CHARYBDIS2: Modelling higher dimensional black hole events

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In collaboration with James A. Frost, Jonathan R. Gaunt, Marc Casals, Sam R. Dolan, M. Andrew Parker and Bryan R. Webber

References: JHEP10(2009)014 [arXiv:0904.0979],
http://projects.hepforge.org/charybdis2/

Acknowledgements

Cambridge SUSY working group

FCT – SFRH/BD/23052/2005

A problem with scales...

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Gravity

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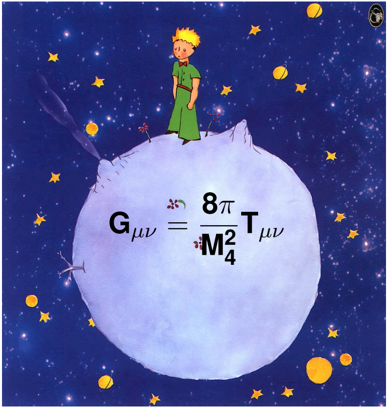

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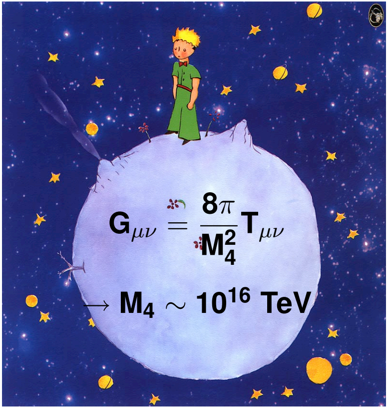

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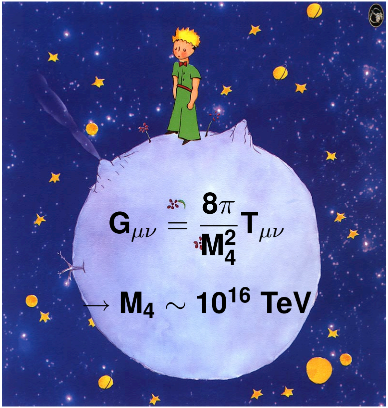
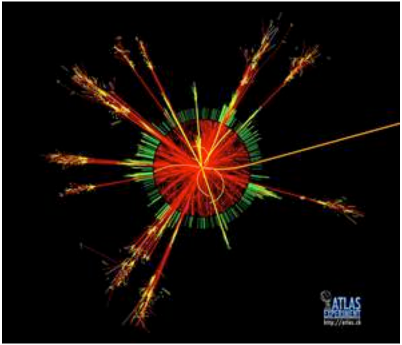


Particle Physics



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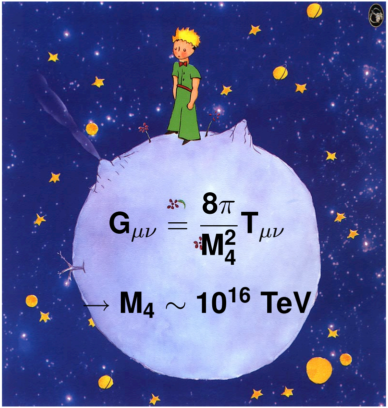

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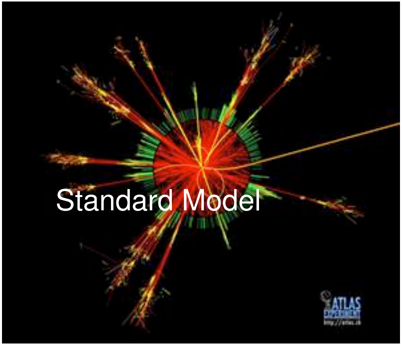

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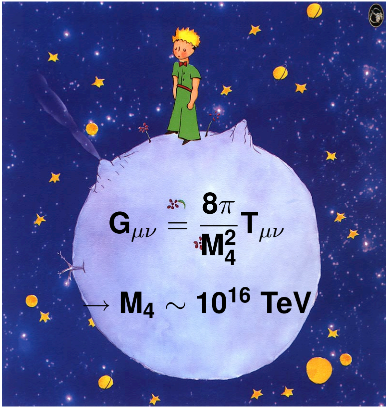

