The discovery reach for mini-black holes with the ATLAS Detector at the LHC

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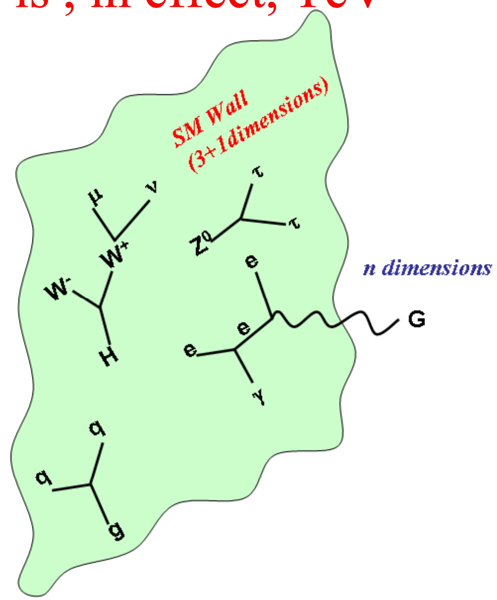
TeV-Scale Gravity

- Hierarchy problem, one of the big unsolved problems in 20 century
  - The large deviation between electroweak scale and the Planck scale: $M_{Pl}(10^{19}GeV) >> M_W(10^2GeV)$
- Extra dimensions
  - One of the solutions of the hierarchy problem
  - Only gravitational field is allowed to expand into the extra dimensions
  - "The Fundamental" d-dimensional Planck scale, M_D is , in effect, TeV scale
- Some approach:
  - Additional large flat dimensions
    - Arkani-Hamed, Dimopoulos and Dvali (ADD)
  - A single warped extra dimension
    - Randall and Sundrum (RS)



Black Hole

- Production
  - If the particles(with center of mass energy = $\hat{s}$) collide with the impact parameter b which is smaller than 2 times Schwarschild radius, $r_h \sim \hat{s}/M_D^2$, Black Hole will be formed
    - If M_D~TeV, LHC can generate TeV-scale mini-black hole!

- Decay
  - Such a mini-black hole decays in $\sim 10^{-26}$s
  - There are 4 decay phase
    - The balding phase: Loose the “hair” (multipole moment)
    - Spin-down phase: Loose angular momentum by emitting high-spin state particles
    - Schwarzschild phase: Hawking evaporation
    - Planck phase: M_{BH}~M_D, need quantum gravity, difficult to calculate

The smaller M_{BH} becomes,
The higher Hawking Temperature becomes

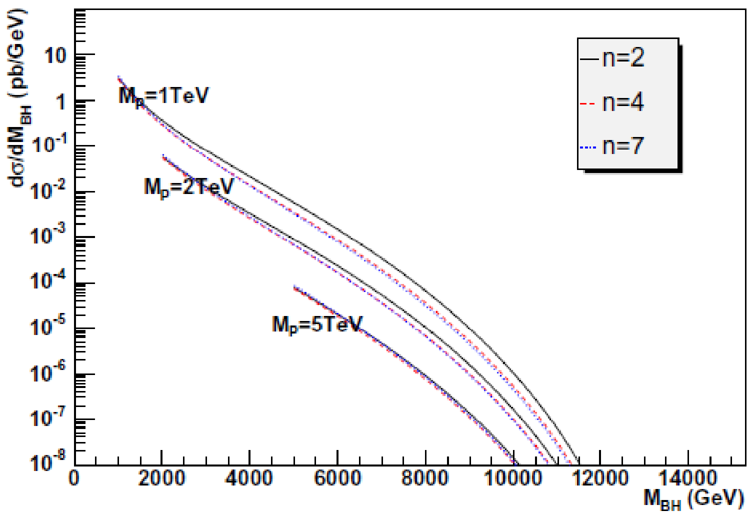
$$T_H = M_D \left[\frac{M_D}{M_{BH}} \left(\frac{n+2}{8\Gamma((n+3)/2)} \right) \right]^{\frac{2}{1+n}}$$

Working Model

- Black Hole Event Generator: CHARYBDIS:
  - Based on ADD model
  - Parton level xsec is calculated with assumption of semi-classical model (valid only when $M_{BH} >> M_D$)

