Black Holes at Accelerators

Bryan Webber, SSI05

- Black hole production
- Measuring the Planck scale
- Black hole decay

- Event simulation & model uncertainties
- Measuring black hole mass
- Determining the number of extra dimensions

Black hole production

- Parton-level cross section:

$$\hat{\sigma}(\hat{s} = M_{BH}^2) = F_n \pi r_S^2$$

- $r_S =$ Schwarzschild radius in 4+n dimensions:

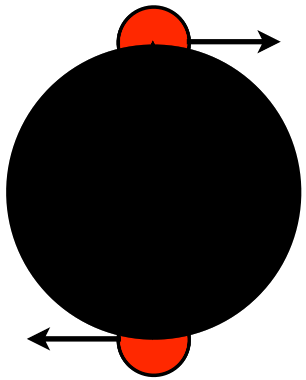
$$r_S = \frac{1}{\sqrt{\pi} M_{PL}} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right) M_{BH}}{(n+2) M_{PL}} \right]^{\frac{1}{n+1}}$$

- $F_n =$ form factor of order unity (hoop conjecture)

- Usually set Planck scale M_{PL} = 1 TeV in this study

  (Dimopoulos-Landsberg $M_{PL} \equiv [G_{(4+n)}]^{-(n+2)}$)

BH formation factor (I)



$$b_{max} = 2r_h = 2r_s \left[1 + a_*^2\right]^{-\frac{1}{n+1}}$$

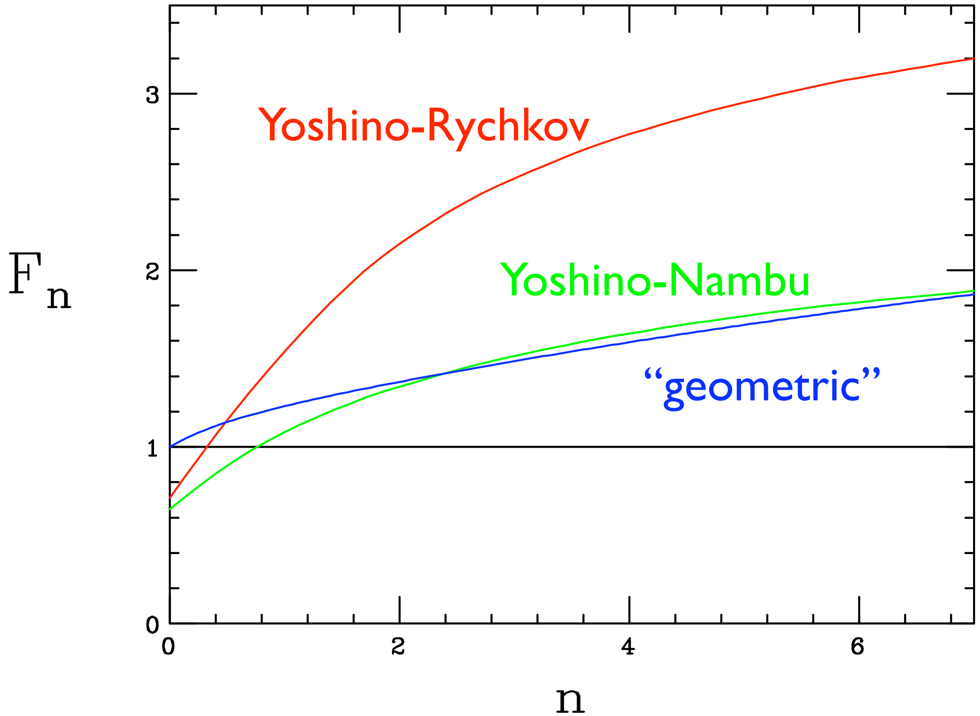
$$a_* = \frac{(n+2)J}{2r_h M_{BH}} \;, \quad J \simeq b M_{BH}/2$$

$$\hat{\sigma} = F_n \pi r_S^2 \simeq \pi b_{max}^2$$

$$\Rightarrow \quad F_n \simeq 4\left[1 + \left(\frac{n+2}{2}\right)^2\right]^{-\frac{2}{n+1}}$$

