Black Hole Production and Large Extra Dimensions

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Black hole (BH) production at colliders is possible when the colliding energy is above the Planck scale, which can effectively be at TeV scale in models of large extra dimensions. In this work, we study the production of black holes at colliders and discuss the possible signatures. We point out the “\(ij \rightarrow BH + \text{others}\)” subprocesses, in which the BH and other standard-model particles are produced with a large transverse momentum. When the BH decays, it gives a signature that consists of particles of high multiplicity in a boosted spherical shape on one side of the event and a few numbers of high \(p_T\) partons on the other side, which provide very useful tags for the event.

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Introduction.—Black holes (BHs) have been illusive objects for decades, as we cannot directly measure any of their properties, not to mention the lack of production of black holes in any terrestrial experiments. This is due to the fact that in order to produce black holes in collider experiments one needs a center-of-mass energy above the Planck scale \((M_P \sim 10^{19} \text{ GeV})\), which is obviously inaccessible at present.

Since the second revolution of string theories, a crop of models with extra dimensions have been proposed to solve various theoretical problems. In an attractive model of large extra dimensions or TeV quantum gravity [1], the effective Planck scale can be as low as a few TeV. This is made possible by localizing the standard model (SM) particles on a brane (using the idea of D-branes in type I or II string theory), while gravity is free to propagate in all dimensions.

In such models, the properties of black holes are modified and interesting signatures emerge [2–4]. The fact that the effective Planck scale is as low as TeV also opens up an interesting possibility of producing a large number of black holes at collider experiments (e.g., LHC) [5,6]. Reference [4] showed that a BH localized on a brane will radiate mainly in the brane, instead of radiating into the Kaluza-Klein states of gravitons of the bulk. In this case, the BH so produced will decay mainly into the SM particles, which can then be detected. This opportunity has enabled investigation of the properties of BH at terrestrial collider experiments.

A black hole is characterized by its Schwarzschild radius \(R_{\text{BH}}\), which depends on the mass \(M_{\text{BH}}\) of the BH. A simplified picture for BH production is as follows. When the colliding partons have a center-of-mass (c.m.) energy above some thresholds of order of the Planck mass and the impact parameter less than the Schwarzschild radius \(R_{\text{BH}}\), a BH is formed and is almost at rest in the c.m. frame. The BH so produced will decay thermally (regardless of the incoming particles) and thus isotropically in that frame.

This possibility has been investigated in a few recent works at the LHC [5–8], and at cosmic ray experiments [9–11]. In Refs. [5–7] black hole production in hadronic collisions is calculated in \(2 \rightarrow 1\) subprocesses: \(ij \rightarrow BH\), where \(i, j\) are incoming partons. The black hole so produced is either at rest or traveling along the beam pipe such that its decay products (of high multiplicity) have a zero net transverse momentum \((p_T)\). Giddings and Thomas [5] and Dimopoulos and Landsberg [6] demonstrated that a BH so produced will decay with a high multiplicity. Banks and Fischler [3] pointed out that one of the most striking signatures of BH production is a complete cutoff of process with \(p_T\) larger than \(R_{\text{BH}}^{-1}\) because the incoming partons can never get close enough to perform an extremely hard QCD scattering.

In this Letter, we point out the “\(ij \rightarrow BH + \text{others}\)” subprocesses, such that the BH is produced with a large \(p_T\) before it decays. In such subprocesses, the “others” are just the ordinary SM particles and usually of much lower multiplicity than the decay products of the BH. Therefore, the signature would be very striking: On one side of the event there are particles of high multiplicity (from the decay of the BH), the total \(p_T\) of which is balanced by fewer particles on the other side. Such a signature is very clean and should have very few backgrounds.

