Phenomenology of Black Holes at Hadron Colliders

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LHC2FC Institute, CERN
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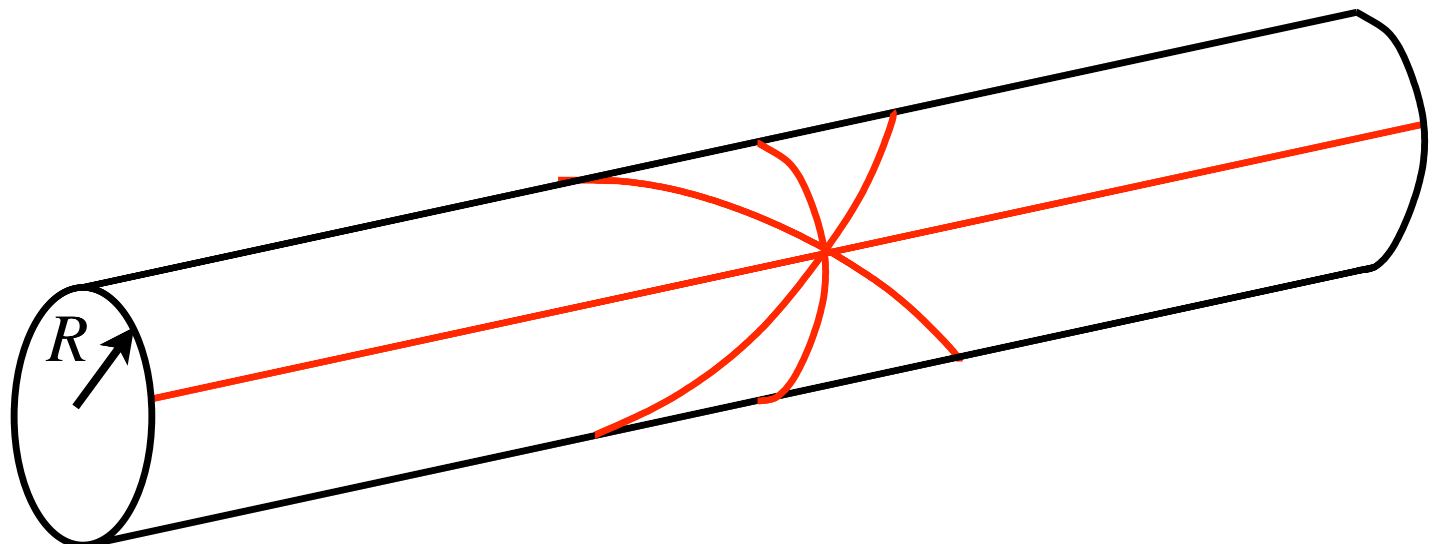
Large Extra Dimensions

- 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

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

$$G_{4+n} = M_D^{-2-n}$$

$$\Rightarrow \quad \overline{M}_{Pl} = M_D \left(\frac{M_D c}{\hbar} R \right)^{n/2}$$

- Hence for $M_D = 1$ TeV we need

$$10^{18}\ \mathrm{GeV} \sim 10^3\ \mathrm{GeV} \times (10^4\ R/\mathrm{fm})^{n/2}$$

➡ 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
- Observable effects of rotation?
- Conclusions and prospects

CHARYBDIS2: M Casals, SR Dolan, J Frost, JR Gaunt, MA Parker, MOP Sampaio, BRW, in preparation

Black hole production

- Expect parton (quark or gluon)-level cross section

$$\sigma\left(\hat{s}=M^2\right)=F_n\pi r_S^2$$

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

$$r_S=\frac{2\pi}{M_D}\left[\frac{1}{(n+2)\pi S_{n+2}}\frac{M}{M_D}\right]^{\frac{1}{n+1}}\quad,\quad S_p=\frac{2\pi^{\frac{p+1}{2}}}{\Gamma\left(\frac{p+1}{2}\right)}$$

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

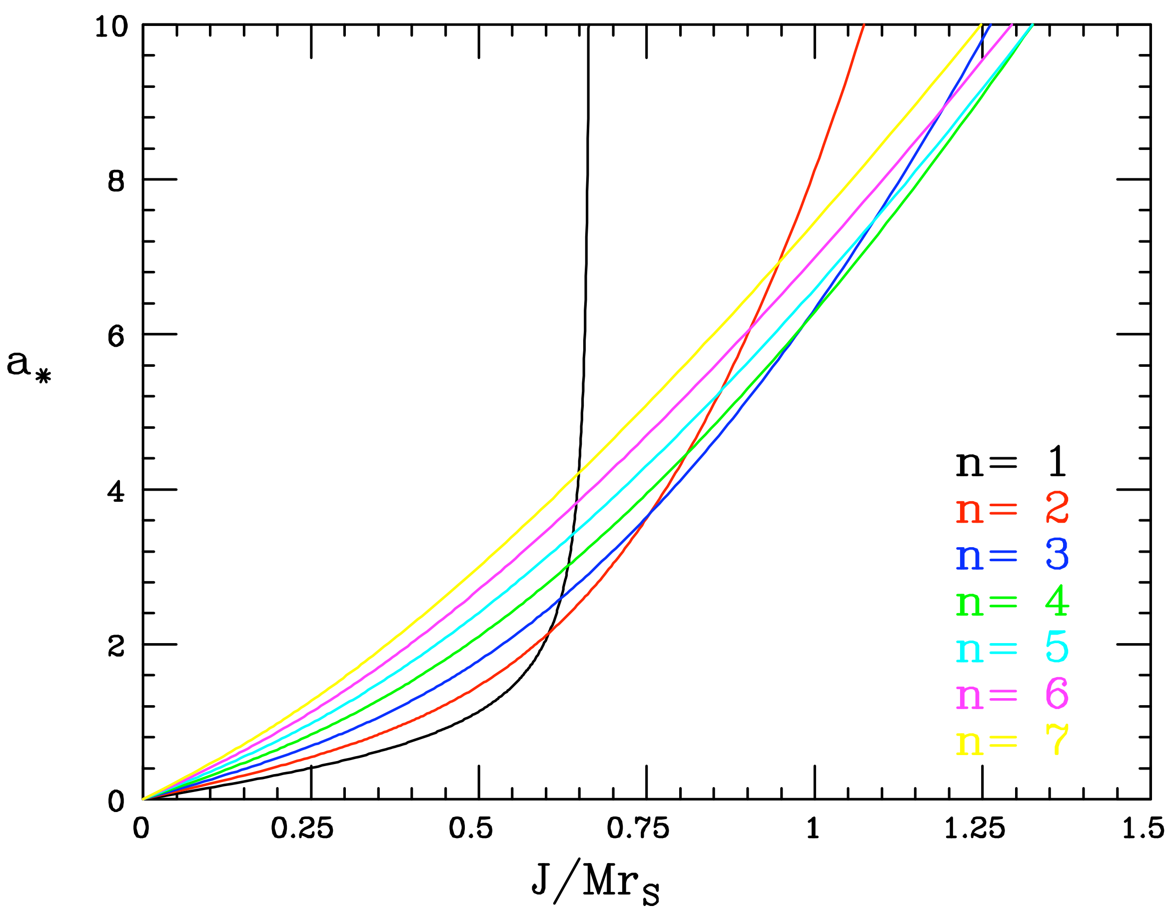
- Usually set Planck scale $M_D=1$ TeV for illustration

Rotating Black Holes

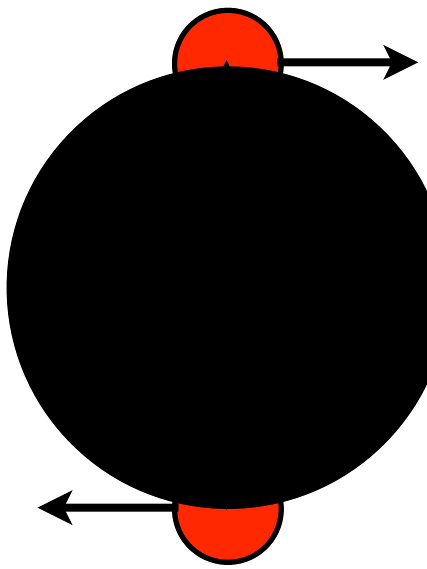
- Myers-Perry (Kerr) solution (Q=0)

$$r_h = r_S \left(1 + a_*^2\right)^{-\frac{1}{n+1}} \quad , \quad A_h = S_{n+2}\, r_h^{n+2} \left(1 + a_*^2\right)$$

- Angular momentum parameter $a_* = \dfrac{(n+2)J}{2Mr_h}$



BH formation factor (1)



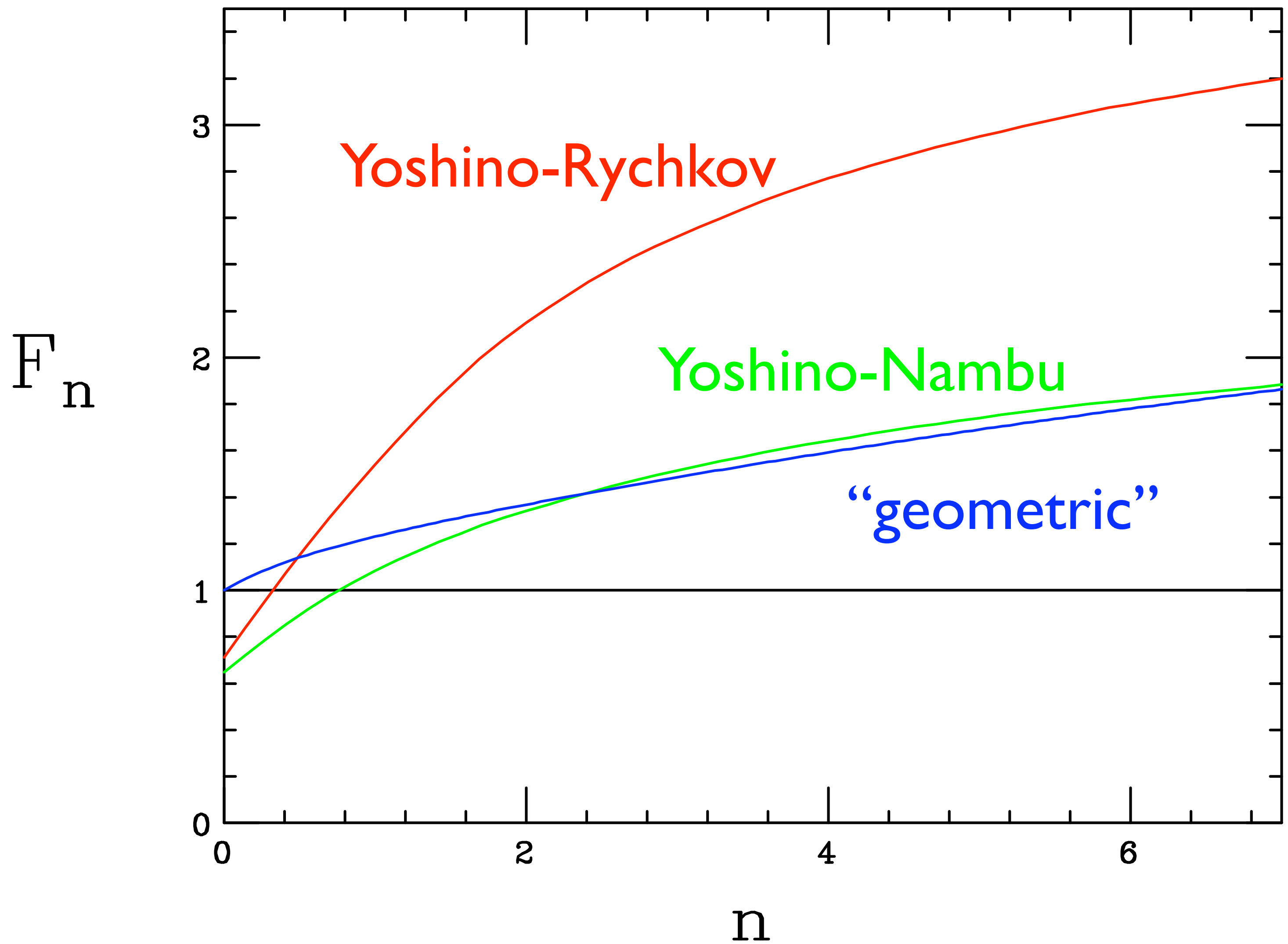
$$b_{max} = 2r_h = 2r_s\left[1 + a_*^2\right]^{-\frac{1}{n+1}}$$

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

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

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

BH formation factor (2)



