Radboud Universiteit

PIERRE AUGER OBSERVATORY

Nikhef

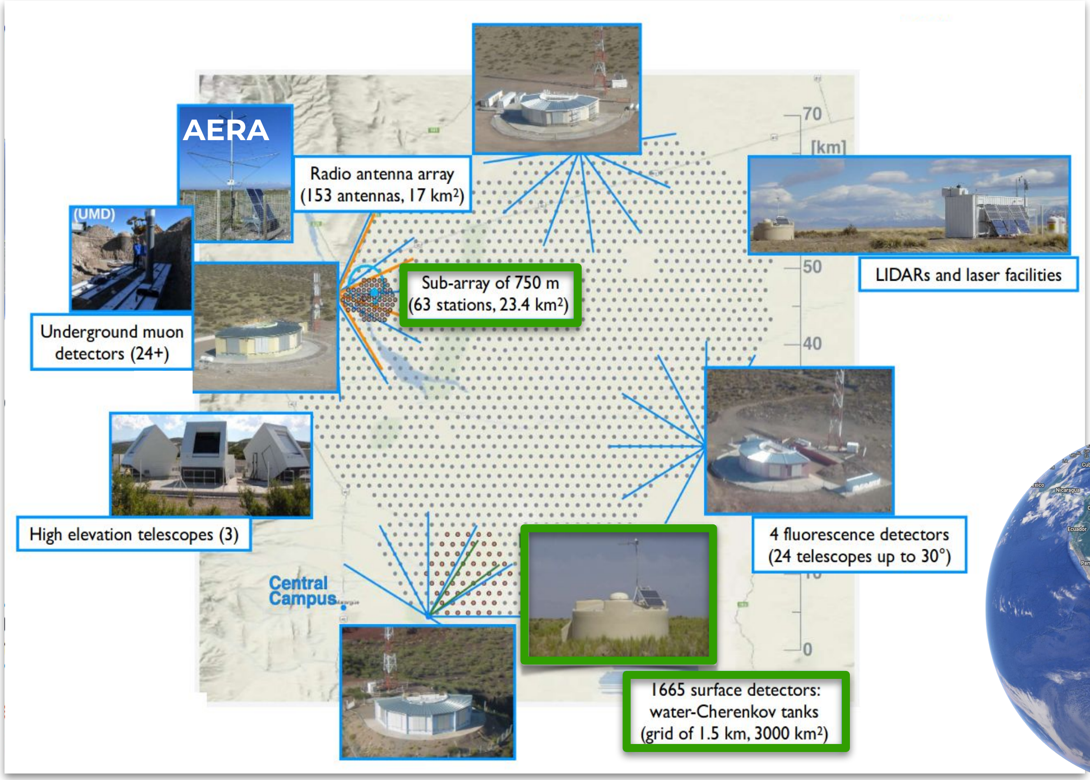
Studies of the *mass composition* of cosmic rays and *proton-proton interaction cross-sections* at ultra-high energies with the **Pierre Auger Observatory**

K. Almeida Cheminant on behalf of the Pierre Auger Collaboration

New Trends in High-Energy and Low-X Physics 2024
Sfântu Gheorghe, Romania

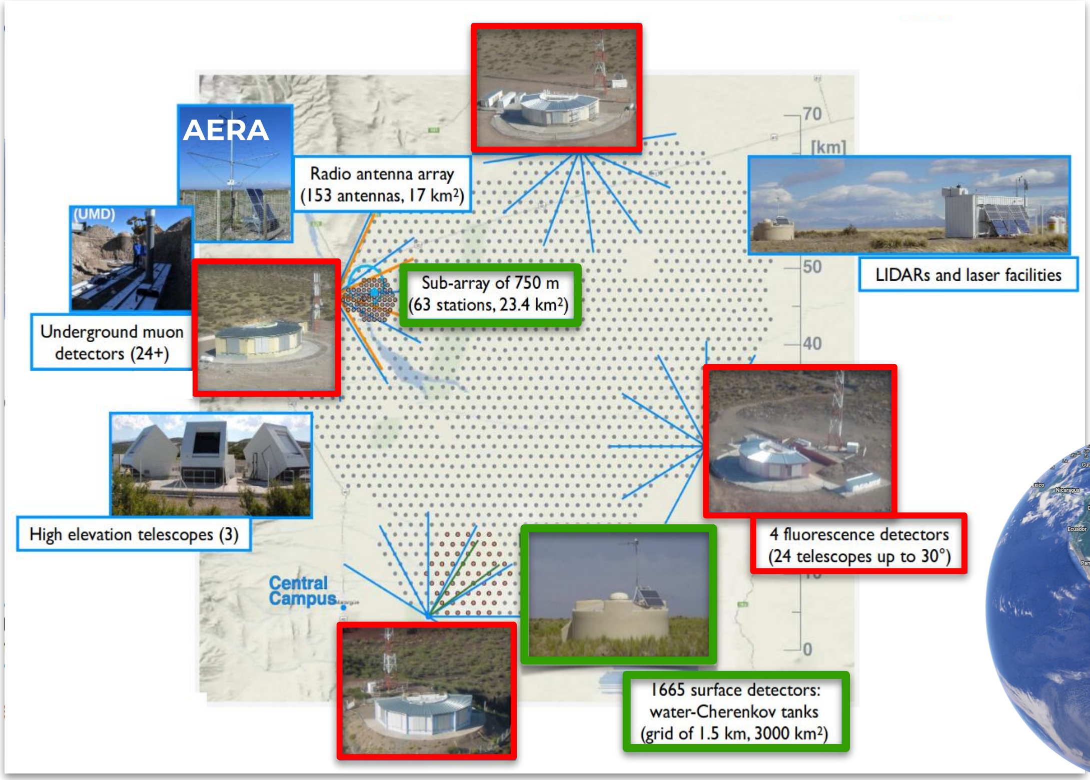
The **P**ierre **A**uger **O**bservatory *(see Olena Tkachenko talk)*

- ★ **Water-Cherenkov Surface Detectors (SD)**: signal of secondary particles at the ground.



The **P**ierre **A**uger **O**bservatory *(see Olena Tkachenko talk)*

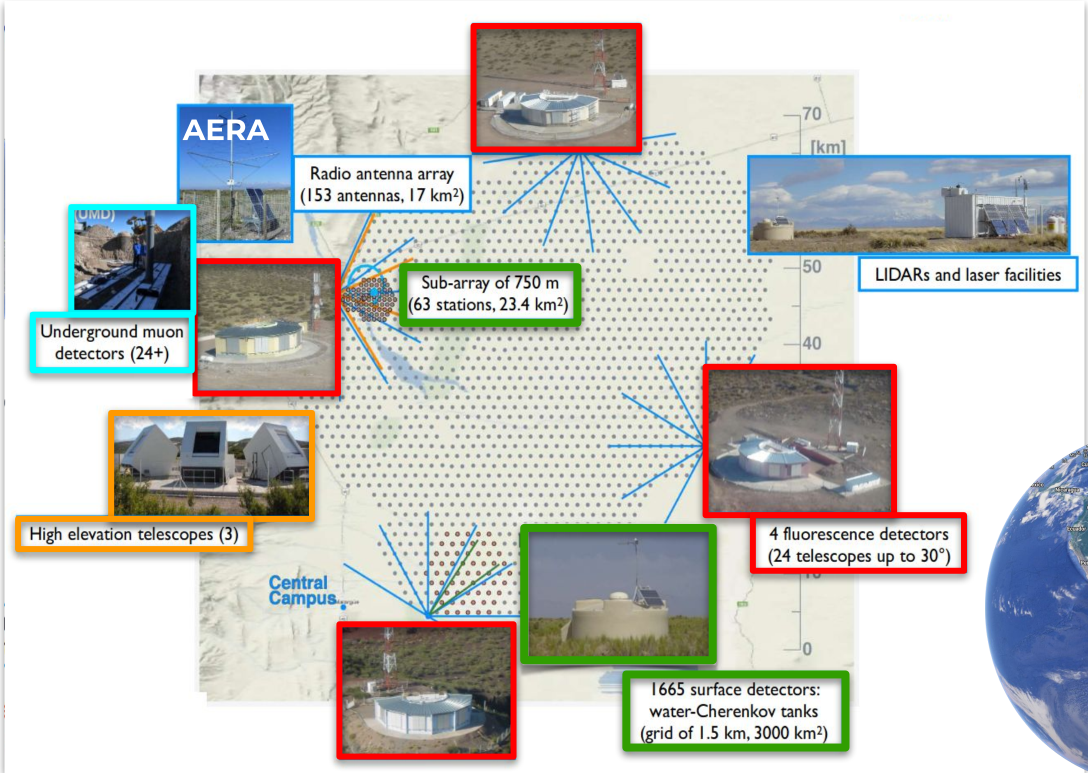
- ★ **Water-Cherenkov Surface Detectors (SD)**: signal of secondary particles at the ground.
- ★ **Fluorescence Detectors (FD)**: longitudinal development of EAS.



The **P**ierre **A**uger **O**bservatory *(see Olena Tkachenko talk)*

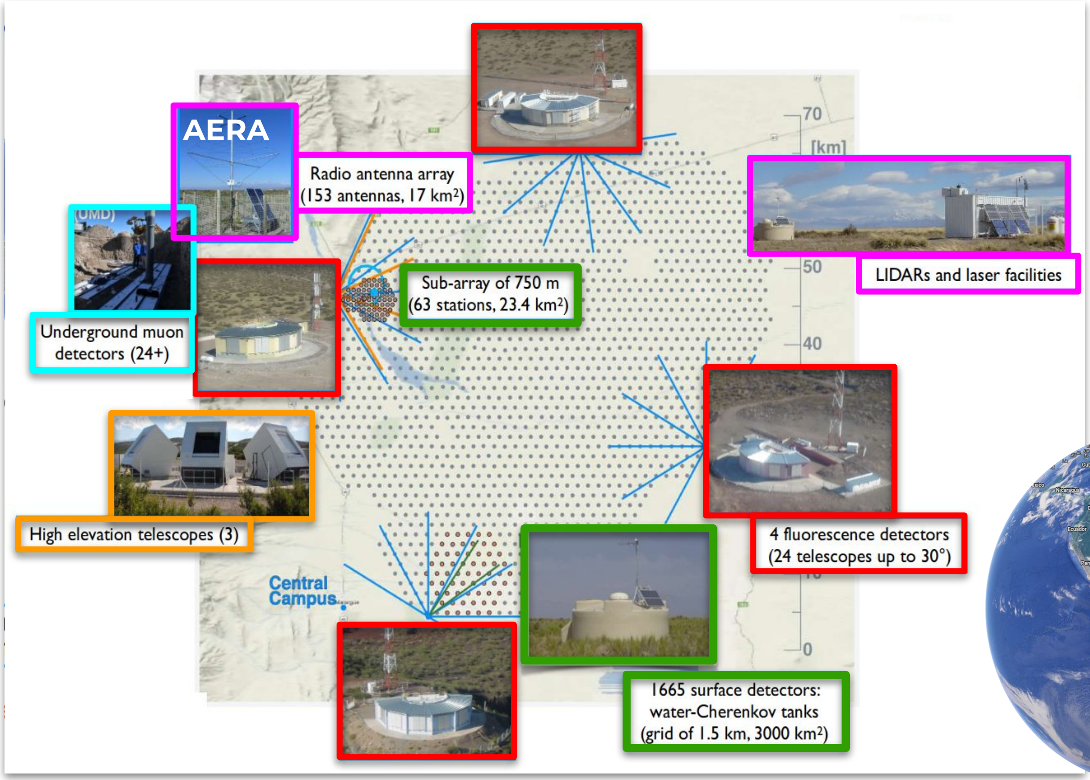
PIERRE AUGER OBSERVATORY

- ★ **Water-Cherenkov Surface Detectors (SD)**: signal of secondary particles at the ground.
- ★ **Fluorescence Detectors (FD)**: longitudinal development of EAS.
- ★ **Underground Muon Detectors**: muon signal.

