Estimation of the cosmic-ray mass composition and proton-proton interaction cross sections from air shower data measured by the Pierre Auger Observatory

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for the Pierre Auger Collaboration

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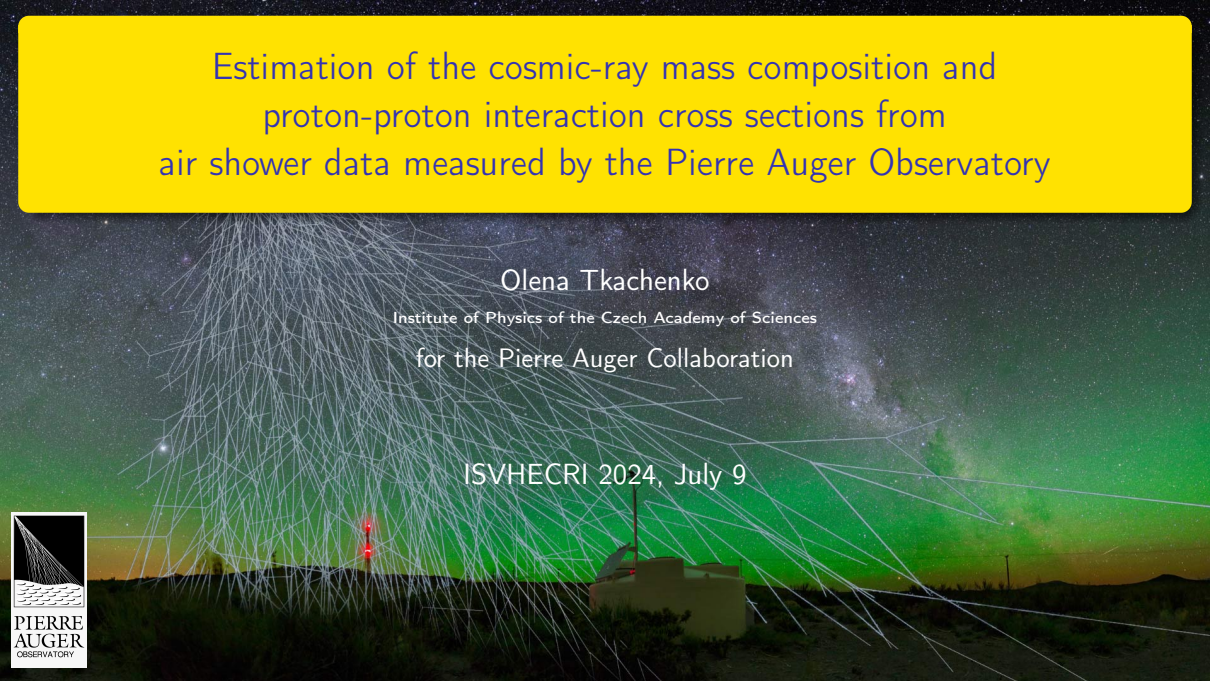
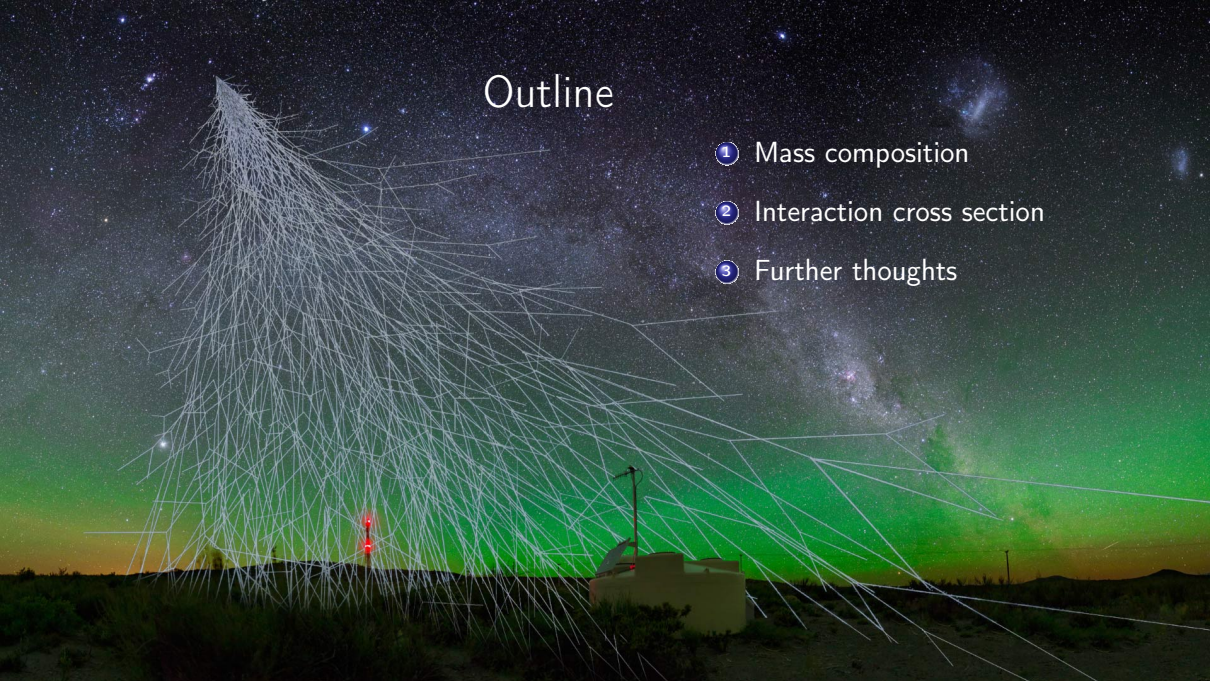


