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Black Hole Phenomenology

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Outline

- **Introduction**
  - Brief Overview of Black Holes in Extra Dimensions
  - Black Hole Lifecycle
- **Modelling and Consequences of Black Hole Rotation**
  - Production
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  - Phenomenology
- **Monte-Carlo Generators and Other Models**
  - Charybdis2
  - BlackMax
- **Conclusions and Outlook**

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Introduction

- Antoniadis, followed by Arkani-Hamed, Dimopoulos and Dvali (**ADD**), and Randall and Sundrum (**RS**) have pioneered the solution of the hierarchy problem by using extra-dimensional space.

- The extra spatial geometry generates the large 4D Planck mass through:
    - **ADD** – a large volume factor for flat extra dimensions
    - **RS** – a high curvature (warped extra dimension).

- The relationship between the (4+n)-dimensional Planck scale and the 4-dimensional one is determined by the volume of the extra dimensions (or the warp factor in **RS**).

- Will focus on ADD.

- Flat extra dimensions are compactified with a size **R**, so the gravitational force **F** law looks like:

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

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

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

Large Extra Dimensions

- Standard Model fields are confined to our 3-brane.
- Gravitational field propagates in the bulk (appears weak)

$$G_4 = \frac{G_{4+n}}{R^n} \longrightarrow \tilde{M}_{PL}^2 \sim M_D^{n+2} R^n$$

- For large or many extra dimensions, the fundamental scale of gravity can be as low as ~1 TeV.

- **Microscopic black holes could be produced at the Large Hadron Collider**.

- LHC – a 'black hole factory'

(**S. Dimopoulos, G. Landsberg,** Phys.Rev.Lett.87:161602,2001, **S. Giddings, S. Thomas**, Phys.Rev.D65:056010,2002)

Constrained by Tevatron data, tabletop experiments and astrophysical observations and measurements (supernovae and neutron star cooling, gamma and cosmic-rays).

Constraints on ED

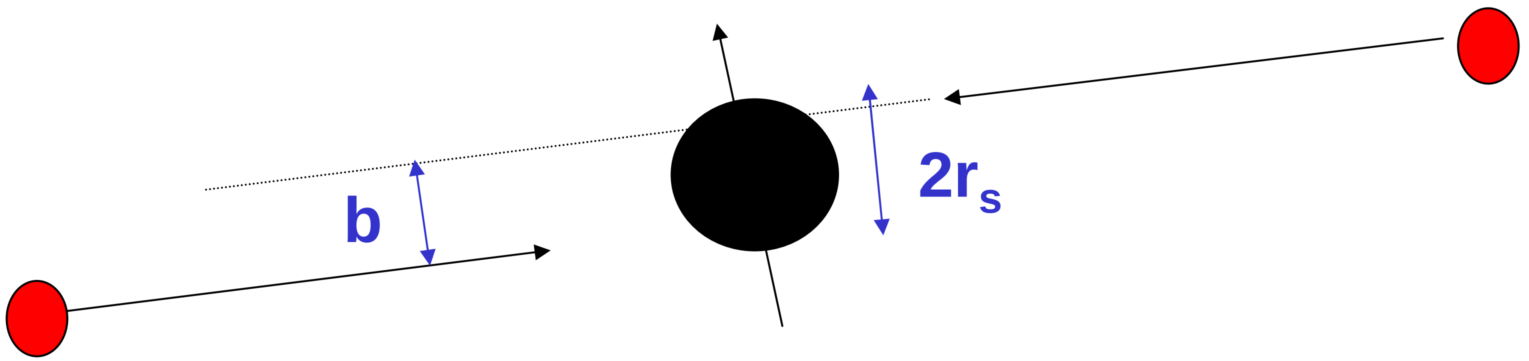
$$M_{Pl}^2 = R^n M_{(4+n)}^{2+n}$$

	R in μm ($n = 2$)	$M_{4+n} \sim 1$ TeV OK
Deviations from r^{-2} in torsion-balance experiments	$\lesssim 55$	$n > 1$
KK graviton production in Supernovae	$\lesssim 5.1 \times 10^{-4}$	$n > 3$
KK gravitons production in the early Universe	$\lesssim 2.2 \times 10^{-5}$	$n > 3$

Tevatron limits are: M_D < 1400 GeV(n=2) to M_D < 940 GeV (n=6)

CDF Collaboration, T. Aaltonen et al., Phys. Rev. Lett. **101** (2008) 181602. arXiv:0807.3132.

Formation



Thorne's Hoop conjecture states that if sufficient mass-energy lies within its Schwarzschild radius, a black hole will form

Parton level cross-section is then:

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

r_s is the Schwarzschild radius in (4+n) dimensions:

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

Neglects angular momentum, parton spin and charge, losses in production/balding and gravitational interactions with b>2r_s

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Evaporation

- Classically, black holes do not emit
- Hawking (1974) showed that a quantum instability can cause black holes to radiate
- Effectively, the large gravitational field leads to pair production at the event horizon
- The spectrum is that of a grey-body, with a characteristic Hawking temperature

$$T_{\mathrm{H}} = \frac{(n+1)}{4\pi\, r_{\mathrm{S}}}$$

- Energy-dependent transmission factors (known as greybody factors) change the spectrum from that of a black body, encoding the chance of escaping from the gravitational field of the black hole.

$$\frac{d^2N}{dt\,d\omega} = \frac{1}{2\pi}\frac{1}{\exp(\omega/T_H)\pm 1}\mathbb{T}^{(n+4)}_{s,l,m}(\omega)$$

$$\frac{d^2E}{dt\,d\omega} = \frac{1}{2\pi}\frac{\omega}{\exp(\omega/T_H)\pm 1}\mathbb{T}^{(n+4)}_{s,l,m}(\omega)$$

Black Hole Fluxes per degree of freedom

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Particles and Fluxes

- Black holes can emit all Standard Model particles, with probabilities approximately according to their degrees of freedom.

Particle type	spin-0	spin-$\frac{1}{2}$	spin-1
Quarks	0	72	0
Gluons	0	0	16
Charged leptons	0	12	0
Neutrinos	0	6	0
Photon	0	0	2
Z^0	1	0	2
W^+ and W^-	2	0	4
Higgs boson	1	0	0
Total	4	90	24

BH Lifecycle

- Such microscopic black holes have a high Hawking temperature and are thought to decay in 4 distinct phases:

  1) **Formation/Balding Phase**
     – the BH loses multipole moments – mainly gravitational radiation
  2) **Spin-down Phase**
     – the rotating BH emits Hawking radiation, losing its angular momentum and some mass
  3) **Schwarzschild Phase**
     – evaporation continues with loss of mass and gradual increase in temperature
  4) **Planck Phase**
     – BH temperature and/or mass reaches M_{PL} - realm of quantum gravity, remnant?

Question: Is this true for very light black holes, whose initial entropy is low?

Semi-Classical Criteria

- Cross-section depends strongly upon Planck mass, but most critically upon the threshold for black hole production.
- i.e. the threshold at which the semi-classical assumptions used in the production model are valid.
- The black hole will become lighter than this as it evolves and emits particles.

- Different ways to assess when the semi-classical limit is valid
  - Compton wavelength < horizon radius
  - Black hole entropy large
- A very conservative limit is to take: $\mathbf{M_{BH} > 5\ M_D}$

- For 7 TeV, this is a very strict limit – applying it reduces the cross-sections to O(10fb) for M_D=1 TeV, and O(pb) for M_D=800 GeV.
- However, some quantum gravitational effects would be expected below this threshold.

Models

There are several other models on the market, and included in the most recent generators which partly avoid this problem.

Stringballs – embed large extra dimensions into string theory.

String balls produced below GR threshold could have cross sections comparable to black holes.

- Thus these states would be even more accessible than black holes at LHC.
- Even if black holes produced at LHC, they will evolve into these string states.

T. Damour & G. Veneziano, "Self-gravitating fundamental strings and black holes", Nucl. Phys. B 568 (2000) 93-119; arxiv:hep-th/9907030v2.

D.M. Gingrich & K. Martell, "Study of highly excited string states at the Large Hadron Collider", Phys. Rev. D 76 (2008) 115009; arXiv:0808.2512v3 [hep-ph].

'**Quantum Black Holes**'

– low mass, low multiplicity resonances near M_{PL}, with large cross-sections.

Based on arguments in 'Black Holes and Quantum Gravity at the LHC'
Patrick Meade, Lisa Randall JHEP 0805:003,2008