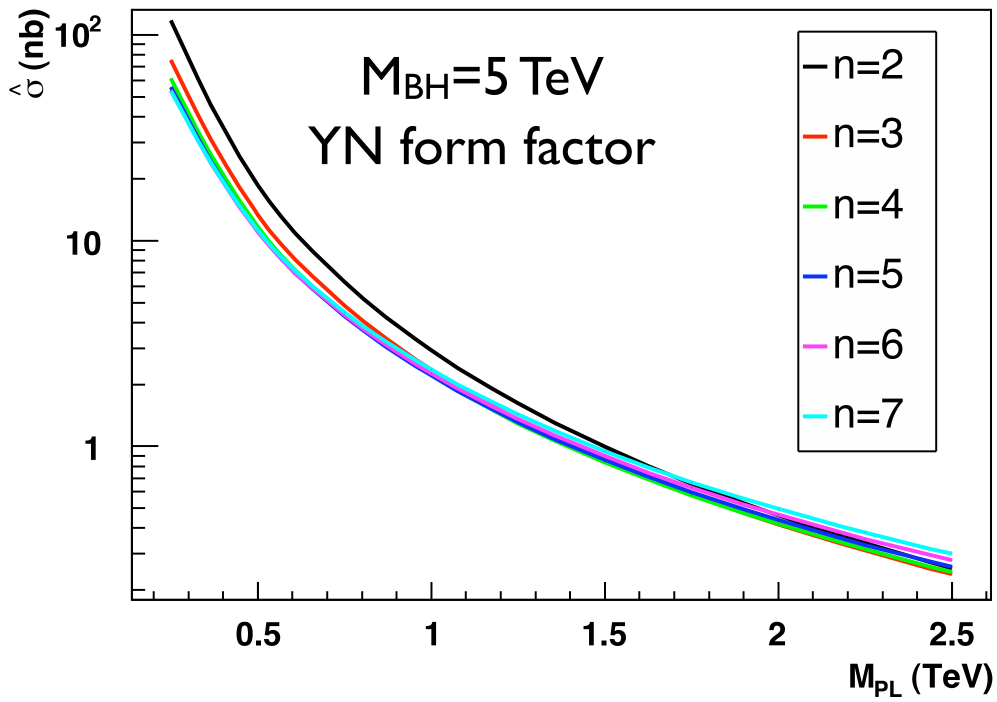
("geometric")

BH formation factor (2)



- H Yoshino & Y Nambu, gr-qc/0209003
- H Yoshino & VS Rychkov, hep-th/0503171

BH cross section vs Planck mass



- Little sensitivity to n
- Measuring σ and M_{BH} gives M_{PL}

BH cross sections at LHC

Topology		Total Cross Section (fb)
5 TeV black hole	$n = 2$	$62,000$
	$n = 4$	$37,000$
	$n = 6$	$34,000$
8 TeV black hole	$n = 2$	580
	$n = 4$	310
	$n = 6$	270
10 TeV black hole	$n = 2$	6.7
	$n = 4$	3.4
	$n = 6$	2.9

➡ Several 5 TeV BH per minute at LHC!

Black hole decay (1)

- Balding phase
  - ➜ loses `hair’ and multipole moments, mainly by gravitational radiation
- Spin-down phase
  - ➜ loses angular momentum, mainly by Hawking radiation
- Schwarzschild phase
  - ➜ loses mass by Hawking radiation, temperature increases
- Planck phase
  - ➜ mass and/or temperature reach Planck scale: remnant = ??

Black hole decay (2)

- We assume Schwarzschild phase is dominant
  - all types of SM particles emitted with Hawking spectrum

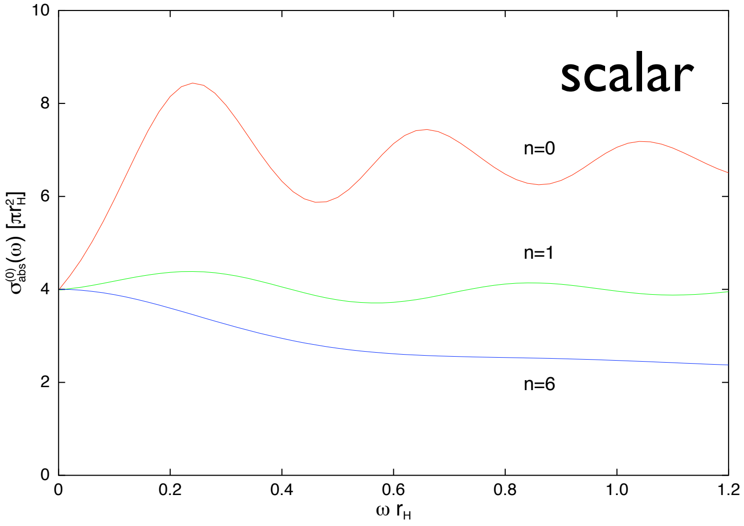
$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \mp 1) T_H^{n+6}}$$

