Quasi-Stable Black Holes at LHC

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We adress 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 at least 100 fm/c will be produced in huge numbers at LHC. We discuss also the possibility of quasi-stable remnants.

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 adress 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 localised 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. In this letter we investigate TeV scale gravity associated with black hole production and evaporation at LHC and beyond.

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. We can consider two cases:

1. The size of the black hole given by its Schwarzschildradius R_H is $\gg L$.
2. If $R_H \ll L$ the topology of the horizon is spherical in $3+d$ spacelike 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

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

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 [2] by making the ansatz

$$\mathrm{d}s^2 = -\mathrm{e}^{2\phi(r)}\mathrm{d}t^2 + \mathrm{e}^{2\Lambda(r)}\mathrm{d}r^2 + r^2\mathrm{d}\Omega_{(d+2)}\ , \tag{2}$$

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

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

with C beeing a constant of integration. We identify C by the requirement that for $r \gg L$ the potential in a spacetime with d compactified extra dimensions

$$V(r) = \frac{16\pi}{(2+d)\Omega_{(2+d)}}\frac{1}{M_f^{2+d}}\frac{1}{L^d}\frac{M}{r} \tag{4}$$

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

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

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

$$R_H^{1+d} = \frac{8\Gamma\left(\frac{3+d}{2}\right)}{(2+d)\pi^{\frac{1+d}{2}}}\left(\frac{1}{M_f}\right)^{1+d}\frac{M}{M_f} \tag{6}$$

with M denoting the black hole mass.

Let us now investigate the production rate of these black holes at LHC. Consider two partons moving in opposite directions. If the partons c.o.m energy $\sqrt{\hat{s}}$ reaches the fundamental Planck scale $M_f \sim 1$ TeV and if the impact parameter is less than R_H, a black hole with Mass $M \approx \sqrt{\hat{s}}$ can be produced. The total cross section for such a process can be estimated on geometrical grounds and is of order $\sigma(M) \approx \pi R_H^2$. This expression contains only the fundamental Planck scale as a coupling constant. As a consequence, if we set $M_f \sim 1$TeV and $d = 2$ we find $\sigma \approx 1\ \text{TeV}^{-2} \approx 400$ pb. However, we have to take into account that in a pp-collison 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

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

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

with $x_F = x_2 - x_1$ and the restriction $x_1 x_2 s = M^2$. We used the CTEQ4 [5] 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.

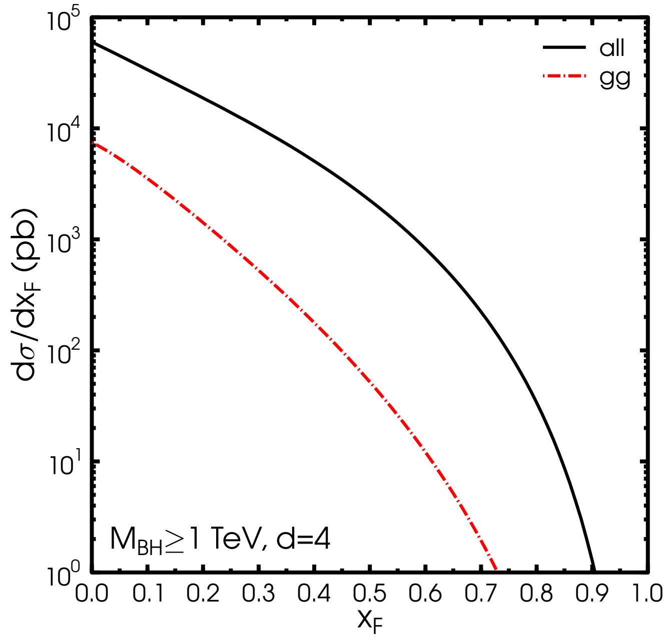

FIG. 1. Feynman x distribution of black holes with $M \geq 1$ TeV produced in pp interactions at LHC with 4 compactified spatial extra dimensions.

The Feynman x distribution scales with the black hole mass like $M^{-2d/(1+d)}$. As a consequence, black holes of lowest masses ($\approx$ 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 entropie S of a black hole is given by its surface area. In the case under consideration $S = \Omega_{(2+d)} \; R_H^{2+d}$. The single particle spectrum of the emitted quanta is then

$$n(\omega) = \frac{\exp[S(M-\omega)]}{\exp[S(M)]} \quad . \tag{9}$$

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 localised on our 3-brane.