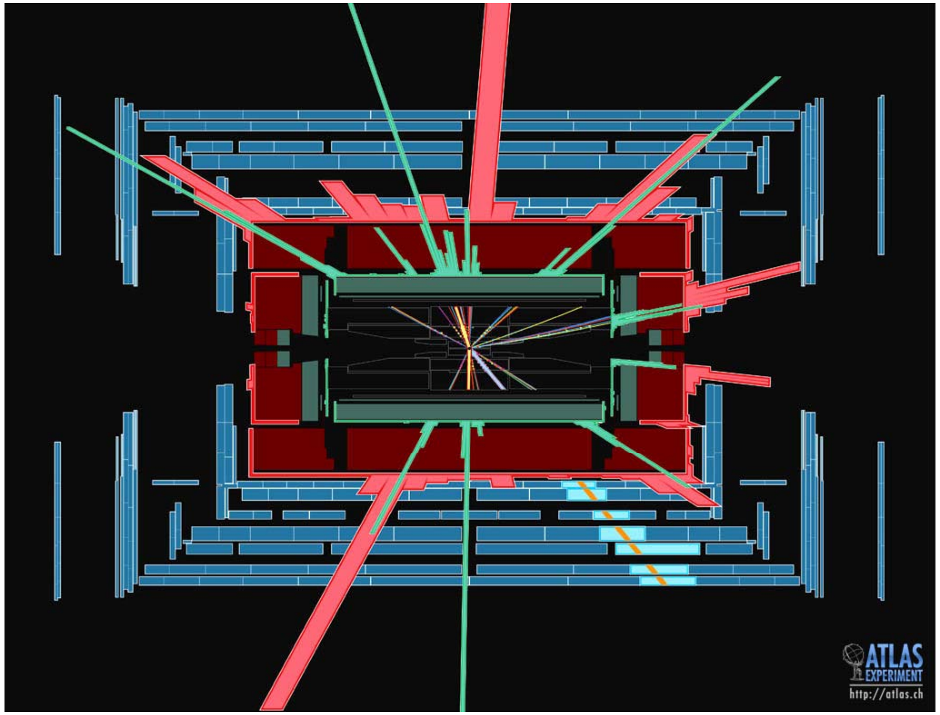
$$\hat{\sigma}_{ab\to BH} = \pi r_h^2 \quad r_h = \frac{1}{\sqrt{\pi} M_D}\left[\frac{M_{BH}}{M_D}\left(\frac{8\Gamma((n+3)/2)}{n+2}\right)\right]^{\frac{1}{1+n}}$$

  - Ignore balding and spin-down phase
  - No graviton emission
  - Available grey-body factor
  - Just a N-body decay at Plank Phase
  - Main input parameters:
    - The Fundamental Plank Scale: M_D
    - Number of extra dimensions: n
    - Minimum BH Mass to be produced ($M_{BH} >> M_D$)



Cross section of Black Hole in 14TeV pp collision

Black Hole Event



ATLAS Event display: Simulation of Black Hole event

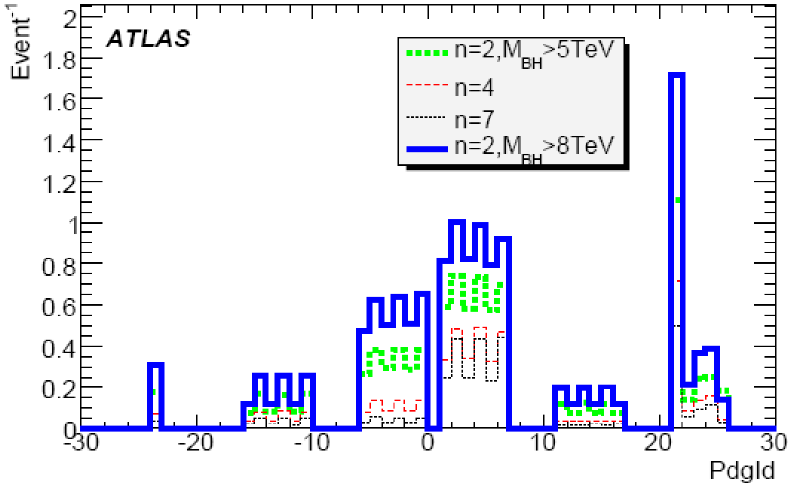
- Large cross section (~1event/s for TeV BH)
- Very crowded events
- High energy particles
- Most of events have leptons
- Easy to trigger

a) CHARYBDIS: $n = 2, m > 5$ TeV

Trigger	L1	L2	EF
j100	1	1	1
j400	0.997	0.997	0.997
3j100	0.998	0.998	0.998
3j250	0.972	0.971	0.971
4j100	0.985	0.985	0.985
4j250	0.865	0.862	0.862

Efficiency for jet trigger

Decay Particles from Black Hole



Pdg Id of emitted particles from BH

- Particles are emitted by Hawking radiation
- Emission probability depends on degree of freedom of quantum variables
- A break of perfect democratic decay comes from conservation of charge, color, etc.

