Measurement of the depth of the maximum of air-shower profiles above $10^{17.7}$ eV at the Pierre Auger Observatory

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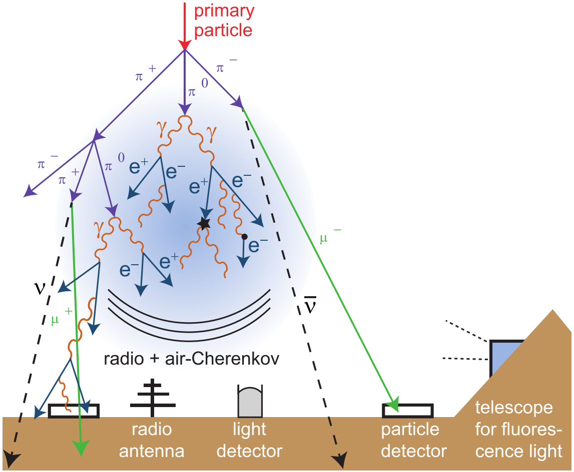
3 September 2026

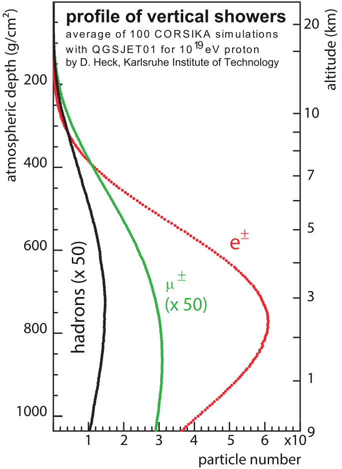
TeV Particle Astrophysics 2026 | August 30 - September 4, Tendō, Japan

Longitudinal profile of cosmic ray showers

- Cosmic-ray showers are caused by impact of primary cosmic rays with our atmosphere

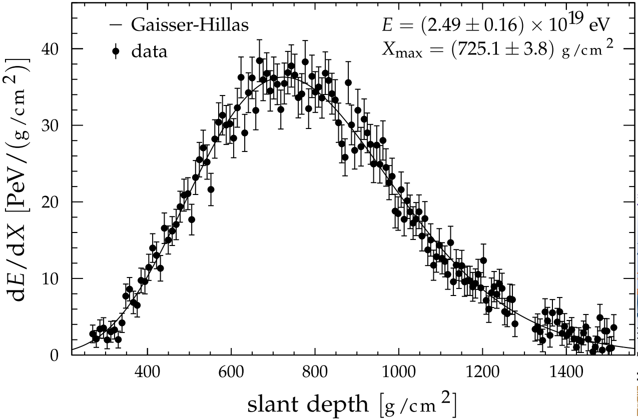
[F. G. Schröder, Prog. Part. Nucl. Phys. 93 (2017) 1–68]

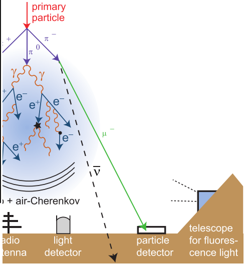




Longitudinal profile of cosmic ray showers

- Cosmic-ray showers are caused by impact of primary cosmic rays with our atmosphere
- Longitudinal profile = energy deposited by cosmic-ray shower as a function of slant depth





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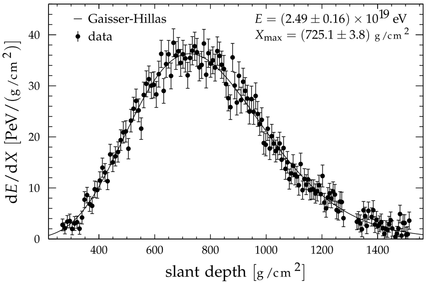
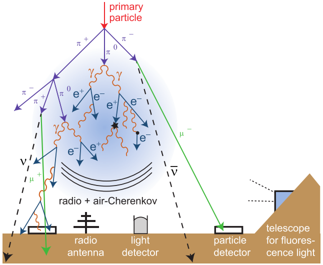
- Slant depth X = mass per unit area traversed by a particle / cosmic-ray shower

$$X(z) = \int_z^{\infty} \rho(r)\, \mathrm{d}r$$





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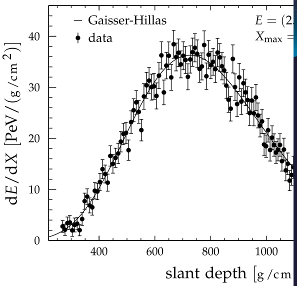

