Collider versus Cosmic Ray Sensitivity to Black Hole Production

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Abstract

In scenarios with extra dimensions and TeV-scale quantum gravity, black holes are expected to be produced copiously at center-of-mass energies above the fundamental Planck scale. The Large Hadron Collider (LHC) may thus turn into a factory of black holes, at which their production and evaporation may be studied in detail. But even before the LHC starts operating, the Pierre Auger Observatory for cosmic rays, presently under construction, has an opportunity to search for black hole signatures. Black hole production in the scattering of ultrahigh energy cosmic neutrinos on nucleons in the atmosphere may initiate quasi-horizontal air showers with distinct characteristics above the Standard Model rate. In this letter, we compare the sensitivity of LHC and Auger to black hole production by studying their respective reach in black hole production parameter space. Moreover, we present constraints in this parameter space from the non-observation of horizontal showers by the Fly’s Eye collaboration. We find that if the ultrahigh energy neutrino flux is at the level expected from cosmic ray interactions with the cosmic microwave background radiation, Auger has only a small window of opportunity to detect black holes before the start of the LHC. If, on the other hand, larger ultrahigh energy neutrino fluxes on the level of the upper limit from “hidden” hadronic astrophysical sources are realized in nature, then the first signs of black hole production may be observed at Auger. Moreover, in this case, the Fly’s Eye constraints, although more model-dependent, turn out to be competitive with other currently available constraints on TeV-scale gravity which are mainly based on interactions associated with Kaluza-Klein gravitons.
1. It has been conjectured quite some time ago that black holes will be produced in the collision of two light particles at center-of-mass (cm) energies above the Planck scale with small impact parameters [1]. This remote possibility seems now within reach in the context of theories with $\delta = D - 4 \geq 1$ flat [2] or warped [3] extra dimensions and a low fundamental Planck scale $M_D \gtrsim \text{TeV}$ characterizing quantum gravity. In these theories one might expect the copious production of black holes in high energy collisions at cm energies above $M_D$ [4, 5, 6].

Recently it has been emphasized [7, 8] that the Large Hadron Collider (LHC) [9], expected to have a first physics run in 2006, may turn into a factory of black holes at which their production and evaporation may be studied in detail (see also Refs. [10, 11]).

Black hole production and subsequent decay in the scattering of ultrahigh energy cosmic neutrinos on nucleons in the atmosphere may initiate quasi-horizontal air showers far above the Standard Model rate. Recently it was argued [12] that the search for such air showers at the Pierre Auger Observatory [13] for extensive air showers, expected to be completed by the end of 2003, might have enough sensitivity to probe black hole physics if the fundamental Planck scale is below 2 TeV. The corresponding experimental signature was worked out in Ref. [14]. Further discussions of cosmic ray issues associated with black hole production may be found in Ref. [15]. In Ref. [16], the detection of black holes at the planned neutrino telescope ICECUBE [17] was considered.

The purpose of the present letter is to compare the sensitivity of the LHC and Auger to black hole production by studying their respective reach in black hole production parameter space. Moreover, we derive constraints on this parameter space from the non-observation of horizontal showers [18] by the Fly’s Eye collaboration [19]. These constraints on TeV-scale gravity complement the ones which arise from the confrontation of collider [20, 21], astrophysical [22], cosmological [23], and cosmic ray [24, 25, 26] data with predictions mainly based on interactions associated with Kaluza-Klein gravitons (for recent reviews, see e. g. Ref. [27]), according to which a fundamental Planck scale as low as $M_D = \mathcal{O}(1) \text{TeV}$ is still allowed for $\delta \geq 4$ flat or $\delta \geq 1$ warped extra dimensions.

In Sect. 2, we review the phenomenological model for black hole production and decay in scenarios with TeV-scale gravity. We determine the contribution of black hole production to the proton-proton and neutrino-nucleon cross section, respectively, for various values of the model parameters. The reach of the LHC in the black hole parameter space follows immediately from these considerations. In Sect. 3, we determine the rate of quasi-horizontal air showers initiated by neutrino-nucleon scattering into black holes expected at Auger. In order to be able to make a fair comparison of the reach of Auger versus the LHC to black hole production, we exploit both conservative lower and upper limits on the presently unknown flux of ultrahigh energy cosmic neutrinos. We recall also the Fly’s Eye upper limit on the ultrahigh energy neutrino flux times the neutrino-nucleon cross section and present various upper limits on the neutrino-nucleon cross section, obtained from various assumptions about the neutrino flux. These upper limits are then turned into exclusion regions in the black hole parameter space. Section 4 contains our conclusions.

