 ± 9.5 EeV

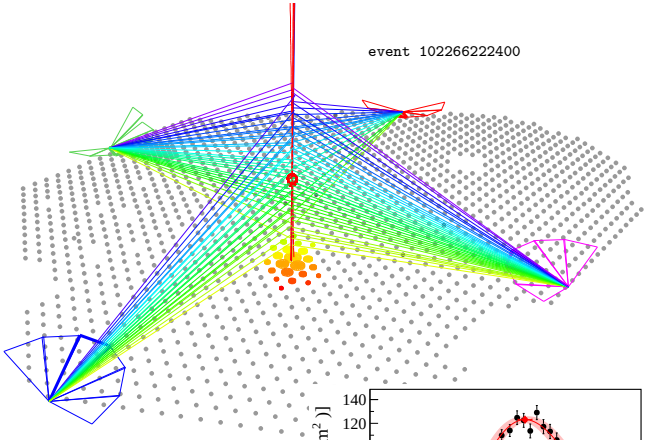
systematics $\lesssim 10\ \mathrm{g\,cm^{-2}}$

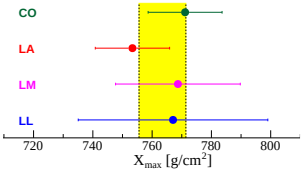
resolution

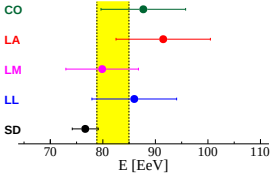
$40\ \mathrm{g\,cm^{-2}}$ at $10^{17.2}$ eV

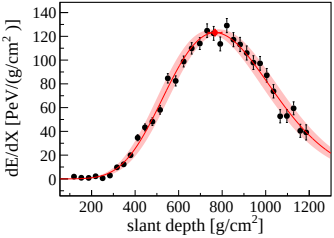
$25\ \mathrm{g\,cm^{-2}}$ at $10^{17.8}$ eV

$15\ \mathrm{g\,cm^{-2}}$ for $E > 10^{19.0}$ eV





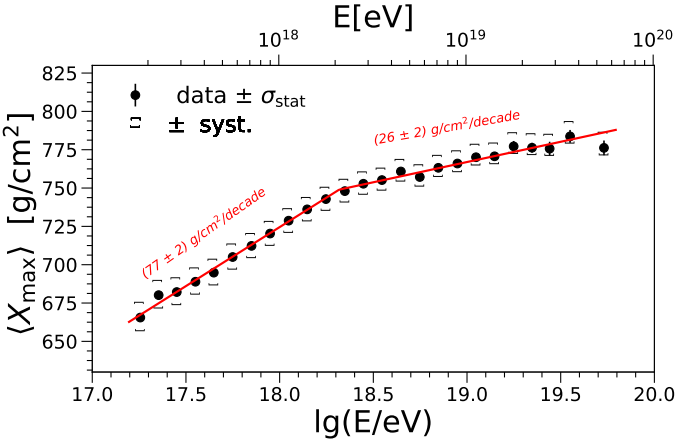




Rate of change of $X_{\max}$ with energy

One of the most reliable observables for mass composition analysis

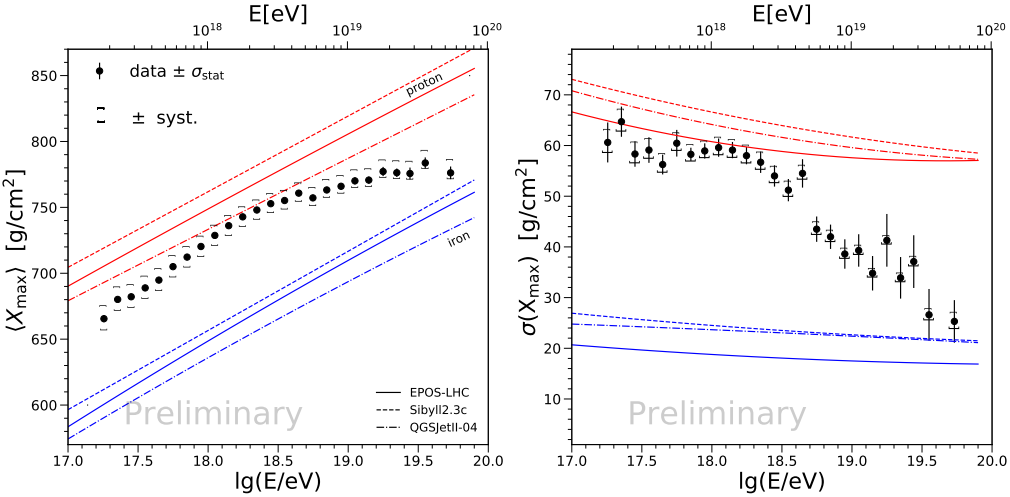
simulations: ≈ 60 [g cm^{-2}/decade] for constant compositions



