

# Probing quantum gravity effects in black holes at LHC

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## Abstract

We study modifications of the Hawking emission in the evaporation of miniature black holes possibly produced in accelerators when their mass approaches the fundamental scale of gravity, set to 1 TeV according to some extra dimension models. Back-reaction and quantum gravity corrections are modelled by employing modified relations between the black hole mass and temperature. We release the assumption that black holes explode at 1 TeV or leave a remnant, and let them evaporate to much smaller masses. We have implemented such modified decay processes into an existing micro-black hole event generator, performing a study of the decay products in order to search for phenomenological evidence of quantum gravity effects.

## 1 Introduction

One of the most exciting features of models with large extra dimensions [1, 2] is that the fundamental scale of gravity  $M_G$  could be as low as the electroweak scale ( $M_G \simeq 1$  TeV) and black holes may therefore be produced in our accelerators [3, 4]. Black holes have been studied in both compact [5] and infinitely extended [6, 7] extra dimensions (see also [8] for recent reviews). The basic feature of black hole production is that its cross section should essentially be given by the horizon area of the forming black hole and grows with the centre of mass energy of the colliding particles as a power which depends on the number of extra-dimensions [3, 4].

Once the black hole has formed (and after possible transients), Hawking radiation [9] is expected to set off. The standard description of this effect leads to the (canonical) Planckian distribution for emitted particles and black hole life-times so short that the decay of micro black holes can be viewed as sudden [10]. This picture has been implemented in numerical codes [11, 12] which

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normally let the black hole decay down to a mass of order  $M_G$  via the Hawking law and then explode into a (selectable) number of decay products. However, energy conservation is not guaranteed *a priori* in the canonical ensemble and the black hole temperature in fact diverges for vanishing black hole mass. Energy conservation is therefore enforced by means of kinematical constraints. From a theoretical point of view, such issues can be taken care of by employing the more consistent microcanonical description of black hole evaporation [13] which has been first applied in the context of large extra dimensions in Refs. [14, 15, 16]. It was then shown that actual life-times can vary greatly depending on the model details [17, 16]. Further, the possibility of ending the evaporation by leaving a stable remnant has also been recently considered [19].

The issue of the end of the evaporation is really an open question theoretically, because we do not have a reliable theory of quantum gravity. One could in fact go as far as to say that theoretical physicists are looking forward to detecting black holes at the Large Hadron Collider (LHC) in order to finally have experimental data about quantum gravity. The very detection of these objects would already be evidence that  $M_G$  is not the (naive) Planck energy (about  $10^{19}$  GeV) and extra dimensions do exist. Furthermore, the late stage of black hole evaporation (when its mass  $M \sim M_G$ ) could tell us more about the details of quantum gravity. The question then naturally arises as whether deviations from the Hawking law induced by the underlying theory of quantum gravity can actually be detected. The purpose of this report is precisely to study if a modified evaporation law at small black hole mass ( $M \sim M_G$ ) can produce detectable differences provided energy conservation is properly enforced. The latter requirement in fact changes the actual distribution of emitted particles even for the case of the standard Hawking law, as we shall also show. For this purpose, we have developed modifications to the CHARYBDIS Monte Carlo code [11], which we shall describe in some details in Section 2.1. Preliminary results from a few test runs are then analyzed in Section 3.

We use units with  $c = \hbar = k_B = 1$  and denote the fundamental gravity length in  $D$  space-time dimensions as  $\ell_D$ .

## 2 Black hole evaporation

The no-hair theorems guarantee that a black hole is characterized by its mass, charges and angular momentum only. The only parameter characterizing an uncharged non-rotating black hole is thus its mass  $M$ . On considering solutions to the Einstein equations (or applying Gauss' theorem) in  $4 + d$  dimensions, one can derive the following relation between the mass and the horizon radius of such a black hole,

$$R_H = \frac{1}{\sqrt{\pi} M_G} \left( \frac{M}{M_G} \right)^{\frac{1}{d+1}} \left( \frac{8 \Gamma\left(\frac{d+3}{2}\right)}{d+2} \right)^{\frac{1}{d+1}}, \quad (2.1)$$

and its temperature is given by

$$T_H = \frac{d+1}{4\pi R_H}. \quad (2.2)$$

Once formed, the black hole begins to evolve. In the standard picture the evaporation process can be divided into three characteristic stages [4]:

