Directional search for ultra-high energy photons with the Pierre Auger Observatory

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Abstract: The Pierre Auger Observatory, located in Argentina, provides an unprecedented exposure for detecting photons with energies above $10^{17}$ eV over most of the sky. In this work, the information from the surface array of water Cherenkov detectors and from the fluorescence telescopes of the Observatory, are combined in a multivariate analysis to search for photons in the EeV energy range. The arrival directions of candidate photons in the Auger Observatory are here analyzed for the first time. No photon point source is detected. Upper limits on regularly emitting non-beamed photon sources in the Galaxy do not exceed 0.25 eV cm$^{-2}$ s$^{-1}$ and constrain models for the acceleration in the Galaxy of the EeV protons.

Keywords: Pierre Auger Observatory, ultra-high energy photons, arrival directions

1 Introduction

The composition of ultra-high energy (UHE) cosmic rays at EeV energies (1 EeV = $10^{18}$ eV) is still unknown. A small fraction might be photons produced in galactic or nearby extragalactic sources. The most prominent production mechanism is the decay of neutral pions produced previously by a “primary process” such as resonant photo-pion production. No UHE photon identification has been reported so far. However, by placing upper limits on the photon flux above EeV energies, severe constraints on “top-down” models were imposed by previous diffuse photon searches [1, 2].

In this contribution the search for photons is extended taking into account event arrival directions to search for photon emitting point sources at EeV energies. At these energies, fluxes of photons are attenuated over intergalactic distances by $e^\pm$ pair production in collisions of UHE photons with cosmic background photons. The detectable volume of EeV photon sources is small compared to the GZK sphere [3, 4], but large enough to encompass the Local Group of galaxies and possibly Centaurus A given an attenuation length of about 4.5 Mpc at EeV energies [5].

The Pierre Auger Observatory [6] provides an unprecedented sensitivity to search for EeV photon point sources. It encompasses over 1660 individual surface detectors (SD) arranged as an array on a triangular grid with 1500 m spacing. This 3000 km$^2$ array is overlooked by a fluorescence detector (FD) consisting of 27 fluorescence telescopes located at five sites. The SD samples the density of the secondary particles of the air shower at the ground while the FD observes the longitudinal development of the shower. The analysis presented in this work uses hybrid data (detected by at least one FD telescope and one SD station). The hybrid measurement technique provides a precise geometry and energy determination with a low energy threshold for detection. Taking advantage of the two detector systems, several observables are defined and combined in a multivariate analysis (MVA) using advanced boosting techniques to search for photon point sources and to place directional upper limits on the photon flux.

2 Directional photon search

The strategy for the directional photon search is based on the selection of a subset of photon-like events, using MVA, to increase the detection probability of photon point sources by reducing the isotropic hadronic background. The selection is optimized direction-wise accounting for the expected background contribution from a given target direction. The $p$-value for the observation of the selected subset is calculated and illustrated in a celestial sky map. Furthermore, directional upper limits on the photon flux are derived.

2.1 Multivariate Analysis

The following observables are taken into account in a MVA:

- Depth of shower maximum $X_{\text{max}}$: It is defined as the atmospheric depth at which the longitudinal development of a shower reaches its maximum in terms of energy deposit. On average, photon induced air showers develop later in the atmosphere compared to hadron induced air showers resulting in larger $X_{\text{max}}$ values.

- Fit of Greisen function to the longitudinal profile: The Greisen function [11] describes the longitudinal profile of pure electromagnetic showers: a better fit to the longitudinal profile is expected for photon initiated showers if compared to hadron ones of the same energy. The $\chi^2$/ndof is used to quantify the goodness of the fit.

- Greisen energy: The only parameter of the Greisen function is the primary energy $E_{p\gamma}$ which is also influenced by the primary particle. The observable is $E_{p\gamma}/E_{\text{FD}}$, where $E_{\text{FD}}$ is the energy obtained from the fit of a Gaisser-Hillas function [12] to the longitudinal profile.

