Ultrahigh Cosmic Rays: The highest energy frontier

Humberto Salazar (FCFM-BUAP)
for the Pierre Auger Collaboration
XIII Mexican Workshop on Particle and Fields, León, Gto, 2011
SCIENTIFIC OBJECTIVES:

Spectrum: CR flux for $E > 10^{18}$ eV

Arrival directions: search for anisotropies (identify the sources)

Composition: light or heavy nuclei, photons, neutrinos, others?

Study of interactions at energies unreachable at accelerators
The Auger Observatory in the Southern Hemisphere

Hybrid shower measurements

Fully deployed in Argentina since June 2008

1600 water Cherenkov stations

24 fluorescence telescopes (30°x30°)
Pierre Auger Observatory in Argentina

1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

27 telescopes
in 4+1 buildings at the periphery

3000 km² area

infill array (750 m spacing)
\(\uparrow\downarrow+\) AERA radio antennas

~65 km

3000 km²

Los Morados

Los Leones

CLF

AMIGA

AERA

Loma Amarilla

HEAT

Coihueco
a hybrid event

Measure Xmax
Energy calibration
angular resolution studies ...
(but duty cycle ~15%)
SD energy calibration with FD

Calibration made using events with independent SD and Hybrid trigger and reconstruction

most energetic event at 75 EeV

839 events

Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)
Hybrid energy spectrum

- very good agreement with SD
- difference in flux with old publication less than 2%
- difference w.r.t PLB due to changes in calibration curve
- very high statistics, spectral features very well defined
Energy shift of 25% applied to Auger combined spectrum
\[ E^3 J(E) \text{ (km}^2 \text{ yr}^{-1} \text{ sr}^{-1} \text{ eV}^2) \]

\[ \gamma_1 = 3.27 \pm 0.01 \]

\[ \gamma_1 = 2.63 \pm 0.02 \]

\[ \log(E_{\text{cut-off}}) = 19.63 \pm 0.02 \]

\[ \log(E_{\text{ankle}}) = 18.62 \pm 0.01 \]

Broken power-law and exp. cut-off

\[ \chi^2/\text{ndf} = 33.7/16 = 2.3 \]

Exposure = 20905 km$^2$ sr yr (60% increase over PLB 685 (2010))

Inclined showers add another 5300 km$^2$ sr yr (→ #724)
Exposure of infill array: (26.4±1.3) km² sr yr
The Auger Sky above 60 EeV

27 events as of November 2007

58 events, 2010 (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).
Update of Correlation with VCV-AGN

AGN position (3.1° circle)
event position

Update including June 2011

33±5%
Total: 28/84
P=0.006

Telescope Array:
8/20 = 40%
with iso-bkg = 24%
Update on Cen A

KS test yields 4% isotropic probability
Largest departure now at 24°: 19 observed / 7.6 expected
$<X_{\text{max}}>$ vs. Energy

- Results compatible with PRL (2010)
- Data are best described with two slopes; break is near the same energy as the ankle feature of the spectrum
- At high energy $<X_{\text{max}}>$ increases slowly with energy.

Low Energy
$D_{10} = 82^{+48}_{-28}$ g/cm$^2$/decade

High Energy
$D_{10} = 27^{+3}_{-8}$ g/cm$^2$/decade

Energy break
$log\left( E_{\text{break}}/eV\right) = 18.38^{+0.07}_{-0.17}$

Below $E_{\text{break}}$ the small lever arm of the fit results in higher statistical uncertainties in $D_{10}$
FIG. 2. $\langle X_{\text{max}} \rangle$ as a function of energy. Lines denote a fit with a broken line in $\log E$. The systematic uncertainties of $\langle X_{\text{max}} \rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.
RMS($X_{\text{max}}$) vs. Energy

Resolution is subtracted from data:
27 g/cm$^2$ → low energy
18 g/cm$^2$ → high energy

- Compatible with published results PRL(2010)
- There is a change in behavior around the same energy as $<X_{\text{max}}>$: above $2.5 \times 10^{18}$ eV there is a fast decrease of RMS($X_{\text{max}}$) towards the values expected for heavy primaries.
Hi-Res $X_m$ - results favor protons

Evidence for proton dominated composition above 1.6 EeV

PRL 104 161101 (2010)

HiRes Collaboration

arXiv:0910.4184

Mean depth of maximum vs energy

Width of distribution vs energy
Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.
Auger exposure to tau Neutrinos

Neutrinos can be identified as “young” showers at very great atmospheric slant depth (either upward or downward).