1. **BALDING PHASE:** the black hole radiates away the multipole moments it has inherited from the initial configuration, and settles down in a hairless state. A certain fraction of the initial mass will also be lost in gravitational radiation.
2. **EVAPORATION PHASE:** it starts with a spin down phase in which the Hawking radiation [9] carries away the angular momentum, after which it proceeds with the emission of thermally distributed quanta until the black hole reaches the Planck mass (replaced by the fundamental scale  $M_G$  in the models we are considering here). The radiation spectrum contains all the Standard Model particles, which are emitted on our brane, as well as gravitons, which are also emitted into the extra dimensions. It is in fact expected that most of the initial energy is emitted during this phase into Standard Model particles [7] although this conclusion is still being debated (see, e.g. Ref. [20]).
3. **PLANCK PHASE:** once the black hole has reached a mass close to the effective Planck scale  $M_G$ , it falls into the regime of quantum gravity and predictions become increasingly difficult. It is generally assumed that the black hole will either completely decay in some last few Standard Model particles or a stable remnant be left which carries away the remaining energy [19].

In our approach we will consider possible modifications to the second and third phases. On one hand, we will modify the Hawking phase by employing a different relation between the horizon radius and the temperature. On the other hand, we will look at the possibility that the evaporation may not end at the fundamental scale  $M_G$  ( $\sim 1$  TeV) but proceeds further until a lower energy has been reached.

## 2.1 Quantum gravity and Monte Carlo generator

Several Monte Carlo codes which simulate the production and decay of micro-black holes (see, e.g. Refs. [11, 12, 21]) are available nowadays. Instead of developing from scratch a new event generator, we have found convenient to adopt the CHARYBDIS code, implementing relevant modifications therein. In the following we are going to describe them in some detail.

In order to let the black hole evaporate below  $M_G$ , one needs to treat the mass of the emitted particles properly. That includes having the correct phase space measure in the Planckian number density for the emitted particles,

$$N_m(\vec{k}) = \frac{d^3k}{e^{\omega/T_H} \pm 1}, \quad (2.3)$$

where  $m$  is the particle mass,  $\vec{k}$  the particle 3-momentum and  $\omega = \sqrt{k^2 + m^2}$ . Moreover, since  $N_m$  depends on  $m$  and not just on the statistics, one cannot assume a fixed ratio of production for fermions versus bosons but particle multiplicity should be used when generating particle types randomly. We therefore use the multiplicities predicted by the Standard Model [22].

In order to include possible quantum gravity effects, we then employ modified expressions for the temperature of the form

$$T = F_i T_H, \quad (2.4)$$

in which, to cover results in the existing literature (for a partial list of approaches to the problem, see Refs. [13, 15, 16, 17, 18]), we shall consider two possible modifying factors,