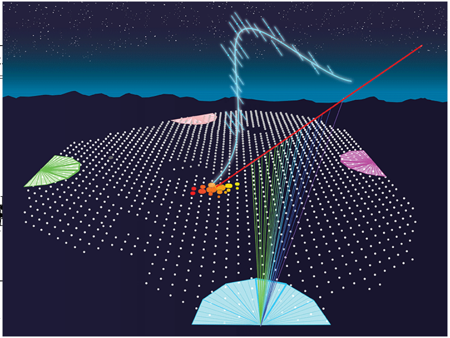

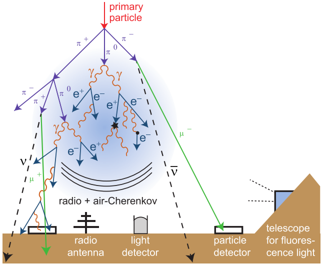

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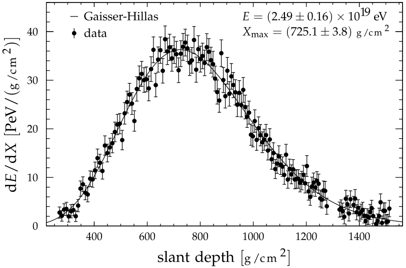
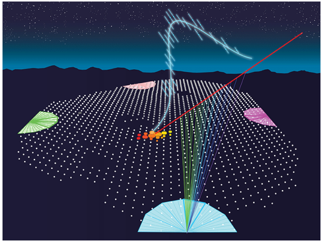
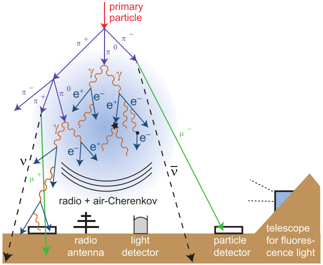
- Depth of the shower maximum $\mathbf{X_{max}}$ **correlated with** mass number **A** of primary particles



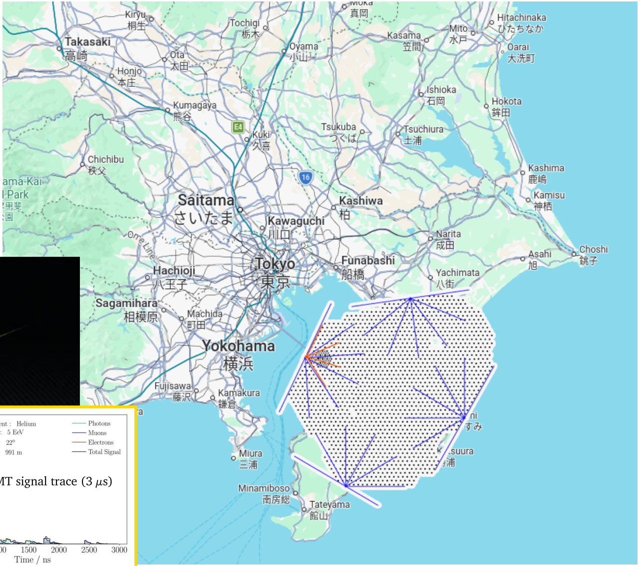


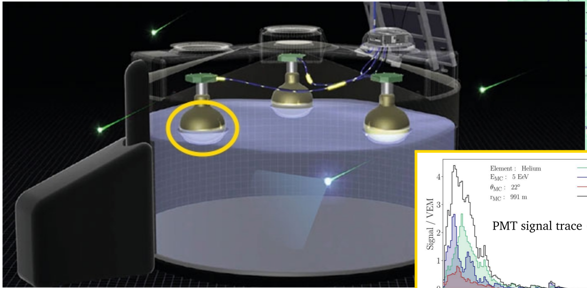


Hybrid Detector of the Pierre Auger Observatory

Surface detector (SD)

