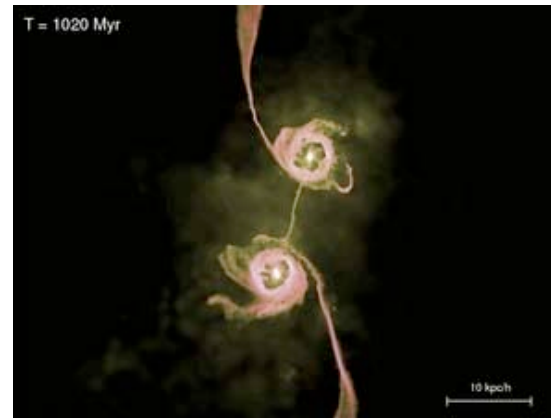


Black Holes at Accelerators

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:

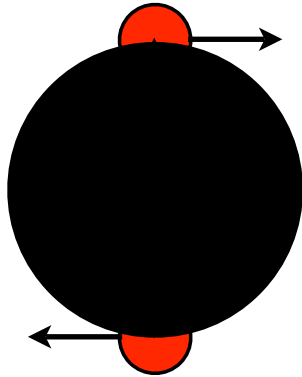
$$\hat{\sigma}(\hat{s} = M_{BH}^2) = F_n \pi r_S^2$$

- $r_S =$ 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)



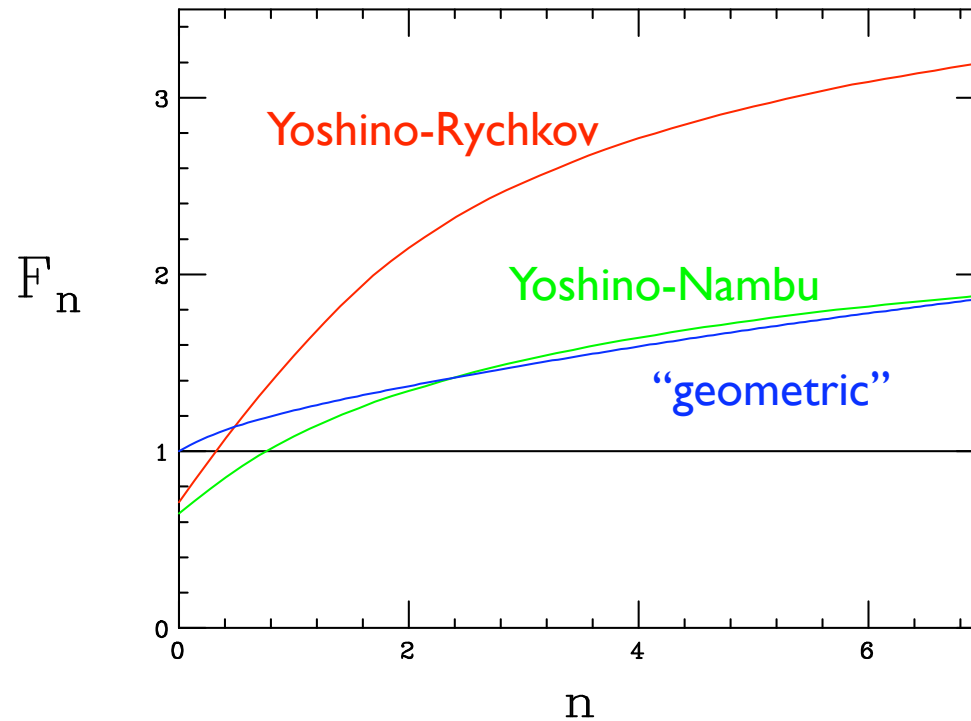
$$b_{max} = 2r_h = 2r_s [1 + a_*^2]^{-\frac{1}{n+1}}$$

