Black Hole Production at a TeV[1]

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Abstract

In this talk I briefly discuss some features of a striking signature of TeV quantum gravity/strings and large extra dimensions: the production of exotic objects such as black holes, and their stringy precursors, the string resonances at large masses which can be dubbed 'string balls'. The focus is on aspects less frequently discussed in other reviews of this subject.

1 Introduction

Let us start by asking one of the most basic questions in theoretical physics: What is the fundamental scale for Quantum Gravity? Answer: *We don't know.* It is only quite recently that we have become fully aware of this. The reason for our ignorance is quite simple: we do not know how to formulate the correct theory of quantum gravity. What we do know is the following: the fundamental energy scale M_* has to be larger than a TeV, for otherwise we should have seen effects of quantum gravity at LEP and the Tevatron[4]. We also know that M_* can be as large as, but not larger than, the familiar Planck scale $M_{(4)} \sim 10^{19}$ GeV, since at this energy four-dimensional gravity becomes strongly coupled and quantum effects surely must become important. The phrase *four-dimensional* in the last statement betrays already the mechanism that allows M_* to be smaller than $M_{(4)}$ [1]. The introduction of large extra dimensions dilutes gravity in an internal n-dimensional volume $V_n = L^n$, and $M_{(4)}$ is revealed as an effective coupling

$$M_{(4)}^2 = M_*^{n+2} L^n \,, \tag{1}$$

describing the strength of gravity only at distances larger than the length scale of the additional dimensions.

The scenario is completed by a mechanism that prevents all particles and interactions, other than gravity, to spread out into these large extra dimensions: they are confined inside a brane, of thickness $\lesssim$ TeV^{-1}, localized in the internal space. By making L^n sufficiently large to allow M_* to be near the TeV scale, one achieves a reformulation of the hierarchy problem.

The great interest in these models has been prompted by the fact that, with M_* as low as a TeV, one obtains spectacular new physics in future colliders such as the LHC. The signatures due to graviton production and exchange have been thoroughly studied (see e.g. [3]). In this talk I will briefly review some aspects of a more striking signature of TeV quantum gravity/strings and large extra dimensions: the production of exotic objects such as black holes [4, 5, 6, 7, 8], and their stringy precursors, the string resonances at large masses which can be dubbed 'string balls' [9]. Both these objects have in common their large mass (larger than fundamental mass scale), and the fact that they have a large degeneracy of internal states. The latter is crucial to their large production cross section.

There are already a number of reviews on this subject [10] to which the reader is referred to for other details, for discussion of topics that I mentioned in my talk but are not included here such as black hole production in cosmic rays [11], and for extensive lists of references. Instead, I will mostly focus on aspects that have been less prominent in former discussions in the literature.

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[4] There are ways of sidestepping even this lower bound [2], but I will not discuss these scenarios here.

2   Black holes on branes

Finding the exact description of a black hole localized on a three-brane, whether the bulk spacetime is compact (as in ADD scenarios) or non-compact (as in the RS2 model), is an outstanding problem in General Relativity. However, the problem can be sidestepped for a black hole formed at a typical collider energy in the range of $O(10)$ TeV. Such a black hole has a size $\sim 10^{-15}$ mm, which is several orders of magnitude smaller than the size that the extra dimensions can presumably have (e.g., for $n = 7$ and $M_* \sim O(\text{TeV})$ we would have $L \sim$ fermi). Therefore, at distances smaller than L we can neglect all finite-size effects from the compact dimensions, and approximate the metric for a neutral, non-rotating black hole by the Tangherlini-Schwarzschild solution in $4 + n$ dimensions. We want this black hole to be stuck to the brane, in such a manner that, at distances $r \ll L$ the metric induced on the brane is

$$ds^2_{brane} \simeq -\left(1 - \frac{\mu}{r^{1+n}}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{\mu}{r^{1+n}}\right)} + r^2 d\Omega^2_{(2)}\,. \tag{2}$$

All the interesting physics (the formation and evaporation of the black hole) happens in a region within a few horizon radii, so this approximate geometry will be enough for our purposes. Note that this is not a solution of the Einstein equations in four dimensions: the additional modes of gravity in the bulk (Kaluza-Klein modes) are not zero in the region near the black hole horizon. It can also be argued that the mass of the black hole as measured from the $4 + n$ dimensional point of view is the same as the one that a four-dimensional observer, probing distances $r \gg L$, would measure [6].

