High energy colliders as black hole factories: The end of short distance physics

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If the fundamental Planck scale is of order of a TeV, as is the case in some extra-dimension scenarios, future hadron colliders such as the CERN Large Hadron Collider will be black hole factories. The nonperturbative process of black hole formation and decay by Hawking evaporation gives rise to spectacular events with up to many dozens of relatively hard jets and leptons with a characteristic ratio of hadronic to leptonic activity of roughly 5:1. The total transverse energy of such events is typically a sizable fraction of the beam energy. Perturbative hard scattering processes at energies well above the Planck scale are cloaked behind a horizon, thus limiting the ability to probe short distances. The high energy black hole cross section *grows* with energy at a rate determined by the dimensionality and geometry of the extra dimensions. This dependence therefore probes the extra dimensions at distances larger than the Planck scale.

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An outstanding problem in physics is the ratio between the four-dimensional Planck scale $G_N^{-1/2}\sim 10^{19}$ GeV and the electroweak scale $G_F^{-1/2}\sim 100$ GeV. Scenarios have emerged recently that address this hierarchy within the context of the old idea that the standard model is confined to a brane in a higher dimensional space. In this case the fundamental Planck scale—the energy at which gravitational interactions become strong—can be as low as the TeV scale. This raises the exciting possibility that future high energy colliders can directly probe strongly coupled gravitational physics. In this paper we investigate the dramatic TeV scale gravity signatures associated with black hole production and evaporation at high energy colliders.

A description of scattering processes at center of mass energies of the order of the fundamental Planck scale requires a full theory of quantum gravity. However, as we will discuss, scattering at energies well above the Planck scale is believed to be described in any theory by semi-classical general relativity. Probably the most interesting phenomenon in this regime is the production and subsequent evaporation of black holes. Black hole intermediate states are in fact believed to dominate *s*-channel scattering at super-Planckian energies. Indeed, the number of such non-perturbative states grows faster than that of any perturbative state; for example, the number of black hole states in D space-time dimensions grows with mass like $\exp(M^{(D-2)/(D-3)})$ while the number of perturbative string states grows like $\exp(M)$. The importance of black holes is also apparent in a geometric picture—scattering impact parameters which are smaller than the Schwarzschild radius associated with the center of mass energy result in black hole formation. In the high energy limit this classical non-perturbative process leads to a cross section which *grows* with energy much faster than that associated with any known perturbative local physics. Some of these features of high energy scattering have been discussed previously in [1].

The observability of black hole production at future colliders of course depends on the value of the fundamental Planck scale. The present bound on the Planck scale in a brane-world scenario with $D=10$ space-time dimensions arising from missing energy signatures at the Fermilab Tevatron run I and CERN e^+e^- collider LEP II associated with perturbative graviton production is just under $M_p \gtrsim 800$ GeV [2,3] in the standard normalization given below. As detailed below, if the fundamental Planck scale is of order a TeV, the black hole cross section at the CERN Large Hadron Collider (LHC) is large enough to qualify the LHC as a black hole factory. This opens up the possibility of detailed experimental study of black hole production and decay, in addition to perturbative quantum gravity processes.

The specific signatures associated with black holes produced in high energy collisions depend on the decay products. The decay of an excited spinning black hole state proceeds through several stages. The initial configuration loses hair associated with multipole moments in a *balding* phase by the emission of classical gravitational and gauge radiation. Gauge charges inherited from the initial state partons are discharged by Schwinger emission. After this transient phase, the subsequent spinning black hole evaporates by semi-classical Hawking radiation in two phases: a brief *spin-down* phase in which angular momentum is shed, and a longer *Schwarzschild* phase. The evaporation phases give rise to a large number of quanta characteristic of the total entropy of the initial black hole. At present it is not possible to describe quantitatively the end point of Hawking evaporation but a reasonable expectation is that when the black hole mass decreases to the fundamental Planck scale it enters a *Planck* phase in which final decay takes place by the emission of a few Planck scale quanta. Most of the black hole decay products are standard model quanta emitted on the brane [4] and are therefore visible experimentally.

The large number of visible quanta emitted in the decay of a black hole gives rise to the very distinctive signature of large multiplicity events with large total transverse energy, as described in detail below. The observation of such events with a parton level cross section which grows with energy would be a smoking gun for black hole production.

As discussed below, black hole production cross sections rise with energy whereas cross sections from other conventional hard perturbative processes should fall. Correspondingly, as the energy grows, the range of impact parameters for which black holes are formed grows, and other hard processes will be cloaked and invisible due to the formation of the event horizon [1]. This means that the era of black hole formation represents the end of experimental short distance physics. Nonetheless, scattering at higher energies can remain interesting, as it can begin to reveal the structure of the extra dimensions on scales large as compared to the Planck scale through features such as the energy dependence of the cross section.

In Sec. I two classes of brane-world scenarios with flat and warped geometries for the extra dimensions are reviewed. The relevant black hole properties of Schwarzschild radius, temperature, and entropy are presented for the two scenarios. The question of applicability of a black hole description for a generic high energy state produced in a collision is also addressed. In Sec. II the cross section for black hole production is discussed. Production rates for the LHC are estimated and shown to be sizable for a Planck scale of a TeV. The initial balding phase of black hole decay in which multipole moment hair is shed by gauge and gravitational radiation is also described. Section III describes the spin-down and Schwarzschild eras of Hawking evaporation. The total number and energy of quanta emitted in this phase is shown to be characteristic of the initial black hole entropy and Hawking temperature, respectively. The spectacular signatures resulting from black hole production and decay which could be observed at the LHC if the fundamental Planck scale is a TeV are described in Sec. IV. Section V includes a discussion of the dependence of the high energy black hole cross section on the dimensionality and geometry of the extra dimensions as a manifestation of the infrared–ultraviolet connection in a theory of gravity, and implications for the future of experimental short-distance physics are also discussed.

I. TeV SCALE GRAVITY AND BLACK HOLES

One scenario for realizing TeV scale gravity is a brane world in which the standard model matter and gauge degrees of freedom reside on a 3-brane within a flat compact space of volume V_{D-4} [5,6]. Gravity propagates in both the compact and non-compact dimensions. The Einstein action

$$S_E=\frac{1}{8\pi G}\int d^Dx\sqrt{-g}\,\frac{1}{2}\mathcal{R} \tag{1.1}$$

implies the relation between the four-dimensional and D-dimensional Newton's constants:

$$G_N=\frac{G_D}{V_{D-4}}. \tag{1.2}$$

The reduced fundamental Planck scale in this case is generally related to the D-dimensional Newton's constant in the phenomenology literature[1] as

$$M_p^{D-2}=\frac{(2\pi)^{D-4}}{4\pi G_D}. \tag{1.3}$$

The fundamental Planck scale can in principle be experimentally accessible in high energy collisions if V_{D-4} is large in fundamental units. For example, $M_p\sim$TeV for $D=10$ with $V_6\sim \mathrm{fm}^6$ [5]. Although the total volume of the compact space must be large in fundamental units, the radii of some of the extra dimensions, R_c, can in principle be not much larger than the fundamental scale. We refer to this as the "flat scenario."

