CATFISH 2.10: Quick Reference Guide

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July 10, 2008

Contents

Preface

This is a quick reference guide to *CATFISH ver. 2.10.* CATFISH (Collider grAv-iTational FIeld Simulator for black Holes) is a Monte Carlo program to simulate black holes at CERN's Large Hadron Collider. The code can be used free of charge for educational/research purposes.

When using CATFISH, the following reference must be acknowledged:

M. Cavaglià, R. Godang, L. Cremaldi and D. Summers, "CATFISH: A Monte Carlo simulator for black holes at the LHC", Comput. Phys. Commun. 177, 506 (2007), [arXiv: hep-ph/0609001].

Author's written permission must be granted for commercial or non-educational use. The CATFISH program and documentation cannot be sold, redistributed, reproduced or altered without permission of the author. The author accepts no liability whatsoever resulting from the use of the program.

Acknowledgements

CATFISH is indebted to Slava Rychkov and Hirotaka Yoshino for contributions to this project.

The implementation of dilepton invariant mass and the editing of this manual was done by Arunava Roy (University of Mississippi).

Figures and detector response simulations have been made by Romulus Godang (University of Mississippi).

The Mac OS X binaries have been compiled by David Sanders (University of Mississippi).

CATFISH thanks Vitor Cardoso, David Cline, Lucien Cremaldi, Alakabha Datta, Doug Gingrich, Romulus Godang, Greg Landsberg, Alexander Melnitchouk, Peter Skands, Don Summers, Xerxes Tata, Hans Wenzel and Graham Wilson for discussions and suggestions.

The trapped-surface model for black hole formation is based on

1. H. Yoshino and Y. Nambu, *Phys. Rev. D* **67**, 024009 (2003), arXiv: gr-qc/0209003.
2. H. Yoshino and V.S. Rychkov, *Phys. Rev. D* **71**, 104028 (2005), arXiv: hep-th/0503171.

The trapped-surface numerical tables of the apparent horizon mass used by CATFISH have been kindly provided by H. Yoshino.

Fragmentation and hadronization of the black hole primary quanta during Hawking evaporation are implemented with the PYTHIA (6.406) code.

This research was carried out at the University of Mississippi and was supported in part by the U.S. Department of Energy contracts DE-AC02-76SF00515 and DE-FG05-91ER40622.

Current version and history of changes

Changes in version 2.10

- Calculation of opposite sign, same flavor dilepton invariant mass implemented (output file `catfish-v2.10.mll`).

Changes in version 2.01

- Bug in the calculation of visible energy when `GRAVITONLOSS=1` fixed (output file `catfish-v2.01.energy`).

Changes in version 2.0

The main new features of CATFISH v2.0 are:

- Black hole remnant and initial gravitational loss are included in PYTHIA's output. If `GRAVITONLOSS=1`, the initial gravitational loss is simulated by two gravitons with opposite momentum and total energy equal to the gravitational energy loss.
- Inconsistencies in the definition of particle masses and black hole remnant mass have been fixed.

Changes in version 1.1

The main new features of CATFISH v1.1 are:

- *Les Houches* interface for external process in PYTHIA has been implemented. CATFISH now includes treatment of initial- and final-state radiation and beam remnant.

- Color charge is conserved.

- Transverse momentum cuts options for (e, μ) and $(\gamma$, hadrons) are included in the input file `catfish-v1.1.inp`.

- Two new output files, `catfish-v1.1.energy` and `catfish-v1.1.pt`, are generated with information on visible/missing energy and visible/missing transverse momentum.

- Hadronization is performed with PYTHIA v6.406 (previously, v6.403).

The physics of CATFISH 2.10

This section reviews theory and phenomenology upon which the CATFISH generator is based. For sake of brevity, the content of this chapter does not cover the whole literature on the subject and is by no means exhaustive. For a more complete discussion of black hole and brane production in low-energy scale gravity and an up-to-date bibliography, the reader is referred to recent reviews on the subject [1, 2, 3, 4, 5].

Hierarchy problem and TeV gravity

The electroweak scale $E_{EW} \sim 1$ TeV and the gravitational scale $E_G \sim 10^{16}$ TeV are separated by sixteen orders of magnitude. The standard model of particle physics successfully explains phenomena up to the electroweak scale. However, little is known of physics above E_{EW}. One of the most challenging issues is to explain the hierarchy problem, *i.e.* the largeness and radiative stability of the ratio E_G/E_{EW}.

A possible solution to the hierarchy problem was proposed in 1998 by Arkani-Hamed, Dimopoulos and Dvali (ADD) [6, 7] and Antoniadis [8]. In the ADD scenario, unification takes place at the electroweak scale, where gravity becomes strong. The observed weakness of gravity follows from the existence of large extra dimensions, i.e. dimensions with size much larger than the fundamental scale. The standard model fields are localized on a three-brane embedded in the extra dimensions [9]. Gravity and possibly other non-standard model fields are allowed to freely propagate outside the three-brane.

The ADD scenario finds its roots in string theory. The idea that the gravitational scale can be lowered by some unknown physics dates back to the early 90's when Antoniadis [10] first proposed that perturbative string theories generally predict the existence of extra dimensions at energies of order of the TeV scale. Moreover, the nonperturbative formulation of string theory predicts the existence of higher-dimensional, nonperturbative extended objects (D-branes) [11]. The presence of branes in the theory leads naturally to the localization of the standard model fields and to the hierarchy in the size of the extra dimensions [12, 13, 14].

Extra dimensions

Classical gravity is described by the Einstein-Hilbert action

$$S_{EH} = \frac{1}{16\pi G_4} \int_{\mathcal{M}} d^4x \sqrt{-g}\mathcal{R}(g)\,, \tag{1}$$

where $\mathcal{M}$ is a four-dimensional hyperbolic manifold with metric $g_{\mu\nu}$, g is the determinant of the metric, $\mathcal{R}(g)$ is the Ricci scalar, and $G_4 = 6.673(10)\cdot 10^{-11}$ m^3 kg^{-1} s^{-2} $= 6.707(10)\cdot 10^{-39}$ $\hbar c$ (GeV/c^2)$^{-2}$ is the gravitational constant (Newton's constant). In natural units G_4 has dimensions of inverse mass squared. The Planck mass

$$M_{\rm Pl} \equiv G_4^{-1/2} \sim 1.22 \cdot 10^{16} \text{ TeV} \tag{2}$$

determines the gravitational scale at which quantum gravitational phenomena become strong. At low energy, gravity manifests itself as a long-range attractive force with coupling constant G_4. The gravitational potential of a massive object with mass M at a distance r is

$$V(r) = -G_4 \frac{M}{r}\,. \tag{3}$$

Experiments with a torsion pendulum/rotating attractor instrument [15, 16] have recently tested the gravitational force at submillimeter length scales without evidence for violations of Eq. (3).

