Mini Black Holes from Ultrahigh Energy Cosmic Neutrinos

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Abstract

We review the perhaps most exciting phenomenology of models with extra spatial dimensions and Planck scale near TeV: the production of mini black holes in ultrahigh energy particle collisions, and the discovery potential of cosmic ray/cosmic neutrino experiments for black hole events before the start of LHC.

1 Introduction

It has been conjectured that mini black holes may be formed in particle collisions at energies higher than the Planck mass and with impact parameters smaller than a critical value [1]. In models with $\delta = D - 4$ extra spatial dimensions, where the Standard Model particles are assumed to reside on a 3-dimensional brane while only gravitons are allowed to propagate into the bulk, the Planck scale, which is the scale characterizing quantum gravity, can be just beyond the electroweak scale [2, 3]. Within such TeV-scale gravity models, above conjecture suggests that particle collisions at energies $\gtrsim$ TeV may result in the production of black holes of masses at this energy scale, provided the colliding particles come close enough [4].

Due to their small masses, these microscopic black holes undergo decay processes rapidly. It is believed that these multi-dimensional black holes should Hawking-radiate [5] mainly into Standard Model particles on the brane rather than into the bulk [6]. Thus direct observations of such black hole events are possible. Estimates show that, depending on the value of the higher-dimensional fundamental Planck scale, the Large Hadron Collider (LHC) may either turn into a black hole factory [7, 8], where the black hole formation conjecture, the Hawking radiation law and the existence of extra spatial dimensions can be verified experimentally, or be able to put constraints on the model parameters from non-observation. On the other hand, it is well known that particle astrophysics experiments are complementary to collider searches for new physics beyond the Standard Model. In the case of black hole production in TeV-scale gravity models, one finds [9, 10, 11, 12, 13, 14] that depending on the fluxes of the ultrahigh energy cosmic neutrinos, cosmic ray facilities such as Auger and neutrino telescopes like AMANDA and RICE may have an opportunity to see the first sign or put constraints on black hole production parameters before LHC starts operating. IceCube has even discovery potential beyond the LHC reach.

In the following sections we give a brief review on the phenomenology of black hole production and decay in the large extra dimension scenario [2], and the prospects of the cosmic ray experiments for detecting black hole events before LHC starts operating. More details and a more complete reference list can be found in e.g. Ref. [15].

2 Black hole production and decay in TeV-scale gravity

TeV-scale gravity is a novel approach to the long-standing hierarchy problem. The idea is to assume that the fundamental scale in physics is the TeV scale, and there are $\delta \geq 1$ compact extra dimensions. The hierarchy between the four-dimensional Planck mass $M_{\rm pl} = (G_{\rm N}/\hbar)^{-1/2} \simeq 1.2 \cdot 10^{19}$ GeV and the fundamental Planck scale $M_D \sim$ TeV arises either due to the large volume of the extra dimensions [2], or through the "warp factor" arising from the background metric [3].

2.1 Black hole production

With the proposal of TeV-scale gravity, the remote possibility of probing the Planck scale physics is now within phenomenological reach. In TeV-scale gravity models, the trans-Planckian energy regime corresponds to

$$\sqrt{s} \gg M_D \qquad \Rightarrow \qquad R_{\rm S} \gg \lambda_{\rm Pl} \gg \lambda_{\rm B}\,, \tag{1}$$

where $\lambda_{\rm Pl}$ is the Planck length, $\lambda_{\rm B}$ the de Broglie wavelength, and

$$R_{\rm S} = \frac{1}{M_D}\left[\frac{\sqrt{s}}{M_D}\left(\frac{2^{\delta}\pi^{\frac{\delta-3}{2}}\Gamma\left(\frac{3+\delta}{2}\right)}{2+\delta}\right)\right]^{\frac{1}{1+\delta}} \tag{2}$$

is the Schwarzschild radius associated with the centre-of-mass (cm) energy $\sqrt{s}$ [16]. In this regime, gravitational interactions dominate over other gauge interactions. The gravitational scattering process in this regime is semiclassical and calculable by non-perturbative approaches only.