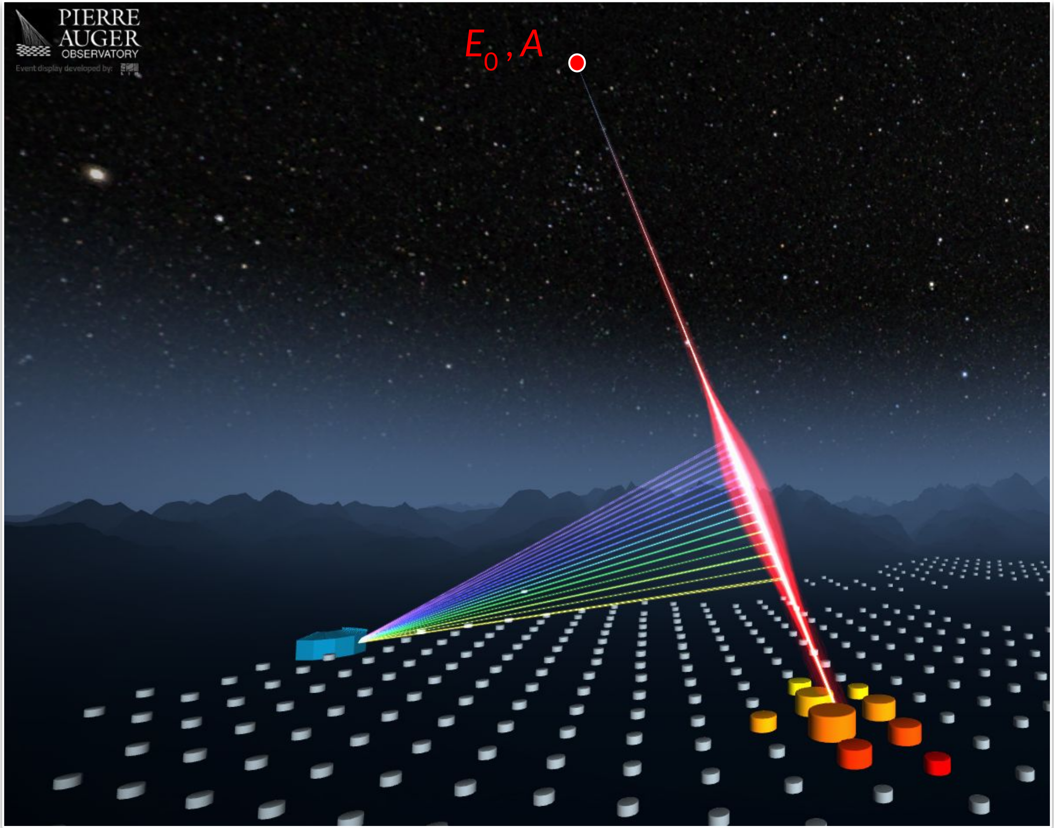


The Pierre Auger Observatory *(see Olena Tkachenko talk)*

- ★ **Water-Cherenkov Surface Detectors (SD)**: signal of secondary particles at the ground.
- ★ **Fluorescence Detectors (FD)**: longitudinal development of EAS.
- ★ **Underground Muon Detectors**: muon signal.
- ★ **And many others**: radio antenna, LIDARs, etc...



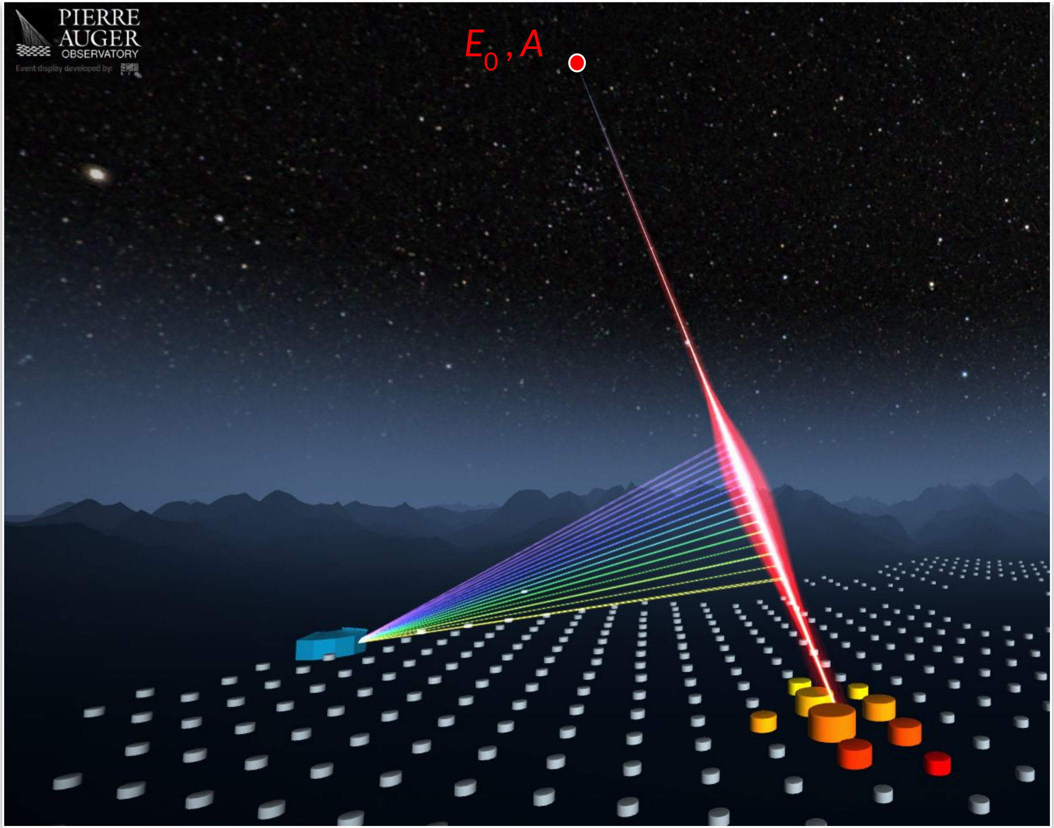
Measuring the longitudinal profile



Primary of energy $\boldsymbol{E_0}$ and mass **A**

➢ Electromagnetic component formed by the decay of $\boldsymbol{\pi^0}$.

Measuring the longitudinal profile

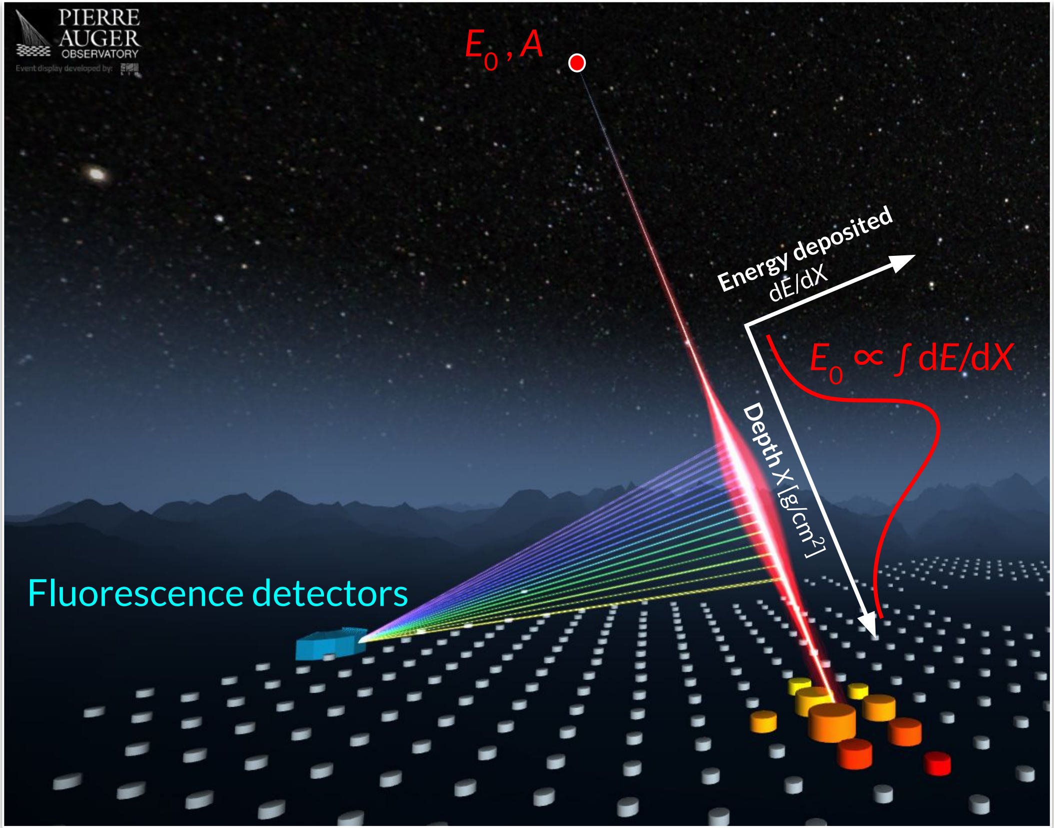


Primary of energy $\boldsymbol{E_0}$ and mass **A**

➢ Electromagnetic component formed by the decay of $\boldsymbol{\pi^0}$.

➢ Detection of isotropic fluorescence light.

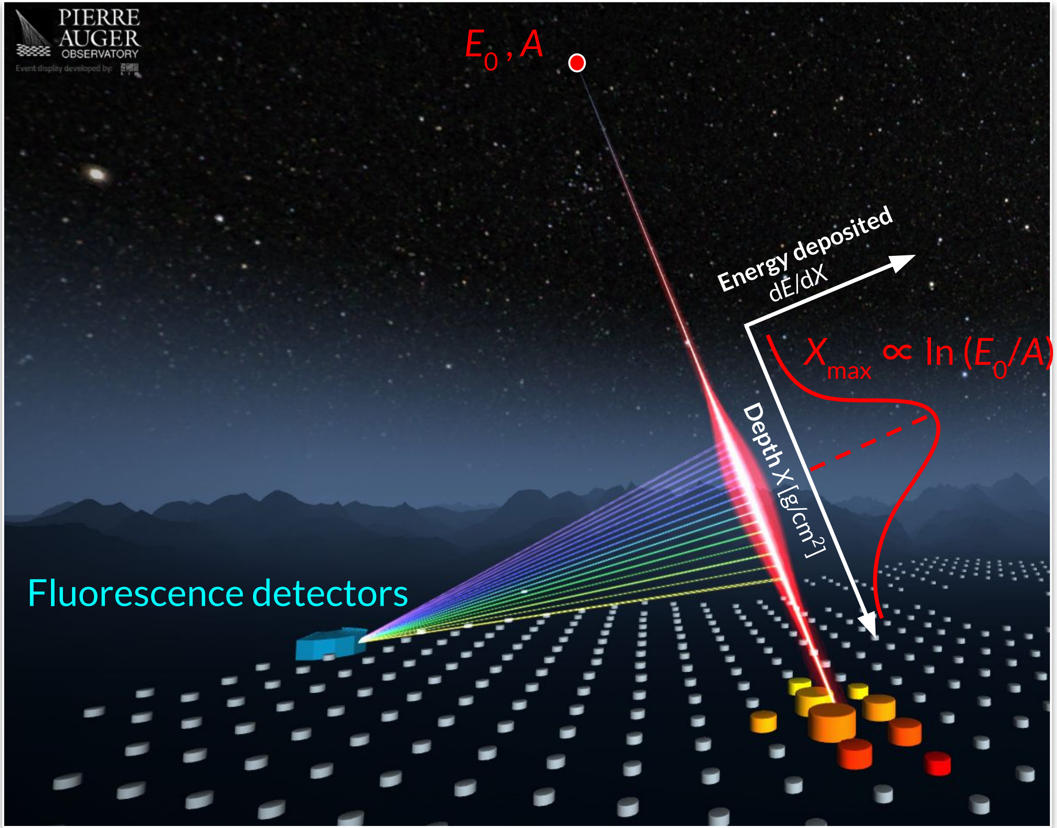
Measuring the longitudinal profile



Primary of energy E_0 and mass **A**

- ➢ Electromagnetic component formed by the decay of π^0.
- ➢ Detection of isotropic fluorescence light.
- ➢ Nearly-calorimetric measurement of energy.