The Auger UHE Neutrino Observatory

Earth Skimming $\nu_\tau$

zenith angle $\sim 90-92^\circ$
Differential limits to diffuse fluxes

Single flavour neutrino limits (90% CL)

- Down-going (2yr)
- EarthSkimming (3.5yr)
- IceCube-40 (333.5 days)
- Anita-II
- Exotic
- Cosmogenic
The UHE Gamma Ray Astronomical Window

Photon showers penetrate deeper than hadronic showers. They can be recognized individually with hybrid measurements. A photon component can be measured statistically by the surface array.
**Upper Limits to the Integral Photon Flux**

<table>
<thead>
<tr>
<th>$E_0$ [EeV]</th>
<th>$N_\gamma$</th>
<th>$\phi^{95%\text{CL}}(E_\gamma &gt; E_0)$ [km$^{-2}$ sr$^{-1}$ y$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>$8.2 \times 10^{-2}$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

**Impact of systematic uncertainties**

(Exposure, $\Delta X_{max}$, $\Delta S_h$, Energy scale, hadronic interaction model and mass composition assumptions)

$\pm 20\%$ ($E_0 = 1$ EeV)

$\pm 15\%$ ($E_0 > 1$ EeV)

*Fraction limits Hybrid 2009 converted to flux scaling for the Auger spectrum*
The proton-air cross section can be deduced from the average penetration length that is related to the tail of $X_{\text{max}}$ distribution.

\[ dN/dX_{\text{max}} \sim \exp \left( -X_{\text{max}}/\Lambda_\eta \right) \]

\[ \Lambda_\eta = [55.8 \pm 2.3_{\text{stat}} \pm 1.6_{\text{sys}}] \text{ g/cm}^2 \]
The relation between penetration length and p-air cross section can be found from simulations after correcting the low energy values using Tevatron measurements, and Glauber theory.

\[
\sigma_{p\text{-air}} = \begin{bmatrix} 505 \pm 22_{\text{stat}} & \pm (28_{\text{sys}} - 34) \end{bmatrix} \text{mb}
\]
Proton-proton cross section
Using Glauber theory is possible to estimate the proton-proton inelastic cross section.

\[ \sigma_{pp}^{\text{prod}} \approx \int d^2 b \left\{ 1 - \left[ 1 - \sigma_{pp}^{\text{inel}} \frac{\rho_A(b)}{A} \right]^A \right\} \]

\[ \sigma_{pp}^{\text{inel}} = [90 \pm 7_{\text{stat}}^{(9)}_{11})_{\text{sys}} \pm 1.5_{\text{Glauber}}] \text{ mb} \]

\[ \sqrt{s_{pp}} = [57 \pm 6] \text{ TeV} \]

\[ (73.5 \pm 0.6_{\text{stat}}^{+1.8}_{-1.3} \text{ syst}) \text{ mb} \]
CONCLUSIONS

Far greater exposure is needed to

- Identify the class of sources via anisotropy
- Measure the spectra of bright sources or source regions
- Determine the particle type(s) above 55 EeV
- If protons, measure interaction properties above 250 TeV (CM)
- Determine the diffuse cosmogenic intensity of neutrinos and photons
- Detect cosmogenic neutrinos and photons
An Air Fluorescence Telescope

Field of View: 30° x 30°

- 2.2m diameter aperture stop with Schmidt corrector ring.
- UV-Filter 300-400 nm
- Camera 440 PMTs
- 3.8m x 3.8m mirror