The phenomenology of trans-Planckian energy scattering in large extra dimension scenarios has been studied in Ref. [17], which focus on the regime of large impact parameter $b \gg R_S$, where the elastic cross section is calculable using the eikonal approximation. On the other hand, in the regime where black hole formation is conjectured [1],

$$\sqrt{s} \gg M_D\,, \quad b < R_{\rm S}\,, \tag{3}$$

[1]String theory predicts that trans-Planckian energy scattering could lead to the creation of "branes" as well. For phenomenological investigations of p-brane production, see e.g. [18].

exact calculations are impossible due to the high non-linearity of the Einstein equations. Nevertheless, a geometrical parametrisation for the black hole production cross section at the parton-level ij,

$$\sigma_{ij}^{\rm bh}(\hat{s}) \approx \pi R_{\rm S}^2 \left(M_{\rm bh} = \sqrt{\hat{s}}\right)\ \Theta\left(\sqrt{\hat{s}} - M_{\rm bh}^{\rm min}\right) , \tag{4}$$

is believed to capture the essential features of this nonperturbative phenomenon [19, 20]. This semiclassical description is assumed to be valid above a minimum black hole mass $M_{\rm bh}^{\rm min} \gg M_D$, which is taken to be a free parameter besides M_D and $\delta = D - 4$. For the case $D = 4$, mass of the final state black hole is estimated to be $\sim \mathcal{O}(50\% \div 80\%)$ of the initial centre-of-mass energy $\sqrt{s}$ [19, 21, 22]. But estimate for the mass of the final black hole in $D > 4$ is not available so far. Besides, it is still not clear how to extend the study to the production of charged and/or spinning black holes in higher dimensions.

2.2 Black hole decay

Hawking has predicted that black holes should evaporate by thermally radiating real particles at the cost of their mass [5]. For black holes produced with $M_{\rm bh} \gg M_D$ it is sufficient to adopt the semiclassical approximation for the purpose of estimating black hole event rates and event signatures in high-energy experiments, since a black hole spends most of its lifetime in the stage where its mass is close to the initial value

Neglecting the backreaction of the emitted particles on the spacetime geometry (described by the greybody factor), a $(4+\delta)$-dimensional Schwarzschild black hole of initial mass $M_{\rm bh} \gg M_D$ radiates thermally as a black body of surface area $\mathcal{A}_{\delta+2}$ at the Hawking temperature $T_{\rm H} = (\delta+1)/4\pi R_S$. It is shown in Ref. [6] that the multi-dimensional black holes localised on the brane radiate at equal rates

$$\frac{dE}{dt} \simeq \sigma_{\delta+4}\,\mathcal{A}_{\delta+2}\,T_{\rm H}^{\,\delta+4} \propto \frac{1}{R_{\rm S}^2} , \tag{5}$$

into a bulk field and into a brane field (the Stefan-Boltzmann constant in $(\delta+4)$-dimensions $\sigma_{\delta+4}$ is found to be almost independent of the number of extra dimensions). The fact that there are much more fields on the brane than in the bulk then leads to the conclusion that small black holes localised on the brane radiate mainly into Standard Model particles on the brane rather than into the bulk. Approximately $\langle n \rangle \approx \frac{M_{\rm bh}}{2\,T_{\rm H}}$ particles [8], mostly hadrons and leptons, will be emitted during $\tau_D \sim 10^{-26}$ s, the lifetime of an average mini black hole.

3 Mini black holes at colliders and from cosmic neutrinos

If the fundamental Planck scale M_D is below 2 TeV, the Large Hadron Collider (LHC), with its design values $\sqrt{s} = 14$ TeV for the proton-proton cm energy and $\mathcal{L} = 10^{34}$ cm^{-2} s^{-1} for the luminosity, will be producing mini black holes copiously. The unique signatures of black hole decay (highly isotropical events, with characteristic spectra and species ratios) [7, 8] should then enable the discrimination against backgrounds from any known extension of the Standard Model.

