Results on Ultra High Energy Cosmic Rays
primary composition and search for photons
with the Pierre Auger Observatory

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Outline

▷ motivation
▷ Auger the hybrid detector
▷ results on UHECR primary composition
▷ search for UHE photons
▷ outlook
Motivation

UHECR origin and nature still unclear: we need a consistent picture

The Pierre Auger Observatory is providing high quality measurements of energy, arrival direction, composition with unprecedented statistics (highest energies and in the galactic-extragalactic transition region)

Photons main messengers of the universe observed up to $10^{14}$ eV! A detectable flux of UHE photons is predicted in different scenarios test alternative models for the origin of UHECR

UHE photons could open the most extreme window for astronomy with consequences for fundamental physics (QED, QCD, LIV) knowledge of magnetic fields – radio background multi-messenger observation (CR, GeV-TeV $\gamma$, $\nu$)
Auger the hybrid detector

**Surface Detector Array**
1680 Cherenkov tanks on 1.5 km grid, 3000km$^2$
→ lateral distribution, 100% duty cycle

**Air Fluorescence Detectors**
4 buildings (24 telescopes 30° x 30° FOV)
→ longitudinal profile, 10-15% duty cycle
(clear moonless nights)

accurate energy and direction measurement
cross checks and redundancy
mass composition studies in complementary ways

“In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side.”

*V.H.Hess, Nobel Lecture, December 1936*
Composition from $X_{\text{max}}$ measurement


P. Auger Observatory data suggest mixed composition at all energies
→ interpretation depends on hadronic interaction models
→ measurements are compatible within experimental uncertainties
none of the model satisfactory explains data yet (shape, absolute value) → constraints by studying $X_{\text{max}}$ distribution (known syst. unc.)
Photon-hadron separation

- Fly’s Eye
- HiRes-MIA
- HiRes 2004
- Yakutsk 2001
- Yakutsk 2005
- CASA-BLANCA
- HEGRA-AIROBICCC
- SPASE-VULCAN
- DICE
- TUNKA

\[ \langle X_{\text{max}} \rangle \text{ (g cm}^{-2}\text{)} \]

\[ \begin{align*}
1200 & \quad 1100 \\
1000 & \quad 900 \\
900 & \quad 800 \\
800 & \quad 700 \\
700 & \quad 600 \\
600 & \quad 500 \\
500 & \quad 400 \\
400 & \quad 300 \\
300 & \quad 200 \\
200 & \quad 100 \\
100 & \quad 0 \\
0 & \quad 10^{14} \\
10^{15} & \quad 10^{16} \\
10^{17} & \quad 10^{18} \\
10^{19} & \quad 10^{20} \\
10^{21} & \quad E_{\text{lab}} \text{ (eV)}
\end{align*} \]

- LPM effect
- Photon with preshower effect

Photon showers develop deeper and contain less muons
→ average separation in \( X_{\text{max}} \) ~200 g cm\(^{-2}\) is detectable!
Search for photon primaries: FD

based on direct observation of shower longitudinal development


→ search for events with deep $X_{\text{max}}$

→ events with observed $X_{\text{max}}$ below expectation for photons

→ dedicated simulations with event energy geometry

→ confirm previous array limits
Search for photon primaries: SD

based on combination of shower front curvature and signal rise time


\[ \text{hadrons} \]

\[ \gamma \]

FADC-time

\[ \rightarrow \text{smaller radius of curvature} \]

\[ \rightarrow \text{slower signal and longer risetime} \]
Upper limits on photon fraction: SD


Combination of risetime and curvature

a priori cut at photon median: if above => candidate!

