String Balls at the LHC
and Beyond

Savas Dimopoulos[a] and Roberto Emparan[b*]

[a] *Physics Department, Stanford University, Stanford, CA 94305-4060, USA*
[b] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*

Abstract

In string theory, black holes have a minimum mass below which they transition into highly excited long and jagged strings — "string balls". These are the stringy progenitors of black holes; because they are lighter, in theories of TeV-gravity, they may be more accessible to the LHC or the VLHC. They share some of the characteristics of black holes, such as large production cross sections. Furthermore, they evaporate thermally at the Hagedorn temperature and give rise to high-multiplicity events containing hard primary photons and charged leptons, which have negligible standard-model background.

---

[*]Also at Depto. de Física Teórica, Universidad del País Vasco, Bilbao, Spain

Introduction: An exciting consequence of TeV-scale quantum gravity [1] is the possibility of producing black holes (BHs) [2–6] at the LHC and beyond. Simple estimates of their production cross section, treating the BHs as general relativistic (GR) objects, suggest enormous event rates at the LHC –as large as a BH per sec [5,6]. Furthermore, decays of the BHs into hard primary photons or charged leptons are a clean signature for detection, with negligible standard model background. The production and decay of the experimentally most accessible light black holes –those with mass M_{BH} near the fundamental Planck scale $M_P \sim$ TeV– is clouded by string-theoretic uncertainties. The purpose of this paper is to discuss these and point out the possible presence and properties of light stringy progenitors of the black holes.

According to string theory, the minimum mass M_{min} above which a black hole can be treated general-relativistically is $M_{min} \sim \frac{M_s}{g_s^2}$, where $M_s \sim$ TeV is the string scale and g_s is the string coupling –which should be smaller than 1, to trust string perturbation theory. Therefore, even for moderately small g_s, there is a significant mass range between M_s and M_{min} inside which the spectrum is intrinsically stringy and the GR approximation fails. Furthermore, the fundamental Planck scale M_P is typically smaller than M_{min}; so the GR approximation can fail even for masses larger than M_P. For example, if there are n new large and m small dimensions ($m + n = 6$) compactified on an m-torus of radius equal to the string length l_s, then $M_P = (2\pi)^{\frac{6-n}{2+n}} g_s^{-2/(2+n)} M_s$; so, M_P is less than M_{min} for any n, if g_s is less than $(2\pi)^{-2/3} \simeq .3$.

An example of a typical value of g_s in theories with large dimensions is $g_s = 2\alpha v_2/(2\pi l_s)^2$ [7], where v_2 is the volume contained by the two small dimensions; if v_2 is a two-torus with radius equal to l_s, then g_s is between 0.2 and 0.02 depending on which α we choose. Of course, increasing the size of v_2, we can geometrically dilute the value of α and accommodate larger values of g_s. We have nothing to add to the rough estimates of [5,6] in the case where g_s is near 1. For the rest of the paper we will consider the cases when g_s^2 is significantly less than 1 and there is a large stringy regime between the scales M_s and M_{min}.

The Correspondence Point: String theory has provided us with a convincing picture of the evolution of a black hole at the last stages of its evaporation [8–12]. As the black hole shrinks, it eventually reaches the "correspondence point" $M_{min} \sim M_s/g_s^2$, and makes a transition to a configuration dominated by a highly excited long string. At this point this "string ball" is compact, of size $\sim l_s$. It continues to lose mass by evaporation at the Hagedorn temperature, and (in six or more space-time dimensions) at a mass slightly below M_{min} it "puffs-up" to a larger "random-walk" size $R_{rw} \sim M^{1/2} l_s^{3/2}$. Evaporation, still at the Hagedorn temperature, then gradually brings the size of the string ball down towards l_s, after which it decays into massless quanta.