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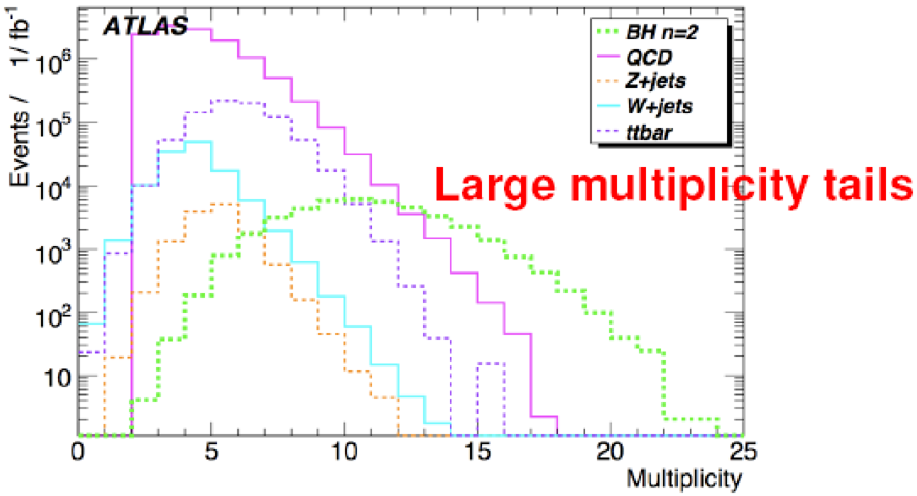
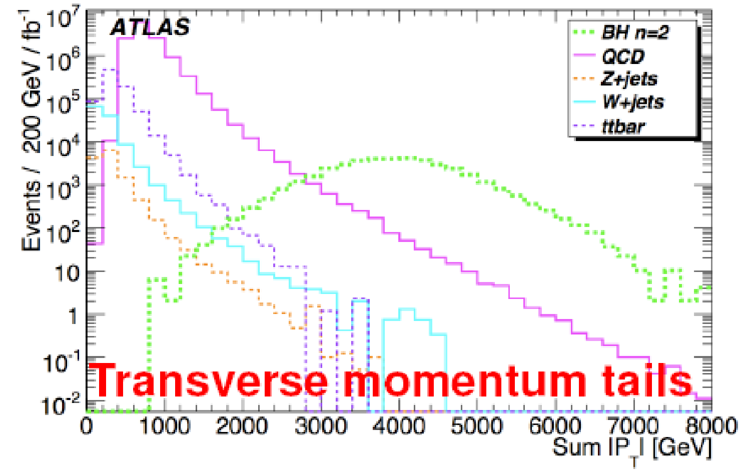
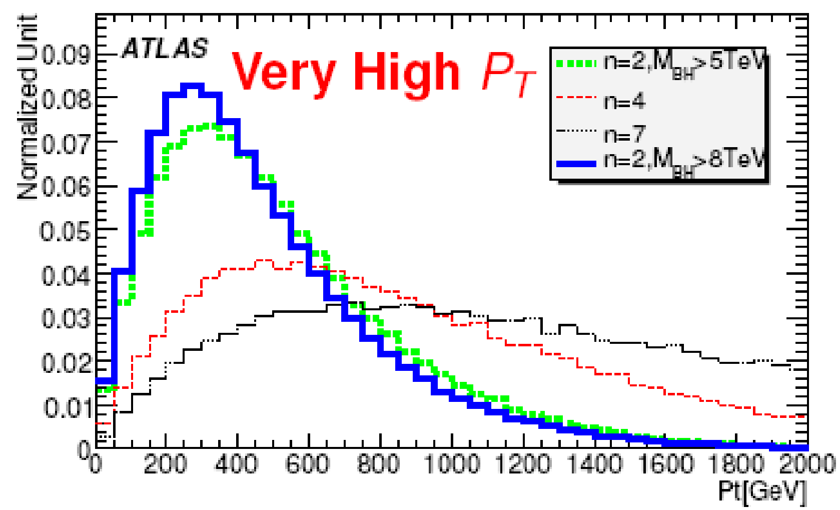
Black Hole Events

Some Classical Signatures see ATLAS CSC note arXiv:0901.0512

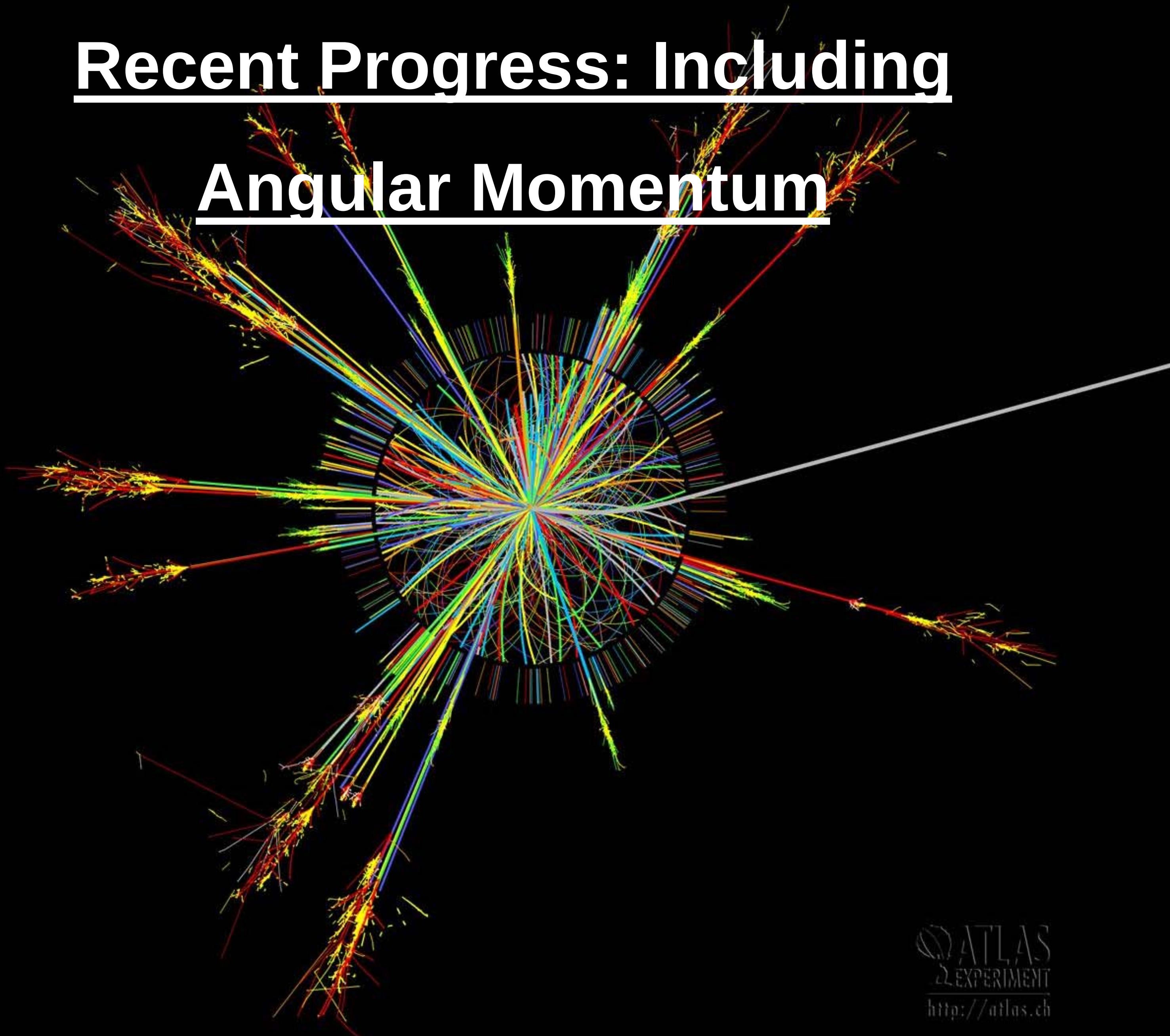




- ➢High multiplicity events with large numbers of jets, often with other particles (e.g. leptons) also present.
- ➢Very High pT particles of all SM species
- ➢High boosts for all SM particles.
- ➢For high multiplicity events, virtually any combination of particles in the final state.



Recent Progress: Including Angular Momentum



Rotation (I)

Over the last few years, there has been much theoretical progress in describing the Hawking radiation emitted from rotating black holes (Ida, Oda & Park, with the calculation of greybody factors.

Dolan, Casals, Kanti, Winstanley mathsci.uc.ie/~sdolan/greybody/
hep-th/0503052, hep-th/0511163, hep-th/0608193
Ida, Oda, Park hep-th/0212108, hep-th/0503052, hep-th/0602188

- **Gravitons still missing**…
- ..... bulk contribution may be large, but doesn't seem so for scalar fields.
- This allows the power fluxes and angular distributions of the particles emitted on the brane from the black hole to be calculated.

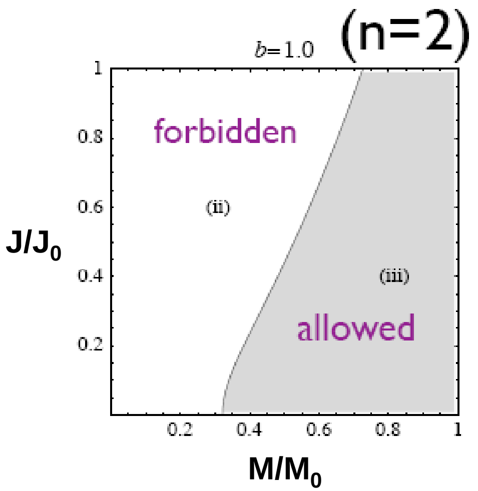
$$\frac{d^2 N}{dt d\omega} = \frac{1}{2\pi} \sum_{j=|h|}^{\infty} \sum_{m=-j}^{j} \frac{1}{\exp(\tilde{\omega}/T_H) \pm 1} \mathbb{T}_k^{(D)}(\omega, a_*)$$

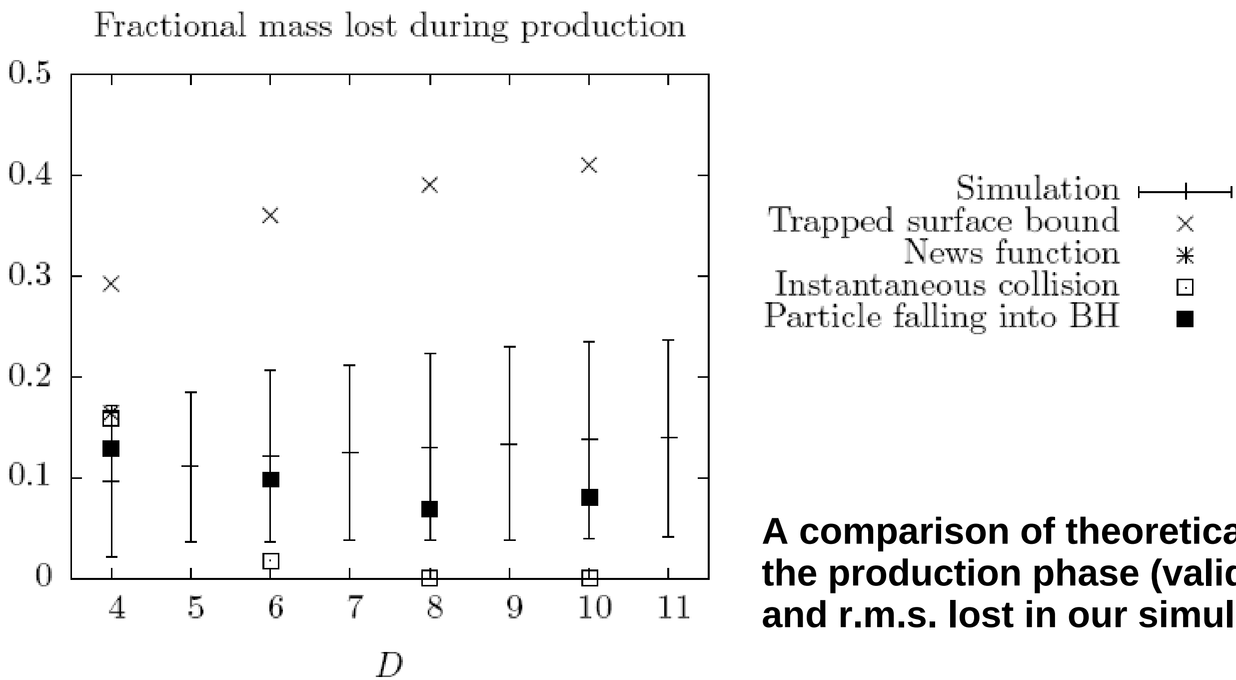
$$\tilde{\omega} = \omega - m a_* / [(1 + a_*^2) r_H]$$

- Grey body factors depend upon oblateness
- Planckian factor contains a spin term.

