Search for photons of energy $E > 10^{18}$ eV with Yakutsk muon data

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Abstract. **Within an event-by-event approach, we analyse the data on the total signal and on the muon component of the air showers detected by the Yakutsk array and constrain the flux of primary gamma-rays at energies above 10^{18} eV.**

***Keywords*: EeV gamma rays, muon data, Yakutsk**

I. Introduction

Gamma rays with energies $(10^{18} \ldots 10^{19})$ eV may serve as an important diagnostic tool which helps to distinguish between various models of the origin of cosmic rays at the highest ($\sim 10^{20}$ eV) energies. Indeed, interactions of the highest-energy protons with the cosmic background radiation result in pion production [1], [2] and an important part of the products of subsequent pion decays are lower energy photons (the so-called GZK photons, see e.g. Ref. [3]). The amount of secondary photons is considerably smaller if a substantial fraction of 10^{20} eV cosmic particles are heavy nuclei [4]. The flux of gamma rays at (1...10) EeV is therefore very sensitive both to the spectrum and to composition of super-GZK cosmic rays of extragalactic origin. On the other hand, a certain (typically larger) amount of EeV photons is predicted in more exotic cosmic-ray models, in particular in top-down models (see e.g. Ref. [5] for a review) and in models with mixing of photons with axion-like particles (see e.g. Ref. [6]). Constraints on the GZK photons would have important consequences for predictions of ultra-high-energy neutrino fluxes.

Up to now, no experiment has reported a limit on the gamma-ray flux at 10^{18} eV. The present work both fills this gap and improves the recently published [7] Auger limit at 2×10^{18} eV.

II. The method

The key idea of the method is the event-by-event comparison of observed muon densities in air showers with those in simulated gamma-ray induced showers which have the same scintillator energy deposit and the same arrival direction as the observed ones. The method is described in detail in Ref. [8]; it has been previously applied to Yakutsk and AGASA muon data at higher energies [9], [10]. One of the advantages of the method is its independence both on the energy reconstruction procedure used by the experiment and on the Monte-Carlo simulation of hadronic air showers: we use simulated gamma-induced showers which are mostly electromagnetic and are therefore well understood and we select the simulated showers by the observable scintillator signal and not by the energy (effectively estimating the energy of each event in the assumption of the photon primary).

The Yakutsk extensive-air-shower array is equipped with five muon detectors of 20 m^2 area each with threshold energy 1 GeV for vertical muons. At present, it is the only installation in the world which is equipped with muon detectors and is capable of studying cosmic rays with energies larger than EeV.

For the present study, we use the sample of events satisfying the following criteria:

1) the event passed the selection cuts for the spectrum reconstruction;
2) the reconstructed core location is inside the array boundary;
3) the zenith angle $< 45°$;
4) the reconstructed energy[1] $E_{\rm rec} \geq 10^{18}$ eV;
5) the reconstructed shower axis is within 300 m from an operating muon detector.

The data set contains 1647 events and corresponds to the effective exposure of $7.4 \times 10^{14}\ \mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr}$.

By making use of the empirical muon lateral distribution function [11], we calculated, for each event, the muon density at 300 m from the shower axis, $\rho_\mu(300)$, which we use as the composition estimator (C-observable). Individual detector readings were evaluated from the raw data reanalyzed for this study. Statistical errors of these detector readings were estimated on the case-by-case basis (details of the reanalyzsis of the Yakutsk muon data will be presented elsewhere). The dominant contribution to the statistical error of $\rho_\mu(300)$ comes from the uncertainty in the determination of the shower axis (for which we use the geometric reconstruction from the main scintillator array). The overall uncertainty of $\rho_\mu(300)$ varies from $\sim 15\%$ to $\sim 40\%$ for individual events.

By making use of the event-by-event method [8] we estimate, for each event, the probability that it has been

[1] Due to fluctuations, a minor fraction λ of photons with $E > 10^{18}$ eV would have $E_{\rm rec} < 10^{18}$ eV; we account for these "lost photons" as described in Ref. [8].

initiated by a primary photon with energy in the range under study. To this end, we use a library of photon-induced showers with different energies and arrival directions, of which we select those which have the same scintillator signal and zenith angle as the observed event, up to reconstruction errors (a detailed description of the method is presented in Ref. [8]). Since all events in the sample have reconstructed energies below 10^{19} eV, we do not expect azimuthal-angle dependence of the shower properties due to geomagnetic cascading; therefore we require consistency between the arrival directions of the observed and artificial showers in zenith angle only. To obtain the limit on the flux of primary photons, we slightly modified the technical part of the procedure of Ref. [8]. Suppose that the integral flux of primary photons over a given energy range is F_γ. Then we expect to detect

$$\bar{n}(F_\gamma) = F_\gamma A(1-\lambda)$$

photon events in average, where A is the exposure of the experiment for a given dataset and λ is the fraction of "lost" photons. Let $\mathcal{P}(n)$ be the probability to have n photons in a dataset (calculated from data following Ref. [8]). To constrain the flux F_γ at the confidence level ξ one requires

$$\sum_n \mathcal{P}(n) W(n, \bar{n}(F_\gamma)) < 1 - \xi\,,$$

where $W(n, \bar{n})$ is the Poisson probability to observe n particles for the average $\bar{n}$.