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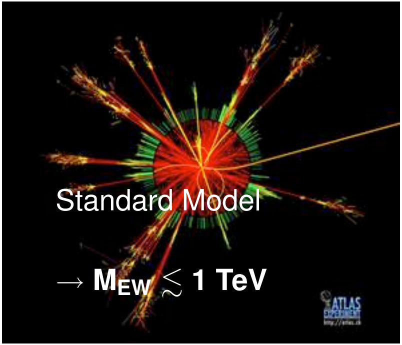

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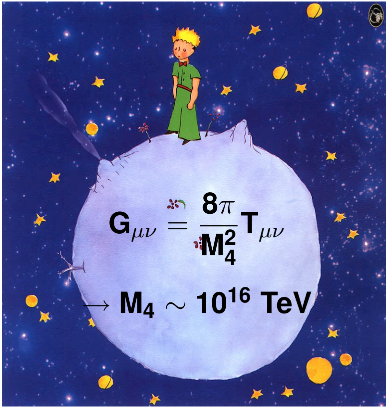

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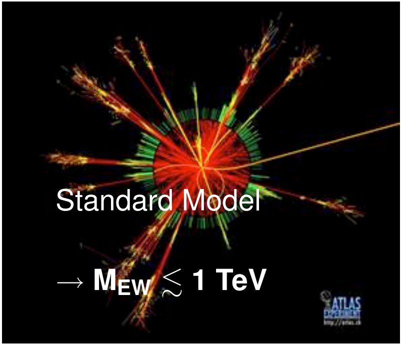

How to explain this hierarchy of scales?

Aim of this talk

The aim of this talk

To introduce the Physics of Black Hole production and decay in theories with extra dimensions.

Describe the incorporation of the theory into a Monte Carlo program `CHARYBDIS2`.

Present some phenomenological features of the results and how they affect observables at the LHC.

Outline

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The Standard Model – Particle content

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"Low" energy degrees of freedom (after symmetry breaking):

- 1 Higgs particle ($s = 0$),
- 3 families of leptons and 3 of quarks ($s = 1/2$),
- 1 non-abelian $SU(3)_C$ gluon field, 3 massive vector bosons, 1 neutral $U(1)$ Maxwell field ($s = 1$).

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$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{m_Z^2}{2}Z_\mu Z^\mu - \frac{1}{4}A_{\mu\nu}A^{\mu\nu}$$

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$$- \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} + \frac{m_Z^2}{2} Z_\mu Z^\mu - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \textit{Interactions}$$

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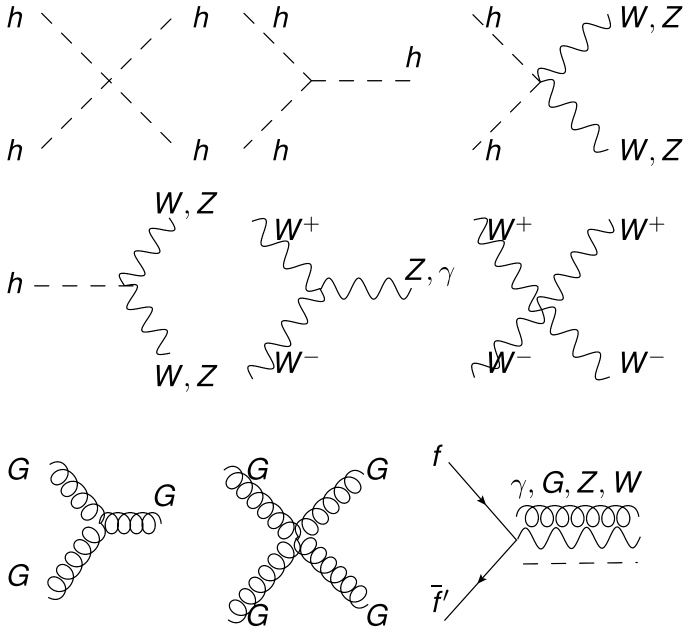