Production (I)

- 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.
- Need a model for the distribution in the allowed region…





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

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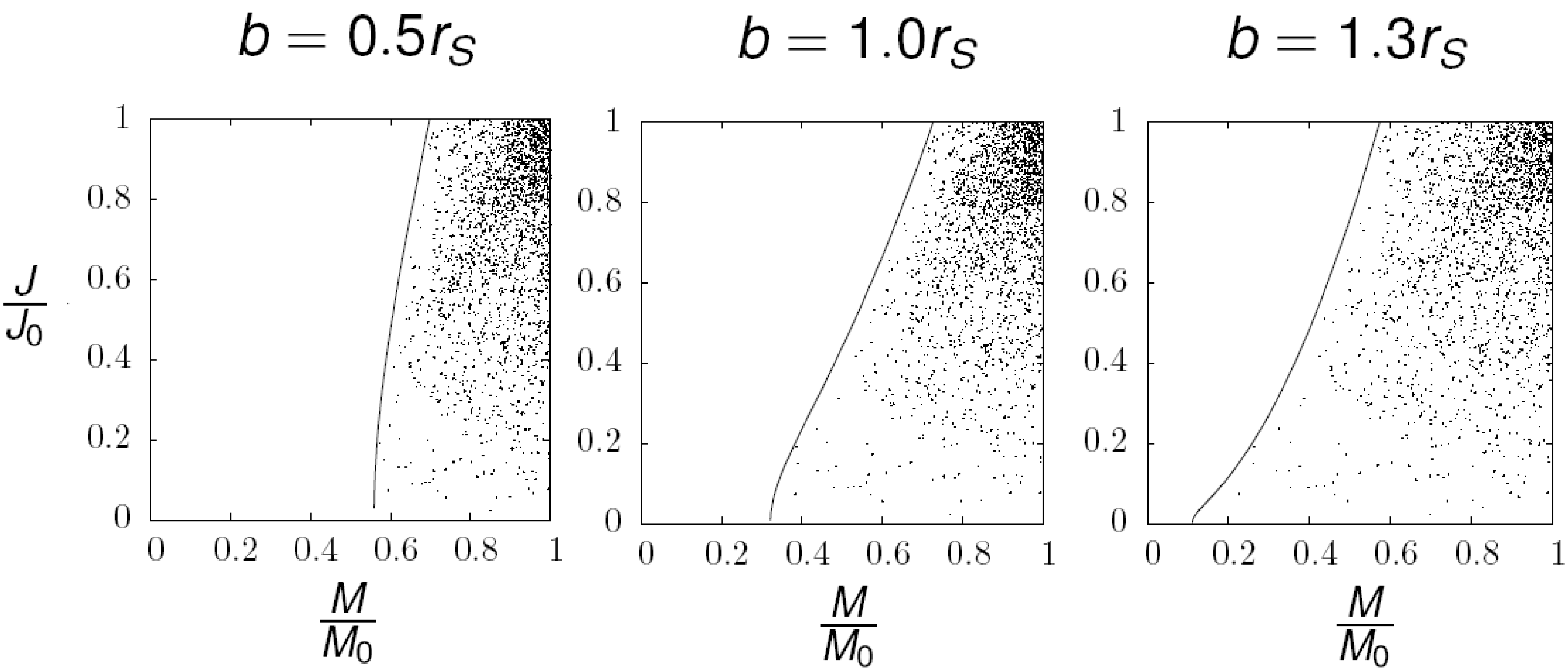
Production (II)

- The Charybdis 2 model is shown below for n=2
- Toggled on/off using generator switch MJLOST.

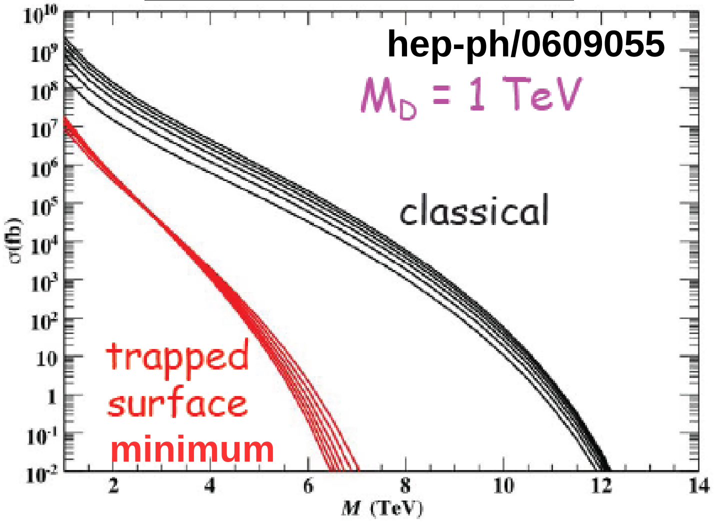
- BlackMax also allows an user-defined fraction of the mass and angular momentum to be lost.

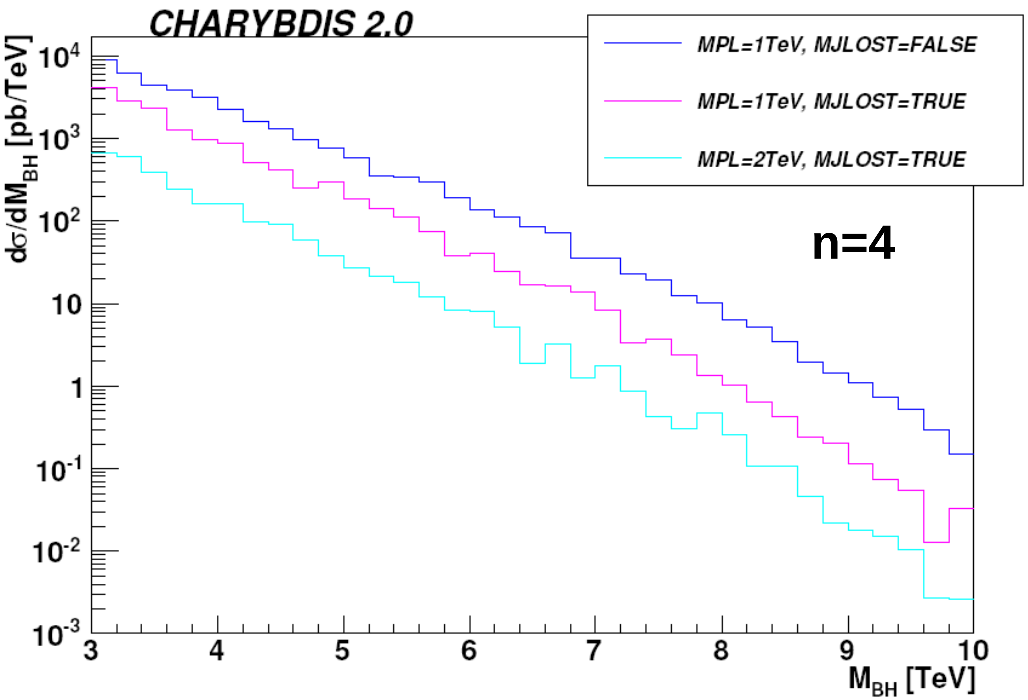


BH Cross-sections

- Black hole cross-sections show a strong dependence upon the Planck mass.
- Differential cross-section heavily affected by models of mass and angular momentum lost in gravitons in production.
- BH cross-sections have large uncertainties – the σ neglecting losses lies orders of magnitude above the minimum bound calculated.

14 TeV Predictions



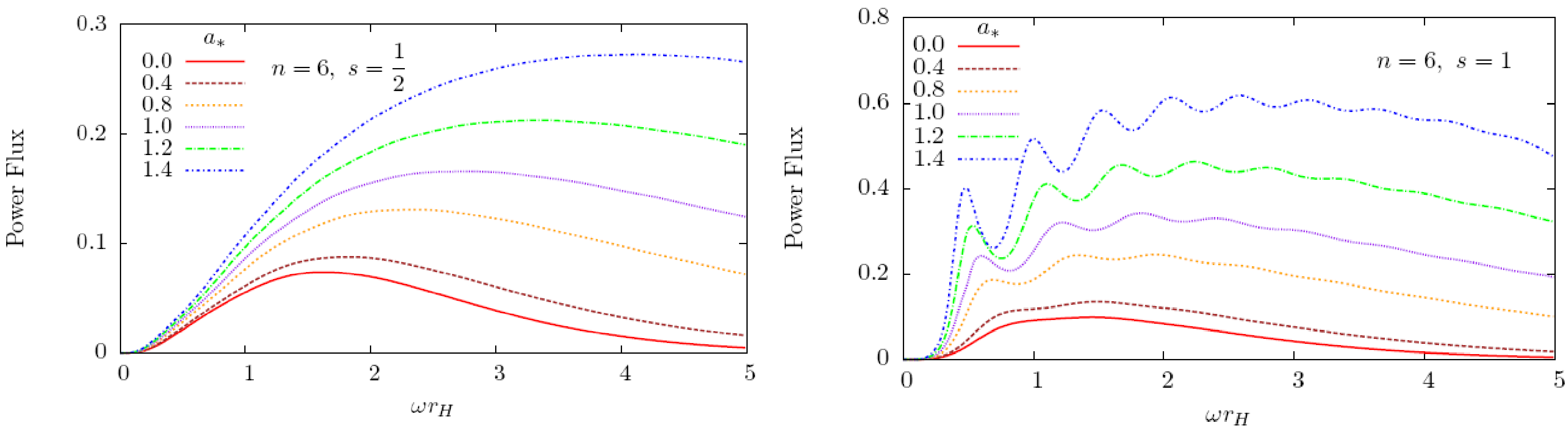


Rotation (II) - Power Spectra

➢Rotation increases the mean energy and total flux dramatically.

