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# Pushing sensitivity of AGASA array to EHE gamma primaries

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We show that, using high quality Monte Carlo EAS simulations and appropriate analysis, the AGASA data on muon density for the higher energy events can be used to put far stringer bounds on photon component than reported before. Based on a simplified model of the AGASA muon counters we find some evidence of gamma primaries. We show also that the hadron composition determination can be significantly biased due to the presence of a few gamma primaries.

## 1. Aims and Motivations

The determination of the gamma component in EHECR is a key ingredient in origin model discrimination. A few limits on this component has been reported [1] [2], [3] [4]. the more stringent above $10^{19}$ eV being that coming from Auger [2]: $26\%$[1]. The AGASA collaboration, in the same rank, has reported a limit of $30\%$ [1] based on 147 events to which the muon density at 1000 m of the core was successfully measured. We intend to show here that based on the same data a much higher sensitivity to gamma primaries can be achieved provided that high quality Monte Carlo (MC) EAS simulations are used in the analysis. We exploit the speed and optimization of the AIRES simulation program [5] to perform such simulations, and show that such small quantities as 4 out of 147 gamma primaries can be detected.

## 2. Simulations and Results

We have produced high quality proton, iron and gamma initiated MC EAS simulations for the AGASA site. We used AIRES, whose speed and optimization allowed us to run simulations with excellent statistical sampling (relative thinning factor $10^{-6}$, weight factor 0.01, see the AIRES manual [5] for details on these parameters). We have also simulated in detail the effects of gamma ray preshowering through the MaGICS special primary module [6]. We used both QGSJET01 [7] andSIBYLL 2.1 [8] hadron models. The zenith angle was constrained to be less than 36 deg, in accordance to the cuts in experimental data reported in [1].

In those simulations it was found that the muon density at 1000 meters from the shower core $\rho(1000)$ for hadron initiated events have a distribution with sharp end, in such a way that all events were seen to lie within a "band" delimited by two straight lines in the plane $\log(E_{prim})$, $\log(\rho(1000))$, with slope 0.93. On the other hand, gamma events have a much broader distributions due to the LPM effect, which enhance greatly shower to shower fluctuations. Anyway, more than $97.5\%$ lie outside (indeed below) the already mentioned "hadron band".

We used our simulations to generate samples of 147 events, intended to mimic the experimental data shown in [1] (to do so, we assumed a spectrum proportional to $E^{-2.5}$), with diverse iron/proton ratios and number of gamma events. Then, parameters sensitive to the iron fraction and to the number of gamma events were evaluated in both the experimental data set and the simulated data sets in order to extract an estimation for both. A critical issue in the generation of such samples is detector simulation; since we do not know the details

[1] recall that this limit was obtained from 17 events only, and will be greatly enhanced as statistics grows

