Black Hole Production in Large Extra Dimensions at the Tevatron: Possibility for a First Glimpse on TeV Scale Gravity

Marcus Bleicher‡, Stefan Hofmann†, Sabine Hossenfelder†, Horst Stöcker†
‡ *SUBATECH, Laboratoire de Physique Subatomique et des Technologies Associées*
University of Nantes - IN2P3/CNRS - Ecole des Mines de Nantes
4 rue Alfred Kastler, F-44072 Nantes, Cedex 03, France
† *Institut für Theoretische Physik*
J. W. Goethe Universität
60054 Frankfurt am Main, Germany

The production of black holes in large extra dimensions is studied for Tevatron energies. We find that black holes may have already been created in small abundance in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. For the next Tevatron run ($\sqrt{s} = 2.0$ TeV) large production rates for black holes are predicted.

Recently the possibility of black hole production in large extra dimension (LXD) at LHC and from cosmic rays has received great attention [1–11]. In these LXD scenarios [12] the Standard Model of particle physics is localized on a three dimensional brane in a higher dimensional space. 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. The fundamental $D = 4 + d$ dimensional scale M_f is then connected to the 4 dimensional Planck scale $M_{\rm Pl}$ via [12]

$$M_{\rm Pl}^2 = M_f^{2+d} V_d \quad . \tag{1}$$

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, CLIC or TESLA could probe the scale of quantum gravity with its exciting new phenomena, namely the production of black holes in high energetic interactions (for LHC energies see [3]). However, the experimental bounds on the Planck mass in the presently discussed scenarios from absence of missing energy signatures is much lower: $M_f \geq 0.8$ TeV for two to six extra dimensions [13–15]. Astrophysical bounds seem to be more stringent and require fundamental scales of order 10-100 TeV for two extra dimensions, larger limits might also be advocated by direct measurements of Newtons law in the sub-millimeter region or proton stability. However, those limits can be overcome by increasing the number of extra dimension or invoking additional theoretical assumptions (for a discussion see e.g. [16]). Thus, we will consider only the well known collider bounds on M_f as limits for our present investigation.

In this letter we investigate whether a first glimpse on a (sub-)TeV scale gravity associated with black hole production might already be observable at the Tevatron. As discussed elsewhere (see e.g. [17,3,4]) the horizon radius of a black hole is given by

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

with M denoting the black hole mass. The production rate black holes is classically given by [1,18,19][1] $\sigma(M) \approx \pi R_H^2$.

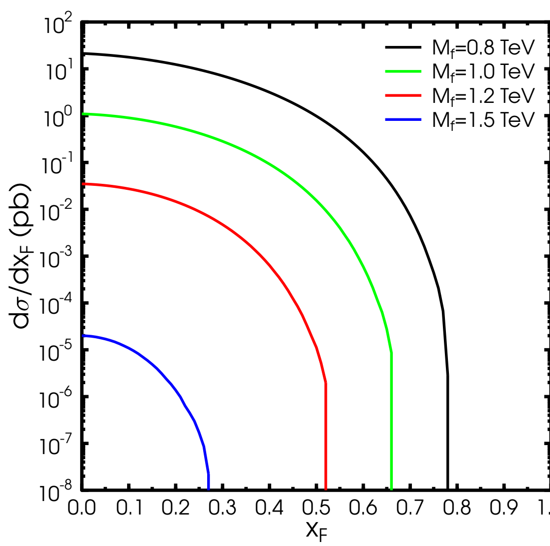

FIG. 1. Feynman x distribution of black holes with $M \geq M_f$ TeV produced in pp interactions at the Tevatron ($\sqrt{s} = 1.8$ TeV) with four compactified spatial extra dimensions and different fundamental scales M_f=0.8 TeV, 1.0 TeV, 1.2 TeV and 1.5 TeV (from top to bottom).

[1] Note that the given classical estimate of the black hole production cross section is still under debate [20,19]. However, for the present calculations the maximal suppression in the cross section is by a factor 10^{-1} [21], which does not invalidate the present arguments.

Since a theory of quantum gravity is still not known, the formation of black holes with masses of the order of the fundamental scale can not be justified from first principles. However, in the following we assume the applicability of classical gravity. As a consequence our predictions are order of magnitude estimates for the most optimistic physical scenario. We will also neglect complications due to the finite angular momentum of the black hole and assume non-spinning black holes (roughly a factor two uncertainty). The influence of finite angular momentum on the formation and evaporation process of black holes is studied in [8,22]. With these assumptions we ask whether black holes might already have been created at the Tevatron in Run I and predict their formation cross section for Run II.

By standard methods, the Feynman x_F distribution of black holes for masses from $M \in [M_f, \sqrt{s} = 1.8$ TeV] is given by

$$\frac{d\sigma}{dx_F} = \sum_{p_1,p_2} \int_{M_f}^{\sqrt{s}} dy \tag{3}$$

$$\frac{2y}{x_1 s} f_1(x_1, Q^2) f_2(x_2, Q^2) \sigma(y, d) \;, \tag{4}$$

with $x_F = x_2 - x_1$ and the restriction $x_1 x_2 s = M^2$. Where the CTEQ4 [23] parton distribution functions f_1, f_2 with $Q^2 = M^2$ are used. All kinematic combinations of partons from projectile p_1 and target p_2 are summed over.

