New hadrons as ultrahigh energy cosmic rays

Michael Kachelrieß
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany

Dmitry V. Semikoz
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany and Institute for Nuclear Research of the Academy of Sciences of Russia, Moscow, 117312, Russia

Maria A. Tórtola
Instituto de Fisica Corpuscular–CSIC, Universitat de Valencia, Edificio Institutos de Paterna, Apt. 22085, E-46071 Valencia, Spain
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Ultrahigh energy cosmic ray (UHECR) protons produced by uniformly distributed astrophysical sources contradict the energy spectrum measured by both the AGASA and HiRes experiments, assuming the small scale clustering of UHECRs observed by AGASA is caused by pointlike sources. In that case, the small number of sources leads to a sharp exponential cutoff at the energy $E<10^{20}$ eV in the UHECR spectrum. New hadrons with a mass of 1.5–3 GeV can solve this cutoff problem. For the first time we discuss the production of such hadrons in proton collisions with infrared or optical photons in astrophysical sources. This production mechanism, in contrast with proton-proton collisions, requires the acceleration of protons only to energies $E \lesssim 10^{21}$ eV. The diffuse gamma-ray and neutrino fluxes in this model obey all existing experimental limits. We predict large UHE neutrino fluxes well above the sensitivity of the next generation of high energy neutrino experiments. As an example we study hadrons containing a light bottom squark. This model can be tested by accelerator experiments, UHECR observatories, and neutrino telescopes.

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I. INTRODUCTION

Ultrahigh energy cosmic rays (UHECRs) with energies above 10^{19} eV have been observed in all relevant experiments, i.e., Volcano Ranch [1], Haverah Park [2], Fly's Eye [3], Yakutsk [4], AGASA [5], and HiRes [6]. Their arrival directions are distributed uniformly over the sky without significant correlation with the galactic or supergalactic plane. This isotropic distribution is consistent with the simplest model for UHE primaries, in which protons are accelerated in extragalactic, uniformly distributed astrophysical sources. However, UHE protons with energies above $E>4\times10^{19}$ eV interact with cosmic microwave background (CMB) photons and lose energy quickly through pion production within 50 Mpc. As a consequence, a cutoff in the UHECR spectrum, already predicted in 1966 by Greisen, Zatsepin, and Kuzmin (GZK) [7], should show up for uniformly distributed sources at $\sim5\times10^{19}$ eV. This cutoff is not observed by the ground array experiment with the largest exposure, AGASA, while the first monocular results of the HiRes fluorescence telescope are in agreement with the GZK cutoff. The exposure at the highest energies of all other experiments is too small to allow for a definite conclusion about the presence or absence of the GZK cutoff.

Fortunately, the Pierre Auger Observatory [8], which is a combination of an array of charged particle detectors with several fluorescence telescopes, is currently under construction. Not only will it be able to resolve possible systematic differences between the ground array and fluorescence telescope techniques, it will also increase the statistics of UHECR data by an order of magnitude. The telescope array project, also based on the fluorescence technique, may serve as the optical component of the planned northern Pierre Auger site [9]. There are also plans for space based observatories such as EUSO [10] and OWL [11] with even bigger acceptance.

Assuming that the GZK cutoff will be confirmed by future experiments does not resolve the UHECR puzzle. Since all experiments including HiRes see events with energies $E>10^{20}$ eV, their sources should be located within the distance $R\lesssim50$ Mpc. Otherwise, the GZK cutoff is extremely sharp and in contradiction even with the UHECR spectrum measured by HiRes (cf. Fig. 6). But there are not many astrophysical sources known within this distance from the Earth that are able to accelerate particles to the highest energies. Moreover, these sources are not located in the directions of observed events. Another problem is a statistically significant (4.6σ for energies above 4×10^{19} eV) clustered component in the arrival directions of AGASA data [12–15]. The sensitivity of the other experiments for clustering at the energies $E>4\times10^{19}$ eV is much smaller, either because of the smaller exposure at the highest energies (Yakutsk) or because of a poor two-dimensional angular resolution (HiRes in monocular mode). At lower energies 10^{19} eV$<E<4\times10^{19}$ eV, a clustered component still exists in the AGASA data [14], but with a reduced significance of 2.3σ. The Yakutsk experiment also observes a clustered component in the energy region $E>2.3\times10^{19}$ eV, with a chance probability of 2×10^{-3} or $\sim3\sigma$ using Gaussian statistics [13].

The puzzle of the GZK cutoff can be solved in two different ways. The first one supposes that the sources of UHECRs are located nearby. Then the extragalactic magnetic field should be strong enough, $B\gtrsim0.3$ μG, to deflect UHECRs with $E>10^{20}$ eV, and magnetic lensing could be responsible for the clustered component [16]. A problem with this solution is the difficulty in constructing realistic maps of the matter and magnetic field distributions in the nearby Universe. Simulations done so far reproduced the energy spectrum and the clustered component assuming 10–100 sources, but without using realistic locations of the sources. Another difficulty is that magnetic lensing, although reproducing the clustered component, predicts in general a broad angular distribution of this component, while the data are within the experimental angular resolution. This solution is even more problematic if future experiments show the absence of the GZK cutoff: fixing the luminosity of the local sources to the UHECR flux above the GZK cutoff then results in a too large UHECR flux at lower energies, where sources from the whole Hubble volume contribute.

The second way to resolve the question of the GZK cutoff is to suppose that the clustered component is due to a neutral particle that is not deflected by (extra) galactic fields. In this case one can look for correlations of UHECR arrival directions with astrophysical objects. Tinyakov and Tkachev recently found a significant (more than 4σ) correlation with BL Lacs [17]. The BL Lacs that correlate with the UHECRs are located at very large (redshift $z\sim 0.1$) or unknown distances. If it can be shown with an increased data set of UHECRs that this correlation also holds at energies $E>(6-10)\times 10^{19}$ eV, then protons alone cannot explain the UHECR data, and a new component in the UHECR spectrum is needed.

The simplest possibility is that this new component is due to extremely high energy ($E\gtrsim 10^{23}$ eV) photons emitted by distant sources. They can propagate several hundred Mpc, constantly losing energy, and thereby creating secondary photons also inside the GZK volume [18]. However, this model requires extremely small extragalactic magnetic fields, $B<10^{-12}$ G, and the minimal possible radio background. In addition, one needs to accelerate protons to $E\gtrsim 10^{24}$ eV in order to create such photons. An acceleration mechanism to these extreme energies is not known.

Another possibility is that the events beyond the GZK cutoff are related to the Z burst model [19]. In this model, UHE neutrinos interact with the relic neutrino background producing via the Z resonance secondary protons and photons. The big drawback of this scenario is the need for an enormous flux of primary neutrinos that cannot be produced by astrophysical acceleration sources without overproducing the GeV photon background [20]. Also, in this model, primary protons have to be accelerated to extremely high energies, $E\gtrsim 10^{23}$ eV, in order to produce $E=10^{22}$ eV neutrinos.

Conventionally, acceleration mechanisms allow acceleration of protons in astrophysical sources only up to $E\lesssim 10^{21}$ eV. If one considers this maximal energy as a serious upper limit, both possibilities discussed above are excluded and some kind of new particle physics beyond the standard model is required. The most radical option is violation of Lorentz invariance [21]. A more conservative, though for some tastes still too speculative, possibility are the decaying superheavy relics from the early Universe [22]. This model cannot explain the correlation of UHECR arrival directions with BL Lacs, and could be excluded if these correlations are also found at energies $E\gtrsim(6-10)\times 10^{19}$ eV. In theories with a fundamental scale of gravity as low as $\mathcal{O}(\mathrm{TeV})$, the interactions of neutrinos with nucleons are enhanced compared to the standard model by the exchange of Kaluza-Klein gravitons [23] or the production of black holes [24]. In Refs. [25] it was claimed that neutrinos could have hadronlike cross sections at UHE and be responsible for the observed vertical air showers. However, unitarization slows down the growth of the neutrino-nucleon cross section [26,27] and, moreover, in the case of exchange of Kaluza-Klein gravitons, the energy transfer to the target nucleon is too small [26]. Thus the neutrino-nucleon cross section can be up to a factor of 100 larger than in the standard model, but neutrinos in both cases still resemble deeply penetrating particles and cannot imitate air showers initiated by nucleons.

Another possibility is that new particles are directly produced in astrophysical sources. A model with an axionlike particle, i.e., a scalar that can mix with a photon in the presence of external magnetic fields, was suggested in Ref. [28]. Axionlike particles can also be produced by photons emitted by astrophysical sources via axion-photon oscillations [29]. In supersymmetric (SUSY) theories with conservation of R parity, the lightest supersymmetric particle (LSP) is stable and can be a HE primary. This possibility was seriously discussed for the first time in connection with Cyg X-3 in the 1980s [30,31]. More recently, the production and interactions of both the neutralino and the gluino as the LSP at UHE were examined in Ref. [32]. The authors concluded that only a light gluino could be produced in reasonable amounts by astrophysical accelerators. Reference [33] calculated the neutralino production in proton-proton collisions and found that neutralinos produced in astrophysical sources cannot be an important UHE primary: Since the production cross section of neutralinos is too small, this model either predicts a negligible flux of UHE neutralinos or is not consistent with measurements of the diffuse gamma-ray background [34] and with existing limits on the neutrino flux at ultrahigh energies. The latter limits were obtained by the Fly's Eye [35], AGASA [36], RICE [37], and GLUE [38] experiments.

SUSY models with a strongly interacting particle as LSP or next-to-lightest SUSY particle (NLSP) are more interesting for UHECR physics. Hadrons containing a gluino were first suggested by Farrar as UHECR primary [39,40]. Her model, a light gluino $\tilde{g}$ together with a light photino such that the photino could serve as cold dark matter candidate, is excluded [41,42]. Motivated by the correlation of UHECRs with BL Lacs, the production of light $\tilde{g}g$ bound states in astrophysical accelerators was suggested in Ref. [43]. However, the light gluino window seems to be now closed also for generic models with a light gluino by Ref. [44].

