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Tevatron—probing TeV-scale gravity today

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Abstract

The production of black holes at Tevatron and LHC in spacetimes with compactified space-like large extra dimensions is studied. Either black holes can already be observed in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV or the fundamental gravity scale has to be above 1.4 TeV. At LHC the creation of a large number of quasi-stable black holes is predicted, with lifetimes beyond several hundred fm/c.

A cut-off in the high-P_T jet cross section is shown to be a unique signature of black hole production. 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.

1. Introduction

A major 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, 2]. In these scenarios the standard model of particle physics is localized on a three-dimensional brane in a higher dimensional space with large compactified space-like large extra dimensions (LXD). 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 the non-compact dimensions. This raises the exciting possibility that the fundamental scale of gravity M_f could be as low as m_W.

As a consequence, future high energy colliders such as the LHC, TESLA or CLIC could probe the fundamental scale of quantum gravity. At this scale short distance physics is dominated by two basic effects:

- Firstly, gravitons will couple to all standard model particles. This leads, for instance, to graviton production in the final states of parton–parton collisions. Final state gravitons result in a jet or photon plus the missing energy signature, i.e. a suppression of $\sigma(\mathrm{pp} \to \mathrm{jet})$ at high P_T depending on M_f, see, e.g., [3].
- Secondly, the probability of producing a black hole in the final state of a parton–parton collision is enhanced by a factor of at least 10^{32} [4, 5]. Black hole production induced by gravitational collapse hides all distance scales smaller than $1/M_f$ and also results in a suppression of high-P_T jets [6, 7].

In competition with future collider physics, the possibility of black hole production from cosmic rays has recently received great attention [8]. However, the experimental bound on M_f in the presently discussed scenarios from the absence of missing energy signatures are rather low: $M_f \geqslant 0.8$ TeV for $d \in \{2, 3, 4, 5, 6\}$ large extra dimensions [9–11][4]. Therefore, a first glimpse towards the fundamental scale of quantum gravity might even be possible with *today's* Tevatron.

The paper is organized as follows. In section 2 we quote the spherical symmetric Schwarzschild solution in D-dimensional spacetimes. In section 3 we investigate whether black hole production might already be observed at Tevatron. The number and Feynman x distribution of black holes produced at Tevatron and LHC are predicted. In section 4 we study the time development of black holes produced in collider experiments. In section 5 we compare final state graviton production and black hole formation in parton–parton collisions.

2. Preliminaries

Let us first characterize black holes in spacetimes with LXDs. We can consider two cases. First, the size of the black hole given by its Schwarzschild radius is $R_H \gg L$. In this case the topology of the horizon is $S(3) \times U(1) \times U(1) \times \cdots$, where $S(3)$ denotes the three dimensional sphere and $U(1)$ the Kaluza–Klein compactification. Secondly, 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 $L \approx (1\,\mathrm{TeV}/M_f)^{1+\frac{2}{d}} 10^{\frac{31}{d}-16}$ mm, M_c is typically of the order of the Earth's mass. As we are interested in black holes produced in parton–parton collisions with a maximum centre-of-mass (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 [13] 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 potential in a spacetime with d compactified extra dimensions

$$V(r) = \left(\frac{2}{2+d}\right)\left(\frac{\Omega_{(2)}}{\Omega_{(2+d)}}\right)\left(\frac{1}{M_f}\right)^{2+d}\frac{1}{L^d}\frac{M}{r} \tag{3}$$

[4] The limits imposed by the cosmic evolution are more stringent, see, e.g., [12].

equals the four-dimensional Newton potential. Note that 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 spacetime [13]. Note that in order to partially fix the coordinate invariance the harmonic gauge condition is imposed. In this way the horizon radius is obtained as

$$R_H^{1+d} = \left(\frac{4}{2+d}\right)\left(\frac{\Omega_{(2)}}{\Omega_{(2+d)}}\right)\left(\frac{1}{M_f}\right)^{2+d} M, \tag{5}$$

with M denoting the black hole mass.

