Black Hole production at the Large Hadron Collider

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Received 15 September 2003;
final version 15 September 2003

The talk upon which this note is based attempted to describe the conjectured stages of microscopic black hole production-and-decay in extra-dimensional scenarios at the LHC. The talk tried to make clear which of these stages could be regarded as theoretically sound, and which should be thought of as mere guesswork. The talk also described new work by Harris *et.al.* who have successfully calculated the (4+n)-dimensional "grey-body factors" which describe the slight differences expected between the emissions of black holes and classical black bodies.

PACS: 04.70.Dy, 14.80.-j, 13.85.Qk
Key words: Black Holes, Large Hadron Collider, LHC,
Extra Dimensions, Grey Body Factors

1 Introduction

It is commonly believed that black hole production will occur as a result of collisions between any two particles with a centre-of-mass energy exceeding the Planck scale. If the Planck scale really is as high as it appears to be ($\sim 10^{18}$ TeV), then current particle colliders are many orders of magnitude away from being able to produce black holes. However, spacetime models with extra dimensions can allow the "fundamental" (4+n)-dimensional Planck scale to be much lower than the "apparent" 4-dimensional Planck scale. This leads to the prospect that black hole production could be within the reach of future TeV colliders like the Large Hadron Collider (LHC).

It is not the intention of this note to discuss the details of the extra-dimensional models which allow TeV scale black hole production. Readers interested in these aspects are referred to discussions elsewhere such as [1–6]. For our purposes it is sufficient to remark upon the common features of these models. Most posit a world based upon a 4-dimensional brane embedded in a (4+n)-dimensional spacetime. Standard Model particles and forces are typically considered confined to the brane, while gravity is the only force deemed able to propagate in "the bulk" (*i.e.* in all (4+n)-dimensions). The apparent weakness of gravity (and thus the large value of the apparent Planck scale) is therefore in these models attributed to the leakage of gravity into the extra dimensions and away from the brane. If M_P is the fundamental (4+n)-dimensional Planck scale, $M_{P(4)}$ is its apparent 4-dimensional analogue, and R is the size of all n extra dimensions, then it may be shown (*e.g.* [1]) that the two scales are related by

$$M_{P(4)}^2 \sim M_P^{n+2} R^n. \tag{1}$$

This relation allows one to put a lower limit on the scale of the extra dimensions R necessary for production of black holes at the LHC. Short-scale tests of gravity, collider experiments, astrophysical and cosmological data all place limits [1, 7] on the allowed number of extra dimensions. The consensus is that $n{=}1$ and $n{=}2$ are ruled out by these tests.

2 Black Hole Production

Many particle physicists, particularly those who have not investigated black hole creation at colliders in much depth, are inclined to believe that the whole topic is "a load of baloney". There seems to be a perception amongst members of this camp that the predictions of the field are little more than "order of magnitude calculations" or "plausible results based on scaling arguments alone". A typical source of derision is the oft-quoted suggestion that the cross section σ for the production of black holes might be described by

$$\sigma \approx \alpha \pi r^2, \tag{2}$$

in which the black hole radius r would depend on the mass of the generated black hole, which itself would depend upon the available collision energy $\sqrt{s}$, and α is a dimensionless constant of proportionality. The superficial similarity between equation (2) and the formula for the area of a circle leads people to believe that black hole theorists are just stabbing in the dark.

While it is true that there *are* many areas of theory in this field which *are* little more than guesswork, (and we will come to them later), I would strongly argue that equation (2) ought *not* to be dismissed as one of them.

Remember that in these models, the fundamental Planck scale M_P could be as little as 1 TeV. This means that particles in collision at the LHC could have centre of mass energies far in excess of M_P. Such collisions may be termed "super-Planckian" (similarly "Planckian" and "sub-Planckian" for the other regimes). It follows that the right theory to consider super-Planckian collisions (at least as far as gravity is concerned) is *classical* general relativity, not a quantum theory.

To reiterate: the assertion is that if the energy scales of a collision are much larger than the (presumably M_P-scale) fluctuations associated with some unknown quantum theory of gravity, then these fluctuations should average out and leave us with the classical prediction.

We will return to the classical super-Planckian predictions in a moment, but as an aside one should remark that even the most enthusiastic "black hole physicist" must throw up her hands and acknowledge that what happens in the *Planckian regime* is anybody's guess! Understanding this regime would surely need a quantum theory of gravity. The reason that interest in the black holes persists, despite such a gaping hole in our knowledge, is the indication that super-Planckian production *alone* could easily provide large hard-to-miss black hole signals for the next generation of colliders (see also Fig. 2).

