Black Hole Production by Cosmic Rays

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Ultrahigh energy cosmic rays create black holes in scenarios with extra dimensions and TeV-scale gravity. In particular, cosmic neutrinos will produce black holes deep in the atmosphere, initiating quasihorizontal showers far above the standard model rate. At the Auger Observatory, hundreds of black hole events may be observed, providing evidence for extra dimensions and the first opportunity for experimental study of microscopic black holes. If no black holes are found, the fundamental Planck scale must be above 2 TeV for any number of extra dimensions.

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Black holes are among the most captivating and inaccessible phenomena in physics. In principle, tiny black holes can be produced in particle collisions with center-of-mass energies above the Planck scale M_*, where they should be well described semiclassically and thermodynamically [1]. However, in conventional four-dimensional theories, $M_* \sim 10^{19}$ GeV. Given currently accessible energies $\lesssim 1$ TeV (10^3 GeV), the study of such black holes is far beyond the realm of experimental particle physics.

In models with extra dimensions, however, the fundamental Planck scale may be much lower. If this is the case, black hole production and evaporation might be observed in particle collisions [2,3]. Beginning later this decade, for example, the Large Hadron Collider (LHC) at CERN will begin operation with parton center-of-mass energies of several TeV. Assuming M_* of order 1 TeV, the authors of Refs. [4,5] have noted the distinctive characteristics of black hole production and find event rates as large as 10^8 per year.

As high as it is, the energy range probed by the LHC is modest compared to that of ultra-high-energy cosmic rays, which have been observed to interact in the Earth's atmosphere with center-of-mass energies in excess of 100 TeV. As we will see, cosmic neutrinos with energies above 10^6 GeV are particularly effective sources of black holes, with production cross sections as much as 2 or more orders of magnitude above standard model (SM) predictions. These black holes decay rapidly, initiating spectacular quasihorizontal showers deep in the atmosphere.

Observation of such showers at the rates we predict would be a strong indication of new TeV-scale physics. In the SM, while Earth-skimming ultra-high-energy neutrinos may be observed with reasonable rates by fluorescence detectors [6] and ground arrays [7], those that pass only through the atmosphere are extremely difficult to detect. Even at the large Pierre Auger Observatory, SM interactions are expected to produce only a fraction of an event per year [8–10]. In contrast, with conservative neutrino flux estimates, we find that Auger could detect hundreds of black holes before the LHC begins operation, providing evidence for TeV-scale gravity and extra dimensions and making possible the experimental study of black holes in the late stages of Hawking evaporation.

Low-scale gravity may be realized if the conventional four spacetime dimensions are supplemented by n additional spatial dimensions. SM matter and gauge fields are typically assumed to be confined to the four dimensions of our world. However, gravity propagates in the full $(4 + n)$-dimensional space with Einstein action

$$S_E = \frac{1}{8\pi} M_*^{2+n} \int d^{4+n}x \sqrt{-g}\, \frac{1}{2}\, \mathcal{R}\,, \qquad (1)$$

where M_* is the fundamental Planck scale. If the n-dimensional space is flat and compact with volume V_n [11], the observed gravitational strength is reproduced provided $M_*^{2+n} V_n \approx (1.2 \times 10^{19}\ \text{GeV})^2$. For large V_n, M_* near the TeV scale is possible: current bounds are $M_* \gtrsim 40$ TeV for $n = 2$, $M_* \gtrsim 400$ GeV for $n = 4$, and $M_* \gtrsim 300$ GeV for $n = 6$ [12]. For $n = 1$, $M_* \sim$ TeV is excluded in this context. However, in alternative scenarios with warped metrics [13], gravity may become strong below 1 TeV, even for $n = 1$ [14]. Our discussion will not depend on the details of these scenarios, as long as the black holes produced are smaller than the compactification radii (curvature scales) in flat (warped) scenarios, and so well approximated by $(4 + n)$-dimensional asymptotically Minkowskian solutions.

In theories with TeV-scale gravity, many effects may alter cosmic ray interactions with observable consequences [15]. However, in contrast to all other processes, our understanding of black hole properties is expected to be qualitatively sound for center-of-mass energies above M_* and increasingly valid the farther above M_* one probes. Black holes, then, may provide a uniquely reliable probe of extra-dimensional effects above M_*, where the full range of cosmic ray energies may be exploited.

