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Black Holes and ATLAS

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Outline

- Introduction
- ATLAS
    - Brief Overview
    - Features relevant for Black Hole Searches
- Schwarzschild Results
    - Working Model
    - Black Hole Characteristics
    - Trigger and Event Selection
    - Black Hole properties
- Next Steps
    - Rotating black holes
- Conclusions and Outlook

Will focus on the experimental side of things…

Introduction

➢Antoniadis, followed by Arkani-Hamed, Dimopoulos and Dvali (ADD), and Randall and Sundrum (RS) have pioneered the solution of the hierarchy problem by using extra-dimensional space.

➢The extra spatial geometry and dimensions generate the hierarchy:

- ➢ADD - additional flat extra dimensions
- ➢RS - single warped extra dimension.

➢Gravitational field propagates in the bulk (appears weak)

➢Standard Model fields are confined to our 3-brane.

➢The relationship between the (4+n)-dimensional Planck scale and the 4-dimensional one is determined by the volume of the extra dimensions (or the warp factor in RS).

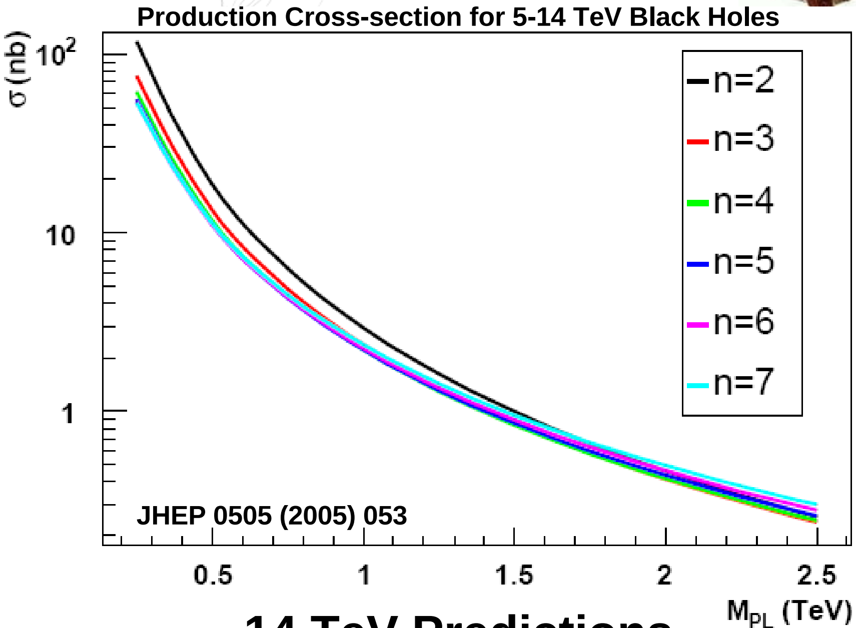
➢For large extra dimensions, the fundamental scale of gravity can be as low as the electroweak scale.

➢**Microscopic black holes could be produced at the Large Hadron Collider**.

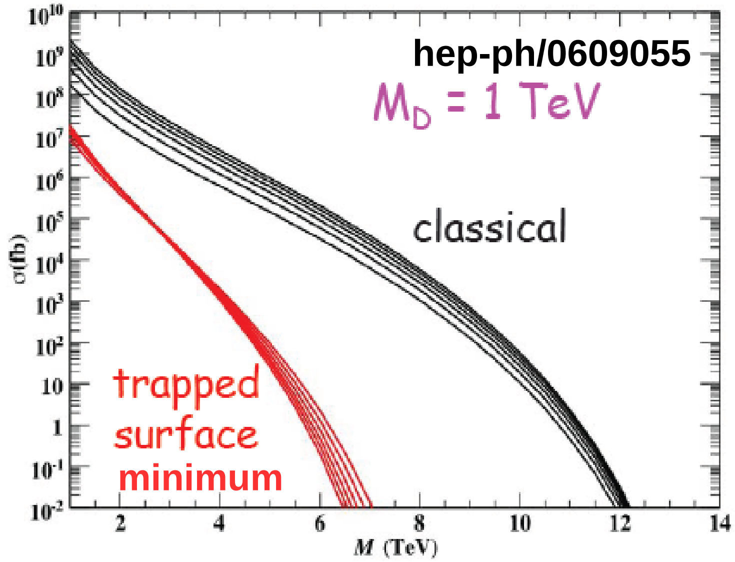
➢Constrained by Tevatron data, tabletop experiments and astrophysical observations and measurements (supernovae and neutron star cooling, gamma and γ-rays).

Black Hole Production

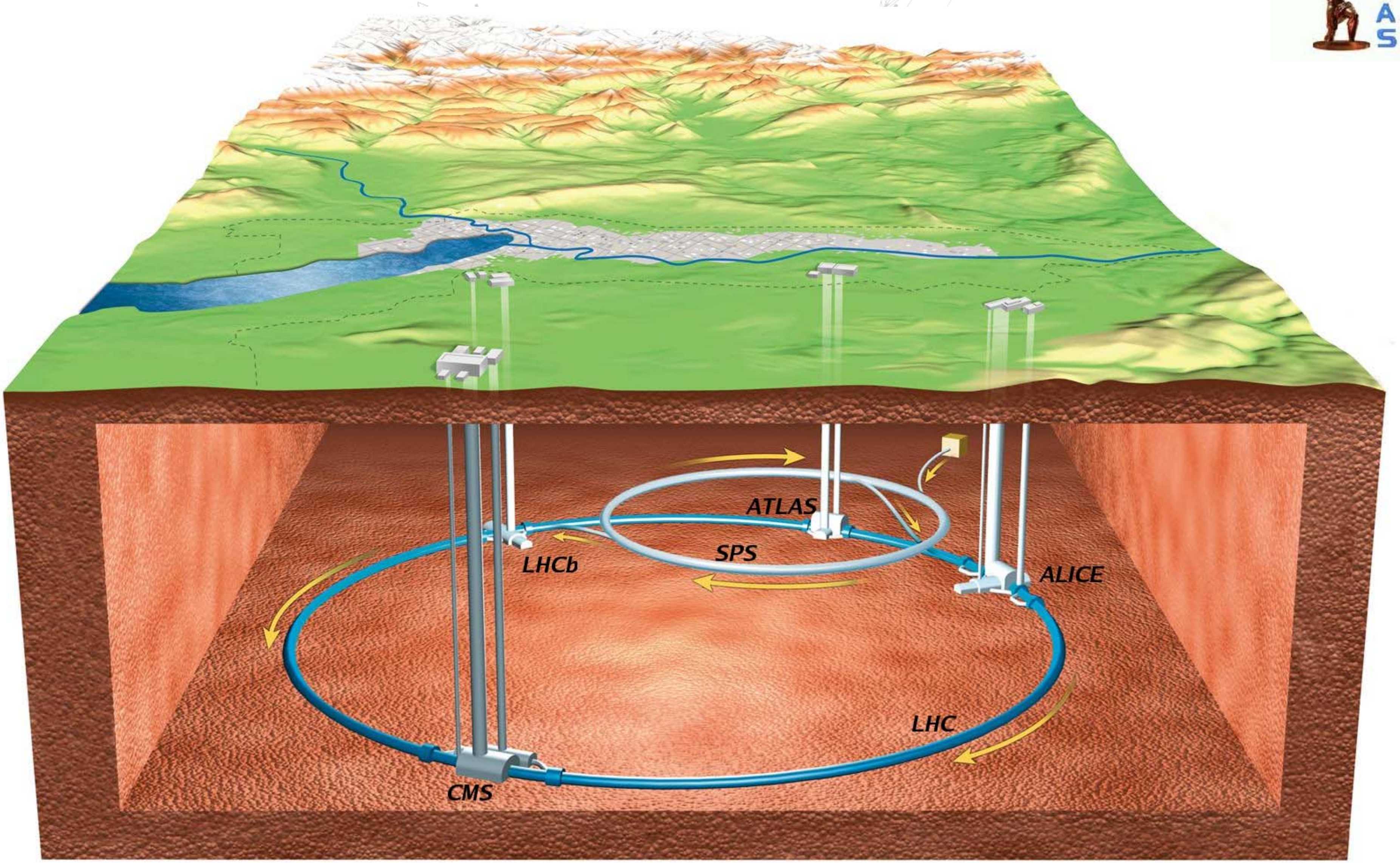
- Such black holes (BH) decay in 4 phases:
  - 1. Balding Phase – loss of multipole moments, gravitons
  - 2. Spin down Phase – loses much of its angular momentum by Hawking emission before its mass
  - 3. Schwarzschild Phase – BH emits Hawking radiation
  - 4. Planck Phase – BH mass reaches M_{PL} - realm of quantum gravity after 10^{-26} seconds
- A general formulation of their production is extremely complex.
- Semi-classical approximations, only valid well above the Planck scale are necessary to enable a quantitative description and predictions.
- A minimum BH mass (for production) must be imposed. Below this, gravitational interactions may look like a contact interaction or compositeness effect – such signatures require different tools and generator settings.



14 TeV Predictions



The Large Hadron Collider



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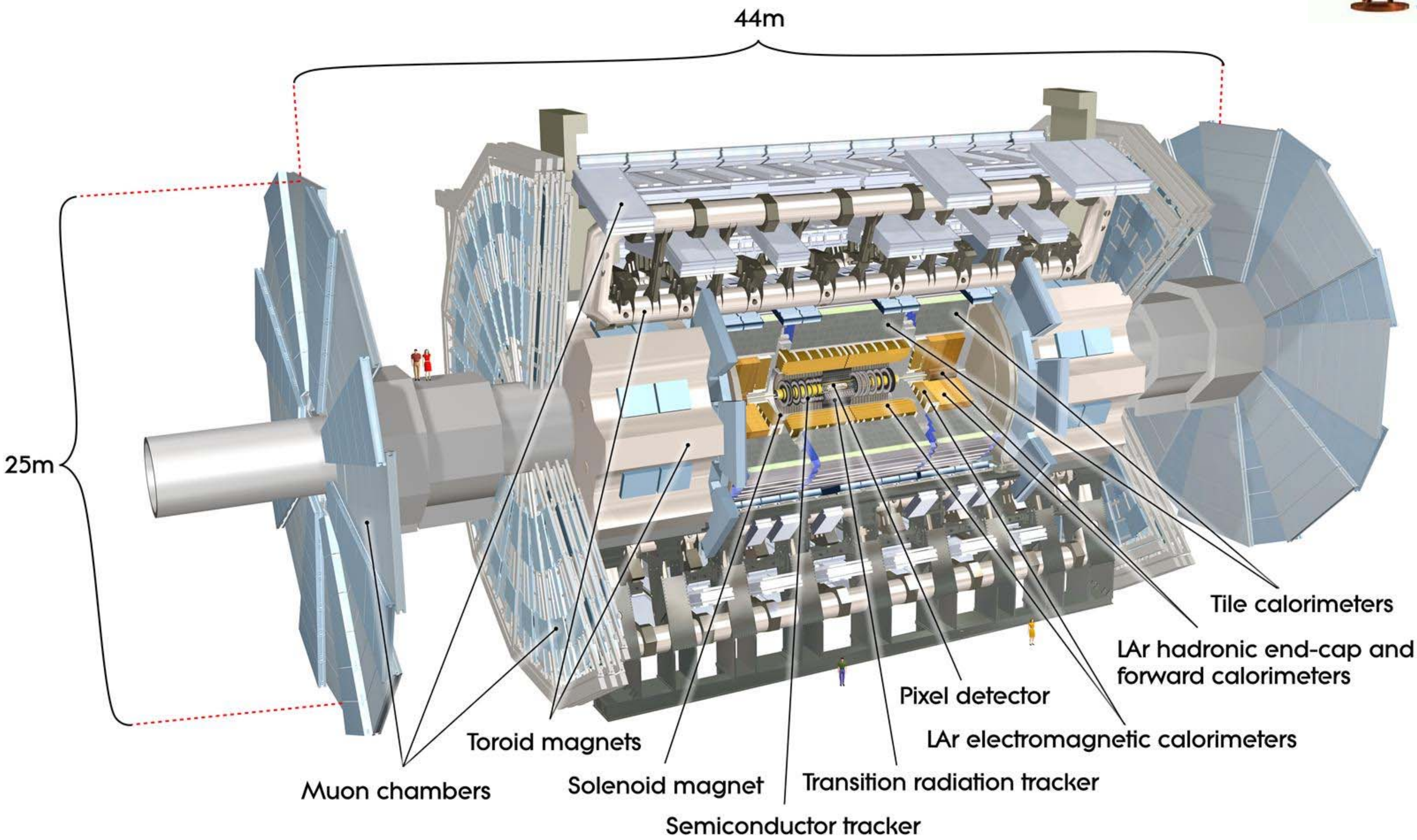
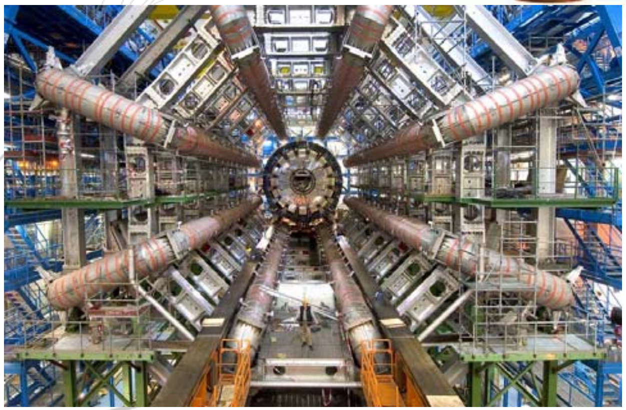
ATLAS (I)



http://atlas.ch/photos/index.html

ATLAS (II)

- Very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and missing transverse energy measurements.
- High precision muon momentum measurements, with the capability to guarantee accurate measurements at the highest luminosity using the external muon spectrometer alone.
- Efficient tracking at high luminosity for high p_T lepton-momentum measurements, electron and photon identification, tau lepton and heavy-flavour identification, and full event reconstruction capability at lower luminosity.
- Large acceptance in pseudorapidity with almost full azimuthal angle coverage everywhere. The azimuthal angle is measured around the beam axis, whereas pseudorapidty relates to the polar angle (the angle from the z direction).
- Triggering and measurements of particles at various p_T thresholds, providing high efficiencies for most physics processes of interest at the LHC.



