

Quasi-stable black holes at the large hadron collider

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We address the production of black holes at LHC and their time evolution in space times with compactified space like extra dimensions. It is shown that black holes with life times of several hundred fm/c can be produced at LHC. The possibility of quasi-stable remnants is discussed.

An outstanding problem in physics is to understand the ratio between the electroweak scale $m_W = 10^3$ GeV and the four-dimensional Planck scale $m_p = 10^{19}$ GeV. Proposals that address this so called hierarchy problem within the context of brane world scenarios have emerged recently [1]. In these scenarios the Standard Model of particle physics is localized on a three dimensional brane in a higher dimensional space. This raises the exciting possibility that the fundamental Planck scale M_f can be as low as m_W . As a consequence, future high energy colliders like LHC could probe the scale of quantum gravity with its exciting new phenomena: A possible end of small distance physics as been investigated by Giddings and Thomas [2] while Dimopoulos and Landsberg opened a new road to study black holes with their work on the production of black holes in high energetic interactions [3]. In this letter we investigate TeV scale gravity associated with black hole production and evaporation at LHC and beyond. For a discussion of black hole production at Tevatron and from cosmic rays, the reader is referred to Refs. [4,5,8].

One scenario for realizing TeV scale gravity is a brane world in which the Standard Model particles including gauge degrees of freedom reside on a 3-brane within a flat compact space of volume V_d , where d is the number of compactified spatial extra dimensions with radius L . Gravity propagates in both the compact and non-compact dimensions.

Let us first characterize black holes in space times with compactified space-like extra dimensions [6]. We can consider two cases:

1. The size of the black hole given by its Schwarzschild radius R_H is $\gg L$.
2. If $R_H \ll L$ the topology of the horizon is spherical in $3 + d$ space like dimensions.

The mass of a black hole with $R_H \approx L$ in $D = 4$ is called the critical mass $M_c \approx m_p L / l_p$ and $1/l_p = m_p$. Since

$$L \approx (1 \text{ TeV} / M_f)^{1+\frac{2}{d}} 10^{\frac{31}{d}-16} \text{ mm} \quad (1)$$

M_c is typically of the order of the Earth mass. Since we are interested in black holes produced in parton-parton collisions with a maximum c.o.m. energy of $\sqrt{s} = 14$ TeV, these black holes have $R_H \ll L$ and belong to the second case.

Spherically symmetric solutions describing black holes in $D = 4 + d$ dimensions have been obtained [7] by making the ansatz

$$ds^2 = -e^{2\phi(r)} dt^2 + e^{2\Lambda(r)} dr^2 + r^2 d\Omega_{(2+d)}, \quad (2)$$

with $d\Omega_{(2+d)}$ denoting the surface element of a unit $3 + d$ -sphere. Solving the field equations $R_{\mu\nu} = 0$ gives

$$e^{2\phi(r)} = e^{-2\Lambda(r)} = 1 - \left(\frac{C}{r}\right)^{1+d}, \quad (3)$$

with C being a constant of integration. We identify C by the requirement that for $r \gg L$ the force derived from the potential in a space time with d compactified extra dimensions

$$V(r) = \frac{1}{(1+d)} \left(\frac{1}{M_f}\right)^{1+d} \frac{M}{M_f} \frac{1}{L^d} \frac{1}{r} \quad (4)$$

equals the force derived from the usual 4-dimensional Newton potential. Note, the mass M of the black hole is defined by

$$M = \int d^{3+d}x T_{00} \quad (5)$$

with $T_{\mu\nu}$ denoting the energy momentum tensor which acts as a source term in the Poisson equation for a slightly perturbed metric in $3 + d$ dimensional space time [7,10]. In this way the horizon radius is obtained as

$$R_H^{1+d} = \frac{2}{d+1} \left(\frac{1}{M_f}\right)^{1+d} \frac{M}{M_f} \quad (6)$$

with M denoting the black hole mass.

Let us now investigate the production rate of these black holes at LHC. Note that we neglect complications due to the finite angular momentum and assume non-spinning black holes in the formation and evaporation process¹. Consider two partons moving in opposite directions. If the partons center of mass energy \sqrt{s} reaches

¹In fact finite angular momentum decreases the production probability by $\approx 50\%$ at LHC energies [8,9].

