Ultra-high energy photon studies with the Pierre Auger Observatory

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Abstract. While the most likely candidates for cosmic rays above $10^{18}$ eV are protons and nuclei, many of the scenarios of cosmic ray origin predict in addition a photon component. Detection of this component is not only of importance for cosmic-ray physics but would also open a new research window with impact on astrophysics, cosmology, particle and fundamental physics. The Pierre Auger Observatory can be used for photon searches of unprecedented sensitivity. At this conference, the status of this search will be reported. In particular the first experimental limits at EeV energies will be presented.

Keywords: UHE photons, upper limits, Auger

I. INTRODUCTION

The composition of ultra-high energy cosmic rays (UHECR), i.e. those above $10^{18}$ eV, is still unknown. The Pierre Auger Observatory [1], the newly completed giant air shower detector, with its unprecedented event statistics, brings us closer than ever to resolving this issue. One of the theoretical candidates for UHECR are photons. The first photon searches based on Auger data resulted in upper limits on photon fractions and fluxes [2], [3]. So far, no primary CR photons were identified, the most significant upper limit on the photon fraction is 2% for photons of energies above 10 EeV, based on the data collected by the surface array of particle counters of the Pierre Auger Observatory. This limit severely constrains the family of 'top-down' models [4] which predict large photon contributions (up to 50%) to the observed CR flux. A smaller contribution with typical values around $\sim 0.1\%$ is expected in 'bottom-up' models. Here, so-called 'GZK-photons' originate during the propagation of charged particles by photopion production with background radiation.

Until now, all UHE photon limits were placed at energies larger than 10 EeV. In this work the first limits for photons of energies down to 2 EeV are presented, based on the data collected by the Pierre Auger Observatory.

II. DATA SET AND SELECTION CUTS

The Pierre Auger Observatory collects data with two independent techniques: a surface array of water Cherenkov detectors (Surface Detector - SD) and a network of fluorescence telescopes (Fluorescence Detector - FD). The analysis presented in this work concerns the hybrid data (i.e. events recorded by both detectors) collected between December 2004 and December 2007. The hybrid data statistics are reduced comparing to the pure SD data because of the limited FD duty cycle (~13% of the total time). On the other hand, the advantage of the hybrid technique is the direct observation of the longitudinal shower profile, reaching also to lower energies.

The requirements for the hybrid event selection include a good quality of shower longitudinal profiles (e.g. enough FD phototubes triggered, good quality of the profile fit, small contamination of direct Cherenkov light) and the shower maximum $X_{\text{max}}$ within the FD field of view (see Ref. [5] and references therein). It has been proven before [2] that $X_{\text{max}}$ is a powerful discriminating variable for photon searches (photon-induced showers in general reach their maxima deeper in the atmosphere than showers initiated by nuclei) and we make use of this fact here.

To avoid biases introduced by the above requirements a set of energy dependent fiducial volume cuts was introduced: nearly vertical showers and those landing too far from the detector were rejected from the analysis. Technical details and a complete list of the data selection cuts with explanations can be found in Ref. [5].

After applying the selection criteria the acceptances for photon and nuclear primaries are similar in the energy region of interest. This is shown in Fig. 1. The presented shower simulations were performed with CORSIKA [6] using QGSJET01 [7] and FLUKA [8] interaction models and processed through a complete...
detector simulation and reconstruction chain [9]. The
application of all the cuts resulted in a data sample of
\( n_{\text{total}}(E_{\text{thr}}) = 2063, 1021, 436 \) and 131 events
above the predefined energy thresholds: \( E_{\text{thr}} = 2, 3, 5 \)
and 10 EeV respectively. To account for the efficiency
dependence on the primary energy, fiducial volume
cut correction factors \( \epsilon_{\text{fvc}}(E_{\text{thr}}) = 0.72, 0.77, 0.77 \)
and 0.77 were introduced for \( E_{\text{thr}} = 2, 3, 5 \) and 10
EeV respectively. These corrections are conservative and
independent of the assumptions on the actual primary
fluxes (see Ref. [5] for details).

The presence of clouds during shower detection could
change the efficiencies shown in Fig. 1. In particular, the
reconstructed values of \( X_{\text{max}} \) could be affected in case
the measured longitudinal profile is partially obscured
by clouds. In consequence, the primary particle could
be misidentified. Thus, events are qualified as photon
candidates only when IR cloud cameras could verify the
absence of clouds. The fraction of events passing this
cloud cut was determined by individual inspection of
subsets of the data sample to be \( \epsilon_{\text{clc}} = 0.51 \).