The Schwarzschild radius for a $(4 + n)$-dimensional, neutral, nonspinning black hole with mass M_{BH} is [16]

$$r_s(M_{\rm BH}^2) = \frac{1}{\sqrt{\pi}\,M_*}\left[\frac{M_{\rm BH}}{M_*}\right]^{1/(1+n)}\left[\frac{8\Gamma(\frac{3+n}{2})}{2+n}\right]^{1/(1+n)}. \quad (2)$$

Black hole formation is expected when partons i and j with center-of-mass energy $\sqrt{\hat{s}}$ pass within a distance $r_s(\hat{s})$, suggesting a geometrical cross section of order

$$\hat{\sigma}(ij \to {\rm BH})(\hat{s}) \approx \pi r_s^2(\hat{s}). \quad (3)$$

We will take this as an adequate approximation and assume that a black hole of mass $M_{\rm BH} = \sqrt{\hat{s}}$ is formed. (Numerical analysis of classical head-on collisions in four dimensions finds $M_{\rm BH} \approx 0.8\sqrt{\hat{s}}$ [17].) The suppression factor of Ref. [18] has been disputed [19]; we have not included it here. The neutrino-nucleon scattering cross section is then

$$\sigma(\nu N \to {\rm BH}) = \sum_i \int_{(M_{\rm BH}^{\rm min})^2/s}^1 dx\, \hat{\sigma}_i(xs) f_i(x,Q), \quad (4)$$

where $s = 2m_N E_\nu$, the sum is over all partons in the nucleon, the f_i are parton distribution functions (pdfs), and $M_{\rm BH}^{\rm min}$ is the minimal black hole mass for which Eq. (3) is expected to be valid. We set momentum transfer $Q = \min\{M_{\rm BH}, 10\ {\rm TeV}\}$, where the upper limit is from the CTEQ5M1 pdfs [20]; $\sigma(\nu N \to {\rm BH})$ is insensitive to the details of this choice. For the conservative fluxes considered below, our results are also rather insensitive to $x < 10^{-5}$. For concreteness, however, we extrapolate to $x < 10^{-5}$ assuming $f_i(x,Q) \propto x^{-[1+\lambda_i(Q)]}$. Finally, we choose $M_{\rm BH}^{\rm min} = M_*$. The relatively mild dependence on $M_{\rm BH}^{\rm min}$ is discussed below.

Cross sections for black hole production by cosmic neutrinos are given in Fig. 1. The SM cross section for $\nu N \to \ell X$ is included for comparison. In contrast to the SM process, black hole production is not suppressed by perturbative couplings and is enhanced by the sum over all partons, particularly the gluon. In addition, while the SM cross section grows rapidly with E_ν, as is well known, the black hole cross section grows even more rapidly: for large n, it has the asymptotic behavior $\sigma \propto E_\nu^{\lambda_i(10\ {\rm TeV})} \approx E_\nu^{0.45}$. As a result of these effects, black hole production may exceed deep inelastic scattering rates by 2 or more orders of magnitude.

Although greatly reduced by black hole production, neutrino interaction lengths $L = 1.7 \times 10^7$ kmwe (pb/σ) are still far larger than the Earth's atmospheric depth, which is only 0.36 kmwe even when traversed horizontally. Neutrinos therefore produce black holes uniformly at all atmospheric depths. As a result, the most promising signal of black hole creation by cosmic rays is quasihorizontal showers initiated by neutrinos deep in the atmosphere. At these angles, the likelihood of interaction is maximized and the background from hadronic cosmic rays is eliminated, since these shower high in the atmosphere. The number of black holes detected is, then,

$$\mathcal{N} = \int dE_\nu\, N_A \frac{d\Phi}{dE_\nu}\, \sigma(E_\nu) A(E_\nu) T, \quad (5)$$

where $A(E_\nu)$ is a given observatory's acceptance for quasihorizontal showers in cm^3 water equivalent steradians (cm^{3}we sr), $N_A = 6.022 \times 10^{23}$ is Avogadro's number, $d\Phi/dE_\nu$ is the source flux of neutrinos, and T is the running time of the detector.