Now back to classical super-Planckian predictions. I think it is fair to say that support for equation (2) has been around for a quite a while in the General Relativity community, even if only at and "order of magnitude" description. Certainly [8] was referring to it in 1999, although the idea was much older. However, it seems not to have been till 2001 that the idea became widely known within the experimental physics community after the publication of [5], which again motivated the result purely on geometrical grounds. Maybe the over emphasis on scaling arguments is what has made the sceptics suspicious. How can they be won over?

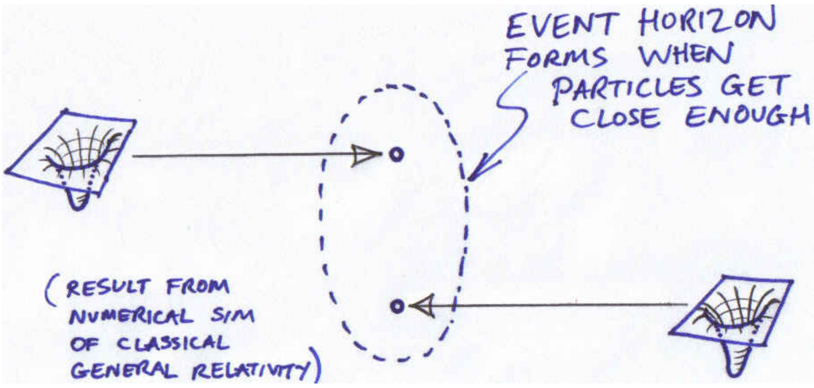

Fig. 1. Schematic illustration of the method by which collider production of black holes is simulated using numerical general relativity.

I find the strongest real support for equation (2) in articles like [9]. The approach of the authors of this and similar papers is to perform a complete numerical $(4+n)$-dimensional General-Relativistic simulation of the whole process of a collision between two relativistic particles. As they vary the energies and impact parameters of the incoming particles, they can monitor whether or not an event horizon forms, and if one does, they can even determine its shape. Each incoming particle is modelled by taking the Schwarzschild solution corresponding to a particle of mass μ, and then infinitely boosting it along one of the incoming directions, while at the same time tuning the mass μ down so as to leave the total energy E fixed. The resulting system has been described as "a massless point particle accompanied by a plane-fronted gravitational shock wave which is the Lorentz-contracted longitudinal gravitational field of the particle" (from [9]). The process is illustrated schematically in Fig. 1. Simulations by this method have confirmed that equation (2) really *is* a reasonable model, and have even determined appropriate values for the constant of proportionality α. For example, [9] finds $\alpha_{n=2} \approx 1.341$ and $\alpha_{n=6} \approx 1.819$.

The growth of α with the number of extra dimensions hints that there is scope for improvement in equation (2). Indeed, it seems one can better fit the numerical results of [9] by replacing the the "linear" notion above (that formation of a black hole requires the particles to have an impact parameter which is less than their combined Schwarzschild radius) with the "volumetric conjecture" that black hole formation occurs in collisions whose minimal characteristic $(n+1)$-dimensional

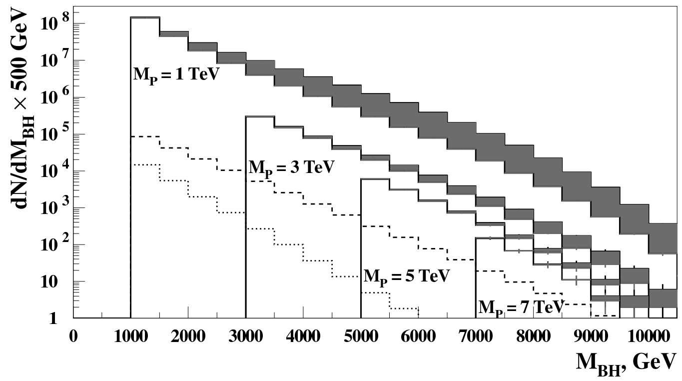

Fig. 2. This figure (from [5]) shows how the cross sections for super-Planckian black hole production at the LHC would compare to the expected SM background (dashed line). The figure assumes 100 fb^{-1} of integrated luminosity, and assumes at least one hard lepton or photon per event. Note the arbitrary cut offs for values of M_{BH} below M_P (the transition to the Planckian regime). Presumably production still happens in this region, the problem is only that we don't know how to calculate it. The dotted line is described in [5].

volume is less than the $(n+1)$-dimensional volume of the black hole into which they might collapse. [Note that these two conjectures are equivalent in ordinary 4-dimensional spacetime.]