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

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

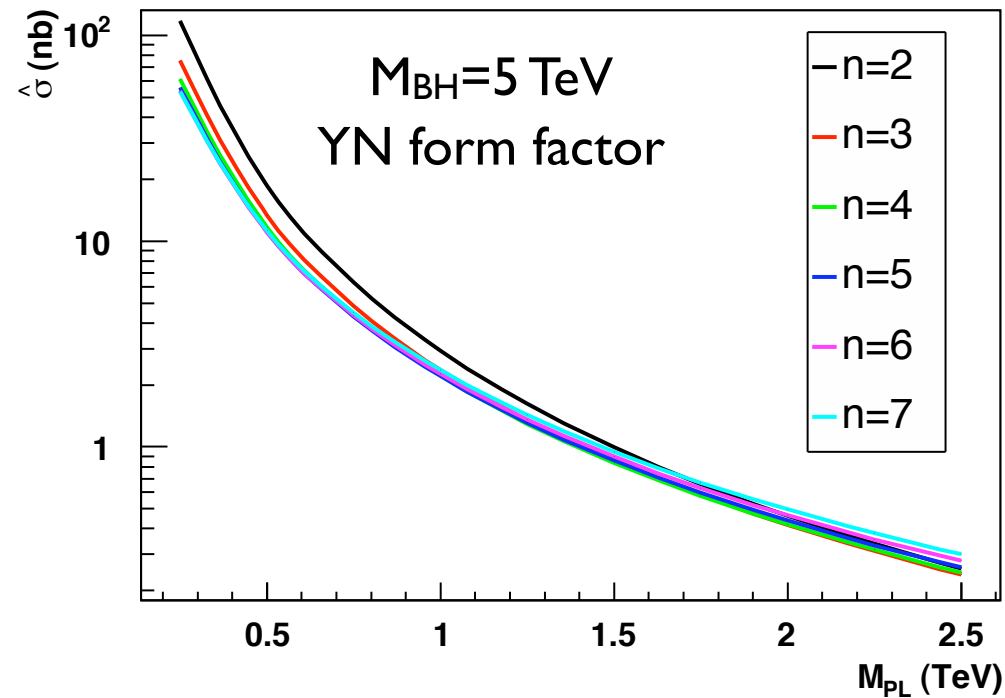
$$\rightarrow F_n \simeq 4 \left[1 + \left(\frac{n+2}{2} \right)^2 \right]^{-\frac{2}{n+1}} \quad (\text{“geometric”})$$

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 (I)

- **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

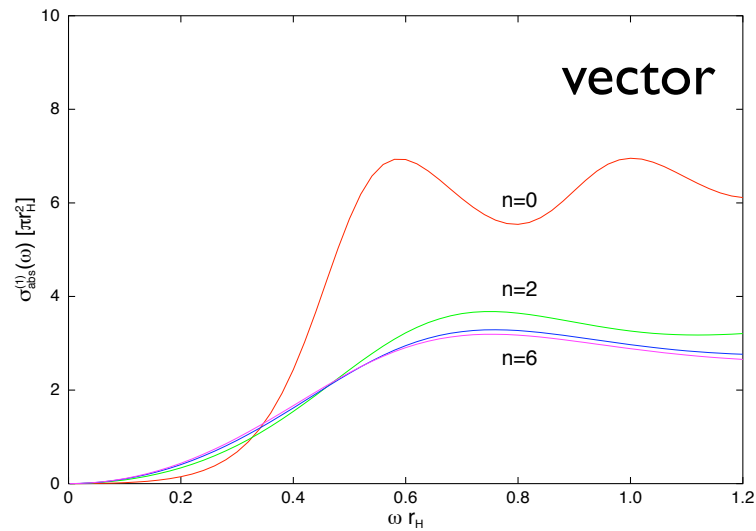
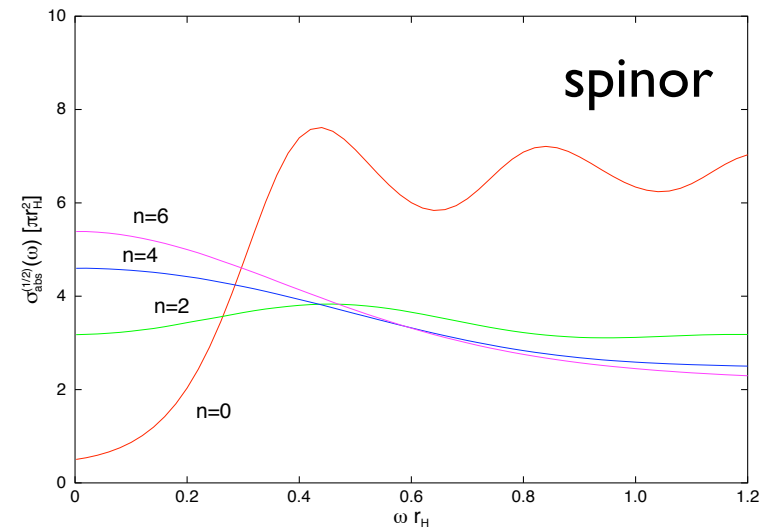
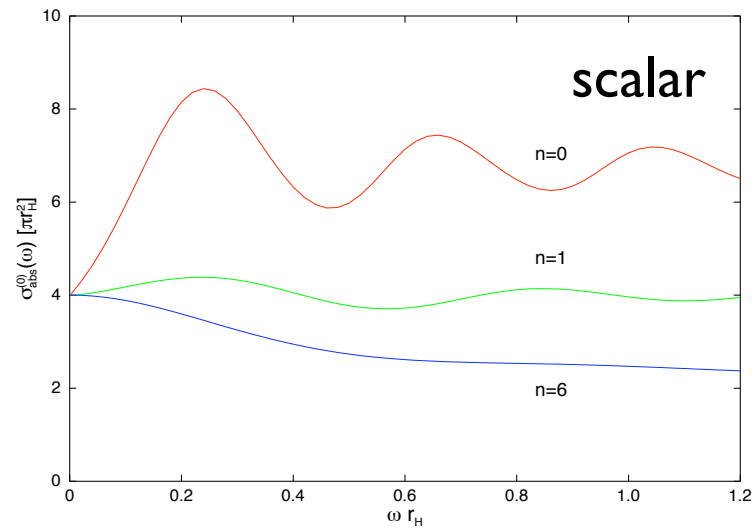
$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \mp 1) T_H^{n+6}}$$

