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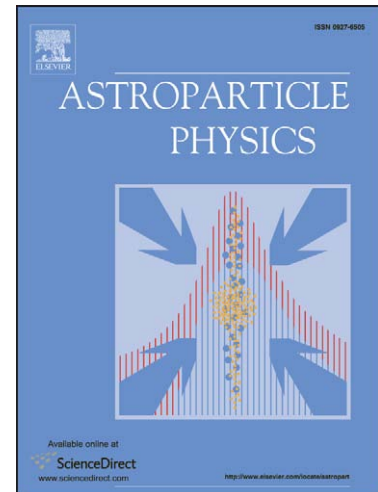
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# Upper limit on the cosmic-ray photon fraction at EeV energies from the Pierre Auger Observatory

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## Abstract

From direct observations of the longitudinal development of ultra-high energy air showers performed with the Pierre Auger Observatory, upper limits of 3.8%, 2.4%, 3.5% and 11.7% (at 95% c.l.) are obtained on the fraction of cosmic-ray photons above 2, 3, 5 and 10 EeV (1 EeV  $\equiv 10^{18}$  eV) respectively. These are the first experimental limits on ultra-high energy photons at energies below 10 EeV. The results complement previous constraints on top-down models from array data and they reduce systematic uncertainties in the interpretation of shower data in terms of primary flux, nuclear composition and proton-air cross-section.

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## 1 Introduction

Data taken at the Pierre Auger Observatory were searched previously for ultra-high energy (UHE) photons above 10 EeV [1,2]. In Ref. [1], the depth of shower maximum  $X_{\max}$  of air showers observed by fluorescence telescopes in hybrid mode (i.e. with additional timing information from the ground array) was used to place an upper limit of 16% on the photon fraction above 10 EeV, confirming and improving on previous limits from ground arrays [3–6]. In Ref. [2], the larger number of events taken with the Auger ground array alone allowed us to place a limit of 2% above 10 EeV, which imposes severe constraints on “top-down” models for the origin of ultra-high energy cosmic rays.

Observations in hybrid mode are also possible at energies below 10 EeV. Decreasing the energy threshold increases the event statistics, which to some extent balances the factor  $\sim 10$  smaller duty cycle compared to observations with the ground array alone. Thus, based on the previous work, the search for photons is now extended to lower energy (here down to 2 EeV). We also improve on our previous (statistics-limited) bound above 10 EeV from Ref. [1].

17 Photons at EeV energies are expected to be produced in our cosmological  
18 neighborhood, as the energy attenuation length of such photons is only of  
19 the order of a few Mpc. Possible sources of EeV photons are the standard  
20 GZK process (see e.g. Refs. [7–9]), the production by nuclei in regions of  
21 intense star light (e.g. in the galactic center [10]), or exotic scenarios such  
22 as top-down models (see Ref. [11] for a review). Compared to our previous  
23 constraints on top-down models from Ref. [2], the bounds derived in this work  
24 provide a test of model predictions in a different energy range and using a  
25 different experimental technique, thus giving an independent confirmation of  
26 the model constraints.

27 Limits on EeV photons reduce corresponding systematic uncertainties in other  
28 analyses of air shower data. For instance, the presence of a substantial photon  
29 component can severely affect the reconstruction of the energy spectrum [12],  
30 the derivation of the proton-air cross-section [13,14], and the interpretation of  
31 the observed average  $X_{\max}$  [15] in terms of a nuclear primary composition.

32 The structure of the paper is as follows. In Section 2 the analysis is described  
33 and applied to the data. The results are discussed in Section 3.

## 34 2 Data and Analysis

35 The present analysis follows closely the one described in detail in Ref. [1]  
36 which is called *Hybrid-1* below. The basic idea is to compare the measured  
37  $X_{\max}$  values to those expected for primary photons, because UHE photon  
38 showers have significantly deeper average  $X_{\max}$ . We provide a summary of  
39 the analysis method, paying special attention to differences or changes in the  
40 approach compared to *Hybrid-1*.

41 The data used here were taken with a total of 18 fluorescence telescopes lo-  
42 cated at three sites (“Los Leones”, “Los Morados” and “Coihueco”) between 1  
43 December 2004 and 31 December 2007. The number of ground stations grew  
44 in this period from about 530 to 1450. Compared to *Hybrid-1* the data set  
45 above 10 EeV increased in size by a factor  $\sim 2.2$ .

46 The event reconstruction [16] is based on an end-to-end calibration of the  
47 fluorescence telescopes [17], monthly models for the atmosphere [18], and an  
48 average aerosol model based on local atmospheric measurements [19]. The  
49 reconstruction of the longitudinal profile is described in [20]. A correction  
50 of  $\sim 1\%$  for the missing energy (energy carried by neutrinos or high-energy  
51 muons) is applied to the reconstructed calorimetric energy, corresponding to  
52 the effective energy of primary photons [21].

