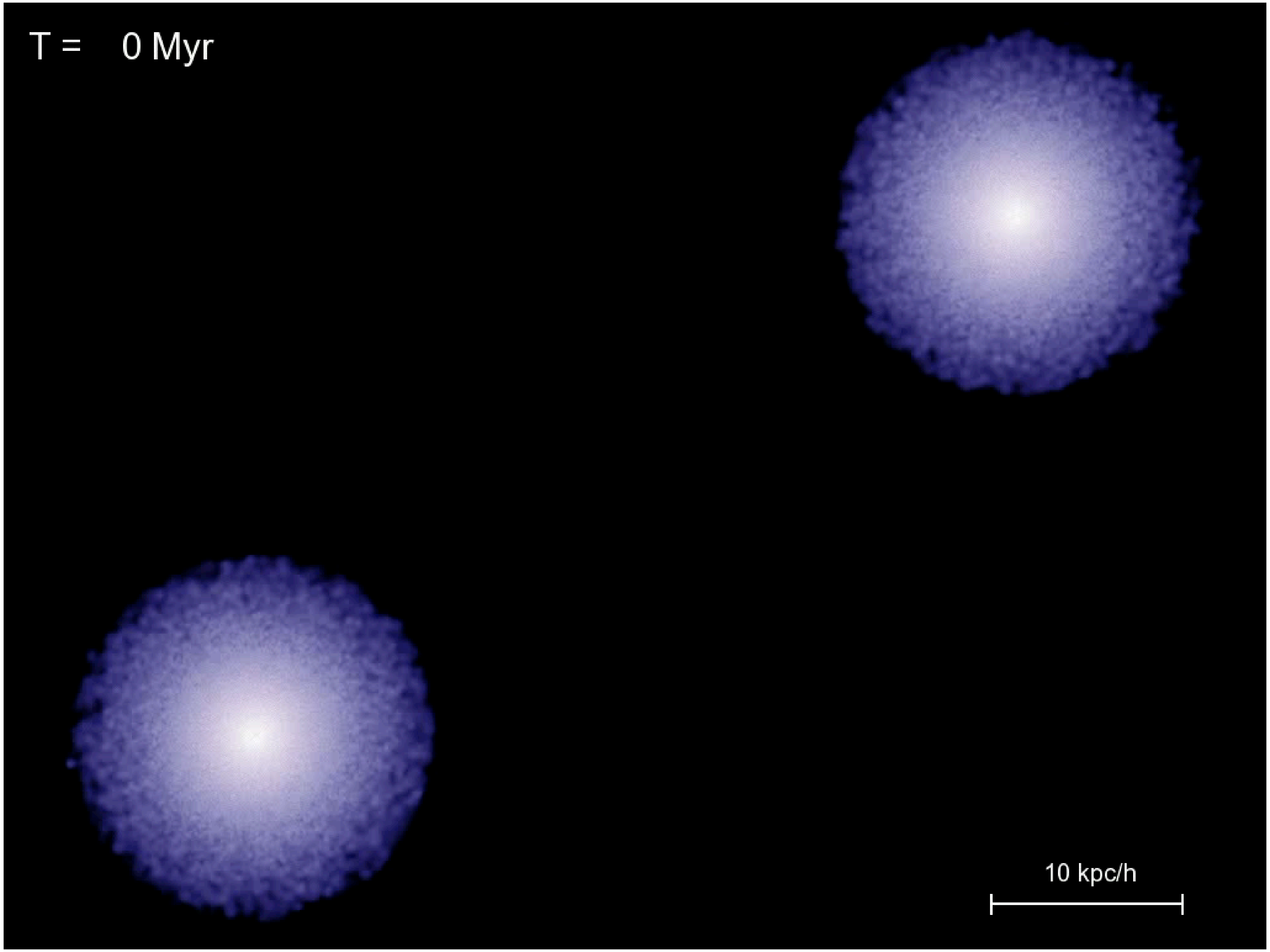
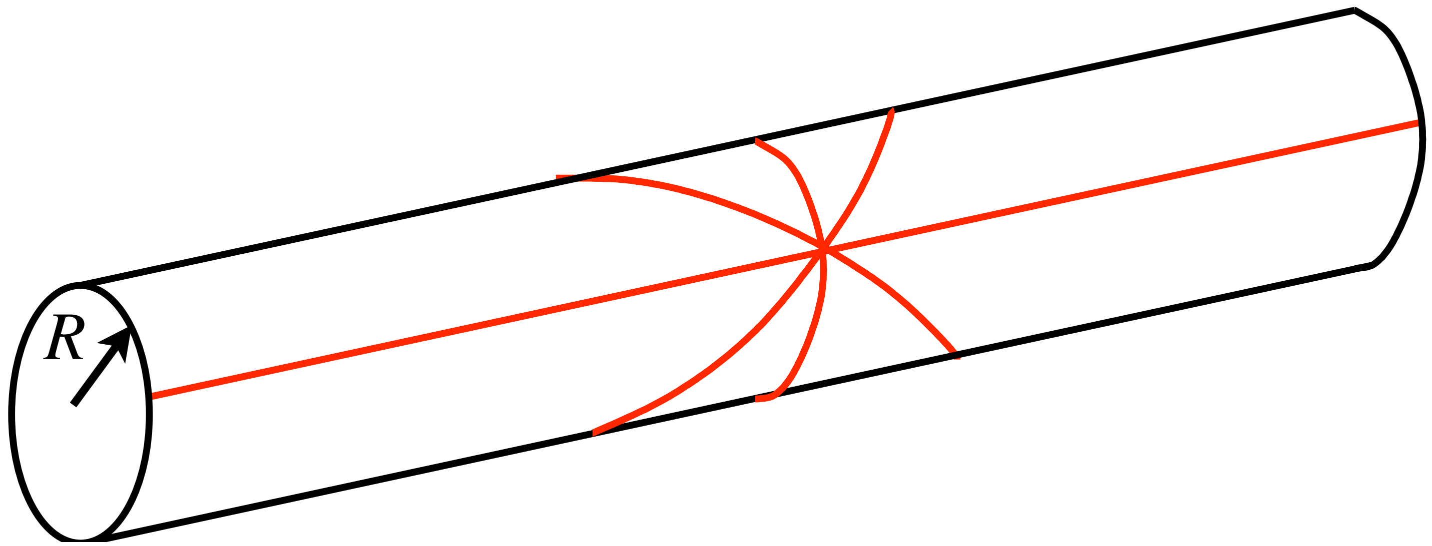
Black Holes at the LHC?

Bryan Webber, Cambridge



Large Extra Dimensions

- For n extra dimensions compactified at scale R



$$F(r < R) \sim G_{4+n} \frac{m_1 m_2}{r^{2+n}}$$

$$F(r > R) \sim G_{4+n} \frac{m_1 m_2}{r^2 R^n}$$

$$\Rightarrow G_4 = \frac{G_{4+n}}{R^n}$$

TeV-Scale Gravity

$$G_4 = G_{4+n}/R^n$$

$$G_{4+n} = M_{PL}^{-2-n}$$

$$\Rightarrow M_{PL}^{(4)} = M_{PL}\left(\frac{M_{PL}c}{\hbar}R\right)^{n/2}$$

- Hence for $M_{PL} = 1$ TeV we need

$$10^{19}\ \mathrm{GeV} \sim 10^3\ \mathrm{GeV} \times (10^4\, R/\mathrm{fm})^{n/2}$$

➡ mm for n=2, nm for n=3, pm for n=4

Black Holes in Particle Collisions

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

Black hole production

- Parton (quark or gluon)-level cross section:

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

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

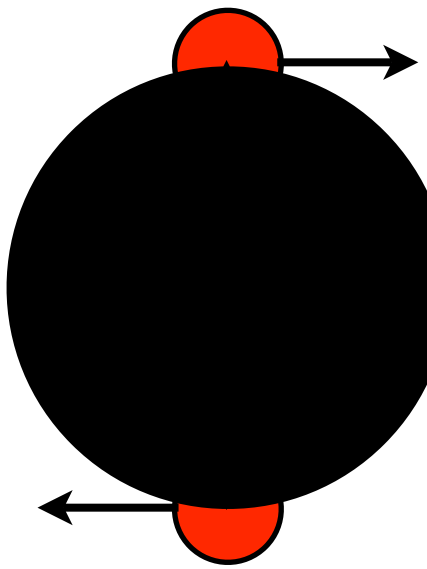
$$r_S = \frac{1}{\sqrt{\pi} M_{PL}} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right) M_{BH}}{(n+2) M_{PL}} \right]^{\frac{1}{n+1}}$$

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

- Usually set Planck scale $M_{PL} = 1$ TeV for illustration

  (Dimopoulos-Landsberg $M_{PL} \equiv \left[G_{(4+n)}\right]^{-\frac{1}{n+2}}$)

BH formation factor (I)



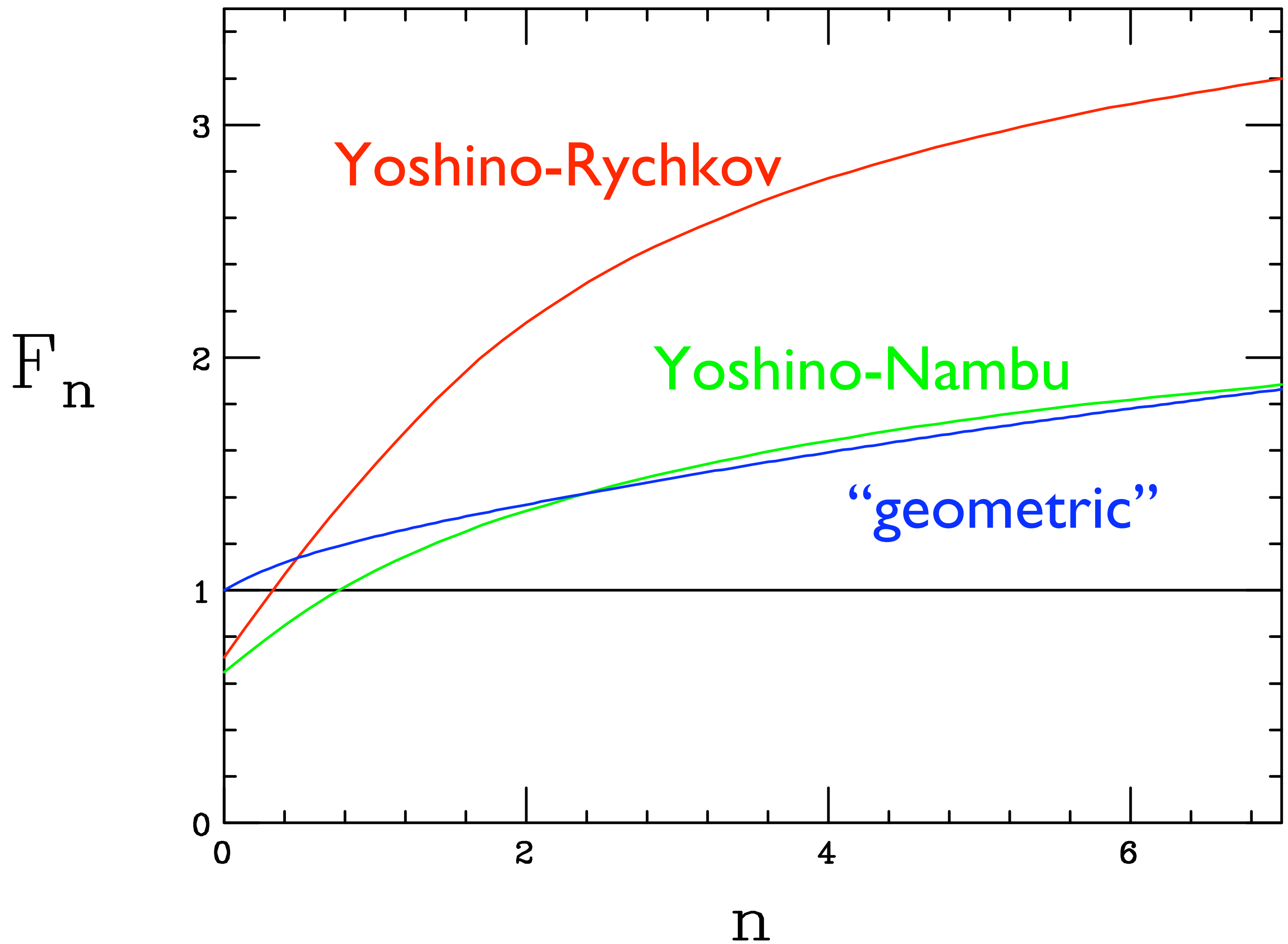
$$b_{max} = 2r_h = 2r_s\left[1 + a_*^2\right]^{-\frac{1}{n+1}}$$

