Black Holes at Hadron Colliders

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Outline

- Introduction
- Theoretical Issues
- Event Generation and Signatures
- Greybody factors

Introduction

- It is now well known that extra dimensions allow $M_p \sim$ TeV

- This means miniature black holes can be produced at the LHC

- The event horizon for a black hole of mass M_{BH} is

$$r_H = \frac{1}{M_p} \left(\frac{M_{BH}}{M_p} \right)^{\frac{1}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{(n+2)\pi^{\frac{n+1}{2}}} \right)^{\frac{1}{n+1}}$$

- By geometrical arguments $\sigma \sim \pi r_H^2$

- The equivalent Hawking temperature is given by

$$T_H = \frac{n+1}{4\pi r_H}$$

Validity of Semi-classical Approach

- This approach will certainly break down at energy scales close to the fundamental Planck scale - a theory of quantum gravity is needed

- How far above it do we need to be?

- Require that $M_{BH} \gg M_p$ so that the approximations used are valid for production and the majority of the decay

- Experimental motivation $\rightarrow$ $M_{BH} > 5M_p$

- Depends on your definition of M_p

Approximating the BH Decay

- The decay takes place in three phases: balding, Hawking (Kerr then Schwarzschild) and Planck phase

- Balding phase
  - Loses asymmetry and settles down to a Kerr solution
  - Not well studied in extra dimensions

- Hawking phase
  - Extra dimensional greybody factors (see later) should allow this to be well modelled

- Planck phase
  - Final phase when $M_{BH} \sim M_p$ or $T_{BH} \sim M_p$
  - Not at all well understood

Theoretical Issues

- In 4D the balding phase is supposed to account for about 16% of the mass loss

- In $(4+n)$ D it may be much more and could be dominated by emission into the bulk

- LHC energies mean we are always on the edge of the semi-classical limits for the formation of the black hole

- The Planck phase is often a significant fraction of the decay, which means the event signature is very sensitive to how it is modelled

- Increasing n, as seems to be theoretically favoured, makes the problem worse as T_H increases for fixed M_{BH}

Simulation Issues

- Although the Planck phase isn't understood, it must be simulated in an event generator

- Any BH event signatures being considered must be independent of how this is done

- Our Monte Carlo has several options *e.g.* a 2-body decay of the remnant once M_{BH} falls below M_p

- If n is large, T_H is high which means the particle multiplicity is low and the Planck phase starts relatively early

- This makes it very difficult to find 'Planck phase-independent' event signatures

Cambridge Black Hole Event Generator

- Some more details will be given by Peter Richardson this afternoon
- Independent hard process which interfaces via Les Houches standards to full MC programs *e.g.* HERWIG and PYTHIA
- Fully takes into account the time dependence of T_H and also BH recoil effects
- Switches allow the Planck phase to be modelled in a variety of different ways for comparison
- Greybody effects included in a preliminary way

Determining the Number of Extra Dimensions

- One method used by several groups has been to use the relationship between T_H and M_{BH} which means that