2. We start with a review of the current understanding of the production and decay of black holes in TeV-scale gravity scenarios [1, 5, 6, 7, 8, 10, 11].

Based on semiclassical reasoning [1], one expects that at trans-Planckian parton-parton cm energies squared, $\hat{s} \gg M_D^2$, and at small parton-parton impact parameters, $b \ll r_S (M_{\text{bh}} = \sqrt{\hat{s}})$,
i.e. at impact parameters much smaller than the Schwarzschild radius $r_S$ of a $(4 + \delta)$-dimensional black hole with mass $M_{bh} = \sqrt{s}$ \[28\]

$$r_S = \frac{1}{M_D} \left[ \frac{M_{bh}}{M_D} \left( \frac{2^\delta \pi^{\frac{\delta-3}{2}} \Gamma \left( \frac{3+\delta}{2} \right)}{2 + \delta} \right) \right]^{\frac{1}{1+\delta}},$$

(1)

a black hole forms with a cross section

$$\hat{\sigma}(ij \to bh) \equiv \hat{\sigma}^{bh}_{ij}(s) \approx \pi r_S^2 \left( M_{bh} = \sqrt{s} \right) \theta \left( \sqrt{s} - M_{bh}^{\min} \right).$$

(2)

Here, $M_{bh}^{\min} \gg M_D$ parametrizes the cm energy above which the semiclassical reasoning mentioned above is assumed to be valid.

Some caveats have to be mentioned, however. As noted in Ref. \[29\], the semiclassical production of black holes resembles largely the problem of baryon and lepton number violating processes ("sphaleron \[30\] production") in multi-TeV ($\sqrt{s} \gg m_W/\alpha_W$) particle collisions in the standard electroweak theory \[31, 32, 33, 34, 35, 36\], which is not yet completely understood \[37\]. In fact, also in the latter case a simple geometric behavior similar to Eq. (2), with the Schwarzschild radius replaced by the sphaleron radius $\sim m_W^{-1}$, was advocated in Refs. \[32, 33\]. In both cases, there might be additional exponential suppression factors rendering semiclassical sphaleron or black hole production unobservable in the TeV range \[29\] (see, however, Ref. \[10\]).

With these caveats understood, one may infer from the estimate (2) the contribution of black hole production to the proton-proton and neutrino-nucleon cross section,

$$\sigma_{pp}(s) = \sum_{ij} \int_0^1 dx_1 \int dx_2 \frac{f_i(x_1, \mu) f_j(x_2, \mu)}{1 + \delta_{ij}} \hat{\sigma}_{ij}^{bh}(x_1 x_2 s),$$

(3)

$$\sigma_{\nu N}(s) = \sum_i \int_0^1 dx f_i(x, \mu) \hat{\sigma}_{\nu i}^{bh}(xs).$$

(4)

Here, $s$ denotes the proton-proton or neutrino-nucleon cm energy squared. The sum extends over all partons in the nucleon, with parton distribution functions $f_i(x, \mu)$ and factorization scale $\mu$. For our numerical integration we have used various sets of parton distributions as they are implemented in the parton distribution library PDFLIB \[38\]. Uncertainties associated with different parton distribution sets are in the $\mathcal{O}(20)$% range and are not explicitly displayed in the following.

The reach of the LHC to black hole production is illustrated in Fig. \[1\] for $\delta = 6$ extra dimensions. The number of black hole events produced in a time interval $\Delta t$, $N_{bh} = \sigma_{pp}^{bh} \cdot L \cdot \Delta t$, has been calculated using the CTEQ5D parton distributions \[39\] with $\mu = \min(\sqrt{s}, 10 \text{ TeV})$ in Eq. (3) and the LHC design values $\sqrt{s} = 14$ TeV for the proton-proton cm energy and $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ for the luminosity \[29\]. As can be seen from Fig. \[1\] the LHC can explore the production of black holes with minimum masses nearly up to its kinematical limit of 14 TeV, if $M_D$ is below 2 TeV.