The hierarchy problem: SM vs Gravity

The action for **gravity coupled to matter** is

$$\mathcal{S} = \int d^4x \sqrt{|g|} \left[\frac{M_4^2}{2} R + \mathcal{L}_{SM} \right]$$

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Operator type	Couplings	at $E \sim 1$ TeV
$T_{\alpha\beta} h^{\alpha\beta}$	E/M_4	10^{-16}
SM Interactions	$\sim e, g_{QCD}, \frac{m_H}{v}, \frac{v}{E}, \frac{m_f}{v}$	$O(10^{-6}) - O(1)$

Solving the hierarchy problem with Extra Dimensions

$$\mathbf{M_4} \sim 10^{16}\mathbf{M_{EW}}$$

Hierarchy due to taking the scale for new physics from gravity (mesoscopic) rather than the electroweak scale (microscopic).

The ADD solution: Assume $\mathbf{M_{EW}}$ is more fundamental.

N. Arkani-Hamed et al. hep-th/9803315 (ADD)

- Assume our space time is 4+n dimensional

$$S_G \sim \int d^{4+n}x\, M_{(4+n)}^{2+n} \sqrt{-g}\, \mathcal{R}^{(4+n)}$$

- Take $M_{EW} \sim 1\,\mathrm{TeV} \to M_{4+n}$ as the fundamental scale
- At large distances

$$S_G \sim \int d^4x\, \overbrace{M_{(4+n)}^{2+n} R^n}^{M_4^2} \sqrt{-g}\, \mathcal{R}^{(4)} \Rightarrow \text{4D gravity diluted}$$

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SM effective theory on a thin brane

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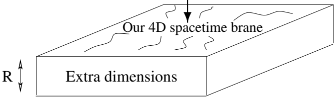

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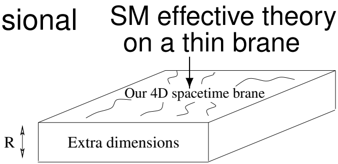

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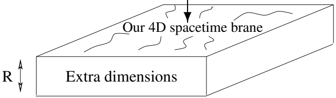

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Consequences of the extra dimensions

So how does gravity look like in ADD?

$$F_{r\ll R} \sim \frac{1}{\mathbf{M}_{(4+n)}^{2+n} r^{2+n}}\,, \qquad F_{r\gg R} \sim \frac{1}{\mathbf{M}_{(4+n)}^{2+n}\mathbf{R}^{n} r^{2}}\left(1 + 2ne^{-\frac{r}{R}} + \ldots\right)$$

1. Predicts **deviations from Newtonian gravity** as we approach short distances.
2. Contains **KK gravitons** from the 4D point of view.
3. **Gravity is higher dimensional** at **very short distances**.

This can be used to put bounds on R as a function of n.

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Bounds on extra dimensions

$M_4^2 = R^n M_{(4+n)}^{2+n}$	R in μm ($n = 2$)	$M_{4+n} \sim 1$TeV OK
Deviations from r^{-2} in torsion-balance	$\lesssim 55$	$n > 1$
KK graviton production @ colliders	$\lesssim 800$	$n > 2$
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- **SM on a 4D brane of thickness L** $\lesssim (1\text{TeV})^{-1} \sim 10^{-13}\mu$m

  To avoid bounds from Electroweak precision and fast proton decay.
  Quarks and leptons may have to be on sub-branes for $L \lesssim (1\text{TeV})^{-1}$.

- **All SM particles propagating on a single brane.**

  Good approximation if process occurs at large scales compared to L.

