Can Black Holes be Produced and Detected at ATLAS?

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Outline

- Black Holes in Models with Extra Dimensions
- Black Hole Production
- Black Hole Decays
- Determining the Number of Extra Dimensions

Black Holes in 4 Dimensions

- Black holes are characterized by an event horizon at radius r_h

- Within this radius, not even light can escape the gravitational force

- Newtonian escape velocity is $v^2 = 2\frac{GM}{r}$

  so a particle with speed c can not escape to infinity if:

  $r < r_h = 2\frac{GM}{c^2}$

- However a black hole *can* emit particles by Hawking evaporation

Black Holes in (4+n) Dimensions (1)

- In theories with extra dimensions the $\sim$ TeV energy scale is considered as fundamental - the 4D Planck Scale ($\sim 10^{18}$ GeV) is derived from it

- Gauss's Law in (4+n) dimensions tells us that:

$$V(r) \sim \frac{M}{M_{p(4+n)}^{n+2}} \frac{1}{r^{n+1}} \text{ for } r \ll R$$

$$V(r) \sim \frac{M}{M_{p(4+n)}^{n+2} R^n} \frac{1}{r} \text{ for } r \gg R$$

- So the two energy scales are related (up to volume factors of order 1):

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

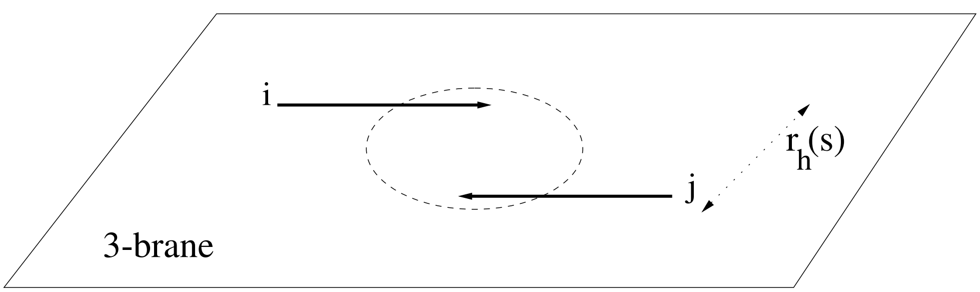
- From this expression the sizes of the extra dimensions can be calculated for different values of n

Black Holes in (4+n) Dimensions (2)

- For black holes in the $r \ll R$ regime, an analagous approach to the 4D one shows that

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

- 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 partons pass within the horizon radius



Cross Section for Black Hole Production

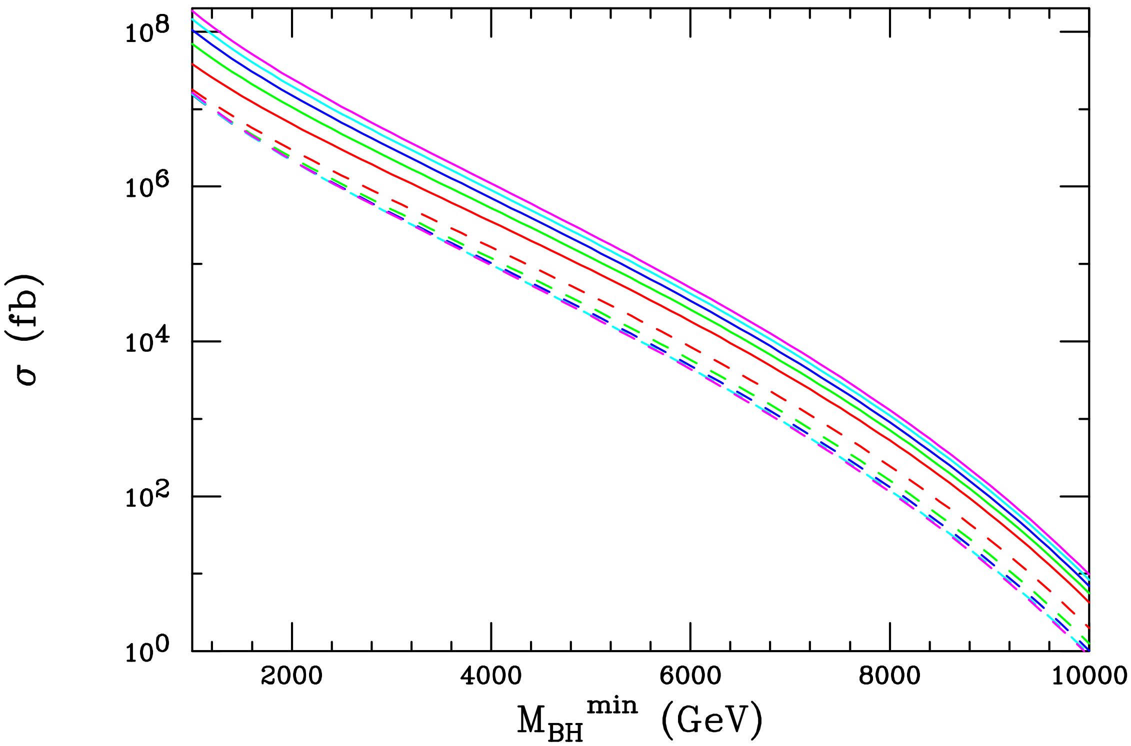
- There has been much discussion in the literature about what the cross section for black hole production is