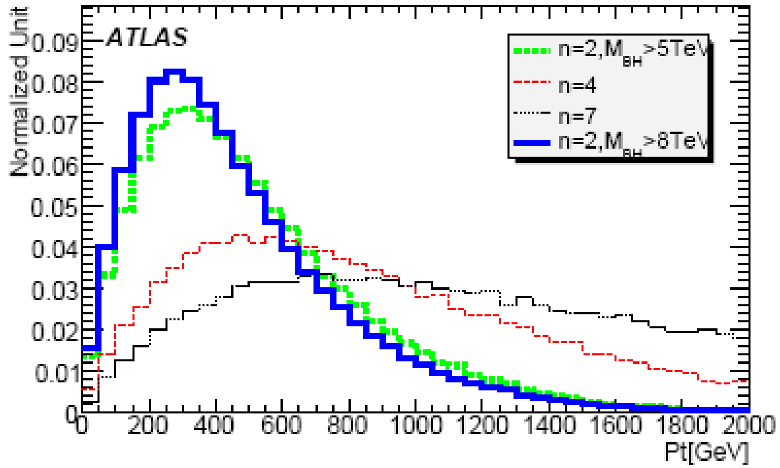
- Emit very high P_T particles
- Higher n shows higher P_T because Hawking temperature is higher

$$\frac{dN}{dE} \propto \frac{(E/T_H)^2}{\exp(E/T_H)+c}$$

Hawking Temperature

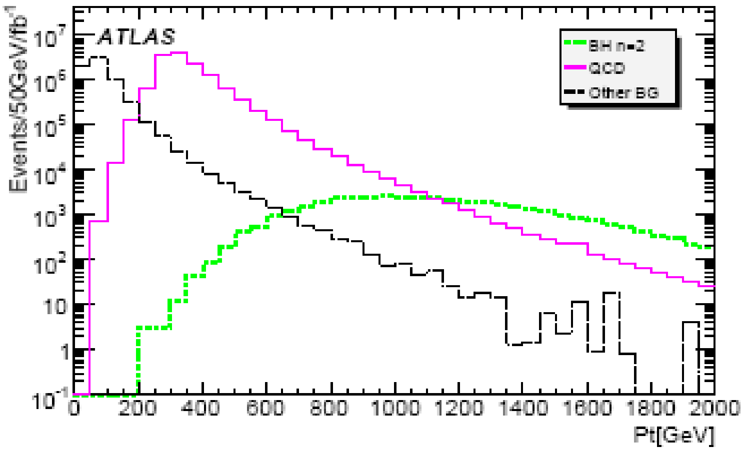
c =-1(1) for boson(fermion)

$$T_H = M_P\left[\frac{M_D}{M_{BH}}\left(\frac{n+2}{8\Gamma((n+3)/2)}\right)\right]^{\frac{2}{1+n}}$$