- $S_3$ parameter: This parameter $S_3$ is sensitive to different lateral distribution functions, due to the presence/absence of the flatter muon component [13]. It is defined as

$$S_3 = \sum_{i=1}^{N} \left[ S_i \cdot \left( \frac{r_i}{1000 \text{ m}} \right)^3 \right],$$

where the sum extends over all $N$ triggered stations, $S_i$ expresses the signal strength of the $i$-th SD station, and $r_i$ the distance of this station to the shower axis.
Shape parameter: The spread of the arrival times of shower particles at a fixed distance from the axis increases for smaller production heights. Consequently, a larger spread is expected in case of deep developing photon primaries compared to hadronic primaries. The shape parameter is the ratio of the early arriving to the late arriving integrated time trace measured in the water Cherenkov tank with the strongest signal

\[ \text{ShapeP}(r, \theta) = \frac{S_{\text{early}}(r, \theta)}{S_{\text{late}}(r, \theta)}. \]  

(2)

The early signal \( S_{\text{early}} \) is defined to be signal integrated over time bins smaller than a scaled time \( t_{\text{scaled}} \leq 0.6 \) \( \mu \)s beginning from the signal start slot. The scaled time accounts for different inclination angles \( \theta \) and distances to the shower axis as

\[ t_{i}^{\text{scaled}}(r, \theta) = t_{i} \cdot \frac{r_{0}}{r} \cdot \frac{1}{c_{1} + c_{2} \cdot \cos(\theta)}, \]  

(3)

where \( t_{i} \) is the real time of bin \( i \) and \( r_{0} = 1000 \) m a reference distance. \( c_{1} = -0.6 \) and \( c_{2} = 1.9 \) are scaling parameters to average traces for different inclination angles. Correspondingly, the late signal \( S_{\text{late}} \) is the integrated signal over time bins larger than \( t_{i}^{\text{scaled}} > 0.6 \) \( \mu \)s until signal end.

In a MVA the introduced input observables are combined using boosted decision trees (BDT) as classifier [8, 9]. Since the observables correlate with energy and zenith angle of the primary particle, BDT need to take this correlation into account during the training process. Therefore energy and zenith angle are added to the classification algorithm as additional input observables.

For the classification process boosted decision trees are trained and tested using CORSIKA \( v. \) 6.900 simulations. A total number of \( \sim 30000 \) photon and \( \sim 60000 \) proton primaries are generated according to a power law spectrum of \( -2.7 \) between \( 10^{17.2} \) eV and \( 10^{18.5} \) eV using QGSJET-01c [14] and GHEISHA as high and low energy interaction model, respectively. During the classification phase photon and proton showers are reweighted according to a spectral index of -2.0 and -3.0, respectively. The MVA output response value is named \( \beta \) and shown in Fig. 1.

2.2 Dataset

Hybrid events collected between January 2005 and September 2011 with reconstructed energy between \( 10^{17.3} \) eV and \( 10^{18.5} \) eV are selected. The energy refers to the calorimetric energy of the shower including 1% missing energy correction for photons. Air showers with zenith angle smaller than 60° and with a good geometry reconstruction are selected for the analysis. To ensure a reliable profile reconstruction we require: a reduced \( \chi^{2} \) of the longitudinal profile fit to the Gaisser-Hillas function smaller than 2.5, the Cherenkov light contamination smaller than 50% and uncertainty of the reconstructed energy less than 40%. To reject misreconstructed profiles, only periods with a detected cloud coverage \( \leq 80\% \) and with a reliable measurement of the vertical optical depth of aerosols [18] are selected. On the SD side we require at least 4 active stations within 2 km from the hybrid reconstructed axis and reject stations with saturated low gain signal. Additionally periods of unstable data taking from the fluorescence detector and surface array have been omitted from the analysis. The final dataset consists of \( N_{\text{data}} = 241466 \) events.

The treatment of arrival directions is based on an un-binned analysis. Assuming that the arrival directions of a point source are smeared out by a two-dimensional symmetric point spread function, \( n_{\text{inc}} = 90\% \) of the expected signal from a point source is contained in a top-hat counting region of radius \( r_{\text{TH}} = 1' \), given an angular resolution of the covered energy range of \( \psi = 0.7' \). Sky maps are pixelized using the HEALPix software [15]. Target centers are taken as the central points of a HEALPix grid using \( N_{\text{side}} = 256 \) (target separation \( \sim 0.3' \)) resulting in 526200 target centers below a declination of 20°. We limit the analysis to declinations larger than \( -85° \) for reasons explained in Sec. 4.