There are many possible sources of ultra-high-energy neutrinos. Here we conservatively consider only the "guaranteed" flux of Greisen neutrinos produced by interactions of the observed ultra-high-energy cosmic rays with the cosmic microwave background [21]. This flux is subject to uncertainties; we adopt the results of Ref. [22], shown in Fig. 2. The flux estimates of Refs. [23] produce similar event rates, while the strong source evolution case of Ref. [24] enhances the results below by over an order of

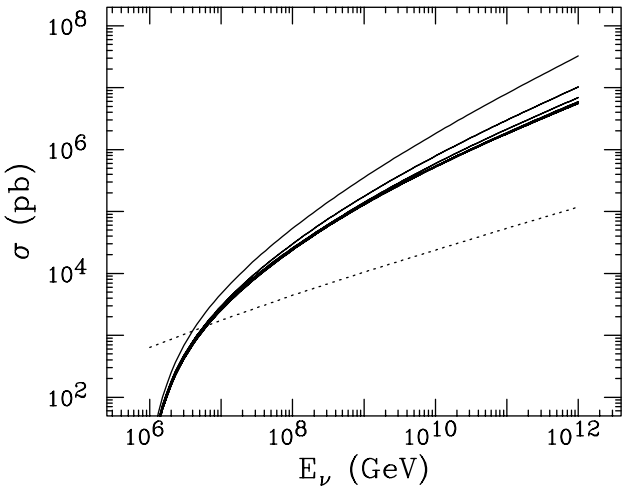

FIG. 1. Cross sections $\sigma(\nu N \to {\rm BH})$ for $M_* = M_{\rm BH}^{\rm min} = 1$ TeV and $n = 1, \ldots, 7$ from above. (The last four curves are virtually indistinguishable.) The dotted curve is for the SM process $\nu N \to \ell X$.

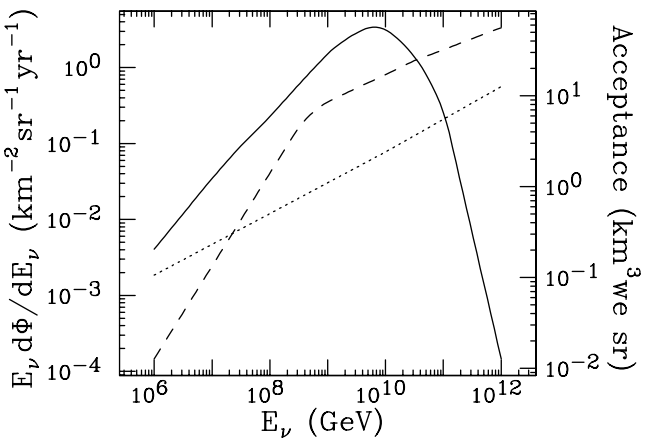

FIG. 2. Neutrino flux from Greisen photoproduction (solid) [22], and ground array (dashed) [8] and fluorescence (dotted) [10] acceptances of one Auger site for quasihorizontal hadronic showers. For fluorescence detection, a duty cycle of 10% has been included.

magnitude. New physics might also increase the neutrino flux. In particular, many proposed explanations of cosmic rays with energies above the Greisen-Zatsepin-Kuz'min (GZK) cutoff [21,25] would boost these event rates by several orders of magnitude.

Quasihorizontal showers may be observed by air shower ground arrays or air fluorescence detectors. The largest near-future cosmic ray experiment is the Auger Observatory, a hybrid detector consisting of two sites, each with surface area 3000 km^2. Construction of the southern site is in progress, with a counterpart planned in the northern hemisphere. Auger acceptances for deeply penetrating air showers have been studied in Refs. [8–10,24]. Black holes decay thermally, according to the number of degrees of freedom available, and so their decays are mainly hadronic [4,5]. We therefore consider the hadronic shower acceptance for ground arrays, including "partially contained" showers [8]. For fluorescence, we use the results of Ref. [10] for showers with zenith angles above 60° initiated at depths greater than 1250 cmwe. These acceptances are given in Fig. 2. A duty cycle of 10% has been included for fluorescence, where observations are limited to cloudless, moonless nights. At $E_\nu \sim 10^{10}$ GeV where the Greisen flux peaks, the ground array is more sensitive, and so we focus on ground array rates below. Note, however, that future detectors, such as Telescope Array and the space-based OWL and EUSO, will improve this fluorescence acceptance by 1 to 3 orders of magnitude [26].