➢More modes corresponding to spheroidal partial waves with larger (l,m) angular momentum contribute to the fluxes

Dolan, Casals, Kanti, Winstanley mathsci.uc.ie/~sdolan/greybody/
hep-th/0503052, hep-th/0511163, hep-th/0608193
Ida, Oda, Park hep-th/0212108, hep-th/0503052, hep-th/0602188



Power spectrum of fields for brane emission with *n* = 6 a range of values of BH a* (oblateness)

Rotation (III) – Angular Distributions

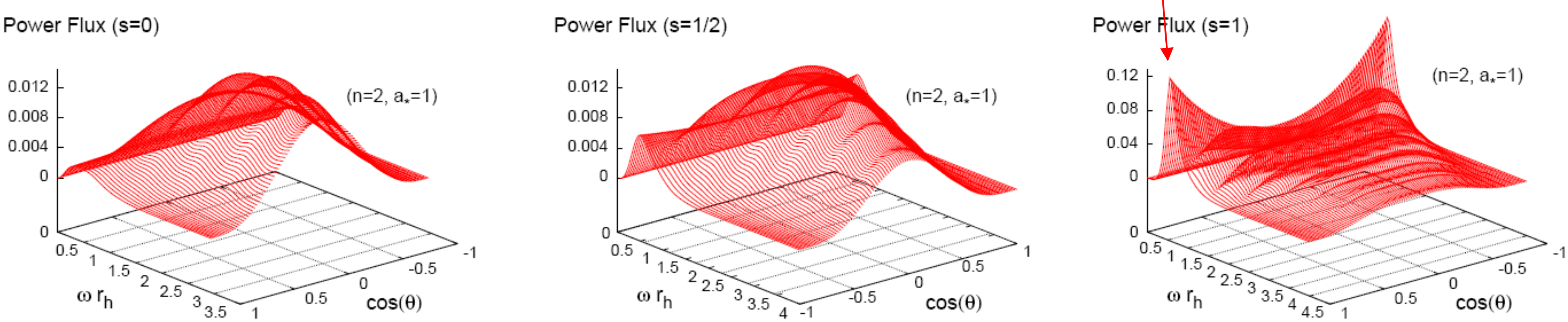
- Rotation breaks the isotropic (symmetrical) emission. Need to use spheroidal functions to describe the modes.

- Higher energy emissions are more equatorial.
- Low energy vector emissions are more axial.
- Each polarisation contributes differently to the angular distributions.
- Azimuthal symmetry remains.

Asymmetries!

Helicity +1

Helicity -1



Angular Power Fluxes for scalars, fermions and vectors

M. Casals, S. R. Dolan, P. Kanti and E. Winstanley, JHEP 0703 (2007) 019 [hep-th/0608193]

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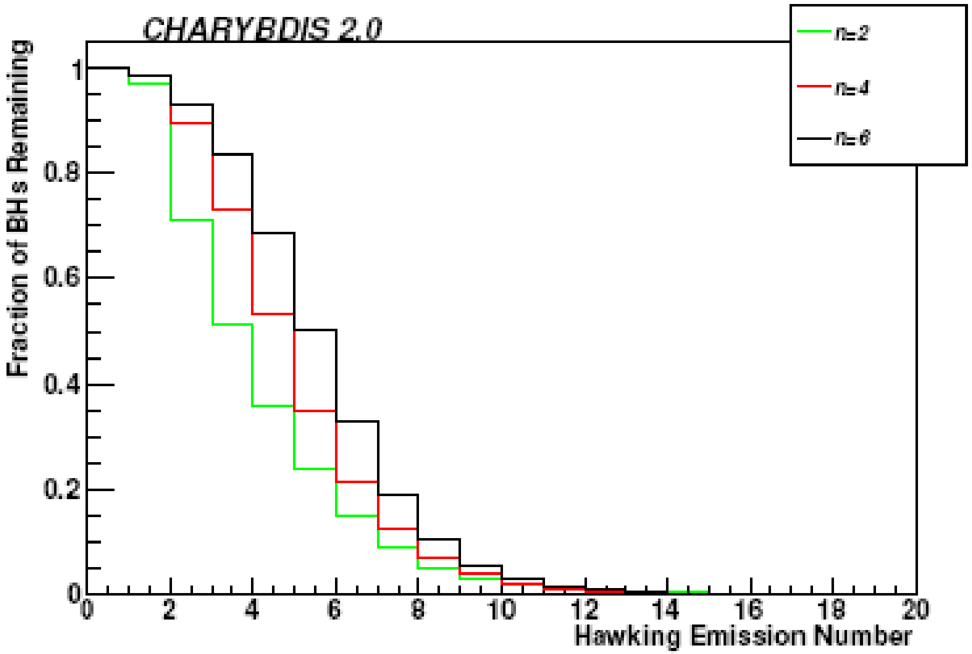
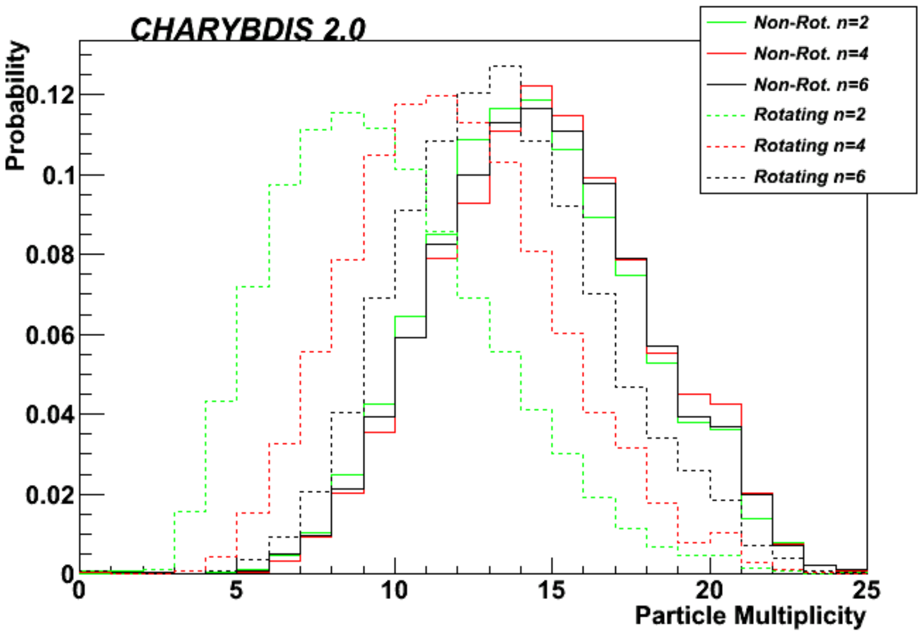
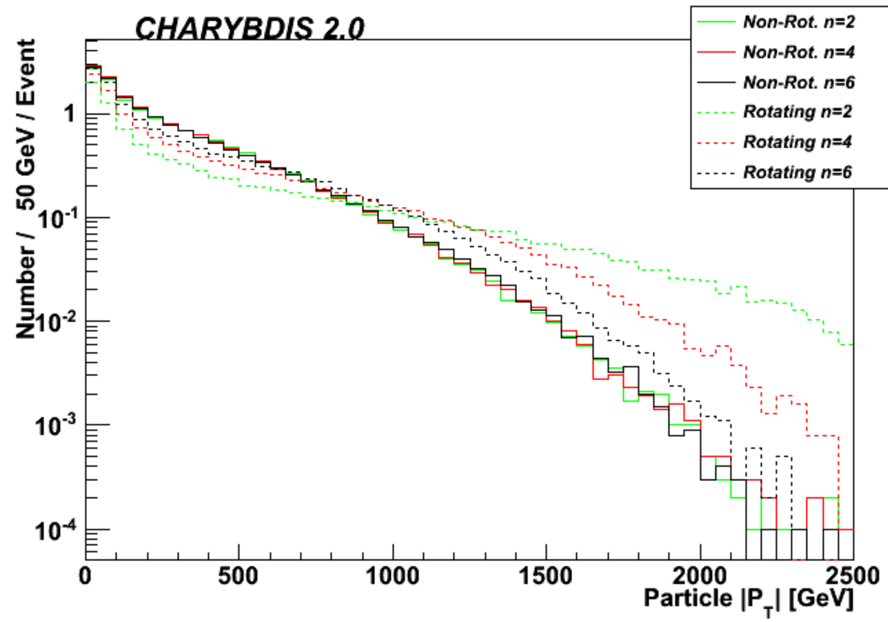
Phenomenology

- Generated using **Charybdis 2**
- M_{PLANCK} = 1 TeV (PDG definition)
- *n* extra dimensions
- 5-14 TeV initial mass, so as to model the LHC experimental reach whilst maintaining the validity of semi-classical assumptions used in the production model.
- AcerDet fast simulation was employed, to illustrate the features of rotating black holes.
- Full Experimental analyses for the measurement of black holes will need to take these into account.