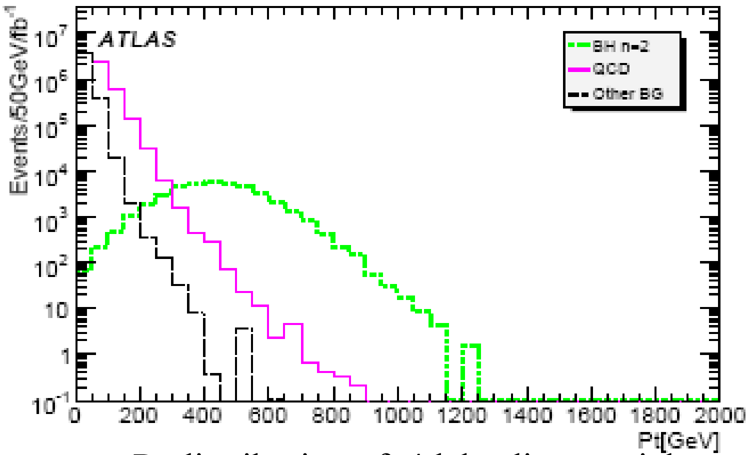


P_T distribution of particles from BH

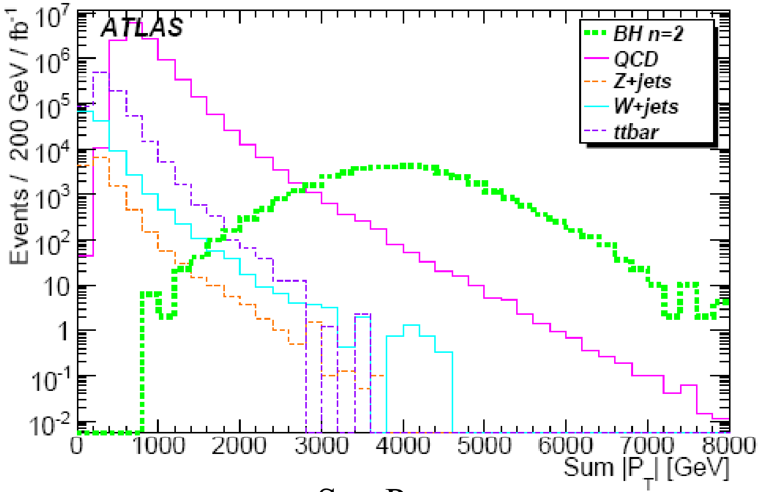
P_T of Particles observed in Events



P_T distribution of leading particle



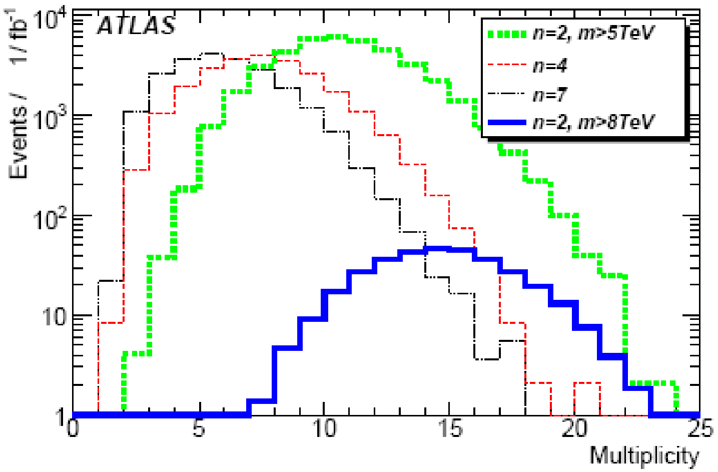
P_T distribution of 4th leading particle



$SumP_T$

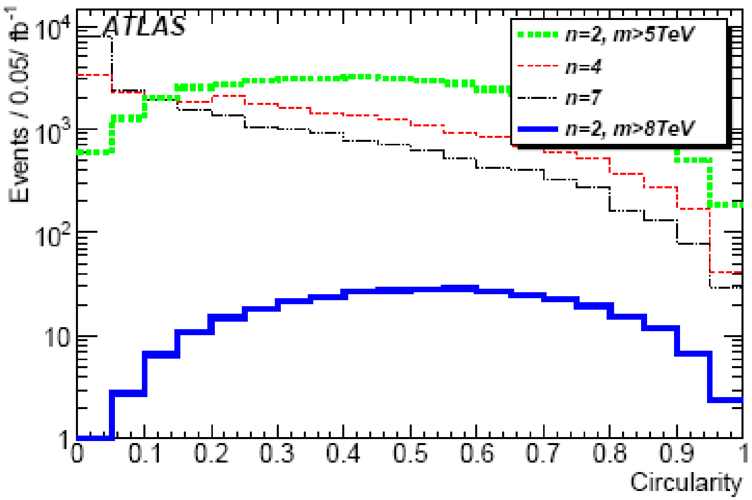
- Even 4th leading particle has very large P_T
- Sum P_T:
  - A scalar sum of P_T of all particles in the event

Multiplicity and Circularity

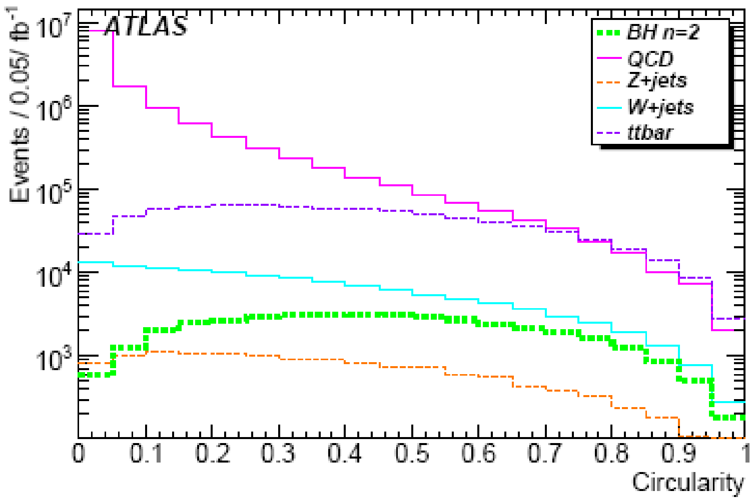


Particle Multiplicity of BH with different parameters

- Higher n shows lower multiplicity
  - Hawking temperature is higher
  - One particle carries larger energy
- Circularity, Sphericity or Thrust are also the candidates of event selections
  - But they strongly depend on multiplicity

