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CHARYBDIS: a black hole event generator

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Abstract: CHARYBDIS is an event generator which simulates the production and decay of miniature black holes at hadronic colliders as might be possible in certain extra dimension models. It interfaces via the Les Houches accord to general purpose Monte Carlo programs like HERWIG and PYTHIA which then perform the parton evolution and hadronization. The event generator includes the extra-dimensional 'grey-body' effects as well as the change in the temperature of the black hole as the decay progresses. Various options for modelling the Planck-scale terminal decay are provided.

Keywords: Beyond Standard Model, Extra Large Dimensions, Hadronic Colliders, Black Holes.

Contents

1. Introduction

Models with extra dimensions have become an area of much interest since the work of Arkani-Hamed, Dimopoulos and Dvali (ADD) [1] and Randall and Sundrum (RS) [2]. Like most models of physics beyond the Standard Model they are seen as a more natural way of explaining the hierarchy problem, that is, why there are about sixteen orders of magnitude between the electroweak energy scale and the Planck scale at which gravity becomes large. Such extra dimension models can also be motivated from string theory.

In extra dimension models, the usual 4-dimensional Planck scale is no longer considered to be a fundamental scale — instead it is derived from the fundamental D-dimensional Planck scale which can be as low as current experimental limits allow ($\sim 1\,\text{TeV}$).

If the fundamental Planck scale is of order a TeV, gravity is strong at such scales and cannot be ignored as is usually the case in particle physics. The possibility then arises of particle accelerators at TeV-scale energies being able to produce miniature black holes. These would then decay rapidly[1] by Hawking evaporation, giving rise to characteristic high-multiplicity final states.

There has already been much discussion in the literature on this issue, but little work has been done trying to realistically simulate black holes at the Large Hadron Collider (LHC). In this work we implement a simple model of black hole production and decay which can be interfaced to existing Monte Carlo programs using the Les Houches accord [4]. The major new theoretical input to the generator is the inclusion of the recently calculated 'grey-body' factors for black holes in extra dimensions [5]–[7]. We also take account of the recoil and change of temperature of the black hole during decay, and provide various models for the termination of the decay process.

[1]This is only true in the ADD model; in the RS model the black holes can be stable on collider time scales [3].

2. Black hole production and decay

The details of production and decay of black holes in extra dimension models are complicated and not particularly well understood. Here we outline the theory and mention some of the assumptions which are usually made.

In theories with extra dimensions the $\sim$ TeV energy scale is considered as fundamental — the 4D Planck scale ($M_{p(4)} \sim 10^{18}$ GeV) is then derived from it. The relationship between the two energy scales is determined by the volume of the extra dimensions. If R is the size of all n extra dimensions it can be shown, using Gauss' Law, that for $r \ll R$ then

$$V(r) \sim \frac{M}{M_p^{n+2}} \frac{1}{r^{n+1}} , \tag{2.1}$$

whereas for $r \gg R$

$$V(r) \sim \frac{M}{M_p^{n+2} R^n} \frac{1}{r} . \tag{2.2}$$

In these expressions M_p is the $(4+n)$-dimensional Planck mass (throughout this paper the conventions of [8] are used for M_p). They show that the two energy scales are related (up to volume factors of order unity) by

$$M_{p(4)}^2 \sim M_p^{n+2} R^n , \tag{2.3}$$

which allows the sizes of extra dimensions to be calculated for different values of n [1]. Short scale gravity experiments and particle collider experiments provide limits on the fundamental Planck scale. However for the smaller values of n, the more stringent constraints come from astrophysical and cosmological data, albeit with larger uncertainties. It is widely agreed that both $n = 1$ and $n = 2$ are ruled out by such data. For a comprehensive recent review of these constraints see, for example, [9].

As the fundamental Planck scale is as low as $\sim$ TeV, it is possible for tiny black holes to be produced at the LHC when two partons pass within the horizon radius set by their centre-of-mass energy. The black holes being considered in this work are in the $r \ll R$ regime, so an analogous approach to the usual 4D Schwarzschild calculation [10] shows the horizon radius for a non-spinning black hole to be

$$r_h = \frac{1}{\sqrt{\pi} M_p} \left(\frac{M_{BH}}{M_p} \right)^{\frac{1}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}} , \tag{2.4}$$

where M_{BH} is the mass of the black hole.

