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Rotating Black Holes at LHC

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Charybdis 2.0

- Models with extra spatial dimensions have been proposed as alternative solutions to the hierarchy problem.
- For large additional or warped dimensions, the fundamental scale of gravity can be as low as the electroweak scale, leaving the possibility of observing gravitational interactions and even black holes, at the LHC.
- Potentially paves the way for the unification of gravity with the Standard Model and study of quantum gravity.

- I present results of a new simulation of black hole production and decay at hadron colliders in models with extra spatial dimensions and TeV-scale gravity - **CHARYBDIS 2.0**.
    - **Provides a full treatment of the spin-down phase of the decay process and of the angular and energy distributions of the associated Hawking radiation.**
    - **Models the loss of angular momentum and energy in the production process.**
    - **Has a wider range and more motivated options for the Planck-scale termination of the decay.**

- Full description and results from Charybdis 2.0**: JAF, J. Gaunt , M.O.P. Sampaio, M. Casals, S.R. Dolan, M.A. Parker & B.R. Webber, [arXiv:0904.0979]**.

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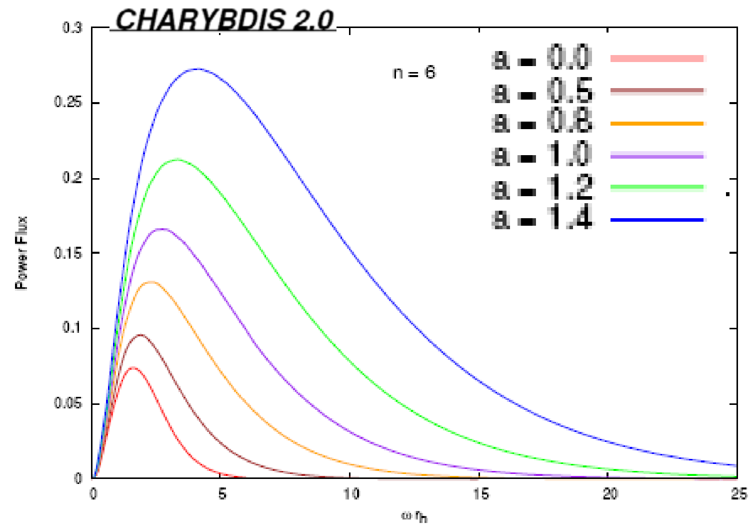
Theory (I) - Rotation

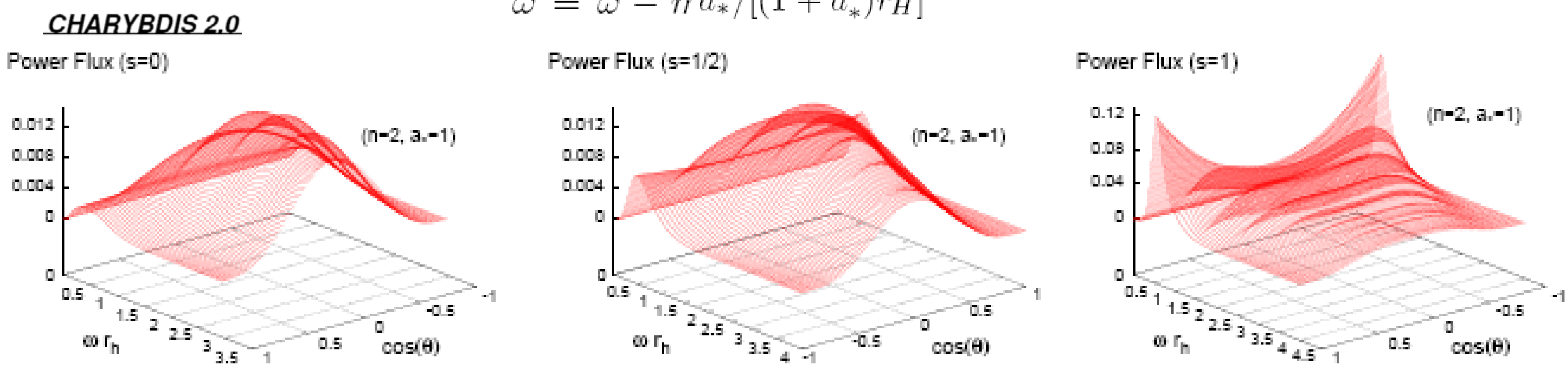
- Over the last few years, there has been much theoretical progress in describing the Hawking radiation emitted from rotating black holes, with the calculation of transmission/reflection coefficients (greybody factors).
- This allows the power fluxes and angular distributions of the particles emitted from the black hole to be calculated.
- Polarisations of the particles are accounted for in their angular distributions.



Power spectrum of a spin-½ field for emission on the brane with *n* = 6 for various values of BH a* (oblateness)

$$\frac{d^2N}{dt\,d\omega} = \frac{1}{2\pi}\sum_{j=|h|}^{\infty}\sum_{m=-j}^{j}\frac{1}{\exp(\tilde{\omega}/T_H)\pm 1}\mathbb{T}_k^{(D)}(\omega, a_*)$$

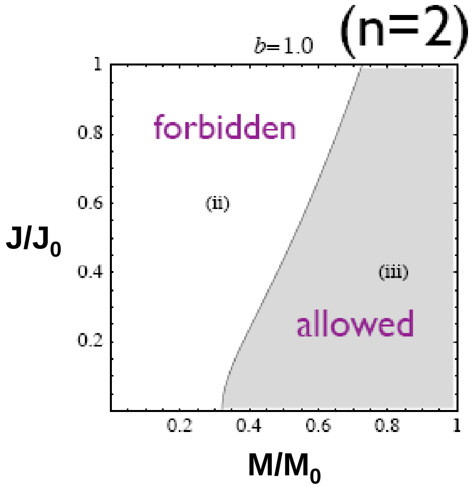
$$\tilde{\omega} = \omega - n\,a_*/[(1+a_*^2)r_H]$$