Another scenario for realizing TeV scale gravity arises from properties of warped extra-dimensional geometries pointed out in [7]. Examples of string theory solutions that generate a hierarchy this way were recently exhibited in [8]. A warped geometry is described by a metric of the form

$$ds^2=e^{2A(y)}dx_4^2+g_{mn}(y)dy^m dy^n. \tag{1.4}$$

Here $dx_4^2=\eta_{\mu\nu}dx^\mu dx^\nu$ is the standard four-dimensional Minkowski line element, and the coordinates y parametrize the extra dimensions of space-time, with metric g_{mn}. The function e^A is the warp factor, and leads to scales for four-dimensional physics that depend on location within the extra dimensions. Gravity propagates in both the compact and non-compact directions. As we see from the action (1.1), in this case the four-dimensional Newton's constant is related to the D-dimensional one by

$$G_N^{-1}=G_D^{-1}\int d^{D-4}y\,\sqrt{g}e^{2A}. \tag{1.5}$$

The standard model confined to a brane at $y=y_0$ within such a geometry will have a Lagrangian of the form

$$S_{SM}=\int d^4x e^{4A(y_0)}\mathcal{L}(e^{2A(y_0)}\eta_{\mu\nu},\psi_i,m_i) \tag{1.6}$$

in which the metric $\eta_{\mu\nu}$ appears accompanied by factors of $e^{2A(y_0)}$. Here ψ_i denote the matter fields, and m_i are mass parameters which naturally take values of order the conventional Planck scale M_p. By rescaling the kinetic terms in Eq. (1.6) to canonical forms, the measured four-dimensional masses all take values of order $e^{A(y_0)}M_p$; alternatively one may use the redundancy under $A\rightarrow A+\lambda$ and $x\rightarrow e^{-\lambda}$ in the metric (1.4) to choose units in which the masses are $\mathcal{O}(M_p)$. If the warp factor e^A is small in the vicinity of the standard model brane, particle masses can take TeV values (or, in the

[1]Here we use the conventions of [3], which differs from the conventions for the Planck mass M_D in the first reference of [2] as $M_p=2^{1/(D-2)}M_D$.

rescaled units, the extra dimensions are large as in the flat scenario), thereby giving rise to a large hierarchy between the TeV and conventional Planck scales. Conversely, high energy scattering processes on the brane at apparent energy scales of order TeV actually probe energies approaching the fundamental Planck scale M_p, and can probe strong gravitational effects including black hole formation [9]. We will refer to this as the "warped scenario."

In either scenario the Planck scale threshold for strong gravity effects can be in the TeV range, and collider physics at such energies may reveal a wealth of fascinating and new physics. If this is the case, a description of the physics in this regime requires a quantum theory of gravity, such as string theory, which would predict many new effects. However, a generic effect in any theory of quantum gravity is the formation of black holes. While a quantitative understanding of black holes with masses of order of the Planck scale is quite difficult, for masses well above this scale black holes exhibit many features well described by semi-classical physics. And, as discussed below, it is possible that black holes not too much heavier than the fundamental Planck scale may be produced at future colliders.

In order to discuss black hole production and evaporation in the laboratory we therefore consider black holes with masses $M \gtrsim (\text{few}) M_p$ where features of the semi-classical analysis are expected to begin to be valid. Several simplifying assumptions are appropriate. To begin with, the brane on which the standard model lives will have a gravitational field which should be accounted for in solving Einstein's equations. While some features of such solutions were discussed in [10–13], we will assume that the only effect of the brane field is to bind the black hole to the brane, and that otherwise the black hole may be treated as an isolated black hole in the extra dimensions; this is the "probe brane approximation." Secondly, initially we assume that the black hole can be treated as a solution in D flat space-time dimensions. This assumption will be valid in the large-dimensions scenario at distance small compared with any radii, $r \ll R_c$, and in the warped scenario at distances small as compared to the curvature scale of the geometry associated with the extra dimensions, which we also denote as R_c. Finally, string theory has a number of other fields such as the dilaton; we will assume that these are fixed and do not play an important role in the relevant black hole solutions. We will also argue that gauge charges do not have a big effect on the black hole solutions, but will see that spin of the black holes is important. For an earlier discussion of some properties of black holes in these approximations, see [14].

Black holes relevant to experimental investigation in the laboratory are therefore neutral but spinning solutions of the D-dimensional Einstein action (1.1). These are the higher-dimensional Kerr solutions discussed in [15]. While we will not rewrite such solutions explicitly, let us recall some of their salient features. In general these have $[(D-1)/2]$ angular momentum parameters J_i, but as argued below only a single angular momentum parameter J parametrizing the four-dimensional spin is relevant. The horizon radius is given by

$$r_h^{D-5}\left(r_h^2+\frac{(D-2)^2J^2}{4M^2}\right)=\frac{16\pi G_D M}{(D-2)\Omega_{D-2}}\xrightarrow{J\to 0} r_h = \left[\frac{4(2\pi)^{D-4}M}{(D-2)\Omega_{D-2}M_p^{D-2}}\right]^{1/(D-3)}, \tag{1.7}$$

where

$$\Omega_{D-2}=\frac{2\pi^{(D-1)/2}}{\Gamma\left(\frac{D-1}{2}\right)}$$

is the area of a unit $D-2$ sphere. Note that the horizon size grows with mass like a power that depends on the space-time dimension, $r_h \propto M^{1/(D-3)}$. For later convenience it is useful to introduce a dimensionless rotation parameter,

$$a_* = \frac{(D-2)J}{2Mr_h}. \tag{1.8}$$

According to Hawking such black holes are unstable semiclassically [16], and decay into an approximately thermal spectrum of particles, with a temperature given by

$$T_H=\frac{D-3+(D-5)a_*^2}{4\pi r_h(1+a_*^2)}\xrightarrow{J\to 0}\frac{D-3}{4\pi r_h}. \tag{1.9}$$

Correspondingly, the black holes have entropy

$$S_{bh}=\frac{M}{(D-2)T_H}\left(D-3-\frac{2a_*^2}{1+a_*^2}\right)\xrightarrow{J\to 0}\frac{r_h^{D-2}\Omega_{D-2}}{4G_D}. \tag{1.10}$$

For a horizon radius $r_h \sim R_c$ the higher dimensional Kerr solutions are no longer a valid description. First consider the flat scenario. For horizon sizes larger than some radii, $r_h \gtrsim R_c$, the relevant solution is instead a lower dimensional black hole solution extended uniformly over the extra dimensions with small radii. The mass dependence of the horizon size for black holes larger than these radii would be that for the lower dimensional space-time. A somewhat similar phenomenon is expected in the warped case. A heuristic argument for the form of the black hole solutions in this case follows from the linearized approximation. There we expect the metric to be of the form

$$ds^2 \simeq -\left(1-\frac{16\pi G_D M}{(D-2)\Omega_{D-2}r^{D-3}}+V(\rho)\right)dt^2+\cdots \tag{1.11}$$

where ρ is the distance transverse to the brane and $V(\rho)$ is an effective gravitational potential associated with the warping and curvature in the extra dimensions. $V(\rho)$ grows with increasing ρ and by definition becomes important for $\rho \sim R_c$. The effective potential slows the growth of the horizon into the extra dimensions [determined by the vanishing of Eq. (1.11)] for increasing black hole mass. We expect this to be qualitatively similar to the inability of the horizon to grow transversely past R_c in the large-dimensions case. The horizon can, however, grow in the flat four-dimensional directions with increasing mass. This implies a crossover of the mass dependence of the horizon size from that for flat D-dimensional space-time given above for $r_h \lesssim R_c$ to $r_h \propto M^{\alpha}$ for $r \gtrsim R_c$, where the power α is bounded from below by the flat D dimensional value and from above by the four-dimensional value, $1/(D-3) \leqslant \alpha < 1$, with a corresponding modification of the temperature and entropy formulas (1.9), (1.10). Note that, in either scenario, there may be multiple thresholds where these formulas change, caused either by the existence of different radii for the extra dimensions, or by different curvature scales encountered in warped compactifications.

