Production of Black Holes in TeV-Scale Gravity

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Abstract: Copious production of microscopic black holes is one of the least model-dependent predictions of TeV-scale gravity scenarios. We review the arguments behind this assertion and discuss opportunities to track the striking associated signatures in the near future. These include searches at neutrino telescopes, such as AMANDA and RICE, at cosmic ray air shower facilities, such as the Pierre Auger Observatory, and at colliders, such as the Large Hadron Collider.

1 Introduction

Black holes are among the most remarkable, but also most mysterious objects in physics. Since Hawking’s prediction of black hole evaporation [1], they play an important role in any attempt towards a theory of quantum gravity. Unfortunately, experimental detection of Hawking radiation from real, massive ($M_{bh}$) astrophysical black holes seems impossible, since the corresponding temperature, as seen by an outside stationary observer, is tiny, $T_H = 6 \cdot 10^{-8}$ K ($M_{\odot}/M_{bh}$). Furthermore, the proposed detection [2] of Hawking radiation from primordial mini black holes – possible relics from the big bang – would be rather indirect. Last, but not least, the production and exploration of microscopic black holes at terrestrial accelerators requires seemingly center-of-mass (cm) energies of order the Planck scale, $\sqrt{s} \gtrsim M_{Pl} = 1/\sqrt{8\pi G_N} = 2 \cdot 10^{18}$ GeV, way beyond energies obtainable even in distant future [3].

The latter, so far remote possibility seems, however, meanwhile within reach in the context of theories with $\delta = D - 4 \geq 1$ flat [4] or warped [5] extra dimensions and a low fundamental Planck scale $M_D \gtrsim$ TeV characterizing quantum gravity. In these theories one expects the copious production of black holes in high energy collisions at cm energies above $M_D$ [6]. Correspondingly, the Large Hadron Collider (LHC) [7], expected to have a first physics run in 2006, may turn into a factory of black holes at which their production and evaporation may be studied in detail [8, 9, 10]. But even before the commissioning of the LHC, the first signs of black hole production may be observed in the scattering of ultrahigh energy cosmic neutrino off nuclei in ice or air [11, 12, 13, 14, 15, 16] and recorded.

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by existing neutrino telescopes, such as AMANDA [17] and RICE [18], or at cosmic ray air shower facilities, such as the Pierre Auger Observatory [19]. Moreover, already now sensible constraints on black hole production can be obtained [13, 14] from the non-observation of horizontal showers by the Fly’s Eye collaboration [20] and the Akeno Giant Air Shower Array (AGASA) collaboration [21], respectively. These constraints turn out to be competitive with other currently available constraints on TeV-scale gravity which are mainly based on interactions associated with Kaluza-Klein gravitons, according to which a fundamental Planck scale as low as \( M_D = \mathcal{O}(1) \) TeV is still allowed for \( \delta \geq 6 \) flat or \( \delta \geq 1 \) warped extra dimensions [22].

In this talk we shortly review the theory and phenomenology of black hole production in TeV-scale gravity scenarios. More details and an exhaustive reference list can be found, e.g., in Ref. [23].

2 Black Hole Production – Theory

Why one expects the copious production of black holes in trans-Planckian scattering at small impact parameters? This expectation is basically relying on two assertions, which are substantiated below: i) Trans-Planckian scattering is semi-classical. ii) There are classical scattering solutions corresponding to the formation of black holes at trans-Planckian energies \( \sqrt{s} \gg M_D \) and at small impact parameters \( b < r_S(\sqrt{s}) \), where \( r_S(M_{bh}) \) is the Schwarzschild radius [24] of a black hole with mass \( M_{bh} \) (cf. Fig. 1 (left)). Correspondingly, one expects a geometric cross-section for black hole formation [8, 9],

\[
\hat{\sigma}_{bh,i} \approx \pi r_S^2(\sqrt{s}) = \frac{\pi}{M_D^2} \left[ \frac{\sqrt{s}}{M_D} \left( \frac{2^4\pi^{\frac{\delta-3}{2}} \Gamma\left(\frac{3+\delta}{2}\right)}{2 + \delta} \right)^2 \right]^\frac{3}{4+\delta}, \quad \text{at } \sqrt{s} \gg M_D, \tag{1}
\]

whose scale is set essentially by the fundamental Planck scale \( M_D \gtrsim \text{TeV} \) and therefore quite sizeable.