53 The following quality cuts are applied to the collected events:

- 54 • number of phototubes in the fluorescence telescope triggered by the shower  
55  $\geq 6$ ;
- 56 • distance of closest approach of the reconstructed shower axis to the surface  
57 detector station with the largest signal is  $< 1.5$  km, and difference between  
58 the reconstructed shower front arrival time at this station and the measured  
59 tank time is  $< 300$  ns;
- 60 • normalized  $\chi_{\text{prof}}^2$  of the longitudinal shower profile fit [20]  $< 6$ , and ratio of  
61  $\chi_{\text{prof}}^2$  to  $\chi_{\text{line}}^2 < 0.9$ , where  $\chi_{\text{line}}^2$  refers to a straight line fit (the latter cut  
62 essentially rejects profiles with too few data points);
- 63 • depth of shower maximum  $X_{\text{max}}$  observed in the telescope field of view (this  
64 cut may be relaxed in future to allow also the search for deeply penetrating  
65 events with  $X_{\text{max}}$  beyond the field of view);
- 66 • minimum angle between the viewing direction of a triggered pixel and the  
67 shower axis  $> 15^\circ$  (to reject events with a large Cherenkov light contamina-  
68 tion);
- 69 • primary energy  $E > f \cdot \text{EeV}$ ,  $f = 2, 3, 5, 10$  (the analysis in *Hybrid-1* was  
70 restricted to  $f = 10$ ).

71 The criterion of  $X_{\text{max}}$  being observed can introduce a bias against the deeply  
72 penetrating photon primaries (e.g. for near-vertical events). To reduce the  
73 dependence of the detector acceptance on composition, fiducial volume cuts  
74 are applied:

- shower zenith angle  $> 35^\circ + g_1(E)$

$$g_1(E) = \begin{cases} 10^\circ (\lg E/\text{eV} - 19.0) & \text{for } \lg E/\text{eV} \leq 19.7, \\ 7^\circ & \text{for } \lg E/\text{eV} > 19.7; \end{cases}$$

- distance of telescope to shower core  $< 24$  km  $+ g_2(E)$

$$g_2(E) = \begin{cases} 12 (\lg E/\text{eV} - 19.0) \text{ km} & \text{for } \lg E/\text{eV} \geq 19.0, \\ 6 (\lg E/\text{eV} - 19.0) \text{ km} & \text{for } \lg E/\text{eV} < 19.0. \end{cases}$$

75 The described cuts are identical to those from *Hybrid-1* for showers  $> 10$  EeV,  
76 but allow now for an extension of the energy range down to 2 EeV.

77 To evaluate the detector acceptance as a function of energy for different pri-  
78 mary particles, simulations have been performed using CORSIKA [22] with  
79 QGSJET01 [23] and FLUKA [24] as high- and low-energy hadronic interaction  
80 models respectively. The Monte Carlo showers have been processed through  
81 a complete detector simulation and reconstruction chain [16,25]. In Fig. 1 we  
82 show the energy-dependent relative exposure obtained after trigger, quality  
83 cuts, and fiducial volume cuts for primary photons, protons and iron nuclei

84 (normalized to 10 EeV protons). After fiducial volume cuts, the acceptance  
 85 for photons is close to the acceptance for nuclear primaries. Thus, the rel-  
 86 ative abundances of photon and nuclear primaries are preserved to a good  
 87 approximation. In a similar way to *Hybrid-1*, we apply, for the derivation of  
 88 an upper limit on the photon fraction, an efficiency correction according to the  
 89 acceptances after fiducial volume cuts which is conservative and independent  
 90 of assumptions about the actual primary fluxes (factor “ $\epsilon_{\text{fvc}}$ ”, see Appendix).

91 Applying the selection cuts to the data, there remain  $n'_{\text{total}}(E_{\text{thr}}^\gamma) = 2063, 1021,$   
 92  $436$  and  $131$  events with energies greater than  $E_{\text{thr}}^\gamma = 2, 3, 5$  and  $10$  EeV re-  
 93 spectively. The label  $\gamma$  in  $E_{\text{thr}}^\gamma$  indicates that the missing energy correction  
 94 for photons has been applied. To obtain  $n_{\text{total}}(E_{\text{thr}}^\gamma)$  from the total number  
 95 of events  $n'_{\text{total}}(E_{\text{thr}}^\gamma)$  after fiducial volume cuts, those events need to be re-  
 96 jected where clouds may have disturbed the observation. The presence of  
 97 clouds could change the efficiencies which are shown in Fig. 1. Also, the recon-  
 98 structed  $X_{\text{max}}$  values may be affected. Particularly, clouds may obscure early  
 99 parts of the shower profile such that the remaining event profile looks deeply  
 100 penetrating and, hence, photon-like. Therefore we only use data where any  
 101 disturbance by clouds can be excluded using information from the IR cloud  
 102 monitoring cameras [26,27]. In *Hybrid-1* all events were individually checked.  
 103 As this is hardly feasible for the events in the present data set (a full automatic  
 104 processing of cloud data is in preparation), the following approach is adopted.  
 105 To determine the efficiency  $\epsilon_{\text{clc}}$  of passing the *cloud cut* we used the sample of  
 106 events with energy above 10 EeV. Accepting only events where any disturbance  
 107 by clouds could be excluded, 67 events out of 131 have been selected, corre-  
 108 sponding to  $\epsilon_{\text{clc}} \simeq 0.51$ . We confirmed that this efficiency also holds at lower  
 109 energy by applying the same criteria to a sub-set of  $\sim 300$  events at  $\sim 3$  EeV.  
 110 The final number of  $n_{\text{total}}(E_{\text{thr}}^\gamma)$  is then given by  $n_{\text{total}}(E_{\text{thr}}^\gamma) = \epsilon_{\text{clc}} \cdot n'_{\text{total}}(E_{\text{thr}}^\gamma)$ .

