Recent results from the Pierre Auger Observatory on ultra high energy cosmic rays

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Ultra High Energy Cosmic Rays (UHECR)

UHECR (E>10^{18} eV):
- Extragalactic
- most likely protons or iron nuclei (other nuclei break up)
- Photoproduction threshold on CMB: GZK cut-off (GZK horizon ~75 Mpc)

Main topics:
- Accurate measurement of the high end of the energy spectrum
- Nature of the primaries
- Identification of possible sources
- Acceleration mechanism
UHECRs observed from the extensive air showers (EAS)

Methods:

• sampling the particle density on ground (surface detector)
• detecting the fluorescence light (fluorescence detector)

In both cases: timing gives the direction and intensity gives the energy; complementarity, very different systematic errors.

The Pierre Auger Observatory is the first large hybrid detector: it combines the strengths of Surface Detector Array & Fluorescence Detectors
Pierre Auger Observatory (PAO)

Located in Mendoza, Argentina

PAO collaboration: 19 countries; VATLY/Vietnam is an associate member

Fluorescence Detectors
24 telescopes in 4 stations, each covering $30^\circ \times 28^\circ$

Surface detectors
1660 Cherenkov tanks, triangular grid of 1.5 km mesh size.

The construction was completed in 2008; progressive data taking since 2004.

-> accumulated the largest data set with the highest precision
Surface Detectors (SD)

- Huge aperture (easily calculated)
  100% duty cycle
- Direction from tank hit times;
  good angular resolution (∼1°)
- Energy measured to ∼15% resolution,
  referred to the signal at 1000m
  from the shower core $S(1000)$
Fluorescence Detectors (FD)
- clear moonless nights: ~13% duty cycle
- precise directions (stereos or hybrids)
- a direct view of shower maximum
- near calorimetric energy measurements from integrated longitudinal profile.
Hybrid events

essential for energy calibration and $X_{\text{max}}$ measurement

Stereo events: $X_{\text{max}}$ independently measured by each station

$E = (1.88 \pm 0.14) \times 10^{19}$ eV

$E = (1.85 \pm 0.19) \times 10^{19}$ eV

(Statistical error, including contributions from geometry, atmosphere)

$X_{\text{max}}$ values: typical resolution $\sim 20\text{g/cm}^2$ (at $10^{19}$ eV)
Energy calibration of the array

Uses a subset of high quality hybrid events ($\chi^2 < 2.5$ for the longitudinal profile fit, depth of maximum in the field of view, etc...) and the SD energy estimator $S(1000)$ referred to $38^\circ$ zenith angle, $S_{38}$.

\[ E_{FD} = a \ S_{38}^b \]

\[
\begin{align*}
  a &= 1.49 \pm 0.06 \text{(stat)} \pm 0.12 \text{(syst)} \\
  b &= 1.08 \pm 0.01 \text{(stat)} \pm 0.04 \text{(syst)}
\end{align*}
\]

Total $E$ uncertainty: 22%
- A clear suppression is observed at $E > 4 \times 10^{19}$ eV, consistent with GZK cut-off
- Iron and proton hypotheses predict very similar cut-offs
- Hypothesis of a single power law is rejected to better than 6 sd
- Sudden change of slope at $4 \times 10^{18}$ eV (ankle) usually associated with the galactic to extragalactic transition

Spectrum includes full statistics available
Depth of Shower Maximum $X_{max}$

Uses high quality hybrid events: $E > 10^{18}$ eV, light emission angle towards the FD $< 20^\circ$, $X_{max}$ in the field of view, good fit to the longitudinal profile, etc...

After all cuts: 6744 events are selected for the $X_{max}$ analysis

Main interest is to distinguish between proton and iron primaries
Clear trend to higher primary masses when energy increases
Interpretation in terms of a simple p-Fe mixture currently inconclusive
Anisotropy

Select UHECRs having $E > 55$ EeV and pointing back within $3.1^\circ$ to a VCV catalogue nearby galaxy ($< 75$ Mpc, GZK horizon):

28 correlating events out of 84, $33 \pm 5\%$

In 2007, there were 18 correlating events out of 27. Present data indicate that only 9 should have been expected.

Possible systematic effects have been searched for without success, implying an important statistical fluctuation.

June 2011
Largest departure now at 24°: 19 observed/ 7.6 expected
Search for multiplets

*motivated by possible deflection in magnetic fields*

- Select alignments with proper energy ordering, $E > 20\ EeV$
- Find 3 multiplets with at least 10 showers
- Reconstruct source
- Highest multiplet is a 12-plet with 6% probability to occur by chance
- No significant evidence for correlated multiplets in present data set.
p-Air Cross-Section at $\sqrt{s} = 57$ TeV

\[ \sigma_{p\text{-air}} = (505 \pm 22_{\text{stat}}^{+26}_{-34})_{\text{sys}} \text{ mb} \]
Other results
- SD related mass composition studies
- photon and neutrino limits
- first harmonic modulation
- Solar Physics: Forbush decreases
- Atmospheric Phenomena: Observation of Elves

New additions
- enlargement of field of view for FD
- radio detection of showers
- Infill array
- muon detectors underground
Summary

*Selected results obtained by the PAO have been presented:*

- Energy spectrum is measured with highest statistics ever, confirming the suppression of the flux above $4 \times 10^{19}$ eV, consistent with the GZK cut-off

- Clear trend to higher primary masses when energy increases from $\langle X_{\text{max}} \rangle$ and $\text{Rms}(X_{\text{max}})$

- Arrival directions correlate with matter/AGN within GZK horizon above 55 EeV; possible excess towards Centaurus A

- p-Air cross section has been measured at $\sqrt{s} = 57$ TeV well beyond LHC energy

*And many more ...*

Thank you for your attention!
Back up ...
**$X_{\text{max}}$ Distributions vs Models**

- **$10^{18}$ eV**
  
  \[ 18.1 > \log(E) > 18.0 \]

- **$> 10^{19.4}$ eV**
  
  \[ \log(E) > 19.4 \]

- **wide distribution**
- **well described with a substantial fraction of protons**

- **narrow distribution**
- **compatible with significant fraction of heavy nuclei**
p-Air Cross-Section

Tail of $X_{\text{max}}$ distribution

Inelastic cross-section

$10^{18} \, \text{eV} < E < 10^{18.5} \, \text{eV}$

tail dominated by protons

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

$\Lambda \Rightarrow \sigma_{p-\text{Air}}$

by tuning models to describe tail seen in data
Inelastic Proton-Proton Cross-Section

Glauber conversion + propagation of modeling uncertainties

\[
\sigma_{pp}^{\text{inel}} = (90 \pm 7_{\text{stat}}^{+8}_{-11})_{\text{sys}} \pm 1.5_{\text{Glauber}} \text{ mb},
\]

Ralf Ulrich for the Pierre Auger Collaboration