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Microscopic Black Hole Production in TeV-Scale Gravity*

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Abstract

Models with extra spatial dimensions and TeV-scale gravity offer the first opportunity to test the conjecture of black hole formation in trans-Planckian energy scattering with small impact parameters. After a brief review of gravitational scattering at ultrahigh energies and scenarios of TeV-scale gravity, search strategies at the LHC, at the Pierre Auger (cosmic ray) Observatory and at the neutrino telescopes AMANDA/IceCube are illustrated with the simplest but nevertheless representative example: production of Schwarzschild black holes and their observation via Hawking radiation in the large extra dimension scenario. Some more general features of the production of higher-dimensional black holes and/or uncertainties in the estimates are also outlined.

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1 Introduction

Black holes play an essential role in our approach to the quantum theory of gravity. The history of quantum gravity is deeply intertwined with the problem of very high energy scattering. It has been conjectured that microscopic 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, 2, 4, 5, 6].

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 characterising quantum gravity, can be just beyond the electroweak scale [7, 8]. Within such TeV-scale gravity models, the conjecture suggests that particle collisions at TeV energies may result in the production of black holes of masses at this energy scale provided the colliding particles come close enough [9, 10, 11, 12, 13, 14].

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 [15] mainly into Standard Model particles on the brane rather than into the bulk [12]. 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 [16, 17], 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 [18, 20, 21, 22, 23, 24] 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 section 2 the general aspects of gravitational scattering at ultrahigh energies will be briefly reviewed. Two scenarios of extra dimension models in which TeV-scale gravity can be realised are outlined in section 3. Section 4 will be devoted to black hole production and evaporation in TeV-scale gravity, with some remarks concerning the working hypothesis adopted. In section 5 we illustrate search strategies at colliders, cosmic ray facilities and neutrino telescopes with the simplest, nevertheless representative example: production and observation via Hawking radiation of the microscopic Schwarzschild black holes in the large extra dimension scenario.

2 Trans-Planckian energy scattering

In this section, we briefly review the current understanding of particle scattering at ultrahigh energies in conventional 4-dimensional theories [1, 2, 3, 4, 5, 6]. We shall present arguments why particle scattering at trans-Planckian energies can be treated semiclassically and why one expects black hole formation for small enough impact parameters.

We start by recalling the two crucial dimensionless parameters which characterise gravitational scattering[1]

$$\alpha_G \equiv \frac{G_{\rm N}\, s}{\hbar} \quad \text{and} \quad \frac{G_{\rm N}\, s}{J} = \frac{R_{\rm S}}{b}\,. \tag{1}$$

Here, $G_{\rm N}$ is Newton's constant, $\sqrt{s}$ is the center-of-mass energy, b the impact parameter and $J = (b/2)\,\sqrt{s}$ the total angular momentum. The Schwarzschild radius associated with a certain centre-of-mass energy,

$$R_{\rm S} \equiv 2\, G_N \sqrt{s}\,, \tag{2}$$

is the length scale at which curvature effects become significant. Other relevant length scales in ultrahigh energy scattering regime include the Planck length $\lambda_{\rm Pl} = \sqrt{G_{\rm N}\hbar}$, which signifies when quantum gravity effects become important, and the string length scale,

$$\lambda_{\rm str} = \sqrt{\alpha'\hbar} = g_{\rm str}^{-1}\, \lambda_{\rm Pl}\,. \tag{3}$$

It is the fundamental length scale when the problem is studied within the context of string theory. Here α' is the Regge slope and $g_{\rm str}$ is the gauge coupling at the string scale. Conventionally, it is of order $g_{\rm str}^2/(4\pi) \sim 0.04$. In the remainder of this section, we shall assume

$$R_{\rm S} \gg \lambda_{\rm str}\,. \tag{4}$$

In this regime, the internal structure of the strings can be ignored and it is sufficient to employ low energy effective field theory. So one is indeed left with the two dimensionless parameters eq. (1) characterising the collision.

The parameter α_G in eq. (1) is the gravitational equivalent of the fine-structure constant. The essential difference lies in its explicit energy dependence, which is characteristic for gravitational interactions since energy itself plays the role of gravitational charge. Trans-Planckian energy scattering is defined by

$$\alpha_G = \frac{G_{\rm N}\, s}{\hbar} \gg 1 \Leftrightarrow \sqrt{s} \gg M_{\rm Pl}\,, \tag{5}$$

with $M_{\rm Pl} = (G_{\rm N}/\hbar)^{-1/2} \simeq 1.2{\cdot}10^{19}$ GeV the Planck mass. 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.

Note however that the second crucial parameter $R_{\rm S}/b$ in eq. (1) can still be varied at will. While trans-Planckian energy scattering is always a semiclassical process, very different physics is expected to emerge depending on the value of $R_{\rm S}/b$.

In the small scattering angle limit, $-t/s \ll 1$ (t is the Lorentz-invariant momentum transfer), or, correspondingly, for large impact parameters $R_{\rm S}/b \ll 1$, the gravitational scattering cross section has been calculated by various semiclassical approaches [1, 2, 3, 4, 5, 6], e.g. in Ref. [1] by solving the Klein-Gordon equation for a particle encountering the gravitational shock wave generated by another a fast-moving particle [25], by employing the eikonal approximation [26] for four-dimensional gravity [3] and for string theory [2], or by describing quantum gravitational

[1] Throughout this paper we set $c = 1$ but keep $\hbar$ in this section.

effects by means of a topological field theory [4]. All calculations agree with the claim that the process is dominated by eikonalised single graviton exchange.

As for smaller impact parameters b, it is conjectured that black hole formation should set in below a critical value of $b/R_{\rm S}$ of order one [1, 2, 3, 4, 5, 6]. Are there sufficient evidences for one to believe in this conjecture?