- Over 1600 water-Cherenkov stations
- 3 arrays: 1500 m, 750 m, 433 m
- Detecting **shower front** on the surface
- $\sim$ 100% duty cycle





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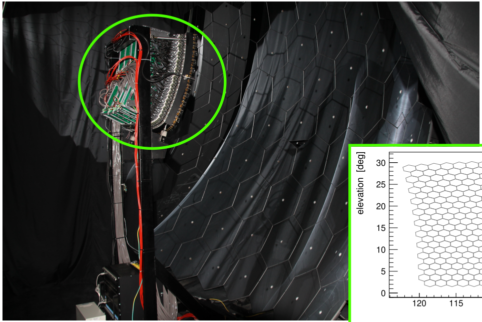
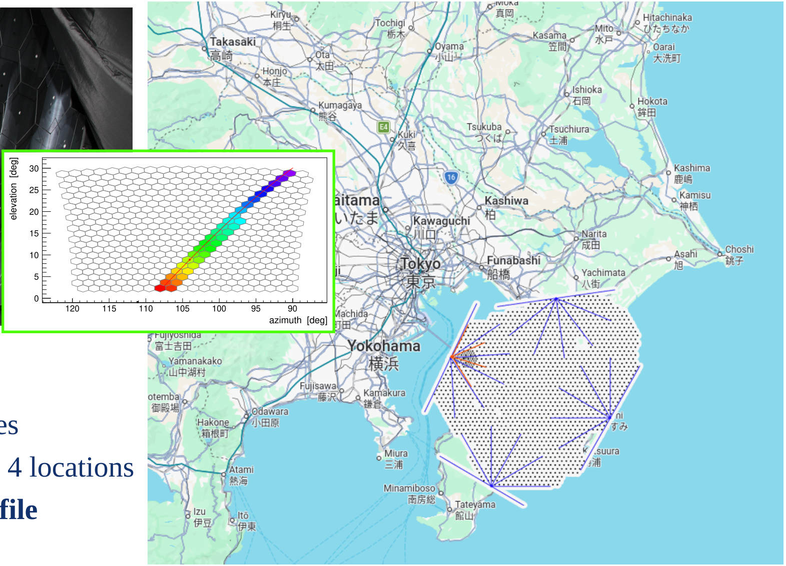


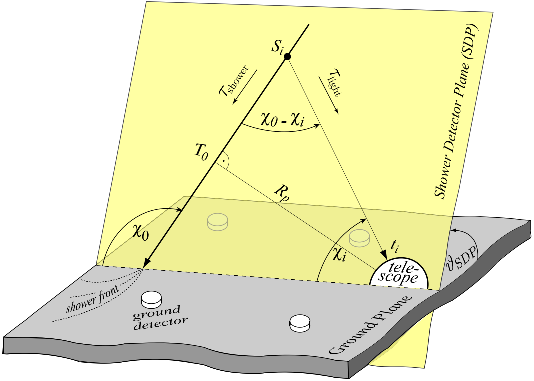


Fluorescence detector (FD)

- 24+3 fluorescence telescopes
- Overlooking SD array from 4 locations
- Detecting **longitudinal profile**
- $\sim$ 15% duty cycle

Latest measurement of $X_{\max}$ [Phys. Rev. D 114 (2026) 043016]

- Analysis of hybrid events **above $10^{17.7}$ eV from 2004 to the end of 2021**
- Hybrid events = events detected by the FD and SD-1500 together
- Shower geometry estimated from the FD and SD-station closest to the shower axis