In this paper, we start from a model-independent, purely phenomenological point of view. Since the observed extensive air showers (EASs) are consistent with simulated EASs initiated by protons, any new primary proposed to solve the GZK puzzle has to produce EASs similar to those of protons. A possibility still open experimentally is that photons are UHECR primaries: at 90% C.L., $\sim$30% of the UHECRs above $E>10^{19}$ eV can be photons [45]. However, the simplest possibility consistent with air shower observations is to require that a new primary is strongly interacting. The requirements of efficient production in astrophysical accelerators as well as protonlike EASs in the atmosphere ask for a light hadron, $\lesssim 3$ GeV, while shifting the GZK cutoff to higher energies results in a lower bound for its mass, $\gtrsim 1.5$ GeV [43]. From these requirements, we derive general conditions on the interactions of new UHE primaries.

As a specific example, we investigate the case of a hadron containing a bottom squark, which we call the "shadron" from now on. Our conclusions, however, are independent of the underlying particle physics model for the shadron. The required properties of the shadron will be parametrized as a function of its mass and production and interaction cross sections. Other suitable realizations of shadrons could be new (meta) stable hadronic states like H-dibaryons [46]. Another candidate could be connected to the exotic, charged hadronic state with mass 2.3 GeV discovered recently by BaBar [47], which was suggested by the experiment as a four-quark state. If this suggestion were true, then this four-quark state could be related to a new metastable neutral hadron.

We find that proton-proton collisions in astrophysical accelerators cannot produce high enough fluxes of new primaries without contradicting existing measurements of photon [34] and neutrino fluxes [35–37]. By contrast, we find no contradiction with existing limits for a light shadron with mass $\lesssim 3$ GeV and the astrophysically more realistic case of UHE proton collisions on optical or infrared background photons. Also, the required initial proton energy is not too extreme, $E \lesssim 10^{21}$ eV, which is compatible with existing acceleration mechanisms. The only essential condition for the sources is that they should be optically thick for protons in order to produce these new hadrons. (This condition is similar for all models with new particles produced by protons.) Below we will show that at least some of the BL Lacs correlated with UHECRs satisfy this condition.

One of the important features of the proposed model, and any model in which the production cross section $\sigma_{p\gamma\to S}$ of a new particle S is much smaller than the total proton-photon cross section $\sigma_{p\gamma}$, is the high flux of secondary high energy neutrinos. This neutrino flux is connected via the relation $F_{\rm CR}\sigma_{p\gamma}/\sigma_{p\gamma\to S}$ to the maximal contribution of S particles to the cosmic ray flux, $F_{\rm CR} \approx 1/E_{20}^2$ eV/cm^2 s sr. It can be detected by future UHECR experiments like the Pierre Auger Observatory [8], the Telescope Array [9], EUSO [10], and OWL [11]. Alternatively, such neutrino fluxes can be detected by triggering onto the radio pulses from neutrino-induced air showers [48]. Acoustic detection of neutrino-induced interactions is also being considered [49]. There are plans to construct telescopes to detect fluorescence and/or Cerenkov light from near-horizontal showers produced in mountain targets by neutrinos at intermediate energies [50,51]. Moreover, if the sources are optically thick for protons, the neutrino flux can be significant both at high energies and down to energies 10^{16}–10^{17} eV, depending on the pion production threshold on optical or infrared photons [52]. Therefore, one may observe neutrinos from the same sources both by future UHECR experiments and by neutrino telescopes like AMANDA [53], ICECUBE [54], GVD [55], ANTARES [56], NESTOR [57], or NEMO [58].

The paper is organized as follows. We start with a discussion of the spectrum of UHECR protons produced by a small number of extragalactic astrophysical sources in Sec. II. Then we consider models containing light strongly interacting particles, shadrons, and their status. In Sec. IV we discuss the propagation of shadrons through the Universe. Their interactions in the atmosphere were investigated in detail before, so we shall just briefly recall the main characteristics in Sec. V. Section VI is devoted to a detailed analysis of shadron production in astrophysical sources. In Sec. VII we discuss all the astrophysical constraints that shadrons have to obey to be viable UHECR primaries. In Sec. VIII, we discuss the particular case of BL Lacs as sources of UHECRs. Finally, we summarize our results in Sec. IX.

II. PROTONS FROM UNIFORMLY DISTRIBUTED SOURCES

The HiRes experiment recently published their data from monocular observations [6]. They showed that the UHECR flux is consistent with the GZK cutoff expected for *uniformly, continuously* distributed sources. As a result, the simplest model of UHECRs—protons accelerated in uniformly distributed, extragalactic sources—seems to be a convincing explanation of their data. The authors of Ref. [59] found as fingerprints of the expected interactions of UHE protons with CMB photons a dip at $E \sim 1\times10^{19}$ eV, a bump [60], and the beginning of the cutoff in the measured spectra of four UHECRs experiments. The agreement of the spectral shape calculated for protons with the measured spectra is excellent, apart from an excess in the AGASA data above $E \gtrsim 8\times10^{19}$ eV. These findings point to an origin of UHECRs below $E \lesssim 10^{20}$ eV in active galactic nucleus (AGN) and to protons as primaries. Despite the fact that the AGASA experiment sees a significant number of events above the GZK cutoff [5], the model of proton primaries from extragalactic sources looks very attractive, because it does not require new physics.

The model of uniformly, *continuously* distributed sources is based on the assumption that the number of UHECR sources is so large that a significant fraction of sources is inside the GZK volume. However, as was shown in a number of works [61,14,62], the small scale clustering of UHECR observed by AGASA allows estimation of the number of UHECR sources assuming that their distribution and luminosity is known. For the simplest model of uniformly distributed, similar sources their number is about several hundreds, 200–400. If we distributed these sources uniformly in the Universe, the number of sources in the GZK volume with $R=50$ Mpc would be of the order of 10^{-3}. This would mean that the nearest source should be at the redshift $z=0.1$.

A more conservative and self-consistent estimate uses the fact that protons with energies $E \geqslant 4\times10^{19}$ eV observed on Earth can propagate at most from redshift $z=0.2$ (see, e.g., Fig. 2 in [18]). Distributing the sources within a sphere at $z=0.2$ around the Earth, the closest source is at the distance $R=100$ Mpc. Note also that in the particular case of BL

Lacs as UHECR sources, which we discuss in Sec. VIII, the closest potential sources are at redshift $z\sim 0.03$.

We show now that the statement that UHECRs with $E \geqslant 10^{20}$ eV are protons from nearby sources is in contradiction with the total number of sources estimated including events below the GZK cutoff. Using Poisson statistics, the total number of sources S is fixed by the number of observed singlets $\overline{N}_1$ and doublets $\overline{N}_2$,

$$\overline{N}_1 \approx S\overline{n}, \tag{1}$$

$$\overline{N}_2 \approx S\frac{\overline{n}^2}{2}, \tag{2}$$

where $\overline{n}$ is the average number of events from a given source and we assumed equal flux from all sources. From Eqs. (1) and (2) one obtains the number of sources

$$S \approx \frac{\overline{N}_1^2}{2\overline{N}_2}. \tag{3}$$

As shown in Ref. [61], the value Eq. (3) is a model-independent lower bound on the number of sources for given values of $\overline{N}_1$ and $\overline{N}_2$. In the model of homogeneous distribution of sources with equal luminosity, the estimate for the number of sources becomes [61]

$$S \approx \frac{\overline{N}_{\rm tot}^3}{\overline{N}_{\rm cl}^2}, \tag{4}$$

where $\overline{N}_{\rm tot}$ is the total number of observed events and $\overline{N}_{\rm cl} = 2\overline{N}_2$ is the number of events in clusters. In Eq. (4), it is assumed that $\overline{N}_{\rm tot} \geqslant \overline{N}_{\rm cl}$. Note that therefore Eq. (4) always gives a larger number of sources than Eq. (3) because of the extra factor $\overline{N}_{\rm tot}/\overline{N}_{\rm cl} \geqslant 1$.

We estimate next the number of sources, assuming that all UHECRs with $E \geqslant 4\times 10^{19}$ eV are protons. Following [61,62], we use 14 events with $E > 10^{20}$ eV and one doublet. Calculating S with Eq. (3) gives $S\sim 100$ as a minimal number of sources, while the more realistic Eq. (4) gives $S \sim 700$. If we apply the same analysis to the AGASA data [14] with $E \geqslant 4\times 10^{19}$ eV, we have $\overline{N}_2 = 6$ (for simplicity we count the triplet as one doublet) and $\overline{N}_1 = 46$. Then Eq. (3) gives $S\sim 176$, while Eq. (4) gives $S\sim 1200$.

Are these two estimates consistent with the idea that all UHECRs are protons? To answer this question, we calculate the expected number of proton sources using $E \geqslant 4 \times 10^{19}$ eV when there are $S\sim 100$–700 sources in the GZK volume. Protons with $E\sim 4\times 10^{19}$ eV can reach us from $z = 0.2$, or $R_{\rm tot}\sim 1000$ Mpc. Conservatively assuming that all events with $E > 10^{20}$ eV come from within the GZK distance $R = 50$ Mpc (in [61,62] $R = 25$ Mpc was used), we obtain with Eq. (3) as the expected number of sources $S_{\rm tot} = (R_{\rm tot}/R_{\rm GZK})^3 \times 100 = 8\times 10^5$. Using instead Eq. (4), the expected number of sources is $S_{\rm tot} = 5.6\times 10^6$. These estimates should be compared to the ones from AGASA clustering data, $S_{\rm AGASA}\sim 176$ or $S_{\rm AGASA}\sim 1200$, using Eq. (3) or Eq. (4), respectively. Since the Poisson probability of observing $S_{\rm AGASA}$ instead of $S_{\rm tot}$ events is practically zero, the chance probability of obtaining these two event numbers is equal to the chance probability of clustering. We conclude therefore that the model in which *all* UHECRs with $E \geqslant 4 \times 10^{19}$ eV are protons from uniformly distributed point sources is inconsistent with the small scale clustering observed by AGASA.

One can argue that 14 UHECR events with $E > 10^{20}$ eV is an optimistically high number and that the real number of such events is much smaller, because the experiments estimate wrongly the energy of UHECR events.