String theory requires that we live in a higher-dimensional spacetime. In the Einstein frame, the gravitational sector of low-energy effective string theories is described by the Einstein action (1) extended to D-dimensions:

$$S = \frac{1}{16\pi G_D} \int_{\mathcal{M}_D} d^Dx \sqrt{-g}\mathcal{R}(g)\,. \tag{4}$$

$n = D - 4$ dimensions must be compactified to yield a four-dimensional effective action. This is generally accomplished by assuming that the higher-dimensional spacetime is a (warped) product of four-dimensional Minkowski spacetime and a compact n-dimensional Riemannian manifold. The spacetime metric is

$$ds^2 = g_{ab}(x)dx^a dx^b = e^{2A(y)} dx^\mu dx^\nu \eta_{\mu\nu} + h_{ij}(y) dy^i dy^j\,, \tag{5}$$

where the Greek indices run from 0 to 3 and the coordinates y $(i, j = 4 \ldots D-1)$ parametrize the compactified dimensions. In such a scenario, the observed Planck scale $M_{\rm Pl}$ is a quantity derived from the D-dimensional fundamental Planck scale

$$M_\star \equiv G_D^{-1/(D-2)}\,. \tag{6}$$

The four-dimensional Newton's constant is related to the D-dimensional gravitational constant G_D by the relation

$$G_4 = \frac{G_D}{V_{D-4}}\,, \qquad \to \qquad M_{\rm Pl}^2 = M_\star^{D-2} V_{D-4}\,, \tag{7}$$

where

$$V_{D-4} = \int d^{D-4}y \sqrt{h}\, e^{2A(y)} \tag{8}$$

is the volume of the extra-dimensional space modulated by the warp factor $e^{A(y)}$. The ratio of the fundamental Planck constant $M_\star$ to the observed Planck constant $M_{\rm Pl}$ depends on the geometry and on the size of the compactified space.

In the ADD solution to the hierarchy problem, $M_\star$ is identified with the electroweak scale. The volume of the extra-dimensional space is large in fundamental Planck units. An upper limit to the size of the compactified space can be obtained by measuring the gravitational potential at small distances. Indeed, if n extra dimensions open up at the scale L, the gravitational potential at scales smaller than L behaves as

$$V(r) \sim -G_{n+4} \frac{M}{r^{n+1}}\,. \tag{9}$$

The non-observation of deviations from the four-dimensional behavior of Eq. (3) constrains the size of the extra dimensions and the fundamental Planck scale. The latest experimental results [15, 16] suggest that the gravitational force follows the inverse square law up to distances of 100 μm. This implies a lower bound on the fundamental Planck scale $M_\star \sim 1$ TeV.

Black holes in hard-scattering processes

If the fundamental Planck scale is $\sim$ TeV, physical phenomena around and above this scale will show deviations from standard model predictions. Sub-Planckian physics is essentially affected by the presence of Kaluza-Klein modes [17, 18, 19, 20]. Super-Planckian physics involves non-perturbative effects. The most striking super-Planckian phenomenon is the formation of black holes and branes in hard-scattering processes [21].

Formation and cross section at parton level

Thorne's hoop conjecture [22] states that an event horizon forms when a mass M is compacted into a region with circumference smaller than twice the Schwarzschild radius $R(M)$ in any direction.

At subnuclear level, this can be achieved by scattering two partons on the brane with center of mass (CM) $\sqrt{s}$ larger than M and impact parameter b smaller than $R(M)$. Therefore, if the gravitational coupling constant is of the order of few TeV, the physics of super-Planckian collisions could soon be detected through observation of subnuclear black holes and branes in particle colliders [23, 24, 25, 26, 27, 28, 29, 30, 31] or ultrahigh energy cosmic ray observatories [32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42].

The cross section for creation of a black hole or brane with radius R is approximately given by the geometrical black disk cross section (BD)

$$\sigma_{BD}(s,n) = \pi R^2(s,n)\,\theta[R(s,n) - b]\,. \tag{10}$$

Gravitational objects with mass of order of the fundamental gravitational scale $M_\star$ have radius of order $M_\star^{-1}$. In symmetric compactification models, the size of extra dimensions is much larger than $M_\star^{-1}$. Therefore, spherical approximation is justified and the geometry of nonperturbative objects is that of a n-dimensional black hole. The spherical approximation breaks down for asymmetric compactifications, where some of the extra dimensions have size of order of the fundamental Planck scale. In that case the geometry of nonperturbative objects is that of strings and branes [26, 27, 28].

The black hole event is described by the inelastic process $ij \to \mathrm{BH} + E(X)$, where $E(X)$ denotes the collisional energy that does not fall beyond the event horizon. Due to the gravitational nature of the process, this energy includes mainly a bulk component of gravitational radiation, although non-standard model gauge fields and a brane component of standard model fields cannot be excluded. If $E(X)$ is zero, the the parton cross section for black hole production is given by Eq. (10). If $E(X) \neq 0$, the cross section is generally smaller and depends on the impact parameter. Note that this treatment is valid only if the black hole is larger than the Compton length of the colliding quanta. (For discussions on the effect of wave packet size on the black hole formation process, see Refs. [43, 44, 45, 46, 47].) A precise calculation of the collisional energy loss is essential to understanding black hole formation.

The hoop conjecture has been tested by different methods [5], the most popular one being the Trapped-Surface (TS) approach [48, 49, 50], The TS model gives a bound on the inelasticity by modelling the incoming partons as two Aichelburg-Sexl shock waves [51]. The Aichelburg-Sexl wave is obtained by boosting the Schwarzschild solution to the speed of light at fixed energy. The resulting metric describes a plane-fronted gravitational shock wave corresponding to the Lorentz-contracted longitudinal gravitational field. The parton scattering is simulated by superposing two shock waves travelling in opposite directions. The union of these shock waves defines a closed TS that allows to set a lower bound on the initial black hole mass M_{BH}. The collisional energy loss depends on the impact parameter and increases as the number of spacetime dimensions increases. The black hole mass monotonically decreases with the impact parameter from a maximum of about 60-70% of the CM energy for head-on collisions.

The TS result is consistent within one order of magnitude with the hoop conjecture. However, this approach neglects mass, spin, charge and finite-size effects of the incoming partons. Size and spin effects are expected to be mostly relevant around the Planck energy. Charge effects could dominate at higher energy. The pointlike approximation fails for directions transversal to the motion [52]. Even with these assumptions, the TS model provides only a lower bound on M_{BH}. Independent estimates of the gravitational collisional energy loss are possible through alternative approaches. The gravitational energy emission in a hard instantaneous collision can be evaluated in the linearized limit [53]. This computation suggests that the TS method overestimates the gravitational energy emitted in the process. For head-on collisions, the instantaneous method predicts that the gravitational energy loss is only about 10% of the CM energy. This result is in agreement with perturbative calculations modelling the parton-parton collision as a plunge of a relativistic test particle into a black hole with mass equal to the CM energy [54].

