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Derivation of upper limit on the photon fraction using the highest-energy AGASA cosmic rays

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A new method to derive an upper limit on photon primaries for small data sets of air showers is described which accounts for shower properties varying with the primary energy and arrival direction. Applying this method to the highest-energy AGASA data, an upper limit on the photon fraction of 51% (67%) at a confidence level of 90% (95%) for primary energies above $1.25 \cdot 10^{20}$ eV is derived.

1. Introduction

Robust experimental limits on the cosmic-ray photon component might be a key to distinguish between theoretical source models for the highest-energy cosmic rays. In particular, some non-acceleration models, usually fitted to the AGASA data at the high-energy end of the spectrum, predict photon dominance above 10^{20} eV [1]. We compare the muon densities measured in AGASA events $> 10^{20}$ eV to simulations of air showers induced by photons, taking photon conversion in the geomagnetic field into account.

To statistically quantify the level of agreement between the primary photon fraction predicted by a model and the observed air shower data, a method is required that accounts for (i) event-by-event fluctuations in the considered shower observable (here: the muon density) for fixed primary parameters (ii) a possible change of average shower properties for the different events in the data sample (e.g. different photon conversion probabilities depending on the direction of the observed event) (iii) the limited event statistics (which is unavoidable at the high-energy end of the cosmic-ray spectrum).

We describe such a method that allows one to test the contribution of photon primaries or any other particle type to cosmic rays and to possibly set an upper limit on the primary fraction with well-defined confidence level. Since only a limit on the primary *fraction* is placed, this method does not rely on a knowledge of the absolute cosmic-ray flux. Moreover, no potential signal background from other primary particle types has to be considered, as only the rejection power to photons is quantified: Any photon-like contributions from other primaries would just weaken the rejection power to photons and increase the numerical value of the derived upper limit. As a consequence, this analysis of photon primaries is also less severely affected by uncertainties from hadronic interaction models usually present in cosmic-ray composition studies.

Applying the new method to AGASA data allows us to exclude photon dominance at highest cosmic-ray energies at 90% confidence level. Thus, it is difficult to obtain a consistent description of the AGASA high-energy data in certain non-acceleration models which, therefore, are disfavoured as the sole explanation for the highest-energy cosmic rays.

A detailed description of the new method and the analysis is given in [2]. In the following, we provide a brief summary with the focus put on the statistical method.

2. Data and simulation

AGASA [3] consisted of 111 array detectors spread over $\simeq$100 km^2 area and 27 muon detectors with an energy threshold of 0.5 GeV for vertically incident muons. The primary energy was determined from the array data with a statistical accuracy of $\simeq$25% for hadron primaries [4]. Assuming photon primaries, the energies reconstructed this way were found to be underestimated by $\simeq$20% for the most-energetic events [3]. Six events were reconstructed with $>$100 EeV which had more than one muon detector within 800-1600 m distance from the shower core [3]. The muon density ρ_j at 1000 m core distance was obtained for each event j=1 . . . 6 with an uncertainty of 40% [3]. The shower parameters of these events are given in Tab. 1.

Electromagnetic cascading of photons in the geomagnetic field is simulated for the AGASA site with the new PRESHOWER code [5]. The atmospheric shower is simulated with CORSIKA 6.18 [6] as a superposition of subshowers initiated by the preshower particles or, if no preshower occurred, with the original primary photon. Electromagnetic interactions are treated by the EGS4 code [7], which was upgraded [6] to take photonuclear reactions as well as the Landau-Pomeranchuk-Migdal (LPM) effect [8] into account. For the photonuclear cross-section, the Particle Data Group extrapolation is chosen [9]. The influence when using different extrapolations is discussed in [2]. Hadronic interactions are simulated with QGSJET 01 [10].

3. Method and Results

In contrast to previous approaches, the information about individual event topologies is used in the new method. For each AGASA event, 100 primary photon showers are generated. The reconstructed primary parameters [4] are adopted as simulation input, taking for the primary energy the statistical experimental resolution and the systematic underestimation in case of photon primaries into account. The distribution $\rho_j^{\rm s}$ of simulated muon densities obtained from CORSIKA for each AGASA event is compared in Fig. 1 to the data. The average values $<\rho_j^{\rm s}>$ and standard deviations $\Delta\rho_j^{\rm s}$ are listed in Tab. 1. The average muon densities for primary photons are a factor 2-7 below the data. Qualitatively, a photon origin of most of the observed events is disfavoured.

