

## Photon air showers at ultra-high energy and the photonuclear cross-section <sup>\*</sup>)

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Experimental conclusions from air shower observations on cosmic-ray photons above  $10^{19}$  eV are based on the comparison to detailed shower simulations. For the calculations, the photonuclear cross-section needs to be extrapolated over several orders of magnitude in energy. The uncertainty from the cross-section extrapolation translates into an uncertainty of the predicted shower features for primary photons and, thus, into uncertainties for a possible data interpretation. After briefly reviewing the current status of ultra-high energy photon studies, the impact of the uncertainty of the photonuclear cross-section for shower calculations is investigated. Estimates for the uncertainties in the main shower observables are provided. Photon discrimination is shown to be possible even for rapidly rising cross-sections. When photon-initiated showers are identified, it is argued that the sensitivity of photon shower observables to the photonuclear cross-section can in turn be exploited to constrain the cross-section at energies not accessible at colliders.

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### 1 Introduction

Photons around and above  $10^{19}$  eV might provide a key to understanding the origin of cosmic rays. Substantial fluxes of these ultra-high energy (UHE) photons are predicted in top-down models of cosmic-ray origin. In addition, UHE photons are produced by the GZK process of resonant photoproduction of pions [1], in analogy to GZK neutrinos.

Experimentally, UHE photons can be discerned from nuclear primaries due to differences in the expected shower signatures. So far, no claim of a photon detection exists and upper limits to UHE photons were set. Any conclusions about UHE photons rely on the comparison of data to detailed simulations of photon-induced showers. Although these photon showers are dominated by electromagnetic interactions, a source of uncertainty is the photonuclear cross-section, which has to be extrapolated over several orders of magnitude in energy from laboratory data for calculating showers induced by UHE photons.

In this work, after giving an overview of the current status of UHE photon

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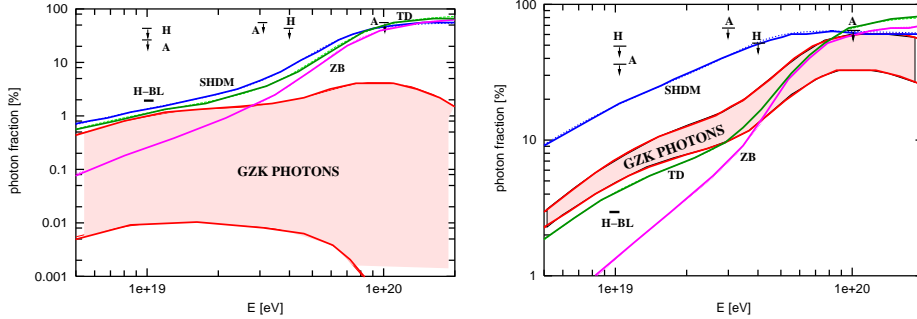


Fig. 1. Production of photons by the GZK process: Bottom-up sources were fitted to the HiRes spectrum (left) and the AGASA spectrum (right). Plotted is the resulting photon fraction, integrated above the primary energy, as a function of the primary energy threshold. The ranges shown for the GZK photons come from varying the source and background parameters. Figures are taken from [7].

studies, both the impact of the uncertainty from the photonuclear cross-section to photon shower features and possible prospects for constraining the cross-section are investigated. The plan of the paper is as follows. In Section 2, scenarios for producing cosmic-ray photons above  $10^{19}$  eV = 10 EeV are briefly described. Features of showers induced by photons are discussed in Section 3. In Section 4, the experimental situation concerning upper limits to photons is summarized. The role of the photonuclear cross-section is investigated in Section 5.

## 2 Cosmic-ray photons

Motivated in particular by reports from the AGASA experiment about a possible continuation of the cosmic-ray energy spectrum without a GZK cutoff, many top-down scenarios were proposed [2]. In these models, cosmic rays are produced by the decay or annihilation of superheavy dark matter [3] or topological defects [4]. A common feature of these models is the prediction of a significant flux of photons arriving at Earth. Also in the Z-burst model [5], large photon fractions are predicted. Stringent upper limits to photons would disfavour many realizations of these top-down models, although some uncertainty exists in calculating the propagation of UHE photons [6].