There has been much discussion in the literature (e.g. [11]–[15]) about what the cross section for black hole production is, but the consensus opinion seems to be that the classical $\sigma \sim \pi r_h^2$ is valid (at least for black hole masses $M_{BH} \gg M_p$). It is unclear for exactly what mass this cross section estimate starts to become unreliable, but for M_{BH} close to the fundamental Planck scale a theory of quantum gravity would be required to determine the cross section. The black holes produced may have any gauge and spin quantum numbers so to determine the $p - p$ or $\overline{p} - p$ production cross section it is necessary to sum over all possible quark and gluon pairings. Although the parton-level cross sections grows with black hole mass, the parton distribution functions (pdfs) fall rapidly at high energies and so the cross section also falls off quickly.

Once produced, these miniature black holes are expected to decay instantaneously on LHC detector time scales (typical lifetimes are $\sim 10^{-26}\ s$). The decay is made up of three major phases:

- The balding phase in which the 'hair' (asymmetry and moments due to the violent production process) is lost;
- A Hawking evaporation [16] phase (a brief spin-down phase during which angular momentum is shed from a Kerr black hole, then a longer Schwarzschild phase);
- A Planck phase at the end of the decay when the mass and / or the Hawking temperature approach the Planck scale.

It has been shown in [17] that the majority of energy in Hawking radiation is emitted into modes on the brane (i.e. as Standard Model particles) but a small amount is also emitted into modes in the bulk (i.e. as gravitons). We assume the latter to be negligible.[2]

In 4D the phase which accounts for the greatest proportion of the mass loss is the Schwarzschild phase [18]. A black hole of a particular mass is characterized by a Hawking temperature and as the decay progresses the black hole mass falls and the temperature rises. It is assumed that a quasi-stationary approach to the decay is valid, that is, the black hole has time to come into equilibrium at each new temperature before the next particle is emitted.

For an uncharged, non-rotating black hole the decay spectrum is described by the following expression:

$$\frac{dN_{s,l,m}}{d\omega dt} = \frac{1}{2\pi}\frac{\Gamma_{s,l,m}}{\exp[\omega/T_H] \mp 1}, \tag{2.5}$$

where s is the spin of the polarization degree of freedom being considered, l and m are angular momentum quantum numbers, and Γ are the so-called 'grey-body' factors. The last term in the denominator is a spin statistics factor which is -1 for bosons and $+1$ for fermions. The Hawking temperature in (2.5) is given by

$$T_H = \frac{n+1}{4\pi r_h}. \tag{2.6}$$

Equation (2.5) can be used to determine the decay spectrum for a particular particle, e.g. electrons. Since there are two polarizations for spin-$\frac{1}{2}$ we obtain:

$$\frac{dN_{e^-}}{d\omega dt} = 2\sum_{l,m}\frac{dN_{1/2,l,m}}{d\omega dt}. \tag{2.7}$$

The expression for a particular flavour of quark would be identical but with an additional colour factor. Slightly more care is required with massive gauge bosons since one of their

[2]For further discussion see [19, 7].

degrees of freedom comes from the Higgs mechanism. This means that, for example,

$$\frac{dN_{W^-}}{d\omega dt} = 2\sum_{l,m} \frac{dN_{1,l,m}}{d\omega dt} + \sum_{l,m} \frac{dN_{0,l,m}}{d\omega dt} \,. \tag{2.8}$$

The grey-body factors modify the spectrum of emitted particles from that of a perfect thermal black body *even* in 4D [16]. They quantify the probability of transmission of the particles through the curved space-time outside the horizon, and can be determined from the absorption cross section for the emitted particle species. For the Schwarzschild phase with $\omega \gg T_H$ geometric arguments show that $\Sigma_{l,m}\Gamma \propto (\omega r_h)^2$ in any number of dimensions, which means that at high energies the shape of the spectrum is like that of a black body. However the low energy behaviour of the grey-body factors is spin-dependent and also depends on the number of dimensions.