To assess the agreement of data and photon expectation, a χ_j^2 value is calculated for each event j as

$$\chi_j^2 = \frac{(\rho_j - <\rho_j^{\rm s}>)^2}{(\Delta\rho_j)^2 + (\Delta\rho_j^{\rm s})^2} \tag{1}$$

with $\Delta\rho_j$ being the measurement uncertainty, $\Delta\rho_j = 0.4 \cdot \rho_j$ [3]. To account for possible deviations of the

Table 1. Reconstructed shower parameters of the AGASA events [3] (upper part of the Table) and simulation results (lower part). The energies are increased by 20% to account for the case of photon primaries [3]. The azimuth angle is given clockwise from north for the incoming direction.

primary energy [EeV]	295	240	173	161	126	125
zenith angle [°]	37	23	14	35	33	37
azimuth angle [°]	260	236	211	55	108	279
ρ_j [m^{-2}]	8.9	10.7	8.7	5.9	12.6	9.3
preshower occurrence [%]	100	100	96	100	93	100
$<\rho_j^{\rm s}>$ [m^{-2}]	4.3	3.1	2.1	2.3	1.7	1.8
$\Delta\rho_j^{\rm s}$ [m^{-2}]	1.1	1.0	0.9	0.6	0.5	0.5
χ_j^2	1.6	3.0	3.4	2.2	4.6	4.0
p_j [%]	20.8	8.3	6.4	13.9	3.1	4.6

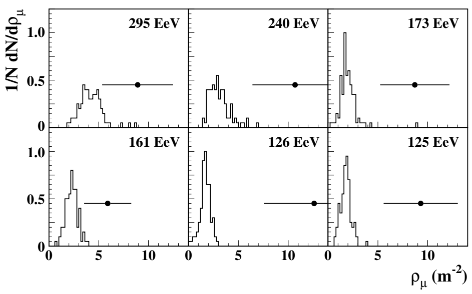

Figure 1. Observed muon densities (points with error bars) compared to the muon densities expected for primary photons (histograms) for the six events. Assigned to each event the primary energy (see Tab. 1). The measured values are above the predictions from primary photon simulations.

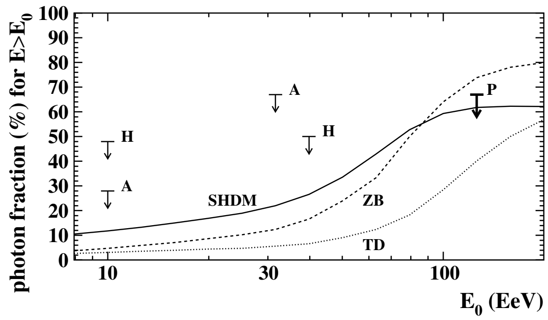

Figure 2. Upper limits on photon fraction (95% CL) from the present analysis (P) and previously from AGASA (A) [3] and Haverah Park (H) [11] compared to some predictions based on super-heavy dark matter (SHDM) [12], Z-bursts (ZB) and topological defect (TD) [13] models.

simulated muon densities from a Gaussian distribution, the probability $p_j(\chi^2 \geq \chi_j^2)$ of a photon-initiated shower to yield a value $\chi^2 \geq \chi_j^2$ is determined by a Monte Carlo technique: A simulated muon density value is taken at random from the distribution ρ_j^{s}, a random shift is performed according to the experimental resolution $\Delta\rho_j$, and a χ^2 value is calculated with Eq. (1), replacing ρ_j by the artificial muon density value. Repeating this many times then gives $p_j(\chi^2 \geq \chi_j^2)$. The values χ_j^2 and p_j are listed for the six events in Tab. 1. The probabilities p_j range from 3% to 21%.

Correspondingly, the probability $p(\chi^2 \geq \sum_{j=1}^{6} \chi_j^2)$ of six photon-initiated events to yield a χ^2 value larger or equal to the measured one can be determined as p = 0.5%. Thus, it is unlikely that all cosmic rays at these energies are photons (rejection with 99.5% confidence). An upper limit on the photon fraction F_γ can be set.