To simulate the shower library, we used CORSIKA 6.611 [12] with FLUKA 2006.3 [13] as a low-energy hadronic interaction model and EPOS 1.61 [14] as a high-energy model. This choice of the hadronic model corresponds to the highest muon density and therefore provides a conservative limit on the gamma-ray flux; however we checked that the difference between EPOS 1.61 and QGSJET II [15] is negligible for photon showers. We used thinning (10^{-5}) with weights limitations [16] to save computational time. The responce of the scintillators was simulated with GEANT in Ref. [17].

Below, we present limits on the fraction of gamma rays among the observed events and on the absolute gamma-ray flux. The flux limits do not depend on the choice of hadronic interaction model used in simulations, nor on the energy reconstruction used in the experiment; the only assumption is that electromagnetic showers are simulated correctly. The fraction limits depend on the energy scale assumed for non-photon primaries.

III. RESULTS

The upper limits on the observed flux and fraction of primary gamma rays are summarized in Table I. We compare the limits with those from previous works in Fig. 1 (for the gamma-ray fraction) and Fig. 2 (for the gamma-ray flux).

The sensitivity of plastic scintillators to electromagnetic showers, strong discriminating power of large-area

$E_{\min}$, eV	95% CL upper limits		
	F_γ, km^{-2}sr^{-1}yr^{-1}	ϵ_γ (shift 0%)	ϵ_γ (shift -30%)
(1)	(2)	(3)	(4)
10^{18}	0.22	0.004	0.006
2×10^{18}	0.13	0.008	0.018
4×10^{18}	0.13	0.041	0.108

TABLE I: Upper limits (95% C.L.) on the integral flux F_γ of photons with $E > E_{\min}$ and on the fraction ϵ_γ of photons in the total integral flux of cosmic rays with $E > E_{\min}$. The flux limits (col. (2)) do not depend on the energy reconstruction procedure; the fraction limits are given for the assumption of correct energy reconstruction for non-photon primaries (col. (3)) and for the assumed overall systematic shift of -30% for non-photon primaries (col. (4)).

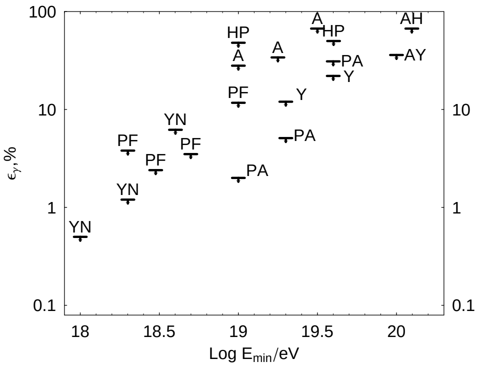

Fig. 1: Limits (95% CL) on the fraction of primary gamma rays in the integral flux of cosmic rays with $E > E_{\min}$ from: this work (YN); the fluorescent detector of the Pierre Auger Observatory (PF) [7]; the surface detector of the Pierre Auger Observatory (PA) [18]; Yakutsk (Y) [10]; reanalises of the AGASA (AH) [19] and AGASA and Yakutsk (AY) [9] data; AGASA (A) [20] and Haverah Park (HP) [21].

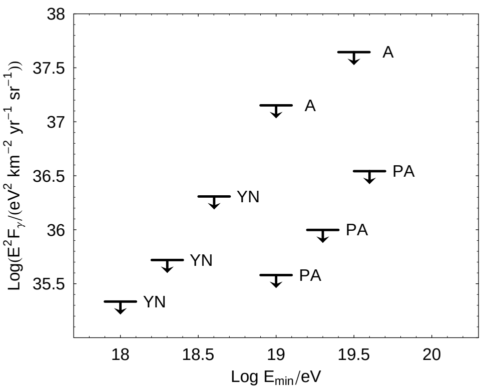

Fig. 2: Limits (95% CL) on the integral flux of primary gamma rays with $E > E_{\min}$ from: this work (YN); the surface detector of the Pierre Auger Observatory (PA) [18] and AGASA (A; assume proton plus gamma composition) [20].

muon detectors, 25-year exposure and a sophisticated analysis method allowed us to put the most stringent limits on the primary photon flux at energies higher than 10^{18} eV and 2×10^{18} eV. These limits challenge previously allowed new-physics models and start to fill the gap between $\sim 10^{16}$ eV and $\sim 10^{19}$ eV limits on the diffuse gamma-ray flux. The flux limits do not depend on the energy reconstruction used by the experiment (a reconstruction in assumption of primary photons is used), nor on the simulations of hadronic showers. The fraction limits also use the energy estimation in assumption of primary photons and also do not rely on simulation of hadronic showers; however they depend on the assumed energy estimation of non-photon primary particles. This dependence is weak in the high-statistics regime, cf. Table I.

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