Even in “conventional” bottom-up models, in which nuclear particles are accelerated in astrophysical sites to highest energies, UHE photons are expected. They arise from the GZK process during propagation. Such GZK photons were studied in detail recently in [7]. In Figure 1, results of these calculations are shown: For various assumptions on source parameters (distribution, emission features) and on radio backgrounds and magnetic fields important for photon propagation, fits were performed both to the HiRes (cutoff-like) [8] and AGASA (no-cutoff-like) [9]

cosmic-ray spectra.

In case of the HiRes spectrum, the range of possible photon fractions extends from almost negligible ( $<0.01\%$ ) to values of 1% above 10 EeV and 5% above 100 EeV. For the completed Pierre Auger Observatory (Northern and Southern site) [10], the latter values would imply event rates of up to  $\simeq 60$  photons/year above 10 EeV and  $\simeq 2-3$  photons/year above 100 EeV. Such a signal seems detectable; in turn, an absence of these GZK photons, and correspondingly an upper limit to photons, might translate into constraints for bottom-up scenarios.

In case of the AGASA spectrum, it turned out that even bottom-up scenarios might allow a fit to a no-cutoff spectrum. The GZK photon fraction is then very large, however. (The term ‘‘GZK photons’’ refers to the way these photons are produced; it does not imply that the observed energy spectrum necessarily exhibits a GZK cutoff.) Thus, a connection between the shape of the energy spectrum and the photon fraction predicted in bottom-up models exists [7]. It seems worthwhile to note that in turn, a small-enough photon limit (e.g. below 2-3% above 10 EeV or below 10-20% above 100 EeV) would then disfavour a no-cutoff-like spectrum for the scenarios regarded in [7], unless specific new physics such as Lorentz invariance violation is invoked (of course, top-down models would be constrained by the same photon limit).

### 3 Air showers induced by photons

In Figure 2, the average depth of shower maximum  $X_{\max}$  is shown vs. primary energy as calculated for different primary particles. The shower maxima of primary photons are separated from those of nuclear primaries by  $\simeq 200 \text{ g cm}^{-2}$  or more at 10 EeV. The elongation rate (slope of the curve) is larger for photons even at relatively small energies. This elongation rate for photons can be understood within the Heitler toy model of shower development [12]. The slope is increased above a few EeV with the LPM effect [13] becoming increasingly important. At even higher energy (above 50 EeV, depending on geomagnetic field), UHE photons may convert in the geomagnetic field and form a preshower [14] before entering the atmosphere.

The directional dependence of the preshower effect is illustrated in Figure 3 (left). In this example, photons of 100 EeV primary energy do not convert when entering almost parallel to the local geomagnetic field lines. For a more perpendicular incidence, in most cases a preshower is formed [15].

If a preshower is formed, the energy is distributed among secondary electrons, positrons and, mostly, photons. As a specific example, in Figure 3 (right) the energy spectrum of preshower particles on top of the atmosphere is shown. As the original particle, a primary photon was assumed for the geometry of the 320 EeV Fly’s Eye event [16]. On average, about 1400 lower-energy particles are produced. Most energy is carried by particles of  $\simeq 10$  EeV energy, i.e. about 1.5 orders of magnitude below the original primary energy [17].

The impact of the LPM and preshower effect is shown for the example of the highest energy Fly’s Eye event in Figure 4. Assuming primary photons, the longi-