In $(2+1)$–dimensional Anti-de Sitter space it has already been shown that a 3–dimensional black hole [27] is inevitably created in head-on particle collisions above some energy threshold [28]. In four-dimensions, Penrose [29] and D'Eath and Payne [30] (see also Ref. [31]) studied the collision of two black holes moving at nearly the speed of light, and showed that closed trapped surfaces can be formed for a range of impact parameters. This study is redone and extended to particle collisions in higher dimensions recently [32] by following the same approach, namely by modelling the gravitational field of each incoming particle by a plane-fronted gravitational shock wave. Also in this case, closed trapped surfaces were found. Furthermore, results from numerical studies on gravitational collapse of rotating stars also show black hole formation below a critical angular momentum J [33]. One may consider this as another supporting argument. For further attempts to prove the black hole formation conjecture, see Refs. [34, 35].

3 TeV-scale gravity

Within models with extra spatial dimensions, the scale characterising quantum gravity can actually be in the TeV range. This puts the remote possibility of microscopic black hole production within phenomenological reach. In this section we shall shortly outline two possible constructions of TeV-scale gravity models: the large compact extra dimension scenario [7] and the warped scenario [8]. (For a review of extra dimensions see e.g. [36]).

In the large extra dimension scenario, it is assumed that gravitons are allowed to propagate freely into the bulk, while other Standard Model fields must be localised on a 3–brane. The 4–dimensional effective action describing long-distance gravity is then obtained by integrating the $D=(\delta+4)$–dimensional gravitational action over the extra dimension coordinates, of which the metric is assumed to be independent

$$S=\frac{-1}{16\pi G_D}\int d^D X\sqrt{-g^{(D)}}\mathcal{R}^{(D)}\;\Rightarrow\;S_{\rm eff}=\frac{-V_\delta}{16\pi G_D}\int d^4x\sqrt{-g^{(4)}}\mathcal{R}^{(4)}\,. \tag{6}$$

Therefore,

$$\frac{V_\delta}{G_D}=\frac{1}{G_{\rm N}}\,,\qquad\text{with}\quad G_D=\frac{(2\pi)^{\delta-1}\hbar^{\delta+1}}{4M_D^{\delta+2}} \tag{7}$$

relating the D-dimensional Newton's constant to the fundamental Planck scale M_D, in the convention of [37].

The hierarchy between the four-dimensional Planck mass $M_{\rm Pl}$ and the fundamental Planck scale M_D arises then from the large volume of the extra dimensions

$$M_{\rm Pl}^2=\frac{4}{(2\pi)^{\delta-1}}\;V_\delta\;M_D^{2+\delta}\,. \tag{8}$$

For a fundamental Planck scale $M_D \sim$ TeV, sizes of the compact extra dimensions are required to be (in the case that all extra dimensions are of the same order)

$$r_c \sim \frac{1}{M_D}\left(\frac{M_{\rm Pl}}{M_D}\right)^{2/\delta} \sim 10^{\frac{32}{\delta}-17} \cdot \left(\frac{1\ {\rm TeV}}{M_D}\right)^{1+2/\delta}\ {\rm cm}\,, \tag{9}$$

and can even be as large as ~ 0.1 mm, since this is the smallest distance ever probed directly so far. One sees also that $\delta = 1$ is immediately ruled out by astronomical data, while for $\delta = 2$ to 6 the compactification radii r_c range from a sub-millimeter to a few fermi.

Warped scenarios provide an alternative approach to explain the hierarchy: the weak scale is generated from the Planck mass through the "warp factor", which is an exponential function of the compactification radius, arising not from gauge interactions but from the background metric.

A simple explicit example of this mechanism is demonstrated in Ref. [8] with two 3-branes and one compact extra dimension, and with the Standard Model fields residing on the "visible" brane. The 3-branes, extending in the x^μ directions, are located at 0 and $r_c\,\pi$ in the fifth dimension. The effects of the branes on the bulk gravitational metric are taken into account, and are expressed by the "vacuum energy" terms $V_{\rm vis}$ and $V_{\rm hid}$ in the action

$$\begin{aligned} S &= S_{\rm gravity} + S_{\rm vis} + S_{\rm hid}\,, \quad S_{\rm gravity} = \int d^4x \int_{-\pi}^{\pi} d\phi\, \sqrt{-g^{(5)}}\,\{-\Lambda + 2\,M^3\,\mathcal{R}^{(5)}\}\,, \\ S_{\rm vis} &= \int d^4x\, \sqrt{-g_{\rm vis}}\,\{\mathcal{L}_{\rm vis} - V_{\rm vis}\}\,, \quad S_{\rm hid} = \int d^4x\, \sqrt{-g_{\rm hid}}\,\{\mathcal{L}_{\rm hid} - V_{\rm hid}\}\,, \end{aligned} \tag{10}$$

where Λ is the cosmological term and M the Planck scale in the five-dimensional spacetime. The solution to the five-dimensional Einstein's equations is required to respect four-dimensional Poincaré invariance in the x^μ directions, and is found to be

$$ds^2 = e^{-2\,k\,r_c\,|\phi|}\,\eta_{\mu\,\nu}\,dx^\mu\,dx^\nu + r_c^2\,d\,\phi^2, \tag{11}$$

where k is the single scale which fine-tunes between Λ, $V_{\rm vis}$ and $V_{\rm hid}$. The warp factor contained in the metric generates an exponential hierarchy between $M_{\rm Pl}$ and the electroweak scale $M_{\rm EW}$:

$$M_{\rm EW} \sim e^{-k\,r_c\pi}\,M_{\rm Pl}. \tag{12}$$

To account for the observed 15 orders of magnitude between $M_{\rm Pl}$ and TeV physical mass scales, only $k\,r_c \approx 10$ need to be required. Therefore, other than in the large extra dimension scenarios, the size of the extra dimension need not be much larger than the natural length scale $M_{\rm Pl}^{-1}$. Furthermore, the largeness of the Planck mass $M_{\rm Pl}$ or the weakness of the gravity for an observer on the visible brane can be interpreted as due to the small overlap of the graviton wave functions in 5 dimensions with the visible brane.

