Suppression of High-P_T Jets as a Signal for Large Extra Dimensions and New Estimates of Lifetimes for Meta stable Micro Black Holes -From the Early Universe to Future Colliders

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We address the production of black holes at LHC in space times with compactified space-like large extra dimensions (LXD). Final state black hole production leads to suppression of high-P_T jets, i.e. a sharp cut-off in $\sigma(\text{pp}\rightarrow\text{jet}+X)$. This signal is compared to the jet plus missing energy signature due to graviton production in the final state as proposed by the ATLAS collaboration.

Time evolution and lifetimes of the newly created black holes are calculated based on the micro-canonical formalism. It is demonstrated that previous lifetime estimates of micro black holes have been dramatically underestimated.

The creation of a large number of quasi-stable black holes is predicted with life times of hundred fm/c at LHC.

Medium modifications of the black holes evaporation rate due to the quark gluon plasma in relativistic heavy ion collisions as well as provided by the cosmic fluid in the early universe are studied.

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 $m_{\text{P}} = 10^{19}$ 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 localised on a three dimensional brane in a higher dimensional space with large compactified space-like extra dimensions (LXD). This raises the exciting possibility that the fundamental scale M_f can be as low as m_W (without extra dimensions $M_f = m_{\text{P}}$. As a consequence, future high energy colliders like LHC and CLIC could probe the scale of quantum gravity with its exciting new phenomena: A possible end of small distance physics has been investigated by Giddings [2] while Dimopoulos and Landsberg speculated 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 colliders and in the early universe.

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 LXDs with radius L. Gravity propagates in both the compact LXDs and non-compact dimensions.

Let us first characterise black holes in space times with LXDs. We can consider two cases. First, the size of the black hole given by its Schwarzschildradius is $R_H \gg L$. In this case the topology of the horizon is $S(3) \times U(1) \times U(1) \times \ldots$, where $S(3)$ denotes the three dimensional sphere and $U(1)$ the Kaluza-Klein compactification. Second, 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 $M_c \approx m_{\text{P}} L/l_{\text{P}}$ and $1/l_{\text{P}} = m_{\text{P}}$. Since $L \approx (1\text{TeV}/M_f)^{1+\frac{2}{d}}\, 10^{\frac{31}{d}-16}$ mm, M_c is typically of the order of the Earth mass. As we are interested in black holes produced in parton-parton collisions with a maximum cms 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 [4] by making the ansatz

$$\mathrm{d}s^2 = -\mathrm{e}^{2\phi(r)}\mathrm{d}t^2 + \mathrm{e}^{2\Lambda(r)}\mathrm{d}r^2 + r^2\mathrm{d}\Omega_{(2+d)} \; , \tag{1}$$

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

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

with C being a constant of integration. We identify C by the requirement that for $r \gg L$ the force derived from

$$V(r) = \frac{1}{1+d} \frac{1}{M_f^{1+d}} \frac{M}{M_f} \frac{1}{L^d} \frac{1}{r} \tag{3}$$

in a space-time with d compactified extra dimensions equals the 4-dimensional Newton force. Note, the mass M of the black hole is

$$M \approx \int \mathrm{d}^{3+d}x \, T_{00} \tag{4}$$

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 [5]. Note that in order to fix partially the coordinate invariance the harmonic gauge condition is imposed. In this way the horizon radius is obtained as

$$R_H^{1+d} = \frac{2}{1+d} \left(\frac{1}{M_f}\right)^{1+d} \frac{M}{M_f} \tag{5}$$

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 cms energy $\sqrt{\hat{s}}$ reaches the fundamental scale $M_f \sim 1$ TeV and if the impact parameter is less than R_H, a black hole with Mass $M \approx \sqrt{\hat{s}}$ might 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 scale M_f as a coupling constant. As a consequence, if we set $M_f \sim 1$TeV and $d = 2$ we find $\sigma \approx \pi$ TeV$^{-2} \approx 1.2$ nb. However, we have to take into account that in a pp-collision each parton carries only a fraction of the total cms energy. The relevant quantity is therefore the Feynman x distribution of black holes at LHC for masses $M \in [M^-, M^+]$ given by

$$\frac{d\sigma}{dx_F} = \sum_{p_1,p_2} \int_{M^-}^{M^+} dy \frac{2y}{x_2 s} f_1(x_1, Q^2) f_2(x_2, Q^2) \sigma(y, d) \;, \tag{6}$$

with $x_F = x_2 - x_1$ and the restriction $x_1 x_2 s = M^2$. We used the CTEQ4 [7] 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.