$$\log(T_H) = -\frac{1}{n+1}\log(M_{BH}) + \text{const}$$

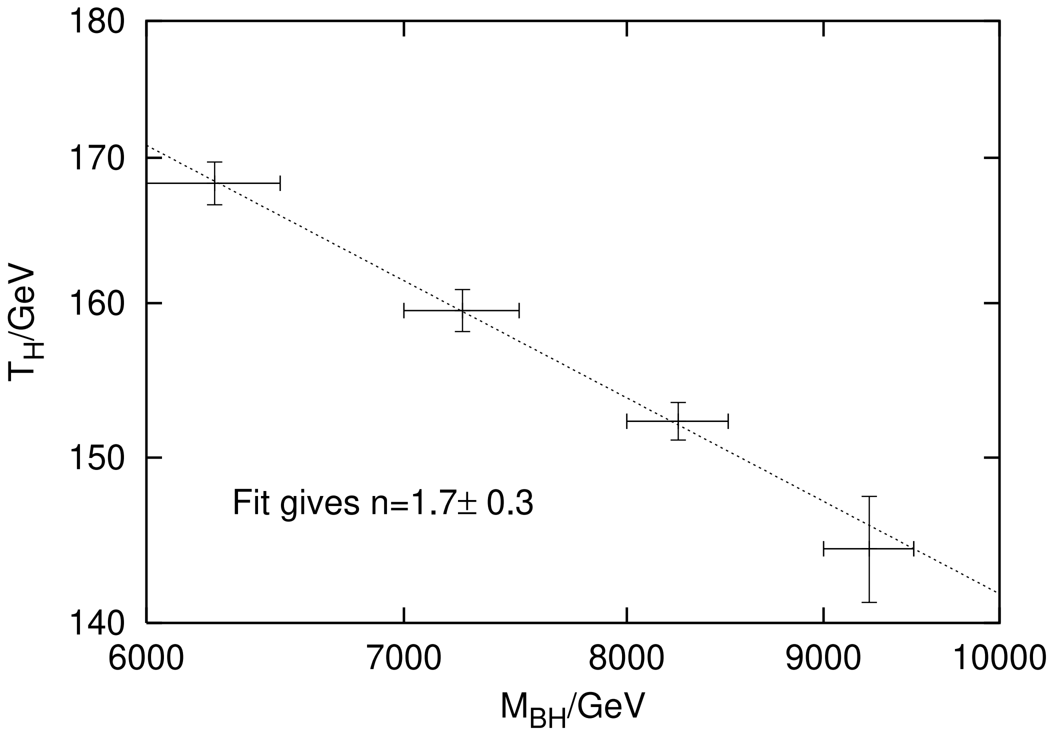
- T_H is found by fitting the Hawking spectrum of *e.g.* electrons or photons

- There are several problems
  - T_H changes as a function of time t
  - Recoil of the BH distorts the spectrum
  - Secondary particles obscure the spectrum
  - Resolution on M_{BH} may not be good
  - Greybody factors modify the spectrum

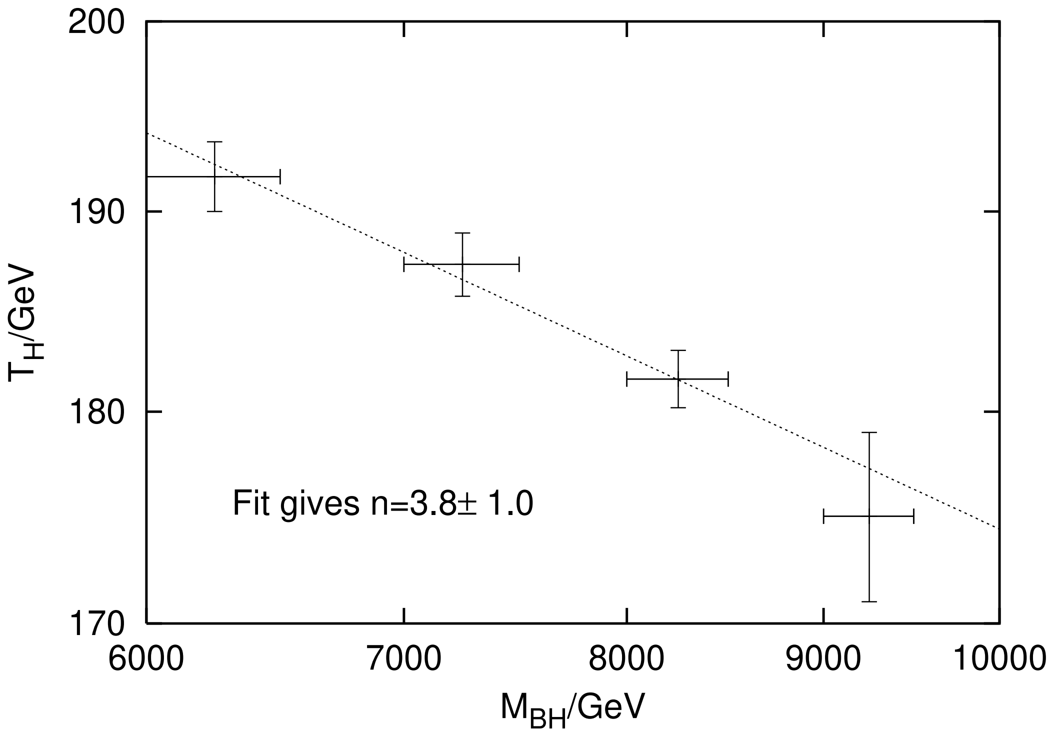
- These issues make this method unpromising ....