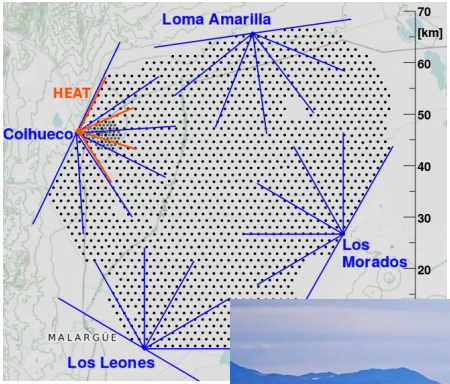


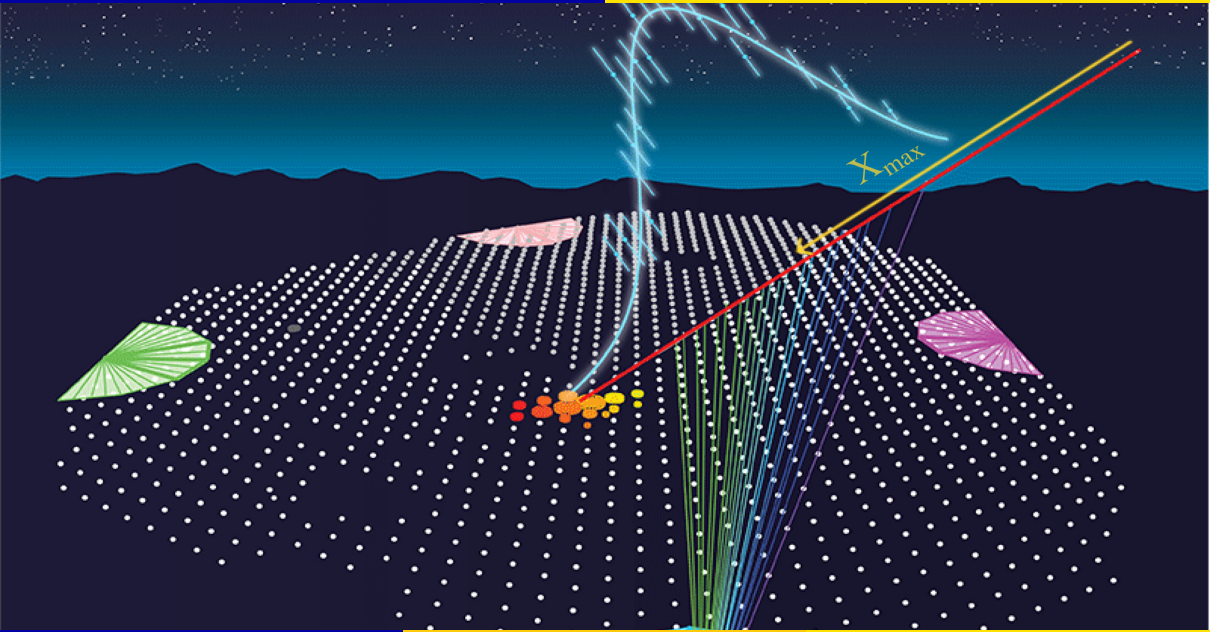
Outline

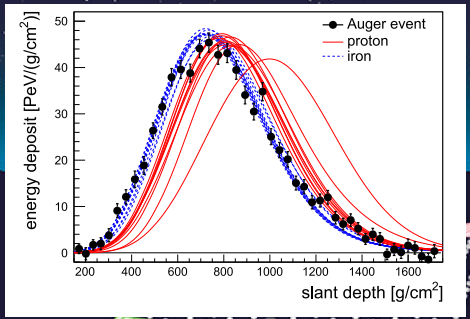
1. Mass composition
2. Interaction cross section
3. Further thoughts

The Pierre Auger Observatory

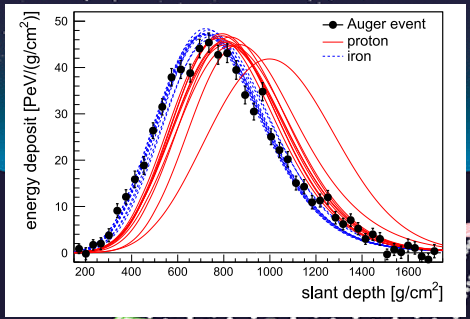
- **A largest detector for UHECRs**:
  - Total area of **3000 km^2**;
  - Located in **Malargue, Argentina**;
- **Hybrid concept**:
  - **Surface Detector Array**:
    - 1660 stations with $\sim$ 100% duty cycle;
  - **Fluorescence Detector**:
    - 27 telescopes with $\sim$ 15% duty cycle;
  - **Radio and muon detectors**.
- **Data taking since 2004**:
  - **Phase I**: 12/2004-12/2021;
  - **AugerPrime** upgarde.




X_{max}


Auger event
proton
iron
energy deposit [PeV/(g/cm^2)]
slant depth [g/cm^2]
0
10
20
30
40
50
200
400
600
800
1000
1200
1400
1600

X_{max}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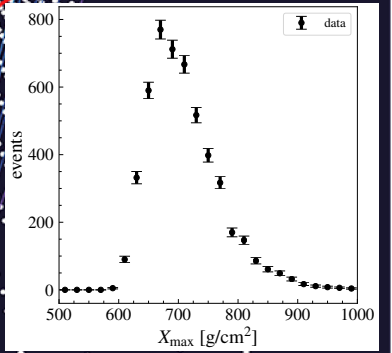
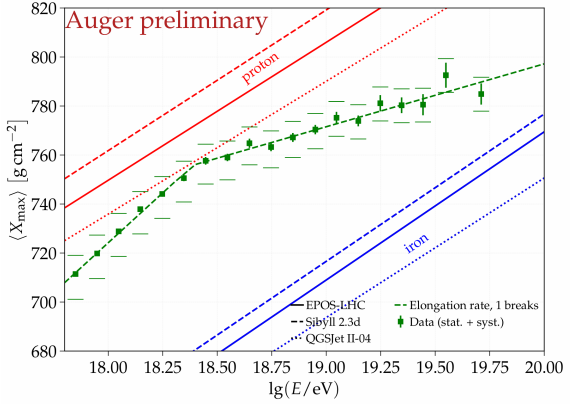
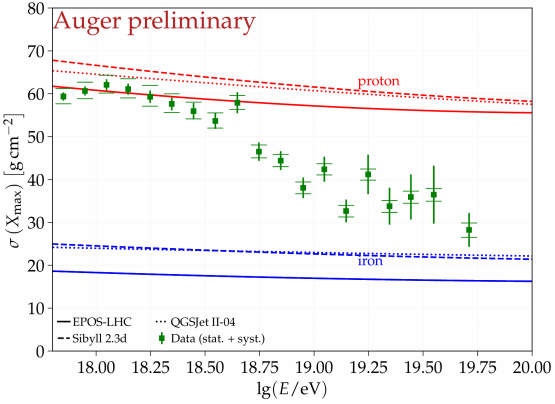