In conclusion, known methods for the estimate of the gravitational loss in relativistic scattering at parton level seem to indicate a black hole mass ranging between 60% and 100% of the CM energy. As of today, the TS value and the BD value can be considered as the lower and upper bounds for the black hole mass, respectively. However, it should be kept in mind that these results rely on several crude assumptions.

Cross section at nucleon level

The total cross section for a super-Planckian black hole event involving two nucleons is obtained by integrating the parton cross section over the parton distribution functions. If the black hole mass depends on the impact parameter, the generally accepted formula for the total cross section of the pp process is

$$(11) \quad \sigma_{pp\to BH}(s,n) = \sum_{ij}\int_0^1 2z dz \int_{x_m}^1 dx \int_x^1 \frac{dx'}{x'} f_i(x',Q) f_j(x/x',Q)\, F\, \sigma_{BD}(xs,n)\,,$$

where $f_i(\cdot,Q)$ are the Parton Distribution Functions (PDFs) with four-momentum transfer squared Q [55, 56] and z is the impact parameter normalized to its maximum value. The cutoff at small x is $x_m = M_{min}^2/(sy^2(z))$, where $y(z)$ and M_{min} are the fraction of CM energy trapped into the black hole and the minimum-allowed mass of the gravitational object, respectively. F is a form factor. The total cross section for the BD model is obtained by setting $F = 1$ and $y^2(z) = 1$.

Different sets of PDFs are defined in the literature. The PDFs are not known at energies above the TeV and for values of momentum transfer expected in black hole formation. Equation (11) is usually calculated by imposing a cut-off at these values. The PDFs also suffer from uncertainties at any momentum transfer that can contribute to the reduction in the total cross section. The uncertainty due to the choice of the PDFs has been evaluated in [37] and is of the order of 10% or less. This value does not include the uncertainty due to the cutoff on the momentum transfer Q. Another source of uncertainty in the PDFs comes from the ambiguity in the definition of Q [57]. This is usually chosen to equal the black hole mass or the inverse of the Schwarzschild radius. Although recent literature inclines toward the latter, there are no definite arguments to prefer either one or to exclude alternative choices. The uncertainty due to the ambiguity in the definition of the momentum transfer is about $\sim 10 - 20\%$ [35].

The form factor and the amount of trapped energy depend in principle on the energy, gravitational scale, geometry and physical properties of the extra dimensions and gravitational object. The TS method gives numerical values of order unity for these quantities, depending on the number of extra dimensions. However, these results depends on the way the TS is identified. Other models [58] give values which are more or less consistent with the TS method. With the lack of further insight, it is common practise in the literature to either choose the TS result or the simple BD model.

The lower cutoff on the fraction of the nucleon momentum carried by the partons is set by the minimum-allowed mass of the gravitational object, M_{min}. This threshold is expected to roughly coincide with the mass for which the semiclassical description is valid. However, this conclusion is based on Hawking's semiclassical theory and may not be valid at energies equal to few times the Planck mass. For example, the existence of a minimum spacetime length l_m sets a the lower bound to the allowed minimum mass [59, 60]:

$$M_{ml} = \frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)} \left(2\sqrt{\pi}\, l_m/M_\star\right)^{n+1} M_\star\,. \tag{12}$$

Black holes with mass less than M_{ml} do not exist, since their horizon radius would fall below the minimum-allowed length. At fixed $M_\star$ the minimum mass grows as l_m^{n+1}. For $n = 6$ or 7 and $l_m M_\star \gtrsim 1$, it follows $M_{ml} \gtrsim M_{min} \gg M_\star$.

Evolution

The initial mass of the black hole determines the the black hole decay, which is expected to happen in four distinct stages: I. radiation of excess multipole moments (balding phase); II. spin-down; III. Hawking evaporation; IV. final explosion or formation of a black hole remnant.

Although some progress has been made, the understanding of balding and spin-down phases is still fragmentary. For example, the emission of radiation from a $(n+4)$-dimensional rotating black hole on the brane is not known for spin-2 fields [63, 64, 65, 66].

Many papers have been devoted to the investigation of black hole evaporation in higher dimensions [67, 68, 69, 70, 71, 72, 73, 74], leading to a better understanding of the Hawking phase. Detection starts in this phase thanks to the visible products of the black hole decay propagating on our brane. Emissivities for all standard model fields have recently been calculated for non-rotating black holes [75, 76]. If the minimal $SU(3) \times SU(2) \times U(1)$ standard model is assumed, most of the black hole mass is radiated as standard model quanta on the brane, although the gravitational emission in the bulk becomes significant for high n. The primary quanta emitted in the Hawking phase and the final decay phase (see below) are quarks, leptons, and gauge bosons. Quarks and gluons from the black hole fragment into hadrons, which can be detected with leptons and decayed weak bosons. However, two points should be stressed [77]: (i) it is not clear what is the effect of rotation on black hole emissivities; (ii) the field content at trans-Planckian energies is not known. Onset of supersymmetry, for example, could lead to other evaporation channels and large emission of undetectable non-standard model quanta during the decay phase even in absence of rotation [30].

Quantum gravitational effects and black hole recoil [78] could also affect the emission of visible quanta on the brane. Examples of quantum gravitational effects are quantum thermal fluctuations and corrections to the Hawking thermodynamics due to the existence of a minimum length [60]. The existence of a minimum scale of the order of the Planck length [79] is a common consequence of most (if not all) theories of quantum gravity such as string theory, non-commutative geometry, canonical quantum gravity, etc. The presence of a cutoff at the Planck scale leads to a modification of the uncertainty principle. Since the Hawking thermodynamical quantities can be derived by applying the uncertainty principle to the black hole, the existence of a minimum length leads to corrections in the thermodynamical quantities [59, 60].

At the end of the Hawking phase, the black hole is expected to non-thermally decay in a number n_p of hard quanta or leave a remnant. In either case we must content ourselves with a phenomenological description, due to the lack of a theory of quantum gravity. The final non-thermal decay is usually described by setting a cutoff to the black hole mass of the order of the Planck mass, $Q_{min} \sim M_\star$, and then equally distributing the energy Q_{min} to a number n_p of quanta. Since the decay is non-thermal, and in absence of any guidance from a theory of quantum gravity, the quanta are democratically chosen among the standard model degrees of freedom. Note that Q_{min} does not necessarily coincide with M_{min}. The former gives the threshold for the onset of quantum gravity effects, whereas the latter gives the minimum-allowed mass of the classical object. From the above definitions, it follows $M_{min} \geq Q_{min}$. The existence of a minimum length gives a natural means to set Q_{min}. In that case, the modified thermodynamical quantities determine the endpoint of Hawking evaporation when the mass of the black hole reaches M_{ml}. This mass can be identified with the mass of the black hole remnant [59, 60].