111 As the present data set above 2 EeV is about a factor  $\sim 15$  larger than the  
 112 one used in *Hybrid-1*, a different statistical method is applied to derive the  
 113 photon limit. For the derivation of the limit in *Hybrid-1*, each selected event  
 114 was individually compared with high-statistics photon simulation, using the  
 115 respective primary energy and direction as simulation input. This method is  
 116 CPU demanding, and tailor-made for a relatively small number of events. We  
 117 therefore adopt for our analysis the method applied in Ref. [2] which needs as  
 118 an input the total number of events, the number of photon candidates (events  
 119 having “photon-like” characteristics, see below) and proper correction factors  
 120 accounting for inefficiencies. The 95% c.l. upper limit  $F_\gamma^{95}(E_{\text{thr}})$  on the fraction  
 121 of photons in the cosmic-ray flux above  $E_{\text{thr}}$  is then given by

$$F_\gamma^{95}(E_{\text{thr}}) = \frac{n_{\gamma\text{-cand}}^{95}(E_{\text{thr}}^\gamma)}{n_{\text{total}}(E_{\text{thr}}^\gamma)}, \quad (1)$$

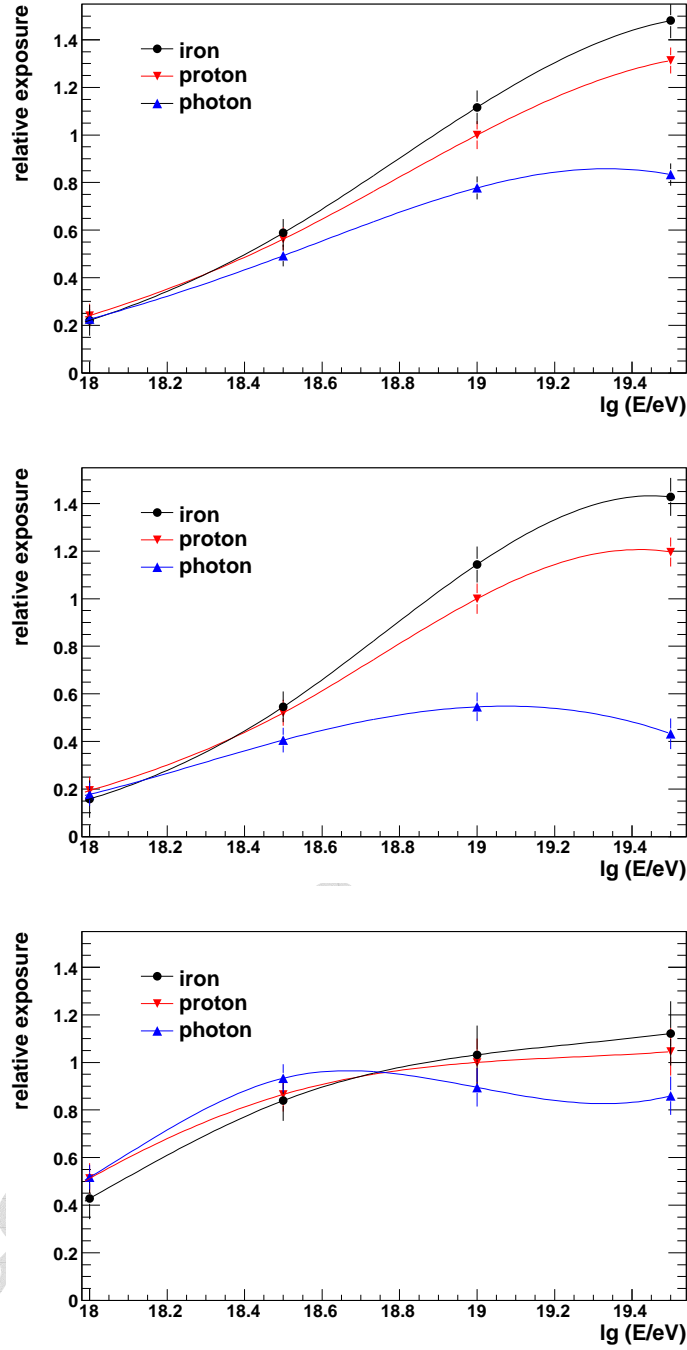


Fig. 1. Relative exposure to primary photons, protons and iron nuclei, normalized to protons at 10 EeV. Top panel requiring hybrid trigger, center panel after applying quality cuts, bottom panel after applying fiducial volume cuts (see text). In order to guide the eye polynomial fits are superimposed to the obtained values.