The rationale behind this picture is the following. On general grounds, the GR description of a neutral black hole in string theory is expected to receive large string corrections around the point where the Schwarzschild radius R_{BH} reaches the string length l_s. On the other hand, both a black hole and a highly excited long string are objects with a large degeneracy of states. Hence, it is natural to expect that when the black hole has evaporated down to a size $R_{BH} \sim l_s$ ($M \sim M_{min}$) it makes a transition to a configuration dominated by a highly excited long string. Note again that this may happen before reaching the Planck scale M_P; string corrections can become important already above the Planck mass.

For this picture to be reliable, the transition at the correspondence point has to be

smooth, at least parametrically. In particular, the number of microstates of both objects must be the same at the transition. The entropy of a long string is proportional to its length, i.e. to its mass, $S_{st} \sim M/M_s$, while the Bekenstein entropy of a black hole is proportional to its area, $S_{BH} \sim (M/M_P)^{(n+2)/(n+1)} \sim g_s^{-2}(g_s^2 M/M_S)^{(n+2)/(n+1)}$ (in $4+n$ dimensions); they match at $M \sim M_{min}$ [8–11]. Similarly, the Hagedorn temperature of the excited string matches the Hawking temperature of a black hole of mass M_{min}. A more subtle point is the comparison between their sizes. The black hole size at the correspondence point is $\sim l_s$. By contrast, an excited string has a tendency to spread as a random-walk. The step size of the random-walk is l_s, and its total length $(M/M_s)l_s$, so the average size of the random-walk, i.e. the radius of the string ball, is $R_{rw} \sim (M/M_s)^{1/2}l_s \gg l_s$. This, however, neglects the gravitational self-interaction of the string, which is responsible for keeping the string compact at $\sim l_s$ near the correspondence point [11,12]. For masses below this point self-gravity becomes less important, and for $n \geq 2$, the rapid fall-off of gravity very soon makes it insufficient to keep the size of the string down at l_s. So, shortly after the black hole/string ball transition, the string abruptly puffs-up from string-scale size to random-walk size [12]. As we will see, this may have observational consequences.

This correspondence picture also suggests that the production cross section for string balls will match the enormous black hole cross section at center of mass energies around M_s/g_s^2, but the transition may involve the effects of strong self-gravity around that energy.

String Ball Production: Let us first calculate the production of a long, highly excited string from the collision of two light string states at high s using string perturbation theory. Highly excited strings are the most likely outcome: due to the exponential degeneracy of string states at high energies, their phase space volume is much larger than that of light states with large kinetic energies. The amplitude for two string states to evolve into a single one, at level $N \sim s$, is most easily obtained by unitarity from the amplitude for forward scattering, $A(s, t \to 0)$: the residue at the resonant pole at $s \sim N$ yields the desired amplitude (squared). Take then the Virasoro-Shapiro four-point amplitude

$$A(s,t) = 2\pi g_s^2 \frac{\Gamma(-1-\alpha's/4)\Gamma(-1-\alpha't/4)\Gamma(-1-\alpha'u/4)}{\Gamma(2+\alpha's/4)\Gamma(2+\alpha't/4)\Gamma(2+\alpha'u/4)} \tag{1}$$

(with $s + t + u = -16/\alpha'$, and $\alpha' = l_s^2$ [13]). Near the pole at $\alpha's/4 \sim N \gg 1$, in the limit $t \to 0$,

$$A(s,t) \sim 2\pi g_s^2 \frac{N^2}{N - \alpha's/4 - i\epsilon} + (\text{terms analytic at } N = \alpha's/4). \tag{2}$$

The production cross section is

$$\sigma_{st} = \frac{\pi \text{Res } A(\alpha's/4 = N, t = 0)}{s} = g_s^2 \frac{\pi^2}{8}\alpha'^2 s. \tag{3}$$

