Black Holes at the Large Hadron Collider

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If the scale of quantum gravity is near TeV, the CERN Large Hadron Collider will be producing one black hole (BH) about every second. The decays of the BHs into the final states with prompt, hard photons, electrons, or muons provide a clean signature with low background. The correlation between the BH mass and its temperature, deduced from the energy spectrum of the decay products, can test Hawking's evaporation law and determine the number of large new dimensions and the scale of quantum gravity.

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Introduction.—An exciting consequence of TeV-scale quantum gravity [1] is the possibility of production of black holes (BHs) [2–4] at the CERN Large Hadron Collider (LHC) and beyond. The objective of this paper is to point out the experimental signatures of BH production. Black holes are well-understood general-relativistic objects when their mass $M_{\rm BH}$ far exceeds the fundamental (higher-dimensional) Planck mass $M_P \sim$ TeV. As $M_{\rm BH}$ approaches M_P, the BHs become "stringy" and their properties complex. In what follows, we will ignore this obstacle and estimate the properties of light BHs by simple semiclassical arguments, strictly valid for $M_{\rm BH} \gg M_P$. We expect that this will be an adequate approximation, since the important experimental signatures rely on two simple qualitative properties: (i) the absence of small couplings and (ii) the "democratic" nature of BH decays, both of which may survive as average properties of the light descendants of BHs. Nevertheless, because of the unknown stringy corrections, our results are approximate estimates. For this reason, we will not attempt selective partial improvements—such as time dependence, angular momentum, charge, hair, and other higher-order general-relativistic refinements—which, for light BHs, may be masked by larger unknown stringy effects. We will focus on the production and sudden decay of Schwarzschild black holes.

Production.—The Schwarzschild radius R_S of a $(4 + n)$-dimensional black hole is given by [5], assuming that extra dimensions are large ($\gg R_S$).

Consider two partons with the center-of-mass (c.m.) energy $\sqrt{\hat{s}} = M_{\rm BH}$ moving in opposite directions. Semiclassical reasoning suggests that, if the impact parameter is less than the (higher-dimensional) Schwarzschild radius, a BH with the mass $M_{\rm BH}$ forms. Therefore the total cross section can be estimated from geometrical arguments [6], and is of order

$$\sigma(M_{\rm BH}) \approx \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{\rm BH}}{M_P}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)\right]^{2/(n+1)} \quad (1)$$

(see Fig. 1a).

This expression contains no small coupling constants; if the parton c.m. energy $\sqrt{\hat{s}}$ reaches the fundamental Planck scale $M_P \sim$ TeV then the cross section is of order TeV$^{-2} \approx 400$ pb. At the LHC, with the total c.m. energy $\sqrt{s} = 14$ TeV, BHs will be produced copiously. To calculate total production cross section, we need to take into account that only a fraction of the total c.m. energy in a pp collision is achieved in a parton-parton scattering. We compute the full particle level cross section using the parton luminosity approach (after Ref. [7]):

$$\frac{d\sigma(pp \to {\rm BH} + X)}{dM_{\rm BH}} = \frac{dL}{dM_{\rm BH}}\,\hat{\sigma}(ab \to {\rm BH})|_{\hat{s}=M_{\rm BH}^2},$$