Downloading, installing, and running CATFISH 2.10

A precompiled version of the code can be downloaded free of charge for educational/research purposes at `http://www.phy.olemiss.edu/GR/catfish`. The source code may be made available to interested parties on a case-by-case basis. Please contact the author for further information.

Official builds

- Precompiled Linux (x86) - tar.gz format (723 KB).
- Precompiled Mac (Intel/PPC) - tar.gz format (773/935 KB).

Linux

System requirements

1. Operating system: Linux x86 platform
2. Intel pentium class processor (233 MHz or faster recommended)
3. 512 MB of RAM (or larger recommended)
4. 200 MB of free hard disk space for 10k event simulations (or larger recommended)
5. Gzip and Tar archive packages (available free at `http://www.gzip.org/` and `http://www.gnu.org/software/tar/tar.html`)

Contents of the CATFISH package

The CATFISH 2.10 Linux distribution includes the following files:

1. `README` (basic installation and running instructions);
2. `catfish-2.10.exe` (executable CATFISH program);
3. `catfish-v2.10.inp` (sample input file);
4. `cteq5m1.tbl` (cteq5 PDF tables);
5. `YR3.dat,...YR7.dat` (numerical tables for the TS model of Ref. [48])
6. `Yoshino3.dat,...Yoshino7.dat` (numerical tables for the TS model of Ref. [49])
7. `read_demo.exe` (sample executable script to read the CATFISH output and make histograms)
8. `read_demo.f` (source of `pythia_demo.exe`).

Installing CATFISH 2.10

To install the CATFISH 2.10 Linux distribution follow these steps:

1. Create a directory named `catfish-v2.10` (`mkdir catfish-v2.10`) and change to that directory (`cd catfish-v2.10`)
2. Click the link to download the installer file (`catfish_Linux-v2.10.tar.gz`)
3. Decompress the archive with the command: `tar -zxvf catfish_Linux-v2.10.tar.gz`
4. Read the file README

Running CATFISH 2.10

1. Change to the directory `catfish-v2.10`.
2. Edit the `catfish-v2.10.inp` file to choose the simulation parameters (see below).
3. Simulations are started by executing the command: `./catfish-v2.10.exe > catfish-v2.10.dat`

The output is dumped into the file `catfish-v2.10.dat` and can be read by the sample script `read_demo.exe` (if `MLIST=1`, see below).

If `MLIST=1`, the sample executable `read_demo.exe` reads the photon distribution from `catfish-v2.10.dat` and creates the files `catfish-v2.10.gamma` and `catfish-v2.10.hist.gamma` (see below).

Mac OS X

System requirements

1. Operating system: OS X 10.3 or higher
2. 512 MB of RAM (or larger recommended)
3. 200 MB of free hard disk space for 10k event simulations (or larger recommended)
4. Gzip and Tar archive packages (available free at `http://www.gzip.org/` and `http://www.gnu.org/software/tar/tar.html`)

Contents of the CATFISH package

The CATFISH 2.10 Mac OS X distribution includes the following files:

1. `README` (basic installation and running instructions);
2. `catfish-2.10.x` (executable catfish program);
3. `catfish-v2.10.inp` (sample input file);
4. `cteq5m1.tbl` (cteq5 PDF tables);
5. `YR3.dat,...YR7.dat` (numerical tables for the TS model of Ref. [48])
6. `Yoshino3.dat,...Yoshino7.dat` (numerical tables for the TS model of Ref. [49])
7. `read_demo.x` (sample executable script to read the CATFISH output and make histograms)
8. `read_demo.f` (source of `read_demo.exe`).

Installing CATFISH 2.10

To install the CATFISH 2.10 Mac OS X distribution follow these steps:

1. Create a directory named `catfish-v2.10` (`mkdir catfish-v2.10`) and change to that directory (`cd catfish-v2.10`)
2. Click the link to download the installer file (`catfish_Mac_OSX-v2.10.tar.gz` or `catfish_Mac_PPC-v2.10.tar.gz`)
3. Decompress the archive with the command: `tar -zxvf catfish_Mac_[version]-v2.10.tar.gz`
4. Read the file README

Running CATFISH 2.10

1. Change to the directory `catfish-v2.10`.
2. Edit the `catfish-v2.10.inp` file to choose the simulation parameters (see below).
3. Simulations are started by executing the command: `./catfish-v2.10.x > catfish-v2.10.dat`

The output is dumped into the file`catfish-v2.10.dat` and can be read by the sample script `read_demo.x` (if `MLIST=1`, see below).

If `MLIST=1`, the sample executable `read_demo.x` reads the photon distribution from `catfish-v2.10.dat` and creates the files `catfish-v2.0.gamma` and `catfish-v2.01.hist.gamma` (see below).

The input file

The file `catfish-v2.10.inp` defines the physical parameters that CATFISH uses in the simulations. To change these parameters simply edit the file. They are divided into two subsets: Black hole parameters and simulation parameters. The black hole parameters determine formation and decay of the black hole. The simulation parameters determine CATFISH output.

The default input file `catfish-v2.10.inp` is:

```
# BLACK HOLE PARAMETERS

# Fundamental Scale (TeV or GeV)
MSTAR 1.0 TeV

# Number of extra dimensions (n)
NEXTRADIM 6

# Gravitational loss at BH formation
# 0–> No
# 1–> Yes
GRAVITONLOSS 1

# Gravitational loss model
# 0–> Yoshino-Nambu model
# 1–> Yoshino-Rychkov model
GRAVITONMODEL 1

# Minimum BH mass at formation (Xmin)
XMIN 2.0

# Quantum BH mass threshold at evaporation (Qmin)
QMIN 1.0
```

```
# Number of final quanta
NP 2

# Momentum transfer model in parton collision
# 1–> Black hole mass
# 2–> Schwarzschild radius
MTR 2

# Conservation of EM Charge
# 0–> No
# 1–> Yes
EMCHARGE 1

# Minimum length parameter
ALPHA 0.

# SIMULATION PARAMETERS

# Number of events
NUMEVENTS 10

# Random seed.
RSEED 314168270

# Pythia PYLIST option
MLIST 1

# (mu,e) and (gamma,hadrom) PT cuts for event energy computations (GeV)
CUTS 5. 15.

# Dilepton Invariant Mass Parameters

# Transverse momentum (GeV)
PTL 15.

# Pseudorapidity
PRAP 2.5

# Dilepton isolation cuts (PTISO in GeV)
PTISO 7.
CONE 0.2
```