Outline

Why BHs? – Strong gravity & the black disk approach

At short distances gravity is higher dimensional

$$\Rightarrow \sqrt{\alpha_G} \sim \frac{E}{M_4} \rightarrow \frac{E}{M_{4+n}} \sim \frac{E}{1\,\mathrm{TeV}}$$

So gravity becomes the strongest force above 1 TeV!

$\Rightarrow$ Small impact parameter, high energy collision $\rightarrow$ BHs!

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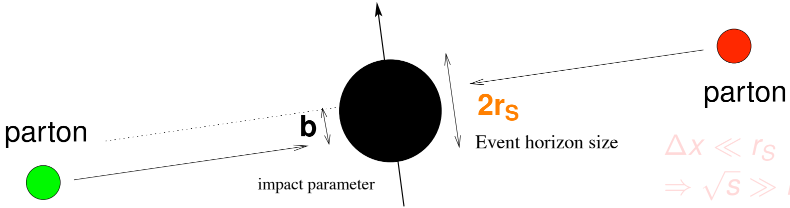

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$\Rightarrow \sqrt{s} \gg M_{4+n}$

Hoop conjecture $\Rightarrow \sigma_{\text{disk}} \sim \pi r_S^2, \quad r_s = \frac{C_n}{M_{4+n}} \left(\frac{\sqrt{s}}{M_{4+n}} \right)^{\frac{1}{n+1}}$

S. B. Giddings and S. D. Thomas, hep-ph/0106219

S. Dimopoulos and G. Landsberg, hep-ph/0106295

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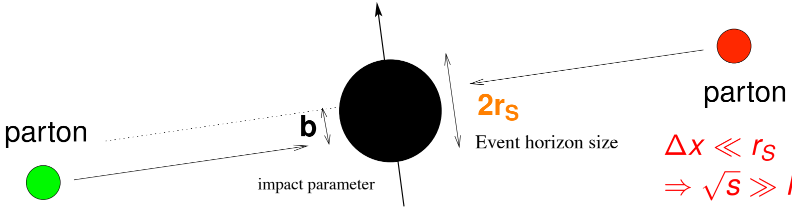

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CHARYBDIS2 @ Work

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

$\sigma_{PP \to BH}$

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

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
$\frac{\mathbf{dN}_h(a_*)}{\mathbf{dtd}\omega\mathbf{d}\Omega}$

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

Store emission in LH common with polarisation
Continue.

Repeat until **NBODYAVERAGE or KINCUT**

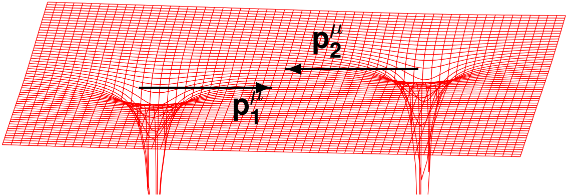
Remnant

NBODYVAR
NBODYPHASE
RMBOIL
RMSTAB

HERWIG
PYTHIA
CHARYBDIS

Outline

Modelling production – The ideal solution



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- Set up spatial metric for **two highly boosted particles**,

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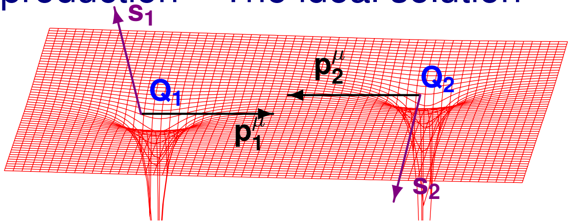

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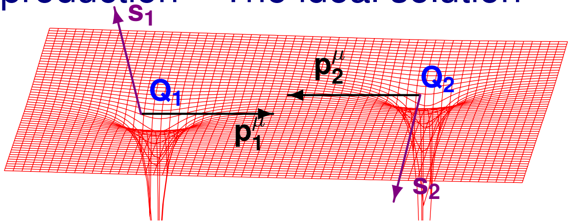