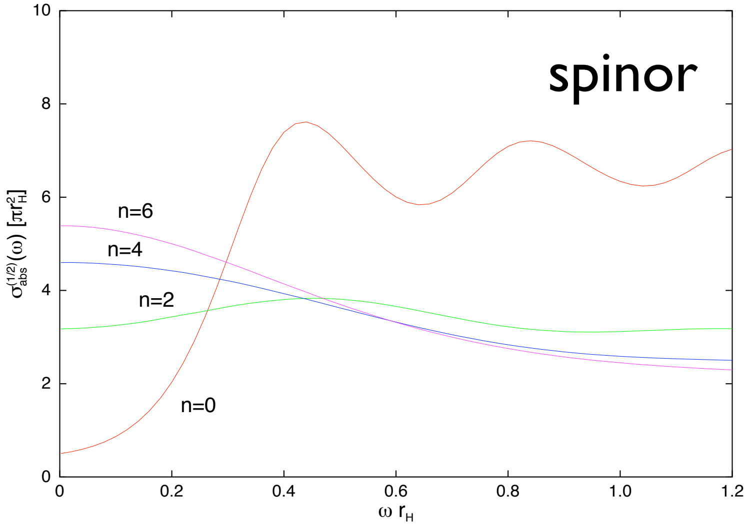
  - Hawking temperature

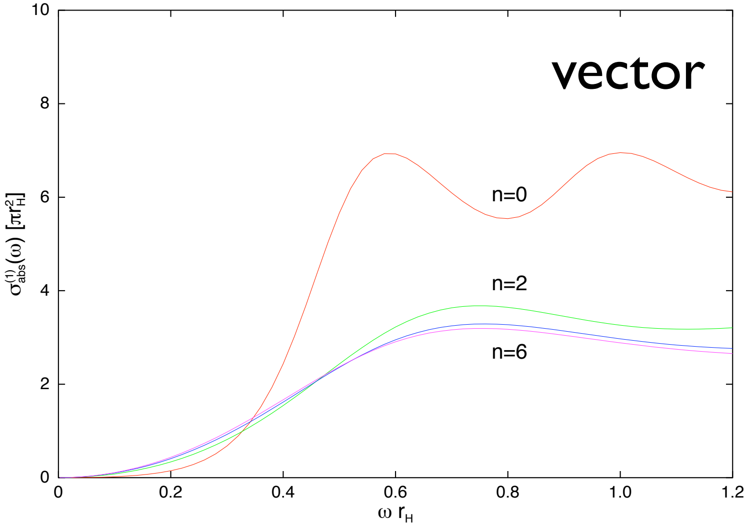
$$T_H = \frac{n+1}{4\pi r_{BH}} \propto (M_{BH})^{-\frac{1}{n+1}}$$

  - γ is (4+n)-dimensional grey-body factor

Grey-body factors







- Emission on brane only
- Low-energy vector suppression
- CM Harris, hep-ph/0502005

Integrated Hawking flux

n	$r_h F^{(0)}$	$r_h F^{(1/2)}$	$r_h F^{(1)}$	$r_h F^{tot}$
0	0.00133	0.000486	0.000148	0.0526
1	0.00631	0.00439	0.00283	0.489
2	0.0173	0.0134	0.0119	1.56
3	0.0364	0.0283	0.0301	3.41
4	0.0655	0.0499	0.0596	6.18
5	0.106	0.0789	0.102	9.98
6	0.160	0.116	0.159	14.9
7	0.229	0.163	0.231	21.1

N.B. $r_h F^{tot} \gg 1$ at large n

➡ Transit time $\gg$ time between emissions

➡ Decay no longer quasi-stationary at large n

Black hole lifetime

	τM_{BH}	
n	$M_{\mathrm{BH}} = 5M_{\mathrm{PL}}$	$M_{\mathrm{BH}} = 10M_{\mathrm{PL}}$
0	47500	761000
1	202	1610
2	23.3	148
3	6.60	37.4
4	2.77	14.6
5	1.43	7.23
6	0.846	4.12
7	0.544	2.59

$$\left(M_{\mathrm{BH}} = 5\ \mathrm{TeV} \Rightarrow M_{\mathrm{BH}}^{-1} \sim 10^{-28}\ \mathrm{s}\right)$$

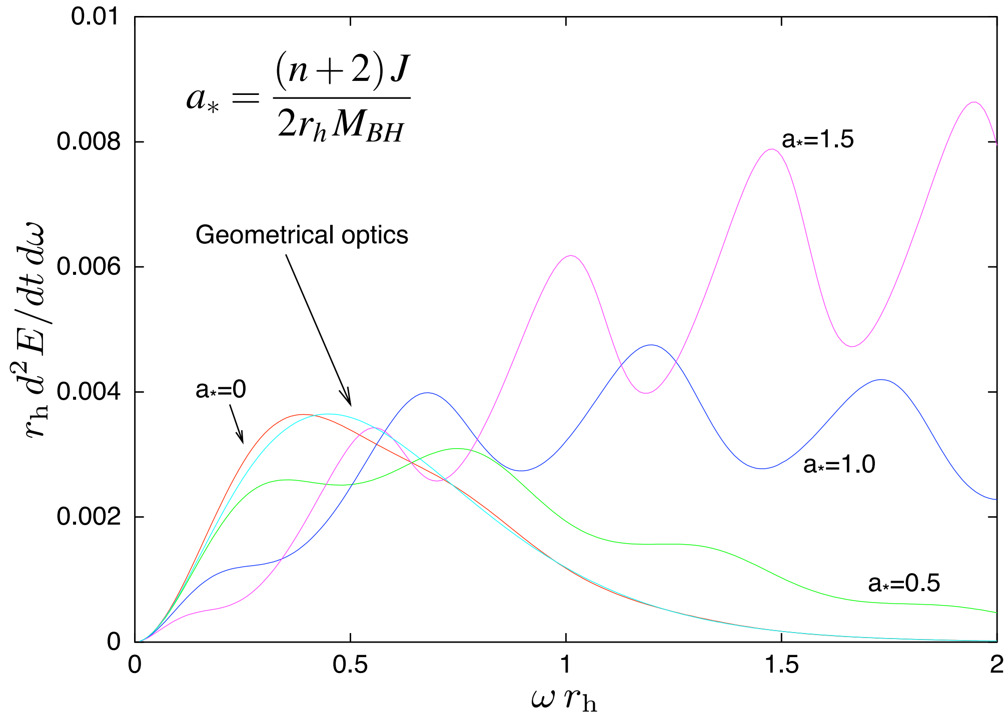
N.B. $\tau M_{\mathrm{BH}} \sim 1$ at large n

➡ Black hole no longer well-defined?