In 4D it has long been known that for $s = 0, \frac{1}{2}$ and 1 the grey-body factors reduce the low energy emission rate significantly below the geometrical optics value [18, 20]. The result is that both the flux and power spectra peak at higher energies than those for a black body at the same temperature. The spin dependence of the grey-body factors means that they are necessary to determine the relative emissivities of different particle types from a black hole. Until recently (see [5]–[7]) these have only been available in the literature for the 4D case [18, 21].

The dependence both on energy and the number of dimensions means that the grey-body factors must be taken into account in any attempt to determine the number of extra dimensions by studying the energy spectra of particles emitted from a black hole. When studying black hole decay, other experimental variables may also be sensitive to these grey-body effects.

Finally, although the Planck phase cannot be properly understood without a full theory of quantum gravity, it is suggested that in this phase the black hole will decay to a few quanta with Planck-scale energies [11].

3. Event generator

3.1 Features of the event generator

There are a number of features of the CHARYBDIS generator which, within the uncertainties of much of the theory, allow reliable simulation of black hole events. Most notable is that, unlike other generators (e.g. [22]), the grey-body effects are fully included. The generator also allows the black hole temperature to vary as the decay progresses and is designed for simulations with either $p-p$ or $\overline{p}-p$.

Due to the difficulty in modelling the balding phase and the lack of a full theory for quantum gravity to explain the Planck phase of the decay, the generator only attempts to model the Hawking evaporation phase (expected to account for the majority of the mass loss). To provide a further simplification only non-spinning black holes are modelled. This is perhaps a less good approximation but comparison with the 4D situation suggests that most of the angular momentum will be lost in a relatively short spin-down phase [23].

It is possible that black hole decay does not conserve baryon number, for example by producing three quarks in a colour singlet. However the treatment of processes which do

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not conserve baryon number is complicated, in both the QCD evolution and hadronization, and has only been studied for a few specific processes [24]–[27]. At the same time the violation of baryon number is extremely difficult to detect experimentally and therefore the effect of including baryon number violation is not expected to be experimentally observable. Therefore CHARYBDIS conserves baryon number in black hole production and decay.

3.2 General description

The black hole event generator developed attempts to model the theory as outlined in the previous section. There are several related parameters and switches which can be set in the first part of the Les Houches subroutine `UPINIT` [4]. No other part of the charybdis1000.F code should be modified.

Firstly the properties of the beam particles must be specified. `IDBMUP(1)` and `IDBMUP(2)` are their PDG codes (only protons and anti-protons are allowed) and the corresponding energies are `EBMUP(1)` and `EBMUP(2)`. Note that these settings will over-write any in the main HERWIG or PYTHIA program files.

The geometric parton-level cross section, $\sigma = \pi r_h^2$, is used but the parameters `MINMSS` and `MAXMSS` allow the mass range for the black holes produced to be specified. This means that the lower mass limit at which this expression for the cross section is thought to become valid can be adjusted.

Three other parameters which must be set before using the event generator are `TOTDIM`, `MPLNCK` and `MSSDEF`. The total number of dimensions in the model being used is given by `TOTDIM` (this must be set between 6 and 11). There are a number of different definitions of the Planck mass (set using `MPLNCK`), but the parameter `MSSDEF` can be set to three different values to allow easy interchange between the three conventions outlined in [11, appendix A]. The conversions between these conventions are summarized in table 1.

MSSDEF	Conversion
1	$\mathtt{MPLNCK} = \left(2^{n-2}\pi^{n-1}\right)^{\frac{1}{n+2}} M_p$
2	$\mathtt{MPLNCK} = M_p$
3	$\mathtt{MPLNCK} = \left(2^{n-3}\pi^{n-1}\right)^{\frac{1}{n+2}} M_p$

Table 1: Definitions of the Planck mass.

It has been suggested that since black hole formation is a non-perturbative process, the momentum scale for evaluating the pdfs should be the inverse Schwarzschild radius rather than the black hole mass. The switch `GTSCA` should be set to `.TRUE.` for the first of these options and `.FALSE.` for the second. It should be noted that, as confirmed in [28], the cross sections quoted in reference [11] were actually calculated with the latter pdf scale. The pdfs to be used are set using the Les Houches parameters `PDFGUP` and `PDFSUF`.