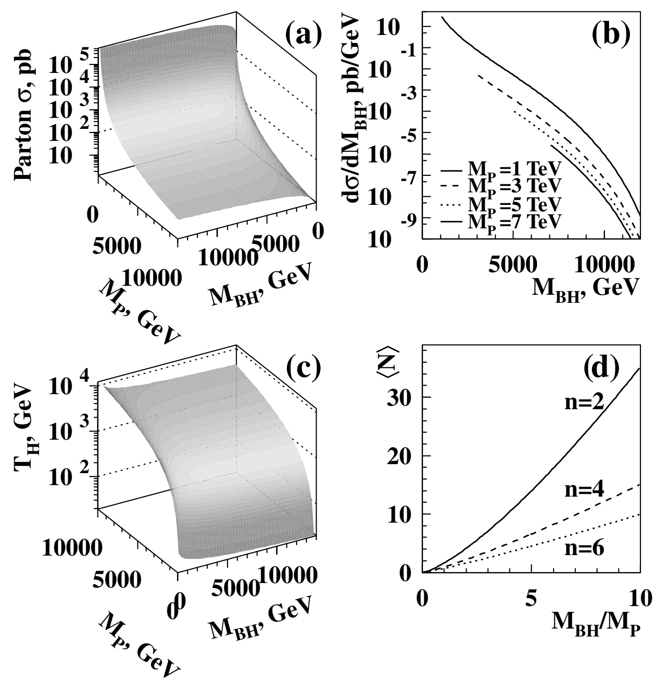

FIG. 1. (a) Parton-level production cross section, (b) differential cross section $d\sigma/dM_{\rm BH}$ at the LHC, (c) Hawking temperature, and (d) average decay multiplicity for a Schwarzschild black hole. The number of extra spatial dimensions $n = 4$ is used for (a)–(c). The dependence of the cross section and Hawking temperature on n is weak and would be hardly noticeable on the logarithmic scale.

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where the parton luminosity $dL/dM_{\rm BH}$ is defined as the sum over all the initial parton types:

$$\frac{dL}{dM_{\rm BH}} = \frac{2M_{\rm BH}}{s} \sum_{a,b} \int_{M_{\rm BH}^2/s}^{1} \frac{dx_a}{x_a} f_a(x_a) f_b\left(\frac{M_{\rm BH}^2}{sx_a}\right),$$

and $f_i(x_i)$ are the parton distribution functions (PDFs). We used the MRSD$-'$ [8] PDF set with the Q^2 scale taken to be equal to $M_{\rm BH}$, which is within the allowed range for this PDF set, up to the LHC kinematic limit. Cross section dependence on the choice of PDF is $\approx$10%.

The differential cross section $d\sigma/dM_{\rm BH}$ for the BH produced at the LHC is shown in Fig. 1b for several choices of M_P. The total production cross section at the LHC for BH masses above M_P ranges from 0.5 nb for $M_P = 2$ TeV, $n = 7$ to 120 fb for $M_P = 6$ TeV, and $n = 3$. If the fundamental Planck scale is $\approx$1 TeV, LHC, with the peak luminosity of 30 fb^{-1}/y will produce over 10^7 black holes per year. This is comparable to the total number of Z's produced at the CERN Large Electron-Positron Collider, and suggests that we may do high precision studies of TeV BH physics, as long as the backgrounds are kept small.

Decay.—The decay of the BH is governed by its Hawking temperature T_H, which is proportional to the inverse radius, and given by [5]

$$T_H = M_P\left(\frac{M_P}{M_{\rm BH}} \frac{n+2}{8\Gamma(\frac{n+3}{2})}\right)^{1/(n+1)} \frac{n+1}{4\sqrt{\pi}} = \frac{n+1}{4\pi R_S} \tag{2}$$

(see Fig. 1c). As the collision energy increases, the resulting BH gets heavier and its decay products get colder.

Note that the wavelength $\lambda = \frac{2\pi}{T_H}$ corresponding to the Hawking temperature is larger than the size of the black hole. Therefore, the BH acts as a point radiator and emits mostly s waves. This indicates that it decays equally to a particle on the brane and in the bulk, since it is sensitive only to the radial coordinate and does not make use of the extra angular modes available in the bulk. Since there are many more particles on our brane than in the bulk, this has the crucial consequence that the BH decays visibly to standard model (SM) particles [4,9].

The average multiplicity of particles produced in the process of BH evaporation is given by $\langle N\rangle = \langle\frac{M_{\rm BH}}{E}\rangle$, where E is the energy spectrum of the decay products. In order to find $\langle N\rangle$, we note that the BH evaporation is a blackbody radiation process, with the energy flux per unit of time given by Planck's formula, $\frac{df}{dx} \sim \frac{x^3}{e^x+c}$, where $x \equiv E/T_H$, and c is a constant, which depends on the quantum statistics of the decay products ($c = -1$ for bosons, $+1$ for fermions, and 0 for Boltzmann statistics).