$$F_1(\ell, \alpha, n) = \frac{R_H^n}{R_H^n + \alpha \ell^n} \quad (2.5)$$

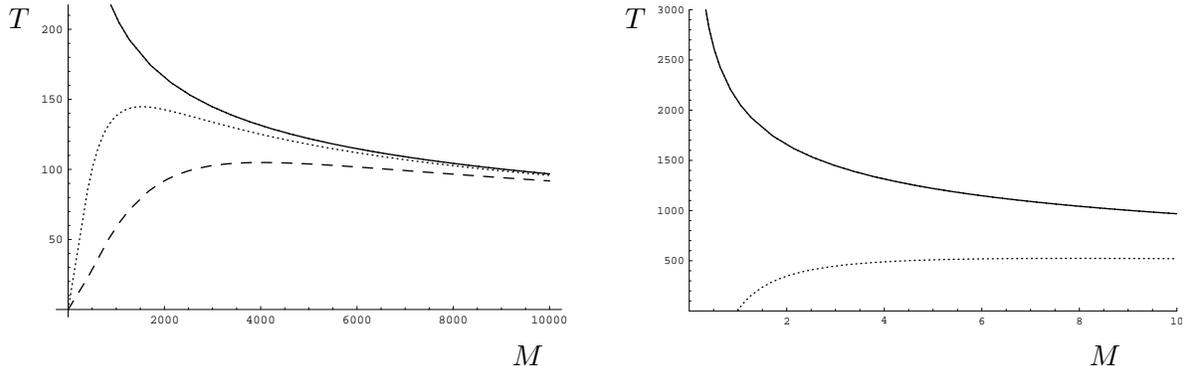


Figure 1: Black hole temperature (in GeV) as a function of the black hole mass (in GeV). In the left panel, we compare the Hawking law (solid line) to the case in Eq. (2.5) for  $\ell = 10^{-3} \text{ GeV}^{-1}$ ,  $\alpha = 5$ ,  $n = 5$  (dashed line) and  $\ell = 10^{-3} \text{ GeV}^{-1}$ ,  $\alpha = 5$ ,  $n = 1$  (dotted line). In the right panel, the Hawking law (solid line) is compared to the modified case (2.6) for  $\ell = 1.14 \cdot 10^{-4} \text{ GeV}^{-1}$ ,  $n_1 = 1$ ,  $n_2 = 1$  (dotted line).

and

$$F_2(\ell, n_1, n_2) = \left[ 1 - \left( \frac{\ell}{R_H} \right)^{n_1} \right]^{n_2}, \quad (2.6)$$

where  $\ell$ ,  $\alpha$ ,  $n$ ,  $n_1$ , and  $n_2$  are parameters that can be adjusted (see below). Note that  $F_1$  leads to a vanishing temperature for vanishing black hole mass (horizon radius), whereas with  $F_2$  the temperature vanishes at finite  $M$  (see [18] and References therein). Specific examples are shown in Fig. 1 together with the standard Hawking law (2.2).

A list of some adjustable parameters is given in Table 1 and we just wish to make a few remarks. The initial black hole mass  $M_0$  can be either fixed (to within the maximum centre mass energy expected at the LHC) or generated randomly. During the decay, when  $M < M_f$  the black hole explodes in a selectable number  $N_f$  of fragments. An important aspect of our analysis is that we set the grey-body factors to 1 for all kinds of particles. It is to be expected that this approximation becomes too restrictive, particularly if the final black hole mass is of the order of (a few) GeV. However, we are not currently aware of any computations of grey-body factors which include massive particles and have left this issue for future developments.

$M_0$	Initial black hole mass	1 – 14 TeV; random
$M_f$	Minimum black hole mass	1 – 1000 GeV
$N_f$	number of final fragments	2 – 6
$d$	number of extra dimensions	2 – 6
$F_i$	modified temperature	1 (no modification), $F_1$ , $F_2$

Table 1: Parameters that can be adjusted in the Monte Carlo generator and their ranges. For each modified temperature, one can also set the corresponding parameters as described in the text.

