Physics and astrophysics of ultra-high energy cosmic rays: recent results from the Pierre Auger Observatory

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NUCLEUS – 2020
Saint Petersburg, Russia.
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The highest energy particles
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Unanswered questions about UHECRs:
The highest energy particles

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★ What are those particles?
★ Where do they come from?
★ How they reach $E > 10^{20}$ eV = 100 EeV?
★ Can we extrapolate hadronic models orders of magnitude in energy?
The highest energy particles

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★ Can we extrapolate hadronic models orders of magnitude in energy?

We need to understand:

★ Composition
★ Production sources
★ Acceleration mechanisms
★ Fundamental interactions
Fluorescence Detector

FD telescopes at Los Morados

Steven Sa

The highest energy particles

Their study has impact on:
The highest energy particles

Their study has impact on:

★ Astrophysics
★ Particle physics

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We need to measure \( E > 10^{19} \text{ eV} = 10 \text{ EeV} \)
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★ Astrophysics
★ Particle physics

We need to measure $E > 10^{19}$ eV = 10 EeV

Spectrum
Composition
Anisotropies
Cross sections
Pierre Auger Observatory: state-of-the-art cosmic ray detector

- **Water Cherenkov stations**
  - SD1500: 1600, 1.5 km grid, 3000 km$^2$
  - SD750: 61, 0.75 km grid, 23.5 km$^2$
  - Live time ~ 100%

- **4 Fluorescence sites**
  - 24 telescopes, 1-30° FOV
  - 3 high elevation FD 30°-60° FOV
  - Live time ~ 13%

- **Underground Muon Detectors**
  - 7 in engineering array phase
  - 61 aside the Infill stations

- **AERA radio antennas**
  - 153 antenas in 17 km$^2$
The Pierre Auger Observatory has detected more muons from cosmic-ray showers than predicted by the most up-to-date particle-physics models.

Thomas Gaisser

The Large Hadron Collider at CERN produces proton collisions with center-of-mass energies that are 13 thousand times greater than the proton's rest mass. At such extreme energies these collisions create many secondary particles, whose distribution in momentum and energy reveals how the particles interact with one another. A key question is whether the interactions determined at the LHC are the same at higher energies. Luckily, nature already provides such high-energy collisions—albeit at a much lower rate—in the form of cosmic rays entering our atmosphere. Using its giant array of particle detectors, the Pierre Auger Observatory in Argentina has found that more muons arrive on the ground from cosmic-ray showers than expected from models using LHC data as input [1]. The showers that the Auger collaboration analyzed come from atmospheric cosmic-ray collisions that are 10 times higher in energy than the collisions produced at the LHC. This result may therefore suggest that our understanding of hadronic interactions (that is, interactions between protons, neutrons, and mesons) from accelerator measurements is incomplete.

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Unlike detectors at accelerators, experiments like Auger do not directly detect the initial collision but only the secondary cascade that it generates. This is simply because the rate of events is too low: At an energy equivalent to 10 times the center-of-mass energy at the LHC, the cosmic-ray flux is only about one particle per square kilometer per year. This is far too low to observe the collision directly with a detector in space or a balloon-borne detector above the atmosphere. Auger, with a detector array that spans 3000 square kilometers, may collect only a few thousand such events per year. In comparison, the LHC can produce a billion proton collisions per second.

Auger observes the first interaction indirectly by analyzing the shower of particles it generates [2]. To detect shower physics.

Figure 1: This illustration shows the detection of a hybrid event from a cosmic-ray shower in the Pierre Auger Observatory. The pixels in the camera of the fluorescence telescope (light blue semicircle) trace the shower profile—specifically, the energy loss of the shower as a function of its penetration into the atmosphere. Particles from the same shower are detected on the ground by an array of water tanks (white dots). The red line shows the trajectory of the shower. (APS/Karin Cain)

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**Figure 6:** FD building at Los Leones during the day. Behind the building is a communication tower. This photo was taken during daytime when shutters were opened because of maintenance.