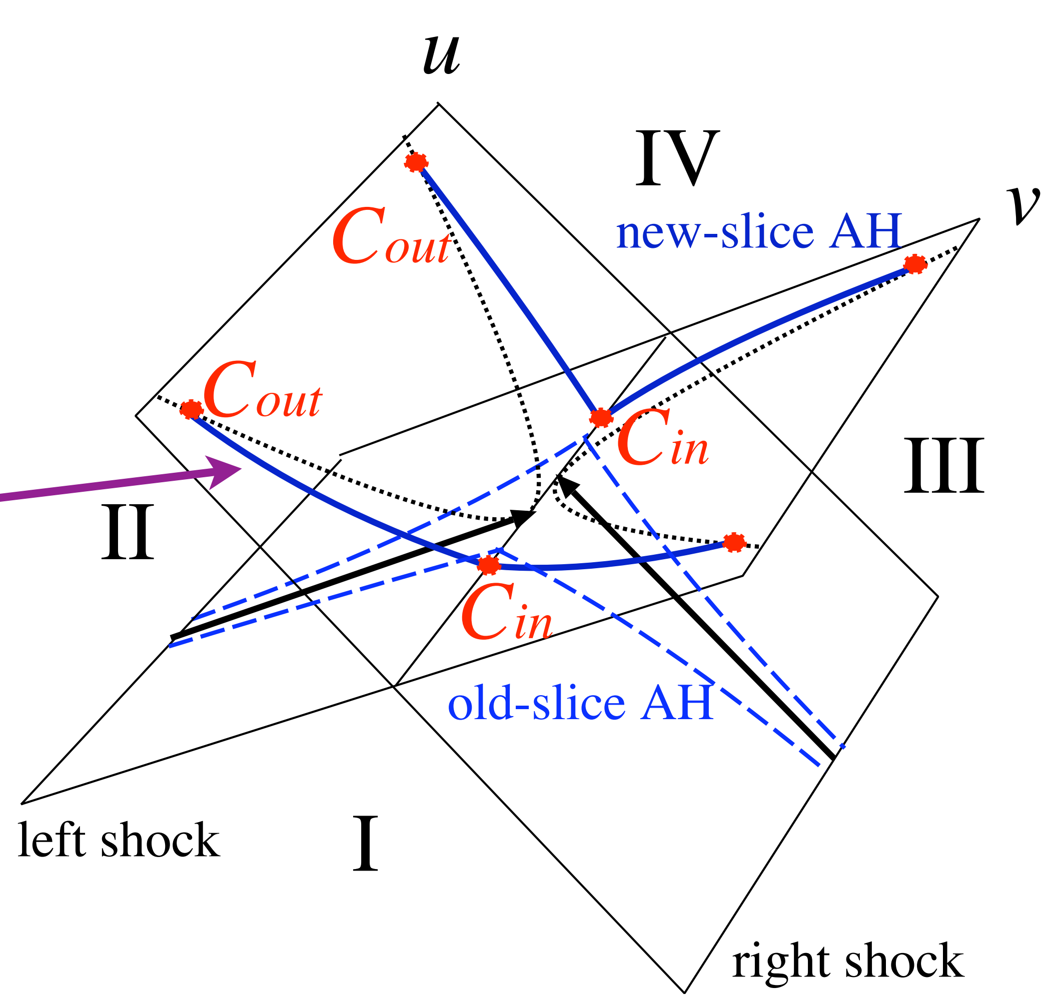
DM Eardley & SB Giddings, gr-qc/0201034

H Yoshino & Y Nambu, gr-qc/0209003

H Yoshino & VS Rychkov, hep-th/0503171

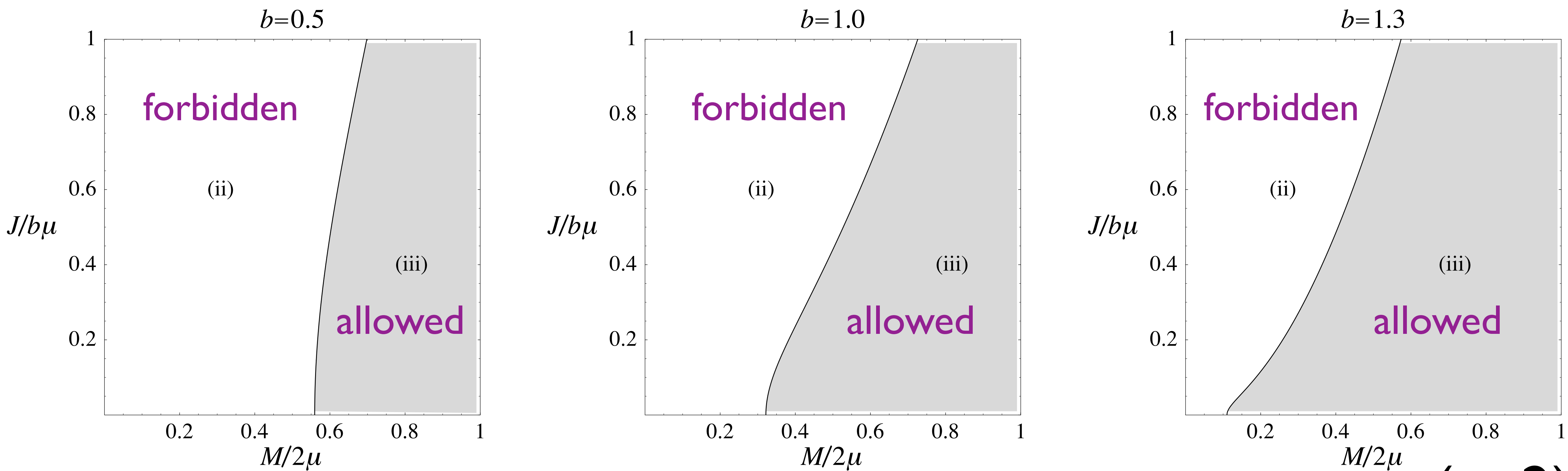
Yoshino-Rychkov Bound on $\hat{\sigma}_{BH}$

AH = apparent horizon
(closed trapped surface)



- 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}: $A_h(M, J) > A_h(M_{lb}, 0)$

Limits on M_{BH} and J_{BH}



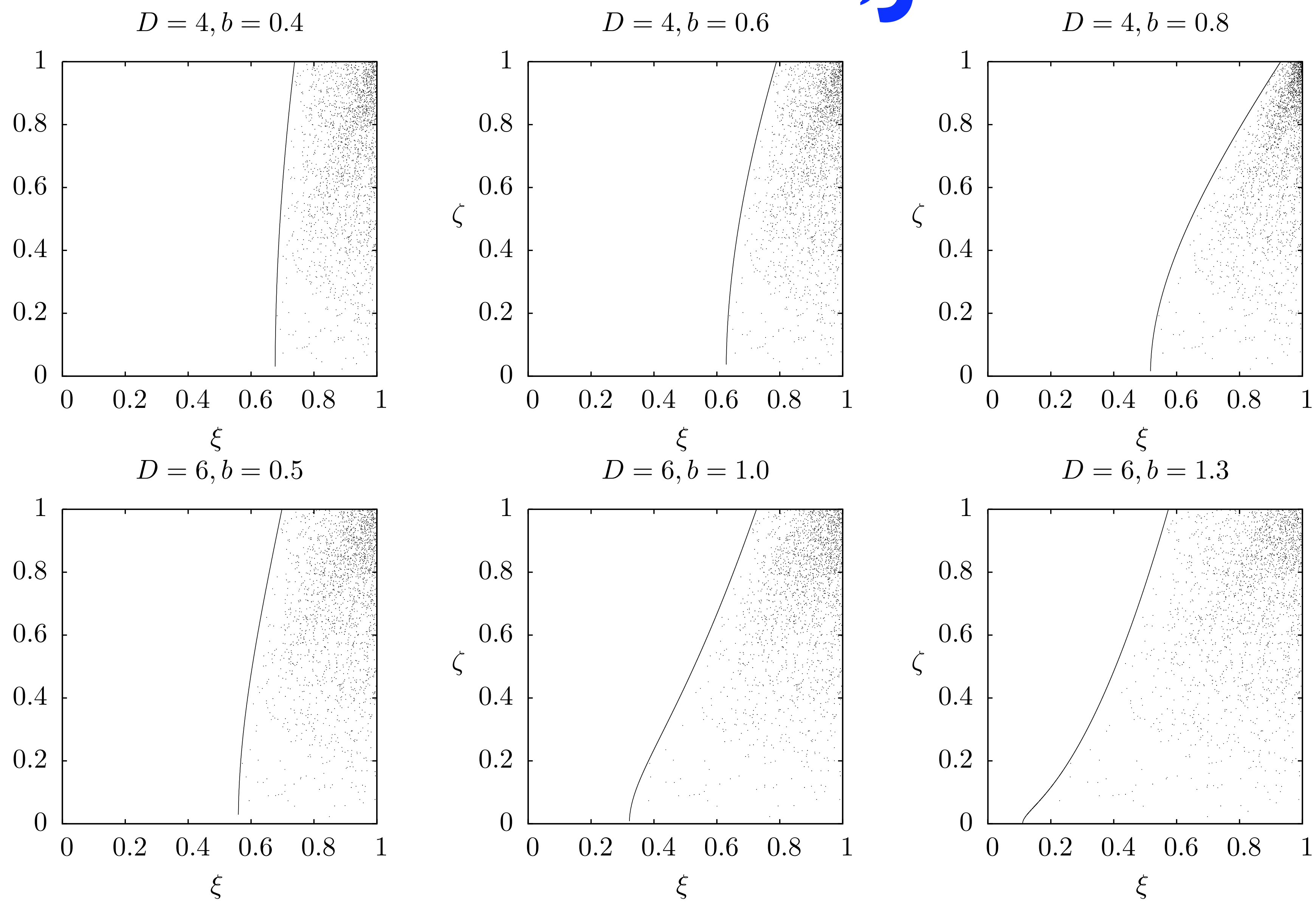
(n=2)

- $\mu \equiv \sqrt{\hat{s}}/2$, so $M/2\mu = 1$ implies $M_{BH}^2 = \hat{s}$
- We need a model for the distribution in the allowed region

Model for M,J Lost

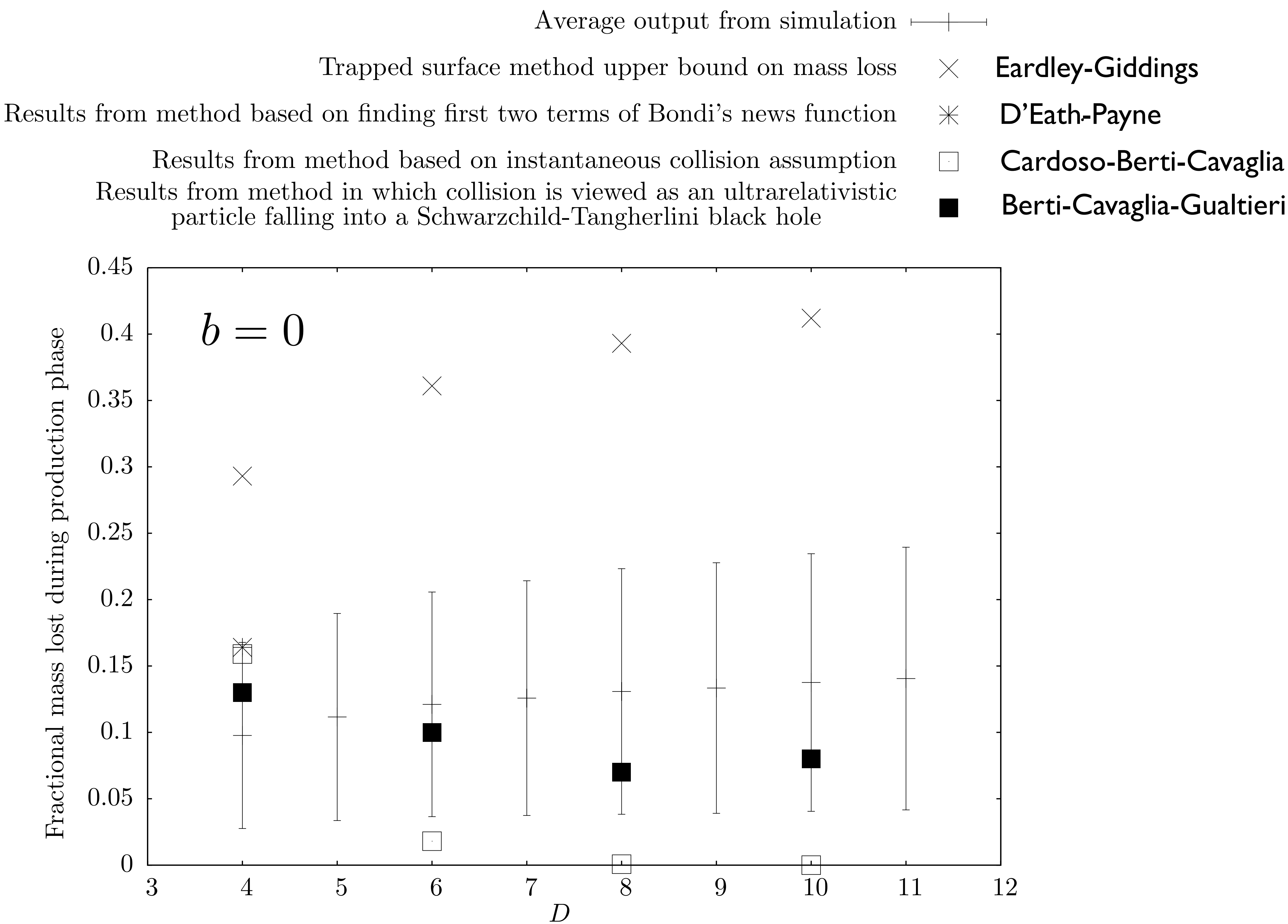
$$\zeta = J/b\mu$$

$$\xi = M/2\mu$$

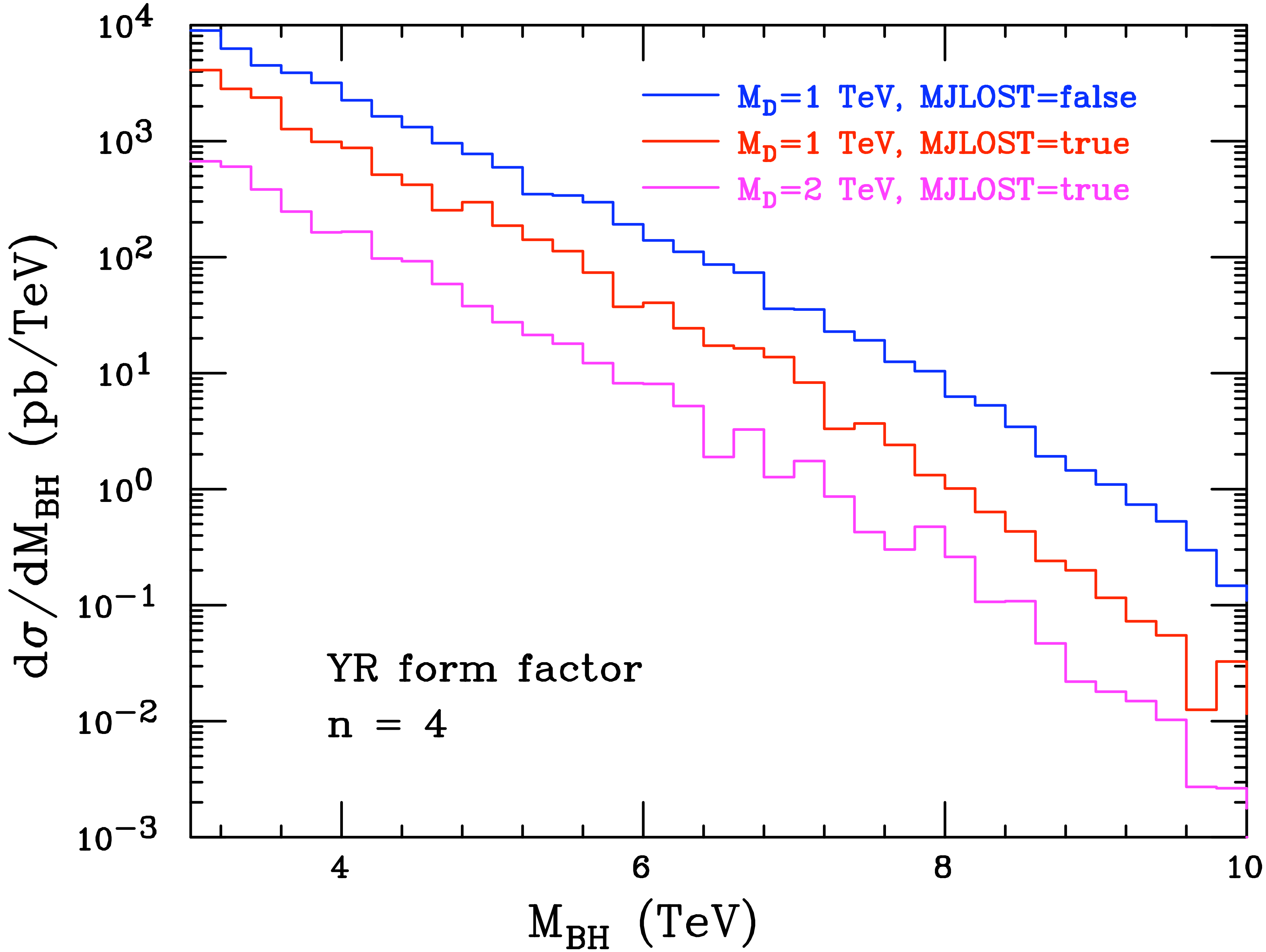


- Distribution vanishes on boundary curve
- Concentrated around $\Omega(M, J) = \Omega(2\mu, b\mu)$

Comparison with other models



BH cross section at LHC



➡ A ~5 TeV BH per minute at LHC!