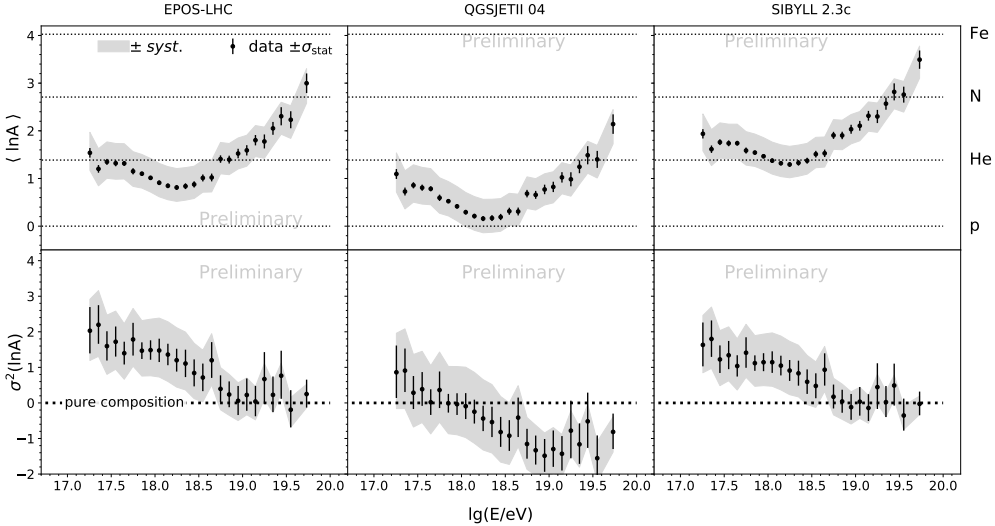
Composition is getting lighter below $E_0 \approx 2$ EeV and heavier afterwards

$X_{\max}$ moments: data vs simulations

Above $E_0 \approx$ 2 EeV both $X_{\max}$ moments are becoming compatible to MC predictions for heavier nuclei



$\langle \ln A \rangle$ and $\sigma^2(\ln A)$ from first two moments of $X_{\max}$ distributions



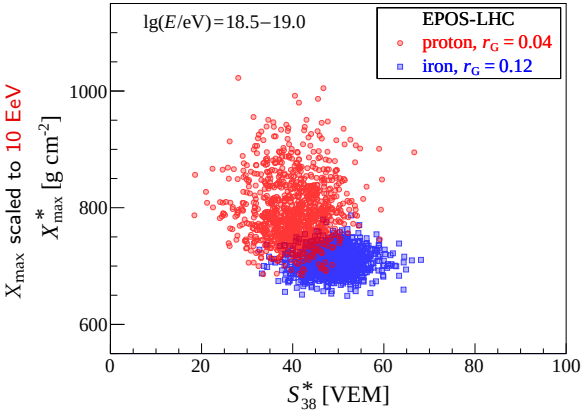
Model-independent decrease of $\sigma(\ln A)$ until $\sim 10^{18.7}$ eV

Less model-dependent constraints on $\sigma(\ln A)$ near the ankle?