Rotation Effects

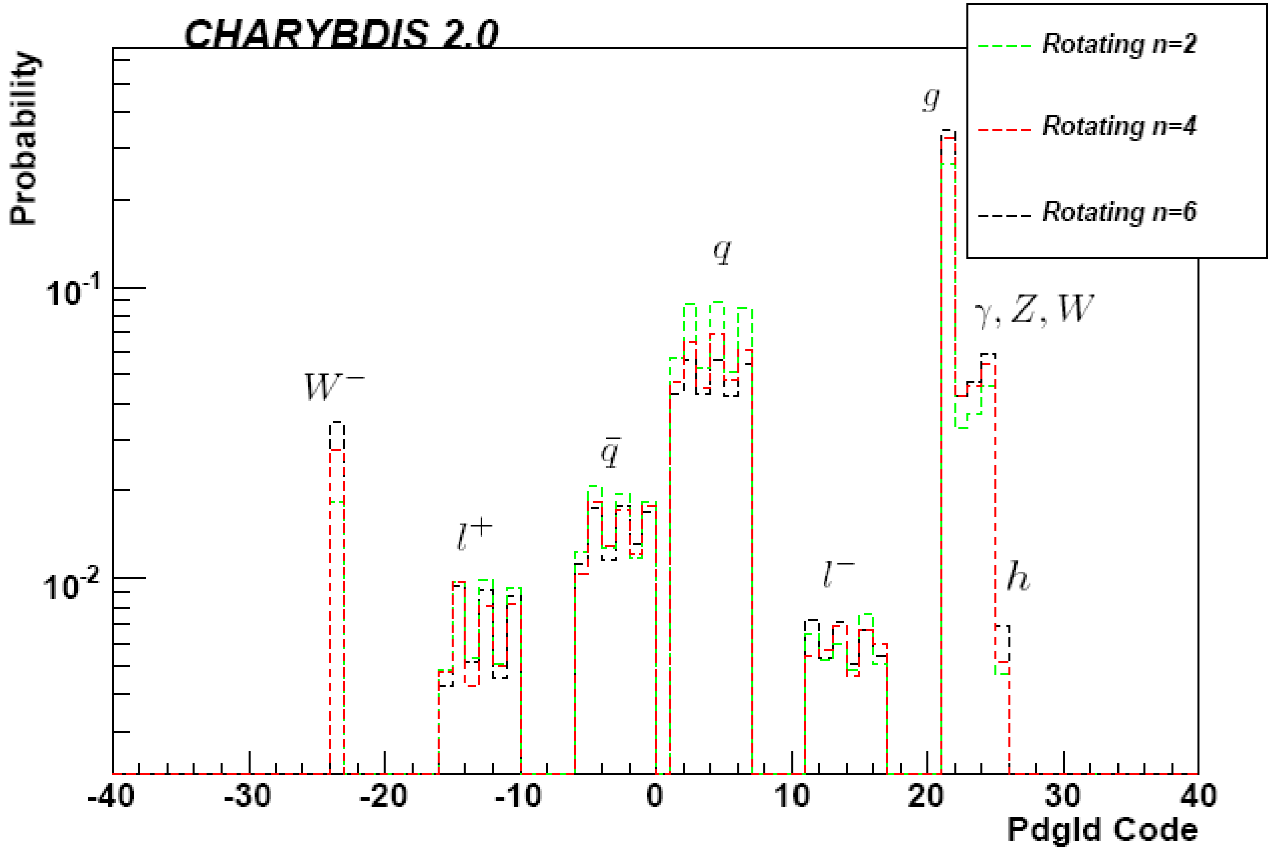




- Rotating black holes (dashed lines) emit far fewer, more energetic particles than their non-rotating, Schwarzschild analogues (solid lines), since the spin term reduces the Boltzmann suppression of high energy emission.

- I.e. The Hawking spectrum with rotation is shifted toward higher energies, with the same M_{BH} shared between fewer particles of higher energy.

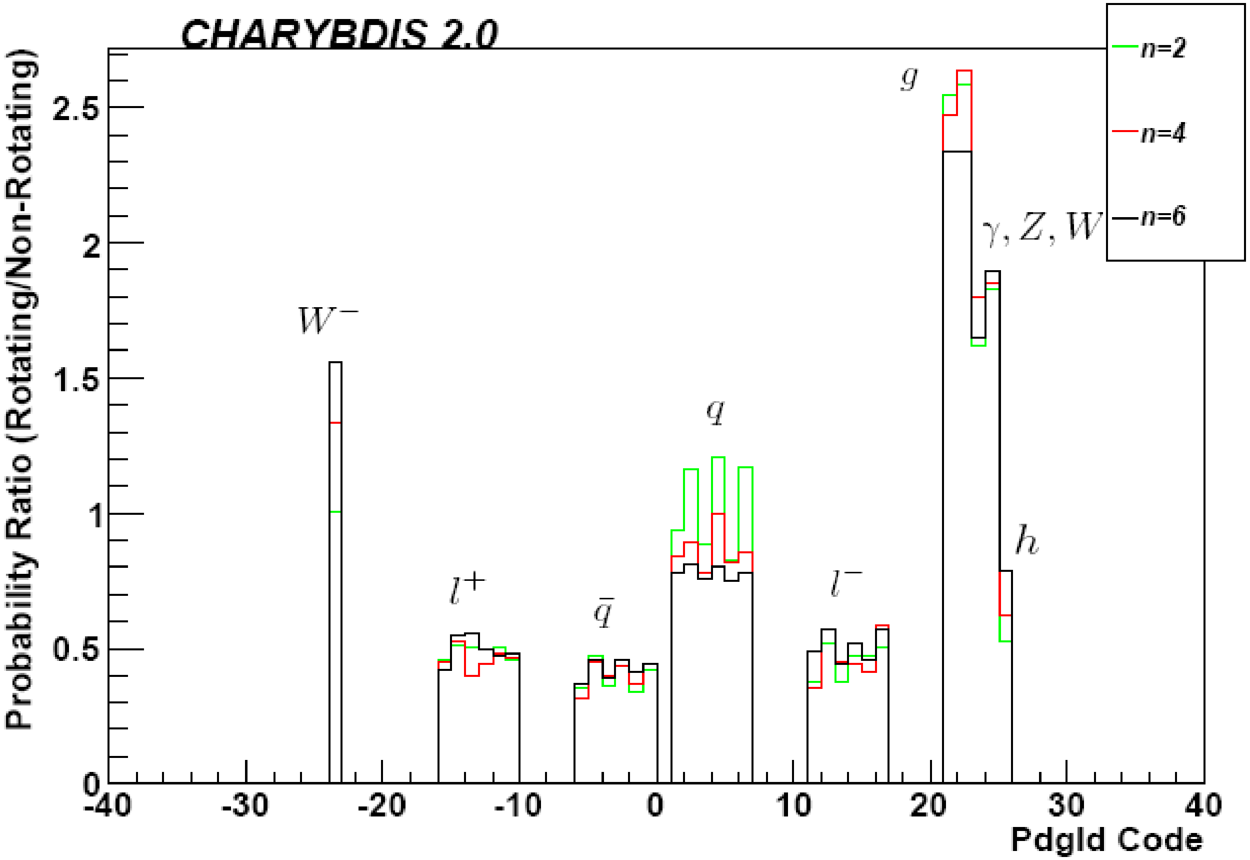
Which Particle Species?



➢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).

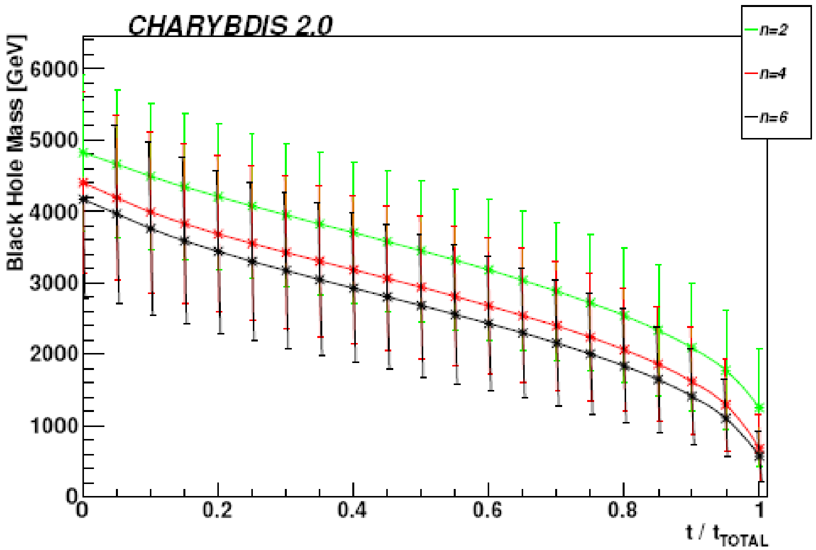
➢NB. Baryon/Lepton number is conserved here so as to enable hadronisation.

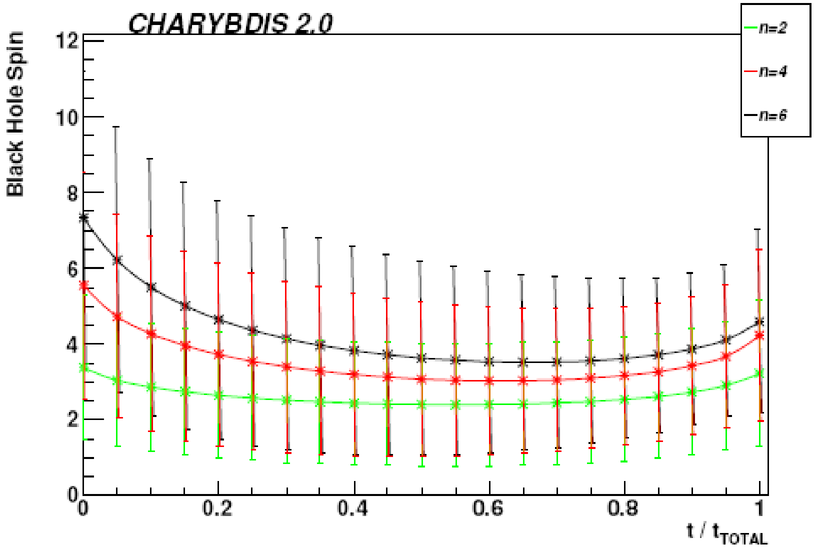
Which Particle Species?



- ➢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.

Black Hole Evolution





- The black holes emit Hawking radiation, losing mass and angular momentum, and gradually becoming hotter (increasing in 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 remains non-negligible throughout evaporation.**

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)

Modern (Rotating) BH MC (I)

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 if desired.

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

Production: Rotating black holes. Can lose a fixed (for each n) 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.

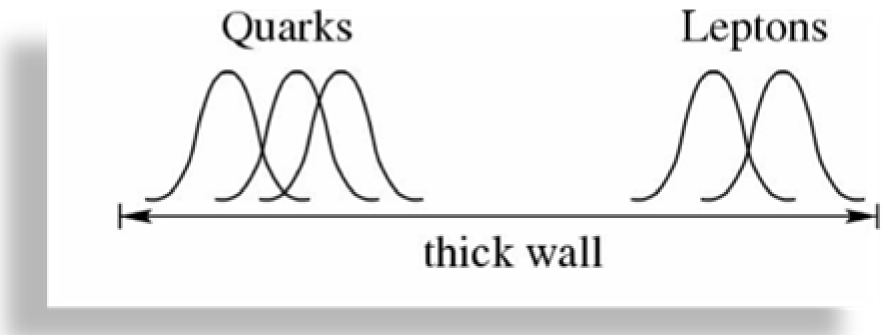
Remnants: Isotropic, phase space. 'Final burst' model with minimal multiplicity to conserve all quantum numbers.