We conservatively take only the four highest energy events from all experiments, including one Fly's Eye event, two AGASA events, and one HiRes event. In this case we have four single events and no doublets. We can estimate the number of sources from the absolute minimal bound Eq. (3) if we assume that the average number of doublets is less then 1, e.g., $\overline{N}_2 = 0.5$. Then there are $S = 16$ sources in the GZK volume with $R_{\rm GZK} = 50$ Mpc. Again, in a volume with $R_{\rm tot} \sim 1000$ Mpc there are $S\sim 128.000$ sources, in comparison with up to 1200 required by AGASA data above $E \geqslant 4 \times 10^{19}$ eV.

Thus, if the clustered component in the AGASA events with energy $E \geqslant 4\times 10^{19}$ eV is due to pointlike sources, the expected number of sources is of the order of several hundreds up to $S\sim 1200$, depending on the estimate used. These sources are distributed in a volume with $R_{\rm tot}\sim 1000$ Mpc. Assuming that the UHECR events with $E > 10^{20}$ eV are protons requires 10–400 sources in the GZK volume with $R_{\rm GZK} = 50$ Mpc. These two facts are in contradiction, if all UHECRs are protons. In other words, if UHECRs with $E \geqslant 4\times 10^{19}$ eV are protons, we should have less than one source, namely, $S \lesssim 0.1$, in the GZK volume.

Let us now discuss the consequences of a small number of sources for the model of uniformly, continuously distributed point sources of protons. For our calculations, we have used the code developed in Ref. [63], in which all important effects (pion production, e^+e^- production, and the expansion of the Universe) are taken into account. Essentially, we have repeated for the case of proton primaries and BL Lacs as sources the calculations made in [18] in more detail for photons. In Figs. 1 and 2 we show with thin solid lines the spectra of continuously distributed sources of protons with emission spectrum $1/E^{2.7}$ and $E_{\rm max} = 10^{21}$ eV as in Ref. [59]. The dotted, thick solid, and dashed lines are for the same model, but with no sources within 50 Mpc, $z_{\rm min} = 0.03$, and $z_{\rm min} = 0.1$ around the Earth, respectively. The minimum distance of $z_{\rm min} = 0.03$ corresponds to the BL Lac distribution.

Let us concentrate on Fig. 1, which shows the measured spectrum of HiRes and where the fit model of [59] with an infinite number of sources (thin solid line) works well. If there are no sources within 50 Mpc (dotted curve), the two highest HiRes data points are well above the model fit. For the BL Lac case where the closest known sources are at $z_{\rm min} = 0.03$, two additional experimental points are away from the fit. Finally, for a uniform distribution of 400 proton

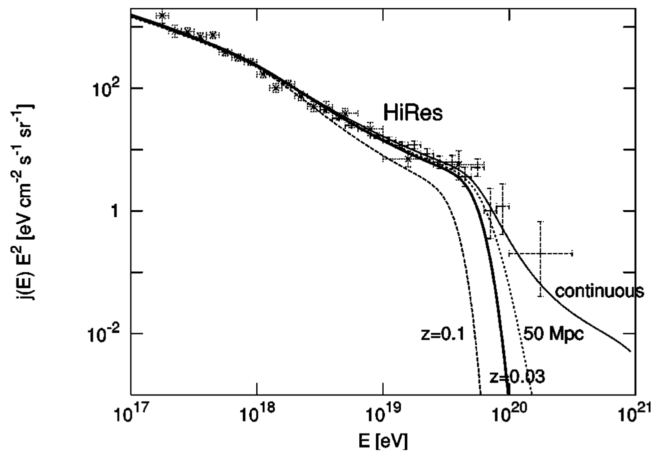

FIG. 1. UHECR flux measured by the HiRes experiment [6]. The thin solid line corresponds to a uniform, continuous distribution of proton sources in the Universe with emission spectrum $1/E^{2.7}$ and $E_{\max}=10^{21}$ eV. The dotted curve is for the same model, but with no sources within 50 Mpc from the Earth. The thick solid line corresponds to no sources within $z_{\min}=0.03$, the dashed line to $z_{\min}=0.1$.

sources over the Universe, or $z_{\min}=0.1$, the disagreement above the cutoff becomes even worse. Note that we are concerned only about energies above $\sim 6\times 10^{19}$ eV; at lower energies, the quality of the fitted model can easily be improved by a readjustment of the fit parameters. The same figure with experimental data from AGASA is shown in Fig. 2.

Thus, if the clustered component of the AGASA data for $E \geqslant 4\times 10^{19}$ eV (which has a statistical significance of 4.6σ) is not a statistical fluctuation or the result of magnetic lensing, the expected relatively small number of UHECR sources is inconsistent with the model of proton primaries emitted by uniformly continuously distributed sources for both the HiRes and AGASA data. This means that both the AGASA and HiRes data require the introduction of a new component (not protons) in the UHECR spectrum. In the following sections we will consider new light hadrons with the mass of 2–3 GeV as such a new component.

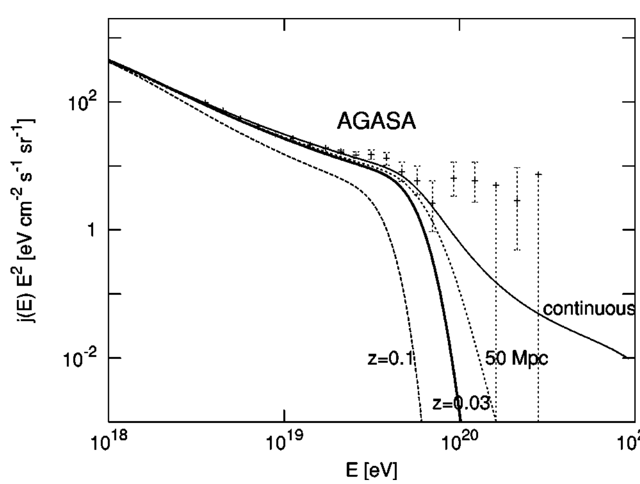

FIG. 2. UHECR flux measured by the AGASA experiment [5]. All other parameters are the same as in Fig. 1.

III. LIGHT STRONGLY INTERACTING PARTICLES: MODELS AND EXPERIMENTAL STATUS

We shall concentrate our discussion on the definite case of the light bottom squark, which is rather predictive and allows various tests of our assumptions. Since a useful UHE primary should be stable or quasistable with lifetime $\tau \gtrsim 1$ month (cf. Sec. IV), only the LSP or the NLSP is a possible candidate as new UHE messenger in SUSY models with (approximately) conserved R parity. The NLSP as UHE primary can be realized if it has a very small mass splitting with the LSP or if the LSP is the gravitino; in the latter case the NLSP decays gravitationally and its lifetime can be long enough.

Theoretically, the best motivated candidates for the LSP are the neutralino $\tilde{\chi}$ and the gravitino $\tilde{G}_{3/2}$. While in minimal supergravity models the LSP is the lightest neutralino (in some part of the parameter space it is the sneutrino), in models with gauge-mediated SUSY the LSP is normally the gravitino. Recently, a light bottom squark $\tilde{b}$ with mass $m_{\tilde{b}} \sim 2$–6 GeV has been suggested [64], motivated by the large bottom quark production cross section measured at the Tevatron [65]: The long-standing puzzle of overproduction of $b\bar{b}$ pairs can be solved if there exists additionally to a light bottom squark a light gluino with mass $m_{\tilde{g}} \sim 12$–16 GeV.

Bottom squarks as LSPs can form either charged $\tilde{B}^- = (\tilde{b}\bar{u})$ or neutral $\tilde{B}^0 = (\tilde{b}\bar{d})$ (plus charge conjugated) two-quark states. Since qu states are generally lighter than qd states, it is likely that the charged $\tilde{B}^{\pm} = (\tilde{b}u)$ is lighter than the neutral $\tilde{B}^0 = (\tilde{b}d)$. But their mass difference will be very small, e.g., for the usual B system $m_{B^0} - m_{B^{\pm}} \sim 0.33 \pm 0.28$ MeV, and we therefore consider the question whether the lightest state would be charged or neutral as open. Moreover, the mass difference in the $\tilde{B}$ system could be smaller than the electron mass, and weak decays would therefore be kinematically forbidden. In this case, both the $\tilde{B}^{\pm}$ and the $\tilde{B}^0$ would be stable. Apart from the two-quark states, there will be baryonic three-quark states, like, e.g., $\tilde{b}ud$. These baryonic states can decay into a baryon and a $\tilde{B}$ if kinematically possible.

Theoretically, the lightest hadronic state could be electrically charged. Is it possible that a light, stable charged hadron evaded detection? At Serpukov and the CERN ISR several searches for such particles were performed in the 1970s [66–68]. For example, the CHLM experiment excluded the range $m \geqslant 2.4$ GeV for stable hadrons with charge $q=1$ [67]. Below 2.4 GeV, the production of antideuterons could hide other hadrons with a similar mass. Since the ratio R of antideuteron to pion production in these experiments is rather high, $R \sim 5\times 10^{-4}$ [68], and the mass resolution of these experiments not too fine, a significant fraction of deuterons could be misidentified as stable charged hadrons. Also, the TRISTAN experiment did not include the deuteron region in their search for massive stable hadrons [69]. While the LEP experiments, in particular DELPHI, could exclude generally charged shadrons down to masses of 2 GeV, the limit in the case of a bottom squark with small couplings to the Z boson is weakened and bottom squarks with masses below 5 GeV are allowed [70]. The ALEPH exclusion limit was not extended to masses below 5 GeV [71]. The CLEO experiment was able to exclude charged hadrons with mass $m \lesssim 3.5$ GeV, but only for fractional charges [72]. However, since there is also no positive evidence for a stable charged hadron, we consider mainly the option that the lightest bottom squark containing hadron is neutral.