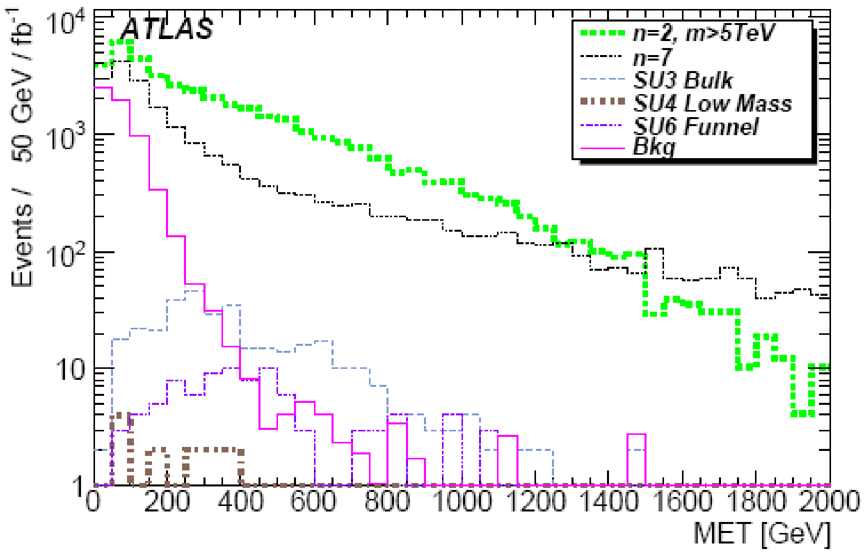


Circularity of Black Holes



Circularity, compared with backgrounds

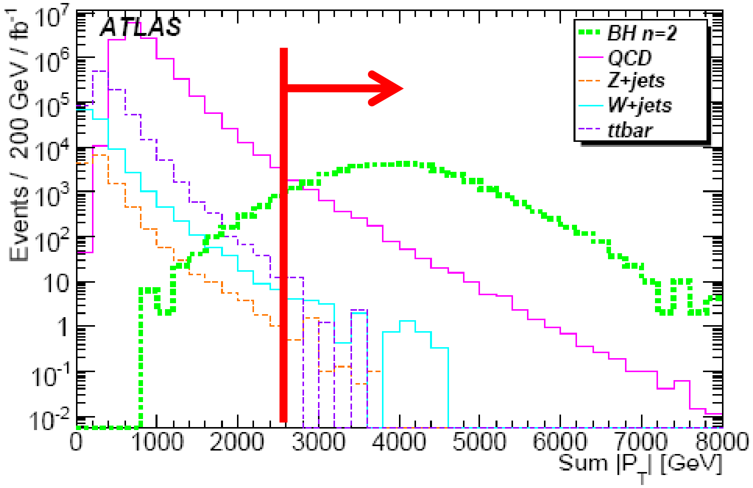
Missing E_T



Missing E_T (with event selection: SumP_T>2500GeV)

- Black Hole emits also high P_T neutrinos
  - Large missing E_T source
- Even compared to SUSY signal, BH has a long tail in high MET region
- Charybdis can not emit graviton and not emit into bulk
  - They may be also large missing E_T source
  - New generator which can treat such features are being investigating

Event Selection 1:Sum P_T



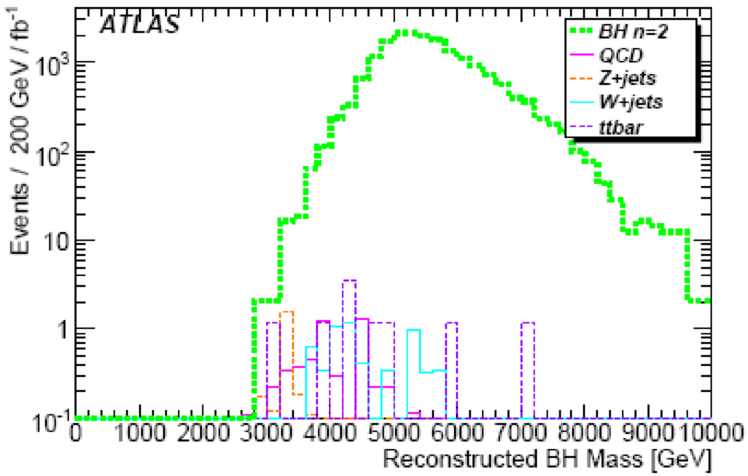
SumP$_T$

- Sum P_T selection
  - Sum P_T > 2.5TeV
  - Require at least 1 of the 50GeV lepton
- Not dependent on particle multiplicity
- Black Hole Mass is reconstructed from particles(only high P_T, >15GeV for e,μ,γ and >20GeV for jet) in the event
- Missing ET is also included as a particle of P_Z=0