data
events
$X_{\max}$ [g/cm^2]
0
200
400
600
800
500
600
700
800
900
1000

Mean and standard deviation of the observed $X_{\max}$ distribtions





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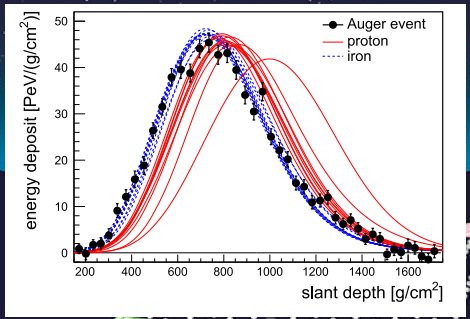
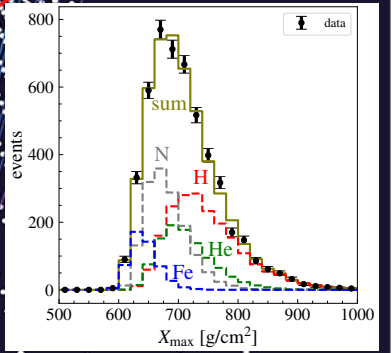
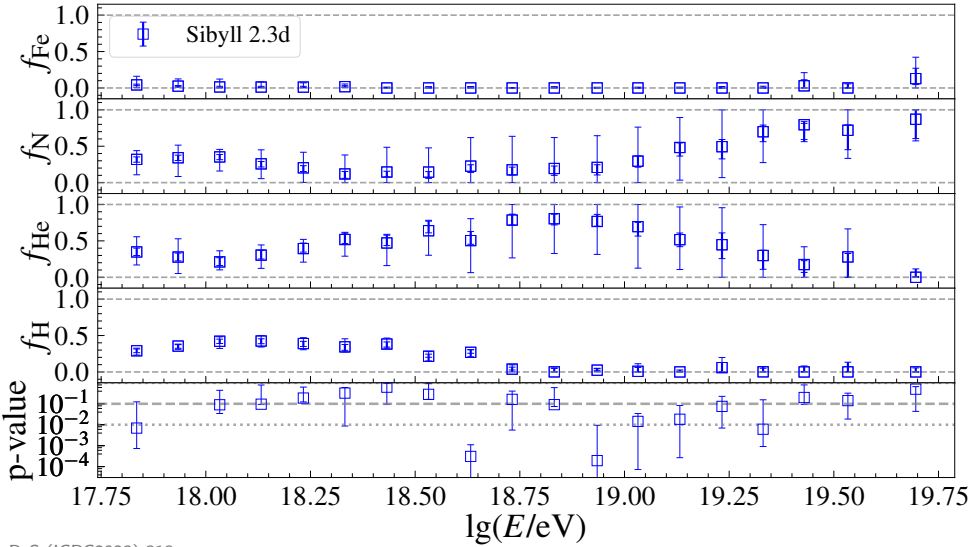

energy deposit [PeV/(g/cm^2)]
slant depth [g/cm^2]
Auger event
proton
iron

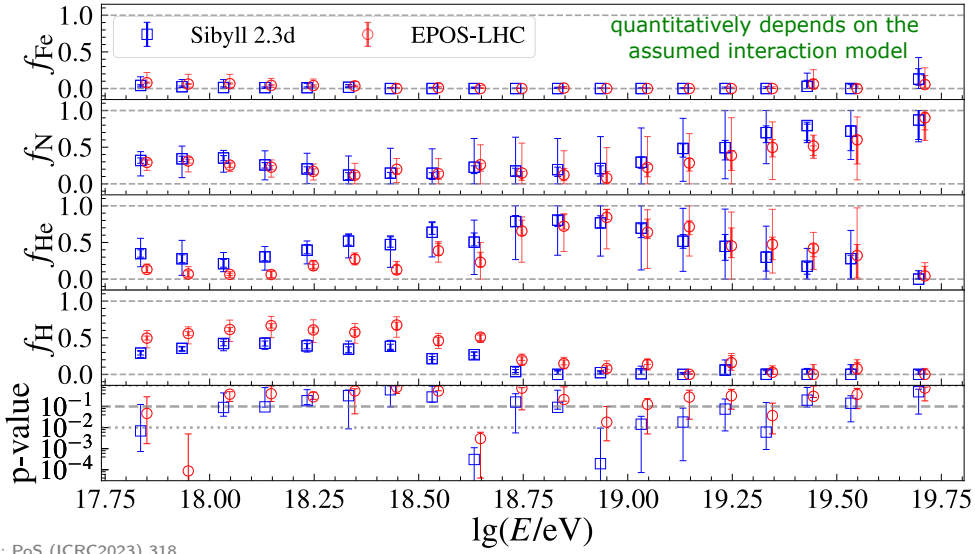

data
sum
N
H
He
Fe
events
X_{max} [g/cm^2]