Black hole decay (1)

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

Black Hole Thermodynamics

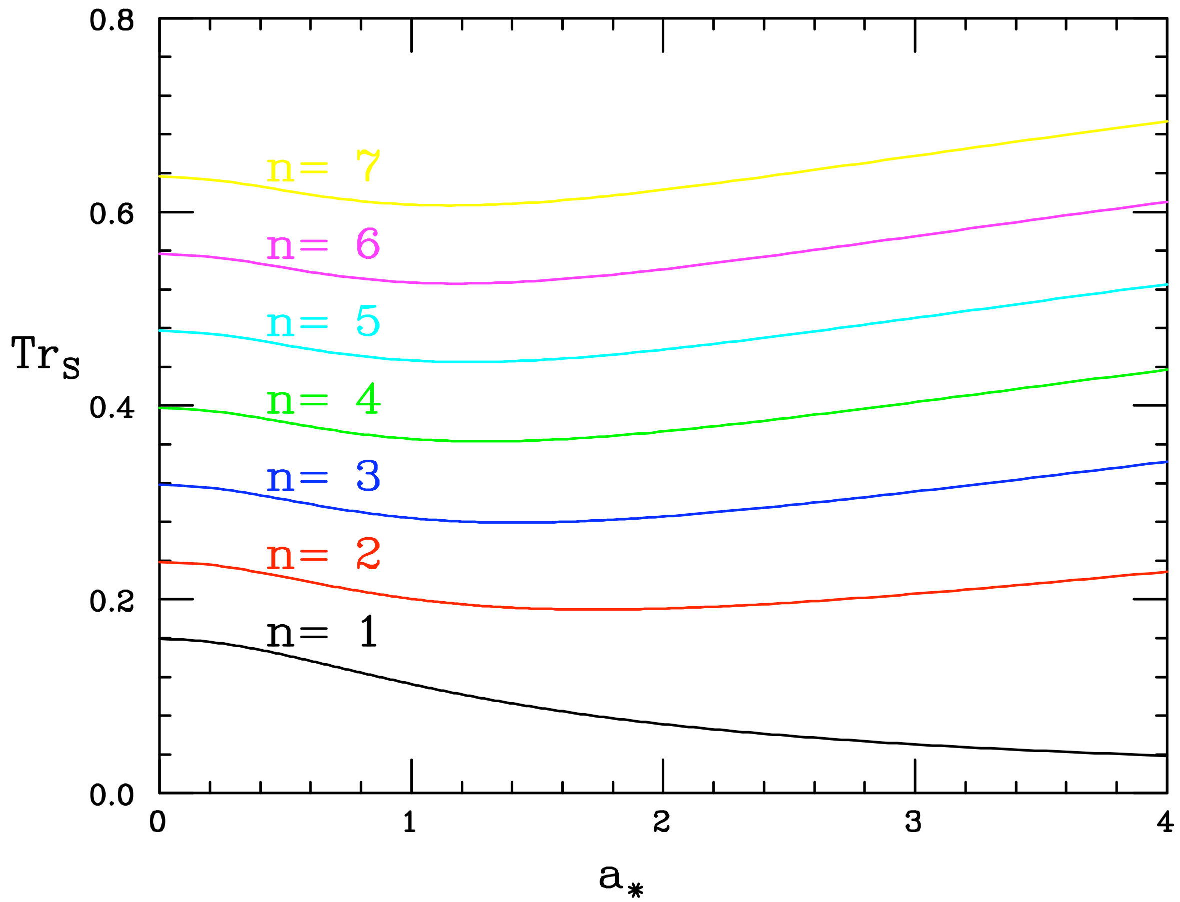
- Bekenstein-Hawking entropy $S = (2\pi)^{1-n} M_D^{n+2} A_h$
- First Law $dU = dM = T\,dS + \Omega\,dJ$
- Hawking temperature $T = \left(\frac{\partial M}{\partial S}\right)_J = \frac{(2\pi)^{n-1}}{M_D^{n+2}} \left(\frac{\partial M}{\partial A_h}\right)_J$

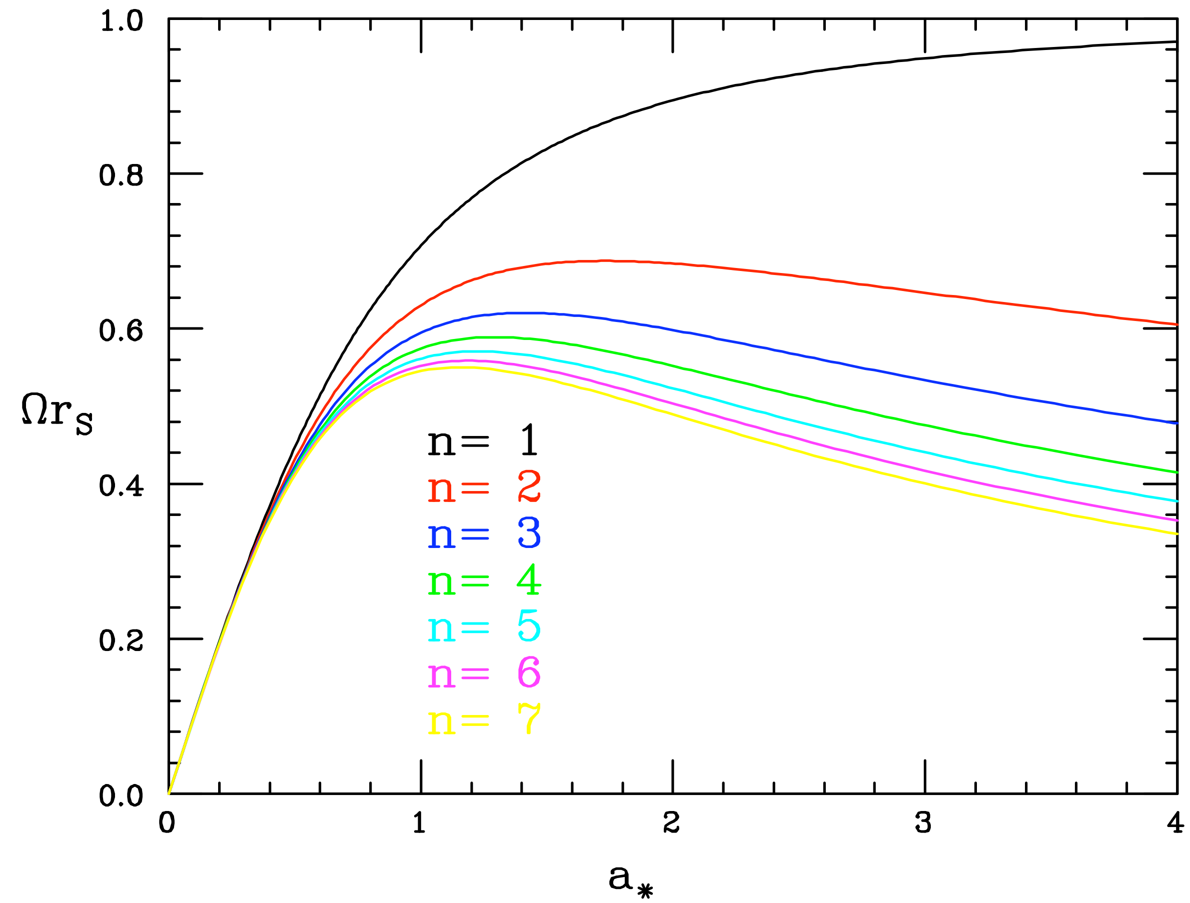
$$\Rightarrow \quad T = \frac{(n+1) + (n-1)a_*^2}{4\pi r_h (1 + a_*^2)}$$

- Angular velocity of horizon $\Omega = \left(\frac{\partial U}{\partial J}\right)_S = \left(\frac{\partial M}{\partial J}\right)_{A_h}$

$$\Rightarrow \quad \Omega = \frac{a_*}{r_h (1 + a_*^2)}$$

Black Hole Properties





- Temperature not strongly J-dependent (but spectrum is)
- For n>1, angular velocity decreases at large J!

Black hole decay (2)

- We assume SM particle emission on brane is dominant
  - ➡ Hawking distribution

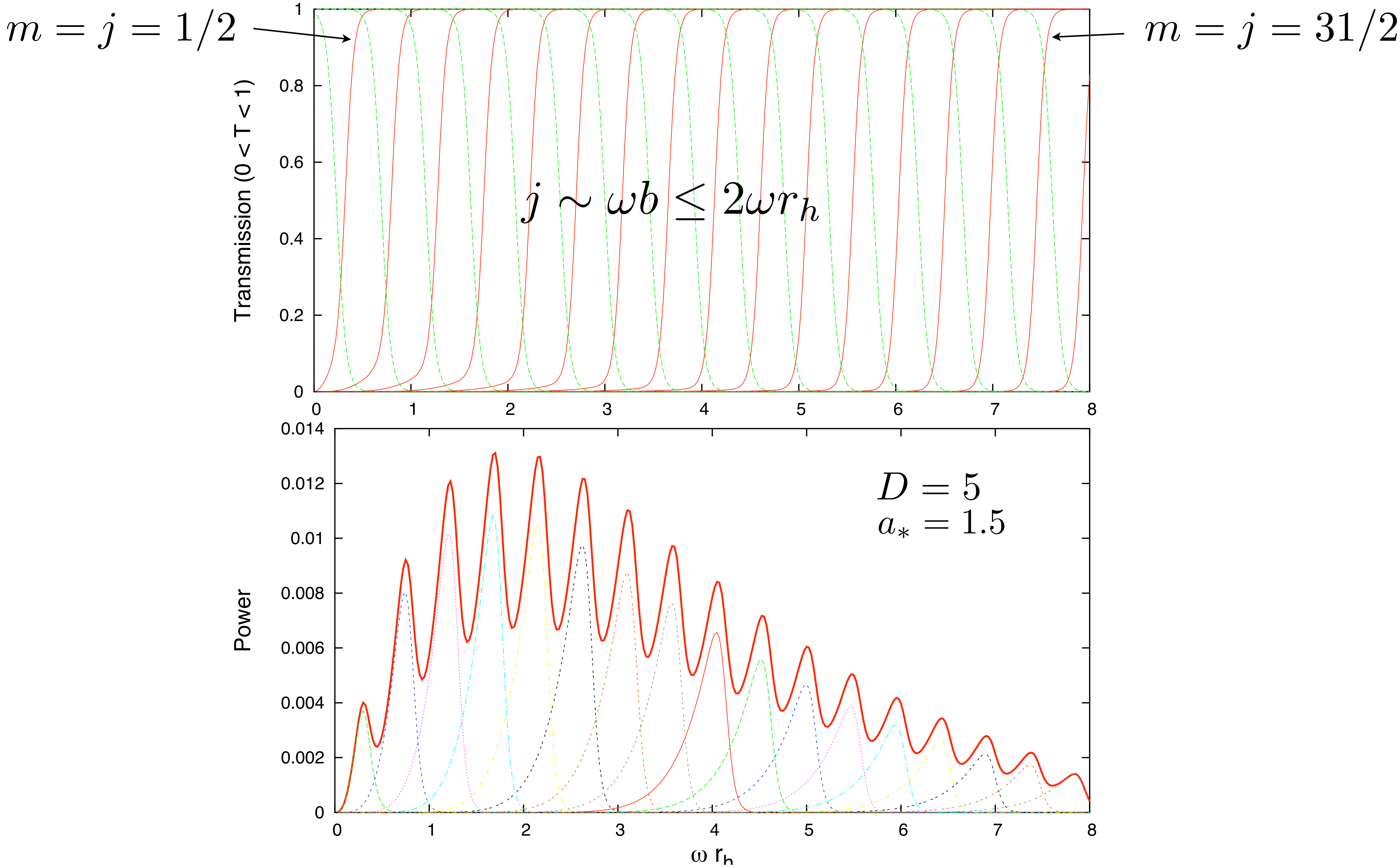
$$\frac{d^3 N_\lambda}{d\cos\theta\, d\omega\, dt} = \frac{1}{4\pi}\sum_{jm}\frac{T_{jm}}{e^{\frac{\omega - m\Omega}{T}} \pm 1}\left|{}_\lambda S_{jm}(\theta,\phi)\right|^2$$

  - ➡ $\omega - m\Omega =$ energy in co-rotating frame: favours $m = j$
  - ➡ T_{jm} is transmission coefficient (greybody factor)
  - ➡ Superradiant bosons: $T_{jm} < 0 \Rightarrow R_{jm} > 1$ for $m > \omega/\Omega$
  - ➡ ${}_\lambda S_{jm}$ is (generalized) spheroidal harmonic
  - ➡ "Democratic" emission: fermions dominate

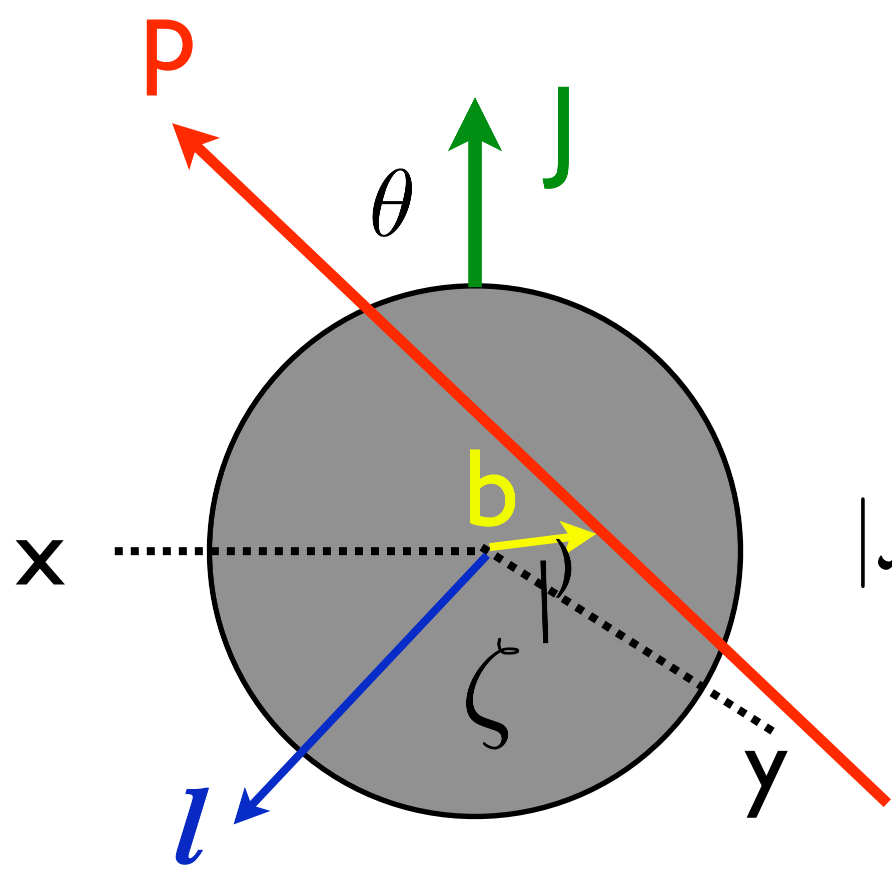
Degrees of Freedom

Particle	Scalar	Spinor	Vector
Quark		72	
Gluon			16
Lepton		12	
Neutrino		6^*	
Photon			2
Z	1		2
W	2		4
Higgs	1		
Total	4	90	24

Fermion power flux (1)



Classical Limit



$$\mathbf{p} = \omega(\sin\theta, 0, \cos\theta)$$

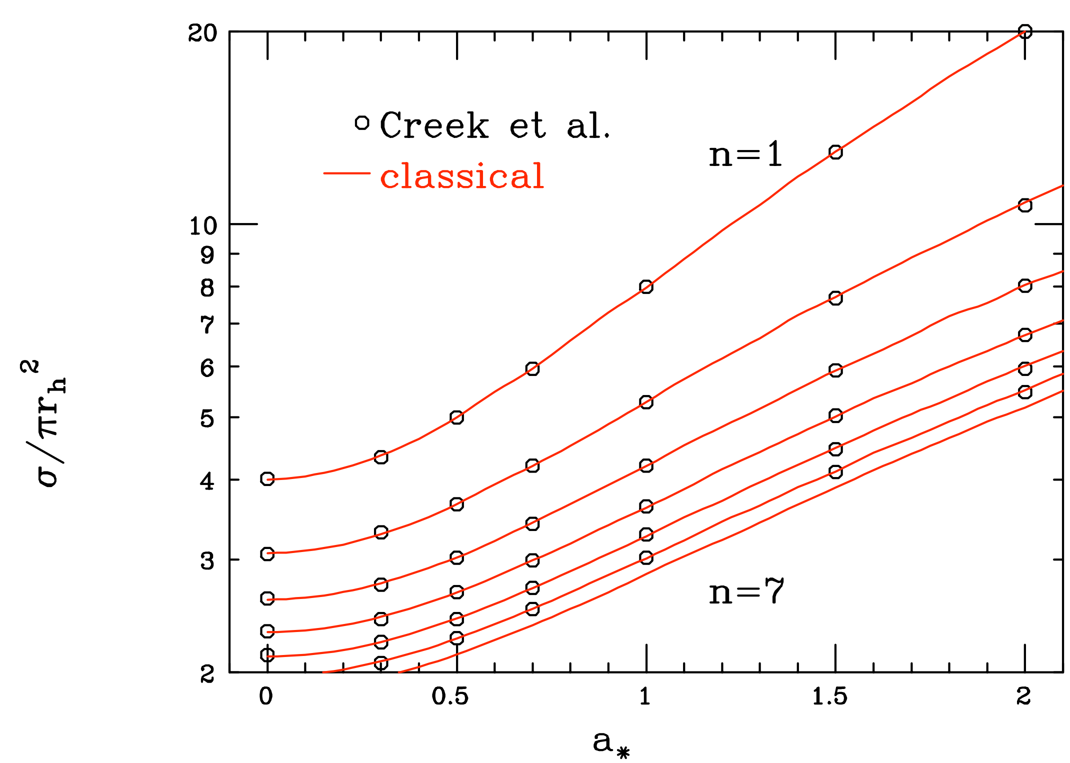
$$\mathbf{b} = b(-\cos\theta\sin\zeta, \cos\zeta, \sin\theta\sin\zeta)$$

$$\boldsymbol{l} = b\,\omega(-\cos\theta\cos\zeta, \sin\zeta, -\sin\theta\cos\zeta)$$