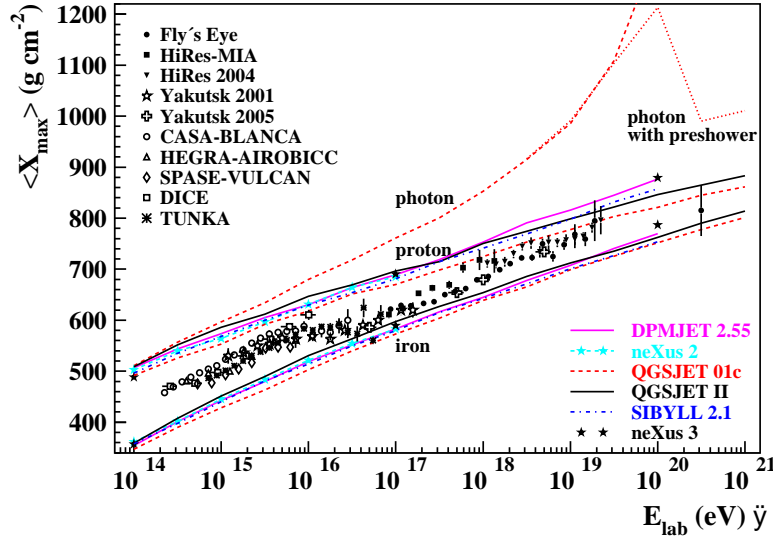


Fig. 2. Average depth of shower maximum  $X_{\max}$  versus primary energy simulated for primary photons, protons and iron nuclei. For nuclear primaries, calculations for different hadronic interaction models are shown. Also shown are experimental data. For references to the experiments and interaction models see [11].

tudinal profiles are shown for calculations with both effects neglected, with only LPM switched on, and for the complete treatment. Due to the extreme energy of the Fly's Eye event, differences between the resulting profiles are enormous. While the LPM effect delays the development and increases fluctuations, the preshower effect counteracts.

#### 4 Data

For the 320 EeV Fly's Eye event, the observed profile [16] differs from the primary photon prediction by about 1.5 standard deviations [18, 17]. The comparison is shown in Figure 4 (right). A photon origin of the Fly's Eye event can not be excluded; profiles calculated for nuclear primaries fit the data better, however [17].

Limits to photons were set by different experiments. Comparing rates of nearly vertical showers to inclined ones, upper limits to the photon fraction of 48% above 10 EeV and 50% above 40 EeV (95% CL) were deduced from Haverah Park data [19]. Based on an analysis of muons in air showers observed by the Akeno Giant Air Shower Array (AGASA), upper limits were estimated to be 28% above 10 EeV and 67% above 32 EeV (95% CL) [20]. In a dedicated analysis of the highest-energy AGASA events, an upper limit of 67% above 125 EeV (95% CL) was set [21]. These limits came from ground arrays. Recently, using  $X_{\max}$  observed

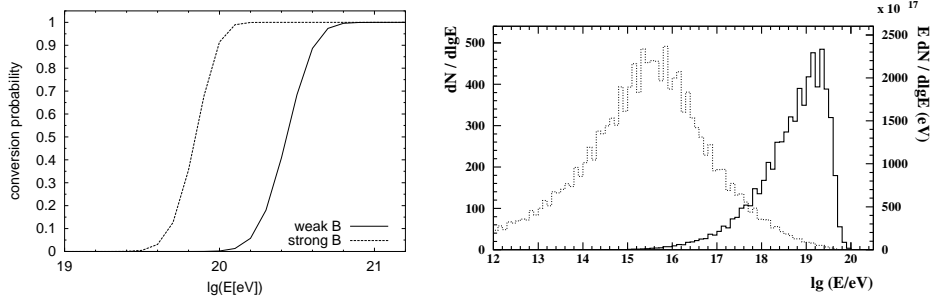


Fig. 3. Preshower features: (Left) Conversion probability versus primary energy for two different arrival directions: Small angle (“weak B”) and almost perpendicular (“strong B”) to the local magnetic field. Calculation performed for the Auger Southern site [15]. (Right) Spectrum of preshower particles (with and without energy weighting) on top of the atmosphere calculated for photons for the geometry of the 320 EeV Fly’s Eye event [17].

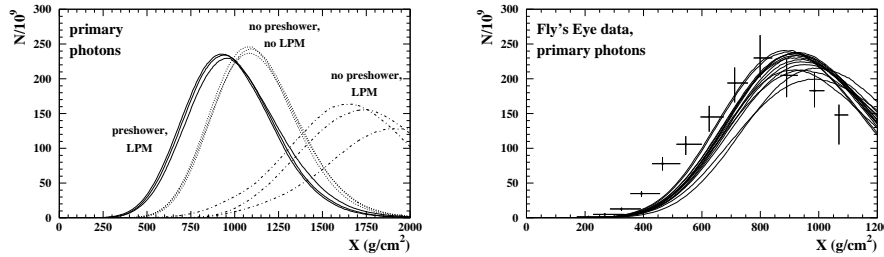


Fig. 4. (Left) Photon shower profiles for the geometry of the 320 EeV Fly’s Eye event for the full simulation (solid), when switching off the preshower effect (dotted-dashed), and when switching off also the LPM effect (dotted) [17]. (Right) Observed profiles of the 320 EeV Fly’s Eye event [16] compared to the full simulation for primary photons [17]. Data points are correlated with respect to shifts in atmospheric depth  $X$ .