Using a Fixed T_H

- Here we fit the electron spectrum only ($n = 2$ and $M_p = 1$ TeV)



Using a Changing T_H



- Fitting with an integrated spectrum instead we can obtain $n = 1.7 \pm 0.1$ but results for higher n are much worse

What are the Alternatives?

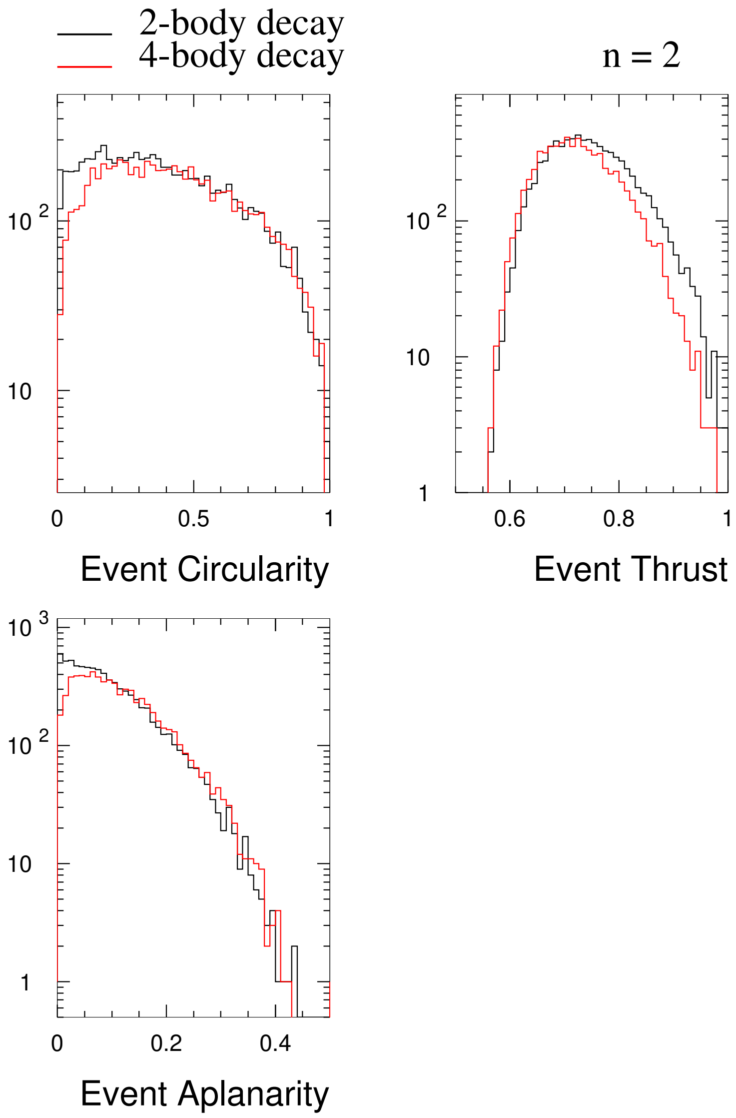
- An alternative is to use the MC program to try to find a kinematic variable which depends (strongly) on n

- This would allow us to directly determine the number of extra dimensions, assuming a correct theory