As discussed in section 2, the Hawking temperature of the black hole will increase as the decay progresses so that later emissions will typically be of higher energy. However to allow comparison with other work which has ignored this effect, there is a switch `TIMVAR` which can be used to set the time variation of the Hawking temperature as on (`.TRUE.`) or off (`.FALSE.`).

The probabilities of emission of different types of particles are set according to the new theoretical results [5]–[7]. Heavy particle production is allowed and can be controlled by

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setting the value of the MSSDEC parameter to 2 for top quark, W and Z, or 3 to include Higgs also (MSSDEC=1 gives only light particles). Heavy particle production spectra may be unreliable for choices of parameters for which the initial Hawking temperature is below the rest mass of the particle being considered.

If GRYBDY is set as .TRUE. the particle types and energies are chosen according to the grey-body modified emission probabilities and spectra. If instead the .FALSE. option is selected, the black-body emission probabilities and spectra are used. The choice of energy is made in the rest frame of the black hole before emission. As overall charge must be conserved, when a charged particle is to be emitted the particle or anti-particle is chosen such that the magnitude of the black hole charge decreases. This reproduces some of the features of the charge-dependent emission spectra in [18] whilst at the same time making it easier for the event generator to ensure that charge is conserved for the full decay.

Although the Planck phase at the end of decay cannot be well modelled as it is not well understood, the Monte Carlo event generator must have some way of terminating the decay. There are two different possibilities for this, each with a range of options for the terminal multiplicity.

If KINCUT=.TRUE. termination occurs when the chosen energy for the emitted particle is ruled out by the kinematics of a two-body decay. At this point an isotropic NBODY decay is performed on the black hole remnant where NBODY can be set between 2 and 5. The NBODY particles are chosen according to the same probabilities used for the rest of the decay. The selection is then accepted if charge and baryon number are conserved, otherwise a new set of particles is picked for the NBODY decay. If this does not succeed in conserving charge and baryon number after NHTRY attempts the whole decay is rejected and a new one generated. If the whole decay process fails for MHTRY attempts then the initial black hole state is rejected and a new one generated.

In the alternative termination of the decay (KINCUT=.FALSE.), particles are emitted according to the energy spectrum until M_{BH} falls below MPLNCK and then an NBODY decay as described above is performed. Any chosen energies which are kinematically forbidden are simply discarded.

In order to perform the parton evolution and hadronization the general purpose event generators require a colour flow to be defined. This colour flow is defined in the large number of colours (N_c) limit in which a quark can be considered as a colour line, an anti-quark as an anti-colour line and a gluon both a colour and anti-colour line. A simple algorithm is used to connect all the lines into a consistent colour flow. This algorithm starts with a colour line (from either a quark or a gluon) and then randomly connects this line with one of the unconnected anti-colour lines (either a gluon or an anti-quark). If the selected partner is a gluon the procedure is repeated to find the partner for its colour line; if it is an anti-quark one of the other unconnected quark colour lines is selected. If the starting particle was a gluon the colour line of the last parton is connected to the anti-colour line of the gluon. Whilst there is no deep physical motivation for this algorithm it at least ensures that all the particles are colour-connected and the showering generator can proceed to evolve and hadronize the event.

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Name	Description	Values	Default
IDBMUP(2)	PDG codes of beam particles	± 2212	2212
EBMUP(2)	Energies of beam particles (GeV)		7000.0
PDFGUP(2)	PDFLIB codes for pdf author group		-1
PDFSUP(2)	PDFLIB codes for pdf set		-1
MINMSS	Minimum mass of black holes (GeV)	$<$ MAXMSS	5000.0
MAXMSS	Maximum mass of black holes (GeV)	$\leq$ c.m. energy	c.m. energy
MPLNCK	Planck mass (GeV)	$\leq$ MINMSS	1000.0
MSSDEF	Convention for MPLNCK (see table 1)	1-3	2
TOTDIM	Total number of dimensions $(4+n)$	6-11	6
GTSCA	Use r_h^{-1}as the pdf momentum scale rather than the black hole mass	LOGICAL	.FALSE.
TIMVAR	Allow T_H to change with time	LOGICAL	.TRUE.
MSSDEC	Choice of decay products	1-3	3
GRYBDY	Include grey-body effects	LOGICAL	.TRUE.
KINCUT	Use a kinematic cut-off on the decay	LOGICAL	.FALSE.
NBODY	Number of particles in remnant decay	2-5	2

Table 2: List of parameters with brief descriptions, allowed values and default settings.

