Experimental Signature for Black Hole Production in Neutrino Air Showers

Luis Anchordoqui and Haim Goldberg

Department of Physics, Northeastern University, Boston, MA 02115, USA

The existence of extra degrees of freedom beyond the electroweak scale may allow the formation of black holes in nearly horizontal neutrino air showers. In this paper we examine the average properties of the light descendants of these black holes. Our analysis indicates that black hole decay gives rise to deeply penetrating showers with an electromagnetic component which differs substantially from that in conventional neutrino interactions, allowing a good characterization of the phenomenon against background. Naturally occurring black holes in horizontal neutrino showers could be detected and studied with the Auger air shower array. Since the expected black hole production rate at Auger is $> 1$ event/year, this cosmic ray observatory could be potentially powerful in probing models with extra dimensions and TeV-scale gravity.

Before proceeding, we take note of a serious challenge to a geometric cross section raised by Voloshin [1]. The criticism centers on the exponential suppression of transitions involving a (few-particle) quantum state to a (many-particle) semi-classical state. In response, the geometric result was reaffirmed by arguing that it connects smoothly to the string scattering cross section in an energy regime characterizing the transition to black hole physics. Whichever point of view one may find more convincing, it seems most conservative at this point to depend on experiment (if possible) to resolve the issue.

With this in mind, the neutrino nucleon cross section reads [2]

$$\sigma_{\nu N \rightarrow BH} = \sum_i \int_{E_{\min}^{BH}}^{1} dx \, \hat{\sigma}_i(x s) \, f_i(x Q^2) ,$$  \hspace{1cm} (3)

where $s = 2m_N E_\nu$, $f_i(x Q^2)$ are parton distribution functions (PDFs), $E_{\min}^{BH}$ is the minimum BH mass, and the sum is carried out over all partons in the nucleon. Following [3], the cross section is calculated using the CTEQ5M1 PDFs [3] with the momentum transfer $Q$ taken to be equal to $M_\nu = \sqrt{s}$.

The energy released in neutrinos by supernova explosions imposes several constraints on the fundamental Planck scale [10]. Namely, $M_\nu \gtrsim 500 - 1600$ TeV, $M_\nu \gtrsim 7 - 60$ TeV and $M_\nu \gtrsim 1$ TeV, for $n = 2, 3, 4$, respectively. Therefore, a straightforward calculation shows that $\sigma_{\nu N \rightarrow BH} > \sigma_{\nu N}^{SM}$, if $n \geq 4$. Here,

$$\sigma_{\nu N}^{SM}(E_\nu) \approx 2.36 \times 10^{-32} (E_\nu / 10^{19} \text{eV})^{0.363} \text{cm}^2 \hspace{1cm} (4)$$

is the total charged current Standard Model $\nu N$ cross section ($10^{16} \text{eV} \lesssim E_\nu \lesssim 10^{21} \text{eV}$) [11]. For $M_\nu \approx 5$ TeV, $M_\nu = 1$ TeV, and neutrino primary energies around $10^{20} \text{eV}$, $\sigma_{\nu N \rightarrow BH} \gtrsim 10^{-31} \text{cm}^2$. Note that although the atmosphere presents a target of thickness of about 1000 g/cm$^2$ to particles arriving vertically, the thickness increases up to $\approx 36000$ g/cm$^2$ to those arriving tangentially to the earth surface (i.e., with horizontal incidence

One of the most outstanding phenomena of TeV-scale quantum gravity [2] is the possible production of semi-classical black holes (BHs) in particle collisions [3]. These BHs are expected to decay promptly, giving rise to large multiplicity events with large total transverse energy and a characteristic ratio of hadronic to leptonic activity of roughly 5:1. Production rates for the Large Hadron Collider (LHC) are found to be sizeable for a fundamental Planck scale $M_\star = 1$ TeV [3]. Additionally, BHs occurring very deep in the atmosphere (revealed as intermediate states of ultra high energy neutrino interactions) may trigger quasi-horizontal showers that could be detected with the Auger Observatory [4]. The goal of this paper is to point out some salient experimental signatures of these air showers.