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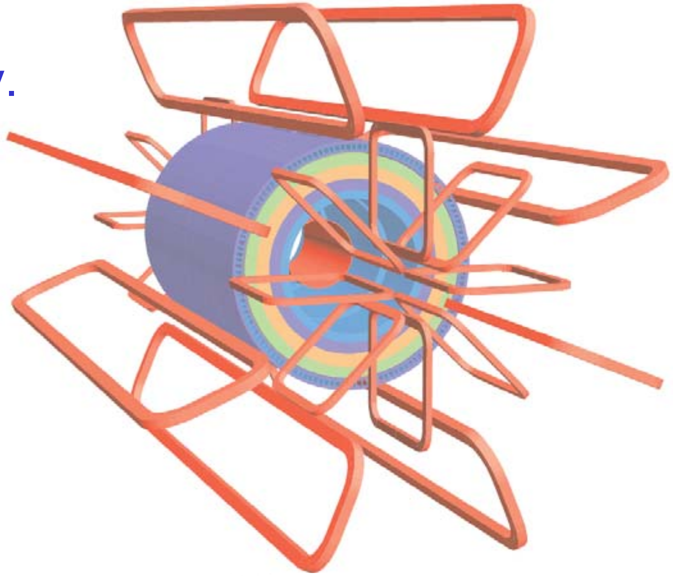
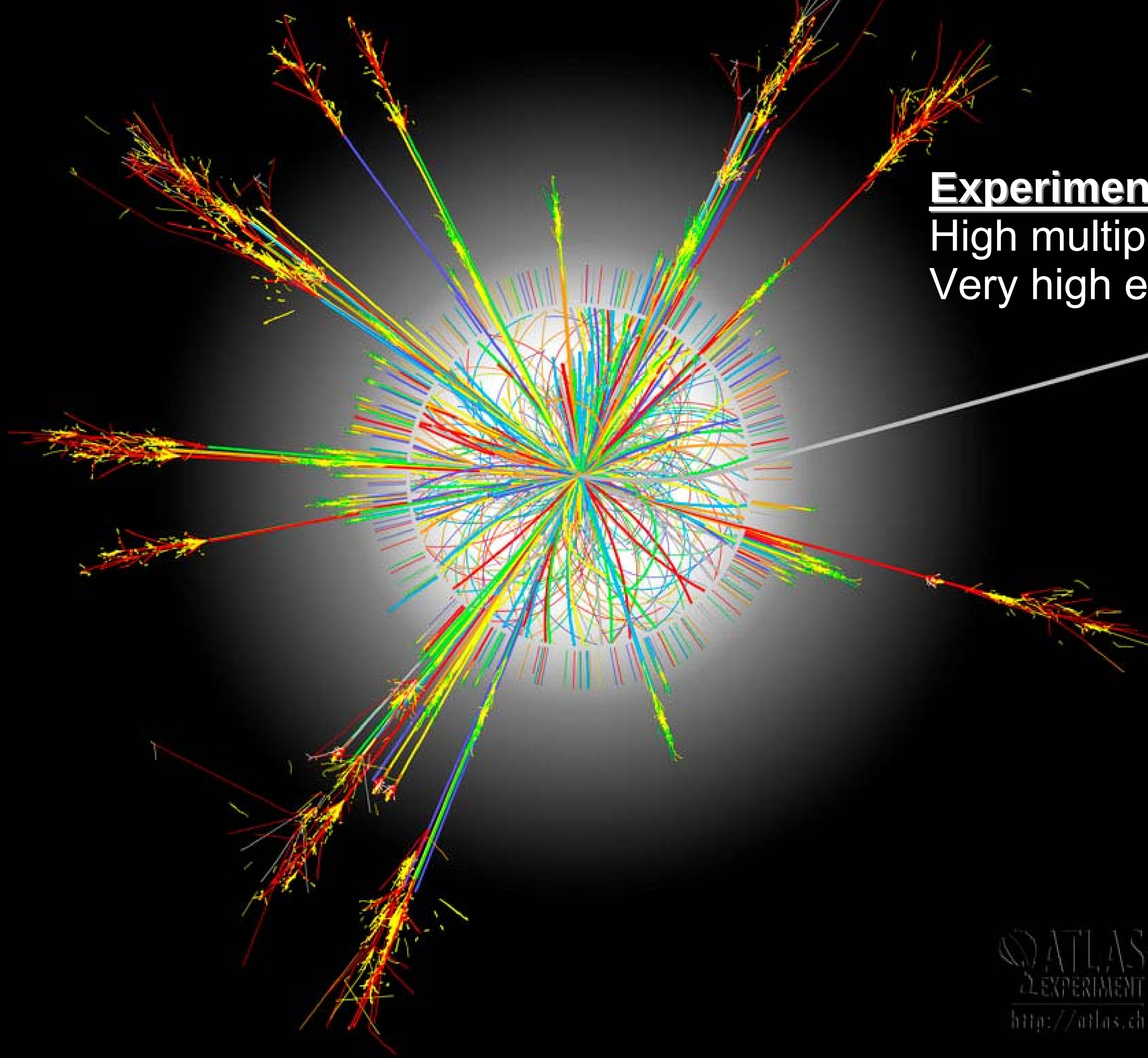


The ATLAS Collaboration, JINST 3(08):S08003

Black Holes in ATLAS



Experimental Challenges

High multiplicity

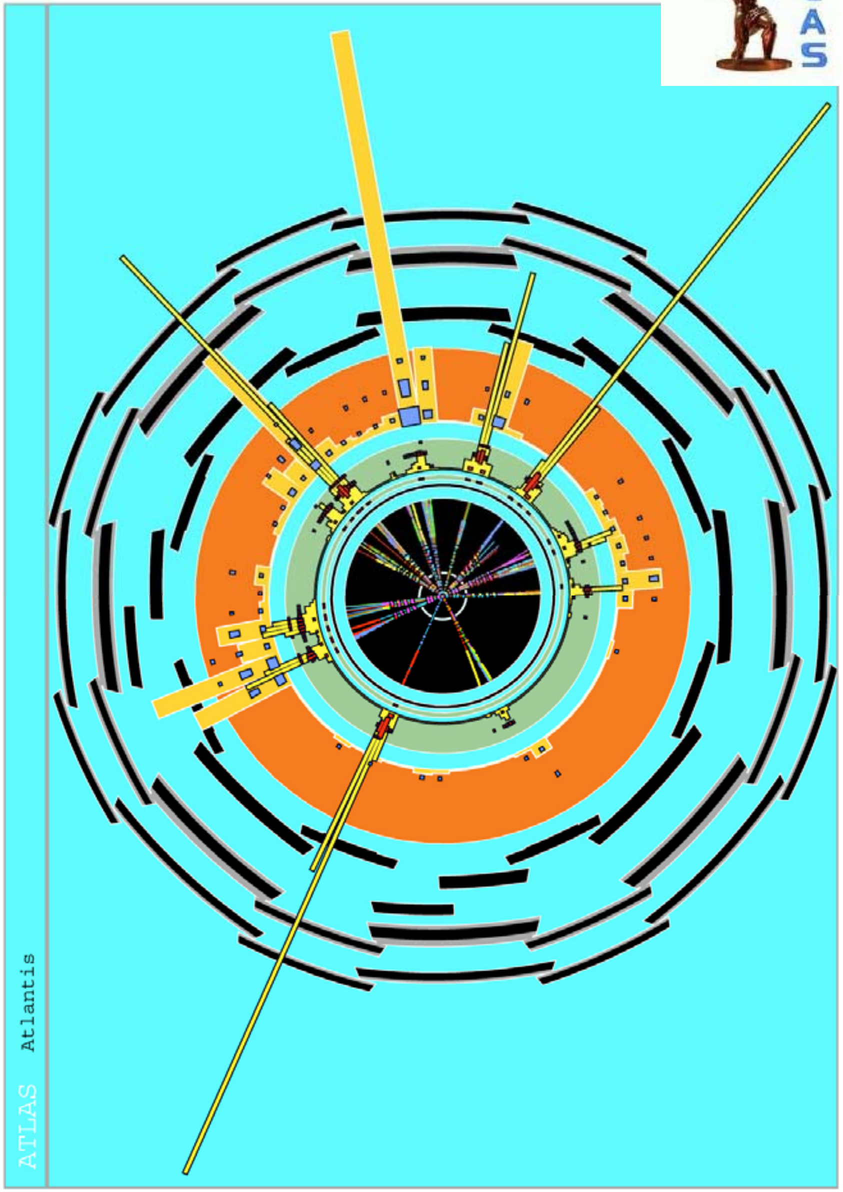
Very high energy & P_T particles

MC / Working Model

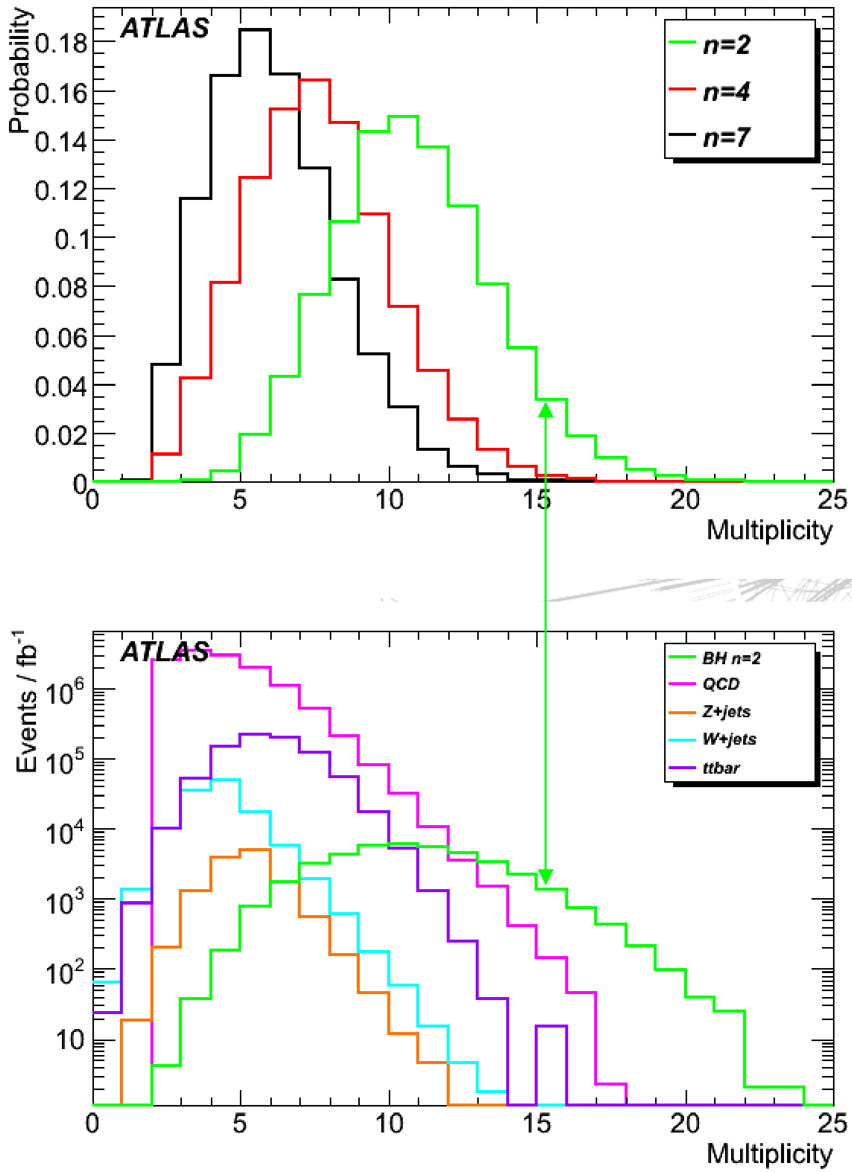
Full ATLAS studies (arXiv:0901.0512) of ADD Schwarzschild Black Holes have been carried out for 14 TeV (and checked for 10 TeV running).

Using the Monte-Carlo event generator CHARYBDIS to produce events with….

- Black-disc geometric cross-sections.
- 2-7 extra spatial dimensions (n).
- Full spin-dependent grey-body factors.
- All Standard Model particles produced.
- Conserves baryon and lepton number.
- Ignores balding and spin-down phases, modelling the Schwarzschild phase (Hawking radiation).
- No graviton emission.
- Theoretical uncertainties modelled by switches (remnant decay, thermal equilibrium, etc.).

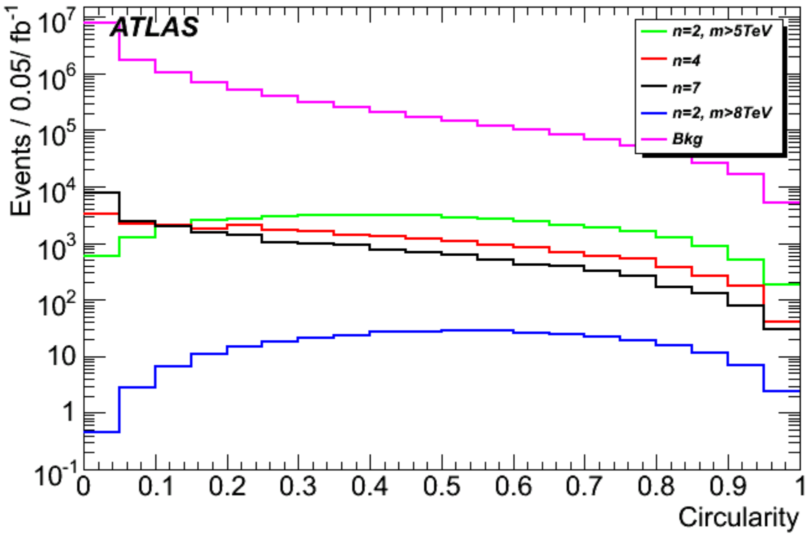


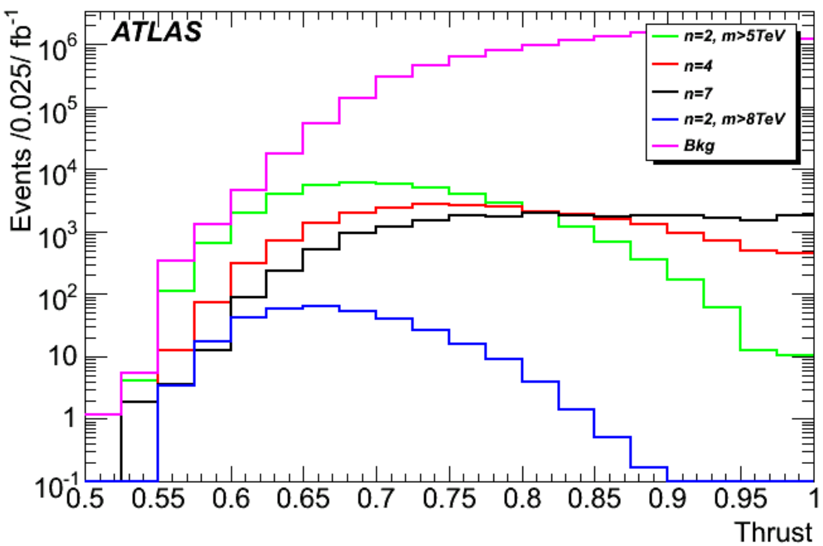
Event Properties (I)



- Black hole events are characterised by a number of high-transverse momentum (P_T) final state particles.
- Large variation – for a given mass, the Hawking temperature is greater at high n, so fewer particles, but with higher energies, are emitted.
- Black hole events can be very crowded – average multiplicity (P_T>15 GeV) of 12
- **BUT** can produce only 4 or 5 particles, similar to backgrounds.
- Background tails extend to high multiplicity.
- Selection needs to be robust over a wide range of theoretical uncertainties and numbers of extra-dimensions.

Event Properties (II)





- **Could event shape variables be used to distinguish a BH signal from background?**
- Not easily. Their discriminating power is reduced since:
  - Signal shape varies strongly with n, and other theoretical parameters.
  - Large background cross-sections cause substantial overlap between distributions.