After the black hole decay, parton-level information is written into the Les Houches common block HEPEUP to enable a general purpose event generator to fragment all emitted coloured particles into hadron jets, and generate all unstable particle decays (see below).

3.3 Control switches, constants and options

Those parameters discussed in the previous section which are designed to be set by the user are summarized in table 2.

3.4 Using charybdis1000.F

The generator itself only performs the production and parton-level decay of the black hole. It is interfaced, via the Les Houches accord, to either HERWIG [29, 30] or PYTHIA [31] to perform the parton shower evolution, hadronization and particle decays. This means that it is also necessary to have a Les Houches accord compliant version of either HERWIG or PYTHIA with both the dummy Les Houches routines (UPINIT and UPEVNT) and the dummy PDFLIB subroutines (PDFSET and STRUCTM) deleted. For HERWIG the first Les Houches compliant version is HERWIG6.500 [32]; for PYTHIA version 6.220 [33] or above is required.[3]

The black hole code itself is available as a gzipped tar file at the web address http://www.ippp.dur.ac.uk/montecarlo/leshouches/generators/charybdis/. The file includes the following code:

- charybdis1000.F (code for the black hole generator)

[3]Versions of PYTHIA above 6.200 support the Les Houches accord but can not handle more than 7 outgoing particles, which is necessary in black hole decays.

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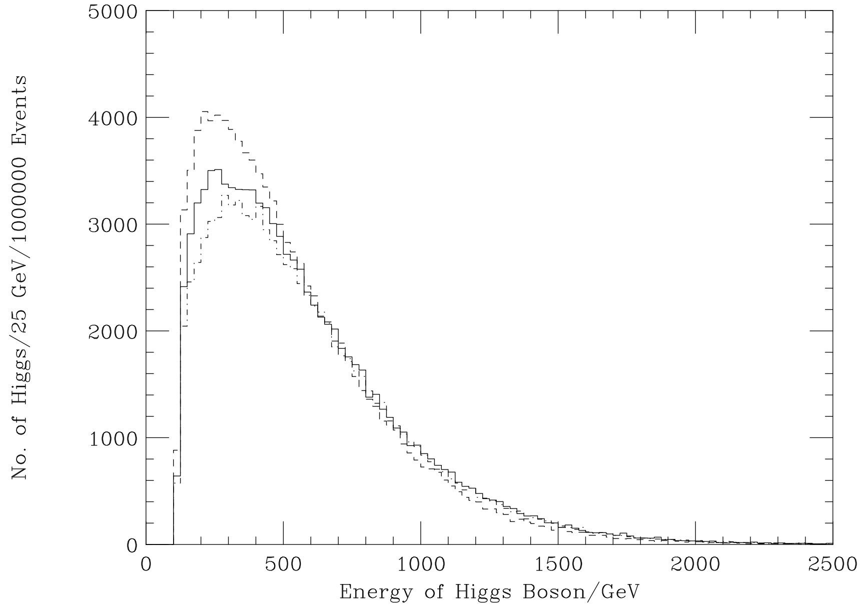

Figure 1: Parton-level energy spectra of Higgs bosons, $m_H = 115\,\mathrm{GeV}$. Solid: predicted energy spectrum of Higgs bosons from decay of black holes with initial masses $5.0-5.5\,\mathrm{TeV}$. Dashed: neglecting time variation of temperature. Dot-dashed: neglecting grey-body factors.

- dummy.F (dummy routines needed if not using PDFLIB)
- mainpythia.f (example main program for PYTHIA)
- mainherwig.f (example main program for HERWIG)
- charybdis1000.inc (include file for the black hole generator)

The general purpose event generator to be used must be specified in the Makefile (i.e. `GENERATOR=HERWIG` or `GENERATOR=PYTHIA`) and also if PDFLIB is to be used (`PDFLIB= PDFLIB` if required, otherwise `PDFLIB=`). The name of the HERWIG or PYTHIA source and the location of the PDFLIB library must also be included.

