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## Testing the correlation of ultrahigh energy cosmic rays with high redshift sources

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We study the correlation between compact radio quasars or 3EG gamma-ray blazars and the arrival direction of cosmic rays above  $10^{19}$  eV using an updated list of air shower detections. Our Monte Carlo simulations reveal no significant correlations above random results, and some previous positive results appear to be an effect of the small sample size. Consequently, there is no evidence for ultrahigh energy cosmic ray primaries being new particles or particles with new interactions beyond the electroweak scale, produced in high-redshift active galactic nuclei.

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Over the last few years, several giant air showers have been detected confirming the arrival of cosmic rays (CRs) with energies greater than a few hundred EeV ( $1 \text{ EeV} \equiv 10^{18} \text{ eV}$ ) [1]. The nature and origin of these extraordinarily energetic particles remain a mystery [2]. The main problem posed by the detection of CRs of such energy, assuming them to be photons, nucleons, or nuclei, is that interactions with the microwave background radiation limit their attenuation length to less than about 50 Mpc. Therefore, if the CR sources were all at cosmological distances, the energy spectrum would exhibit the so-called Geisen-Zatsepin-Kuzmin (GZK) [3] cutoff around 80 EeV. Since this is not observed, an astrophysical origin requires the sources to be within about 100 Mpc. Furthermore, apart from the energetic difficulties of accelerating particles to such energies [4], the seeming isotropy on large angular scales of the observed arrival directions up to the highest energies [5] leaves only two possibilities for the source locations: (1) There must be many nearby sources, at least one close to each arrival direction, but no such convincing source candidates within 100 Mpc have been found [6]; (2) there are only very few nearby sources which then requires strong deflection [7] in galactic and/or extragalactic magnetic fields of micro Gauss strength close to existing upper limits [8].

Recently, Farrar and Biermann [9] have pointed out the existence of a strong correlation between compact radio quasars (CRQSOs) and CR events with energies above 80 EeV at  $1\sigma$  level, i.e., events with nominal energies high enough that the full  $1\sigma$  error bar is above 80 EeV. Specifically, they have argued that the arrival directions of the CRs of such energies point back to CRQSOs (redshifts in the range  $z = 0.3\text{--}2.2$ ) with a probability of chance association of  $5 \times 10^{-3}$ . If such a correlation is real, it could only be due to particles generated in these high-redshift sources, which should traverse unscathed through the primeval radiation evading the GZK cutoff and being deflected by less than the experimental angular resolution, of the order of a degree. Note that in such scenarios the ratio of the signal of neutral

particle flux to the charged particle background depends on many parameters such as the acceleration process and charged particle deflection by large scale magnetic fields, but should become large above the GZK cutoff. In the previous analysis the CRQSO correlation appeared not to depend strongly on the energy threshold [10].

Since the energies of the known strongly or electromagnetically interacting particles drop below  $\approx 80$  EeV during the propagation from high redshift distances regardless of the initial energy [2], and since within the standard model neutrinos cannot give rise to the observed showers due to their small interaction cross section, a clearly established correlation would most likely indicate new physics. Possibilities involving neutral, undeflected particles that have been discussed in the literature include undiscovered neutral hadrons with masses above a few GeV [11], and neutrinos attaining cross sections in the millibarn range above the electroweak scale, which would make them primary candidates for air showers observed at the highest energies. Sufficiently heavy neutral particles would avoid pion production and thus the GZK cutoff, whose threshold energy increases linearly with rest mass  $m$ ,  $E_{th} = m_\pi(m + m_\pi/2)/\varepsilon$ , where  $m_\pi$  is the pion mass and  $\varepsilon$  is the background photon energy. Such particles have been discussed in the context of supersymmetry with a light gluino, although this possibility appears to be close to being ruled out [12]. If new physics becomes relevant around TeV energies, increased neutrino-nucleon cross sections can occur due to the exchange of graviton Kaluza-Klein modes in the context of extra dimensions [13] or due to an exponential increase of the number of degrees of freedom in the context of string theory [14].

In the absence of new physics only neutrinos producing nucleons and photons via resonant  $Z$  production with the relic neutrino background within about 50 Mpc from the Earth could give rise to angular correlations with high-redshift sources [15]. However, this requires enormous neutrino fluxes and/or extreme clustering of relic neutrinos with masses in the eV range for the interaction rates to be sufficiently high [16].