Spin-down phase

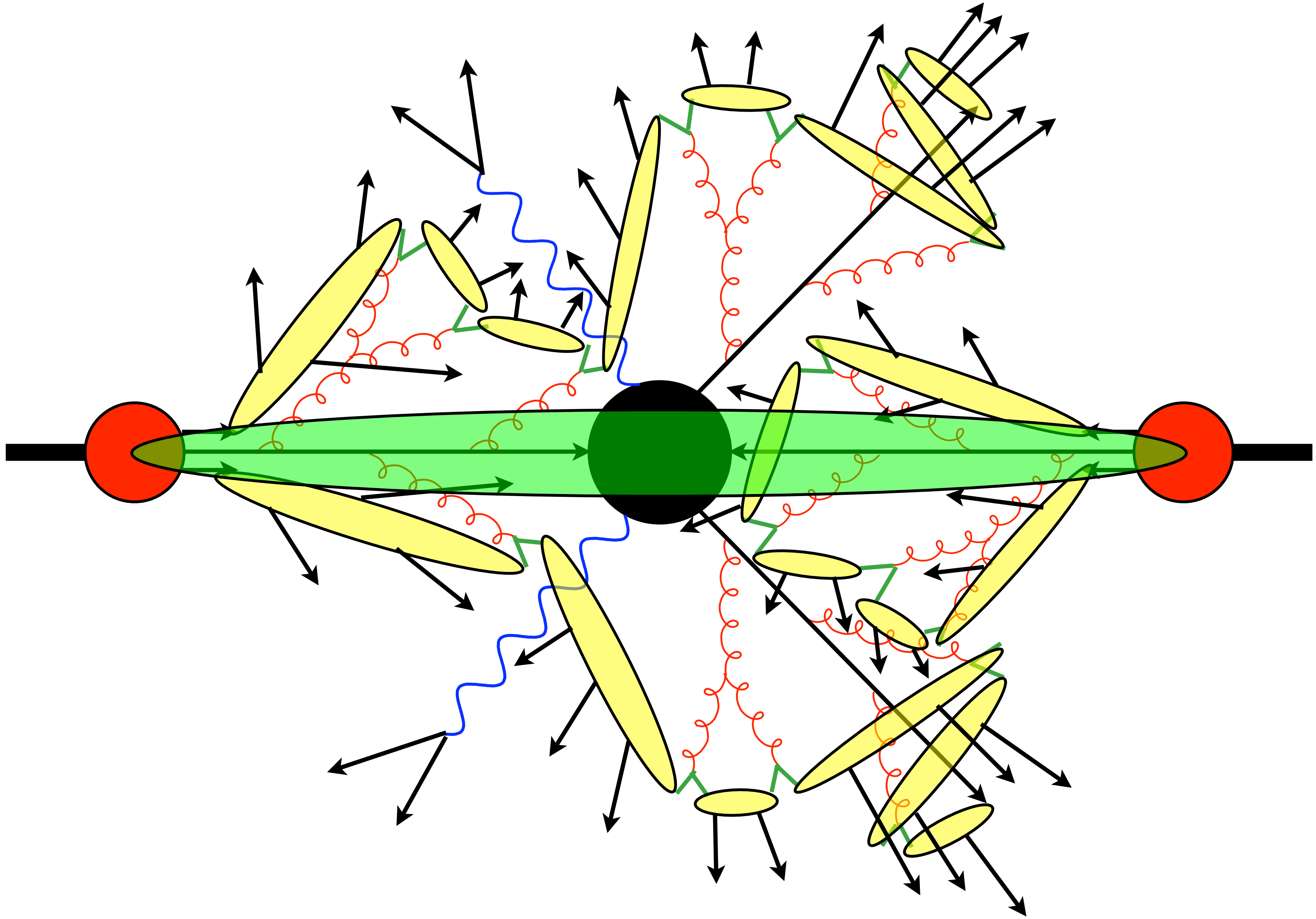
- Few results available for spinning BH

Power spectrum for scalar emission on brane (n=1)