Triggers

Jet Triggers

n=2, M_{BHMIN}=5 TeV

Trigger	LVL1	LVL2	EF
Jet100	1	1	1
Jet400	0.997	0.997	0.997
3Jet100	0.998	0.998	0.998
3Jet250	0.972	0.971	0.971
4Jet100	0.985	0.985	0.985
4Jet250	0.865	0.862	0.862

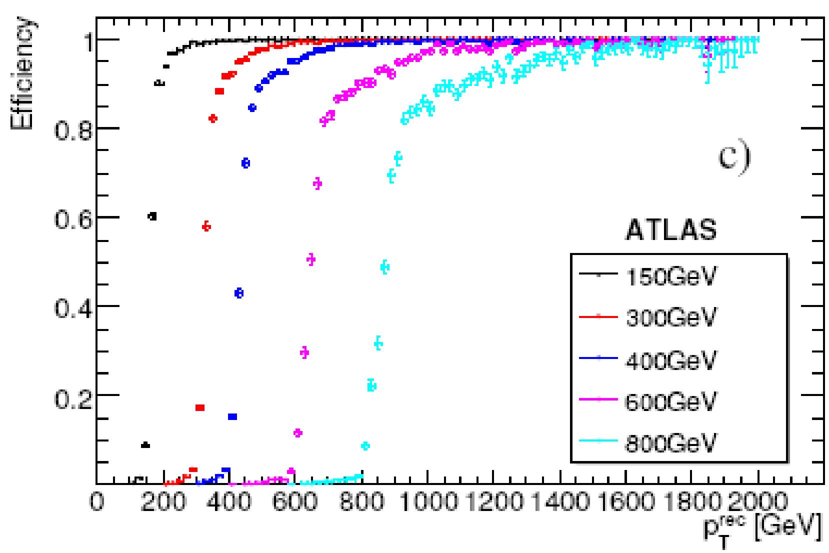
n=4, M_{BHMIN}=5 TeV

Trigger	LVL1	LVL2	EF
Jet100	1	1	1
Jet400	0.997	0.997	0.996
3Jet100	0.952	0.952	0.952
3Jet250	0.886	0.885	0.885
4Jet100	0.807	0.806	0.806
4Jet250	0.612	0.607	0.607

n=7, M_{BHMIN}=5 TeV

Trigger	LVL1	LVL2	EF
Jet100	1	1	1
Jet400	0.990	0.987	0.985
3Jet100	0.807	0.806	0.805
3Jet250	0.710	0.704	0.704
4Jet100	0.525	0.522	0.522
4Jet250	0.343	0.341	0.341

- The highest single jet threshold trigger gives an excellent efficiency for all signal samples, and should be robust against all types of black holes.
- Important that it is unprescaled.
- Multijet triggers provide alternatives, should detector issues temporarily require all single jet triggers to be prescaled.



Simulated trigger efficiencies for different trigger thresholds as functions of the offline reconstructed jet Pt at LVL3

Selection & Efficiencies

- Two efficient methods to select BH events were determined:
- **Method One:** A cut on the sum of scalar P_T > 2.5 TeV and a requirement of one lepton (e,μ) with P_T > 50 GeV
- **Method Two**: A cut of four objects with P_T > 200 GeV, one a lepton (e, μ)

One:

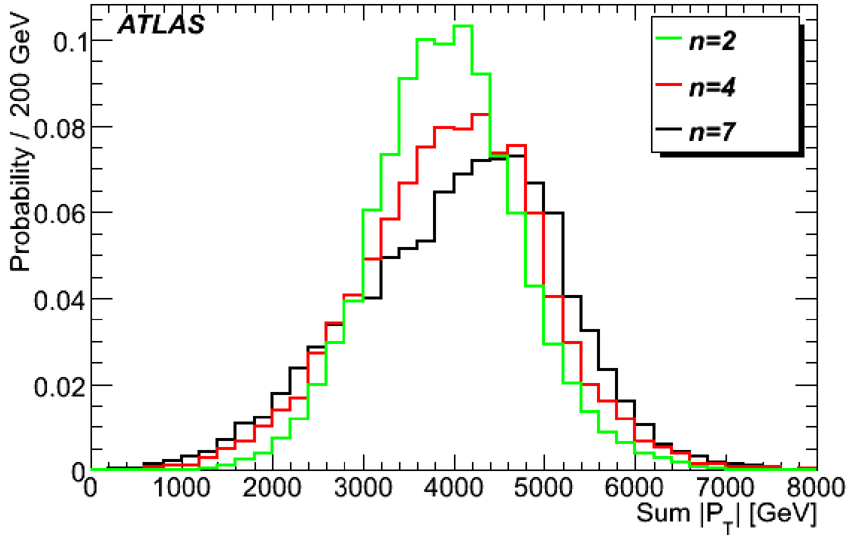
Dataset	Before selection (fb)	After requiring a lepton (fb)	acceptance
$n=2, m>5$ TeV	$40.7 \pm 0.1 \times 10^3$	$18.6 \pm 0.2 \times 10^3$	0.46
$n=4, m>5$ TeV	$24.3 \pm 0.1 \times 10^3$	6668 ± 83	0.27
$n=7, m>5$ TeV	$22.3 \pm 0.1 \times 10^3$	3574 ± 60	0.17
$n=2, m>8$ TeV	338.2 ± 1	212 ± 16	0.63
$t\bar{t}$	$833 \pm 100 \times 10^3$	$8.2^{+2.43}_{-2.43}$	9.8×10^{-6}
QCD dijets	$12.8 \pm 3.7 \times 10^6$	$5.37^{+3.25}_{-2.02}$	4.3×10^{-7}
$W_{\ell\nu} + \geq 2$ jets	$1.9 \pm 0.04 \times 10^6$	$4.67^{+8.75}_{-0.93}$	2.4×10^{-6}
$Z_{\ell\ell} + \geq 3$ jets	$51.8 \pm 1 \times 10^3$	$2.57^{+0.95}_{-0.64}$	5.0×10^{-5}

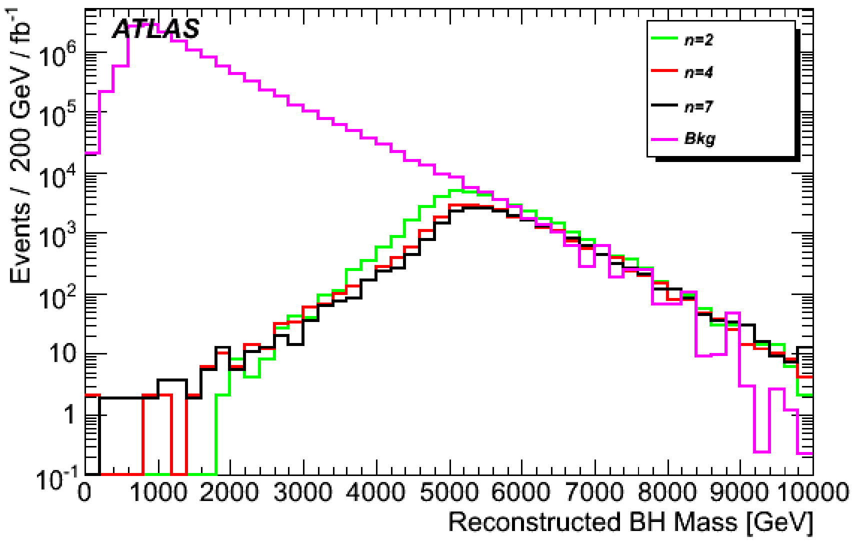
Two:

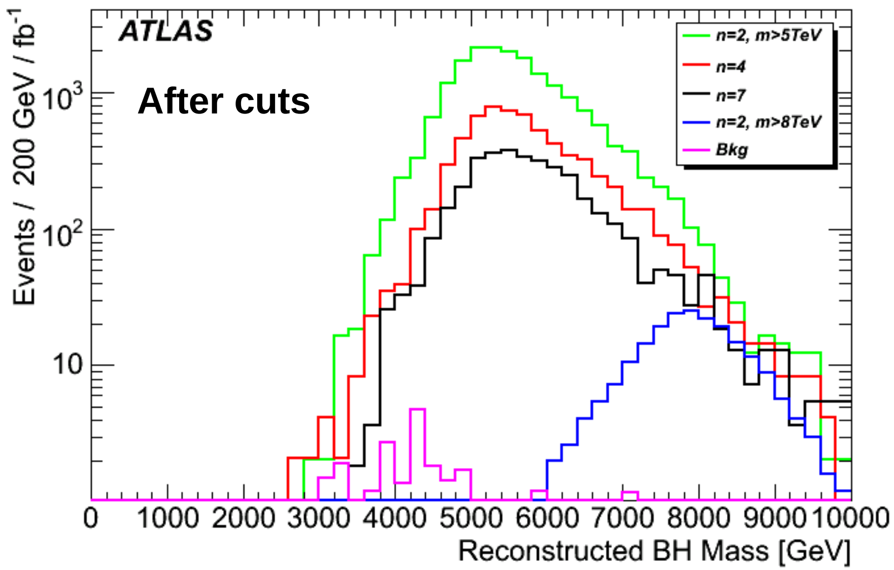
Dataset	Before selection (fb)	After lepton requirement (fb)	Acceptance
$n=2, m>5$ TeV	40.7×10^3	$14.0 \pm 0.2 \times 10^3$	0.34
$n=4, m>5$ TeV	24.3×10^3	4521 ± 126	0.19
$n=7, m>5$ TeV	22.3×10^3	1956 ± 82	0.087
$n=2, m>8$ TeV	338	164 ± 3	0.49
$t\bar{t}$	833×10^3	36^{+12}_{-9}	4.3×10^{-5}
QCD dijets	12.8×10^6	6^{+107}_{-3}	5.6×10^{-7}
W+jets	560×10^3	56^{+24}_{-13}	1×10^{-3}
Z+jets	51.8×10^3	19^{+90}_{-3}	4×10^{-4}
$\gamma(\gamma)$+jets	5.1×10^6	0^{+40}_{-0}	$< 10^{-5}$

Signal Selection

- ➢The scalar summation of $|P_T|$ demonstrates high signal efficiency across all samples and good background discrimination.
- ➢Cutting on $\Sigma\ |P_T| > 2.5$ TeV reduces backgrounds drastically, leaving mainly high P_T QCD.
- ➢Requiring a lepton (P_T>50 GeV) reduces this still further.





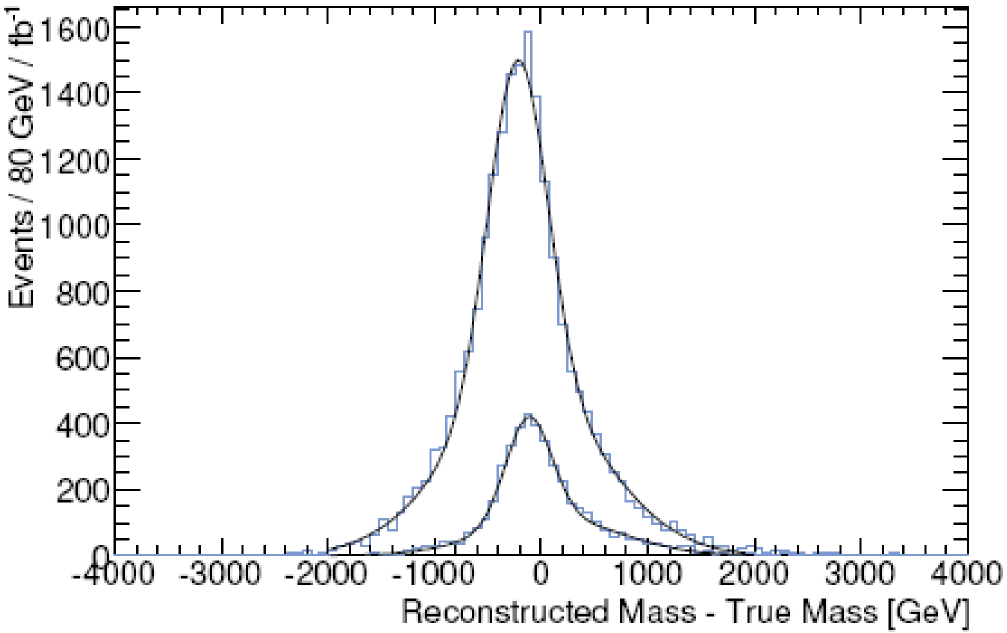


Mass Resolution

➢Accurate mass resolution is vital in any measurement of the production cross-section.

➢Improved after a cut on Missing E_T < 100 GeV, at a cost of some signal efficiency.

		Normalisation	Mean (GeV)	Resolution (GeV)
Without MET Cut	Narrow	1018 ± 26	-217 ± 5	276 ± 9
	Wide	276 ± 30	-148 ± 9	722 ± 13
With MET Cut	Narrow	318 ± 12	-116 ± 8	215 ± 9
	Wide	108 ± 7	118 ± 18	635 ± 16

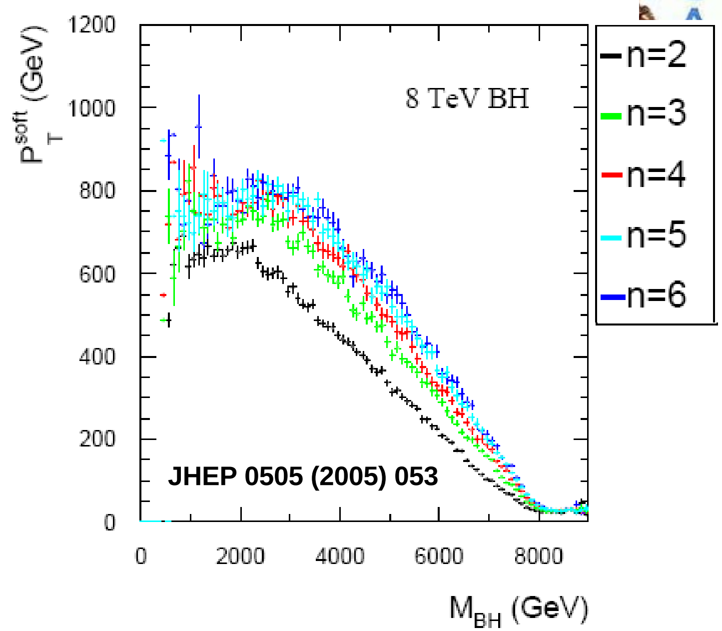


How many extra dimensions?

➢Initial attempts tried to reconstruct the Hawking temperature dependence with black hole mass, either averaged over an event, or on an emission-by-emission basis.

➢Unfortunately, the effect is small and is strongly affected by the theoretical uncertainties.

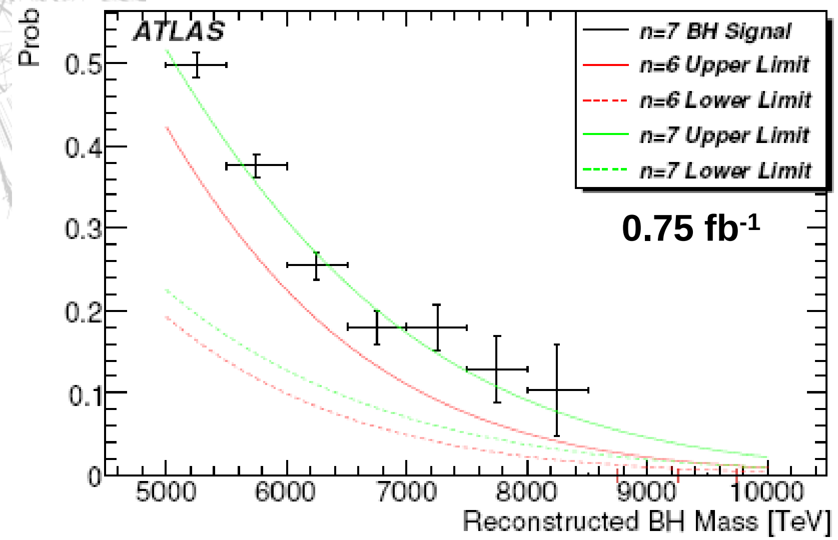
➢Cannot extract n without great trust in Monte-Carlo.



➢One method for estimating n, given an estimate of the Planck scale, was first described in JHEP 0505 (2005) 053,

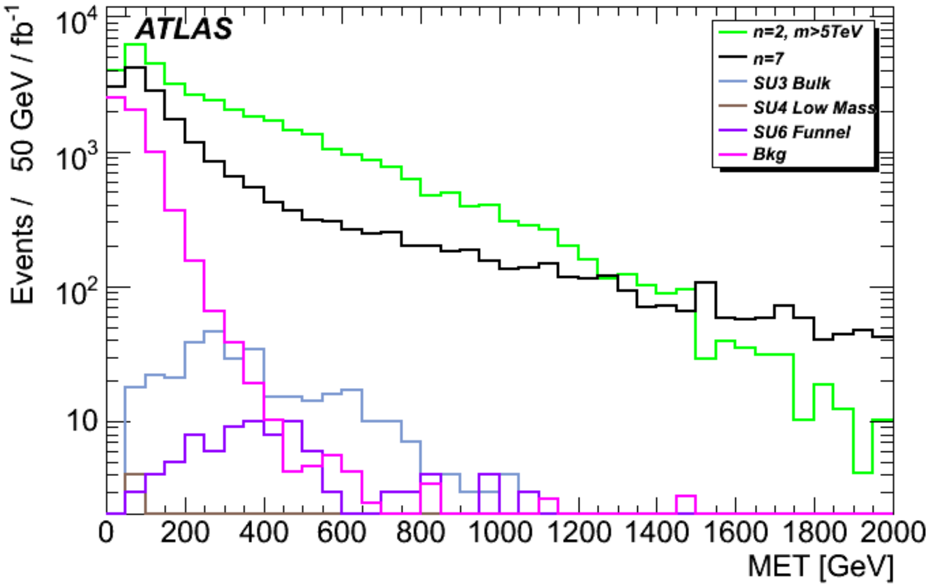
➢Now compatible with cuts for signal selection and background rejection.