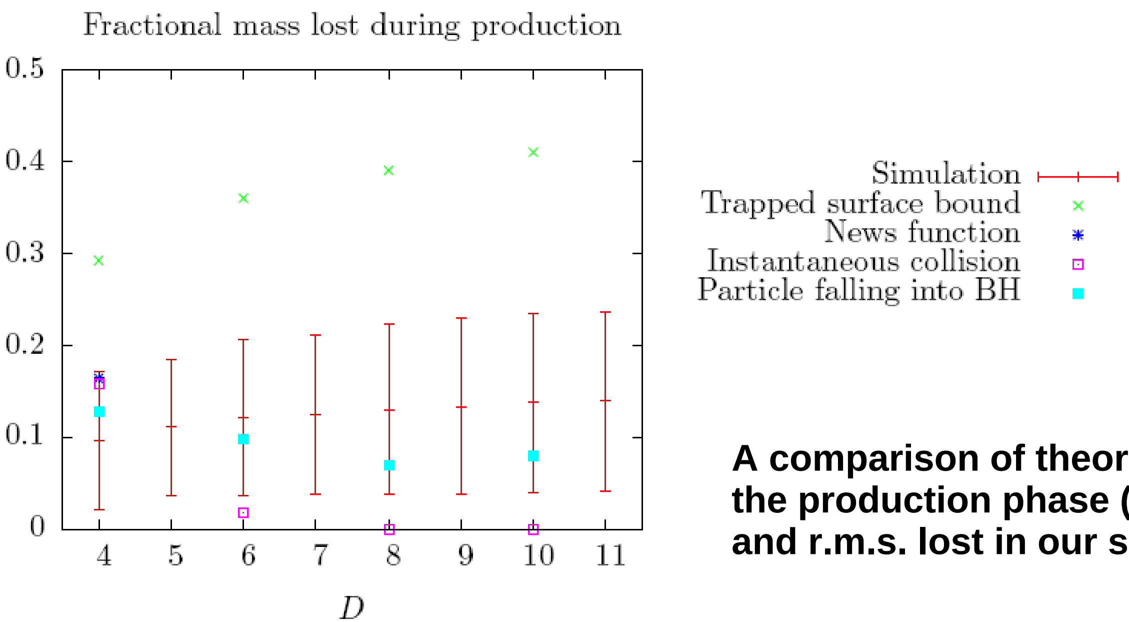


Angular Power Fluxes for scalars, fermions and vectors

Theory (II) - Production

- The production phase is described using classical physics, provided that the parton collision energy is sufficiently larger than the Planck scale.
- Trapped surface methods give lower bounds on the parton-level cross-section, mass (m) and angular momentum (J) trapped for a given impact parameter, b.
- The most complete study for non-zero b comes from Yoshino and Rychkov (hep-th/0503171) with bounds up to the maximum b for which an apparent horizon (and consequently, a black hole) forms.
- Toggled on/off using generator switch MJLOST.





A comparison of theoretical results for the mass lost in the production phase (valid for b=0), with the average and r.m.s. lost in our simulation for the case b=0

Theory (III) - Decay

- We must always decide what to do when the black hole reaches the **remnant phase**, the point at which the black hole mass and/or temperature lies at the Planck scale.

- Charybdis 1.0x modelled this using a fixed multiplicity remnant decay of 2-5 particles. We used switch KINCUT to either ignore or terminate decay when a kinematically disallowed decay ($E>\sim M_{BH}/2$) is proposed.

- Natural default in Charybdis 2.0 – calculate the expected flux and terminate the decay when this becomes small. i.e. If we expect only one further Hawking emission, go to a 2-body remnant now

$$\langle N \rangle \simeq \frac{dN}{dt}\delta t \simeq \frac{dN}{dt} M \left(\frac{dE}{dt}\right)^{-1} = M r_H \frac{\sum_i g_i \left(\frac{1}{r_H}\frac{dN}{dt}\right)_i}{\sum_j g_j \left(\frac{dE}{dt}\right)_j} .$$

Flux – motivated model

- Charybdis 2.0 also allows us to use a variable-body model for the remnant phase. This has been suggested to be correct when the flux is large and black hole no longer has time to re-equilibrate between emissions. Under these circumstances, the multiplicity follows a Poisson distribution.

- String-motivated ‘Boiling’ model – at Planck scale, BH looks like a stringball, with a max temperature/minimum length scale.

- Can also model low multiplicity black holes, producing either fixed or Poisson-distributed multiplicity, using the rotating black hole distributions and Hawking spectra if desired.

Generator Details

- Charybdis 2.0 outputs .xml Les Houches Event files
- Compatible with standard generators for hadronisation and parton showering.
- Should allow easy interfacing and production.
- The new parameters and model switches are listed below

Name	Description	Default
BHSPIN	Simulate rotating black holes	True
BHJVAR	Allow black hole spin axis to vary	True
MJLOST	Simulation of m, J lost in Balding phase	True
RMSTAB	Stable Remnant Model	False
NBODYAVERAGE	Use flux criterion for remnant	True
NBODYVAR	Variable-multiplicity remnant model	False
NBODYPHASE	Use phase space for remnants	False
SKIP2REMNANT	Bypass spin-down phase	False
BOILING	Use Boiling remnant model	False
RMMINM	Minimum mass for boiling model	100 GeV

- Plots on succeeding pages show a selection of black hole samples with M_{PLANCK} = 1 TeV (PDG definition) and *n* extra dimensions at generator-level and after LHC AcerDet fast simulation.