122 where  $n_{\gamma\text{-cand}}^{95}$  is the 95% c.l. upper limit on the number of photon candidates  
 123 and  $n_{\text{total}}$  the total number of selected events. As it is not known in advance  
 124 whether photons indeed compose only a negligible fraction of the cosmic-ray



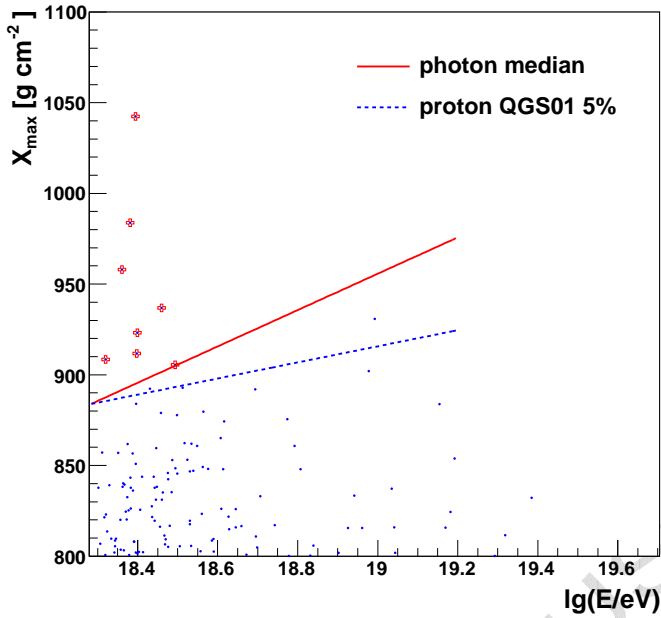


Fig. 2. Closeup of the scatter plot of  $X_{\max}$  vs. energy for all events (blue dots) with  $X_{\max}$  above  $800 \text{ g cm}^{-2}$  and energy above  $2 \text{ EeV}$ , after quality, fiducial volume and cloud cuts. Red crosses show the 8 photon candidate events (see text). The solid red line indicates the typical median depth of shower maximum for primary photons, parameterized as  $X_{\max}^{\gamma, \text{med}} = a \cdot y + b$ , for  $y = \lg(E/\text{EeV})$ ,  $y = [0, 1.2]$ , where  $a = 100 \text{ g cm}^{-2}$  and  $b = 856 \text{ g cm}^{-2}$ . The dashed blue line results from simulations of primary protons using QGSJET 01. A fraction of 5% of the simulated proton showers had  $X_{\max}$  values larger than indicated by the line.

flux, we apply the missing energy correction appropriate for photons to all  
 125 events and take here  $n_{\text{total}}(E_{\text{thr}}^{\gamma})$ . This is conservative (larger value of  $F_{\gamma}^{95}$ ),  
 126 since using the missing energy correction for hadrons (factor  $\simeq 1.07 - 1.14$   
 127 [28,21]) would increase the total number of events above  $E_{\text{thr}}$ , i.e.  $n_{\text{total}}(E_{\text{thr}}^{\gamma}) <$   
 128  $n_{\text{total}}(E_{\text{thr}}^{\text{had}})$ .  
 129

A scatter plot of  $X_{\max}$  vs. energy for all events above  $E_{\text{thr}}^{\gamma} = 2 \text{ EeV}$  with  $X_{\max} \geq$   
 130  $800 \text{ g cm}^{-2}$  surviving quality, fiducial volume and cloud cuts is shown in Fig. 2.  
 131 Statistical uncertainties in individual events are typically a few percent in  
 132 energy and  $\sim 15 - 30 \text{ g cm}^{-2}$  in  $X_{\max}$ . Systematic uncertainties are  $\sim 22\%$  in  
 133 energy [29] and  $\sim 11 \text{ g cm}^{-2}$  in  $X_{\max}$  [15].  
 134

The upper limit on the number of photon candidates  $n_{\gamma\text{-cand}}^{95}$  is given by  
 135  $n_{\gamma\text{-cand}}^{95} = n_{\gamma\text{-cand,obs}}^{95} / \epsilon_{\text{obs}}$ , where  $n_{\gamma\text{-cand,obs}}^{95}$  is the 95% c.l. upper limit on  
 136 the number of photon candidates  $n_{\gamma\text{-cand,obs}}$  extracted (“observed”) from the  
 137 data set and  $\epsilon_{\text{obs}}$  is the corresponding efficiency.  $n_{\gamma\text{-cand,obs}}$  is taken as the  
 138 number of events which have the observed  $X_{\max}$  above the median  $X_{\max}^{\gamma, \text{med}}$  of  
 139 the distribution expected for photons of that energy and direction (“pho-  
 140

