Discovering Black Holes with ATLAS

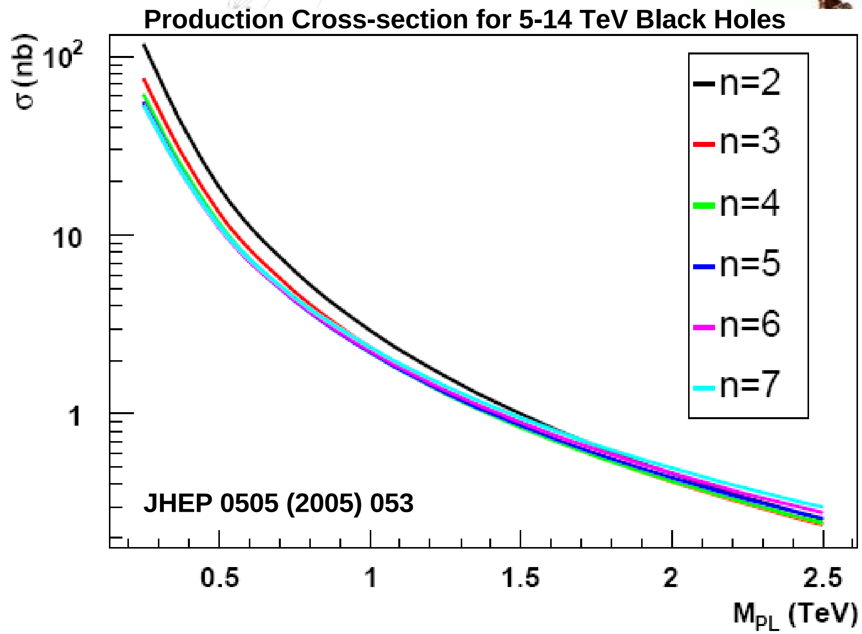
James Frost - On behalf of the ATLAS Collaboration

Introduction

- Arkani-Hamed, Dimopoulos and Dvali (ADD), and Randall and Sundrum (RS) 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

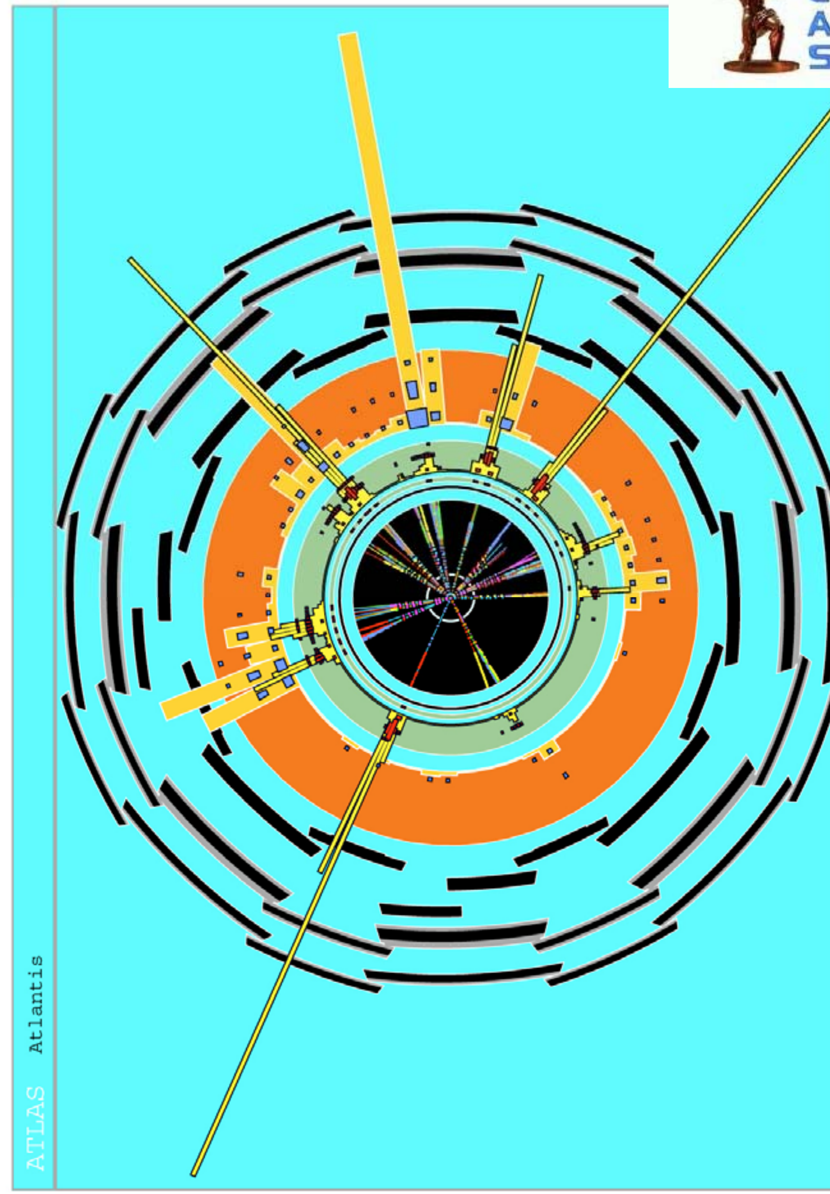


- A general formulation of their production is extremely complex.
- Semi-classical approximations, only valid well above the Planck scale are necessary to enable a quantitative description and predictions.
- A minimum BH mass must be imposed. Below this, gravitational interactions may look like a contact interaction or compositeness effect – such signatures require new tools and generators.

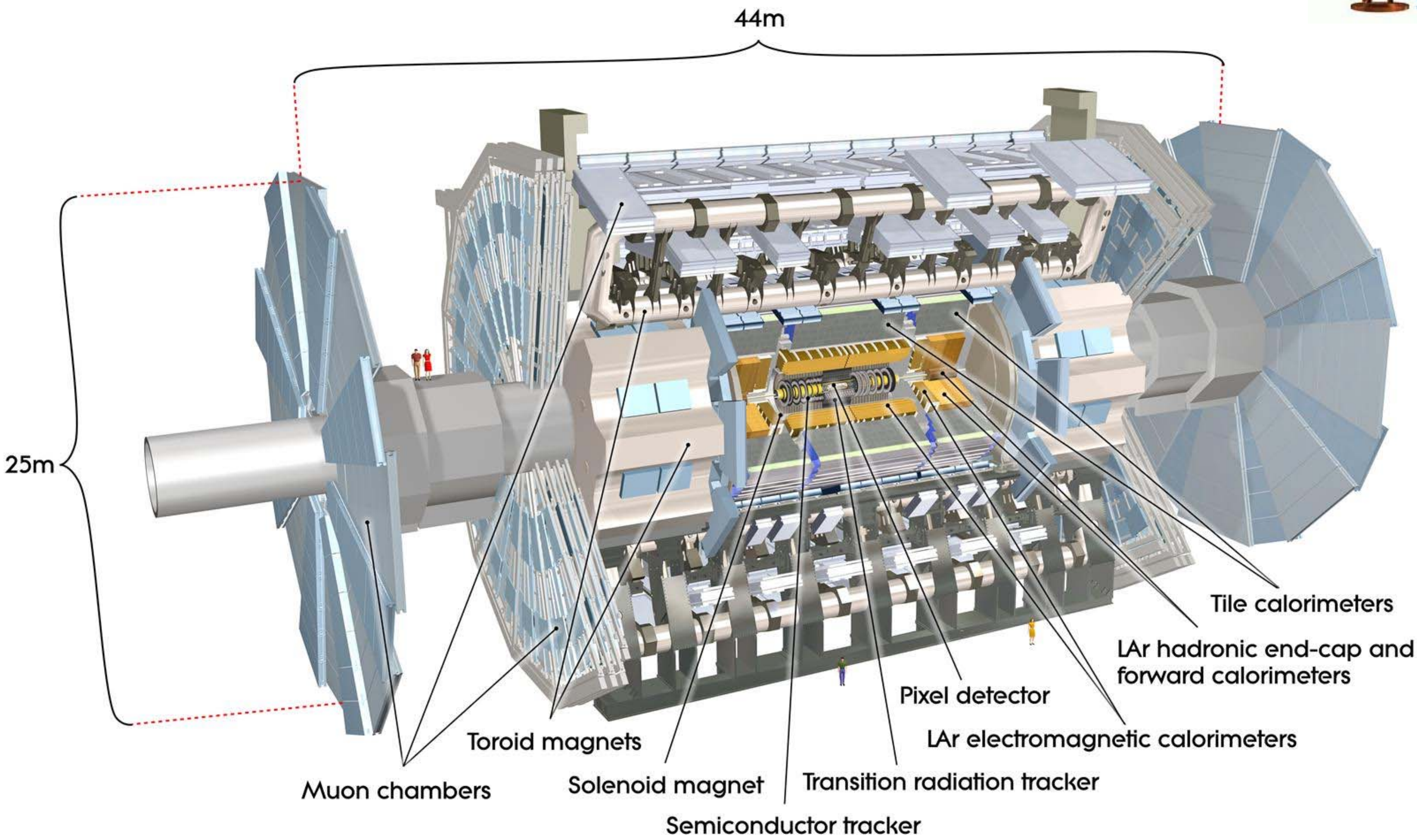
MC / Working Model

We use the Monte-Carlo event generator CHARYBDIS to produce events:

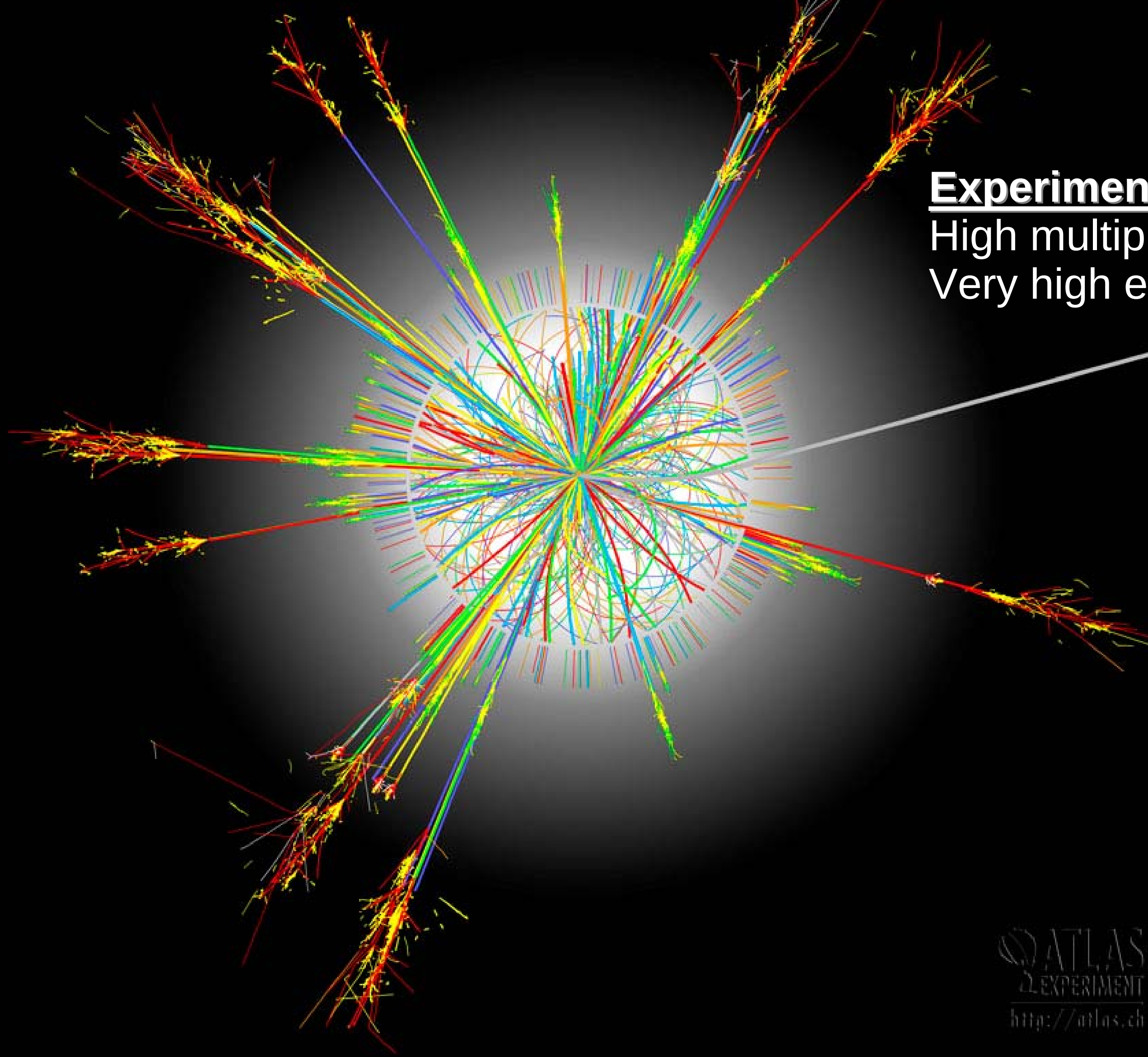
- Black-disk geometric cross-sections.
- 2-7 extra spatial dimensions (n).
- Full spin-dependent grey-body factors.
- All Standard Model particles produced.
- Conserves baryon and lepton number.
- Ignores balding and spin-down phases, modelling the Schwarzschild phase (Hawking radiation).
- No graviton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



ATLAS

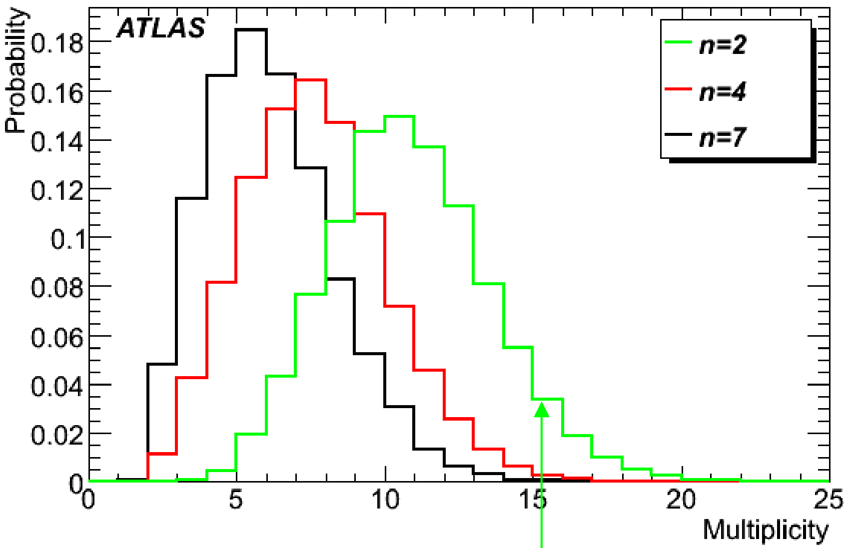

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

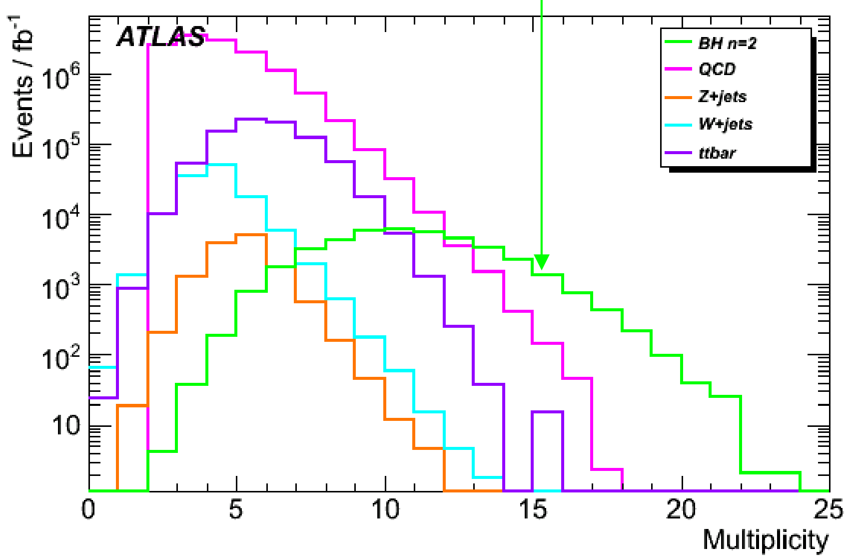
Black Holes in ATLAS



Experimental Challenges
High multiplicity
Very high energy & P_T particles

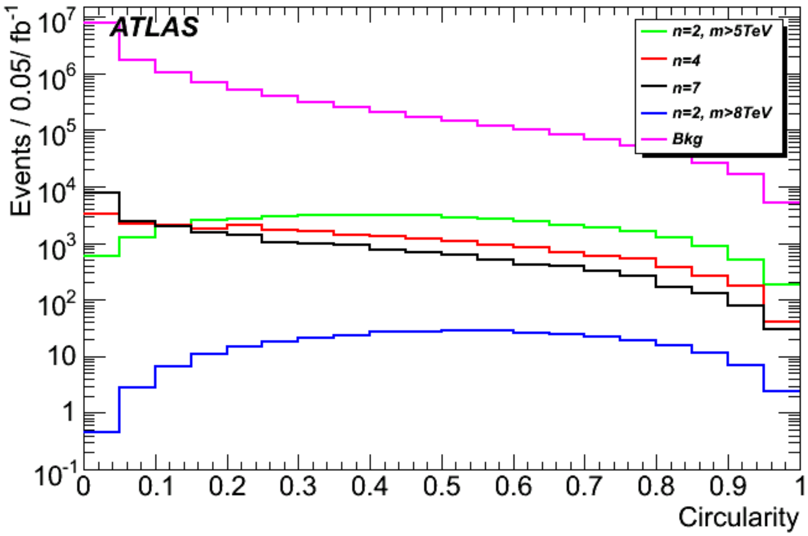
Event Properties (I)