by fluorescence telescopes in hybrid events, a limit of 26% above 10 EeV (95% CL) was obtained by the Pierre Auger Collaboration [22]. These upper limits are compared to some model predictions in Figure 5.

With increased event statistics, much stronger constraints on the photon flux or the discovery of UHE photons can be expected. There exists a minimum possible value for an upper limit that ideally could be reached for a given event statistics. This is due to the fact that, assuming a fraction  $F_\gamma$  of photons in the primary flux, a set of  $n_m$  primaries picked at random is expected to *ab initio* contain no primary photon with probability  $(1 - F_\gamma)^{n_m}$ . The relation between the minimum possible

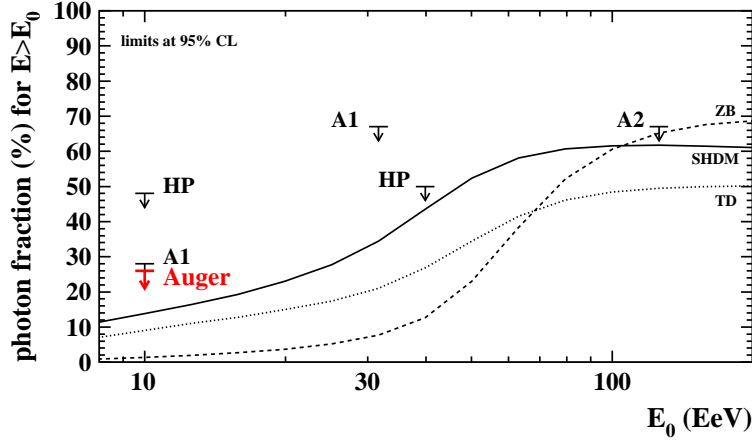


Fig. 5. Upper limits (95% CL) to cosmic-ray photon fraction derived from Haverah Park (HP) [19] and AGASA (A1) [20], (A2) [21] data and by the Auger Observatory [22], compared to some estimates based on top-down models [7] (Figure taken from [22]).

Table 1. Numerical examples for the relation  $n_m \leftrightarrow F_\gamma^{\min}$  for the minimum fraction  $F_\gamma^{\min}$  that could be excluded with  $n_m$  events (or: the minimum number of events  $n_m^{\min} \leftrightarrow F_\gamma$  required to exclude a fraction  $F_\gamma$ ) for a confidence level  $\alpha = 95\%$ .

6	10	30	100	300	1000
$\leftrightarrow 39.3\%$	$\leftrightarrow 25.9\%$	$\leftrightarrow 9.5\%$	$\leftrightarrow 3.0\%$	$\leftrightarrow 1.0\%$	$\leftrightarrow 0.3\%$

fraction  $F_\gamma^{\min}$  that could be excluded for a given event number  $n_m$  (or in turn: the minimum event number  $n_m^{\min}$  required to possibly exclude a certain fraction  $F_\gamma$ ) is given by

$$F_\gamma^{\min} = 1 - (1 - \alpha)^{1/n_m}, \text{ and } n_m^{\min} = \frac{\ln(1 - \alpha)}{\ln(1 - F_\gamma)}, \quad (1)$$

with  $\alpha$  being the confidence level of rejection. This theoretical limit is reached only if for each individual shower, the observations allowed us to completely rule out photons as primary particle. Some numerical examples are listed in Tab. 1.