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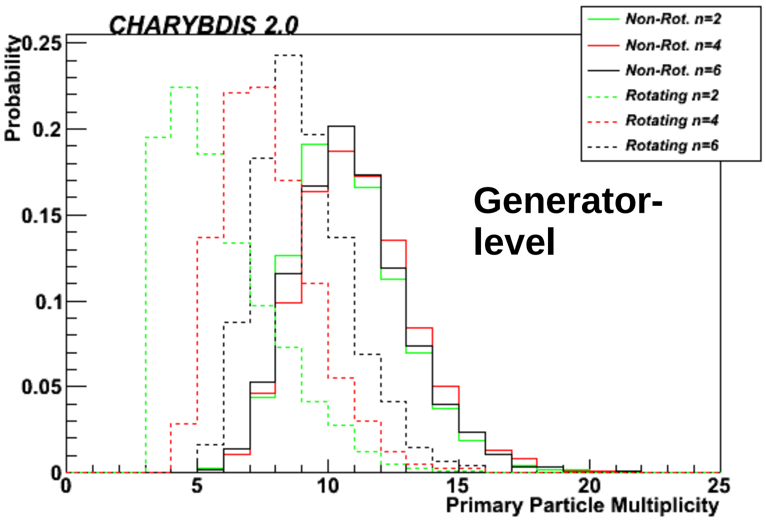
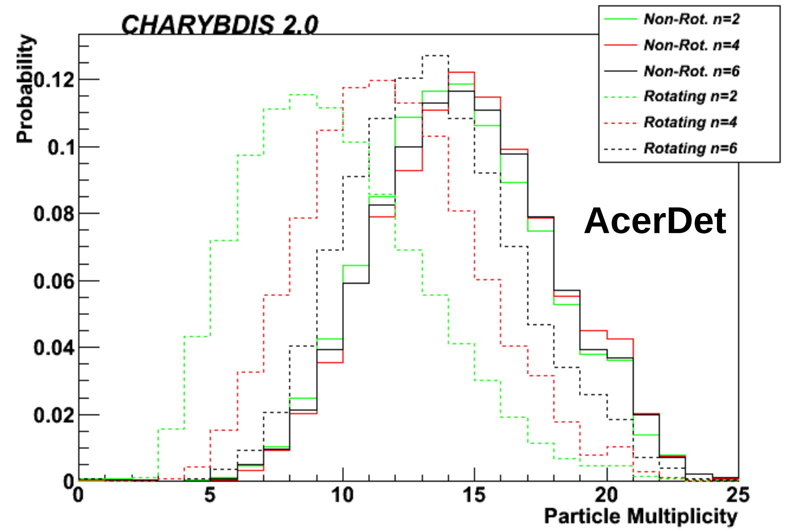
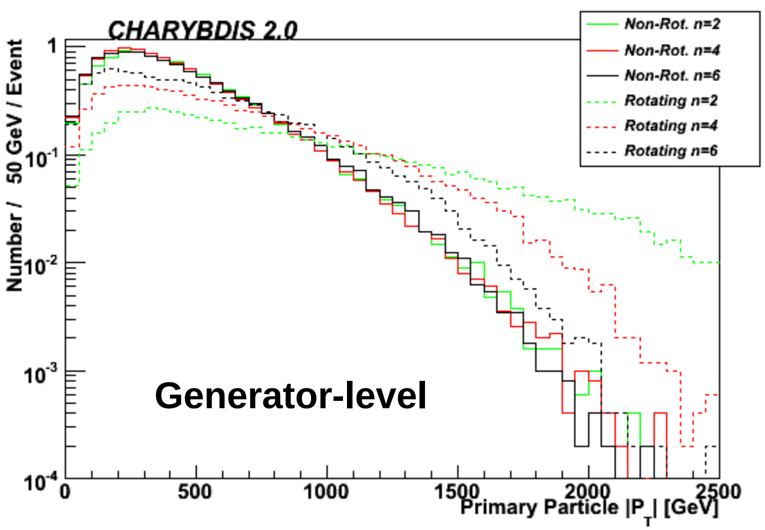
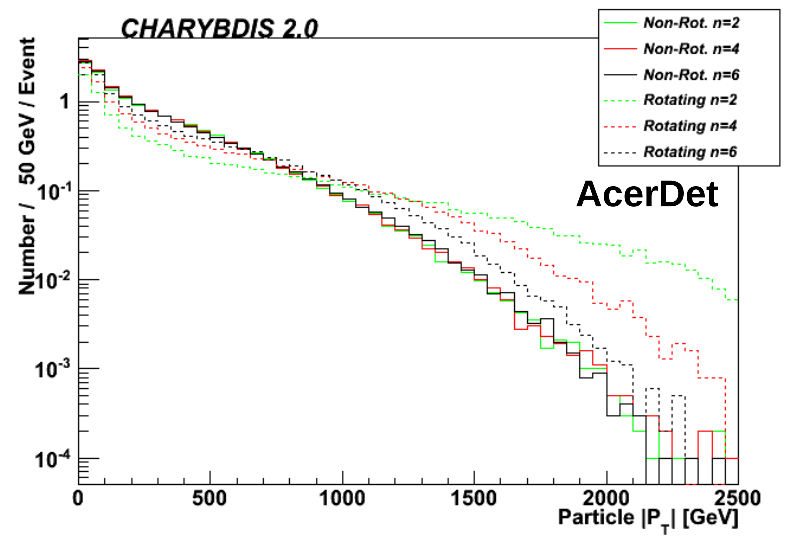
Rotation Effects