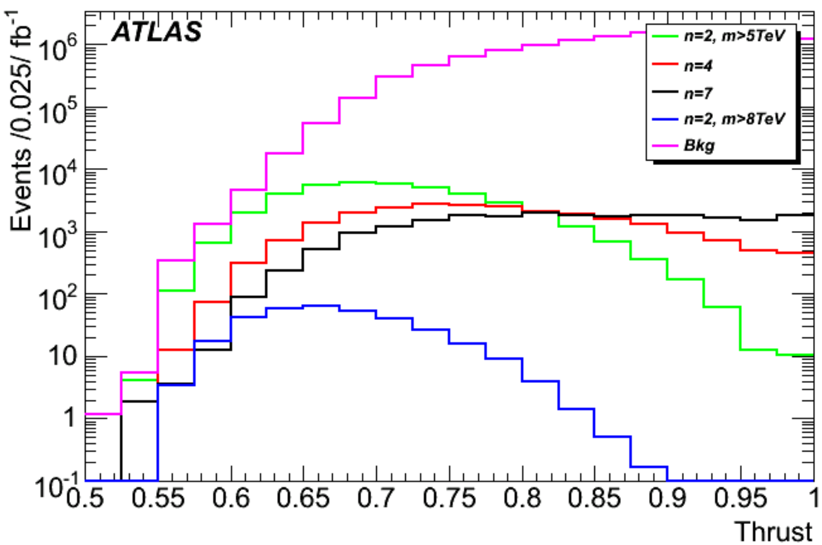




- Black hole events are characterised by a number of high-transverse momentum (P_T) final state particles.
- Large variation – for a given mass, the Hawking temperature is greater at high n, so fewer particles, but with higher energies, are emitted.
- Black hole events can be very crowded – average multiplicity (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.

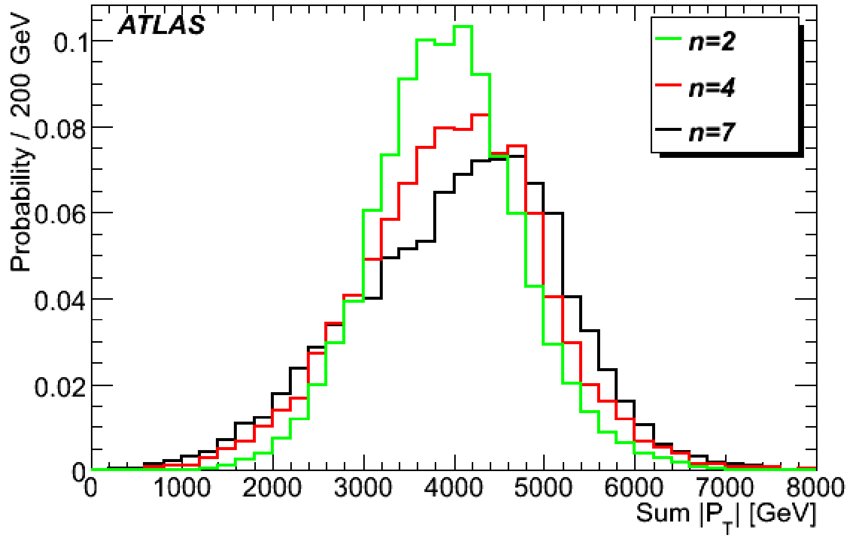
Event Properties (II)



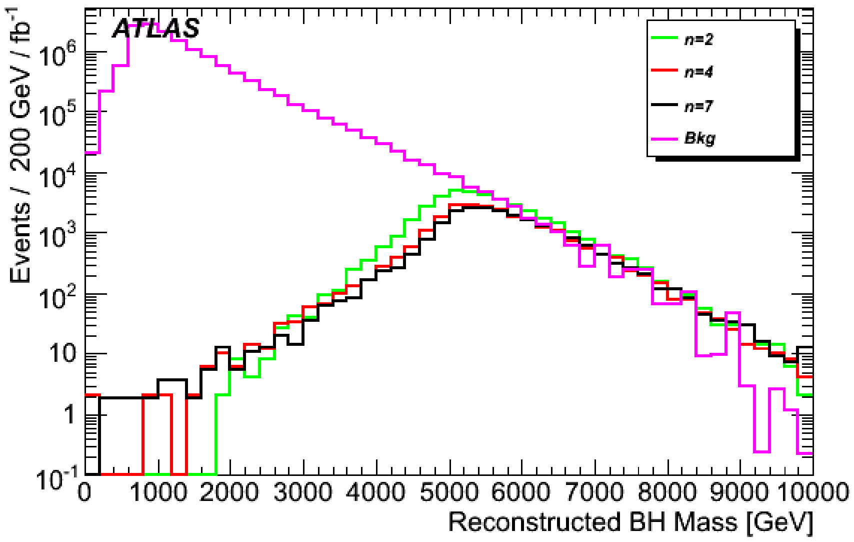


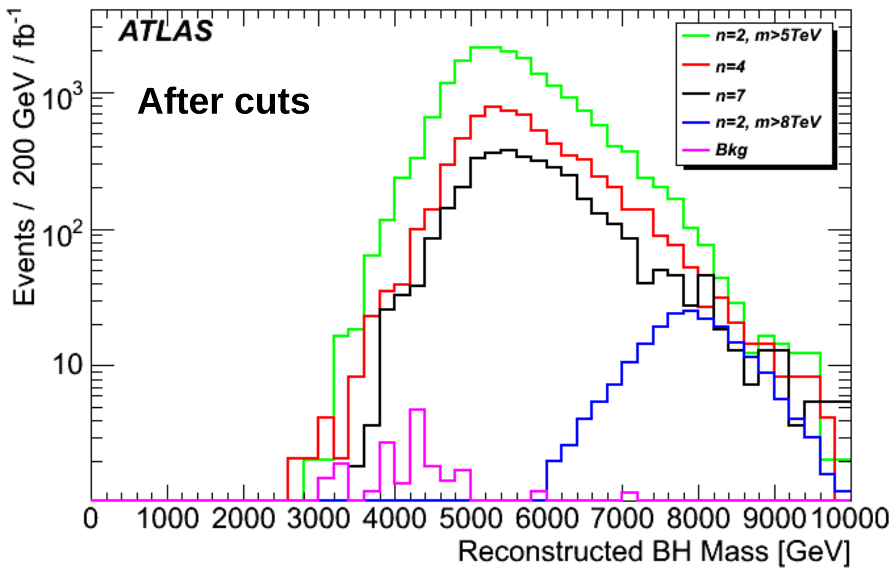
- <u>Could event shape variables be used to distinguish a BH signal from background?</u>
- Not easily. Their discriminating power is reduced since:
  - Signal shape varies strongly with n, and other theoretical parameters.
  - Large background cross-sections cause substantial overlap between distributions.
- Event shapes variables depend strongly on BH parameters – not suited to hard cuts due to large background cross-section.

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.





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:

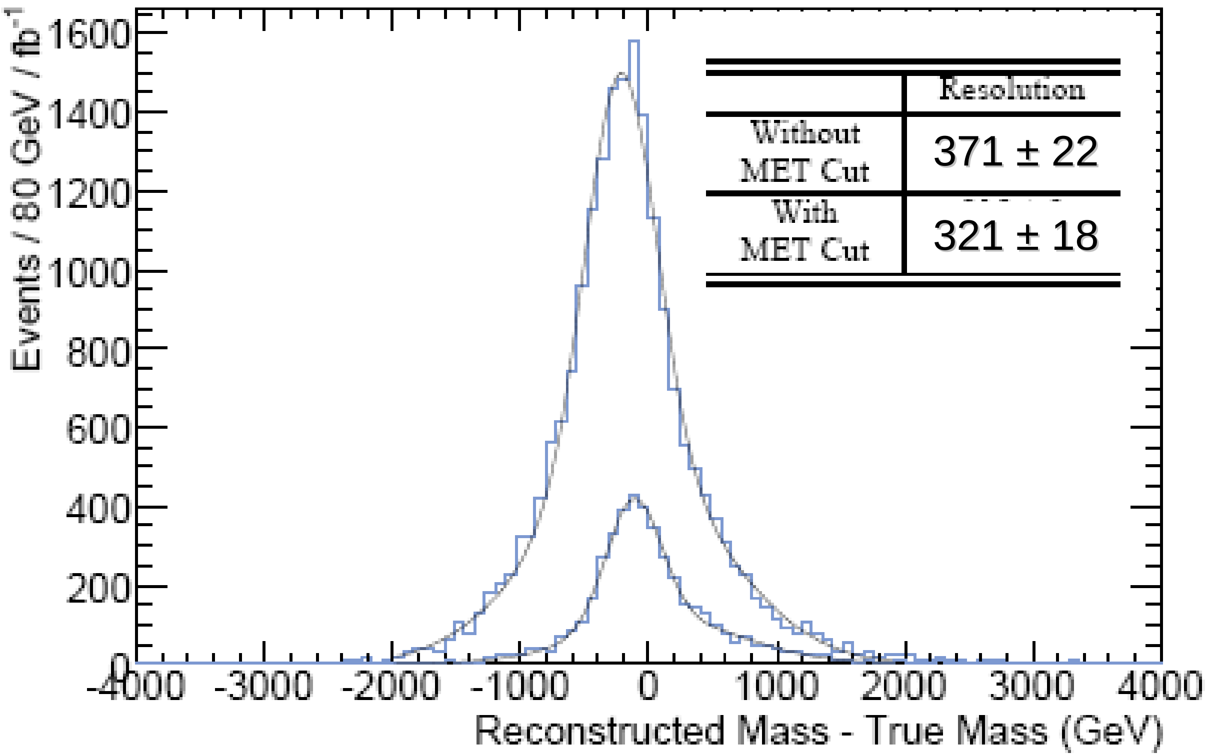
Dataset	Before selection (fb)	After requiring a lepton (fb)	acceptance
$n=2, m>5$ TeV	$40.7\pm0.1\times10^3$	$18.6\pm0.2\times10^3$	0.46
$n=4, m>5$ TeV	$24.3\pm0.1\times10^3$	6668 ± 83	0.27
$n=7, m>5$ TeV	$22.3\pm0.1\times10^3$	3574 ± 60	0.17
$n=2, m>8$ TeV	338.2 ± 1	212 ± 16	0.63
$t\bar{t}$	$833\pm100\times10^3$	$8.2^{+2.43}_{-2.43}$	9.8×10^{-6}
QCD dijets	$12.8\pm3.7\times10^6$	$5.37^{+3.25}_{-2.03}$	4.3×10^{-7}
$W_{\ell\nu}+\geq2$ jets	$1.9\pm0.04\times10^6$	$4.67^{+8.75}_{-0.93}$	2.4×10^{-6}
$Z_{\ell\ell}+\geq3$ jets	$51.8\pm1\times10^3$	$2.57^{+0.95}_{-0.64}$	5.0×10^{-5}