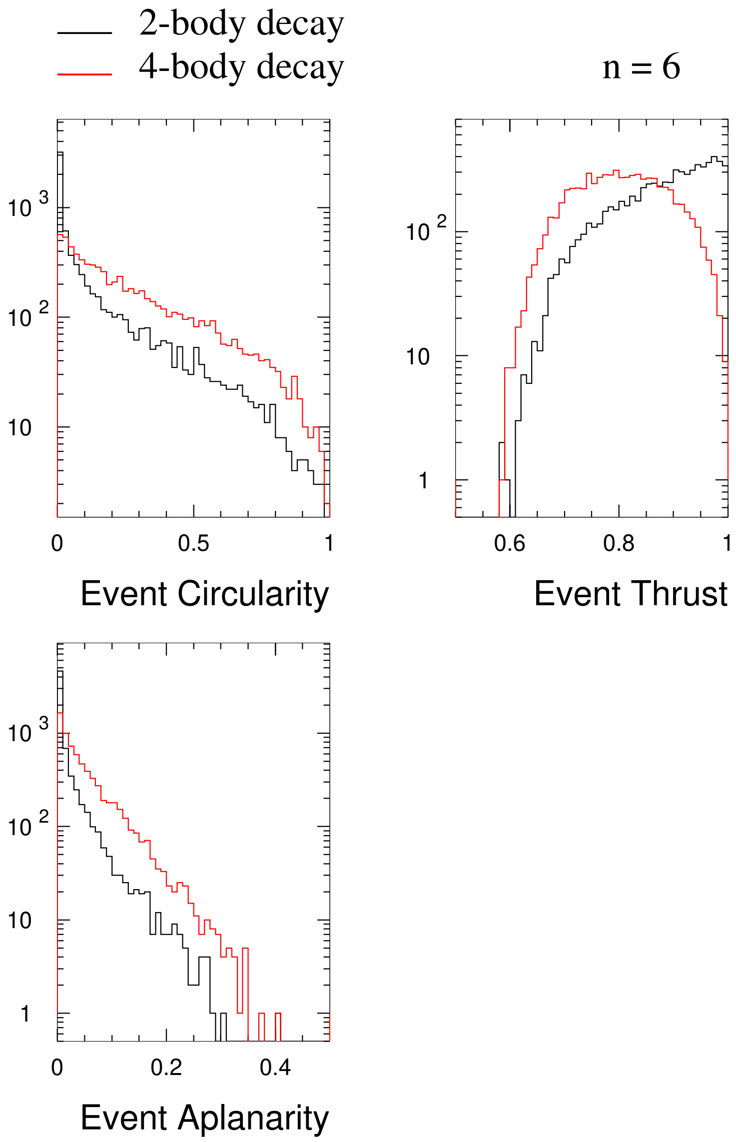
- It *wouldn't* provide direct evidence for Hawking radiation in extra dimensions

- Ali Sabetfakhri (ATLAS, Cambridge) has looked at the following:
  - p_T of different jets
  - Jet multiplicities
  - Event shape variables

Event Shape Variables for $n = 2$

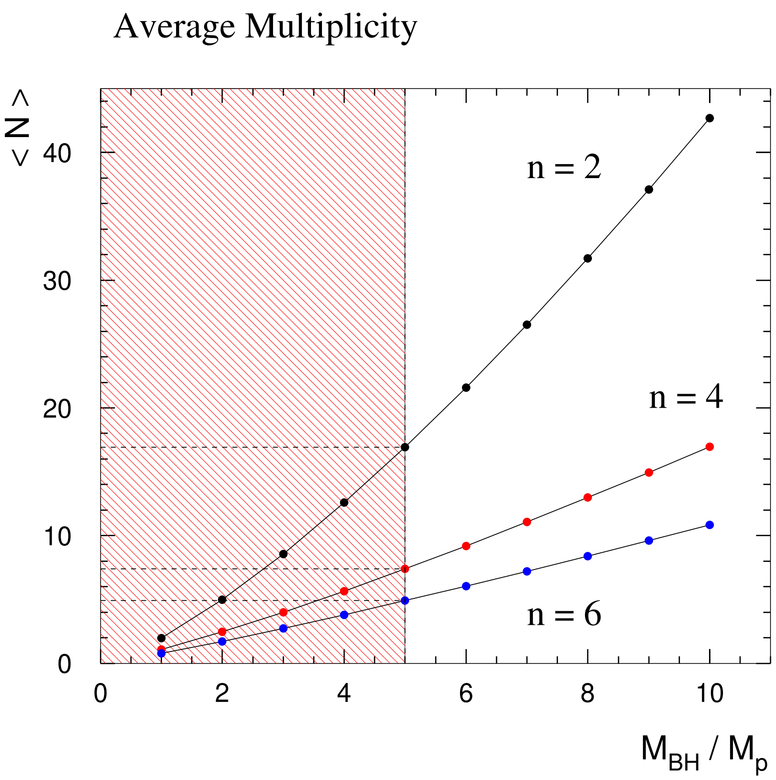


Event Shape Variables for $n = 6$



Can Different n be Distinguished?

- There are two main problems
  - The rate of change of variables with n decreases at larger n
  - For larger n the multiplicity is getting too low



Greybody Factors

- We saw that one approach for finding the number of extra dimensions is by using the Hawking spectrum from the black hole

- This has a number of problems as has already been seen

- Here we discuss one of these issues - greybody factors - which is also important for alternative methods of trying to determine n

- Greybody factors have at least two important features
  - They modify the spectrum of emitted particles from that of the perfect thermal black body
  - They modify the ratios of different particle types

What are Greybody Factors?