3. Production of black holes

Let us now investigate the production rate of these black holes at future and existing colliders. Since no fundamental S-matrix theory for parton–parton interactions with a black hole in the final state exists, we will consider the following model. 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 $\sigma(M) \approx \pi R_H^2$[14, 15]. This expression contains only the fundamental scale M_f as a coupling constant. The classical estimate of the black hole production cross section is still in discussion, see, e.g., [15, 16]. However, the maximal uncertainty in the cross section is of a factor 10^{-1}[17].

In a pp-collision one has to take into account that each parton carries only a fraction of the total cms energy. An important quantity is therefore the Feynman x distribution of black holes for masses $M \in [M_f, \sqrt{s}]$[5] given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_F} = \int_M \mathrm{d}y \sum_{p_1, p_2} \frac{2y}{x_1 s} f_1\big(x_1, Q^2\big) f_2\big(x_2, Q^2\big) \sigma(y, d), \tag{6}$$

with $x_F = x_2 - x_1$ and the restriction $x_1 x_2 s = M^2$. Here the CTEQ4 [18] parton distribution functions f_1, f_2 with $Q^2 = M^2$ are employed. All kinematic combinations of partons from projectile p_1 and target p_2 are summed over.

Figure 1 (left) depicts the momentum distribution of black holes produced in $\bar{p}p$-collisions at Tevatron energies $\sqrt{s} = 1.8$ TeV. Most black holes are formed in scattering processes of valence quarks and are of lowest mass $M \approx M_f$. Since the cross section varies only around 10% for different numbers d of large extra dimensions, we only show the result for $d = 4$.

Figure 1 (right) depicts the integrated production cross section of black holes (full line) at Tevatron as a function of the fundamental scale M_f. A strong dependence on the fundamental gravity scale M_f is observed. For the lowest possible $M_f \approx 0.8$ TeV from the absence of missing energy signatures, significant black hole production in p̄p-collisions at $\sqrt{s} \approx 1.8$ TeV is predicted. For higher values of M_f the production of black holes at the Tevatron is strongly suppressed. Using an integrated luminosity of 10 fb^{-1} per year and optimistic estimates of M_f, one expects an abundance of black holes produced at Tevatron. Even up to scales of

[5] At LHC energies, the maximum of black hole masses is set to $M = 10$ TeV, due to the limits imposed by the chosen set of PDFs. However, since the production of high mass black holes is strongly suppressed, this restriction is negligible.

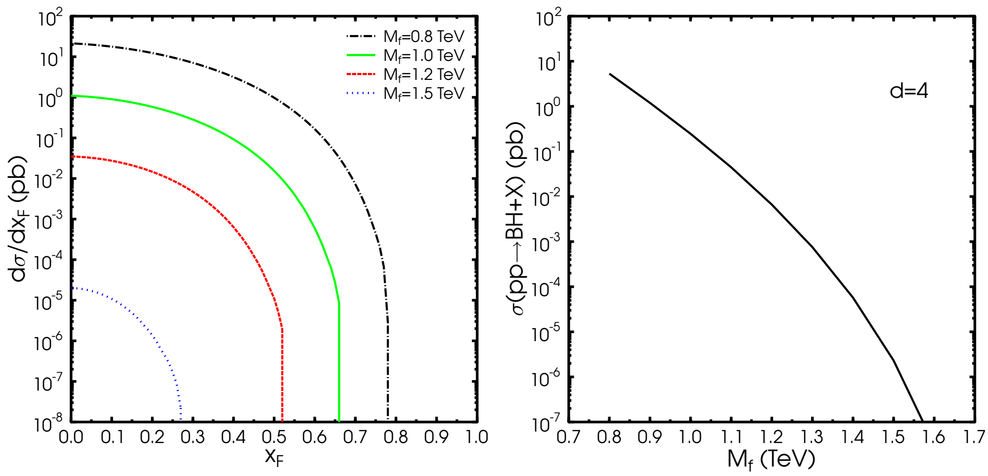

Figure 1. Left: Feynman x distribution of black holes with $M \geqslant M_f$ produced in pp-collisions at the Tevatron with four compactified spatial extra dimensions. Different curves correspond to $M_f = 0.8, 1.0, 1.2, 1.5$ TeV (increasing from top to bottom) [19]. Right: integrated black hole production cross section in four extra dimensions at Tevatron ($\bar{\text{p}}\text{p}@\sqrt{s} = 1.8$ TeV) as a function of the fundamental scale M_f [19].