### 5 Photonuclear cross-section

The experimental results for UHE photons are based on comparisons to photon shower simulations. For the simulation, an extrapolation of the photonuclear cross-section is needed. This is in particular important for the production of secondary muons in primary photon showers. For hadron primaries, most muons are produced

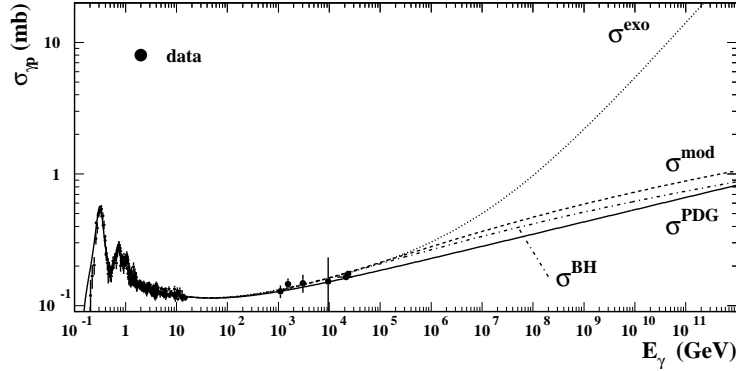


Fig. 6. Data [25] and PDG extrapolation ( $\sigma^{\text{PDG}}$ ) [25, 26] of the photonuclear cross-section  $\sigma_{\gamma p}$ . Also shown are two parametrizations with larger cross-sections at ultra-high energy, denoted  $\sigma^{\text{mod}}$  [31] and  $\sigma^{\text{exo}}$  [27] (see text), and another recent fit  $\sigma^{\text{BH}}$  [30].

in the decay of pions and kaons generated in collisions of shower hadrons with the target air nuclei. In photon-induced showers, however, photoproduction is the main process that transfers energy from the electromagnetic to the hadronic channel. Muons are then produced in a second step in the hadronic sub-showers that were initiated by a photonuclear interaction. Changing the photonuclear cross-section influences the rate of transferring energy to hadrons and, thus, the production of secondary muons.

Also the position of depth of shower maximum is affected: Increasing, for instance, the photonuclear cross-section makes primary photon showers more similar to hadron-induced cascades. Qualitatively, in this example, the  $X_{\text{max}}$  values would become smaller for UHE photon showers, i.e. values closer to the average  $X_{\text{max}}$  for primary hadrons (see Figure 2) would emerge.

In the extreme case, an unconverted primary photon can undergo photoproduction in the first interaction of the shower cascade. This would result in a shower that hardly can be distinguished from that of a hadron primary. The probability for such a process is small, though. The electromagnetic Bethe-Heitler pair production cross-section is about 500 mb whereas the photoproduction cross-section is expected to be of the order 10 mb at  $\simeq 10$  EeV. However, the LPM effect reduces the Bethe-Heitler cross-section at ultra-high energy, and an uncertainty exists for extrapolating the photonuclear cross-section.

In Figure 6, data and some published extrapolations for the cross-section  $\sigma_{\gamma p}$  are shown. Large differences between the extrapolations are evident. With respect to photon shower studies, several questions arise: Is there a theoretical maximum for the allowed increase of the cross-section (smaller values would make the experimental limits to UHE photons even more severe)? What is the impact on photon shower features when adopting different cross-section extrapolations? Is photon shower dis-

crimination still possible even for very rapidly rising cross-sections? And, finally: If we were to observe photon showers, could this be used in turn to constrain the photonuclear cross-section in an energy range inaccessible at colliders?

To answer these questions, photon shower simulations were performed for various cross-section assumptions with CORSIKA [23], taking preshower formation [15] and the LPM effect [13, 24] into account. We consider here the extrapolation of the Particle Data Group,  $\sigma^{\text{PDG}}$  [25, 26], as a baseline assumption. The most rapidly rising photoproduction cross-section is obtained if the hard pomeron model of Donnachie and Landshoff [27] is extrapolated to high energy. This model does not account for unitarity corrections that are expected to become important at very high energy. Therefore, it should be considered as a rather extreme extrapolation that could represent an upper limit of possible low-energy data extrapolations. In the following, we will refer to this cross-section extrapolation as  $\sigma^{\text{exo}}$  (exotic).