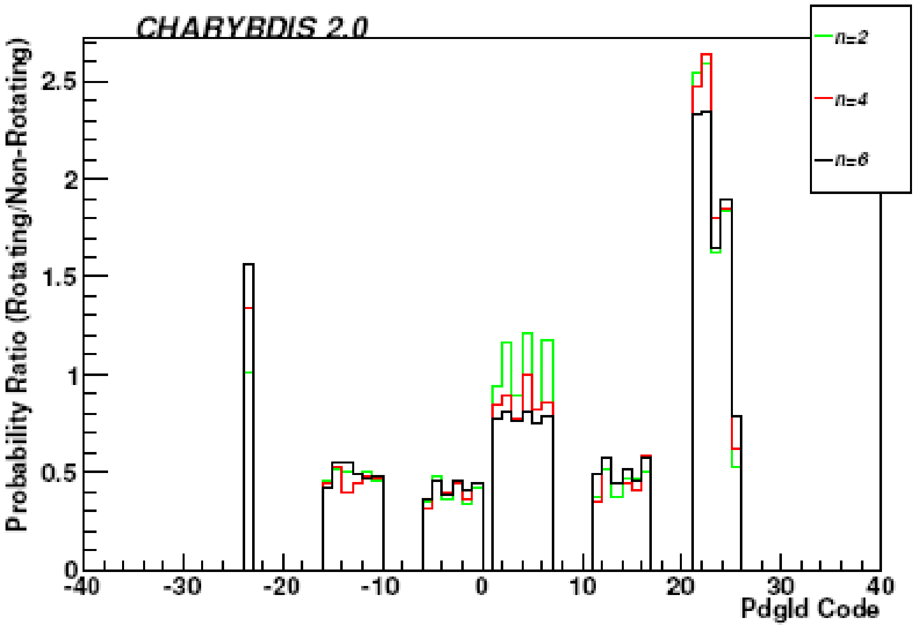


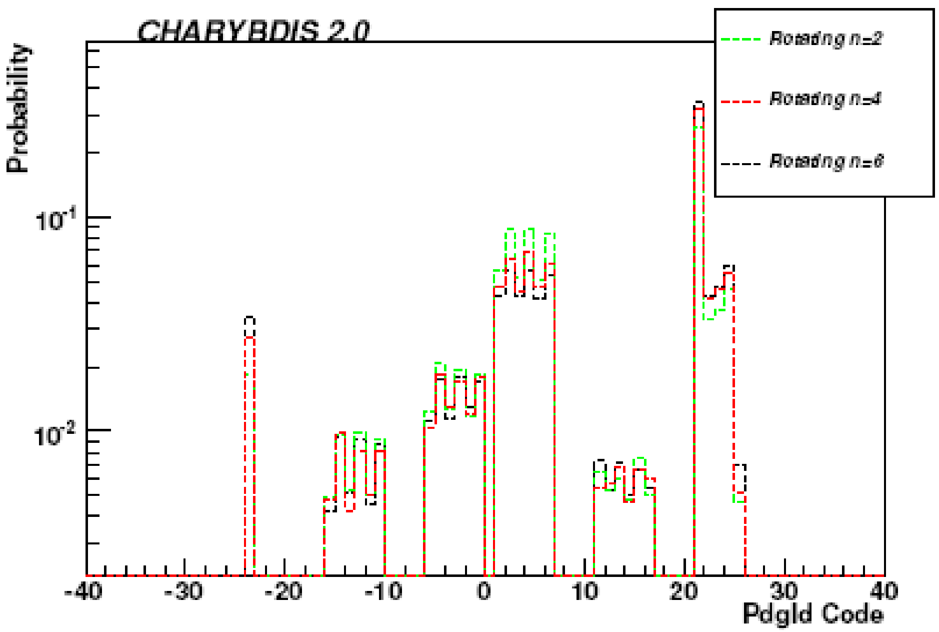
➢Rotating black holes (dashed lines) emit far fewer, more energetic particles than their non-rotating, Schwarzschild analogues (solid lines), since the spin term reduces the Boltzmann suppression of high energy emission.





Which Particle Species?





- Primary particle spectra (emitted directly by the black hole) are changed dramatically.
- Vector emission is enhanced by a factor of ~2.5; scalar (Higgs) emission slightly reduced.
- Decreased probability of an event containing a charged lepton – used in studies of non-rotating black holes for signal selection and background rejection.
- Little variation with *n* – were it possible to reconstruct it, it would be powerful evidence of gravitational interaction/black holes (assuming model assumptions are valid).

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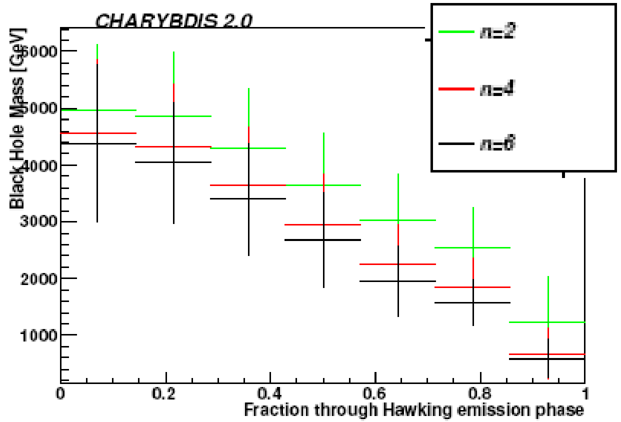
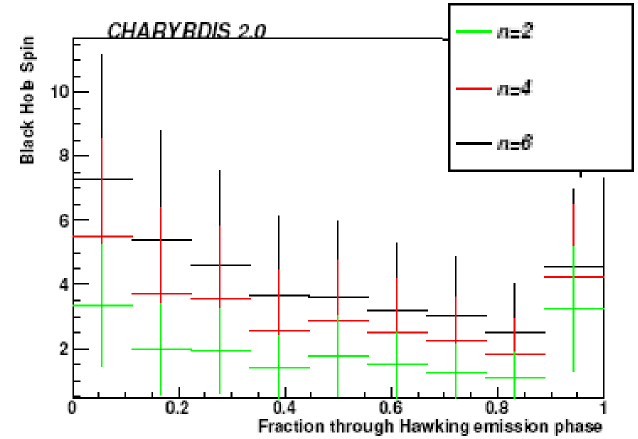
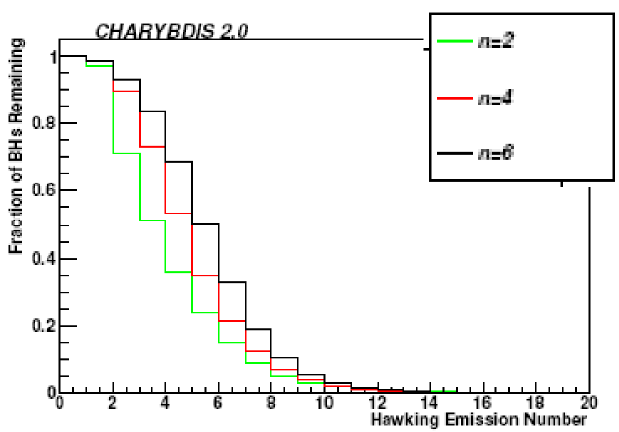
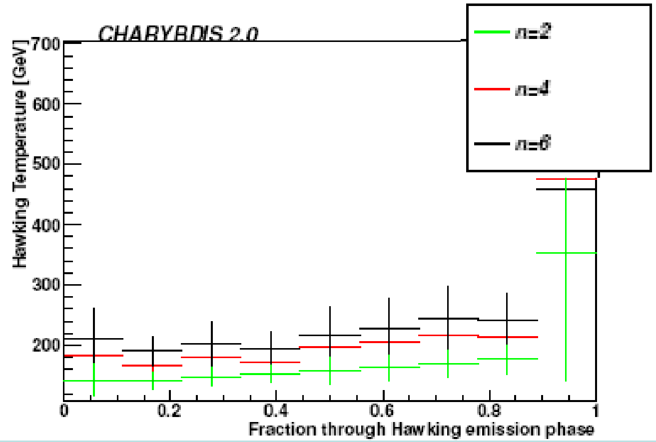
Black Hole Evolution (I)