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

$$\dot{M} = -\mathcal{A}_D \int_0^M \mathrm{d}\omega \sum_{j=1}^{(M/\omega)} \omega^{D-1} n(j\omega) \quad . \tag{10}$$

Neglecting finite size effects Eq.(10) becomes

$$\dot{M} = \mathcal{A}_D \, \mathrm{e}^{-S(M)} \sum_{j=1}^{\infty} \left(\frac{1}{j}\right)^D \times \int_M^{(1-j)M} \mathrm{d}x \, (M-x)^{D-1} \mathrm{e}^{S(x)} \Theta(x) \quad , \tag{11}$$

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 emmits only a single quanta per energy interval. We finally arrive at

$$\dot{M} = \mathcal{A}_D \zeta(D) \int_0^M \mathrm{d}x \, (M-x)^{D-1} \mathrm{e}^{S(x)-S(M)} \, . \tag{12}$$

Fig. 2 shows the decay rate (12) in GeV/fm as a function of the initial mass of the black hole.

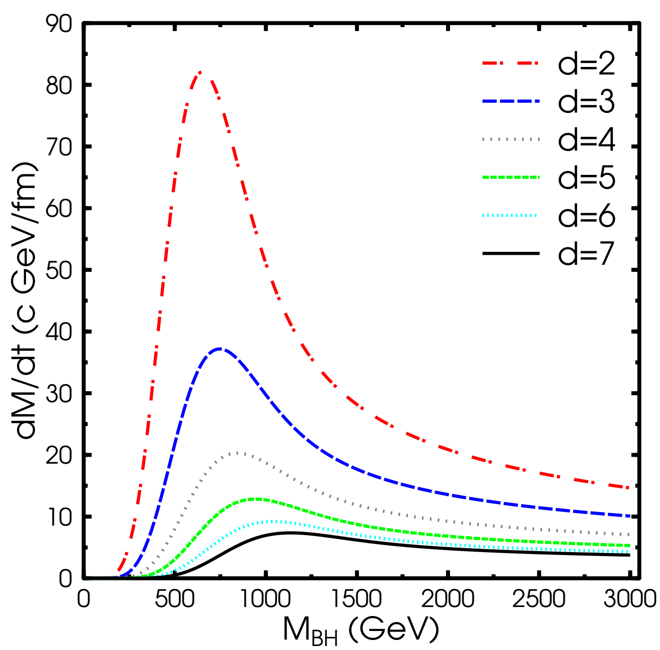

FIG. 2. Decay rate in GeV/fm as a function of the initial mass of the black hole. Different linestyles correspond to different numbers of extra dimensions d.

The decay rate scales like

$$\dot{M} \sim \mathrm{e}^{-M^{(2+d)/(1+d)}} \, , \tag{13}$$

which shows the expected behaviour, i. e. the havier a black hole the more stable it is against decay. 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.

From (12) 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 $M \sim$ TeV at least exist for 100 fm/c (for d=2). 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.

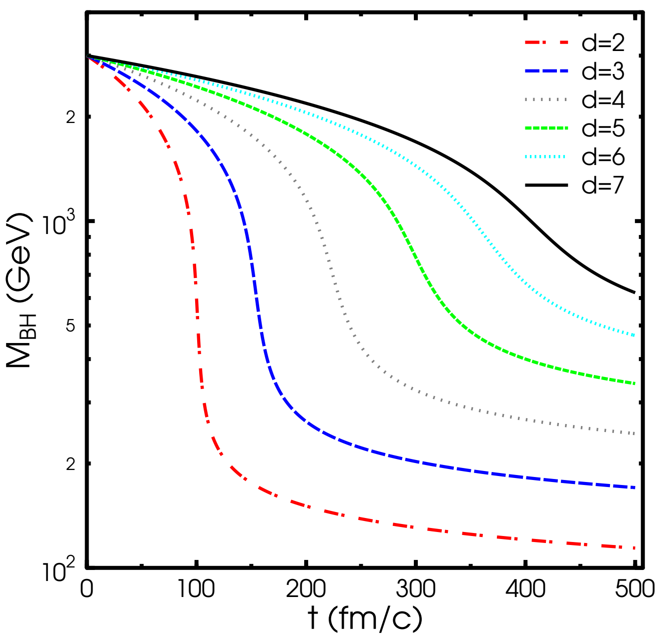

FIG. 3. Time evolution of a black hole. Different line styles correspond to different numbers of extra dimensions d.

In conclusion, we have predicted the rapidity 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 ($M_f \sim$ TeV, $d = 2$) the lifetime is at least 100 fm/c.

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