Phenomenology of extra dimension scenarios includes deviation from Newtonian gravity in distances smaller than the compactification radii, Kaluza-Klein graviton emission and exchange[2], and the possible production of microscopic black holes in trans-Planckian energy scattering. Lower

[2]For an exhaustive list of references in this context, see also Ref. [22].

	M_6	M_8	M_{10}
LEP II	1.45	0.87	0.61
astroph.	1881	8.8	0.61
	M_6	M_7	M_8
LHC	$4.0 \div 8.9$	$4.5 \div 6.8$	$5.0 \div 5.8$

Table 1: 95% C.L. lower limits on the fundamental Planck scale M_D (in TeV) in the large extra dimension scenario [7], derived from the searches for Kaluza-Klein graviton emission in the $e^+e^- \to \gamma G$ channel by the L3 Collaboration [39], and limits from astrophysical considerations [40]. Expected lower limits on M_D (in TeV) for $D = 6, 7, 8$ from the searches for graviton emission in the $pp \to gG$ channel at the LHC [39] are also listed.

limits on the fundamental Planck scale M_D in the large extra dimension scenario are derived from sub-millimeter tests of Newton's law by Cavendish-type experiments [38], from collider searches for graviton emission and exchange in scattering processes [39], as well as from astrophysical and cosmological considerations, such as the rate of supernova cooling and the diffuse γ–ray spectrum [40]. Some of the lower limits are listed in Table 1.

To summarise, a fundamental Planck scale as low as $M_D \sim \mathcal{O}(1)$ TeV is still allowed for $\delta \geq 4$ flat or $\delta \geq 1$ warped extra dimensions. More about the experimental bounds on extra dimension models can be found in e.g. Ref. [41].

4 Black hole production and evaporation in TeV-scale gravity

The old conjecture of black hole formation in trans-Planckian energy particle collisions has attracted again a great deal of attention, thanks to the interesting proposal that the fundamental Planck scale lies just beyond the electroweak scale. In this section we introduce our working hypothesis for black hole production and evaporation in the context of TeV-scale gravity. Some caveats/uncertainties in the estimates are also pointed out.

4.1 Black hole production

We start again by specifying the regime of our interests and recalling the relevant length scales therein. In TeV-scale gravity, the trans-Planckian energy regime corresponds to

$$\sqrt{s} \gg M_D \quad \Rightarrow \quad R_{\rm S} \gg \lambda_{\rm Pl}, \gg \lambda_{\rm B}, \tag{13}$$

where

$$\lambda_{\rm Pl} = G_D{}^{\frac{1}{\delta+2}} \tag{14}$$

is the Planck length in $D = (4+\delta)$-dimensions, $\lambda_{\rm B} = \hbar/\sqrt{s}$ the de Broglie wavelenth, and

$$R_{\rm S}\left(\sqrt{s}\right) = \frac{1}{M_D}\left[\frac{\sqrt{s}}{M_D}\left(\frac{2^{\delta}\pi^{\frac{\delta-3}{2}}\Gamma\left(\frac{3+\delta}{2}\right)}{2+\delta}\right)\right]^{\frac{1}{1+\delta}}, \tag{15}$$

is the Schwarzschild radius associated with the centre-of-mass energy $\sqrt{s}$. Higher-dimensional Schwarzschild black hole of radius $R_{\rm S}\left(M_{\rm bh}\right)$ was originally obtained as a solution to the vacuum Einstein equations [42]. In extra dimension models containing branes, this solution is valid if one assumes that the brane tension does not perturb it strongly. A Schwarzschild black hole is $(4+\delta)$–dimensional if its radius, eq. (15), is small compared to the compactification radius of the extra dimenions, $R_{\rm S} \ll r_c$. Since in the large extra dimension scenario the above conditions are always fulfilled, we shall restrict our further discussion to this scenario.

Phenomenology of trans-Planckian energy scattering in large extra dimension scenarios has been studied in Ref. [37, 43], 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,

$$\sqrt{s} \gg M_D\,, \quad b < R_{\rm S}\,, \tag{16}$$

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,

$$\sigma_{ij}^{\rm bh}(s) \approx \pi R_{\rm S}^2\left(M_{\rm bh} = \sqrt{s}\right)\ \Theta\left(\sqrt{s} - M_{\rm bh}^{\rm min}\right), \tag{17}$$

is believed to capture the essential features of this nonperturbative phenomenon [10, 16, 17, 32, 35, 44] (see also Ref. [45]). 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 $\delta = D - 4$. Note however that there is still an ongoing debate on whether the production cross section for large black holes, i.e. black holes with masses $M_{\rm bh} \gg M_D$, is exponentially suppressed, as suggested by Voloshin [46].

Let us end this subsection with some remarks concerning the working hypothesis (17).

- In Ref. [44] this problem is studied in string theory by applying the correspondence principle [47], according to which a transition between black holes and highly excited long strings –"string balls" occurs at the correspondence point $M_{\rm bh}^{\rm min} \sim M_{\rm str}/g_{\rm str}^2$. By assuming a string mass scale of $M_{\rm str} \sim$ TeV and working in the weak-coupling limits $g_{\rm str}^2 \ll 1$, where there exists a broad stringy regime between the scales $M_{\rm str}$ and $M_{\rm bh}^{\rm min}$, $M_{\rm bh}^{\rm min} \gg M_D \gg M_{\rm str}$, the cross section for string ball production is calculated and it matches the geometric cross section for black hole production at the correspondence point.