**Figure 7:** Schematic view of a fluorescence telescope with a description of its main components.

**Figure 8:** Photo of a fluorescence telescope at Coihueco.

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APS/Karin Cain
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3,338 hybrid events in the fit

\[ E_{\text{FD}} = A S_{38}^B \]

\[ A = (1.86 \pm 0.03) \times 10^{17} \text{ eV} \]

\[ B = 1.031 \pm 0.004 \]
The particles produced in air showers initiated by low-energy cosmic rays pass through the stations occurring for individual stations. The time fraction when the entire array was not transmitting data communication issues in the data transmission to CDAS or other on-site problems occasionally more than 95% of all stations have been functioning. Lower values correspond to DAQ downtime, software. The T2 trigger selects signals with amplitudes exceeding a threshold (limited data transmission bandwidth, the trigger algorithms are implemented locally in the station monitoring the conditions of the station hardware, the number of triggers a station is transmitting data Acquisition System (CDAS) and then exported to a MySQL database server [amplitude of the output from the last PMT dynode to the one from the anode) are sent to the Central observables related to the PMTs to higher-level variables used in advanced analyses. In this work, that the detectors will continue to take high-quality data over the next decade.

Figure 1: Long Term Performance of the Pierre Auger Observatory

Number of active SD stations normalized to the number of deployed SD stations as a function of time.

FD lidar scan

Cloud camera image

Satellite cloud probability map

V. Harvey for the P. Auger Collab. ICRC 2019
K. Choi for the P. Auger Collab. ICRC 2019
The Pierre Auger Collaboration

About 400 members from 90 institutions in 16 countries
Quadruple hybrid event

65 km between FD
Energy spectrum

Data: about 15 years of SD
- 215,030 events
- Zenith angles below 60°
- Energies larger than $2.5 \times 10^{18}$ eV

Steepening at $10^{19}$ eV never observed previously

$J(E) \times E^3$ [km$^{-2}$ yr$^{-1}$ sr$^{-1}$ eV$^2$]

Spectral index $\pm \sigma_{stat} \pm \sigma_{sys}$

$\gamma_1 = 3.29 \pm 0.02 \pm 0.10$
$\gamma_2 = 2.51 \pm 0.03 \pm 0.05$
$\gamma_3 = 3.05 \pm 0.05 \pm 0.10$
$\gamma_4 = 5.1 \pm 0.3 \pm 0.1$

Pierre Auger Collab., Phys. Rev. Lett, 2020
Energy spectra in three declination bands (SD)

\[
J(E) \times E^3 \quad \text{[km}^2 \text{yr}^{-1} \text{sr}^{-1} \text{eV}^2]\]

bands of equal exposure

\[
\begin{align*}
\text{full f.o.v. fit} \\
\bullet -90.0^\circ \leq \delta < -42.5^\circ \\
\square -42.5^\circ \leq \delta < -17.3^\circ \\
\bigstar -17.3^\circ \leq \delta < +24.8^\circ 
\end{align*}
\]

\[
J_{\Delta \delta}(E) / J(E)
\]

P. Auger Collab., Phys. Rev. D, 2020
Mass composition sensitivity

Depth of shower maximum

\[ \langle X_{\text{max}}^p \rangle \approx \langle X_{\text{max}}^{Fe} \rangle + (80 - 100) \text{ g cm}^{-2} \]

\[ \sigma(X_{\text{max}}^p)/\sigma(X_{\text{max}}^{Fe}) \approx 3 \]

Number of muons

\[ N_\mu(Fe)/N_\mu(p) \approx 1.4 \]

Relative positions and orientation of elements are nearly model-independent.