Two:

Dataset	Before selection (fb)	After lepton requirement (fb)	Acceptance
$n=2, m>5$ TeV	40.7×10^3	$14.0\pm0.2\times10^3$	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^{+40}_{-3}	4×10^{-4}
$\gamma(\gamma)$+jets	5.1×10^6	0^{+40}_{-0}	$<10^{-5}$

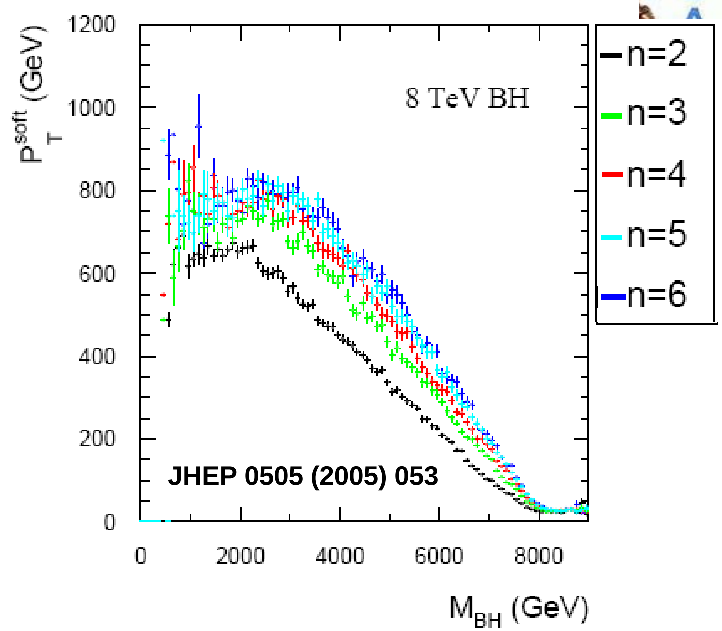
Mass Resolution

- 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.

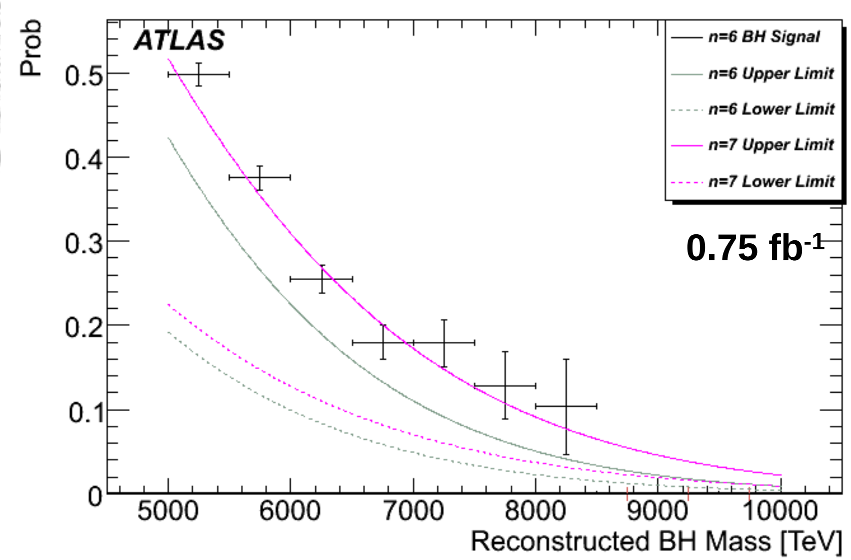


How many extra dimensions?

- 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.

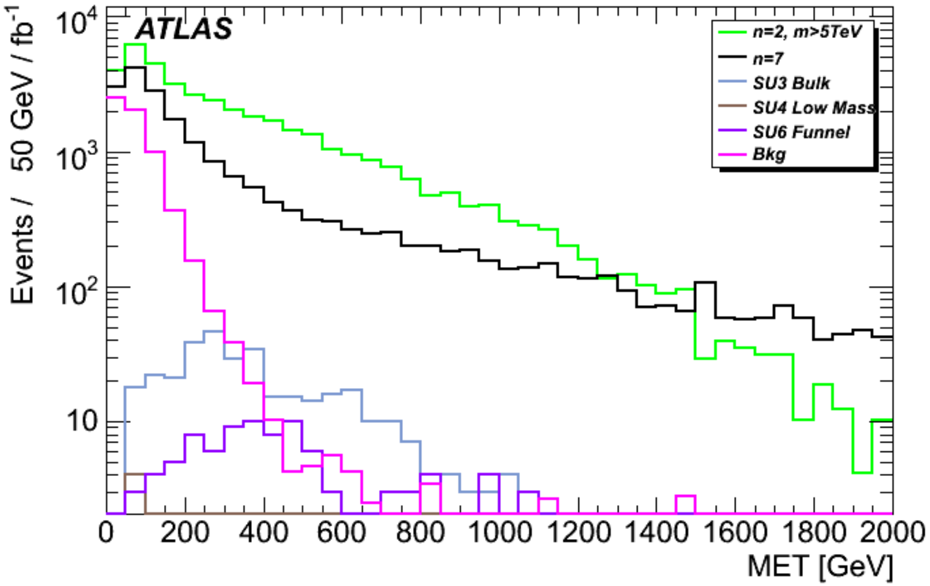


- One method for estimating n, given an estimate of the Planck scale, was first described in JHEP 0505 (2005) 053,
- Now compatible with cuts for signal selection and background rejection.
- The method is insensitive to some of the model uncertainties, such as threshold behaviour.



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.

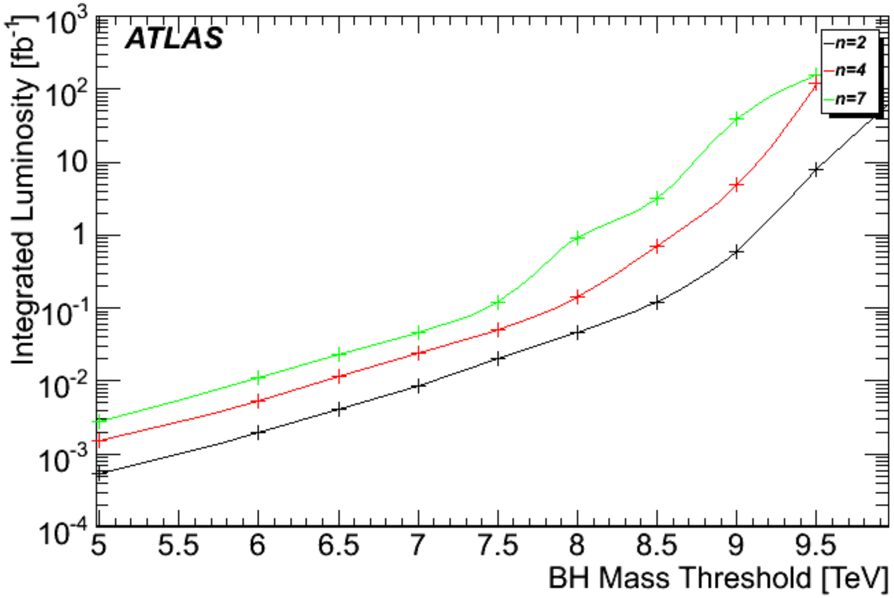
➢The high cross-section at very high MET allows BH models to be distinguished from much of SUSY space, in which points with both high cross-section and producing such very high values of MET are rare.