We start the discussion by reviewing the relevant BH properties. BHs are believed to be described by semi-classical general relativity when their mass $M_{BH} \gg M_\star$. As $M_{BH}$ approaches $M_\star$, string excitations can become important and the BH properties rather complex. The ensuing discussion will be framed in the context of flat extra dimensions, and we will comment on the warped scenario after presenting our results. In what follows, we rely on simple semiclassical arguments assuming that stringy effects are under control if $M_{BH}/M_\star \gtrsim 5$. The Schwarzschild radius $R_S$ of a $(4+n)$ dimensional BH is [2]

$$R_S = \frac{1}{\sqrt{\pi} M_\star} \left[ \frac{M_{BH}}{M_\star} \frac{8 \Gamma(\frac{n+3}{2})}{n+2} \right]^{\frac{1}{n+1}}. \hspace{1cm} (1)$$

Hence, if one envisions a head-on collision involving partons $i$ and $j$ with c.m. energy $\sqrt{s} = M_{BH}$ and impact parameter less than $R_S$, semiclassical reasoning suggests that a BH is formed. The total cross section of the process can be estimated from geometrical arguments [3,4], and is of order

$$\hat{\sigma}_{ij \rightarrow BH}(\hat{s}) \approx \pi R_S^2 = \frac{1}{M_\star^2} \left[ \frac{M_{BH}}{M_\star} \frac{8 \Gamma(\frac{n+3}{2})}{n+2} \right]^{\frac{1}{n+1}}. \hspace{1cm} (2)$$
energy in this channel is not deposited in the atmosphere, but is instead the total energy in the jet. With the infrared cutoff set approximately 54 , the average multiplicity per jet is roughly \( M_{BH}/(2 T_H) \) , or equivalently,

\[
\langle N \rangle \approx \frac{2 \sqrt{\pi}}{n+1} \left( \frac{M_{BH}}{M_*} \right)^{\frac{n+2}{n+1}} \left[ 8 \frac{x^{n+2}}{n+2} \right]^{\frac{1}{n+1}},
\]

where \( T_H \) is the Hawking temperature.

Most of the large multiplicity of observable quanta emitted in the BH decay is expected to come through hadronic jets produced by the quarks. The precise nature of the fragmentation process is unknown. We shall use here the quark \( \rightarrow \) hadron fragmentation spectrum originally suggested by Hill [12]

\[
\frac{dN_h}{dx} \approx 0.08 \exp \left[ 2.6 \sqrt{\ln(1/x)} \right] (1-x)^2 \\
\times \left[ x \sqrt{\ln(1/x)} \right]^{-1},
\]

that is consistent with the so-called “leading-log QCD” behavior and seems to reproduce quite well the multiplicity growth as seen in colliders experiments. Here, \( x \equiv E/E_{\text{jet}} \), \( E \) is the energy of any hadron in the jet, and \( E_{\text{jet}} \) is the total energy in the jet. With the infrared cutoff set to \( x = 10^{-3} \), the average multiplicity per jet is approximately 54 . The main features of the jet fragmentation process derived from \( dN_h/dx \approx (15/16) x^{-3/2} (1-x)^2 \) (which provides a reasonable parametrization of Eq. (7)) for \( 10^{-3} < x < 1 \) are listed in Table I. Now, assuming that the BH decays into all Standard Model particles (with equipartition among the particle species) and that each quark produces one hadronic jet, we obtain the “visible” BH decay spectrum.

We turn now to the analysis of the atmospheric cascade development triggered by the BH secondaries. In order to propagate the particles in the atmosphere we use the algorithms of \( \text{AIRESQ} \) (version 2.1.1) [13]. The showering of each charged hadron in the spectrum is simulated by a proton cascade of energy \( E \), whereas the shower induced by a \( \tau^0 \) decay [14] is replaced by a superposition of 2 photon showers of energy \( E/2 \). In ~ 1/3 of the events, the leptonic channel generates electromagnetic showers simulated by hard gamma rays. In the remaining cases, the energy in this channel is not deposited in the atmosphere, and we will exclude such events from our consideration.

The BH secondaries are injected with a primary zenith angle of 80° at 6.5 km above sea level (a.s.l.), setting the observation level at 1.5 km a.s.l. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons. The geomagnetic field was set to reproduce the RMS fluctuations.