Black hole parameters

The physics of black hole formation and decay is determined by the following set of external parameters and switches in `catfish-v2.10.inp`:

1. Fundamental Scale: `MSTAR` (FLOATING, TeV or GeV);
2. Number of extra dimensions: `NEXTRADIM` (INTEGER, 3 ... 6)
3. Gravitational loss at black hole formation: `GRAVITONLOSS` (INTEGER, 0 or 1)
4. Gravitational loss model: `GRAVITONMODEL` (INTEGER, 0 or 1)
5. Minimum black hole mass at formation: `XMIN` (FLOATING $\geq 1.$, normalized to $M_\star$ or M_{ml})
6. Quantum black hole mass threshold at evaporation: `QMIN` (FLOATING $\geq 1.$, normalized to $M_\star$ or M_{ml})
7. Number of final quanta: `NP` (INTEGER, 0 or 2. . . 18)
8. Momentum transfer model in parton collision: `MTR` (INTEGER, 1 or 2)
9. Conservation of EM Charge: `EMCHARGE` (INTEGER, 0 or 1)
10. Minimum length parameter: `ALPHA` (FLOATING $\geq 0.$)

Note that the entries in the `catfish-v2.10.inp` file are **case sensitive**. Lines beginning with # are not processed by the program.

Fundamental Planck scale

The Planck mass $M_\star$ (`MSTAR`, FLOATING) is inputed in TeV or GeV. Conventions are those of Section I: $M_{\rm Pl}^2 = M_\star^{D-2} V_{D-4}$, where V_{D-4} is the volume of the extra dimensions in fundamental units.

`MSTAR` can be easily converted to other definitions that have been used in the literature by the following relations:

- Giudice-Rattazzi-Wells notations [17]. The observed Planck mass $M_{\rm Pl}$ is defined as in Eq. (2). The fundamental Planck mass is $M_D = [8\pi/(2\pi)^n]^{-\frac{1}{n+2}} M_\star$. For a n-dimensional symmetric toroidal compactification with radii R the fundamental Planck scale is $M_D = (8\pi G_4 R^n)^{-\frac{1}{n+2}}$, where $L = 2\pi R$ is the length of the extra dimensions. The D-dimensional Newton constant G_D is defined as $G_D = (2\pi)^n/(8\pi M_D^{2+n})$.

- Cullen-Perelstein notations [18]. The D-dimensional Newton's constant G_D is defined as in Eq. (7). The fundamental Planck mass M_D is defined as $M_D = [(2\pi)^{D-4}/(4\pi G_D)]^{\frac{1}{D-2}}$. For symmetric toroidal compactifications with radii R $M_D = (4\pi G_4 R^n)^{-\frac{1}{n+2}} = [4\pi/(2\pi)^n]^{-\frac{1}{n+2}} M_\star$.

- Han-Lykken-Zhang notations [19]. The relation between the observed Planck mass and the fundamental scale M_s is $M_{\rm Pl}^2 = \Omega_{n-1}(2\pi)^{-n} V_n M_s^{n+2}$, where $\Omega_{n-1} = 2\pi^{n/2}/\Gamma(n/2)$ is the volume of the unit sphere in $n-1$ dimensions. For a symmetric toroidal compactification the previous relation simplifies to $M_{\rm Pl}^2 = \Omega_{n-1} R^n M_s^{n+2}$. The relation between M_s and $M_\star$ is $M_s = [\Omega_{n-1}/(2\pi)^n]^{-\frac{1}{n+2}} M_\star$.

- EOT-WASH notations [15]. The fundamental Planck mass $M^\star$ is defined by the relation

  $$R^\star = \frac{1}{M^\star}\left(\frac{M_{\rm Pl}}{M^\star}\right)^{2/n}, \tag{13}$$

  where $R^\star$ is the radius of the symmetric compactification. For a toroidal compactification, setting $R^\star = L/(2\pi)$, we find the following relations:

  $$M^\star = (2\pi)^{\frac{n}{n+2}} M_\star = (8\pi)^{\frac{1}{n+2}} M_D\,. \tag{14}$$

CATFISH 2.10 has no lower or upper bound on the Planck mass $M_\star$. However, experimental constraints exclude values of $M_\star \lesssim 1$ TeV and black holes do not form at the LHC if $M_\star > 14$ TeV. Therefore, caution must be used in choosing `MSTAR`.

Number of extra dimensions

The number of extra dimensions n is set by the global parameter `NEXTRADIM` (INTEGER). Since $n = 1$ and $n = 2$ are excluded experimentally, and most of the theoretical models are limited to $n \leq 7$, `NEXTRADIM` can take only values in the range $3 \ldots 7$. (Warped scenarios such as the Randall-Sundrum models [82, 83] with a single extra dimension are experimentally viable. Since most of the results in the literature concerning black holes at colliders have been derived for flat extra-dimensional scenarios, CATFISH does not allow $n = 1$ to mimic black hole production in warped models.)

Gravitational loss

CATFISH includes three models for black hole formation and cross section: BD, Yoshino-Nambu TS model [48], and Yoshino-Rychkov improved TS model [49]. The switch `GRAVITONLOSS` allows to choose between BD and TS. If `GRAVITONLOSS` is set to 1 (TS), the switch `GRAVITONMODEL` allows to choose the Yoshino-Nambu model or the Yoshino-Rychkov model. If `GRAVITONLOSS` is set to 0 (BD), the parameter `GRAVITONMODEL` is not processed by the code.

Minimum black hole mass at formation

The minimum black hole mass M_{min} is set by the global parameter `XMIN` (FLOATING). The value of `XMIN` is **given in units of $M_\star$ or M_{ml}** (if a minimum length is present). Therefore, the parameter `XMIN` must be larger than one, i.e. $M_{min} \geq \mathrm{Max}(M_\star, M_{ml})$.

Quantum black hole mass threshold at evaporation

The evaporation ends when the black hole mass reaches the quantum threshold Q_{min}. The latter is fixed by the global `QMIN` (FLOATING) **in units of $M_\star$** (M_{ml}) if `ALPHA` is zero (nonzero).

Number of final quanta at the end of black hole decay

CATFISH allows for two different choices of final black hole decay: Final explosion in a number of quanta (≤ 18) or a black hole remnant. If `NP` (INTEGER) is zero, the black hole settles down to a remnant with mass Q_{min}. If `NP` $= 2 \ldots 18$, the black hole decays in a number `NP` of quanta with total CM energy equal to Q_{min} with a n-body process.