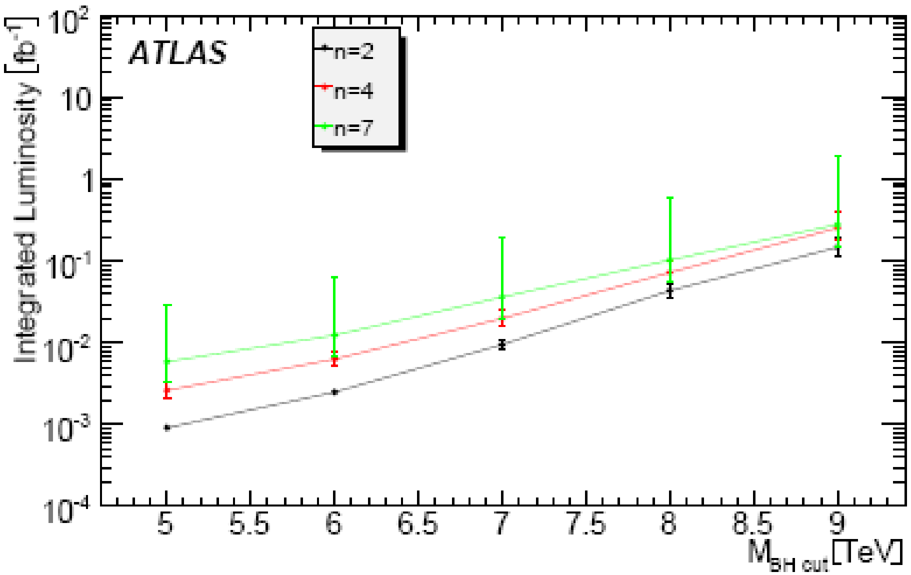
➢Selection allows less accurate mass reconstruction, limiting its use in cross-section measurement and discovery.

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

Discovery Reach

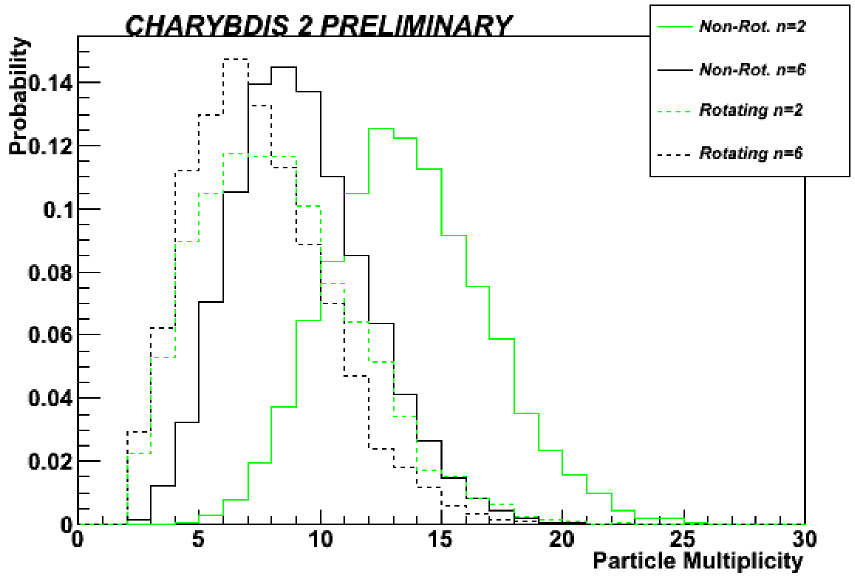
Producing a robust discovery potential for black holes is difficult, due to the large theoretical errors and semi-classical assumptions used to model them - valid only well above the Planck scale. The lack of theoretical understanding makes it impossible to model the threshold region.

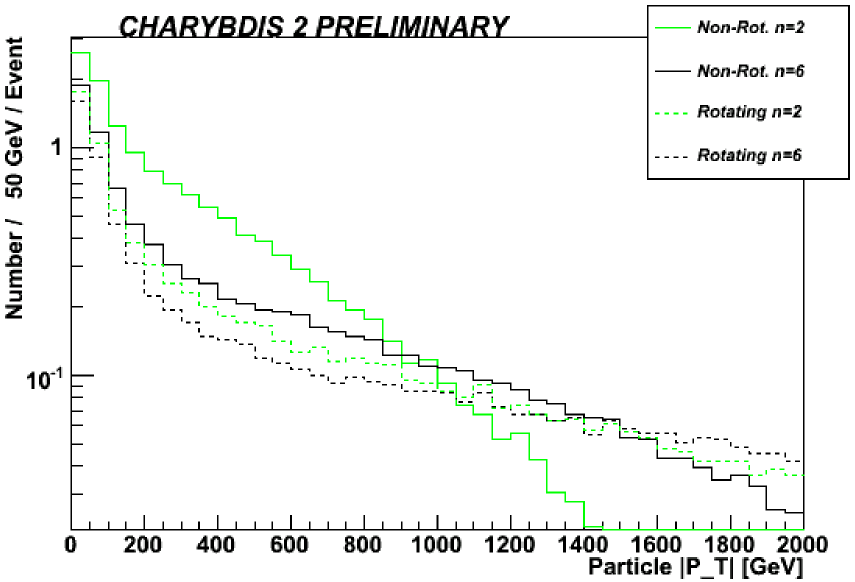




Outlook

- ➢Rapid theoretical progress is beginning to produce more sophisticated tools and Monte-Carlo generators.
- ➢Grey-body factors solved for rotating black holes – large effects.
- ➢Parameterisation of mass-energy lost in balding.
- ➢Phenomenological treatment of low multiplicity stringy/composite scattering.
- ➢Effect of 2008 run at 10 TeV on signal and background cross-sections and shapes.
- ➢First LHC beams coming soon…!