Measuring the longitudinal profile

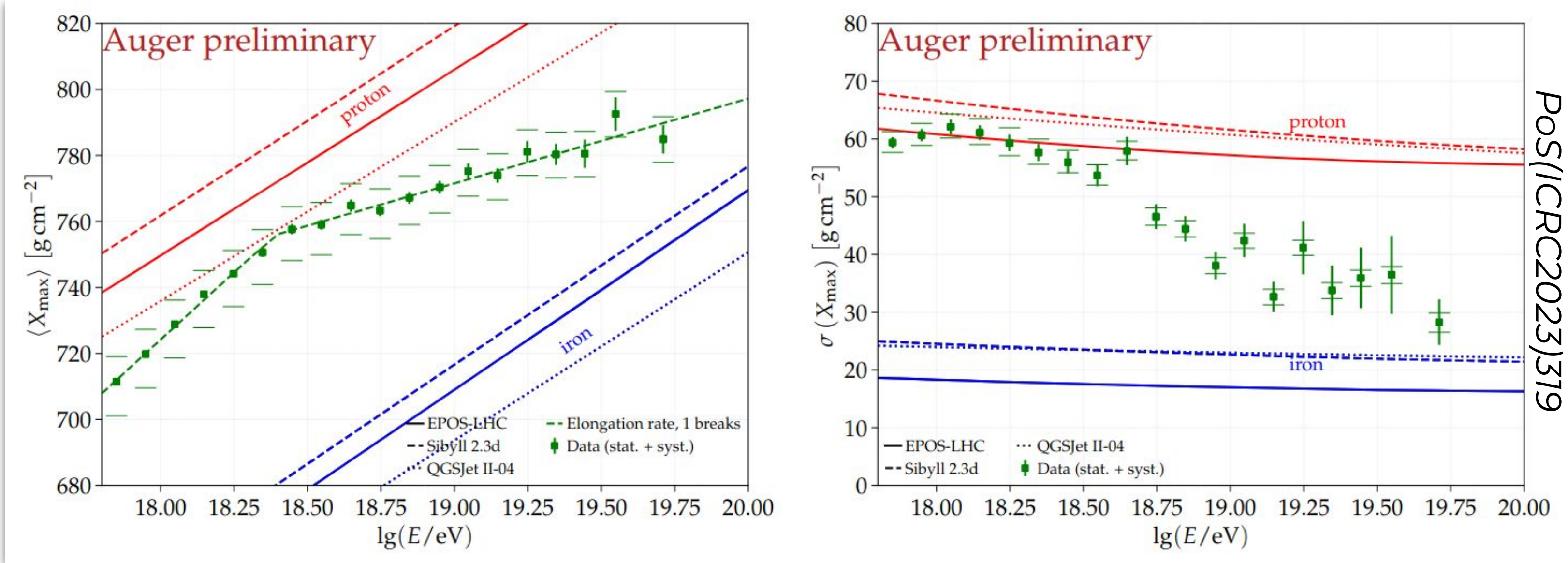


Primary of energy $\boldsymbol{E_0}$ and mass **A**

- Electromagnetic component formed by the decay of $\boldsymbol{\pi^0}$.
- Detection of isotropic fluorescence light.
- Nearly-calorimetric measurement of energy.
- Measurement of the depth of maximum development $\mathbf{X_{max}}$.

(dependent of the **inelastic cross-section** → deeper shower for lower primary mass).

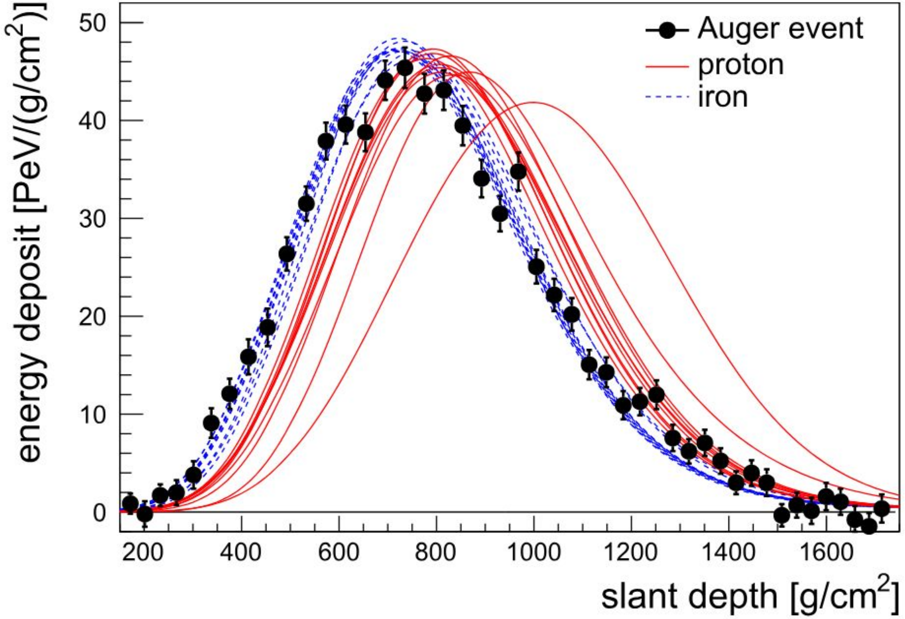
X_{max} measurements



PoS(ICRC2023)319

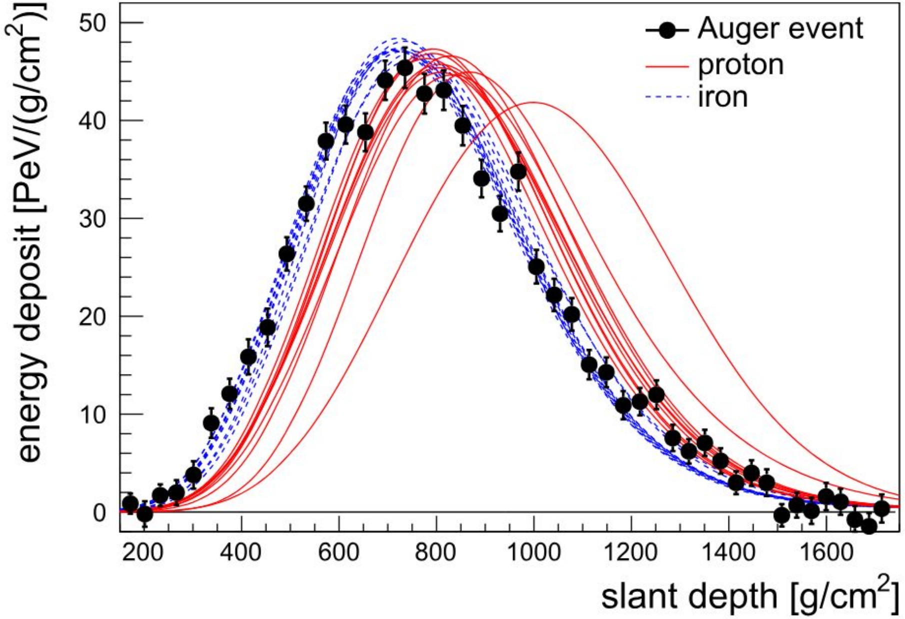
- Composition getting lighter up to a few EeV.
- Above a few EeV, towards mixed and heavier composition.
- Trends supported by X_{max} fluctuations measurements.

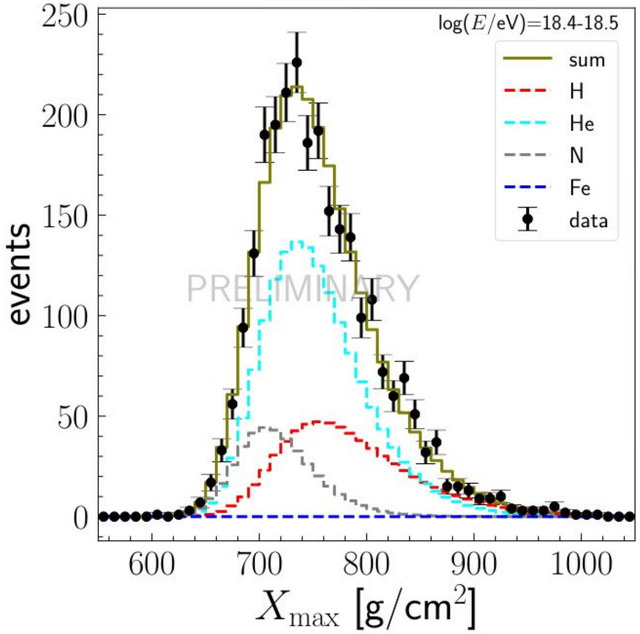
X_{max} measurements



- **Large fluctuations** prevent primary identification on an event-by-event basis.

