Results from the Pierre Auger Southern Observatory

Outline

- Energy spectrum
- Energy calibration
- Anisotropy, searches
- Arrival directions
- Primary photon limit
- Composition or primary particle type

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Cosmic rays

Primaries are likely to be sub-atomic particles: $\gamma$, e, p, nuclei

Secondaries: $\gamma$, e, p, n, $\pi$, $\mu$...

Low energy: few/hand/second.

High energy: Flux falls very steeply with energy.
Historical high points

1912
Victor Hess discovers “penetrating radiation” from space

1938
Pierre Auger discovers Extensive air showers

Auger varied distance and lead covering

Fast electronic counters
The Auger Project studies the most energetic cosmic rays

Cosmic ray flux spans 32 orders of magnitude over 12 orders of magnitude in energy

Auger is focused on the high end: $E > 10^{18} \text{ eV}$

Flux measured in $\# / \text{km}^2 / \text{year}$

Sources, acceleration mechanism unknown

GZK feature starts around $5 \times 10^{19} \text{ eV}$

primary + CMB $\rightarrow$ primary + $\pi$

and primary loses energy

Length scale $\approx 50 \text{ Mpc}$

Macroscopic energies: $2 \times 10^{20} \text{ eV} = 30 \text{ Joules}$

= tennis ball at 75 mph

= laptop falling from shoulder height

= a person walking slowly
**Light Measured by FD**
- Production, Propagation, Detection
- Longitudinal distribution

**Integral = energy parameter**

**Depth in the Atmosphere**

**N photons**

**SD level**

**Sea level**

**Particles Measured by SD**
- Models, Simulations
- Lateral distribution

**Integral = energy parameter**

**N/m²**

**S₁₀₀₀ = energy parameter**

**Distance from core impact point**

**1km**

**EM shower**

**Shower front**

**Shower core hard muons**
The Auger South Detector

3000 km², 1600 water Cerenkov tanks. Hex grid with 1.5 km spacing
About 1100 tanks deployed now.
24 hour operation

**SD + FD = Hybrid.** Key to present analyses.
Auger surface detector unit
Auger Fluorescence Detector

24 telescope units, six each at four sites
3.4 meter dia. mirrors
440 PMTs per camera
The Auger campus in Malargue, Mendoza Province, Argentina

Auger Collaboration:
63 institutes, 370 collaborators

Argentina, Australia, Bolivia, Brazil, Czech Republic, France, UK, Germany, Italy, Mexico, Netherlands, Poland, Slovenia, Spain, USA, Vietnam
Example event
$\theta \sim 48^\circ$, $\sim 70$ EeV

Typical flash ADC trace
Detector signal (VEM) vs time (ns)

Lateral density distribution

PMT 1
PMT 2
PMT 3
Surface Detector Event
\( \Theta \approx 60^\circ, \approx 86 \text{ EeV} \)

Flash ADC Trace for detector late in the shower

Lateral density distribution

ID 787469

PMT 1
PMT 2
PMT 3
Hybrid Event

$\theta \sim 30^\circ, \sim 8$ EeV

Flash ADC traces

Lateral Distribution Function

Core Distance [m]
Same Hybrid Event
\( \Theta \sim 30^\circ, \sim 8 \text{ EeV} \)

Substantial improvement in geometry compared to monocular.
Next:
Detector resolutions, performance, monitoring

• Angular resolution
• SD calibration – “VEM”, uniform trigger and response (SD energy scale provided by FD)
• SD signal resolution and tank trigger efficiency
• FD absolute calibration
• Atmospheric measurements and monitors
Angular resolution on Arrival Direction

Surface Detector angular resolution depends on number of tanks and arrival zenith angle.
Angular Resolution is improved by hybrid detector

Hybrid (68% CL)  
0.6 degrees (mean)  