the fundamental Planck scale $M_f \sim 1$ TeV and if the impact parameter is less than R_H , a black hole with Mass $M \approx \sqrt{s}$ can be produced. The total cross section for such a process can be estimated on geometrical grounds [11,12] and is of order $\sigma(M) \approx \pi R_H^2$. This expression contains only the fundamental Planck scale as a coupling constant. Note that the given classical estimate of the black hole production cross section has been under debate [13,14]. Investigations by [15] justify the use of the classical limit². Further, the recent works done by Jevceki and Thaler [16] and those done by Eardley and Giddings [17] support this estimate. Thus, we proceed with the classical approximation. Setting $M_f \sim 1$ TeV and $d = 2$ one finds $\sigma \approx 1 \text{ TeV}^{-2} \approx 400 \text{ pb}$. However, we have to take into account that in a pp-collision each parton carries only a fraction of the total c.o.m. energy. The relevant quantity is therefore the Feynman x distribution of black holes at LHC for masses $M \in [M^-, M^+]$ given by

$$\frac{d\sigma}{dx_F} = \sum_{p_1, p_2} \int_{M^-}^{M^+} dy \quad (7)$$

$$\frac{2y}{x_2 s} f_1(x_1, Q^2) f_2(x_2, Q^2) \sigma(y, d), \quad (8)$$

with $x_F = x_2 - x_1$ and the restriction $x_1 x_2 s = M^2$. We used the CTEQ4 [19] parton distribution functions f_1, f_2 with $Q^2 = M^2$. All kinematic combinations of partons from projectile p_1 and target p_2 are summed over.

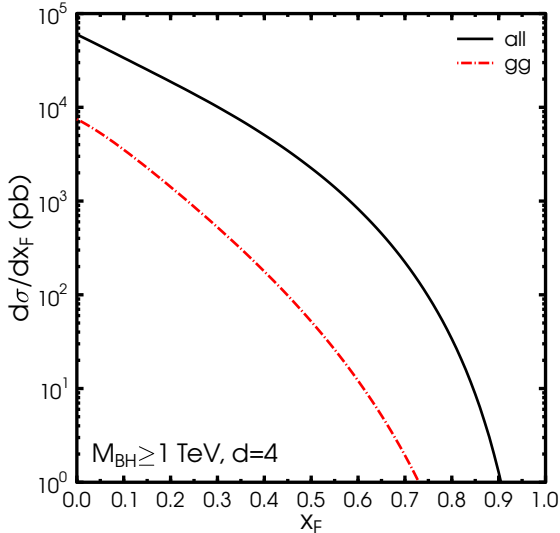


FIG. 1. Feynman x distribution of black holes with $M \geq 1$ TeV produced in pp interactions at LHC with 4 compactified spatial extra dimensions.

²Even if this additional suppression would be present, the maximal suppression in the cross section is by a factor 10^{-1} [18].

Fig. 1 depicts the momentum distribution of produced black holes in pp interactions at $\sqrt{s} = 14$ TeV. The Feynman x distribution scales with the black hole mass like $M^{2(2+d)/(1+d)}$. As a consequence, black holes of lowest masses (≈ 1 TeV) receive a major contribution from gg scattering, while heavier black holes are formed in scattering processes of quarks. Since for masses below 10 TeV heavy quarks give a vanishing contribution to the black hole production cross section, those black holes are primarily formed in scattering processes of *up* and *down* quarks.

Let us now investigate the evaporation of black holes with $R_H \ll L$ and study the influence of compact extra dimensions on the emitted quanta. In the framework of black hole thermodynamics the entropic S of a black hole is given by its surface area. In the case under consideration $S \sim M_f^{(2+d)} \Omega_{(d+3)} R_H^{2+d}$ [10] with $\Omega_{(d+3)}$ the surface of the unit $d + 3$ -sphere

$$\Omega_{(d+3)} = \frac{2\pi^{\frac{d+3}{2}}}{\Gamma(\frac{d+3}{2})}. \quad (9)$$

The single particle spectrum of the emitted quanta is then

$$n(\omega) = \frac{\exp[S(M - \omega)]}{\exp[S(M)]}. \quad (10)$$

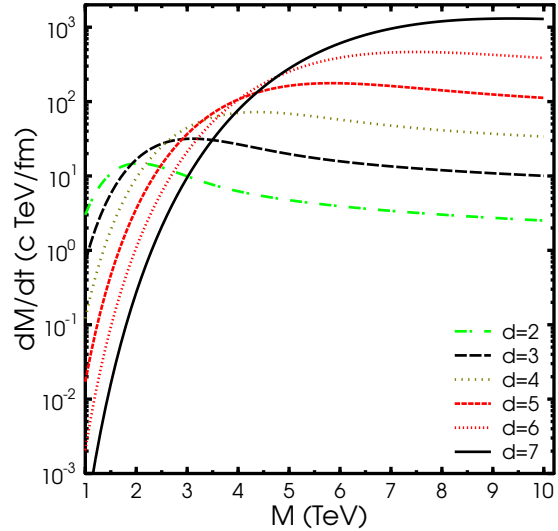


FIG. 2. Decay rate in TeVc/fm as a function of the initial mass of the black hole. Different line styles correspond to different numbers of extra dimensions d .