The spectrum of the BH decay products in the massless particle approximation is given by $\frac{dN}{dE} \sim \frac{1}{E}\frac{df}{dE} \sim \frac{x^2}{e^x+c}$. For averaging the multiplicity, we use the average of the distribution in the inverse particle energy:

$$\left\langle\frac{1}{E}\right\rangle = \frac{1}{T_H} \frac{\int_0^\infty dx\, \frac{1}{x}\frac{x^2}{e^x+c}}{\int_0^\infty dx\, \frac{x^2}{e^x+c}} = a/T_H\,, \tag{3}$$

where a is a dimensionless constant that depends on the type of produced particles and numerically equals 0.68 for bosons, 0.46 for fermions, and $\frac{1}{2}$ for Boltzmann statistics. Since a mixture of fermions and bosons is produced in the BH decay, we can approximate the average by using Boltzmann statistics, which gives the following formula for the average multiplicity: $\langle N\rangle \approx \frac{M_{\rm BH}}{2T_H}$. By using Eq. (2) for Hawking temperature, we obtain

$$\langle N\rangle \approx \frac{2\sqrt{\pi}}{n+1}\left(\frac{M_{\rm BH}}{M_P}\right)^{(n+2)/(n+1)}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)^{1/(n+1)}. \tag{4}$$

Equation (4) holds for $M_{\rm BH} \gg T_H$, i.e., $\langle N\rangle \gg 1$; otherwise, the Planck spectrum is truncated at $E \approx M_{\rm BH}/2$ by the decay kinematics [10]. The average number of particles produced in the process of BH evaporation is shown in Fig. 1d.

We emphasize that, throughout this paper, we ignore time evolution: As the BH decays, it gets lighter and hotter and its decay accelerates. We adopt the "sudden approximation" in which the BH decays, at its original temperature, into its decay products. This approximation should be reliable since the BH spends most of its time near its original mass and temperature, because that is when it evolves the slowest; furthermore, that is also when it emits the most particles. Later, when we test the Hawking mass-temperature relation by reconstructing Wien's dispacement law, we will minimize the sensitivity to the late and hot stages of the BHs life by looking at only the soft part of the decay spectrum. Proper treatment of time evolution, for $M_{\rm BH} \approx M_P$, is difficult, since it immediately takes us to the stringy regime.

Branching Fractions.—The decay of a BH is thermal: It obeys all local conservation laws, but otherwise does not discriminate between particle species (of the same mass and spin). Theories with quantum gravity near a TeV must have additional symmetries, beyond the standard SU(3) $\times$ SU(2) $\times$ U(1), to guarantee proton longevity as well as conservation of approximate lepton number(s) and flavor [11]. There are many possibilities: discrete or continuous symmetries, four-dimensional or higher-dimensional "bulk" symmetries [12]. Each of these possible symmetries constrains the decays of the black holes. Since the typical decay involves a large number of particles, we will ignore the constraints imposed by the few conservation laws and assume that the BH decays with roughly equal probability to all of $\approx$60 particles of the SM. Since there are six charged leptons and one photon, we expect $\sim$10% of the particles to be hard, primary leptons and $\sim$2% of the particles to be hard photons, each carrying hundreds of GeV of energy. This is a very clean signal, with negligible background, as the production of SM leptons or photons in high-multiplicity events at the LHC occurs at a much smaller rate than the BH production (see Fig. 2). These events are also easy to trigger on, since they contain at least one prompt lepton or photon with the energy above 100 GeV, as well as energetic jets.

Test of Hawking radiation.—Furthermore, since there are three neutrinos, we expect only $\sim$5% average missing transverse energy ($\not{E}_T$) per event, which allows us to precisely estimate the BH mass from the visible decay products. We can also reconstruct the BH temperature by fitting the energy spectrum of the decay products to Planck's formula. Simultaneous knowledge of the BH mass and its temperature allows for a test of Hawking radiation and can provide evidence that the observed events come from the production of BH, and not from some other new physics.