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

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

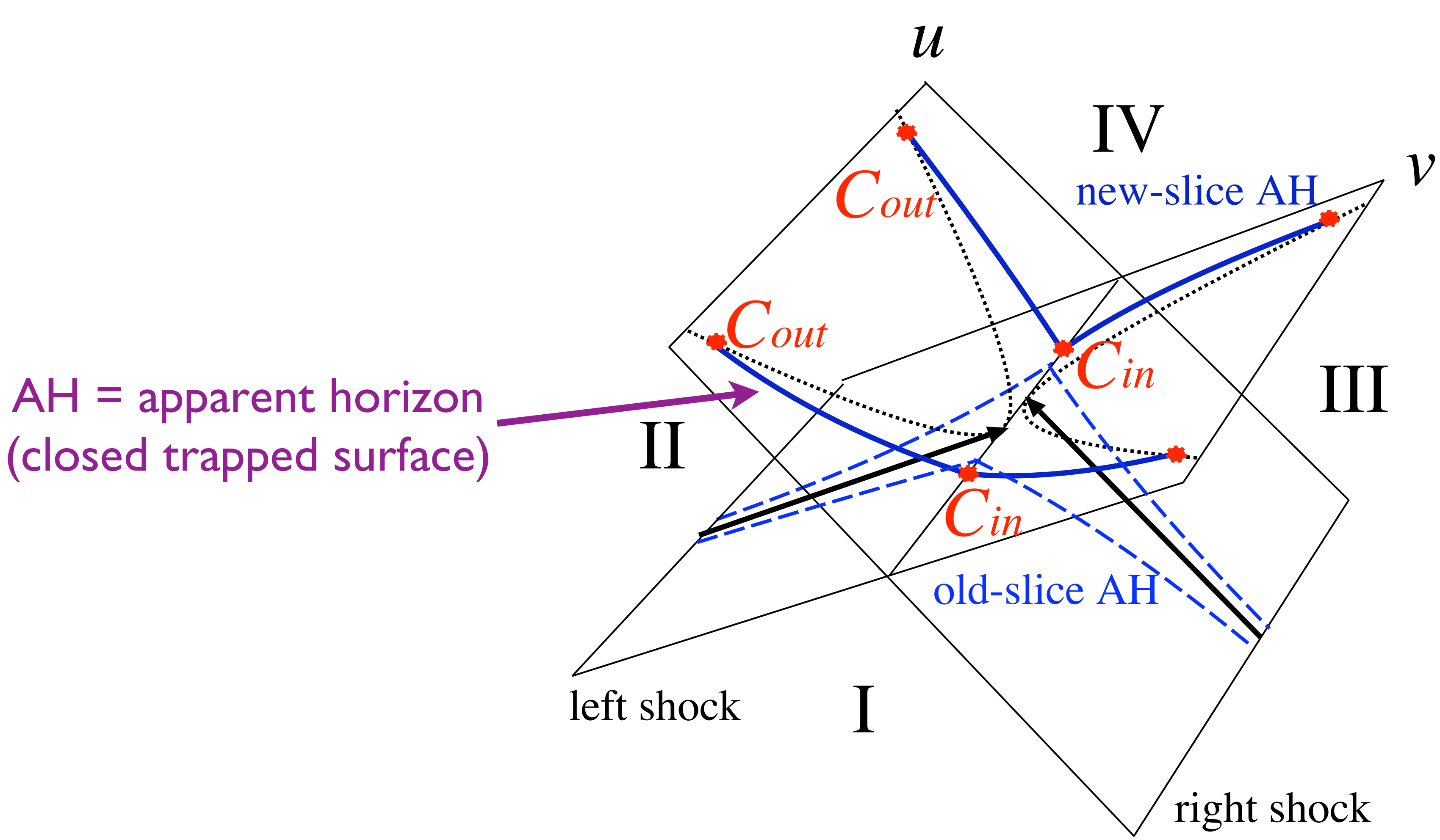
$$F_n \simeq 4\left[1 + \left(\frac{n+2}{2}\right)^2\right]^{-\frac{2}{n+1}}$$ ("geometric")

BH formation factor (2)



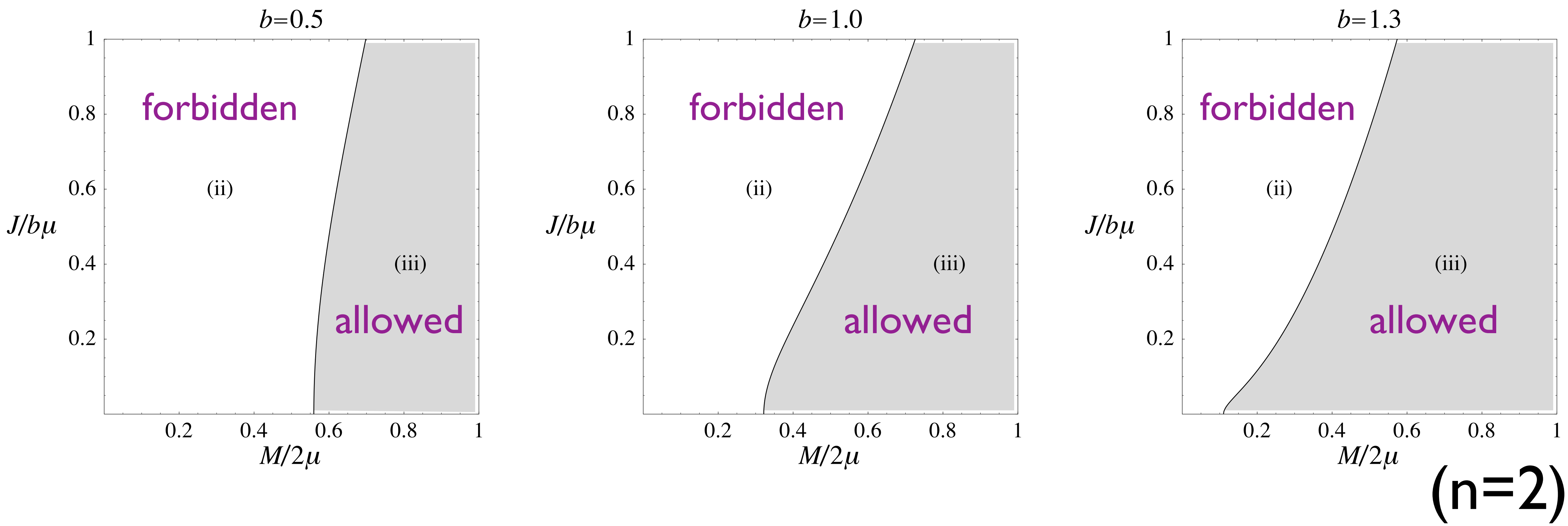
- H Yoshino & Y Nambu, gr-qc/0209003
- H Yoshino & VS Rychkov, hep-th/0503171

Yoshino-Rychkov Bound on $\hat{\sigma}_{BH}$



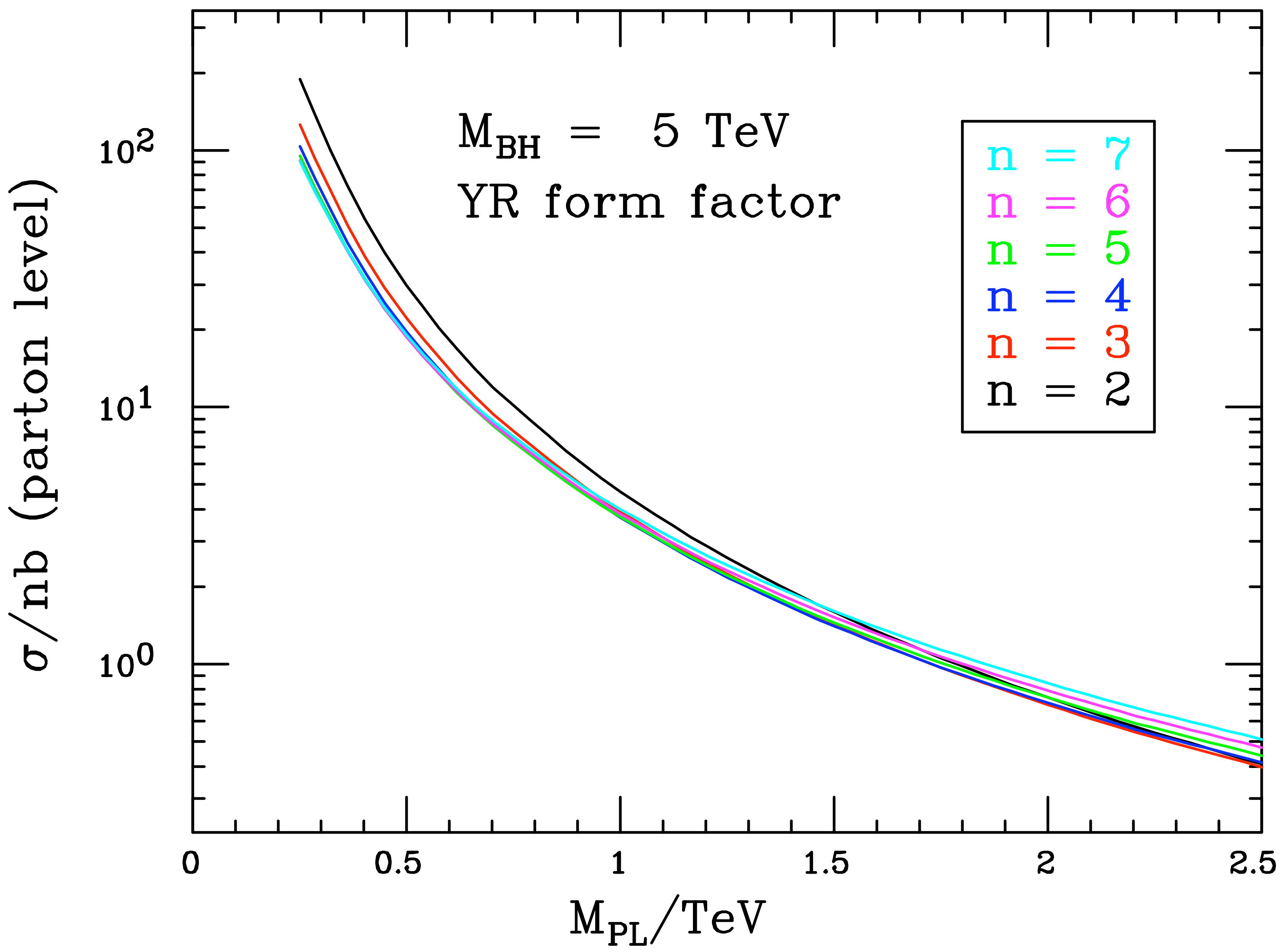
- YN bound is πb^2_{max} for AH on past lightcone (boundary of region I)
- YR bound is πb^2_{max} for AH on future lightcone (boundary of regions II & III)
- Area of AH sets limits on M_{BH} and J_{BH}