Next we recall that a light bottom squark is consistent with electroweak precision observables and with the LEP Higgs boson mass limit [73]. Reference [74] showed that this scenario implies a light top squark, $m_{\tilde{t}_1} \lesssim 98$ GeV, offering the Tevatron run II experiments the possibility to (dis)prove indirectly the light bottom squark case. The observation of a $\bar{\tilde{b}}\tilde{b}$ resonance in e^+e^- annihilation is difficult to extract from the background because the $\bar{\tilde{b}}\tilde{b}$ resonance has to be produced in a p wave [75]. Its contribution to $e^+e^- \to$ hadrons is small compared to the error of these measurements. Since the lightest $\tilde{B}$ behaves as a stable particle in any accelerator experiment, its identification would require a dedicated analysis. We consider therefore a bottom squark with mass 1.5–3 GeV as a viable option and shall investigate its use as a UHE primary in the subsequent sections.

Finally, we discuss the case of rather short-lived shadrons. Possible decays are $\tilde{b} \to b + \tilde{G}_{3/2}$ in models where the gravitino is the LSP or decays like $\tilde{G} \to \pi + \nu$, etc., if R parity is violated. In Ref. [76], it was argued that these decays can be excluded by proton decay experiments. If the lifetime of $\tilde{g}$ or $\tilde{b}$ is close to the required lower limit of ~ 1 month, the shadrons produced by cosmic rays and contained in the detector material have time to decay during the buildup and start phases of the experiment. Since these experiments are deep underground, they are well shielded and cosmic rays or shadrons cannot reach the detectors. In the case of a detector using purified detector material, shadrons originally contained could also be extracted in the purification process, depending on the chemical properties of the shadrons.

Light bottom squarks do not contradict cosmological limits: The relative abundance of gluinos is $n_{\tilde{g}}/n_\gamma \sim 10^{-20}$–$10^{-17}(m_{\tilde{g}}/\mathrm{GeV})$ [77] and possible decays do not disturb big bang nucleosynthesis (BBN) [78]. If baryon number also resides in baryons $\tilde{N}$ containing bottom squarks, then their number is suppressed by $n_{\tilde{N}}/n_B \sim \exp(-M_{\tilde{N}}/T_{\mathrm{QCD}}) \sim \exp(-3/0.16) \sim 10^{-7}$, where T_{QCD} is the temperature of the QCD phase transition. Again there is no conflict with BBN.

We should stress that light bottom squarks in SUSY theories serve merely as examples. Any particle physics model that has a (quasi)stable particle with mass 1.5–3 GeV and interacts strongly with protons should have similar consequences for the physics of UHECRs.

IV. PROPAGATION THROUGH THE UNIVERSE: HOW TO AVOID GZK CUTOFF

Strongly interacting particles S propagating through the Universe interact with CMB photons producing pions, if their energy is above the single pion production threshold,

$$E_{\mathrm{th}} = \frac{m_\pi^2 + 2 m_\pi M_S}{4\epsilon_0}. \tag{5}$$

Here, m_π and M_S denote the mass of a pion and of S, respectively. For the following simple estimates, we neglect the Bose-Einstein distribution of the photon energies and use just the average energy of a CMB photon, $\epsilon_0 = \pi^4 T_0/30\zeta(3) \approx 6.4\times 10^{-4}$ eV. In order to avoid the GZK cutoff, the cross section of strongly interacting hadrons S with photons should be smaller than that of nucleons,

$$\sigma_{S\gamma} = B\left(\frac{m_p}{M_S}\right)^2 \sigma_{p\gamma}, \tag{6}$$

where the suppression factor in the resonant case comes from the different center-of-mass momenta in the Breit-Wigner formula. The dimensionless parameter B is $B(s) \lesssim 1$, because the assumed resonant state (the equivalent of the Δ resonance) has a mass larger than S.

Thus, strongly interacting UHE particles with $E \gg E_{\mathrm{th}}$ will interact with CMB photons on the typical scale

$$l_{\mathrm{int}} = \frac{1}{\sigma_{S\gamma} n_0} = (8 \;\; \mathrm{Mpc}) \frac{\sigma_{p\gamma}}{\sigma_{S\gamma}}, \tag{7}$$

where the CMB number density is $n_0 = 410$ cm^{-3} and $\sigma_{p\gamma} = 10^{-28}$ cm^2 is the multipion production cross section. During each interaction, the particle S loses the fraction $y \sim 0.5$ of its energy until its energy is close to E_{th}. There, the energy fraction lost reduces to m_π/M_S, while the cross section can be increased due to resonances.

If one defines the radius R_{GZK} as the distance after which a particle S with $E \gg E_{\mathrm{th}}$ has lost 95% of its initial energy, then

$$R_{\mathrm{GZK}} = \frac{\ln 20}{y\sigma_{S\gamma} n_\gamma} \sim 48 \frac{\sigma_{p\gamma}}{\sigma_{S\gamma}} \;\; \mathrm{Mpc}. \tag{8}$$

In the case of protons, this effect was first considered by Greisen, Zatsepin, and Kuzmin in 1966 [7] and it is called the GZK effect. The threshold energy for protons from Eq. (5) is $E = 1\times 10^{20}$ eV. However, protons with energies $E_{\mathrm{GZK}} = 4\times 10^{19}$ eV can still interact with the high energy tail of the CMB distribution.

Let us now consider the case of a new, strongly interacting particle S from a general point of view. If it is heavier than a proton, then its GZK cutoff is both softened and shifted to higher energies. The first effect arises because of the smaller energy transfer near threshold, while the second one is due to a smaller resonant cross section with CMB photons. Let us now turn to our specific examples $\tilde{G} = (\tilde{g}g)$, $\tilde{B}^0 = (\tilde{b}d)$, and $\tilde{B}^\pm = (\tilde{b}u)$. The first case was studied in Ref. [43]. It was found that $\sigma_{\tilde{G}\gamma}$ is at least a factor of 8 smaller than $\sigma_{p\gamma}$, even for such low masses as $m_{\tilde{g}} = 1.5$ GeV. This small cross section, together with the reduced energy losses per scattering, leads to a shift of the GZK cutoff close to the maximal energies of astrophysical

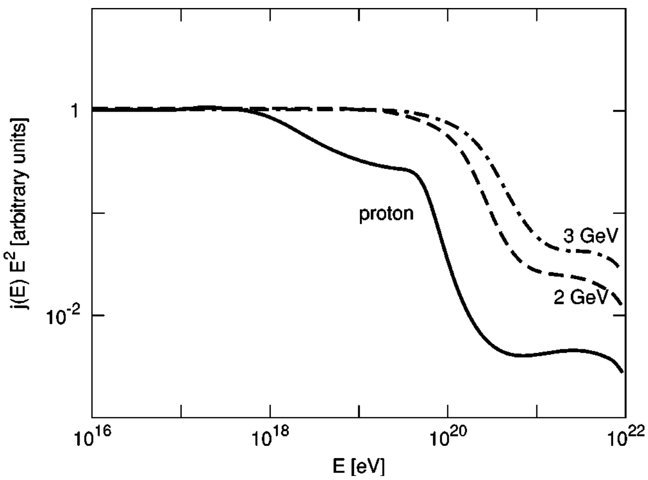

FIG. 3. Energy spectrum of $\tilde{B}^0$ hadrons with injection spectrum E^{-2} and uniformly distributed sources for $M_{\tilde{B}}=2$ and 3 GeV; for comparison a proton spectrum is also shown. At energies 10^{18} eV $<E<6\times10^{19}$ eV the proton spectrum is also suppressed due to e^+e^- production.

accelerators [43]. While in the case of $\tilde{G}$ some information about the mass spectrum of low lying $\tilde{g}$ containing hadrons is available [79], this information is missing for $\tilde{B}^{0,\pm}$. Since knowledge of the low lying resonances of $\tilde{B}$ is essential to perform a detailed calculation of its energy losses on CMB photons, we can only estimate the energy losses. To be conservative, we assume that the resonant contribution to $\tilde{B}\gamma$ scattering is suppressed only by its larger mass, or $B=1$ in Eq. (6), and by the smaller energy transfer close to threshold, $y=m_\pi/M_{\tilde{B}}$. Using as the smallest value for $M_{\tilde{B}}\sim2$ GeV then shifts $E_{\rm th}$ by a factor of 2, which together with the other suppression factors causes only a mild GZK effect at high enough energies. The resulting spectrum is shown for $\tilde{B}^0$, an injection spectrum E^{-2}, and uniformly distributed sources for $M_{\tilde{B}}=2$ and 3 GeV in Fig. 3. In the case of the charged $\tilde{B}^\pm$, additionally e^+e^- pair production has to be considered. For comparison we show in Fig. 3 the proton spectrum from the same distribution of sources.

Another important condition is that the particle S should be stable, traveling through the Universe. The lifetime t_S should be bigger than

$$t_S=\frac{R_U}{c}\frac{M_S}{E_{\rm UHE}}\approx 12\ \text{days}\ \frac{R_U(\text{Gpc})M_S(\text{GeV})}{E_{20}}, \qquad (9)$$

where R is measured in Gpc, M_S in GeV, and $E_{20}=E/(10^{20}\ \text{eV})$. Note that this allows the possibility that the gravitino is the LSP and the gluino or bottom squark is the NLSP. In this case, the NLSP decays only via gravitational interaction and thus has a long enough lifetime to serve as UHECR messenger. On the other hand, all experimental constraints from searches for anomalous heavy isotopes can easily be avoided in this scenario.

Thus any new strongly interacting messenger particle with multi-GeV mass and lifetime bigger than a year can travel over cosmological distances and solve the GZK problem. In particular, gluinos and bottom squarks containing mesons and baryons can serve as messenger particles.

V. INTERACTIONS IN THE ATMOSPHERE

The interactions of glueballinos with nucleons were considered in detail in Ref. [43]. There, the Monte Carlo simulation QGSJET [80], which describes hadron-hadron interactions using the quark-gluon string model of the supercritical Pomeron in the framework of the Gribov-Regge approach, was extended to include light gluinos. Moreover, extensive air showers were simulated and the resulting lateral and longitudinal shower profiles were compared to those of EASs initiated by protons. The authors of Ref. [43] concluded that glueballinos with mass $\gtrsim5$ GeV resemble a penetrating particle and can already be excluded using existing data, while EASs initiated by glueballinos with mass $\lesssim3$ GeV can be differentiated from proton showers only by future experiments with larger statistics.