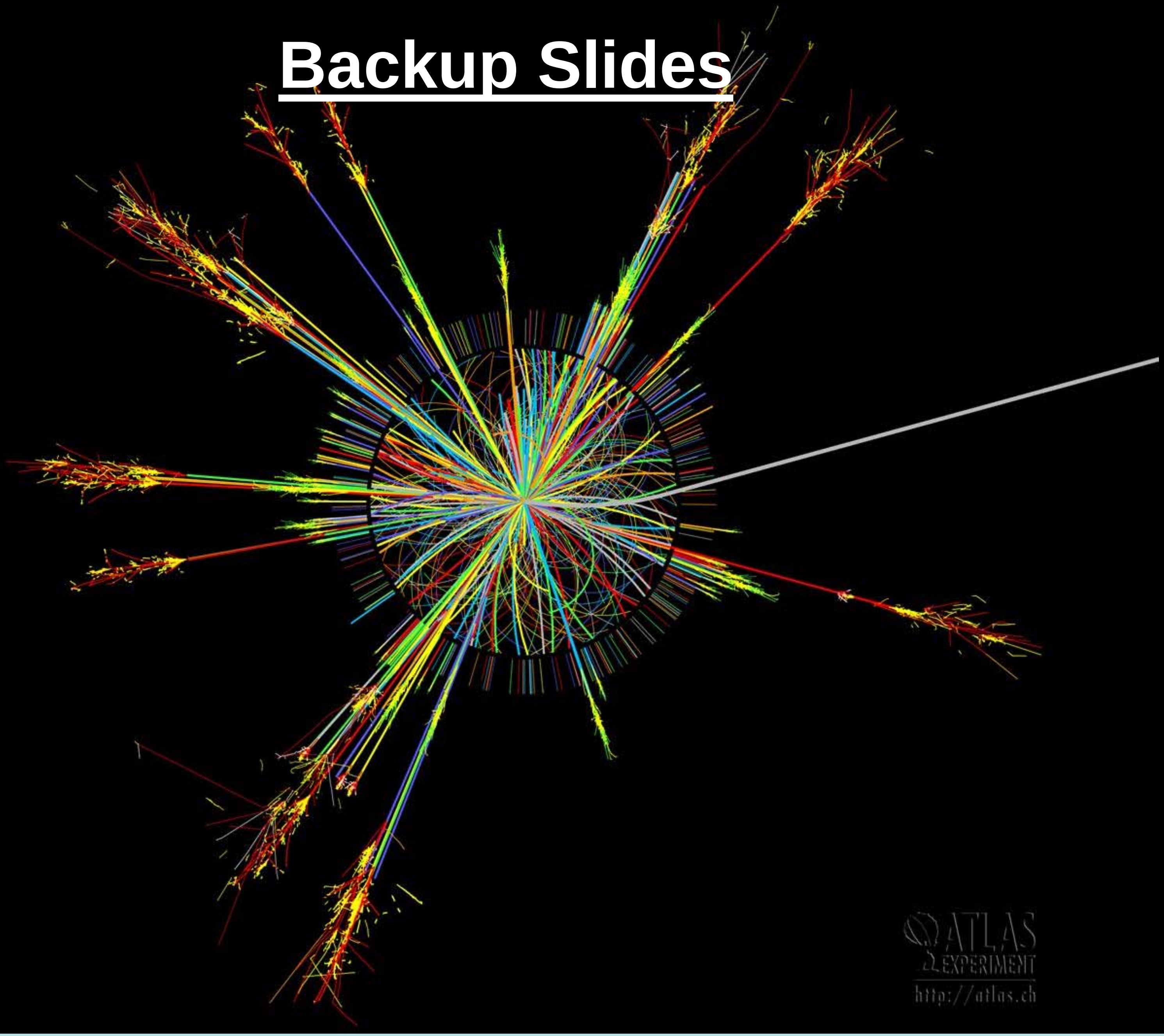




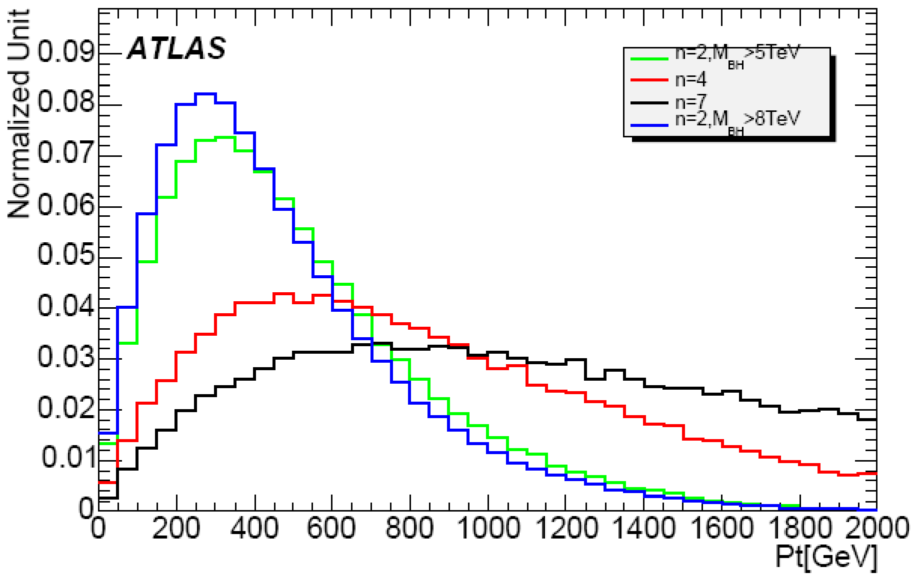
Conclusions

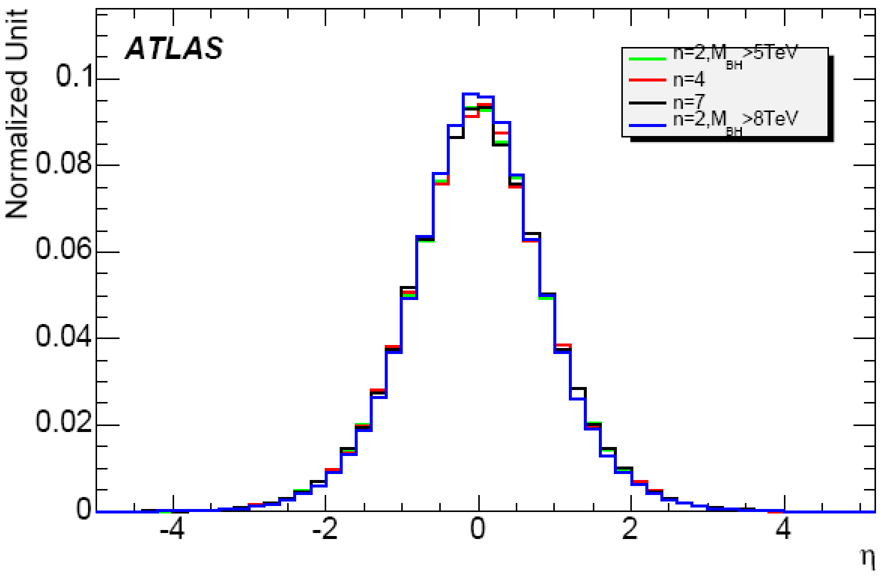
- The ATLAS detector will be able to probe the existence of extra dimensions, the discovery of which would give us powerful insights into quantum gravity.
- The search for black holes with the first 100pb^{-1} - 1fb^{-1} of LHC data was simulated and investigated – to be published shortly.
- Black hole events will pass the 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.
- Black holes 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 will 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.

Backup Slides



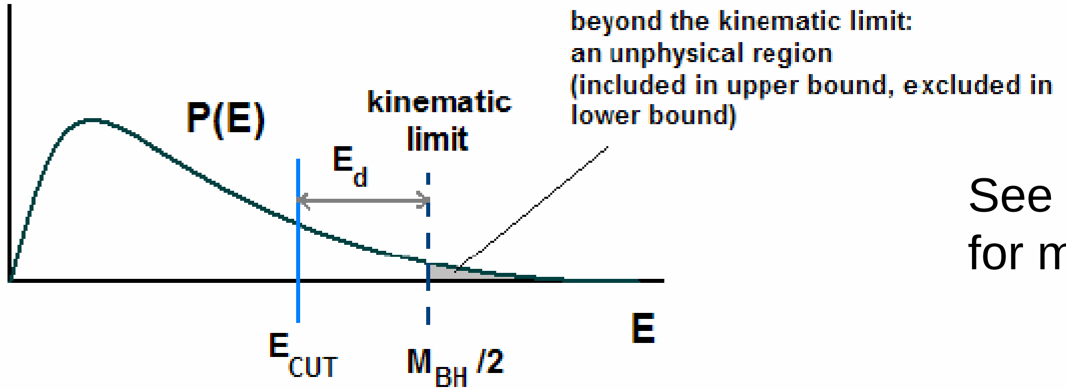
Generator-level Distributions





Details of Calculation of n

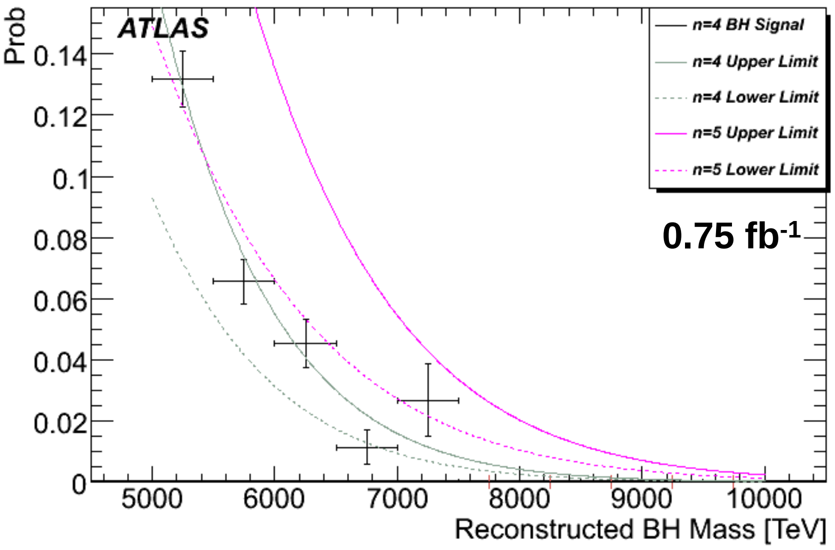
- A particle emitted in the BH frame with an energy close to half the BH mass (within an energy E_d-here chosen to be 300 GeV), must have been the first particle emitted.
- The particle energy spectrum for a given number of extra dimensions and Planck mass is known, but will be amended near the kinematic 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.

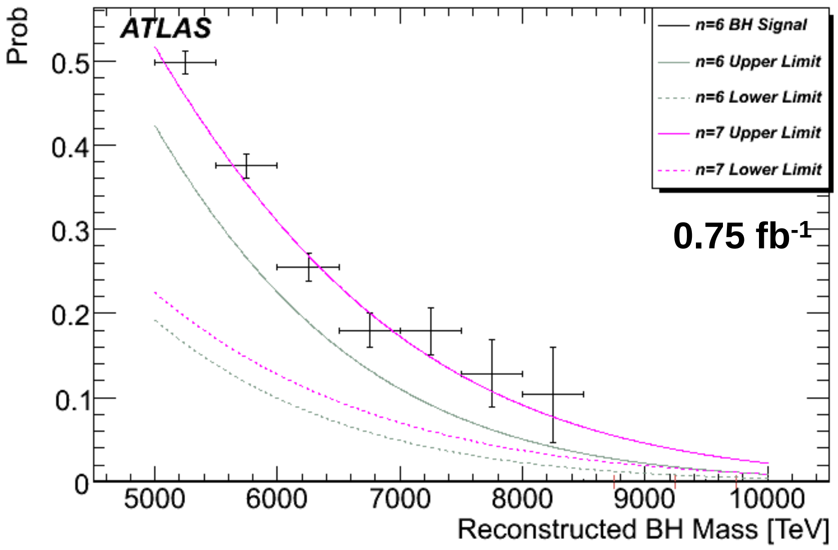


See hep-ph/0411022 for more details

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

How many extra dimensions?