Limits on M_{BH} and J_{BH}



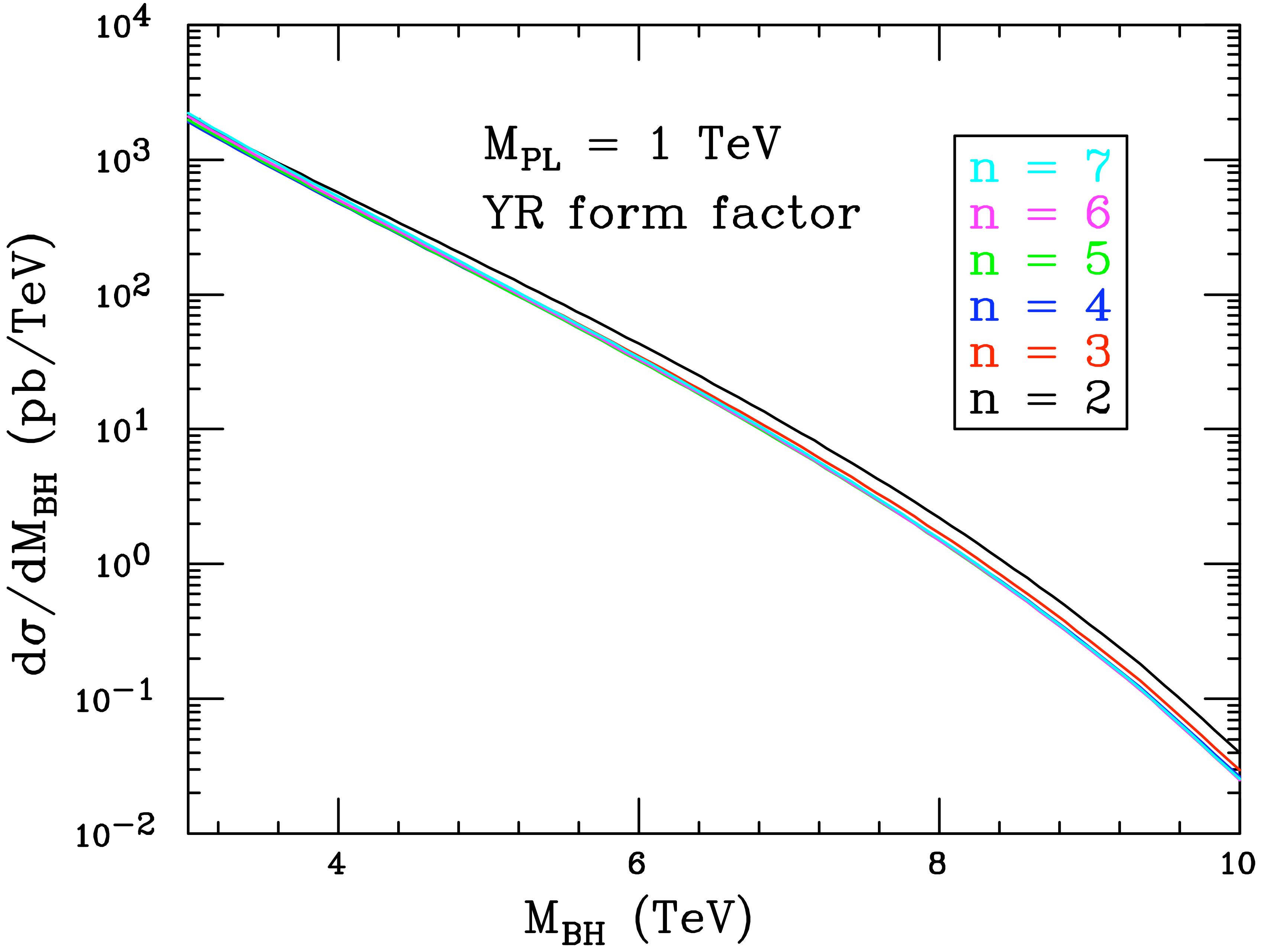
- $\mu \equiv \sqrt{\hat{s}}/2$, so $M/2\mu = 1$ implies $M_{BH}^2 = \hat{s}$
- We'll assume $M_{BH} \simeq 2\mu = \sqrt{\hat{s}}$, $J_{BH} \simeq b\mu \simeq bM_{BH}/2$

BH cross section vs Planck mass



- Little sensitivity to n
- Sensitive to assumption that $M_{BH} \simeq \sqrt{\hat{s}}$

BH cross sections at LHC



➡ 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'll assume Schwarzschild phase is dominant
  - ➡ all types of SM particles emitted with Hawking spectrum

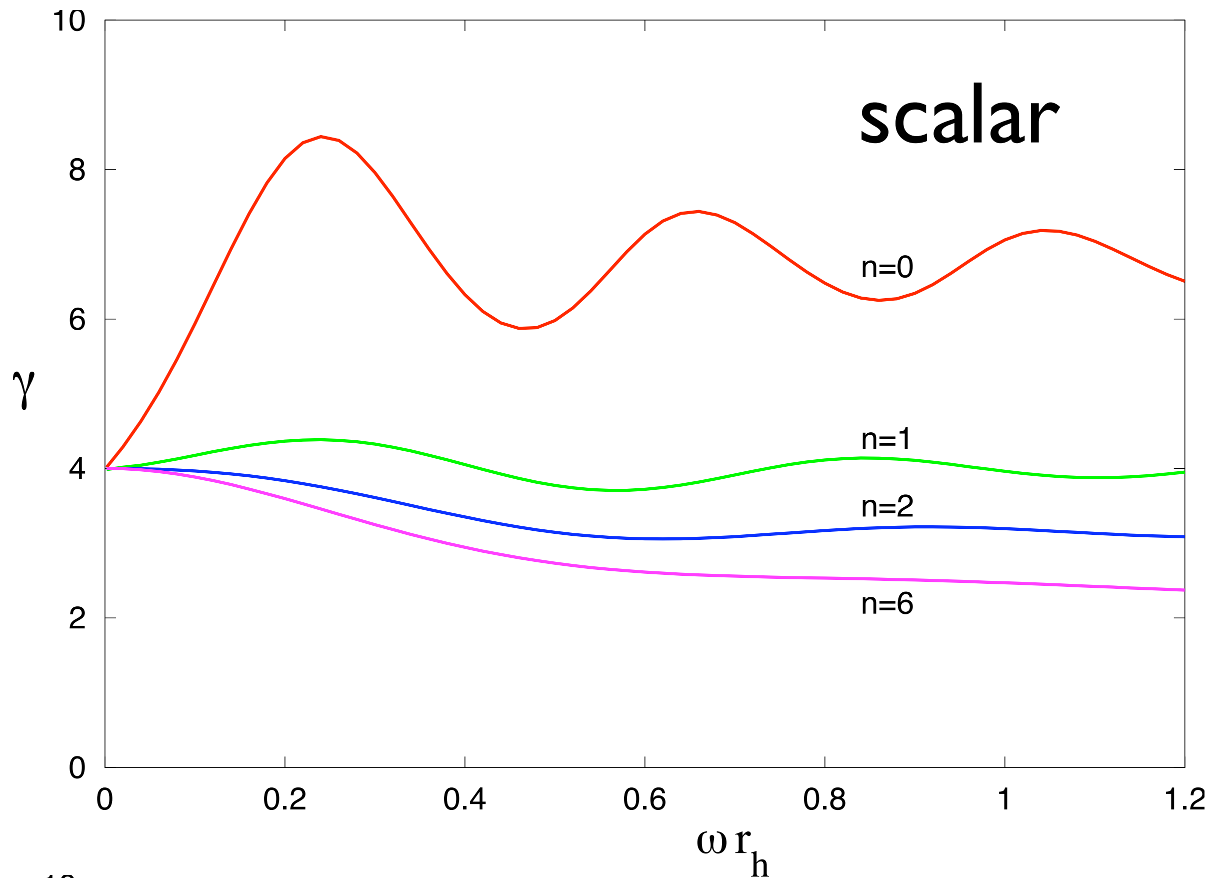
$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \mp 1) T_H^{n+6}}$$