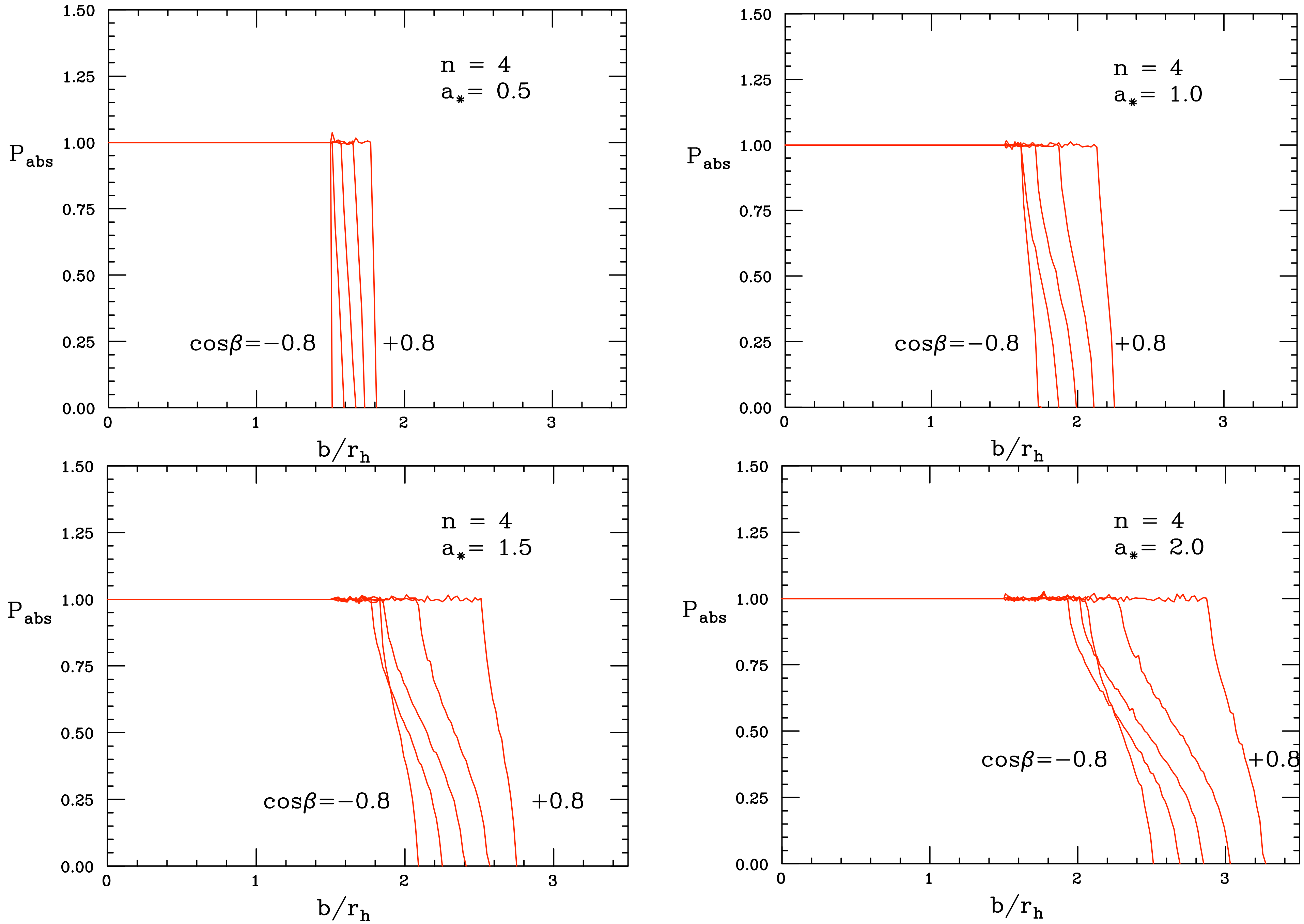
$$\boldsymbol{l}\cdot\mathbf{J}/lJ \equiv \cos\beta = -\sin\theta\cos\zeta$$

$$|\mathcal{A}_{lm}|^2 \to P_{abs}(b,\theta,\zeta) = \Theta\left(b_c(\theta,\zeta) - b\right)$$

$$\sigma_{class} = \frac{1}{4}\int d\cos\theta\, d\zeta\, b_c^2(\theta,\zeta)$$

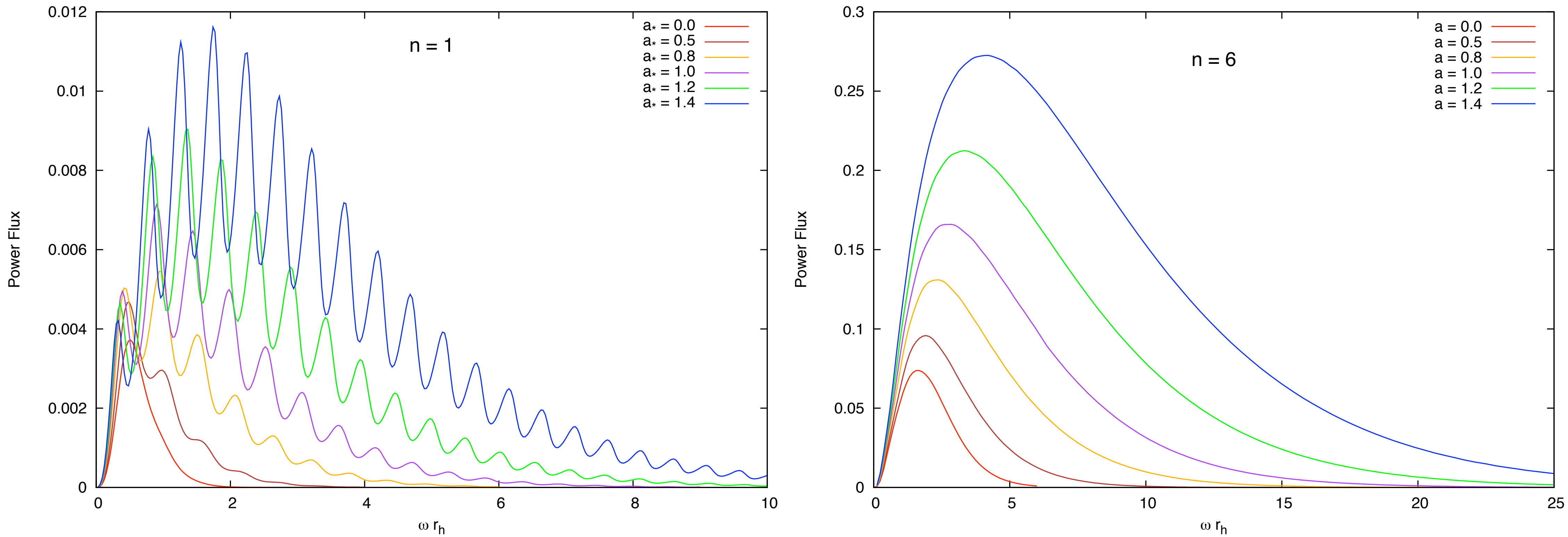


Classical impact parameter profile



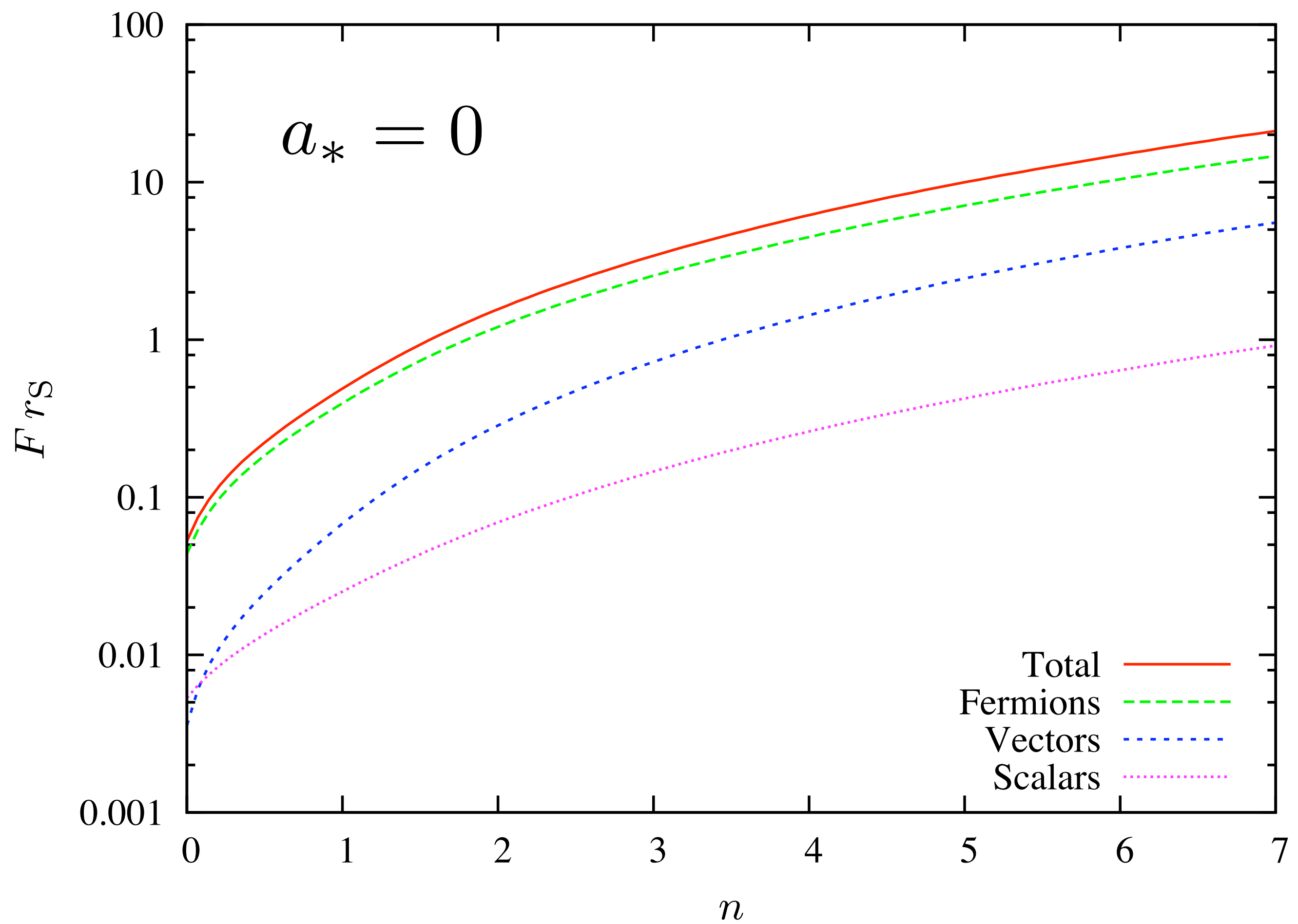
- Black disc grows with a_*
- Absorption/emission largest for $l||\mathbf{J}$

Fermion power flux (2)



- Rapid increase with a_* and/or n
- Smoother profile at large n

Integrated Hawking flux

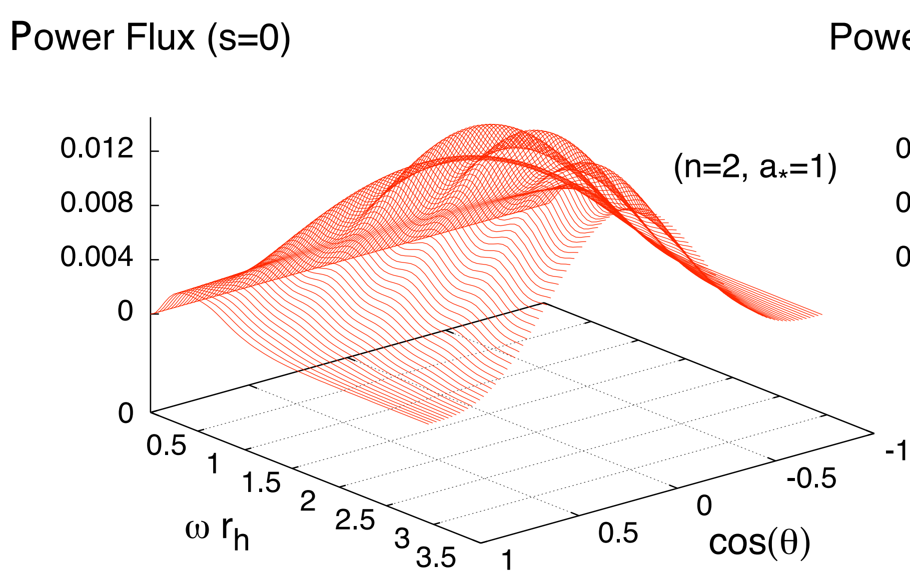


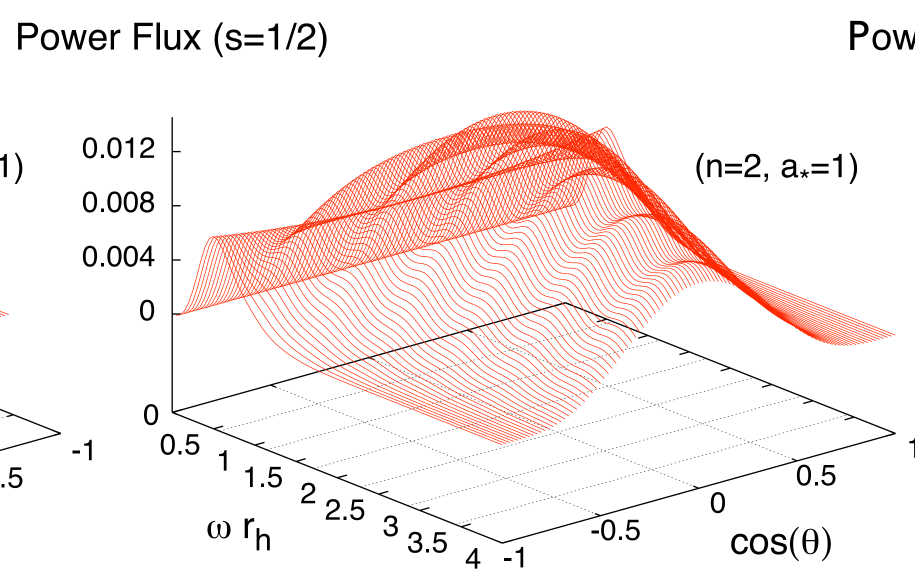
- $F^{tot}\, r_S \gg 1$ at large n
- Will be enhanced by rotation