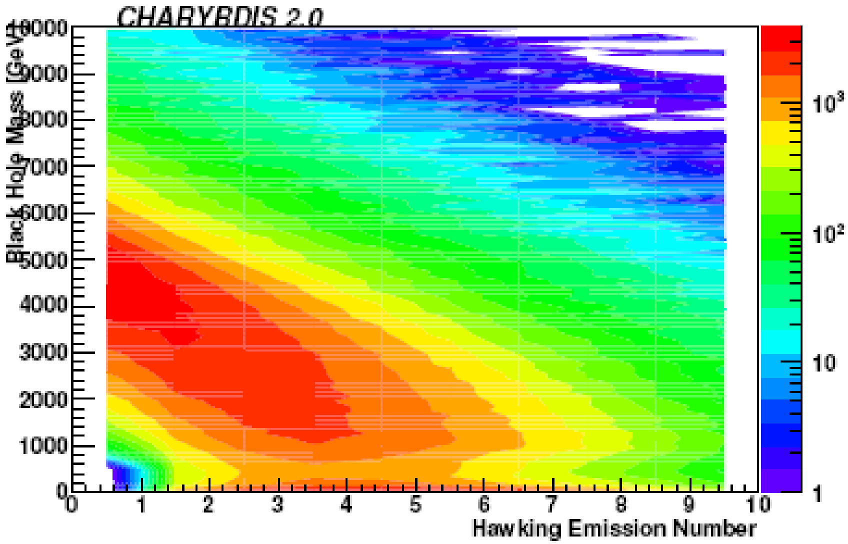
- The black holes emit Hawking radiation, losing mass and angular momentum, and gradually becoming hotter (increasing Hawking temperature).
- Angular momentum is lost more rapidly than mass, the majority being lost in the first two or three emissions, whereafter the black hole loses mass whilst the angular momentum remains relatively low, but non-zero. There is **not** a quick spin-down phase, followed by a longer Schwarzschild phase - **the spin-down persists throughout evaporation**.

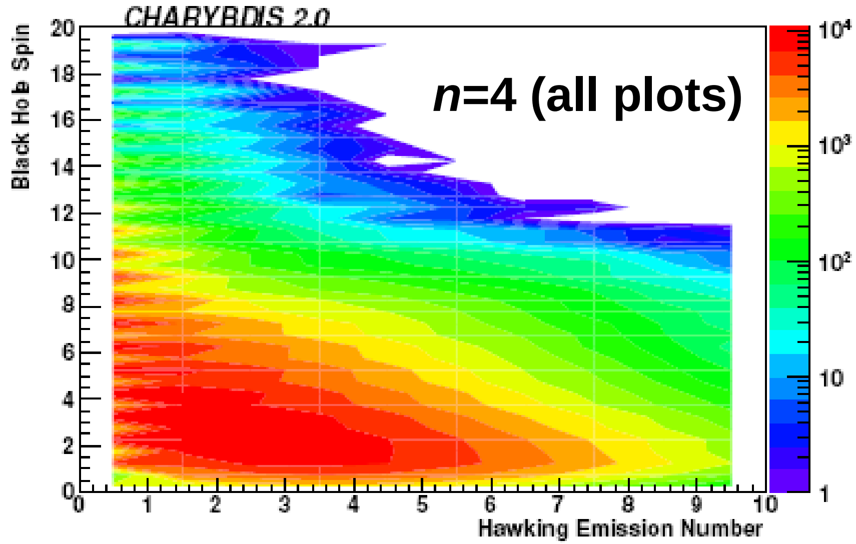


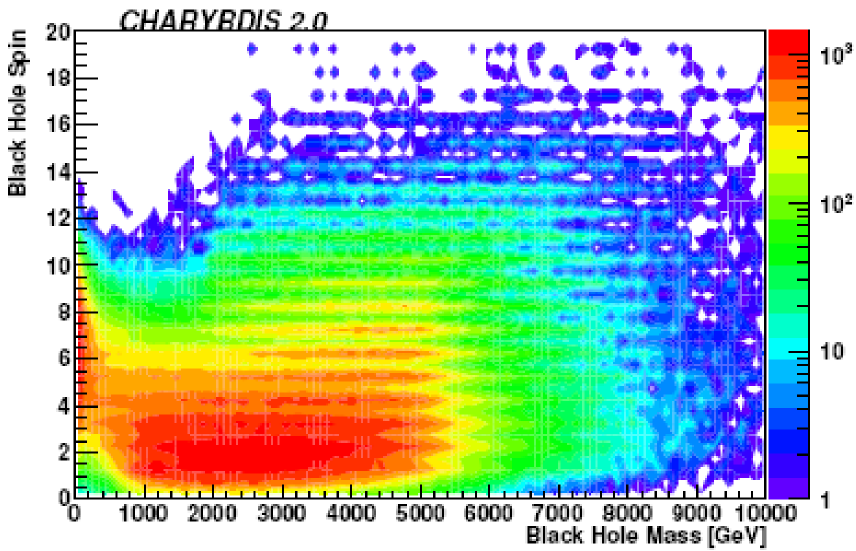


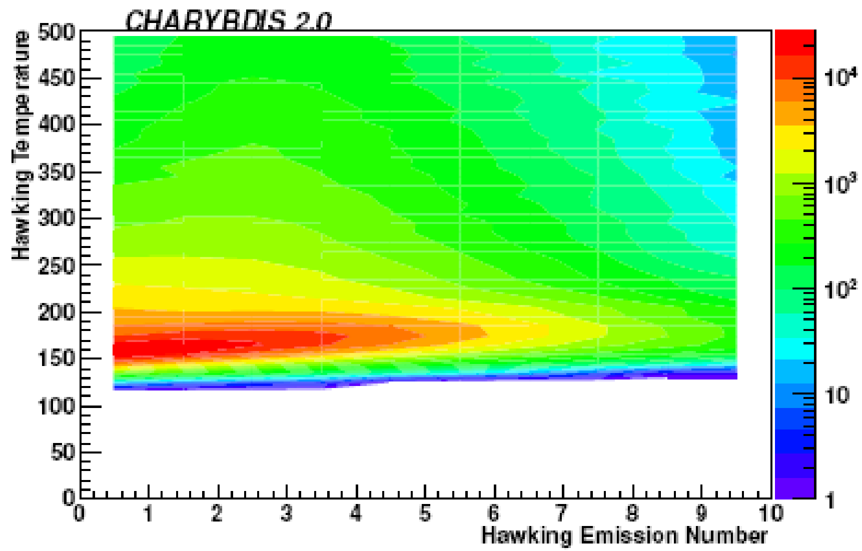
Black Hole Evolution (II)