The Pierre Auger Observatory Upgrade - Preliminary Design Report
arXiv:1604.03637
Energy evolution of $X_{\text{max}}$

![Graphs showing energy evolution of $X_{\text{max}}$ for different particle energies.](image)

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Yushkov for the P. Auger Collab.  ICRC 2019
P. Auger Collab.  JCAP 2013
Mixed composition – four-component analysis (FD)

- Large proton fraction below the ankle
- Mixed composition, heavier at higher energy
- Fit quality not always good
- Flux suppression beyond $10^{19.5}$ eV

J. Bellido for the Pierre Auger Collab., ICRC 2017
Mixed composition – four-component analysis (FD)

- Large proton fraction below the ankle
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Mixed composition – four-component analysis (FD)

Fred Sarazin (fsarazin@mines.edu)
Physics Department, Colorado School of Mines

J.Bellido for the Pierre Auger Collaboration, ICRC 2017

• Large proton fraction below the ankle
• Mixed composition, heavier at higher energy
• Fit quality not always good
• Flux suppression beyond $10^{19.5}$ eV
Combined fit of composition and spectrum

Astrophysical Interpretation

Identical sources homogeneously distributed in a comoving volume

Power-law spectrum with rigidity-dependent exponential cutoff

\[
\frac{dN_{\text{inj},i}}{dE} = \begin{cases} 
J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\text{cut}} \\
J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp \left(1 - \frac{E}{Z_i R_{\text{cut}}}\right), & E/Z_i > R_{\text{cut}}
\end{cases}
\]

Seven free parameters

\(J_0, \gamma, R_{\text{cut}}, p_H, p_{\text{He}}, p_{\text{Ni}}\) and \(p_{\text{Si}}\)

P. Auger Collab., Phys. Rev. Lett, 2020
Combined fit of composition and spectrum

Astrophysical Interpretation

Softening at $1.3 \times 10^{19}$ eV:
cut-off of helium spectrum with CNO contribution with photodisintegration effect

Steepening above $5 \times 10^{19}$ eV:
combination of Greisen-Zatsepin-Kuzmin effect and cut-off at sources at $5Z \times 10^{19}$ eV

P. Auger Collab., Phys. Rev. Lett, 2020
Model-independent decrease of $\sigma(\ln A)$ until the ankle ($\sim 10^{18.7}$ eV)

$\ln A$ of (p, He, N, Fe) 
$\approx (0.0, 1.4, 2.6, 4.0)$
Indications on underproduction of muons in MC

Muon density with underground muon detectors (left) and inclined showers (right)

Data are above MC predictions for iron, large systematics in $h \ln A_i$ from SD

$2 \cdot 10^{17}$

$10^{18}$

$2 \cdot 10^{18}$

$E/\text{eV}$

$0.6$

$1.0$

$1.4$

$1.8$

$2.2$

$2.6$

$3.0$

$3.4$

$\langle \rho_{35} \rangle/m^{-2}/(E/10^{18}\text{eV})$

$p$

$Fe$

F. Sanchez for the P. Auger Collab., ICRC 2019

F. Riehn for the P. Auger Collab., ICRC 2019

Data is above MC predictions for iron

Muons density with underground muon detectors

Muons density in inclined showers

see talk of Dariusz Gora on 08/09 for more details

Auger 2019 Preliminary
The p-air cross-section

Tail of the Xmax distribution is sensitive to $\sigma_{\text{inel}}^{\text{p-air}}$

Two energy bins:
- $10^{17.8} \text{ eV} < E < 10^{18} \text{ eV}$
- $10^{18} \text{ eV} < E < 10^{18.5} \text{ eV}$

Tail dominated by protons

$$\frac{dN}{dX_{\text{max}}} \sim \exp\left(-\frac{X_{\text{max}}}{\Lambda_\eta}\right)$$

$\Lambda_\eta \rightarrow \sigma_{\text{p-Air}}$ by tuning models to reproduce tail seen in data

R. Ulrich, Auger Coll., ICRC 2015, ArXiv 1509.03732

Auger Coll., Phys, Rev. Let. 109 (2012) 062002
Cross section measurement

Intervals of energy used:
LAB $10^{17.8} - 10^{18}$ eV, $10^{18} - 10^{18.5}$ eV
COM pp $38.7$ TeV $55.5$ TeV

- Glauber theory used to convert p-air to inelastic pp cross section
- Largest source of systematic uncertainty is helium fraction
- Amounts to 6% bias in calculated values if fraction at 25%

*The data is consistent with a rising cross section with energy.*
Neutrino search: old and young showers
Sensitivity: all flavours and channels