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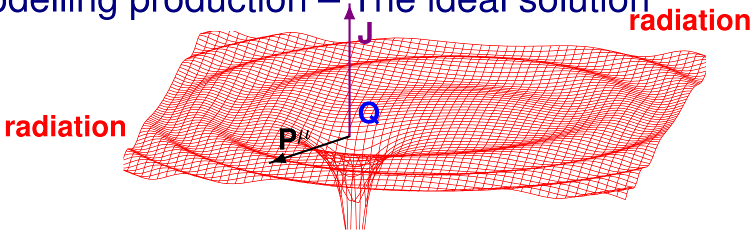

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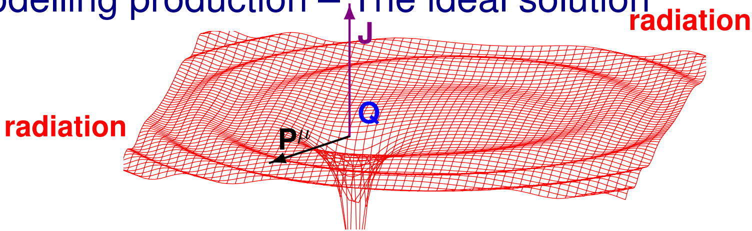

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- Obtain final Black Hole + radiation $\rightarrow$ **4D so far.**

U. Sperhake, V. Cardoso, F. Pretorius, E. Berti, J. Gonzalez, arXiv:0806.1738 $b = 0$

M. Shibata, H. Okawa, T. Yamamoto, arXiv:0810.4735 $b \neq 0$

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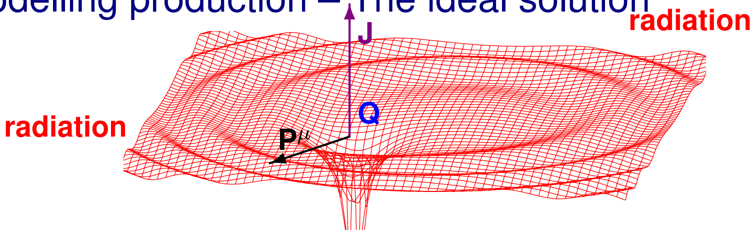
Modelling production – The ideal solution



Ideally:

- Set up spatial metric for **two highly boosted particles**,
- Include the **spin** and **charge**,
- Evolve this system using Einstein's equations,
- Obtain final Black Hole + radiation $\rightarrow$ **4D so far.**

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Modelling production – Trapped surface bounds

H. Yoshino and V. S. Rychkov hep-th/0503171

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$$\sigma_{PP\to BH} = \sum_{i,j}^{\text{partons}} \int_{\tau_m}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} \mathbf{f_i(x)f_j}\left(\frac{\tau}{\mathbf{x}}\right) \mathbf{F_n}\sigma_{\mathbf{disk}}(\tau \mathbf{s})$$

$\Rightarrow \sigma_{\mathbf{PP\to BH}} = \mathbf{70}, \mathbf{160}, \mathbf{280}\,\mathrm{pb} \Rightarrow 1s^{-1}$ @ design at 7 TeV $\Rightarrow 10^{-4}$ suppression.

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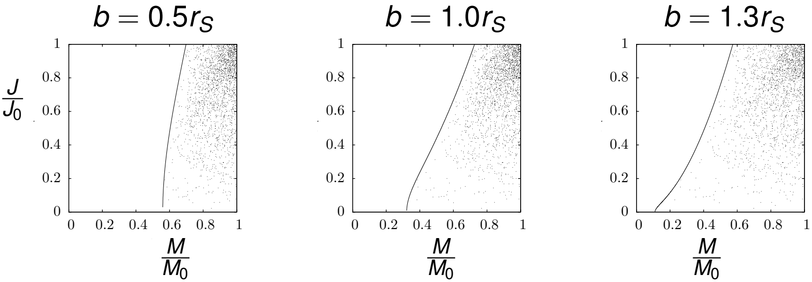