Surface array (68% CL)  
< 2.2° for 3 station events (E< 3EeV, θ < 60°)  
< 1.7° for 4 station events (3<E<10 EeV)  
< 1.4° for 5 or more station events (E>10 EeV)
SD tank calibration in terms of :VEM” = Vertical Equivalent Muon

First take measures in a test tank with external paddle trigger

For each tank:

Adjust HV to give rate for each PMT = 100Hz in channel 50 FADC (balances gains)

Then continually adjust PMT trigger thresholds to give 100 Hz 3-fold coincidence/tank (uniform trigger across array, compensates drifts)

Relate muon “hump” to the VEM found using a test tank.
TWIN TANKS: trigger and fluctuations measurements, also timing studies

11 m apart. Two twin sets are currently in place.

\[
\frac{\sigma}{\text{VEM}} = \frac{P_0^2}{\text{VEM}}
\]

\[
P_0 = (1.06 \pm 0.05)
\]

\[
\chi^2 / \text{ndf} = 4.763 / 7
\]

p0 = 1.061 ± 0.04855

Tank trigger efficiency measured with twin tanks and using LDF.
FD Absolute Calibration Drum

Construction uses diffusively reflecting materials to enhance uniformity of illumination at output surface.

Surface uniformity is measured using CCD imaging techniques.

Absolute intensity measurement is based on NIST-calibrated photodiode at 375nm.

Started multi-wavelength calibrations with Xe flasher+filters and lower wavelength UV LEDs.
Flat-fielding brings uniformity to the camera response.

FD absolute calibration drum fills the aperture with a known, uniform flux of photons.

August 2006: Campaign with roving laser at 4km and drum, both at 337nm, same night.
Atmospheric monitoring is also key to understanding the response of the FD…and hence the SD.

**Central laser facility has several uses:**
- Timing studies
- Angular resolution
- Aerosol measurements

Laser energy from two FD buildings

Extracting aerosols from laser shots
And the molecular atmosphere is measured by a systematic series of balloon launches.

Reconstructed energy is not drastically effected, but $X_{\text{max}}$ can shift systematically, and possibly by a significant amount if standard atmosphere is assumed.
Additional sky monitoring...

LIDARs at each FD “shoot the shower” for large events looking for clouds.

Cloud cameras at each FD continually monitor the sky and take snapshots for cloud cover.
Auger Physics results:

• Energy spectrum  
  (astro-ph/0507150    ICRC ’05)

• Photon fraction upper limit  

• Galactic center anisotropy  

• Highest energy events (ICRC 2005)
First Estimate of the Primary Energy Spectrum

- Measurement is from the southern sky
- 24/7 SD measurement for greater statistics...
- ...calibrated by the FD for a sample of events
- Does not depend on air-shower models, interaction models, or assumptions on the primary particle type

Data set: 1 Jan 2004 – 1 June 2005 (ICRC 2005 analysis)

Array size = ½*full size = ½ * 3000 km² (time average = 22%)
Exposure = 1750 km² str yr (about equal to AGASA, below HiRes)
3525 events above $10^{18.5}$ eV; full efficiency above $3*10^{18}$ eV

Selection: core surrounded by working triangle; hottest tank has 5 working nearest neighbors. Zenith angle < 60°
Model independent “CIC”

SD signal is attenuated for steeper showers...

...attenuation is measured from data by assuming near isotropy of cosmic rays

$CIC(\theta) = \frac{S(1000)_\theta}{S(1000)_{38^\circ}}$

$(38^\circ$ is the median zenith angle)

Pick a zenith angle bin and measure $S(1000)$ distribution. Number of events above some cut on $S(1000)$ is $I_0$ events. Other zenith angle bins should have same number of events above another value of $S(1000)$. Slid a cut on $S(1000)$ in this new bin of zenith angle until number events above cut is $I_0$ events. ➞ Find $S(1000)$ attenuation with zenith angle.
FD calibrates SD

A set of well monitored hybrid events...

...calibrates all the SD events.