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1 We define $M_D$ as in Ref. \[20\]. Equation (1) is valid as long as $r_s \ll R_c$, with $R_c$ being the compactification or curvature radii in the flat or warped scenario, respectively.

2 If one uses, instead, the other natural factorization scale $\mu = r_s^{-1}$ \[7, 10\], which is typically much smaller than $\sqrt{s}$, the predicted production rates decrease by a factor of $\mathcal{O}(2)$. 

3
Figure 1: Accessible region in the black hole production parameters at the LHC for $\delta = 6$ extra dimensions. The solid and the dotted lines are contours of constant numbers of produced black holes per year ($10^7$ s) with a mass larger than $M_{\text{bh}}^\text{min}$, for a fundamental Planck mass $M_D$. The shaded dotted, $M_D = M_{\text{bh}}^\text{min}$, and shaded solid, $M_D = (1/5) M_{\text{bh}}^\text{min}$, lines give a rough indication of the boundary of applicability of the semiclassical picture [7].

Figure 2: Cross section $\sigma_{\nu N}^{\text{bh}}$, Eq. (4), for black hole production in neutrino-nucleon scattering, for $M_D = 1$ TeV, $M_{\text{bh}}^\text{min} = 5$ TeV, and $\delta = 2, 4, 6$ extra dimensions (solid lines, from bottom to top). Also shown is the Standard Model (SM) charged current (CC) neutrino-nucleon cross section (dashed-dotted line).
In order to appreciate the event numbers indicated in Fig. 1, let us mention the expected signature of black hole decay, which is quite spectacular. Once produced, black holes decay primarily via Hawking radiation \[40\] into a large number of \( O(20) \) hard quanta, with energies approaching several hundreds of GeV. A substantial fraction of the beam energy is deposited in visible transverse energy, in an event with high sphericity. From previous studies of sphaleron production, which has quite similar event characteristics \[33, 34, 35, 36\], as well as from first event simulations of black hole production \[8\], it is clear that only a handful of such events is needed at the LHC to discriminate them from perturbative Standard Model background.

The contribution of black hole production to the neutrino-nucleon cross section is displayed in Fig. 2, for \( M_D = 1 \) TeV, \( M_{bh}^{\text{min}} = 5 \) TeV, and various values of \( \delta \), as a function of the neutrino’s energy in the nucleon’s rest frame, \( E_\nu = s/(2 m_N) \), with \( m_N = (m_p + m_n)/2 \) being the nucleon mass. Here, the CTEQ3D \[41\] parton distributions with \( \mu = \min (\sqrt{s}, 10 \) TeV) have been used in Eq. (3). The Standard Model charged current contribution, also shown in Fig. 2, has been taken from Ref. \[42\], which compares favorably with the one presented in Ref. \[43\]. For the time being, we ignore possible unitarity corrections which might reduce the Standard Model contribution somewhat \[44\].

3. Let us consider now the rate of quasi-horizontal air showers initiated by neutrino-nucleon scattering into black holes expected at the Pierre Auger Observatory. For neutrino-nucleon cross sections below \( O(10) \) \( \mu b \), the neutrino flux attenuation in the upper atmosphere can be neglected, and the number of black hole initiated horizontal air showers with an energy larger than a threshold energy \( E_{th} \) expected to be measured at Auger in a time interval \( \Delta t \) is given by

\[
N_{bh}^{\text{sh}} (> E_{th}) = \Delta t N_A \rho_{\text{air}} \int_{E_{th}}^{\infty} dE_\nu F_\nu(E_\nu) \sigma_{\nu N}^{bh}(E_\nu) A(E_\nu),
\]  

(5)

where \( N_A \) is Avogadro’s constant, \( \rho_{\text{air}} \simeq 10^{-3} \) g cm\(^{-3}\) is the air density, \( F_\nu = \sum_i (F_{\nu_i} + F_{\bar{\nu}_i}) \) is the sum of the differential diffuse neutrino fluxes, and \( A \) is the detector acceptance \[45\]. Note, that Eq. (5) assumes that 100% of the incident neutrino energy goes into visible, hadronic or electromagnetic shower energy, as it is the case for Standard Model, \( \nu_e \) and \( \bar{\nu}_e \) initiated charged current interactions, as well as for sphaleron \[34, 35, 36\] and black hole \[5, 12\] production and decay, at least to a good approximation.