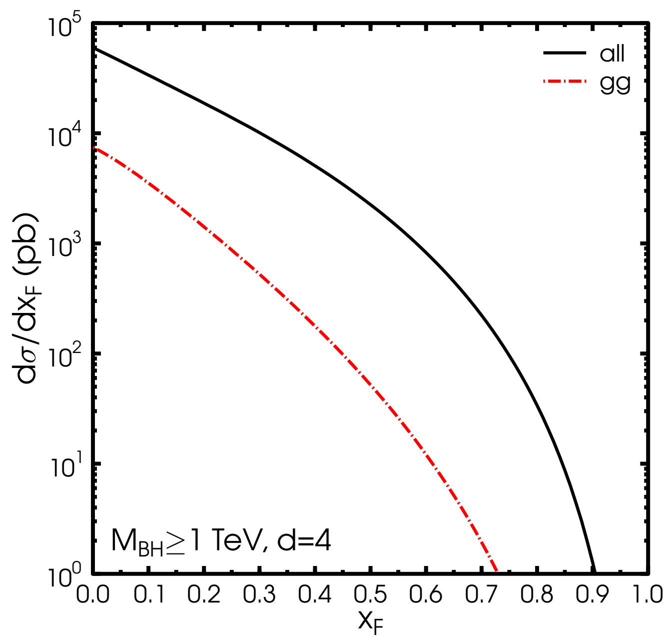

FIG. 1. Feynman x distribution of black holes with $M \geq 1$ TeV produced in pp interactions at LHC with 4 compactified spatial extra dimensions [15].

Fig. 1 depicts the momentum distribution of produced black holes in pp interactions at $\sqrt{s} = 14$ TeV. 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 valence quarks.

The possibility of producing black holes in pp collisions at LHC has dramatic consequences. First of all this would result in a sharp cut-off in $\sigma(\text{pp}\to\text{jet}+X)$ as a function of the transverse jet energy at $E_T \sim M_f$. A different extra dimension signature occurring in the same process was discussed in an ATLAS proposal [8]. The authors of this proposal found for specific model parameters a significant decrease in $\sigma(\text{pp}\to\text{jet}+X)$ at $E_T \sim M_f$ due to gravitons G in the final states. This effect is somehow contraintuitive since the coupling of any Kaluza-Klein state to our brane is still suppressed by $1/m_{\text{P}}^2$. For instance, the total cross section [9] for the subprocess $q\bar{q} \to \gamma G$ is of order $\sigma(q\bar{q} \to \gamma G) \sim \alpha_s/m_{\text{P}}^2 N(\sqrt{\hat{s}})$, where N denotes the number of Kaluza-Klein states with masses below $\sqrt{\hat{s}}$. Since the momenta of the Kaluza-Klein states perpendicular to our brane are quantised in integer multiples of $1/L$ and the norm of these momenta are the four-dimensional masses of the Kaluza-Klein states, one has $N(\sqrt{\hat{s}}) \approx L\sqrt{\hat{s}}/2\pi$ for each extra dimension. As a result, $\sigma(q\bar{q} \to \gamma G) \sim \alpha_s/M_f^2(\sqrt{\hat{s}}/M_f)^d$. Hence, the total cross section rapidly increases with the partons cms energy and for $\sqrt{\hat{s}} \sim M_f$ it is comparable to parton parton cross sections in pQCD. However, this jet plus missing transverse energy signature strongly depends on the model parameters and is for $M_f > 5$TeV extremely difficult to measure in the minimal scenario with $d = 2$. In contrast, a small scale cut-off due to black holes in the final state would be a strong signature. One might argue that for $M_f > 5$TeV this signature would be difficult to measure, too. This is not necessarily true, since a small scale cut-off corresponds to a black hole in the final state, which radiates off quanta at Temperatures $T_H \sim M_f(M_f/M)^{1/(d+1)}$. The process of evaporation can result in a bump of the standard cross section for jet production at much lower energies $E \sim T_H$. The previous discussion will be given in detail in a forthcoming publication [10].