- The consensus opinion seems to be that the classical $\sigma = \pi r_h^2$ is valid for black hole masses well above the Planck scale

- For masses close to the fundamental Planck scale a theory of quantum gravity would be required to calculate the cross section

- Although the parton level cross section grows with black hole mass, the parton distribution functions fall rapidly at these high energies

Production Cross Sections



- $M_p = 1$ TeV, various values of n

  Solid lines: GT, dashed lines: DL

Can Black Holes be Produced at ATLAS?

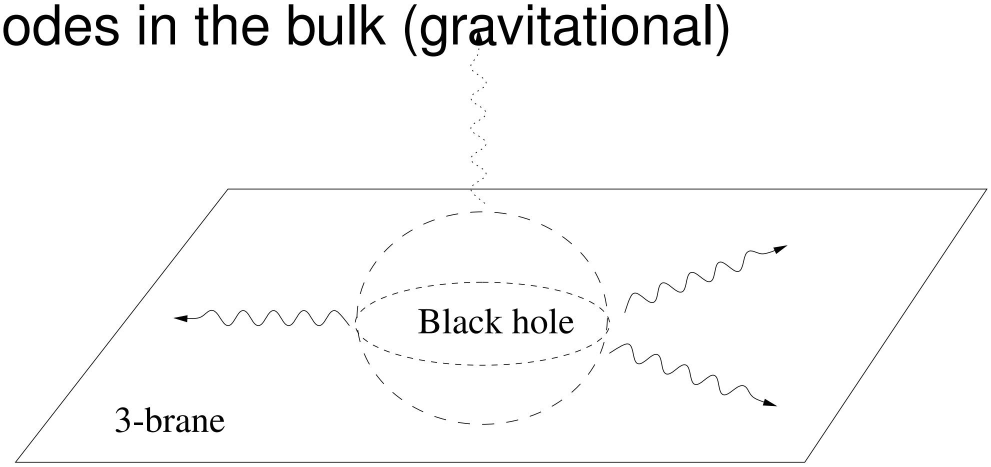
Yes...

...provided our world has extra dimensions and we have correctly understood the black hole production process

Phases of the Decay

- The decay of these tiny black holes is (probably) instantaneous on LHC detector time scales and is made up of three major phases
  - Balding phase
  - Hawking evaporation phase (a brief spin-down phase, then a longer Schwarzschild phase)
  - Planck phase

- Hawking radiation is emitted predominantly into modes on the brane (SM particles) but also into modes in the bulk (gravitational)



Schwarzschild Phase

- As the decay progresses, the black hole mass falls and so the temperature rises

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

- Assume a quasi-stationary approach is valid - black hole has time to come into equilibrium at each new temperature

- Decay spectrum $\frac{dN_{i,E,l,m}}{dEdt} = \frac{1}{2\pi}\frac{\gamma_{i,E,l,m}}{exp[(E/T_H]\mp 1}$

  where

  - i denotes particle type
  - l,m are angular momentum quantum numbers
  - γ are the so-called 'grey-body' factors

Grey-body Factors

- Grey-body factors modify the spectrum of emitted particles from that of a perfect thermal black-body *even* in 4 dimensions