However, until the LHC starts operating, cosmic rays provide the only access to the required energy scales. Cosmic rays of energies up to $\simeq 10^{21}$ eV have been observed. The "cosmogenic" neutrinos, expected from the cosmic ray interactions with the Cosmic Microwave Background (e.g. $p\gamma \to \Delta \to n\pi^+ \to \nu_\mu \bar{\nu}_\mu \nu_e ...$), are more or less guaranteed to exist among ultrahigh energy cosmic neutrinos predicted from various sources (for recent reviews, see Ref. [23]). Thus, if TeV-scale gravity is realised, ultrahigh energy cosmic rays/cosmic neutrinos should have been producing mini black holes in the atmosphere throughout earth's history. For cosmic ray facilities such as Fly's Eye, AGASA and Auger, the clearest black hole signals are neutrino-induced quasi-horizontal air showers which occur at rates exceeding the Standard Model rate by a factor of $10 - 10^2$ (see Fig. 1 (left)), and have distinct characteristics [9, 10, 11, 12]. Black hole production could also enhance the detection rate at neutrino telescopes such as AMANDA/IceCube, ANTARES, Baikal and RICE significantly, both of contained and of through-going events [13, 14].

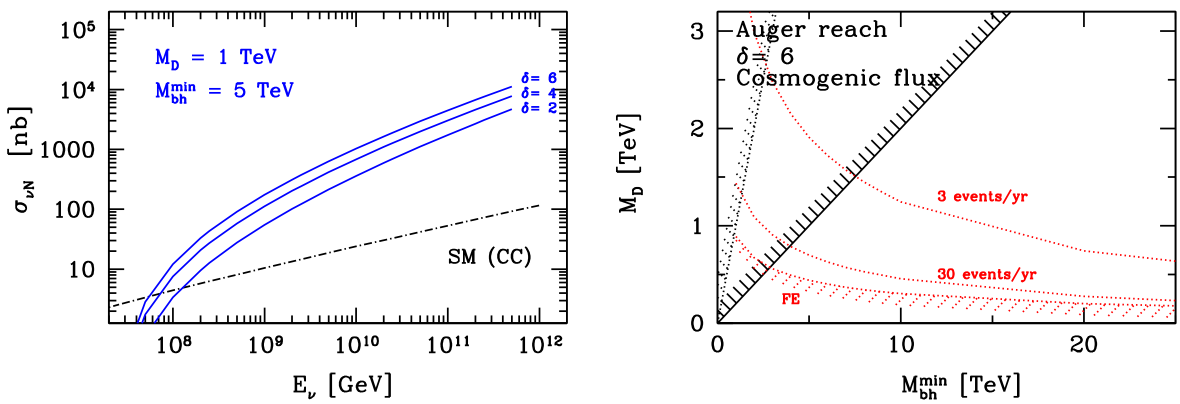

Figure 1: Left: Cross section for black hole production in neutrino-nucleon scattering, as a function of the incident neutrino energy. Right: Projected Auger reach in the black hole production parameters for $\delta = 6$ large extra dimensions, by exploiting the cosmogenic neutrino flux from Ref. [24] with cutoff energy 3×10^{21} eV for the ultrahigh energy cosmic rays. The shaded dotted, $M_D = M_{\rm bh}^{\rm min}$, and shaded solid, $M_D = (1/5)M_{\rm bh}^{\rm min}$, lines give a rough indication of the boundary of applicability of the semiclassical picture [7]. Also shown is the constraint arising from the non-observation of horizontal air showers by the Fly's Eye collaboration (shaded dotted line labeled "FE"). The constraint imposed by AGASA obtained in Ref. [11] lies slightly above the 30 events/yr contour line for Auger.

The reach of cosmic ray facilities in the black hole production has been investigated in detail [10, 11] by exploiting the cosmogenic neutrino fluxes. It is argued in Ref. [11] that an excess of a handful of quasi-horizontal events are sufficient for a discrimination against the Standard Model background. An inspection of Fig. 1 (right) thus leads to the conclusion that, already for an ultrahigh energy neutrino flux at the cosmogenic level estimated in Ref. [24], the Pierre Auger Observatory, expected to become fully operational in 2003, has the opportunity to see first signs of black hole production.

On the other hand, the non-observation of horizontal air showers reported by the Fly's Eye and the AGASA collaboration provides a stringent bound on M_D, which is competitive with existing bounds on M_D from colliders as well as from astrophysical and cosmological considerations, particularly for larger numbers of extra dimensions ($\delta \geq 5$) and smaller threshold ($M_{\rm bh}^{\rm min} \lesssim 10$ TeV) for the semiclassical description, eq. (4).