- ➔ 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

n	τM_{BH}	
	$M_{\text{BH}} = 5M_{\text{PL}}$	$M_{\text{BH}} = 10M_{\text{PL}}$
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

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

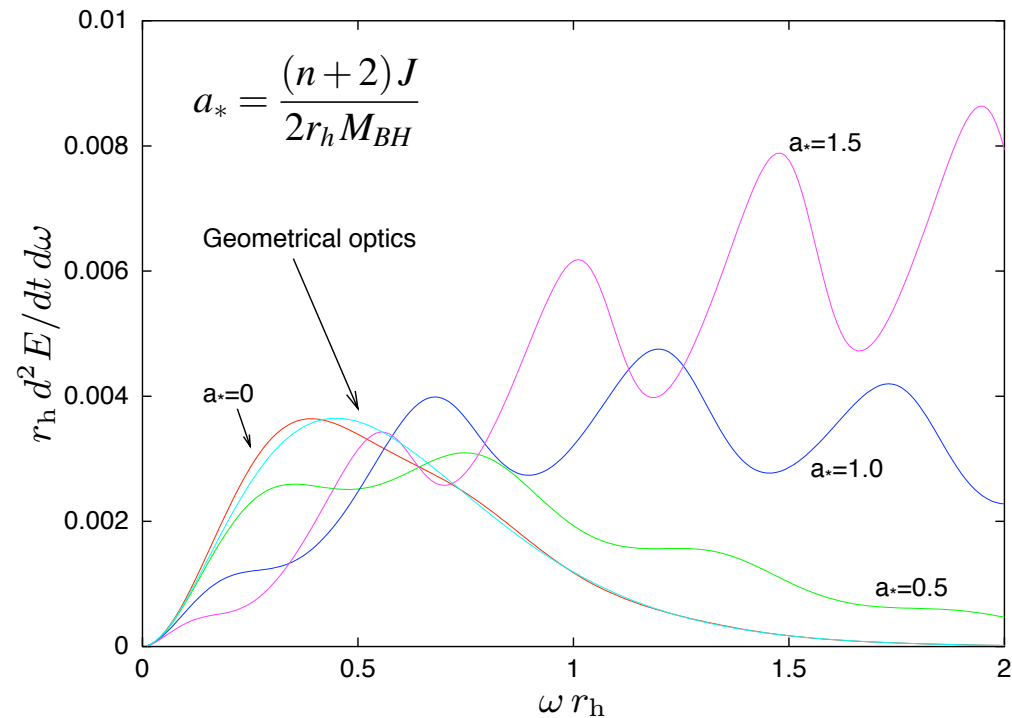
N.B. $\tau M_{\text{BH}} \sim 1$ at large n

➔ Black hole no longer well-defined?