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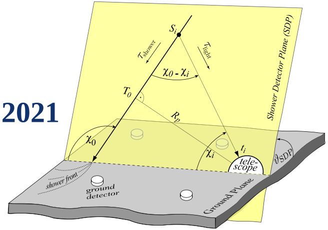
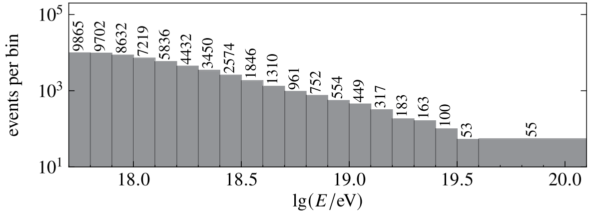
- After reconstruction, **high quality** of the events is ensured by **strict selection criteria**

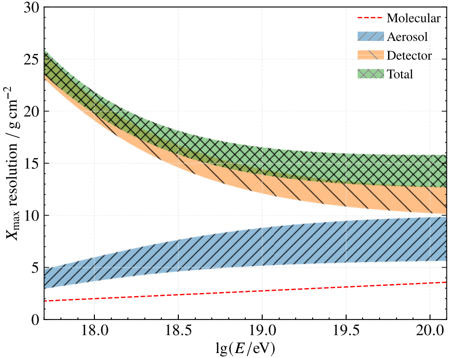


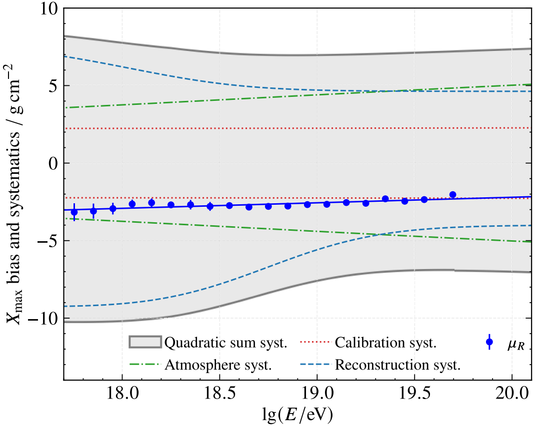


	Events	ε/%
Air-shower candidates	5,311,333	
Preselection:		
Hardware status	4,283,450	80.6
Aerosols	3,479,008	81.2
Hybrid geometry	1,249,849	35.9
Profile reconstruction	1,038,782	83.1
Clouds	769,699	74.1
$E \geq 10^{17.7}$ eV	281,562	36.6
Quality and fiducial selection:		
P(hybrid)	277,378	98.5
$X_{\max}$ observed	218,904	78.9
Quality	156,015	71.3
Fiducial field of view	60,189	38.6
Profile	58,887	97.8
Unique air-shower events	58,453	

True $X_{\max}$ distributions and systematics

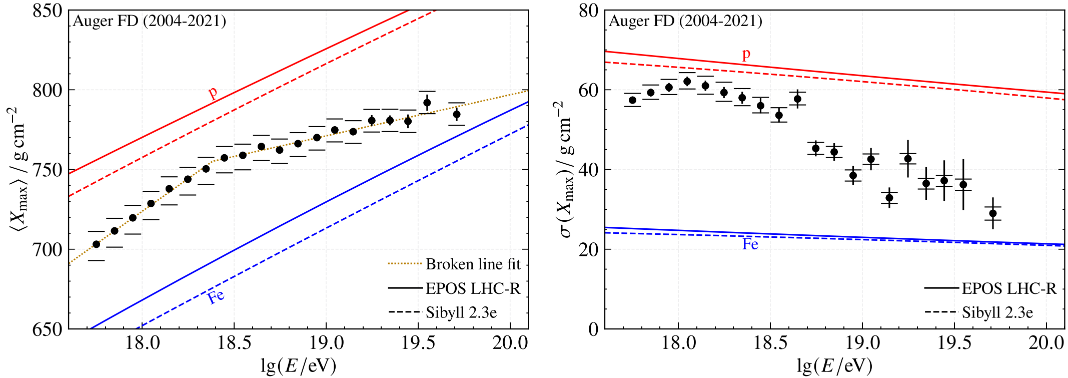
- To get the true $X_{\max}$ distributions - take into account detector response and acceptance
- Sibyll 2.3d simulations used to obtain $X_{\max}$ bias, resolution and acceptance
- Scale uncertainty - effects of calibration, reconstruction and atmosphere