➢The method is insensitive to some of the model uncertainties, such as threshold behaviour.



Discovery at High MET?

➢Black Hole events have a great range of Missing E_T (MET), with a long tail toward 2 TeV.



➢A signal at high MET is **not necessarily** SUSY, especially if the spectrum extends into the TeV range.

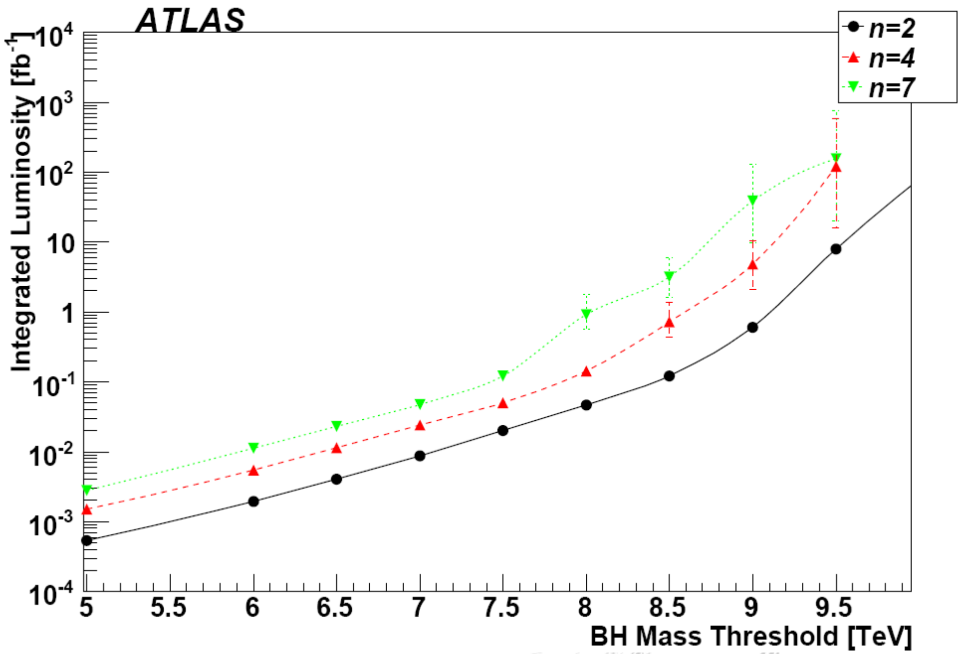
➢The high cross-section at very high MET allows BH models to be distinguished from much of SUSY space, in which points with both high cross-section and producing such very high values of MET are rare.

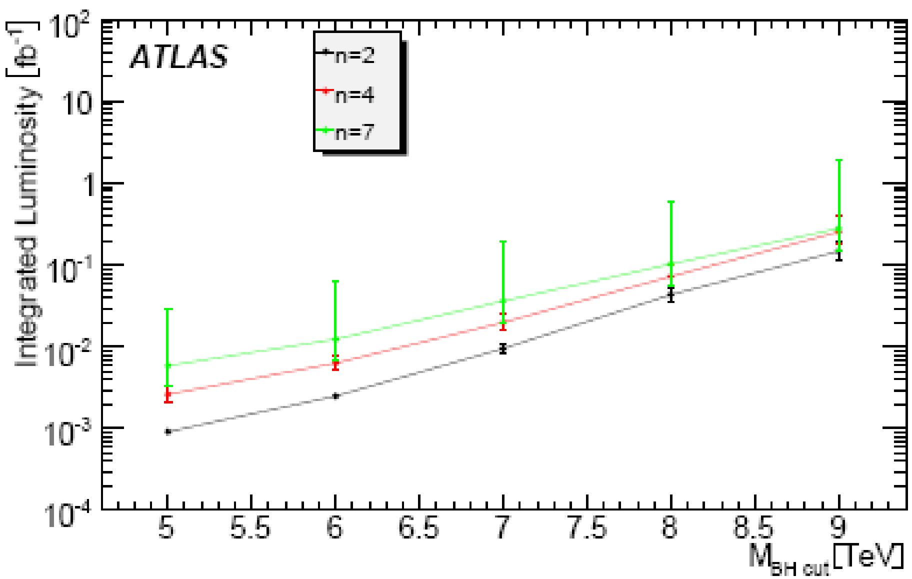
➢Selection allows less accurate mass reconstruction, limiting its use in cross-section measurement and discovery.

➢Plots show the distribution of events after the cut on $\Sigma\ |P_T| < 2.5$ TeV.

Discovery Reach

Producing a robust discovery potential for black holes is difficult, due to the large theoretical errors and semi-classical assumptions used to model them - valid only well above the Planck scale. The lack of theoretical understanding makes it impossible to model the threshold region.





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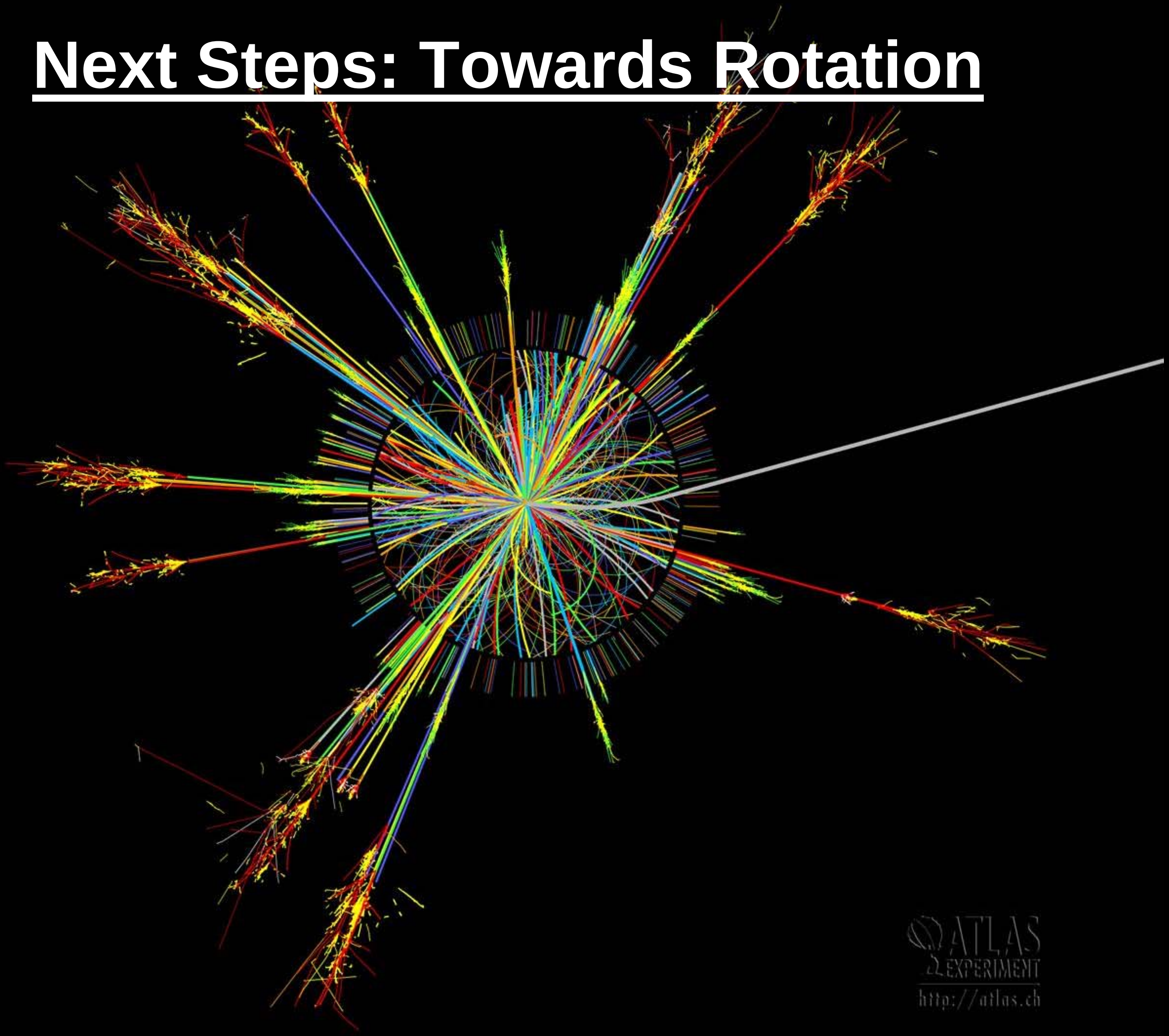
Schwarzschild/ATLAS Conclusions

- Schwarzschild Black Hole events will pass the ATLAS trigger, and can be separated efficiently from background events.
- For a flat ADD extra-dimensional scenario, with a Planck scale ~1 TeV, ATLAS will be able to discover microscopic black holes produced by the LHC up to the kinematic limit, if the large, semi-classical cross-section estimates are valid.
- Schwarzschild black holes (at 14 TeV) above a 5 TeV threshold could be discovered in the first few pb^{-1} of data, while 1 fb^{-1} would allow a discovery were the production threshold to be 8 TeV.
- ATLAS should be able to reconstruct the mass of such black holes accurately, with a resolution of ~320 GeV.
- Methods for estimating the number of extra dimensions, given an estimate of the Planck scale (from eg. a threshold in the inclusive cross-section), are known.
- The theoretical uncertainties inherent in the model have been explored and, where possible, quantified. The semi-classical approximations must still be used; the difficulty in making predictions near the Planck scale remains the major obstacle.

Next Steps: Towards Rotation



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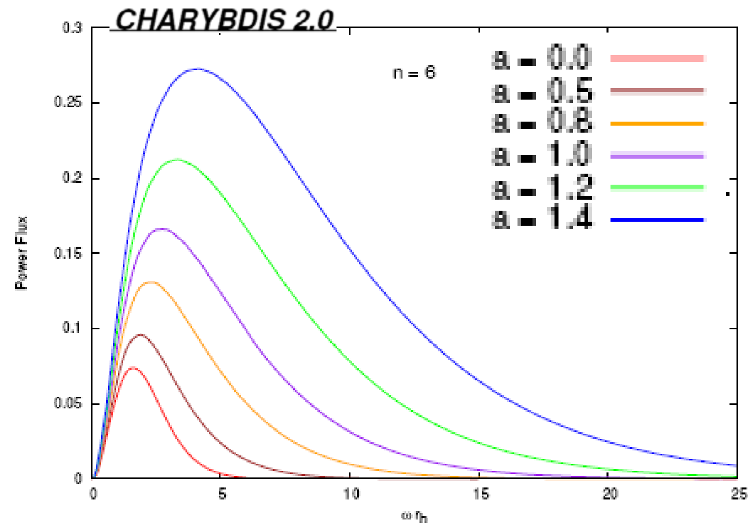
Theory - Rotation

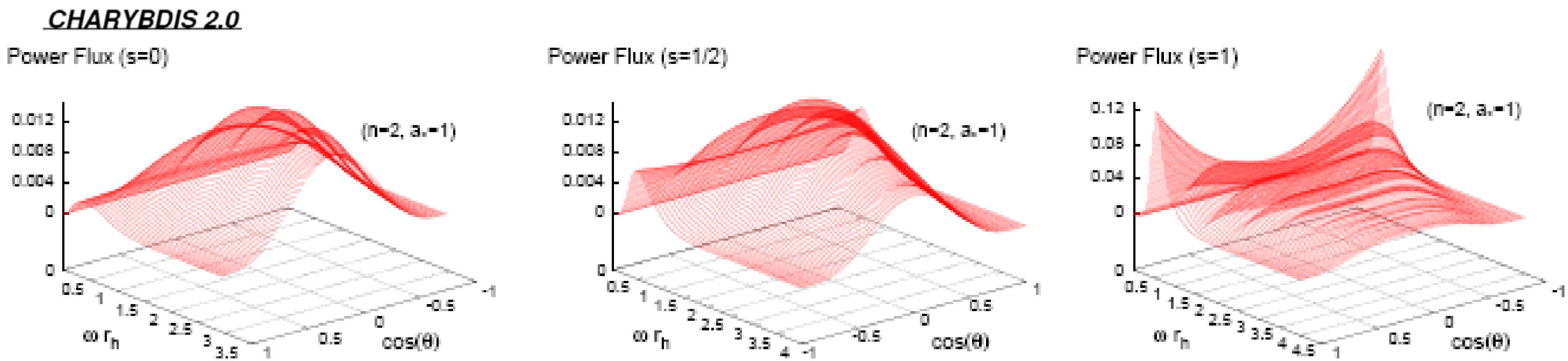
- Over the last few years, there has been much theoretical progress in describing the Hawking radiation emitted from rotating black holes, with the calculation of greybody factors.
- This allows the power fluxes and angular distributions of the particles emitted from the black hole to be calculated.
- Polarisations of the particles are accounted for in their angular distributions.

$$\frac{d^2N}{dtd\omega} = \frac{1}{2\pi}\sum_{j=|h|}^{\infty}\sum_{m=-j}^{j}\frac{1}{\exp(\tilde{\omega}/T_H)\pm 1}\mathbb{T}_k^{(D)}(\omega, a_*)$$

$$\tilde{\omega} = \omega - ma_*/[(1+a_*^2)r_H]$$



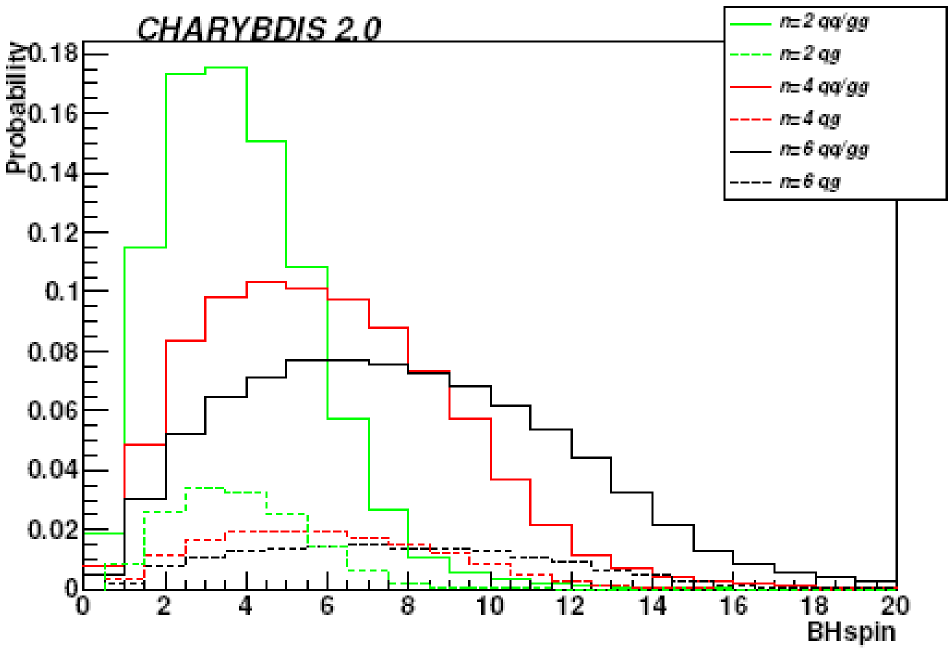
Power spectrum of a spin-½ field for emission on the brane with *n* = 6 for various values of BH a* (oblateness)