Event Efficiency: Sum P_T selection

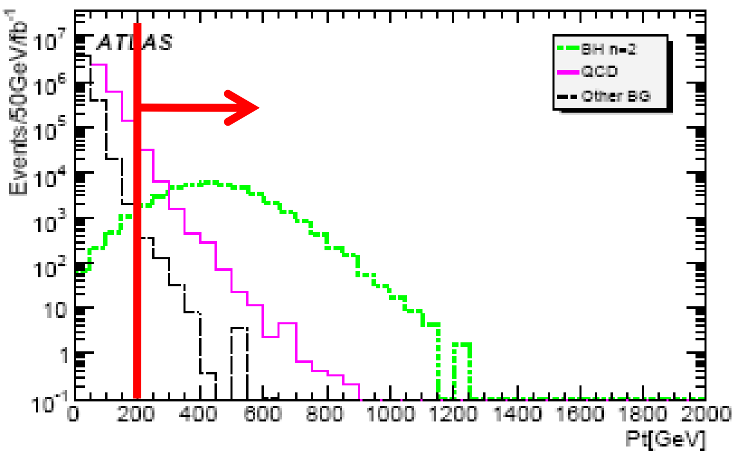
Dataset	Before selection (fb)	$\sum\|p_T\| > 2.5$ TeV (fb)	After requiring a lepton (fb)	acceptance
$n=2, m>5$ TeV	$40.7\pm0.1\times10^3$	$39.2\pm0.3\times10^3$	$18.6\pm0.2\times10^3$	0.46
$n=4, m>5$ TeV	$24.3\pm0.1\times10^3$	$22.6\pm0.2\times10^3$	6668 ± 83	0.27
$n=7, m>5$ TeV	$22.3\pm0.1\times10^3$	$20.1\pm0.2\times10^3$	3574 ± 60	0.17
$n=2, m>8$ TeV	338.2 ± 1	338.1 ± 2.5	212 ± 16	0.63
$t\bar{t}$	$833\pm100\times10^3$	$23.6^{+12.2}_{-6.7}$	$8.2^{+2.43}_{-2.43}$	9.8×10^{-6}
QCD dijets	$12.8\pm3.7\times10^6$	5899^{+1773}_{-1771}	$5.37^{+3.25}_{-2.02}$	4.3×10^{-7}
$W_{\ell\nu}+\geq2$ jets	$1.9\pm0.04\times10^6$	$12.3^{+9.0}_{-1.8}$	$4.67^{+8.75}_{-0.93}$	2.4×10^{-6}
$Z_{\ell\ell}+\geq3$ jets	$51.8\pm1\times10^3$	$2.75^{+2.02}_{-2.01}$	$2.57^{+0.95}_{-0.64}$	5.0×10^{-5}

Table 6: Acceptance for each signal and background dataset in fb after requiring $\sum|p_T|>2.5$ TeV, and a lepton with $p_T>50$ GeV.



Reconstructed Black Hole Mass

Event Selection 2: Multi Object



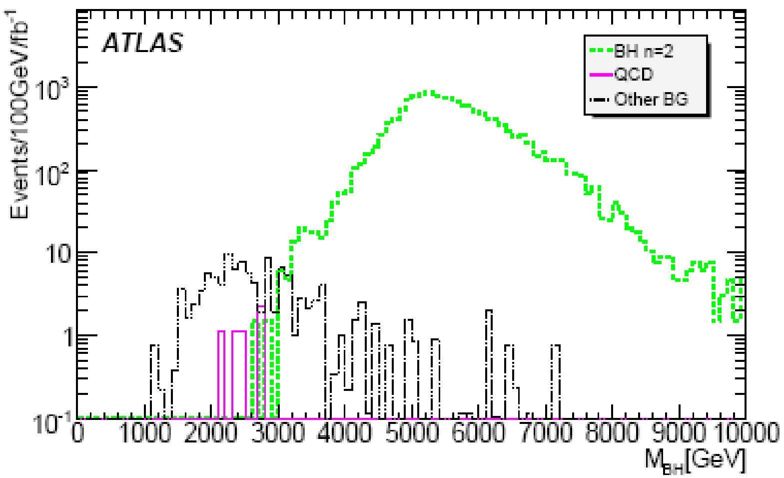
P_T distribution of 4th leading particle

- Multi Object selection
  - Require 4 Objects: P_T>200GeV
  - Including at least 1 lepton
- Assume high multiplicity
- Less efficiency for high n

Event Efficiency: Multi Object selection

Dataset	Before selection (fb)	After multi-object requirement (fb)	After lepton requirement (fb)	Acceptance
$n=2, m>5$ TeV	40.7×10^3	$38.9\pm0.4\times10^3$	$14.0\pm0.2\times10^3$	0.34
$n=4, m>5$ TeV	24.3×10^3	$17.9\pm0.3\times10^3$	4521 ± 126	0.19
$n=7, m>5$ TeV	22.3×10^3	9953 ± 185	1956 ± 82	0.087
$n=2, m>8$ TeV	338	338 ± 4	164 ± 3	0.49
$t\bar{t}$	833×10^3	129 ± 27	36^{+12}_{-9}	4.3×10^{-5}
QCD dijets	12.8×10^6	$38.9\pm1.9\times10^3$	6^{+107}_{-3}	5.6×10^{-7}
W+jets	560×10^3	99^{+28}_{-22}	56^{+24}_{-13}	1×10^{-3}
Z+jets	51.8×10^3	29^{+90}_{-4}	19^{+90}_{-3}	4×10^{-4}
$\gamma(\gamma)$+jets	5.1×10^6	285^{+87}_{-76}	0^{+40}_{-0}	$<10^{-5}$

Table 7: Acceptance of the 4-object requirements for each dataset in fb. 90% confidence limits are used when no events passed the requirements.