Very recently, the Haverah Park experiment presented the analysis of inclined showers ( $60^\circ < \text{zenith angle} < 80^\circ$ ) which includes two events above 100 EeV [17]. In addition,

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TABLE I. Cosmic ray events considered in the study. Errors in position are given, except for the AGASA experiment, which was considered as a circle of  $1.6^\circ$  radius (see text). Errors in energy for AGASA events were taken as 30% (see text).

UHECRs	energy [ $\times 10^{20}$ eV]	RA (deg)	DEC (deg)
FE320	3.20+0.92-0.94	85.2 $\pm$ 0.5	48.0+5.2-6.3
HP120	1.20 $\pm$ 0.10	179.0 $\pm$ 2.7	27 $\pm$ 2.8
HP105	1.05 $\pm$ 0.08	201.0 $\pm$ 8.7	71 $\pm$ 2.5
HP123	1.23+1.0-0.36	86.7 $\pm$ 1	31.7 $\pm$ 1.2
HP114	1.14 $\pm$ 0.09	318.3 $\pm$ 1	3.0 $\pm$ 2.3
Ag213	2.13	18.75	21.1
Ag144	1.44	241.5	23.0
Ag150	1.50	294.5	-5.8
Ag134	1.34	280.9	48.3
Ag120	1.20	349	12.3

the Akeno Giant Air Shower Array (AGASA) has reported several remarkable CR events, scattered across half the sky, [5,18], that doubled the original sample used in Ref. [9]. Thus, and in light of the theoretical scenarios mentioned above, it is worthwhile to test again the possible correlation between the arrival direction of the most energetic CRs and CRQSOs with flat spectrum. These quasars are strong radio emitters, a fact that along with their compactness and variability, is indicative of strong beaming. The bulk of the observed nonthermal emission of these objects is thought to be produced in strong, relativistic jets of charged particles emitted by the active nucleus, which is likely formed by an accreting supermassive black hole.

An interesting subgroup of these sources is formed by the gamma-ray emitting blazars, which are presumably the most energetic of them all. There are 66 blazars detected with high confidence by the Energetic Gamma Ray Experiment Telescope (EGRET) of the Compton Gamma Ray Observatory, 47 of them in the declination range we are interested in [19]. The 3EG catalogue currently contains the most complete sample of high energy blazars detected so far. Although the most popular models for gamma-ray emission in these objects are of leptonic nature, there exists a very interesting family of hadronic models where the high-energy emission is the result of a proton-initiated cascade [20]. These models open up the possibility that primaries for ultrahigh energy cosmic rays (UHECRs) above  $10^{19}$  eV could come from secondary reactions in the hadronic showers, making very energetic EGRET active galactic nuclei (AGN) detections potential candidates for the sources of UHECR events. We shall use then these 47 EGRET sources as well as the 451 CQSOs with flat spectrum and declination above  $-10^\circ$  taken from the surveys of Ref. [21], to test again the hypothesis advanced by Farrar and Biermann. We shall use the new and enlarged AGASA UHECR sample [18] plus the highest energy events detected by Haverah Park [17,22] and Fly's Eye [23]; see Table I.

In order to establish the level of positional coincidence between QSOs and UHECR events and evaluate its significance, we shall adopt the code recently developed by Romero *et al.* [24] for gamma-ray bursts and unidentified

TABLE II. Positional coincidence (PC), i.e., the number of real matches within angular resolution, and simulated positional coincidence (SPC), from an isotropic distribution, between the highest energy CRs and CRQSOs for different threshold energies. 27 EeV  $-1\sigma$  means, for instance, that the UHECR events considered have nominal energies such that, subtracting to it a  $1\sigma$  energy error, the result is above 27 EeV. The last column indicates the Poisson probability of random occurrence of any number of coincidences bigger or equal than the real PC. Columns Ag, HP, and FE stand for the number of considered events of AGASA, Haverah Park, and Fly's Eye, respectively.

