Search for cosmogenic photons with the Pierre Auger Observatory

Mariangela Settimo
LPNHE, Universites Paris VI and Paris VII
The Ultra-High Energy (UHE) range

\[ E_{\text{max}} \text{ at source or propagat. effect (GZK)?} \]

\[ E^2 \phi(E) \left[ \text{GeV}^{1.6} \text{ m}^{-2} \text{s}^{-1} \text{ sr}^{-1} \right] \]

\[ 10^{13} \quad 10^{14} \quad 10^{15} \quad 10^{16} \quad 10^{17} \quad 10^{18} \quad 10^{19} \quad 10^{20} \]

\[ E \quad [\text{eV}] \]

\[ 10^{-1} \quad 1 \quad 10 \quad 10^2 \quad 10^3 \quad 10^4 \]

\[ 10^2 \quad 10^3 \quad 10^4 \]

\[ \text{Grigorov} \quad \text{JACEE} \quad \text{MGU} \quad \text{Tien-Shan} \quad \text{Tibet07} \quad \text{Akeno} \quad \text{CASA-MIA} \quad \text{HEGRA} \quad \text{Fly’s Eye} \quad \text{Kascade} \quad \text{Kascade Grande 2011} \quad \text{AGASA} \quad \text{HiRes 1} \quad \text{HiRes 2} \quad \text{Telescope Array 2011} \quad \text{Auger 2011} \]

\[ \text{Pierre Auger Observatory} \]

\[ \text{LHC 14 TeV} \]

\[ \text{Knee} \quad \text{Ankle} \quad \text{Flux suppression} \]
The Ultra-High Energy (UHE) range

\[ E^{\gamma.4} F(E) \left[ \text{GeV}^{1.6} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

- Grigov
- JACEE
- MGU
- Tien-Shan
- Tibet07
- Akeno
- CASA-MIA
- HEGRA
- Fly’s Eye
- Kascade
- Kascade Grande 2011
- AGASA
- HiRes 1
- HiRes 2
- Telescope Array 2011
- Auger 2011

Pierre Auger Observatory

Flux suppression

\[ E_{\text{max}} @ \text{source or propagat. effect (GZK)} ? \]

Photo-pion production (GZK effect)

Cosmogenic photons and neutrinos

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0 \]

\[ E_{\text{GZK}} \sim 5 \times 10^{19} \text{eV}, \lambda \sim 6 \text{Mpc} \]

Inelasticity: \( \sim 20\% \) (10\% for each \( \gamma \))
Flux predictions for cosmogenic photons

Photon flux predictions sensitive to:
- **source properties** (injection spectrum, maximum energy, primary types, source distrib./evol.)
- **propagation** (electromagnetic cascades in EBL, magnetic fields)

**expected flux:** $\sim 0.1\text{-}1\%$ of the all-particle spectrum above $10^{19}$ eV

Depending on the observations, some astrophysical scenarios can be constrained/disfavored.
The Pierre Auger Observatory: the hybrid design

Based on 2 complementary and independent techniques

Fluorescence Detector (FD)
24 + 3 telescopes in 4 sites
10-15% duty cycle

Real Event, $E = 7 \times 10^{19}$ eV

3000 km$^2$

Argentina

Based on 2 complementary and independent techniques

Hybrid events: observed at the same time by at least 1 fluorescence telescope + 1 SD

Surface Detector array (SD)
1600 + 60 water Cherenkov stations, 100% duty cycle

Mariangela Settimo, “ILP day”, Paris 13 March 2014
Hybrid events ($E > 10^{18}$ eV):
- Deeper development of the air showers (larger $X_{max}$)
- Smaller detected signal in SD and steeper lateral distribution function

SD events ($E > 10^{19}$ eV):
- Deeper shower development and smaller number of muons
  - Larger risetime of the SD signals

Risetime: $t_{1/2} = t_{50\%} - t_{10\%}$
Upper limits on photon flux

<table>
<thead>
<tr>
<th>Energy [eV]</th>
<th>Integral Flux E &gt; E_0 [km^2 sr^-1 yr^-1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>10^-3</td>
</tr>
<tr>
<td>19</td>
<td>10^-2</td>
</tr>
<tr>
<td>20</td>
<td>10^-1</td>
</tr>
</tbody>
</table>

Upper limits 95% C.L.

