New Results from the Ultra-High Energy Frontier

Angela V. Olinto
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**TALKS you should have heard**

Chuck Dermer — *Evidence for UHECRs from Fermi obs of AGN & GRBs*
Eli Waxman — *What do we know about the identity of CR sources?*
**Lukas Nellen** — *Limits on the diffuse flux of neutrinos at UHE from Auger*

**TALKS you should hear**

*Tuesday, July 14 - 14:30-18:30 Parallel Session 8 (Kavli aud.)*

“Cosmic rays at the knee and above”
Gian Carlo Trinchero — *Kascade-Grande results*
Cao Zhen — *LHAASO results*
Serap Tilav — *CRs at the knee and above with IceTop and IceCube*
Pierre Sokolsky — *Telescope Array & TALE*
Martin Lemoine — *Cosmic rays around the ankle*
Pierre Sokolsky — *HiRes results*
**Nicolas Busca** — *Spectrum and composition of UHECRs by Auger*
**Piera Ghia** — *Anisotropies of UHECRs by the Auger Observatory*
Denis Allard — *Interpretation of spectrum and composition of UHECRs*
Kumiko Kotera — *Ultra high energy nuclei*

*Friday, July 17 - 9:00–11:00 Plenary Session 10 (Panofsky)*
**Miguel Mostafa** — *The Pierre Auger Northern Observatory*
from $10^{18}$ eV = EeV to ~ $10^{20}$ eV
Exposures $10^3 \text{ km}^2 \text{ sr yr}$

- Fly'e Eye
- AGASA
- HiRes
- Auger
- TA

**Surface Arrays**

**Fluorescence Telescopes**
The Pierre Auger Collaboration
91 Institutions, 463 Collaborators, 18 countries

Argentina, Australia, Bolivia*, Brazil, Czech Republic, Croatia, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, United Kingdom, USA, Vietnam*

* associate
Auger South

Completed in 2008

1660 tanks in a 3,000 km² Surface Array
4 Fluorescence Detector Sites
Auger South

wide energy range: from $10^{17}$ eV to $10^{20}$ eV

3,000 km$^2$ array of water Cherenkov detectors

Fluorescence Telescopes (10% duty)
Surface Array
surface detector station
Water Cherenkov Station

- Communications antenna
- GPS antenna
- Electronics enclosure
- Solar panels
- Battery box
- Plastic tank with 12 tons of very pure water
- 3 photomultiplier tubes looking into the water collect light left by the particles
Los Leones Fluorescence
aperture box
shutter
filter UV pass
safety curtain
corrector lens
(aperture x2)
segmented spherical mirror
440 PMT camera
1.5° per pixel
4 times 6 telescopes overlooking the site
A Hybrid Event

Time Stamp: 776331144 (GPS sec), 338958438 (GPS nsec)

Shower-Detector Plane
FD Los Leones CS
\( \theta_{\text{tot}} = 149.28 \)
\( \theta_{\text{neg}} = 147.65 \)

Elevation angle \( \theta \) (deg)
Azimuthal angle \( \phi \) counter-clockwise from East (deg)

Time fit
\( \chi^2 \) = 65.09
\( R_p = 16203 \) m
\( T_s = 13.609 \) \( \mu \) s
\( \chi^2/\text{dof} = 49.66/55 \)

Shower Axis
\( \theta = 62.32 \pm 0.20 \)
\( \phi = 118.62 \pm 0.08 \)

Sd Event 931431 in site CS
Core location for Eye 1
Easting 468739 \( \pm \) 59
Northing 6087031 \( \pm \) 80
Altitude = 1390 m a.s.l.