$M_f \approx 1.4$ TeV signals of black hole production might still be detectable in past- or present-day experimental data.

Let us now turn to the momentum distribution of the produced black holes in pp-interactions at LHC energies $\sqrt{s} = 14$ TeV as shown in figure 2 (left). Heavy quarks still give a vanishing contribution to the black hole production cross section. Black holes are still primarily formed in scattering processes of valence quarks.

The total cross section of black hole formation as a function of the fundamental scale M_f is depicted in figure 2 (right). In contrast to the Tevatron, the LHC is able to explore new physics up to a fundamental scale of $M_f \approx 10$ TeV. This new physics might also lead to the creation of multi-dimensional objects in colliders (p-branes) in competition with black hole (0-brane) production. The cross section of p-brane production [20] has been recently estimated to be up to a factor of 100 larger compared to the 0-brane formation discussed here.

4. Evaporation of black holes

Let us now investigate the evaporation of black holes with $R_H \ll L$ and study the influence of compact extra dimensions on the statistics of 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 $S \sim M_f^{2+d}\Omega_{(2+d)}R_H^{2+d}$. The single particle spectrum of the emitted quanta in the microcanonical ensemble is then [21]

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

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 [22].

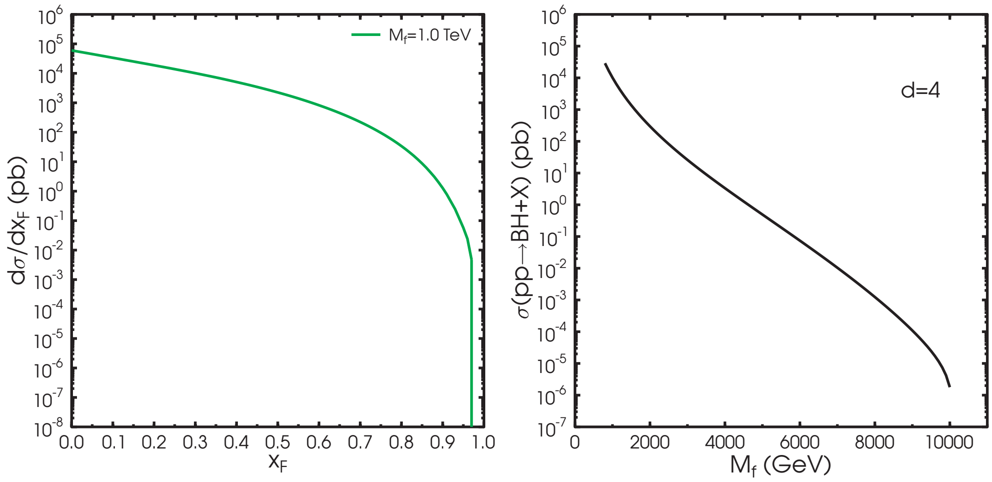

Figure 2. Left: Feynman x distribution of black holes with $M \geqslant 1$ TeV produced in pp-interactions at LHC with four compactified spatial extra dimensions [5]. Right: integrated black hole production cross section in four extra dimensions at LHC (pp @ $\sqrt{s} = 14$ TeV) as a function of the fundamental scale M_f.

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,

$$\dot{M} = -\mathcal{A}_D \int_0^M \mathrm{d}\omega \sum_{j=1}^{(M/\omega)} \omega^{D-1} n(j\omega). \tag{8}$$

Neglecting finite size effects, equation (8) becomes

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

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 led to the interpretation that the black hole emits only a single quanta per energy interval. We finally arrive at

$$\dot{M} = \mathcal{A}_D \zeta(D) \int_0^M \mathrm{d}x\, (M-x)^{D-1}\, \mathrm{e}^{S(x)-S(M)}. \tag{10}$$

Figure 3 shows the decay rate (10) in GeV fm^{-1} as a function of the initial mass of the black hole. The decay rate shows the expected behaviour, i.e. the heavier a black hole the more stable it is against decay. Since the temperature T_H of the black hole decreases as $M^{-1/(1+d)}$ it is evident that extra dimensions help in stabilizing the black hole, too.