- A (AGASA), Shinozaki et al., 2002
- Y (Yakutsk), Glushkov et al., 2010
- TA (Telescope Array), ICRC 2013

Gelmini et al., 2008
Ellis et al., 2006

- Most stringent limits available in the EeV range
- Top-down models disfavored
- GZK flux region within reach

Upper limits to the integral photon fraction:

- Hybrid: 0.4%, 0.5%, 1.0%, 2.6% and 8.9% @ E > 1, 2, 3, 5 and 10 EeV
- SD: 2.0%, 5.1%, 31% @ E > 10, 20, 40 EeV
Expected sensitivity in the near future

A new trigger designed (installed in the stations on June 2013):

- select station with small signals, not dominated by the muonic component
- **especially effective for photons**

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**Hy 2023, SD 2023:**
- current analysis
- no additional bkg
- no candidates
- no background

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Data analysis in progress

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prove the existence of the GZK effect and constrain astrophysical scenarios
Outlook

Observation/Non-observation of UHE photons:

- Independent prove of the GZK effect
- Clarify the nature of the observed flux suppression
- Flux of cosmogenic photons sensitive to source properties (primary mass, injection spectra, distribution) and extragalactic environment
  - hints/constraints on astrophysical scenarios for the origin of ultra-high energy cosmic rays
- Disfavor/constrains top-down models
- Open the most extreme window for astronomy
- Impact on the measurements of energy spectrum, cross sections, mass composition and possible consequences for fundamental physics (LIV)

stay tuned!
Thank you
Backup slides
The Ultra-High Energy (UHE) range

Auger 2013 preliminary

$E \left[ \text{eV} \right]$

$10^{18}$

$10^{19}$

$10^{20}$

Flux suppression

Ankle

Proton, $E_{\text{cut}} = 10^{20} \text{ eV}$

Proton, $E_{\text{cut}} = 10^{20.5} \text{ eV}$

Iron, $E_{\text{cut}} = 10^{20} \text{ eV}$

Iron, $E_{\text{cut}} = 10^{20.5} \text{ eV}$

$\Delta E / E = 14\%$

$E_{\text{max}} @ \text{source or propagat. effect (GZK)}$

photo-pion production (GZK effect)

Cosmogenic photons and neutrinos

$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$

$E_{\text{GZK}} \sim 5 \times 10^{19} \text{ eV}, \ \lambda \sim 6 \text{ Mpc}$

Inelasticity: $\sim 20\%$ (10\% for each $\gamma$)
Pre-shower: impact on EAS development (II)

- Faster shower development
- Small shower-to-shower fluctuations
- Competition of LPM and preshower
Shower development for different primaries

Iron
- Proton
- Photon

Light primaries develop deeper than heavy component

Photon induced showers deeper than hadrons (on average)

Vertical showers

E = 100 TeV

A qualitative view
(CORSIKA simulations: [http://www-ik.fzk.de/corsika/](http://www-ik.fzk.de/corsika/))
- **FD:**
  - Deeper development of the air showers

- **SD:**
  - Smaller detected signal at a given distance
  - Fewer triggered stations

\[ S_b = \sum_i S_i \left( \frac{R_i}{1000} \right)^4 \]

\( S_i \): station signal [VEM]
\( R_i \): station distance to the shower axis [m]

Details on \( S_b \): G. Ros et al., arXiv 1104.3399
Search for photons with SD: $E > 10$ EeV

- Events observed by SD-alone
- radius of curvature and risetime $t_{1/2}$ at 1000 m used for photons identification
Search for photons with SD: $E > 10$ EeV

- Events observed by SD-alone
- radius of curvature and risetime $t_{1/2}$ at 1000 m used for photons identification

Deviations of data from the mean value of R and $t_{1/2}$ expected for photon showers combined with a Principal Component Analysis

PCA training on 5% on data
Upper limits on photon flux

**upper limits 95% C.L.**

<table>
<thead>
<tr>
<th>$E_0$ [EeV]</th>
<th>$N_\gamma$</th>
<th>$\phi_{95CL}^{CL}(E_\gamma &gt; E_0)$ [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, $\Delta X_{\text{max}}$, $\Delta S_\theta$, Energy scale, hadronic interaction model and mass composition assumptions)

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

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

Upper limits to the integral photon fraction assuming the **Auger Spectrum**

0.4%, 0.5%, 1.0%, 2.6% and 8.9% @ $E \geq 1$, 2, 3, 5 and 10 EeV