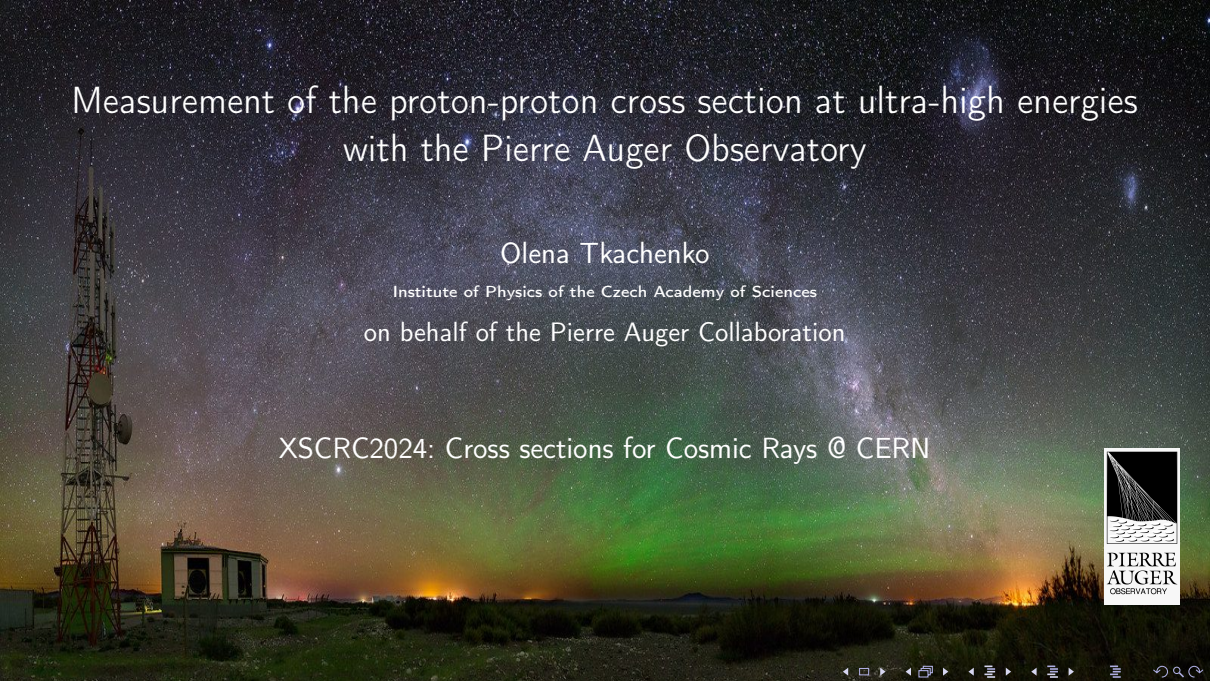
Measurement of the proton-proton cross section at ultra-high energies with the Pierre Auger Observatory

Olena Tkachenko

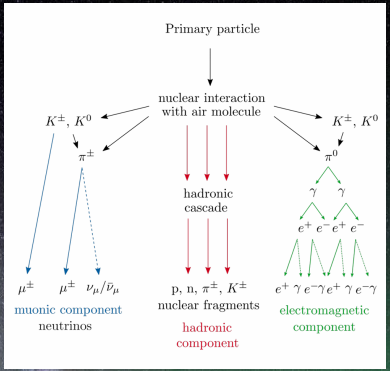
Institute of Physics of the Czech Academy of Sciences

on behalf of the Pierre Auger Collaboration

XSCRC2024: Cross sections for Cosmic Rays @ CERN



Extensive Air Showers



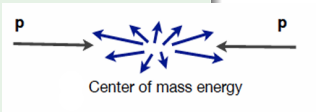
The Pierre Auger Observatory

- Located in **Malargue, Argentina**
- Total area of **3000 km^2**
- **Surface Detector** (SD)
  - 1660 stations
  - 100% duty cycle
- **Fluorescence Detector** (FD)
  - 27 telescopes
  - 15% duty cycle
- **Radio and muon detectors**
- **Phase I**: 2004-2022
- **AugerPrime** upgrade: completed in 2023
- **Phase II**: till $>$ 2035

Particle Physics with UHECR

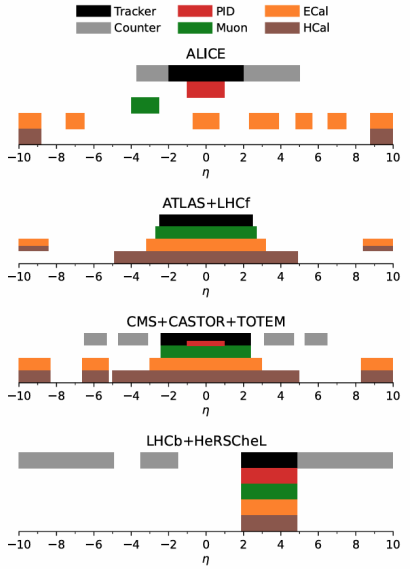
LHC

- $\sqrt{s}$ =14 TeV (p-p) ==> $E_{\mathrm{CR}} \sim 10^5$ TeV
- $\eta \leq 5$
- p-p, Pb-Pb, p-Pb, Pb-p