Correlation between $X_{\max}$ and signal in the surface detector

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

general characteristics of air showers / minor model dependence



signal at 1000 m from the core scaled to 10 EeV, 38°

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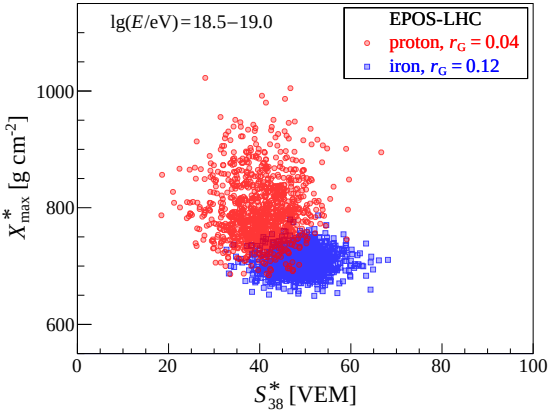

Correlation for EPOS-LHC

pure beams $\sigma(\ln A) = 0$

$+0.04$ for proton

$+0.12$ for iron

r_G — ranking correlation coefficient [R. Gideon, R. Hollister, JASA 82 (1987) 656]

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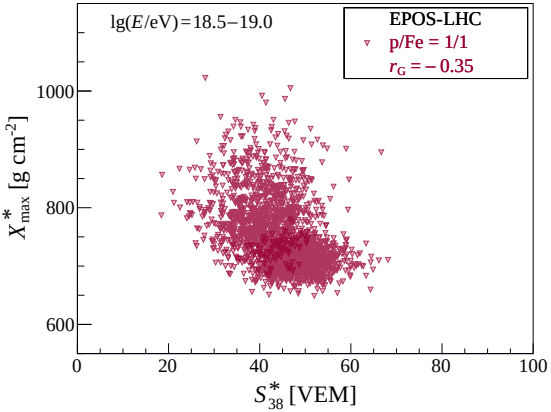

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maximal mixing $\sigma(\ln A) \approx 2$

-0.35 for p/Fe$= 1/1$

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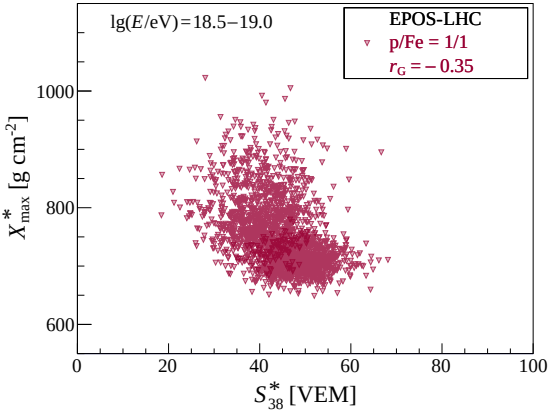

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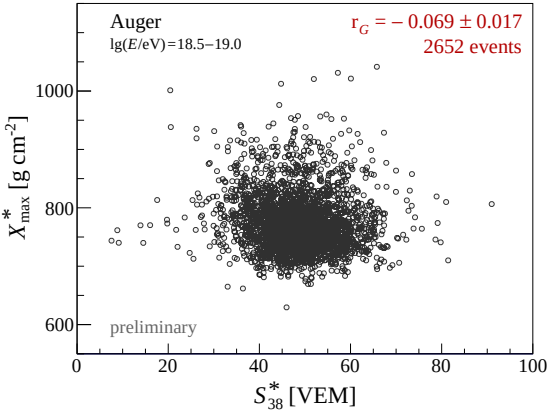
More negative correlation $\Rightarrow$ more mixed composition

Correlation in data compared to pure beams



correlation for protons

EPOS-LHC	QGSJetII-04	Sibyll 2.3c
$+0.04$	$+0.12$	$+0.04$

difference to data

$\approx 6.0\sigma$	$\approx 11.0\sigma$	$\approx 6.0\sigma$

difference is larger for other pure beams

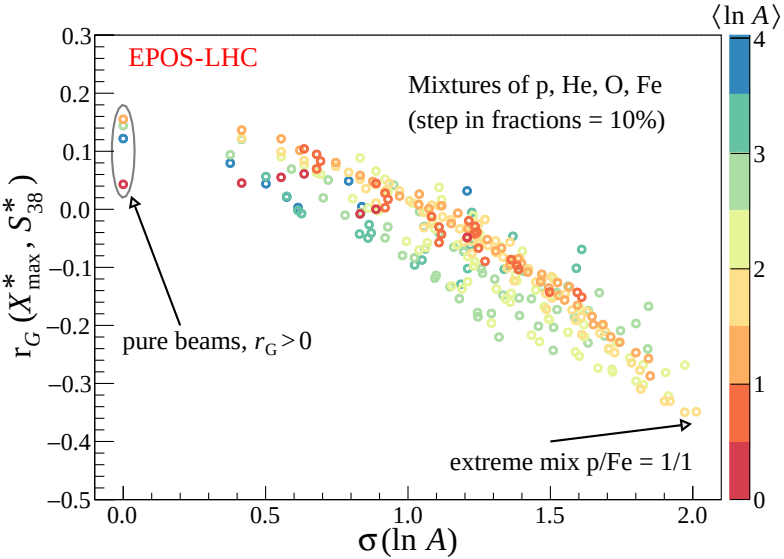
difference is $> 5\sigma$ for all p − He mixes