Mean and standard deviation of $X_{\max}$

- Elongation rate $D_{10} = \frac{\mathrm{d}\langle X_{\max}\rangle}{\mathrm{d}\lg E}$ breaks at $\lg\left(E_{\text{break}}/\text{eV}\right) = 18.38 \pm 0.02(\text{stat})^{+0.01}_{-0.01}(\text{sys})$
  $\Rightarrow$ energy dependence of $\langle X_{\max}\rangle$ leans towards heavier elements
- Decreasing $\sigma\left(X_{\max}\right) \Rightarrow$ transition to predominantly heavy primaries at ultra-high energies



Transition from $X_{\max}$ to $\ln A$

- Mean and standard deviation of $X_{\max}$ are related to the statistical moments of $\ln A$ distributions
- Recalculation (interpretation) depends on hadronic-interaction models

$$\langle \ln(A) \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

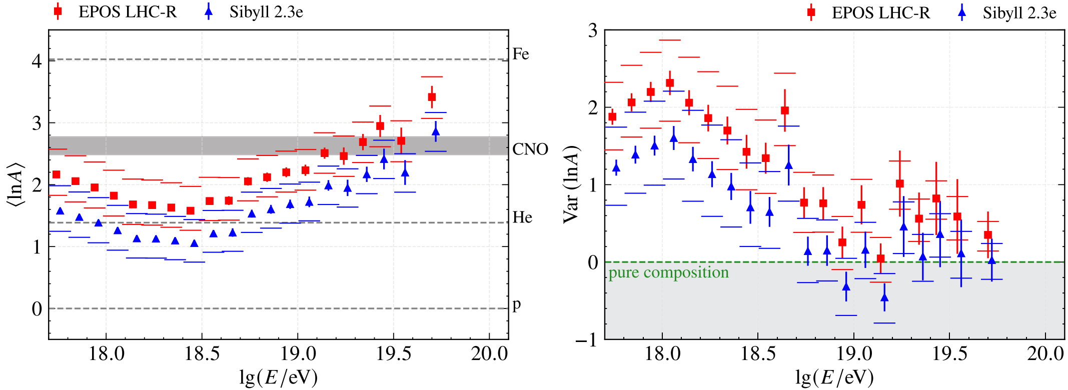
$$V\left(\ln(A)\right) = \frac{\sigma^2(X_{\max}) - \sigma^2_{\mathrm{sh}}\left(\langle \ln(A) \rangle\right)}{b\,\sigma_p^2 - f_E^2}$$

$$f_E = \frac{\langle X_{\max} \rangle_{\mathrm{Fe}} - \langle X_{\max} \rangle_p}{\ln(56)}$$

[JCAP 02 (2013) 026]

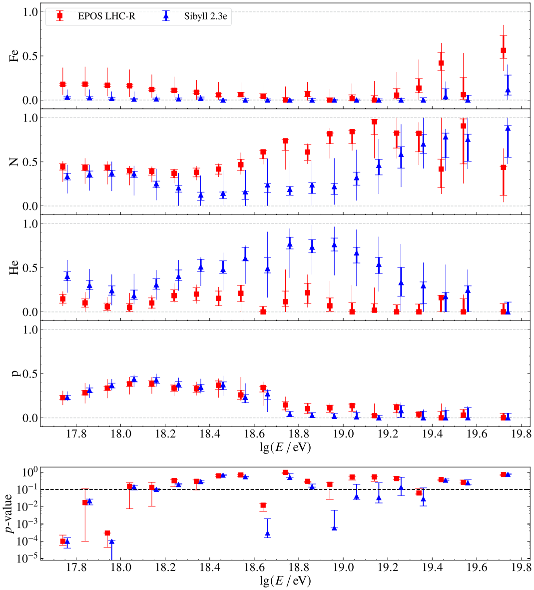
Mean and variance of ln A

- Moments of ln A calculated from $X_{\max}$ using Sibyll 2.3e and EPOS LHC-R simulations
- About 0.5 g/cm^2 difference in $\langle \ln A \rangle$ between the two models



