Experimental Signature for Black Hole Production in Neutrino Air Showers

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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.

One of the most outstanding phenomena of TeV-scale quantum gravity [1] is the possible production of semiclassical black holes (BHs) in particle collisions [2]. 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 $M_{\ast} = 1$ TeV [3,4]. 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 [5]. 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 semiclassical general relativity when their mass $M_{BH} > M_{\ast}$. As $M_{BH}$ approaches $M_{\ast}$, string excitations can become important and the BH properties rather complex. In what follows, we rely on simple semiclassical arguments assuming that stringy effects are under control if $M_{BH}/M_{\ast} \gtrsim 5$. The Schwarzschild radius $R_{S}$ of a (4+n) dimensional BH is [6]

$$R_{S} = \frac{1}{\sqrt{\pi} M_{\ast}} \left[ \frac{M_{BH}}{M_{\ast}} \frac{8 \Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{1/n}. \quad (1)$$

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

$$\hat{\sigma}_{ij\rightarrow BH}(\hat{s}) \approx \pi R_{S}^{2} = \frac{1}{M_{\ast}^{2}} \left[ \frac{M_{BH}}{M_{\ast}} \frac{8 \Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{1/n}. \quad (2)$$

Before proceeding, we take note of a serious challenge to a geometric cross section raised by Voloshin [7]. The criticism centers on the exponential suppression of transitions involving a (few-particle) quantum state to a (many-particle) semi-classical state. In response [8], 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 [5]

$$\sigma_{\nu N\rightarrow BH} = \sum_{i} \int_{M_{BH}^{min} / s}^{1} dx \, \hat{\sigma}_{i}(x) \, f_{i}(x, Q^{2}) \ , \quad (3)$$

where $s = 2m_{N}E_{\nu}$, $f_{i}(x)$ are parton distribution functions (PDFs), $M_{BH}^{min}$ is the minimum BH mass, and the sum is carried out over all partons in the nucleon. Following [5], the cross section is calculated using the CTEQ5M1 PDFs [9] with the momentum transfer $Q$ taken to be equal to $M_{BH} = \sqrt{s}$. The energy released in neutrinos by supernova explosions imposes several constraints on the fundamental Planck scale [10]. Namely, $M_{\ast} \gtrsim 50 - 84$ TeV, $M_{\ast} \gtrsim 4 - 7$ TeV and $M_{\ast} \gtrsim 1$ 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,

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

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 $M_{BH} \approx 5$ TeV, $M_{\ast} = 1$ TeV, and neutrino primary energies around $10^{20}$ eV, $\sigma_{\nu N\rightarrow BH} \gtrsim 10^{-31}$ 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 $\approx 360000$ g/cm$^{2}$ to those arising tangentially to the earth surface (i.e., with horizontal incidence to the ground). Consequently, the probability of BH production is not negligible. Specifically, more than one BH event per year could be detected by the ground array of the Auger Observatory [5].
Thus, for \( M_{\text{BH}} \gg M_\pi, \) \( \tau_{\text{BH}} \gg t \), the BH is a well-defined resonance and may be thought as an intermediate state in the \( s \)-channel. Therefore, if one assumes that the BH evaporates instantaneously at its original temperature into its decay products, the average multiplicity is roughly \( M_{\text{BH}}/(2 T_H) \) [4], or equivalently,

\[
\langle N \rangle \approx \frac{2 \sqrt{\pi}}{n + 1} \left[ \frac{M_{\text{BH}}}{M_\pi} \right]^{\frac{n + 3}{2}} \left[ \frac{8 \Gamma(n + \frac{3}{2})}{n + 2 \Gamma(n + 1)} \right]^{\frac{1}{2}}.
\]

TABLE I. Properties of jet hadronization

<table>
<thead>
<tr>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( \int_{x_1}^{x_2} N_h , dx )</th>
<th>( \int_{x_1}^{x_2} x , N_h , dx )</th>
<th>( x_{\text{equivalent}} )</th>
</tr>
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<td>0.182</td>
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<tr>
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<td>0.0750</td>
<td>3</td>
<td>0.155</td>
<td>0.052</td>
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<td>0.0350</td>
<td>9</td>
<td>0.167</td>
<td>0.018</td>
</tr>
<tr>
<td>0.0047</td>
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<td>9</td>
<td>0.062</td>
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<tr>
<td>0.0010</td>
<td>0.0047</td>
<td>30</td>
<td>0.069</td>
<td>0.002</td>
</tr>
</tbody>
</table>