The calculations of Ref. [43] were done only for the special case of a glueballino. However, $\tilde{B}$ hadrons with the same mass should have very similar interaction properties. The main reason for this is that the coupling of the Pomeron to a hadron as well as the slope of its coupling depend essentially on the size of the hadron, and therefore on its reduced mass. Minor differences arise because of the different constituent masses of quarks and gluons, resulting in different momentum distributions of gluinos and squarks in different hadrons with the same mass. Otherwise, the soft and semihard interactions have the same dependence on its mass. Finally, the hard interactions of the constituents at UHE energies are practically mass independent in the low mass range of interest. We conclude therefore that $\tilde{B}$ hadrons with mass $\lesssim3$ GeV also produce EASs consistent with present observations.

VI. PRODUCTION OF SUSY PARTICLES IN ASTROPHYSICAL SOURCES

Protons are the most natural candidates for the observed UHECRs with energies above the ankle $E>10^{19}$ eV. There are several mechanisms that could be responsible for the acceleration of protons to the highest energies. The most popular one is particle acceleration in shock fronts or Fermi acceleration of the first kind. However, there are other, more exotic mechanisms such as, e.g., particle acceleration in the vicinity of black holes rotating in an external magnetic field (see, for example, [81]).

Independent of the specific acceleration mechanism, a simple estimate of the maximal possible energy up to which a source can accelerate particles was suggested by Hillas [82]. It is based on the relation $E_{\max}=qBL$, where q is the charge of the accelerated particle, B the magnetic field strength in the acceleration region, and L its size. Only a few astrophysical objects are able to accelerate particles to UHE according to this simple criterion. Plausible candidates for acceleration to UHE are AGNs, and several AGN subclasses have been suggested as sources of UHECRs. The general perception is that it is possible to accelerate protons in objects like AGNs up to $E_{\max}\lesssim 10^{21}$ eV, but that acceleration to higher energies is extremely difficult because of energy losses.

A. Proton-proton interactions

We start with a perturbative calculation of the production cross section of bottom squarks in proton-proton collisions. The main contribution to the total cross section is given by the gluon-gluon subprocess, first calculated at leading order in [83]. The center-of-mass energy $\sqrt{s}$ of this process is rather high, $\sqrt{s}\gtrsim 300$ TeV, and we restrict ourselves therefore to a leading-order calculation. We have used the CTEQ6 parton distribution functions [84] with the scale $\mu^2=\hat{s}$ and calculated as the main contribution to the total production cross section the parton subprocesses $gg\to\tilde{g}\tilde{g}$ and $gg\to\tilde{b}\tilde{\bar{b}}$. For the relatively large gluino masses still allowed, $m_{\tilde{g}}\gtrsim 6$ GeV, the cross section of $gg\to\tilde{g}\tilde{g}$ is too small and we do not discuss this case in the following.

The bottom squark production cross section as a function of the UHE proton energy E_p in the lab frame is shown in Fig. 4(a) for masses $M_{\tilde{b}}=3,4$, and 5 GeV. At energies $E_p\sim 10^{13}$ GeV, this cross section reaches several millibarns. The fast increase of the cross section with energy is caused by the growing number of accessible soft gluons with smaller and smaller $x_{\min}(s)$ values. Therefore, the price to be paid for such a large cross section is the small energy fraction transferred, $\langle y_{\rm ls}\rangle=\langle E_{\tilde{b}}/E_p\rangle\sim 10^{-3}$ for $E_p=10^{20}$ eV; see Fig. 4(b). Such small values of y make it impossible to produce UHE bottom squarks in pp collisions: even if the primary protons had energy $E_p=10^{23}$ eV, the average energy of the produced bottom squark would be only 10^{19} eV. Since 10^4 more energy will be dumped into neutrinos and photons than into bottom squarks, it is impossible to explain the UHECR flux $F_{\rm CR}$,

$$F_{\rm CR}(E)=\left(\frac{10^{20}\ \text{eV}}{E}\right)^2\frac{\text{eV}}{\text{cm}^2\ \text{s sr}},\qquad (10)$$

with bottom squarks without overproducing photons and neutrinos. The photons produced will cascade down to GeV energies and overshoot the diffuse gamma-ray flux measured by EGRET [34] by two orders of magnitude. In principle, one can argue that it is possible to transfer this energy already in the source to energies below those measured by EGRET, thereby avoiding the EGRET bound. However, at the same time the neutrino flux of the order of 10^5 eV/cm^2 s sr will overshoot existing limits on the neutrino flux, given by Fly's Eye [35], AGASA [36], and RICE [37].

B. Proton-photon interactions

We consider next the perturbative calculation of the production cross section of bottom squarks in proton-photon collisions. Now, the most important subprocesses for squark

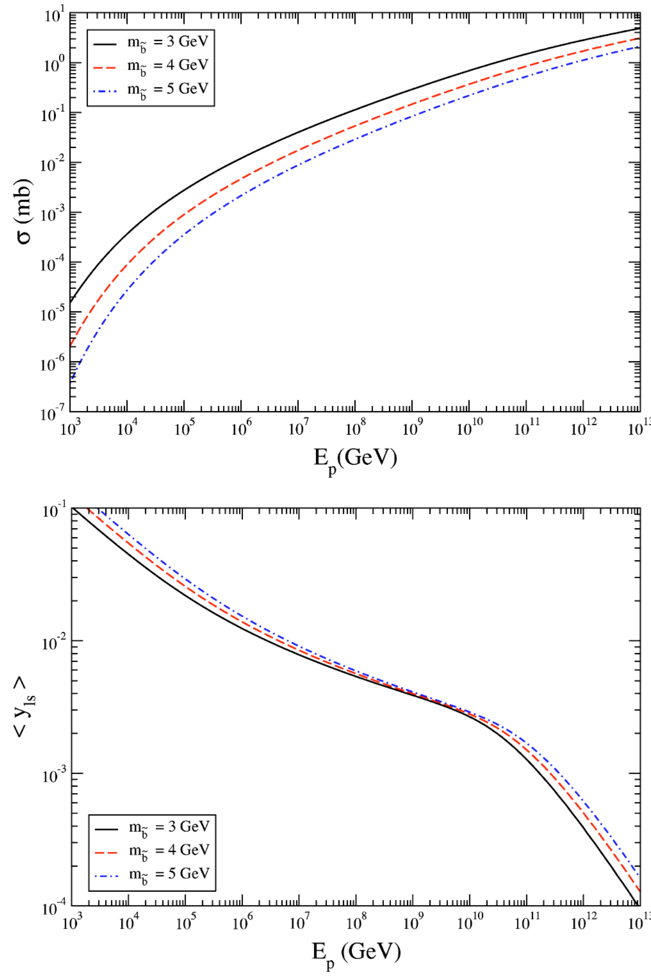

FIG. 4. (a) Bottom squark production cross section in proton-proton interactions as a function of UHE proton energy. (b) Energy fraction transferred to bottom squarks from initial protons as a function of UHE proton energy.

production is the parton subprocess $\gamma g\to\tilde{b}\tilde{\bar{b}}$. The cross section for bottom squark production is shown in Fig. 5(a). Even compared to the relatively small total $p\gamma$ cross section, which is of the order of 0.1 mb, this cross section is small. However, now the center-of-mass energy can be much smaller: the typical energy of an infrared or optical target photon is in the range 0.1–10 eV; hence $\sqrt{s}$ is between the production threshold and several 100 GeV. Therefore, the energy fraction transferred is now much higher; see Fig. 5(b). However, the combination of these two suppression factors is again very small. Normalizing the UHE $\tilde{g}$ or $\tilde{b}$ flux to the UHECR flux, Eq. (10), would produce 10^6 times higher neutrino and photon fluxes, which is again in contradiction both with diffuse gamma-ray flux measurements and with neutrino bounds.

Apart from the perturbative contribution to the cross section calculated above, nonperturbative contributions have to be considered, where at small momentum transfer hadrons interact with each other. A calculation of this kind could be performed in the vector dominance model. Then the total

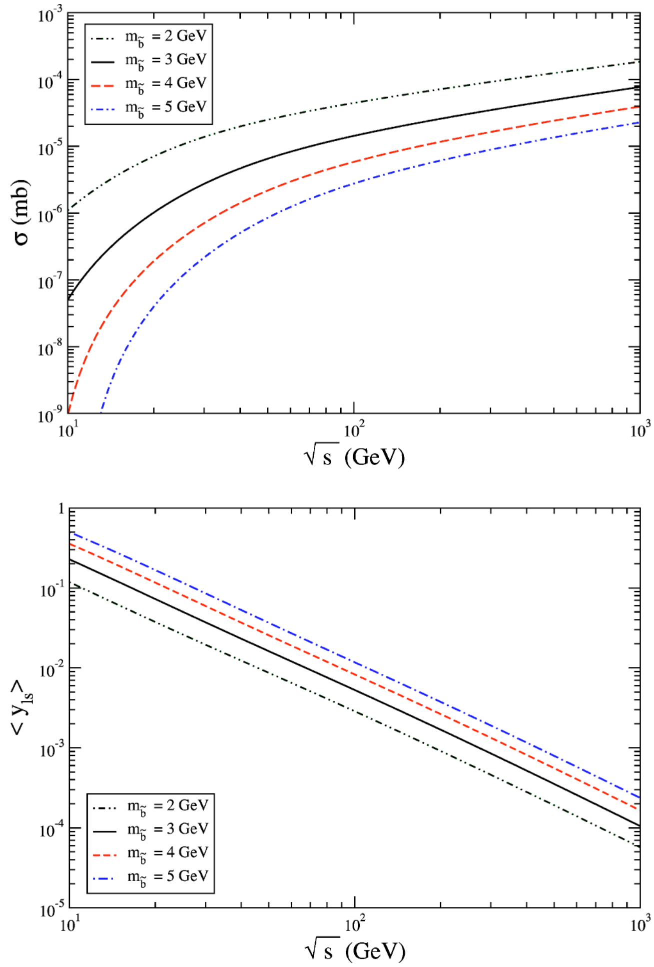

FIG. 5. (a) Perturbative part of bottom squark production cross section in proton-photon interaction as a function of center-of-mass energy. (b) Part of the energy transferred to bottom squarks from initial protons as a function of center-of-mass energy in perturbation theory.