Mass composition



Fitted data: PoS (ICRC2023) 318

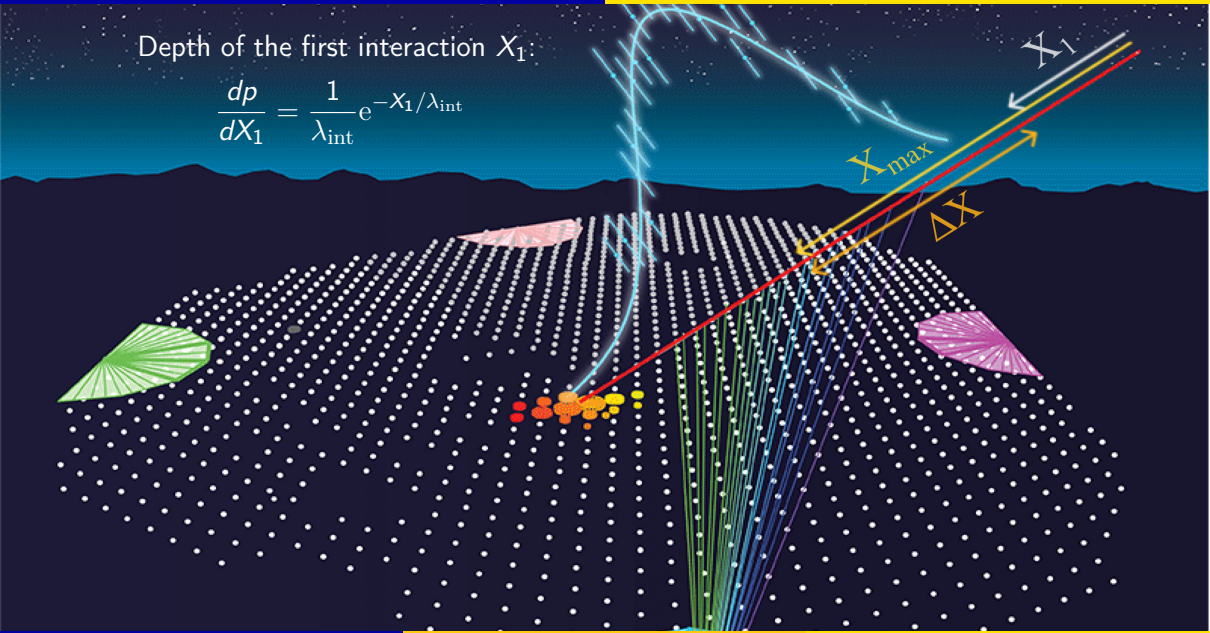
Mass composition



Fitted data: PoS (ICRC2023) 318

Depth of the first interaction X_1:

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\rm int}} e^{-X_1/\lambda_{\rm int}}$$