- These factors give the probability of emitted particles getting through the effective potential barrier at the black hole's horizon

- They are more easily calculated by considering the reflection coefficient for a wave from infinity incident on the black hole

- They are energy-dependent ($\rightarrow$ modification of spectrum) and spin-dependent ($\rightarrow$ modification of particle emissivities)

$$\frac{dN_{i,l,m}}{d\omega dt} = \frac{1}{2\pi}\frac{\gamma_{i,l,m}(\omega r_H)}{exp[(\omega/T_H)\mp 1]}$$

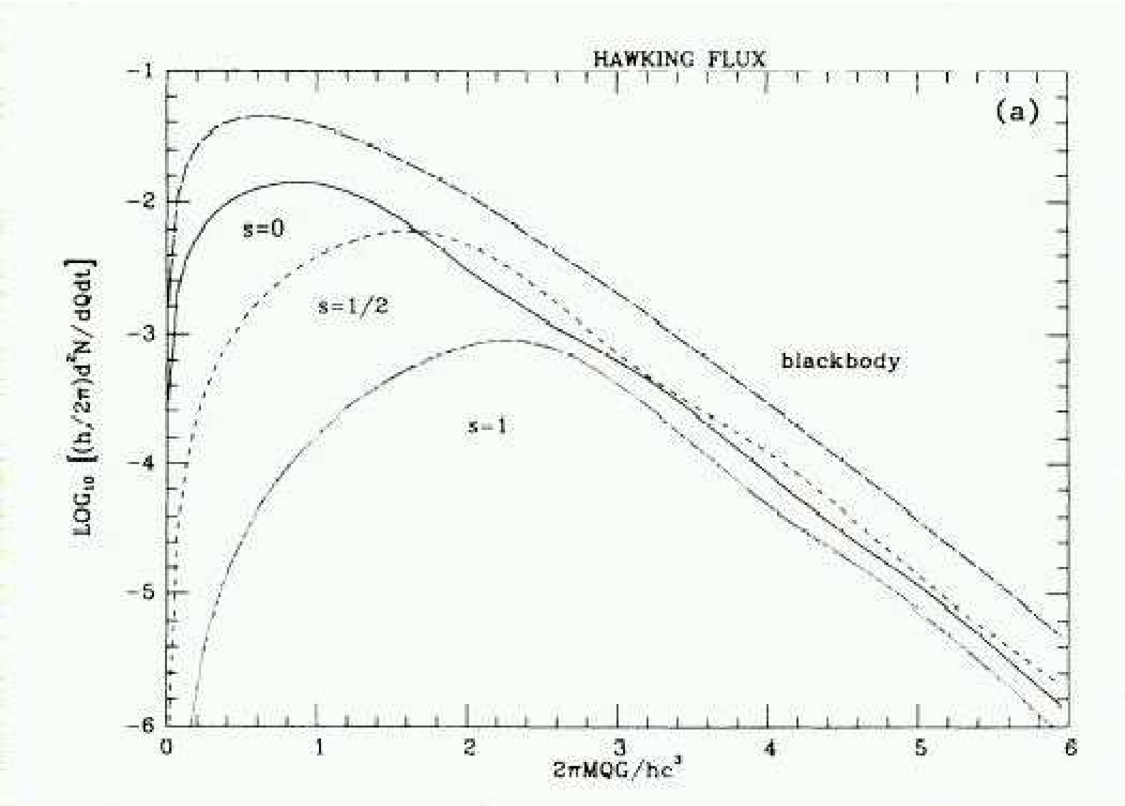
- Note: The later plots show

$$\sigma = \frac{\Gamma}{\omega^2} = \frac{\sum_{l,m}\gamma_{l,m}}{\omega^2}$$

Greybody Factors in 4D

- Greybody factors are *not* an 'exotic' phenomenon - the 4D case was extensively studied by Page in the 1970s

- This plot shows the effect of the 4D greybody factors on the emitted particle spectra



4 D $\longrightarrow (4+n)$ D

- In 4D the greybody factors modify the spectra significantly, particularly for higher spin particles

- Any attempt to verify the Hawking spectrum would give a negative result unless the greybody factors were included

- What about in higher dimensions ....?