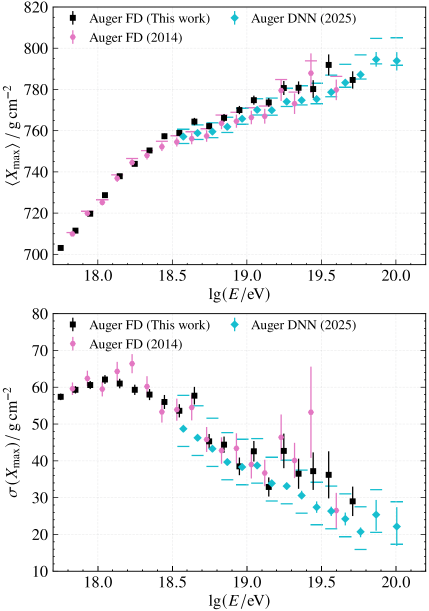
Primary particle fractions

- Fitting $X_{\max}$ distributions from data with $X_{\max}^{\mathrm{MC}}$ distributions of four different nuclei
- Relative fractions used as fit parameter
- Sibyll 2.3e:
  - He dominant from $10^{18.5}$ eV to 10^{19} eV
  - after that, N dominates until the end
  - Fe consistent with zero at all energies
- EPOS LHC-R:
  - N dominant until Fe becomes significant
  - End of spectrum $\rightarrow \sim 50/50$ N/Fe



Comparison with previous results

- Auger DNN → $X_{\max}$ from SD using deep learning
- FD 2014 → data from 2004 to the end of 2012
- Offset between new and old analyses caused by different treatment of aerosols
- Ongoing joint study comparing Auger and TA $X_{\max}$



Summary

Data-driven conclusions:

- Break in $X_{\max}$ as a funcion of energy $\Rightarrow$ **change of composition towards heavier nuclei**
- $X_{\max}$ distributions narrowing with **increasing energy** $\Rightarrow$ heavier and **less-mixed composition**

Model-dependent conclusions:

- Average mass around **CNO group at the highest energies**
- Mass fractions $\Rightarrow$ **p disappearing** above $\sim 10^{18.7}$ eV, composition mostly dominated by N

- **Data** for self-contained studies of mass composition and hadronic interactions **available on zenodo**

BACKUP SLIDES

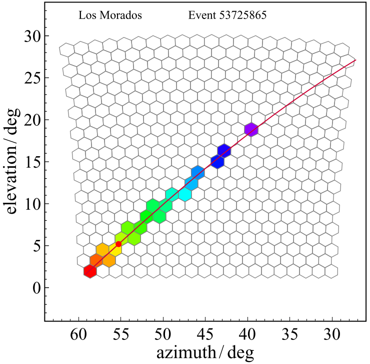
Deepest event in the X_{max} dataset

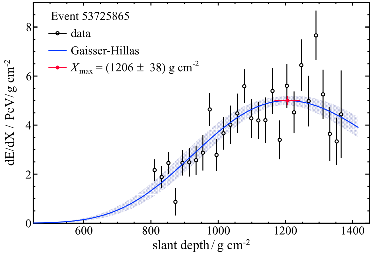
- Event from June 2019, $X_{max} = 1206 \pm 38$ g/cm^2 in the FD site passing all selection cuts (LM)