SD energy parameter
First Auger Energy Spectrum

\[
\frac{dI}{d \ln(E)} \equiv E \frac{dI}{dE}
\]

vs.

\[\log(E)\]

Energy systematic

- \(N_2\) yield 15%
- FD abs cal 12%
- total FD 25%
- Stats of FD → SD correlation
- Total: 30% to 50%, low to high energy
...and other measurements

2) R.U. Abbasi et al. Phys Lett B (to be published)
Primary photons

- “Top down” models predict large fraction of primaries are photons (TD, SHDM, ZB) at high energies
- Photons result in deep \( X_{\text{max}} \) position (SD: muon poor)
- Present Auger measurement based on sample of 29 hybrid events – direct measurement of \( X_{\text{max}} \)

\[ \Delta X_{\text{max}} \text{ uncertainties: profile fit, atmosphere, geometry, cross section... Total = 28 (stat)+23(syst) g/cm}^2 \]
Event by event simulation

Data and many photon simulations for one of the 29 hybrid events selected

Standard deviations from photon expectation for 29 events

Each event is compared to the distribution expected for photons.

Event sample consists of 29 hybrid events: $E > 10^{19}$ eV with strict quality cuts, geometry (Update to ICRC 2005, which had 16 events).
Auger Upper Limit on Primary Photon flux

16% upper limit (95%CL) on primary photon flux above $10^{19}$ eV.
Confirms and improves previous limits by ground arrays.
Outlook for Limit on Primary Photon flux

Use of SD measurements, such as the 10-50% rise time at 1000 m core distance, will help

Current analysis extrapolated to 10 times more data, as expected in a couple of years \( \approx 5\% \) above \( 10^{19} \), and a good limit at few* \( 10^{19} \)
Anisotropy Studies Around the Galactic Center at EeV Energies

Previous measurements of excesses near galactic center

AGASA 4.5 $\sigma$, 22% excess

SUGAR 2.9 $\sigma$, 85% excess
Data from 1/04 to 3/06.

- 5° circle windows (about SUGAR window size)
- $10^{17.9} < E < 10^{18.5}$ eV (SUGAR range, slightly larger than AGASA energy range)

Auger over densities are consistent with statistical fluctuations of a uniform distribution.

Do not confirm AGASA: we see 2116 expecting 2160 with AGASA selection (more than 4 times number of events seen by AGASA). Also scaling energy do not see excess.

Do not confirm Sugar: we see 286 expecting 290.

Do not see excess in galactic plane or super-galactic plane.
The highest energy events in Auger data from 1/2004 – 6/2005 (ICRC ’05 data set)