It has been claimed that it may not be possible to observe the emission spectrum directly, since most of the energy is radiated in Kaluza-Klein modes. However, from

the higher dimensional perspective this seems to be incorrect and most of the energy goes into modes on the brane. In the following we assume that most of the emitted quanta will be localized on our 3-brane [20].

Summing over all possible multi-particle spectra we obtain the black holes evaporation rate \dot{M} through the Schwarzschild surface \mathcal{A}_D in D space-time dimensions,

$$\dot{M} = -\mathcal{A}_D \frac{\Omega_{(d+3)}}{(2\pi)^{d+3}} \int_0^M d\omega \sum_{j=1}^{(M/\omega)} \omega^{D-1} n(j\omega) \quad . \quad (11)$$

Neglecting finite size effects Eq.(11) becomes

$$\dot{M} = \mathcal{A}_D \frac{\Omega_{(d+3)}}{(2\pi)^{d+3}} e^{-S(M)} \sum_{j=1}^{\infty} \left(\frac{1}{j}\right)^D \times \int_M^{(1-j)M} dx (M-x)^{D-1} e^{S(x)} \Theta(x) \quad , \quad (12)$$

with $x = M - j\omega$, denoting the energy of the black hole after emitting j quanta of energy ω . Thus, ignoring finite size effects we are lead to the interpretation that the black hole emits only a single quanta per energy interval. We finally arrive at

$$\dot{M} = \mathcal{A}_D \zeta(D) \frac{\Omega_{(d+3)}}{(2\pi)^{d+3}} e^{-S(M)} \times \int_0^M dx (M-x)^{D-1} e^{S(x)} \quad . \quad (13)$$

Fig. 2 shows the decay rate (13) in $\text{TeV}c/\text{fm}$ as a function of the initial mass of the black hole. Since the Temperature T_h of the black hole decreases like $M^{-1/(1+d)}$ it is evident that extra dimensions help stabilizing the black hole, too. One should note that the mass decay law presented here is more complicated than the one derived in [21]. This is due to the micro canonical treatment used here compared to the grand canonical approach given in [21]. The grand canonical approach is suited only in settings when the energy of the emitted particle can be neglected as might be the case for astrophysical black holes. For a detailed comparison between the micro canonical and the canonical approach the reader is referred to [22,10].

From (13) we calculate the time evolution of a black hole with given Mass M . The result is depicted in Fig. 3 for different numbers of compactified space like extra dimensions. As can be seen again, extra dimensions lead to an increase in lifetime of black holes. The calculation shows that a black hole with $M \sim 10$ TeV at least exist for 100 fm/c for $d > 5$ and is sensitive to the number of extra dimensions. If the black hole has been created at large x_F its apparent lifetime in the center of mass frame may even be larger by a factor seven due to relativistic time delay. Afterwards the mass of the black hole drops

below the fundamental Planck scale M_f . The quantum physics at this scale is unknown and therefore the fate of the extended black object. However, statistical mechanics may still be valid. If this would be the case it seems that after dropping below M_f a quasi-stable remnant remains.

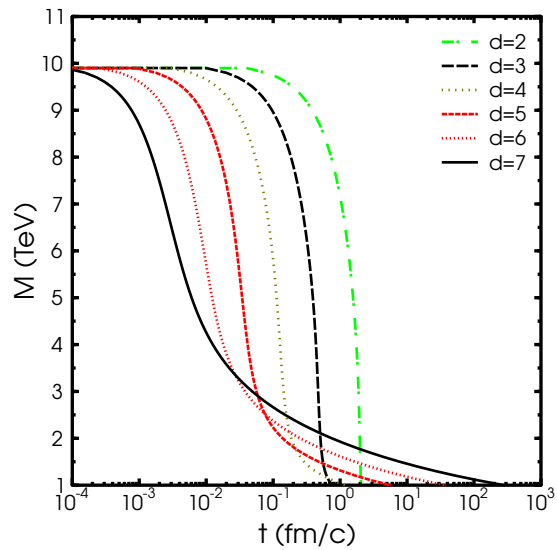


FIG. 3. Time evolution of a black hole. Different line styles correspond to different numbers of extra dimensions d .

In conclusion, we have predicted the momentum distribution of black holes in space times with large and compact extra dimensions. Using the micro canonical ensemble we calculated the decay rate of black holes in this space time neglecting finite size effects. If statistical mechanics is still valid below the fundamental Planck scale M_f , the black holes may be quasi-stable. In the minimal scenario ($M_f \sim 10$ TeV, $d > 5$) the lifetime is at least 100 fm/c .

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Note added in proof: In previous proceedings (J.Phys.G28:1657,2002; hep-ph/0111052 and Proceedings of the XL International Winter meeting on Nuclear Physics, p.58), we have published figures for the lifetimes and evaporation rates of black holes with an omitted pre-factor that has been included here.

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