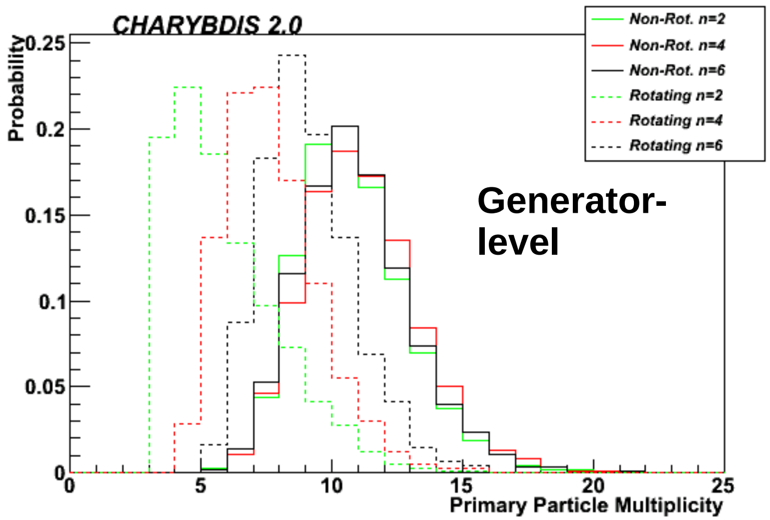
Angular Power Fluxes for scalars, fermions and vectors

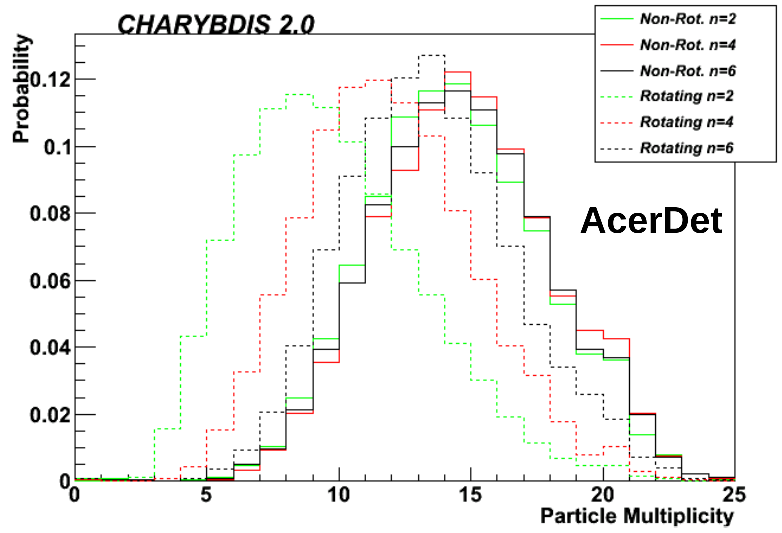
Phenomenology

- Plots on succeeding pages show a selection of black hole samples:
  - Generated using Charybdis 2 (arXiv:0904.0979)
  - M_{PLANCK} = 1 TeV (PDG definition)
  - *n* extra dimensions
  - 5-14 TeV initial mass, so as to model the LHC experimental reach whilst maintaining the validity of semi-classical assumptions used in the production model.
  - This is **not** a full ATLAS experimental analysis, but illustrates the features of rotation that experimental strategies will need to take into account.

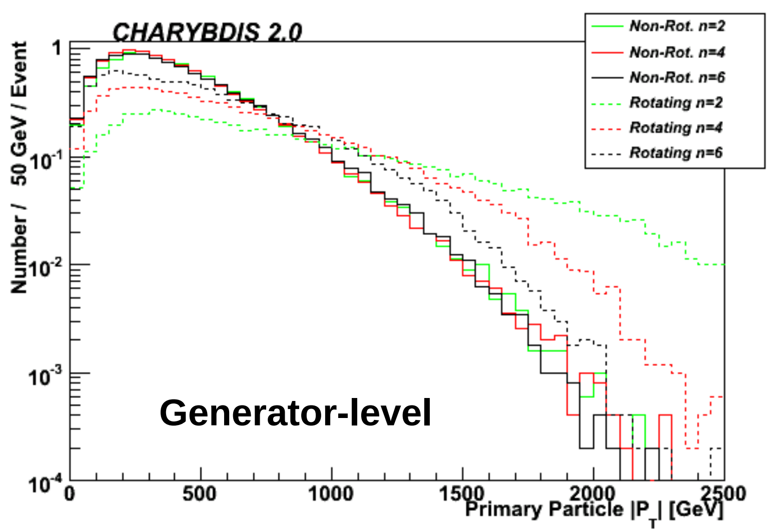


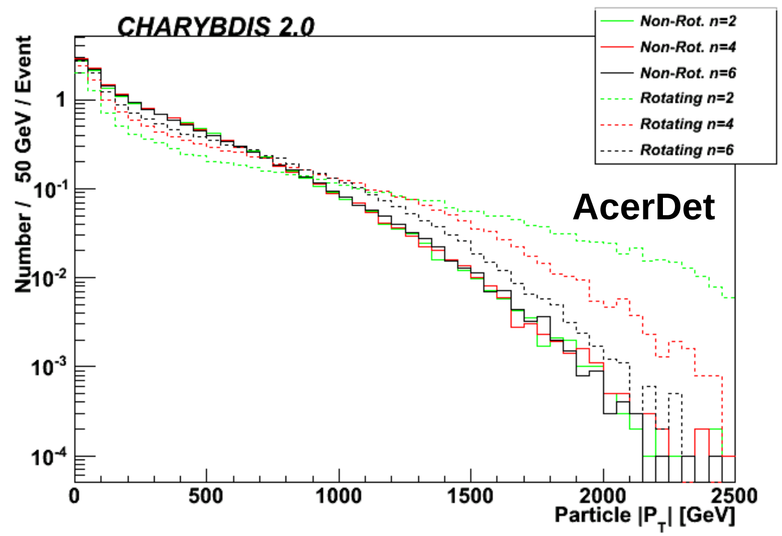
Rotation Effects





➢Rotating black holes (dashed lines) emit far fewer, more energetic particles than their non-rotating, Schwarzschild analogues (solid lines), since the spin term reduces the Boltzmann suppression of high energy emission.





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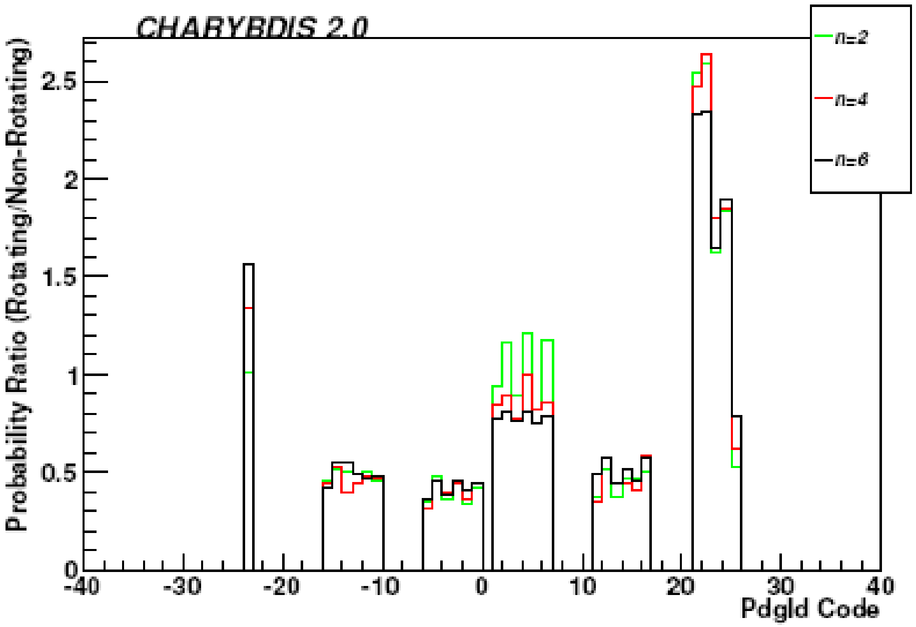
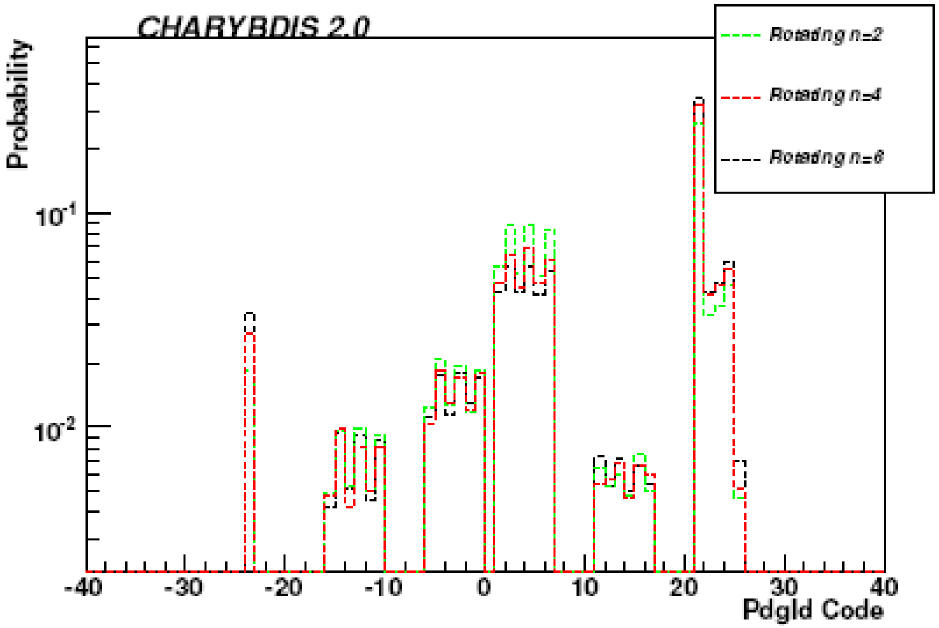
Which Particle Species?

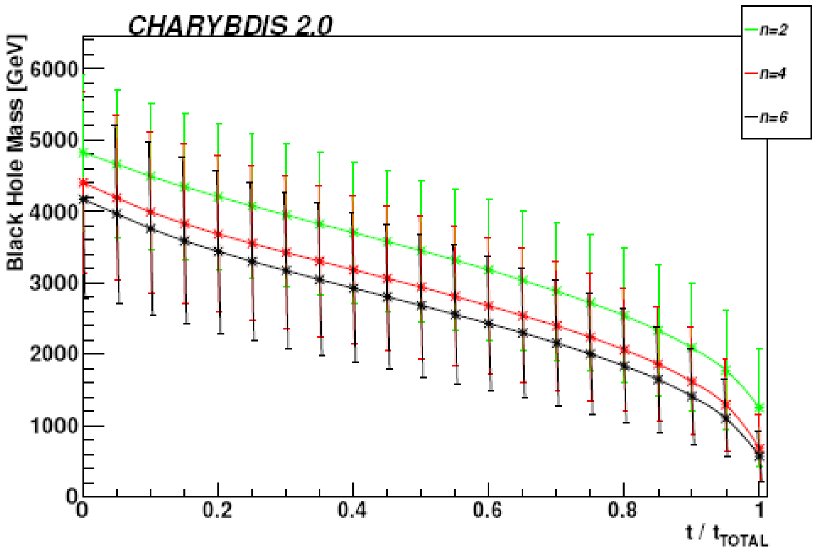


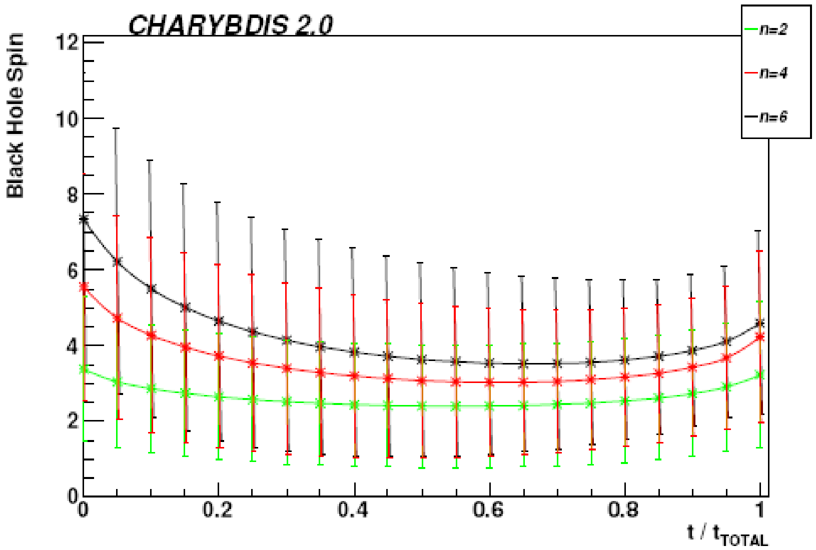


- Primary particle spectra (emitted directly by the black hole) are changed dramatically.
- Vector emission is enhanced by a factor of ~2.5; scalar (Higgs) emission slightly reduced.
- Decreased probability of an event containing a charged lepton – used in studies of non-rotating black holes for signal selection and background rejection.
- Little variation with *n* – were it possible to reconstruct it, it would be powerful evidence of gravitational interaction/black holes (assuming model assumptions are valid).

- NB. Baryon/Lepton number is conserved here so as to enable hadronisation.

Black Hole Evolution (I)



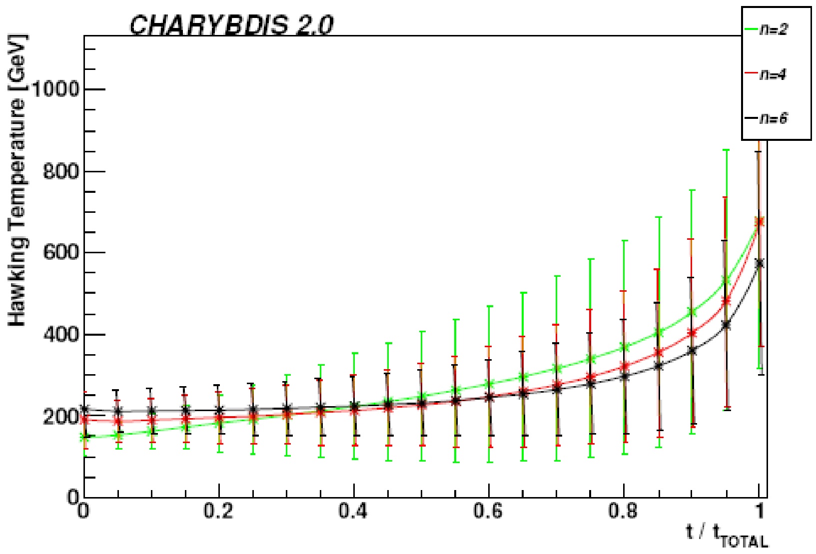


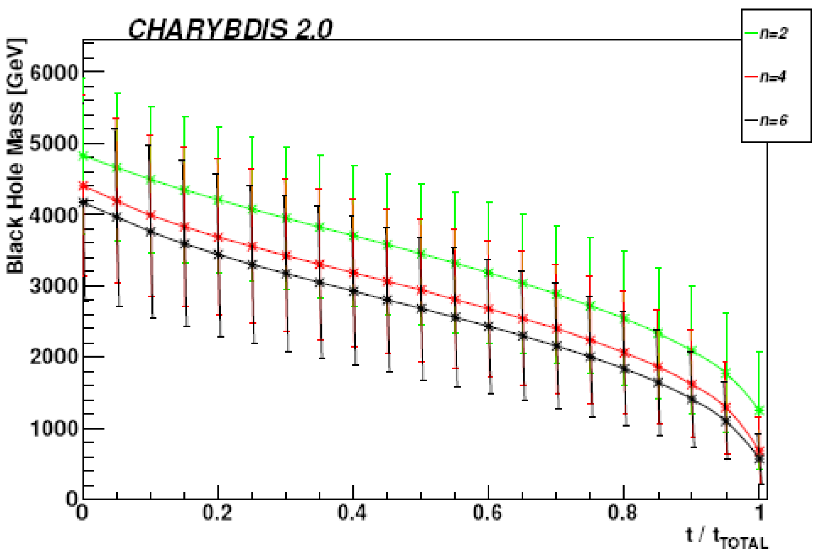
➢The black holes emit Hawking radiation, losing mass and angular momentum, and gradually becoming hotter (increasing in Hawking temperature).