- $E_{tot}^{LM} = 4.2 \pm 0.6$ EeV

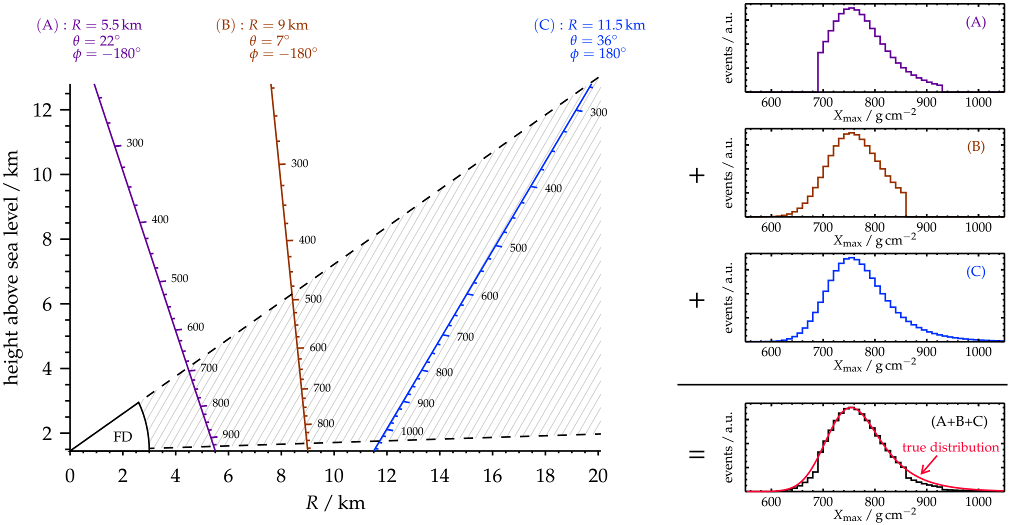
- Compatible with proton-initiated shower

- Heavier nuclei disfavored





X_{max} bias caused by the geometrical FOV of the telescopes



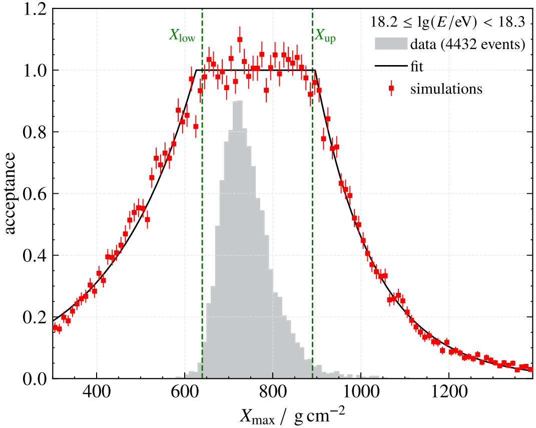
- Bias removed by the fiducial FOV cut - more details about this cut in the paper

X_{max} acceptance

- X_{max} acceptance ε as a function of X_{max}
- Proton showers with Sibyll 2.3d across a wide range of X_{max}
- Studying how many showers of given X_{max} are recorded and pass all the cuts

$$\varepsilon(X_{max}) = \begin{cases} e^{+(X_{max}-X_1)/\lambda_1}, & X_{max} < X_1; \\ 1, & X_1 \leq X_{max} \leq X_2; \\ e^{-(X_{max}-X_2)/\lambda_2}, & X_2 < X_{max}. \end{cases}$$

- Vertical lines = fiducial FOV range



$X_{\max}$ bias and resolution

- Distribution of the difference between reconstructed and generated $X_{\max}$ parametrized as sum of two Gaussian distributions

$$R(X_{\max}^{\rm rec} - X_{\max}^{\rm gen}) = fG(\mu,\sigma_1) + (1-f)G(\mu,\sigma_2)$$

- μ is the $X_{\max}$ reconstruction bias

- Detector resolution of $X_{\max}$ is obtained as
  $$\sigma(X_{\max}^{\rm rec} - X_{\max}^{\rm gen}) = \sqrt{f\sigma_1^2 + (1-f)\sigma_2^2}$$

- Other contributions come from the alignment of the telescopes, from the aerosols and from the uncertainty in atmospheric density profile