Photon Search @ the Pierre Auger Observatory

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Photon energy goes to an extreme

\[ \gamma_{\text{VHE}} + \gamma_{\text{e}} \rightarrow e^+e^- \]

Figure from J.Knapp
Why do we study ultra high energy photons?

- Pointing back to the UHECR source
  \[ p + p \rightarrow p + p + \pi^0 \]
- Indirect **test of mass composition** and without relying on the hadronic models

\[ \gamma_{2.7K} + ^{56}\text{Fe} \rightarrow ^{55}\text{Fe} + n \]
\[ \gamma_{2.7K} + p \rightarrow \Delta^+ \rightarrow p + \pi^0 \text{ or } n + \pi^+ \]

- Possible **new physics**? (Lorentz invariance violation)

Galaverni, Sigl PRL 2008
Why do we study ultra high energy photons?

• Verify cosmological models (decay of Super Heavy Dark Matter / relic ν interact with UHE ν and create Z - Burst)

• Constrain astrophysical scenarios such as source energy spectrum, extragalactic magnetic field
The Pierre Auger Observatory
-A hybrid detection

- 3000 km² located in Argentina
- 875 g cm⁻² (vertical above sea level)
- 1660 water-Cherenkov detectors
  (~100% duty cycle)
- 4 fluorescence telescope sites (moonless clear nights ~ 13%)
- Calorimetric measurement of the energy

\[ p + p \rightarrow p + p + N(\pi^+ + \pi^- + \pi^0) \]

FD
Fluorescence detector

E_{cal} = \int dE/dX \, dX

SD
Surface detector
Photon induced air shower signature:
* larger $X_{\text{max}}$
* smaller $N_\mu$
Photon signature: FADC time trace in the water-Cherenkov detector

proton and photon simulations

Vertical shower

\[ 30 < S < 40 \text{ VEM}, \quad 650 < r < 700 \text{ m} \]

Inclined shower
‘Traditional’ methods for SD photon searches

Challenges:
- Photons may have $X_{\text{max}}$ below ground
- Problems of thinning etc to get reliable simulations ...

Signal risetime $t_{1/2}$

Radius of curvature $R_c$

Atmospheric depth [gr cm$^{-2}$]

First interaction

Early muons

Late muons: em. particles

$S_b$

$X_1$, $X_R$, $X_{\text{max}}$, $\Delta X$

$\Delta$
A new SD method – the **entity** method

- A parameter based on information from the beginning of the time trace
- **Muons** arrive earlier than the EM component

Vertical, mean component traces, proton simulations

<table>
<thead>
<tr>
<th>Proton MC</th>
<th>983 events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>800-900 m</td>
</tr>
<tr>
<td></td>
<td>20-30 VEM</td>
</tr>
<tr>
<td>$E_{rec} &lt; 10^{18.5}$ eV</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing signal vs. time for different particles](image)
Procedure for calculating the entity parameter

1. Use data to parameterise the mean FADC trace and signal variances.

2. Calculate for the time-trace at a station with $r$, $S$, $\theta$ and polar angle.

3. Calculate mean for $\log(\chi^2 / \text{NDF})$ from data and photon for stations at $r$, $S$, $\theta$ and polar angle.

4. Likelihood ratio

$$LL_{\text{normalised}} = \log \frac{\prod_{i=1}^{n} (P_i, P_2 \ldots)}{\prod_{i=1}^{n} (P_1^\gamma, P_2^\gamma \ldots)} \div n$$
The entity method: photon-hadron separation

0 - 60 degree

\[ E_{\text{rec}}^\gamma > 10^{19} \text{ eV} \]

01/2004 - 08/2012

Preliminary!!!

<table>
<thead>
<tr>
<th>Entries</th>
<th>7150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-2.4 ± 0.027</td>
</tr>
<tr>
<td>RMS</td>
<td>1.6 ± 0.019</td>
</tr>
<tr>
<td>Integral</td>
<td>2.7e+04</td>
</tr>
</tbody>
</table>

Merit Factor \( \sim 2.6 \)

Preliminary!!!

data

photon

Number of Events

Entity Likelihood Ratio

\[ -8 \quad -6 \quad -4 \quad -2 \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \]
Hybrid search (fluorescence telescope + surface detector)

(lateral distribution function)

Monte Carlo Simulations
Energy = $10^{18.5}$ eV

$X_{\text{max}}$  

LDF

ICRC 2011
Directional photon search

- Hybrid data
- Multivariate analysis only select a subset of data that is photon-like
- $10^{17.3} - 10^{18.5}$ eV
- 0.7° angular resolution
- Background estimated using scrambling method.
Directional photon search

- Upper limit on regularly emitting non-beamed photon source in the galaxy: 0.25 eV cm\(^{-2}\) s\(^{-1}\) (spectrum index \(\gamma = -2\))

more from: D. Kuempel et al. ICRC 2013
Conclusions

• The Pierre Auger Observatory is *the* project that is most sensitive to ultra-high energy photons

✓ Previous diffuse photon searches used both FD and SD variables

✓ A new method – the entity method - covers $0 < \theta < 60^\circ$ with high-separation power for photon-hadron discrimination

✓ Photon directional search sets limits on energy flux densities
Back up

**Exposure**

- SD 1500 m: 82318 events
- SD inclined: 11074 events
- Hybrid: 11155 events
- SD 750 m: 29585 events

**Energy calibration**

- $S_{35}$ / 15 VEM - SD 750 m
- $S_{38}$ / 5 VEM - SD 1500 m
- $N_{19}$ - SD inclined

Auger, ICRC 2013
Back up

Directional sensitive
40% for 100EeV photons from the whole sky

Figure from P. Homola
Landau–Pomeranchuk–Migdal (LPM) effect

- reduces cross section for pair production ($\gamma$) and bremsstrahlung (e)
- destructive interference between interactions at multiple nuclei
- relevant at high energy (greater than $10^{18}$ eV) of primary particle
- in simulations mostly implemented through a suppression factor that statistically discards interactions
Super-Heavy Relic Particles  
(John Ellis, Rocky Kolb, Luis Masperi...)  

Cryptons/Wimpzillas/Vortons  
– can explain some of the dark matter  

Super Heavy Relic Particle  
$10^{22}$ eV  

(i) preferential decay to quark--anti-quark pairs rather than quark triplets  

(ii) Can TEST predicted high flux of photons NOW (– neutrinos later)  

Thanks to Chris Wileman
Back up - LIV

Testing Lorentz Invariance Violation (LIV) → photon dissperssion relation modified?

\[ \omega^2 = k^2 + \xi_n k^2 \left( k / M_p \right)^n \rightarrow e^+e^- \text{ production threshold modified} \]

e.g. \( \pi^0 \rightarrow \gamma \gamma \quad \gamma \to e^+e^- \) cascading of photons supressed

If LIV:

\( \xi_1, \xi_2 > 0 \)

Upper limits based on UHECR observations:

\( \xi_1 < 2.4 \times 10^{-15} \)
\( \xi_2 < 2.4 \times 10^{-7} \)
Back up: the risetime delta method from H.Cook (PhD thesis)

Merit factor $\sim 1.7$  
Photon Spectrum is $E^{-2}$

Merit factor $\sim 1.7$
Back up: component traces for proton and photon

\( \theta \sim 0^\circ \)

\( r \sim 850 \text{ m} \)

\( S \sim 25 \text{ VEM} \)

~Only difference is \( \mu \)

\( \theta \sim 60^\circ \)

\( r \sim 550 \text{ m} \)

\( S \sim 70 \text{ VEM} \)
Possible background form leading π0 protons. Nμ and Xmax