primary composition near the ankle is mixed

nuclei with $A > 4$ needed to explain data

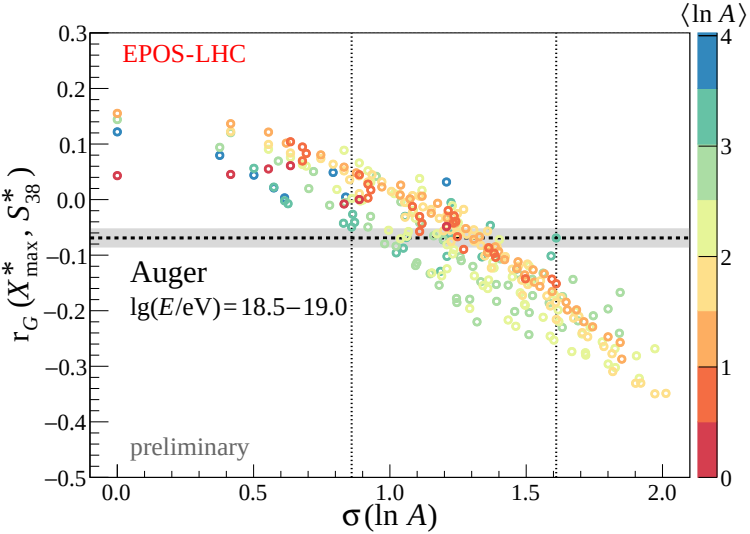
systematics plays only a minor role $\sigma_{syst}(r_G) \lesssim {}^{+0.01}_{-0.02}$

Dependence of correlation on $\sigma(\ln A)$



Constraints on $\sigma(\ln A)$ from observed $r_G(X^*_{max}, S^*_{38})$

Data are compatible to $0.85 \lesssim \sigma(\ln A) \lesssim 1.60$



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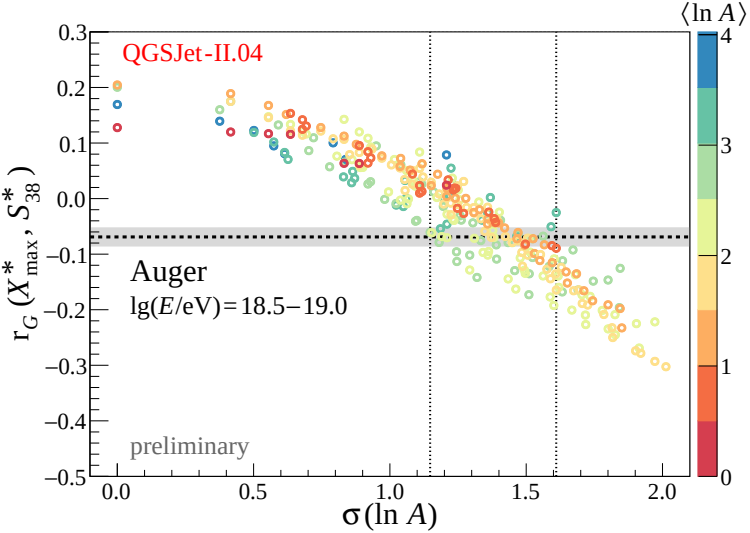