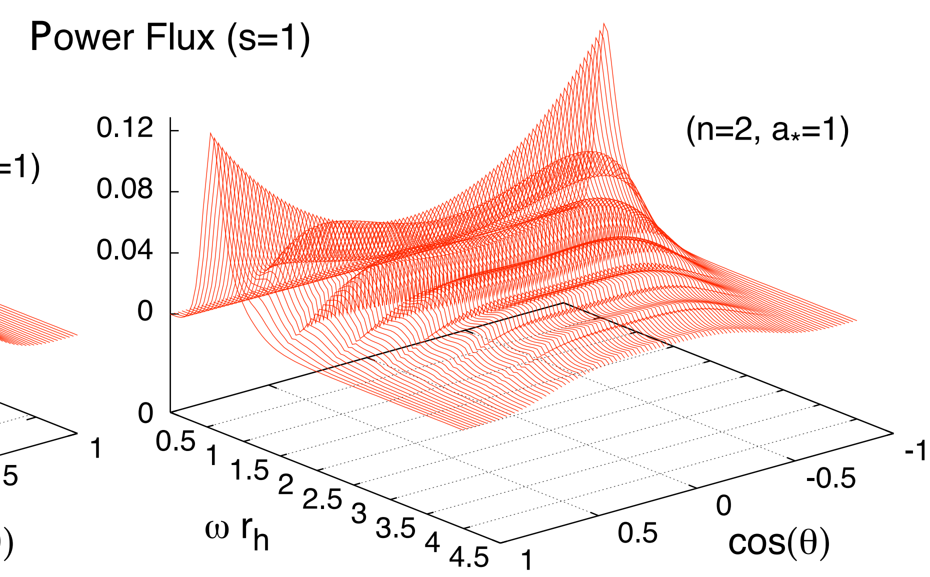
➡ Transit time $\gg$ time between emissions

➡ Decay no longer quasi-stationary at large n

Angular distributions







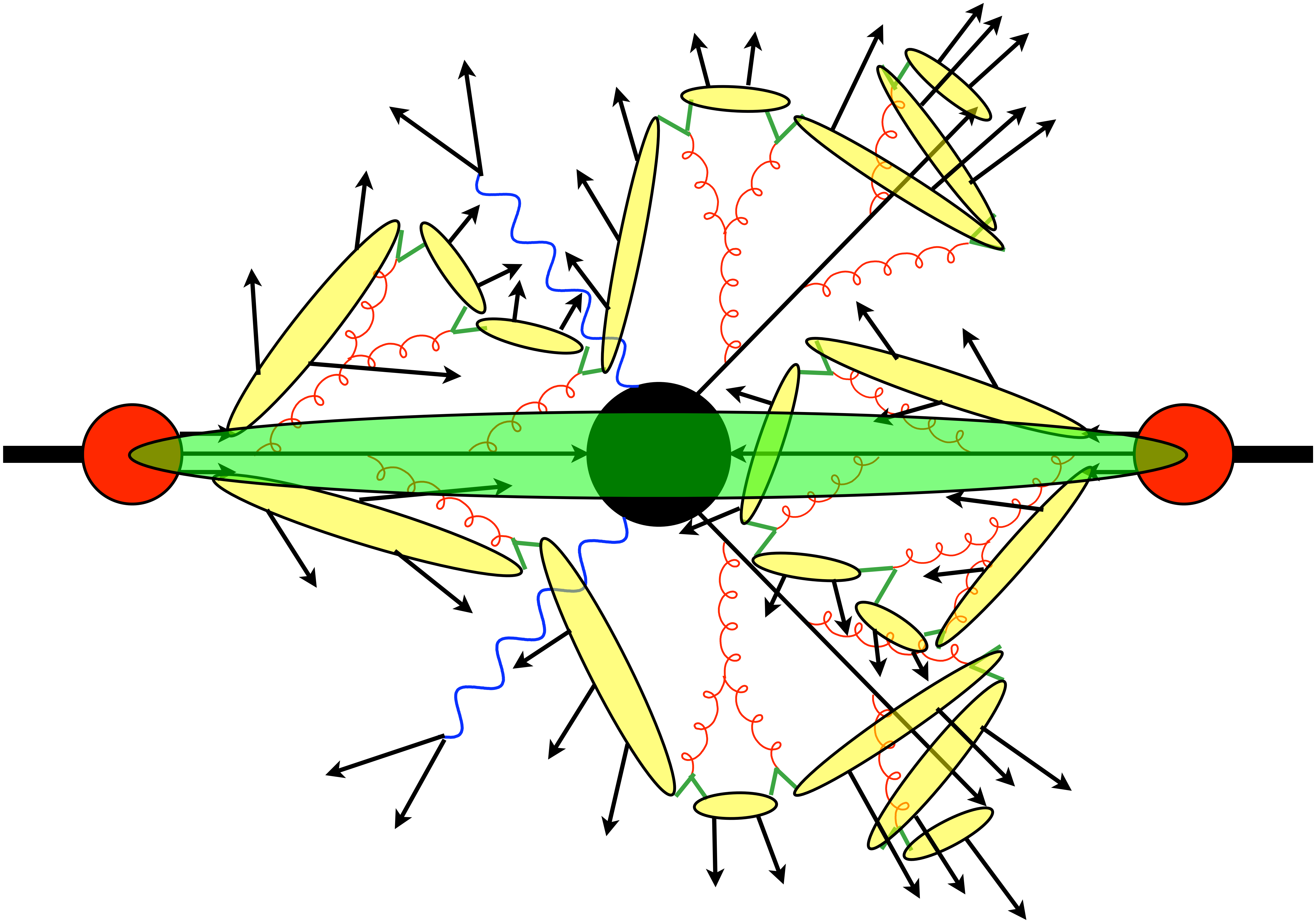
- Equatorial (centrifugal) bulge
- Strong polar (& polarized) emission of vectors

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
- BlackMax (Dai et al., arXiv:0711.3012)
  - ➜ J≠0; energy loss option; variable T; split branes; g.b.f.
- CHARYBDIS2 (Casals et al., in preparation)
  - ➜ J≠0; energy loss model; variable T; remnant options; g.b.f.

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

LHC event simulation



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.
NBODY	Remnant decay multiplicity	2-5	2

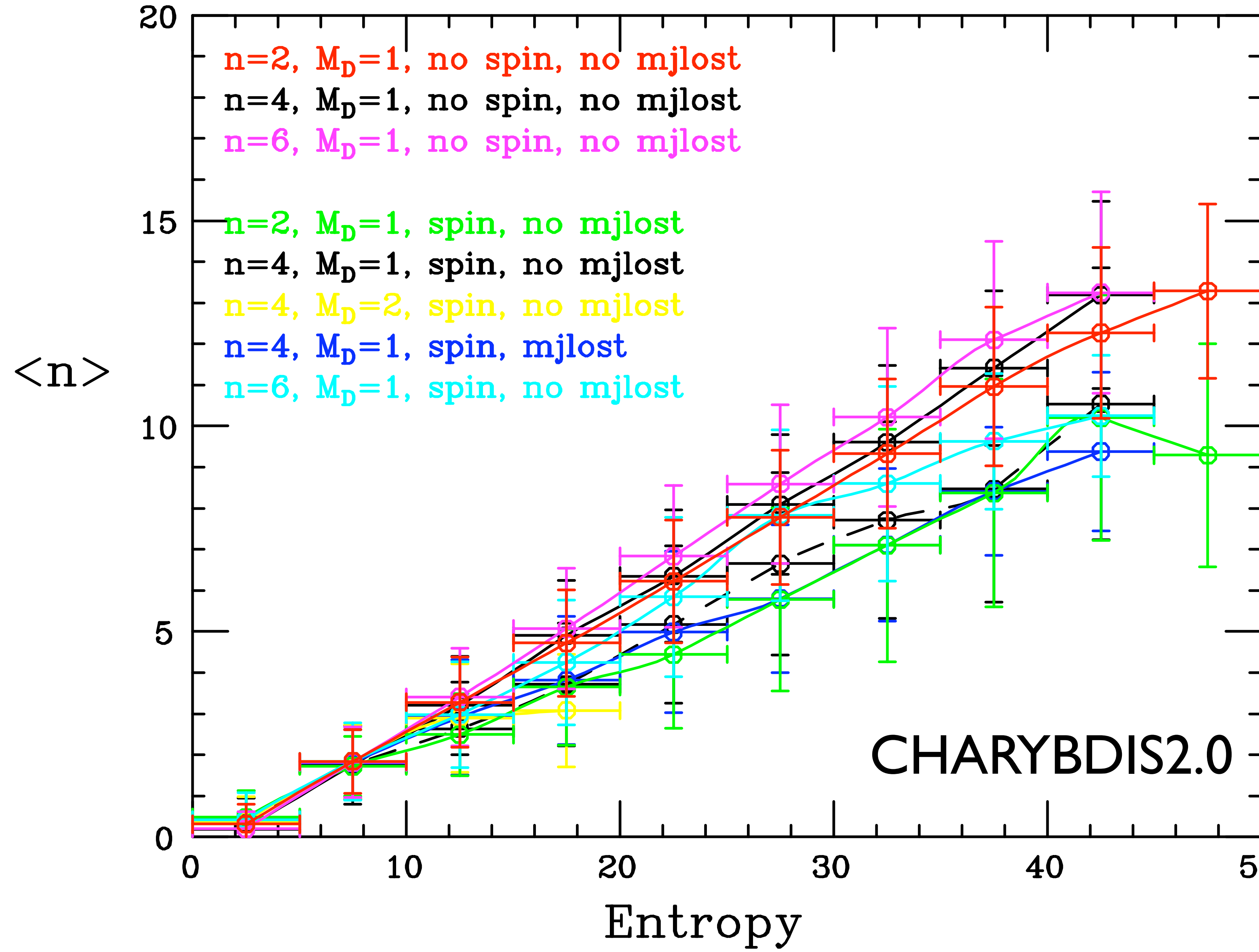
New CHARYBDIS2 parameters

Name	Description	Values	Default
MJLOST	M,J loss in production	logical	.TRUE.
BHSPIN	Include BH rotation effects	logical	.TRUE.
BHJVAR	Vary BH spin axis in decay	logical	.TRUE.
RMBOIL	Boiling remnant model	logical	.FALSE.
THWMAX	Boiling temperature (GeV)	real	1000
RMMINM	Minimum remnant mass (GeV)	real	350
NBODYVAR	Variable n-body remnant decay	logical	.TRUE.
RMSTAB	Stable remnant model	logical	.FALSE.

Back-reaction issues

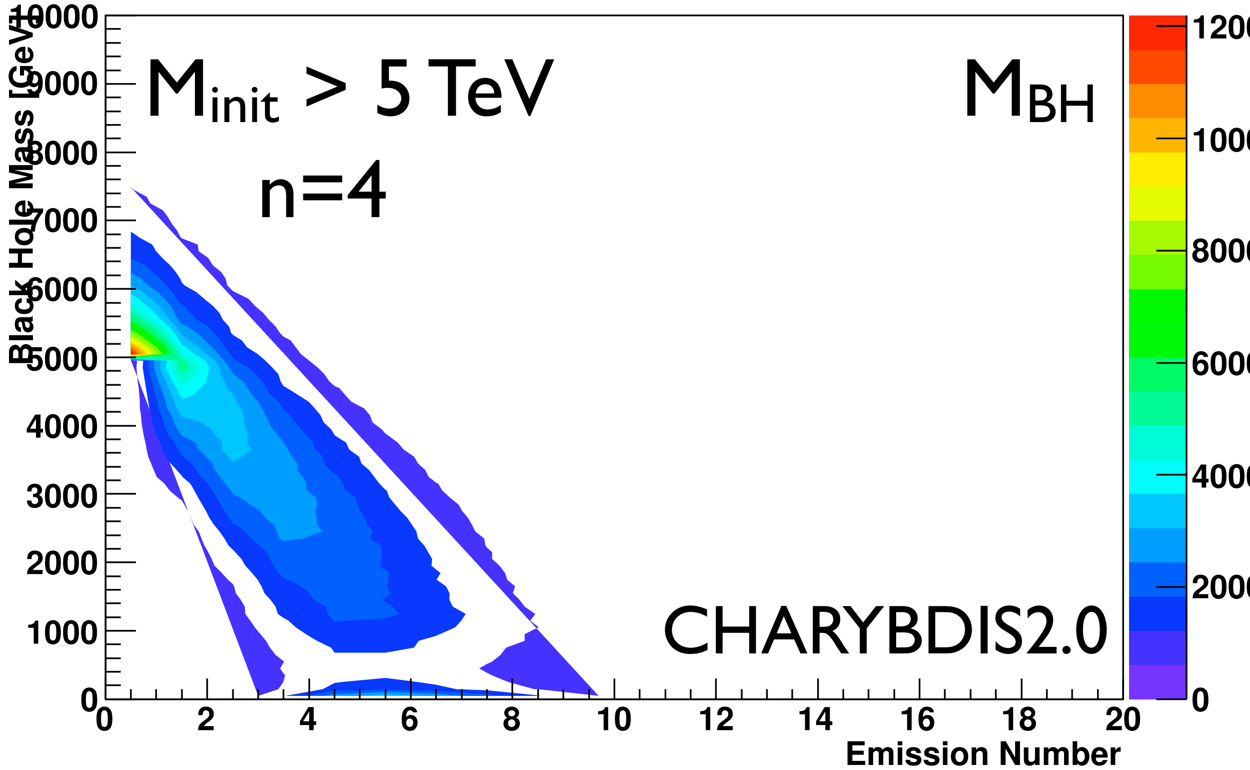
- Emissions cause black hole recoil (on brane)
  - ➜ Black hole gets significant p_t
- Angular momentum emission (j,m) changes J
  - ➜ Fixed axis option: J' = J-m
  - ➜ Variable axis option: $(J', m_{J'})$ chosen using Clebsch-Gordan probabilities