EAS

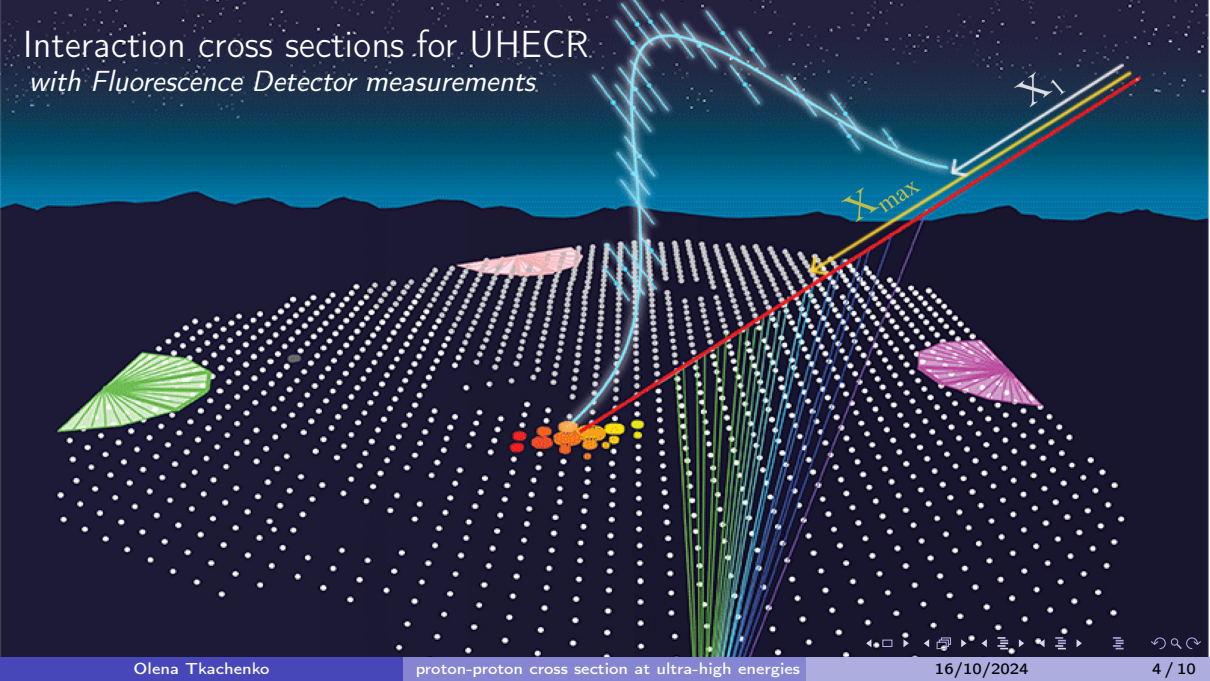
- $E_{\mathrm{CR}} \geq 10^6$ TeV
- $\eta \approx$ 7-11
- p-air, He-air...Fe-air, π-air