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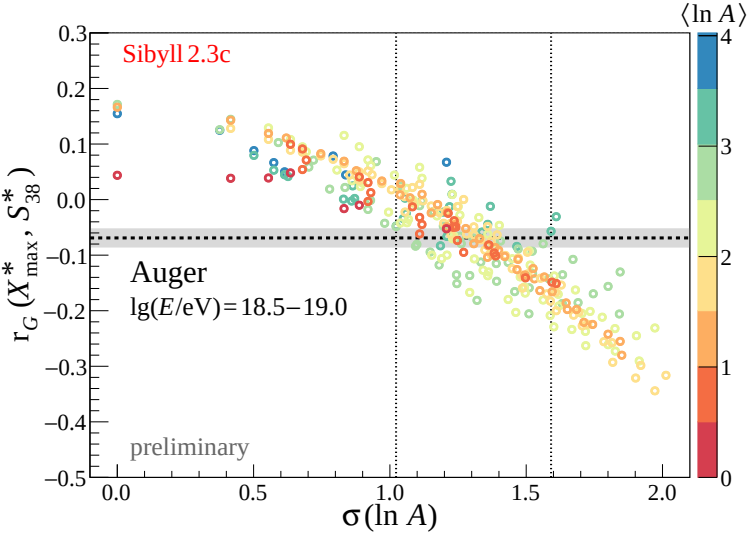
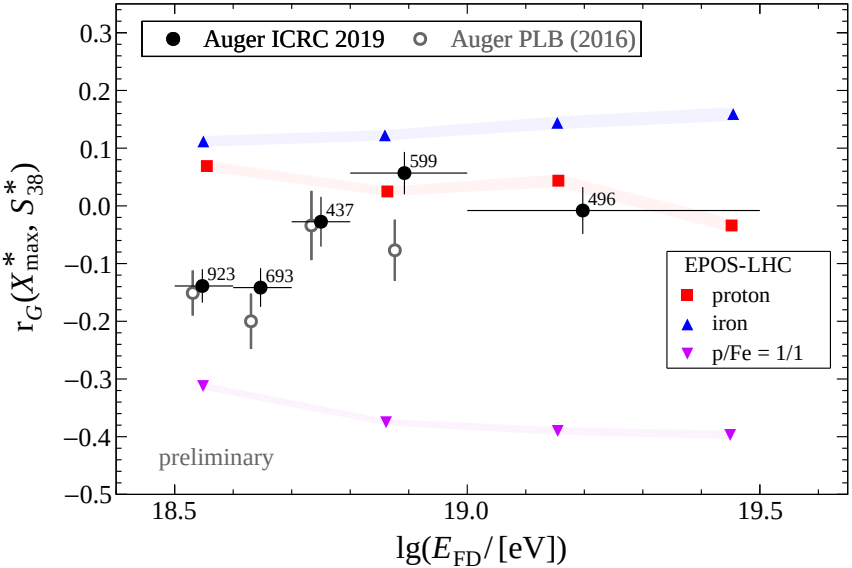


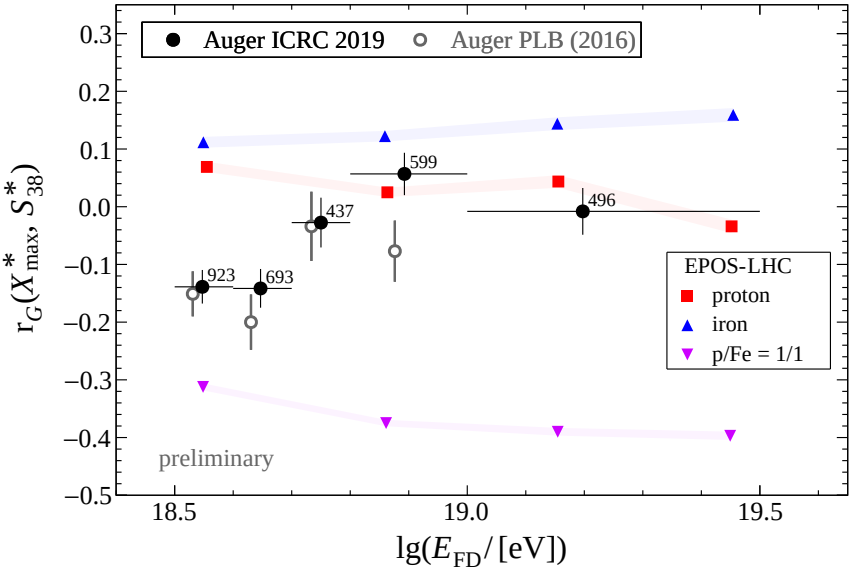
Energy dependence

new data are compatible to [Auger PLB 762 (2016)]: $\chi^2/\mathrm{ndf} = 5.4/4$ (p-value $= 0.25$)