The \(ij \rightarrow BH + \text{others}\) subprocesses can easily be formed when the c.m. energy of the colliding particles are larger than the BH mass; the excess energy will be radiated as other SM particles. Thus, a picture of \(ij \rightarrow BH + \text{others}\) is justified. Besides, such processes are of immense interest because they involve qualitatively new phenomena, e.g., violation of global quantum (lepton, baryon) numbers. The resulting cross section is large enough for detection. Even at \(p_T > 500\) GeV the production cross section is as large as 24 fb for \(n = 4, M_D = 1.5\) TeV, and \(y = (M_{\text{BH}})_{\text{min}}/M_D = 5\) (a BH with a mass \(\sim 7.5\) TeV), which gives 2400 clean events for an integrated luminosity of 100 fb\(^{-1}\) at the LHC, as will be shown later. The event rate is still large enough for detection. Here we have imposed a very restricted requirement on the BH entropy \((S_{\text{BH}} \sim 25)\) to ensure the validity of the classical BH description. Otherwise, if we relaxed this entropy constraint, the production cross sections would be increased tremendously, but the cross sections have to
be interpreted with care because of the presence of large string effects in this regime.

Production.—The Schwarzschild radius $R_{\text{BH}}$ of a BH of mass $M_{\text{BH}}$ in $4 + n$ dimensions is given by \cite{12}

$$R_{\text{BH}} = \frac{1}{M_D} \left( \frac{M_{\text{BH}}}{M_D} \right)^{1/(n+1)} \left( \frac{2^n \pi^{(n-3)/2} \Gamma\left(\frac{n+3}{2}\right)}{n + 2} \right)^{1/(n+1)},$$

(1)

where $M_D$ is the effective Planck scale in the model of large extra dimensions defined by

$$M_{D}^{n+2} = \frac{(2\pi)^{n}}{8 \pi G_{4+n}},$$

(2)

where $G_{4+n}$ is the gravitational constant in $D = 4 + n$ dimensions (used in the Einstein equation: $R_{AB} - \frac{1}{2} g_{AB} R = -8\pi G_{4+n} T_{AB}$). The radius is much smaller than the size of the extra dimensions. BH production is expected when the colliding partons with a center-of-mass energy $\sqrt{s} \approx M_{\text{BH}}$ pass within a distance less than $R_{\text{BH}}$. A black hole of mass $M_{\text{BH}}$ is formed and the rest of the energy, if there is any, is radiated as ordinary SM particles. This semiclassical argument calls for a geometric approximation for the cross section for producing a BH of mass $M_{\text{BH}}$ as

$$\sigma(M_{\text{BH}}^2) \approx \pi R_{\text{BH}}^2.$$  \hspace{1cm} (3)

In the $2 \to 1$ subprocess, the c.m. energy of the colliding partons is just the same as the mass of the BH, i.e., $\sqrt{s} = M_{\text{BH}}$, which implies a subprocess cross section

$$\hat{\sigma}(\hat{s}) = \int \frac{d(M_{\text{BH}}^2)}{\hat{s}} \pi R_{\text{BH}}^2 \delta(1 - M_{\text{BH}}^2/\hat{s}) = \pi R_{\text{BH}}^2.$$  \hspace{1cm} (4)

On the other hand, for the $2 \to k (k \geq 2)$ subprocesses, the subprocess cross section is

$$\hat{\sigma}(\hat{s}) = \int_{(M_{\text{BH}})_{\text{min}}/\hat{s}}^{1} d(M_{\text{BH}}^2) \pi R_{\text{BH}}^2.$$  \hspace{1cm} (5)

Another important quantity that characterizes a BH is its entropy given by

$$S_{\text{BH}} = \frac{4\pi}{n + 2} \left( \frac{M_{\text{BH}}}{M_D} \right)^{\frac{(n+2)}{(n+1)}}$$

$$\times \left( \frac{2^n \pi^{(n-3)/2} \Gamma\left(\frac{n+3}{2}\right)}{n + 2} \right)^{1/(n+1)}.$$  \hspace{1cm} (6)

To ensure the validity of the above classical description of BH \cite{13}, the entropy must be sufficiently large, of order 25 or so. We verified that when $M_{\text{BH}}/M_D \gg 5$, the entropy $S_{\text{BH}} \approx 25$, and below that string effects are important. Therefore, to avoid getting into the nonperturbative regime of the BH and to ensure the validity of the semiclassical formula, we restrict the mass of the BH to be $M_{\text{BH}} > yM_D$, where $y = (M_{\text{BH}})_{\text{min}}/M_D$ is of order 5.