Spin-down phase

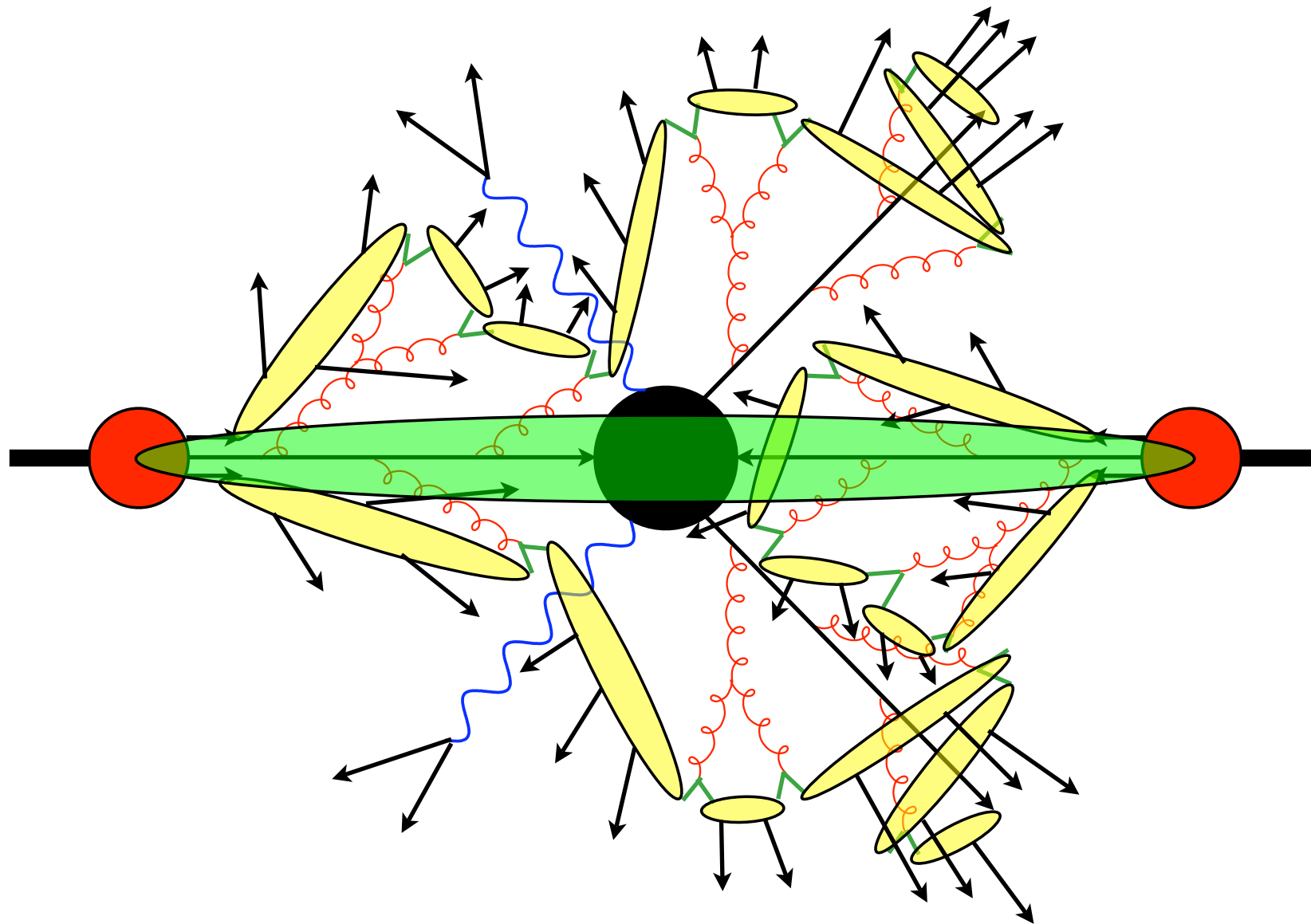
- Few results available for spinning BH

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



➔ CM Harris & P Kanti, hep-th/0503010

LHC Event Simulation



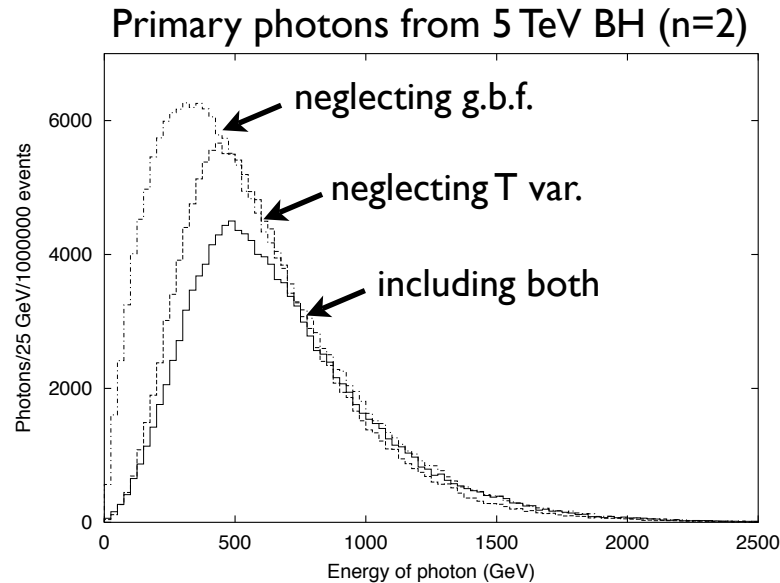
HERWIG Event Generator

- 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 type	Particle emissivity (%)			
	GRYBDY=.TRUE.		GRYBDY=.FALSE.	
	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