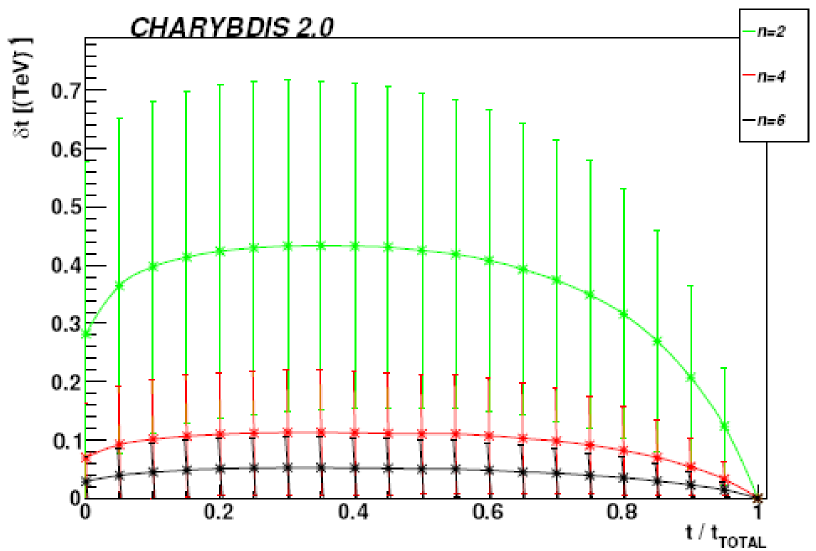
➢Angular momentum is lost more rapidly than mass, the majority being lost in the first two or three emissions, whereafter the black hole loses mass whilst the angular momentum remains relatively low, but non-zero. There is **not** a quick spin-down phase, followed by a longer Schwarzschild phase - **the spin remains non-negligible throughout evaporation.**

Black Hole Evolution (II)

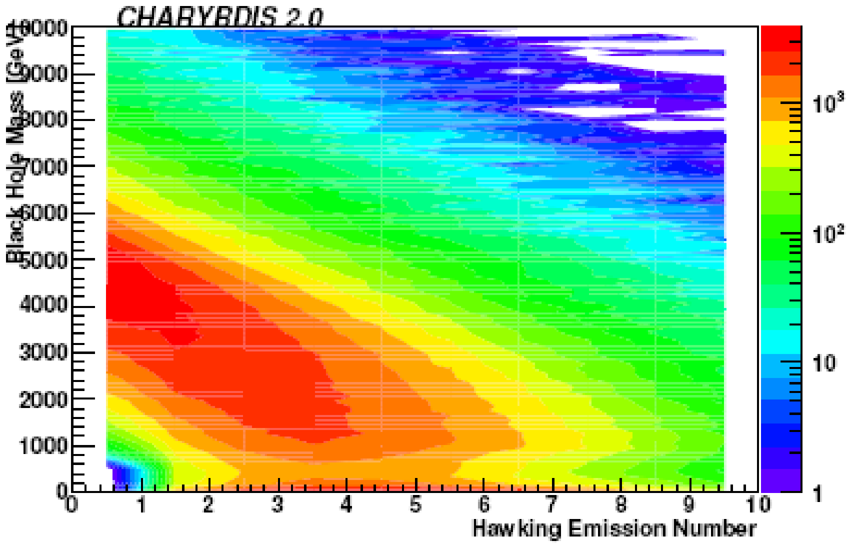
➢The change in BH parameters is gradual, except at the end of the evaporation phase, when the low mass, short time interval between emissions and high temperature all indicate a departure from semi-classicality and the onset of the Planck/remnant phase.

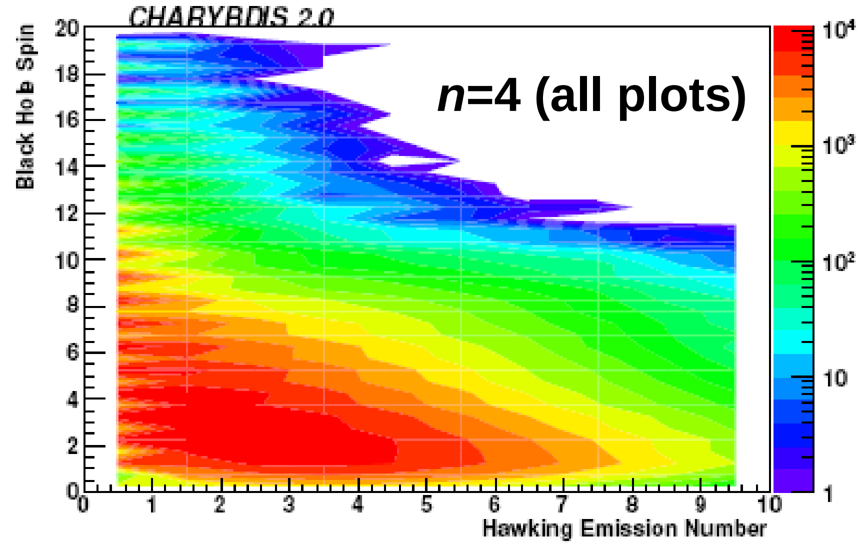


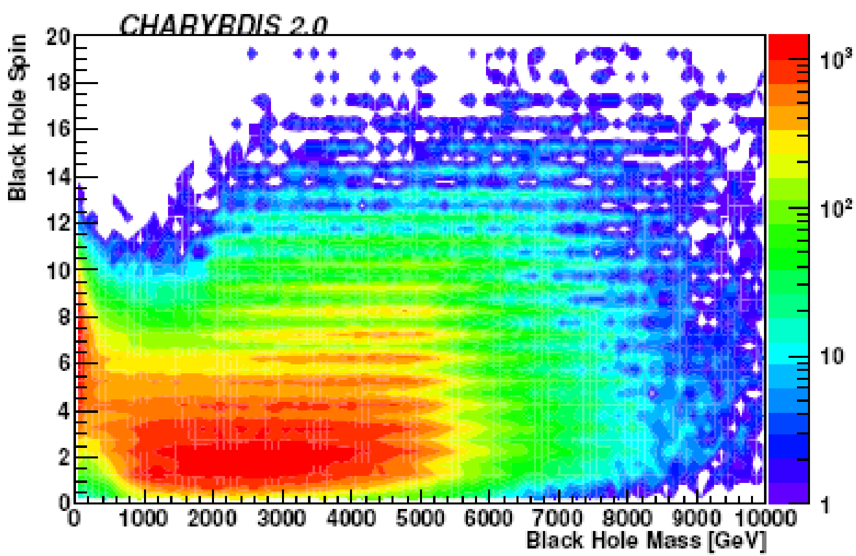


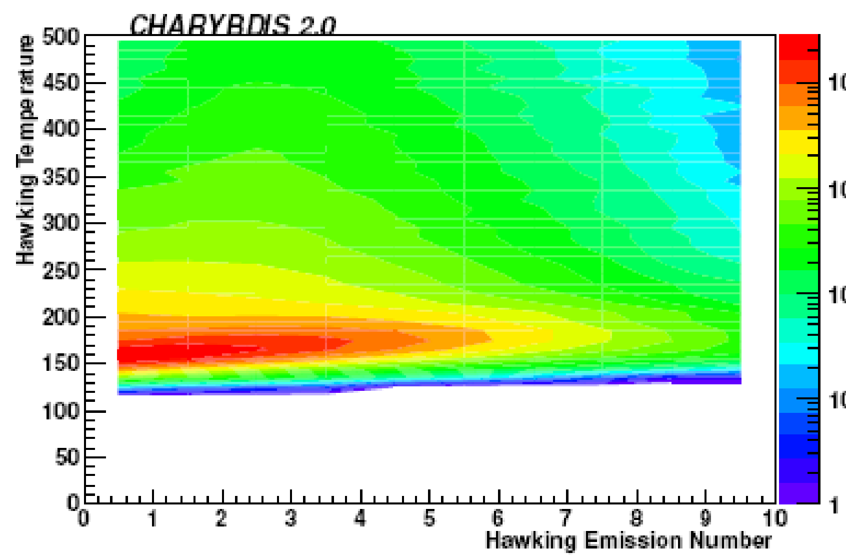


Black Hole Evolution (III)









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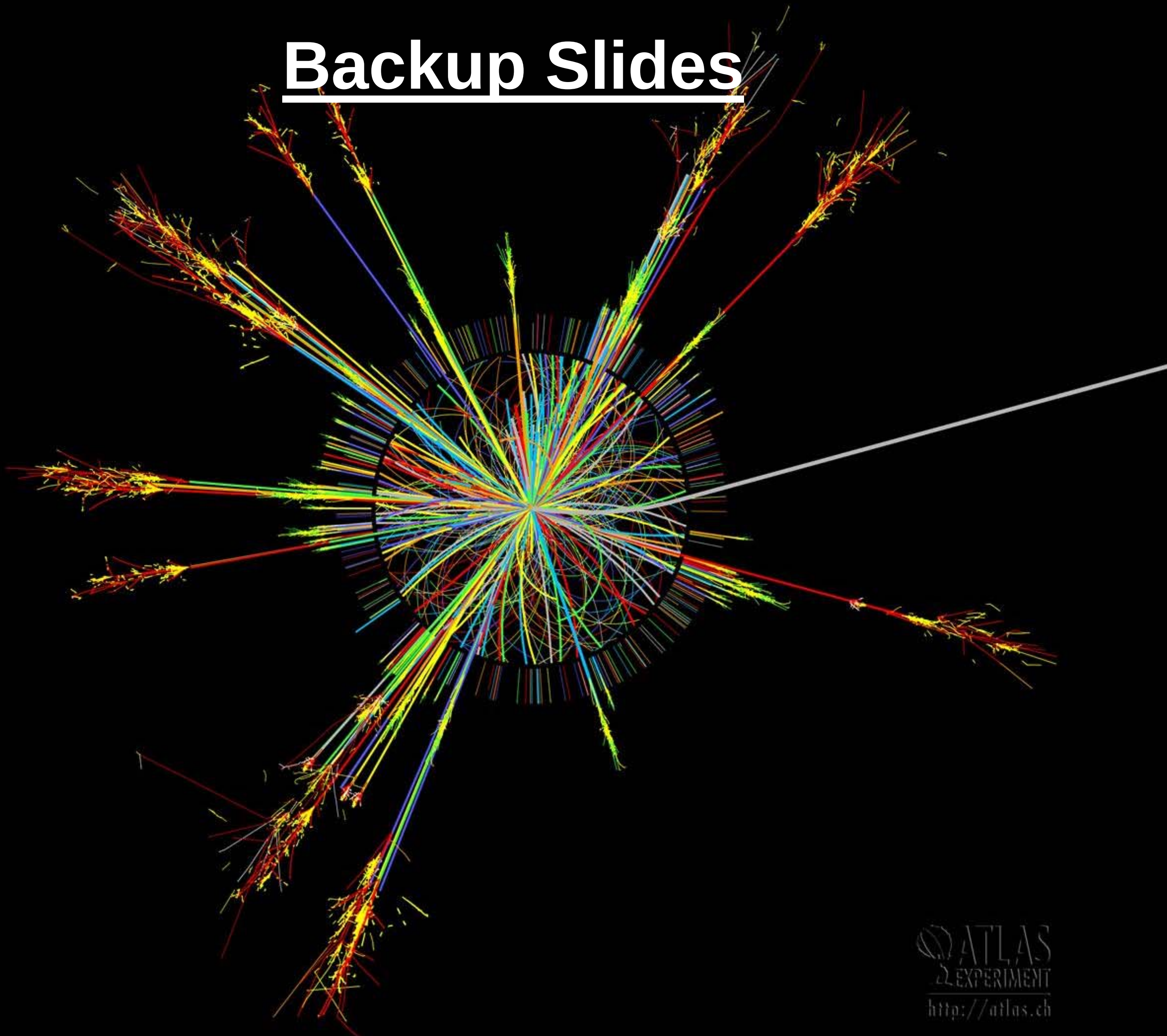
Rotating Conclusions

- Angular momentum has strong effects upon the properties of the black hole events.
- The isotropic evaporation of a spinless, Schwarzschild black hole is **NOT** a good approximation.
- Black hole **rotation** is not lost immediately after production, but **persists throughout the evaporation** – even after allowing for a substantial loss of angular momentum in production/balding.
- At LHC and foreseeable energies, there is a lengthy spin-down phase, with little or no non-rotating, Schwarzschild phase.
- Rotating black holes look hotter – produce **fewer, more energetic particles** … and consequently look less spherical and more like backgrounds – unfortunately **NOT** as easy as previously thought! (see eg. arXiv:0901.0512)
- Rotation has large effects upon the particle species present in black hole events – an increase in vector particles, mainly at the expense of fermions – relatively fewer leptons, more gluonic jets, more (highly boosted) vector bosons, more photons.
- Obviously important to get maximum value out of LHC data by looking for the correct signature! – important to use CHARYBDIS 2 or BLACKMAX, as they include the effects of BH rotation.
- Plots from: **Phenomenology of Production and Decay of spinning Extra-Dimensional Black Holes at Hadron Colliders, JAF et al. [arXiv:0904.0979].**

Outlook

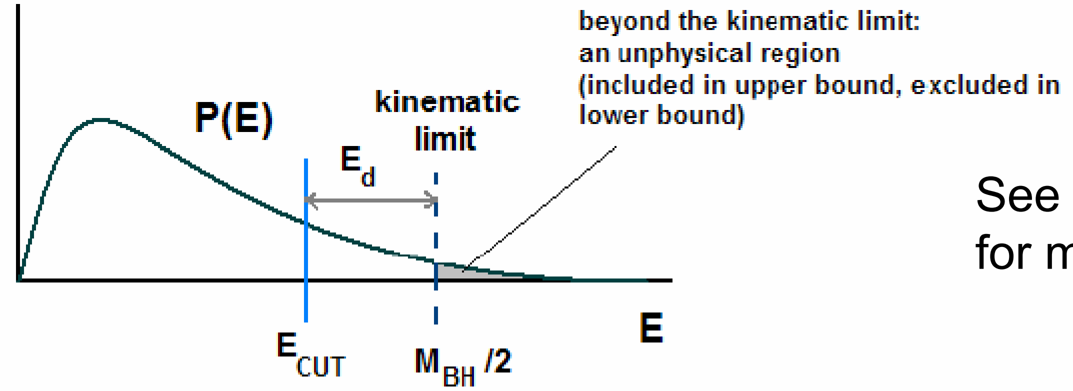
- There has been much recent progress in both theory and experimental tools to describe microscopic black holes that could be produced at the LHC.
- The ATLAS detector will be able to probe the existence of extra dimensions, the discovery of which would give us powerful insights into quantum gravity.
- The search for non-rotating black holes with the first $100pb^{-1}$ - $1fb^{-1}$ of LHC data has been simulated and investigated in detail (arXiv:0901.0512).
- Angular momentum has large effects upon the properties of the black hole events, and its inclusion is vital for experimental searches.
- We're now moving to more detailed detector simulation and reconstruction to improve/update experimental strategies and searches for rotating black holes.
- See Cigdem's talk for further discussion and comparison of generators.
- Looking forward to real data!