Momentum transfer model in parton collision

CATFISH uses the (stable) cteq5 PDF distribution [55, 80] to compute the total cross section and the differential cross section. Since the use of different PDF distributions produces a negligible uncertainty in the cross sections, other PDF distributions are not implemented. The uncertainty due to the choice of the momentum transfer is generally larger. The switch `MTR` allows to choose between two alternative definitions of momentum transfer: Black hole mass (`MTR`=1) or Schwarzschild radius inverse (`MTR`=2).

Conservation of local charges

CATFISH v. 2.10 allows conservation of color and electric charges. Color charge is always conserved. The switch `EMCHARGE` controls conservation of EM charge in the decay process (Hawking evaporation + final decay). If the EM charge switch is set to 0 (FALSE), there is no constraint on the total charge of the emitted quanta Q_E. If `NP`=0, physical charge conservation implies the relation $Q_E+Q_R+Q_B=2e$, where Q_E is the total charge of the Hawking quanta, Q_R is the charge of the black hole remnant and Q_B is the charge of the beam remnant. In that case, the black hole remnant can be either neutral or charged, depending on the event. The choice `EMCHARGE`=0 and `NP`$\neq 0$ is unphysical and should be avoided.

If the EM charge switch is set to 1 (TRUE), the absolute value of the total charge of the emitted quanta is $|Q_E| \leq 4e/3$, i.e. the maximum possible total charge of the scattering partons. In that case, the excess charge $2e-Q_E$ is assigned to the beam remnant and, if $n_p=0$, the black hole remnant is considered neutral. This is justified from the fact that the black hole charge should have been shed earlier in the evaporation process. (See, however, Ref. [84] for a different viewpoint.) The collider phenomenology of a charged remnant is not known and it is not clear how to track it in a detector in a meaningful way.

Minimum spacetime length

The parameter `ALPHA` (FLOATING) is defined as half the ratio between the minimum length and the fundamental length $L_\star = M_\star^{-1}$. If `ALPHA` is set to zero, i.e. no minimum length is present, CATFISH evaporates the black hole according to the Hawking theory. If `ALPHA` is nonzero, the black hole evolution proceeds according to the modified thermodynamics of Ref. [59, 60]. In both cases the evaporation ends when the black hole reaches the mass Q_{min}.

Simulation parameters

The list of simulation parameters is very simple:

1. Number of events: `NUMEVENTS` (INTEGER ≥ 1)
2. Random seed: `RSEED` (INTEGER)
3. Pythia PYLIST option: `MLIST` (INTEGER, 1 . . . 3 or 5 or 7 or 11 . . . 13)
4. (μ,e) and (γ,hadron) P_T cuts (GeV): `CUTS` (FLOATING FLOATING).

Statistically meaningful simulations require at least NUMEVENTS ≥ 5000. A detailed explanation of PYTHIA's `MLIST` parameter can be found in the PYTHIA manual (`http://www.thep.lu.se/~torbjorn/pythia/lutp0613man2.pdf`). Cuts on the transverse momentum P_T for (μ,e) and (γ,hadron) exclude the particles in the beam pipe from the computation of various energies and transverse momenta for each event (entries in the output files `catfish-v2.10.energy` and `catfish-v2.10.pt`, see below). All particles (black hole + beam) appear in the output if both `CUTS` values are set to zero. The default is 5 GeV for $\mu^\pm$, $e^\pm$ and 15 GeV for γ and hadrons.

Dilepton invariant mass parameters

The dilepton invariant mass is defined as

$$M_{12} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2} = \sqrt{2\mathbf{p}_1\mathbf{p}_2(1 - \cos\alpha)}\,,$$

where α is the angle between the two particles. To select opposite sign, same flavor dilepton events the following cuts are necessary to remove standard model background.

1. Transverse momentum of the leptons: `PLT` (FLOATING, GeV)
2. Pseudorapidity of the leptons: `PRAP` (FLOATING)
3. Lepton isolation cut: `PTISO` (FLOATING, GeV)
4. Cone: `CONE` (FLOATING)

The cone is defined as the distance between the two particles in the η-ϕ plane ($= \sqrt{\Delta\eta^2 + \Delta\phi^2}$) where $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity and ϕ and θ are the azimuthal and polar angles of the lepton w.r.t. beam axis, respectively. These cuts were implemented following [61]. Opposite sign, same flavor isolated dileptons have been used to discriminate BHs and supersymmetry at the LHC [62].

Standard Model background estimation

The QCD background can be estimated with PYTHIA. For example, the background for opposite sign same flavor dileptons from $t\bar{t}$ events can be calculated with the code

```
C user/common block variable declarations
C ----------------- PYTHIA SETUP ---------------------------------
C...Number of events to generate
NEV=10
C...Processes to generate
MSEL=6 !  or use MSUB to select specific processes
CALL PYINIT('CMS','p','p',14000.0D0)
C ----------------- EVENT LOOP -----------------------------------
DO 1000 IEV=1,NEV
CALL PYEVNT
CALL PYEDIT(1)
C...user analysis routines (eg.  find OSSF dileptons)
1000 CONTINUE
```

The MSEL=6 switch includes the PYTHIA processes 81, 82, 84 and 85, corresponding to the production of $t\bar{t}$ pairs by quark-quark interactions, gluon-gluon fusion, etc. Alternatively, single processes can be selected with the MSUB option. Further details can be found in Sect. 9.2 of the PYTHIA manual.