production cross section can be split into two parts,

$$\sigma^S_{p\gamma} \approx \sum_i \alpha w_i \sigma_{ip} + \frac{3\alpha e_q^2}{2\pi}\int_{k_\perp^2 > Q_0^2} \frac{dk_\perp^2}{m_{\tilde{b}}^2 + k_\perp^2}\sigma_{\gamma\to qq}(s,k_\perp^2), \tag{11}$$

where the sum i extends over the vector mesons i with weight w_i and the second part describes the perturbative process $\gamma\to\bar{\tilde{b}}\tilde{b}$ matched to the first contribution at $Q^2=Q_0^2$ [85]. The second contribution can be evaluated at UHE and gives $\sigma^S_{p\gamma}\sim(m_\pi/m_{\tilde{b}})^2\sigma_{p\gamma}$. The dominant subprocess of the first part is the t channel exchange of $\tilde{B}$ mesons. It is therefore natural to expect that this contribution is also suppressed relative to the photon-proton total cross section in the multipion production region by the ratio m_π^2/M_S^2. We shall therefore parametrize the bottom squark production cross section as

$$\sigma^S_{p\gamma} = A\frac{m_\pi^2}{M_S^2}\sigma_{p\gamma}, \tag{12}$$

where $A(s)\lesssim 1$ is a dimensionless factor depending on s. We expect $A(s)\sim 1$ in the high energy region and $A(s)\to 0$ for $s\to 4m_{\tilde{b}}^2$. The transferred energy can be as high as 10–50 %. The required photon energies are of the order of 0.1–10 eV.

Since we are interested in shadron masses around 1.5–3 GeV, we can compare the value predicted by Eq. (12) with the total charm production cross section in proton-photon collisions. Reference [86] collected experimental data [87] in the energy range from $\sqrt{s}=10$ to 200 GeV; the cross section increases from 10^{-3} mb at $\sqrt{s}=20$ GeV to 10^{-2} mb at $\sqrt{s}=200$ GeV. According to Eq. (12), we would expect a cross section $(m_\pi/M_D)^2\sigma_{p\gamma}\sim 5\times 10^{-3}\sigma_{p\gamma}\sim 10^{-3}$ mb. Hence we conclude that Eq. (12) is a rather conservative estimate.

Close to threshold, t channel exchange of $\tilde{B}$ mesons proceeds as $p+\gamma\to(ud\tilde{b})+(\bar{\tilde{b}}u)$ and $p+\gamma\to(uu\tilde{b})+(\bar{\tilde{u}}d)$. Thus at moderate UHE energies the UHECR flux should consist of the usual protons, and positive and neutral $\tilde{b}$ hadrons. At the highest energies, when several $\tilde{b}$ hadrons are produced, additional negatively charged $\tilde{b}$ hadrons appear.

Let us compare these numbers with the parameters of astrophysical objects. The important difference to proton-proton interactions is that the energy of background photons are normally much smaller than the proton mass and thus also the center-of-mass energy is reduced. The required center-of-mass energy to produce particles with mass in the multi-GeV range is around $s=50\ \mathrm{GeV}^2\ s_{50}$. It should be somewhat higher than the threshold $4M^2$ to avoid the kinematical suppression effects near threshold. The typical photon energy then is

$$\epsilon = \frac{s}{2E_p} = 0.25\frac{s_{50}}{E_{20}}\ \mathrm{eV}. \tag{13}$$

Photons of such energies exist in many astrophysical objects which can accelerate protons. However, the accelerated protons should interact inside these objects with photons. In other words, the propagation length l_{int} of protons should be smaller than the size R of the interaction region,

$$l_{\mathrm{int}} = \frac{1}{\sigma_{p\gamma}n_\gamma} < R. \tag{14}$$

For example, the time variability of several days in the optical spectrum of AGN cores corresponds to a region size of $R=10^{16}$ cm [88]. The photon density can be estimated from the optical and infrared luminosity,

$$n_\gamma = \frac{L}{4\pi c R^2 \epsilon_\gamma} = 10^{13}\frac{1}{\mathrm{cm}^3}\frac{L_{44}}{R_{16}^2\epsilon_{-1}}, \tag{15}$$

where the quantities introduced are the dimensionless luminosity $L_{44}=L/(10^{44}\ \mathrm{erg/s})$, the region size $R_{16}=R/(10^{16}\ \mathrm{cm})$, and the typical photon energy $\epsilon_{-1}=\epsilon/(0.1\ \mathrm{eV})$. Substituting the multipion production cross section $\sigma_{p\gamma}\approx 10^{-28}\ \mathrm{cm}^2$ and Eq. (15) into the condition (14), we obtain

$$\tau=\frac{R}{l_{\rm int}}=10\frac{L_{44}}{R_{16}\epsilon_{-1}}\gg 1. \tag{16}$$

Thus, if the parameters of the source are similar to those in Eq. (16), protons produced inside such sources will interact with background photons and can potentially produce secondary hadrons *S*. However, the produced hadrons still need to escape from the astrophysical source. The escape condition is the inverse of the one given in Eq. (14): The optical depth for the new hadrons should be small assuming the same source parameters. Then the escape condition is

$$\sigma_{S\gamma}<\frac{1}{\tau_{p\gamma}}\sigma_{p\gamma}, \tag{17}$$

where the optical depth for protons $\tau_{p\gamma}$ is defined by Eq. (16). In the case of a light glueballino, the suppression of the $\sigma_{S\gamma}$ cross section can be of the order of 0.1 in comparison to $\sigma_{p\gamma}$ at center-of-mass energies of the order of 10 GeV [43]. This is consistent with Eq. (17), if the parameters of the astrophysical object are the same as in Eq. (16). In the case of a light bottom squark we suppose that 0.1 is also a reasonable estimate for the suppression factor in the $\sigma_{S\gamma}$ cross section and leave the detailed analysis for future investigation.

Thus, new light hadrons can be produced in astrophysical objects from 10^{21} eV protons, interacting with infrared or optical photons of energies 0.1–10 eV, if the sources are optically thick for protons, Eq. (16). The model for such a source can be similar, for example, to the one of Stecker *et al.* [89]. Produced hadrons will escape from the same objects if their interactions with photons are suppressed in comparison to those of protons, Eq. (17). However, simultaneously with the new hadrons large fluxes of neutrinos and photons will unavoidably be produced. In the next section we discuss the experimental constraints on these fluxes.

We have used AGN cores as a working example of astrophysical accelerators, which, as we have shown, can obey the condition of high optical depth for protons, Eq. (16), and allow shadrons to escape, Eq. (17). Any other astrophysical object that is able to accelerate protons to the highest energies and obeys these conditions can be a source of shadrons as well.

VII. ALLOWED PARAMETERS OF NEW HADRONS CONSISTENT WITH GAMMA-RAY AND NEUTRINO BOUNDS

As was shown in the previous section, only interactions of UHE protons with infrared or optical background photons of energy 0.1–10 eV can produce a significant amount of new strongly interacting hadrons *S*, without overproducing the diffuse photon and neutrino backgrounds. The essential condition for this mechanism is the high optical depth for protons, Eq. (16). However, this condition need not be satisfied by all UHE proton sources. Sources with small optical depth for protons will just emit UHE protons, which will be responsible for UHECRs below the GZK cutoff. The few sources of UHE shadrons will be responsible for only the highest energy cosmic rays with $E>10^{20}$ eV and maybe, partly, for the clustered component at lower energies. It is also not excluded that few sources of this kind will be responsible for most or all UHECRs above 4×10^{19} eV.

We do not specify the proton acceleration mechanism in the astrophysical objects here. We just suppose that these sources can accelerate protons up to 10^{21} eV. The proton spectrum should be relatively hard in this case, $1/E^{\alpha}$ with $\alpha\leqslant 2$. The exact shape of the spectrum is not important, because the optical depth for protons is high and most of them are absorbed. The pion production threshold for an optical background of 10 eV is $E_{\rm th}=2\times10^{16}$ eV. Thus the flux of protons with energy above this threshold will be reduced by the factor $\exp[-\tau(E)]$. If the optical depth is high, $\tau(E)\gg 1$, all protons will be absorbed in the source, and the proton flux does not overshoot the measured spectrum of UHECRs.

We used the propagation code [63] for the calculation of the energy spectra of secondary protons, photons, and neutrinos. As initial spectrum, we chose a proton spectrum peaked at the energy 10^{21} eV (see Fig. 6). The continuation of this spectrum to lower energies is possible for any power law up to $\alpha\leqslant 2$. Even an initial proton spectrum with $1/E^2$ will not contradict UHECR observations at high energies, but will lead only to a higher flux of UHE neutrinos at energies $10^{16}\text{eV}\leqslant E\leqslant 10^{20}$ eV.

In Fig. 6 we present one example of such a calculation. Cosmic ray data from AGASA [5] and HiRes [6] are shown with error bars. The contribution of the new hadrons *S* to the UHECR spectrum at the highest energies is shown with a thick solid line. We have conservatively used the AGASA spectrum at the highest energies as normalization—choosing HiRes data as reference would increase the parameter space for the new hadron. The exact shape of the *S* particle spectrum is not well defined, because it depends on many unknown parameters like the spectrum of background photons in the source, the distribution of the sources, the initial proton spectrum, and the energy dependence of the production cross section. However, the amplitude of this flux is related to the amplitude of the initial proton flux through Eq. (12). For any given mass M_S, parameter *A* in Eq. (12), and average transfer energy $\langle y\rangle=\langle E_S/E_p\rangle$, this fixes the normalization of the initial proton flux, which is marked by $p_{\rm ini}$ in Fig. 6. The value of the initial proton flux shown in Fig. 6 corresponds for $M_S=2$ GeV to $\langle E_S/E_p\rangle\approx 0.1$ and $A\sim 1$.