From (10) one directly calculates the time evolution of a black hole with given mass M. The result is depicted in figure 4 for different numbers of compactified space-like extra dimensions. As can be seen, extra dimensions dramatically increase the lifetimes of black holes. For $M = 10$ TeV the calculation predicts decay times of up to 500 fm/c. Later, 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 were the case it seems that after dropping below M_f a quasi-stable remnant remains.

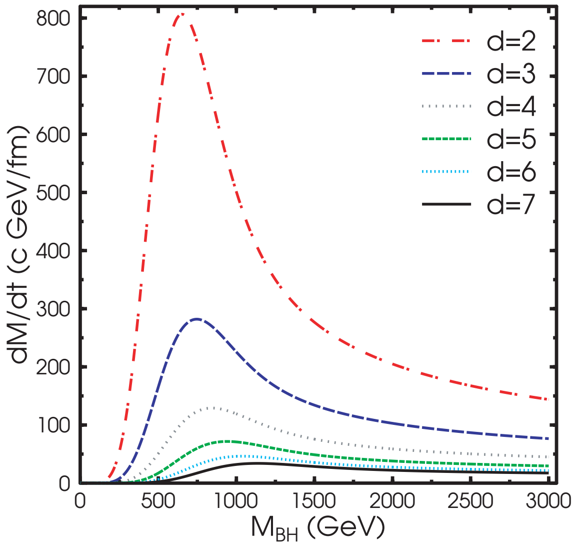

Figure 3. Decay rate in GeV fm^{-1} as a function of the initial mass of the black hole [5]. Different line styles correspond to different numbers of extra dimensions d.

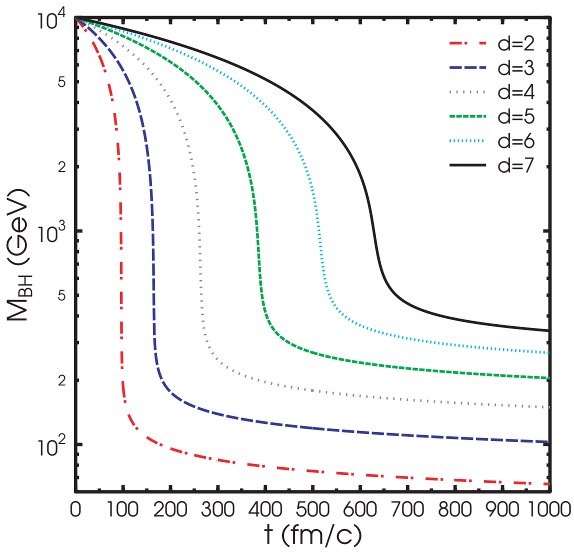

Figure 4. Time evolution of a black hole [5]. Different line styles correspond to different numbers of extra dimensions d.

5. Signatures

Up to energy scales of $M_f \approx 1.4$ TeV signals of black hole creation might be observed in present (Tevatron) or future (LHC, TESLA, CLIC) experimental data. 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 $\sigma(\mathrm{pp} \to \mathrm{jet} + X)$ as a function of the transverse jet energy at $E_T \sim M_f$. The cut-off on transverse momentum due to black hole production at the Tevatron