As for neutrino telescopes, investigations (see Fig. 2 (left)) show that due to their small volume $V \approx 0.001 \div 0.01$ km^3 for contained events, the currently operating underwater/-ice neutrino telescopes AMANDA and Baikal cannot yield a large enough contained event rate to challenge the already existing limits from Fly's Eye and AGASA. Even IceCube does not seem to be really competitive, since the final effective volume $V \approx 1$ km^3 will be reached only after the LHC starts operating and Auger has taken data for already a few years. But sensible constraints on black hole production can be expected from RICE, a currently operating radio-Cherenkov neutrino detector with an effective volume ≈ 1 km^3 for 10^8 GeV electromagnetic cascades, using already available data.

The ability to detect muons from distant neutrino reactions increases an underwater/-ice detector's effective neutrino target volume dramatically. In the case that the neutrino flux is at the level of the cosmogenic one, only a few ($\lesssim 1$) events from Standard Model background are expected per year. Thus, with an effective area of about 0.3 km^2 for down-going muons above 10^7 GeV and 5 years data available, AMANDA should be able to impose strong constraints if no through-going muons above 10^7 GeV are seen in the currently available data (see Fig. 2 (right)). Moreover, in the optimistic case that an ultrahigh energy cosmic neutrino flux significantly higher than the cosmogenic one is realised in nature, one even has discovery potential for black holes at IceCube beyond the reach of LHC, though discrimination between Standard Model background and black hole events becomes crucial.

4 Conclusion

TeV-scale gravity models offer the first opportunity to test the conjecture of black hole formation in trans-Planckian energy collisions and the prediction of Hawking radiation at colliders. The LHC will be producing black holes copiously if the fundamental Planck scale M_D is below 2 TeV, while the reach of the cosmic ray facilities and the neutrino telescopes depends on the unknown ultrahigh energy cosmic neutrino fluxes. It is found that, already for an ultrahigh energy neutrino flux at the level expected from cosmic ray interactions with the cosmic microwave background radiation, cosmic ray experiments are able to put sensible constraints on black hole production parameters and/or bounds on TeV-scale gravity, which are among the most stringent ones to date.

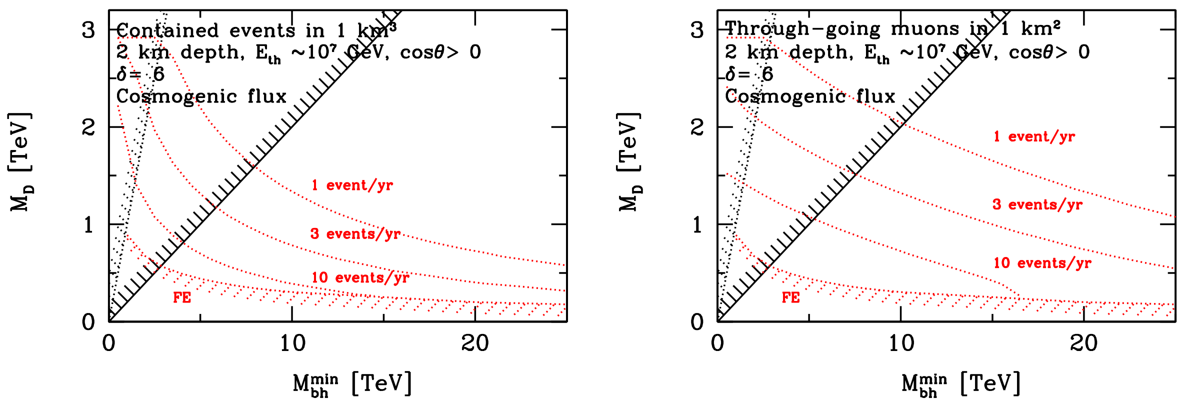

Figure 2: Reach of the neutrino telescopes in the black hole production parameters for $\delta = 6$ large extra dimensions, with the shaded dotted, $M_D = M_{\rm bh}^{\rm min}$, shaded solid, $M_D = (1/5)M_{\rm bh}^{\rm min}$, lines and the shaded dotted line labeled "FE" same as in Fig. 1 (right). Left: for contained events in an under-ice detector at a depth of 2 km and with an 1 km^3 fiducial volume. Right: for through-going muons in an under-ice detector at a depth of 2 km and with an 1 km^2 effective area. Both by exploiting the cosmogenic neutrino flux from Ref. [24] with cutoff energy 3×10^{21} eV for the ultrahigh energy cosmic rays.