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

An alternative: Split Fermions

N. Arkani-Hamed, M. Schmaltz, ***Phys. Rev. D 61****:033005 (2000)*

In order to suppress a direct QQQL coupling
we must separate quarks form leptons



Quarks and leptons are localized at different points on a thick brane
Or alternatively, on different branes

The model yields exponentially small coupling (wave function overlap) between quarks and leptons

Dangerous QQQL interaction is suppressed

Stabilising the Proton: virtual black holes can no longer mediate proton decay (F. Adams, G. Kane, M. Mbonye, M. Perry Int.J.Mod.Phys.A16:2399-2410,2001; S. Hawking, Phys.Rev.D53:3099-3107,1996)

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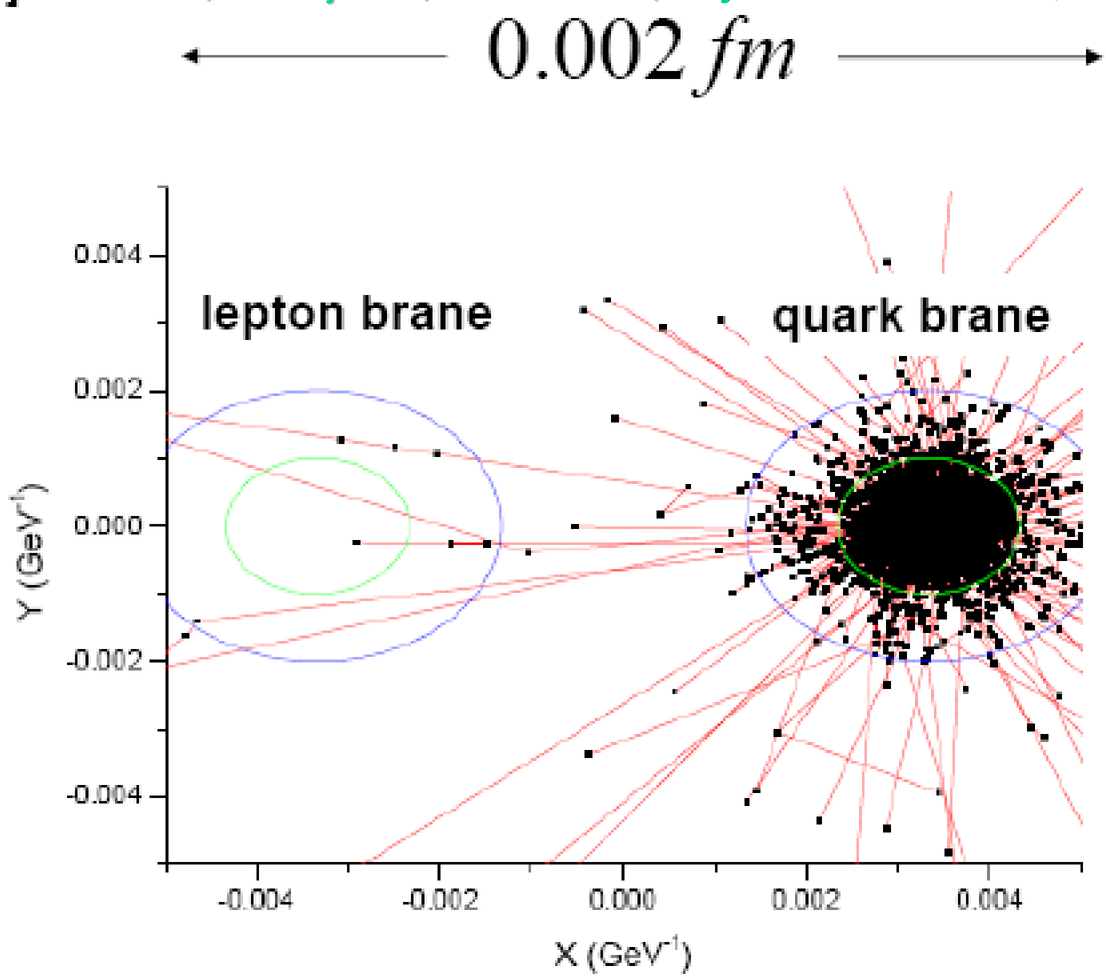
Split Fermion Brane Extra Dimensions

0711.3012 [hep-ph]   D. Dai, D. Stojkovic, G. Starkman, **Phys.Rev.D73**:104037,2006



Different Phenomenology:

Far fewer leptons produced – signature becomes still more dominated by jets.

Reduced cross-sections

Bulk component of angular momentum equivalent to that on the brane.

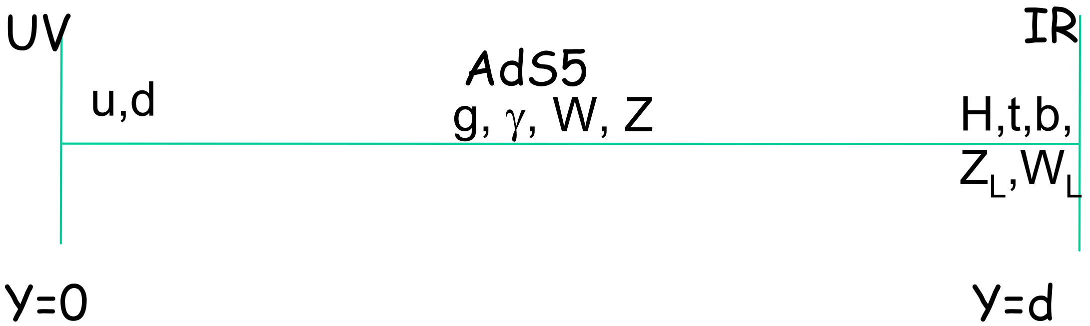
Split UED

Can even look at BHs in split UED models:

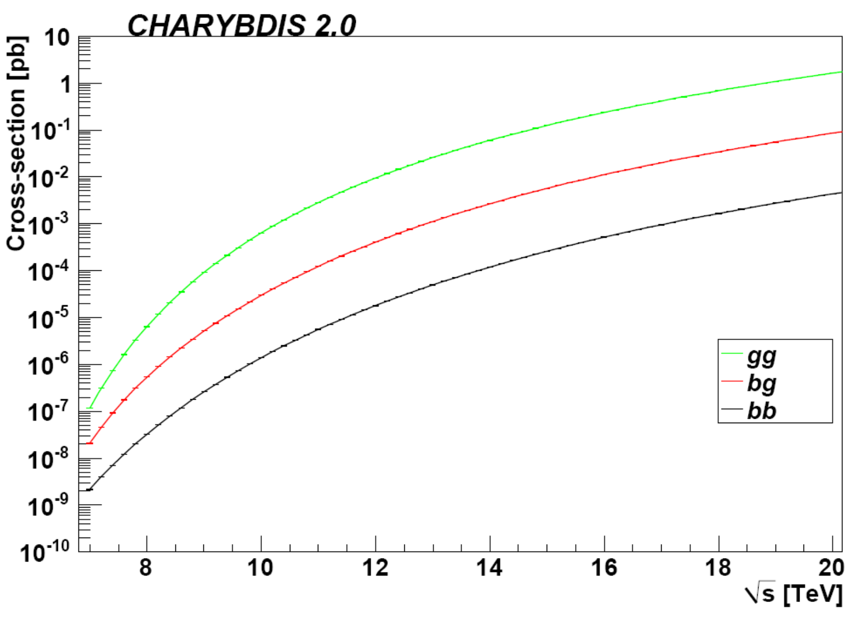
e.g. arxiv:0903.1971, arxiv:1004.4635, arxiv:1002.0602

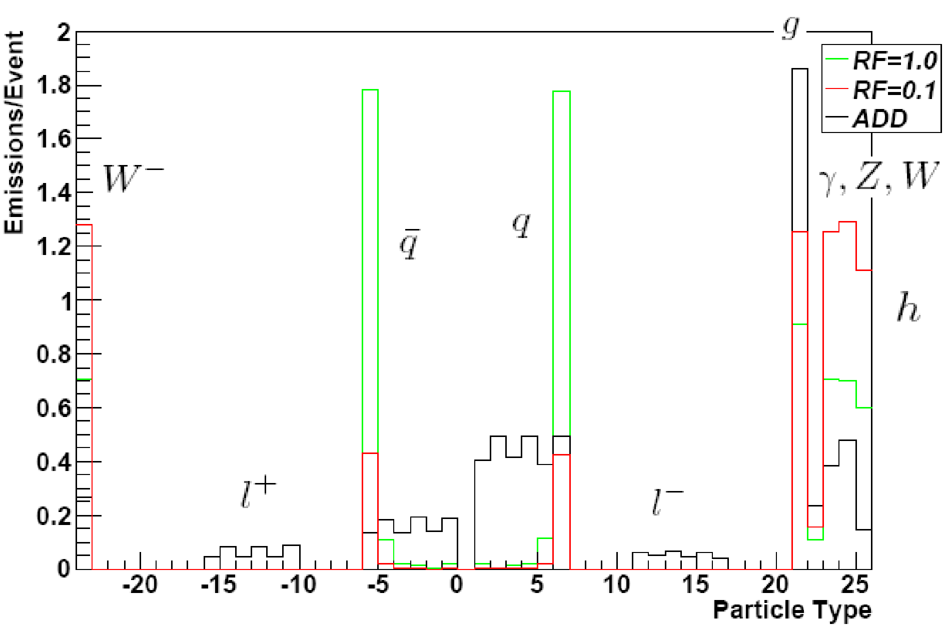
-Light quarks do not 'feel' TeV gravity, leads to a drastic drop in cross-section.