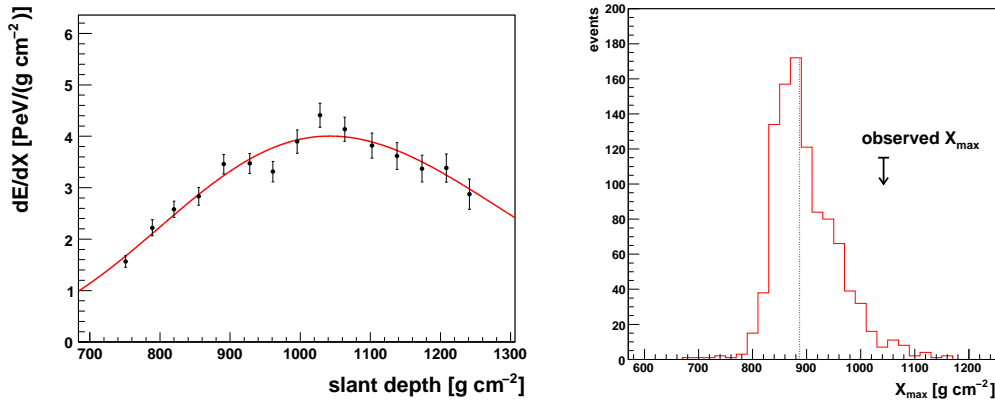


Fig. 3. Left panel: shower profile (black bullets) of the deepest  $X_{\text{max}}$  candidate event in the analyzed sample (id 3554364), along with the Gaisser-Hillas fit (red line). Right panel: the observed  $X_{\text{max}}$  value (black arrow) along with the  $X_{\text{max}}$  distribution from the dedicated photon simulation (histogram); see Tab. 1 for statistical uncertainty. The dashed line indicates the median of the photon distribution.

ton candidate cut”). Additionally, on these particular events individual cloud checks have been performed, and only events that pass this cloud check are finally considered as photon candidates. In Fig. 2, typical values of  $X_{\text{max}}^{\gamma, \text{med}}(E)$  are indicated as a function of energy (solid red line). To extract the specific value of  $X_{\text{max}}^{\gamma, \text{med}}$  for each individual event, dedicated simulations with primary photons have been performed for all potential candidate events, assuming the corresponding energy and geometry.

There are  $n_{\gamma\text{-cand, obs}} = 8, 1, 0, 0$  photon candidate events with energies greater than 2, 3, 5 and 10 EeV, respectively. These candidate events are marked by red crosses in Fig. 2 and the event parameters are listed in Table 1. As an illustration, the shower profile of the candidate with the deepest  $X_{\text{max}}$  is displayed in the left panel of Fig. 3; in the right panel the measured  $X_{\text{max}}$  value is shown along with the results of the dedicated photon simulations.

We checked with simulations whether the observed number of photon candidate events is significantly larger than the expectation in case of nuclear primaries only, i.e. whether primary photons appear to be required to explain the photon candidates. The quantitative estimation of the background expected from nuclear primaries suffers from substantial uncertainties, namely the uncertainty of the primary composition in this energy range (a larger background to photons would originate from lighter nuclear primaries) and the uncertainty in the high-energy hadronic interactions models (for instance, reducing the proton-air cross-section allows proton primaries to penetrate deeper into the atmosphere). From simulations using QGSJET01 as the hadronic interaction model, we found that the observed number of photon candidate events is well within the number of background events expected from a pure proton and a pure iron composition. For energies larger than 2 EeV about 30 events are

167 expected in the analyzed time window for proton and 0.3 for iron. The cor-  
 168 responding numbers above 3, 5, 10 EeV are about 12, 4, 1 events for proton  
 169 and about 0.2, 0.1, 0.0 events for iron. Scenarios of a mixed composition, as  
 170 also favored by our results on  $\langle X_{\max} \rangle$  [15], can reproduce the observation.  
 171 We conclude that the observed photon candidate events may well be due to  
 172 nuclear primaries only. This also holds for the candidate event with the largest  
 173  $X_{\max}$  shown in Fig. 3: proton showers with comparable or larger  $X_{\max}$  value  
 174 occur at a level of a few out of thousand simulated events.

175 We now continue to derive the upper limit to the photon fraction.  $n_{\gamma\text{-cand,obs}}^{95}$   
 176 is calculated from  $n_{\gamma\text{-cand,obs}}$  using the Poisson distribution and assuming no  
 177 background, i.e.  $n_{\gamma\text{-cand,obs}}$  is not reduced by subtracting any event that may  
 178 actually be due to nuclear primaries. This procedure represents the most con-  
 179 servative approach as it maximizes the value of  $n_{\gamma\text{-cand,obs}}^{95}$ . The efficiency  $\epsilon_{\text{obs}}$   
 180 of photons passing all cuts is given by  $\epsilon_{\text{obs}} = \epsilon_{\text{fvc}}\epsilon_{\text{pcc}}$  where  $\epsilon_{\text{fvc}} \simeq 0.72 - 0.77$   
 181 (see Tab. 2) comes from the acceptance after *fiducial volume* cuts (see Ap-  
 182 pendix) and, by construction,  $\epsilon_{\text{pcc}} = 0.50$  is given by the *photon candidate* cut  
 183 above the median of the  $X_{\max}$  distribution for photons. Thus, the upper limit  
 184 is calculated according to

$$F_{\gamma}^{95}(E_{\text{thr}}) = \frac{n_{\gamma\text{-cand,obs}}^{95}(E_{\text{thr}}^{\gamma}) \frac{1}{\epsilon_{\text{fvc}}} \frac{1}{\epsilon_{\text{pcc}}}}{n'_{\text{total}}(E_{\text{thr}}^{\gamma}) \epsilon_{\text{clc}}}. \quad (2)$$