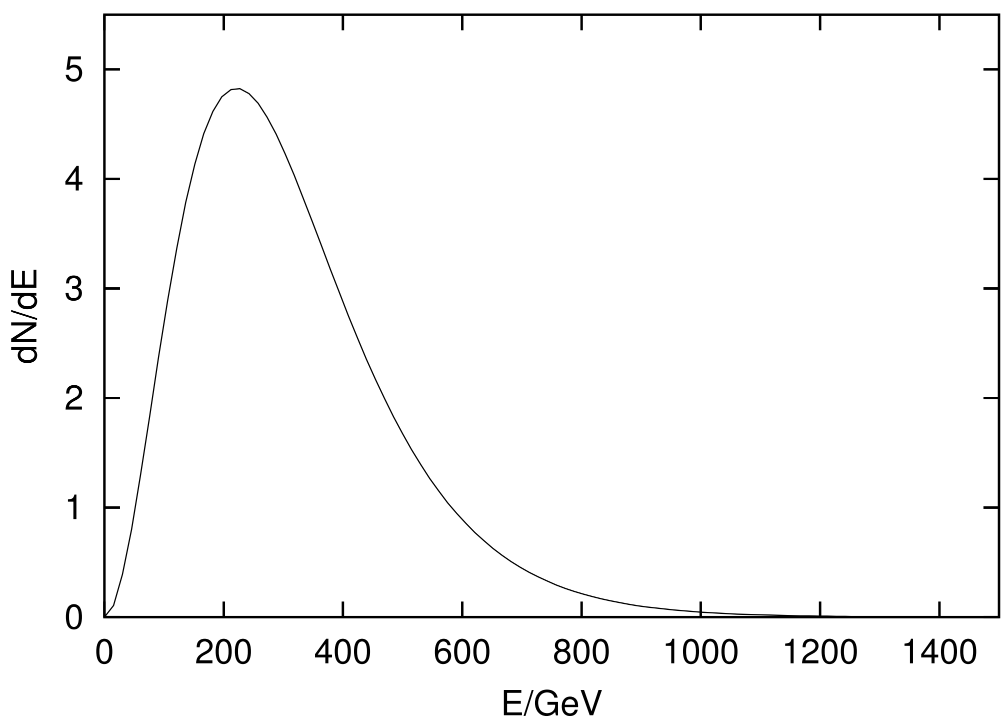
- For $E \gg T_H$ then geometric arguments show that $\Sigma_{l,m}\gamma \propto (r_h E)^2$ in any number of dimensions

- Work in progress by March-Russell should help in determining the low energy form for different spins in different numbers of dimensions

- Like others, we approximate the spectrum as black-body and use relative emissivities for different spin particles based on the 4D case

Black-body Spectrum

- A Planck spectrum for fermions with a Hawking temperature of 100 GeV:



- Note that for either fermions or bosons the peak in the energy spectrum is at around $2T_H$

Simulation of Black Hole Decay in Herwig

- Only the (spinless) Hawking evaporation phase (accounts for the majority of the mass loss)
- Includes black hole recoil (more complicated?)
- Allows the increase in T_H with time to be taken into account
- Method used should shed excess electric charge at the start as required theoretically

Experimental Signatures

- Large cross sections
- Large total deposited energy and visible transverse energy typically of order $\frac{1}{3}$ of the total
- Large multiplicity events
- High sphericity events
- Hadronic:leptonic activity in approximate ratio 5:1

Studying the Number of Extra Dimensions

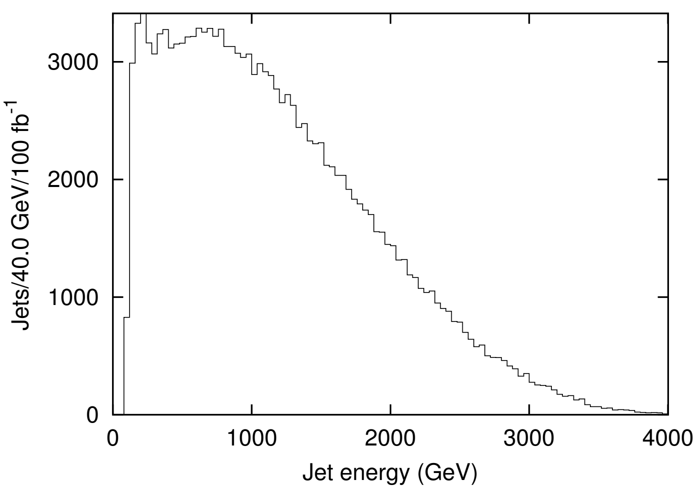
- Method inspired by Dimopoulos & Landsberg in hep-ph/0106295
- Simple detector model using GETJET with ATLAS resolutions
- Apply cuts to simulate ATLAS, remove possible backgrounds and improve analysis
- Use electrons and photons to try to find T_H for different bins in initial black hole mass (M_{BH})
- Use a log-log plot of T_H vs M_{BH} to try to find the number of extra dimensions