***n*=4 (all plots)**









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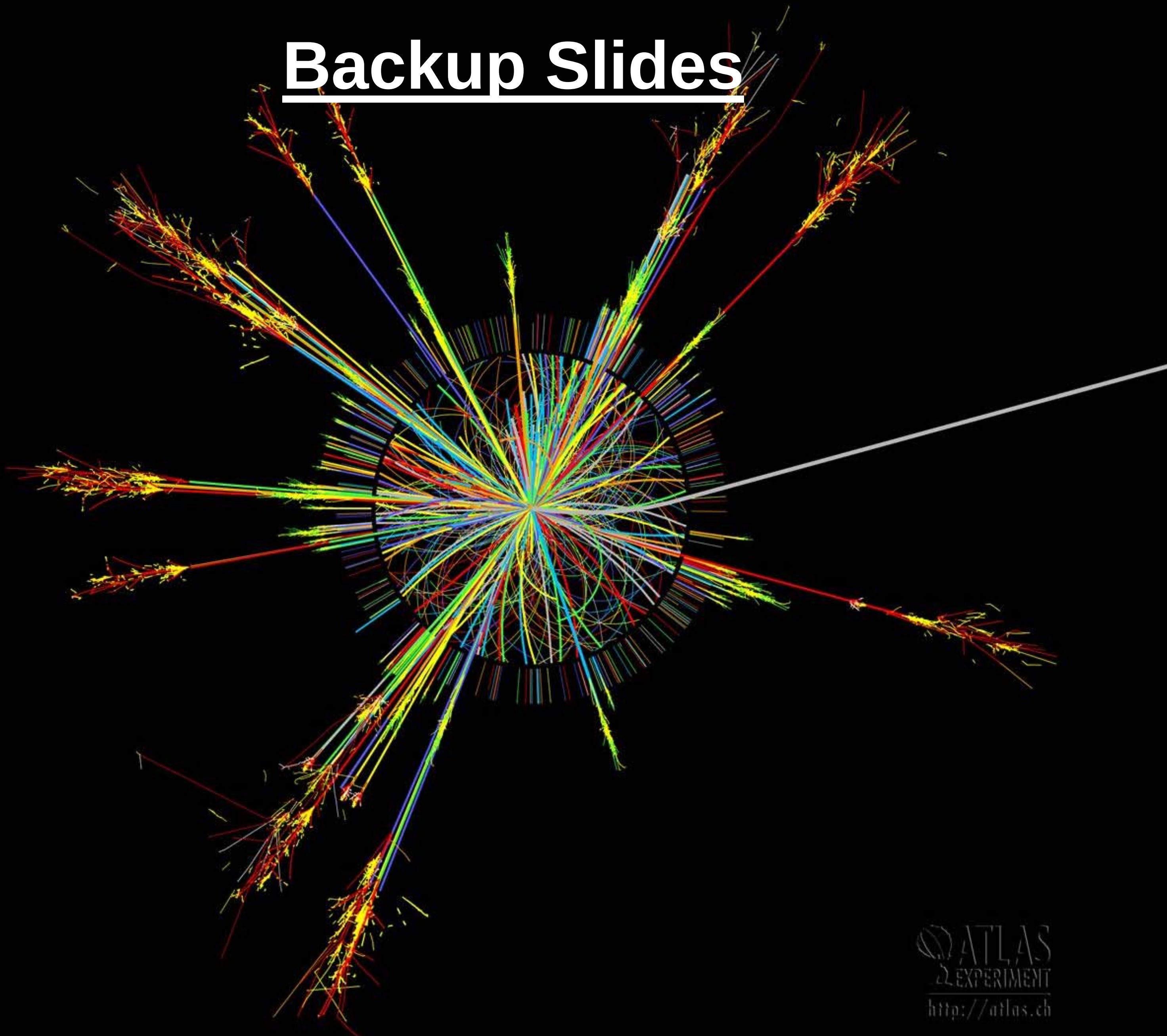
Conclusions/Outlook

- Angular momentum has strong effects upon the properties of the black hole events.
- The isotropic evaporation of a spinless, Schwarzschild black hole is **NOT** a good approximation.
- Black hole **rotation** is not lost immediately after production, but **persists throughout the evaporation** – even after allowing for a substantial loss of angular momentum in production/balding.
- At LHC and foreseeable energies, there is a lengthy spin-down phase, with little or no non-rotating, Schwarzschild phase.
- Rotating black holes look hotter – produce **fewer, more energetic particles**.
- … and consequently look less spherical and more like backgrounds – unfortunately **NOT** as easy as previously thought! (see eg. arXiv:0901.0512)
- Rotation has large effects upon the particle species present in black hole events – an increase in vector particles, mainly at the expense of fermions – relatively fewer leptons, more gluonic jets, more (highly boosted) vector bosons, more photons.
- Obviously important to get maximum value out of LHC data by looking for the correct signature! – important to use CHARYBDIS 2 or BLACKMAX, as they include the effects of BH rotation.
- Moving to more detailed detector simulation and reconstruction to improve/update experimental strategies and searches.
- Full details in: Phenomenology of Production and Decay of spinning Extra-Dimensional Black Holes at Hadron Colliders, [arXiv:0904.0979].

Backup Slides



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BH Lifecycle

- Traditionally such black holes (BH) have a high Hawking temperature and decays in 4 phases:
  - **1. Formation/Balding Phase**
    – the BH loses multipole moments – mainly gravitational radiation
  - **2. Spin down Phase**
    – the rotating BH loses its angular momentum before its mass
  - **3. Schwarzschild Phase**
    – the BH emits Hawking radiation, losing mass and increasing in temperature
  - **4. Planck Phase**
    – BH temperature and/or mass reaches M_{PL} - realm of quantum gravity, remnant?

BH 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 (JAF, et al., arXiv:0904.0979)
  - 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)

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Modern BH MC

CHARYBDIS 2.0: JAF, Gaunt, Sampaio et al. **arXiv:0904.0979**

Production: Rotating black holes. Consistent model of mass/angular momentum loss and cross-section – dependent upon impact parameter and *n*, correct spin dependent upon partons.