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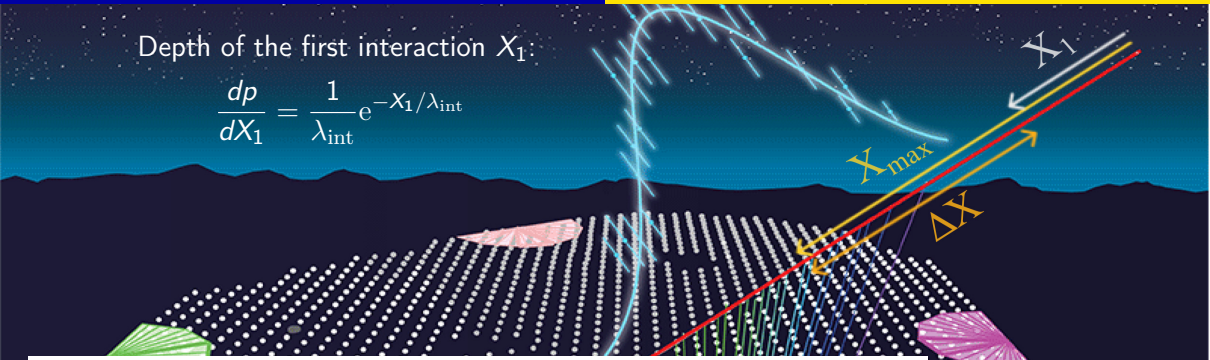
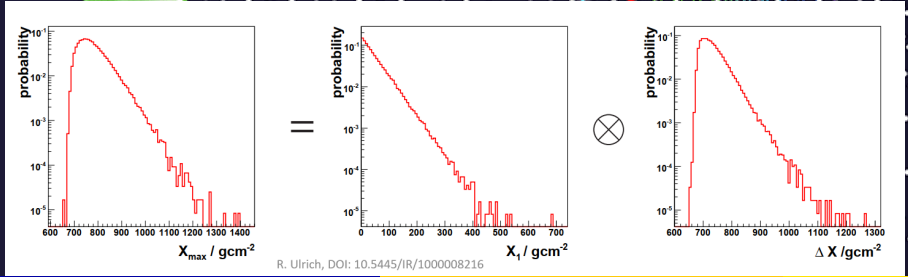
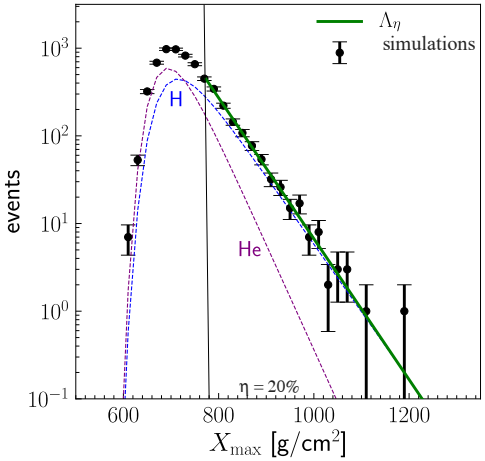




R. Ulrich, DOI: 10.5445/IR/1000008216

Measurement of the (proton-proton) interaction cross section



$X_{\max}$ distribution tail:

- $f(X_{\max}) \sim \mathrm{e}^{-X_{\max}/\Lambda_\eta}$;
- fitted η=20%;
- proton-dominated;
- up 25% He $\Rightarrow$ systematic uncertainy.

Following the analysis strategy for the proton-air cross section described in Phys. Rev. Lett. 109, 062002 (2012)

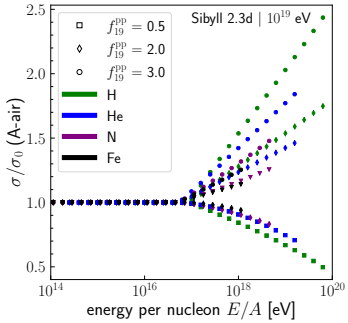
Rescaling of the interaction cross-section

Rescaling the cross-section:

$$\sigma^{\mathrm{pp}}_{\mathrm{mod}} = \sigma^{\mathrm{pp}}_{\mathrm{orig}} f^{\mathrm{pp}}(E_0, E),$$

with a linear scaling factor[1] $f^{\mathrm{pp}}(E_0, E)$:

$$f^{\mathrm{pp}}(E_0, E) = 1 + H(E - E_0)(f^{\mathrm{pp}}_{\lg E_1} - 1)\frac{\lg(E/E_0)}{\lg(E_1/E_0)}.$$



- Nucleus-nucles rescaling $\Rightarrow$ via Glauber theory[2];
- For Sibyll interaction model;
- Modifications are above $E_0 \approx 10^{17}$ eV;
- f_{lgE1} is the rescaling factor at $E_1 = 10^{19}$ eV.

[1] R. Ulrich *et al*, *Phys. Rev. D 83 (2011)* 054026 .

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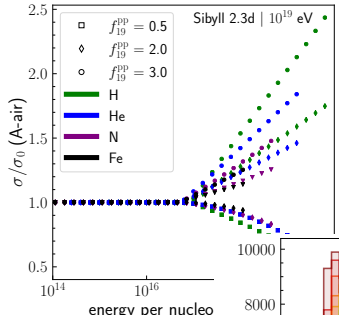