J. Albrecht *et al.* Astrophys. Space Sci. 367, 2022

Interaction cross sections for UHECR

with Fluorescence Detector measurements

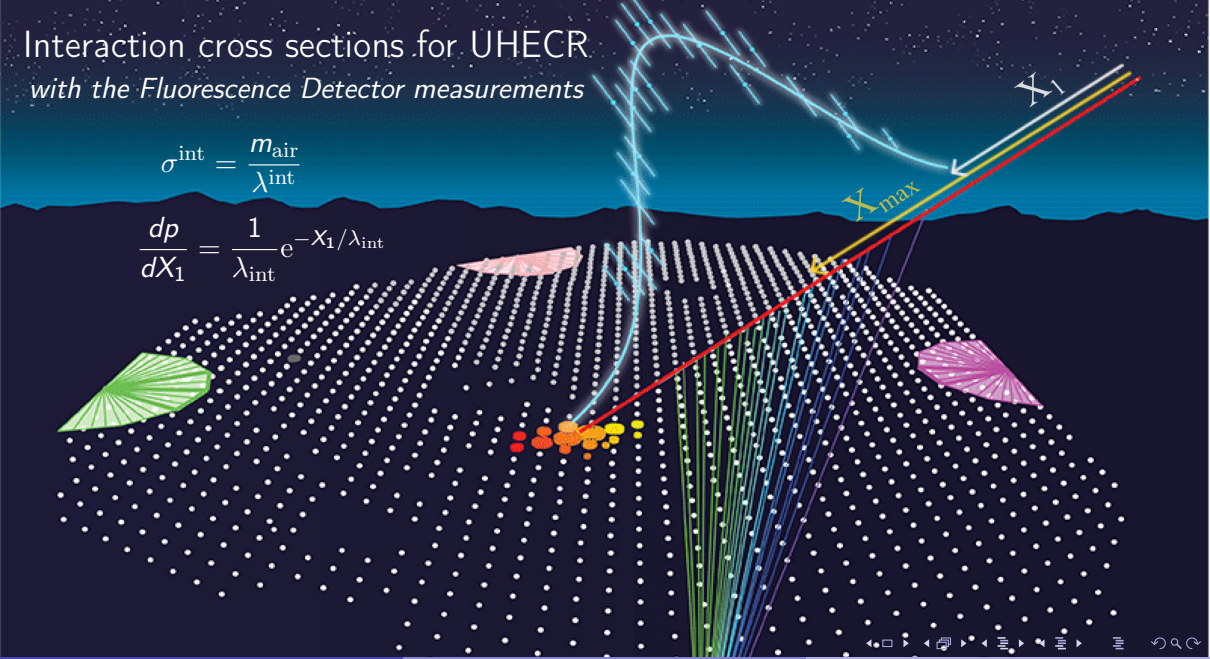


Interaction cross sections for UHECR

with the Fluorescence Detector measurements

$$\sigma^{\text{int}} = \frac{m_{\text{air}}}{\lambda^{\text{int}}}$$

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

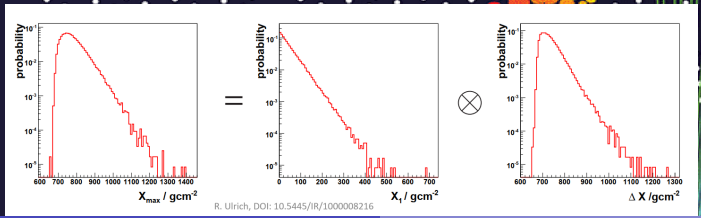


Interaction cross sections for UHECR

with the Fluorescence Detector measurements

$$\sigma^{\text{int}} = \frac{m_{\text{air}}}{\lambda^{\text{int}}}$$

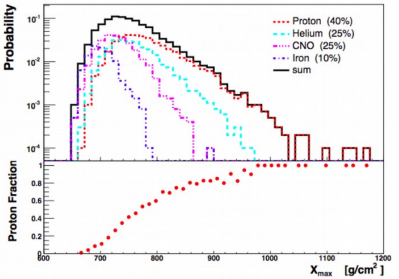
$$\frac{dp}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$



R. Ulrich, DOI: 10.5445/IR/1000008216

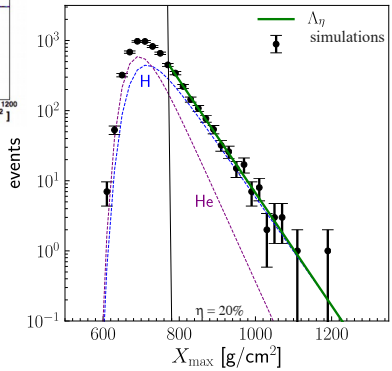
Measurement of the proton-air (proton-proton) interaction cross section: Fit to the tail of the $X_{\max}$ distribution

- The exponential tail of the $X_{\max}$ distribution:
  - most sensitive to the interaction cross section
  - dominated by protons
- most important systematics: He contamination up to 25% $\Rightarrow \sim 6\%$ uncertainty
- fiducial cuts to get an unbiased tail.

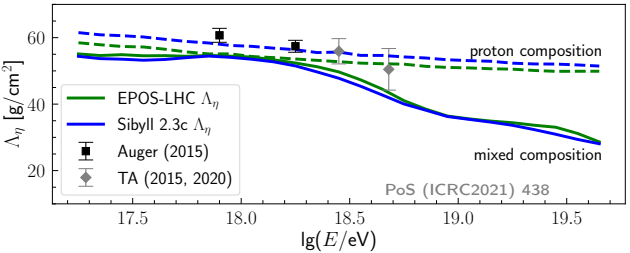


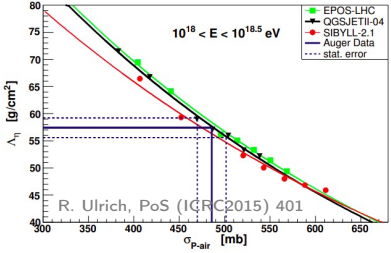
$X_{\max}$ distribution tail:

$$f(X_{\max}) \sim^{-X_{\max}/\Lambda_\eta}$$

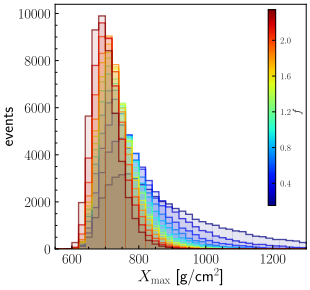


Measurement of the proton-air (proton-proton) interaction cross section: Fit to the tail of the $X_{\max}$ distribution