*What is the impact on photon showers?* The impact due to switching from  $\sigma^{\text{PDG}}$  to  $\sigma^{\text{exo}}$  is quite significant, increasing the number of ground muons by roughly 70–80% [21]. The effect on  $X_{\text{max}}$  is a rather moderate reduction by  $\simeq 30 \text{ g cm}^{-2}$  for photons that formed a preshower before entering the atmosphere [28], see Figure 7. The reduction is found to be much larger (up to  $100 \text{ g cm}^{-2}$  or more) for unconverted photons.

Recent theoretical work on a possible maximum cross-section seems to indicate that cross-section values larger by a factor 2 or more than  $\sigma^{\text{PDG}}$  are very unlikely [29]. A recent fit to the low-energy data,  $\sigma^{\text{BH}}$  [30], stays also close to  $\sigma^{\text{PDG}}$ . Using these cross-sections, the uncertainty of ultra-high energy shower predictions is rather moderate. For example, assuming the extrapolation  $\sigma^{\text{mod}}$  [31] (see Fig. 6) results in a change of  $\simeq 7 \text{ g cm}^{-2}$  in  $X_{\text{max}}$  and  $\simeq 10\%$  in muon number. Thus, it seems that a reasonable estimate of the present uncertainty from extrapolating the photonuclear cross-section is  $\simeq 10 \text{ g cm}^{-2}$  and  $\simeq 15\%$  for  $X_{\text{max}}$  and muon number, respectively.

*Is photon shower discrimination possible even for rapidly rising cross-sections?* Assuming an exotic scenario such as  $\sigma^{\text{exo}}$ , the discrimination power for photons is reduced, but still photons are on average expected to have fewer muons (factor 2) and larger  $X_{\text{max}}$  ( $50\text{--}100 \text{ g cm}^{-2}$ ) compared to protons. The separation to heavier nuclei is even larger. Thus, if UHE photons exist, we have good chances to identify them. In particular, the preshower effect can be used as a tool for photon identification: The detection of the characteristic dependence of  $X_{\text{max}}$  and muon number, or of observables related to these, on primary direction and energy (both the average values of the shower observables and their fluctuations) would be an unambiguous signal of primary photons.

*Could the photonuclear cross-section be constrained at ultra-high energy by air shower observations?* When UHE photon showers are identified, their observed shower features could in turn be used to constrain the photonuclear cross-section at highest energies. The differences in  $X_{\text{max}}$  and muon number when assuming  $\sigma^{\text{PDG}}$  or  $\sigma^{\text{exo}}$  can be determined even with relatively small event statistics. Thus, it might be possible to convert the observed shower features into an upper limit to the photonuclear cross-section. It may also be useful to look for specific photon

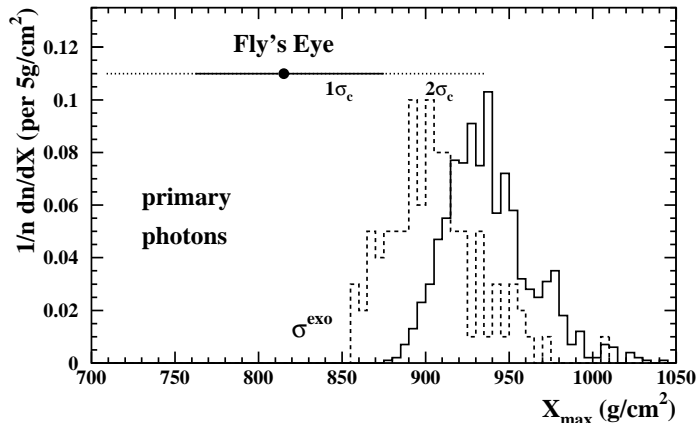


Fig. 7. Shower maximum distribution of primary photons compared to the reconstructed value of the Fly's Eye event. The measured depth is shown with the  $1\sigma$ - and  $2\sigma$ - uncertainty. In addition to the simulations with standard photonuclear cross-section, results when assuming the extrapolation  $\sigma^{exo}$  (see Fig. 6) are given [28].

event classes: For instance, photon events with a very delayed first interaction (due to LPM suppression) would be much less frequent in the  $\sigma^{exo}$  scenario, as they would start a hadronic cascade at some point. The rate of deeply starting photon-like events would constrain the photonuclear cross-section at these primary energies.

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