If the code is extracted to be run separately then the following should be taken into account:

- charybdis1000.F will produce the HERWIG version by default when compiled, the flag `-DPYTHIA` should be added if the PYTHIA version is required;
- dummy.F will by default produce the version for use without `PDFLIB`, the flag `-DPDFLIB` should be added if `PDFLIB` is being used.

3.5 List of subroutines

Table 3 contains a list of all the subroutines of the generator along with their functions. Those labelled by HW/PY are HERWIG / PYTHIA dependent and are pre-processed according to the `GENERATOR` flag in the Makefile. Many of the utility routines are identical to routines which appear in the HERWIG program.

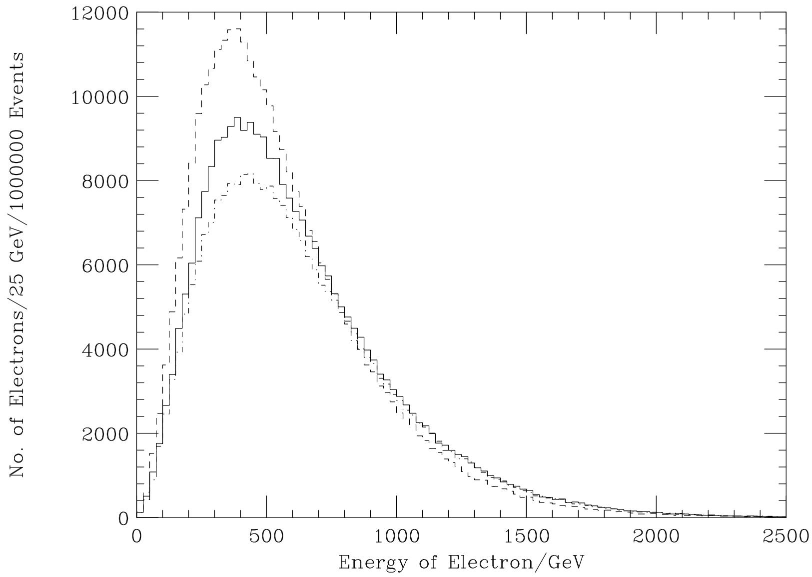

Figure 2: Parton-level energy spectra of electrons and positrons. As figure 1 but for electron and positron spectra.

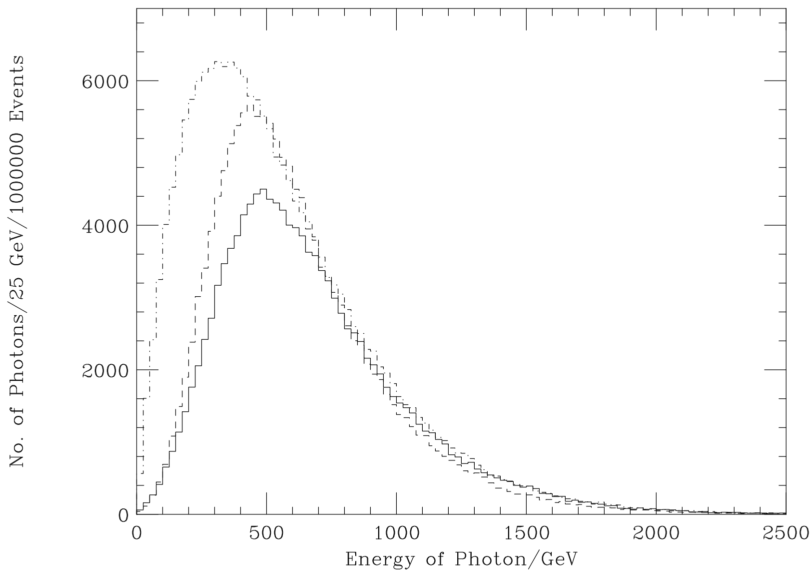

Figure 3: Parton-level energy spectra of photons. As figure 1 but for photon spectra.