➜ CM Harris & P Kanti, hep-th/0503010

LHC Event Simulation



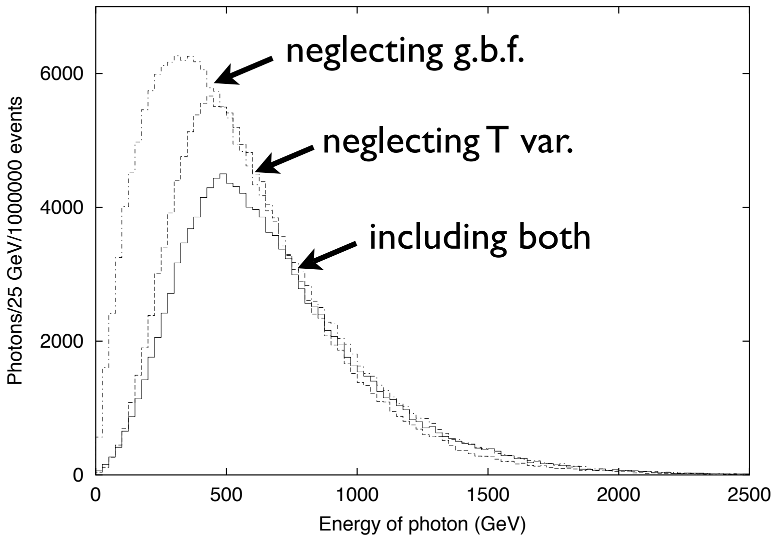
HERWIG Event Generator

- Most important SM & MSSM processes at LO
  - ➡ spin correlations included
  - ➡ parton showers at leading log (LL)
  - ➡ no showering from SUSY particles
- MC@NLO provides some SM processes at NLO
  - ➡ see S Frixione & BW, hep-ph/0506182 & refs therein
- Interface to CHARYBDIS black hole generator

Main CHARYBDIS parameters

Name	Description	Values	Default
TOTDIM	Total dimension (n+4)	6-11	6
GTSCA	Use scale ($1/r_S$) not M_{BH}	logical	.FALSE.
TIMVAR	Use time-dependent T_H	logical	.TRUE.
MSSDEC	Include t,W,Z(2), h(3) decay	1-3	3
GRYBDY	Include grey-body factors	logical	.TRUE.
KINCUT	Use kinematic cutoff	logical	.FALSE.
NBODY	Multiplicity from remnant	2-5	2

Effects of grey-body factors



	Particle emissivity (%)			
	GRYBDY=.TRUE.		GRYBDY=.FALSE.	
Particle type	Generator	Theory	Generator	Theory
Quarks	63.9	61.8	58.2	56.5
Gluons	11.7	12.2	16.9	16.8
Charged leptons	9.4	10.3	8.4	9.4
Neutrinos	5.1	5.2	4.6	4.7
Photon	1.5	1.5	2.1	2.1
Z^0	2.6	2.6	3.1	3.1
W^+ and W^-	4.7	5.3	5.7	6.3
Higgs boson	1.1	1.1	1.0	1.1

- Vector boson suppression 20-30%
- Generator-theory differences due to masses & charge conservation

Exploring Higher Dimensional Black Holes at the Large Hadron Collider

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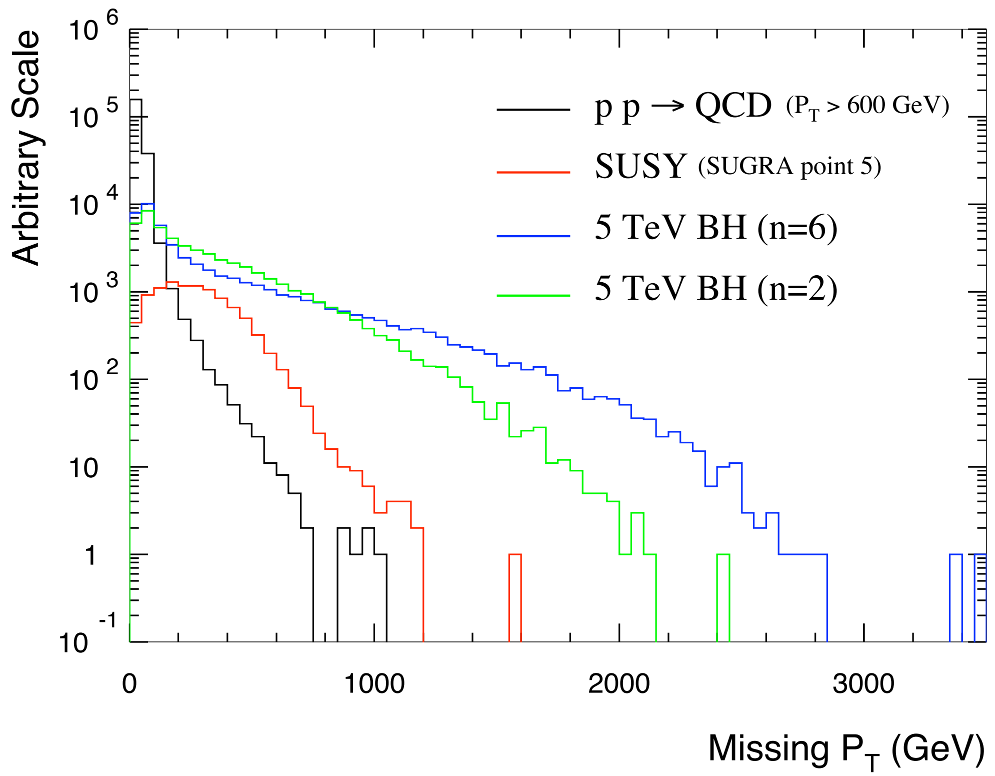
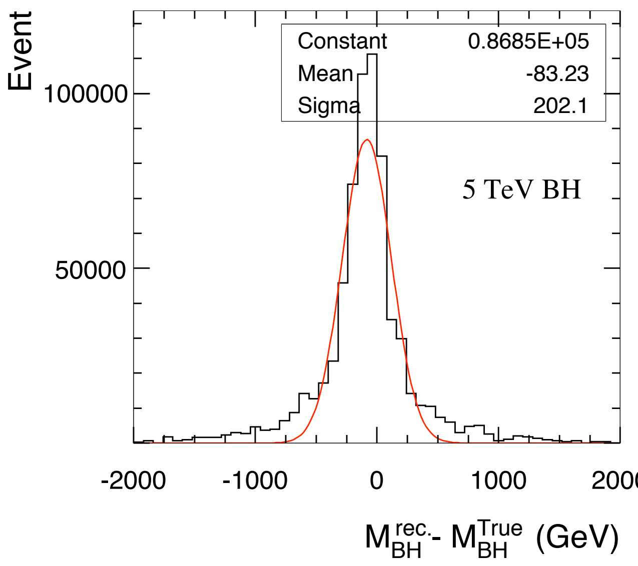
- hep-ph/0411022, JHEP05(2005)053; see also CM Harris, PhD thesis, hep-ph/0502005; CM Harris et al (CHARYBDIS event generator) hep-ph/0307035, JHEP08(2003)033
- earlier work: SB Giddings & S Thomas, hep-ph/0106219; S Dimopoulos & G Landsberg, hep-ph/0106295