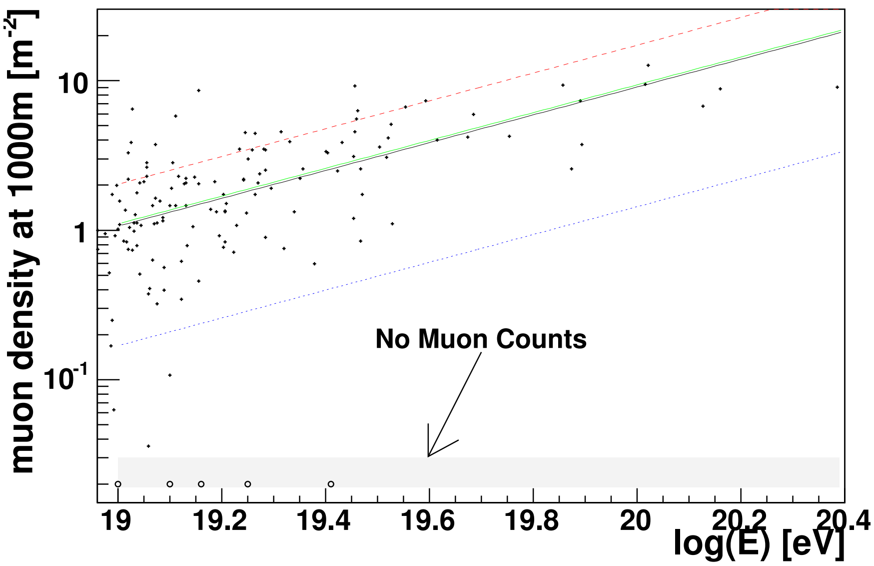


**Figure 1.** AGASA Experimental data [1] for muon density at 1000 m from the core vs. energy. The lines are those described in the text: from top to bottom, 1,2,3 and 4.

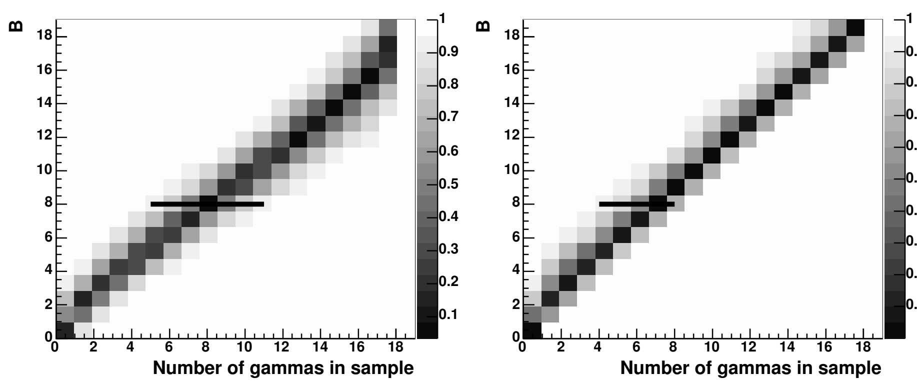


**Figure 2.** $A$ versus number of gamma primaries for the generated MC samples, with each of our two detector models. The thick lines correspond to the experimental values for the number of gamma events at 95% CL given the observed value $B = 8$.

of the detectors, we have built two realistic and somewhat independent models in order to cross check the results. We think that, even if we cannot trust fully the models, they are accurate enough to trust conclusions on the array sensitivity to the studied observables.

In figure 1 we show the AGASA experimental data set for the highest energy events to which the muon density at 1000 meters from the core could be measured [1], together with the lines used to define the parameters