Longitudinal Profile Eye 1 Sd Event 931431
Energy Estimate:
\( X_{\text{tot}} = 171 \pm 30 \) g/cm²
\( N_{\text{tot}} = 1.4 \times 10^6 \pm 1.7 \times 10^6 \)
\( \lambda = 70 \pm 60 \) g/cm²
\( X_e = 0 \) g/cm²
\( \chi^2/\text{dof} = 205/191 \)
\( E_{\text{tot}} = 2.1 \times 10^9 \pm 2.5 \times 10^7 \) eV
\( E_e = 22.5 \) EeV

Shower size

Atmospheric depth \( X \) (g/cm²)
# Hybrid Era

<table>
<thead>
<tr>
<th>HYBRID</th>
<th>SD only</th>
<th>FD only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>A &amp; M indep</td>
<td>depend</td>
</tr>
<tr>
<td>Aperture</td>
<td>E, A, M indep</td>
<td>indep</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>~ 0.2°</td>
<td>~1-2°</td>
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**E** = energy, **A** = mass, **M** = hadronic model
ULTRA HIGH ENERGY COSMIC RAYS

Anisotropies

SPECTRUM

Composition
Spectrum at the Highest Energies

\[ E_{cm} = \text{PeV} \left( \frac{E_{\text{uhecr}}}{\text{ZeV}} \right)^{1/2} (2A)^{1/2} \]
GZK effect
Greisen, Zatsepin, Kuzmin 1966

\[ p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow n + \pi^+ \]
Attenuation length

Graph showing nucleon interaction and attenuation lengths as a function of energy (E) in eV, with curves for various particles and lengths labeled.
Auger & HiRes spectra (2008)
Auger & HiRes spectra (2008)

GZK effect
Recent Spectra

See Nicolas Busca’s & Pierre Sokolsky’s talks
Systematics

See Nicolas Busca’s & Pierre Sokolsky’s talks
$E^3 J$

See Nicolas Busca’s talk

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

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

$10^37$ $10^38$

$lg(E/eV)$

$18$ $18.5$ $19$ $19.5$ $20$ $20.5$

$\sigma_{sys}(E)=22\%$

Auger combined

SD + FD
GZK fits to spectrum

See Denis Allard’s talk
UHECR spectrum can be fit by models with different primaries.
Attenuation length

\[ e^+e^- \]

\[ \pi \]

Interaction length

Attenuation length
GZK Horizon - Protons

See Denis Allard’s talk
Horizons:

$10^{19}$ eV $\sim 1$ Gpc

$10^{20}$ eV $< 100$ Mpc
Horizons:

$10^{19} \text{ eV} \sim 1 \text{ Gpc}$

$10^{20} \text{ eV} < 100 \text{ Mpc}$

Distance Indicator!!!!

The Ability to Point to Sources!
Distribution of Galaxies
Correlations with nearby AGN or mass distribution

Rejected the isotropy hypothesis
Auger VCV correlation

VCV catalog of AGN: $z < 0.018$, $\theta \sim 3^\circ$, $E > 57$ EeV

27 events test prescription: 99% isotropy rejection,

See Piera Ghia’s talk
Nearby VCV AGN – 21% sky

See Piera Ghia’s talk
First 27 events

Exploratory scan – 12/15 events correlated (3.2 expected)
Prescription passed when 8/13 correlated (2.7 expected)

See Piera Ghia’s talk
The Auger Sky above 60 EeV

27 events as of November 2007

58 events now (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).

Log(Likelihood)

See Piera Ghia’s talk
HiRes: no significant correlation VCV in the North

Black - AGN’s
Blue - HiRes data
Red - correlated events

See Pierre Sokolsky’s talk
Centaurus A

See Piera Ghia’s talk
Centaurus A

Proton Primaries?

See Piera Ghia’s talk

See Martin Lemoine’s talk
Composition observable: shower maximum average & RMS

Iron
Proton
Gamma

Auger level

Depth g/cm$^2$

Ne $\times 10^7$
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.
Shower maximum over 2 decades in E

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

- Auger ICRC07

- Proton lines
- Iron lines

- QGSJETII-03
- QGSJET01
- SIBYLL2.1
- EPOS1.6

\( E \quad [\text{eV}] \)
Shower Depths of Maximum $X_{\text{max}}$

Auger ICRC 2009

Heavy nuclei?