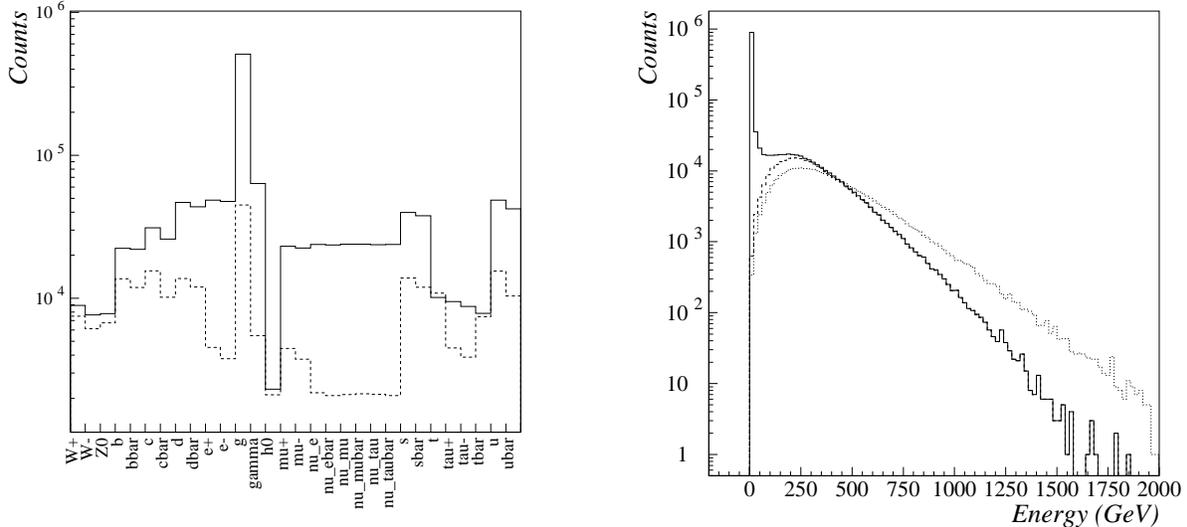


Figure 2: Left panel: abundance of Standard Model particles produced during the evaporation of 10 TeV black holes, for a run of 10000 events with the modified law (2.5) (solid histogram) and with the standard CHARYBDIS generator (dashed histogram). The fundamental scale of gravity is set to 1 TeV, temperature parameters are the same as in left panel of Fig. 1 and number of extra dimensions  $d = 2$ . Right panel: energy distribution of the emitted particles obtained with the modified law (2.5) (solid histogram), including only particles emitted when the black hole has a mass exceeding 1 TeV (dashed histogram), and with the standard CHARYBDIS generator (dotted histogram).

### 3 Simulation results

The standard CHARYBDIS generator simulates the evaporation of a micro-black hole according to the Hawking’s law until the black hole mass reaches the fundamental scale of gravity  $M_G$  in a given model of extra dimensions (e.g., at 1 TeV). Once the scale  $M_G$  is reached, the black hole remnant is decayed into a few bodies simply according to phase space. As described in the previous section, in our modified version we implemented ways to cope with the evaporation well below the fundamental scale, down to negligible black hole masses. We shall thus compare the outcomes of the generator for the standard and modified versions from a phenomenological point of view.

In the simulations run this far, we noted that modified temperatures (2.5) and (2.6) produced qualitatively similar results when the black hole mass such that  $R_H > \ell$ . Further, the case of Eq. (2.6) corresponds to a remnant of radius  $R_H = \ell$  which has been considered elsewhere [19]. We shall therefore refer only to the results obtained for the temperature modified by the factor  $F_1$  with the parameters given in the caption of Fig. 1. Since the temperature behaviour at low mass values is no longer divergent and tends to zero for  $M = 0$  in this case, we do expect a continuous emission of increasingly softer particles until the black hole evaporates completely. Once the black hole mass has decreased below the threshold for producing a given particle, such a particle can no longer be emitted. Hence one expects that the production of the heavier particles, i.e. massive gauge bosons and top quarks, is scarcely affected, while the emission of soft low mass (or massless) particles is

largely enhanced.

A comparison of the relative abundance of the Standard Model particles produced by the black hole evaporation with and without using the modified law of the form (2.5) – before parton evolution and hadronization are performed – is shown in the left panel of Fig. 2. In the right panel of Fig. 2 we show the energy distribution of the emitted particles. As expected, the modified law dramatically changes the spectrum at low energy, leaving the spectrum at large energy moderately affected. This translates into a much larger multiplicity of isotropically emitted soft particles which might be a possible phenomenological signature of quantum gravity effects.

## 4 Conclusions

We have considered possible modifications for the decay of micro-black holes around the fundamental scale of gravity  $M_G$  (of order 1 TeV). Inspired by the microcanonical description of the Hawking evaporation and other treatments in the literature, we have studied modified statistical laws for the temperature together with the requirement of energy conservation enforced up to the end of the evaporation at a scale  $M_f \ll M_G$ .

The numerical simulations we have run so far suggest that such modification mainly affect the total number of light and massless particles emitted at very small energy. On lowering the minimum black hole mass  $M_f$  increases this number. The detection of the isotropic emission of a large number of soft isolated particles (i.e. not associated to jet-like topologies) could be an evidence in favour of a specific decay law or of a specific theory of quantum gravity.

In our analysis we have not explicitly considered the case in which black holes leave stable remnants since it has already been reported in Ref. [19]. Let us just mention that very large values of  $\alpha$  and/or  $\ell$  in the modified temperature (2.5) (together with energy conservation) would make it very hard for the black holes to continue the emission for  $M \ll M_G$  and stable remnants would be effectively produced.

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