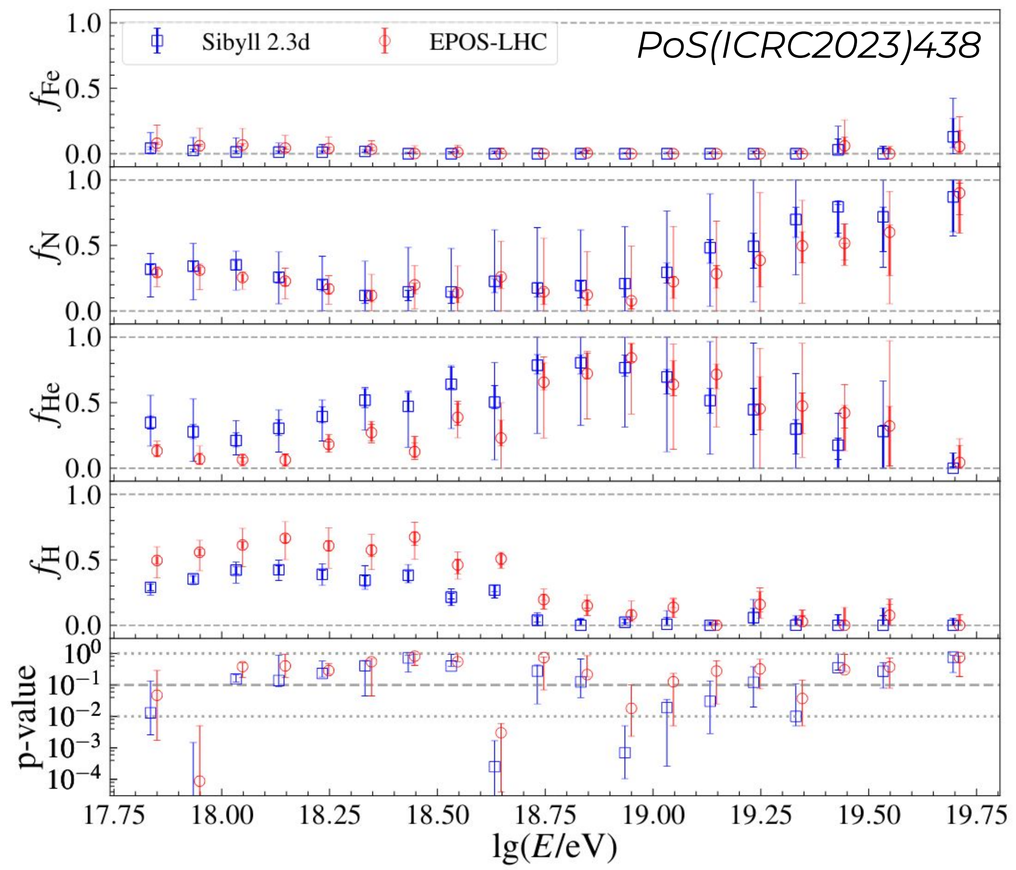
X_{max} measurements & Fractions





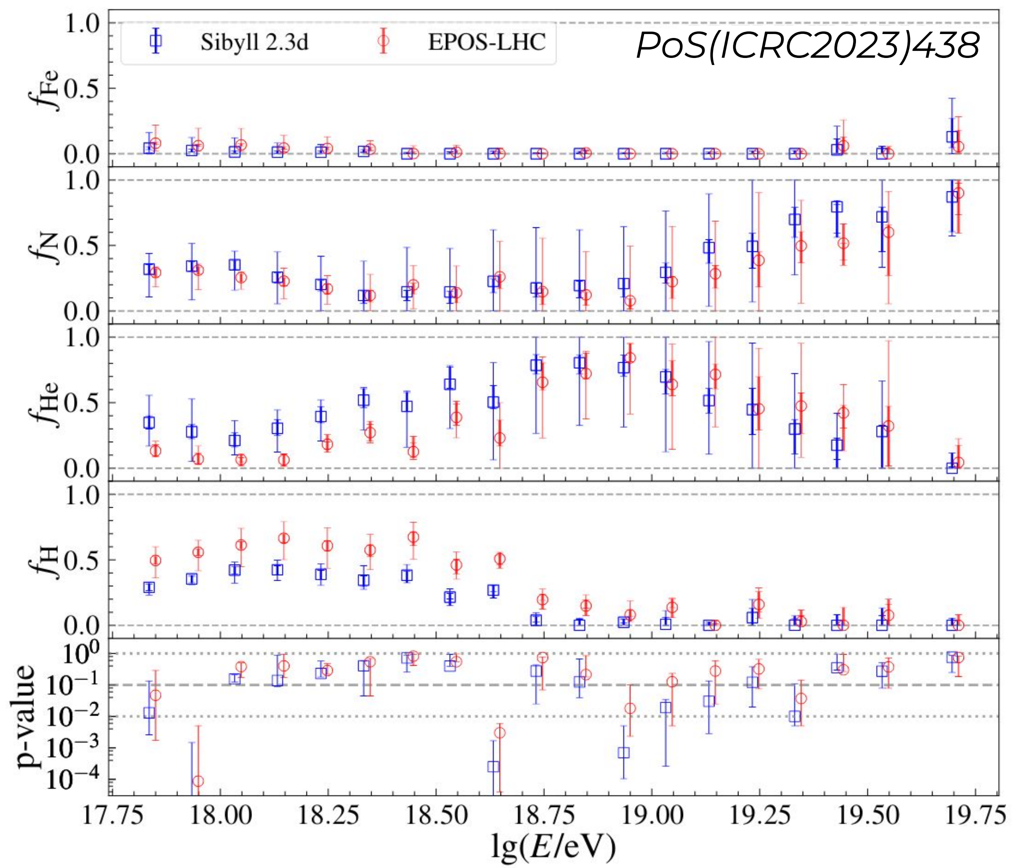
- **Large fluctuations** prevent primary identification on an event-by-event basis.
- **Fit** the X_{max} distribution for different energy bins by considering MC simulations of different primaries.

X_{max} measurements & Fractions



- Air showers simulated with **CONEX** (1D) and 2 different high-energy **hadronic models**.
- **Mix of primaries**: H, He, N and Fe.
- From **$10^{17.8}$ eV** to above **$10^{19.6}$ eV**.
- **10^4** showers / primary / energy bin.
- **Systematics** driven by the X_{max} scale uncertainties.

X_{max} measurements & Fractions

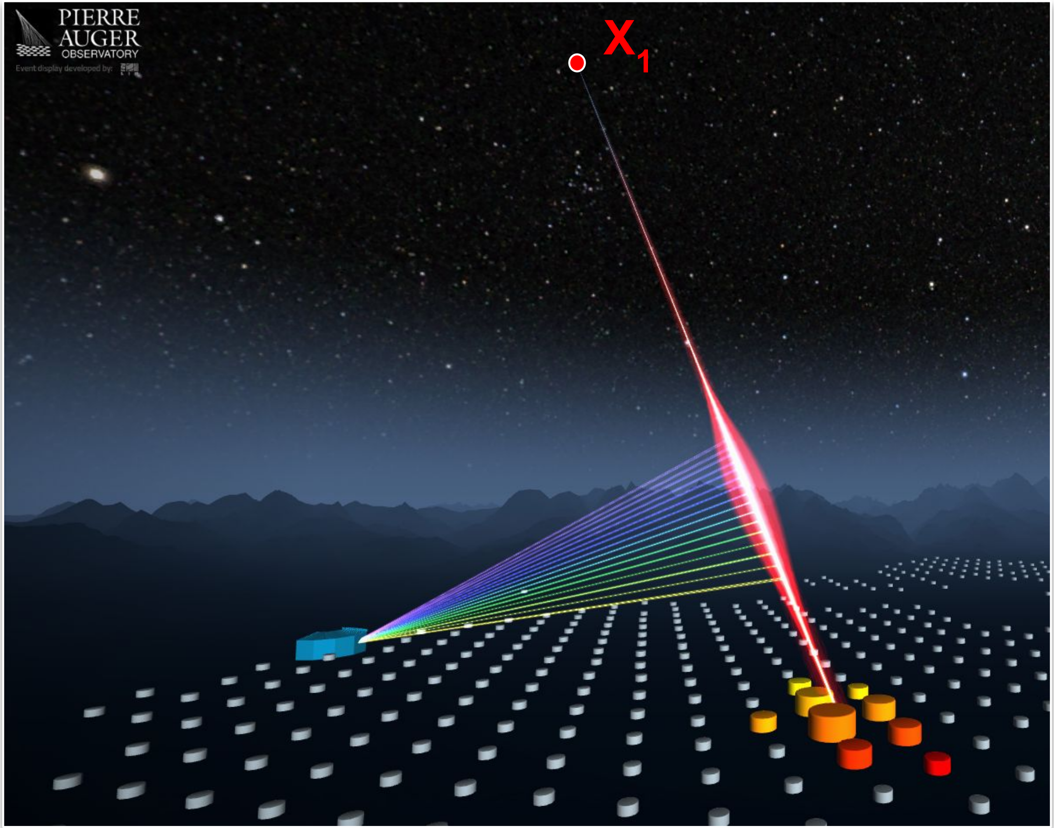


- Air showers simulated with **CONEX** (1D) and 2 different high-energy **hadronic models**.
- **Mix of primaries**: H, He, N and Fe.
- From **$10^{17.8}$ eV** to above **$10^{19.6}$ eV**.
- **10^4** showers / primary / energy bin.
- **Systematics** driven by the X_{max} scale uncertainties.

Mix of H, He and N, with He and N dominating at the highest energies.

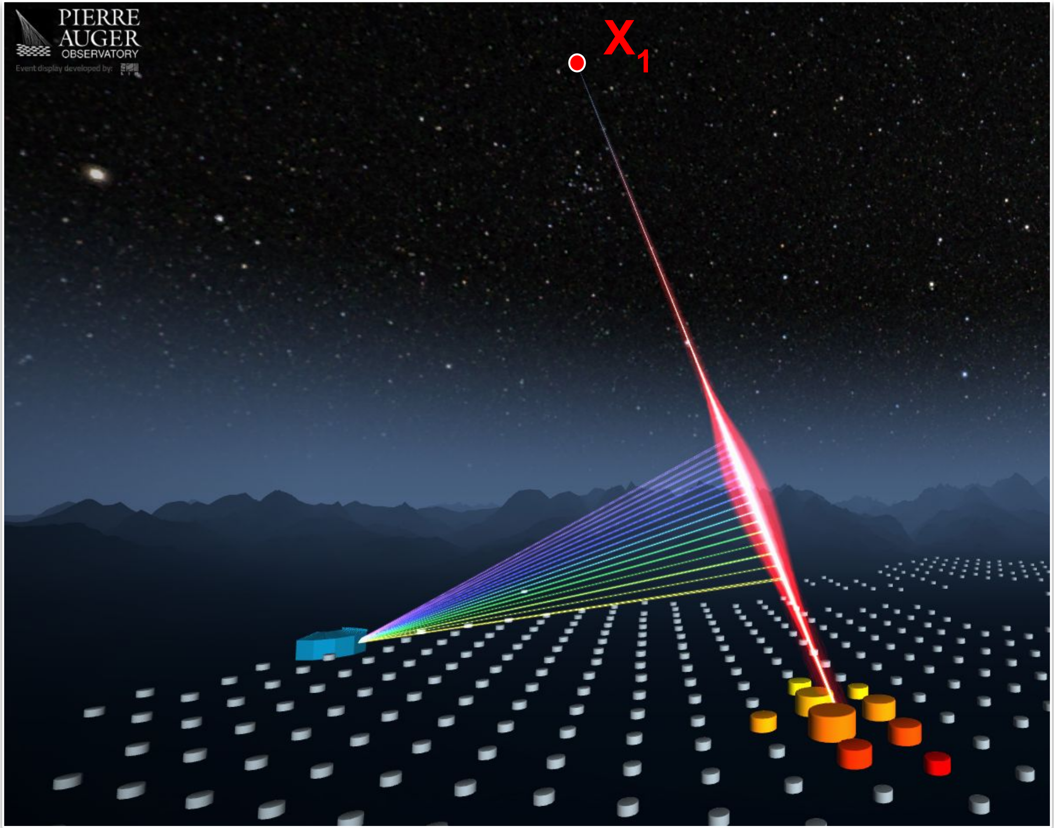
Fraction of **Fe** consistent with **zero**.

Proton-Proton cross-section measurements



- **Depth of first interaction X_1** related to proton-air cross-section.
  ⚠️ not directly accessible!

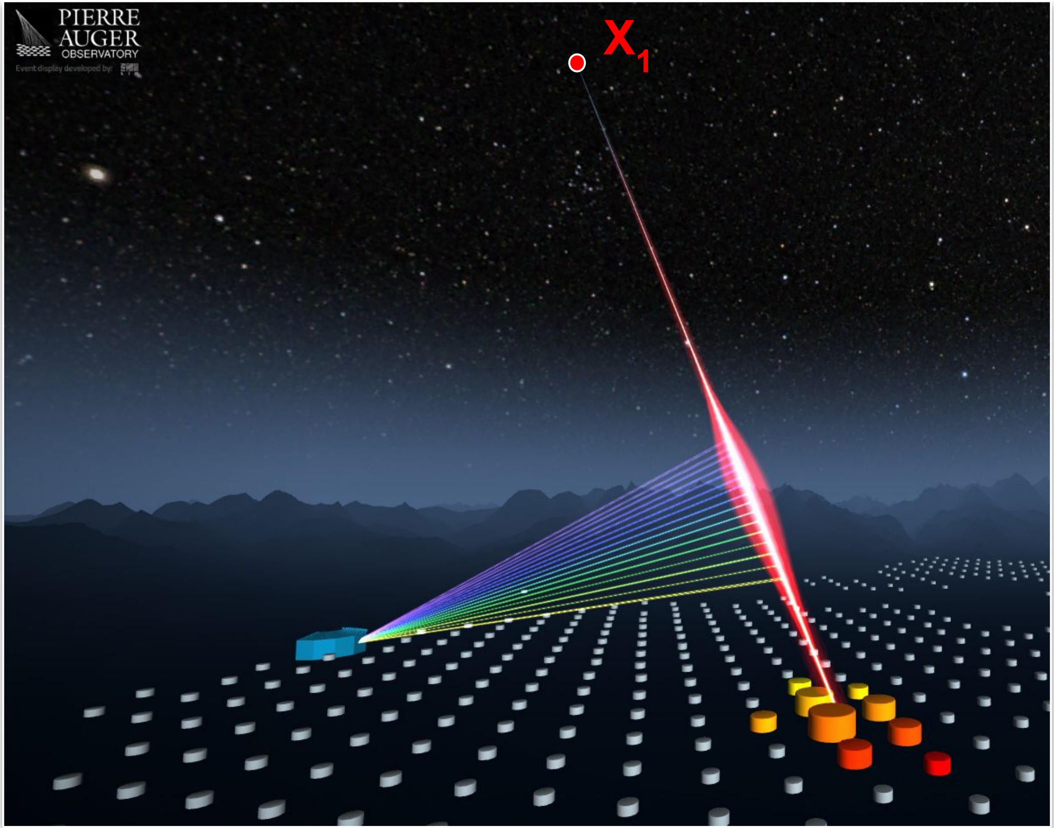
Proton-Proton cross-section measurements



- **Depth of first interaction X_1** related to proton-air cross-section.
  ⚠️ not directly accessible!