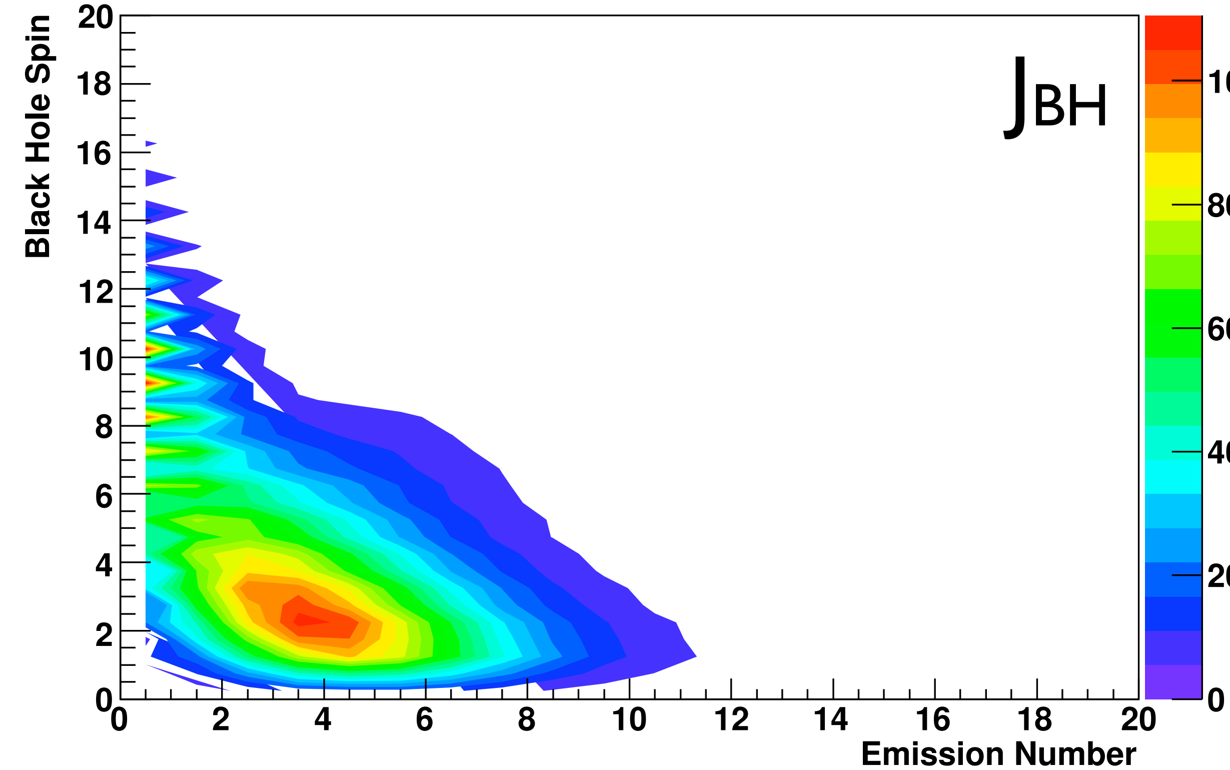
Primary Multiplicity vs Entropy

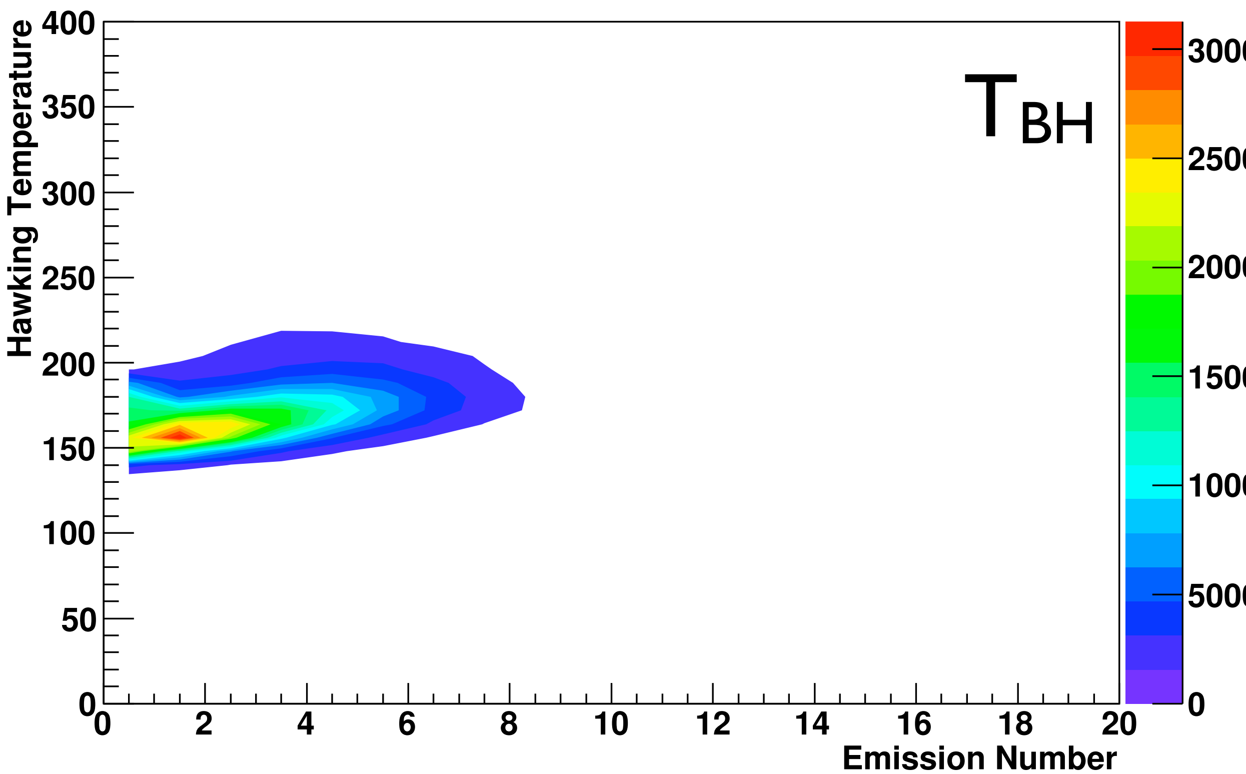


- "Error bars" show r.m.s. fluctuations
- $\langle n \rangle \simeq S/4$ is approximately universal

Black Hole Spin-Down

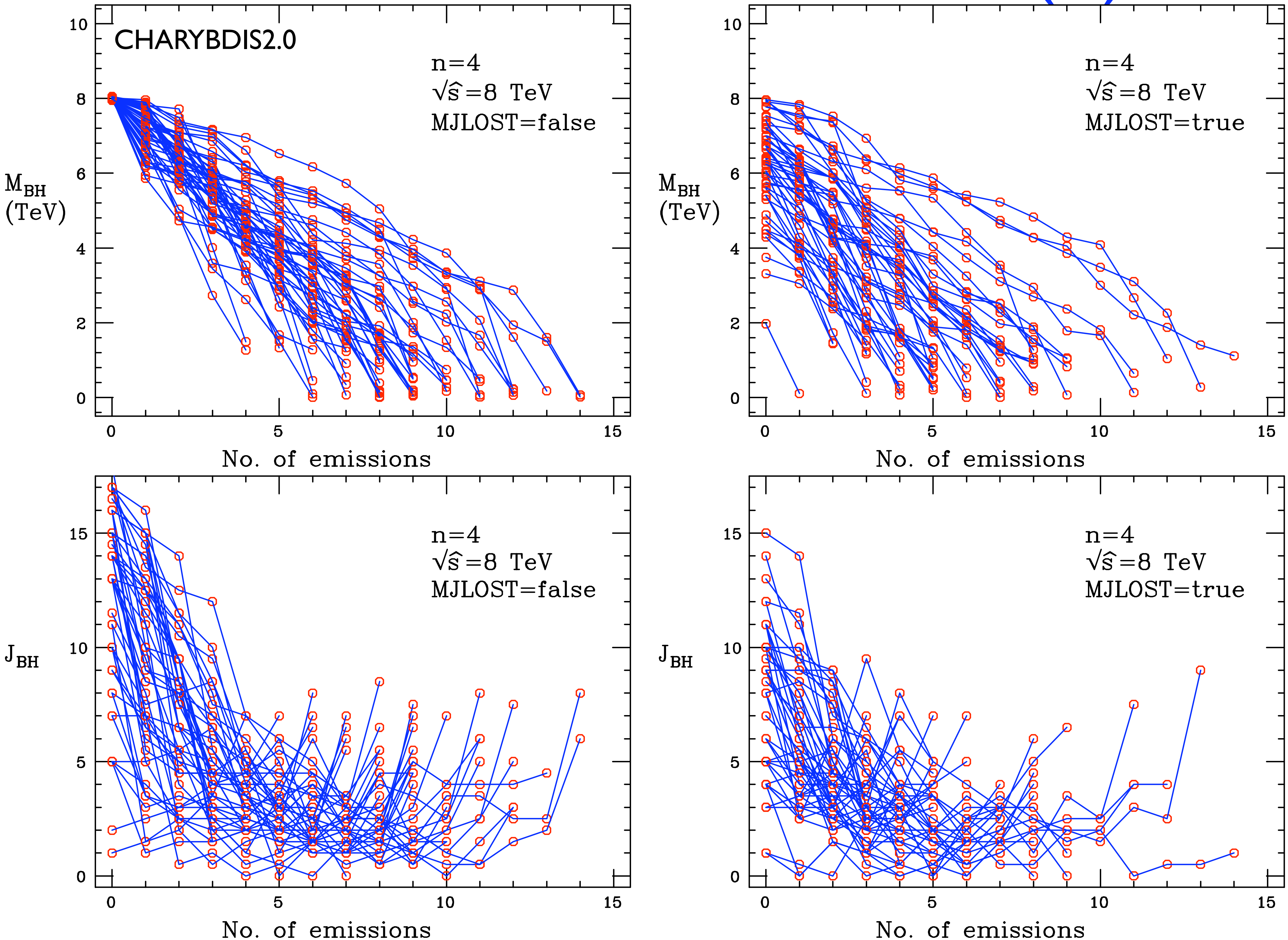




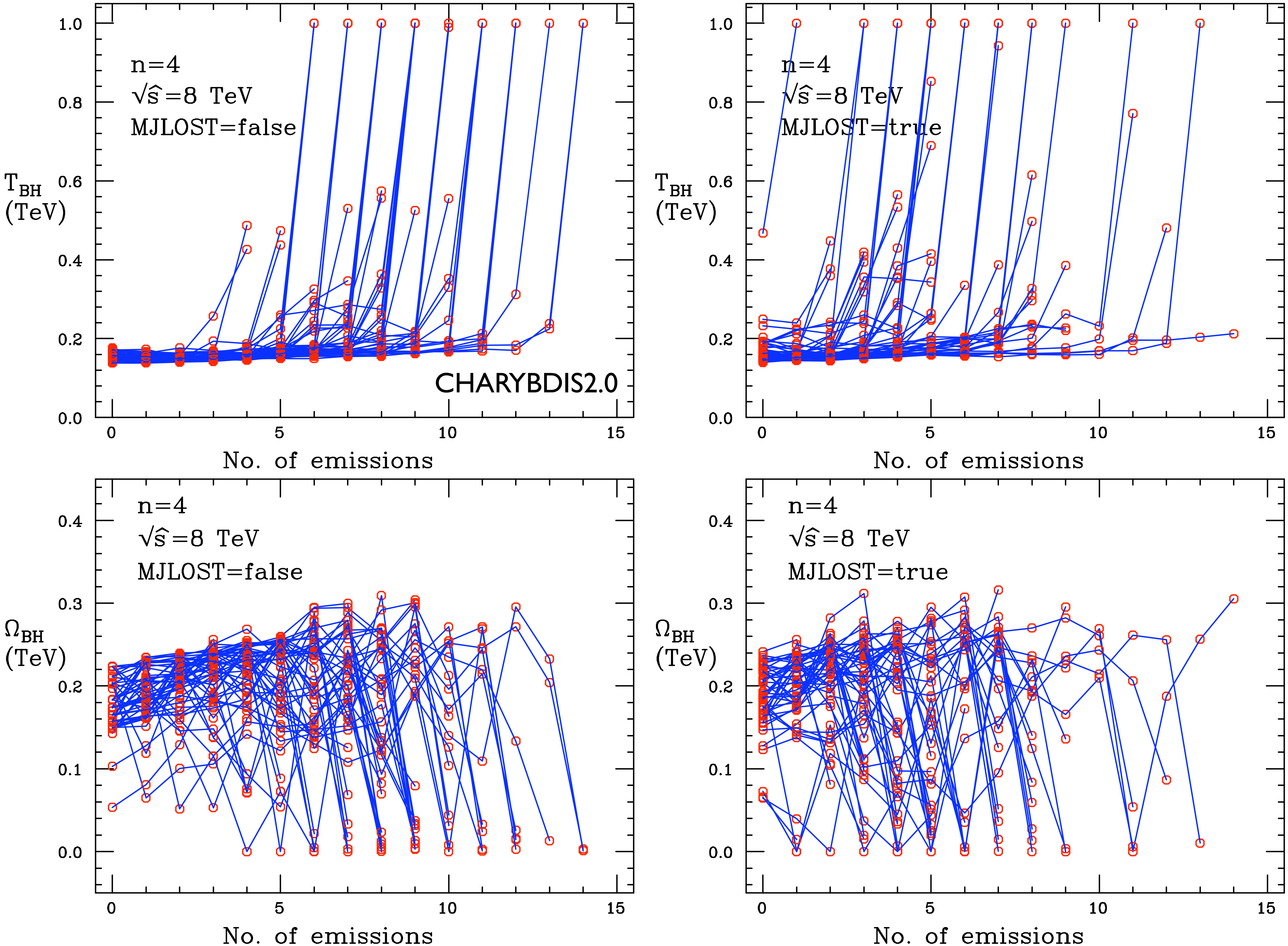


- Typical $J_{BH} \sim M_{BH}/M_D$
- $T_{BH} \sim$ constant

Black Hole Histories(I)

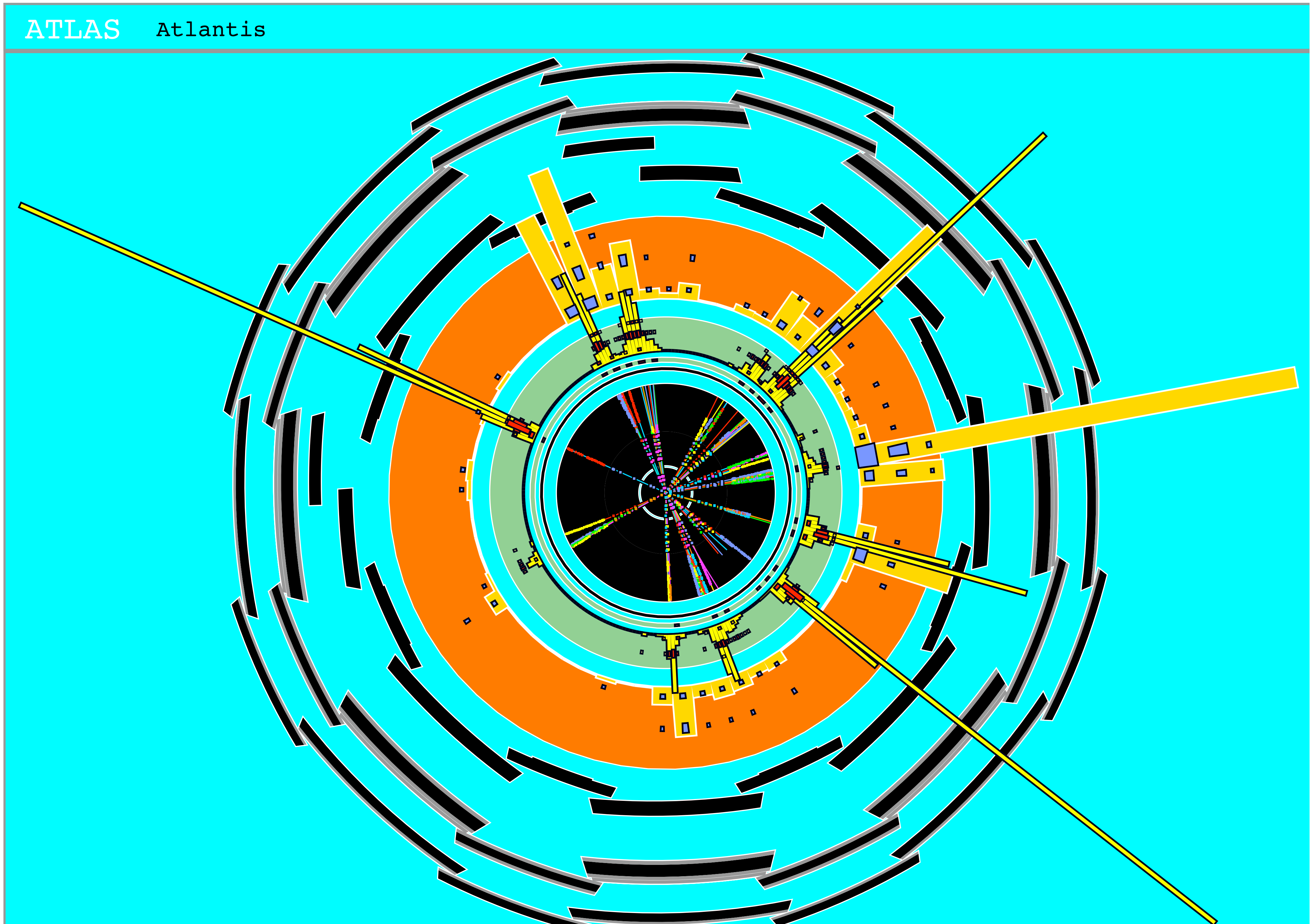


Black Hole Histories (2)