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\( r (s) \)

\( i \)

\( j \)

\( r_S(\sqrt{s}) \)

\( r_S \)

\( M_D \)

\( \delta \)

\( \hat{\sigma}_{bh} \)

\( \pi \)

\( M_D^2 \)

\( \sqrt{s} \)

\( M_{bh} \)

\( \frac{\sqrt{s}}{M_D} \)

\( \frac{2^4\pi^{\frac{\delta-3}{2}} \Gamma\left(\frac{3+\delta}{2}\right)}{2 + \delta} \)

\( \left[ \frac{\sqrt{s}}{M_D} \left( \frac{2^4\pi^{\frac{\delta-3}{2}} \Gamma\left(\frac{3+\delta}{2}\right)}{2 + \delta} \right)^2 \right]^\frac{3}{4+\delta} \)

\( \sqrt{s} \gg M_D \)

1For an exhaustive list of references in this context, see Ref. [23].
Figure 2: Left: Accessible region in the black hole production parameters at the LHC for $\delta = 6$ extra dimensions (adapted from Ref. [13]). The solid and the dotted lines are contours of constant numbers of produced black holes per year ($10^7$ s) with a mass larger than $M_{\text{bh}}^\text{min}$, for a fundamental Planck mass $M_D$. The shaded dotted, $M_D = M_{\text{bh}}^\text{min}$, line gives a rough indication of the boundary of applicability of the semi-classical picture. The shaded solid line gives the constraint $M_D > 0.61$ TeV ($\delta = 6$) from LEP II searches [22]. Right: Black hole final state in a detector simulation [31].

Ad i) The fact that trans-Planckian scattering is semi-classical can be most easily seen through a dimensional analysis, in which one keeps $c = 1$, but restores the appropriate powers of $\hbar \neq 1$. Relevant quantities to be considered are the fundamental Planck scale $M_D$ and the fundamental Planck length $\lambda_D$ – the length below which quantum gravity fluctuations of the geometry are important – in terms of the $D = 4 + \delta$ dimensional gravitational constant $G_D$,

$$M_D^{2+\delta} = \frac{(2\pi)^{\delta-1}}{4} \frac{\hbar^{1+\delta}}{G_D}, \quad \lambda_D^{2+\delta} = \hbar G_D,$$

as well as the de Broglie wave length $\lambda_B$ of the scattering quanta and the Schwarzschild radius $r_S$,

$$\lambda_B = 4\pi \frac{\hbar}{\sqrt{s}}, \quad r_S = \frac{1}{\sqrt{\pi}} \left[ \frac{8 \Gamma\left(\frac{3+\delta}{2}\right)}{2 + \delta} \right]^{\frac{1}{1+\delta}} \left(G_D \sqrt{s}\right)^{\frac{1}{1+\delta}}.$$  \hspace{1cm} (3)

An inspection of Eqs. (2) and (3) reveals that in the semi-classical ($\hbar \to 0$) limit, with $G_D$ and $\sqrt{s}$ fixed, the quantities $M_D, \lambda_D, \lambda_B \to 0$, whereas $r_S$ remains finite. Therefore, semi-classics corresponds to the trans-Planckian regime, $\sqrt{s} \gg M_D$. Moreover, in this regime, the Schwarzschild radius $r_S (\gg \lambda_D \gg \lambda_B)$ characterizes the dynamics.