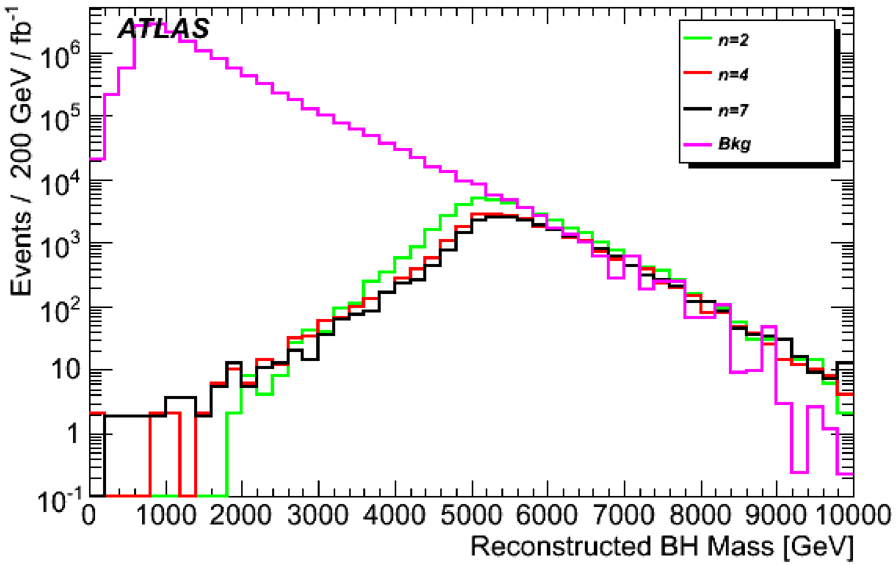


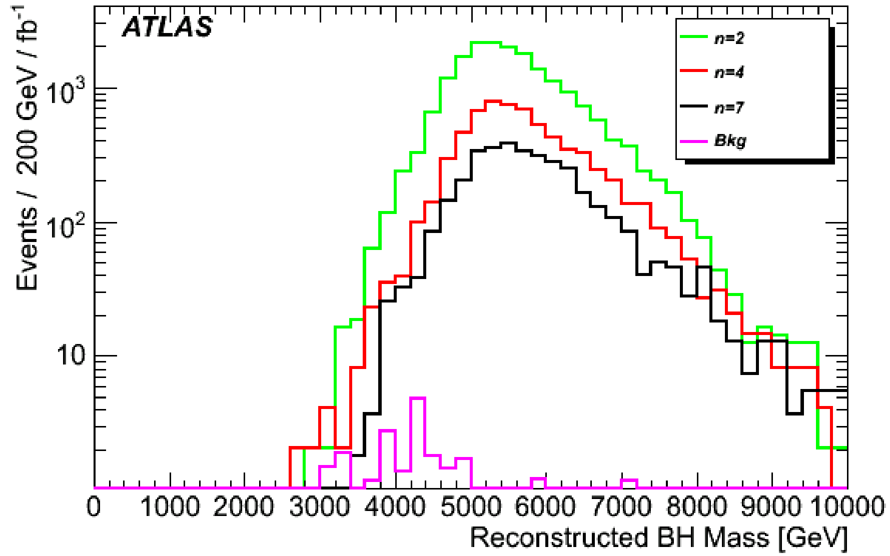
- Calculating the number of extra dimensions in a manner that is free from the theoretical uncertainties and independent of potential model parameters is difficult. Care must also be taken not to bias the selection such that the subsample passing the selection cuts is unrepresentative of the true BH distribution.

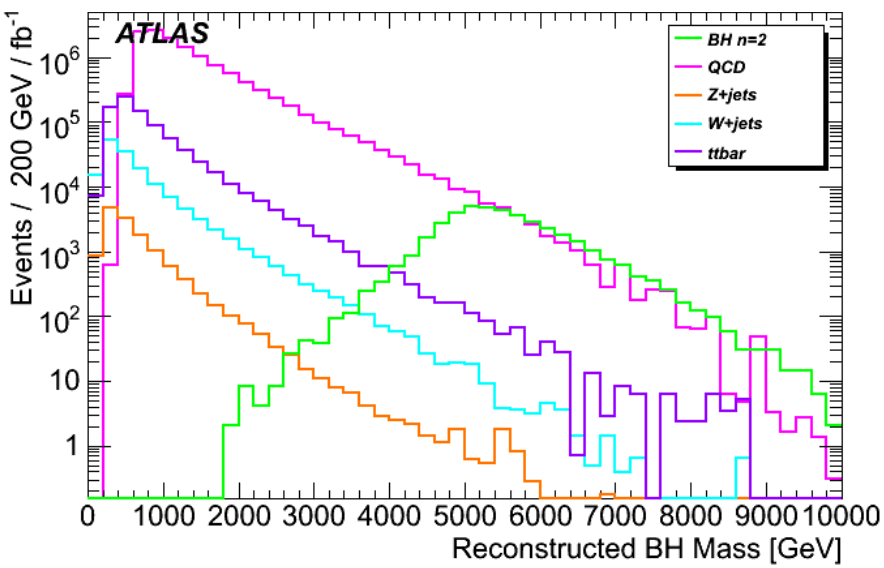
- One method showing potential was first described in hep-ph/0411022, and has been made compatible with cuts for signal selection and background rejection. The probability of a hard emission (y-axis) for any number of extra dimensions should lie between upper and lower bounds that can be calculated theoretically as a function of BH mass (x-axis)

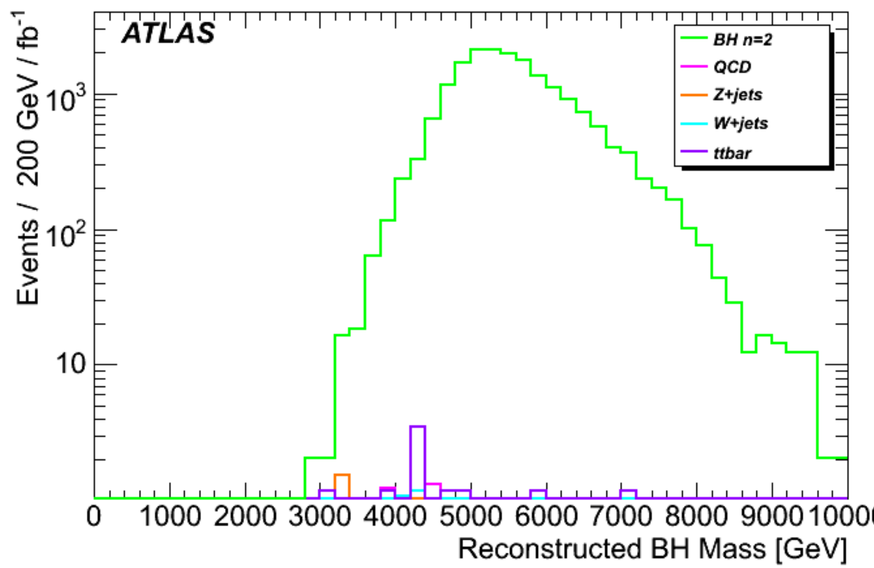
- Method is insensitive to some of the model uncertainties, such as the decay of the remnant, and the behaviour near the Planck threshold.

Background Rejection









Theoretical Parameters

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

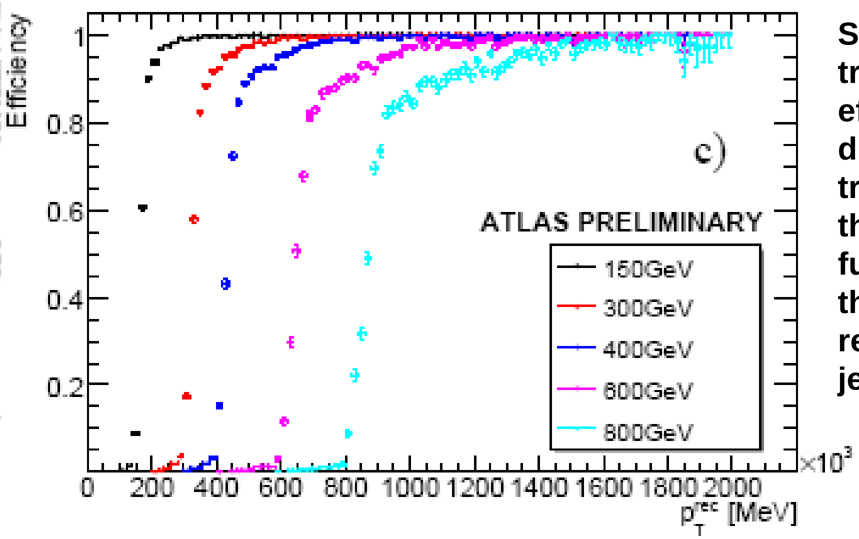
Theoretically uncertain parameter	Description	Canonical Value	Alternate Value
Use a kinematic cut-off on the decay	If an unphysical, kinematically-disallowed decay energy is selected: True: End BH decay and do remnant decay into N-bodies False: Continue to emit particles until $M_{BH} = M_{PL}$, then 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