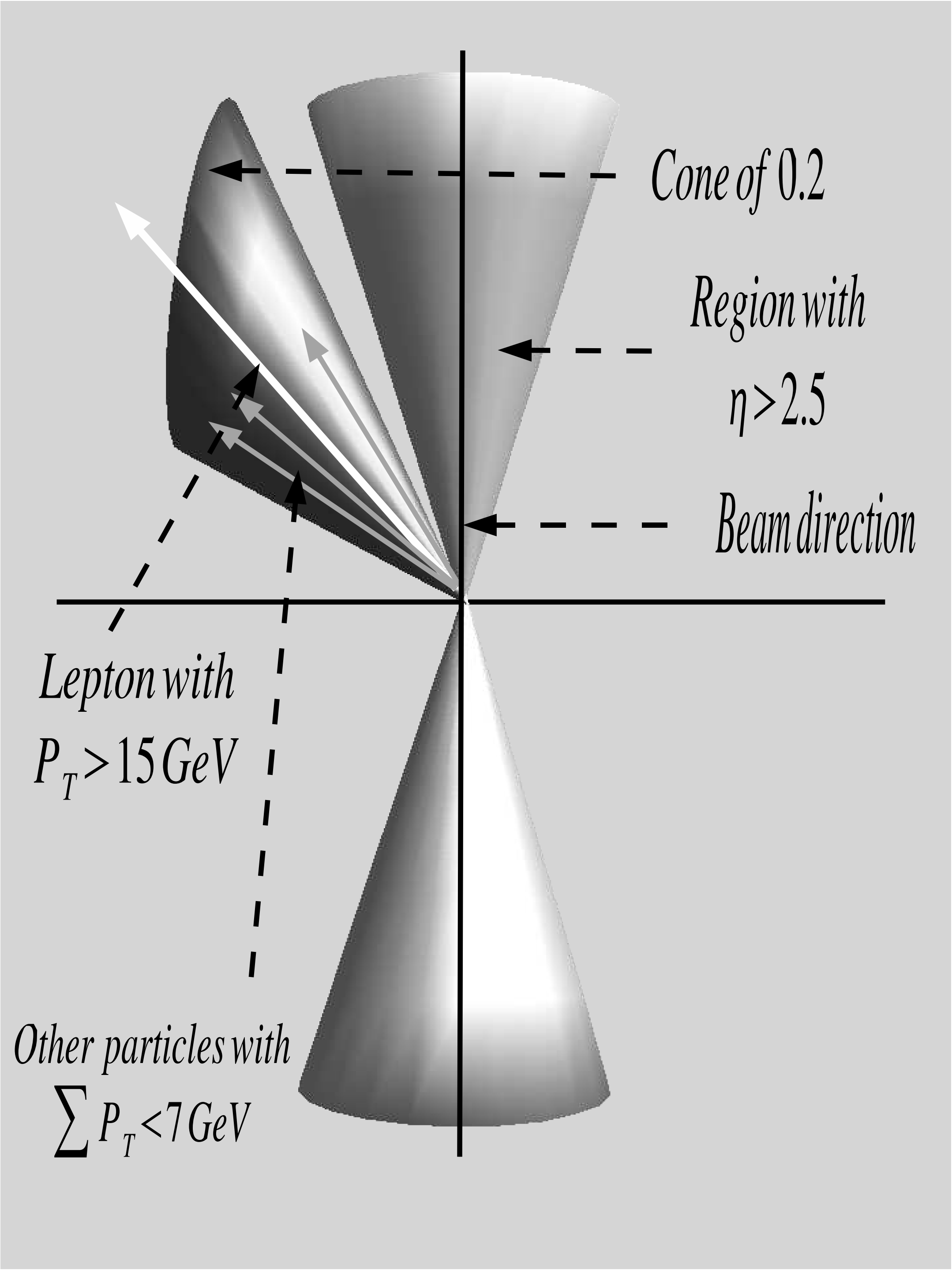

Figure 1: Illustration of the parameters used in the dilepton section of the input file. Beam direction is along the z axis. After the collision, particles are analyzed within a cone of 0.2 to find high P_T isolated leptons. The region with $\eta > 2.5$ is excluded.

The output files

The catfish-v2.10 executable program provides the following output:

1. ASCII-formatted PYTHIA output according to the `MLIST` option (see PYTHIA manual).
2. If `MLIST`=1 and PYTHIA's output is dumped into the file `catfish-v2.10.dat`, the sample script `read_demo.f` provides an example of data extraction (photon distribution). The executable `read_demo.exe` reads the photon distribution from catfish-v2.10.dat and creates the files `catfish-v2.10.gamma` and `catfish-v2.10.hist.gamma`. The format of `catfish-v2.10.gamma` is:

   `#` `E (GeV/c`^{2}`)` P_z `(GeV/c)` P_T `(GeV/c)`

   where # is the photon event number, E is the photon energy, and P_z and P_T are the z and transverse components of the photon momentum, respectively. The file `catfish-v2.10.hist.gamma` gives the histograms of E, P_z and P_T for a bin of `10 GeV/c`^{2} (`E`) or `10 GeV/c` (P_z and P_T).

   The source read_demo.f can be easily modified to extract different information.
3. At the end of the catfish-v2.10 run the following files are created):
   (a) `catfish-v2.10.sry`: Summary file
   (b) `catfish-v2.10.energy`: Various energy-related quantities (in GeV). Format: `EVENT #, E1, E2,...E11`, where:

      `E1`=Total missing energy (=CM Energy-`E2`)
      `E2`=Total visible energy (=`E10+E11`)
      `E3`=Missing energy in initial gravitons (=0. for `GRAVITONLOSS`=0.)
      `E4`=Total graviton+neutrino energy in the decay phase (=`E5+E6`)
      `E5`=Total graviton energy in the decay phase
      `E6`=Total neutrino energy in the decay phase

`E7`=Total missing energy in the beam pipe (=`E8+E9`) (`E7`=0. for `CUTS`=0. 0.)

`E8`=Missing energy in the beam pipe of $\mu^\pm$ and $e^\pm$ (`E8`=0. for `CUTS`=0. 0.)

`E9`=Missing energy in the beam pipe of γ and hadrons (`E9`=0. for `CUTS`=0. 0.)

`E10`=Total visible energy in $\mu^\pm$ and $e^\pm$.

`E11`=Total visible energy in γ and hadrons.

(c) `catfish-v2.10.pt`: Various transverse momentum-related quantities (in GeV). Format: `EVENT #, P1, P2,...P7`, where:

`P1`=Missing P_T

`P2`=Total Visible P_T (=`P6+P7`)

`P3`=Total graviton P_T in the decay phase

`P4`=Total neutrino P_T in the decay phase

`P5`=Total graviton+neutrino P_T in the decay phase (=`P3+P4`)

`P6`=Total visible P_T in $\mu^\pm$ and $e^\pm$

`P7`=Total visible P_T in γ and hadrons.

(d) `catfish-v2.10.cell`: Number of jets [PYTHIA's `PYCELL`]. Format: `EVENT #, NJET`

(e) `catfish-v2.10.fowo`: Fox-Wolfram moments [PYTHIA's `PYFOWO`]. Format: `EVENT #, H0,H1,H2,H3`

(f) `catfish-v2.10.jmas`: High/low jet mass [PYTHIA's `PYJMAS`]. Format: `EVENT #, PMH, PML`

(g) `catfish-v2.10.sphe`: Sphericity [PYTHIA's `PYSPHE`]. Format: `EVENT #, SPH, APL`

(h) `catfish-v2.10.thru`: Thrust [PYTHIA's `PYTHRU`]. Format: `EVENT #, THR, OBL`

(i) `catfish-v2.10.mll`: Opposite sign, same flavor dilepton invariant mass. Format: `EVENT #, MLL`

See PYTHIA's manual for the definition of the above quantities and further details.

Physics implementation in CATFISH 2.10

This section briefly reviews some of the main characteristics of the CATFISH program.