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 entropy S of a black hole is given by its surface area. In the case under consideration $S \sim \Omega_{(2+d)}\ R_H^{2+d}$. The single particle spectrum of the emitted quanta in the microcanonical ensemble is then [11]

$$n(\omega) = \frac{\exp[S(M-\omega)]}{\exp[S(M)]} \quad . \tag{7}$$

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.

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,

$$\dot{M} = -\mathcal{A}_D\ \frac{\Omega_{(2+d)}}{(2\pi)^{3+d}} \int_0^M \mathrm{d}\omega \sum_{j=1}^{(M/\omega)} \omega^{D-1} n(j\omega) \quad . \tag{8}$$

Neglecting finite size effects eq.(8) becomes

$$\dot{M} = \mathcal{A}_D\ \frac{\Omega_{(2+d)}}{(2\pi)^{3+d}}\ \mathrm{e}^{-S(M)} \sum_{j=1}^{\infty} \left(\frac{1}{j}\right)^D \int_M^{(1-j)M} \mathrm{d}x\ (M-x)^{D-1} \mathrm{e}^{S(x)} \Theta(x) \quad , \tag{9}$$

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

$$\dot{M} = \mathcal{A}_D\ \frac{\Omega_{(2+d)}}{(2\pi)^{3+d}}\ \zeta(D) \int_0^M \mathrm{d}x\ (M-x)^{D-1} \mathrm{e}^{S(x)-S(M)} \ . \tag{10}$$

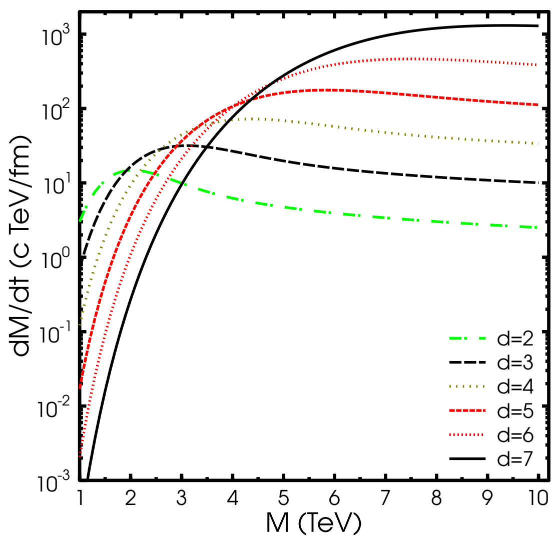

FIG. 2. Decay rate in TeV/fm as a function of the initial mass of the black hole [15]. Different line styles correspond to different numbers of extra dimensions d.

Fig. 2 shows the decay rate (10) in TeV/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 stabilising the black hole, too.

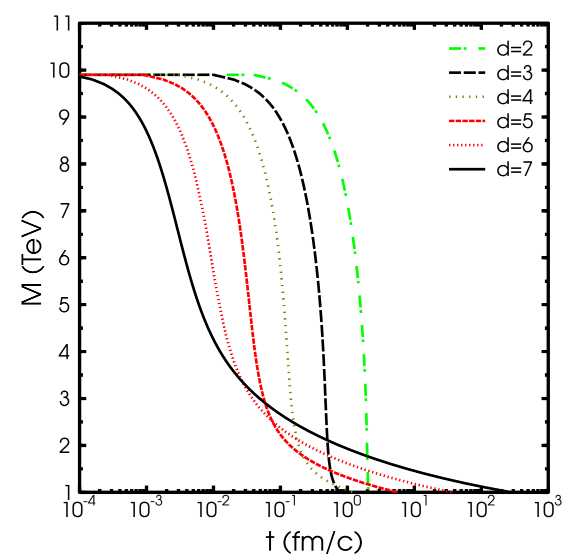

FIG. 3. Time evolution of a black hole [15]. Different line styles correspond to different numbers of extra dimensions d.