If the fundamental Planck scale is of order of a TeV, center of mass energies not too much larger than the fundamental Planck scale will be available for producing black holes. It is therefore important to address the applicability of the description of a generic massive state as a semi-classical black hole in this mass range. For masses of order of the fundamental Planck scale there is no control over quantum gravity effects which are likely to invalidate the semi-classical and statistical thermodynamic pictures. A precise criterion for the quantum corrections to be small is hard to formulate and would ideally be studied in the context of a quantum theory for gravity. One measure of the quantum corrections to a semi-classical black hole is the change in Hawking temperature per particle emission. A necessary condition for the quantum back-reaction on the black hole geometry to be small and for a quasi-static classical description of the metric to be good, is that this quantity is small compared with the Hawking temperature [17]

$$T_H \left| \frac{\partial T_H}{\partial M} \right| \ll T_H . \tag{1.12}$$

A second criterion based on the statistical thermodynamic interpretation of a black hole is that the fluctuations in a micro-canonical description be small. Since the number of degrees of freedom in an ensemble describing a black hole is roughly the entropy, small statistical fluctuations require $1/\sqrt{S_{bh}} \ll 1$. These criteria are related, since from Eqs. (1.7), (1.9), and (1.10)

$$\frac{\partial M}{\partial T_H} = (2-D) S_{bh} . \tag{1.13}$$

The first criteria is then equivalent to $S_{bh} \gg 1$, while the second more stringent statistical one is $\sqrt{S_{bh}} \gg 1$. Numerically for $D=10$ the entropy is $S \simeq 4(M/M_p)^{8/7}$. With a fundamental Planck scale of $M_p \simeq 1$ TeV the entropy of a 5 TeV mass black hole is $S_{bh}(5M_p) \simeq 27$, while for a 10 TeV mass black hole $S_{bh}(10M_p) \simeq 59$. Since a specific numerical criterion on the mass at which the black hole description becomes valid is subjective, we consider both masses given above for the cross section estimates below. For a smaller number of space-time dimensions the growth of the entropy with mass is more rapid, implying a slightly lower mass for which the black hole description should be valid.

Another necessary requirement for the validity of a description of black hole production and decay is that the lifetime determined by the Hawking evaporation process be sufficiently larger than the mass, $\tau M \gg 1$. In this case a black hole is a well defined resonance, and may be thought of as an intermediate state in the s channel. The parametric dependences and numerical estimates for black hole lifetimes are presented in Sec. III. Numerically, for $D=10$ and $M_p = 1$ TeV the lifetime of a 5 TeV mass black hole is estimated very roughly to be $\tau(5M_p) \sim 10 M^{-1}$, while for a 10 TeV mass black hole $\tau(10M_p) \sim 12 M^{-1}$.

In a weakly coupled string theory another requirement for the validity of a semi-classical black hole description comes from possible stringy corrections to the classical geometry. Black holes with horizon size less than the string length would receive large corrections. Conversely, a generic string state larger than the string scale is a semi-classical black hole [18]. In typical models where the string and Planck scales are not widely separated the above conditions on the validity of a black hole description of a generic massive state produced in a high energy collision are not significantly modified. For example, in $D=10$, the string and Planck scales are related by $L_{\rm string} \sim 1/(g^{1/4} M_p)$, with g the string coupling. In cases where the Planck scale is significantly higher than the string scale, there is an intermediate regime where excited string states would be produced; for some discussion of the phenomenology of such a scenario see [19].

II. BLACK HOLE PRODUCTION AND BALDING

Particle scattering at super-Planckian energies is dominated in the s channel by black hole production. In this limit the eikonal approximation for the initial state becomes valid and is described by a metric which contains a pair of Aichelburg-Sexl shock waves [20] with impact parameter b. A classical picture of black hole formation in this metric should capture the essential features of the scattering process in the high energy limit. For an impact parameter $b \lesssim r_h$, where r_h is the Schwarzschild radius associated with the center of mass energy $\sqrt{s}$, the incident relativistic particles pass within the event horizon. Formation of the event horizon should occur before the particles come in causal contact and be a classical process. Once inside the event horizon, no matter how violent and non-linear the subsequent collision, formation of an excited black hole state results. The process of scattering two particles, i and j, confined on a 3-brane to form a D-dimensional black hole as shown in Fig. 1 may then be modeled by a scattering amplitude described by an absorptive black disk with area πr_h^2. This gives a cross section

$$\begin{aligned}\sigma_{ij\to bh}(s) &= F(s)\pi r_h^2 \\ &= F(s)\pi \left(\frac{4(2\pi)^{D-4}\sqrt{s}}{(D-2)\Omega_{D-2}\, M_p^{D-2}} \right)^{2/(D-3)}\end{aligned} \tag{2.1}$$

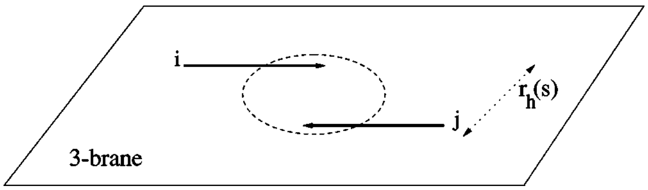

FIG. 1. Two partons, *i* and *j*, form a black hole by passing within the event horizon determined by the Schwarzschild radius associated with the center of mass energy $\sqrt{s}$.

where $F(s)$ is a dimensionless order one form factor coefficient, and where a black hole is by definition any matter or energy trapped behind the event horizon formed by the collision. Even though the process of black hole formation is a highly non-linear, non-perturbative process, formation of the event horizon ensures that the black disk approximation gives the correct magnitude and parametric dependence of the amplitude in the high energy limit. The precise mass of the black hole formed in a collision depends on the amount of energy and matter which becomes trapped behind the event horizon. In the high energy limit this in turn depends on the impact parameter *b*. So a range of black hole masses will result for a given center of mass energy

$$F(s)=\int dM\,\frac{dF(s,M)}{dM}. \tag{2.2}$$

However, since the cross section is dominated geometrically by large impact parameters, $b \lesssim r_h$, the average black hole mass should be of order of the ij center of mass energy, $\langle M\rangle \lesssim \sqrt{s}$. The precise order one coefficient $F(s)$ appearing in the cross section (2.1), as well as the distribution $dF(s,M)/dM$, could be calculated in the high energy limit numerically within classical general relativity by evolving the colliding Aichelburg-Sexl shock waves and integrating over a range of impact parameters.