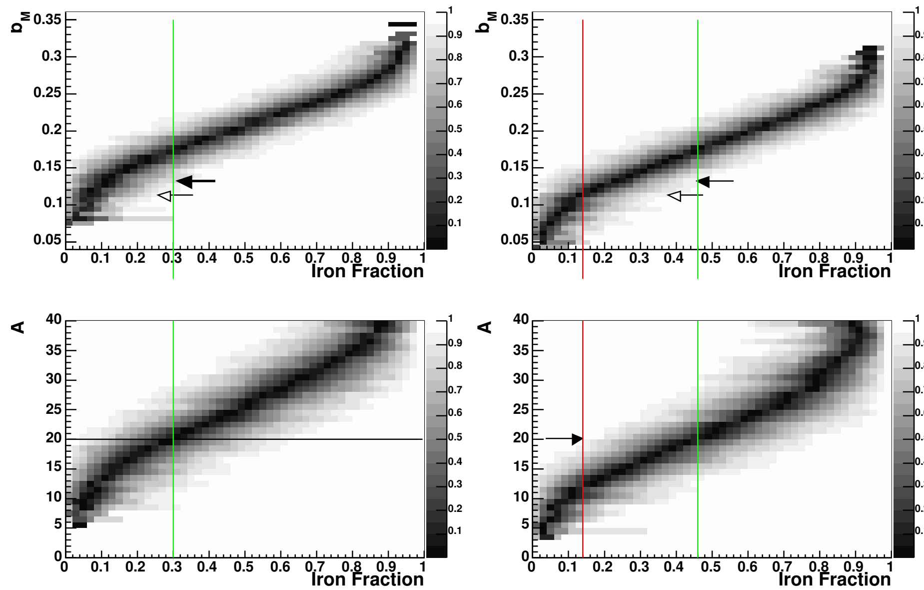


**Figure 3.** $b_M$ and $A$ vs iron fraction for the generated MC samples, with no systematics in energy (left) and with a systematic overestimation of 40% (right). The solid arrows shows the experimental $b_M^{(corrected)}$ and $A$, while the empty ones shows the value for $b_M$. The vertical lines mark the iron fraction deduced from that values.

sensitive to iron fraction and number of gamma events, as described below. The lines, of the form $\log(\rho) = b + m\log(E - E_0)$ where we fixed arbitrarily $E_0$ to be 19.1 eV, and we selected $m = 0.93$ in accordance to the slope observed for the hadron band limiting lines mentioned above[2]. Observe that with this choices the only free parameter is $b$. We first find a line such that half the events lie above it (line 3 of the figure), and call $b_M$ the value of $b$ for that line. Since iron events tend to produce more muons at 1000 meters than the proton ones, $b_M$ happens to be sensitive to the iron fraction. After a number of gamma primaries is estimated (as explained below), a "corrected" $b_M$ ($b_M^{(corrected)}$, line 2 of the plot) can be found. Other line used for analysis correspond to $b = 0.4$ (line 1); the number of events lying above this line, $A$, is another parameter also sensitive to the iron fraction, for the same reasons (observe, however, that is quite independent from $b_M$). Both indicators are dependent on systematic missestimation of primary energy, since such systematic error shift both lines. We could not find any efficient indicator for iron fraction showing independence of energy systematics. Finally, a line with $b = b_M - 0.8$ (line 4) is used to define the indicator $A$, the number of events below that line, which is sensitive to the number of gamma events. Since this line is defined relative to that with $b = b_M$, $A$ is seen to be quite insensitive to energy systematics. The values of these parameters are: $b_M = 0.12$, $b_M = 0.135$, $A = 20$, $B = 8$.

We then produced MC samples as explained above with random iron fraction, 8000 of them without gamma events and 16000 with random number of gamma events between 0 and 20 (8000 for each detector model)[3], and for each of them we found their corresponding $b_M$, $A$ and $B$. In figure 2 the relation between $b$ and the

[2]Notice, however, that we can choose whatever value of $m$ we want, provided we use it the same way for real and simulated data; the chosen value is expected to be close to optimal, as such lines "follow the trend" for hadronic data.

[3]QGSJET and SIBYLL data are merged in order to obtain some model independence.

number of gamma events in that samples is displayed in the form of Kolmogorov profiles, such that for each value of $B$ the corresponding values for the number of gamma events with their CL are apparent[4]. The number of gamma events at $95\%$ CL for the experimental value $B = 20$ are shown with thick lines. We can see that the data set of [1] can be used to detect such a small quantity as 4 gamma events out of 147, which is far more stringent than the $30\%$ bound reported by the AGASA collaboration [1]. We claim that such improvement is achieved because of the better statistical sampling used in the simulations, since for the analysis in [1] the standard Hillas algorithm with thinning factor $10^{-5}$ has been used [9] Also if we trust our detector models we can see that this data support some evidence of gamma events (this is of course not conclusive due to our lack of detailed knowledge of the detectors). In figure 3 the same is done for the relations of $b_M$ and $A$ to the iron fraction. This is done also under the hypothesis of a systematic overestimation in energy of $40\%$. In the case of $b_M$ we can see a significative difference depending whether we take or not the candidate gamma events. It is also observed that the estimations based on $b_M$ and $A$ are compatible (more if we consider $b_M^{(corrected)}$), strengthening our trust in the detector model.

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