- For simplicity the mass of the black hole is taken to be equal to the inital centre-of-mass energy $\sqrt{s}$, though part of it should escape to infinity in the form of gravitational radiation. Penrose [29] has studied the collision of two black holes moving at nearly the speed of light using the approach of colliding plane gravitational shock waves [25], and found an

apparent horizon for a range of impact parameters. By making use of the cosmic censorship conjecture he derived a lower bound on the mass of the final Schwarzschild black hole as $M_{\rm bh} > \sqrt{s/2}$ for head-on collision. D'Eath and Payne [30] obtained an improved estimate as $M_{\rm bh} \approx 0.84\,\sqrt{s}$ from their mass-loss formula (for estimates obtained by other approaches, see e.g. Ref. [48]). Recently, Eardley and Giddings [32] redo this work for head-on collisions in $D \geq 4$ and non-zero impact parameters $b \neq 0$ in $D = 4$ dimensions using the same approach. By finding a marginally trapped surface $\mathcal{S}$ in $D = 4$ and by applying the area theorem, they derived a lower bound on the mass of the final black hole as a function of the impact parameter b, ranging from $0.71\,\sqrt{s}$ for $b = 0$ to $0.45\,\sqrt{s}$ for $b = b_{\rm max} \approx 3.219\,G_{\rm N}\,(\sqrt{s}/2)$. Lower limit on $M_{\rm bh}$ in head-on collisions $b = 0$ for various dimensions D were also obtained. But corresponding estimate for the case $D > 4, b \neq 0$ is not available so far.

- Generally speaking, one expects spinning black holes to form in particle collisions with nonzero impact parameters (see Ref. [49, 19] for a first attempt to include this effect). The higher-dimensional generalisation of the Kerr solution obtained in Ref. [42] contains $[(D-1)/2]$ angular momentum parameters J_i, and it is found that the properties of higher-dimensional rotating black holes are essentially different from the four-dimensional ones. In the case of the production of the $(4+\delta)$-dimensional black holes from the particle collisions on the 3-brane, only one angular momentum mode J is excited. But it is still not clear whether one can simply insert the Kerr radius determined from

$$r_k \left[1 + r_k^{-2} \cdot \frac{(\delta+2)^2\ J^2}{4M_{\rm bh}^2}\right]^{\frac{1}{\delta+1}} = R_{\rm S} \tag{18}$$

  into the geometric cross section, eq. (17), instead of $R_{\rm S}$.

- In general one also expects black holes to inherit the electric charges from the initial state partons. In Ref. [50] one finds a discussion on the charge of black holes and naked singularities produced in particle collisions in the warped scenario. But a generalisation of the Reissner-Nordstroem solution in the large extra dimension scenario is not available yet.

- It is proposed that in string theories, trans-Planckian energy scattering should generally lead to the creation of higher-dimensional, non-perturbative gravitational objects (p-branes), since spherically symmetric black holes are regarded as one particular class of them (0-branes). In Ref. [51] it is found that in some cases, p-brane formation could be competitive with black hole production, and has important phenomenological consequences [52].

4.2 Black hole decay

In general, after its formation in high energy particle collisions, a black hole loses electric charge via the Schwinger process [53] and angular momentum via superradiance [54] rapidly. These processes are accompanied by the Hawking effect [15], which reduces the black hole mass and hence its surface area.

As the black hole evaporates down to a mass of order of the Planck scale, one must again appeal to the theory of quantum gravity. It is also for this reason still not clear what is left over

after the decay of a black hole. Within string theory, a black hole evaporates only down to the correspondence point $M_{\rm bh}^{\rm min} \sim M_{\rm str}/g_{\rm str}^2$. It then makes a transition to a "string ball", as mentioned in section 4.1. Ref. [44] gives a detailed description of the string ball decay processes.

But since a black hole spends most of its lifetime in the stage where its mass is close to the initial value, it is sufficient to adopt the following semiclassical approximation for the purpose of e.g. estimating black hole event rates and event signatures at colliders or at cosmic ray facilities, which will be illustrated in the next section. For investigations of black hole evaporation in extra dimensions, see e.g. Ref. [16, 50, 55, 56, 57].

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 with a surface area $\mathcal{A}_{\delta+2}$ at the Hawking temperature $T_{\rm H}$, which are

$$\begin{aligned} \mathcal{A}_{\delta+2} &= R_{\rm S}^{\delta+2} \cdot \Omega_{\delta+2}\,, \qquad \text{with} \quad \Omega_{\delta+2} = \frac{2\pi^{(\delta+3)/2}}{\Gamma(\frac{\delta+3}{2})}, \\ T_{\rm H} &= \frac{\delta+1}{4\pi R_{\rm S}}\,, \end{aligned} \tag{19}$$

in $(4+\delta)$-dimensions. It is shown in Ref. [12] that the multi-dimensional black holes localised on the brane radiate at equal rates

$$\frac{dE}{dt} \simeq \sigma_{\delta+4}\, \mathcal{A}_{\delta+2}\, T_{\rm H}^{\,\delta+4} \propto \frac{1}{R_{\rm S}^2}\,, \tag{20}$$

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 δ). 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. This raises the possibility of examining the black hole formation conjecture in future high-energy experiments via the observation of Hawking radiation, provided TeV-scale gravity is realised in nature.