Backup Slides



Details of Calculation of n

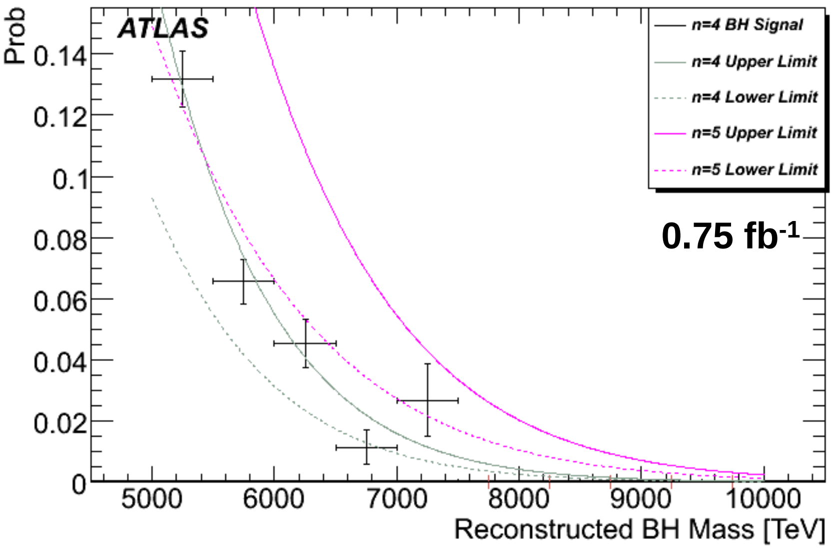
- A particle emitted in the BH frame with an energy close to half the BH mass (within an energy E_d-here chosen to be 300 GeV), must have been the first particle emitted.
- The particle energy spectrum for a given number of extra dimensions and Planck mass is known, but will be amended near the kinematic cut at half the (current) black hole mass.
- Upper and lower bounds on the probability of a particle emission with close to half the energy of the black hole can be calculated.
- The upper bound includes all the probability distribution of emission in the unphysical region, the lower bound excludes all of it.

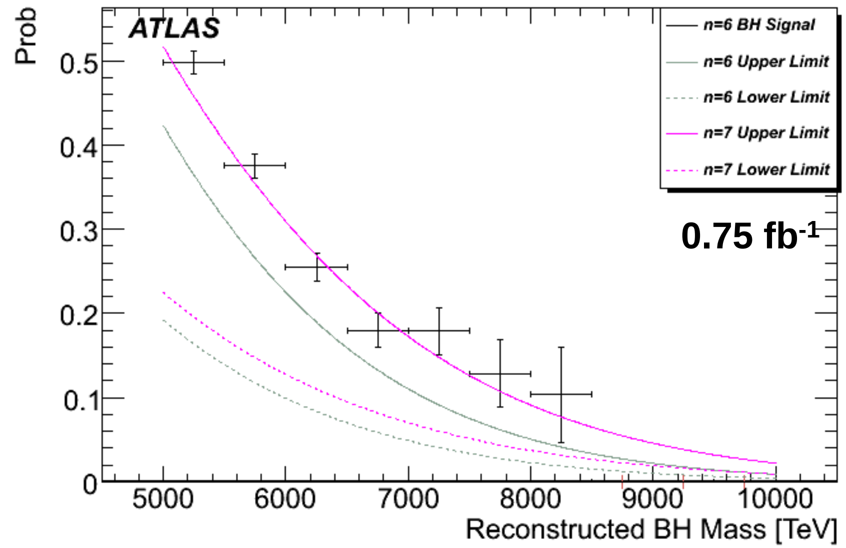


See hep-ph/0411022 for more details

- A corrective factor is applied to account for the possibility of a soft first emission

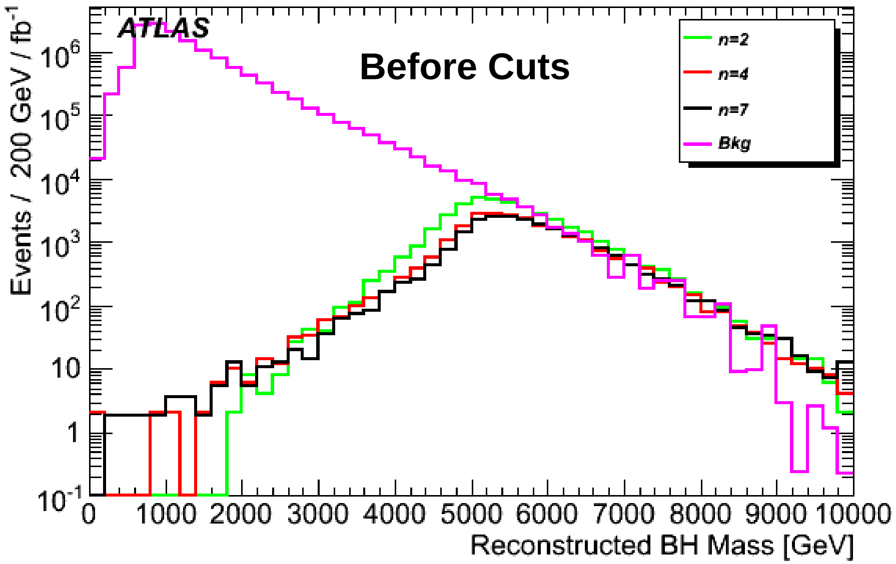
How many extra dimensions?

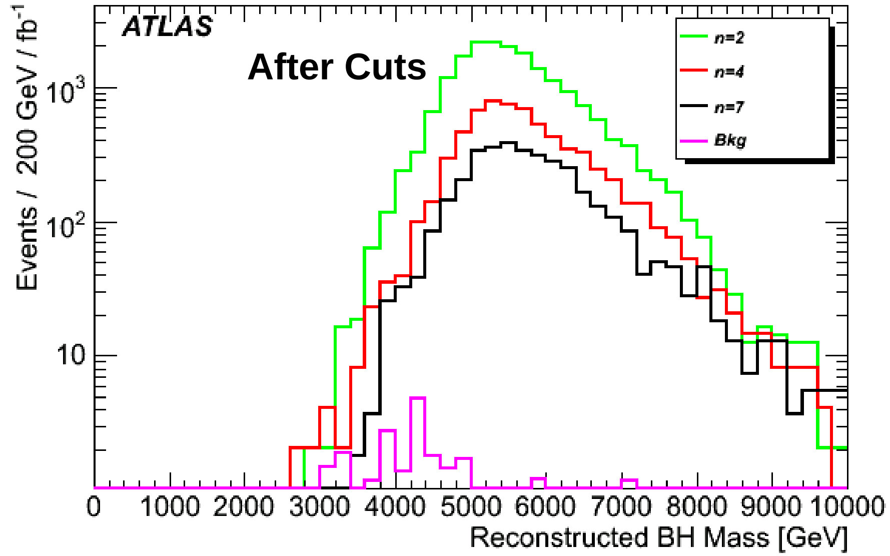


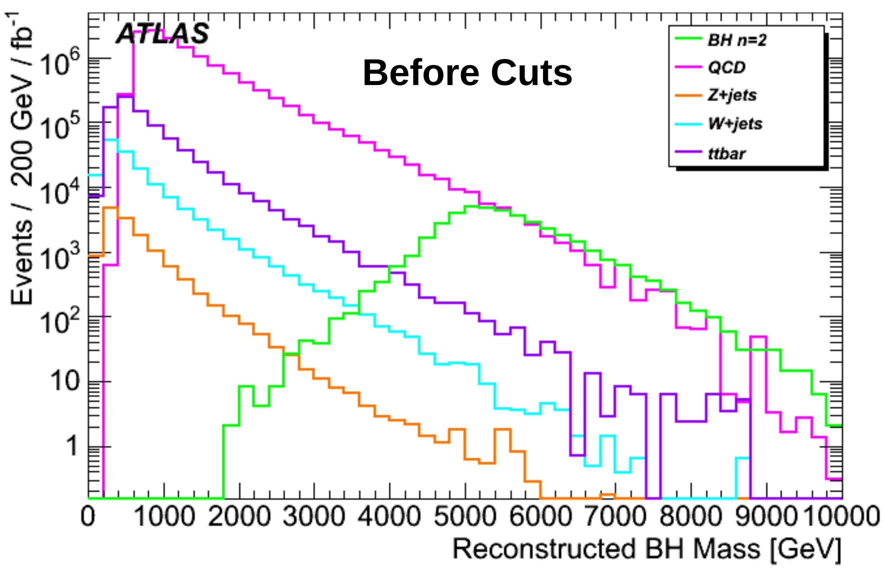


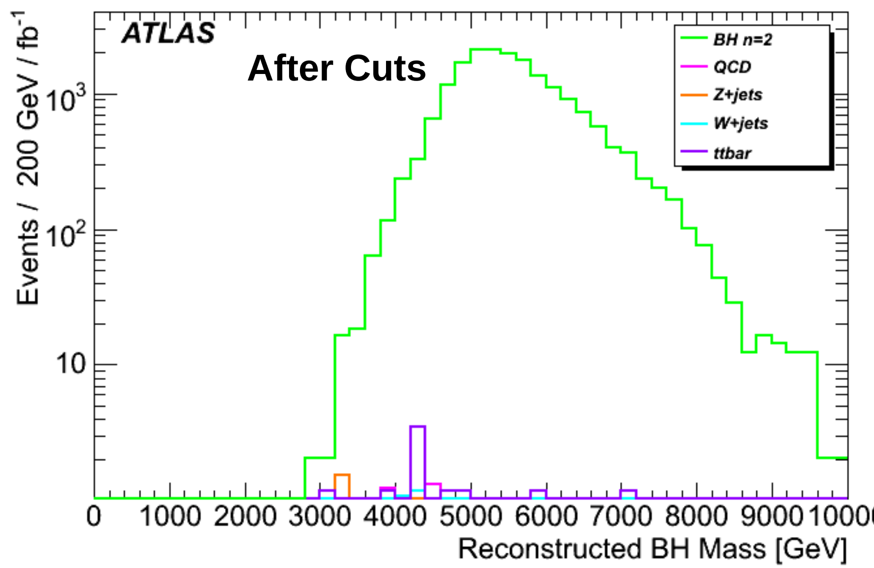
- Calculating the number of extra dimensions in a manner that is free from the theoretical uncertainties and independent of potential model parameters is difficult. Care must also be taken not to bias the selection such that the subsample passing the selection cuts is unrepresentative of the true BH distribution.
- One method showing potential was first described in hep-ph/0411022, and has been made compatible with cuts for signal selection and background rejection. The probability of a hard emission (y-axis) for any number of extra dimensions should lie between upper and lower bounds that can be calculated theoretically as a function of BH mass (x-axis)
- Method is insensitive to some of the model uncertainties, such as the decay of the remnant, and the behaviour near the Planck threshold.

Background Rejection

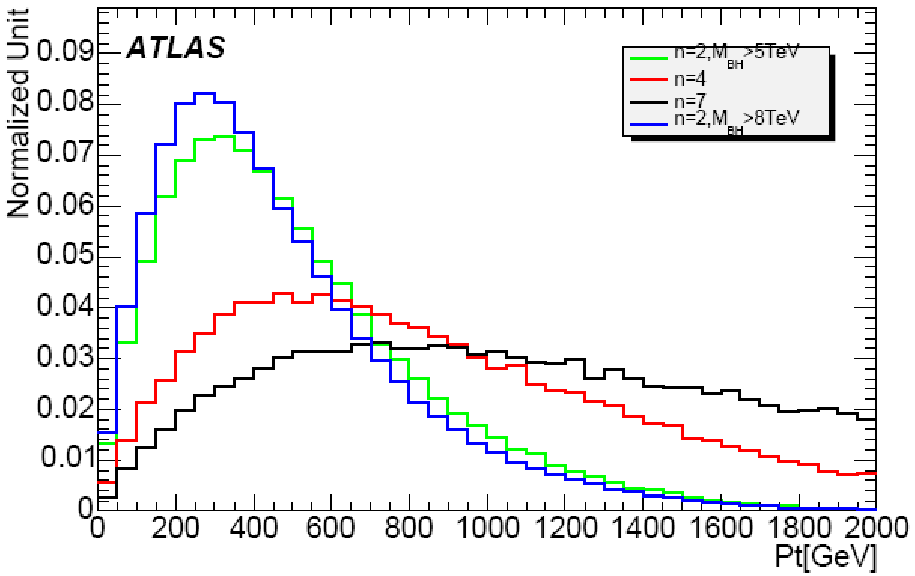


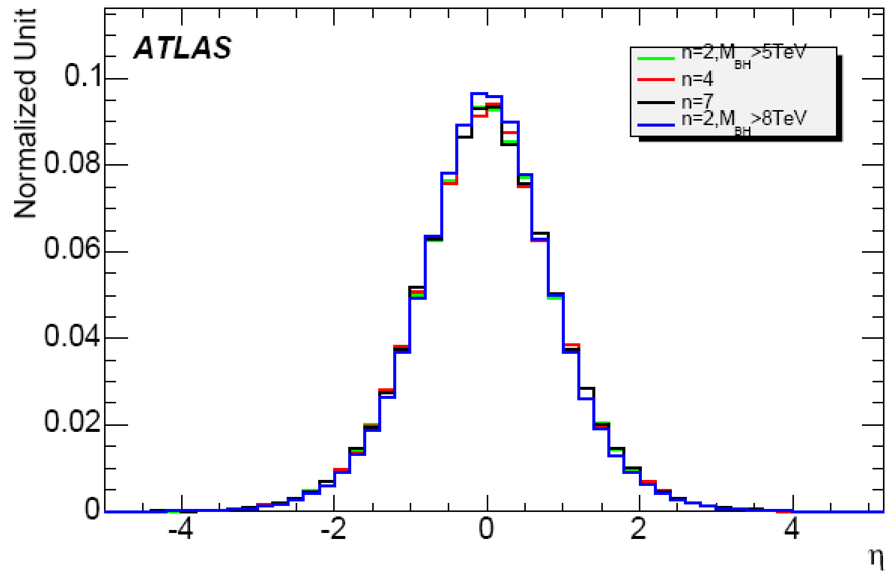






Generator-level Distributions



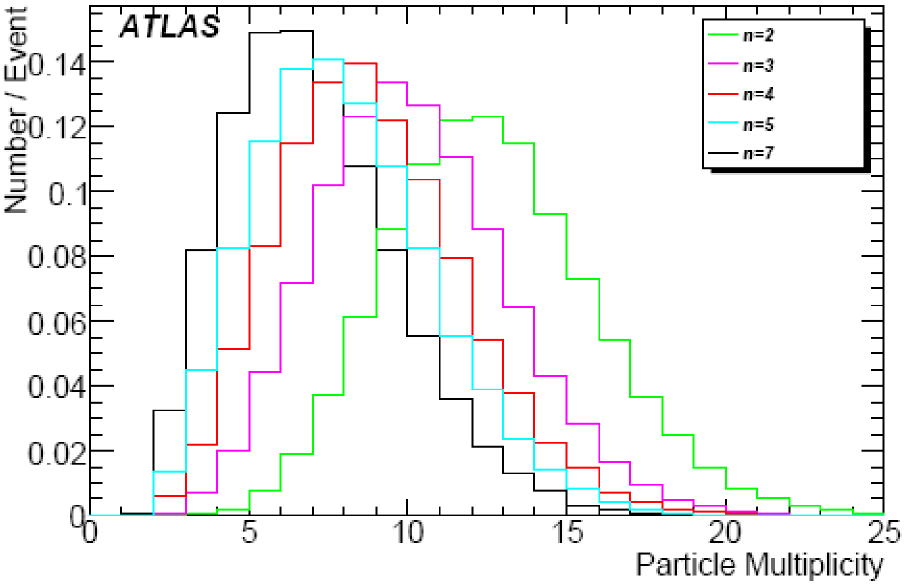


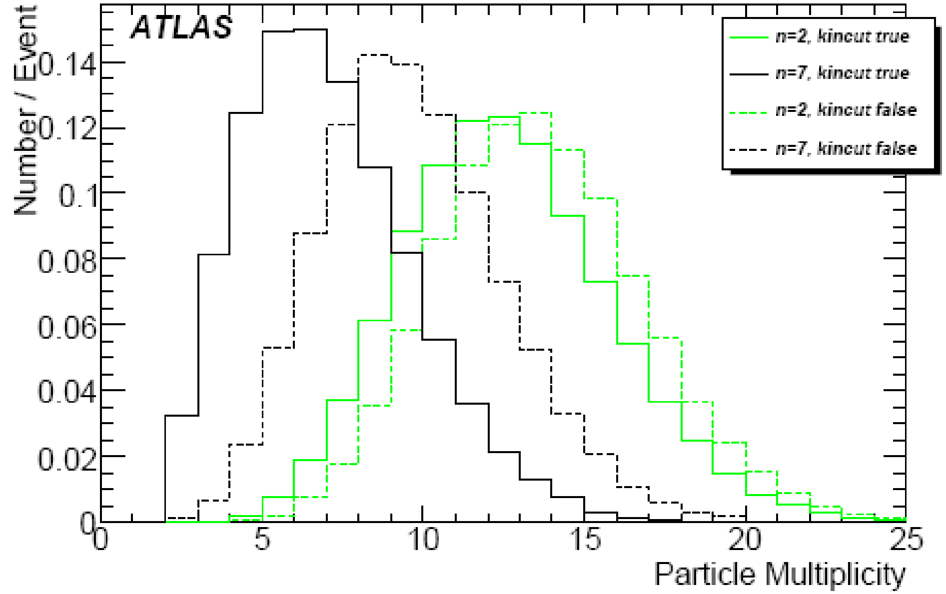
Theoretical Parameters

- There are a number of theoretical uncertainties associated with the model
- These were investigated using ATLFAST samples.