Energy cutoff	Ag	HP	FE	PC	SPC	Prob.
27 EeV $-1\sigma$	58	—	—	12	8.7 $\pm$ 2.75	0.13
80 EeV $-1\sigma$	5	4	1	4	2.7 $\pm$ 1.33	0.27
50 EeV $-2\sigma$	4	4	1	4	2.6 $\pm$ 1.28	0.26
70 EeV $-2\sigma$	1	3	1	3	2.0 $\pm$ 1.01	0.31

galactic gamma-ray source studies. This code calculates angular distances between different kinds of celestial objects in selected catalogs, and establishes the level of positional correlation between them. Numerical simulations using large numbers of synthetic populations (thousands of them were made for each correlation study), sampled randomly and uniformly in right ascension and declination, are then performed in order to determine the probability of pure chance spatial association. In the present case, we generate synthetic populations of the same number of ultrahigh energy cosmic ray events as observed and compare them with the actual positions of CRQSO and gamma-ray blazars. We have first taken into account that the uncertainties in the arrival directions of each of the UHECRs is maintained, i.e., we consider the same positional errors as those reported for the observed events, and second, that the artificial sets of UHECR events are constrained (as the actual ones) to the declination range  $\delta > -10^\circ$ . The treatment of the positional errors is as follows: we consider a circle around the centroid of each UHECR event; this circle has a radius equal to the reported  $1\sigma$  position error for the UHECR. If a CRQSO or EGRET blazar is within this circle, we say that there is a positional coincidence. This procedure was adopted for all events. In the case of the Fly's Eye and other experiments, where there is an elongated error box, it was substituted by a circle of similar area. We are not giving a higher significance to directional coincidences with small offsets than to coincidences that are not so close, just because the original errors of the UHECRs are of the order of degrees. The reader is referred to Ref. [24] for more details about the procedure.

The results of our analysis are shown in Tables II (CRQSOs) and III (gamma-ray blazars), where we present, from left to right, the adopted energy cutoff, the number of real events detected by AGASA (Ag), Haverah Park (HP), and Fly's Eye (FE), the number of real positional matches found, the number expected from pure chance estimated by the simulations, and finally the probability that the results be the mere effect of chance. In establishing the positional correlations, both real and simulated, we have adopted an average error of  $1.6^\circ$  for the AGASA events, as recommended in

TABLE III. Same as Table I, but for gamma-ray blazars taken from the third EGRET catalog.

Energy cutoff	Ag	HP	FE	PC	SPC	Prob.
27 EeV $-1\sigma$	58	—	—	1	$0.7 \pm 0.88$	0.46
80 EeV $-1\sigma$	5	4	1	1	$0.3 \pm 0.59$	0.26
50 EeV $-2\sigma$	4	4	1	1	$0.3 \pm 0.52$	0.26
70 EeV $-2\sigma$	1	3	1	1	$0.2 \pm 0.47$	0.19

Ref. [18]. As a consequence, the highest energy event of AGASA (Ag213) is not coincident with any CRQSO, contrary to what was mentioned in Ref. [9]. For the remaining errors we have kept those used by Farrar and Biermann. AGASA reports an angular cone radius defined such that in 68% of the events, the true direction is contained within the error cone, and it results to be  $1.6^\circ$  including systematic errors. Errors in energy for AGASA events were taken as 30%.

From our results using the newest complete UHECR sample, it can be seen that the probabilities for the actual coincidence level to be a random occurrence significantly rise with respect to the previous work by Farrar and Biermann. The actual coincidences are all less than  $2\sigma$  away from the simulated mean value.<sup>1</sup> In order to test the consistency between our results and those of Farrar and Biermann for the case of CRQSOs, we repeated the analysis for the most restrictive cutoff in Table I (70 EeV  $-2\sigma$ ) without taking into account the recent data reported by Haverah Park, and considering the positional error for Ag213 to be big enough for the CRQSO possible counterpart to be included (i.e., an error of  $1.8^\circ$  as in [25]). This situation reproduces the case reported by Farrar and Biermann (i.e., the event sample excluding AG110) [10] and yields a simulated positional coincidence of  $1.75 \pm 0.90$ , with a chance association probability of 6%, as compared to their number of 1.6% [10]. This difference is the result of the use of a different statistical technique, particularly in the treatment of positional errors which in our case were taken into account using top-hat functions. We remark, however, that the samples of both UHECR events and CRQSOs were the same. Although for the old data set our analysis method yields chance probabilities larger by a factor 3–4 than theirs, this does not change our main conclusion, namely that for the new data set the chance probabilities increase by a factor  $>5$  (within our analysis) and therefore become insignificant. One may as well ask what are the results of the analysis when only the newest data are taken into account. Taking then only the UHECRs not included in the analysis by Farrar and Biermann, we find—using the 80 EeV  $-1\sigma$  and 50 EeV  $-2\sigma$  cutoffs—that there is only one real positional coincidence with QSOs. Using the 70 EeV  $-2\sigma$  cutoff there are no real

coincidences at all. In all cases, the mean value of the expected random result is always  $1\sigma$  away from the real result (here, the random result is even bigger), and it is totally compatible with it. No correlation is found using only the newest data.