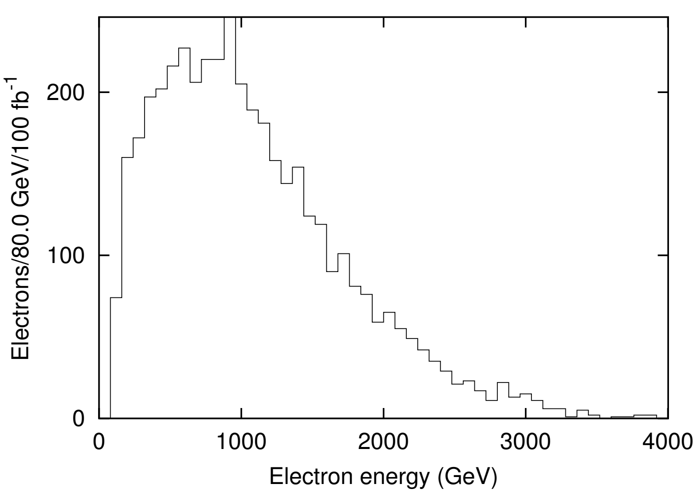
Experimental Issues

- Require events with high mass ($\geq$ 1 TeV)
- E_T^{miss} consistent with zero used to improve mass resolution
- Require $\geq$ 4 jets in final state with energy above 100 GeV
- Backgrounds from the $Z(ee) + jets$ and $\gamma + jets$ SM processes will be small
- Use isolation cut to remove secondary electrons and photons

Effect of Isolation Cuts

- Energy specta of jets and isolated electrons ($T_H \sim 400$ GeV)





Finding the Hawking Temperature

- Landsberg argues that since the black hole spends most of its time near the initial T_H, the time variation of the temperature can be ignored

- Therefore fit the Planck spectrum up to $M_{BH}/2$ (kinematic limit for pair production) to find the initial value of T_H

- This is part of the reason for the $N \geq 4$ multiplicity requirement - it ensures that not too many of the emissions are likely to be affected by the kinematic cut-off

Finding the Number of Extra Dimensions

- Now that T_H is known for a variety of different bins in M_{BH}, it is possible to fit for the number of extra dimensions n

- $T_H = M_P \left(\frac{M_P}{M_{BH}} \frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)} \right)^{\frac{1}{n+1}} \frac{n+1}{4\sqrt{\pi}}$

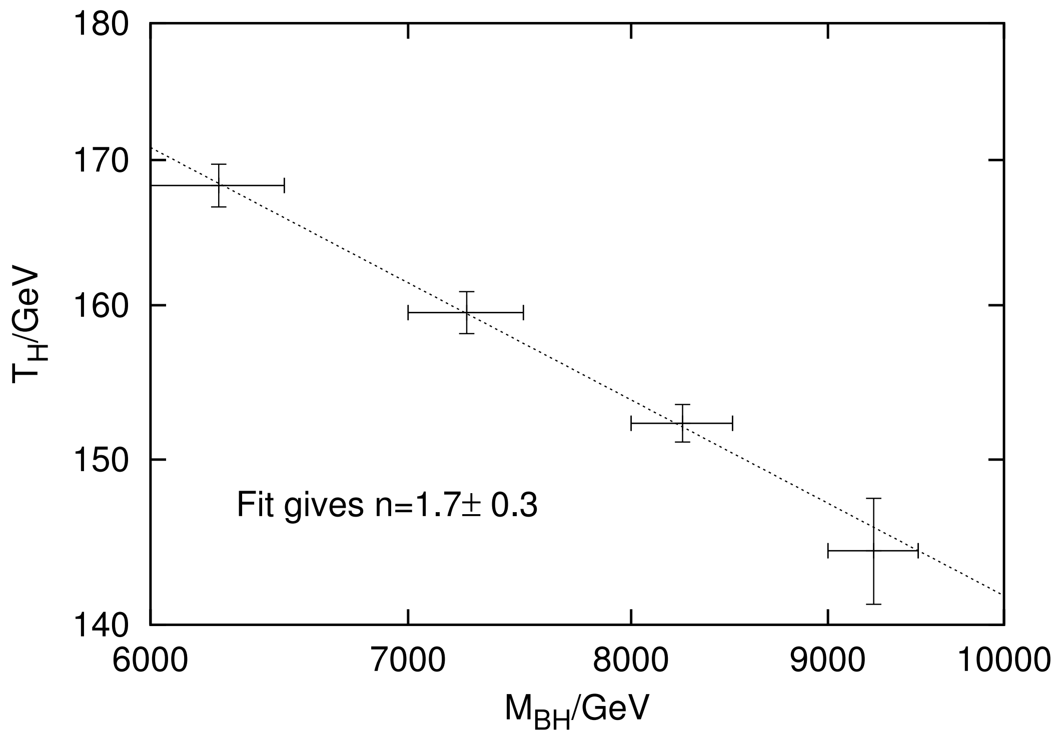
  which means that:

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

- By minimizing chi-squared using a fitting program like MINUIT it is possible to obtain a value for n

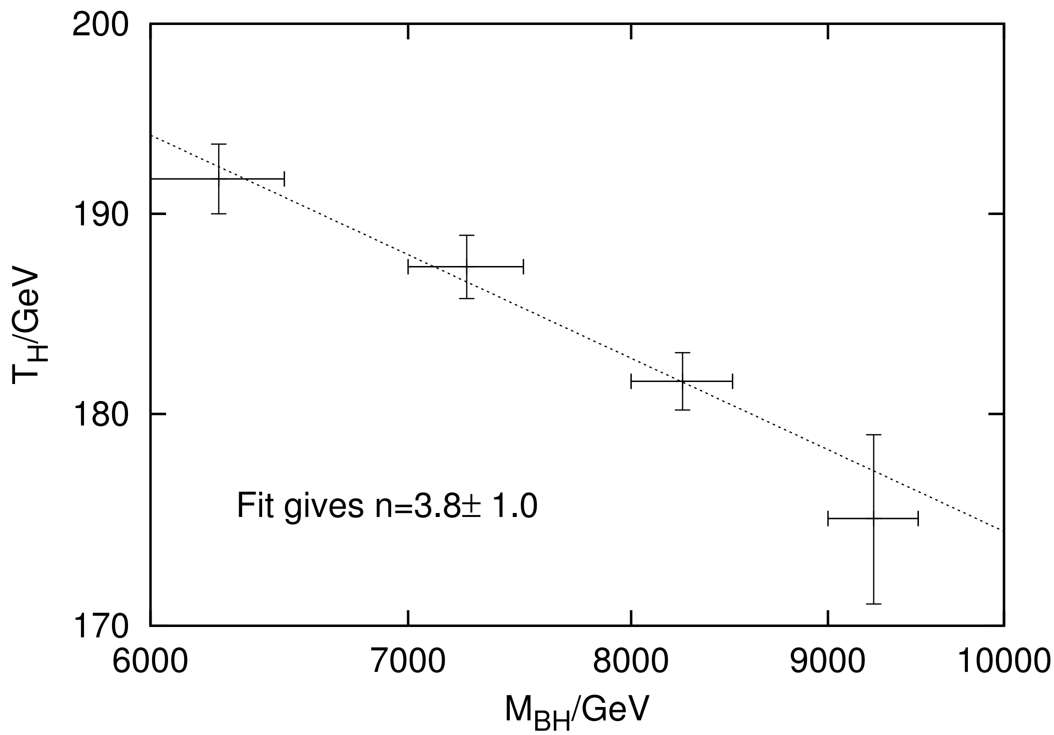
How well does this work? (1)

- For a particular set of parameters ($n = 2$ and $M_P = 1$ TeV) with the time variation of the temperature 'turned off':



How well does this work? (2)

- For the same parameters with the time variation of the temperature on:



Improvements

- It seems it is not possible to simply ignore the time variation of the Hawking temperature - the temperature determined from the fitted spectrum is not the initial T_H we require

- Improve by numerically integrating the Planck spectrum and fitting this - care must be taken to model the final cut-off time on the integral

- For the particular parameters used above, the results are much improved:

  Now the fit gives $n = 1.7 \pm 0.1$

Final Comments

- For parameters with lower cross sections and/or lower multiplicities (due to higher T_H) the determination of n is still not reliable

- Reasons for this include the modelling of the kinematic cut-off in the spectrum and the effects of the black hole recoil

- There may be scope to improve this modelling for the spectrum fitting - but we really need to understand the black hole decay better

- Unfortunately others phases of the decay, spinning holes, other higher dimensional objects produced *etc.* are only going to make the situation more complicated!

Can Black Holes be Detected at ATLAS?

Yes...

...but it may be very difficult to extract much information about extra dimensions in spite of the potentially huge cross sections