Given the cross sections of Fig. 1 and the flux and acceptances of Fig. 2, the number of events is determined by Eq. (5). The results for ground arrays are given in Fig. 3. Tens to hundreds of events are possible for $M_* \approx 1$ TeV. Tens of black holes may also be detected by fluorescence. For larger M_*, $\hat{\sigma}(ij \to \mathrm{BH})$ falls rapidly as $M_*^{-(4+2n)/(1+n)}$. Nevertheless, requiring three events for discovery, black hole production probes Planck scales as high as 3 TeV for $n = 1$, and 2 TeV for all n. If no events are seen, barring a neutrino flux significantly below our conservative estimate, a stringent lower bound of $M_* \gtrsim 2$ TeV may be set for all n.

The results of Fig. 3 are for $M_{\mathrm{BH}}^{\mathrm{min}} = M_*$. While the semiclassical approximation is invalid for $M_{\mathrm{BH}} \approx M_*$, this is a calculational, not physical, limitation and does not imply that production of black holes or similar states in this mass range is suppressed [19]; in fact, it may just as well be enhanced. Nevertheless, it is comforting to know that our results are not strongly sensitive to this assumption. In Fig. 4, the dependence on $M_{\mathrm{BH}}^{\mathrm{min}}$ is shown. For $M_{\mathrm{BH}}^{\mathrm{min}} = 5M_*$, event rates are reduced by factors of 2 for $n = 1$ and 4 for large n. While these reductions are substantial, they are extremely mild relative to the case at colliders. At the LHC, the requirement $M_{\mathrm{BH}} > 5M_*$ suppresses event rates by factors of a hundred or more [5]. For cosmic rays, while the black hole mass distribution is still peaked at low masses as a result of enhancements from pdfs at low x, the reduction is far more modest.

If an anomalously large quasihorizontal shower rate is found, it may be identified as due to black hole production in several ways. First, although a large rate may be attributed to either an enhanced flux or an enhanced black hole cross section, these possibilities may be distinguished by searches for Earth-skimming neutrinos [6,7]. While an enhanced flux increases these rates, a large black hole cross section will suppress them, since the hadronic decay products of black hole evaporation will not escape the Earth's crust.

Second, showers from black hole production have distinctive characteristics. In the SM, typical hadronic showers, as initiated by nucleons or nuclei, occur high in the atmosphere. Deep atmospheric showers arise only from $\nu N \to \ell X$, resulting in a hadronic shower initiated by the struck quark, possibly accompanied by an electromagnetic

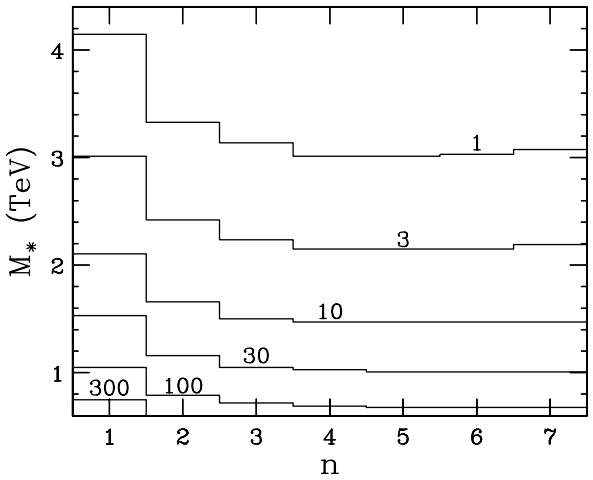

FIG. 3. The number of black holes detected by the ground array in 5 Auger site years as a function of $M_* = M_{\mathrm{BH}}^{\mathrm{min}}$ and the number of extra dimensions n.