The cross section for black hole production (2.1) has a number of interesting and important features. Since it is a classical non-perturbative gravitational phenomenon, it contains no small numbers or coupling constants. As such, black hole production would not appear at any order in perturbation theory. Most strikingly, the cross section *grows* with the center of mass energy like a power which depends on the dimensionality of space-time. This is connected with the rapid growth of the density of black hole states at large mass. It may also be understood as a manifestation of the infrared-ultraviolet connection within gravitational theories—super-Planckian energies correspond to large rather than short distances. A power law growth of the cross section with energy does not result from any known perturbative local physics, and is one of the most characteristic features of black hole formation. Additionally, in the high energy limit in which the classical picture of formation is valid, a black hole can be formed for any incident center of mass energy. The black hole may therefore be thought of as a intermediate resonance with effectively a continuum of states representing the large number of black hole states. In this language the intermediate black hole state produced in a given collision should not be thought of as a single massive degree of freedom, but rather as a state with a number of degrees of freedom (given by the entropy) in approximate statistical thermodynamic equilibrium. For black hole masses close to the fundamental Planck scale a full quantum treatment is necessary to address analogous non-perturbative scattering processes. However, for center of mass energies for which semi-classical black holes are well defined objects a semi-classical description of the event horizon should be applicable and the geometric cross section (2.1) should therefore provide a reliable estimate. As discussed in Sec. I, this may be achieved for masses not far above the fundamental Planck scale.

The non-perturbative process of black hole formation in high energy collisions also has an effect on the amplitudes for other processes. Hard perturbative processes at center of mass energies well above the fundamental Planck scale should be highly suppressed. This may be understood from the statistical thermodynamic properties of semi-classical black holes [1]. The amplitude for a massive black hole with a significant entropy to decay to a state with a few very energetic particles is Boltzmann suppressed. And since a generic state at energies far above the fundamental Planck scale is well approximated by a black hole, the high energy amplitude for $2\rightarrow$ few scattering is Boltzmann suppressed compared with the Hawking emission final state resulting from an intermediate black hole. This suppression may also be understood geometrically. In the high energy limit an event horizon forms before the particles come in causal contact. Any hard processes taking place at short distances are therefore cloaked behind a horizon and cannot lead to final state hard quanta which escape the scattering center. This feature also has the effect of suppressing initial state radiation in the high energy limit.

The only colliders envisioned which can reach energies well above the TeV scale, and therefore potentially produce black holes, are hadron colliders. In order to obtain the $pp\rightarrow bh$ cross section, the parton cross section (2.1) must be convoluted with the parton distribution functions (as long as the cross section is smaller than the geometric area of the proton). An intermediate resonance produced in a parton collision must carry the gauge and spin quantum numbers of the initial parton pair. In the high energy limit, black hole states exist with gauge and spin quantum numbers corresponding to any possible combination of quark or gluon partons within the protons. The $pp\rightarrow bh$ cross section therefore includes a sum over *all* possible parton pairings

$$\begin{aligned}\sigma_{pp\rightarrow bh}(\tau_m,s)&=\sum_{ij}\int_{\tau_m}^{1}d\tau\int_{\tau}^{1}\frac{dx}{x}f_i(x)f_j(\tau/x)\sigma_{ij\rightarrow bh}(\tau s)\\&\equiv h(\sqrt{\tau_m})\sigma_{ij\rightarrow bh}(s)\end{aligned} \tag{2.3}$$

where here $\sqrt{s}$ is the collider center of mass energy, x is the parton-momentum fraction, $\tau = x_i x_j$ is the parton-parton center of mass energy squared fraction, $\sqrt{\tau_m s}$ is the minimum center of mass energy for which the parton cross section into black holes is applicable, and the black hole mass is assumed to be $M\simeq\sqrt{\tau s}$. The sum over parton distributions $f_i(x)$ includes a factor of two for $i\neq j$. The sum over all initial par-

TABLE I. Large Hadron Collider $pp\rightarrow bh$ integrated cross sections for black holes of mass larger than M with $M_p=1$ TeV for $D=8,10$. Black holes formed in parton collisions are assumed to have mass equal to the parton-parton center of mass energy with form factor coefficient $F(s)=1$.

M	$D=8$	$D=10$
5 TeV	1.6×10^5 fb	2.4×10^5 fb
7 TeV	6.1×10^3 fb	8.9×10^3 fb
10 TeV	6.9 fb	10 fb

ton pairings represents another enhancement of the high energy black hole cross section compared with standard perturbative processes. This is in addition to the lack of small couplings and growth with energy.

The momentum scale squared, Q^2, at which a parton distribution function is evaluated is determined by the inverse length scale associated with the scattering process. For perturbative hard scattering in a local field theory this momentum scale is given by the momentum transfer, which in the s channel is the parton-parton center of mass energy $Q^2\sim s$. For the non-perturbative process of s-channel black hole formation in a theory of gravity, however, the relevant length scale is the Schwarzschild radius rather than the black hole mass, $Q^2\sim r_h^{-2}$. This is a consequence of the infrared-ultraviolet properties of black hole formation—scattering at super-Planckian energies corresponds to large distances.

The LHC with a center of mass energy of 14 TeV offers the first opportunity for black hole production if $M_p\sim$ TeV. Because of the rapid decrease of the parton distributions at large x, the LHC production cross section falls rapidly with black hole mass for any space-time dimension D even though the intrinsic parton-parton cross section grows with energy. For the production of black holes more massive than 5 TeV at the LHC, with $M_p=1$ TeV and $D=10$, using the CTEQ5 structure functions [21], the integrated cross section function is $h(0.36)\simeq0.02$, corresponding to a cross section of 2.4×10^5 fb.[2] This is a very large cross section by new physics standards and is only a factor of a few smaller than that for $pp\rightarrow t\bar{t}$. With a luminosity of 30 $\mathrm{fb}^{-1}\mathrm{yr}^{-1}$ such a cross section would correspond to a black hole production rate of 1 Hz, and would qualify the LHC as a black hole factory. For the production of black holes more massive than 10 TeV at the LHC, with $M_p=1$ TeV and $D=10$, the integrated cross section function is $h(0.71)\simeq5\times10^{-7}$, corresponding to a cross section of roughly 10 fb. Even at these large masses this corresponds to a production rate of 3 day^{-1}. Black hole production cross sections at the LHC for $D=8,10$ with $M_p=1$ TeV and assuming a form factor coefficient $F(s)=1$ are summarized in Table I.[2]

With TeV scale gravity, black hole production would become the dominant process at hadron colliders beyond the LHC. For example, with $M_p=1$ TeV and $D=10$, the Very Large Hadron Collider (VLHC) with 100 TeV center of mass energy and $100\,\mathrm{fb}^{-1}\mathrm{yr}^{-1}$ luminosity would produce black holes of average mass roughly 10 TeV at a rate of order kHz, and would produce black holes heavier than 50 TeV at a rate of roughly 0.5 Hz.

The rate of growth of the black hole cross section with a center of mass energy depends on the black hole density of states as a function of mass. In a flat background of large uniform volume, and for black holes smaller than the transverse size of the extra dimensions, it depends on the space-time dimensionality as indicated in Eq. (2.1). In principle, the radii of some of the extra dimensions could be comparable to the fundamental Planck scale, $R_c\gtrsim M_p^{-1}$. In this case the cross section dependence on the center of mass energy would increase as a function of energy as the threshold for producing black holes of size $r_h\sim R_c$ was crossed. Alternately, the radius of curvature for a warped background can also be comparable to or larger than the Planck scale, $R_c\gtrsim M_p^{-1}$ (see, e.g., [8]). This would also increase the energy dependence of the cross section. These dependences illustrate that massive black holes probe features of the extra dimensions on scales larger than the Planck scale—another manifestation of the infrared-ultraviolet connection in gravitational theories.