Protons? – Higher Cross section and/or high multiplicity at high energy.

See Nicolas Busca’s talk
Shower Depths of Maximum $X_{\text{max}}$

No Information for anisotropic trans-GZK energy regime!
( Crucial for prediction of the diffuse cosmogenic neutrino & photon fluxes)

See Nicolas Busca’s talk
If protons – Cross Section Limits

Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]

Cross section (proton-air) [mb]

Energy [eV]

Mielke et al. 1994
Baltrusaitis et al. 1984
Nam et al. 1975
Siohan et al. 1978
Honda et al. 1999
Knurenko et al. 1999
ICRC07 ARGO-YBJ
ICRC07 EAS–TOP
ICRC07 HiRes

Limit from Auger RMS($X_{max}$)

accelerator data (p–p) + Glauber

QGSJET01c
EPOS 1.61
SIBYLL 2.1
QGSJETII.3
Hadronic Interactions
Parameters

Scaling factor at $10^{19}$ eV

(Ralf Ulrich, 16-Oct-2008)
HiRes

HiRes stereo data

See Pierre Sokolsky’s talk

Auger hybrid data

Fig. 28.— Results of fitting HiRes stereo data $X_{max}$ distribution to Gaussian truncated at 2 x RMS (black points). Superimposed are curves representing expectations based on QGSJET1 and QGSJET2 proton and iron Monte Carlo. Gaussian-in-age parametrization used in reconstruction.
Composition from heavy to light

back to heavy? Or different

Hadronic models??

ULTRA HIGH ENERGY PHYSICS

SPECTRUM

Composition
ULTRA HIGH ENERGY COSMIC RAYS

Anisotropies

SPECTRUM

Composition
Consistent picture needs high statistics composition
Measurements above 60 EeV
Cosmogenic (GZK) Neutrinos & Photons

\[ p^+\gamma_{\text{cmb}} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma \rightarrow n + \pi^+ \]

\[ n \rightarrow p + e^- + \nu_e \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

GZK Cutoff - Greisen, Zatsepin, Kuzmin 1966
Neutrino Fluxes

Highly Composition dependent

Allard et al ‘09
Neutrinos can be identified as “young” showers at very great atmospheric slant depth (either upward or downward).

See Lukas Nellen’s talk

Auger exposure to tau Neutrinos

Earth Skimming $\nu_\tau$
zenith angle $\sim 90-92^\circ$
Testing UHE Neutrino Interactions

Need to know the expected GZK neutrino flux from UHECRs

Tyler, AO, Sigl ‘01

Anchordoqui et al ‘03
Neutrino Fluxes
ULTRA HIGH ENERGY COSMIC RAYS

- Anisotropies
- Photons
- SPECTRUM
- Neutrinos
- Composition
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.

Photon attenuation length exceeds $10^3$ Mpc for $E > 2$ EeV
UHE Photon Limits

(strongly constrain top-down scenarios)
UHECR Recent Results

The GZK feature in the spectrum observed

Sky anisotropies > 60 EeV
   ➞ The GZK sphere is populated!

10 < E < 50 EeV composition looks heavy

UHE neutrino limits
UHE photon limits
Exposure Evolution

see talk by Miguel Mostafa
Auger North:
4400 detectors
1.42 mi Square Grid
21,000 km² (8000 mi²)

Auger South:
1600 detectors
1.5 km Triangular Grid
3000 km² (1200 mi²)

State of Colorado

see talk by Miguel Mostafa

Auger North

Auger South
to scale
Auger North

Detector Layout

1 mile

400 station in-fill 1mi spacing (2000 km²)

5 FD eyes – 39 telescopes
Ultra High Energy Frontier
next decade

Discover the Sources of Ultra High Energy Cosmic Rays
Observe UHE neutrinos & photons
Study Particle Interactions $E_{CM}>100$ TeV
Thank you!