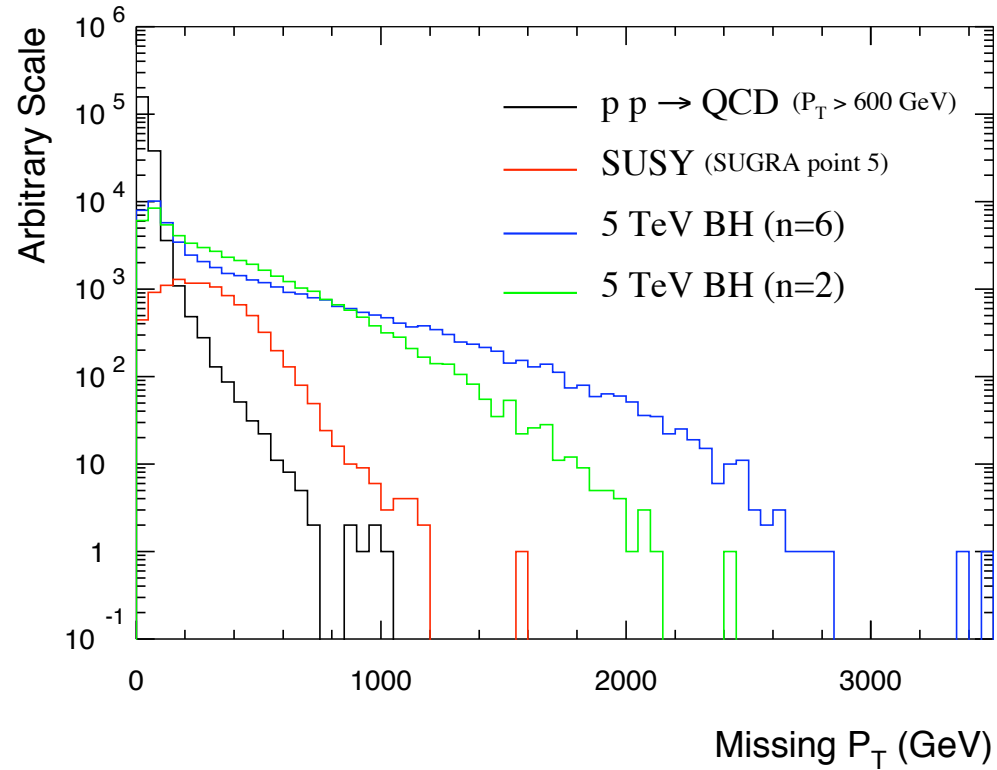
C.M. Harris[†], M.J. Palmer[†], M.A. Parker[†], P. Richardson[‡], A. Sabetfakhri[†] and B.R. Webber[†]

