Recent results from the Pierre Auger Observatory

Particle astrophysics @ 10s M TeV

Radomír Šmída
The primary goal: study the most energetic cosmic rays (CRs)
Their flux is extraordinarily low: ca. 1 CR / km² yr @ 10¹⁹ eV

Pampa Amarilla in Argentina

Good atmospheric conditions
Low population
Large area
Flat
Low vegetation density

Construction between 2004 and 2008

450 scientists, engineers, technicians & students from 16 countries
The Pierre Auger Observatory

Hybrid detector w/ two complementary measurement techniques

Surface detector (SD):
- 1660 water Cherenkov stations
- 1.5 km (0.75 km) distance
- 3 PMTs / station
- 100% duty cycle
- Geometrical exposure

Fluorescence detector (FD):
- 27 telescopes @ 4 sites
- 440 PMTs / telescope
- FOV: 180° x 30° (60°)
- Longitudinal shower development
  → model-independent energy
  → maximum of shower development $X_{\text{max}}$

Additional detectors and rich R&D program:
- Underground muon detector (AMIGA)
- Radio detector (AERA)
- GHz antennas

Pierre Auger Coll., NIMA 798 (2015)
The energy spectrum

Energy uncertainty ±14%

Strong flux suppression

Origin?

Flux above $10^{20}$ eV: 2 ev. / 10,000 km$^2$ sr yr

F. Fenu @ ICRC 2017
The energy scale

Improvements of aerosol analysis technique

M. Malacari @ ICRC 2017

Multiple scattering & shape of aerosol scat. phase function

Novel techniques:

1. airborne isotropic light source data

L. Tomankova, PhD (2016)

Autonomous drone
Can be calibrated in a laboratory
15 – 30 minutes flight

2. radio signal measurement

Array of antennas (30 – 80 MHz)
CoREAS simulations
100% duty cycle

R. Krause @ ICRC 2017
The composition

FD data → longitudinal profile

Quality and FOV selection cuts
only < 1% of triggered data survive

$X_{\text{max}}$ systematics unc. ±10 g/cm²

Difference between proton and Fe nucleon
is on the level of 100 g/cm²

$X_{\text{max}}$ acceptance is corrected for residual distortions

The shape of longitudinal energy-deposit profiles
is universal, i.e. it does not depend on the primary particle or details of the first interaction.

Pierre Auger Coll., PRD 90, 122005 (2014)
The composition

The same conclusion from $\sigma(X_{\text{max}})$.

Change of the elongation rate @ $2 \times 10^{18}$ eV

(26 $\pm$ 2) g/cm$^2$/decade

(79 $\pm$ 1) g/cm$^2$/decade

Auger FD ICRC17 (prel.) ± stat.

± sys.
The composition

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

\[ \sigma(X_{\text{max}}) \ [\text{g/cm}^2] \]

\[ E = 2 \times 10^{17} \text{ EeV} \implies E_{\text{cm}} = 72 \text{ TeV (proton - nitrogen)} \]

Hadronic interaction models extrapolated to only 5x higher energy than studied at the LHC.

One of the highest energy FD events: \( E = 8 \times 10^{19} \text{ EeV}, X_{\text{max}} = 762 \text{ g/cm}^2 \)

J. Bellido @ ICRC 2017
P. Sanchez @ ICRC 2017
Particle physics

The proton-air cross section

The 20% most deeply penetrating showers

R. Ulrich @ ICRC 2015, arXiv:1509.03732

Valuable data for hadronic interaction models
Large-scale anisotropy

Equatorial coordinate system

Auger events: $E \geq 8 \times 10^{18}$ eV, $\theta < 80^\circ$, 85% sky coverage

A dipole anisotropy with a significance of $5.4\sigma$

O. Taborda @ ICRC 2017
Large-scale anisotropy

The Galactic center

Galactic coordinate system

A dipole of an amplitude $6.5^{+1.5}_{-0.9}\%$
Large-scale anisotropy

Supergalactic coordinate system

Credit to S. Molerach
Intermediate-scale anisotropy

Active Galactic Nuclei
- 2FHL AGNs
- flux proxy: $\Phi(> 50 \text{ GeV})$
- 17 objects within 250 Mpc

Star-forming of Starburst Galaxies
- Fermi-LAT search list (Ackermann+2016)
- $\Phi(> 1.54, \text{GHz}) > 0.3 \text{ Jy}$
- flux proxy: $\Phi(> 1.54, \text{GHz})$
- 23 objects within 250 Mpc

Likelihood ratio analysis
- smearing angle $\psi$
- $H_0$: isotropy
- $H_1$: $(1 - f) \times \text{isotropy} + f \times \text{fluxMap}(\psi)$
- $TS = 2 \log(H_1/H_0)$
Intermediate-scale anisotropy

Parameters:
- the smearing angle,
- the anisotropy fraction,
- energy \((2 – 8) \times 10^{19} \text{ eV}\).

A posteriori significance of 3.9\(\sigma\)

Penalized for energy scan only.
(Does not include a selection of catalogues, previous searches and hidden trials.)

Interesting hint of an anisotropy, which will be studied with new data.

\[ f = 10\%, \; \psi = 13^\circ \]
AugerPrime – upgrade of the Observatory

The composition at the highest energies → This is the key to understanding the origin and properties of the most energetic cosmic rays.