→ data & photons well separated no photon candidate
Experimental limits and predictions

\[ E > 10^{19} \text{ eV}: \]

**SD:**
Based on SD signal rise time and shower curvature

**FD:**
Astropart. Phys 27 (2007), 155
Based on Xmax

95% CL


top-down models severely constrained!

for reference to models & exp. data see
FD limits in the EeV range

- larger hybrid events sample
  - reconstruction quality cuts
  - fiducial volume cuts
  - cloud coverage correction
FD limits in the EeV range

▶ larger hybrid events sample

- reconstruction quality cuts
- fiducial volume cuts
- cloud coverage correction

▶ powerful statistical method

$X_{\text{max}}$ as discrimination variable
and cut at median of
MC photon distribution
(eff $\equiv 0.5$)
FD limits in the EeV range

- detector efficiency study
  - detailed detector simulation (CORSIKA, FLUKA, QGSJET01)
  - different inducing primaries (iron, proton, photon)

- relative acceptance correction
  conservative approach

\[
F_{ul} = \frac{N_\gamma \text{ c.l.} \cdot 1/\varepsilon_{\text{min}} \cdot 1/f}{N_{\text{total}} \cdot \varepsilon_{\text{cl}}}
\]

- \( N_\gamma \): observed candidates above cut (95% cl)
- \( \varepsilon_{\text{min}} \): min relative detector acceptance
- \( f \): photon candidate cut efficiency = 0.5
- \( \varepsilon_{\text{cl}} \): pass the cloud check
First limits on photon fraction in EeV range

systematics:
- $X_{\text{max}}$, Energy
- cloud rejection
- relative efficiency
- simulations

<table>
<thead>
<tr>
<th>E (EeV)</th>
<th>$F_{\text{ul}}$ (95% c.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>10</td>
<td>11.7</td>
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GZK from Gelmini et al., 2005
astro-ph/0506128
The Pierre Auger Observatory is a unique tool for studying UHECR with high performance and unprecedented statistics

→ first results on composition favor mixed composition
→ still no UHE photon observation but upper limits on photon fraction
  - favor astrophysical origin of UHECR and constrain alternative models
  - reduce systematics in measurements of CR-induced air showers
    (energy spectrum, p-air cross section, mass composition)
  - provide test of Lorentz Invariance

Extensions at lower energy (HEAT, AMIGA) will improve on the detector performance in a crucial region where the transition between galactic and extragalactic component is expected

The Northern site Auger will provide full sky coverage and increase statistics at the highest energies!

→ towards UHE photon observation: 0.1% fractions will be accessible with Auger South + North
Thanks!
Data selection cuts

▷ Quality cuts:

**hybrid geometry:**
- triggered FD pixels $\geq 6$
- tank-axis distance $< 1.5$ km
- SD-FD time res $< 300$ns

**profile reconstruction:**
- observed $\chi_{\text{max}}$
- $\chi_{\text{GH}}^2 / \text{Ndof} < 6$
- $\chi_{\text{GH}}^2 / \chi_{\text{line}}^2 < 0.9$
- min view angle $> 15^\circ$

▷ Fiducial cuts:

- axis zenith angle $> 35^\circ + g_1(E)$
- core distance $< 24$ km $+ g_2(E)$

▷ Cloud cuts: information from cloud monitoring devices
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric uncertainties</td>
<td>&lt; 6 g cm(^{-2})</td>
</tr>
<tr>
<td>Profile reconstruction</td>
<td>5 g cm(^{-2})</td>
</tr>
<tr>
<td>Geometry reconstruction</td>
<td>5 g cm(^{-2})</td>
</tr>
<tr>
<td>Multiple scattering</td>
<td>&lt; 6 g cm(^{-2})</td>
</tr>
<tr>
<td>FD camera alignment</td>
<td>&lt; 3 g cm(^{-2})</td>
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<tr>
<td>Relative acceptance</td>
<td>(~ 10 g cm(^{-2}))</td>
</tr>
<tr>
<td>Total (X_{\text{max}}) uncertainty</td>
<td>15 g cm(^{-2}) E&lt;(10^{18}) eV</td>
</tr>
<tr>
<td></td>
<td>11 g cm(^{-2}) E&gt;(10^{18}) eV</td>
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<tr>
<td>Energy scale</td>
<td>22%</td>
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