Of central importance in the evaluation of the event rate (5) is the expected differential flux \( F_\nu \) of ultrahigh energy neutrinos to which we turn our attention next (for recent reviews, see Ref. \[46\]). Though atmospheric neutrinos, i.e. neutrinos produced in hadronic showers in the atmosphere, are certainly present, their flux in the ultrahigh energy region is anticipated to be negligible \[47\]. Much more promising, but also more or less guaranteed are the so-called cosmogenic neutrinos which are produced when ultrahigh energy protons inelastically scatter off the cosmic microwave background radiation \[48\] in processes such as \( p\gamma \rightarrow \Delta \rightarrow n\pi^+ \), where the produced pion subsequently decays \[49, 50, 51\]. Recent estimates of these fluxes can be found in Refs. \[52, 53, 54, 55\], some of which are shown in Fig. 3.

Whereas the cosmogenic neutrino fluxes, discussed above, represent reasonable lower limits on the ultrahigh energy neutrino flux, it is also useful to have an upper limit on the latter \[56, 57\]. Per construction, the upper limit from “visible” hadronic astrophysical sources, i.e. from those sources which are transparent to ultrahigh energy cosmic protons and neutrons, is of the order
Figure 3: Predictions of the cosmogenic neutrino flux, $F_\nu = \sum_i [F_{\nu_i} + F_{\bar{\nu}_i}]$. Short-dashed line: Flux from Ref. \[50\] (cf. Ref. \[12\]). Long-dashed (long-dashed–dotted) line: Flux from Ref. \[52\] for cosmological evolution parameters $m = 2$, $z_{\text{max}} = 2$ ($m = 4$, $z_{\text{max}} = 4$). Solid (dotted) line: Flux from Ref. \[53\], assuming a maximum energy of $E^{\text{max}} = 3 \cdot 10^{20(21)}$ eV for the ultrahigh energy cosmic rays. Shaded: Theoretical upper limit of the neutrino flux from “hidden” astrophysical sources that are non-transparent to ultrahigh energy nucleons \[57\].

The projected sensitivity of Auger to black hole production can now be investigated, for a given neutrino flux, by calculating the event rate \[5\]. Throughout, we shall use the acceptance of the ground array of Auger corresponding to hadronic horizontal showers (highest curve in Fig. 4 of Ref. \[45\]). Figure 4 (top) illustrates the reach in black hole production parameter space, for $\delta = 6$ extra dimensions, for the predicted cosmogenic neutrino fluxes from Ref. \[53\]. We see, that in this case only a handful of events per year can be expected at Auger from the fiducial region of parameter space ($M_{\text{min}}^{\text{bh}} \gtrsim 5 M_D$), with a background from “normal” horizontal air showers initiated by $\nu_s$ and $\bar{\nu}_s$ of about 0.03 (0.05) events per year, for the flux from Ref. \[53\] with $E^{\text{max}} = 3 \cdot 10^{20(21)}$ eV. A very similar reach of Auger as the one obtained using the flux labeled $E^{\text{max}} = 3 \cdot 10^{21}$ eV in Ref. \[53\] (dotted line in Fig. 4 (top)) is obtained using either the flux labeled ($m = 4$, $z_{\text{max}} = 4$) in Ref. \[52\] (cf. Fig. 3) or the most recent prediction of the flux from Ref. \[55\].

3 The old prediction of the cosmogenic neutrino flux from Ref. \[50\] (cf. Fig. 3), which has been used recently for estimates of black hole detection rates at cosmic ray facilities \[12, 16\], violates the upper limit from “visible” hadronic astrophysical sources \[56, 57\] by a factor $\mathcal{O}(2 \div 3)$.