Idea: Use two detectors with different responses to the electromagnetic and muonic (air shower) component.

Both $N_\mu$ and $X_{\text{max}}$ can be reconstructed from WCD and SSD.

Water Cherenkov detector (WCD)

Scintillator surface detector (SSD)

Additional upgrades:
- New electronics & extended dynamic range
- Extended FD-observation by 50%
- Bigger AMIGA array

A. Castellina, D. Martello, D. Schmidt, R. Smida, T. Suomijarvi @ ICRC 2017
AugerPrime – first results

First detectors since mid Sep 2016

Z. Zong @ ICRC 2017
Conclusions

The experiment is performing very well and collects valuable data about air showers.

Important results:

- The energy spectrum has strong suppression above $4 \times 10^{19}$ eV of unknown origin.
- The composition changes at $2 \times 10^{18}$ eV, missing data at the highest energies.
- Interesting particle physics with air showers: proton-air cross section & excess of muons.
- Large-scale anisotropy: a dipole above $8 \times 10^{18}$ eV.
- A hint of an anisotropy on intermediate-scale above $3.9 \times 10^{19}$ eV.

Still many open questions → strong motivation for AugerPrime.

AugerPrime is under way, first SSDs are taking data since Oct 2016.
Back-up
The composition

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

- Auger FD ICRC17 (prel.) ± stat.
- Auger SD ICRC17 (prel.) ± stat
- ± sys.

J. Bellido @ ICRC 2017
P. Sanchez @ ICRC 2017
M. Unger @ ICRC 2017
The composition fractions

4-component fit of Xmax distribution
$10^6$ TeV photons, neutrinos and ... 

Diffuse and targeted searches for photons and neutrinos \( \rightarrow \) reaching GZK predictions for optimistic models

M. Niechciol @ ICRC 2017  
E. Zas @ ICRC 2017

PeVatron in the Galactic centre

Neutrons  

Ultrarelativistic monopoles  
Pierre Auger Coll., PRD 94, 082002 (2016)

UHE neutrinos from LIGO GW  
Pierre Auger Coll., PRD 94, 122007 (2016)
Motivation for the upgrade

To provide additional measurements to allow us to address the following questions:

1. The origin of the flux suppression at the highest energies

   *Measurement of the mass composition beyond the reach of the FD.*

2. Proton contribution in the flux suppression region \((E > 5 \times 10^{19} \text{ eV})\)

   *Search of point sources and estimate the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors.*

3. Fundamental particle physics at energies beyond reach of man-made accelerators

   *Study extensive air showers and hadronic multiparticle production.*

Mass composition measurement above \(5 \times 10^{19} \text{ eV}\) with a sensitivity to the proton flux as small as 10%.
How to do it?

Measure with the Pierre Auger Observatory (designed 15 yrs ago) until the end of 2024. MOUs have been signed in Nov 2015.

Proposed upgrades:

1) Upgrade surface detector electronics & a small PMT
2) Scintillator SD (SSD) to measure the mass composition with 100% duty cycle
3) Finish AMIGA to have a direct muon measurement
4) Extended FD operation

Event statistics will more than double compared with the existing data set, with the critical added advantage that every event will now have mass information.

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SD electronics and small PMT

1. Increase of the data quality (better timing, dynamic range and μ identification):
   a) faster sampling of ADC traces (40 → 120 MHz)
   b) more precise absolute timing accuracy (new GPS receiver)
   c) increase the dynamic range by adding a 1” PMT (SD PMTs are 9”)

2. Faster data processing and more sophisticated local triggers
   (more powerful processor and FPGA)

3. Improved calibration and monitoring capabilities

4. New components:
   a) Connection to the SSD and any additional (R&D) detectors
   b) Prolong lifetime and reduce failure rate

Prototype is being tested.
Complementarity of particle response used to discriminate electromagnetic and muonic components of air showers.

Both, $N_\mu$ and $X_{\text{max}}$, can be reconstructed from WCD and SSD.
**Scintillator detector**

- **Fibers routing**
- **WLS fibers**
- **Extruded scintillator bars**
  - (1600 x 50 x 10 mm)
- **Alu enclosure**
- **PMT/SiPM**
- **Sunroof**
- **Support frame**
The underground muon detector

61 AMIGA muon detectors (30 m$^2$) are planned

Will be deployed on a 750m grid (a total area of 23.5 km$^2$)

LDF, $E = 2 \times 10^{18}$ eV
Standard FD operation

FD provides exceptional information (e.g. model-independent energy reconstruction & mass composition measurement).

The main limitation of the FD is its duty cycle (15% nowadays).

The current criteria for FD measurement:
1. The sun more than 18° below the horizon
2. The moon remains below horizon for longer than 3 hours
3. The illuminated fraction of the moon must be below 70%

Measurement periods (~17 nights long), limit on the PMT illumination (i.e. no rapid aging), and the PMT response stays linear.

By relaxing criteria #2 and #3 the FD duty cycle can be increased by 50%, while keeping very high selection efficiency and reconstruction.
Extended FD operation

**Clear sky, no moonlight**

- 15% duty cycle
- Increase by 50% by measurement during high night sky background

**40 times higher NSB (90% moon)**

- $E = 7 \times 10^{19} \text{ eV}$
- $E = 72 \pm 3 \text{ EeV}$
- 10x reduced PMT gain by reducing supplied HV.
- Successful test has been done last year.