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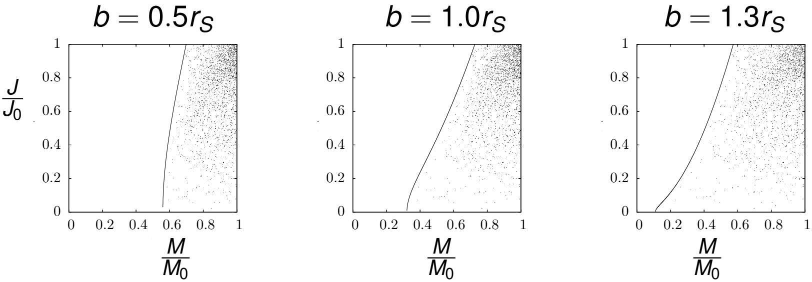

MJLOST=.TRUE. – Uses bound for each $0 < b < b_{max}$.

CHARYBDIS2 @ Work

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

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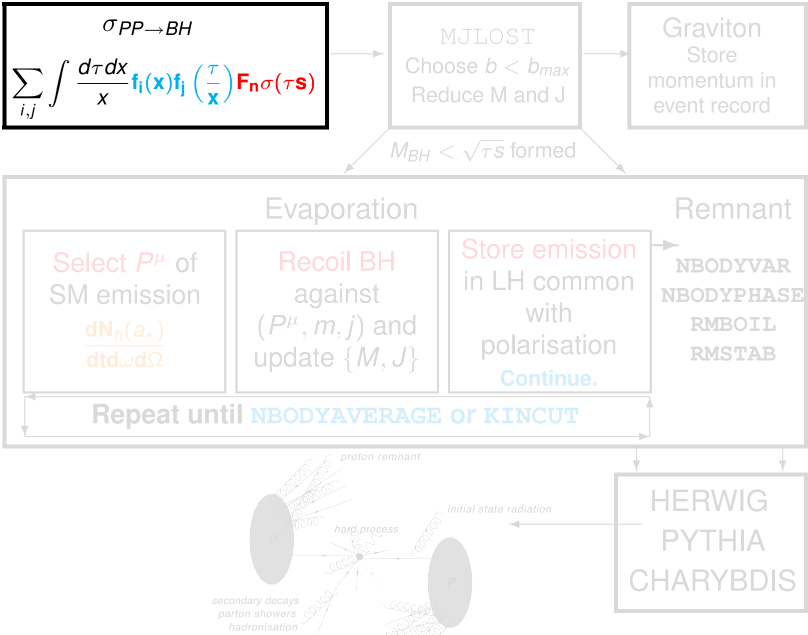

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MJLOST
Choose $b < b_{max}$
Reduce M and J

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

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NBODYPHASE
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Outline

The Hawking phase – Particle creation

- After formation, classically nothing else happens! (if BH relatively slowly rotating, otherwise instabilities).

$$ds^2 = \left(1 - \frac{\mu}{\Sigma r^{n-1}}\right) dt^2 + \frac{2a\mu \sin^2\theta}{\Sigma r^{n-1}} dt d\phi - \frac{\Sigma}{\Delta} dr^2 -$$

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- 1974, Hawking's quantum instability $\Rightarrow$ BH decays $10^{-26} s$.
- **Gravity couples Universally**

$s = 0$	**Higgs +** W_L/Z_L	**4**
$s = 1/2$	**Quarks + Leptons**	**90**
$s = 1$	**G +** γ **+** W_T/Z_T	**24**

$$\mathcal{S}_{brane} = \int d^4x \sqrt{|g|} \left(-f^4 + \mathcal{L}_0 + \mathcal{L}_{\frac{1}{2}} + \mathcal{L}_1\right)$$

R. Sundrum hep-ph/9805471

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- The decay can be described through **Hawking radiation**
- The **time between emission** of one particle is **large** (true for large BH mass)
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1. Harder spectrum
2. $m = j$ ($m > 0$) dominant
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3. Similar for Scalars and Vectors