4 For an early determination of such an upper limit, see Ref. \[58\]. Fluxes of this size are predicted in the context of the Z-burst scenario \[59\] for the highest energy cosmic rays.
We have refrained from displaying the reach of Auger as obtained from the predicted cosmogenic neutrino flux of Ref. \[50\] (cf. Fig. 3), which has been used recently for estimates of black hole detection rates at cosmic ray facilities \[12, 16\], since this prediction is disfavored by more recent calculations \[52, 53, 54, 55\].

For a fair comparison of the event rates at Auger with the ones at the LHC, we have to discuss how many black hole initiated air showers are needed to discriminate the signal from the Standard Model background. Besides the enhanced rate for horizontal showers, what is the characteristic signature of black hole production in neutrino-induced air showers? In Ref. \[14\] it was shown that these showers may have an “anomalous” electromagnetic component: about an order of magnitude bigger than Standard Model \(\nu_\mu\)-initiated showers and at least an order of magnitude smaller than Standard Model \(\nu_e\)-initiated showers. It was argued that this represents a very clean signal and, correspondingly, that a total number of about \(\mathcal{O}(20)\) black hole events could give significant statistics to test this phenomenon. An inspection of Fig. 4 (top) leads then to the conclusion that Auger has only a small window of opportunity to detect black holes before the start of the LHC, if the ultrahigh energy neutrino flux is at the level of the cosmogenic one predicted by recent calculations \[52, 53, 54, 55\].

What is the region of black hole production parameter space which can be probed by Auger under the most optimistic, but still conceivable conditions regarding the ultrahigh energy neutrino flux? An answer to this question is provided by Fig. 4 (bottom), which shows the reach in black hole production parameter space, for \(\delta = 6\) extra dimensions, for the upper limit on the neutrino flux from “hidden” hadronic astrophysical sources from Ref. \[57\] (cf. Fig. 3). The region of black hole production parameter space accessible in this case is impressive and extends much beyond LHC. Note that the Standard Model background is here about 3 events/year. If such large ultrahigh energy neutrino fluxes are realized in nature, then the first signs of black hole production may be observed at Auger.

Also shown in Fig. 4 are the constraints arising from the non-observation of horizontal showers by the Fly’s Eye collaboration \[18\], which are obtained as follows. The Fly’s Eye collaboration puts upper limits on the product of the total neutrino flux times neutrino-nucleon cross section \[18, 60\] that may be parametrized \[34\] by the following power-law, least-squares fit:

\[
(F_\nu \sigma_{\nu N})(E_\nu) \leq 3.74 \cdot 10^{-42} \left( \frac{E_\nu}{1 \text{ GeV}} \right)^{-1.48} \text{ GeV}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \equiv (F_\nu \sigma_{\nu N})_{\text{Fly's Eye}} (E_\nu),
\]

for \(10^8 \text{ GeV} \leq E_\nu \leq 10^{11} \text{ GeV}\) and \(\sigma_{\nu N}(E_\nu) \leq 10 \mu\text{b}\).

Thus, for a given, predicted neutrino flux \(F_\nu^{\text{pred}}\), the Fly’s Eye constraint \[18\] translates into an upper limit on the \(\nu N\) cross section, \(\sigma_{\nu N}(E_\nu) \leq (F_\nu \sigma_{\nu N})_{\text{Fly's Eye}} (E_\nu)/F_\nu^{\text{pred}}(E_\nu)\) \[25\] (for an early reasoning along these lines using older data, see Ref. \[61\]), which is shown in Fig. 5 for various flux predictions from Fig. 3. Finally, a comparison of the prediction \(\sigma_{\nu N} = \sigma_{\nu N}^{\text{SM}} + \sigma_{\nu N}^{\text{bh}}\), where \(\sigma_{\nu N}\) is the Standard Model contribution, with the upper limits of Fig. 5 yields then excluded regions in black hole production parameter space, as those shown in Fig. 4.

\[5\] Here, again, it is assumed that 100% of the incident neutrino energy goes into visible, hadronic or electromagnetic shower energy. Otherwise, one has to take into account that the limit applies only for the visible energy \[25\].
Figure 4: Projected Auger reach in the black hole production parameters for $\delta = 6$ extra dimensions. The shaded dotted, $M_D = M_{\text{bh}}^{\min}$, and shaded solid, $M_D = (1/5)M_{\text{bh}}^{\min}$, lines give a rough indication of the boundary of applicability of the semiclassical picture [7].