Total number of particles emitted is characteristic of the entropy of the initial black hole

$$S_{\rm bh} = \frac{\mathcal{A}_{\delta+2}}{4\,G_D}\,. \tag{21}$$

During its lifetime,

$$\tau_D \sim \sigma_{\delta+4}\,\frac{1}{M_D}\left(\frac{M_{\rm bh}}{M_D}\right)^{\frac{\delta+3}{\delta+1}} \sim 10^{-26}\ {\rm s} \quad \left(\gg M_{\rm bh}^{-1}\right)\,, \tag{22}$$

(for an average mini black hole of $M_{\rm bh} \sim \mathcal{O}(10)$ TeV), a mini black hole emits approximately

$$\langle n \rangle \approx \frac{M_{\rm bh}}{2\,T_{\rm H}} \tag{23}$$

particles [17], mostly hadrons and leptons.

5 Search for black hole events

Based on the expectation for production and evaporation of microscopic black holes in TeV-scale gravity scenarios outlined in the last section, we want to report in this section on recent investigations of the corresponding phenomenology at future colliders and cosmic ray facilities.

5.1 Microscopic black hole production at colliders

If TeV-scale gravity is realised in nature, 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 black holes copiously at a rate $d\mathcal{N}_{\rm bh}/dt = \sigma_{pp}^{\rm bh} \cdot \mathcal{L}$, with

$$\sigma_{pp}^{\rm bh}(s) = \sum_{ij} \int_0^1 dx_1 dx_2 \, \frac{f_i(x_1,\mu) f_j(x_2,\mu) + f_i(x_2,\mu) f_j(x_1,\mu)}{1+\delta_{ij}} \, \hat{\sigma}_{ij}^{\rm bh}(x_1 x_2 s) \,, \tag{24}$$

the contribution of black hole production to the proton-proton cross section. The sum extends over all partons in the nucleon, with parton distributions $f_i(x,\mu)$ and factorisation scale μ. For $\hat{\sigma}_{ij}^{\rm bh}$, the black hole production cross section at the parton level, the geometric parametrisation (17) is usually adopted.

Black hole detection at the LHC has been investigated in detail [16, 17, 58]. First event simulations [17] show that the expected signature of black hole events at the LHC is the production of a number of $\mathcal{O}(20)$ 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. Therefore, only a handful of such events is needed at the LHC to discriminate it against perturbative Standard Model background.

However, as can be seen in Fig. 1, the LHC will become a black hole factory only if M_D is below 2 TeV. In this case, not only the black hole formation conjecture and the existence of large extra dimensions can be verified, but also the higher-dimensional Hawking evaporation law can be tested from the correlation between the black hole mass and the black hole temperature deduced from the energy spectrum of its decay products [17]. Otherwise, the non-observation of black hole events at the LHC will not give more stringent limits on the large extra dimension model than those to be derived from the searches for the manifestations of Kaluza-Klein gravitons listed in Table 1.

5.2 Microscopic black holes from ultrahigh energy cosmic neutrinos

Particle astrophysics experiments have demonstrated their complementarity to collider searches for New Physics in many aspects. In the case of black hole production in TeV-scale gravity, cosmic ray facilities such as Pierre Auger Observatory and neutrino telescopes such as AMANDA/IceCube and RICE also have an opportunity to see the first sign or place sensible constraints before LHC starts operating in 2007.

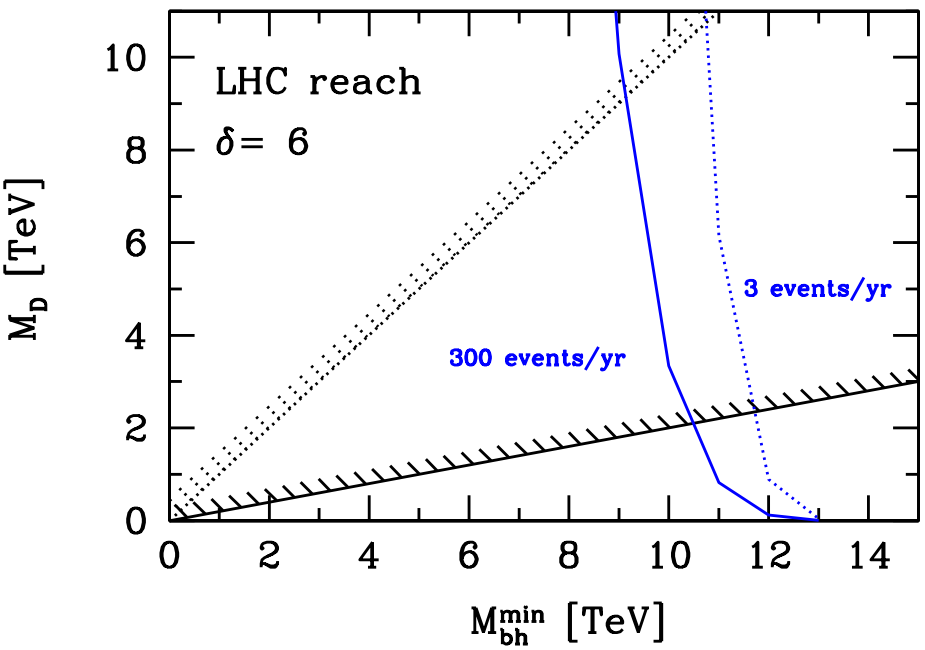

Figure 1: Accessible region in the black hole production parameters at the LHC for $\delta = 6$ extra dimensions. The solid and the dotted lines are contours of constant numbers of produced black holes per year of masses larger than $M_{\rm bh}^{\rm min}$ by a fundamental Planck scale M_D. The shaded 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 a boundary of applicability of the semiclassical picture [16].