- There is no reason to believe that the energy spectra won't be significantly altered in this case as well

- We need to take this into account if we are to trying to extract the number of extra dimensions from a black hole signature

Calculation of Greybody Factors

- The procedure (at least in 4D) is relatively simple:
  - Write down the wave-equation in your co-ordinate system of choice
  - This wave equation is always found to be separable in radial and angular parts
  - Apply boundary conditions to the radial part that require the solution on the black hole horizon to be purely in-going
  - Solve the second-order differential equation to find the ratio between in-going and out-going amplitudes at infinity
  - Convert this into the reflection coefficient and hence the greybody factor

Analytic Method

- The method used by Page for the 4D case was as follows:
  - Find an analytic solution close to the horizon
  - Find an analytic solution at infinity
  - Match these solutions in the intermediate regime
  - Expand to find γ in powers of ωr_H
- Such results must be *very* carefully interpreted
  - The leading order term for the lowest value of l is found only to be reliable for very small values of ωr_H
- Plotting the result prior to the final expansion gives only a limited improvement

Numerical Method

- It seems the only way to obtain accurate greybody factors over a reasonable range of ωr_H is to tackle the problem numerically

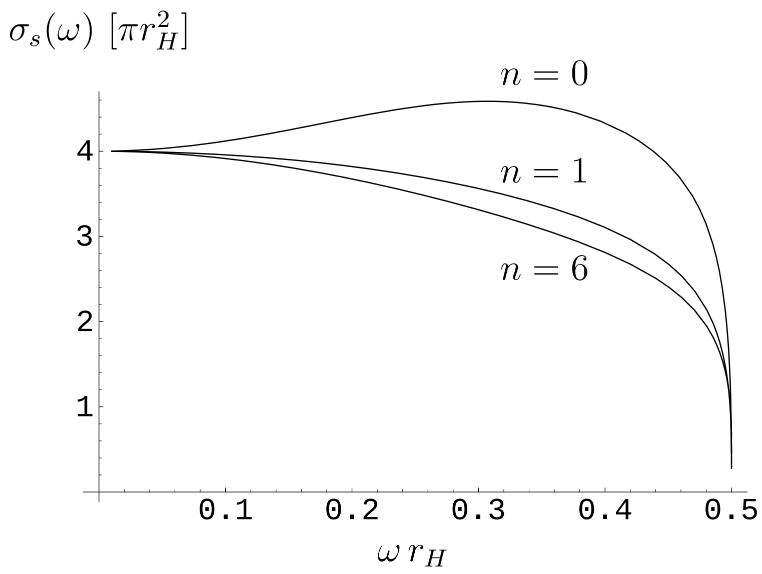
- Such an approach isn't without problems - see later

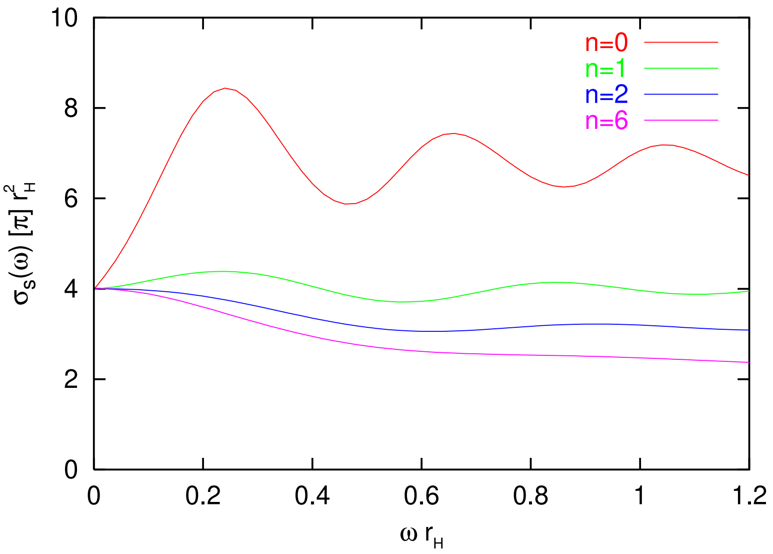
- Using a numerical approach the generalisation to $4+n$ dimensions is easy - just start from a slightly different radial wave equation

- Note that all my work is for emission of particles on the brane - this means only the metric in the wave equation changes, not the wave functions themselves which are still 4D