Evaporation: Inclusion of black hole rotation through greybody factors, angular distributions and energy spectra. Polarisations taken into account. Variable temperature (though with the option to turn time variation off (equivalent to instant evaporation with no time to re-equilibrate).

Remnant options – criteria – MPLANCK or expected flux. Pure phase space, with/without Hawking spectrum for particle species, angular distribution, energy spectrum. Fixed/variable multiplicity determined by <N> from Hawking spectrum. String motivated 'boiling' model.

Alternatives: straight to 2->N (N≥2) bodies, using input from the Hawking spectrum.

BLACKMAX 2.0: Dai, Starkman et al. **arXiv:0711.3012**

Production: Rotating black holes. Option to lose constant fraction of mass/angular momentum.

Evaporation: Inclusion of black hole rotation through greybody factors, angular distributions and energy spectra. Variable temperature. Suppression of spin-up modes.

Remnants: Isotropic, phase space. Minimal multiplicity.

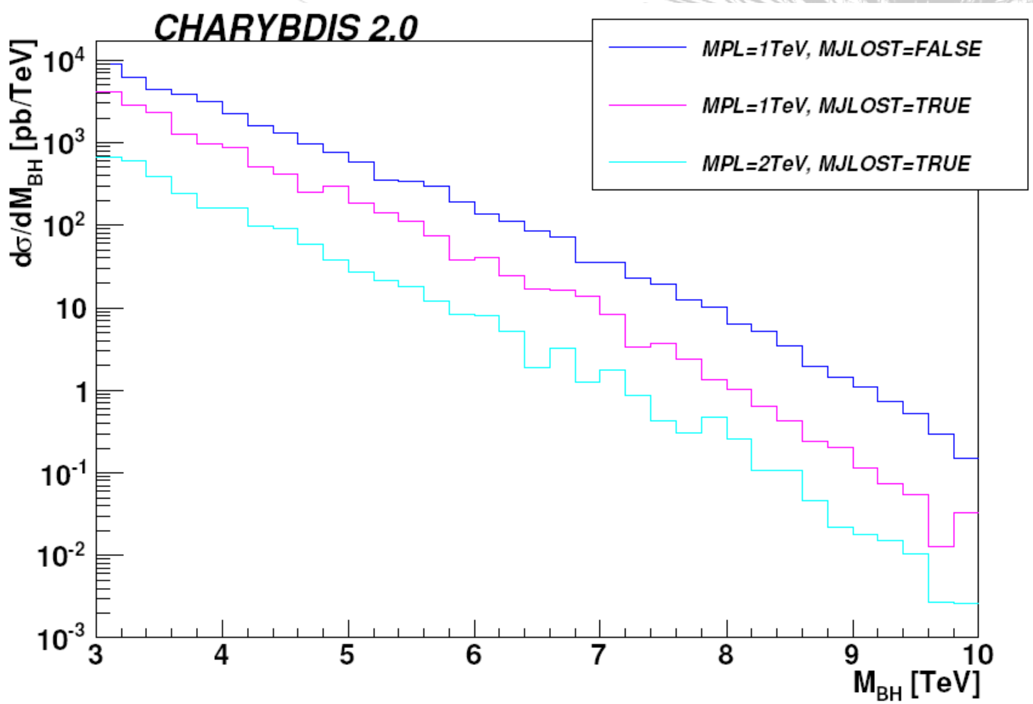
Alternatives (without rotation): non-zero brane tension (5-6D), split fermion branes, brane/bulk graviton emission, 2->2 di-jet like BH processes.

Cross-sections

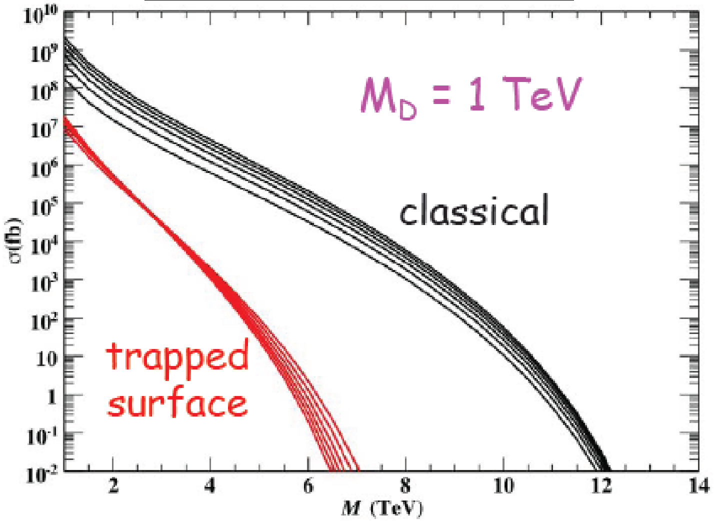
➢Black hole cross-sections show a strong dependence upon the Planck mass.

➢Differential cross-section heavily affected by models of losses in production/balding.

➢BH cross-sections are themselves uncertain – GR (Mach shock) simulations give σ orders above the minimum from trapped surface calculations



14 TeV Predictions



➢Since production is dominated by quarks at high x, a drop in beam energy to 10 TeV does have a large effect on cross-sections.