Dolan, Casals, Kanti, Winstanley `mathsci.ucc.ie/~sdolan/greybody/`
hep-th/0503052, hep-th/0511163, hep-th/0608193
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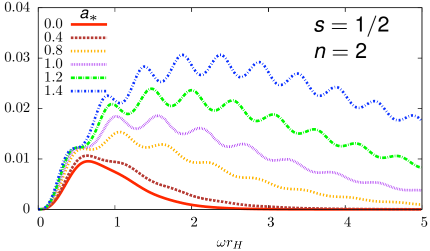

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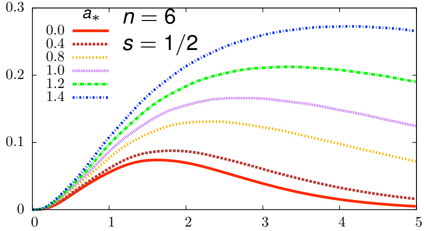

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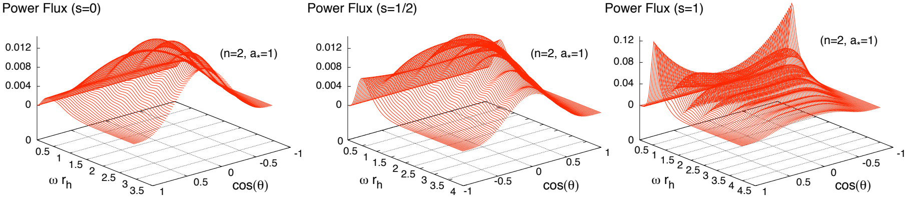
Hawking radiation – Angular spectrum

1. High rotation makes angular distributions **equatorial**.
2. However note lower energy vectors with **axial peaks!**:
   - Each peak comes from different polarisation contributions.
   - Study of **asymmetries in vector boson decays**.
   - Similar effect for fermions.



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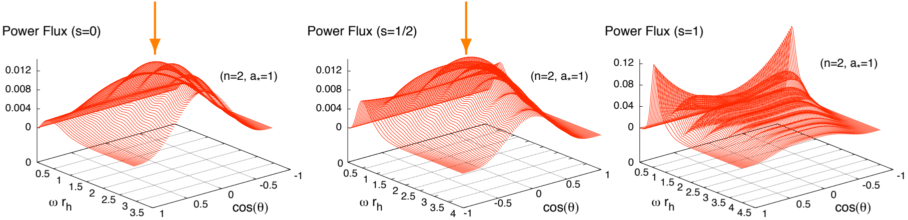

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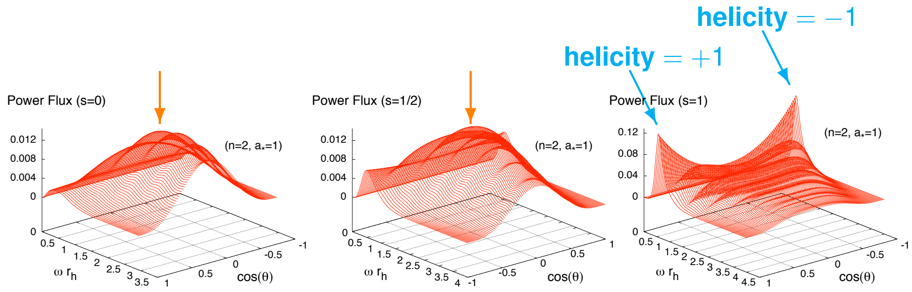

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Hawking radiation – Back-reaction ($D = 10$ example)