Note that: (a) although we have used an amplitude with tachyons as external states, the result should be the same (up to polarization factors of the initial states) for any colliding particles with rest mass $\ll \sqrt{s}$. (b) In the limit $s \gg 1/\alpha'$, $t \to 0$, the amplitude (1) has long strings as resonances in the s-channel. Alternatively, the t-channel is dominated by the exchange of a massless closed string over a large distance: the cross section (3) is obtained

from single graviton exchange. Since the latter is universal, it follows that any theory of strings that contains a graviton will lead, up to numerical factors, to the same result (3). (c) The external states are closed strings. Open strings can also exchange closed strings, hence gravitons, so the result above will still be true for them[1]. For open strings there is also the possibility that the intermediate t-channel state is a single open string, instead of a closed string. The Veneziano amplitude, appropriate for that case, gives the cross section for production of a long open string as $\sigma_{ost} = \pi g_o^2 \alpha'$, *i.e.* it is constant. Here g_o is the coupling of open strings. Normally, $g_o^2 \sim g_s$, which implies that this cross section will be subleading with respect to (3) at energies above $M_s/\sqrt{g_s}$ and, for simplicity, we will ignore it. (d) The cross section (3) saturates the unitarity bounds at around $g_s^2 s \alpha' \sim 1$ [14]. This implies that the production cross section for string balls grows with s as in (3) only for $M_s < \sqrt{s} \leq M_s/g_s$, while for $\sqrt{s} > M_s/g_s$ it will remain constant at a value $\sigma_{st} \sim l_s^2$.[2] This matches the black hole cross section $\sigma_{BH} \sim l_s^2 (g_s^2 M/M_s)^{\frac{2}{n+1}}$ at the correspondence point. Conversely, in light of the correspondence principle, the computation of the string ball cross section at the correspondence point can be viewed as a calculation of the black hole production cross section. The agreement with the geometric cross section used in references [3,5,6] may help dispel concerns that the BH production rate is suppressed [15].

In summary, the elementary (parton) cross section for string ball/BH production is

$$
\sigma \sim \begin{cases}
\dfrac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \leq M_s/g_s \,, \\[2ex]
\dfrac{1}{M_s^2} & M_s/g_s < M_{SB} \leq M_s/g_s^2 \,, \\[2ex]
\dfrac{1}{M_P^2}\left(\dfrac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH} \,.
\end{cases}
\tag{4}
$$

M_{SB} (M_{BH}) is the mass of the string ball (black hole), and we have used $\alpha' = M_s^{-2}$.

The first two mass ranges lead to string balls, the third to black holes. The cross section interpolates between them and, in all cases, is large. For example, if $M_s \sim$ TeV, the cross section in the middle range is ~ 400 pb. If there were no kinematical suppressions, given the LHC luminosity of 30 fb^{-1}/year, this would give about 10^7 events per year. However, a string ball is made out of long jagged string and, consequently, is heavier than M_s; to produce it we need to rely on rare collisions between partons carrying a significant fraction of the total LHC energy ~ 14 TeV. The calculation of string ball production is quantitatively close to that of heavy BH production [5,6]. From fig. 2 of ref. [5] we see that even for a fundamental scale of up to ~ 4 TeV, there is a significant number of BHs with mass ~ 10 TeV produced. We expect the same for string balls. As the ratio of M_{SB}/M_s drops to a few, we may legitimately question the "long and jagged string" picture of a string ball. Here we have been assuming that the cross section we use to estimate the production of long strings is adequate for $M_{SB}/M_s \sim 3$. Of course, at the VLHC the parameter space to be explored and the reliability of our estimates will expand significantly.

---

[1] s-channel factorization of the amplitude with external open strings leads to the production of *two* long open strings. This doubling will be unimportant to what follows.

[2] We thank G. Veneziano for this point.

We do not expect the string balls to be the very first indication of TeV-gravity; low-lying string states and missing energy through graviton evaporation are more likely "discovery" candidates. String balls are interesting because they are a new form of matter which bridges strings and gravity.

String Ball Evaporation: Highly excited long strings (averaged over degenerate states of the same mass) emit massless particles with a thermal spectrum at the Hagedorn temperature [16]. Hence, the conventional description of evaporation in terms of black body emission can be applied[3]. In our case, the emission can take place either in the bulk (into closed strings) or on the brane (into open strings). The temperature is the same in both cases, $T = T_H = \frac{M_s}{2\sqrt{2}\pi}$ (for type II strings).

