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Prospects of searches for ultra-high energy photons

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Abstract: The observation of ultra-high energy (UHE) photons above 10^{18} eV would open a new window of cosmic-ray research with possible impact on astrophysics, cosmology, particle and fundamental physics. The advent of new giant air shower experiments, particularly the Pierre Auger Observatory, offers a unique potential to search for such photons. Status and prospects of experimental photon searches are reported. Implications of the (non-) observation of UHE photons as well as the contribution of UHE photon searches to multimessenger observations of the universe are discussed.

Introduction

Photons are the main messenger particles for exploring the universe. Over the last decades, the wavelength range of photon observation was dramatically expanded and stretches now from radiowaves to high-energy gamma rays. The current maximum energy of photons observed is $\sim 10^{14}$ eV [1]. At $10^{15} - 10^{16}$ eV, the universe becomes opaque to extragalactic photons, see Fig. 1. At ultra-high energy (UHE) above 10^{18} eV, energy loss lengths increase again to values of order ~ 10 Mpc. An observation of such UHE photons would bring the expansion of photon wavelengths beyond the optical to its highest end, and it would open a new window in cosmic-ray research with significant impact on related research fields.

The large UHE photon fluxes predicted from non-acceleration models [2] did not show up in data from air shower experiments so far (see [4] for a summary), and the exposure accumulated by the Pierre Auger Observatory [5] can provide a severe test of non-acceleration models from photon searches.

In analogy to GZK neutrinos, a "guaranteed" source of UHE photons is provided by the resonant photo-pion production from UHE nucleons interacting with the CMB. Due to the differences between photon and neutrino propagation, experimental searches for GZK photons and neutrinos complement each other, with GZK photons (neutrinos) testing more local (distant) production sites. An enhanced production of $>10^{18}$ eV photons can also occur from nuclear primaries passing near the galactic center region [6].

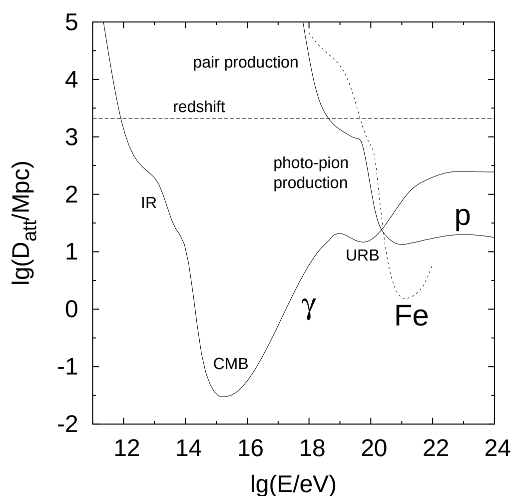

Figure 1: Energy loss length of photons for interactions with infrared (IR), cosmic microwave (CMB) and universal radio (URB) backgrounds. Uncertainties exist for the URB and the IR background. For comparison, curves for protons and iron nuclei are added. Values are compiled from Refs.[2, 3].

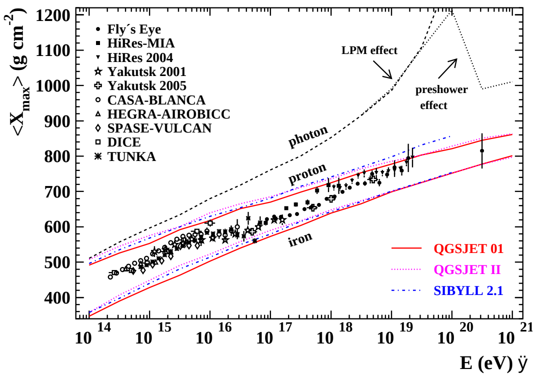

Figure 2: Average depth of shower maximum $<X_{\rm max}>$ versus energy simulated for primary photons, protons and iron nuclei. The impact of the LPM [7] and preshower [8] effects on $<X_{\rm max}>$ is visible. The splitting of the photon line at $\sim 3\times 10^{19}$ eV indicates that $<X^{\gamma}_{\rm max}>$ above these energies depends also on the specific trajectory through the geomagnetic field. The calculations are based on CORSIKA [9] using different hadronic interaction models for the nuclear primaries (SIBYLL 2.1 [10], QGSJET 01 [11], QGSJET II [12]) and the PRESHOWER code [13] for the UHE photons. See Ref. [14] for references to the experimental data.

The expected GZK photon flux is uncertain by more than an order of magnitude because of uncertainties in the source and propagation parameters. A benchmark value for the fraction of GZK photons in the cosmic-ray flux is $\sim$0.1%, see Fig. 4.

In the following, we investigate the possibility to observe GZK photons, and we sketch examples for possible science impact in case of UHE photon observations. For a more detailed summary, see Ref. [4].

UHE photon search with air showers

A great advantage of UHE photon searches over composition studies of nuclear primaries is the minor dependence of photon simulations on hadronic interaction models, which allows one to draw robust conclusions when comparing shower data to photon shower calculations.