Black holes which are formed in high energy collisions have non-vanishing angular momentum which is determined by the impact parameter. Since the impact parameter is only non-vanishing in directions along the brane, the angular momentum lies within the brane directions. For a given parton-parton center of mass energy a range of angular momenta will result for the range of the impact parameters which lead to a black hole. The order one form factor coefficient of the cross section (2.1) therefore in general depends on both the mass and angular momentum of the black hole formed in a collision

$$F(s)=\int dM\,dJ\,\frac{d^2F(s,M,J)}{dM\,dJ}. \tag{2.4}$$

Since the production cross section is dominated geometrically by impact parameters $b\lesssim r_h$, the black holes will typically be formed with large angular momentum components in the brane directions, $\langle J\rangle\sim Mr_h$. The direction of the spin axis within the standard model brane is perpendicular to the collision axis in the high energy limit. In the high energy limit, the distribution of both masses and angular momenta could be calculated numerically within general relativity as described above, and are presumably correlated through the initial impact parameter.

Before any radiation of excess energy, the black hole state will also carry gauge quantum numbers of the initial state parton pair. In addition, since formation is a violent process the initial horizon is likely to be very asymmetric. The excited black hole state then carries additional hair corresponding to multipole moments for the distribution of gauge charges and energy momentum within the asymmetric configuration.

An excited black hole state produced in a collision will shed the hair associated with the multipole moments during

[2]We thank Tom Rizzo for cross section estimates.

an initial transient balding phase. In the large mass limit this occurs through classical gauge radiation to gauge fields on the brane, and through gravitational radiation. The frequency of this radiation, or equivalently the energy of emitted quanta, is determined by the frequency of oscillation of the multipole moments. Both the frequency of multipole oscillation and the balding time scale are characterized by the Schwarzschild radius, $\omega \sim 1/r_h$ and $\tau_b \gtrsim r_h$. The rate of energy loss for gauge and gravitational radiation in the balding phase can be estimated parametrically. Power emitted in gauge radiation should be dominated by the dipole mode, $d_i \sim g r_h$, where g is a gauge coupling constant. Ignoring any prefactors the parametric dependence of such dipole power loss is

$$P_{\text{gauge}} \sim \frac{\alpha}{r_h^2}, \tag{2.5}$$

where α is a fine structure constant. Power emitted in gravitational radiation should be dominated by the energy-momentum quadrupole moment, $Q_{ij} \sim M r_h^2$. Again ignoring any prefactors the parametric dependence of such quadrapole power loss is

$$P_{\text{gravity}} \sim \frac{G_D M^2}{r_h^{D-2}}. \tag{2.6}$$

The ratio of gauge to gravitation radiation in the balding phase is then parametrically

$$\frac{P_{\text{gauge}}}{P_{\text{gravity}}} \sim \frac{\alpha}{(r_h M_p)^{D-2}} \tag{2.7}$$

suggesting that gravitational radiation dominates. It is intuitively apparent that with order one gauge charges, gauge radiation is insignificant in the large mass limit.

In four dimensions the total mass loss by classical gravitational radiation in the balding phase for an excited black hole produced by collision of neutral relativistic particles is estimated to be 16% [22]. This result should be indicative of the total energy lost by an excited black hole during the balding phase also in the higher dimensional case since, first, gravitational radiation is expected to dominate, and second, because the energy-momentum multipole moments generated during the process of formation take values within the standard model brane. For production of large mass excited black holes by collision of relativistic charged particles in the high energy limit, numerical work at the classical level could significantly improve these rough estimates. For black hole masses near the fundamental Planck scale these estimates may receive potentially important quantum corrections.

The gauge charges inherited by the black hole from the initial state partons should discharge through the emission of a small number of quanta via the Schwinger process [23,24]. This should take place either during the balding phase, or near the beginning of the evaporation phases discussed below. So at the end of the transient balding phase, an excited black hole produced in a high energy collision has lost most

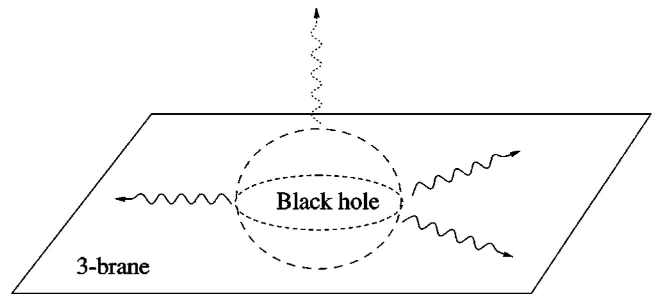

FIG. 2. A D-dimensional black hole bound to a 3-brane. The black hole emits Hawking radiation predominantly into brane modes (solid lines) and also into bulk modes (dotted lines). Gray body factors for brane modes are determined from the metric induced by the D-dimensional black hole geometry on the brane.

of its hair and is characterized essentially by the mass and angular momentum, and is therefore described by a spinning Kerr solution.

III. BLACK HOLE SPIN DOWN AND EVAPORATION

After the balding phase, the black hole will decay more slowly via the semi-classical Hawking evaporation process [16]. It emits modes both along the brane and into the extra dimensions, as illustrated in Fig. 2. If the standard model is comprised solely of brane modes, the bulk modes will be gravitational and thus invisible. Furthermore, as argued in [4], radiation along the brane is the dominant mechanism for mass loss. This follows from the observation that Hawking evaporation takes place predominantly in the S wave. The emissivity to a given brane or bulk mode is then roughly comparable, and the large number of standard model brane modes then dominate the evaporation process. Our discussion therefore neglects the bulk modes. We also assume that the only relevant modes on the brane are those of the standard model, although the discussion easily generalizes. (Note in particular that in four dimensions for a large number of scalar modes, there is no Schwarzschild phase discussed below; J/M^2 asymptotes to a fixed value [25].)

For black holes with temperatures down to the order of 100 GeV, all standard model particles may be treated as essentially massless; for temperatures smaller than this phase space suppression for the heavy gauge bosons and top quark must be included. For a massless particle the emission rate per unit energy E and time is

$$\frac{dN_{i,E,l,m,\lambda}}{dE\,dt} = \frac{1}{2\pi} \frac{\gamma_{i,E,l,m,\lambda}}{\exp\{(E - m\Omega)/T_H\} \mp 1} \tag{3.1}$$

where here i denotes species, l,m angular quantum numbers, λ polarization, and

$$\Omega = \frac{1}{r_h} \frac{a_*}{1 + a_*^2} \equiv \frac{1}{r_h} \Omega_* \tag{3.2}$$

is the surface angular frequency of the black hole, and Ω_* the dimensionless frequency. The γ are gray-body (tunneling) factors which modify the spectrum of emitted particles from that of a perfect thermal black body. Estimates for gray body factors in the four-dimensional case are given in [26,27]. The gray body factors for Hawking emission into brane modes in the higher dimensional case will differ quantitatively from the purely four-dimensional case, but should have the same qualitative features. For $Er_h \ll 1$ they vanish as E^{2l+1}, whereas for $Er_h \gg 1$ geometric optics predicts the $J=0$ values $\gamma \approx \theta(Kr_hE-l)$, with θ the step function and K a constant, and the $J\neq 0$ values $\gamma \approx e^{-\zeta l}$ with $\zeta = \mathcal{O}(1)$.