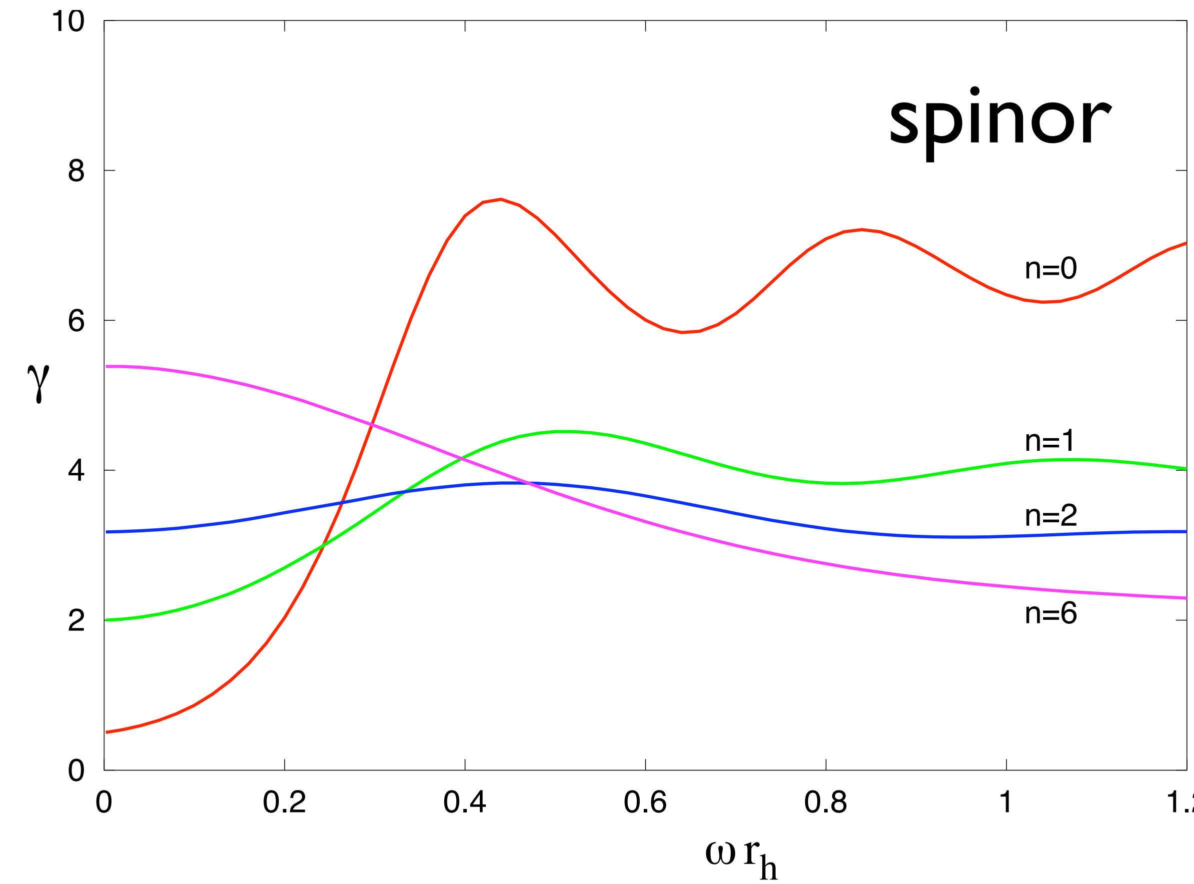
  - ➡ Hawking temperature

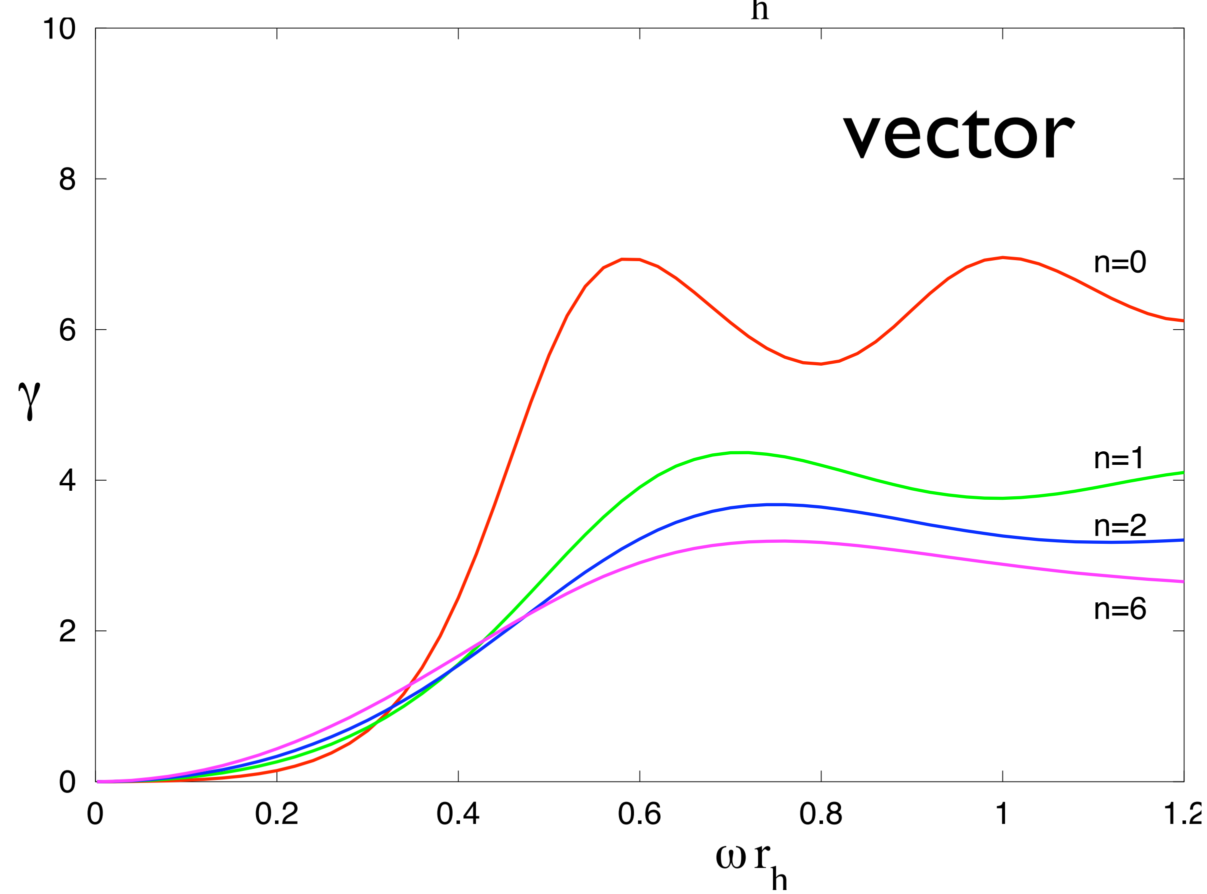
$$T_H = \frac{n+1}{4\pi r_{BH}} \propto (M_{BH})^{-\frac{1}{n+1}}$$

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

Grey-body factors

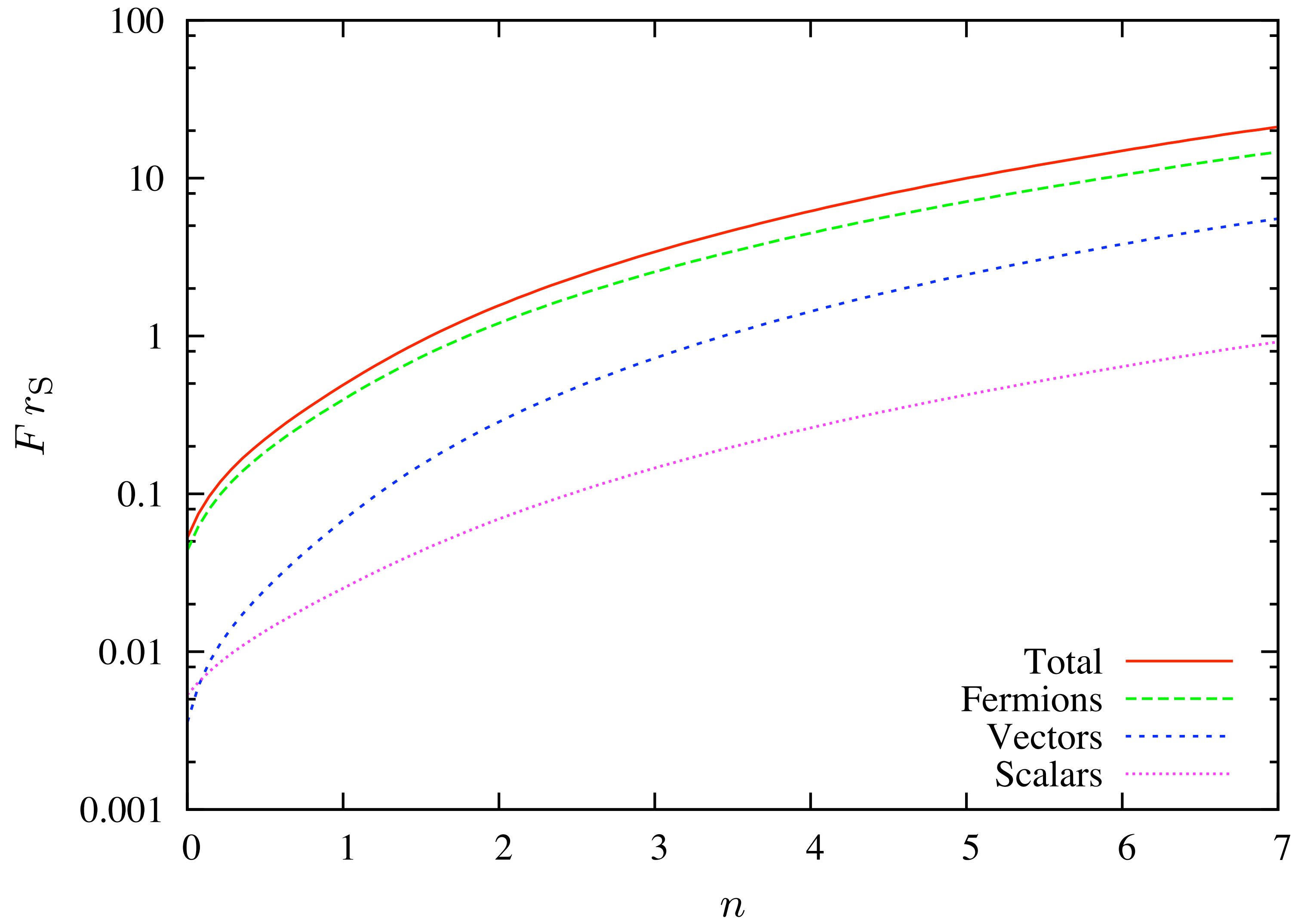






- Emission on brane only
- Low-energy vector suppression
- CM Harris, hep-ph/0502005