- Completely changed particle spectrum – only t, W, Z, g, γ



JAF, S-C Park, in prep

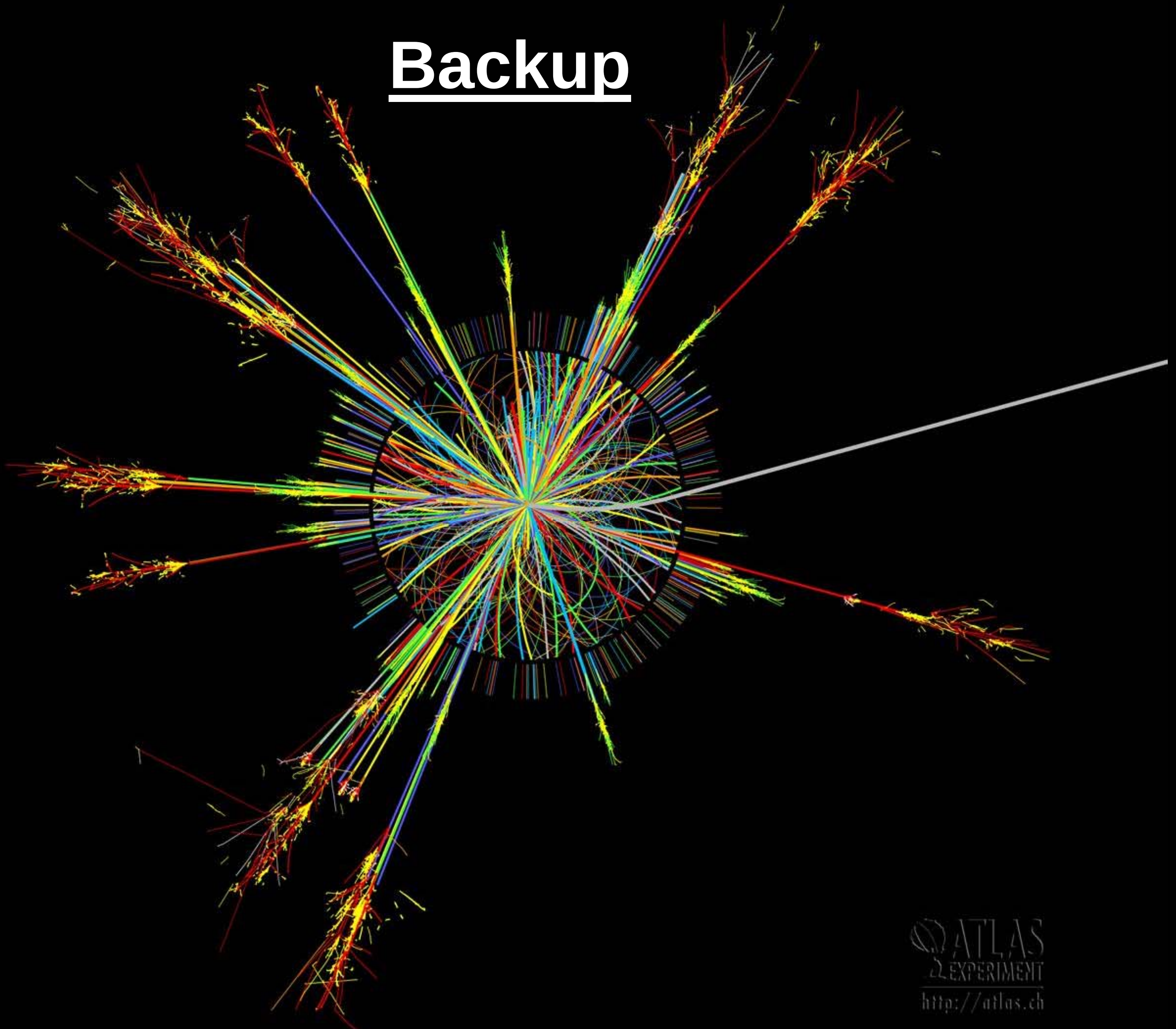




Conclusions/Outlook

- There has been much recent progress in both theory and experimental ability to describe microscopic black holes that could be produced at the LHC.
- They have a startling, quite unique signature – multiple, high PT particles, of all SM flavours, with a high cross-section for production.
- Verifying this would require much greater study and study of the boosted final states – BHs produce boosted tops, W and Z in abundance. Investigating any signature in detail would require investigating these highly boosted emissions more closely.
- BH 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.
- Rotating black holes look hotter – produce **fewer, more energetic particles**
- Some changes in the particle species present – an increase in vectors, mainly at the expense of fermions – relatively fewer leptons, more gluonic jets, more (highly boosted) vector bosons, more photons.
- Two dedicated Monte-Carlo generators exist: CHARYBDIS 2 and BLACKMAX. Important to use these as they include the effects of BH rotation.
- More difficult to probe an assuredly TransPlanckian regime at 7 TeV, but cross-sections can still be large. Expect to see LHC results soon…!

Backup



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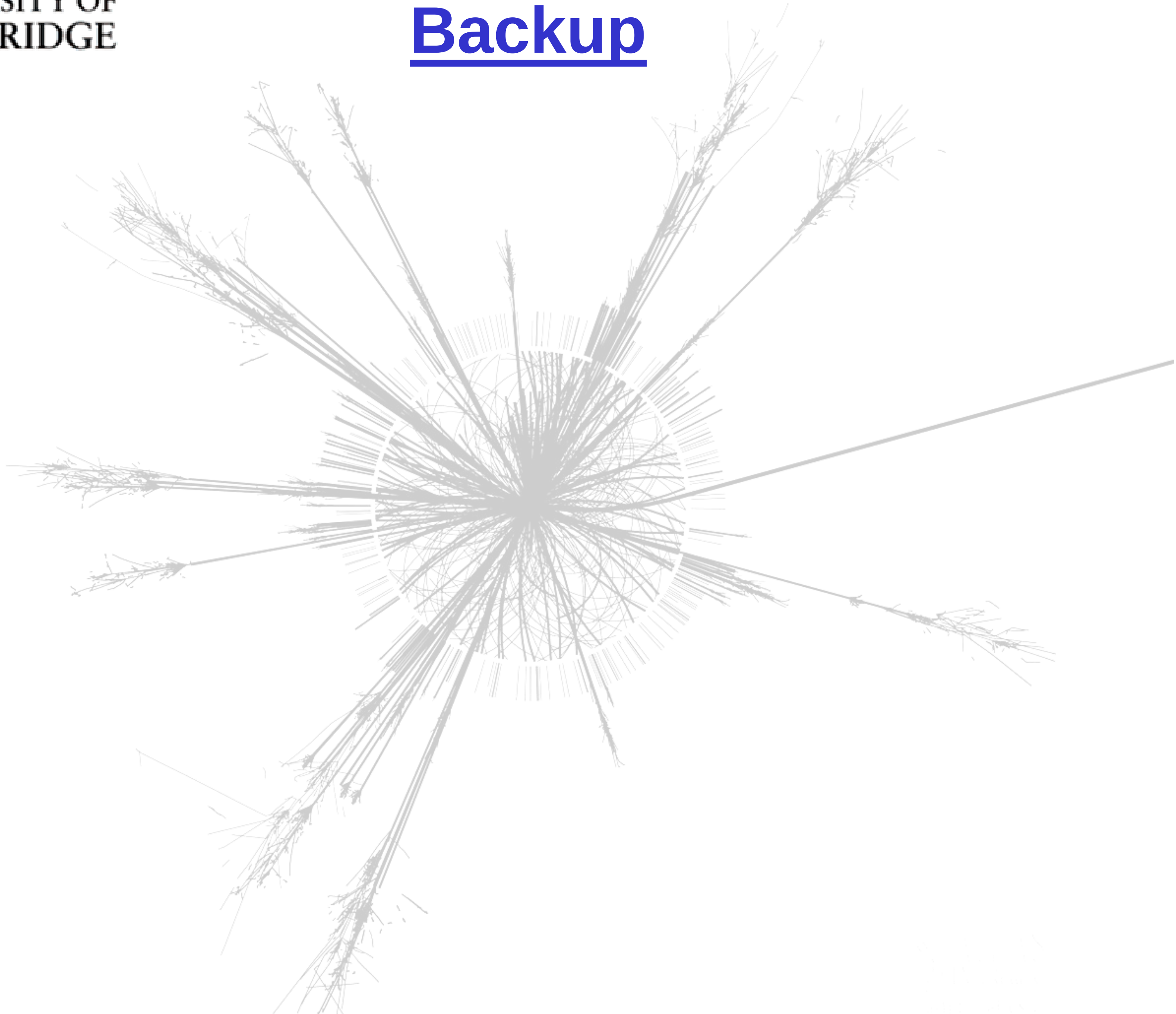
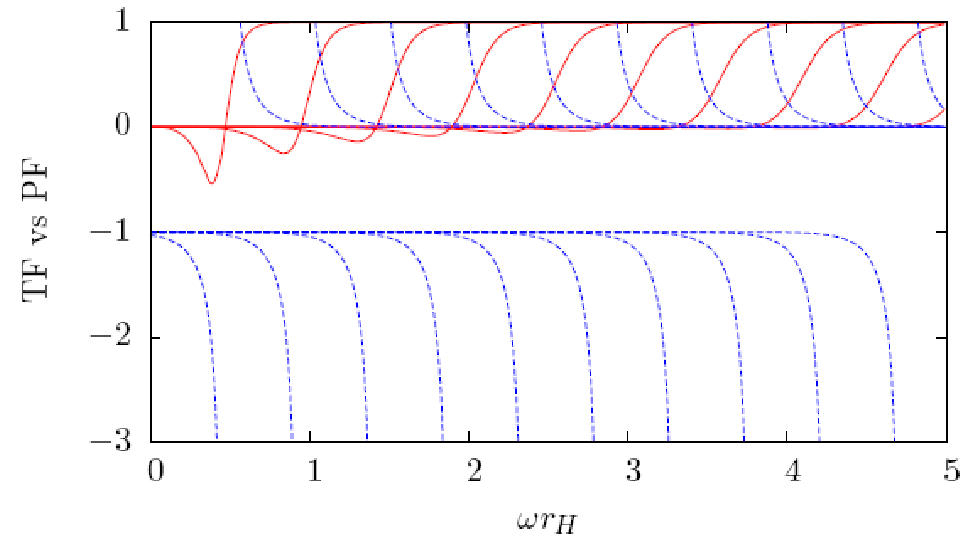
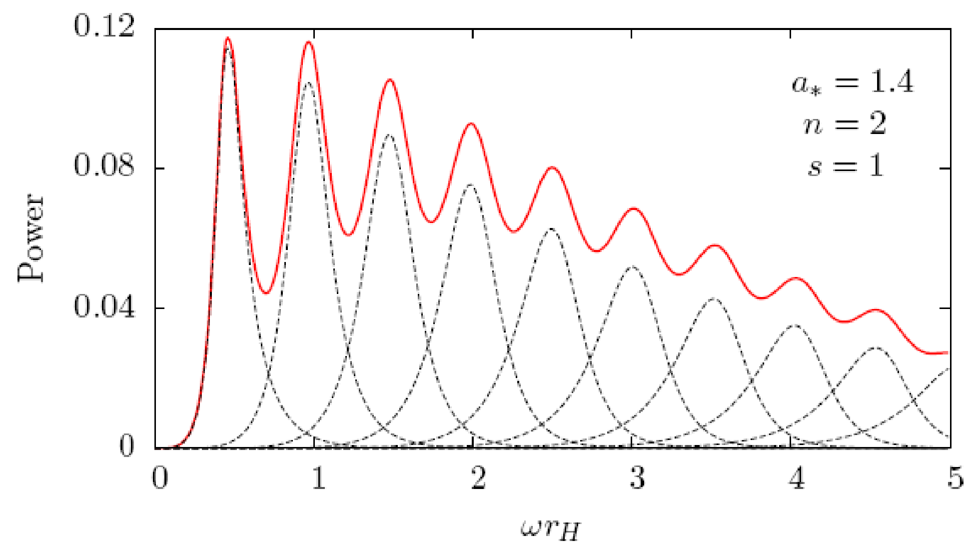


Mode Contributions

- ➢Planckian factors and Transmission coefficients give narrow modes that lead to an oscillatory power spectra.
- ➢This is emphasised in the super-radiant region.