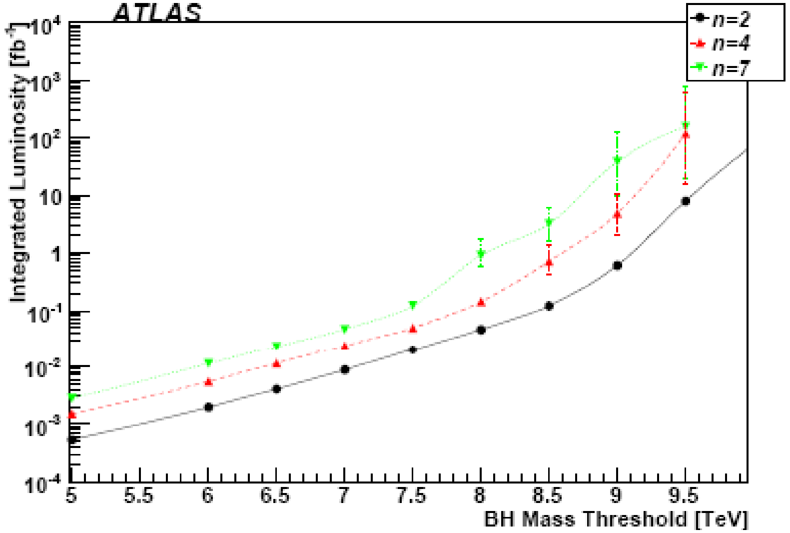


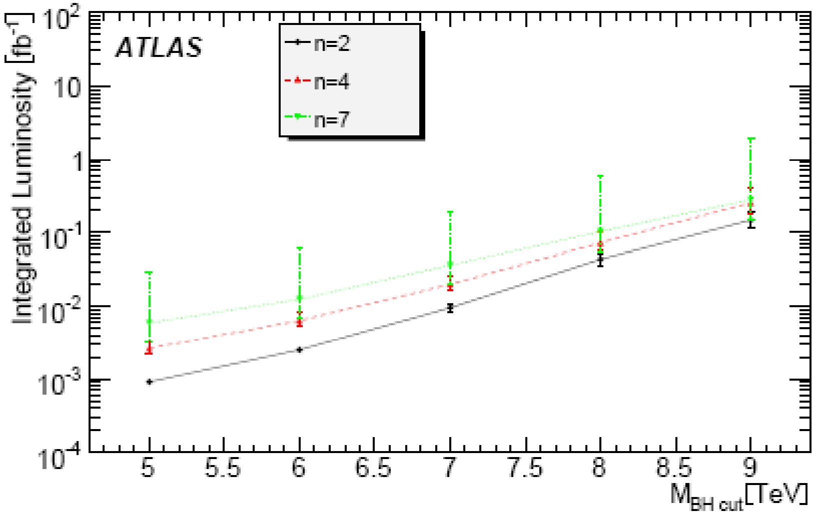
Reconstructed Black Hole Mass

Discovery Potential for M_P=1TeV Black Hole

Discovery Potential:

- Integrated Luminosity for S/√B > 5 && S>10



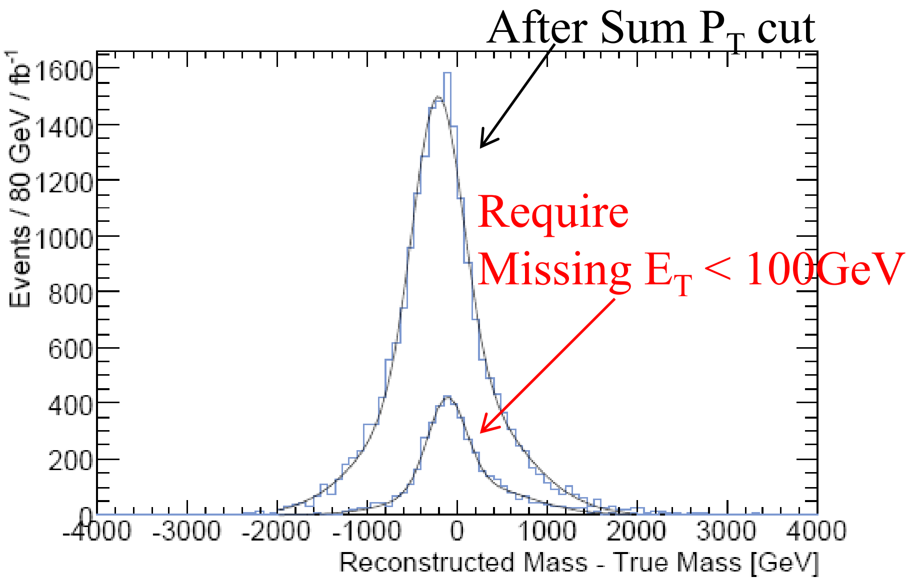


- Discovery Potential with $SumP_T$ selection
- Horizontal axis shows production threshold of M_{BH}

- Discovery Potential with Multi Object Selection
- Horizontal axis shows additional cut on reconstructed M_{BH}

- There is large uncertainty when M_{BH} is close to M_P
  - Our assumption (semi-classical calculation) is not reliable
- We set minimum M_{BH} at 5TeV, and above two methods have been studied for calculation discovery potential
- Only a few pb^{-1} is needed for 5TeV discovery