3   Scattering at $E > M_*$ and Black Hole Formation

Given our ignorance about the correct theory of quantum gravity, one might think that we cannot say anything at all about scattering at energies beyond the fundamental Planck scale M_*. This is not quite correct.[5] While there is certainly a gap in our ability to perform calculations at energies near the fundamental scale of quantum gravity, $E \sim M_*$, a number of generic arguments based on a crucial property of General Relativity, namely the appearance of horizons, allow us to argue for a description of some features of scattering in the transplanckian energy regime. There are certainly effects that, at present, we do not even have a proper theory to calculate, but in many instances an asymptotic observer will be causally cut off from them. The crucial point is cosmic censorship, which can be taken to say, quite liberally, that the extreme high energy regime will be shrouded by a horizon. Two particles scattering at transplanckian center-of-mass energy, $\sqrt{s}$, and small impact parameter b, will produce a large concentration of energy in a small volume, and therefore will induce a large spacetime curvature, larger than the fundamental scale. To a low-energy observer, this will be equivalent to a curvature singularity. Then, if cosmic censorship holds, a horizon will appear, hiding these higher-energy effects from the observers outside.

This generic argument assumes that in the collision of two transplanckian particles their energy actually gets concentrated in a small volume. One may worry that the emission of a large fraction of energy into initial state radiation might prevent this. However, this does not seem to be the case. The analyses of [16] show that trapped surfaces do form in the collision of classical transplanckian particles. Quite generically, these trapped surfaces appear before the colliding particles are at a distance where quantum gravity corrections (e.g. higher-dimension operators in the low energy effective action) must be taken into account. Once the trapped surfaces arise, a singularity will inevitably develop, and a horizon is expected to censor it out. The area of the apparent horizon (the outer envelope of the trapped surfaces), which cannot be larger than the area of the event horizon, is found to be smaller than, but still close to the area of a black hole of mass equal to $\sqrt{s}$. Hence follows a (dimension-dependent) upper bound on the fraction of gravitational radiation that is classically produced.[6]

Low energy effective field theory predicts the failure of General Relativity at energies near or above the Planck scale by the effect of higher-dimension operators in the low energy effective action becoming

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[5]Ideas similar or related to those in this section have been discussed previously in, e.g., [12, 13, 5, 14, 7, 15].

[6]Still, the question remains of whether the radiation of quantum origin is also small. I thank Riccardo Rattazzi for discussions on this issue.

as important as the Einstein-Hilbert term. What the argument above says is that the effects of these operators will be largely confined inside a black hole horizon. An alternative view, using a spacetime description, would be the following: a region of large curvature can be enclosed by a surface where all curvatures are moderate; say, below a given cutoff curvature radius. This region can be cutoff and then replaced by boundary conditions at its surface. The main assumption, analogous to the locality of counterterms in the low energy effective action, is that the specification of these boundary conditions is sufficient to encode all the effects that the physics at higher curvatures would have on the lower curvature regions. The situation changes if a horizon appears, since it not only excises the large curvature region, but the horizon itself also provides a set of boundary conditions (i.e., thermal) that is largely independent of the details of the large curvatures inside the horizon[7].

These considerations reveal an essential property of quantum gravity: its softness at high energies. The higher the energy of the collision, the larger the horizon that forms, and therefore the less important that the quantum gravity corrections will be for an observer outside the horizon. So gravitational scattering at very high energies becomes softer and softer. Ultimately, the outcome of the scattering will be the Hawking radiation emitted in the decay of the black hole, whose wavelength is comparable to the black hole size, and therefore larger for higher energy collisions. This softness is also a property that can be observed in the eikonalized gravitational scattering amplitudes, in which one can have a large momentum transfer, but built out of a very large number of small momentum transfers, so at the end one does not probe the very shortest distances [12, 13]. It is also strongly reminiscent of the softness of strings in the regime of deep inelastic scattering. The reasons for it are at first sight quite different. One can see the parallels both in the Regge regime and in the deep inelastic scattering regime, and in fact the black hole/string correspondence principle suggest such a connection, which to our knowledge has not been discussed in detail in the literature. The correspondence principle also allows us to use string theory to perform a simple calculation that leads to the correct estimate for the black hole production cross section. This will be discussed in Sec. 5 below.

