particle physics measurements at the highest energies with the Pierre Auger Observatory

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The Pierre Auger Observatory
- precision Fluorescence Detector 4x180°x30° telescopes images development of electromagnetic shower component
- high statistics Surface Detector 3000 km² ground array samples electromagnetic and muonic shower at ground level

New FD energy scale: +15% / +10%; (22% --> 14% uncertainty)
Exploring the highest energy beams
Neutrinos? Photons? Nuclei (p – Fe)?

Main variables relate to
depth of shower maximum: $X_{\text{max}} = X_1 + DX$
particle content at ground: Signal = $\mu + e/\gamma$

Outline:
- Limits of $\nu/\gamma$
- $X_{\text{max}} \rightarrow$ Cross-Section
  $\rightarrow$ Nuclear Mass
- Muons $\rightarrow$ Multiplicity
  $\rightarrow$ new $X_{\text{max}}$
- Hadronic Interactions
Limits on neutrino and photon fluxes
constraining production models, GZK predictions not reached yet

60° to 95° neutrino showers:
0 candidates (vs 0.2-0.6 from GZK; 2.2 IceCube PeV extrapolation with $E^{-2}$)

Deep electromagnetic $\gamma$ showers:
multivariate selection from nuclei
New directional limits $< 0.1 \gamma$/km²/yr

also low energy galactic neutrons are constrained using directions
Exploring the nuclei beam with $X_{\text{max}} = X_1 + DX$

Depends on cross-section and multiplicity of first interactions
Shower maximum of light nuclei is deeper and fluctuates more

Can select proton sample in $X_{\text{max}}$ tail to measure cross-section

Unbiased selection:
using only geometries in which all the tail can be observed
p-air cross-section @ 1–3 EeV (laboratory frame)

3082 events out of 11628 allow unbiased observation of tail; 783 are in the exponential fitting range

cross-section: 505 +/- 22 (stat) +/- 18 (syst) mb
from changes in hadronic interaction models: (-8, + 19) mb
from unknown beam contamination [25% He, <0.5% γ]: (-30, +10) mb
proton cross-section @ 57 ±6 TeV (centre-of-mass)

proton-proton cross-section obtained with Glauber model

Uncertainties from the modelling of the elasticity slope, diffractive ratios, and nuclear density profile, constrained with models in good agreement with extrapolation of also later LHC results.
Towards measurements at higher energies

\[ \langle X_{\text{max}} \rangle \text{ [g/cm}^2] \]

E [eV]

10^{18}  10^{19}  10^{20}

EPOS-LHC
QGSJet II-04
Sibyll2.1

Protons at lower energies... may be not so at higher energies...
Interpretation depends on hadronic interaction modelling
Towards measurements at higher energies

Xmax unbiased selection in all the possible range

Protons at lower energies... may be not so at higher energies...

Interpretation depends on hadronic interaction modeling
Nuclear mass composition and hadronic models

\[
\langle X_{\text{max}} \rangle = \langle X_{\text{max}} \rangle_p - f(E) \langle \ln A \rangle;
\]
\[
\sigma^2(X_{\text{max}}) = \langle \sigma^2 \rangle + f^2(E) (\langle \ln A^2 \rangle - \langle \ln A \rangle^2)
\]

Mass increases with decreasing dispersion \(\Rightarrow\) hard spectrum source? but some tension with models tuned to accelerator (LHC) data and extrapolated in both energy and rapidity for cosmic ray physics.
Nuclear mass composition and hadronic models

$X_{\text{max}}$ distribution depends on the $\ln A$ distribution in the beam

$$<X_{\text{max}}> = <X_{\text{max}}>_p - f(E) <\ln A>;$$

$$\sigma^2(X_{\text{max}}) = <\sigma^2> + f^2(E) (<\ln A^2> - <\ln A>^2)$$

Mass increases with decreasing dispersion $\Rightarrow$ hard spectrum source?

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and extrapolated in both energy and rapidity for cosmic ray physics
SD analysis: muon numbers in ground signals

Dependence on zenith angle (at 10 EeV) and total energy (at 62°)

Fraction of muon signal at 1000 m

Three consistent analyses but only Fe at 10 EeV is disfavoured

Slope vs. constant lnA @1.7 σ
Increasing the "Xmax" data sample with SD muons

$\langle X_{\mu_{\max}} \rangle$ from arrival times in inclined showers, far from the core

Results generally consistent with $\langle X_{\max} \rangle = \langle X_{\mu_{\max}} \rangle + \Delta$

same cross-section ($\langle X_{1} \rangle$), different development ($\langle DX \rangle$)
Towards a consistent picture of showers

both \( \langle X_{\text{max}} \rangle \) and \( \langle X_{\mu \text{max}} \rangle \) should follow from the same \( \langle \ln A \rangle \), with same \( \langle X_1 \rangle \), different \( \langle DX \rangle \)

interpretation sensitive also to particle physics variables of shower development multiplicity, inelasticity, baryon ratio and rapidity gap distributions

High energy cosmic rays can be used to improve hadronic models
Summary

No neutral particle signals yet
  constrain exotic production and galactic models
  cosmogenic production in reach soon
Protons at EeV scale (pp @ 60 TeV)
  cross-section consistent with LHC extrapolation
  good calibration point for following analyses
Heavier nuclei at higher energies?
  can be difficult for astrophysical source models
  hadronic interaction models are also not perfect
Hadronic interactions tested with more observables
  models will be improved by the Auger data
  direct measurements and consistency checks
Hadronic interaction models and FD/SD consistency

Simultaneous fit of longitudinal FD profile and lateral SD profile need rescalings to get coherent results.
Electromagnetic and Muonic longitudinal profiles

![Graphs showing proton and iron distributions with X [g cm\(^{-2}\)] on the x-axis and dN/dX [cm\(^2\) g\(^{-1}\)] on the y-axis. Each graph contains multiple curves in red and blue colors, indicating different samples or conditions. The graphs are labeled with "Proton" and "Iron".
\( \langle X_{\text{max}} \rangle \text{ [g/cm}^2] \)

\[ E \text{ [eV]} \]

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Single line: \( \chi^2 / \text{Ndf} = 128.1 / 16, P = 1.5 \cdot 10^{-19} \)

Broken line: \( \chi^2 / \text{Ndf} = 10.3 / 14, P = 0.74 \)
Changes in elongation rate with new energy scale