Remnant Phase (I)

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- We must always decide what to do when the black hole reaches the **Planck/remnant phase**, the point at which the black hole mass and/or temperature lies at the Planck scale.
- **Two** things are needed: A **criterion** for the onset of this phase, and a **model** for the final state

- Natural default in **Charybdis 2** – 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

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

- Otherwise, the **Charybdis 1** switch KINCUT can be used either as TRUE to terminate decay when a kinematically disallowed decay ($E>\sim M_{BH}/2$) is proposed, so as FALSE, to continue emission until the BH mass reaches M_{PL}.

New Remnant Options

- Charybdis 1.0x modelled this using a fixed multiplicity remnant decay of 2-5 particles.

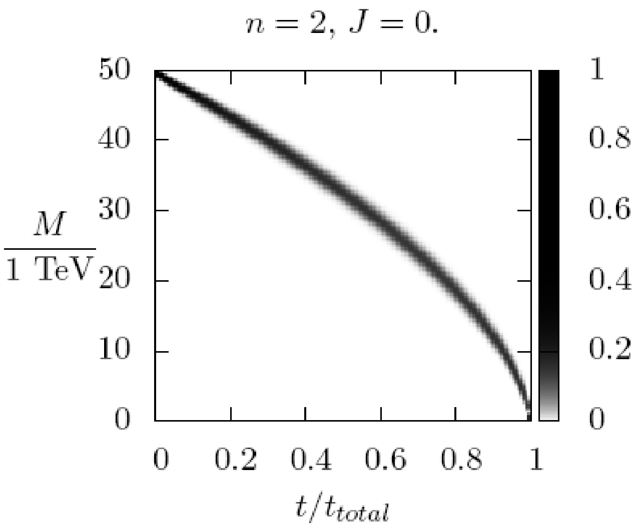
- Charybdis 2.0 also allows us to use a variable-body model for the remnant phase. This has been suggested to be correct when the flux is large and black hole no longer has time to re-equilibrate between emissions. Under these circumstances, the multiplicity follows a Poisson distribution.

- String-motivated 'Boiling' model – at Planck scale, BH looks like a stringball, with a max temperature/minimum length scale. Dimopoulos et al. hep-ph/0108060

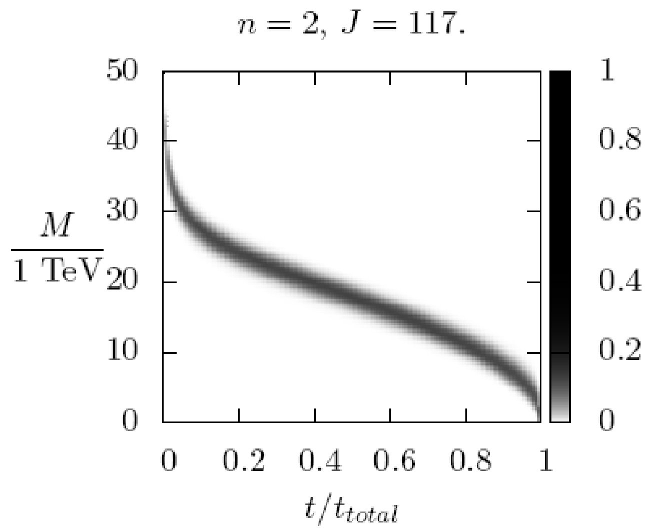
- Can also model low multiplicity black holes, producing either fixed or Poisson-distributed multiplicity, using the rotating black hole distributions and Hawking spectra if desired.

- Stable remnant option – where the final object has **B=0**, **Q=0,±1** and acts as a heavy fundamental particle. B. Koch et al. hep-ph/0507138

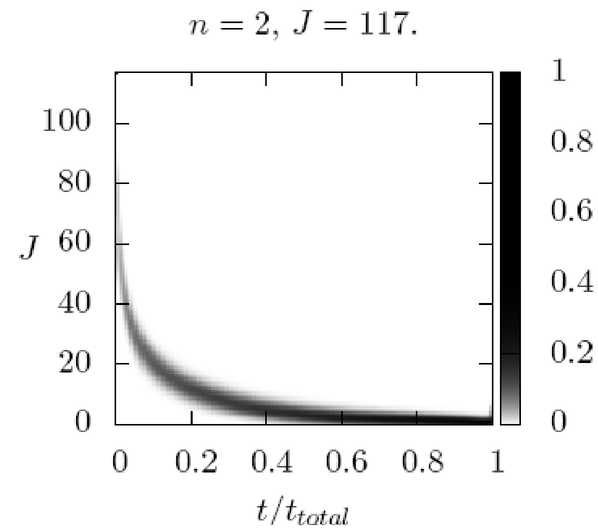
Evolution – 50 TeV



Non-rotating



Highly rotating



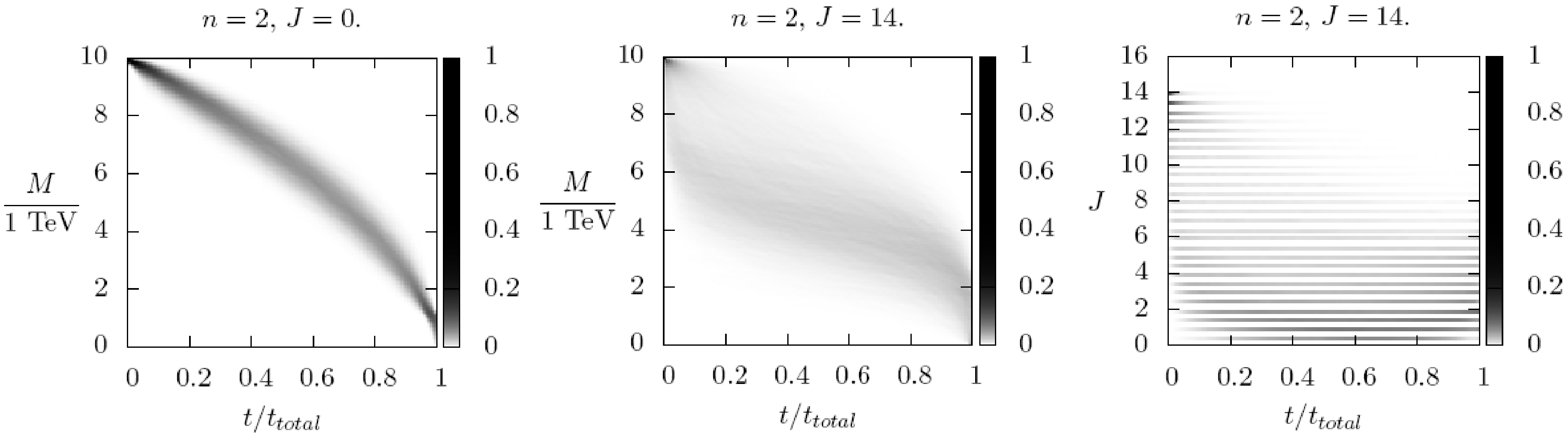
Angular Momentum

- Show expected semi-classical behaviour

- **Schwarzschild** – steady loss of mass until low mass Planck phase

- **Rotating** – mass lost rapidly first (spin down phase) then Schwarzschild phase with low angular momentum and steady loss of mass

Evolution – 10 TeV



Non-rotating **Highly rotating** **Angular Momentum**

- Evaporation is less smooth, due to fewer emissions.
- Statistical fluctuations larger, and trends less definite

- **Schwarzschild** – fluctuations larger, but the trend is still clear
- **Rotating** – trend is more dispersed. Often rapid initial mass and angular momentum decrease as expected, but spin often non-negligible throughout decay.

CHARYBDIS2 @ Work

http://projects.hepforge.org/charybdis2/

$\sigma_{PP \to BH}$

$$\sum_{i,j} \int \frac{d\tau dx}{x} f_i(x) f_j\left(\frac{\tau}{x}\right) F_n \sigma(\tau s)$$

→ MJLOST

Choose $b < b_{max}$

Reduce M and J

→ **Graviton**

Store momentum in event record

$M_{BH} < \sqrt{\tau s}$ formed

Evaporation

Select P^μ of SM emission $\frac{dN_h(a_*)}{dt d\omega d\Omega}$

Recoil BH against (P^μ, m, j) and update $\{M, J\}$

Store emission in LH common with polarisation

Continue.

Repeat until NBODYAVERAGE or KINCUT

Remnant

NBODYVAR

NBODYPHASE

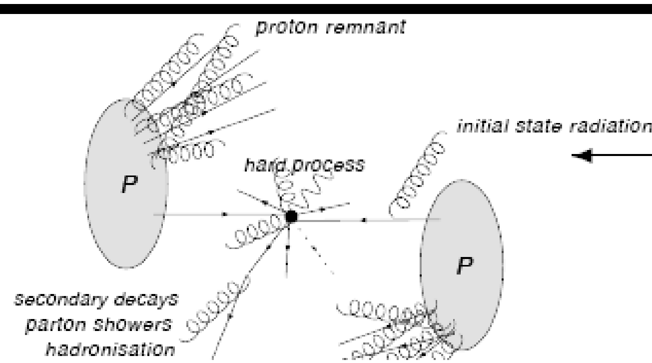
RMBOIL

RMSTAB

→ HERWIG

PYTHIA

CHARYBDIS



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