FIG. 1. Density distributions at ground level of \( e^\pm \) as a function of the distance to the shower axis. The primary zenith angle is 80° and \( E_{\nu} = 10^{20} \) eV. The error bars indicate the RMS fluctuations.

| TABLE I. Properties of jet hadronization |
|-----------------------------------------|
| \( x_1 \) | \( x_2 \) | \( \int_{x_1}^{x_2} N_h \, dx \) | \( \int_{x_1}^{x_2} x N_h \, dx \) | \( x_{\text{equivalent}} \) |
|--------------|--------------|-----------------|-----------------|-----------------|
| 0.0750       | 1.0000       | 3               | 0.546           | 0.182           |
| 0.0350       | 0.0750       | 3               | 0.155           | 0.052           |
| 0.0100       | 0.0350       | 9               | 0.167           | 0.018           |
| 0.0047       | 0.0100       | 9               | 0.062           | 0.007           |
| 0.0010       | 0.0047       | 30              | 0.069           | 0.002           |

In order to obtain a clear signature of BH production, one should be able to identify its subsequent cascade...
in the whole cosmic ray sample. For large zenith angles (above 80°), an air shower initiated by a neutrino can be distinguished from that of an ordinary hadron by its shape. Ordinary hadrons interact high in the atmosphere. As a consequence, at ground level the electromagnetic part of the shower is totally extinguished (more than 6 equivalent vertical atmosphere were gone through) and only the muon channel survives. Besides, the shower front is extremely flat (radius > 100 km) and the particle time spread is very narrow (∆t < 50 ns). Unlike hadrons, neutrinos may interact deeply in the atmosphere, triggering showers in the volume of air immediately above the detector. The shower thus presents a curved front (radius of curvature of a few km), with particles well spread over time, O(μs). If primaries are mainly electronic and muonic neutrinos (as expected from pion decays) two types of neutrino showers can be distinguished: “mixed” (with full energy) or “pure hadronic” (with reduced energy), respectively. In the charged current interaction of a ν_e, an ultra high energy electron is produced which initiates a large electromagnetic cascade parallel to the hadronic cascade. In contrast, the charged current interaction of a ν_μ produces a muon which is not detectable at Auger. For the same total energy of the primary, the presence of a hard electromagnetic channel in BH production provides a clean signature when compared with the “pure hadronic” shower characterizing the ν_e interaction. To analyze the differences between the BH-like shower and ordinary ν_e shower, we mimic the latter as a superposition of a quark jet (equivalent to the set of hadrons listed in Table I) carrying around 20% of the original energy + a photon shower. Again, all particles in the sample are injected at 6.5 km a.s.l. and with a primary zenith angle of 80°.

In Fig. 1 we show the e± density at ground level (as a function of their distance to the shower axis), obtained from ordinary ν_μ-shower and a BH-like shower. We set M_{BH} = 5 TeV, and E_ν = 10^{20} eV. Then, for 4 ≤ n ≤ 7, from Eq. (8) we get ⟨N⟩ ≈ 5. At 50 m from the core, the ratio of the number of e± in a BH-like shower to that in a typical ν_μ shower is ∼ 10^{-3}. At about 1 km from the core this ratio rises to ∼ 10^{-1}. Note that the differences far from the shower-core are also statistically significant for surface detector experiments like the Auger Observatory [10]. In Fig. 2 we show the resulting distributions of muons at ground level. This profile is seen to be a rather poor discriminator between BH and ordinary showers (of the same total energy), in spite of the fact that each of the four hadronic jets from black hole decay has the same energy as the single jet in the standard charged current interaction. There are sufficient muons produced by the lepton shower to largely close the gap between the profiles.

In the presence of maximal ν_μ/ν_τ-mixing, ν_τ-shower must also be considered. However, since the mean flight distance ∼ 50E/km/EeV, and the distance between position of first impact and ground is ∼ 30 km, only τ’s with energy ≲ 8 × 10^{17} eV will decay. Thus, ν_τ showers above this energy will be indistinguishable from ν_μ showers.

We comment briefly on the warped scenario. If the curvature spills into the extra dimensions the fundamental Planck scale can be lowered all the way to ≈ 1 TeV already for n = 1. For BH radii smaller than the curvature scale of the warp geometry, we expect validity of the flat space approximation. This leads to larger cross sections and jet multiplicities. The signature we have described remains robust when increasing the multiplicity up to about 15, because the properties of the electromagnetic shower depends almost exclusively on the ratio of hadronic to leptonic activity.