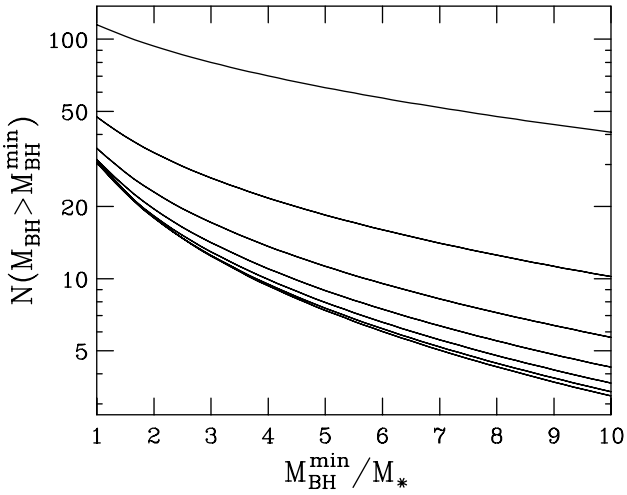

FIG. 4. The number of black holes detected by the ground array in 5 Auger site-years as a function of $M_{\mathrm{BH}}^{\mathrm{min}}$ for $M_* = 1$ TeV and $n = 1, \ldots, 7$ from above.

shower carrying most of the incident energy, depending on the neutrino flavor. Black hole events are markedly different. The black hole rest lifetime is $\tau \sim (1/M_*) \times (M_{\rm BH}/M_*)^{(3+n)/(1+n)}$. Since $M_*^{-1} \sim {\rm TeV}^{-1} \sim 10^{-27}$ s, even the largest black holes produced evaporate effectively instantaneously. In contrast to SM showers, however, black hole showers have small electromagnetic components, and the average multiplicity in black hole decays is [4,5]

$$\langle N \rangle \approx \frac{M_{\rm BH}}{2T_H} = \frac{2\sqrt{\pi}}{1+n}\left[\frac{M_{\rm BH}}{M_*}\right]^{(2+n)/(1+n)} \times \left[\frac{8\Gamma(\frac{3+n}{2})}{2+n}\right]^{1/(1+n)}, \quad (6)$$

where T_H is the Hawking temperature. Large mass black holes therefore decay to large numbers of quarks and gluons, and black hole showers will appear more nucleuslike than SM events, with the discrepancy growing with black hole mass. Nucleus showers differ from nucleon showers in several ways [27]. $X_{\rm max}$, the atmospheric depth at which the number of particles in a shower reaches its maximum, is significantly lower for nuclei, and shower-to-shower fluctuations in $X_{\rm max}$ and the number of electrons are also smaller. Black holes and SM events may therefore be distinguished based on shower characteristics, at least on a statistical basis. Note from Fig. 4 that a fairly smooth distribution of black hole masses is expected. If large numbers of black holes are found, the correlations of shower energy with $M_{\rm BH}$ and $X_{\rm max}$ with $\langle N \rangle$ will also allow tests of Hawking evaporation and possibly even measurements of n and M_* through Eq. (6).

Before closing, we comment on the possible relevance of black hole production to the GZK paradox. As noted above, the cross sections of Fig. 1 may be enhanced, especially for $M_{\rm BH} \sim M_*$, where the behavior of black holes and related objects is very poorly understood. In addition, if effectively four-dimensional black holes are produced, as may be possible in warped scenarios with small curvature scales, we find cross sections of 10 mb for $E_\nu \sim 10^{12}$ GeV. If these or other enhancements are large enough to bring the cross sections to the 100 mb level, cosmic neutrinos will be primaries immune to GZK-type cutoffs that produce hadronic showers high in the atmosphere, providing a viable resolution to the GZK puzzle. While the required enhancement is large and speculative, the qualitative merits of black hole production as a solution to the GZK paradox are suggestive and deserve further study.

To summarize, in TeV-scale gravity scenarios, ultrahigh energy cosmic neutrinos will produce black holes in the Earth's atmosphere, leading to anomalously large rates for quasihorizontal hadronic showers. If the LHC is to be a black hole factory, at least tens to hundreds of black holes will be detected at the Auger Observatory before the LHC begins operation. Such events are powerful probes of extra dimensions, and may provide information about black holes in the late stages of evaporation.

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