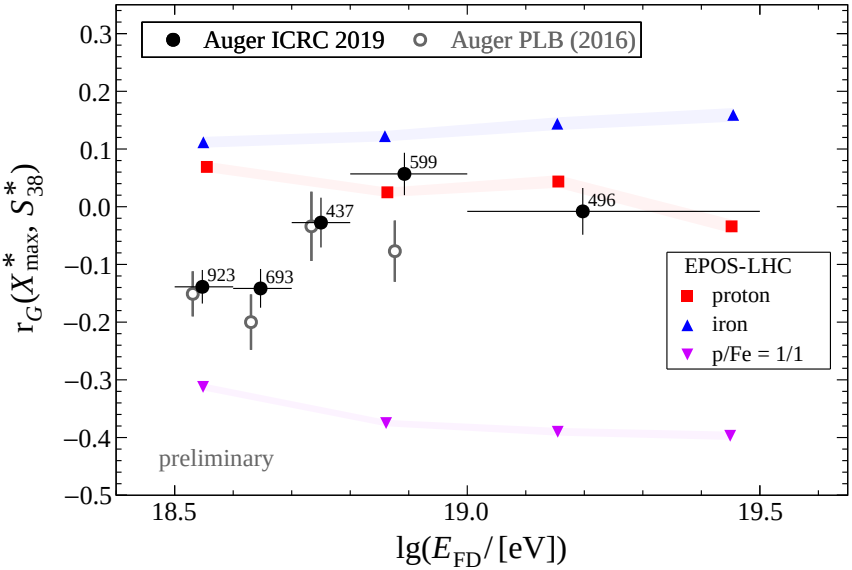
Energy dependence

$\lg(E/\mathrm{eV}) = 18.5 - 18.7$ (1616 events): $r_G = -0.141 \pm 0.022$, at 6.4σ from zero



Energy dependence

above the ankle $\lg(E/\mathrm{eV}) > 18.7$ data are compatible to decrease of $\sigma(\ln A)$



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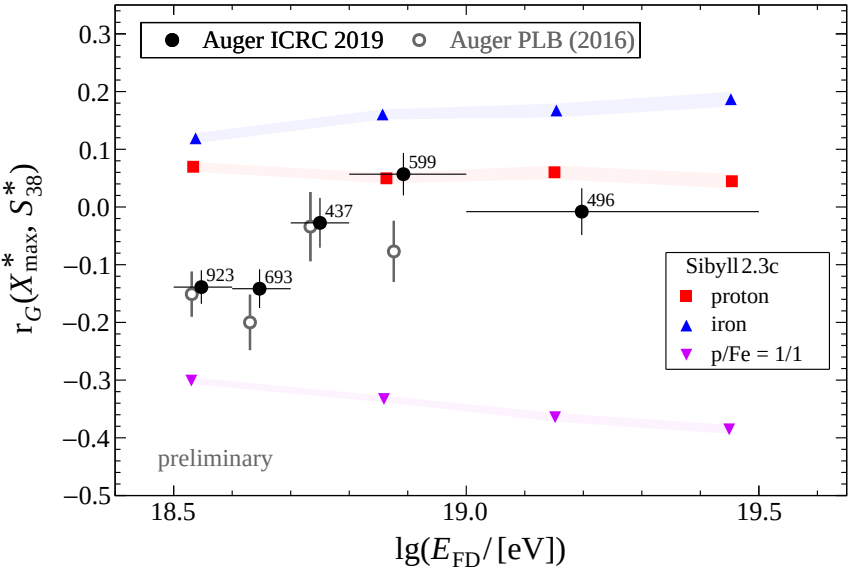