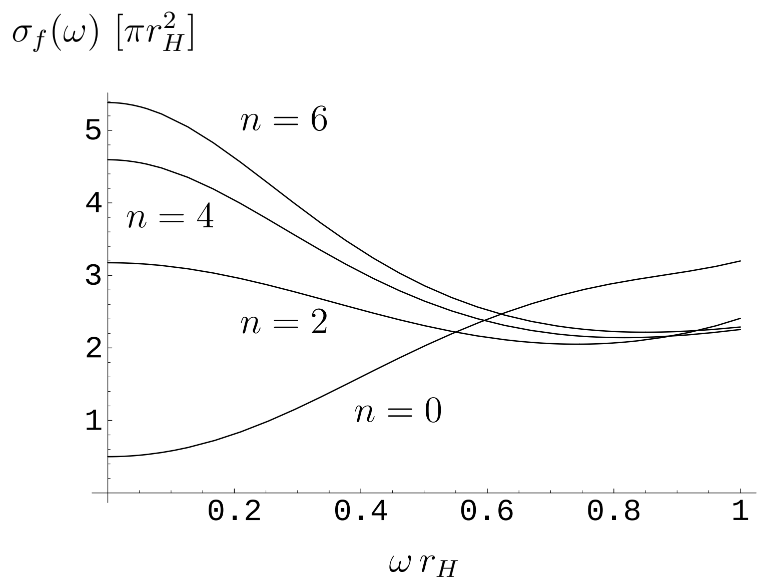
- At present only non-spinning black holes are considered