Theoretically uncertain parameter	Description	Canonical Value	Alternate Value
Use a kinematic cut-off on the decay	If an unphysical, kinematically-disallowed decay energy is selected: True: End BH decay and do remnant decay into N-bodies False: Continue to emit particles until $M_{BH} = M_{PL}$, then do remnant decay	True	False
Allow T_H to change with time	As the black hole decays, its radius and mass becomes smaller and its Hawking temperature rises. True: Hawking temperature is recalculated between emissions False: Hawking temperature fixed at initial value	True	False
Number of extra dimensions		2, 4, 7	3,5
Planck Scale	Quantum gravity scale	1 TeV	2 TeV
Decay remnant to N-bodies	When the black hole reaches the remnant phase, it decays into N-bodies	2-body decays	4-body decays

Theoretical Parameters (II)

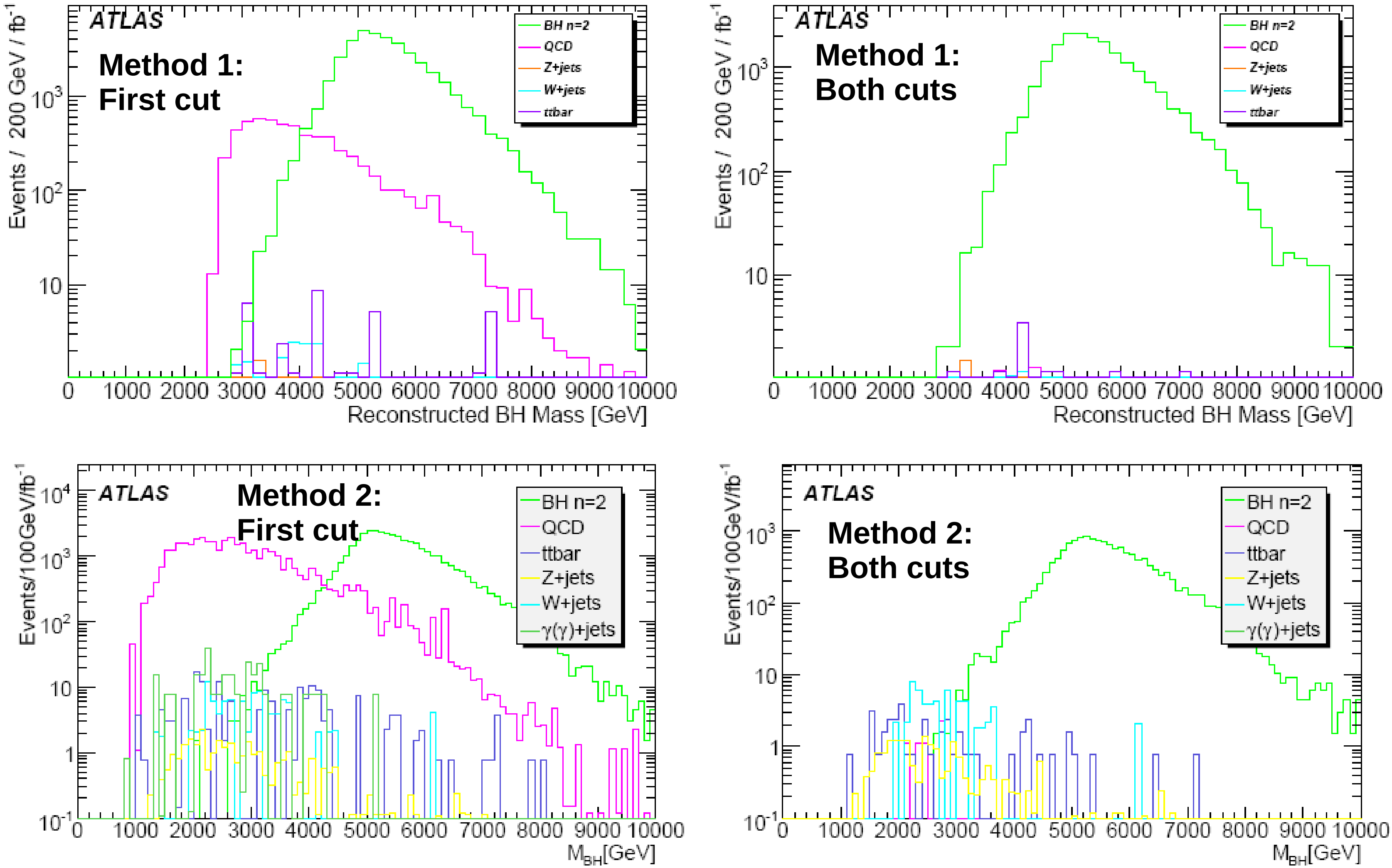




n	Full Sim	Fast Sim	Kin. Cut off	T_H-variation off	4-body remnant
2	45.8	42.9	47.2	48.7	47.9
3	-	33.2	-	-	-
4	27.4	26.6	-	-	-
5	-	21.7	-	-	-
7	16.1	15.9	29.2	16.6	27.4

Signal acceptance (%) for different model assumptions.

Two Methods


ATLAS
Method 1:
First cut
BH n=2
QCD
Z+jets
W+jets
ttbar
Events / 200 GeV / fb-1
Reconstructed BH Mass [GeV]
ATLAS
Method 1:
Both cuts
BH n=2
QCD
Z+jets
W+jets
ttbar
Events / 200 GeV / fb-1
Reconstructed BH Mass [GeV]
ATLAS
Method 2:
First cut
BH n=2
QCD
ttbar
Z+jets
W+jets
γ(γ)+jets
Events/100GeV/fb-1
M_BH[GeV]
ATLAS
Method 2:
Both cuts
BH n=2
QCD
ttbar
Z+jets
W+jets
γ(γ)+jets
Events/100GeV/fb-1
M_BH[GeV]

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BH Event Generators

- TRUENOIR (Dimopoulos & Landsberg, hep-ph/0106295)
  - ➔ J=0 only; no energy loss; fixed T; no g.b.f.
- CHARYBDIS (Harris, Richardson & BW, hep-ph/0307305)
  - ➔ J=0 only; no energy loss; variable T; g.b.f. included
- CATFISH (Cavaglia et al., hep-ph/0609001)
  - ➔ J=0 only; energy loss option; variable T; g.b.f. included
- BlackMax (Dai et al., arXiv:0711.3012)
  - ➔ J≠0; energy loss option; variable T; split branes; g.b.f.
- CHARYBDIS2 (JAF, et al., arXiv:0904.0979)
  - ➔ J≠0; energy loss model; variable T; remnant options; g.b.f.

➔ All need interfacing to a parton shower and hadronization generator (PYTHIA or HERWIG)

Modern (Rotating) BH MC

CHARYBDIS 2.0: JAF, Gaunt, Sampaio et al. **arXiv:0904.0979**

Production: Rotating black holes. Consistent model of mass/angular momentum loss and cross-section – dependent upon impact parameter and *n*, correct spin dependent upon partons.

Evaporation: Inclusion of black hole rotation through greybody factors, angular distributions and energy spectra. Polarisations taken into account. Variable temperature (though with the option to turn time variation off (equivalent to instant evaporation with no time to re-equilibrate).

Remnant options – criteria – MPLANCK or expected flux. Pure phase space, with/without Hawking spectrum for particle species, angular distribution, energy spectrum. Fixed/variable multiplicity determined by <N> from Hawking spectrum. String motivated 'boiling' model.

Alternatives: straight to 2->N (N≥2) bodies, using input from the Hawking spectrum.

BLACKMAX 2.0: Dai, Starkman et al. **arXiv:0711.3012**

Production: Rotating black holes. Option to lose constant fraction of mass/angular momentum.

Evaporation: Inclusion of black hole rotation through greybody factors, angular distributions and energy spectra. Variable temperature. Suppression of spin-up modes.

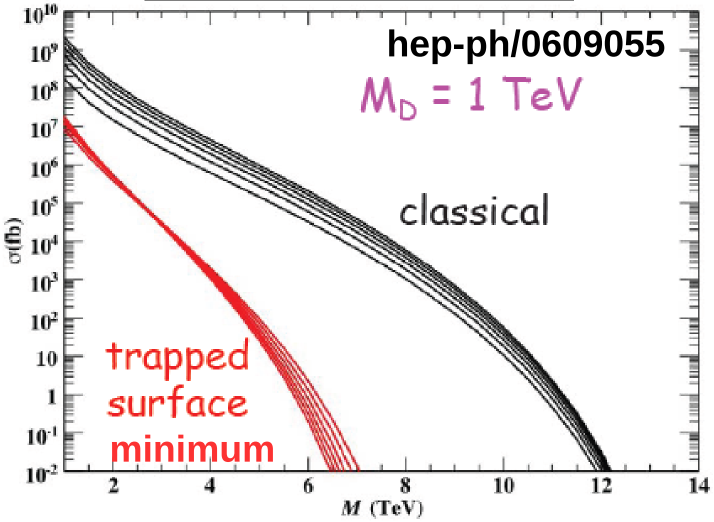
Remnants: Isotropic, phase space. Minimal multiplicity.

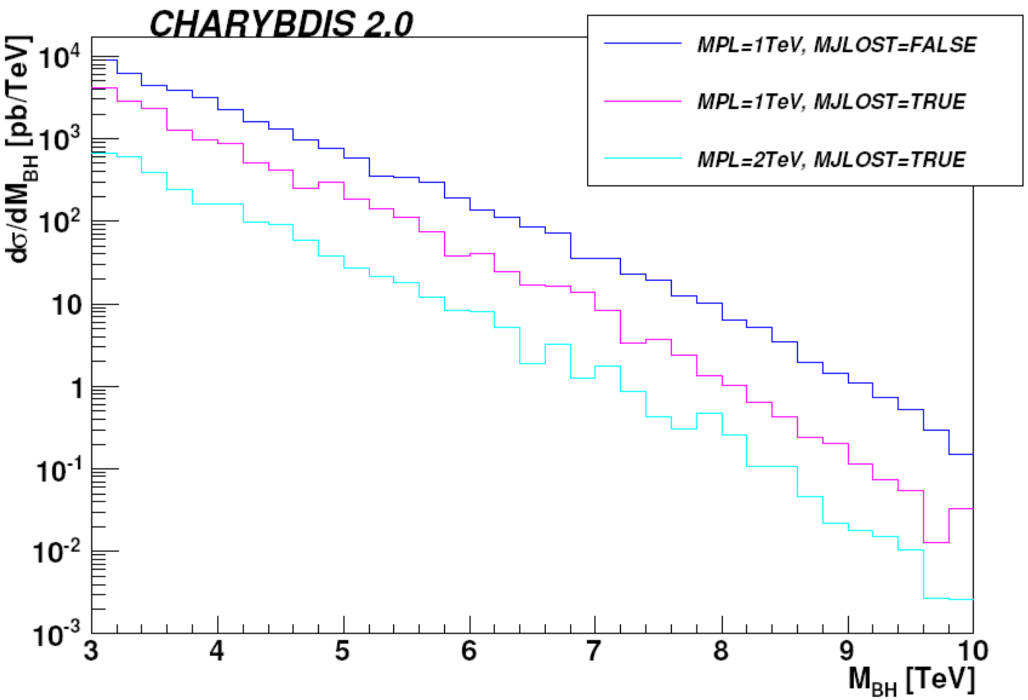
Alternatives (without rotation): non-zero brane tension (5-6D), split fermion branes, brane/bulk graviton emission, 2->2 di-jet like BH processes.

BH Cross-sections

- Black hole cross-sections show a strong dependence upon the Planck mass.
- Differential cross-section heavily affected by models of losses in production/balding.
- BH cross-sections have large uncertainties – the σ neglecting losses lies orders of magnitude above the minimum bound calculated.

14 TeV Predictions





- Since production is dominated by quarks at high *x*, a drop in beam energy to 10 TeV does have a large effect on cross-sections.

CHARYBDIS2 @ Work

http://projects.hepforge.org/charybdis2/

$\sigma_{PP \to BH}$

$$\sum_{i,j} \int \frac{d\tau\, dx}{x} f_i(x) f_j\left(\frac{\tau}{x}\right) F_n \sigma(\tau s)$$

→ MJLOST
Choose $b < b_{max}$
Reduce M and J

→ Graviton
Store momentum in event record

$M_{BH} < \sqrt{\tau s}$ formed

Evaporation

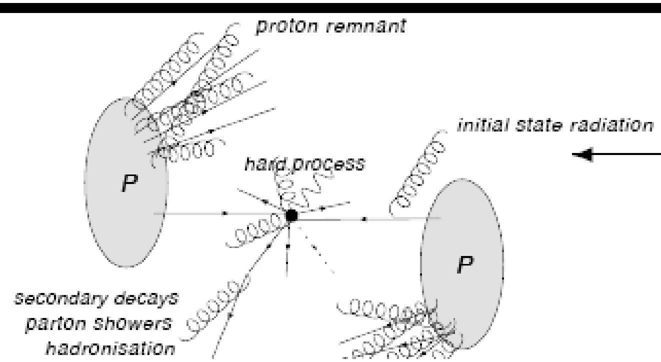
- Select P^μ of SM emission $\frac{dN_h(a_*)}{dt d\omega d\Omega}$
- Recoil BH against (P^μ, m, j) and update $\{M, J\}$
- Store emission in LH common with polarisation
  Continue.

Repeat until NBODYAVERAGE or KINCUT

Remnant

NBODYVAR
NBODYPHASE
RMBOIL
RMSTAB

→ HERWIG
PYTHIA
CHARYBDIS



Backup