As background photons in the source we used infrared or optical photons with energies $0.1\text{eV}\leqslant\epsilon\leqslant 10$ eV and number density $n_\gamma=5\times10^{12}/\text{cm}^3$. This corresponds to the luminosity $L=5\times10^{43}$ erg/s, if the radius of the emission region is $R=10^{16}$ cm. After several interactions with the background photons the accelerated protons lose all their energy and produce photons and neutrinos. The neutrino flux should obey the existing experimental limits of AGASA [36], Fly's Eye [35], RICE [37], and GLUE [38], which are shown in Fig. 6. Photons cascade down to the GeV and sub-GeV region. The existing diffuse gamma-ray flux measurement by EGRET restricts the photon flux in the MeV–GeV region (see Fig. 6). However, if high magnetic fields exists in the source, then

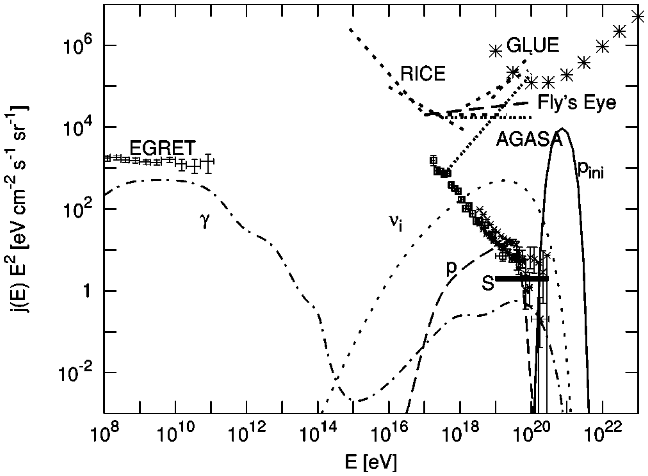

FIG. 6. Flux of new hadrons S (thick solid line) and protons (dashed line) together with cosmic ray data from AGASA [5] and HiRes [6]. Protons accelerated to the energy $E=10^{21}$ eV (line p_{ini}) produce secondary photons (dash-dotted line) and neutrinos (dotted line). Photon flux constraint from EGRET [34] and upper limits on the diffuse neutrino fluxes from AGASA [36], Fly's Eye [35], RICE [37], and the Goldstone experiment (GLUE) [38] as indicated.

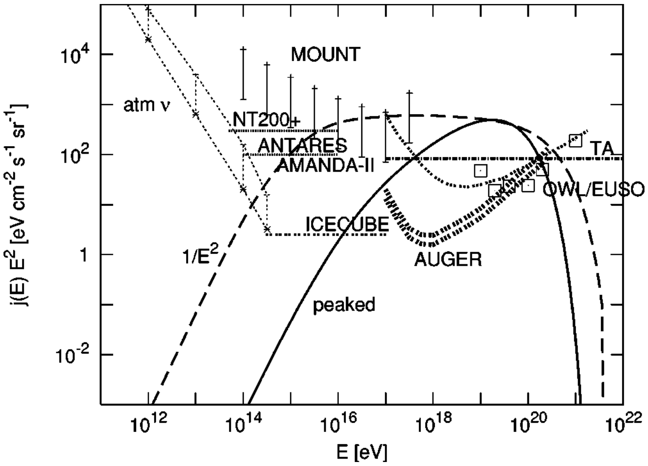

FIG. 7. The neutrino flux for one flavor in the model used in Fig. 6 and sensitivities of the currently being constructed Auger project to electron/muon and tau-neutrinos [91], and the planned projects telescope array (TA) [92] (dashed-dotted line), MOUNT [50], and, indicated by squares, OWL [93], NT200+ [94], ANTARES [56], AMANDA-II and ICECUBE [54], as indicated. Also shown (dashed line) is an extreme scenario with initial proton spectrum $1/E^2$, leading to a neutrino flux extending to relatively low energies where Baikal, ANTARES and AMANDA-II will be sensitive, and the atmospheric neutrino flux for comparison.

part of the photon energy can cascade down into the sub-MeV region, where the bounds on the diffuse photon background are at least a factor of 10 times weaker than in the GeV region. Another part of the photon flux can produce large scale jets [90], thereby again redistributing energy into the sub-MeV region. This uncertainty of the value of the photon flux makes the existing bounds on the neutrino flux much more important.

Protons escaping from the source at high energies will cascade down to energies below the GZK cutoff and can contribute to the observed UHECR spectrum, as shown in Fig. 6. We have supposed that there are no UHECR sources within $R_{\mathrm{GZK}}=100$ Mpc around the Earth. As a result, the proton spectrum has a sharp cutoff *below* 10^{20} eV (see Fig. 6). Thus, if no nearby UHECR sources exist, then even the HiRes data are inconsistent with the minimal model of protons coming from uniformly (but rare) distributed UHECR sources.

In Fig. 7, we show the UHE neutrino flux (per flavor) in our model for two extreme initial proton fluxes: protons with a spectrum peaked at $E\sim10^{21}$ eV and with a $1/E^2$ spectrum up to $E_{\max}\sim10^{21}$ eV. Both cases are consistent with present experimental limits. In the same figure, we show the sensitivities of future experiments to neutrino fluxes: the Auger project to electron or muon and tau neutrinos [91], the telescope array (TA) [92], the fluorescence/Čerenkov detector MOUNT [50], and, indicated by squares, the space based OWL [93] (we take the latter as representative also for EUSO), the water-based Baikal (NT200+) [94], ANTARES [56] (the NESTOR [57] sensitivity would be similar to ANTARES according to Ref. [95]), the ice-based AMANDA-II with sensitivity similar to ANTARES, and km^3 ICECUBE [54]. We assume that the proposed water based km^3 detectors like GVD [55] and NEMO [58] will have sensitivities similar to that of ICECUBE. As one can see in Fig. 7, future experiments will easily detect UHE neutrino flux in any model of new light hadrons. In these models, neutrino fluxes are as shown unavoidably high—contrary to the case of neutrinos produced by UHECR protons interacting with CMB photons. In the latter case, the neutrino flux can be as high as in Fig. 7, but could also be much lower, depending on the initial proton spectrum and the distribution of sources [96].

VIII. DISCUSSION: BL LACS AS UHECR SOURCES

The results of the previous section do not depend on the particular type of astrophysical accelerator. However, we normalized the astrophysical parameters to those of AGN cores on purpose. First of all, AGNs are some of the best candidates for proton acceleration to UHE. Second, a statistically significant correlation of UHECRs with BL Lacs, a subclass of blazars (AGNs with jets directed to us) with weak emission lines, has been found [17,97]. Motivated by this correlation, we discuss the particular case of BL Lacertae as sources of new hadrons in this section.

In Ref. [17], it was shown that the correlation with BL Lacs requires a new, neutral component in the UHECR spectrum. Here we have suggested that this component is due to new, neutral shadrons. The trajectories of these shadrons should point toward their sources, apart from small deflections due to possible magnetic moments. As we have showed in the previous sections, shadrons are good candidates for UHECRs and can be produced in AGN cores if the condition Eq. (16) is satisfied. Now we address the question of whether the BL Lacs shown to correlate with UHECRs in [17,97] obey this condition.

As an example, we have checked this condition for BL Lac RX J10586+5628, which is located at redshift z

$=0.144$ and correlated with AGASA doublet $E=(7.76,5.35)\times 10^{19}$ eV. First of all, let us note that protons with these energies cannot reach us from the distance $D=680$ Mpc (we supposed the actual "best fit" cosmological model with $\Omega_M=0.3$, $\Omega_\Lambda=0.7$, $H_0=70$ km/s Mpc). The optical magnitude in the V band of this object is 15.8, which gives as optical luminosity $L=6\times 10^{44}$ erg/s. Since the spectra of BL Lacs are broad in the optical region (see, e.g., the spectrum of RX J10586+5628 in [98]), the density of 0.5 eV photons is high enough in a region of size $R=10^{16}$ cm to obey the condition Eq. (16) and thus to produce shadrons from accelerated protons.

If the UHECR primaries are new particles created in proton interactions in the source, large secondary neutrinos and photon fluxes are unavoidable. The neutrino fluxes are too small to be detectable by current experiments, but photons can cascade down into the MeV-GeV region in the source, and can be measured. Let us compare the UHECR flux of the BL Lac RX J10586+5628 with its gamma-ray flux in the MeV–GeV region, measured by EGRET. The two events observed by AGASA with energy $E=(7.76,5.35)\times 10^{19}$ eV allow us to estimate the integrated UHECR flux, $\int dEEF(E)\sim 0.05$ eV/cm^2/s, while the integrated EGRET flux in the region 100–800 MeV is approximately $\int dEEF(E)\sim 10$ eV/cm^2/s [99]. If we suppose that the EGRET flux is mostly due to proton energy losses, the ratio of fluxes is 5×10^{-3}—a value consistent with our model. However, the comparison above can be considered only as an order of magnitude estimate. First, the flux measured by EGRET could be produced by other interactions. Second, the energy injected by protons into electromagnetic cascades in the core of RX J10586+5628 can be redistributed out of the line of sight and thus may not contribute to the EGRET measurement. The next generation of TeV gamma-ray telescopes, like H.E.S.S. [100], MAGIC [101], and VERITAS [102], will have sensitivities in the 10–100 GeV energy region, allowing measurements of gamma-ray fluxes from distant sources similar to BL Lac RX J10586+5628. Such measurements can be complementary to the observations of UHECRs from the same objects and will allow us to restrict or confirm a wide class of UHECR models (including the one we are considering here) which imply the production of secondary particles from protons.

The high optical depth of photons in Eq. (16) guarantees that protons lose energy in the interaction region and produce shadrons with a ratio of $\sigma_S/\sigma_{p\gamma}\sim 5\times 10^{-3}$. For an optical depth of $\tau=5$, only the fraction $e^{-5}=6.7\times 10^{-3}$ of initial protons will escape from the source without interaction. Thus the flux of produced shadrons is in this case similar to the flux of escaping UHE protons. This example shows how the same source can be a source of UHE protons and at same time a source of new UHE hadrons. If the optical depth τ is smaller, the source will predominantly produce protons; if it is higher, it will mostly produce S hadrons.