1. Find an **air-shower observable** that is sensitive to the proton-air cross-section.

Proton-Proton cross-section measurements

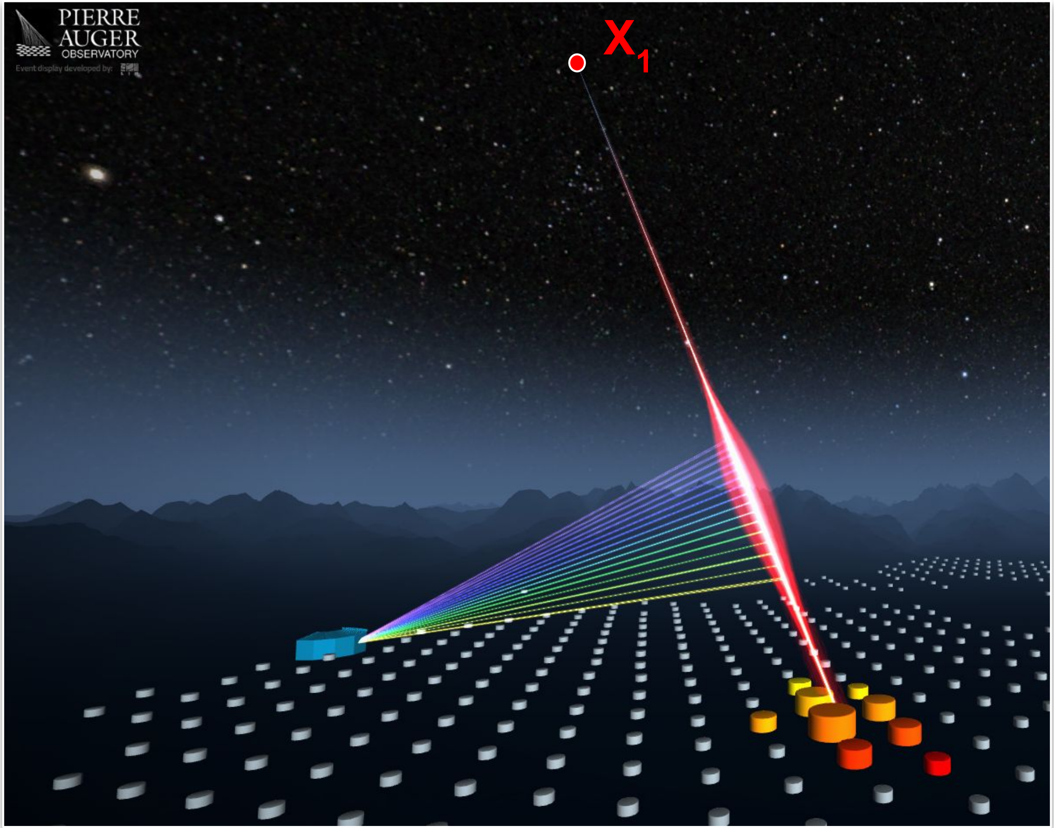


- **Depth of first interaction X_1** related to proton-air cross-section.
  ⚠️ not directly accessible!

1. Find an **air-shower observable** that is sensitive to the proton-air cross-section.

2. **Convert this observable to a proton-air cross-section** measurement using MC simulations.

Proton-Proton cross-section measurements

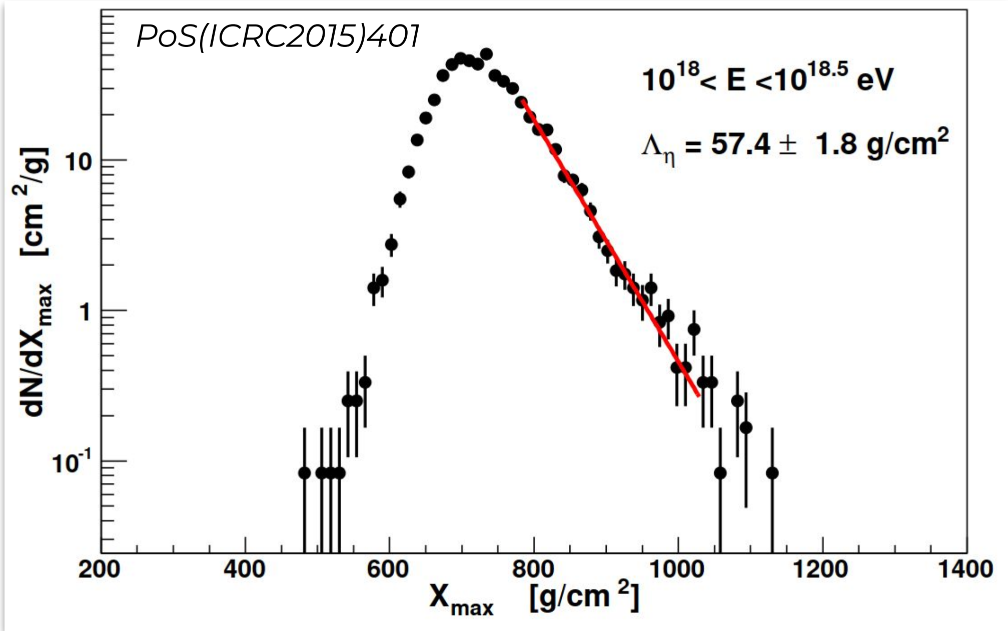


- **Depth of first interaction X_1** related to proton-air cross-section.
  ⚠️ not directly accessible!

1. Find an **air-shower observable** that is sensitive to the proton-air cross-section.
2. **Convert this observable to a proton-air cross-section** measurement using MC simulations.
3. Use *Glauber* formalism to infer on the **proton-proton cross-section**.

Proton-Proton cross-section measurements

1. Observable: X_{max} distribution tail



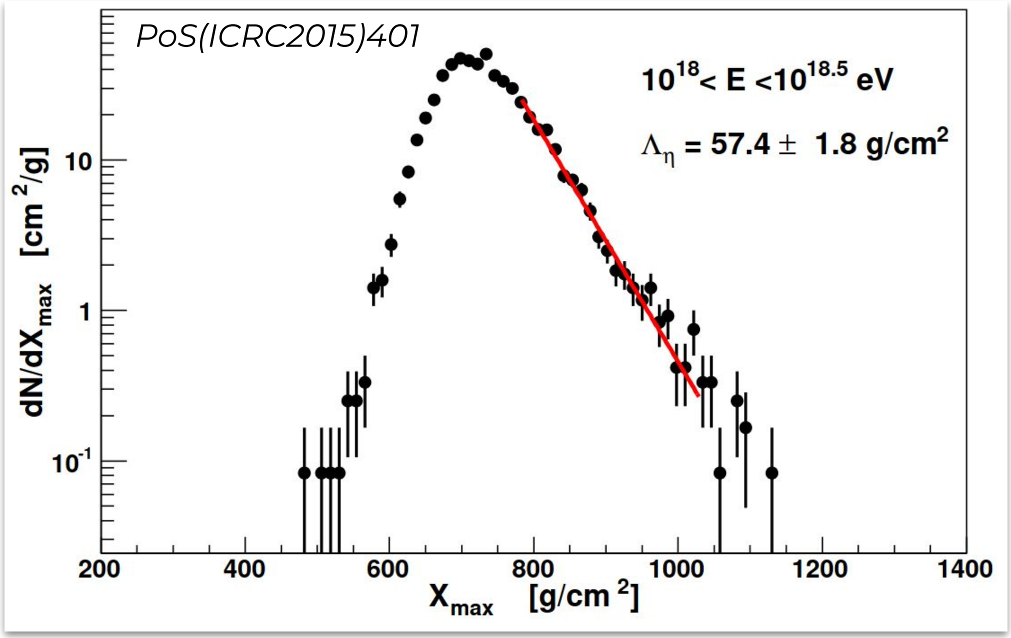
- Fitting the X_{max} interval containing the **20% of the deepest showers** (proton-dominated region)

$$\mathrm{d}N/\mathrm{d}X_{\mathrm{max}} \propto \exp(-X_{\mathrm{max}}/\Lambda_\eta)$$

→ measurement of $\mathbf{\Lambda}_\eta$, sensitive to the proton-air cross-section.

Proton-Proton cross-section measurements

1. Observable: X_{max} distribution tail



- ➢ Fitting the X_{max} interval containing the **20% of the deepest showers** (proton-dominated region)

$$\mathrm{d}N/\mathrm{d}X_{\mathrm{max}} \propto \exp(-X_{\mathrm{max}}/\Lambda_\eta)$$

→ measurement of $\mathbf{\Lambda}_\eta$, sensitive to the proton-air cross-section.

- ➢ Systematics uncertainties driven by **25% helium contamination**.

Proton-Proton cross-section measurements

2. Proton-air cross-section

- **UHECR measurements at energies greater** than what is achievable at the LHC.
→ LHC-tuned hadronic models relying on **extrapolations** to extend predictions to the UHE domain.

Proton-Proton cross-section measurements

2. Proton-air cross-section

- **UHECR measurements at energies greater** than what is achievable at the LHC. → LHC-tuned hadronic models relying on **extrapolations** to extend predictions to the UHE domain.

- The model-dependent mapping from Λ_η to $\sigma_{\text{p-air}}$ has an energy-dependent **rescaling** factor to account for the extrapolations uncertainties:

$$f(E) = 1 + H(E - E_0)(f_{19} - 1)\frac{\lg(E/E_0)}{\lg(10^{19}/E_0)}$$

(based on **PRD 83:054026, 2011**)

  - E_0 - the energy up to which hadronic models are tuned to LHC data (~ 10^{17} eV) → no rescaling below this energy.
  - f_{19} - rescaling at 10^{19} eV (model-dependent) that best reproduces Λ_η.

Proton-Proton cross-section measurements

2. Proton-air cross-section

- **UHECR measurements at energies greater** than what is achievable at the LHC.
  → LHC-tuned hadronic models relying on **extrapolations** to extend predictions to the UHE domain.