At transplanckian energies one must go beyond perturbation theory, but it is the *classical* gravitational dynamics that dominates the evolution of the system[8]. This is apparent both in the case where a black hole forms, and also in the eikonal analysis of the scattering. It can be interpreted as saying that one must consider diagrams with an arbitrary number of vertex insertions, but where graviton loops are absent; matter lines in the diagrams are taken to be on-shell.

A full calculation of the production cross section, using classical General Relativity, is a very complicated task. A simple estimate can be obtained by taking into account the above-mentioned bounds on initial state radiation, and other factors, such as the fact that the capture cross section of a black hole is actually larger than its area, which may raise the cross section. For practical purposes, it seems reasonable to estimate the black hole production cross section as the geometric cross section

$$\sigma \simeq \pi R_H^2 \sim \frac{1}{M_*} \left(\frac{\sqrt{s}}{M_*} \right)^{\frac{2}{n+1}} . \tag{3}$$

Since this cross section does not contain any small numbers that might suppress it, at energies above $M_* \sim$ TeV it leads to enormous cross sections, on the order of TeV$^{-2} \sim O(100)$ pb. More careful estimates result in production rates at the LHC as large as a black hole per second [8, 7].

4   Black hole decay

Once the black hole forms, it will decay very rapidly due to Hawking evaporation. But, where is this radiation emitted? This is a crucial point, since if the radiation were emitted into the KK modes of the bulk graviton it would escape our detectors and we would not be able to distinguish black hole formation from other missing energy events. In fact, a simple argument appears to lead precisely to this conclusion: Since the extra dimensions are assumed to be much larger than the black hole, from the point of view of a four-dimensional observer there is an enormous number of light KK modes, of mass

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[7]The extent to which the properties of the horizon are so universal and independent of the physics at short distances is closely related to the black hole no-hair conjecture, and to the problem of information loss.

[8]Semiclassical, if one also includes the decay via Hawking radiation.

smaller than the Hawking temperature. Emission into these modes would then overwhelm the radiation of the Standard Model particles that are emitted along the brane. Viewed another way, the phase space available for emission into the bulk is much larger than for emission along the brane, making virtually zero the fraction of energy that could possibly be detected.

Even if it was clear from early on that TeV-gravity scenarios greatly enhance black hole production [4, 5], these arguments prevented further discussion of their possible detection at colliders. However, in [6] a number of counterarguments were given to conclude that the outcome of the evaporation is emitted mostly along the brane and therefore can actually be detected. This opened the door to the studies of the actual phenomenology of the process [7, 8].

Instead of repeating the arguments of [6], here I will present an ellaboration of an equivalent but slightly different argument, originally due to L. Susskind.

The (erroneous) argument based on the fact that the number of KK modes is much larger than the number of brane modes assumes that Hawking radiation is emitted with roughly the same probability into all these KK modes and into the brane modes. Let us revisit this line of reasoning, but instead of labelling the KK modes by the momentum in the extra dimensions, in a plane-wave basis decomposition, we will decompose the modes in a basis of spherical harmonics. Then we classify the modes according to their partial-wave number ℓ. Viewed this way, the fact that there are many more modes coming from the $4+n$-dimensional bulk than from the four-dimensional brane is reflected in the fact that, for large ℓ, the degeneracy of a mode of given ℓ grows in the former case as $\propto \ell^{n+1}$, much faster than the degeneracy on the four-dimensional brane, which is well-known to be $2\ell + 1$, i.e., $\propto \ell$. Imagine now a hot object of characteristic size R, which is radiating thermally at a typical wavelength $\lambda \ll R$. There will be radiation into modes of partial-wave number up to the large value $\ell_{max} \sim R/\lambda$. Since there are many more of these modes in higher dimensions, much more radiation will go into the bulk than into the brane.