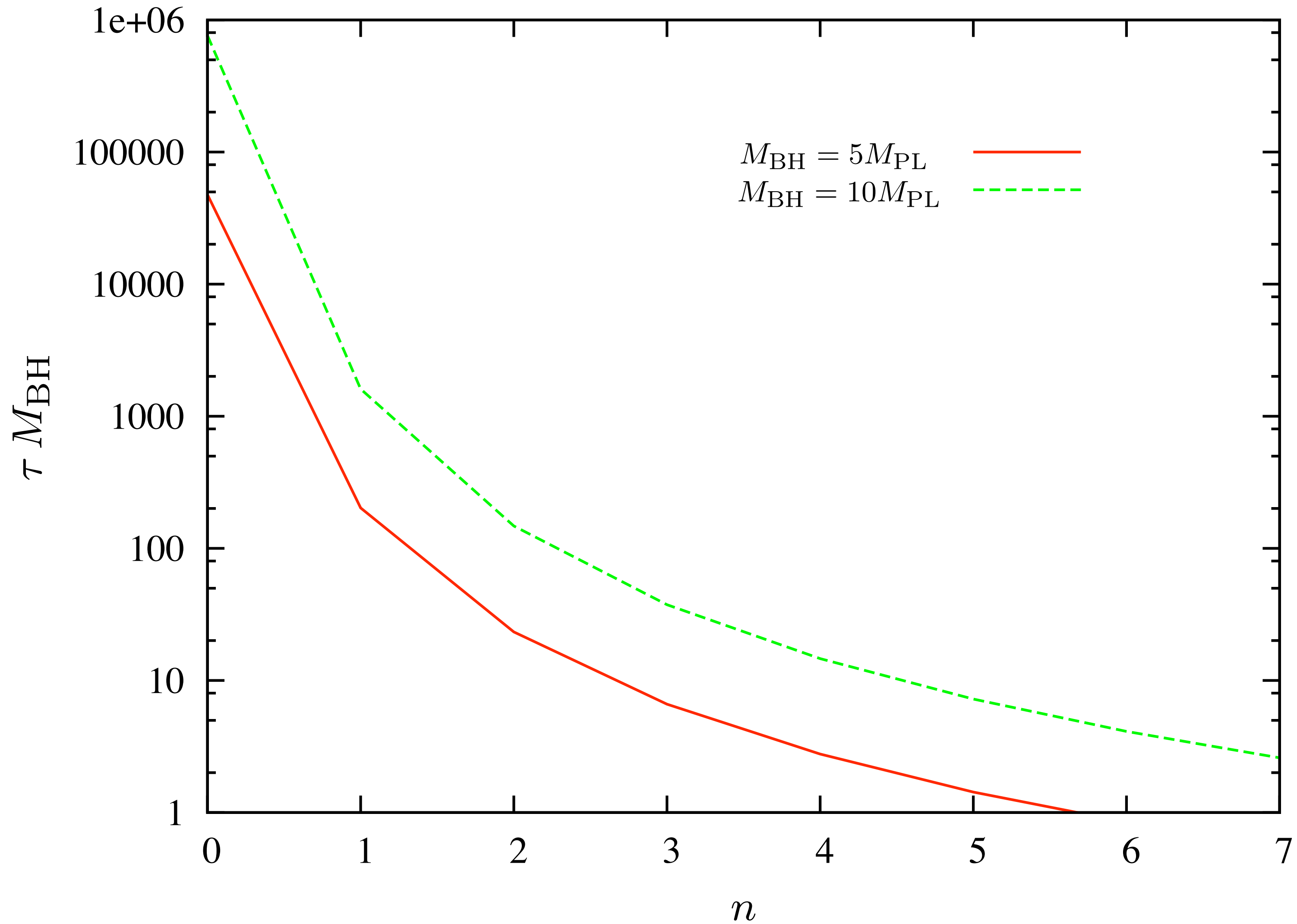
Integrated Hawking flux



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

- Transit time $\gg$ time between emissions
- Decay no longer quasi-stationary at large n

Black hole lifetime



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

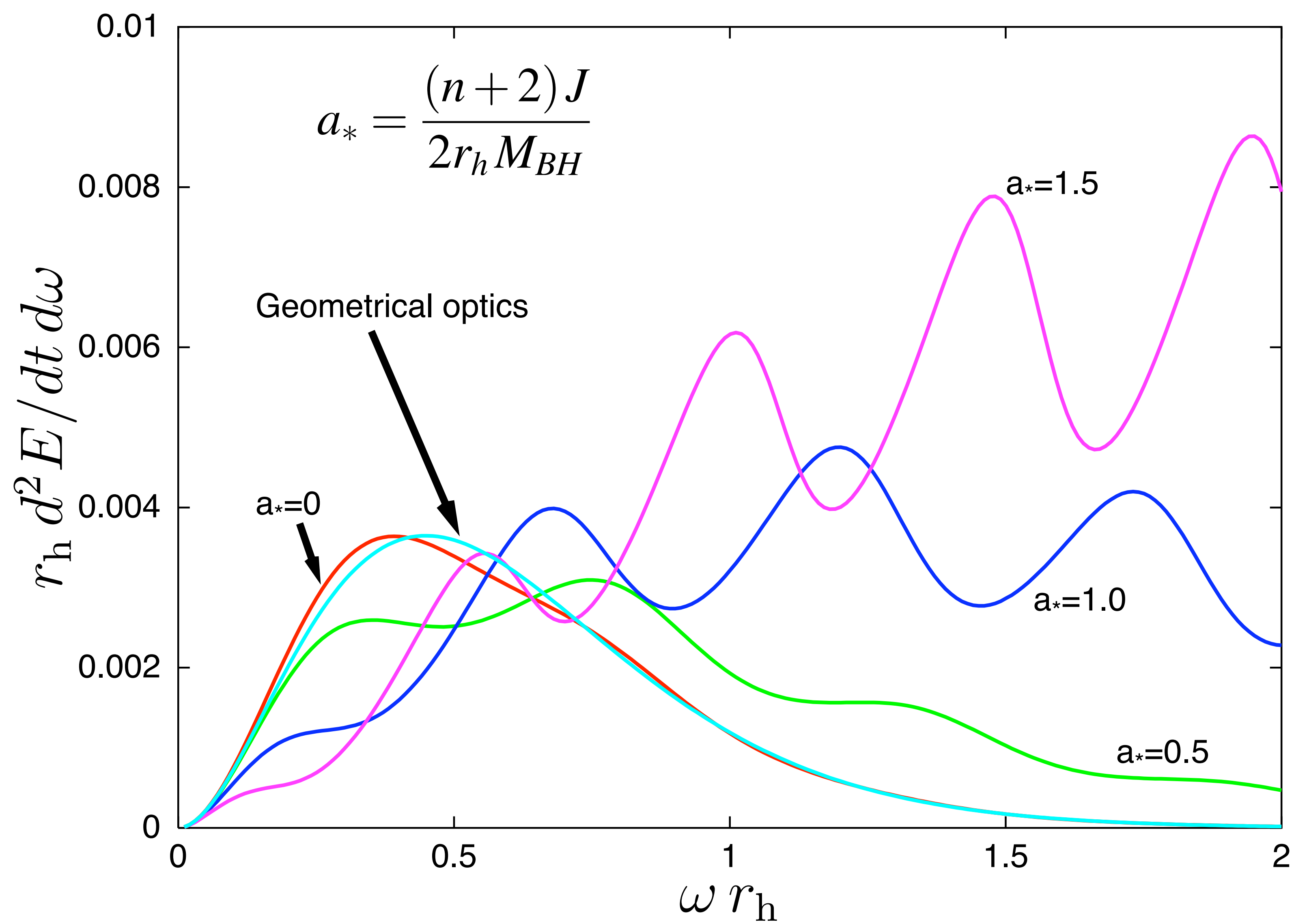
N.B. $\tau M_{\rm BH} \sim 1$ at large n

➡ Black hole no longer well-defined?

Spin-down phase (1)

- Some results becoming available for spinning BH

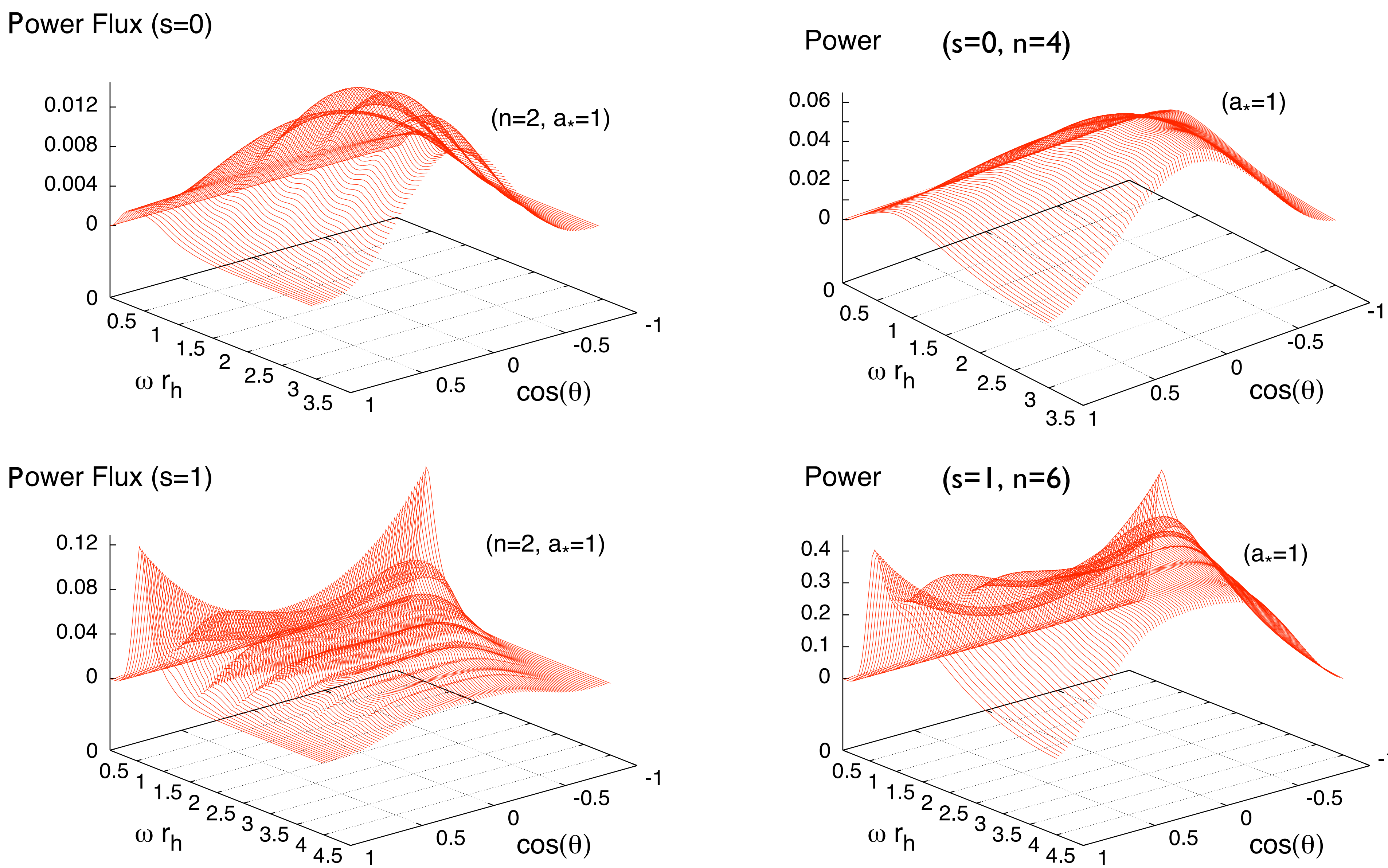
Power spectrum for scalar emission on brane (n=1)