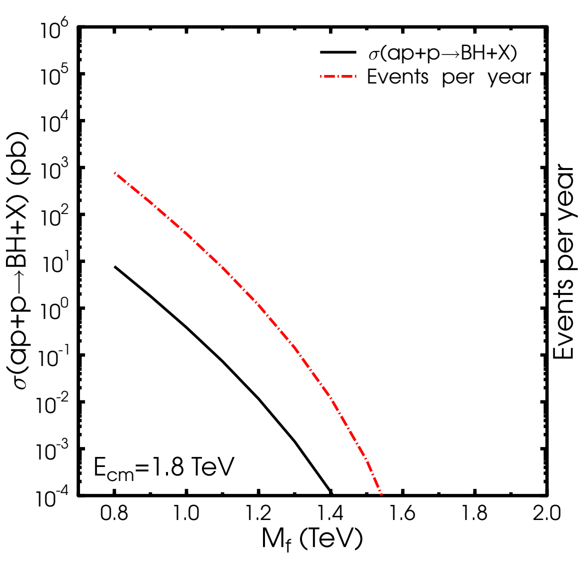

FIG. 2. Black hole production cross section (full line) and black hole yield per year (dashed line) at Tevatron as a function of the fundamental scale M_f for $d = 4$ extra dimensions, $\sqrt{s} = 1.8$ TeV, $\mathcal{L} = 100$ pb^{-1}.

Fig. 1 depicts the momentum distribution of produced black holes in pp interactions at $\sqrt{s} = 1.8$ TeV. Most black holes are of lowest mass ($M_{\rm BH} \approx M_f$) and are formed in scattering processes of valence quarks. Here we show the result for $d = 4$ extra spatial extra dimensions. A strong dependence on the fundamental gravity scale M_f is observed. For the lowest possible $M_f \approx 800$ GeV, significant black hole production in $\overline{p}p$ at $\sqrt{s} = 1.8$ TeV is predicted. Higher fundamental scales suppress the production of black holes at the Tevatron strongly.

Fig. 2 shows the production cross section for black holes as a function of the fundamental scale M_f (full line). Using an integrated luminosity of 100 pb^{-1} per year, the dashed line gives the expected abundance of black holes produced at Tevatron per year. For most optimistic values of $M_f \approx 0.8 - 1.2$ TeV signals of black hole creation might have be observable in past or present day experimental data.

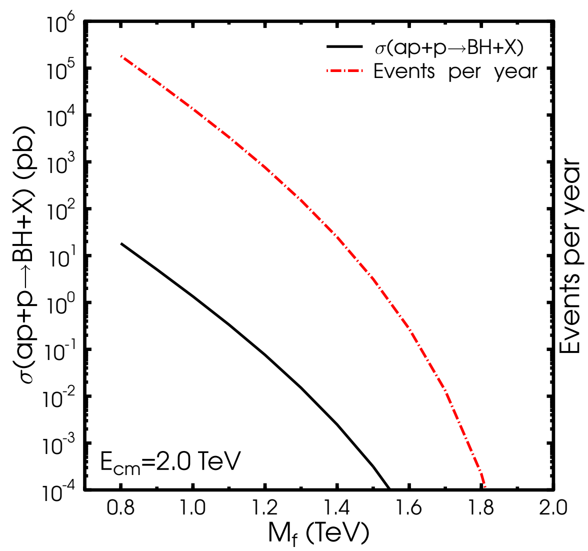

FIG. 3. Black hole production cross section (full line) and black hole yield per year (dashed line) at Tevatron as a function of the fundamental scale M_f for $d = 4$ extra dimensions, $\sqrt{s} = 2.0$ TeV, $\mathcal{L} = 10$ fb^{-1}.

With the update of the Tevatron for Run II higher luminosities at an increased center of mass energy ($p\overline{p}$ at $\sqrt{s} = 2.0$ TeV) are available. Prediction of black hole creation cross sections for these runs are shown in Fig. 3 as a function of the fundamental scale M_f (full line). Here, an integrated luminosity of 10 fb^{-1} per year is expected, which translates into a huge abundance of black holes produced at Tevatron per year (dashed line). If the fundamental scale of gravity is M_f is below[2] ≈ 1.5 TeV,

[2]The actual identification of a black hole is a difficult task: detailed studies about the signal characteristics, backgrounds and experimental cuts are necessary. For the lightest black

first signals of black hole creation might be observed at Tevatron before the start of LHC.

Note that it has been argued whether it is possible to observe the emission spectrum of a black hole directly, since most of the energy maybe 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 [24]. The life time of the black holes is predicted to be ≈ 10 fm/c [4]. It can be observed by the emission of multiple jets with energies of $\approx 100 - 150$ GeV or might even produce new kinds of elementary particles [11].

In conclusion, the production cross section and the momentum distribution of black holes in space times with large and compact extra dimensions has been discussed. It has been demonstrated that for most optimistic values for the mass scale of quantum gravity, a first glimpse on black hole production might be possible from todays Tevatron ($\sqrt{s} = 1.8$ TeV) data. For the Run II ($\sqrt{s} = 2.0$ TeV) the calculation predicts the production of several thousand black holes per year, if the fundamental scale M_f is not too high. This might make the study of TeV scale gravity experimentally accessible long before the start of LHC.

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holes discussed here this is even theoretically difficult, without further knowledge of the quantum theory of gravity. It is clearly out of the scope of this letter and will be neglected here.

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