Top: Exploiting the cosmogenic neutrino flux from Ref. [53] (cf. Fig. 3). The solid (dotted) line(s) assumes a maximum energy $3 \cdot 10^{20(21)}$ eV for the ultrahigh energy cosmic rays and represents the contour of 1 resp. 10 detected horizontal air shower per year ($10^7$ s) initiated by neutrino-nucleon scattering into a black hole with a mass larger than $M_{\text{bh}}^{\min}$, for a fundamental Planck mass $M_D$. The shaded dotted line labeled “FE” indicates the constraint arising from the non-observation of horizontal showers by the Fly’s Eye collaboration [18].

Bottom: Exploiting the upper limit on the neutrino flux from “hidden” hadronic astrophysical sources from Ref. [57] (cf. Fig. 3). The solid lines represent the contour of 1 and 10 detected horizontal air shower per year ($10^7$ s) initiated by neutrino-nucleon scattering into a black hole with a mass larger than $M_{\text{bh}}^{\min}$, for a fundamental Planck mass $M_D$. The shaded solid line labeled “FE” indicates the constraint arising from the non-observation of horizontal showers by the Fly’s Eye collaboration [18].
Figure 5: Upper limit on the neutrino-nucleon cross section obtained from the Fly’s Eye limit, for various predictions of the ultrahigh energy neutrino flux, $F_\nu = \sum_i [F_{\nu_i} + F_{\bar{\nu}_i}]$ (line styles as in Fig. 3). Also shown is the Standard Model (SM) charged current (CC) neutrino-nucleon cross section (dashed-dotted line).

From an inspection of Fig. 4 (bottom) one finds that the Fly’s Eye constraints on black hole production, although more model dependent, compare favourably with the currently available limits on TeV-scale gravity [27], at least as long as a neutrino flux on the level of the upper limit from “hidden” hadronic sources is realized in nature. In the case of the more conservative cosmogenic neutrino flux, however, the Fly’s Eye constraints are only marginally competitive with the above mentioned limits (cf. Fig. 3 (top)).

4. We considered the reach of the LHC and the Pierre Auger Observatory to black hole production in the context of extra dimension scenarios with TeV-scale gravity. Moreover, we have also derived constraints in the black hole production parameter space from the non-observation of horizontal showers by the Fly’s Eye collaboration. We found that if the ultrahigh energy neutrino flux is at the (almost guaranteed) level of the cosmogenic one predicted by recent calculations [52, 53, 54, 55], Auger has only a small window of opportunity before the start of the LHC to observe the first signs of black hole production in horizontal air showers initiated by ultrahigh energy neutrinos. If, on the other hand, larger ultrahigh energy neutrino fluxes on the level of the upper limit from “hidden” hadronic astrophysical sources [57] are realized in nature, then the first signs of black hole production may be observed at Auger. Moreover, in this case, the Fly’s Eye constraints, although more model-dependent, turn out to be competitive with other currently available constraints on TeV-scale gravity which are mainly based on interactions associated with Kaluza-Klein gravitons.

It remains to be seen from a full simulation whether the characteristics of Standard Model and black hole initiated air showers are sufficiently distinctive [14] to successfully attribute an eventual excess in events to black hole production rather than to an enhancement in the ultrahigh energy neutrino flux. From the experience with the phenomenology of sphaleron production [35] we think
it is worthwhile to work out also the signature expected to be seen in neutrino telescopes such as AMANDA/ICECUBE [17] and RICE [62], which might offer additional ways to look for black holes before the start of the LHC.

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References

[1] G. ’t Hooft, Phys. Lett. B 198 (1987) 61; Nucl. Phys. B 304 (1988) 867; D. Amati, M. Ciafaloni and G. Veneziano, Phys. Lett. B 197 (1987) 81; Int. J. Mod. Phys. A 3 (1988) 1615; Phys. Lett. B 216 (1989) 41; Nucl. Phys. B 347 (1990) 550; Phys. Lett. B 289 (1992) 87; Nucl. Phys. B 403 (1993) 707; I. Y. Aref’eva, K. S. Viswanathan and I. V. Volovich, Nucl. Phys. B 452 (1995) 346 [Erratum-ibid. B 462 (1995) 613].