➜ CM Harris & P Kanti, hep-th/0503010

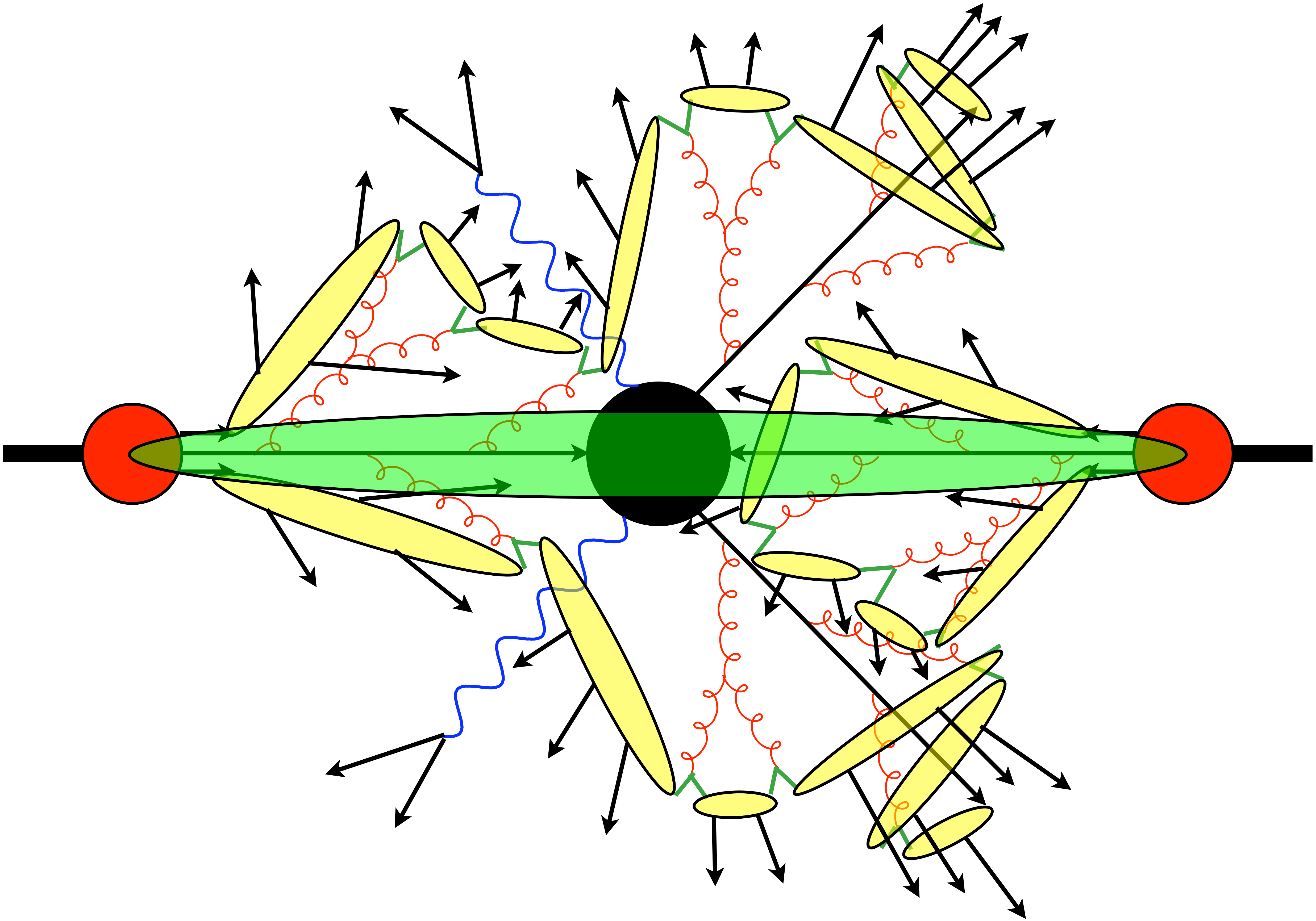
Spin-down phase (2)

- Angular distribution of scalar & vector emission



➔ M Casals, P Kanti & E Winstanley, hep-th/0511163

LHC Event Simulation



Black Hole 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

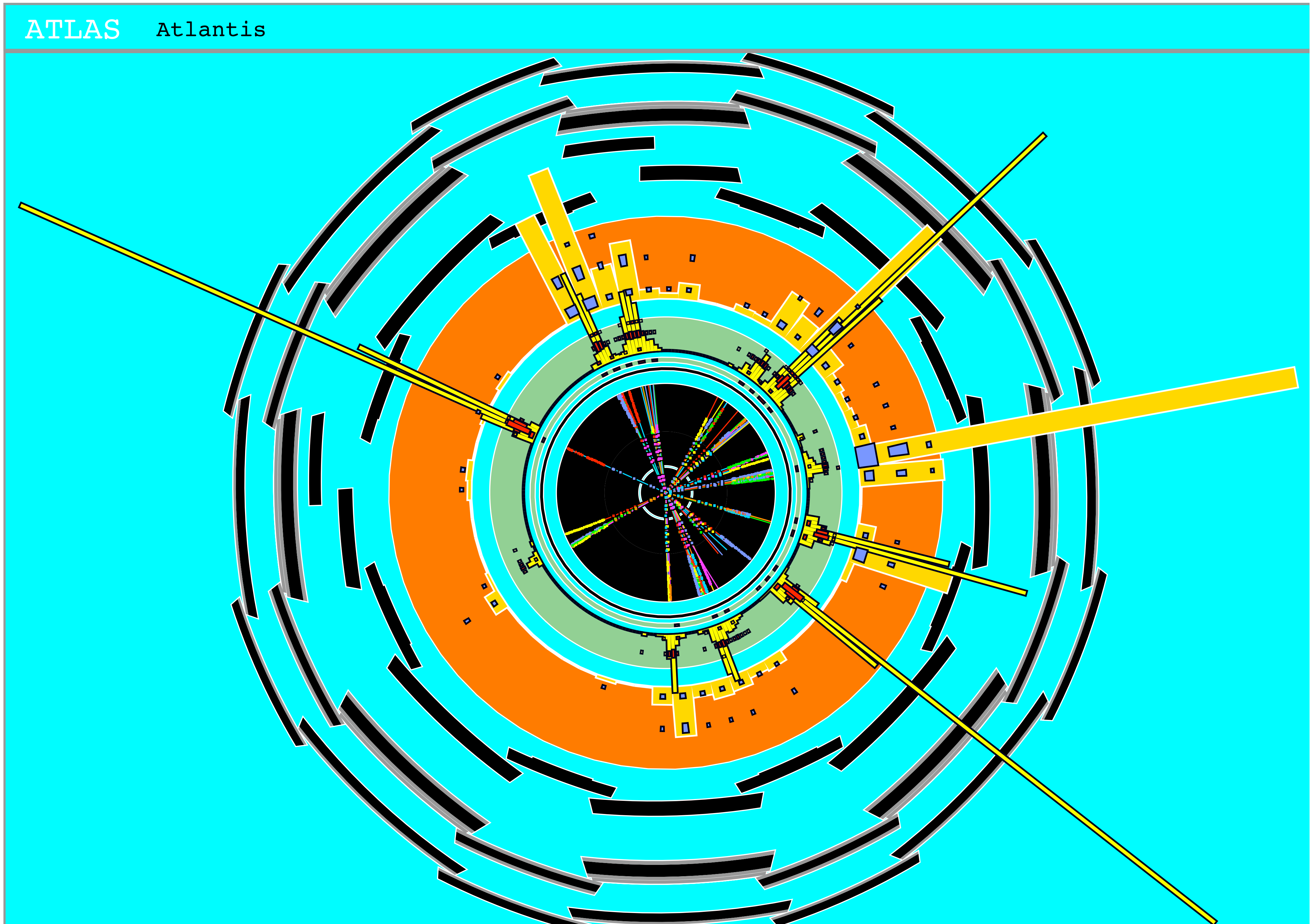
➡ All need interfacing to a parton shower and hadronization generator (PYTHIA or HERWIG)

Main CHARYBDIS parameters

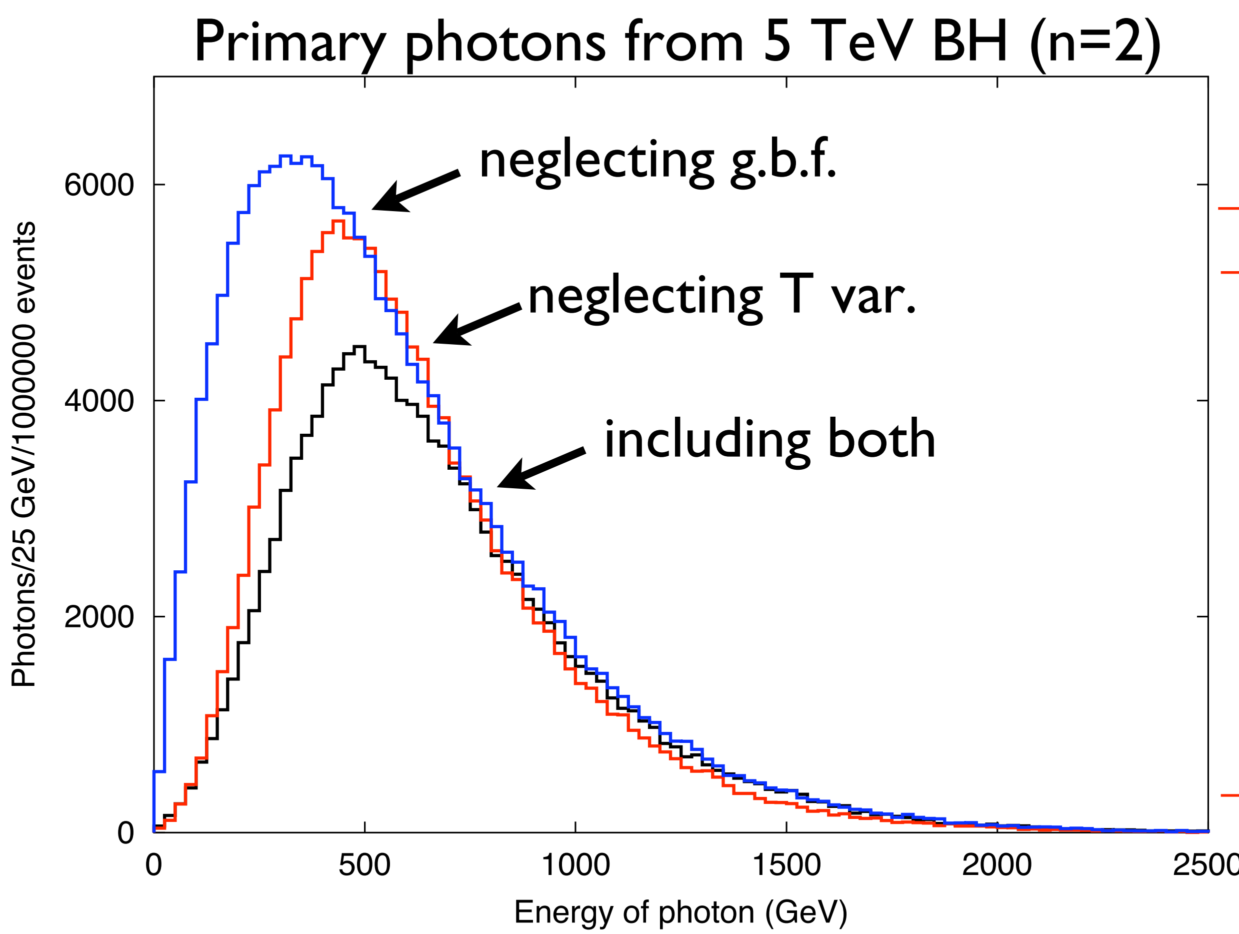
Name	Description	Values	Default
TOTDIM	Total dimension (n+4)	6-11	6
MPLNCK	Planck mass (GeV)	real	1000
GTSCA	Use scale ($1/r_S$) not M_{BH}	logical	.FALSE.
TIMVAR	Use time-dependent T_H	logical	.TRUE.
MSSDEC	Include t,W,Z(2), h(3) decay	1-3	3
GRYBDY	Include grey-body factors	logical	.TRUE.
KINCUT	Use kinematic cutoff	logical	.TRUE.