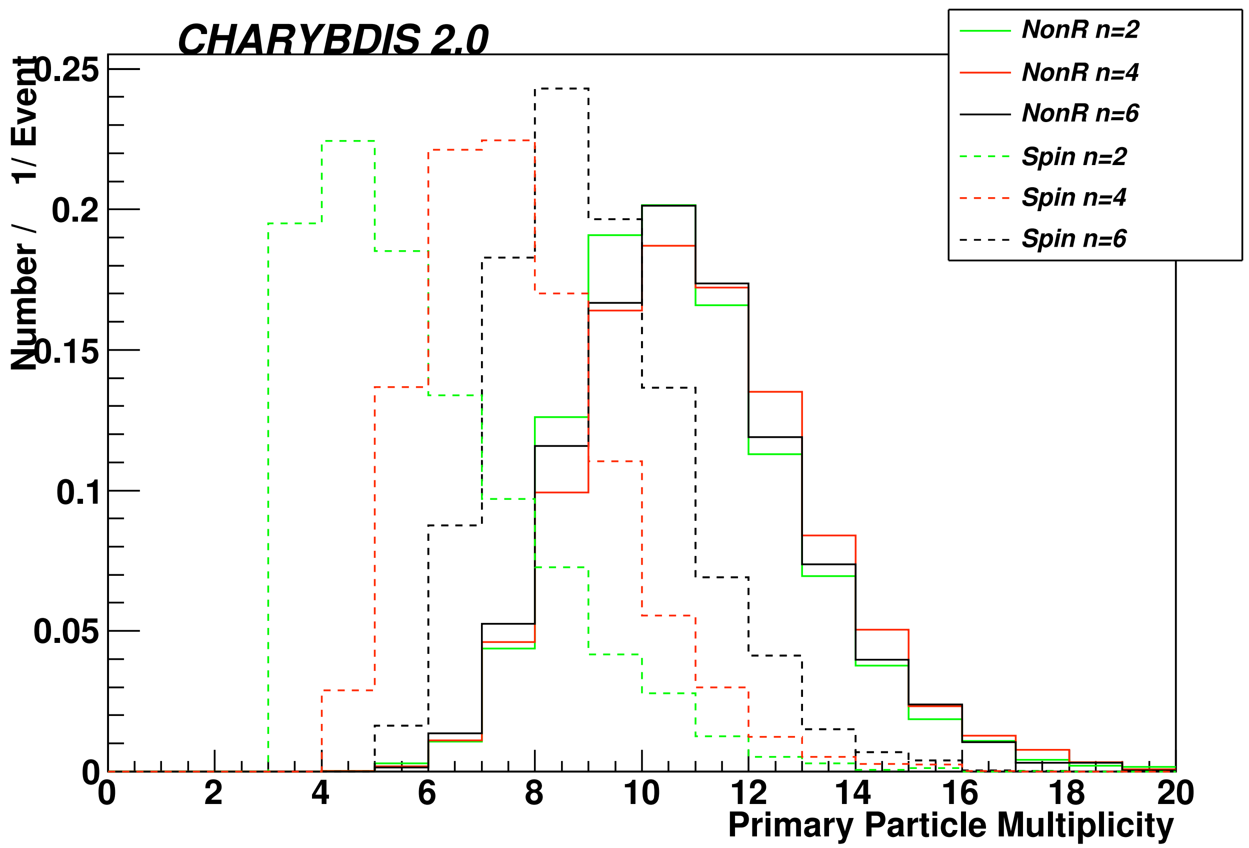


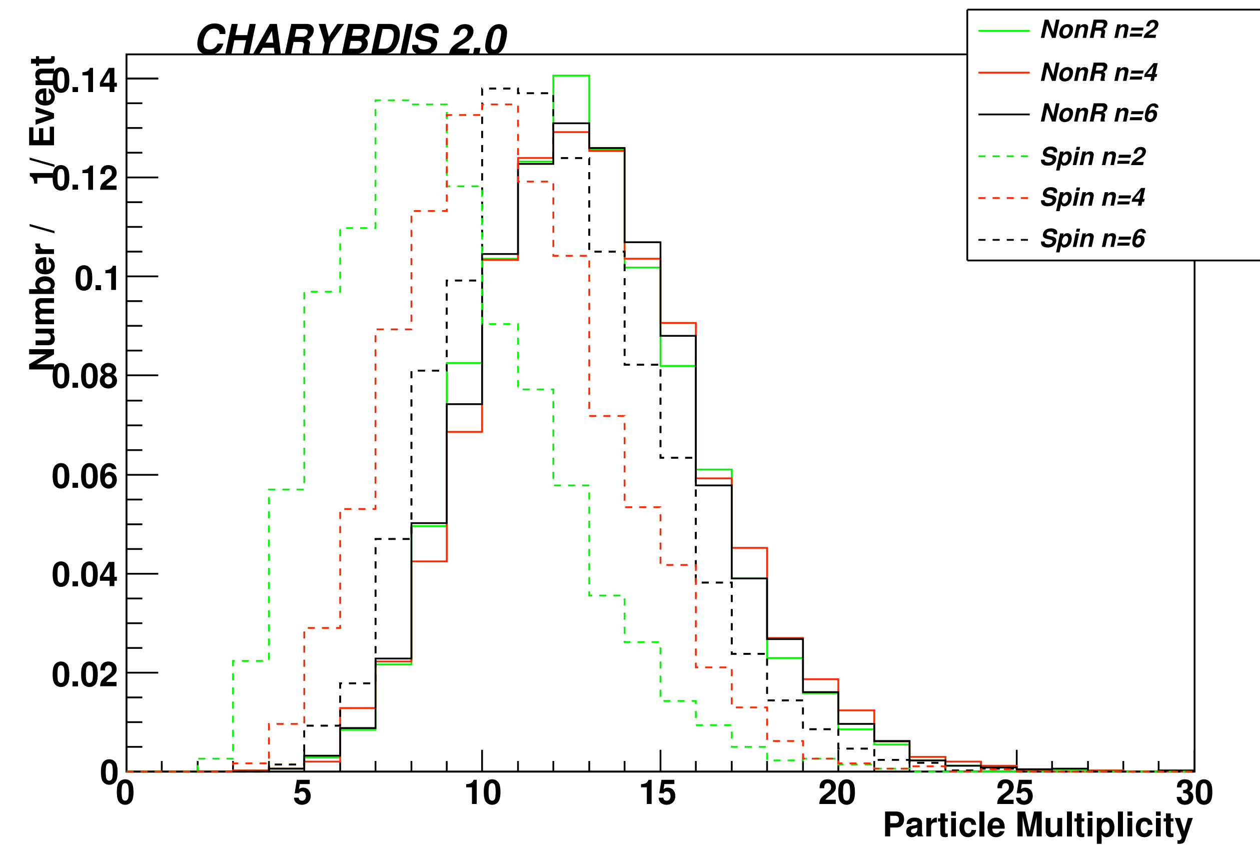
CHARYBDIS Event at LHC

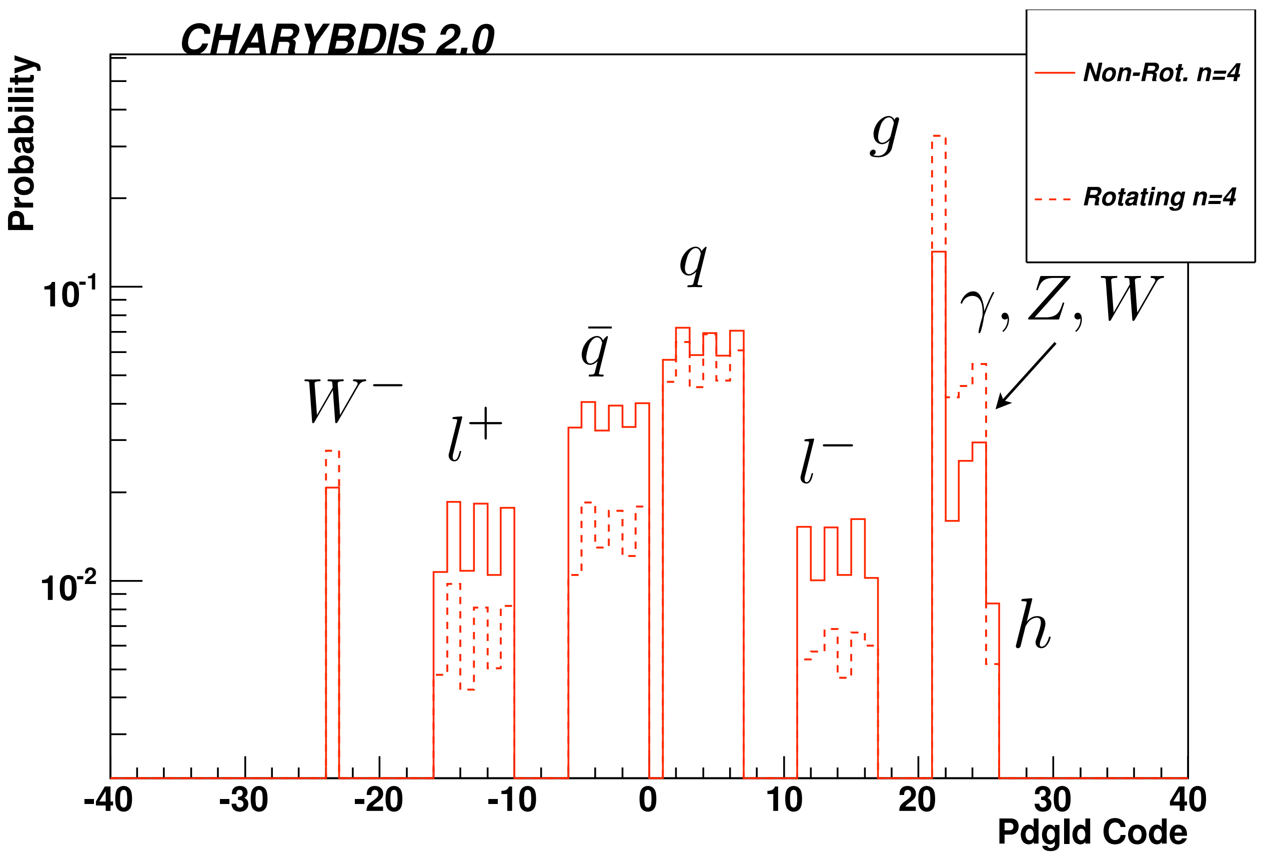
TOTDIM = 10 MPLNCK = 1 TeV M_{BH} = 8 TeV



Observable effects of BH spin?

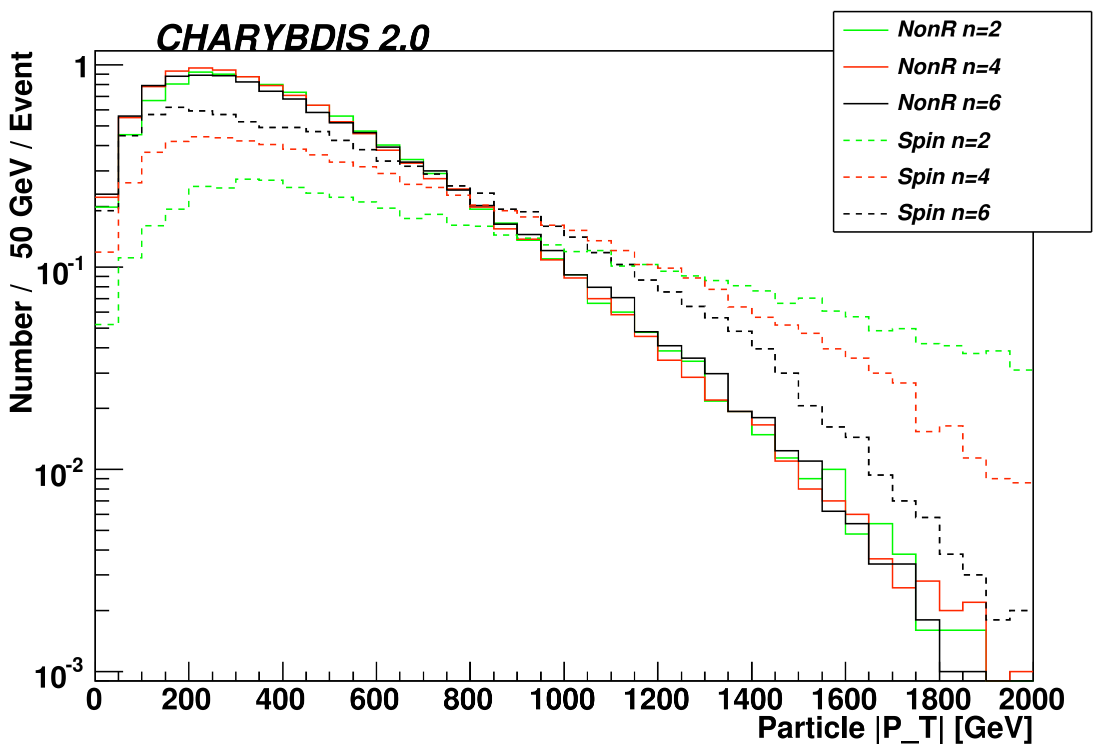


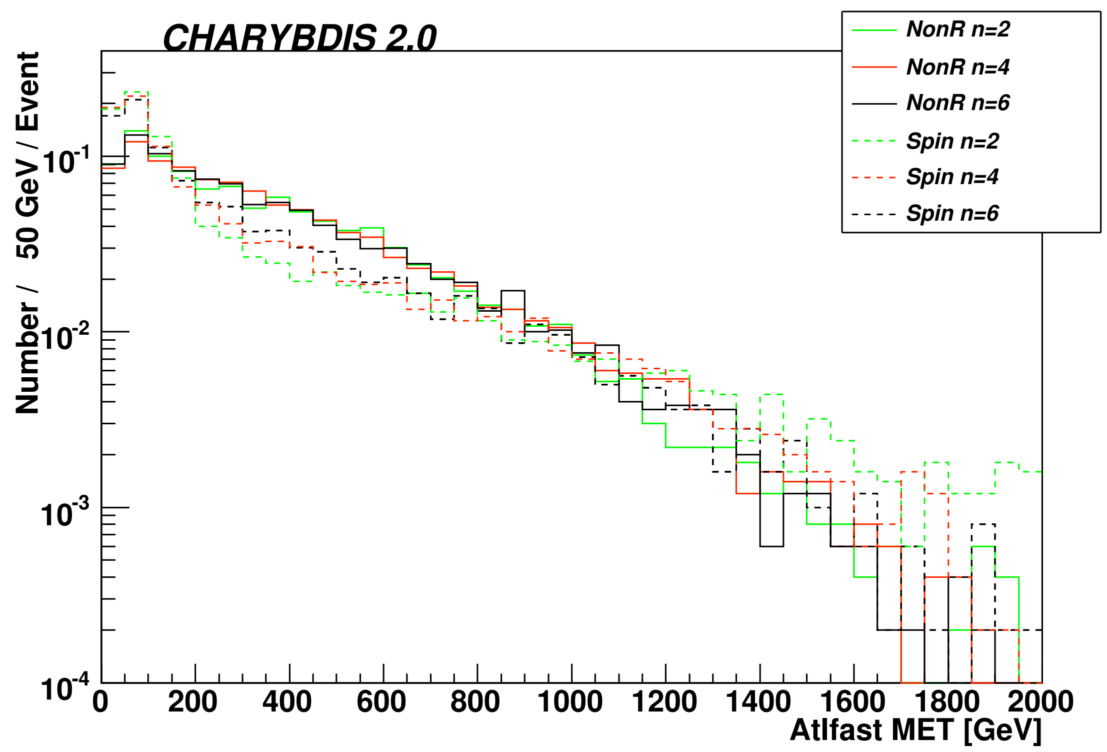


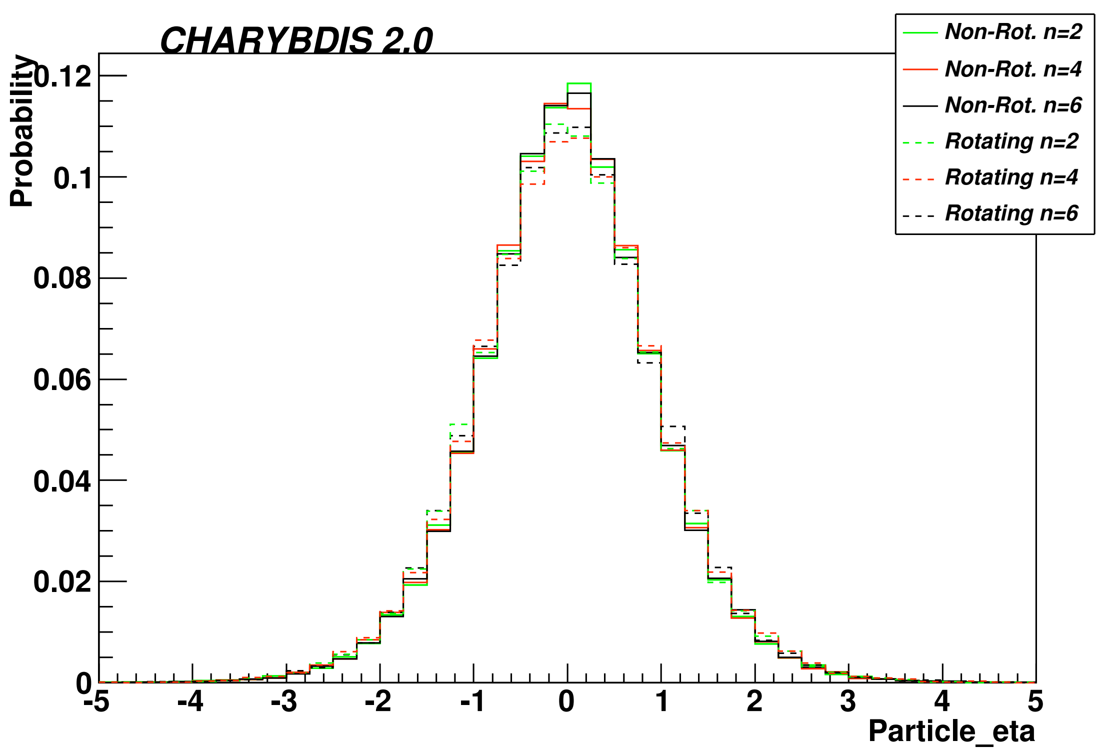


- Higher power flux
  - Fewer, more energetic particles
- Enhanced vector emission
  - More gluons, photons, W, Z
  - Aligned with BH axis, polarized