However, a black hole is not this sort of object. The typical wavelength of Hawking radiation is actually on the order of, or a little larger than, the black hole size, $\lambda_H \gtrsim R_{bh}$. So the black hole emits predominantly into s-wave modes with $\ell = 0$. The black hole does not make use of the large number of highly degenerate ℓ-angular modes that the higher-dimensional bulk provides. Since s-waves are non-degenerate, their number of modes is the same whether the field propagates in four or $4+n$ dimensions, so each brane mode is emitted at roughly the same rate as a bulk mode. In other words, the black hole does not see the angular directions, only the radial direction, which is common to modes propagating in any number of dimensions. In typical brane-world scenarios there are ~ 60 Standard Model modes propagating along the brane, versus a single graviton propagating in the bulk. Then the black hole will radiate mainly on the brane.

The evaporation time for one of these black holes will be extremely short. The black hole will typically be only a factor $\sim O(10)$ larger than the TeV scale, so its lifetime will be $\tau \sim O(10)$ TeV$^{-1} \sim 10^{-27}$ s, much shorter-lived than a typical hadronic resonance. The collider signatures for this Hawking radiation were analyzed in [7, 8]. One should look for events with high multiplicity, due to the large number of quanta emitted during the evaporation. Events could be tagged by the presence of promt leptons and photons, of energy $\sim O(100)$ GeV, and of similarly very energetic jets.

5   String balls

The semiclassical description of a black hole must break down when its mass is close to the fundamental mass scale of gravity M_*. But in string theory, if the string coupling g_s is weak, this description breaks down even at higher masses. When the black hole radius R_H gets smaller than the string length ℓ_s (and the black hole temperature gets higher than the Hagedorn temperature), the string corrections to the low energy effective action cannot be argued, as we did before, to be hidden inside the horizon, so one must resort to a stringy description. The critical mass where this happens, i.e., the minimum mass for which a semiclassical description of the black hole is reliable, is

$$M_{min} \sim M_s/g_s^2 \,, \tag{4}$$

and, for small g_s, this can be quite larger than $M_* \sim g_s^{-2/n+2} M_s$. In particular, this means that if $g_s \lesssim 0.3$, the LHC may not be able to probe the regime of black holes.

In this case, what one would be producing, instead of a black hole, is a highly excited configuration, a long, jagged, very massive string resonance: a *string ball*[9]. Over the years, a concept of correspondence between black holes and strings has been developed [17], according to which a black hole that evaporates down to the mass (4) makes a transition into a string ball. Subsequently, the string ball evaporates by emitting massless string modes at the Hagedorn temperature.

The production cross section for a string ball can be computed using string perturbation theory, by factorizing the four-point amplitude for forward, elastic string scattering in the resonant s-channel – one of the earliest calculations in string theory. This yields

$$\sigma \sim g_s^2 s/M_s^4 \,. \tag{5}$$

When viewed in the t channel, this four-point amplitude is dominated by graviton exchange. The latter indeed determines both the factor g_s^2, from tree-level exchange of a closed-string state, and the energy dependence $\propto s$, from the graviton pole. Therefore the result is universal for all string theories, since they all contain a graviton. So, besides factors that depend on the polarization of the ingoing particles, the result is independent of the initial states, as long as they are much lighter than $\sqrt{s}$.

This perturbative calculation will receive corrections at energies where the unitarity bounds are saturated, $g_s^2 s/M_s^2 \sim 1$. Above these energies, it seems reasonable to assume that the cross section saturates and remains constant at $\sigma \sim l_s^2 \sim M_s^{-2}$. This cross section then extends up to the energies (4) where the black holes form, and interpolates between all these regimes in a parametrically smooth manner. This simple argument provides evidence in favor of the geometric cross section (3).

It is clear that in scenarios with string scale near the TeV, string balls will be produced at rates as large as the black hole production rates discussed above. In fact, it may happen that only the string ball regime is accesible to the LHC. The decay modes and properties of string balls are also quite similar to those of black holes. A main difference is that the temperature of the radiation emitted (the average energy of the decay products) is fixed at the Hagedorn temperature, and is essentially independent of the mass of the string ball, whereas for black holes the temperature is smaller for larger black holes. This may help distinguish between both kinds of objects, and may also allow for a determination of parameters such as the string mass M_s.

Acknowledgements

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