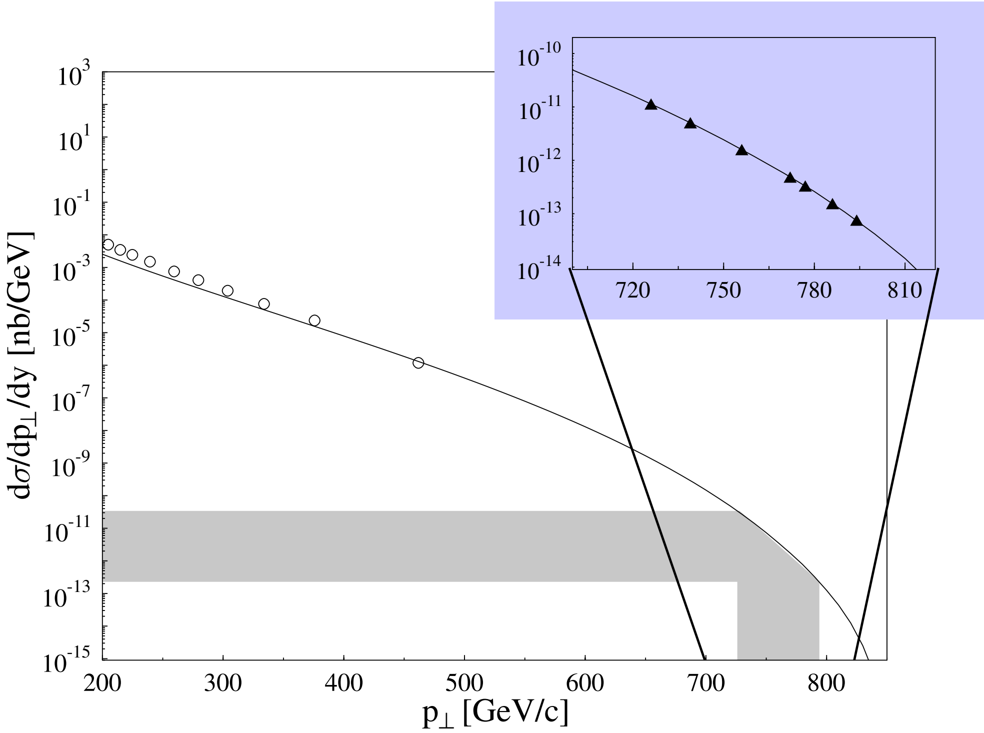

Figure 5. Main figure: invariant transverse momentum spectrum of the jet production cross section in $\bar{p}p$ at $\sqrt{s} = 1.8$ TeV. Data are denoted by circles. The line represents a leading order pQCD calculation. Small figure: zoom in of the distribution. The triangles depict the $p_\perp$ cut-offs depending on the number of extra dimensions for $M_f = 0.8$ TeV.

is demonstrated in figure 5: the total jet production cross section up to 400 GeV in $p_\perp$ is unchanged compared to the QCD predictions (cf the experimental data). One observes a sharp cut-off around 700–800 GeV in $p_\perp$ depending on the number of extra dimensions (denoted by the triangles in the small figure in figure 5).

A different extra-dimensional signature occurring in the same process was discussed in an ATLAS proposal [3]. The authors of this proposal found for specific model parameters a significant decrease in $\sigma(\mathrm{pp} \to \mathrm{jet} + X)$ at $E_T \sim M_f$ due to gravitons G in the final states. This effect is somehow contra-intuitive since the coupling of any Kaluza–Klein state to our brane is still suppressed by $1/m_{\mathrm{P}}^2$. For instance, the total cross section [23] for the subprocess $\mathrm{q}\bar{\mathrm{q}} \to \gamma\mathrm{G}$ is of order $\sigma(\mathrm{q}\bar{\mathrm{q}} \to \gamma\mathrm{G}) \sim \alpha_s/m_{\mathrm{P}}^2 N(\sqrt{\hat{s}})$, 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 quantized 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, $\sigma(\mathrm{q}\bar{\mathrm{q}} \to \gamma\mathrm{G}) \sim \alpha_s/M_f^2(\sqrt{\hat{s}}/M_f)^d$.

Hence, the total cross section rapidly increases with the cms energy of the partons 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 for $M_f > 5$ TeV is 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 an increase in 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 paper [24].

6. Conclusions

The production cross section and yield of black holes per year at Tevatron is calculated as a function of M_f. For $M_f \leqslant 1.4$ TeV signals of black hole creation might be observable in past or present experimental data. If no signals are discovered, the fundamental scale M_f is at least 1.4 TeV.

- For the lowest possible $M_f = 0.8$ TeV (allowed by the absence of missing energy signatures), approximately 10^5 black holes per year might already be produced at Tevatron.
- Within the microcanonical formalism it is shown that for a black hole with an initial mass of 10 TeV the lifetime may exceed 500 fm/c.
- As a characteristic signature for black hole production we predict a sharp high-P_T cut-off in the jet production cross section since short distance physics on scales below $1/M_f$ are hidden behind the horizon of the black hole.

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