To summarise this section; the rate of super-Planckian black hole production at hadron colliders in models with large extra dimensions appears to be well understood. In contrast, much less (almost nothing) is known about Planckian black hole production!

3 Black Hole Life Cycle

Fig. 3 illustrates the conjectured life cycle of a black hole produced at the LHC. The first stage, production, has been discussed at some length in the preceding section. What about the decay stages? There is widespread agreement that the (initial) decay of super-Planckian black holes should be treated classically. That is to say that, as in the stellar case, the initially formed hole is expected to shake off its higher angular momentum modes quickly, as gravitational radiation, until the hole is described by a small set of parameters (namely its mass, spin, and charges). This stage (termed "hair loss") would be expected to be followed by a combination of the two next phases; "spin-down" (the process by which the angular momentum is gradually lost to the surroundings) and the evaporation phase, in which vacuum fluctuations in the vicinity of the horizon cause the black hole to gradually lose mass through nearly-thermal Hawking radiation. Most calculations (*e.g.* [4]) suggest that the majority ($\sim 90\%$) of the radiation emitted in the spin-down and evaporation phases consists of Standard Model particles radiated on the brane, rather than via gravitons into the bulk (mainly due to the larger number of Standard Model

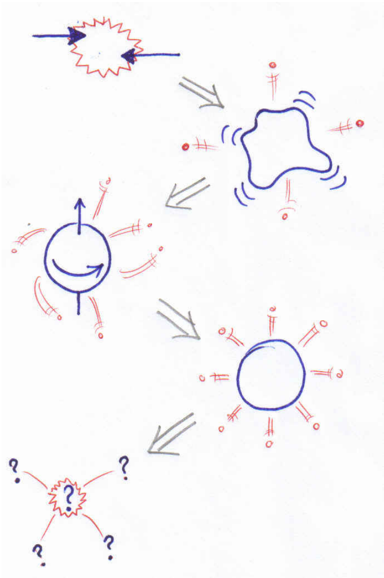

Fig. 3. Schematic illustration of the life cycle of a (super-Planckian) black hole produced in particle collision. From top to bottom; 1) production, 2) hair loss, 3) spin down, 4) hawking radiation, and 5) remnant decay.

degrees of freedom available). With neutrinos only accounting for about 5% of the Standard Model radiation, approximately 85% of the energy released in the decay is expected to be visible to LHC experiments like ATLAS and CMS.

Provided the mass of the black hole stays well above the Planck scale, there is agreement that the process described above should be a reasonable description of physics. What happens in the subsequent Planckian phase or "remnant decay" (when the mass approaches M_P) is anyone's guess, however, and is parametrised in a variety of ways by generators. About the only things that are agreed upon is that the decay should probably conserve momentum, and maybe even the long-range charges carried by the hole. Whether the remnant decay should conserve things like baryon number, however, is not known.

But even when considering only the *classical* part of the decay, problems arise when the black hole starts to approach the Planck mass.

Take for example the Hawking radiation. Hawking radiation from a heavy black hole of mass M is essentially thermal at a temperature,

$$T \propto M^{\frac{-1}{n+1}}, \tag{3}$$

where the constant of proportionality depends on the Planck scale and n but not M. In actual fact the radiation is probably not quite thermal (the differences being parametrised by so-called "grey-body factors" which we will come to later) but we can ignore these details for the moment. Now for any fixed temperature T, the spectrum of a black body has a tail which extends to arbitrarily high energies. This means that for any given energy E, however large, there is a small but finite chance that the energy of the next thermal emission will exceed E. Of course, this tail falls off so rapidly that it is irrelevant under normal circumstances. The hot cup of tea on your desk will never radiate its entire heat energy in one photon, even if you wait many times the age of the universe. In fact, because your cup of tea gets *colder* with every bit of energy it loses, it gets harder and harder for your tea to toast you with each passing second!

With black holes the situation is reversed.

Equation 3 tells us that that the temperature of the black hole *rises* as the black hole loses mass. As a result, the mean energy of emission grows rapidly while the available mass from which to form the radiation dwindles. There eventually comes a time (particularly as the black hole mass approaches the Planck mass) when the probability of the next emission using up *more* energy than the mass of the black hole becomes very large. Of course, such emissions should not be taken seriously. We don't expect them to be physically valid. What they are telling us instead is that when the black hole becomes too small and hot, assumptions that went into the initial prediction of thermal radiation must now be breaking down. The black-body spectrum is clearly no longer the right thing to use in this regime.