<table>
<thead>
<tr>
<th>Event Id</th>
<th>$\theta$</th>
<th>$S(1000)$</th>
<th>Multiplicity</th>
<th>$r_{opt}$</th>
<th>$\beta$</th>
<th>$E$(EeV)</th>
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</thead>
<tbody>
<tr>
<td>1096757</td>
<td>45.1 ± 0.2</td>
<td>344 ± 15 ± 33</td>
<td>21</td>
<td>1322</td>
<td>—</td>
<td>86 ± 9</td>
</tr>
<tr>
<td>1225537</td>
<td>34.4 ± 0.2</td>
<td>364 ± 10 ± 13</td>
<td>14</td>
<td>909</td>
<td>2.48 ± 0.06</td>
<td>79 ± 4</td>
</tr>
<tr>
<td>787469</td>
<td>59.7 ± 0.2</td>
<td>204 ± 8 ± 11</td>
<td>31</td>
<td>1173</td>
<td>2.03 ± 0.06</td>
<td>76 ± 5</td>
</tr>
<tr>
<td>762238</td>
<td>47.3 ± 0.2</td>
<td>248 ± 11 ± 12</td>
<td>18</td>
<td>1135</td>
<td>2.22 ± 0.07</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>1102721</td>
<td>23.8 ± 0.2</td>
<td>318 ± 22 ± 52</td>
<td>12</td>
<td>1467</td>
<td>—</td>
<td>63 ± 11</td>
</tr>
<tr>
<td>1233429</td>
<td>54.3 ± 0.2</td>
<td>201 ± 9 ± 16</td>
<td>21</td>
<td>1261</td>
<td>—</td>
<td>63 ± 6</td>
</tr>
<tr>
<td>1018639</td>
<td>26.9 ± 0.2</td>
<td>294 ± 19 ± 26</td>
<td>10</td>
<td>1196</td>
<td>2.93 ± 0.13</td>
<td>59 ± 6</td>
</tr>
<tr>
<td>1264145</td>
<td>16.3 ± 0.2</td>
<td>289 ± 12 ± 11</td>
<td>11</td>
<td>910</td>
<td>2.65 ± 0.11</td>
<td>56 ± 3</td>
</tr>
<tr>
<td>1263529</td>
<td>20.7 ± 0.2</td>
<td>264 ± 20 ± 34</td>
<td>7</td>
<td>1470</td>
<td>—</td>
<td>51 ± 8</td>
</tr>
<tr>
<td>634746</td>
<td>51.6 ± 0.2</td>
<td>174 ± 9 ± 12</td>
<td>14</td>
<td>1203</td>
<td>—</td>
<td>48 ± 4</td>
</tr>
</tbody>
</table>

Energy scale set by FD

$LDF$ form

$$S(r) = A \left( \frac{r}{r_x} \right)^{-\beta} \left( 1 + \frac{r}{r_x} \right)^{-\beta}$$
Our largest event hit outside the array...and had some other issues.
Auger physics results

1. First Estimate of the Primary Cosmic Ray Energy Spectrum above 3 EeV from the Pierre Auger Observatory

2. Upper limit on the primary photon fraction from the Pierre Auger Observatory
   - Bodes well for neutrino detection

3. Detection of very Inclined Showers with the Auger Observatory

4. A Description of some ultra-high energy cosmic rays observed with the Pierre Auger Observatory

5. Anisotropy Studies Around the Galactic Center at EeV Energies with Auger Data
   - See no ‘hot spots’, no previous source confirmed, no positive prescription result

6. Search for localized excess fluxes in Auger sky maps and prescription results
The future...

Twenty years of taking data in Malargue will turn up things we have not yet imagined.

Data sets will be orders of magnitude larger than any existing (By ICRC 2007 factor of 7 larger than ICRC 2005).

The southern detector accepts more than half the sky, but that isn’t enough.

Galaxy distribution 7-21 Mpc

Auger south data (to 60°) miss much of northern sky
For full-sky coverage we need Auger North

Southeast corner of Colorado, near small cities of Lamar and Springfield

≈3 hour drive
DIA to site
Lamar Community College

UVB instruments here
LCC will make approx. 5 acres of land available for central campus.
Same size as fenced area of main campus in Malargue.

Location is southern edge of Lamar on highway 287, just north of proposed array.
Atmospheric Monitoring at Colorado Auger North Site

Auger and the CSU-UVB Monitoring and Research Group

UVB radiometer at 332 nm, 368 nm and other UV and visible wavelengths.

18 months of daytime data since December 2003.

Group operates 34 sites across North America since 1993. Installed at Lamar CC Dec 2003

Powers county buildings provide temporary home for Auger
AVOD

TIME OF DAY

Three days UVB

Nov 3, 2004

Nov 4, 2004

Nov 5, 2004

TIME OF DAY (OR NIGHT)

integral

{AVOD}

One night LIDAR

May 4, 2005

Attenuation

AVOD Dec 03 to May 05 and six LIDAR nights

DATE

AVOD
• Auger Observatory results have been presented from the first running period, which has been during the construction.

• Auger South is over 3/4 finished.

• Aim to complete the southern observatory soon.

• Plans and a proposal for the Northern Auger Observatory are moving forward.