For a compact string ball of size l_s there is only this scale in the problem. Arguing as in [19,4] one concludes that the radiation is distributed roughly equally into all brane and bulk modes. Another way to understand this [20] is to note that the wavelength $\lambda = \frac{2\pi}{T_H}$ corresponding to the Hawking temperature is larger than the size of the black hole. So, the BH (or the compact string ball) is, to first approximation, a point-radiator and, consequently, emits mostly s-waves. This indicates that it decays equally to a particle on the brane and in the bulk, since s-wave emission is sensitive only to the radial coordinate and does not make use of the extra angular modes available in the bulk. Because there are many more species of particles (~ 60) on our brane than in the bulk, this has the crucial consequence that the radiator decays visibly to standard model (SM) particles [4,20].

However, when the string ball puffs-up to the larger random-walk size, its spatial extent can approach or exceed the wavelength of the emitted quanta, which implies that it can use more of the higher angular modes that the additional dimensions provide. We can estimate how many of these will become available. First note that the radius of the string ball has increased to $l_s\sqrt{M/M_s}$, which near the correspondence point (when the string ball is largest) is l_s/g_s. A black body of radius R emits modes with angular momentum $l \leq l_{max} = \omega R$, where $\omega = T_H = M_s/2\sqrt{2}\pi$ is the frequency of the radiation. So for $R = l_s/g_s$ we get $l_{max} = 1/2\sqrt{2}\pi g_s$; for g_s around 0.1 this means $l = 1$ or 2. In $4 + n$ dimensions the degeneracy of angular momentum modes is $\frac{2l+n+1}{n+1}\binom{l+n}{l}$ compared to the degeneracy $2l + 1$ in 4 dimensions. For $n = 2$ and $l = 1$ (2) the relative enhancement for the bulk modes is $5/3$ ($33/8$), which implies an increase of the radiation into the bulk, but still outnumbered by the brane modes. The same conclusion follows from the black body radiation formula $dE_D/dt \sim A_D T^D$ (A_D is the area of the radiator in D dimensions) [4,19]: for a random-walk-size string ball at the Hagedorn temperature the relative enhancement of bulk radiation is $(dE_{4+n}/dt)/(dE_4/dt) \sim (2\sqrt{2}\pi g_s)^{-n}$, which is again of order one for $n = 2$ and $g_s \sim 0.1$. With more extra dimensions, larger angular momentum, and smaller g_s the above formulas give a rapid relative increase in the number of bulk modes, which eventually dominate the radiation. This, however, is a temporary effect: as the string ball decays, its size shrinks towards l_s and, once again, it becomes a small radiator emitting mostly on the brane.

A string ball of mass M will decay, on the average, into roughly M/T_H particles of mean

---

[3]The string ball may also break into two large pieces by opening two new endpoints on the three-brane. However, the results of [17,18] suggest that it will not disintegrate completely through this mechanism. Then it will evaporate mostly via thermal radiation.

TABLE I. New particles and their associated mass scales. Typically, $M_s < M_P < M_s/g_s^2$.

Particles	Mass Scale
1. Higher-dimensional graviton	M_P
2. Low-lying string excitations	M_s
3. String Balls	$M_s \ll E \leq M_s/g_s^2$
4. Black Holes	$E > M_s/g_s^2$

energy $\sim T_H$. Just like BHs, the ensemble of string balls should decay about equally to each of the ≈ 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 charged leptons and $\sim 2\%$ of the particles to be hard photons, each carrying hundreds of GeV of energy. This is a clean signal, with negligible background, as the production of leptons or photons through SM processes in high-multiplicity events at the LHC occurs at a much smaller rate than the string ball production. These events are also easy to trigger on, since they contain at least one prompt lepton or photon with energy above 100 GeV, as well as energetic quark and gluon jets. Measuring the mean energy of the decay products determines the Hagedorn temperature and, consequently, the string mass scale M_s.

The fraction of missing energy in string ball events could be an interesting probe of TeV-gravity physics. The neutrinos' contribution is small, since they account for just $\sim 5\%$ of the final particles. On the other hand, significant amounts of missing energy –resulting from bulk emission from a puffed-up string ball– could signal the presence of several large new dimensions.