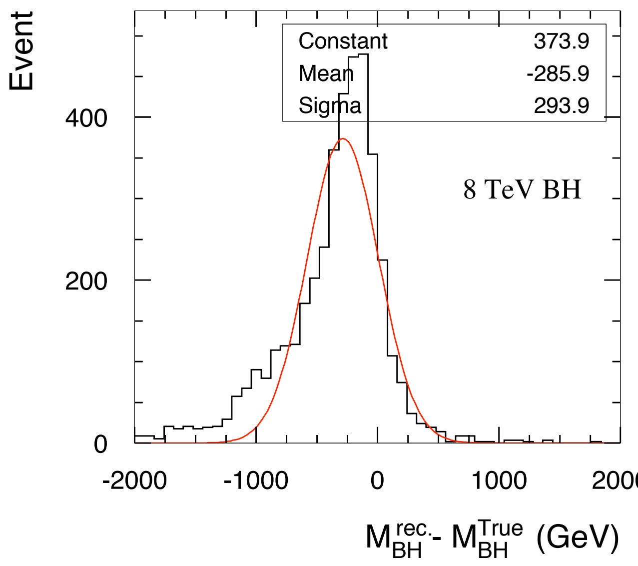
Missing transverse energy



➡ Typically larger $\not{E}_T$ than SM or even MSSM

Measuring black hole masses

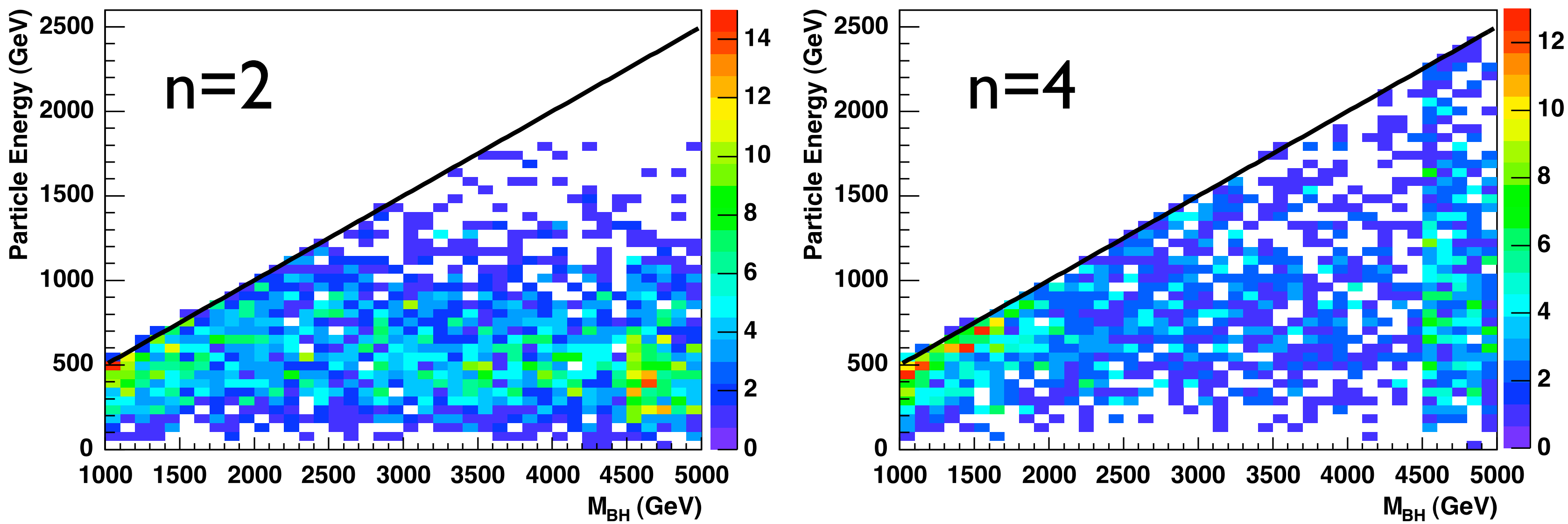




Need $\not\!\!E_T < 100$ GeV for adequate resolution

➡ $\Delta M_{BH} / M_{BH} \sim 4\%$

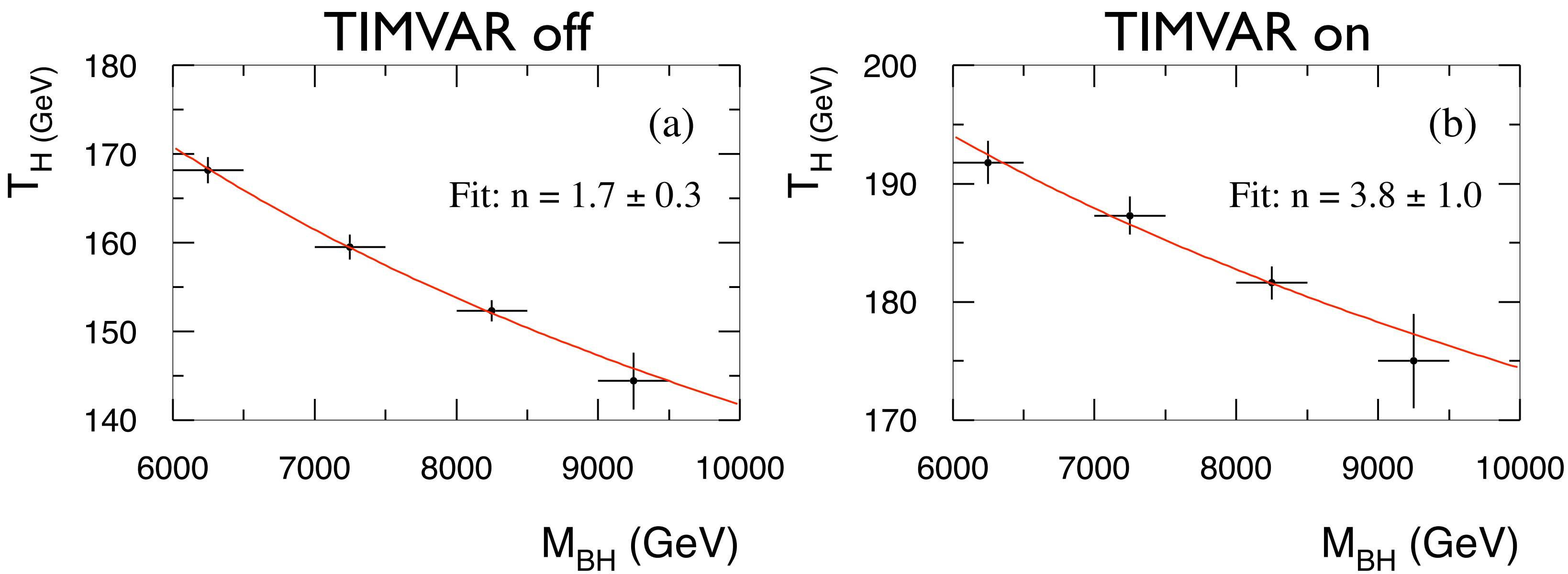