III. THE PHOTON UPPER LIMITS AT EEV

To calculate the photon limit, the number of photon
candidates \( n_{\gamma} \) has to be specified for all the considered
values of \( E_{\text{thr}} \). This is done by constructing the photon
candidate cut as the median of the \( X_{\text{max}} \) distribution
for photons. The relevant efficiency correction is then
\( \epsilon_{\text{pcc}} = 0.5 \). The values of the median were extracted with
dedicated simulations performed for primary photons
with geometry and energy corresponding to all the
potential photon candidates. A parametrization for the
typical median photon depth of shower maximum is
shown as a solid line in Fig. 2, where the \( X_{\text{max}} \) values are
plotted versus the reconstructed event energy above
the lowest considered threshold (2 EeV) for all the events
with \( X_{\text{max}} \geq 800 \text{ g cm}^{-2} \) after executing all the cuts
discussed before. Statistical uncertainties are typically
a few percent in energy and \( \sim 15-30 \text{ g cm}^{-2} \) in \( X_{\text{max}} \)
while systematic uncertainties are \( \sim 22\% \) in energy and
\( \sim 11 \text{ g cm}^{-2} \) in \( X_{\text{max}} \). The photon candidates are located
above the pcc line in Fig. 2: \( n_{\gamma_{\text{cand}}} = 8, 1, 0, 0 \) for the
considered threshold energies \( E_{\text{thr}} = 2, 3, 5 \) and 10
EeV respectively. It has been checked that the observed
number of photon candidates is within the expectations
in case of nuclear primaries only. In Fig. 2 the 5% tail of
the proton \( X_{\text{max}} \) distribution is shown. We therefore
conclude that the observed photon candidate events may
well be due to nuclear primaries only.

With the candidate number and the efficiency corrections
defined above, the 95% c.i. upper limit for photon
fraction can be calculated as
\[
F_{\gamma}^{95}(E_{\text{thr}}) = \frac{n_{\gamma_{\text{cand}}}(E_{\text{thr}})}{n_{\text{total}}(E_{\text{thr}})} \frac{1}{\epsilon_{\text{fvc}} \epsilon_{\text{pcc}}} \frac{1}{\epsilon_{\text{clc}}} \tag{1}
\]
where \( n_{\gamma_{\text{cand}}}(E_{\text{thr}}) \) is the 95% c.i. upper limit on
the number of photon candidates. \( n_{\gamma_{\text{cand}}}(E_{\text{thr}}) \) was
calculated using the Poisson distribution and conserva-
tively assuming no background of nuclear primaries. The
resultant 95% c.i. upper limits on the photon fractions are
3.8%, 2.4%, 3.5% and 11.7% for the primary energies
above 2, 3, 5 and 10 EeV respectively.

The robustness of these results was checked against
different sources of uncertainties. The variation of the
selection criteria within the experimental resolution essen-
tially does not affect the results. The effective total
uncertainty in \( X_{\text{max}} \) for this analysis amounts to
\( \sim 16 \text{ g cm}^{-2} \) (see Ref. [5] for details). Increasing (re-
ducing) all the reconstructed \( X_{\text{max}} \) values by 16 \text{ g cm}^{-2}
increases (reduces) the number of photon candidates
only for the two lowest energy thresholds: 2 and 3 EeV.
The corresponding variations of the photon upper limits
are: \( F_{\gamma}^{95}(E_{\text{thr}} = 2 \text{ EeV}) = 4.8\% \) (3.8% – no variation)
and \( F_{\gamma}^{95}(E_{\text{thr}} = 3 \text{ EeV}) = 3.1\% \) (1.5%).

IV. DISCUSSION

The current upper limits on photon fractions compared
to theoretical predictions are plotted in Fig. 3. The Auger
hybrid photon upper limits above 2, 3, and 5 EeV
placed with this analysis are the first photon upper
limits below 10 EeV. The limit above 10 EeV is an
update of the previous Auger hybrid limit published in
Ref. [2]. The predictions of 'top-down' models were
tested here in a new energy range and the constraints
from the Auger SD limits were confirmed by data taken
with the fluorescence technique. It should be noted that
the presented limits together with the one published in
Ref. [2] are the only ones based on fluorescence data. It
is also worth mentioning that the previous 10 EeV SD
The northern site of the Observatory will bring another opportunity related to the UHE photon search. Thanks to the difference between the local geomagnetic fields at the two sites a possible detection of UHE photons at Auger South may be confirmed in an unambiguous way at Auger North by observing the well predictable change in the signal from geomagnetic cascading of UHE photon showers [11].

The photon upper limits placed by the Auger Collaboration also address fundamental physics questions. The GZK photons are expected to be absorbed on scales of a few Mpc by pair production with background photons if Lorentz symmetry holds. On the other hand, violation of Lorentz invariance could lead to the observation of an increased photon flux. The new constraints placed on the violation of Lorentz invariance based on our photon limits are substantially more stringent than previous ones [12]. A future detection of UHE photons will further impact fundamental physics and other branches of physics (see e.g. [13]).

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