There are a few important experimental techniques that we will use to carry out the numerical test. First of all, to improve precision of the BH mass reconstruction we will use only the events with $\not{E}_T$ consistent with zero. Given the small probability for a BH to emit a neutrino or a graviton, total statistics won't suffer appreciably from this requirement. Since BH decays have large jet activity, the $M_{\rm BH}$ resolution will be dominated by the jet energy resolution and the initial state radiation effects, and is expected to be $\sim$100 GeV for a massive BH. Second, we will use only photons and electrons in the final state to reconstruct the Hawking temperature. The reason is twofold: final states with energetic electrons and photons have very low background at high $\sqrt{\hat{s}}$, and the energy resolution for electrons and photons remains excellent even at the highest energies achieved in the process of BH evaporation. We do not use muons, as their momenta are determined by the track curvature in the magnetic field, and thus the resolution deteriorates fast with the muon momentum growth. We also ignore the τ-lepton decay modes, as the final states with τ's have much higher background than inclusive electron or photon final states, and also because their energies cannot be reconstructed as well as those for the electromagnetic objects. The fraction of electrons and photons among the final-state particles is only $\sim$5%, but the vast amount of BHs produced at the LHC allows us to sacrifice the rest of the statistics to allow for a high precision measurement. (Also, the large number of decay particles enhances the probability to have a photon or an electron in the event.) Finally, if the energy of a decay particle approaches the kinematic limit for pair production, $M_{\rm BH}/2$, the shape of the energy spectrum depends on the details of the BH decay model. In order to eliminate this unwanted model dependence, we use only the low part of the energy spectrum with $E < M_{\rm BH}/2$.

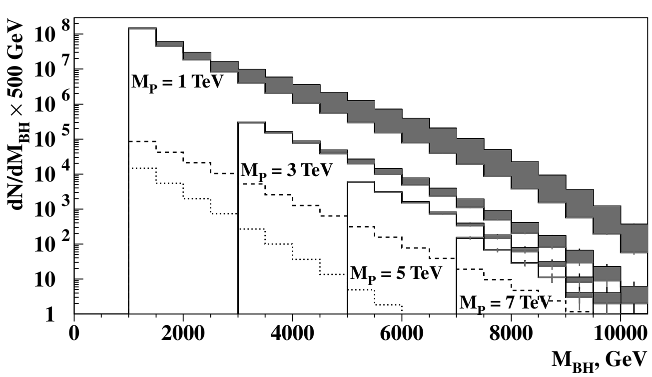

FIG. 2. Number of BHs produced at the LHC in the electron or photon decay channels, with 100 fb^{-1} of integrated luminosity, as a function of the BH mass. The shaded regions correspond to the variation in the number of events for n between 2 and 7. The dashed line shows total SM background [from inclusive $Z(ee)$ and direct photon production]. The dotted line corresponds to the $Z(ee) + X$ background alone.

The experimental procedure is straightforward: we select the BH sample by requiring events with high mass (>1 TeV) and mutiplicity of the final state ($N \geq 4$), which contain an electron or a photon with energy >100 GeV. We smear the energies of the decay products with the resolutions typical of the LHC detectors. We bin the events in the invariant mass with the bin size (500 GeV) much wider than the mass resolution. The mass spectrum of the BHs produced at the LHC with 100 fb^{-1} integrated luminosity is shown in Fig. 2 for several values of M_P and n. Backgrounds from the SM $Z(ee)$ + jets and γ + jets production, as estimated with PYTHIA [13], are small (see Fig. 2).

To determine the Hawking temperature as a function of the BH mass, we perform a maximum likelihood fit of the energy spectrum of electrons and photons in the BH events to Planck's formula (with the coefficient c determined by the particle spin), below the kinematic cutoff ($M_{\rm BH}/2$). This fit is performed by using the entire set of the BH events (i.e., not on an event-by-event basis) separately in each of the $M_{\rm BH}$ bins. We then use the measured $M_{\rm BH}$ vs T_H dependence and Eq. (2) to determine the fundamental Planck scale M_P and the dimensionality of space n. Note that to determine n we can also take the logarithm of both sides of Eq. (2):

$$\log(T_H) = \frac{-1}{n+1}\log(M_{\rm BH}) + \text{const}, \qquad (5)$$

where the constant does not depend on the BH mass, but only on M_P and on detailed properties of the bulk space, such as the shape of extra dimensions. Therefore, the slope of a straight-line fit to the $\log(T_H)$ vs $\log(M_{\rm BH})$ data offers a direct way of determining the dimensionality of space. This is a multidimensional analog of Wien's displacement law. Note that Eq. (5) is fundamentally different from other ways of determining the dimensionality of space-time, e.g., by studying a monojet signature or a virtual graviton exchange process, also predicted by theories with large extra dimensions.