- The model-dependent mapping from Λ_η to $\sigma_{p\text{-air}}$ has an energy-dependent **rescaling** factor to account for the extrapolations uncertainties:

$$f(E) = 1 + H(E - E_0)(f_{19} - 1)\frac{\lg(E/E_0)}{\lg(10^{19}/E_0)}$$

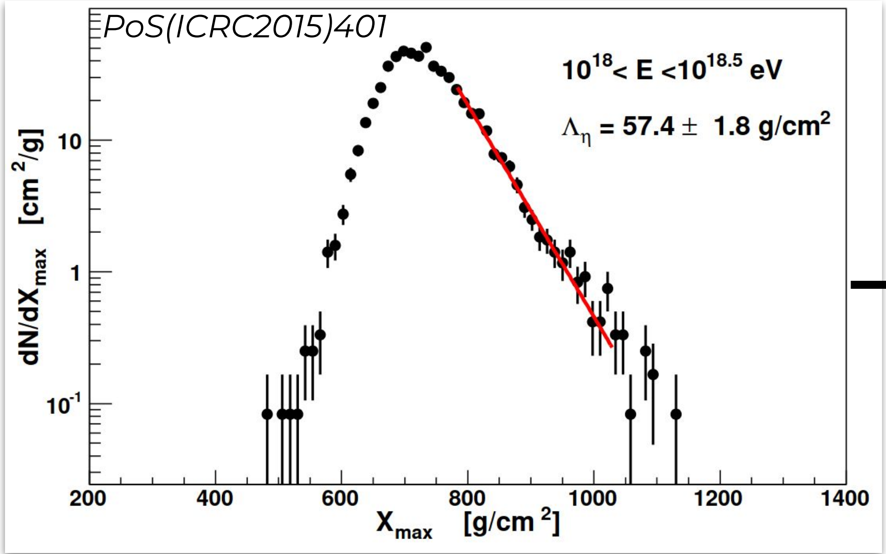
(based on **PRD 83:054026, 2011**)

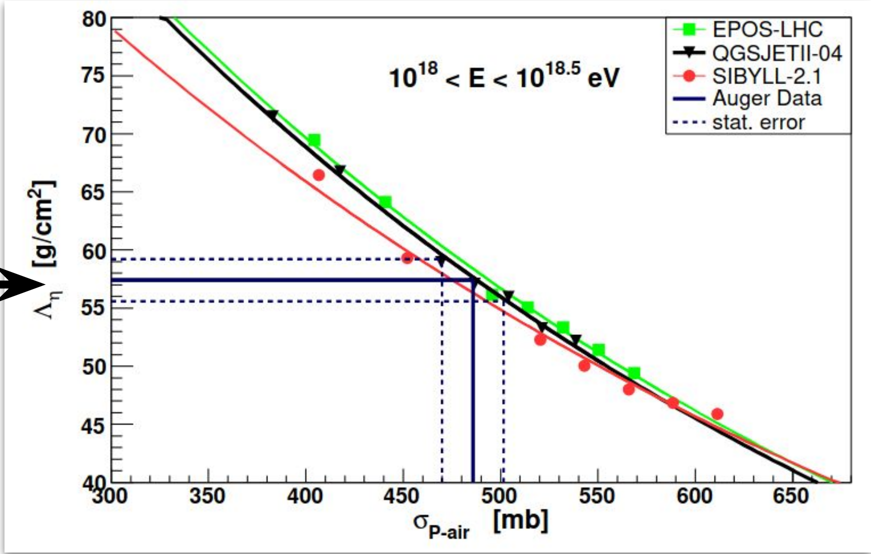
  - E_0 - the energy up to which hadronic models are tuned to LHC data (~ 10^{17} eV)
    → no rescaling below this energy.
  - f_{19} - rescaling at 10^{19} eV (model-dependent) that best reproduces Λ_η.

- The hadronic cross-sections are rescaled by $f(E)$ in the MC simulations.

Proton-Proton cross-section measurements

2. Proton-air cross-section

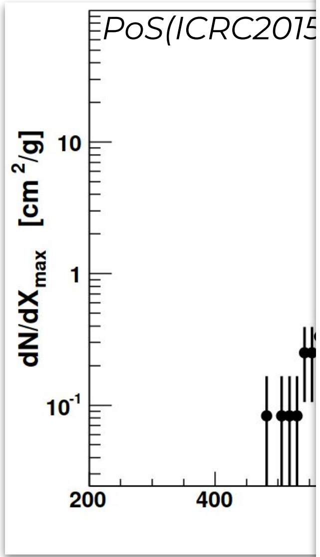


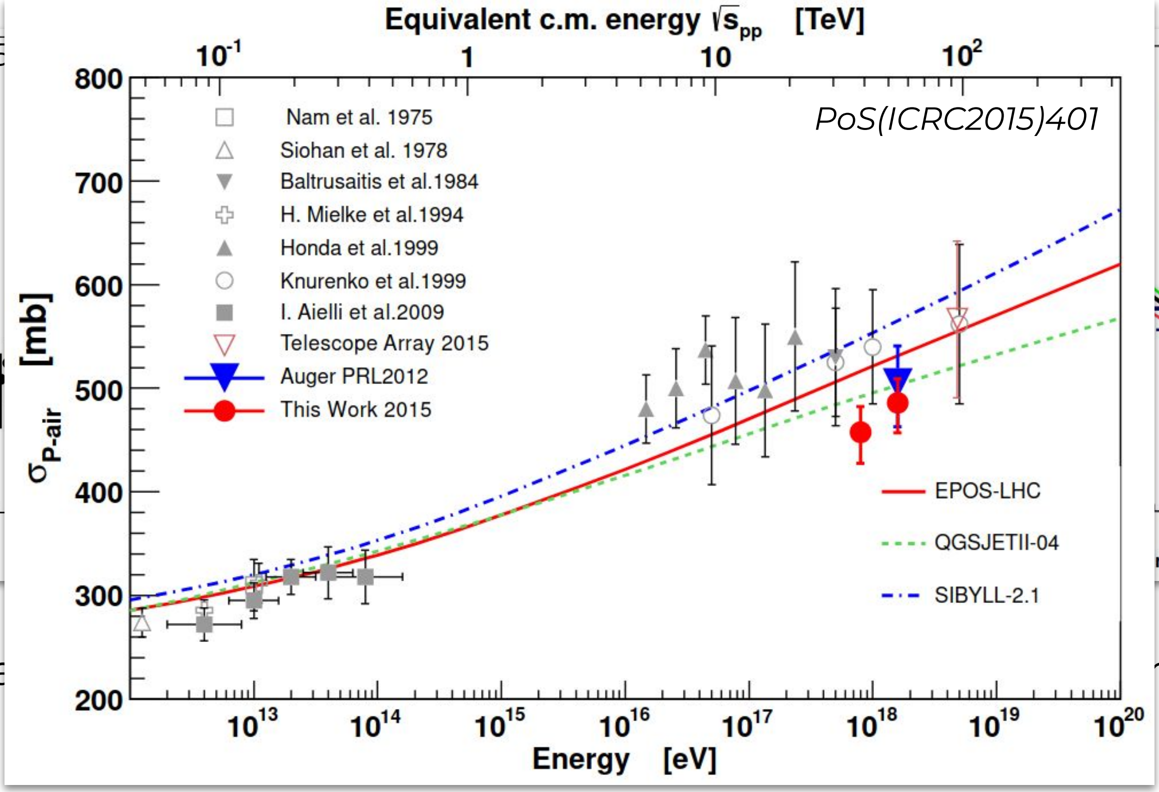


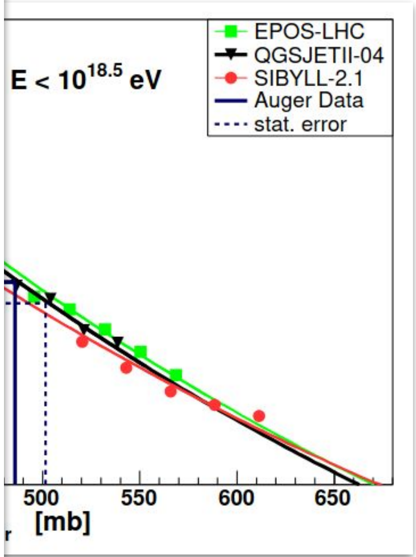
- **Systematics** driven by helium contamination in the tail, hadronic models uncertainties and Λ_η systematics.

Proton-Proton cross-section measurements

2. Proton-air cross-section





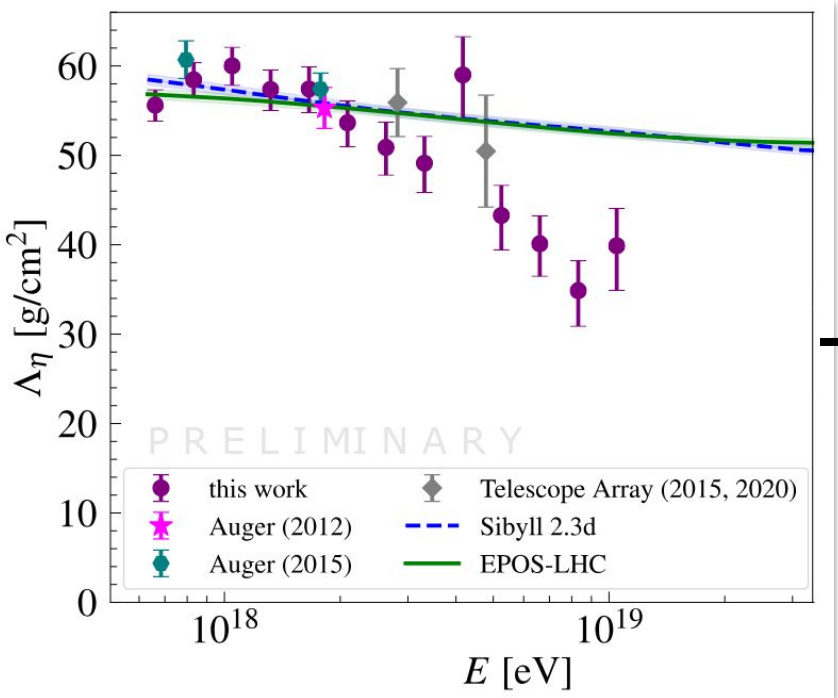


➢ Systema … nic models
uncerta …

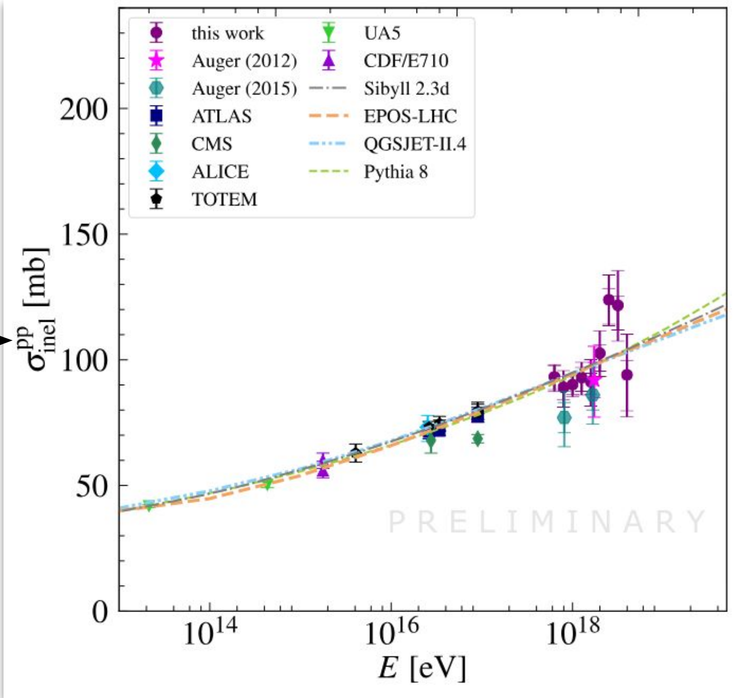
Proton-Proton cross-section measurements

3. Proton-proton cross-section

➢ Study recently **updated by *Olena Tkachenko*** to include up-to-date hadronic models and additional energy bins.