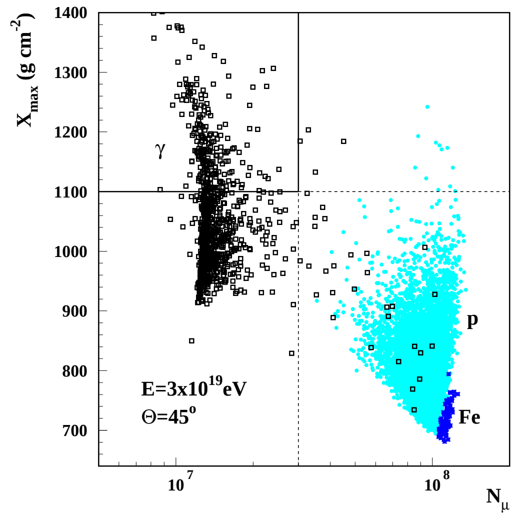

Figure 3: $X_{\rm max}$ versus N_μ for different primaries at 3×10^{19} eV. Simulations were performed for photons (1000 events), protons (10000 events), and iron nuclei (100 events) with PRESHOWER [13], CONEX [15] and QGSJET 01 [11]. No detector effects are included. The lines illustrate possible cuts to achieve small misidentification rates for photon identification. Fluctuations predicted for protons may depend on the hadron generator.

UHE photon showers can well be distinguished from nuclear primary events due to the larger depth of shower maximum and the smaller number of muons, see Figs. 2 and 3.

From air shower simulations, misidentification rates (e.g. protons erraneously identified as photons) of below 0.1% appear to be in reach, particularly when performing a combined selection cut in depth of shower maximum and number of muons (Fig. 3).

The Auger detectors have sensitivity both to the depth of shower maximum and the number of muons [16, 17]. In terms of event statistics, the benchmark value of 0.1% corresponds (for energies above $\sim 10^{19}$ eV) to $\sim$2 photons/year for the full Auger South array and to $\sim$10 photons/year for the completed Auger Observatory (Auger South plus an extended Auger North). An estimate of the Auger sensitivity to photons is given in Fig. 4. Details of this estimate, which does not include a full detector MC, are given in [4]. Photon fractions below 0.1% may be in reach within a few years of operation of the completed Auger Observatory.

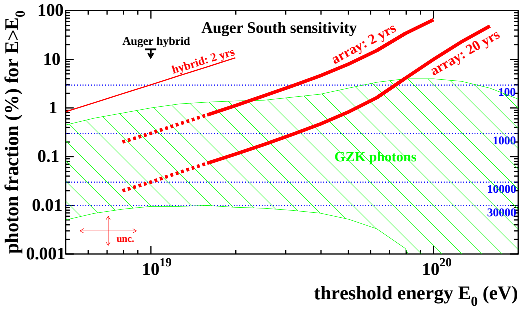

Figure 4: Fraction of photons in the integral cosmic-ray flux as a function of the threshold energy. The GZK photon prediction is taken from [18]. Photon fractions of 0.1-0.01% were obtained in recent calculations [19, 20]. For reference, the limit from Auger hybrid data [16], obtained with 29 events, is shown. Numbers on the right-hand side give the minimum number of events required to place a 95% c.l. limit at the level indicated by the horizontal lines. An estimate for the sensitivity (see [4] for details) of the array of the southern Auger Observatory is shown for two and twenty years of operation based on the Auger spectrum [21] and assuming a flux suppression above $E_{\rm GZK}$. Also shown is the estimated sensitivity using hybrid data, which are less numerous but reach to smaller energy. The uncertainty of the sensitivity estimates is indicated at the lower left corner. At around 10^{19} eV (dashed lines), additional threshold effects may become increasingly important for the array. If complemented by an extended northern array, a sensitivity level of below 0.1% can be reached within a few years of operation.

Possible impact of photon observations

Photons, as the gauge boson of the electromagnetic force, at such enormous energy can be regarded as unique messengers and probes of extreme and, possibly, new physics.

UHE photons may be helpful for source diagnostics, as photons point back to the location of their production. Also photon fluxes expected at the Earth depend on source paramters (source distribution, energy spectra ..., see e.g. [18]).

Already a small sample of photon-induced showers may provide relatively clean probes of aspects of QED (preshower process, LPM effect) and QCD (photonuclear interactions, e.g. [22]) at ultra-high energy.

Propagation features of UHE photons are sensitive to the MHz radio background or magnetic fields [23, 24, 20]. UHE photon propagation might also be sensitive to the existence of, for instance, space time foam [25], branes [26], or axions [27]. Photon propagation may be modified in certain models of quantum gravity [28].

There are several connections to Lorentz invariance violation [29]. The production of GZK photons can be affected as well as interactions of photons during propagation and when initiating a cascade at the Earth. Particularly, photon conversion in the geomagnetic field (the preshower process) may be suppressed.

Conclusion

UHE photons are tracers of highest-energy processes and new physics. Showers initiated by such photons can well be distinguished from those by nuclear primaries. When complemented by a large northern site, the Pierre Auger Observatory is expected to be sensitive to photon fractions of 0.1% and below and can realistically aim at photon observations on a reasonable timescale. The search for UHE photons contributes to multimessenger observations of the universe. Stringent limits to photons would already provide useful information; the observation of UHE photons would open a new window of cosmic-ray research.

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