[2] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 436 (1998) 257; N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Rev. D 59 (1999) 086004.

[3] L. J. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370.

[4] P. C. Argyres, S. Dimopoulos and J. March-Russell, Phys. Lett. B 441 (1998) 96; T. Banks and W. Fischler, hep-th/9906038; I. Y. Aref’eva, hep-th/9910269.

[5] R. Emparan, G. T. Horowitz and R. C. Myers, Phys. Rev. Lett. 85 (2000) 499.

[6] S. B. Giddings and E. Katz, hep-th/0009176; R. Emparan, Phys. Rev. D 64 (2001) 024025.

[7] S. B. Giddings and S. Thomas, hep-ph/0106219.

[8] S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. 87 (2001) 161602.

[9] L. R. Evans, CERN-OPEN-2001-027, presented at: 18th International Conference on High Energy Accelerators, Tsukuba, Japan, 26 - 30 Mar 2001.

[10] S. Dimopoulos and R. Emparan, hep-ph/0108060.

[11] S. Hossenfelder, S. Hofmann, M. Bleicher and H. Stöcker, hep-ph/0109085; S. B. Giddings, hep-ph/0110127; K. Cheung, hep-ph/0110163; R. Casadio and B. Harms, hep-th/0110255.

[12] J. L. Feng and A. D. Shapere, hep-ph/0109106.
[13] D. Zavrtanik [AUGER Collaboration], Nucl. Phys. Proc. Suppl. 85 (2000) 324; A. Zepeda, in: E. Nardi (Ed.), 3rd Latin American Symposium On High-Energy Physics, 2-8 Apr 2000, Cartagena de Indias, Colombia, Bristol, IOP, 2000.

[14] L. Anchordoqui and H. Goldberg, hep-ph/0109242.

[15] R. Emparan, M. Masip and R. Rattazzi, hep-ph/0109287.

[16] Y. Uehara, hep-ph/0110382.

[17] F. Halzen et al. [AMANDA Collaboration], in: B.L. Dingus, D.B. Kieda, M.H. Salamon (Eds.), 26th International Cosmic Ray Conference (ICRC 99), Salt Lake City, UT, 17-25 Aug 1999, Melville, AIP, 2000, pp. 428-431.

[18] R. M. Baltrusaitis et al., Phys. Rev. D 31 (1985) 2192.

[19] R. M. Baltrusaitis et al., Nucl. Instrum. Meth. A 240 (1985) 410.

[20] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 544 (1999) 3 and erratum to appear hep-ph/9811291 v2.

[21] E. A. Mirabelli, M. Perelstein and M. E. Peskin, Phys. Rev. Lett. 82 (1999) 2236; T. Han, J. D. Lykken and R. Zhang, Phys. Rev. D 59 (1999) 105006; J. L. Hewett, Phys. Rev. Lett. 82 (1999) 4765; P. Mathews, S. Raychaudhuri and K. Sridhar, Phys. Lett. B 450 (1999) 343; T. G. Rizzo, Phys. Rev. D 59 (1999) 115010; P. Mathews, S. Raychaudhuri and K. Sridhar, Phys. Lett. B 455 (1999) 115; K. Cheung, Phys. Lett. B 460 (1999) 383; C. Adloff et al. [H1 Collaboration], Phys. Lett. B 479 (2000) 358; H. Davoudiasl, J. L. Hewett and T. G. Rizzo, Phys. Rev. Lett. 84 (2000) 2080.

[22] S. Cullen and M. Perelstein, Phys. Rev. Lett. 83 (1999) 268; V. Barger, T. Han, C. Kao and R. J. Zhang, Phys. Lett. B 461 (1999) 34; C. Hanhart, D. R. Phillips, S. Reddy and M. J. Savage, Nucl. Phys. B 595 (2001) 335; C. Hanhart, J. A. Pons, D. R. Phillips and S. Reddy, Phys. Lett. B 509 (2001) 1; S. Hannestad and G. Raffelt, Phys. Rev. Lett. 87 (2001) 051301; hep-ph/0110067.