Voloshin \cite{8} pointed out that the semiclassical argument for the BH production cross section is not given by the geometrical cross section area, but, instead, suppressed by an exponential factor:

$$\exp\left(-\frac{S_{\text{BH}}}{n+1}\right).$$  \hspace{1cm} (7)

The suppression factor makes the production of the BH concentrate on $M_{\text{BH}}$ close to $M_D$. Thus, if the available energy in the collision is larger than the $M_D$ the rest of the energy is more likely to radiate as the SM particles. There are, however, counterarguments \cite{13,14} that the simple geometric formula should be valid. (There is also a counter-counter argument from Voloshin \cite{15}. Nevertheless, before the issue is resolved we present the results with and without the suppression factor.)

In this work, we first consider both forms of cross sections: (i) the naive $\pi R_{\text{BH}}^2$ and (ii) the $\pi R_{\text{BH}}^2$ multiplied with the exponential factor of Eq. (7). But we shall see immediately that the suppression factor renders the cross section to be too small for detection. In Fig. 1, we show the differential cross section $d\sigma/dM_{\text{BH}}$ for the process $pp \to BH + 1$ parton at the LHC for $n = 4$, $y = (M_{\text{BH}})_{\text{min}}/M_D = 5$, and $M_D = 1.5$ TeV, which is consistent with the existing limit on $M_D$ \cite{16}. We can see that when the exponential suppression factor is used, the spectrum of $M_{\text{BH}}$ will shift closer to $M_D$. The average value $\langle M_{\text{BH}} \rangle$ for the geometric approximation is about 8.0 TeV, while using the exponential suppression factor the $\langle M_{\text{BH}} \rangle \approx 7.8$ TeV. However, the cross section is suppressed more than 2 orders of magnitude relative to the naive geometric cross section. From here on we shall not be concerned with this suppression factor anymore. We also show the graphs for $y = 2.5$, a less stringent

![FIG. 1. The differential cross section $d\sigma/dM_{\text{BH}}$ for $pp \to BH + 1$ parton versus the mass $M_{\text{BH}}$ at the LHC for $n = 4$, $M_D = 1.5$ TeV, and $y = (M_{\text{BH}})_{\text{min}}/M_D = 2.5, 5$. “Geometric approx.” means that we used Eq. (3) to calculate the cross section while “exp. suppressed” means that we also included the suppression factor in Eq. (7).](image-url)
requirement on the BH entropy. Obviously, the production cross section is much larger. However, careful interpretation is needed because in this BH mass region it might involve nonperturbative string corrections.

The main difference between the $2 \to 1$ and $2 \to k$ ($k \geq 2$) subprocesses is that in $2 \to k$ the BH will have a transverse momentum. We approximate the $2 \to k$ subprocess by a $2 \to 2$ subprocess and assume the BH is produced in association with a massless parton. Since the mass of the BH is larger than the effective Planck mass, the c.m. energy $\sqrt{s} \approx M_{BH}$ is of order of a few TeV and would give a large transverse momentum to the BH. We show in Fig. 2 the transverse momentum spectrum for the production $pp \to BH + 1$ parton. The average value of $p_T$ is about 330 GeV for $n = 4$, $M_D = 1.5$ TeV, and $y = 5$.