A test of Wien's law at the LHC would provide confirmation that the observed $e + X$ and $\gamma + X$ event excess is due to the BH production. It would also be the first experimental test of Hawking's radiation hypothesis. Figure 3 shows typical fits to the simulated BH data at the LHC, corresponding to 100 fb^{-1} of integrated luminosity, for the highest fundamental Planck scales that still allow

TABLE I. Determination of M_P and n from Hawking radiation. The two numbers in each column correspond to fractional uncertainty in M_P and absolute uncertainty in n, respectively.

M_P	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
$n = 2$	1%/0.01	1%/0.02	3.3%/0.10	16%/0.35	40%/0.46
$n = 3$	1%/0.01	1.4%/0.06	7.5%/0.22	30%/1.0	48%/1.2
$n = 4$	1%/0.01	2.3%/0.13	9.5%/0.34	35%/1.5	54%/2.0
$n = 5$	1%/0.02	3.2%/0.23	17%/1.1		
$n = 6$	1%/0.03	4.2%/0.34	23%/2.5	Fit fails	
$n = 7$	1%/0.07	4.5%/0.40	24%/3.8		

for determination of the dimensionality of space with reasonable precision. The reach of the LHC for the fundamental Planck scale and the number of extra dimensions via Hawking's radiation extends to $M_P \sim 5$ TeV and is summarized in Table I [14].

Note, that the BH discovery potential at the LHC is maximized in the $e/\mu + X$ channels, where background is much smaller than that in the $\gamma + X$ channel (see Fig. 2). The reach of a simple counting experiment extends up to $M_P \approx 9$ TeV ($n = 2$–7), where one would expect to see a handful of BH events with negligible background.

Summary.—Black hole production at the LHC may be one of the early signatures of TeV-scale quantum gravity. It has three advantages:

(i) Large cross section: No small dimensionless coupling constants, analogous to α, suppress the production of BHs. This leads to enormous rates.

(ii) Hard, prompt, charged leptons and photons: Thermal decays are flavor blind. This signature has practically vanishing SM background.

(iii) Little missing energy: This facilitates the determination of the mass and the temperature of the black hole, and may lead to a test of Hawking radiation.

It is desirable to improve our primitive estimates, especially for the light black holes ($M_{\text{BH}} \approx M_P$); this will involve string theory. Nevertheless, the most telling signatures of BH production—large and growing cross sections; hard leptons, photons, and jets—emerge from qualitative features that are expected to be reliably estimated from the semiclassical arguments of this paper.

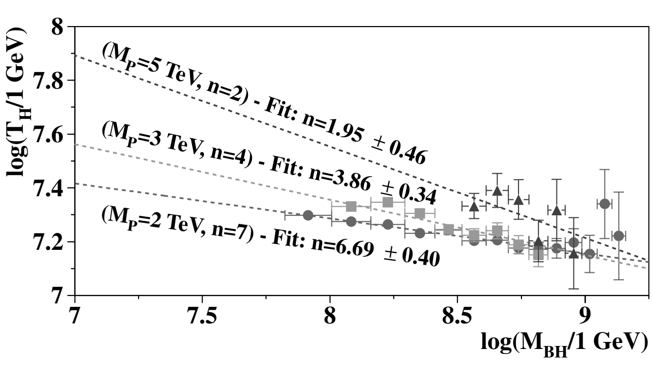

FIG. 3. Determination of the dimensionality of space via Wien's displacement law at the LHC with 100 fb^{-1} of data.

Perhaps black holes will be the first signal of TeV-scale quantum gravity. This depends on, among other factors, the relative magnitude of M_P and the (smaller) string scale M_S. For $M_S \ll M_P$, the vibrational modes of the string may be the first indication of the new physics.

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Note added.—After the completion of this work, a related paper [15] appeared in the LANL archives.

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