185 Applied to the data, upper limits of 3.8%, 2.4%, 3.5% and 11.7% on the  
 186 fraction of cosmic-ray photons above 2, 3, 5 and 10 EeV are obtained at 95%  
 187 c.l.. Table 2 provides a summary of the quantities used in the derivation of  
 188 the integral upper limits.

189 We studied the robustness of the results against different sources of uncer-  
 190 tainty. Varying individual event parameters or the selection criteria, within the

Table 1

Characteristic parameters for the eight events surviving the photon candidate cut  
 ( $\Delta X_{\max}$  refers to the statistical uncertainty).

id	$X_{\max}$ [g cm <sup>-2</sup> ]	$\Delta X_{\max}$ [g cm <sup>-2</sup> ]	$E_{\gamma}$ [EeV]
2051232	923	17	2.5
2053796	905	32	3.1
2201129	958	29	2.3
2566058	908	20	2.1
2798252	937	29	2.9
3478238	984	12	2.4
3554364	1042	12	2.5
3690306	912	27	2.5

Table 2

Summary of the quantities used in the derivation of the integral upper limits on the photon fraction for  $E_{\text{thr}}^\gamma = 2, 3, 5,$  and  $10$  EeV. Not listed are the efficiencies  $\epsilon_{\text{clc}} = 0.51$  and  $\epsilon_{\text{pcc}} = 0.50$  which do not depend on  $E_{\text{thr}}^\gamma$ .

$E_{\text{thr}}^\gamma$ [EeV]	$n_{\gamma\text{-cand,obs}}$	$n_{\gamma\text{-cand,obs}}^{95}$	$n'_{\text{total}}$	$\epsilon_{\text{fvc}}$	$F_\gamma^{95}$ [%]
2	8	14.44	2063	0.72	3.8
3	1	4.75	1021	0.77	2.4
5	0	3.0	436	0.77	3.5
10	0	3.0	131	0.77	11.7

191 experimental resolution, leaves the results essentially unchanged. Uncertain-  
 192 ties in the determination of the efficiency factors used in Eq. 2 are estimated  
 193 to correspond to an uncertainty  $\Delta F_\gamma^{95}/F_\gamma^{95} \simeq 0.15$ . Increasing (reducing) *all*  
 194 reconstructed  $X_{\text{max}}$  values by  $\Delta X_{\text{max}}^{\text{syst}} = 11 \text{ g cm}^{-2}$  [15] changes the number of  
 195 photon candidates above 2 EeV by +1 ( $\pm 0$ ) and above 3 EeV by  $\pm 0$  ( $-1$ ),  
 196 while it does not affect the higher energies. The limits then become 4.1%  
 197 (3.8%) above 2 EeV and 2.4% (1.5%) above 3 EeV. The energy scale  $E_{\text{thr}}$   
 198 which the limit  $F_\gamma^{95}(E_{\text{thr}})$  refers to, has a 22% systematic uncertainty [29].  
 199 Hence, the numerical values of the limits  $F_\gamma^{95}$  derived here refer to an effec-  
 200 tive energy threshold  $E_{\text{thr}}^{\text{eff}} = k_E \times E_{\text{thr}}$ , with  $k_E = 0.78 \dots 1.22$ . Related to an  
 201 increase (reduction) of the energy scale is a small upward (downward) shift of  
 202 the  $X_{\text{max}}$  value used for the photon candidate cut, leading to stronger (weaker)  
 203 criteria for an event to pass this cut. This shift amounts to  $\sim 7 \text{ g cm}^{-2}$  for a 22%  
 204 change of the energy scale. Finally, an uncertainty  $< 10 \text{ g cm}^{-2}$  on the simu-  
 205 lated photon  $X_{\text{max}}$  values comes from the need to extrapolate the photonuclear  
 206 cross-section to high energy [30]. Adding in quadrature the discussed uncer-  
 207 tainties in  $X_{\text{max}}$  gives an effective total uncertainty of  $\sim 16 \text{ g cm}^{-2}$ . Increasing  
 208 (reducing) *all* reconstructed  $X_{\text{max}}$  values by this amount changes the number  
 209 of photon candidates above 2 and 3 EeV by +3 ( $\pm 0$ ) and by +1 ( $-1$ ). Ac-  
 210 cordingly the limits then become 4.8% (3.8%) above 2 EeV and 3.1% (1.5%)  
 211 above 3 EeV, while the limits above 5 and 10 EeV are unchanged.