The BH lifetime, governed by the Hawking evaporation process, is [2]

\[
\tau_{\text{BH}} \sim \frac{1}{M_\pi} \left( \frac{M_{\text{BH}}}{M_\pi} \right)^{\frac{2 + n}{2}}.
\]

Thus, for \( M_{\text{BH}} \gg M_\pi, \) \( \tau_{\text{BH}} M_{\text{BH}} \gg 1 \), the BH is a well-defined resonance and may be thought as an intermediate state in the \( s \)-channel. Therefore, if one assumes that the BH evaporates instantaneously at its original temperature into its decay products, the average multiplicity is roughly \( M_{\text{BH}}/(2 T_H) \) [4], or equivalently,

\[
\langle N \rangle \approx \frac{2 \sqrt{\pi}}{n + 1} \left[ \frac{M_{\text{BH}}}{M_\pi} \right]^{\frac{n + 3}{2}} \left\{ \frac{8 \Gamma(n + \frac{3}{2})}{n + 2 \Gamma(n + 1)} \right\}^{\frac{1}{2}},
\]

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]

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

that is consistent with the so-called “leading-log QCD” behavior and seems the 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 ARIESQ (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 \( \pi^0 \) decay [14] is replaced by a superposition of 2 photon showers of energy \( E/2 \). The leptonic channel is described by hard gamma rays. 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 that prevailing upon the Auger experiment. The results of these simulations were processed with the help of the AIRE S analysis package. Secondary particles of different types in individual showers were sorted according to their distance \( R \) to the shower axis. We extract in a separate file all \( \mu^\pm \) and \( e^\pm \).

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 ($\Delta t < 50$ ns). Unlike hadrons, neutrinos may interact deeply in the atmosphere, triggering showers in the volume of air immediately above the detector [15]. The shower thus presents a curved front (radius of curvature of a few km), with particles well spread over time, $O(\mu s)$. 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 $\nu_e$, 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 $\nu_{\mu}$ produces a muon which is not detectable at Auger. The presence of a hard leptonic channel in BH decays (electromagnetic shower) provides a clean signature when compared with the “pure hadronic” shower characterizing the $\nu_{\mu}$ interaction—the latter will have a very small electromagnetic component. To analyze the differences between the BH-like shower and ordinary $\nu_e$ 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 $80^\circ$.

In Fig. 1 we show the $e^\pm$ density at ground level (as a function of their distance to the shower axis), obtained from ordinary $\nu_e$-shower and a BH-like shower. We set $M_{BH} = 5$ TeV, and $E_\nu = 10^{20}$ eV. Then, from Eq.(6) we get $\langle N \rangle \approx 5$. At 50 m from the core, the ratio of the number of $e^\pm$ in a BH-like shower to that in a typical $\nu_e$ shower is $\sim 10^{-3}$. At about 1 km from the core this ratio rises to $\sim 10^{-1}$. Note that the differences far from the shower-core are also statistically significant for surface detector experiments like the Auger Observatory [16]. 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, 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. It is worth noting that the signature we have described remains robust when increasing the mass of the BH, even taking into account shower-to-shower fluctuations.

In the presence of maximal $\nu_{\mu}/\nu_{\tau}$-mixing, $\nu_{\tau}$-showers must also be considered. However, since the mean flight distance $\sim 50E$ km/EeV, and the distance between position of first impact and ground is $\sim 30$ km, only $\tau$’s with energy $\lesssim 8 \times 10^{17}$ eV will decay. Thus, $\nu_{\tau}$ showers above this energy will be indistinguishable from $\nu_{\mu}$ showers.

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 $\nu_{\mu}$-showers and at least an order of magnitude smaller than $\nu_e$-showers. This represents a very clean signal, and 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

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