Conclusions: TeV-gravity theories have at least four new types of particles and three associated mass scales, as shown in the table. If $g_s \sim 1$, the mass scales coincide and calculability is lost; BHs are expected to dominate the dynamics above M_s. If $g_s^2 \ll 1$, then there is a separation between the mass scales and we expect to probe the physics of the particles roughly in the order 1, 2, 3, 4. In this case LHC may be able to probe the physics of string balls, but is less likely to produce BHs. Higher energy colliders, such as the VLHC, will have a better chance of studying BHs. Through their evaporation, black holes will evolve into string balls and, eventually, into low-lying string states, giving us a glimpse of all the stages of this exciting physics.

Acknowledgements

REFERENCES

[1] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **429** (1998) 263 [hep-ph/9803315]; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **436** (1998) 257 [hep-ph/9804398]; N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. D **59** (1999) 086004 [hep-ph/9807344].

[2] P. C. Argyres, S. Dimopoulos and J. March-Russell, Phys. Lett. B **441** (1998) 96 [hep-th/9808138].

[3] T. Banks and W. Fischler, hep-th/9906038.

[4] R. Emparan, G.T. Horowitz, and R.C. Myers, Phys. Rev. Lett. **85**, 499 (2000) [hep-th/0003118].

[5] S. Dimopoulos and G. Landsberg, hep-ph/0106295. Results presented at the Les Houches Workshop "Physics at the TeV Colliders" (May 30, 2001) and the "Avatars of M-Theory" conference, ITP at Santa Barbara (June 7, 2001), http://online.itp.ucsb.edu/online/mtheory_c01/dimopoulos.

[6] S. B. Giddings and S. Thomas, hep-ph/0106219.

[7] G. Shiu and S. H. Tye, Phys. Rev. D **58** (1998) 106007 [hep-th/9805157].

[8] M. J. Bowick, L. Smolin and L. C. Wijewardhana, Phys. Rev. Lett. **56** (1986) 424.

[9] L. Susskind, hep-th/9309145; E. Halyo, A. Rajaraman and L. Susskind, Phys. Lett. B **392** (1997) 319 [hep-th/9605112]; E. Halyo, B. Kol, A. Rajaraman and L. Susskind, Phys. Lett. B **401** (1997) 15 [hep-th/9609075].

[10] G. Veneziano, in *NATO Advanced Study Workshop on Hot Hadronic Matter: Theory and Experiment,* Divonne-les-Bains, France, 27 Jun - 1 Jul 1994.

[11] G. T. Horowitz and J. Polchinski, Phys. Rev. D **55** (1997) 6189 [hep-th/9612146]; Phys. Rev. D **57** (1998) 2557 [hep-th/9707170].

[12] T. Damour and G. Veneziano, Nucl. Phys. B **568** (2000) 93 [hep-th/9907030].

[13] M. B. Green, J. H. Schwarz and E. Witten, "Superstring Theory. Vol. 1," CUP, Cambridge, UK (1987); J. Polchinski, "String theory. Vol. 1," CUP, Cambridge, UK (1998).

[14] D. Amati, M. Ciafaloni and G. Veneziano, Phys. Lett. B **197** (1987) 81; Int. J. Mod. Phys. A **3** (1988) 1615.

[15] M. B. Voloshin, hep-ph/0107119.

[16] D. Amati and J. G. Russo, Phys. Lett. B **454** (1999) 207 [hep-th/9901092].

[17] D. A. Lowe and L. Thorlacius, Phys. Rev. D **51** (1995) 665 [hep-th/9408134].

[18] S. A. Abel, J. L. F. Barbón, I. I. Kogan and E. Rabinovici, JHEP **9904** (1999) 015 [hep-th/9902058].

[19] R. Emparan, G.T. Horowitz, and R.C. Myers, J. High Energy Phys. **01** (2000) 7 [hep-th/9911043].

[20] L. Susskind, private communication.