Rescaling
+
Glauber



Mass Composition & Proton-Proton cross-section

- We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

$$\sigma^{\rm pp}_{\rm mod} = \sigma^{\rm pp}_{\rm orig} f(E)$$

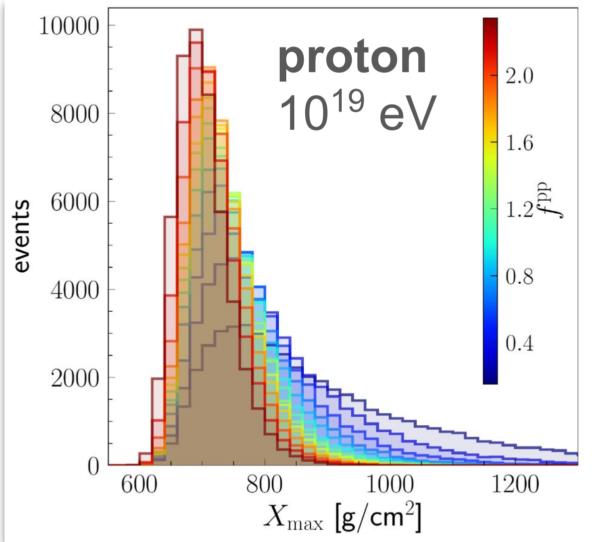
Mass Composition & Proton-Proton cross-section

- ➢ We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

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

- ➢ We follow the following scheme:

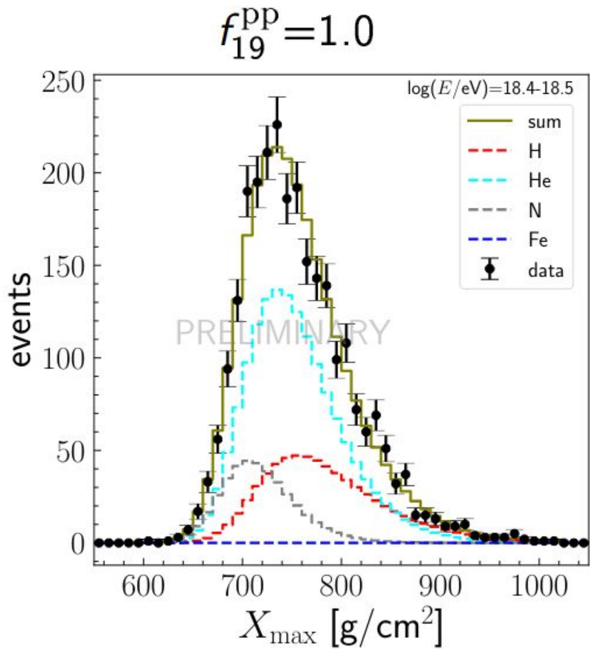
f_{19} → σ^{pp}_{mod} → Glauber → σ^{p-Air}_{mod} → CONEX → X_{max} distr.



Mass Composition & Proton-Proton cross-section

- We investigate the impact of a **modified $\boldsymbol{\sigma}_{\mathbf{pp}}$** on the Auger mass composition.

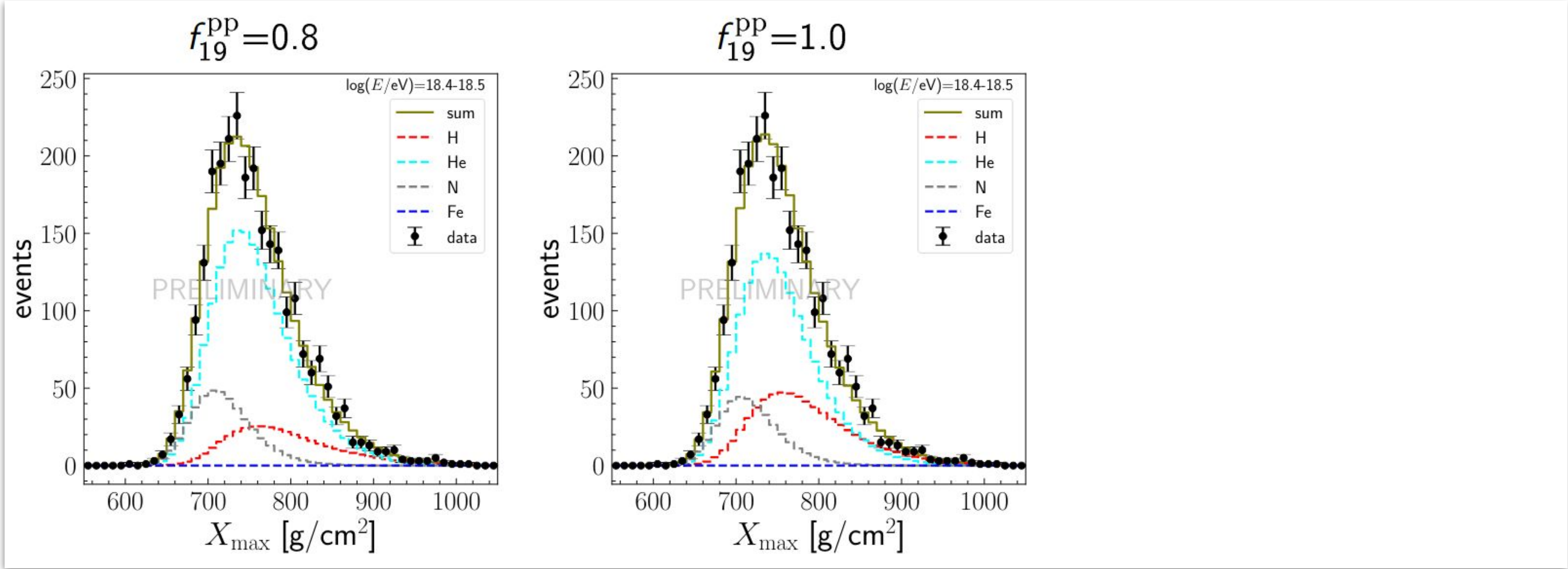
$$\sigma^{\mathrm{pp}}_{\mathrm{mod}} = \sigma^{\mathrm{pp}}_{\mathrm{orig}} f(E)$$



Mass Composition & Proton-Proton cross-section

➢ We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

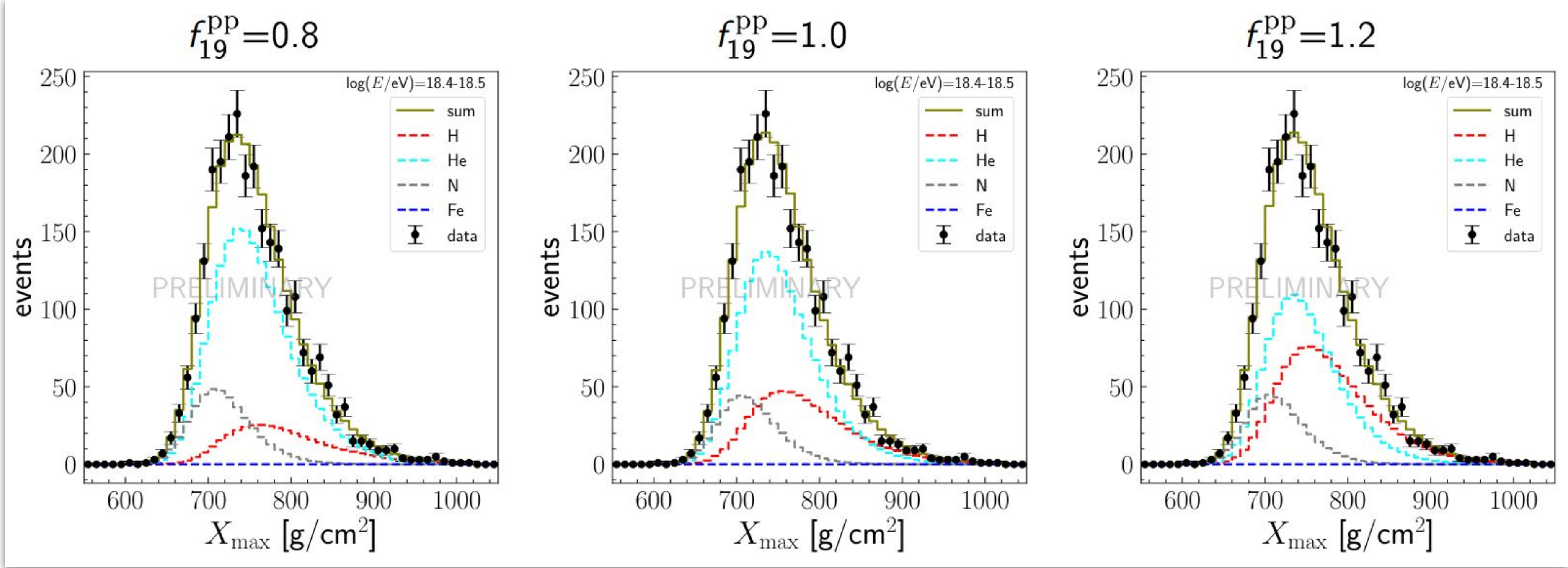
$$\sigma^{pp}_{mod} = \sigma^{pp}_{orig} f(E)$$



Mass Composition & Proton-Proton cross-section

- We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

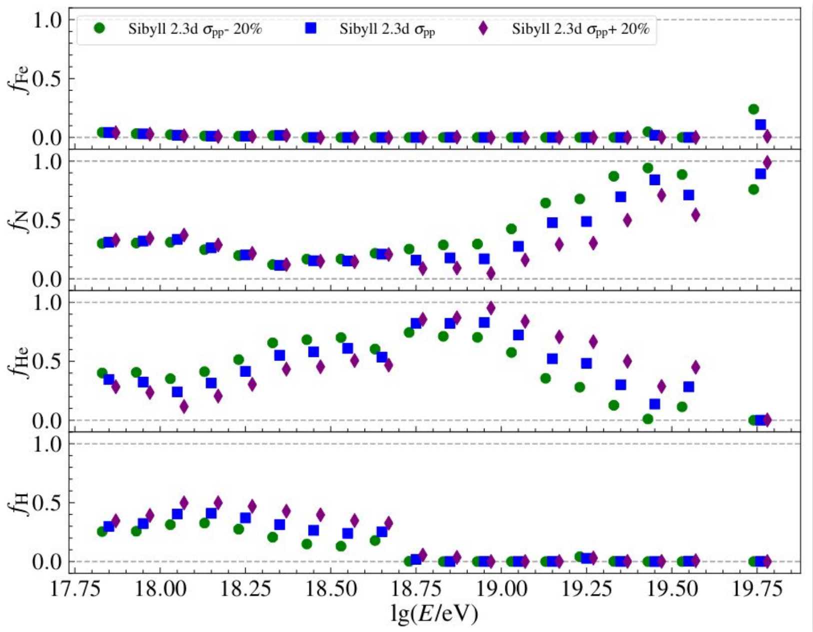
$$\sigma^{pp}_{mod} = \sigma^{pp}_{orig} f(E)$$



Mass Composition & Proton-Proton cross-section

- We investigate the impact of a **modified $\boldsymbol{\sigma}_{\mathbf{pp}}$** on the Auger mass composition.