The evaporative time evolution of M and J for the black hole follows by summing Eq. (3.1) over modes to which the black hole can evaporate. The relevant equations are most easily studied in dimensionless variables [28]; in particular, define $x=Er_h$ and $T=T_*/r_h$. The evolution equations then become

$$Mr_h^2 \frac{d\ln M}{dt} = -f, \quad \frac{Jr_h}{a_*}\frac{d\ln J}{dt} = -g \tag{3.3}$$

with

$$\begin{pmatrix} f \\ g \end{pmatrix} = \frac{1}{2\pi}\sum_{i,l,m,\lambda}\int_0^\infty dx \frac{\gamma_{i,E,l,m,\lambda}(x,a_*)}{\exp\{(x-m\Omega_*)/T_*\}\mp 1}\begin{pmatrix} x \\ m/a_* \end{pmatrix}. \tag{3.4}$$

Dimension dependence enters these equations both through the gray body factors and the dependence of the Schwarzschild radius on mass and angular momentum.

The parametric dependence of the black hole lifetime on mass follows directly from Eq. (3.3)

$$\tau = \frac{C}{M_p}\left(\frac{M}{M_p}\right)^{(D-1)/(D-3)} \tag{3.5}$$

where C is a numerical constant obtained by integrating Eq. (3.3), and which depends on the dimensionality D, and initial angular momentum J. This parametric dependence may also be derived from the Stefan-Boltzmann law associated with Hawking emission. Equations (3.3) have been solved numerically in the four-dimensional case by Page [28]. The half-life for spin down is computed from

$$\frac{d\ln J}{d\ln M} = \frac{D-2}{2}\frac{g}{f}. \tag{3.6}$$

In the four-dimensional case this half-life is 7% of the black hole lifetime. In the present case f and g differ from Page's in the dimension dependence of the gray body factors and in the number of species considered, but the results should be similar. During spin down the angular momentum is shed in quanta with typically $l=m\sim 1$ and energy $E\sim 1/r_h$. In the four-dimensional case this phase accounts for about 25% of the mass loss. The remaining mass is lost in a Schwarzschild phase characterized by the decay of the $J\approx 0$ black hole. In the four-dimensional case, the constant C is numerically found to be [26,29,30]

$$C^{-1} \simeq (40n_0 + 19n_{1/2} + 7.9n_1 + 0.90n_2)\times 10^{-3} \tag{3.7}$$

where n_s denotes the total number of polarization degrees of freedom for spin s. For the standard model, this gives $C \simeq 0.5$ in four dimensions. If the dimension dependence of the gray body factors is ignored, this may be used to crudely estimate the constant C in the higher dimension case by taking account of the dimension dependence of the Schwarzschild radius on mass. In $D=10$ this gives roughly $C\sim 6.5$.

The energy spectrum of particles emitted in the Hawking process is derived by integrating Eq. (3.1) over the lifetime of the spin down and Schwarzschild phases up to a cutoff time τ_P where the Planck phase discussed below begins. This gives

$$\frac{dN_{i,E,l,m,\lambda}}{dE} = \int_0^{\tau-\tau_P}\frac{dt}{2\pi}\frac{\gamma_{i,E,l,m,\lambda}[r_h(t)E,a_*(t)]}{\exp\{[r_h(t)E-m\Omega_*(t)]/T_*(t)\}\mp 1}. \tag{3.8}$$

In particular, consider the Schwarzschild phase. For $E \gg 1/r_h \sim T_H$, the scaling of the gray body factors discussed above gives $\Sigma_{l,m}\gamma \propto (r_hE)^2$. This results in [31] in a spectrum which falls like E^{1-D} at high energies, and is power suppressed [26] at low energies

$$\frac{dN}{dE} \sim \begin{cases} E^{1-D}, & E \gtrsim T_H, \\ E^{\eta}, & E \lesssim T_H, \end{cases} \tag{3.9}$$

where η is a positive power, and T_H is the Hawking temperature of the initial black hole. The dominant radiation is at energies $1/r_h \sim T_H$ determined by the initial black-hole mass. The total number of particles emitted is characteristic of the entropy (1.10) of the initial black hole $N\sim S_{bh}$. The evaporation phases may therefore be thought of as literally the evaporate escape of the degrees of freedom which make up the black hole state produced in the collision. Numerical estimates for T_H and S_{bh} in $D=10$ are presented in the next section. Numerical study of the evaporation equations is required to improve all the rough estimates presented above.

The relative emissivities for various types of particles depend on the gray body factors. In four dimension these ratios may be extracted from the relative coefficients given in Eq. (3.7). Summing over four-dimensional transverse degrees of freedom, the relative emissivity for massless spin 0, spin $\frac{1}{2}$, spin 1, and spin 2 particles in the four-dimensional case is 42%:40%:16%:2%. These ratios should be indicative of those in higher dimensions. Numerical calculation of gray body factors, $\gamma_{i,E,l,m,\lambda}$, in the higher dimensional case should be pursued in order to improve these estimates.

Note that for black holes with $r_h > R_c$, the above expressions and estimates for the lifetime, decay spectra, etc. must be modified to account for the effective change in dimensionality discussed in Sec. I.

A discussion of the end point of Hawking evaporation requires a full theory of quantum gravity. The semi-classical description breaks down when the Hawking temperature reaches the fundamental scale $T_H \sim M_p$. At this point the black hole reaches a final Planck phase of decay. We expect the black hole in this phase to decay to several quanta with energies of order of the Planck or string scale.

Finally, in the case of primordial black holes in four dimensions with the standard Planck scale, there are controversial claims that a photosphere forms around an evaporating black hole, and thermally degrades the Hawking spectra [32]. However, in the higher dimensional case with TeV Planck scale, the much smaller total entropy of a given mass black hole implies that the outgoing Hawking radiation is sufficiently dilute so as not to thermalize. This may also be understood from the much shorter lifetime in the higher dimensional case which implies that the outgoing radiation is emitted in a relatively thin shell of thickness order the lifetime τ, which is too thin to thermalize.

IV. EXPERIMENTAL SIGNATURES

The potentially large production cross section at hadron colliders presents the possibility of studying black hole formation and decay in some detail. The various stages of decay described above give rise to distinctive distributions of decay products in both type, energy spectrum, multiplicity, and angular distribution. For definiteness we consider the signatures which could be observed at the LHC associated with parameters of $M_p \simeq 1$ TeV and $D=10$. The signatures for other space-time dimensions are qualitatively similar, and modifications for $M_p \gtrsim 1$ TeV are mentioned briefly below.

At the LHC, because of the rapidly falling parton structure functions a typical black hole of any given mass is produced without a large boost in the laboratory frame, $\langle \gamma\beta \rangle \lesssim 1$. This implies that the decay products are also not highly boosted in the laboratory frame. So the angular and energy distributions described below are largely preserved in the laboratory frame for a typical event, although there are exceptional events with sizable boost factors for lower mass black holes.