Effect of energy cutoff $E < M_{BH}/2$



Energy distribution of primary emissions vs M_{BH}

➡ Cutoff affects spectrum at low mass and/or high n

Effects of time dependence

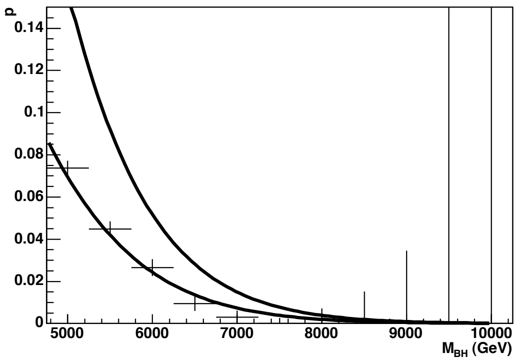


Fits to primary electron spectrum for n=2

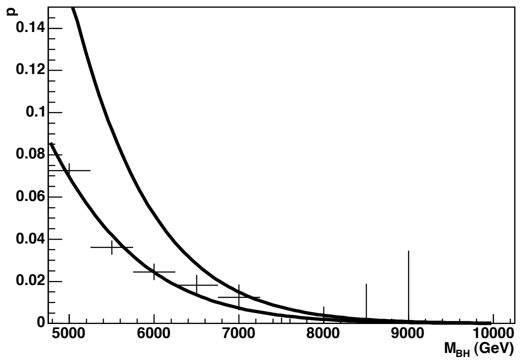
➡ Neglecting time variation of T_H leads to over-estimate of n