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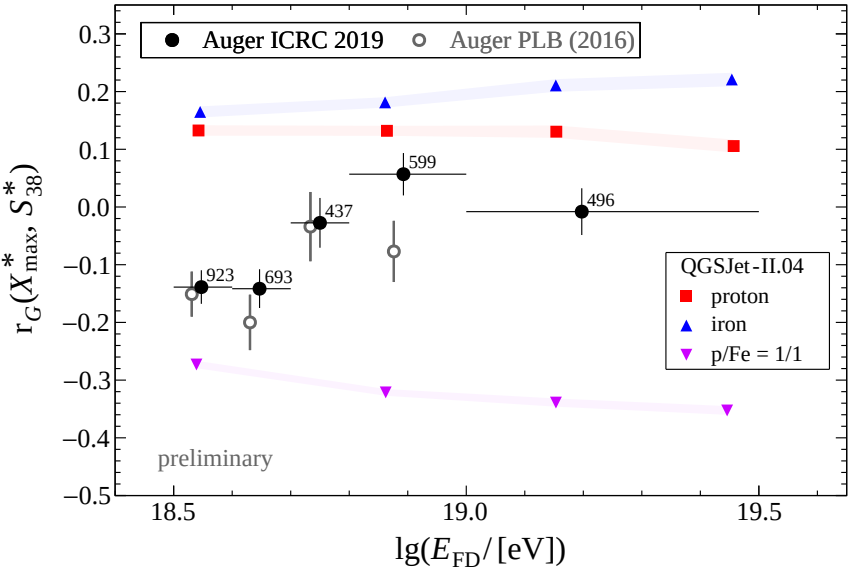


Results (independent of the hadronic models)

$X_{\max}$ analysis

$\langle \ln A \rangle$: decreasing up to 2 EeV and increasing afterwards

$\sigma(\ln A)$: decreasing up to the ankle, more constant at higher energies

$r_{\mathrm{G}}(X^*_{\max}, S^*_{38})$ analysis for $\lg(E/\mathrm{eV}) = 18.5 - 19.0$

below the ankle the correlation in data is significantly, at 6.4σ from zero, negative

pure compositions and proton-helium mixes (all having $r_{\mathrm{G}} > 0$) are excluded

data are compatible to mixed compositions with $\sigma(\ln A) = 0.85 - 1.60$

above the ankle there are indications on decrease of $\sigma(\ln A)$ (more statistics is needed)

backups

The Pierre Auger Observatory

Fluorescence detector (FD)
[longitudinal profile]

duty cycle 15 %

24 + 3 fluorescence telescopes
at 4 locations

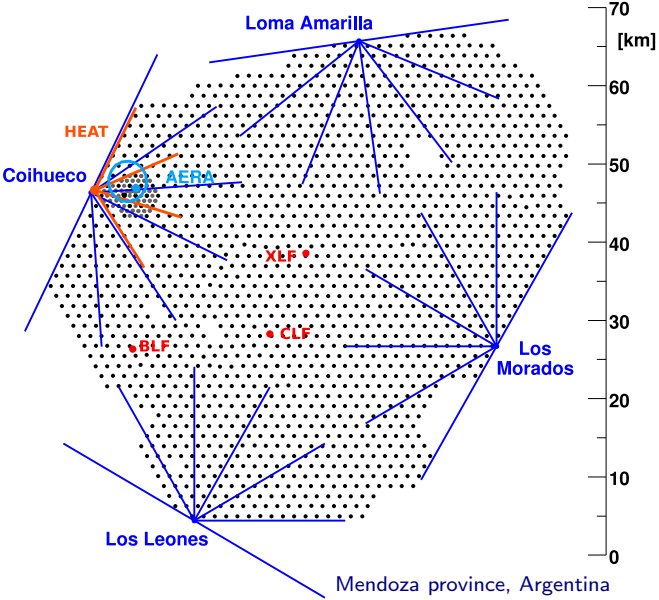
Surface detector (SD)
[lateral distribution]

duty cycle 100 %

1660 water-Cherenkov stations
at 1500 m spacing, 3000 km^2

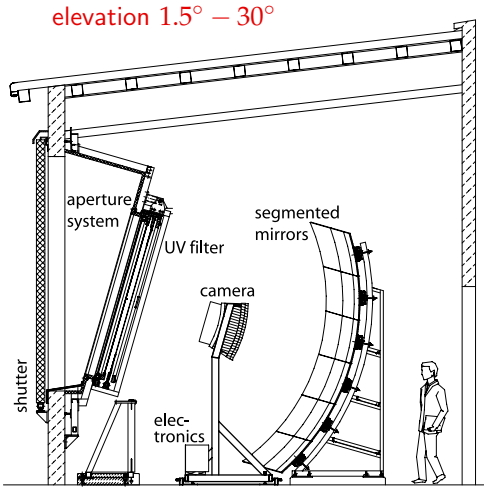
61 water-Cherenkov stations
at 750 m spacing, 23.5 km^2