Triggers

Single Jet Trigger

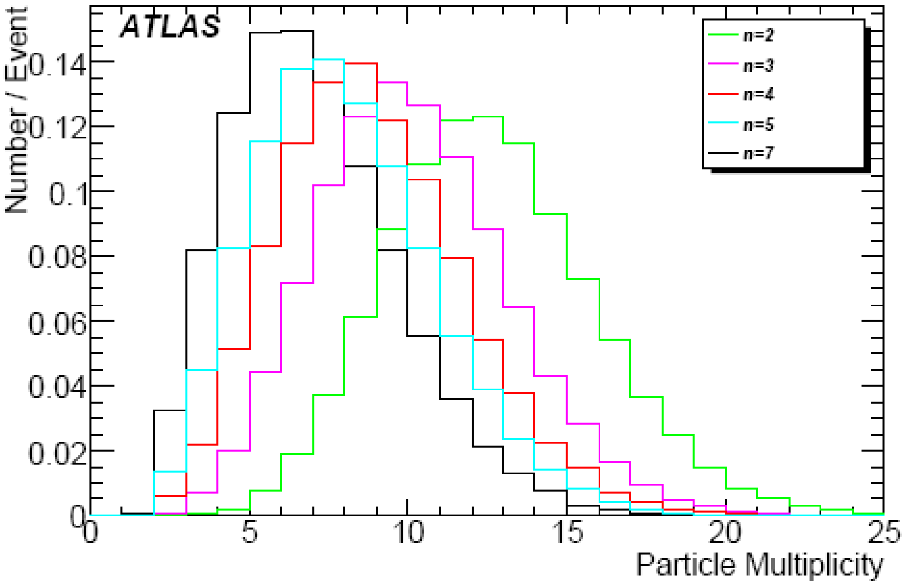
	n=8, BH_Min = 5TeV			n=11, BH_Min = 5TeV		
Thresh	L1	L2	EF	L1	L2	EF
150GeV	100%	100%	100%	100%	99,9%	99,8%
200GeV	99,9%	99,9%	99,9%	100%	99,9%	99,8%
250GeV	99,9%	99,9%	99,9%	99,7%	99,6%	99,5%
300GeV	99,8%	99,8%	99,8%	99,5%	99,5%	99,4%
400GeV	99,7%	99,7%	99,6%	99,0%	98,7%	98,5%
600GeV	98,6%	98,0%	97,7%	97,8%	97,5%	97,3%
800GeV	97,3%	93,1%	91,3%	96,9%	94,4%	93,5%

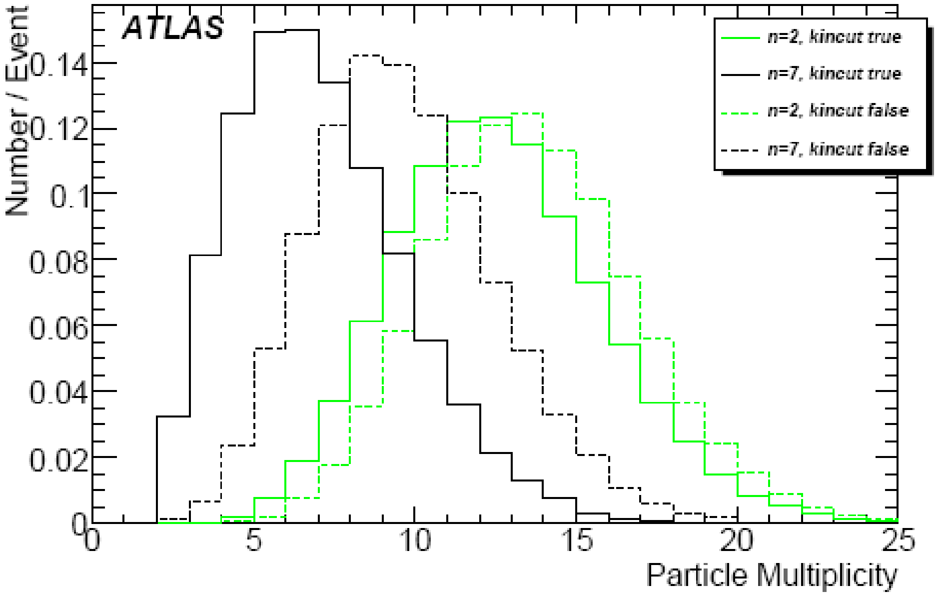
- The highest single jet threshold trigger gives an excellent efficiency for all signal samples, and should be robust against all types of black holes.
- Important that it is unprescaled.



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

Theoretical Parameters (II)

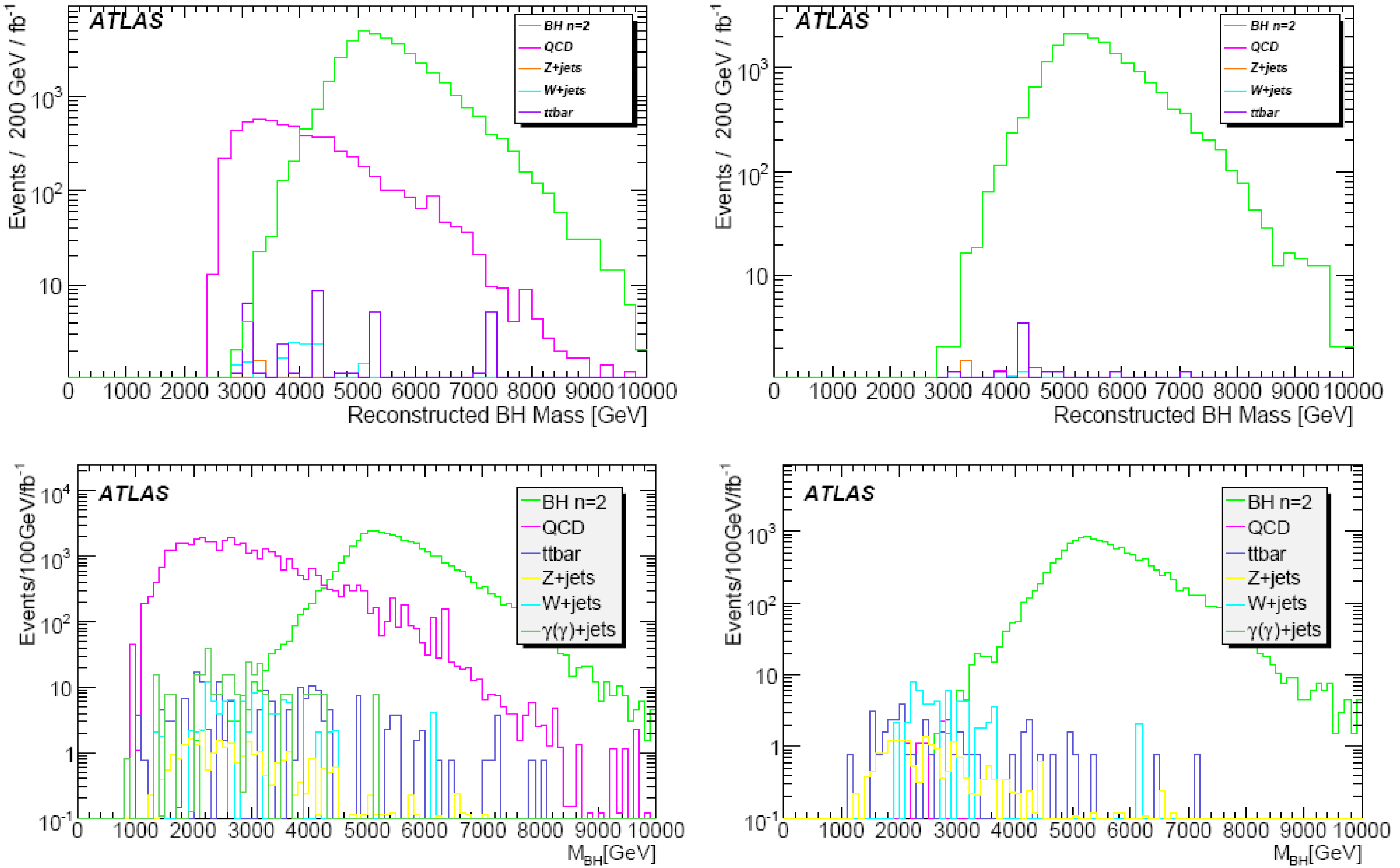




n	Full Sim	Fast Sim	Kin. Cut off	T_H-variation off	4-body remnant
2	45.8	42.9	47.2	48.7	47.9
3	-	33.2	-	-	-
4	27.4	26.6	-	-	-
5	-	21.7	-	-	-
7	16.1	15.9	29.2	16.6	27.4

Signal acceptance (%) for different model assumptions.

Two Methods


ATLAS
BH n=2
QCD
Z+jets
W+jets
ttbar
Events / 200 GeV / fb-1
Reconstructed BH Mass [GeV]
ATLAS
BH n=2
QCD
Z+jets
W+jets
ttbar
Events / 200 GeV / fb-1
Reconstructed BH Mass [GeV]
ATLAS
BH n=2
QCD
ttbar
Z+jets
W+jets
γ(γ)+jets
Events/100GeV/fb-1
MBH[GeV]
ATLAS
BH n=2
QCD
ttbar
Z+jets
W+jets
γ(γ)+jets
Events/100GeV/fb-1
MBH[GeV]