CHARYBDIS Event at LHC

TOTDIM = 10 MPLNCK = 1 TeV M_{BH} = 8 TeV



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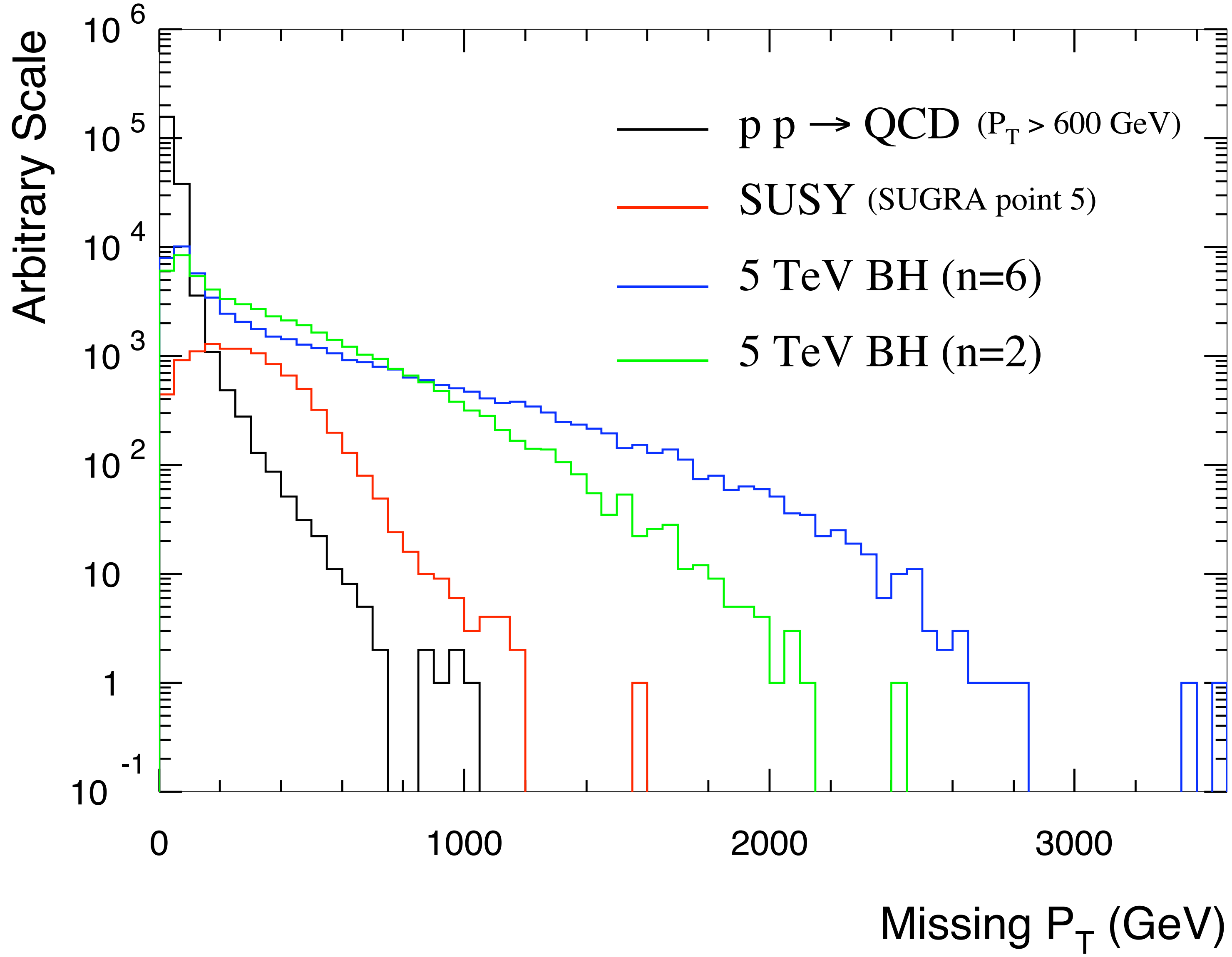
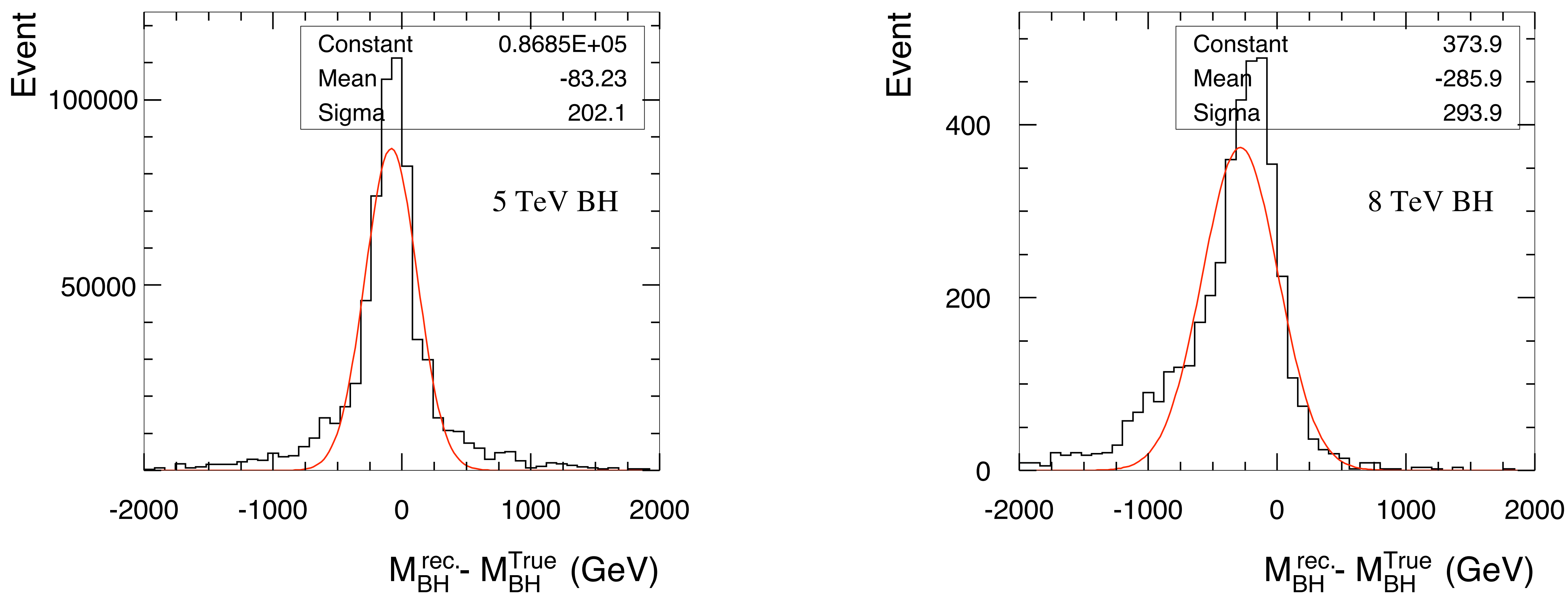
- hep-ph/0411022, JHEP05(2005)053; see also CM Harris, PhD thesis, hep-ph/0502005; CM Harris et al (CHARYBDIS event generator) hep-ph/0307035, JHEP08(2003)033
- earlier work: SB Giddings & S Thomas, hep-ph/0106219; S Dimopoulos & G Landsberg, hep-ph/0106295