3.6 Sample plots

Figures 1–3 show the results, at parton level, of neglecting the time variation of the black hole temperature (`TIMVAR=.FALSE.`, dashed line) or the grey-body factors (`GRYBDY =.FALSE.`, dot-dashed line) for initial black hole masses in the range from `MINMSS=5000.0` to `MAXMSS =5500.0`, with the default values for the other parameters. The solid line is for simulations with the default parameter settings (but with the same reduced range of initial black hole masses used in the other two cases).

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Name	Description
	Les Houches routines
`UPINIT`	Initialization routine
`UPEVNT`	Event routine
	Particle decays
`CHDFIV`	Generates a five-body decay
`CHDFOR`	Generates a four-body decay
`CHDTHR`	Generates a three-body decay
`CHDTWO`	Generates a two-body decay
	Hard subprocess and related routines
`CHEVNT`	Main routine for black hole hard subprocess
`CHFCHG`	Returns charge of a SM particle
`CHFMAS`	Returns mass of a SM particle (HW/PY)
`CHHBH1`	Chooses next particle type if `MSSDEC=1`
`CHHBH2`	Chooses next particle type if `MSSDEC=2`
`CHHBH3`	Chooses next particle type if `MSSDEC=3`
`CHPDF`	Calculates the pdfs (HW/PY)
	Random number generators
`CHRAZM`	Randomly rotates a 2-vector
`CHRGEN`	Random number generator (HW/PY)
`CHRLOG`	Random logical
`CHRUNI`	Random number: uniform
	Miscellaneous utilities
`CHUBHS`	Chooses particle energy from spectrum
`CHULB4`	Boost: rest frame to lab, no masses assumed
`CHULOB`	Lorentz transformation: rest frame→lab
`CHUMAS`	Puts mass in 5th component of vector
`CHUPCM`	Centre-of-mass momentum
`CHUROB`	Rotation by inverse of matrix R
`CHUROT`	Rotation by matrix R
`CHUSQR`	Square root with sign retention
`CHUTAB`	Interpolates in a table
	Vector manipulation
`CHVDIF`	Vector difference
`CHVEQU`	Vector equality
`CHVSUM`	Vector sum

Table 3: List of subroutines with brief descriptions.

The effect of time variation is to harden the spectra of all particle species. However, the effect of the grey-body factors depends on the spin, in this case slightly softening the spectra of scalars and fermions but hardening the spectrum of gauge bosons.

Results of a fuller study of signatures of black hole production and decay at the LHC will be presented elsewhere [34].

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References

[1] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The hierarchy problem and new dimensions at a millimeter*, *Phys. Lett.* **B 429** (1998) 263 [hep-ph/9803315]; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *New dimensions at a millimeter to a fermi and superstrings at a TeV*, *Phys. Lett.* **B 436** (1998) 257 [hep-ph/9804398].

[2] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [hep-ph/9905221].

[3] R. Casadio and B. Harms, *Can black holes and naked singularities be detected in accelerators?*, *Int. J. Mod. Phys.* **A 17** (2002) 4635 [hep-th/0110255].

[4] E. Boos et al., *Generic user process interface for event generators*, hep-ph/0109068.

[5] P. Kanti and J. March-Russell, *Calculable corrections to brane black hole decay, I. The scalar case*, *Phys. Rev.* **D 66** (2002) 024023 [hep-ph/0203223].

[6] P. Kanti and J. March-Russell, *Calculable corrections to brane black hole decay, II. Greybody factors for spin 1/2 and 1*, *Phys. Rev.* **D 67** (2003) 104019 [hep-ph/0212199].

[7] C.M. Harris, P. Kanti and J. March-Russell, *Hawking radiation from a (4+n)-dimensional black hole: exact results for the Schwarzschild phase*, in preparation.

[8] S. Dimopoulos and G. Landsberg, *Black holes at the LHC*, *Phys. Rev. Lett.* **87** (2001) 161602 [hep-ph/0106295].

[9] J. Hewett and M. Spiropulu, *Particle physics probes of extra spacetime dimensions*, *Ann. Rev. Nucl. Part. Sci.* **52** (2002) 397 [hep-ph/0205106].

[10] R.C. Myers and M.J. Perry, *Black holes in higher dimensional space-times*, *Ann. Phys. (NY)* **172** (1986) 304.