### 212 3 Discussion

213 The derived upper limits are shown in Fig. 4 along with previous experimental  
 214 limits and model predictions (see Ref. [34] for a review and references). These  
 215 new bounds are the first ones at energies below 10 EeV and, together with  
 216 *Hybrid-1*, the only ones obtained so far from fluorescence observations (all  
 217 other limits coming from ground arrays). The results complement the previous  
 218 constraints on top-down models from Auger surface detector data. It should  
 219 be noted that due to the steep flux spectrum, even the previous Auger bound  
 220 of 2% above 10 EeV only marginally constrains the photon contribution above

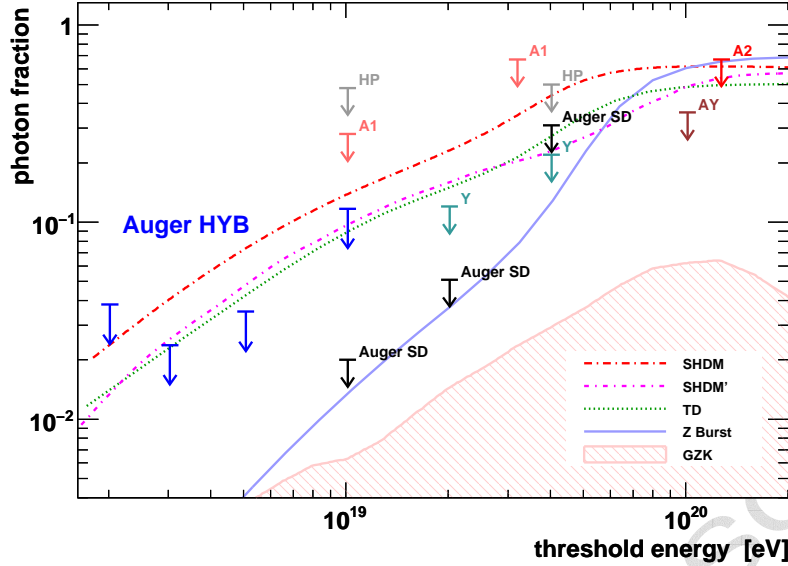


Fig. 4. Upper limits on the photon fraction in the integral cosmic-ray flux for different experiments: AGASA (A1, A2) [3,4], AGASA-Yakutsk (AY) [31], Yakutsk (Y) [32], Haverah Park (HP) [5,6]. In black the limits from the Auger surface detector (Auger SD) [2] and in blue the limits above 2, 3, 5, and 10 EeV derived in this work (Auger HYB). The shaded region shows the expected GZK photon fraction as derived in [7]. Lines indicate predictions from top-down models, see [8,33] and [34].

221 lower threshold energies (for instance, even above 5 EeV,  $\sim 75\%$  of the events  
 222 are in the previously untested energy range of 5–10 EeV).

223 The photon limits derived in this work also help to reduce certain systematic  
 224 uncertainties in other analyses of air shower data such as (i) energy spectrum:  
 225 the Auger method of reconstructing the energy spectrum does not suffer from  
 226 a large contamination from photons at EeV energies; (ii) nuclear primary  
 227 composition: the interpretation of observables sensitive to the primary parti-  
 228 cle (for instance the observed average  $X_{\max}$ ) in terms of a nuclear primary  
 229 composition can only be marginally biased by contributions from photons; (iii)  
 230 proton-air cross-section: the possible contamination from photons was one of  
 231 the dominant uncertainties for deriving the proton-air cross-section [13,14],  
 232 and this uncertainty is now significantly reduced (to  $\sim 50$  mb for data at EeV  
 233 energies, which corresponds to a relative uncertainty of  $\sim 10\%$ ).

234 In future photon searches, the separation power between photons and nuclear  
 235 primaries can be enhanced by adding the detailed information measured with  
 236 the surface detectors in hybrid events. For an estimate of the future sensitivity  
 237 of Auger to photons see Ref. [34]. The information on event directions can also  
 238 be used in future analyses; for instance, an excess flux of photons from the  
 239 direction of the galactic center (e.g. Ref. [10]) can be searched for.

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279 **A Acceptance correction**

The fraction of photons  $f_\gamma$  in the cosmic-ray flux integrated above an energy threshold  $E_{\text{thr}}$  is given by

$$f_\gamma(E \geq E_{\text{thr}}) = \frac{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE + \sum_i \int_{E_{\text{thr}}} \Phi_i(E) dE} \quad (\text{A.1})$$

280 where  $\Phi_\gamma(E)$  denotes the differential flux of photons and  $\Phi_i(E)$ ,  $i = \text{p, He, ...}$   
281 the fluxes of nuclear primaries.

The fraction of photons  $f_\gamma^{\text{det}}$  as registered by the detector is given by

$$f_\gamma^{\text{det}}(E \geq E_{\text{thr}}) = \frac{\int_{E_{\text{thr}}} A_\gamma(E) \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} A_\gamma(E) \Phi_\gamma(E) dE + \sum_i \int_{E_i} A_i(E) \Phi_i(E) dE} \quad (\text{A.2})$$

282 with  $A_\gamma(E)$  and  $A_i(E)$  being the detector acceptances to photons and nuclear  
283 primaries, respectively.  $E_i$  denotes the effective threshold energy for primary  
284 nucleus  $i$ .