Ad ii) There are basically two regimes in trans-Planckian scattering: The soft regime of large impact parameters, $b \gg r_S(\sqrt{s})$, which is adequately described by semi-classical eikonal methods for elastic small angle ($\theta \sim (r_S/b)^{\delta+1} < 1$) scattering [3, 25], and the hard regime of small impact parameters, $b \ll r_S(\sqrt{s})$, in which one expects the gravitational collapse to a black hole, since at particle crossing an amount $\sqrt{s}$ of energy is localized within a radius $b < r_S$ (cf. Fig. 1 (left)). This is basically a variant of Thorne’s hoop conjecture [20] in classical general relativity, according to which a horizon forms if and only if a mass $M$ is compacted into a region whose circumference in every direction is less than $2\pi r_S(M)$. Indeed, for small enough impact parameter $b < b_{\text{max}}$, a marginally trapped surface forms at the overlap between two gravitational shockwaves describing the
incoming partons at trans-Planckian energies (cf. Fig. 1 (right)), as has been convincingly demonstrated in Refs. [27, 28, 29]. Correspondingly, a geometrical cross-section $\approx \pi b_{\text{max}}^2$ is expected, and a lower bound on $b_{\text{max}}$ leads to a lower limit of e.g.

$$\sigma_{\text{bh}}^{ij} \gtrsim 0.65 \pi r_s^2(\sqrt{s}) \ , \quad M_{\text{bh}} \gtrsim 0.5 \sqrt{s},$$

(4)
in the case of $D = 4$, substantiating the estimate (1) (see Ref. [30] for further discussion).

3 Black Hole Production – Phenomenology

The reach of the LHC to black hole production is illustrated in Fig. 2 (left) for $\delta = 6$ extra dimensions. As can be seen, the LHC can explore the production of black holes with minimum masses nearly up to its kinematical limit of 14 TeV. In order to appreciate the event numbers indicated in Fig. 2 (left), let us mention the expected signature of black hole decay, which is quite spectacular. Once produced, black holes decay primarily via Hawking radiation [1] into a large number of $O(20)$ 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 (cf. Fig. 2 (right)). From previous studies of electroweak sphaleron production [32], which has quite similar event characteristics [33], as well as from first event simulations of black hole production [9], it is clear that only a handful of such events is needed at the LHC to discriminate them from perturbative Standard Model background.

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. $p\gamma \rightarrow \Delta \rightarrow n\pi^+ \rightarrow \nu_\mu \bar{\nu}_\mu \nu_e...$), are more or less guaranteed to exist among ultrahigh energy cosmic neutrinos predicted from various sources (cf. Ref. [34] for a most recent discussion). Thus, if TeV-scale gravity is realised in nature, 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 $10 \div 10^2$ (see Fig. 3 (left)), and have distinct characteristics [11, 12, 13, 14]. 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 [15, 16].

The reach of cosmic ray facilities in black hole production has been thoroughly investigated by exploiting the cosmogenic neutrino fluxes of Fig. 3 (right) [13, 14]. It is argued in Ref. [14] that an excess of a handful of quasi-horizontal events are sufficient for a discrimination against the Standard Model background. An inspection of Fig. 4 (left) thus leads to the conclusion that the Pierre Auger Observatory, expected to become fully operational in 2003, has the opportunity to see first signs of black hole production. Moreover, as also shown in Fig. 3 (left), the non-observation of horizontal air showers reported by the Fly’s Eye [20] and the AGASA [21] 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 ($M_{\text{bh}}^{\text{min}} < \sim 10 \text{ TeV}$) for the semi-classical description.

As for neutrino telescopes, investigations show [15, 16] (cf. Fig. 4 (right)) that due to their small volume $V \approx 0.001 \div 0.01 \text{ km}^3$ for contained events, the currently operating 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 $V \approx 1 \text{ km}^3$ 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 $\approx 1 \text{ km}^3$ for $10^8 \text{ GeV}$ 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
Figure 5: Reach in the black hole production parameters for $\delta = 6$ extra dimensions, for through-going muons in an under-ice detector at a depth of 2 km and with an 1 km$^2$ effective area (1 yr = $3.16 \cdot 10^7$ s) [15].

**Left:** Exploiting the cosmogenic neutrino flux from Fig. 3 (right). **Right:** Exploiting the upper limit on the neutrino flux from “hidden” hadronic astrophysical sources from Fig. 3 (right).

Flux is at the level of the cosmogenic one, only $\lesssim 1$ 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 (cf. Fig. 3 (left)). 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 (cf. Fig. 3 (right)).

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