And what about thermal equilibrium? As the black hole gets hotter and emissions get closer together and constitute ever greater fractions of the black hole's mass, can we still meaningfully say that all parts of the black hole have enough time between emissions to equilibriate to a new temperature? Not everyone seems to agree on this. This leads to competing schemes. In some of these the temperature is treated as a function of the mass of the black hole *as it decays*, whereas in others it is treated as a fixed parameter governed by the *initial* mass of the black hole. Black hole event generators (such as [10]) give options that allow users to specify which of these modes they desire.

Whatever temperature scheme is used, there still remains the question of which spectrum to use for the radiation in order to guarantee that emissions do not exceed the black hole's own mass M, even when it is still well above the Planck scale. Some people just cut the usual black body spectrum off above M, while others treat the first attempted emission above M as a signal that the decay be considered to have entered the non-classical remnant decay "early".

In summary, one would have to concede that there is more disagreement over the precise way collider produced black holes should be expected to decay, than over the way they might form. Nevertheless, there is agreement that the vast majority of the decay products should be visible to LHC experiments as Standard Model particles. The events should be easy to spot, being high-multiplicity, high-invariant-mass, spherical events. The Hawking radiation produced in the decay is expected to make up most of the debris and to be composed of about 2% photons, 5% neutrinos, 10% charged leptons, and the remainder as hadronic jets.

4 Experimental Signals

The talk upon which this note is based did not dwell long on the *experimental* issues relating to the discovery of black hole at the LHC, but a few comments on them would seem relevant here.

If black holes are produced at the LHC, it looks like their events will be relatively easy to spot. As mentioned above, they are characterised by high-multiplicity, high-invariant-mass, and high sphericity (in the centre of mass frame!). With only $\sim 15\%$ of the decay products being invisible, relatively simple reconstruction techniques should serve to reconstruct the masses of black holes on an event-by-event basis to $\sim 20\%$ accuracy or better.

More exciting is the prospect of determining the number of extra dimensions. If the initial temperature of the black holes could be determined on an event-by-event basis, then equation (3) could be used to recover the value of n. One suggested method for obtaining T for a given event is, roughly speaking, to perform a maximum likelihood fit of the observed electron, muon and photon energies to a black body spectrum, interpreting the temperature so obtained as the Hawking temperature of the black hole. In practice, errors can be improved by first collecting events into bins of reconstructed black hole masses. Early proponents of this method [5] were pretty upbeat about its prospects, but the results of [11] seem to be suggesting that the value of n obtained by this method can be very sensitive to the parts of the physics that we don't know much about. In other words, if you change your temperature model from fixed to varying (or generate according to one model and interpret the results according to another) then you can get very differing results. The investigations in [11] seek to identify variables which are less sensitive to the unknown physics of remnant decay and temperature models, or at least to understand how the results vary with the assumptions. It seems to be a tricky problem, and I don't think there will be an easy answer.

5 Grey-body Factors

One of the recent advances in the theory of black hole decay concerns the "grey-body factors" mentioned earlier. These describe the modifications to the black body spectrum which are expected to arise from the (spin dependent) scattering of the emitted particles from the potential well of the black hole. Analytic grey body factors for black holes in 4-dimensions have been known for some time. The way one would try to generalise these to higher numbers of dimensions has also been known for a while. Indeed, attempts have already been made to produce analytic approximations to the $(4{+}n)$-dimensional grey-body factors [12, 13]. The new grey-body results reported at the conference "Physics at LHC, LHC-Praha-2003" concerned the work of Harris *et. al.* [14] which has shown that the range of validity of the above approximations to the $(4{+}n)$-dimensional grey-body factors is much smaller then previously thought. Harris *et. al.* go on to remedy this situation, by calculating *exact* $(4{+}n)$-dimensional grey-body factors for scalars, fermions, and spin-1 particles by numerical means. The resulting grey-body factors for $n = 2, 3, 4, 5, 6$ and 7 extra dimensions have been incorporated into the CHARYBDIS event generator [10].

6 Summary

In extra dimensional scenarios where all fields except the graviton are confined to a 4-brane, the fundamental Planck scale can be as low as 1 TeV without violating present experimental bounds. This leads to the prospect that microscopic black holes could be produced in large numbers at the LHC, and seen via their evaporative decays into (predominantly) Standard Model particles. This note reviews the credibility of some aspects of the theory concerning the production and decay of these black holes, and comments on how they might be identified experimentally.

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