The first stage of decay for an excited black hole produced in a high energy collision is the balding phase. As discussed in Sec. II the energy lost in the process of shedding multipole hair is a small but non-negligible fraction of the excited black hole mass, perhaps 15%. In the large mass limit, gravitational radiation is expected to dominate the energy loss in this phase. For black hole masses not too far above the fundamental Planck scale some fraction of the energy may be emitted in gauge quanta. The energy of the quanta emitted in this phase is determined by the multipole frequencies which are characterized by the Schwarzschild radius, $E \sim 1/r_h$. This energy scale coincides with that of the Hawking temperature at the end of the balding phase. As discussed below, the Hawking temperature of a 10 TeV black hole for $D=10$ is roughly 150 GeV, and slightly less for a smaller number of space-time dimensions. In this case the balding phase could give rise to probably at most only a few gauge quanta, predominantly gluons, with energies of the order of 100–200 GeV. Distinguishing any visible quanta emitted during the balding phase from those emitted during the evaporation phase discussed below would seem to be difficult.

The highest multiplicity of particles from black hole decay comes from the spin-down and Schwarzschild-Hawking evaporation phases. The characteristic energy scale for these particles is the initial Hawking temperature of the black hole after the balding phase. Numerically, the Hawking temperature for $D=10$ is

$$T_H \simeq 0.2 M_p (M_p/M)^{1/7}. \tag{4.1}$$

The distribution of energies extends up to roughly the fundamental Planck scale with a spectrum $dN/dE \sim E^{1-D}$. The total number of particles emitted by evaporation in this phase is roughly the entropy of the initial black hole after the balding phase. Numerically, the entropy for $D=10$ is

$$S = \frac{7M}{8T_H} \simeq 4(M/M_P)^{8/7}, \tag{4.2}$$

so a large number of relatively hard primary partons arise from the evaporation phase. For example, for a 10 TeV mass black hole, of order 50 quanta with a typical energy of order 150–200 GeV result from the evaporation phase. As described below, almost all of these emitted particles appear as visible energy. For smaller space-time dimension the Hawking temperature is slightly lower for a given black hole mass. In this case a slightly higher multiplicity of somewhat lower energy quanta would be released in the evaporation phases.

Perhaps the most distinctive feature of the evaporation phase, aside from the high multiplicity, is the distribution in type of particle emitted. Because of the large fraction of standard model states which are strongly interacting, most of the emitted particles are strongly interacting. As described in Sec. III, the relative emissivities depend on the intrinsic spin of the emitted particle through the gray body factors. Using the relative emissivities quoted in Sec. III, the standard model fractions of quarks and gluons, leptons, massive gauge bosons, neutrinos and gravitons, Higgs boson, and photons emitted from a non-rotating black hole in four dimensions, ignoring particle masses, is 72%:11%:8%:6%:2%:1%. Accounting for the decay of top quarks, massive gauge bosons, and the Higgs boson, the ratio of hadronic to leptonic activity (primary e, μ, and τ) in the evaporation process in this case is roughly 5:1, while the ratio of hadronic to photonic activity is roughly 100:1. Taking account of heavy quark and tau semi-leptonic decays would decrease these ratios slightly. The specific ratios in the higher dimensional case with Hawking evaporation along the standard model brane requires integration of the evaporation equations given in Sec. III, including appropriate gray body factors and black hole angular momentum. However, the four-dimensional values are expected to be indicative of those for the higher dimensional case. The fraction of energy which is visible resulting from the evaporation phases is therefore expected to be in the 85–90 % range.

Additional states to which the black hole could evaporate, such as supersymmetric partners, would of course modify the specific ratios of final state partons. However, such states which decay to visible particles are sure to be identified at the LHC, and so the total amount of Hawking radiation which appears as visible energy, as well as the ratios of hadronic to leptonic and hadronic to photonic activity, will be calculable parameters in the large black hole mass limit.

Another feature of the evaporation phase is the angular distribution of emitted particles. As described in Sec. II, a typical black hole is produced with a large angular momentum. The spin-down process of Hawking evaporation emits quanta predominantly in the $l=m\sim 1$ modes. The angular dependence of the particles emitted during the evaporation phase is then roughly

$$\frac{dN}{d\varphi}\sim N_0+2N_1\sin^2\varphi \tag{4.3}$$

where N_0 and N_1 are the number of particles radiated in the Schwarzschild and spin-down evaporation processes, respectively, where the subscript refers to the l value, $N_0+N_1\simeq N$, and φ is the angle with respect to the spin axis in the rest frame. In four dimensions the spin-down phase accounts for about 25% of the evaporative mass loss, and is expected to be similar in the higher dimensional case with Hawking radiation on the brane. It might therefore be possible in large multiplicity events to discern the magnitude of initial black hole spin and the direction of the spin axis from the angular distribution of emitted particles. The distribution of both the magnitudes and spin axis directions measured from a large number of events would provide information about the nonperturbative process of black hole formation which determines the initial spin. For example, deviations of the spin axis from a direction perpendicular to the collision axis in the rest frame may occur for black hole masses not too far above the fundamental Planck scale.

The end point of the black hole evaporation is the Planck phase in which the black hole completely decays. Without a fundamental theory of gravity it is hard to quantify this phase. But any visible partons emitted in this phase would have energies characteristic of the Planck or perhaps string scales. The identity and distributions of the highest energy final state partons within a black event would provide information about the Planck phase and the end point of Hawking evaporation.

Because of the large cross section, large total visible energy, and large multiplicity of final state partons, black hole production gives rise to very spectacular events at a hadron collider. For a 10 TeV black hole with $D=10$, on the order of 50 visible final state primary partons result, each with typical energy in the 100–200 GeV range from the balding and evaporative decay phases, with a few hard visible partons up to energies of the order of the fundamental Planck scale from the end of the evaporation phase and Planck decay phase. Since most of the black hole decay products result from the evaporation phase, the ratio of the total hadronic to leptonic activity is expected to be roughly 5:1. In addition, most of these particles are emitted in $l,m\lesssim 1$ modes leading to a fairly spherical distribution of primary final state partons in the black hole rest frame. Since a typical black hole is produced with only a moderate boost factor, this results in events with a high degree of sphericity. For a completely spherical event corresponding to a spinless black hole at rest in the laboratory frame, the transverse energy is $\frac{1}{2}$ of the total energy. The moderate boost and high sphericity imply that the total visible transverse energy of a typical black hole event is between $\frac{1}{3}$ and $\frac{1}{2}$ of the total deposited visible energy.

Another feature of the large multiplicity in a black hole event is that any missing energy either from primary emission by the black hole of gravitons, neutrinos, or other noninteracting particles, such as a (quasi)-stable neutralino, or from neutrinos in subsequent cascade decays tends to average out within a given event. However, there can be exceptional events in which the missing energy fluctuates upward, from for example, emission of two charged or strongly interacting particles recoiling against a hard graviton in the Planck decay phase.

Since the transverse energy is an invariant it provides a very good measure of the black hole mass. This is true on a statistical basis if the initial black hole spins are averaged, and is also true for a given large multiplicity event if the relative multiplicities N_0, N_1 discussed above can be extracted. As discussed above, most of the energy emitted in the evaporation phases is visible. So depending on the spin, the black hole mass should therefore by very roughly of order twice the visible transverse energy—this ratio could be reliably calculated by numerical simulation of cascade decays of the primary partons to determine the precise fraction of energy which is visible.