A possible observable sensitive to n

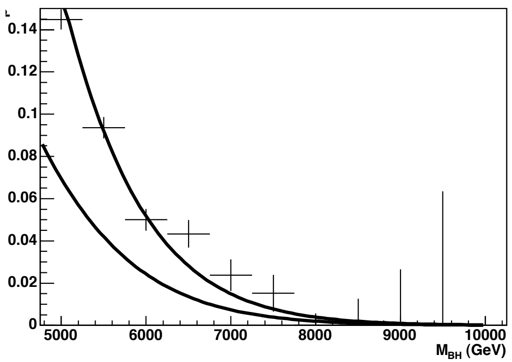
$$P(E_{max} > M_{BH}/2 - 400\ \mathrm{GeV})$$



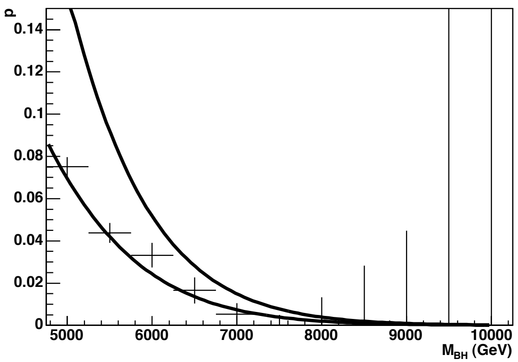
(a) Test case (see section 3)



(b) No time variation



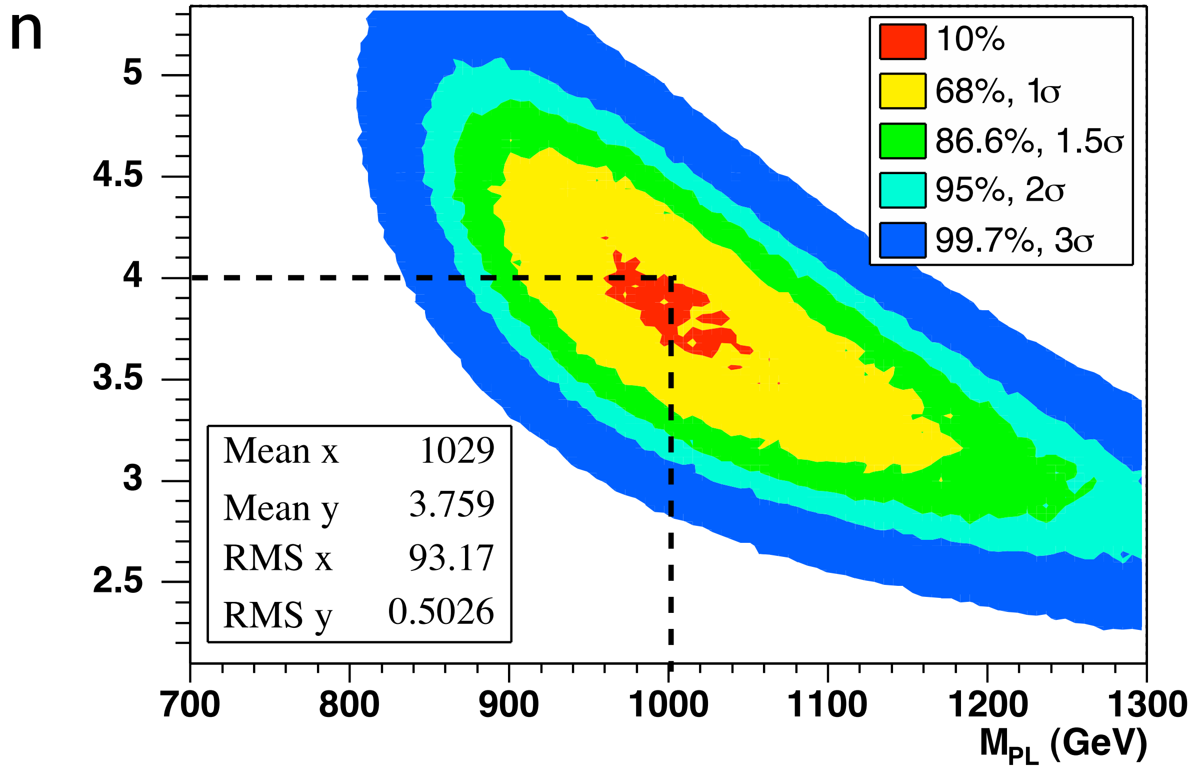
(c) Kinematic cut on



(d) 4-body remnant decay

➡ Not highly sensitive to model assumptions

Combined measurement of M_{PL} and n



➡ $\Delta M_{PL} / M_{PL} \sim 15\%$, $\Delta n \sim 0.75$

Conclusions

- Large cross section if Planck mass ~ 1 TeV
- Clear signature, with large $\not{E}_T$
- But BH mass measurement needs small $\not{E}_T$
- BH decay not well understood: early phases, time variation, spectrum cutoff, Planck-scale remnant ....
- Measuring n difficult but may be possible