3 Search method

To select photon-like air showers an optimized cut on the \( \beta \)-distribution is performed. The fraction of photon and measured events, \( \epsilon_{\beta}^{0} \) and \( \epsilon_{\beta}^{\text{data}} \), passing a specific cut on the \( \beta \)-distribution is illustrated in Fig. 2. To estimate \( \epsilon_{\beta}^{\text{data}} \) more accurately, a declination dependence is taken into account

\[ \epsilon_{\beta}^{\text{data}} = \epsilon_{\beta}^{0} \cdot \delta, \]  

where \( \delta \) is given by

\[ P(\leq n_{\text{data}} | n_{\beta}^{p} + n_{\beta}^{\text{target}}) = a_{\text{CL}} \cdot P(\leq n_{\text{data}} | n_{\beta}^{p}) , \]  

(4)

1. Note that the effect is superimposed also by geometrical effects in the relation between spread and primary composition. Also the competition between the signals from electromagnetic and muonic shower components contributes to this effect.

2. The selected energy range accounts for high statistics and negligible impact of high energy phenomena such as LPM or preshower effects.
with $\alpha_{\gamma} \equiv 1 - \text{CL}$ and the expected background contribution $n_{b}^{E}$ (cf. [20]). Since $n_{b}^{E}$ (and hence $n_{\text{data}}$) is not an integer in general, a continuous function of the Poisson expectation is used. The lowest upper limit $n_{\text{zech}}^{\text{UL}}$ is determined by minimizing

$$n_{\text{zech}}^{\text{UL}} = \min \left( \frac{n_{i}(\beta)}{e_{\gamma}^{\beta}} \right). \quad (5)$$

The directional photon flux upper limit from a point source is the limit on the number of photons from a given direction divided by the directional acceptance (cf. Sec. [3]) from the same target at a confidence level of CL = 95%. The upper limit on the number of photons is calculated using Eqn. (4) and given by

$$f^{UL} = \frac{n_{\text{zech}}^{\text{UL}}}{n_{\text{inc}} \cdot \varepsilon}, \quad (6)$$

where $n_{\text{inc}} = 0.9$ is the expected signal fraction in a top-hat search region and $\varepsilon$ the photon exposure (cf. Sec. [3]).

When performing a blind search for photon point sources the probability $p$ of obtaining a test statistic at least as extreme as the one that was actually observed is calculated, assuming that the hypothesis of an isotropic distribution is true. The test statistic is obtained from the ensemble of scrambled datasets (cf. Sec. [3]) assuming a Poisson distributed background. This $p$-value is calculated for a specific target direction as

$$p = 1 - \left( \sum_{i=0}^{n_{\text{data}}-1} \text{Poisson}(i, n_{b}) \right), \quad (7)$$

where Poisson$(i, n_{b})$ is the Poisson probability to observe $i$ events expecting a background count of $n_{b}$. The chance probability $p_{\text{chance}}$ to observe that $p_{\text{min}}$ anywhere in the sky is given by

$$p_{\text{chance}}(p_{\text{min}} \leq p_{\text{min}}) = \varepsilon_{\text{zech}}^{\beta} \cdot \varepsilon_{\text{prof}}^{\beta}, \quad (8)$$

where $p_{\text{zech}}^{\min}$ is the minimum $p$-value of a simulated scrambled dataset.

**Figure 2:** Fraction of events passing $\beta_{\text{cut}}$ for primary photons (black) and measured averaged hybrid data (red). The shaded area represents the expectation of a purely hadronic composition derived from MC simulations.

**Figure 3:** Integral distribution of $p$-values. For better visibility $-\log(p)$ is shown. The observed distribution is shown as black line, the mean expected as red line. The blue shaded region corresponds to 95% containment of simulated data sets.