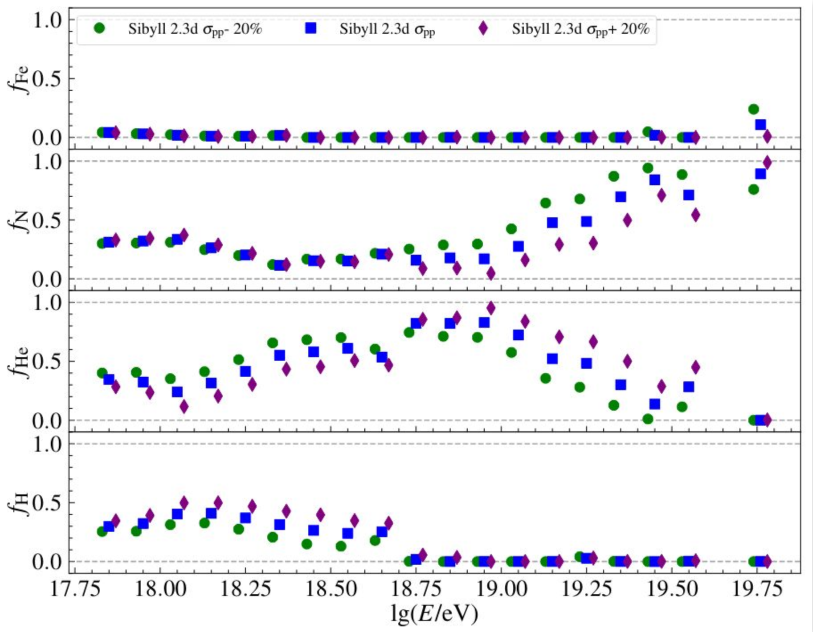
$$\sigma^{\rm pp}_{\rm mod} = \sigma^{\rm pp}_{\rm orig} f(E)$$

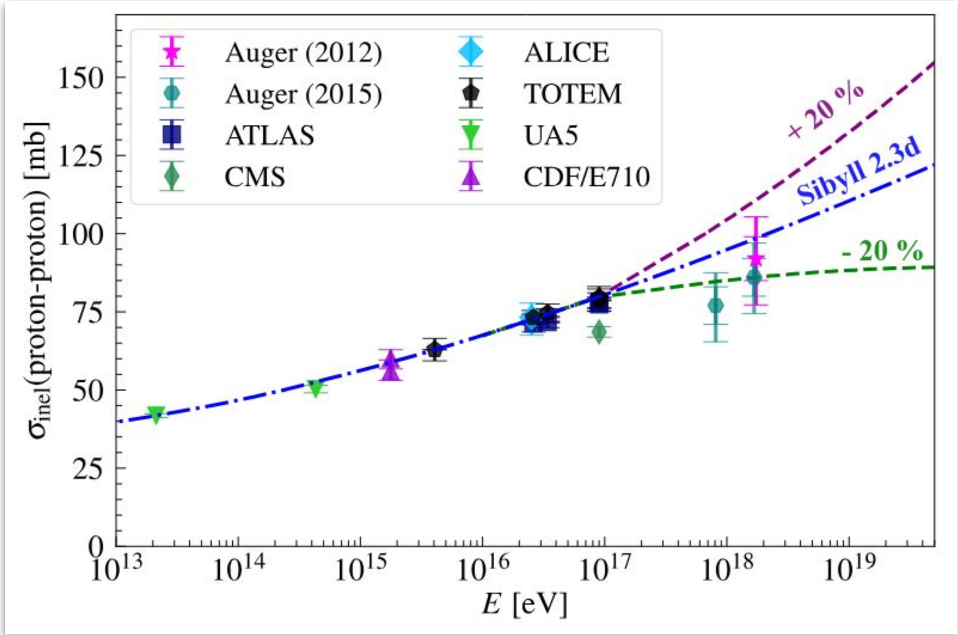


Mass Composition & Proton-Proton cross-section

➢ We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

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

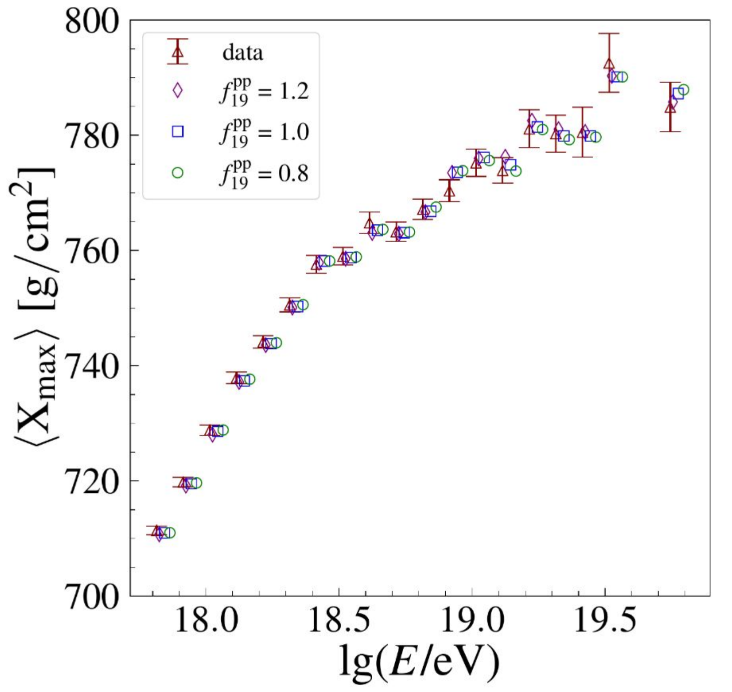




Mass **C**omposition & **P**roton-**P**roton cross-section

- We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

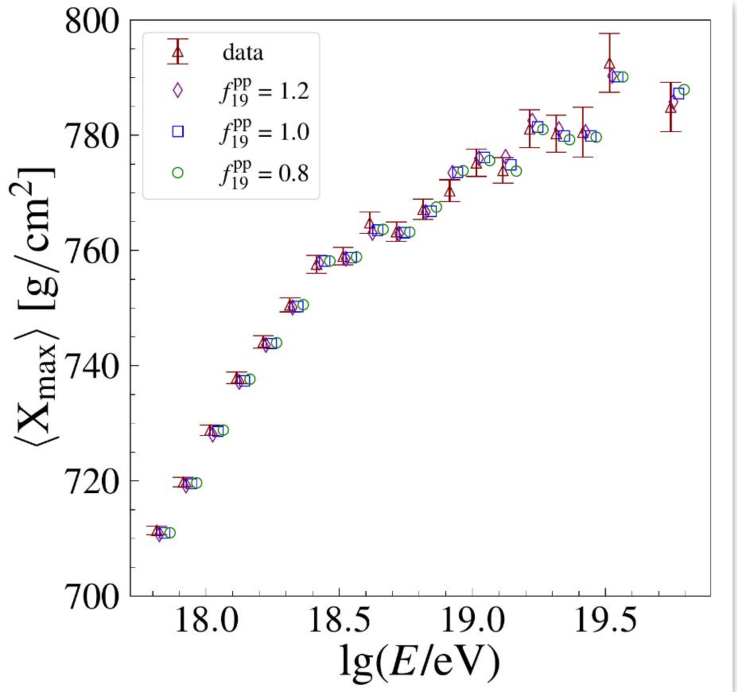
$$\sigma^{pp}_{mod} = \sigma^{pp}_{orig} f(E)$$

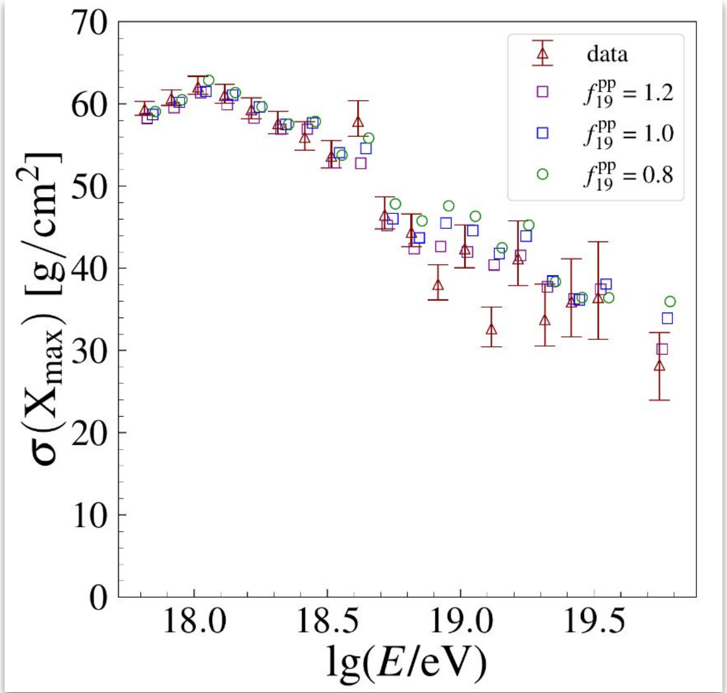


Mass Composition & Proton-Proton cross-section

- We investigate the impact of a **modified σ_{pp}** on the Auger mass composition.

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

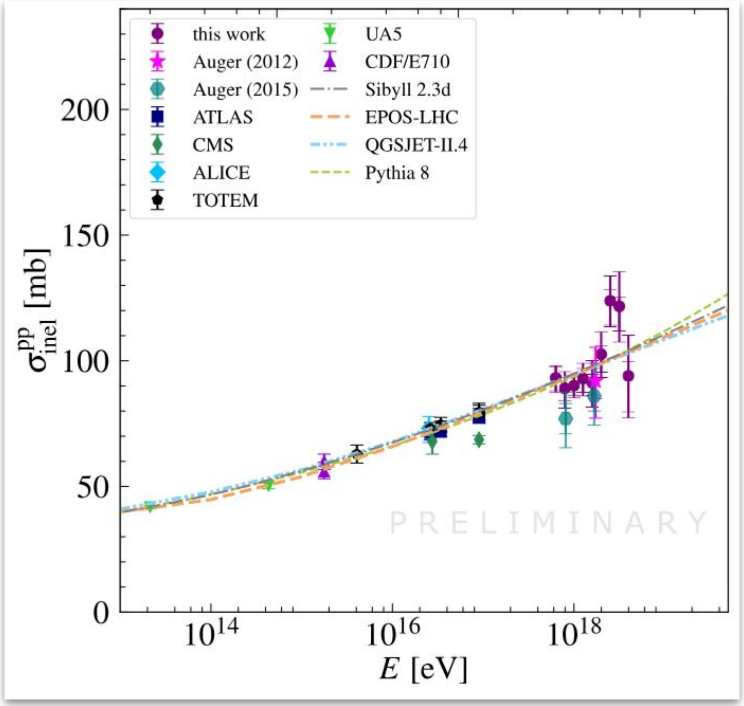




Summary & Outlook

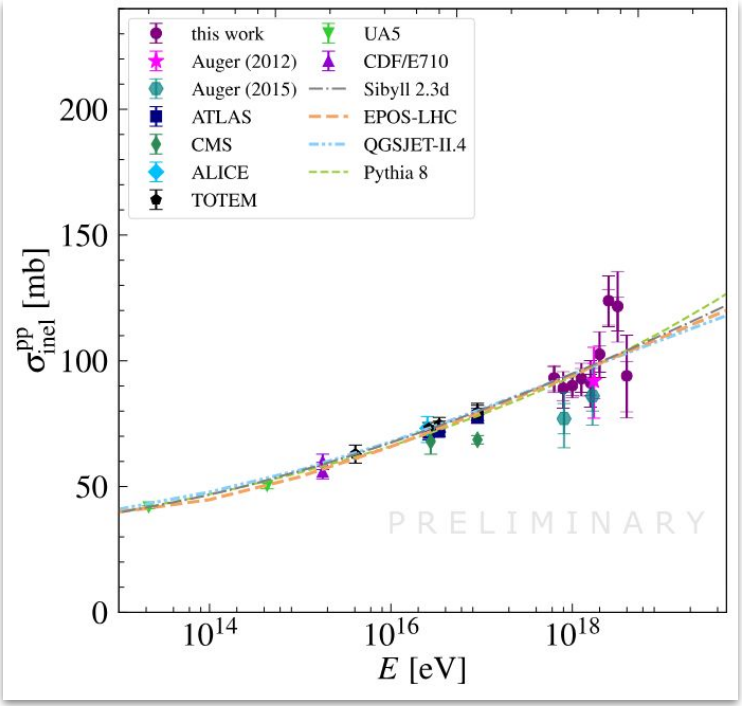
- ➢ Mass composition fit results consistent with other analysis:
  - ★ Light component at low energies.
  - ★ Intermediate mass nuclei at higher energies.

- ➢ p-p cross-section measurements consistent with model extrapolations.



Summary & Outlook

- ➢ Mass composition fit results consistent with other analysis:
  - ★ Light component at low energies.
  - ★ Intermediate mass nuclei at higher energies.
- ➢ p-p cross-section measurements consistent with model extrapolations.



Perspectives

- ➢ Upgrade of the Pierre Auger Observatory → a better mass discrimination is expected (*see next talk by Jan Ebr*).
- ➢ p-O collisions.
- ➢ Forward direction measurements (FASER, LHCf, FPF, and others).