Nucl. Instrum. Meth. A798 (2015) 172



Fluorescence Detector

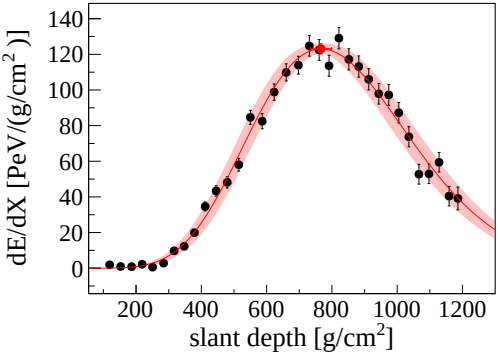
FD telescopes at Los Morados



Fluorescence Detector

FD telescopes at Los Morados

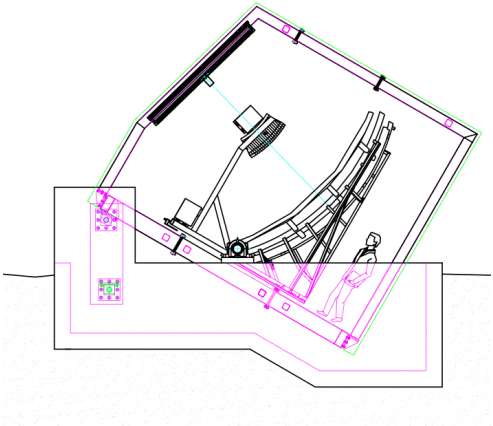
X_{max}, calorimetric energy



High Elevation Auger Telescopes (HEAT)

Detection of showers with $E < 10^{18}$ eV

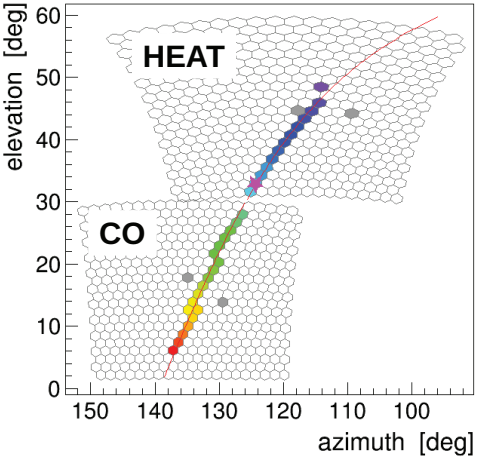
elevation $30^\circ - 58^\circ$



High Elevation Auger Telescopes (HEAT)

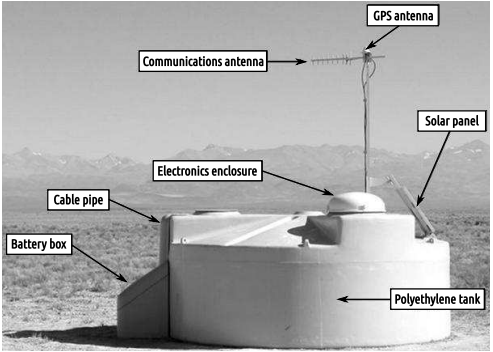
Detection of showers with $E < 10^{18}$ eV

FOV combined with Coihueco FD site



Surface detector

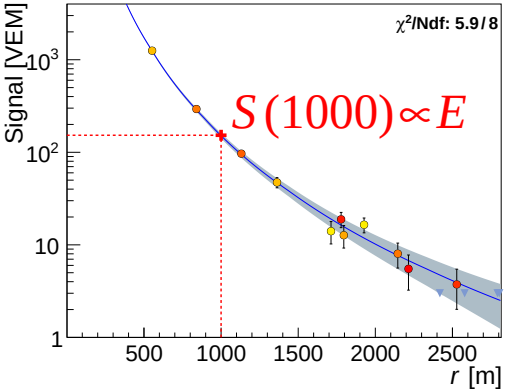
Water-Cherenkov station



Surface detector

Water-Cherenkov station

signal at 1000 m from the core



mass composition sensitivity: muons contribute from 40 to 90% to $S(1000)$ depending on zenith angle