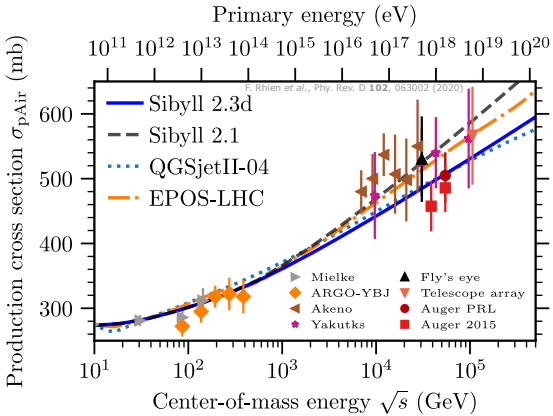


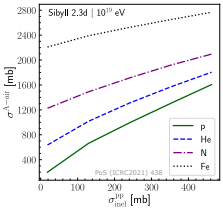
$$f(E_0, E) = 1 + H(E - E_0)(f_{\lg E_1} - 1)\frac{\lg(E/E_0)}{\lg(E_1/E_0)}.$$

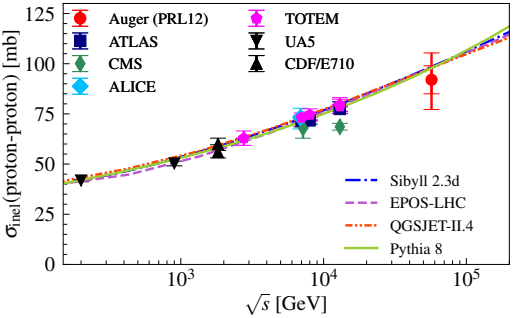


* $f_{\lg E1}$ is the rescaling factor at $E = E_1$ (here $E_1 = 10^{19}$ eV);
* Threshold E_0 sets an energy above which cross-sections are modified;
* Modified implementation of Sibyll 2.3d hadronic interaction model.

Interaction cross sections for UHECR

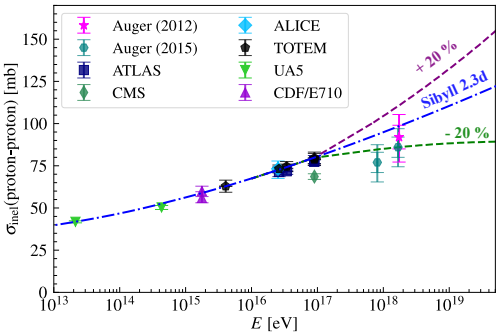






$\sigma_{\mathrm{A-Air}}$ ⟷ Glauber formalism ⟷ σ_{pp}

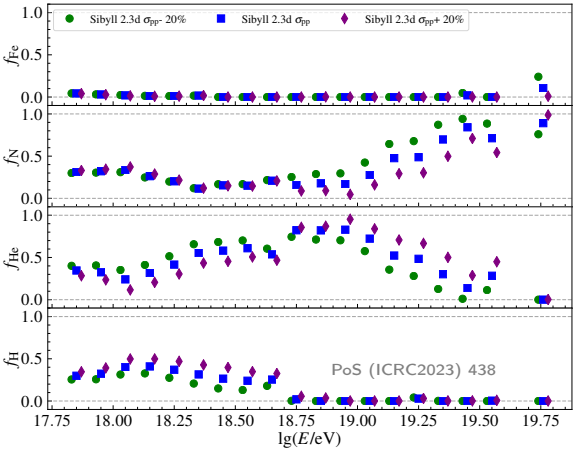
Interplay between mass composition & interaction cross section



Work in progress:

Simultaneous estimation of the proton-proton cross section and mass comosition =>

- no assumption on composition (cross section) in the cross section (composition) estimate



Summary

- The measurements from the Pierre Auger Observatory allow for the determination of interaction cross sections at the highest energies;
- The tail of the Xmas distribution is particularly sensitive to the particle interaction cross sections;
- The proton-proton cross sections inferred from the data are in a good agreement with the extrapolations from the accelerator measurements;
- Further studies on the more precise estimation of the interaction cross sections for a broader energy range and the reduction of the systematic uncertainties are in progress.

Further perspectives:

- Findings from the AugerPrime upgrade of the Observatory;
- New generation of hadronic interaction models;
- p-O collisions at LHC and forward experiments.