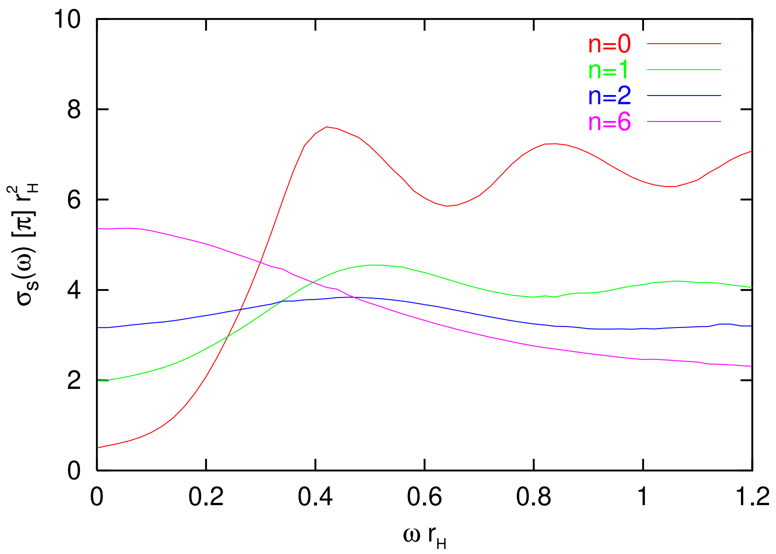
Results for the Spin-0 Case



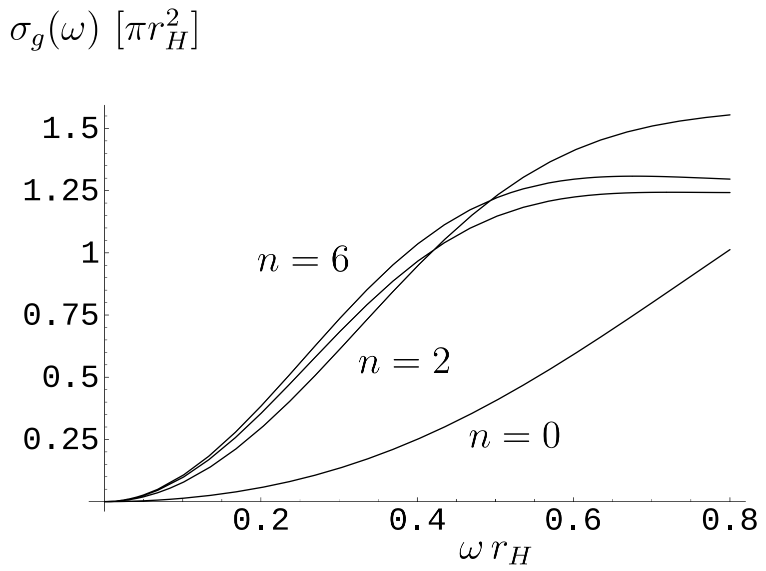


Results for the Spin-$\frac{1}{2}$ Case





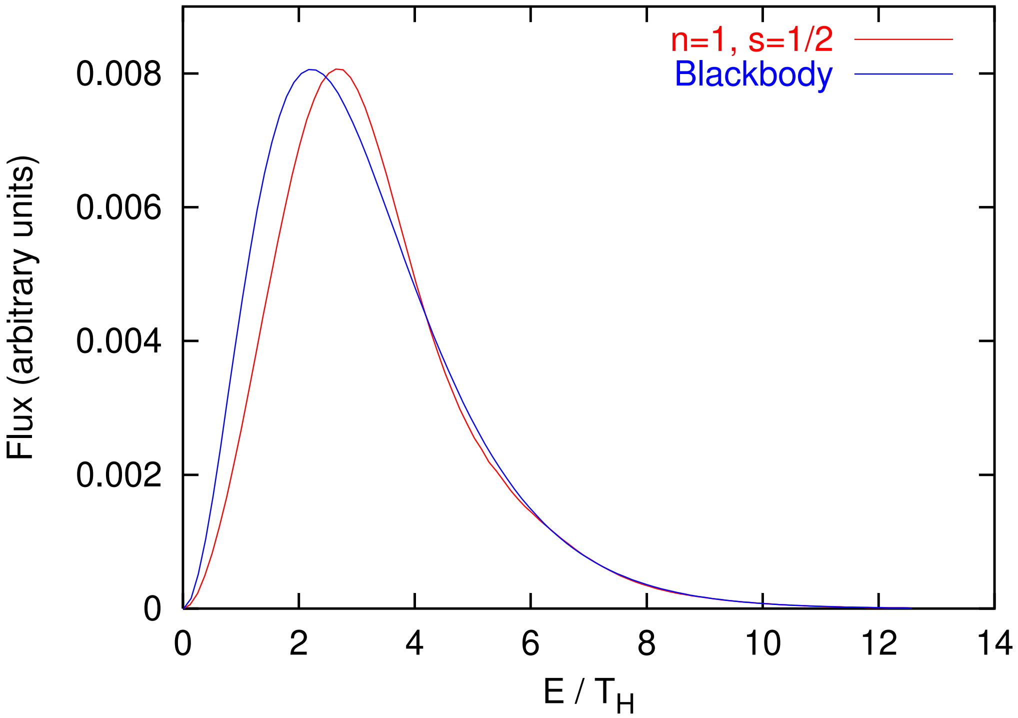
Results for the Spin-1 Case



- No numerical results in this case as yet due to numerical problems
  - Methods used to avoid these in the $n = 0$ case do not easily generalise to the $4 + n$ case

Using the Greybody Factors

- Plot flux or power energy spectra for $n \neq 0$



- Calculate particle emission probabilities for $n \neq 0$ ....

Particle Emission Probabilities

- Relative emission probabilities for different spins:

	$s = 0$	$s = \frac{1}{2}$	$s = 1$
$n = 0$	1.0	0.37	0.11
$n = 1$	1.0	0.69	?
$n = 2$	1.0	0.75	?
$n = 6$	1.0	0.58	?
'Black body'	1.0	0.75	1.0

- These allow relative emission probabilities for different particle species to be calculated:

	q	$l^{\pm}$	ν	g	γ	Z	$W^{\pm}$	H
$n = 0$	66.5	11.1	5.5	4.5	0.6	3.1	6.2	2.5
'Black body'	56.5	9.4	4.7	16.8	2.1	3.1	6.3	1.0

Implementation in Monte Carlo

- If $s = 1$ results can be obtained for higher n, then the Monte Carlo program can emit the different particles with the correct probabilities for each n

- It will also be possible to emit each particle species according to the correct energy spectrum

- When there is more theoretical agreement about the $n \neq 0$ wave equation it should be simple to extend to rotating black holes as well, allowing the spin-down Kerr phase to be modelled as well

Summary and Outlook

- An exciting area *but* there are still many theoretical uncertainties

- We can do a better job than at present in correctly modelling the Kerr and Schwarzschild phases in the Monte Carlo
  - Correct particle emission probabilities
  - Correct particle energy spectra

- More work on the balding phase would be useful

- The 14 TeV provided by the LHC means distinguishing higher numbers of dimensions (*e.g.* $n = 5$ and $n = 6$) will always be tricky unless the Planck phase can be better understood

- With thanks to: Peter Richardson, Ali Sabetfakhri, Bryan Webber, John March-Russell, Pangiota Kanti and members of the Cambridge SUSY Working Group