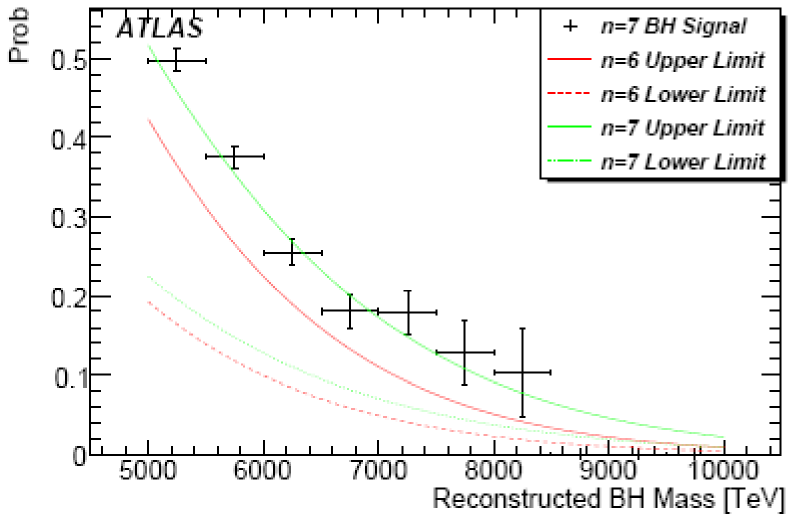
Mass Reconstruction

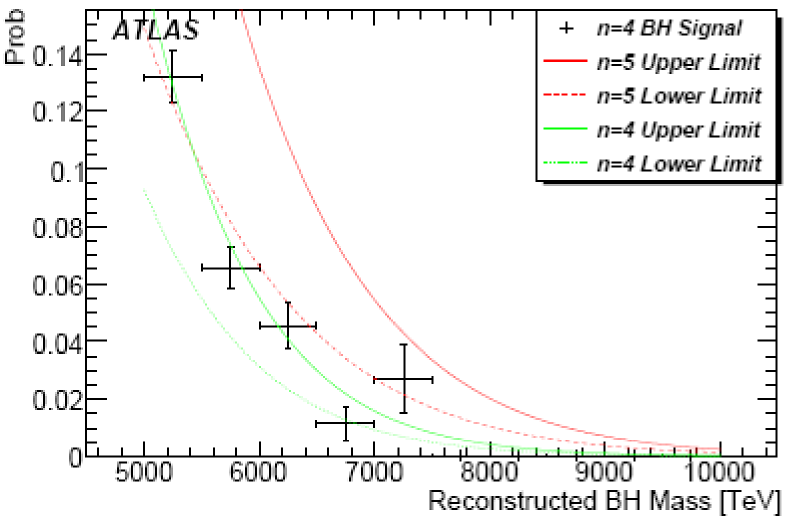


- Mass information is important for more study: cross section, Planck Scale and number of extra dimensions
- A part of mass information is missed as a momentum of an undetected particle
  - A requirement of small missing E_T can improve the center value and also the resolution

		Normalisation	Mean (GeV)	Resolution (GeV)
Without $\not{E}_T$ requirement	Narrow	1018 ± 26	-217 ± 5	276 ± 9
	Wide	276 ± 30	-148 ± 9	722 ± 13
With $\not{E}_T$ requirement	Narrow	318 ± 12	-116 ± 8	215 ± 9
	Wide	108 ± 7	118 ± 18	635 ± 16

Measurement of Features of TeV-Scale Gravity





- A attempt to estimate the features using energy spectrum of Hawking radiation had been studied
  - But non-Hawking radiation effects(such a grey-body factor) and detector effects make it difficult
- One of the possibility is extract from xsec
  - Xsec strongly depends on M_P
  - n dependence is not so strong
- Left figures show one of the other methods
  - Using emission probability of high energy particles ($E \sim M_{BH}/2$)
  - Such particles should be generated at fist of BH decay
  - Then, they should be radiated by Hawking radiation with generated M_{BH}

Summary

- Black hole production is one of the helpful signal for TeV scale gravity
  - Which can solve one of the big homework in 20century
- LHC is the first experiment which can produce TeV energy objects directly
  - LHC has a potential of generating mini(TeV scale)-black holes
- The ATLAS experiment has an enough potential for detection of black holes
  - Most of events passed trigger, separation from backgrounds is easy
  - Only a few pb^{-1} is needed for 5TeV discovery
    - Black Hole may be discovered in a few days
  - With $100pb^{-1}$, the discovery potential reaches to 8TeV black holes
- Some methods to estimate the parameters of TeV-scale gravity have been studied
- There are uncertainties which are inherent in the model especially around $M_{BH} \sim M_D$
  - But if the semi-classical estimation is valid even only in $M_{BH} >> M_D$, we will see the mini-black holes in an early stage of the ATLAS experiment