[†] *Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK.*

[‡] *Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK.*

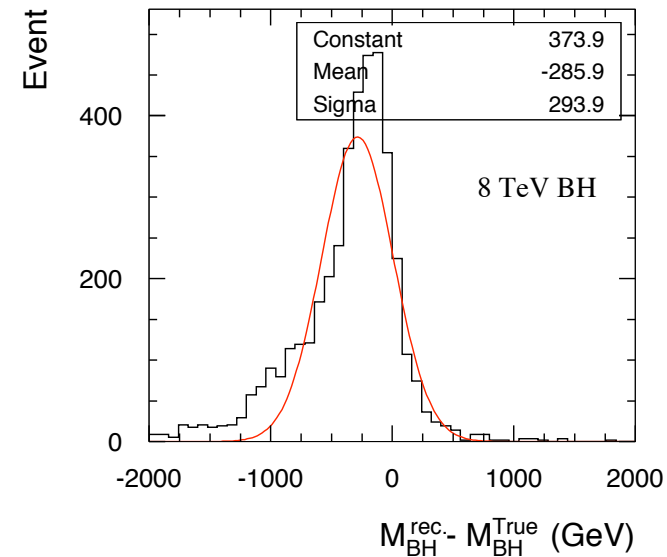
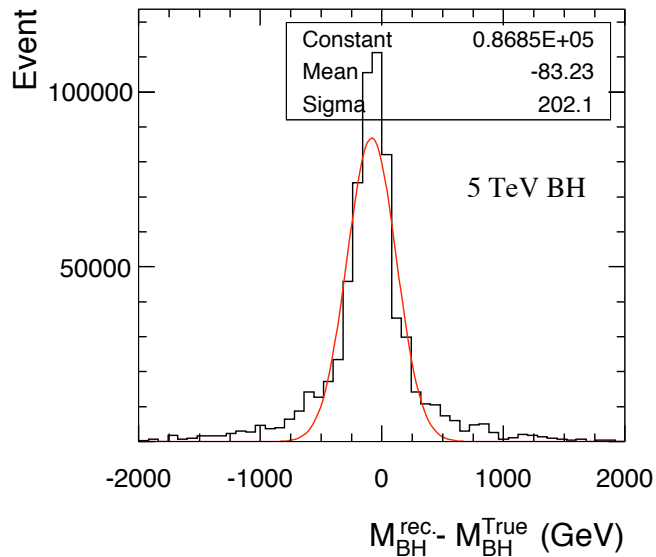
- ➔ hep-ph/0411022, JHEP05(2005)053; see also CM Harris, PhD thesis, hep-ph/0502005; CM Harris et al (CHARYBDIS event generator) hep-ph/0307035, JHEP08(2003)033
- ➔ earlier work: SB Giddings & S Thomas, hep-ph/0106219; S Dimopoulos & G Landsberg, hep-ph/0106295