285 Thus, the upper limit  $f_\gamma^{\text{ul,det}}$  obtained to the registered data,  $f_\gamma^{\text{ul,det}} > f_\gamma^{\text{det}}$ ,  
286 needs to be corrected to resemble an upper limit on the fraction of photons  
287 in the cosmic-ray flux. For the present analysis, a conservative and model-  
288 independent correction is applied as follows. The approach adopted here ex-  
289 tends the one introduced in *Hybrid-1*, as we now also treat the case of  $A_\gamma(E) \neq$   
290 const.

291  $E_{\text{thr}}$  corresponds to the analysis threshold energy assuming primary photons.  
292  $E_i$  is related to  $E_{\text{thr}}$  by the ratios of the missing energy corrections  $m_\gamma$  (for  
293 photons) and  $m_i$  (for nuclear primaries),

$$E_i = E_{\text{thr}} \cdot \frac{m_i}{m_\gamma}. \quad (\text{A.3})$$

294 Since  $m_\gamma \simeq 1.01$  [21] and  $m_i \simeq 1.07 - 1.14$  [28],  $E_i > E_{\text{thr}}$ . Thus, replacing  $E_i$   
295 by  $E_{\text{thr}}$ ,

$$\begin{aligned} f_\gamma^{\text{det}}(E \geq E_{\text{thr}}) &> \frac{\int_{E_{\text{thr}}} A_\gamma(E) \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} A_\gamma(E) \Phi_\gamma(E) dE + \sum_i \int_{E_{\text{thr}}} A_i(E) \Phi_i(E) dE} \\ &\geq \frac{\int_{E_{\text{thr}}} A_\gamma^{\text{min}} \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} A_\gamma^{\text{min}} \Phi_\gamma(E) dE + \sum_i \int_{E_{\text{thr}}} A_i(E) \Phi_i(E) dE}, \end{aligned} \quad (\text{A.4})$$

296 where  $A_\gamma^{\min}$  refers to the minimum value of  $A_\gamma(E \geq E_{\text{thr}})$  and using  $a/(a+b) \geq$   
 297  $a'/(a'+b)$  for  $a \geq a' \geq 0$  and  $b > 0$ .

298 Next, the acceptance ratio  $\epsilon_i(E) = A_\gamma^{\min}/A_i(E)$  is introduced,

$$f_\gamma^{\text{det}}(E \geq E_{\text{thr}}) > \frac{\int_{E_{\text{thr}}} A_\gamma^{\min} \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} A_\gamma^{\min} \Phi_\gamma(E) dE + \sum_i \int_{E_{\text{thr}}} \frac{A_\gamma^{\min}}{\epsilon_i(E)} \Phi_i(E) dE} . \quad (\text{A.5})$$

299 From Fig. 1 the minimum acceptance ratio  $\epsilon_{\min}(E_{\text{thr}}) \leq \epsilon_i(E \geq E_{\text{thr}})$  can be  
 300 extracted for each threshold energy  $E_{\text{thr}}$ . In the current analysis,  $\epsilon_{\min}(E_{\text{thr}}) \equiv$   
 301  $\epsilon_{\text{fvc}}(E_{\text{thr}}) \simeq 0.72, 0.77, 0.77, 0.77$  for  $E_{\text{thr}} = 2, 3, 5, 10$  EeV. Hence, it follows:

$$\begin{aligned} f_\gamma^{\text{det}}(E \geq E_{\text{thr}}) &> \frac{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE + \frac{1}{\epsilon_{\text{fvc}}(E_{\text{thr}})} \sum_i \int_{E_{\text{thr}}} \Phi_i(E) dE} \\ &> \epsilon_{\text{fvc}}(E_{\text{thr}}) \cdot \frac{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE}{\int_{E_{\text{thr}}} \Phi_\gamma(E) dE + \sum_i \int_{E_{\text{thr}}} \Phi_i(E) dE} \\ &= \epsilon_{\text{fvc}}(E_{\text{thr}}) \cdot f_\gamma(E \geq E_{\text{thr}}) , \end{aligned} \quad (\text{A.6})$$

302 where it was used that  $\frac{1}{\epsilon_{\text{fvc}}(E_{\text{thr}})} > 1$ .

Consequently, an upper limit  $F_\gamma^{\text{ul}}$  to the fraction of photons in the cosmic-ray flux can conservatively be calculated as

$$F_\gamma^{\text{ul}} = f_\gamma^{\text{ul,det}}/\epsilon_{\text{fvc}} > f_\gamma^{\text{det}}/\epsilon_{\text{fvc}} > f_\gamma . \quad (\text{A.7})$$

303 The upper limit obtained this way does not depend on assumptions about the  
 304 differential fluxes  $\Phi_\gamma(E)$  and  $\Phi_i(E)$ .

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