Special purpose triggers are not required to accept black hole events because of the large total transverse hadronic energy and non-negligible leptonic fraction. Even without a dedicated search, such events would appear in any number of new physics analyses which utilize hadronic or leptonic activity. In fact, if the fundamental Planck scale is a TeV, because of the relatively large cross section, it is likely that black hole production and decay would represent a significant background in many new physics searches.

The most striking features of black hole decay are both the large multiplicity and total transverse energy of the decay products. At a hadron collider an obvious cut to select black hole events is therefore large total transverse hadronic energy of at least a few times the fundamental Planck scale, and (very) large multiplicity of relatively hard jets. A requirement of relatively hard leptonic activity could also be applied. The requirement of a large multiplicity of final state partons significantly reduces the background from perturbative processes which typically only have a few hard final state partons from cascade decays of the primaries. In addition, black hole events have the feature that the multiplicity and average final state primary parton energy in any event is correlated with the black hole mass (as indicated by the event total transverse visible energy) in a manner determined by the Hawking evaporation process. Specifically, the multiplicity is higher and average energy per primary final state parton lower for higher mass events. This is another manifestation of the infrared-ultraviolet connection of gravity—higher energy events have lower energy per particle. A growing parton-parton cross section for events satisfying these cuts, along with a roughly 5:1 ratio of hadronic to leptonic activity, would represent a smoking gun for black hole production and decay.

A calorimetric measurement of the number of identified black hole events as well as the average multiplicity and final state parton energy as a function of total event energy would give a measure of the black hole production cross section. This in turn is sensitive the dimensionality and geometry of the extra dimensions.

A measurement of the distribution of multiplicities and spectra of primary final state partons energies as a function of black hole mass, as indicated by event transverse visible energy, over a large number of events would allow a quantitative test of the Hawking evaporation process. Even though black holes produced in high energy collisions Hawking radiate mainly to standard model particles on the brane, a precise measurement of the decay spectrum would be sensitive to the number of extra dimensions through the effect on the evaporation evolution equations.

The final signal of black hole production is the suppression of hard scattering processes at energies at which black hole production becomes important. As described in Sec. II, perturbative hard scattering processes are Boltzmann suppressed at energies well above the fundamental Planck scale by the statistical thermodynamic properties of black holes, or equivalently because such hard processes are hidden behind the event horizon formed during collision. Such a suppression would be apparent in, for example, the Drell-Yan or two jet cross sections at very high energies.

In summary, the spectacular experimental signatures associated with black hole production and decay at a hadron collider include the following: a very large total cross section with production rates at the LHC approaching up to the order of 1 Hz possible; the parton level cross section *grows* with energy at a rate determined by the dimensionality and geometry of the extra dimensions; large total deposited energy up to a sizable fraction of the beam energy, with visible transverse energy typically of order $\frac{1}{3}$ the total energy; large multiplicity events, with up to many dozens of relatively hard jets and leptons; the average energy per primary final state parton decreases with total event transverse energy as indicated by the relation between initial Hawking temperature and black hole mass; the ratio of hadronic to leptonic activity of roughly 5:1 from the Hawking evaporation phase; high sphericity events due to large multiplicity and the moderate black hole boost factor in the laboratory frame; the angular distribution within a given event is characteristic of the initial black hole spin; some events contain a few hard visible quanta with energy up to the order of the fundamental Planck scale from the Planck decay phase; and suppression of hard perturbative scattering processes at energies for which black hole production becomes important.

A search for all of these features together should be essentially free of background from any perturbative physics or instrumental sources. An observation of these signatures would represent compelling evidence for black hole production and decay and TeV scale gravity. It is likely that a detailed study of the potentially large number of such events could provide information about both the process of production of black holes in high energy collisions, as well as the Planck decay phase and the end point of Hawking evaporation.

The use of black hole signatures at the LHC to set a specific lower limit on the fundamental Planck scale would require additional work. This includes a detailed study of potential backgrounds. Just as important would be a theoretical estimate of the energy at which the black hole description of intermediate states in both production and decay becomes reliable, which is not available at this time. However, the LHC center of mass beam energy is fixed at 14 TeV, and the applicability of the description of high energy scattering through black hole states is likely limited to energies more than at least a few times the fundamental Planck scale. So if the fundamental Planck scale is larger than a few TeV it seems unlikely that the non-perturbative effect of black hole production and decay is a relevant description of gravitational effects at the LHC—perturbative gravitational effects would likely be more relevant. There is, therefore, a window of opportunity for $M_p \lesssim$ few TeV in which the LHC would be a black hole factory, with very dramatic signatures. The window is limited mainly by the center of mass beam energy, and the rapidly falling parton distributions. The window would of course be much larger for the VLHC.

V. CONCLUSIONS

The signatures outlined above—in particular very high multiplicity events with a large fraction of the beam energy converted into transverse energy with a growing cross section—should serve as clear signals for the formation and Hawking evaporation of black holes at colliders. The observability of black hole production and decay is, of course, critically dependent on the magnitude of the fundamental Planck scale M_p. But once this threshold is crossed, the production rate is large and rapidly rising. Note that for $D=10$ the present bound of about $M_p \gtrsim 800$ GeV [3] from missing energy signatures due to perturbative graviton emission will not be significantly improved by the Tevatron run II since this process is energy rather than rate limited by the rapidly growing density of perturbative graviton states. We therefore arrive at the surprising conclusion that if the fundamental Planck scale is of the order of a TeV the LHC will be a black hole factory, and that this possibility cannot obviously be excluded before LHC begins operation. It is also amusing to note that, if the Planck scale is indeed of the order of a TeV, formation of black holes through binary collisions could be observed at LHC by the end of the decade, quite possibly before being observed astrophysically by the Laser Interferometric Gravitational Wave Observatory (LIGO).

Perhaps one of the most stunning features of such a scenario is that, because of the infrared-ultraviolet properties of gravity, black hole production seems to represent the *end* of experimental investigation of short-distance physics by relativistic high-energy collisions. Through the formation of event horizons, black hole formation in the high center of mass energy scattering effectively cloaks hard processes. At high center of mass energies the non-perturbative production of black holes dominates all perturbative processes. And as we have argued, at high energies black hole production is increasingly a long-distance, semi-classical process. However, there *can* be interesting features in high energy scattering experiments as the thresholds R_c for sizes or curvature scales of the extra dimensions are reached and passed. This would provide information about the structure of the extra dimensions that is complimentary to that found by studying the perturbative graviton Kaluza-Klein spectrum at lower center of mass energies. Note also that the growing cross sections for black hole production would simplify design requirements for future colliders which typically anticipate a hard scattering cross section which falls like the square of the center of mass energy.

A collider study of black hole creation would certainly be an astounding pursuit, although it may be that the most conceptually profound physics would be unraveled at energies in the vicinity of the Planck scale. Here one would hope to reveal the microphysics of quantum gravity and the possible breakdown of space-time structure.

Note added. While this work was in progress, we learned that some aspects of black hole production were also under consideration by another group; that work has appeared subsequent to our paper's appearance [33].

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