The most distinct signature for cosmic ray facilities to look for are quasi-horizontal air showers, initiated by black holes produced in the scattering of ultrahigh energy cosmic neutrinos on nucleons in the atmosphere [18, 20, 22]. Neutrinos interact only weakly in the Standard Model so an enhancement in the total cross section due to the contribution from black hole production

$$\sigma_{\nu N}^{\rm bh}(s) = \sum_i \int_0^1 dx\ f_i(x,\mu)\hat{\sigma}_{\nu N}^{\rm bh}(xs) \tag{25}$$

would be quite noticeable (see Fig. 2).

A cosmic ray facility of acceptance $\mathcal{A}$ would expect such events at a rate (neglecting the neutrino flux attenuation in the upper atmosphere)

$$\frac{d\mathcal{N}_{\rm sh}^{\rm bh}}{dt}(>E_{\rm th}) = N_A\ \rho_{\rm air} \int_{E_{\rm th}}^{\infty} dE_\nu\ F_\nu(E_\nu)\sigma_{\nu N}^{\rm bh}(E_\nu)\mathcal{A}(E_\nu)\,, \tag{26}$$

where N_A is the Avogadro's constant and $\rho_{\rm air} \simeq 10^{-3}$ g cm^{-3} the air density. Equation (26) assumes that 100% of the incident neutrino energy goes into visible, hadronic or electromagnetic

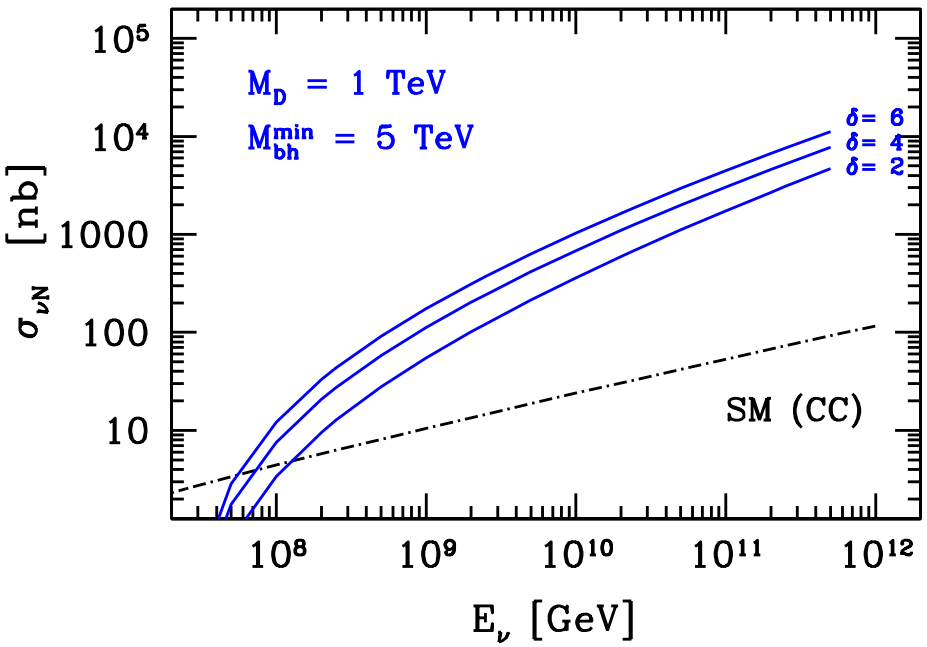

Figure 2: Cross section $\sigma_{\nu N}^{\rm bh}$, eq. (25), for black hole production in neutrino-nucleon scattering, as a function of the incident neutrino energy E_ν. Solid lines from bottom to top correspond to $\delta = 2, 4, 6$ large extra dimensions and $M_D = 1$ TeV, $M_{\rm bh}^{\rm min} = 5$ TeV. The Standard Model (SM) charged-current (CC) neutrino-nucleon cross section is also shown (dashed-dotted line).

shower energy. But most uncertainties come from the unknown ultrahigh energy neutrino fluxes $F_\nu(E_\nu)$.

Cosmic neutrinos of energies higher than 10^7 GeV from various sources are predicted (for recent reviews, see Ref. [59]). Among all, the cosmogenic ones expected from cosmic ray interactions with CMBR (e.g. $p\gamma \to \Delta \to n\pi^+ \to \nu_\mu \bar{\nu}_\mu \nu_e ...$) are more or less guaranteed to exist. By exploiting the cosmogenic neutrino fluxes (recent estimates for these fluxes can be found in Ref. [60, 61]) one thus obtains a conservative lower limit on the projected Auger sensitivity to black hole production (Fig. 3).

In Ref. [20] it was shown that these showers may have an "anomalous" electromagnetic component: about one order of magnitude larger than Standard Model ν_μ-initiated showers and at least an order of magnitude smaller than Standard Model ν_e-initiated showers. It was argued that this represents a very clean signal and, correspondingly, that for the ground array of the Auger Observatory a total number of about $\mathcal{O}(20)$ black hole events could give significant statistics for a discrimination against the signal from the Standard Model background, which is estimated to be ~ 0.15 events/yr assuming the same cosmogenic neutrino flux [60].