Missing transverse energy



➔ Typically larger \cancel{E}_T than SM or even MSSM

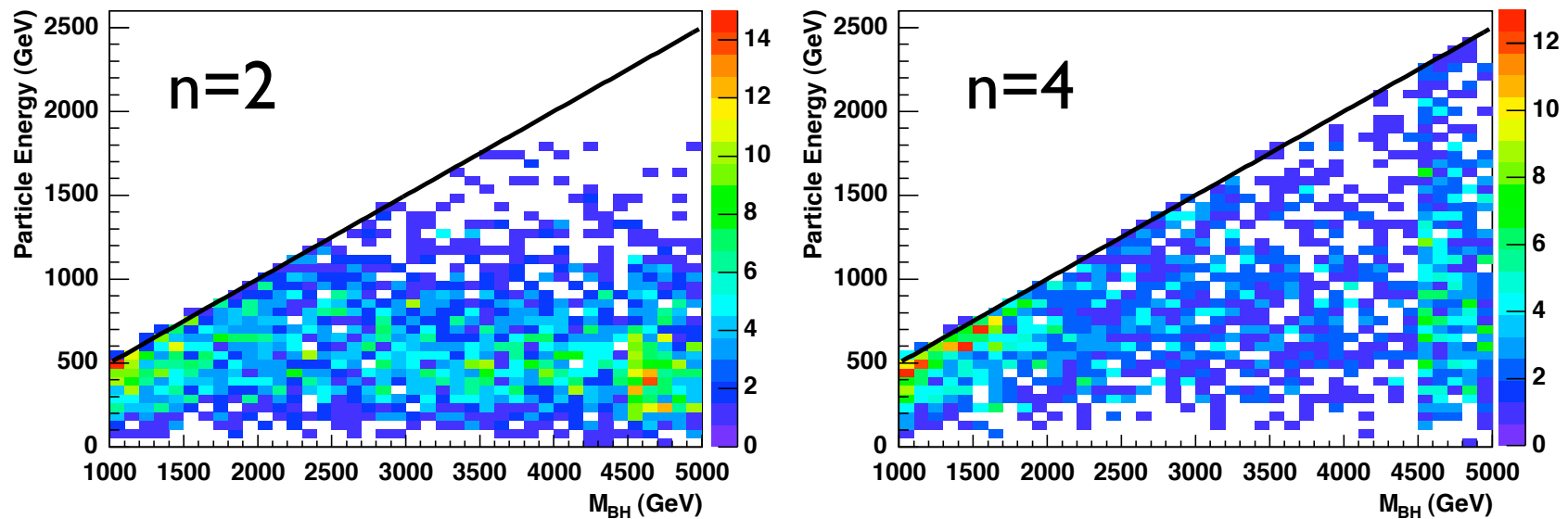
Measuring black hole masses



Need $E_T < 100$ GeV for adequate resolution

→ $\Delta M_{\text{BH}} / M_{\text{BH}} \sim 4\%$

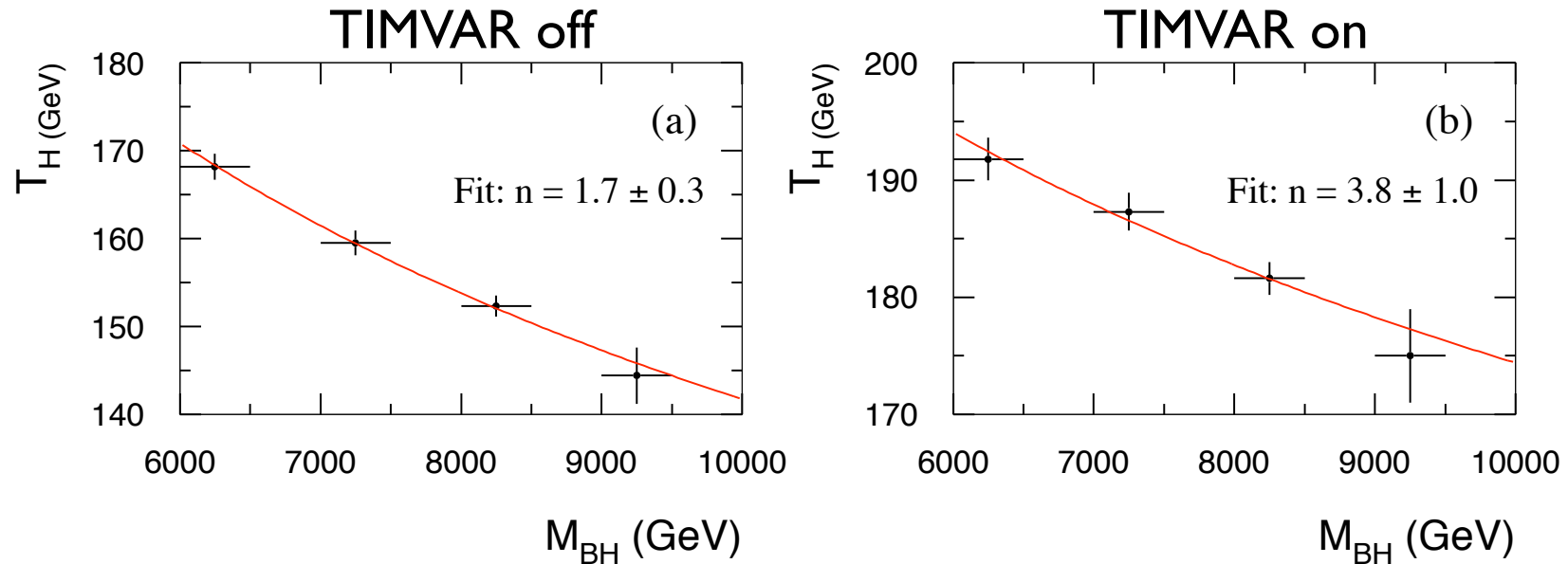
Effect of energy cutoff $E < M_{\text{BH}}/2$



Energy distribution of primary emissions vs M_{BH}

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

Effects of time dependence

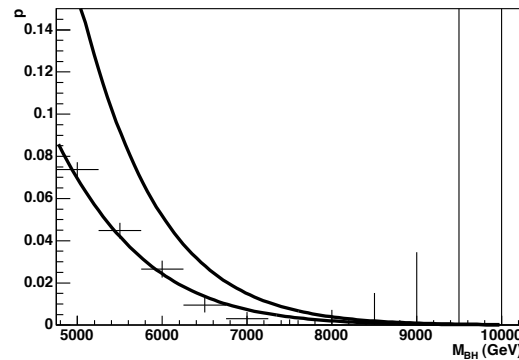


Fits to primary electron spectrum for $n=2$

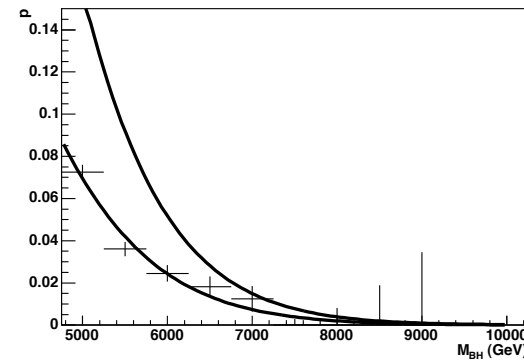
➔ Neglecting time variation of T_H
leads to over-estimate of n