It should be noted that, due to the small event statistics, the upper limit cannot be smaller than a certain value. Assuming a fraction F_γ 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 $(1 - F_\gamma)^{n_{\mathrm{m}}}$. For n_{m}=6, this probability is $\simeq$5% for F_γ=40%. Thus, in the present case only hypothetical photon fractions $F_\gamma \geq$40% could in principle be tested at a confidence level α = 95%. In general, the relation between the minimum possible fraction F_γ^{min} that could be excluded for a given event number n_{m} (or in turn: the minimum event number $n_{\mathrm{m}}^{\mathrm{min}}$ required to possibly exclude a certain fraction F_γ) is given by

$$F_\gamma^{\mathrm{min}} = 1 - (1 - \alpha)^{1/n_{\mathrm{m}}} \ , \ \text{and} \quad n_{\mathrm{m}}^{\mathrm{min}} = \frac{\ln(1 - \alpha)}{\ln(1 - F_\gamma)} \ . \tag{2}$$

with α being the confidence level of rejection. This theoretical limit is reached only if for each event j, the observations allowed us to exclude a photon origin ($p_j \to 0$). Some numerical examples are listed in Tab. 2.

Table 2. Numerical examples for minimum fraction $F_\gamma^{\mathrm{min}}(n_{\mathrm{m}})$ that could be excluded with n_{m} events (or: minimum number of events $n_{\mathrm{m}}^{\mathrm{min}}(F_\gamma)$ required to exclude fraction F_γ) for a confidence level α = 95%.

6 ev ↔ 39.3%	10 ev ↔ 25.9%	30 ev ↔ 9.5%	100 ev ↔ 3.0%	300 ev ↔ 1.0%	1000 ev ↔ 0.3%

For deriving an upper limit F_γ^{ul}<100%, scenarios have to be tested in which n_γ=0 $\ldots n_{\mathrm{m}}$ showers out of n_{m}

events might be initiated by photons. For a hypothetical photon fraction F_γ, the probability q that a set of n_m events contains n_γ photons is $q(F_\gamma, n_\gamma, n_\mathrm{m}) = F_\gamma^{n_\gamma}(1-F_\gamma)^{n_\mathrm{m}-n_\gamma}\binom{n_\mathrm{m}}{n_\gamma}$. This probability is multiplied by the probabilities $p_\gamma(n_\gamma)\cdot p_{\overline{\gamma}}(n_\mathrm{m}-n_\gamma)$, with $p_\gamma(n_\gamma)$ being the probability that the n_γ most photon-like looking events are generated by photons, and $p_{\overline{\gamma}}(n_\mathrm{m}-n_\gamma)$ being the probability that the remaining $n_\mathrm{m}-n_\gamma$ events are due to non-photon primaries. $p_\gamma(n_\gamma)$ is determined by the MC technique as the probability to obtain values $\chi^2 \geq \sum_{i=1}^{n_\gamma}\chi^2_{k_i}$, with $p_\gamma(0)$=1 and with $\chi^2_{k_i}$=χ^2_j from Tab. 1, where index k_1 refers to the event with smallest value χ^2_j, and $\chi^2_{k_i}\leq\chi^2_{k_{i+1}}$. To derive an upper limit on photons, the probabilities $p_{\overline{\gamma}}(n_\mathrm{m}-n_\gamma)$ are set to unity. Summing over all possibilities n_γ=0 . . . n_m then gives the probability $P(F_\gamma)$ to obtain χ^2 values at least as large as found in the data set,

$$P(F_\gamma) = \sum_{n_\gamma=0}^{n_\mathrm{m}} q(F_\gamma, n_\gamma, n_\mathrm{m})\cdot p_\gamma(n_\gamma)\cdot p_{\overline{\gamma}}(n_\mathrm{m}-n_\gamma)\ . \tag{3}$$

This probability depends on the assumed photon fraction F_γ. For the considered AGASA data set one obtains $P(F_\gamma{=}51\%) = 10\%$ and $P(F_\gamma{=}67\%) = 5\%$. Therefore, the upper limit on the primary photon fraction is $F_\gamma^\mathrm{ul} = 51\%$ (67%) at 90% (95%) CL. The derived bound is the first limit on the photon contribution above the GZK cutoff energy. The limit refers to the photon fraction integrated above the primary photon energy that corresponds to the lowest-energy event in the data sample, which in the present analysis is 125 EeV.

In Fig. 2, upper limits derived previously at lower energy and the current bound are compared to some predictions based on non-acceleration models. Models predicting photon dominance at highest energies are disfavoured by the presented upper limit.

The new method can easily be applied also to data from other air shower experiments, see e.g. [14].

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