Effects of BH Spin (2)







- Harder spectrum & MET
- Oblate distribution
  - (Slightly) higher rapidities

Exploring Higher Dimensional Black Holes at the Large Hadron Collider

(CHARYBDIS1: J_{BH}=0)

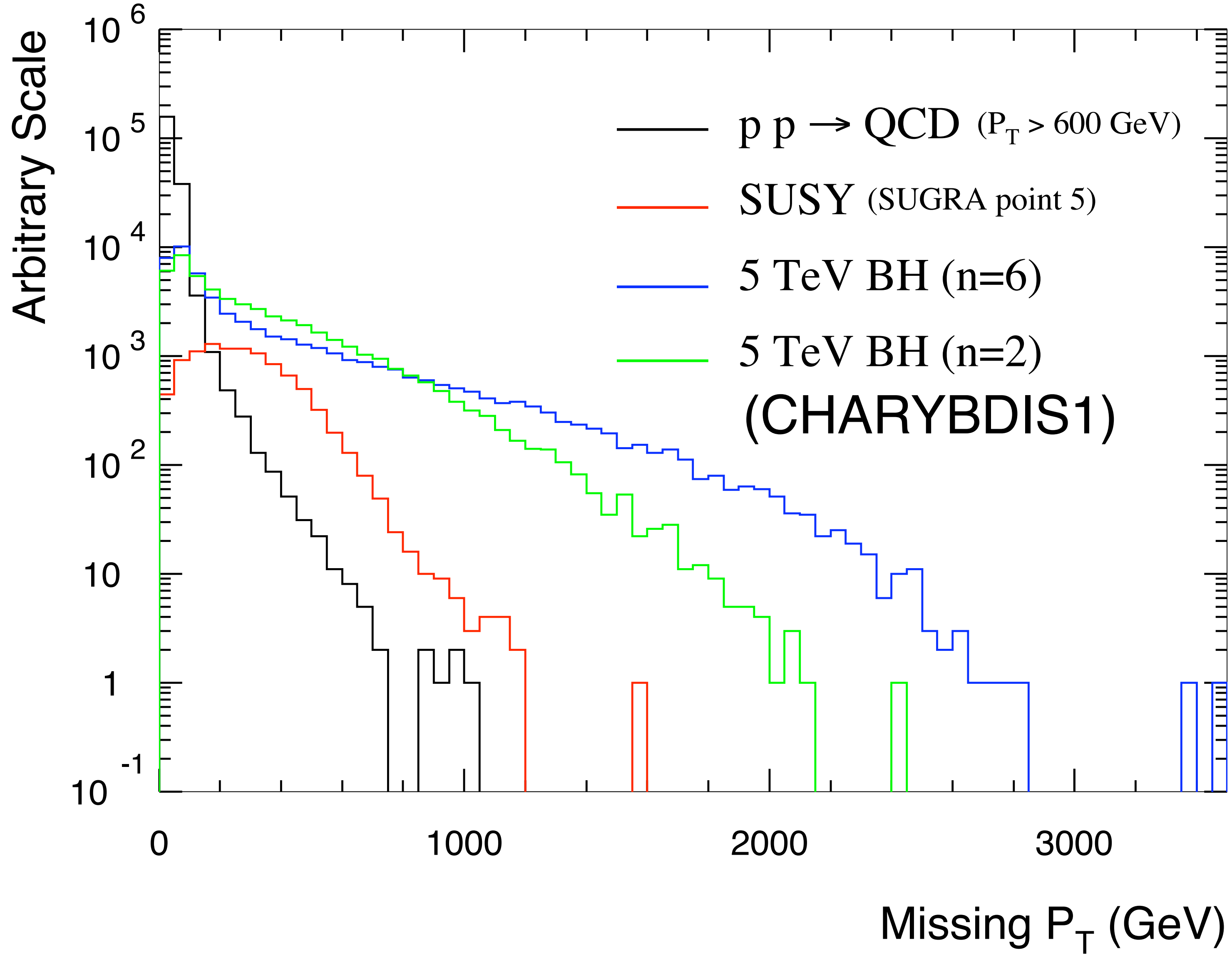
C.M. Harris[†], M.J. Palmer[†], M.A. Parker[†], P. Richardson[‡], A. Sabetfakhri[†] and B.R. Webber[†]

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

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

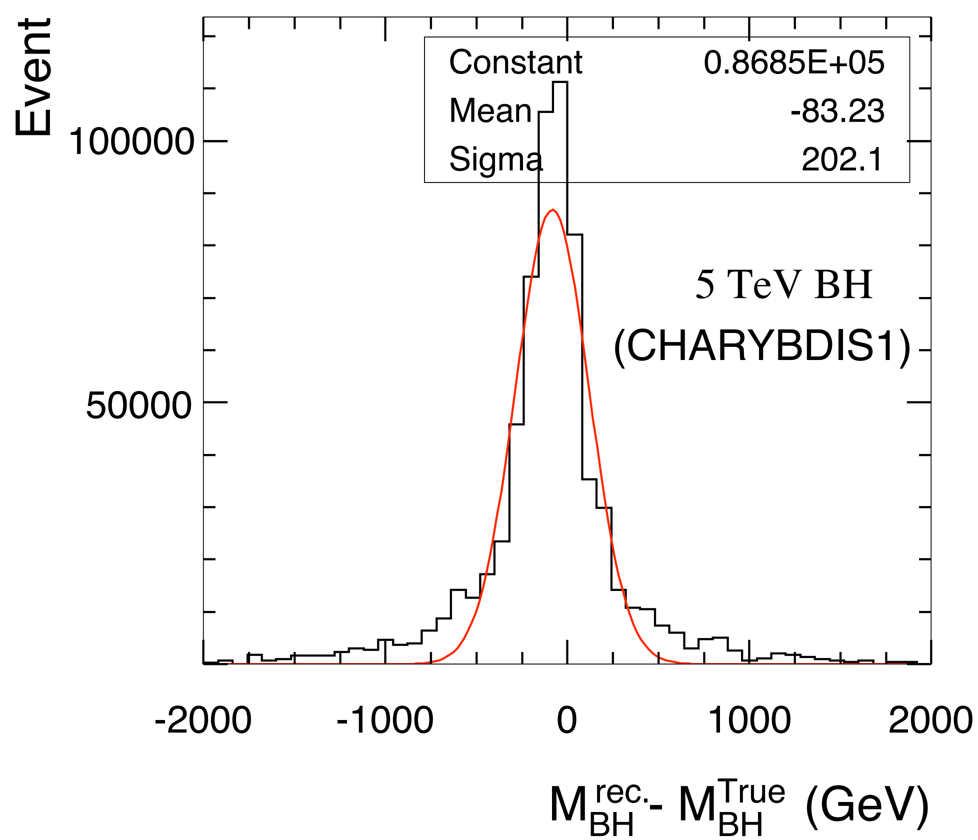
- hep-ph/0411022, JHEP05(2005)053; CM Harris, PhD thesis, hep-ph/0502005; CM Harris et al (CHARYBDIS event generator) hep-ph/0307035, JHEP08(2003)033
- earlier work: SB Giddings & S Thomas, hep-ph/0106219; S Dimopoulos & G Landsberg, hep-ph/0106295

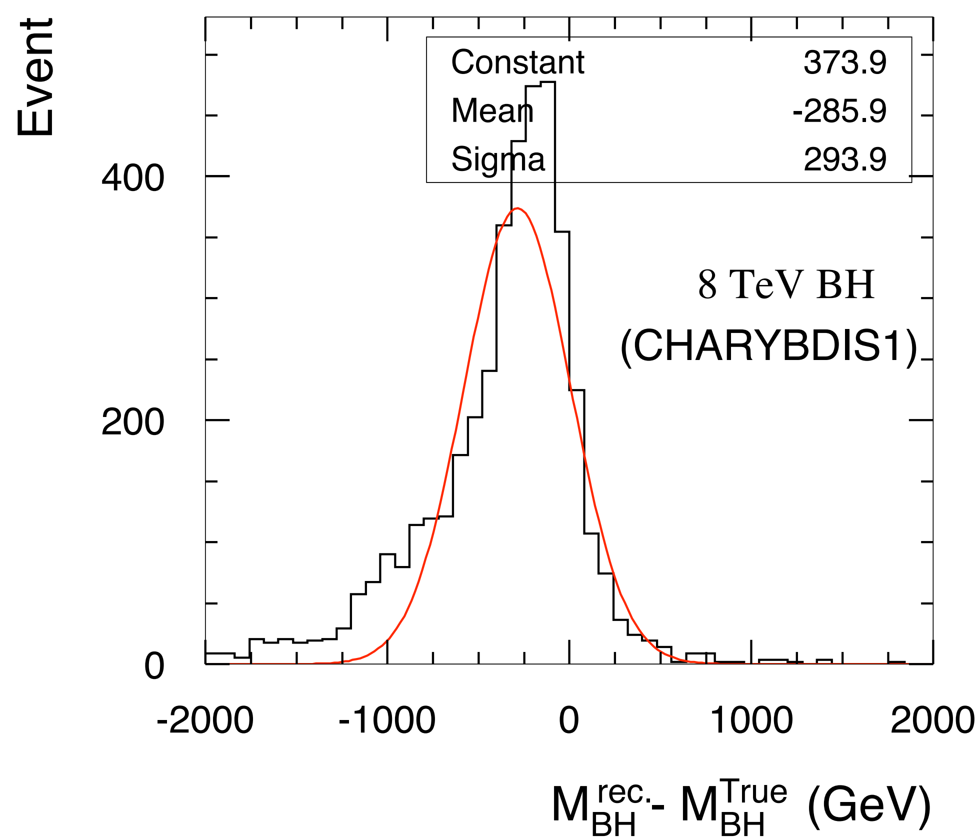
Missing transverse energy



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

Measuring black hole masses

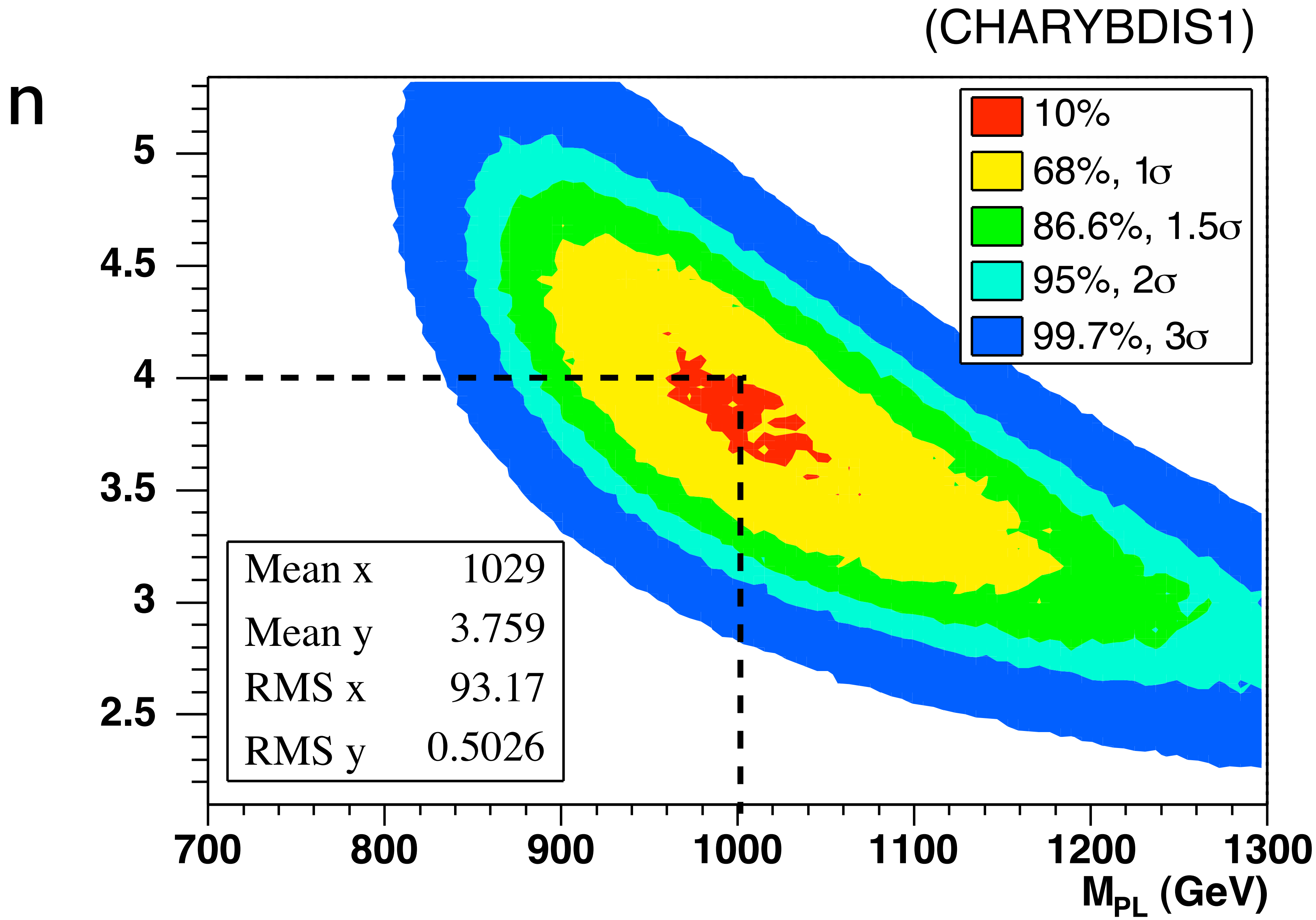




- Need $\not{E}_T < 100$ GeV for adequate resolution

➡ $\Delta M_{BH}/M_{BH} \sim 4\%$

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 scale ~ TeV
- Clear signature, with large $\not{E}_T$
- But BH mass measurement needs small $\not{E}_T$
- Particle spectra, angular distributions and multiplicities strongly affected by BH spin
- Measuring n, M_D difficult but may be possible
- CHARYBDIS2 will be released soon!