Structure of the Monte Carlo

CATFISH steps to simulate a black hole event are:

1. Two proton beams of energy $7 + 7$ TeV are injected in the Monte Carlo (CM frame).
2. The cross section for the process is computed.
3. The initial black hole mass is sampled from the differential cross section.
4. The black hole is decayed through the Hawking mechanism and final hard event (or black hole remnant).
5. The unstable quanta from the black hole and beam remnant are hadronized or decayed instantaneously by PYTHIA.

Initial black hole mass and beam remnant

The distribution of the initial black hole masses is given by the differential cross section $d\sigma/dM_{BH}$, where $M_{BH} = \sqrt{xs}$.

The part of CM energy of the pp collision which is not trapped or lost in gravitational radiation at formation is attributed to the beam remnant, which is hadronized by PYTHIA. The beam remant can be excluded from the output by setting nonzero P_T cuts.

Black hole evaporation

Due to the lack of results for the balding and spin-down phases described above, energy losses in these stages are assumed to be either negligible or included in the energy loss during formation. Since the TS model likely overestimates the actual energy loss, this is a reasonable assumption. However, we stressed above that balding and spin-down effects could significantly affect the event signatures. We plan to include balding and spin-down effects in updated versions of the code, as soon as theoretical results become available.

A similar approach is used in the Hawking phase, where CATFISH uses only the emissivities of non-rotating spherically-symmetric black holes [75, 76]. (Emissivities for rotating black holes are not fully known.) This is a reasonable assumption, given that the black hole is expected to be bald and spinless by the time the evaporation phase begins. Moreover, intrinsic uncertainties in event reconstruction should hide at least some of the differences between rotating and non-rotating field emissivities. The particle content at trans-Planckian energy is assumed to be the minimal $SU(3) \times SU(2) \times U(1)$ standard model with three families and a single Higgs boson on a thin brane. For black holes with mass $\sim$ few TeV the Hawking temperature is generally above 100 GeV. Therefore, all standard model DoFs can be considered massless. (Considering massive gauge bosons does not affect the conclusions significantly.) The spin-0, -1/2 and -1 DoFs on the brane are 1 (Higgs field), 90 (quarks + charged leptons + neutrinos) and 27 (gauge bosons), respectively. The longitudinal DoFs of the weak bosons are included in the counting. The DoFs c_i and the relative emissivities $\Gamma_{\mathcal{P}_i}$ and $\Gamma_{\mathcal{R}_i}$ [75, 76] are given in Table I – III, respectively. In the notations of Ref. [75, 76] the total decay multiplicity is [77]

$$N = \frac{(n+1)S}{4\pi} \frac{\sum_i c_i \mathcal{R}_i \Gamma_{\mathcal{R}_i}}{\sum_j c_j \mathcal{P}_j \Gamma_{\mathcal{P}_j}}\,, \tag{15}$$

where S is the initial entropy of the black hole and the emissivity normalizations for spin-s fields are:

$$\mathcal{P}_s = \begin{cases} 2.9 \times 10^{-4} & s=0 \\ 1.6 \times 10^{-4} & s=1/2 \\ 6.7 \times 10^{-5} & s=1 \\ 1.5 \times 10^{-5} & s=2 \end{cases}\,, \qquad \mathcal{R}_s = \begin{cases} 1.4 \times 10^{-3} & s=0 \\ 4.8 \times 10^{-4} & s=1/2 \\ 1.5 \times 10^{-4} & s=1 \\ 2.2 \times 10^{-5} & s=2 \end{cases}\,. \tag{16}$$

The decay multiplicities per species N_i are

$$N_i = N \frac{c_i \mathcal{R}_i \Gamma_{\mathcal{R}_i}}{\sum_j c_j \mathcal{R}_j \Gamma_{\mathcal{R}_j}}\,. \tag{17}$$

The presence of a minimum length affects the evaporation phase. CATFISH uses the dimensionless parameter $\alpha = l_m M_\star/2$ to determine the minimum length. If there is no minimum length, i.e. $\alpha = 0$, the Monte Carlo evaporates the black hole according to the Hawking theory with varying temperature. If $\alpha \neq 0$, the black hole evolves according to the thermodynamic relations of Ref. [59, 60]. The evaporation ends when the black hole reaches the mass Q_{min}. This is set in units of $M_\star$ (M_{ml}) if the minimum length is zero (nonzero). Note that the black hole minimum formation mass M_{min} and the endpoint of Hawking evaporation Q_{min} are independent parameters.

	c_i
Quarks	72
Charged leptons	12
Neutrinos	6
Photon	2
EW bosons	9
Gluons	16
Higgs	1
Graviton	1

Table 1: DoFs c_i for the standard model fields on a thin brane. The graviton is assumed to propagate in all $(n+4)$ dimensions. Following Ref. [75, 76], the $(n+4)(n+1)/2$ graviton helicities are included in the emissivities (see Table 2 and 3 below). Therefore, the graviton counts as one DoF. Longitudinal DoFs are included in the EW boson counting.

	n=3	n=4	n=5	n=6	n=7
Higgs	1	1	1	1	1
Fermions	0.89	0.87	0.85	0.84	0.82
Gauge Bosons	1.0	1.04	1.06	1.06	1.07
Gravitons	2.7	4.8	8.8	17.7	34.7

Table 2: Fraction of radiated power per DoF and species i, $\Gamma_{\mathcal{P}_i}$, normalized to the Higgs field. The graviton values include all the helicity states. (From Ref. [75, 76].)

Four-momentum is conserved at each step in the evaporation process by taking into account the recoil of the black hole on the brane due to the emission of the Hawking quanta. The initial energy of the black hole is distributed democratically among all the Hawking quanta with a random smearing of ±10%. This smearing factor is introduced on a purely phenomenological basis to take into account quantum uncertainties in the emission of each particle.

	n=3	n=4	n=5	n=6	n=7
Higgs	1	1	1	1	1
Fermions	0.78	0.76	0.74	0.73	0.71
Gauge Bosons	0.83	0.91	0.96	0.99	1.01
Graviton	0.91	1.9	2.5	5.1	7.6

Table 3: Fraction of emission rates per DoF and species i, $\Gamma_{\mathcal{R}_i}$, normalized to the Higgs field. The graviton values include all the helicity states. (From Ref. [75, 76].)

Contributions and future developments

The CATFISH program is stable and has been widely tested. However, as any computer code, the author cannot certify that CATFISH is bug free. Should you find any bug in the program, please contact the author:

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Due to the enormous amount of literature in the subject, not all theoretical advances in the field are included in the code at this stage. Updates and extensions of code and manual will appear on the CATFISH web site

`http://www.phy.olemiss.edu/GR/catfish`

The author apologizes in advance for any omission and/or missing references.

Contributions to the CATFISH project from independent researchers and/or suggestions are welcomed. If you want to contribute to the CATFISH Monte Carlo program, please contact the author at the above address.

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