Decay.—The main phase of the decay of BH is via the Hawking evaporation. The evaporation rate is governed by its Hawking temperature, which is given by [12]

$$T_{BH} = \frac{n + 1}{4 \pi R_{BH}}, \quad (8)$$

which scales inversely with some powers of $M_{BH}$. The heavier the BH, the lower the temperature is. Thus, the evaporation rate is slower. The lifetime of the BH scales inversely with the Hawking temperature as given by

$$\tau \sim \frac{1}{M_D (M_{BH} / M_D)^{(n+3)/(n+1)}} \quad (9)$$

From the above equation, it is obvious that the lifetime of a BH becomes much longer in models of large extra dimensions than in the usual 4D theory. However, the lifetime is still so short that it will decay once being produced and no displaced vertex can be seen in the detector. For another viewpoint on the BH decay please see Ref. [17].

Another important property of the BH decay is the large number of particles, in accord with the large entropy in Eq. (6), in the process of evaporation. It was shown [5,6] that the average multiplicity $\langle N \rangle$ in the decay of a BH is order of 10–30 for $M_{BH}$ being a few times of $M_D$ for $n = 2–6$. Since we are considering the BH that has an entropy of order 25 or more, it guarantees a high multiplicity BH decay. The BH decays more or less isotropically, and each decay particle has an average energy of a few hundred GeV. Therefore, if the BH is at rest, the event is very much like a spherical event with many particles of hundreds of GeV pointing back to the interaction point. Moreover, the ratio of hadronic to leptonic activities in the BH decay is about 5:1 [5]. On the other hand, if the BH is produced in association with other SM particles (as in $2 \to k$ subprocesses), the BH decay will be a boosted spherical event on one side, the transverse momentum of which is balanced by a few number of particles on the other side. A cartoon for such a typical event in the $(y, z)$ plane is shown in Fig. 3. This is a high $p_T$ event. On one side of the event is the decay products of high multiplicity of the BH in a boosted spherical shape. The original momentum of the BH in the $(y, z)$ plane is also shown, which is balanced by the momentum of the energetic parton, which is on the other side of the event. Such spectacular events should have negligible background.

In addition, since at the LHC multiparton collisions and overlapping events may be likely to happen, a careful discrimination is therefore necessary, especially, in the case that the BH is produced at rest or moving along the beam pipe (i.e., in $2 \to 1$ subprocess). In our study, the $2 \to 2$ subprocess affords an easier signature experimentally. The high $p_T$ parton emerging as a jet, a lepton, jets, or leptons provides an easy tag.

FIG. 2. The transverse momentum spectrum for the BH production in association with a massless parton at the LHC for $n = 4$, $M_D = 1.5$ TeV, and $y = (M_{BH})_{min} / M_D = 2.5, 5$.

FIG. 3. A cartoon showing a typical event of black hole production with a large transverse momentum.
Another concern of BH production is the event rate because the higher the $p_T$ the smaller the cross section is. The production cross section for $p_T > 500$ GeV is as large as 24 fb for $n = 4$, $M_D = 1.5$ TeV, and $y = (M_{BH})_{\text{min}}/M_D = 5$, which corresponds to 2400 events for an integrated luminosity of 100 fb$^{-1}$. Such a large number of clean events should be observable at the LHC. The production cross sections for other values of $n$, $M_D$, and $y$ are listed in Table I. The cross sections listed for $y = (M_{BH})_{\text{min}}/M_D \approx 4$ should be interpreted with care, because the smaller the ratio $(M_{BH})_{\text{min}}/M_D$ the stronger the string effect is and the classical description for BH may not be valid. Nevertheless, the numbers listed here can be used for comparison with other published results.

In this Letter, we have emphasized the importance and the advantages of using the 2 $\rightarrow$ 2 subprocess for BH production, which allows a substantial transverse momentum kick to the BH, and at the same time produces an energetic high $p_T$ parton, which provides a critical tag to the event. The observation here serves as an interesting extension to the previous work, in which the consideration is given only to BH production with the BH at rest.

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