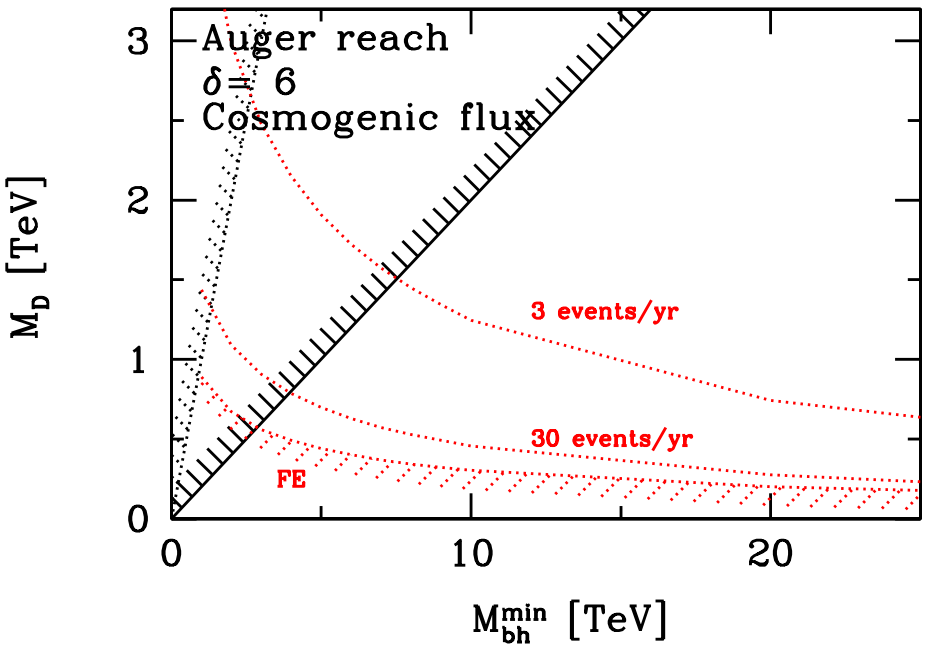

Figure 3: Projected Auger reach in the black hole production parameters for $\delta = 6$ large extra dimensions, by exploiting the cosmogenic neutrino flux from Ref. [60] with cutoff energy 3×10^{21} eV for the ultrahigh energy cosmic rays. The shaded dotted, $M_D = M_{\rm bh}^{\rm min}$, and shaded solid, $M_D = (1/5)M_{\rm bh}^{\rm min}$, lines give a rough indication of the boundary of applicability of the semiclassical picture [16]. The dotted lines respresent the contour of 3 and 30, respectively, detected horizontal air showers per year initiated by neutrino-nucleon scattering into a black hole of mass larger than $M_{\rm bh}^{\rm min}$, for a fundamental Planck scale M_D. 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" [62]). The constraint imposed by AGASA, first obtained in Ref. [19], is slightly above the 30 events/yr contour line for Auger.

Somewhat later it is argued in Ref. [19] that, based on the comparison with the earth-skimming neutrino events, an excess of a handful of quasi-horizontal black hole events are sufficient for a discrimination against the Standard Model background. An inspection of Fig. 3 thus leads to the conclusion that, already for an ultrahigh energy neutrino flux at the cosmogenic level estimated in Ref. [60], 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 listed in Table. 1, 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. (17).

The sensitivity of neutrino telescopes such as AMANDA/IceCube, ANTARES, Baikal, NESTOR and RICE to black hole production in the scattering of ultrahigh energy cosmic neutrinos on nucleons in the ice or water has been investigated in Ref. [23] and compared to the one expected at the cosmic ray facilities and at the LHC. The underwater/-ice neutrino telescopes are sensitive not only to the contained black hole events but also to the through-going muons produced in the black hole decay outside the detector.

The projected reach in the black hole production parameter space for contained events in an under-ice detector corresponding to the IceCube porposal (2 km depth, fiducial volume 1 km^3), as well as for through-going muons in an under-ice detector at a depth of 2 km and with an effective area of 1 km^2, are shown in Fig. 4. A cosmogenic neutrino flux from Ref. [60] is again assumed. Taking into account the small effective volume, $V \approx 0.001 - 0.01\text{km}^3$, of the currently operating AMANDA and Baikal neutrino telescopes and the time schedule of IceCube (expects to reach the final effective volume $V \approx 1\text{km}^3$ only after the start of the LHC), the best perspective for black hole detection on the basis of the contained events must be assigned to RICE, a currently operating radio-Cherenkov neutrino detector with an effective volume of $\approx 1\text{km}^3$ for 10^8 GeV electromagnetic cascades. Using already available data, RICE could set sensible constraints on black hole production parameters.

The ability to detect muons from distant neutrino reactions increases an underwater/-ice detector's effective neutrino target volume dramatically. With an effective area of about 0.3 km^2 for down-going muons above 10^7 GeV and 5 years data available, AMANDA achieves an exposure of about 1km^2 yr. In the case that the neutrino flux is just at the level of the cosmogenic one, only a few ($\lesssim 1$) through-going events from Standard Model background are expected per year. Therefore, AMANDA should be able to impose strong constraints on the black hole production parameters if the currently available data show no through-going muons above 10^7 GeV. Furthermore, if an ultrahigh energy cosmic neutrino flux significantly higher than the cosmogenic one is realised in nautre, 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. For other quite similar investigations on the sensitivity of neutrino telescopes to black hole production, see Ref. [24].

6 Conclusion

Models with extra spatial dimensions and TeV-scale gravity offer the first opportunity to test the conjecture of black hole formation in trans-Planckian energy collisions and the prediction of black hole evaporation by near-future high energy experiments. The LHC will be producing microscopic black holes copiously if the fundamental Planck scale M_D is below 2 TeV, while the reach of the cosmic ray facilities and neutrino telescopes depends on the unknown ultrahigh energy cosmic neutrino flux.