It will be interesting to check the UHECR data at lower energy, $E\sim(2–4)\times 10^{19}$ eV, for correlations with RX J10586+5628. This would be the typical energy of protons from this object with $z=0.144$, taking into account energy losses on the way to the Earth. The comparison of the low energy proton flux with a possible UHE flux of new hadrons can be used to check the consistency of our model with the assumption that BL Lacs are UHECR sources.

In Ref. [103], Tinyakov and Tkachev examined correlations of BL Lacs with the arrival directions of UHECRs, allowing for charges $Q=-1,0,+1$ of the primaries. They showed that the deflection of charged particles in the galactic magnetic field can significantly increase the correlation with BL Lacs. If primaries can have charge $Q=0,+1$, they found that 19 of 57 AGASA events correlate with BL Lacs, which have magnitude $m<18$ in optics. The probability that this correlation is by chance is 2×10^{-4}.

They assumed that the charged particles are protons and the neutral ones photons. This interpretation has two important drawbacks. First, both the highest energy event with $E=2\times 10^{20}$ eV and charge $Q=+1$, and the event 16 of Table 1 in [103] with energy $E=4.39\times 10^{19}$ eV and charge $Q=+1$, which correlates with a BL Lac at $z=0.212$, can only be explained as background events. Second, they were forced to assume that most of the BL Lacs with unknown redshift are located nearby, $z\leqslant 0.1$.

Now, if we assume that the UHECR primaries correlated with BL Lacs are new light hadrons which can have charge $Q=-1,0,+1$, for example, $\tilde{B}^-$, $\tilde{B}^0$, and $\tilde{B}^+$, then the assumptions above are not required. Shadrons with $Q=+1$ can easily come from high redshift sources up to $z\sim 0.5$ or even higher. Thus one does not need to assume that BL Lacs with unknown redshift are located nearby nor exclude "unsuitable" sources from Table 1 in [103]. Note also that some of the events with $Q=+1$ can still be protons. Also, let us recall that the deflection in the magnetic field in the ultrarelativistic case does not depend on particle mass, and hadrons with $M=2–3$ GeV and charge $Q=+1$ will be deflected in the same way as protons.

Moreover, the model with light charged hadrons also predicts the existence of particles with negative charge. However, because these particles will be produced in the sources due to $p^+\gamma$ reactions, new particles with $Q=+1$ or $Q=0$ will dominate. Particles with $Q=-1$ can be produced in such reactions only well above the production threshold, and their expected number should be less than the number of particles with $Q=+1$ and $Q=0$. Moreover, UHE protons can increase the number of particles with $Q=+1$ at lower energies. Thus, a prediction of our model is the existence of a small number of negatively charged UHE cosmic rays, whose average energy is larger than events with $Q=+1$ and $Q=0$.

It is impossible to check the last statement statistically with current data; however, some hint can be found in Ref. [97]. The authors of this paper chose as a subset of BL Lacs those that are simultaneously EGRET sources. They found that 14 BL Lacs correlate with 65 UHECRs from AGASA and Yakutsk data, if they allow as charges $Q=+1$ and $Q=0$. The chance probability of this correlation is 3×10^{-7} which is more than 5σ using Gaussian statistics. In this data set eight BL Lacs out of 14 are UHECR sources and emit 13 UHECRs. If one supposes, that UHECR primaries with Q

$=-1$ also exist, two more UHECRs correlate with the *same* BL Lacs. These two events have energy $E>5\times10^{19}$, which is much larger than the average energy in this data set. Three other UHECR primaries from this data set can have either $Q=-1$ or $Q=0$. All of them also have large energies $E>5\times10^{19}$.

One more assumption made by Tinyakov and Tkachev is a cut on the BL Lac magnitude in the optical range, $m<18$ [17,103]. They found that such a cut maximizes the correlation with BL Lacs. However, they were not able to explain why the correlated BL Lacs are those that are brightest in the optical range. In our model of new particle production, such a criterion is obvious: the optical background is high enough only in the brightest BL Lacs. Hence, only they are able to produce shadrons in $p\gamma$ reactions. BL Lacs with lower optical luminosity produce protons, which lose energy and contribute to the UHECR spectrum at lower energies. Another interesting hint is the value $m=18$. In Fig. 3 of Ref. [52], the dependence of the source magnitude on redshift was shown under the condition that the sources are optically thick for protons. This line crosses the value $m=18$ at redshifts of order $z\sim0.5$–0.6. This distance is similar to the one over which shadrons with $M=2$–3 GeV can still propagate.

Thus, we conclude that the correlation of UHECRs with BL Lacertae objects, which was found in [17] and investigated in detail in [97,103], suggests that at least some, if not most, UHECR primaries with $E>4\times10^{19}$ should be *new* particles with $Q=-1,0,+1$. Explanation of the BL Lacs correlation with $Q=+1$ particles by protons seems unlikely. The model of new light hadrons, for example, $\tilde{B}^-$, $\tilde{B}^0$, and $\tilde{B}^+$, naturally explains this correlation as well as the cut on the BL Lacs magnitude, $m<18$.

IX. CONCLUSIONS

The HiRes experiment recently published their UHECR data, which show a cutoff at the highest energies, as expected in the conservative model of a uniform, continuous distribution of astrophysical sources accelerating protons up to energies $E\lesssim10^{21}$ eV. On the other hand, a clustered component in the arrival directions of UHECRs with $E>4\times10^{19}$ eV is present in the AGASA data with a statistical significance of 4.6σ. If one assumes that this clustered component is due to pointlike astrophysical sources, the predicted total number of sources of UHECRs with $E\geq4\times10^{19}$ eV is of the order of 400–1200. In this paper we showed that this number of sources is so small that the model of continuously distributed proton sources is a bad approximation at the highest energies. The latter approximation requires 10^3–10^4 times more sources than are estimated from the clustering data. In other words, the closest proton source is located outside the GZK sphere $R>50$ Mpc, and the energy spectrum of UHECRs has a sharp exponential cutoff at the energy $E<10^{20}$ eV, which is inconsistent with even the HiRes data (see Fig. 1). Including the AGASA data makes this discrepancy even worse.

Moreover, a statistically significant correlation at the level of 4σ of the arrival directions of UHECRs with BL Lac objects was found [17]. The closest BL Lacs with known redshift are located at cosmological distance $z=0.03$, and protons with $E>10^{20}$ eV cannot reach us from these sources. Some events at lower energies also cannot be protons, because the redshift of these sources is too high. For example, BL Lac RX J10586+5628 is located at $z=0.144$ or at the distance 700 Mpc. Protons coming from this object can have a maximal energy around $(2-4)\times10^{19}$ eV, while the correlated UHECRs have much higher energies, $E=(7.76,5.35)\times10^{19}$ eV.

Our findings above suggest the existence of particles that can be produced at distant astrophysical objects like BL Lacs, propagate through the Universe without significant energy losses, and produce air showers in the Earth atmosphere similar to those of protons.

In this work we investigated the possibility that such particles are new light hadrons. We showed that such hadrons can be produced in astrophysical objects in interactions of accelerated protons with a background of optical photons, if the size of the interaction region is larger than the interaction length of the protons. The interaction of the new hadrons with background photons should be suppressed to allow them to escape from the sources without significant energy losses. This fact, as well as the requirement that the energy losses of the new particles propagating in the CMB are suppressed compared to protons, restricts the new hadrons to be heavier than 1.5–2 GeV. Since the primary protons also produce large neutrino and gamma-ray fluxes, which are bounded by experimental limits and measurement, only hadrons with masses below 3 GeV are allowed. The possibility of traveling over cosmological distances without decay restricts the lifetime of these particles to be larger than one month.

As a specific example we considered hadrons containing light bottom squarks. This case agrees with all existing astrophysical observations, if the shadron mass is in the window 1.5 GeV$\lesssim M_S\lesssim3$ GeV. Such a new hadron can explain the observation of UHECRs at the highest energies.

If BL Lacs are indeed UHECR sources, our model of new light hadrons allows us to solve several puzzles connected with these objects. First, all correlated UHECRs with zero charge can be our new hadrons with $Q=0$. Second, our model offers a simple explanation for why only optically bright BL Lacs correlate with UHECRs: only if the density of optical photons in a BL Lac is high is the probability of protons to interact and produce our new hadrons large enough. The magnitude $m=18$ can correspond to the redshift $z\sim0.5$–0.6, a distance from which our new particles can still reach the Earth without significant energy losses.

In Ref. [103] it was shown that the correlation with BL Lacs increases if one supposes that some UHECRs have nonzero charge. In particular, a significant correlation was found if some UHECRs have a positive charge $Q=+1$. It was suggested that these positively charged particles are protons. However, this assumption forced the authors of Ref. [103] to assume that most of the BL Lacs with unknown redshift are located at distances $z<0.1$. Furthermore, they had to assume that some of the UHECRs that cannot be protons are correlated just by chance.

These two assumptions can be relaxed in our model if one assumes that new hadrons with nonzero charge are also long lived. However, the existence of such hadrons is disfavored from accelerator experiments.

An important consequence of our model is an unavoidably high UHE neutrino flux. This flux is well within the sensitivity region of all future UHECR experiments and can also be detected by km^3 neutrino telescopes like ICECUBE (or GVD and NEMO). In the case of an initial proton spectrum proportional to $1/E^{\alpha}$ with $\alpha \sim 2$, even 0.1 km^3 neutrino telescopes like AMANDA II, ANTARES, and NESTOR will be able to detect the diffuse neutrino flux in the 10^{16} eV energy region.

Another consequence of our model is a cutoff in the UHECR spectrum, which can be observed around $E \sim 10^{21}$ eV at future UHECR experiments like the Pierre Auger Observatory, the telescope array, and EUSO.

New hadrons with 1.5–3 GeV mass can be searched for in existing accelerator experiments like CLEO and *B* factories or with a dedicated experiment as proposed in [43].

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