From (10) 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 exists for ~ 100 fm/c (for $d > 5$). Afterwards the mass of the black hole drops below the fundamental 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.

Therefore, it is interesting to study the in medium modification of the BH's evaporation rate (11). In general the evaporation rate becomes

$$\dot{M} = \dot{M}_{\rm loss} + \dot{M}_{\rm gain}$$

The loss term describes the evaporation rate which receives contributions from the production of Kaluza-Klein states and Standard Model particles. The Kaluza-Klein states will be radiated into the $(3+d)$-dimensional space while Standard Model particles are produced on our brane only. In the following we assume that most of the emitted quanta will be localised on our 3-brane. The gain term takes into account the absorption of medium particles on our brane.

An illustrative application is a medium with a homogeneous energy density ρ on our brane which is constant in time. The evaporation rate vanishes for

$$\rho \approx 10^4 \left(\frac{M_f}{\rm GeV}\right)^2 \left(\frac{M_f}{M}\right)^{\frac{2}{1+d}} \frac{\rm GeV}{\rm fm^3}\ , \tag{11}$$

which is 10^9 times the energy density of the quark gluon plasma for $M_f = 1$TeV and $M \approx 10 M_f$. In turn, if the density of the medium corresponds to the energy density of the quark gluon plasma, the evaporation rate vanishes for an initial mass of the black hole of $M \approx 10^{18}$GeV.

One particular interesting scenario is the evaporation of black holes in the early universe. The medium is then provided by the total cosmic fluid density ρ. The standard cosmological evolution is rediscovered from the brane world scenario whenever $\rho/m_{\rm P}^2$ is large compared to $(M_f^{2+d}/m_{\rm P}^2)^{(2/d)}$, so that the early time cosmology is analogous to standard cosmology. In this early phase the cosmic evolution is given by the standard Friedmann equation in $D=4$, $H^2 \sim \rho/3m_{\rm P}^2$. Thus,

$$\dot{M}_{\rm gain} \approx \left(\frac{M}{M_f}\right)^{\frac{2}{1+d}} \left(\frac{m_{\rm P}}{M_f}\right)^2 H^2\ . \tag{12}$$

The black hole stops evaporating due to the gain of energy from in-falling medium particles. For $T > 1$TeV this happens when the following relation for the mass of the black hole and the temperature of the cosmic fluid holds:

$$\frac{M(t)}{M_f} \approx \frac{10}{g_*(t)} \left(\frac{M_f}{\rm GeV}\right)^{1+d} \left(\frac{\rm GeV}{T(t)}\right)^{2+2d}\ , \tag{13}$$

where g_* counts the effective degrees of freedom of all relativistic particles. The relevance of in-medium modifications of the evaporation process for early universe physics will be explored in a forthcoming publication [14] in more detail.

In conclusion, we have predicted the momentum distribution of black holes in space-times with LXDs. We discussed the high P_T suppression of jets due to the formation of black holes in the final state as a clear signature for extra dimensions. We compared this observable to the jet plus missing energy signature proposed by ATLAS. The high P_T suppression shows up as a sharp cut-off in $\sigma(\text{pp}\to\text{jet}+X)$ in contrast to a rather smooth decrease caused by gravitons in the final state. Using the micro canonical ensemble we calculated the decay rate of black holes neglecting finite size effects. If statistical mechanics is still valid below the fundamental scale M_f, the black holes may be quasi-stable. In the scenarios ($M_f \sim$ TeV, $d > 5$) the lifetime is of order 100 fm/c. This motivated the study of in-medium modifications of the black hole evaporation rate. We estimated the evaporation rate for a black hole surrounded by a homogeneous energy density which is constant in time and for a black hole in the early universe.

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