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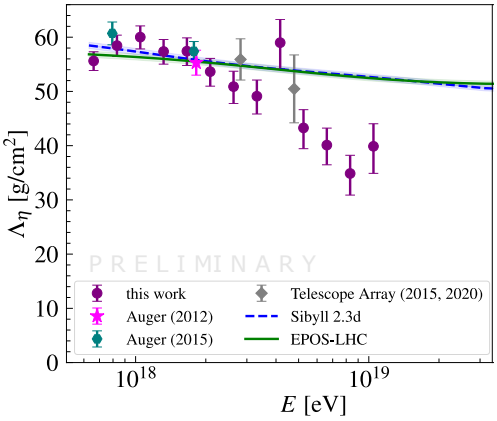
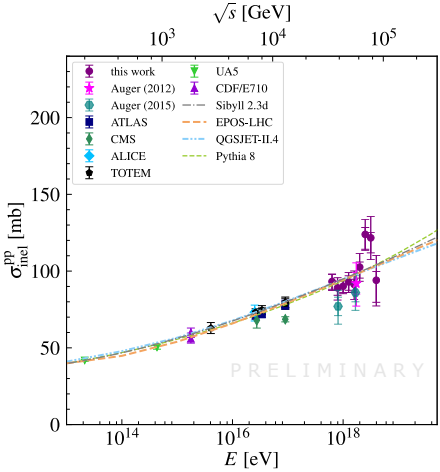


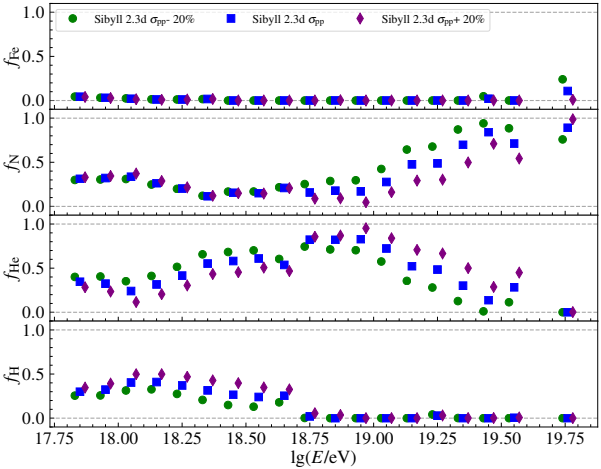
look-up tables

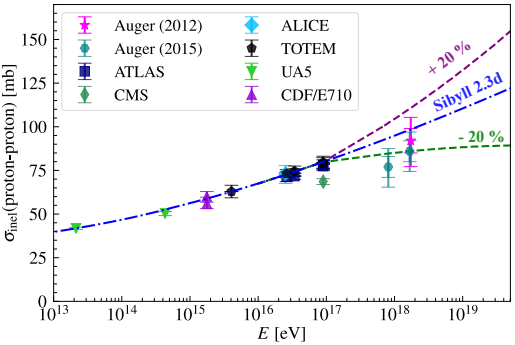
⇒

from air shower simulations



Mass composition vs cross section





Rescaling by $\pm$ 20% at 10^{19} eV

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Mass composition vs cross section: possibility of simultaneous estimation

Why? - *Assumptions in the separate analyses:*

- *Mass composition:* a validity of a certain interaction model;
- *Cross-section:* proton-dominated tail of the X_{max} distribution.

Mass composition - cross section: possibility of simultaneous estimation

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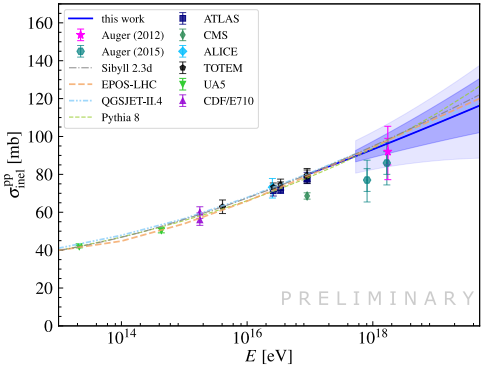
How?

1. Fit the composition using the model predictions with the rescaled cross section;
2. Find the best-fit combination of the fitted parameters.



Summary & Outlook

- From the oberved $X_{\max}$ distributions we can derive the mass composition and the interaction cross section of UHECRs;
- The results agree with the previous findings:
  - The composition is dominated by a lighter component at the lower E and a heavier component at the higher E;
  - The proton proton cross section agrees with the extrapolations from the low-energy accelerator data.
- The estimated mass composition depends on the hadronic interaction properties, i.e. cross section, and vice versa.

Future perspectives:

- Improvements in the analysis of both quantites from the $X_{\max}$ data;
- Further insights on mass and interaction properties, e.g. from deep-learning methods and the AugerPrime upgrade.