Three selection criteria
* Downward-going low zenith (2 and 4)  DGL (60° - 75°)
* Downward-going high zenith (2, 4 and 5) DGH (75° - 90°)
* Earth-skimming (3)  ES (90° - 95°)
Selecting $\nu$ in data

**Inclined selection**
- Elongated pattern: $L > W$
- Apparent speed signal $\approx c$
- Angular reconstruction $60^\circ - 75^\circ$ & $75^\circ - 90^\circ$

**Select young showers**
- Broad EM component

$<\text{AOP}>$ area over peak of digitized signal

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P. Auger Coll., Phys. Rev. D 91, 092008 (2015); Ap JL 755:L4 (2012)
No candidates: **constraints** on proton-dominated astrophysical models and source evolution.
Photon limits

Photons characterized by:
* deep Xmax in FD
* small signal in SD

SHDM models barely compatible to hybrid and strongly constrained by SD limits

\[ p + \gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p + \pi^0 \]
\[ \pi^0 \rightarrow \gamma + \gamma \]

Significant increase of exposure needed to constrain recent GZK proton scenarios

J. Rautenberg for the P. Auger Collaboration ICRC 2019
P. Auger Collab. JCAP 2017
Modulation in flux of ultrahigh energy cosmic rays with $E \geq 8$ EeV

Exposure > 92000 km$^2$ sr yr
for events with $\theta < 80^0$

Rayleigh analysis in right ascension

The effective aperture of the array is determined every minute.
Large Scale anisotropy

3-D Dipole above 8 EeV at \((\alpha, \delta) = (98^0, -25^0)\)

\[ d = (6.0^{+1.2}_{-0.8}) \text{\%} \] at 6\(\sigma\) from isotropy

Phase in R.A. \(\alpha_d = 98^0 \pm 9^0\)
is nearly opposite to the
Galactic center \(\alpha_{GC} = -94^0\)

Magnitude and direction of
dipole support extragalactic
origin of UHECRs with \(E > 4\) EeV

E. Roulet for the P. Auger Collab., ICRC 2019
Both amplitude and deviation of phase from the GC increase with energy.

Dipole amplitude with energy and scenarios of extragalactic sources with a mixed CR composition.
In August 2017 the Advanced LIGO and Advanced Virgo experiments discovered a gravitational wave from a binary neutron star merger, known as GW170817. A short gamma-ray burst following the event was observed by the Fermi and INTEGRAL satellites. Subsequent optical observations allowed the localization of the merger in the galaxy NGC 4993.

The Pierre Auger Observatory together with dedicated neutrino experiments ANTARES and IceCube were searching for high-energy neutrinos correlated with this event. Figure 4 shows the sensitive regions and summarizes the results of the search. No neutrino candidates directionally coincident with the merger were found within ±500 s or within the 14-day period following the merger. This non-detection is consistent with model predictions of a short GRB observed o-axis. Nevertheless, the main message is that the Pierre Auger Observatory joined the common effort of numerous instruments and plays an active role in the new, multimessenger era in astronomy and astrophysics.

Future prospects
The lack of clear correlation of UHECR arrival direction with astrophysical sources or structures and the evidence of a dipole structure on a large scale suggest that the UHECRs are not formed predominantly by protons as was commonly expected when Auger was first envisioned. The flux suppression above 40 EeV has been observed with more than 20 significance. Given the fact that the composition is getting heavier with higher energy as seen in $X_{\text{max}}$ measurements, the question arises whether the suppression is caused by propagation (GZK effect) or by the exhausted power of the cosmic accelerators. Hadronic interaction models fail to describe sufficiently well all aspects of air showers despite the great improvement in recent years, especially from LHC data. Another mass sensitive observable effective especially in the flux suppression region would be instrumental in answering the current burning questions.