It is found that, already for a cosmic neutrino flux at the level expected from the cosmic ray primary interactions with the cosmic microwave background radiation, the Pierre Auger Observatory has an opportunity to see first signs of black hole production before the start of the LHC. The non-observation of horizontal air showers by the Fly's Eye and AGASA experiments imposes

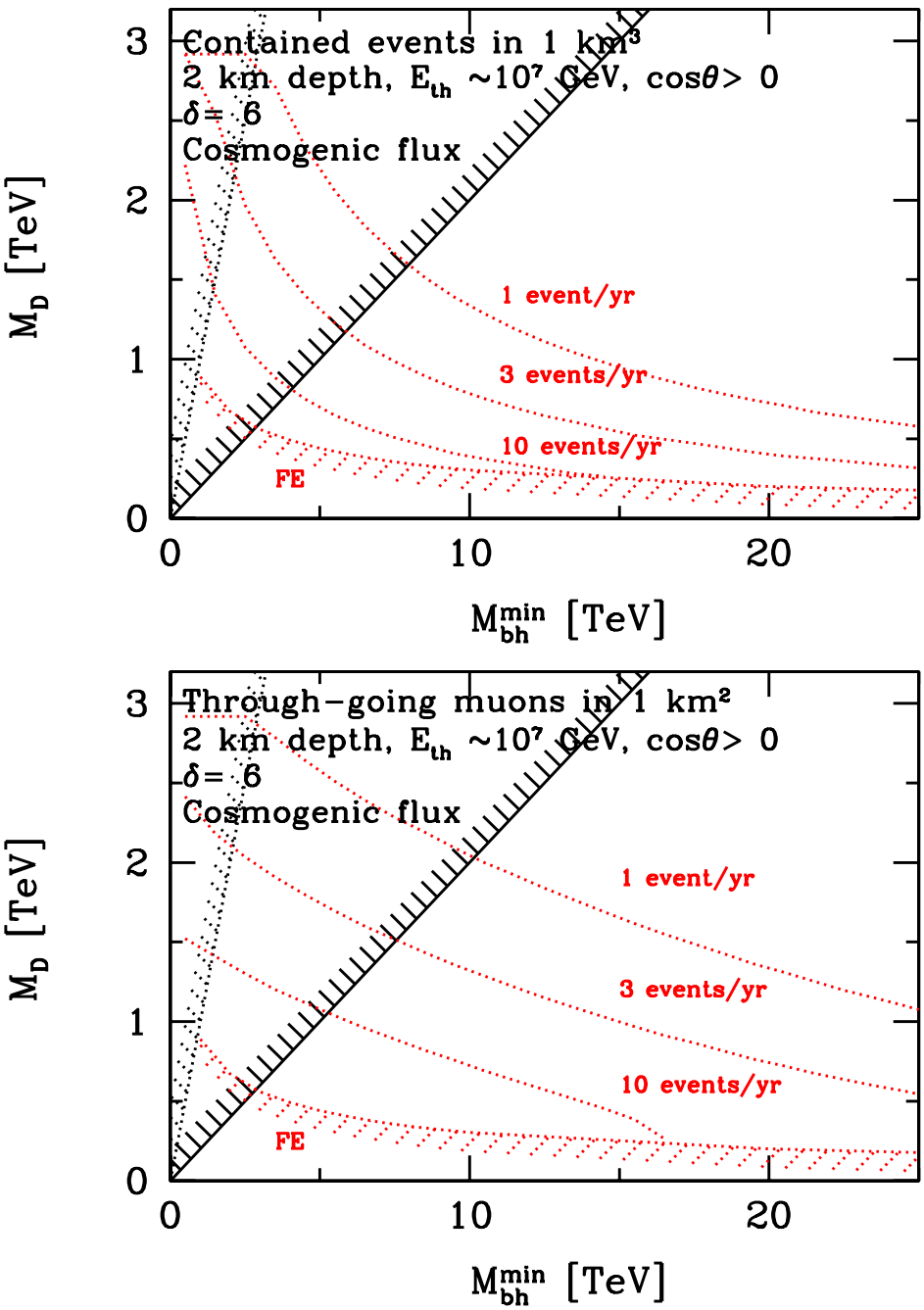

Figure 4: Reach of the neutrino telescopes in the black hole production parameters for $\delta = 6$ large extra dimensions, with the shaded dotted, $M_D = M_{\rm bh}^{\rm min}$, shaded solid, $M_D = (1/5)M_{\rm bh}^{\rm min}$, lines and the shaded dotted line labeled "FE" same as in Fig. 3. Top: for contained events in an under-ice detector at a depth of 2 km and with an 1 km^3 fiducial volume. Bottom: 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. [60] with cutoff energy 3×10^{21} eV for the ultrahigh energy cosmic rays.

a stringent bound on M_D, which is competitive with existing bounds from colliders as well as from astrophysical and cosmogolical considerations. Further sensible constraints on the black hole production parameters and/or bounds on low-scale gravity are expected from neutrino detectors AMANDA and RICE, using already available data for through-going muons and contained events, respectively. Moreover, in the optimistic case that an ultrahigh energy cosmic neutrino flux is significantly higher than the cosmogenic one, one even has discovery potential for black holes at the under-ice neutrino detector IceCube beyond the reach of LHC.

We have illustrated the search strategies at colliders, cosmic ray facilities and neutrino telescopes, and compared their reaches with the simplest, nevertheless representative example: production of Schwarzschild black holes in large extra dimension scenarios. There still remains much work to be done.

On the theoretical side, before the full quantum theory of gravity is developed, one can still improve/extend the estimate of the black hole production cross section in $D \geq 4$ dimensions semiclassically. Other tasks not necessarily requiring the knowledge of quantum gravity include the construction of higher-dimensional black hole solutions with charges and angular momenta in different models, and evaluating the grey-body factor for the decay of the higher-dimensional black holes.

While the above theoretical refinements may not affect the expected black hole signatures very much, more simulations for various detectors need to be done, in order to develop successful tools to discriminate black hole events against Standard Model backgrounds.

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