Two extra checks can be taken into consideration. Firstly, one may wonder whether the inclusion of the Fly’s Eye (FE) event has any strong impact in our results. The FE experiment was probably insufficiently uniform in right ascension; however, the influence of the FE experiment in our study is very low, since only one event is an UHECR. Nevertheless, we have explored what happens with our results when only the HP and AGASA events are taken into account. Simulations showed that the real positional coincidence is compatible ( $1\sigma$ ) with the random results for all considered cutoffs. Secondly, one may wonder if a precise modeling of the actual exposure of the combined experiments can modify the results. This, however, would make a direct comparison with the previous work by Farrar and Biermann impossible. Nevertheless, one can consider that the UHECRs events are fixed in their actual positions, while the quasistellar objects (QSOs) are randomly distributed. By fixing the UHECRs we do respect the exposures of the experiments, and as we certainly expect the QSOs to be a uniform population, we ask in this way what is the probability to find a chance association between the UHECRs detected and a random uniform distribution. Our results show that when this is done, there is no reason at all to consider that the correlation of UHECRs with QSOs is significant: again the actual coincidences are all less than  $2\sigma$  away from the simulated mean value.

The correlation with gamma-ray blazars is also likely the result of chance: we obtain chance probabilities of 26% for the highest energy events and of 46% for the events with an energy cutoff at 27 EeV. For CRQSOs the probabilities are somewhat lower, but still not significant, and are notably above the values given in Ref. [9].

Virmani *et al.* [26] recently have also performed a correlation study. Their analysis shows a remarkable correlation between UHECRs and CRQSOs, apparently in contradiction with our result. However, most of their correlation signal comes from events with large uncertainty both in energy and in position. It can be seen that independently of the statistical test, the correlation between UHECRs and CRQSOs decreases when considering only the highest energy events ( $E > 8 \times 10^{19}$  eV at 1 standard deviation) that are relevant for new physics because they have no contamination from the expected proton pile-up around the photopion production threshold. Furthermore, the QSO sample used by Virmani *et al.* is a subsample of ours, formed only by 285 radio loud quasars with flat spectrums obtained from Kuhr’s catalog and checked with NED. Apparently BL LACs or blazars were not considered, nor were undetermined cases. The possibility of the latter being usual radio galaxies is small because of the flat spectral index, and consequently both Farrar and Biermann’s and our present study took them into account. Virmani *et al.* also included UHECR events from the SUGAR experiment, which is the only UHECR detector that was operative in the southern hemisphere. These events strongly contribute to their correlation signal as can be seen

<sup>1</sup>Note also that a UHECR event, ( $E \approx 150$  EeV) which satisfies a restrictive cutoff energy being at least  $\geq 50$  EeV at  $2\sigma$  level, has no CQSO within its error box. Even when doubling the error and searching for background sources with NED, no CQSO appears there.

from their Table 1. However, due to the large detector spacing in SUGAR, their energy and angular resolution were much poorer than for other experiments and it is not clear whether the events seen were above the GZK cutoff [27]. Finally, the UHECR sample in the northern hemisphere used by Virmani *et al.* is different from ours: we considered 10 UHECR events at most, 8 of them were studied by Virmani *et al.*, but two recent events from Haverah Park were not. The positional error in AGASA was  $1.6^\circ$  in our case [18] and  $1.8^\circ$  in theirs. Taking into account these differences, the statistical methods used by Virmani *et al.* would also give a much weaker correlation signal.

In light of these results, our conclusion is that the association of CRQSOs and gamma-ray emitting blazars with UHECRs above the GZK cutoff appears to not be compelling. Hence, there is currently no support for new multi-GeV

neutral hadronic particles, or for neutrino-nucleon cross sections in the millibarn range, as explanations of the highest energy cosmic rays; at least not if these particles are conjectured to be produced in the classes of sources considered here. We further note that such scenarios, if there were evidence for them, would require the sources to accelerate protons at least up to  $\sim 10^{22}$  eV, since the neutral primary candidates have to be produced as secondaries. While standard acceleration theory requires rather extreme parameters to achieve that, we note that only a few dozen such sources in the whole visible universe would suffice.

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