The Observatory is undergoing a major upgrade in order to reflect these facts. Each WCD is being equipped with a 4 m$^2$ plastic scintillator mounted on the top. A prototype upgraded station can be seen in Figure 5. The two detectors provide complementary information about the electromagnetic and muonic components of the shower, so both particle contents can be derived. An enlarged dynamic range will permit the study of signals closer to the shower core. A more powerful, modernized electronics will allow the integration of the additional devices and faster FADCs (120 MHz instead of 40 MHz) will make it possible to further study the temporal aspect.
GW170817 v limits

- Time windows: ±500 s, 14-days
- No neutrino candidate found
- Only optimistic model constraint by observations
- Consistent with model predictions of short GRB observed off-axis and low luminosity GRB

- Complementary searches
- An unprecedented joint effort of experiments sensitive to high-energy neutrino

ANTARES, IceCube and the P. Auger Observatory, AJL, 2017
Future of UHECR physics
Figure 16. Evolution of the exposure of past, current, and upcoming (solid lines) UHECR experiments as a function of time for ground-based and space experiments. Proposed experiments are also shown (dashed lines).

The project concept of OWL, based on the simultaneous detection of UHECRs by UV telescopes placed on two satellites, was recently developed in the POEMMA project. This project, based on the use of Schmidt optics with 45° FOV and a large photodetector camera, can become a space instrument of record characteristics and surpass in terms of exposure the ground-based Auger and TA installations (see Figure 16).

4.3 The Current Status and Perspectives of UHE Neutrino Experiments

Currently the UHE neutrino flux is best confined by the IceCube Observatory and the Auger Observatory at the level of $\sim 3 \times 10^8$ GeV cm$^{-2}$ sr$^{-1}$ around EeV (all-flavor). Figure 17 summarizes the sensitivity of current and proposed experiments that target EeV neutrinos.

The Askaryan Radio Array (ARA) and ARIANNA are in-ice radio arrays which detect UHE neutrinos via the Askaryan effect. As an alternative to the expensive ice-Cherenkov technique the three experiments equipped with radio antennas are located in Antarctica and optimized for UHE neutrino detection, namely two in-ice arrays, the Askaryan Radio Array (ARA) and ARIANNA, and a balloon-borne interferometer ANITA. The propose GRAND will use large arrays of cost-effective radio antennas to detect particle cascades produced in media and air by UHE tau neutrinos. POEMMA will also detect tau neutrinos, by observing the Cherenkov radiation produced by upward-going tau decays.

Trinity, an Earth-based imaging telescope experiment,
The Pierre Auger Observatory Upgrade (AugerPrime)

Physics goals

* composition measurement at $10^{20}$ eV
* composition-enhanced anisotropy studies
* particle physics with air showers

Components of upgrade

* New Surface Scintillator Detector (SSD) on top of SD stations
* Radio Detector at each SD station
* SD electronics improvements
* Upgrade of the Underground Muon Detector (23.5 km$^2$)
* Increase of the FD operation time
Status of AugerPrime

SD station with new scintillator and new radio antenna

**Engeneering array**  (12 stations) data since 2016

**Pre-production** SSD array (77 stations) since March 2019

**866 SSD stations deployed**  (October 2020)

J. Stasielak for the P. Auger Collab.  ICNFP 2020
AugerPrime data

Lateral distribution of signals measured by different detectors of a real event, as a function of the distance to the shower core.
Conclusion and perspectives

**Spectrum**
* Measured precisely with new features well established

**Composition**
* Evidence of mixed composition above 10 EeV
* SD: Slowing down of the evolution toward heavier primaries at the flux suppression and beyond?

**Anisotropy**
* Large-scale: evidence for extragalactic origin of UHECRs for E> 8 EeV.
* Dipole consistent with mixed composition and galactic magnetic field deflections

**Photons**
* No photons with EeV energies detected so far
* Upper limits: severe constraints on non-acceleration models
* Predictions from some GZK-based models are within reach

**Neutrinos**
* No neutrino found
* Sensitivity peaks at ~ EeV (peak of cosmogenic neutrinos)
* Diffuse bounds constrain UHE neutrinos models

**Follow-up of Gravitational-Wave events:**
* GW170817: upper limits with Antares and IceCube
* Active role in multimessenger era!
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Plenty of AugerPrime data in the next decade!
Thank you