Evolution

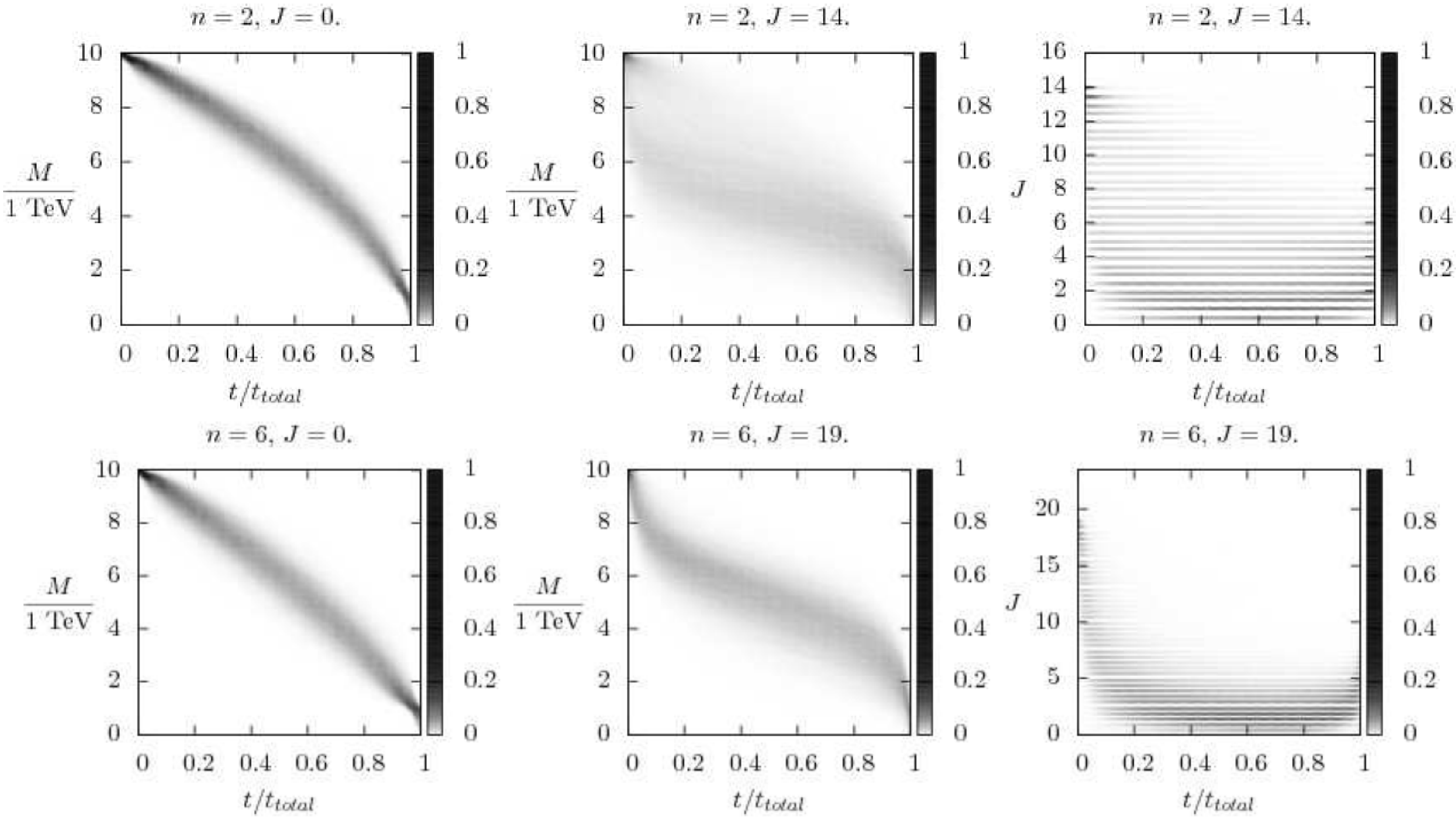
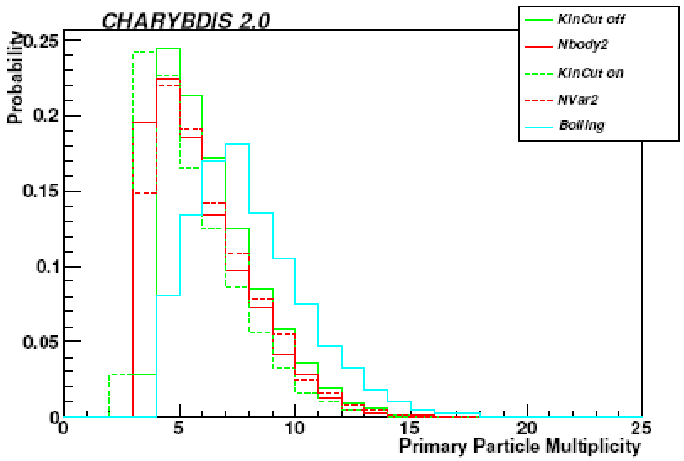
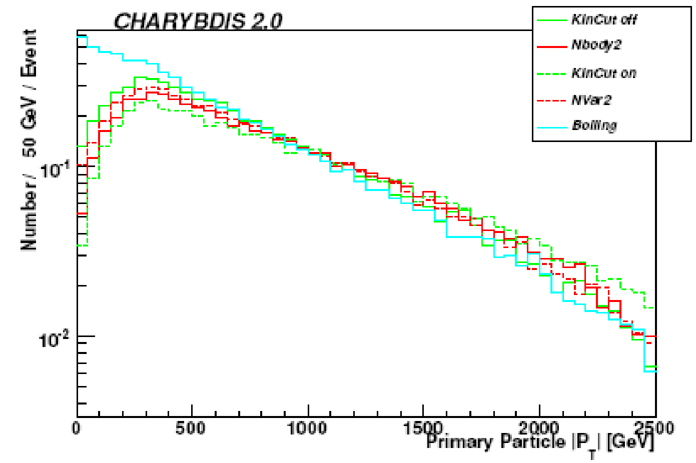


Figure 8: Probability maps for physical parameters, constructed from 10^4 trajectories for different BH events with fixed initial conditions M, J (for each horizontal line). Each trajectory contributes with weight 1 to the bins it crosses on the $\{P, t/t_{total}\}$ plane where P is the relevant parameter. Note that the time is normalised to the total time for evaporation t_{total}. The horizontal lines for the plots on the right are due to the discretisation of J in semi-integers.

Remnant Options





Legend	Remnant Criterion	Fixed/Variable	Remnant No./Mean
Kincut on	$M_{BH} < M_{PL}$ (KINCUT=.TRUE.)	Fixed	2
Kincut off	$M_{BH} < M_{PL}$ (KINCUT=.FALSE.)	Fixed	2
Nbody2	Flux (NBODYAVERAGE=.TRUE.)	Fixed	2
Nbody3	Flux (NBODYAVERAGE=.TRUE.)	Fixed	3
Nbody4	Flux (NBODYAVERAGE=.TRUE.)	Fixed	4
Nvar2	Flux (NBODYAVERAGE=.TRUE.)	Variable	2
Nvar3	Flux (NBODYAVERAGE=.TRUE.)	Variable	3
Nvar4	Flux (NBODYAVERAGE=.TRUE.)	Variable	4
Boiling	$M_{RMMINM} < M_{BH} < M_{PL}$	Variable	2

Backup