A possible observable sensitive to n

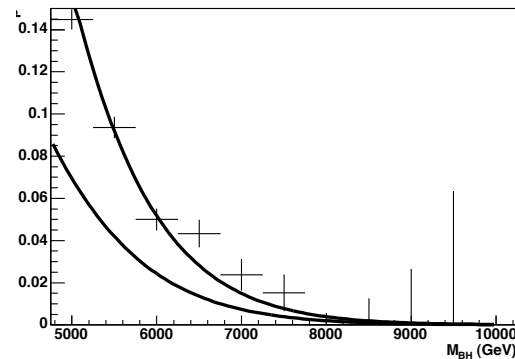
$$P(E_{max} > M_{BH}/2 - 400 \text{ GeV})$$



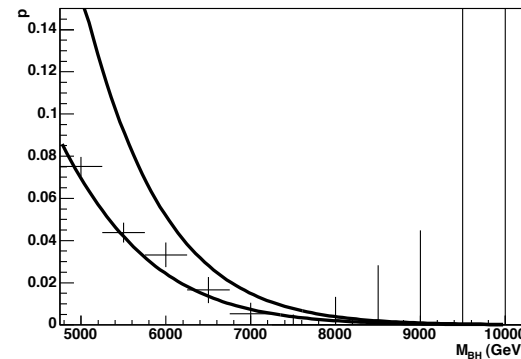
(a) Test case (see section 3)



(b) No time variation



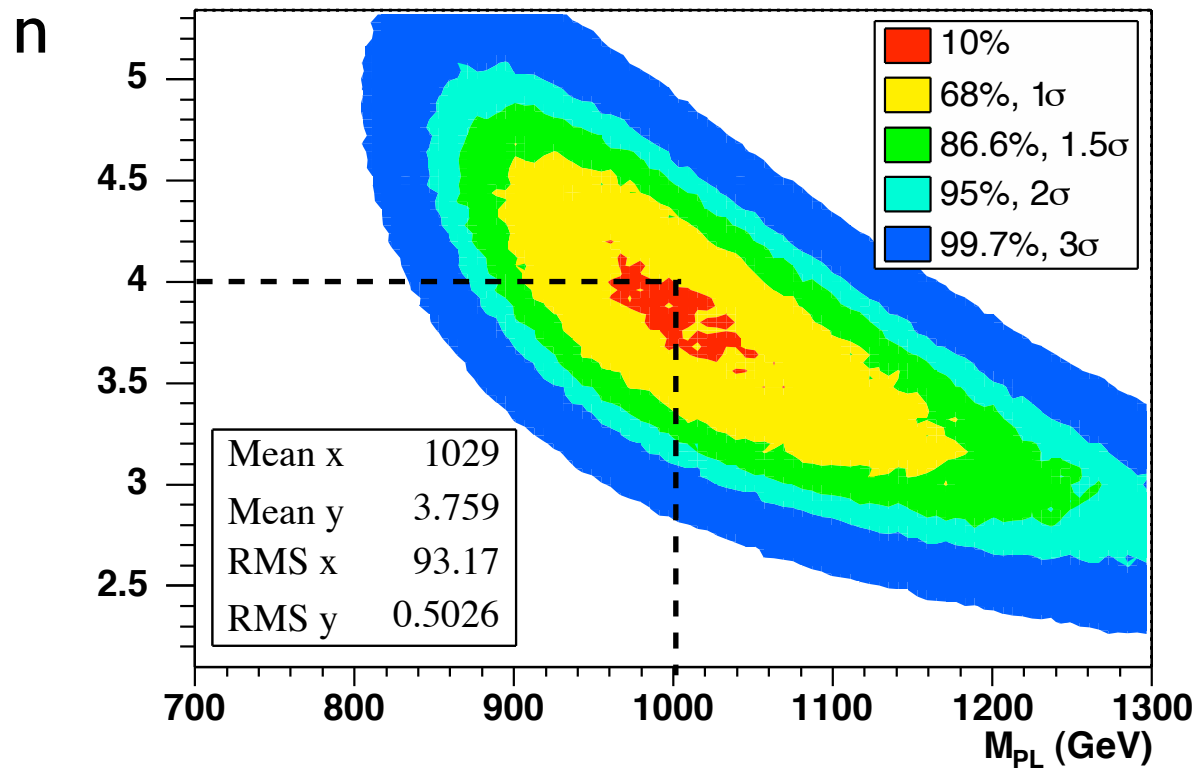
(c) Kinematic cut on



(d) 4-body remnant decay

➔ Not highly sensitive to model assumptions

Combined measurement of M_{PL} and n



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

Conclusions

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