### 4 Background expectation and photon acceptance

The contribution of an isotropic background is obtained using the scrambling technique [18]. In a first step the arrival directions (in local coordinates) of the events are smeared out randomly according to their individual reconstruction uncertainty. In a second step $N_{\text{data}}$ events are formed by choosing randomly a local coordinate and, independently, a Coordinated Universal Time (UTC) from the pool of measured directions and times. This procedure is repeated 5000 times. The mean number of arrival directions within a target is then the expected number for that particular sky location. The expected number of events after cutting in the $\beta$ distribution can be calculated as $n_{b}^{E} = n_{b} \cdot e_{\text{data}}^{\beta}(\delta)$. As each telescope bay has different azimuthal trigger probabilities events are binned telescope-wise before scrambling the data. Since the described scrambling technique is less effective to the southern galactic pole region declinations $\delta > -85^\circ$ are omitted from the analysis.

To derive an upper limit on the photon flux an estimate of the exposure of the detector to photon primaries is needed. The exposure for the hybrid detector is not constant with energy and is not uniform in right ascension. Thus, detailed simulations have been performed to take into account the status of the detector and the dependence of its performances with energy and direction (both zenith and azimuth). For the exposure calculation applied here, time dependent simulations have been performed, following the approach described in [17]. The total exposure can be derived as:

$$\varepsilon = \varepsilon_{\text{prof}} \cdot \varepsilon_{\gamma}^{\beta}, \quad (9)$$

where $\varepsilon_{\text{prof}}$ indicates the exposure at profile reconstruction level, i.e. before applying a multivariate cut, and $\varepsilon_{\gamma}^{\beta}$ the photon efficiency applying a $\beta_{\text{cut}}$.

3. At the pole, the estimated background would always be similar to the observed signal. Therefore a possible excess or deficit of cosmic rays from the pole would always be masked.
5 Results and discussion

The integral distribution of \(-\log(p)\) values is shown in Fig. 3. The corresponding sky map of \(-\log(p)\) values is illustrated in Fig. 4. The minimum p-value observed is \(p_{\text{min}} = 4.5 \times 10^{-6}\) corresponding to a chance probability that \(p_{\text{min}}\) is observed anywhere in the sky of \(p_{\text{chance}} = 36\%\).

Directional photon flux upper limits of point sources (95\% confidence level) are derived using Eqn. (6) and shown as a celestial map in Fig. 3. The mean value is 0.035 photons km\(^{-2}\) yr\(^{-1}\) with a maximum of 0.14 photons km\(^{-2}\) yr\(^{-1}\) corresponding to an energy flux of 0.06 eV cm\(^{-2}\) s\(^{-1}\) and 0.25 eV cm\(^{-2}\) s\(^{-1}\) respectively, assuming an E\(^{-2}\) energy spectrum. The energy flux in TeV gamma rays exceeds 1 eV cm\(^{-2}\) s\(^{-1}\) for some galactic sources with a differential spectral index of E\(^{-\gamma}\) [21, 22]. Suppose those gamma rays arise from the decay of \(\pi^0\) mesons produced by interactions of protons accelerated at the source. A source with a differential spectral index of E\(^{-\gamma}\) puts equal energy in each decade, resulting in an expected energy flux of 1 eV cm\(^{-2}\) s\(^{-1}\) in the EeV decade. No energy flux that strong in EeV gamma rays is observed from any TeV source in the field of view or from any other target direction. These limits on regularly emitting non-beamed photon sources in the Galaxy constrain models for the acceleration in the Galaxy of the EeV protons that are measured [23].

Various sources of systematic uncertainties have been investigated and the impact on the mean flux upper limit is estimated. A change of the photon flux spectral index by +0.5 and −0.5 changes the limit by about −34\% and +51\%, respectively. Simulation uncertainties of the fraction of photon (\(\epsilon_p^\beta\)) and measured events (\(\epsilon_{\text{data}}^\beta\)) passing a \(\beta_{\text{cut}}\) including a possible directional dependence contribute less than 6\%. A systematic uncertainty of the Auger energy scale of +20\% and −20\% changes the upper limit by about +11\% and −14\%, respectively. The size of the top-hat counting region and, correspondingly, the impact of a changing angular resolution results in a +9\% change for a top-hat radius of 0.74\° (67\% containment) and a +11\% change for a top-hat radius of 1.5\° (99.5\% containment). Studying the impact of different hadronic interaction models in the MVA introduces a change of 9\% for the mean upper limit of the photon flux.

References