[23] L. J. Hall and D. R. Smith, Phys. Rev. D 60 (1999) 085008; M. Fairbairn, Phys. Lett. B 508 (2001) 335; S. Hannestad, Phys. Rev. D 64 (2001) 023515.

[24] S. Nussinov and R. Shrock, Phys. Rev. D 59 (1999) 105002; P. Jain, D. W. McKay, S. Panda and J. P. Ralston, Phys. Lett. B 484 (2000) 267.

[25] C. Tyler, A. V. Olinto and G. Sigl, Phys. Rev. D 63 (2001) 055001.

[26] M. Kachelriess and M. Plümacher, Phys. Rev. D 62 (2000) 103006; L. A. Anchordoqui, T. P. McCauley, S. Reucroft and J. Swain, Phys. Rev. D 63 (2001) 027303; L. Anchordoqui, H. Goldberg, T. McCauley, T. Paul, S. Reucroft and J. Swain, Phys. Rev. D 63 (2001) 124009; J. Alvarez-Muniz, F. Halzen, T. Han and D. Hooper, hep-ph/0107057; M. Kachelriess and M. Plümacher, hep-ph/0109184.
[48] K. Greisen, Phys. Rev. Lett. 16 (1966) 748; G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4 (1966) 78 [Pisma Zh. Eksp. Teor. Fiz. 4 (1966) 114].

[49] V. S. Berezinsky and G. T. Zatsepin, Phys. Lett. B 28 (1969) 423; V. S. Berezinsky and G. T. Zatsepin, Sov. J. Nucl. Phys. 11 (1970) 111 [Yad. Fiz. 11 (1970) 200].

[50] F. W. Stecker, Astrophys. J. 228 (1979) 919.

[51] C. T. Hill and D. N. Schramm, Phys. Rev. D 31 (1985) 564; C. T. Hill, D. N. Schramm and T. P. Walker, Phys. Rev. D 34 (1986) 1622; F. W. Stecker, C. Done, M. H. Salamon and P. Sommers, Phys. Rev. Lett. 66 (1991) 2697 [Erratum-ibid. 69 (1991) 2738].

[52] S. Yoshida and M. Teshima, Prog. Theor. Phys. 89 (1993) 833.

[53] R. J. Protheroe and P. A. Johnson, Astropart. Phys. 4 (1996) 253 [Erratum-ibid. 5 (1996) 215].

[54] S. Yoshida, H. Dai, C. C. Jui and P. Sommers, Astrophys. J. 479 (1997) 547.

[55] R. Engel and T. Stanev, Phys. Rev. D 64 (2001) 093010.

[56] E. Waxman and J. N. Bahcall, Phys. Rev. D 59 (1999) 023002; J. N. Bahcall and E. Waxman, Phys. Rev. D 64 (2001) 023002.

[57] K. Mannheim, R. J. Protheroe and J. P. Rachen, Phys. Rev. D 63 (2001) 023003.

[58] V. S. Berezinsky, in: J. G. Learned (Ed.), DUMAND Summer Workshops, Khabarovsk and Lake Baikal, 22-31 Aug 1979, Hawaii DUMAND Center, University of Hawaii, 1980, pp. 245-261.

[59] D. Fargion, B. Mele and A. Salis, Astrophys. J. 517 (1999) 725; T. J. Weiler, Astropart. Phys. 11 (1999) 303; S. Yoshida, G. Sigl and S. J. Lee, Phys. Rev. Lett. 81 (1998) 5505; Z. Fodor, S. D. Katz and A. Ringwald, hep-ph/0105064.

[60] M. H. Reno and C. Quigg, Phys. Rev. D 37 (1988) 657.

[61] V. S. Berezinsky and A. Y. Smirnov, Phys. Lett. B 48 (1974) 269.

[62] G. Frichter [RICE Collaboration. AMANDA Collaboration], prepared for: B.L. Dingus, D.B. Kieda, M.H. Salamon (Eds.), 26th International Cosmic Ray Conference (ICRC 99), Salt Lake City, UT, 17-25 Aug 1999, Melville, AIP, 2000.