Missing transverse energy



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

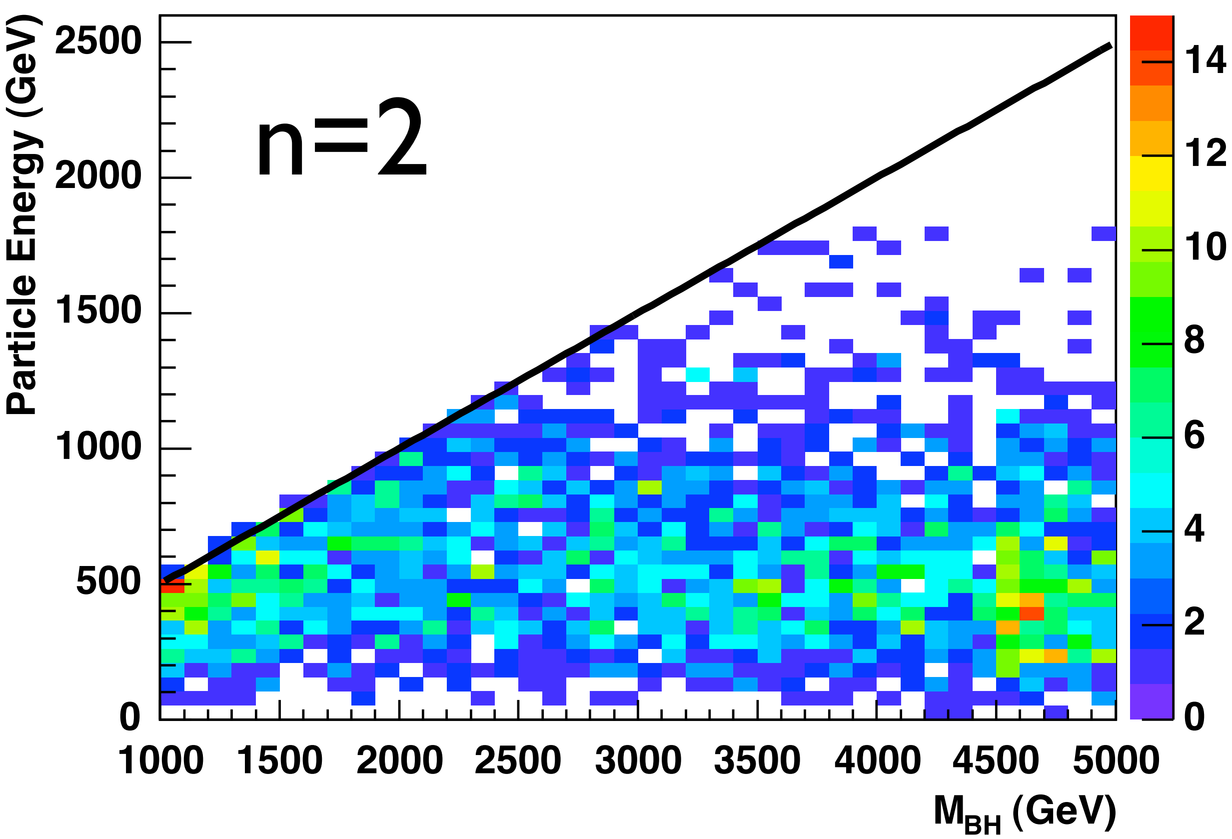
Measuring black hole masses

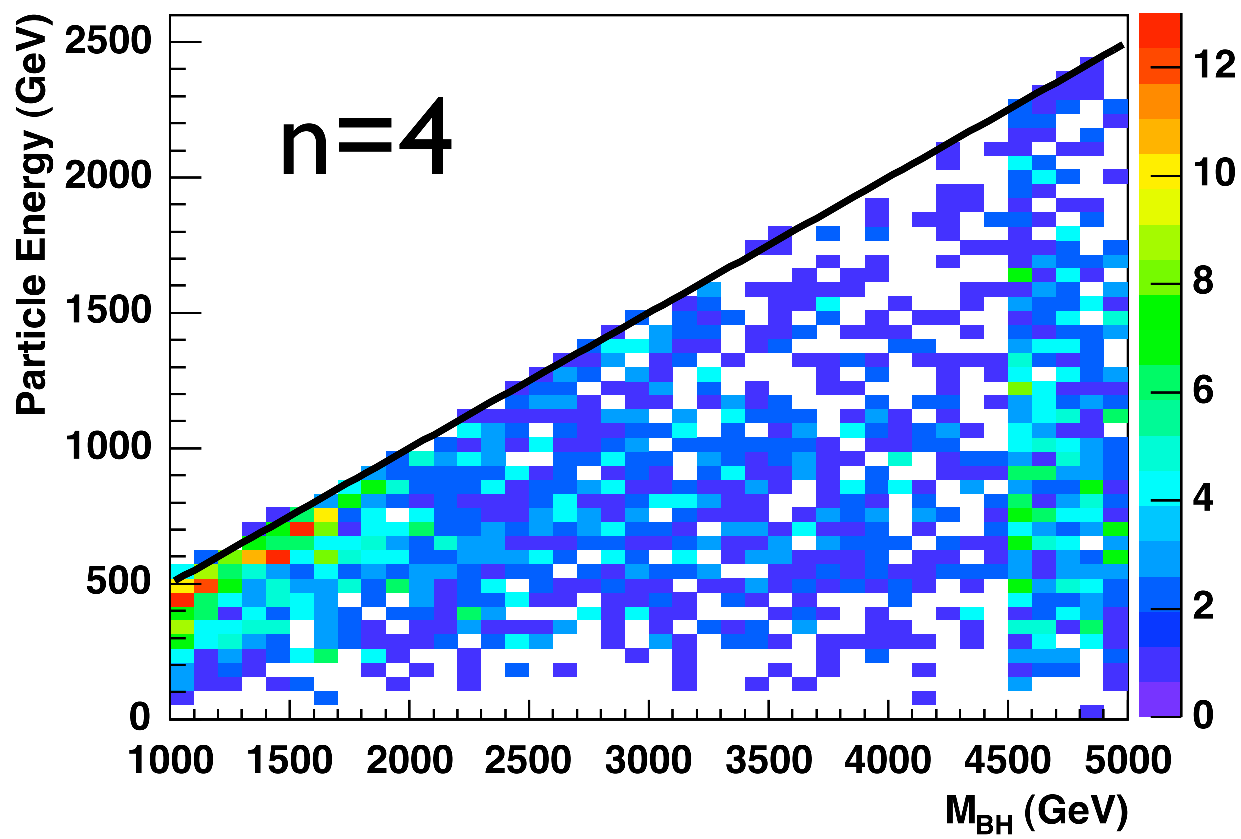


- Need $\not{E}_T < 100$ GeV for adequate resolution

➡ $\Delta M_{BH}/M_{BH} \sim 4\%$

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

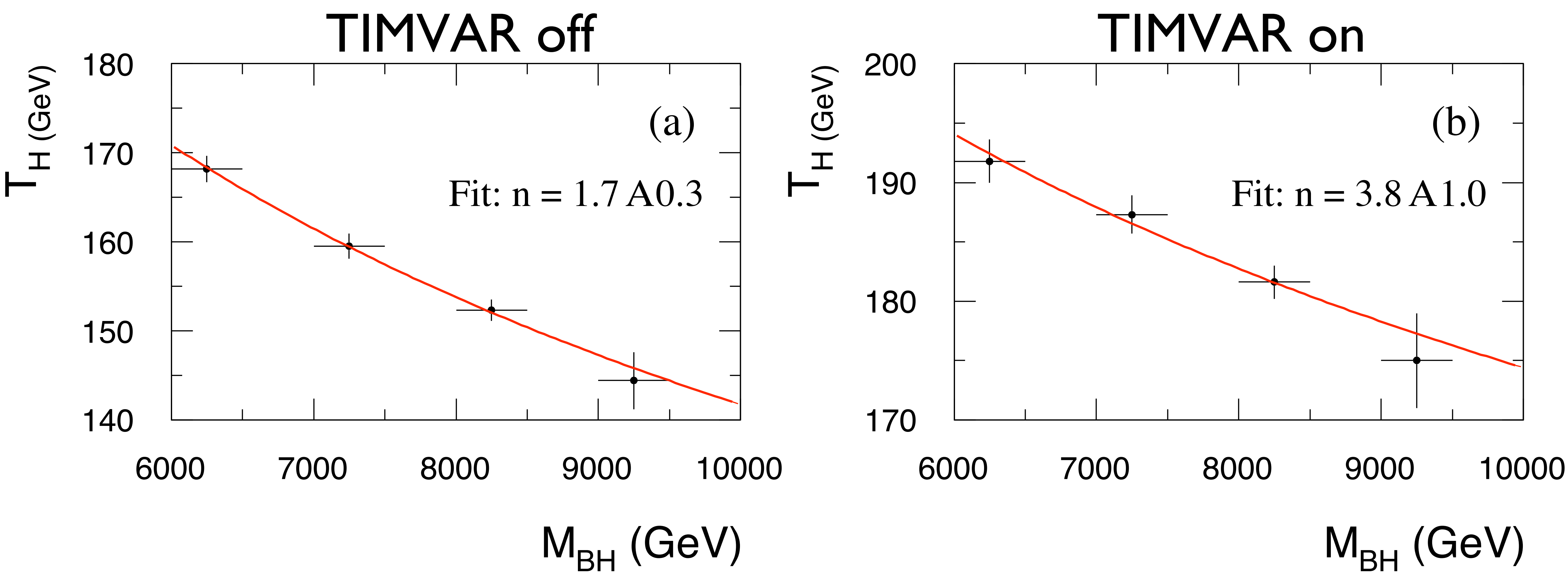




Energy distribution of primary emissions vs M_{BH}

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

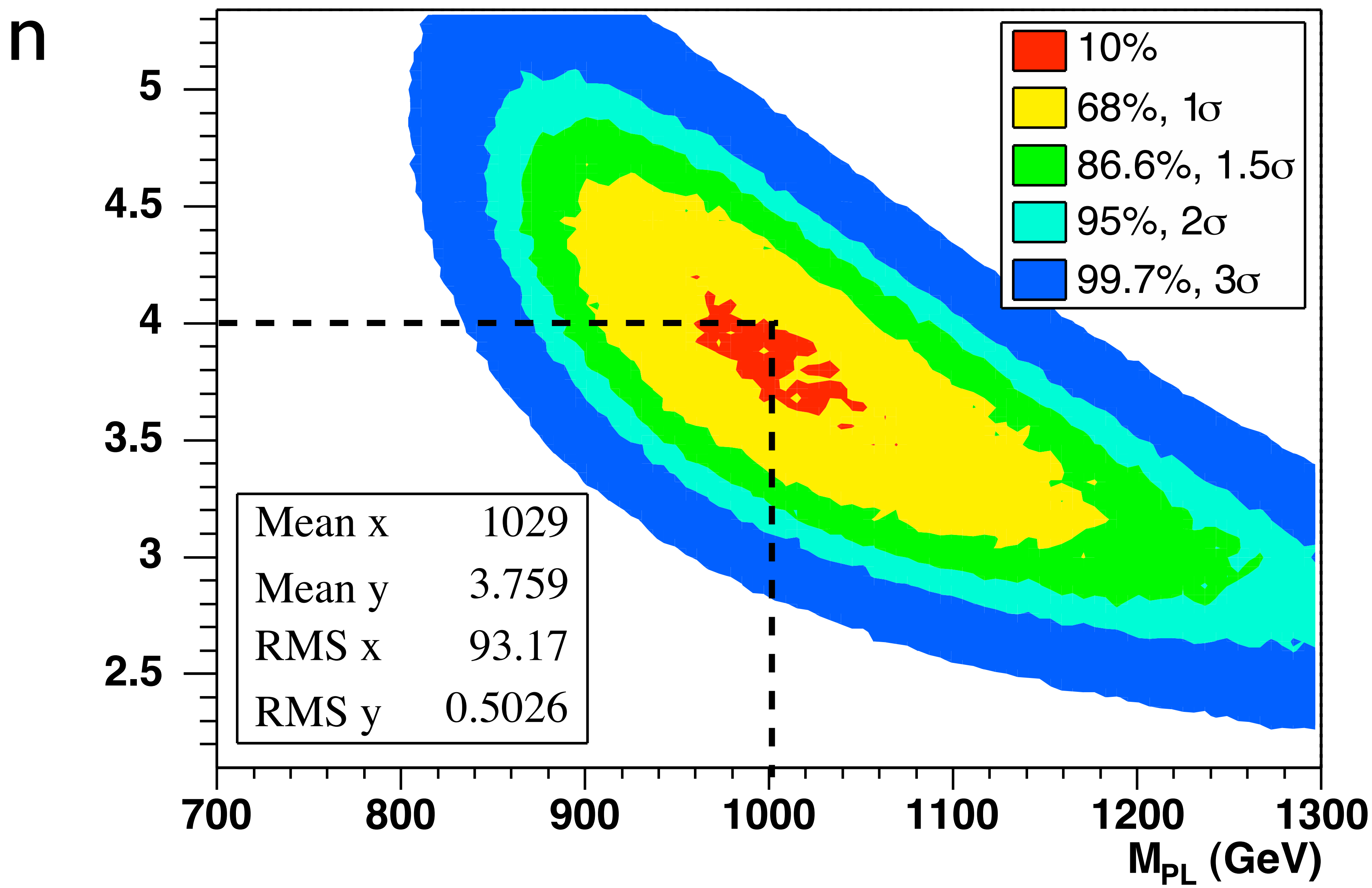
Effects of time dependence



Fits to primary electron spectrum for n=2

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

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
- Soon: spin-down phase in CHARYBDIS