In summary, cosmic neutrinos with horizontal incidence to the ground may interact with the earth atmosphere producing BHs that decay instantaneously via Hawking evaporation. We have shown that such a reaction chain gives rise to deeply penetrating showers with an ‘anomalous’ electromagnetic component: about an order of magnitude bigger than ordinary ν_μ-shower and at least an order of magnitude smaller than ν_τ-shower. This represents a very clean signal. Our focus on a BH subsample in which the leptonic channel generates electromagnetic showers will lower the event rate to about 0.7/year (for n = 4, decreasing slowly for larger n). Thus, a 10-year collection of data at Auger could give significant statistics to test this phenomenon, yielding perhaps one of the early signatures of TeV-scale quantum gravity.
ACKNOWLEDGMENTS

We would like to thank Jonathan Feng for some valuable discussion. This work has been supported in part by the National Science Foundation.

[1] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B 429, 263 (1998); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B 436, 257 (1998); N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Rev. D 59, 086004 (1999); L. J. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999).

[2] P. C. Argyres, S. Dimopoulos and J. March Russell, Phys. Lett. B 441, 96 (1998); R. Emparan, G. T. Horowitz and R. C. Myers, Phys. Rev. Lett. 85, 499 (2000); T. Banks, W. Fischler, hep-th/9906038; S. B. Giddings, hep-ph/0110012; K. Cheung, hep-ph/0110163.

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

[4] S. Dimopoulos and G. Landsberg, hep-ph/0106293.

[5] J. L. Feng and A. D. Shapere, hep-ph/0109106.

[6] R. C. Myers and M. J. Perry, Ann. Phys. 172, 304 (1986).

[7] M. B. Voloshin, hep-ph/0107119.

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

[9] H. L. Lai et al. (CTEQ Collaboration), Eur. Phys. J. C 12, 375 (2000).

[10] S. Cullen and M. Perelstein, Phys. Rev. Lett. 83, 268 (1999); V. Barger, T. Han, C. Kao and R. -J. Zhang, Phys. Lett. B 461, 34 (1999); L. J. Hall and D. R. Smith, Phys. Rev. D 60, 085008 (1999); S. Hannestad and G. G. Raffelt, Phys. Rev. Lett. 87, 051301 (2001); S. Hannestad and G. G. Raffelt, hep-ph/0110006.

[11] R. Gandhi, C. Quigg, M. H. Reno and I. Sarcevic, Phys. Rev. D 58, 093009 (1998).

[12] C. T. Hill, Nucl. Phys. B 224, 469 (1983).

[13] S. J. Sciutto, in Proc. XXVI International Cosmic Ray Conference, (Edts. D. Kieda, M. Salamon, and B. Dingus, Salt Lake City, Utah, 1999) vol.1, p.411, astro-ph/9905185.

[14] Note that in our energy regime the lifetime flight distance of any $\pi^0$ is at least an order of magnitude smaller than the pion mean free path.

[15] This may change if there are new sufficiently strong interactions for neutrinos at very high energies. For instance, virtual exchange of bulk gravitons (Kaluza–Klein modes) leads to extra contributions to $\sigma_{\nu N}$. S. Nussinov and R. Shrock, Phys. Rev. D 59 105002 (1999); P. Jain, D. W. McKay, S. Panda, and J. P. Ralston, Phys. Lett. B 484, 267 (2000); C. Tyler, A. Olinto and G. Sigl, Phys. Rev. D 63, 055001 (2001); L. Anchordoqui, H. Goldberg, T. McCauley, T. Paul, S. Reucroft and J. Swain, Phys. Rev. D 63, 124009 (2001). Additionally, $\sigma_{\nu N}$ can be made large due to an exponential increase of the number of degrees of freedom in the context of string theory. G. Domokos and S. Kovesi-Domokos, Phys. Rev. Lett. 82, 1366 (1999). Both effects could have a direct influence in the evolution of extensive air showers, allowing earlier neutrino cascade developments. A recent string-based calculation (F. Cornet, J.I. Illana, M. Masip Phys. Rev. Lett. 86, 4235 (2001)), as well as eikonalization analyses of the multigraviton exchange process (M. Kachelriess and M. Plumacher, Phys. Rev. D 62, 103006 (2000); R. Emparan, M. Masip and R. Rattazzi, hep-ph/0109287) suggest that such early shower development is very unlikely.

[16] A full simulation for projected ground level detection at Auger is in progress.