[11] S.B. Giddings and S. Thomas, *High energy colliders as black hole factories: the end of short distance physics*, *Phys. Rev.* **D 65** (2002) 056010 [hep-ph/0106219].

[12] M.B. Voloshin, *Semiclassical suppression of black hole production in particle collisions*, *Phys. Lett.* **B 518** (2001) 137 [hep-ph/0107119].

[13] S.B. Giddings, *Black hole production in TeV-scale gravity and the future of high energy physics*, *eConf* **C010630** (2001) P328 [hep-ph/0110127].

[14] M.B. Voloshin, *More remarks on suppression of large black hole production in particle collisions*, *Phys. Lett.* **B 524** (2002) 376 [hep-ph/0111099].

[15] D.M. Eardley and S.B. Giddings, *Classical black hole production in high-energy collisions*, *Phys. Rev.* **D 66** (2002) 044011 [gr-qc/0201034].

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[16] S.W. Hawking, *Particle creation by black holes*, *Commun. Math. Phys.* **43** (1975) 199.

[17] R. Emparan, G.T. Horowitz and R.C. Myers, *Black holes radiate mainly on the brane*, *Phys. Rev. Lett.* **85** (2000) 499 [hep-th/0003118].

[18] D.N. Page, *Particle emission rates from a black hole: massless particles from an uncharged, nonrotating hole*, *Phys. Rev.* **D 13** (1976) 198.

[19] M. Cavaglia, *Black hole multiplicity at particle colliders (Do black holes radiate mainly on the brane?)*, *Phys. Lett.* **B 569** (2003) 7 [hep-ph/0305256].

[20] J.H. MacGibbon and B.R. Webber, *Quark and gluon jet emission from primordial black holes: the instantaneous spectra*, *Phys. Rev.* **D 41** (1990) 3052.

[21] N. Sanchez, *Absorption and emission spectra of a Schwarzschild black hole*, *Phys. Rev.* **D 18** (1978) 1030.

[22] S. Dimopoulos and G. Landsberg, *Proceedings International Workshop on Future of Particle Physics*, Snowmass 2001.

[23] D.N. Page, *Particle emission rates from a black hole, II. Massless particles from a rotating hole*, *Phys. Rev.* **D 14** (1976) 3260.

[24] M.J. Gibbs, A. Ringwald, B.R. Webber and J.T. Zadrozny, *Monte Carlo simulation of baryon and lepton number violating processes at high-energies*, *Z. Physik* **C 66** (1995) 285 [hep-ph/9406266].

[25] M.J. Gibbs and B.R. Webber, *HERBVI: a program for simulation of baryon and lepton number violating processes*, *Comput. Phys. Commun.* **90** (1995) 369 [hep-ph/9504232].

[26] H.K. Dreiner, P. Richardson and M.H. Seymour, *Parton-shower simulations of R-parity violating supersymmetric models*, *J. High Energy Phys.* **04** (2000) 008 [hep-ph/9912407].

[27] T. Sjöstrand and P.Z. Skands, *Baryon number violation and string topologies*, *Nucl. Phys.* **B 659** (2003) 243 [hep-ph/0212264].

[28] T. Rizzo, private communication.

[29] G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour and L. Stanco, *HERWIG: a Monte Carlo event generator for simulating Hadron Emission Reactions With Interfering Gluons. Version 5.1 - April 1991*, *Comput. Phys. Commun.* **67** (1992) 465.

[30] G. Corcella et al., *HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, *J. High Energy Phys.* **01** (2001) 010 [hep-ph/0011363].

[31] T. Sjöstrand, P. Eden, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, *High-energy-physics event generation with PYTHIA 6.1*, *Comput. Phys. Commun.* **135** (2001) 238 [hep-ph/0010017].

[32] G. Corcella et al., *HERWIG 6.5 release note*, hep-ph/0210213.

[33] T. Sjöstrand, L. Lönnblad and S. Mrenna, *PYTHIA 6.2: physics and manual*, hep-ph/0108264.

[34] C.M. Harris, M.A. Parker, P. Richardson, A. Sabetfakhri and B.R. Webber, in preparation.