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; Nucl. Phys. B 403 (1993) 707.

[2] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B **429** (1998) 263 [arXiv:hep-ph/9803315]; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B **436** (1998) 257 [arXiv:hep-ph/9804398].

[3] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 3370 [arXiv:hep-ph/9905221].

[4] P. C. Argyres, S. Dimopoulos, and J. March-Russell, Phys. Lett. B **441** (1998) 96 [arXiv:hep-th/9808138]; T. Banks and W. Fischler, arXiv:hep-th/9906038.

[5] S. W. Hawking, Nature **248** (1974) 30; Commun. Math. Phys. **43** (1975) 199.

[6] R. Emparan, G. T. Horowitz, and R. C. Myers, Phys. Rev. Lett. **85** (2000) 499 [arXiv:hep-th/0003118].

[7] S. B. Giddings and S. Thomas, Phys. Rev. D **65** (2002) 056010 [arXiv:hep-ph/0106219].

[8] S. Dimopoulos and G. Landsberg, Phys. Rev. Lett. **87** (2001) 161602 [arXiv:hep-ph/0106295].

[9] J. L. Feng and A. D. Shapere, Phys. Rev. Lett. **88** (2002) 021303 [arXiv:hep-ph/0109106].

[10] A. Ringwald and H. Tu, Phys. Lett. B **525** (2002) 135 [arXiv:hep-ph/0111042].

[11] L. A. Anchordoqui, J. L. Feng, H. Goldberg, and A. D. Shapere, Phys. Rev. D **65** (2002) 124027 [arXiv:hep-ph/0112247]; arXiv:hep-ph/0207139.

[12] L. Anchordoqui and H. Goldberg, Phys. Rev. D **65** (2002) 047502 [arXiv:hep-ph/0109242].

[13] M. Kowalski, A. Ringwald, and H. Tu, Phys. Lett. B **529** (2002) 1 [arXiv:hep-ph/0201139].

[14] J. Alvarez-Muniz, J. L. Feng, F. Halzen, T. Han, and D. Hooper, Phys. Rev. D **65** (2002) 124015 [arXiv:hep-ph/0202081]; S. I. Dutta, M. H. Reno, and I. Sarcevic, Phys. Rev. D **66** (2002) 033002 [arXiv:hep-ph/0204218].

[15] H. Tu, to appear in the Proceedings of the 5th Moscow International School of Physics and 30th ITEP Winter School of Physics, Moscow, Russia, 2002, arXiv:hep-ph/0205024.

[16] R. C. Myers and M. J. Perry, Annals Phys. **172** (1986) 304.

[17] G. F. Giudice, R. Rattazzi, and J. D. Wells, Nucl. Phys. B **630** (2002) 293 [arXiv:hep-ph/0112161]; R. Emparan, M. Masip, and R. Rattazzi, Phys. Rev. D **65** (2002) 064023 [arXiv:hep-ph/0109287].

[18] E. J. Ahn, M. Cavaglia, and A. V. Olinto, arXiv:hep-th/0201042; P. Jain, S. Kar, S. Panda, and J. P. Ralston, arXiv:hep-ph/0201232; L. A. Anchordoqui, J. L. Feng, and H. Goldberg, Phys. Lett. B **535** (2002) 302 [arXiv:hep-ph/0202124]; K. Cheung, Phys. Rev. D **66** (2002) 036007 [arXiv:hep-ph/0205033].

[19] D. M. Eardley and S. B. Giddings, Phys. Rev. D **66** (2002) 044011 [arXiv:gr-qc/0201034].

[20] S. Dimopoulos and R. Emparan, Phys. Lett. B **526** (2002) 393 [arXiv:hep-ph/0108060].

[21] R. Penrose, presented at the Cambridge University Seminar, Cambridge, England, 1974 (unpublished).

[22] P. D. D'Eath and P. N. Payne, Phys. Rev. D **46** (1992) 658; Phys. Rev. D **46** (1992) 675; Phys. Rev. D **46** (1992) 694.

[23] R. J. Protheroe, Nucl. Phys. Proc. Suppl. 77 (1999) 465; R. Gandhi, Nucl. Phys. Proc. Suppl. 91 (2000) 453; J. G. Learned and K. Mannheim, Ann. Rev. Nucl. Part. Sci. 50 (2000) 679.

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