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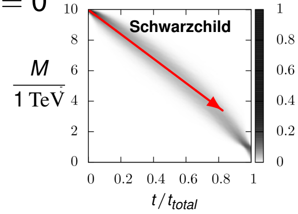
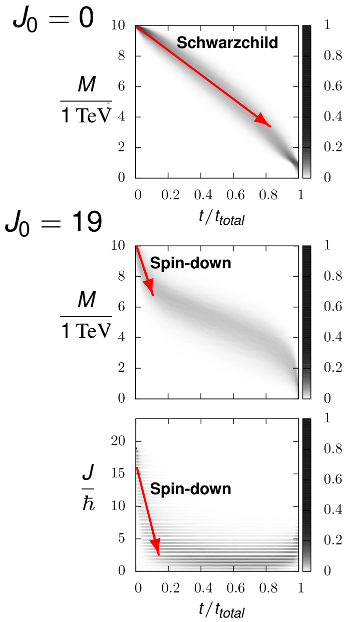


Non-rotating

- Mass drops linearly.
- $T \sim r_S^{-1} \rightarrow$ speed up last $\sim 15\%$ t.

Hawking radiation – Back-reaction ($D = 10$ example)



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- Initial spin down $\sim 15\% t$.
  J drops by $\sim 80\%$.
  M drops by $\sim 30\%$
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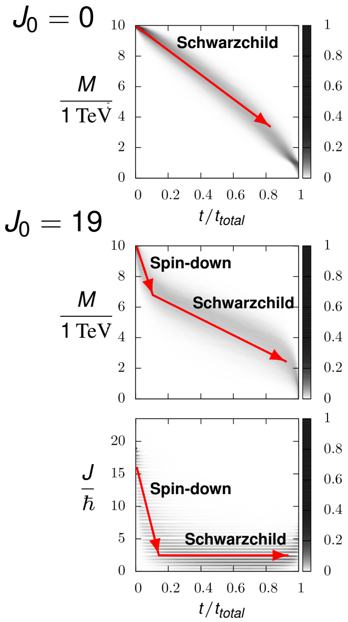

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http://projects.hepforge.org/charybdis2/

$$\sigma_{PP\to BH} \quad \sum_{i,j}\int \frac{d\tau\, dx}{x} \mathbf{f_i(x) f_j}\left(\frac{\tau}{\mathbf{x}}\right) \mathbf{F_n}\sigma(\tau \mathbf{s})$$

→ 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 $\frac{dN_h(a_*)}{dt\,d\omega\,d\Omega}$
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Repeat until NBODYAVERAGE or KINCUT

Remnant

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NBODYPHASE
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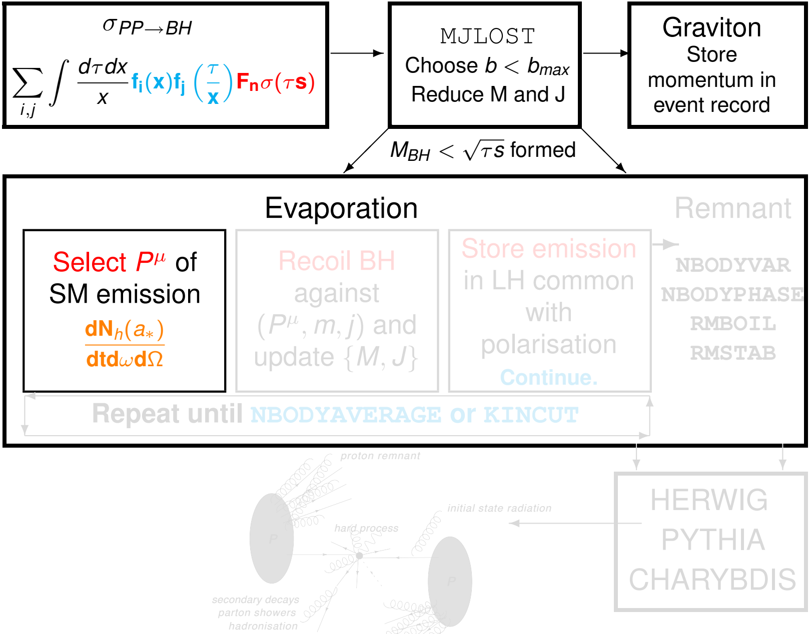

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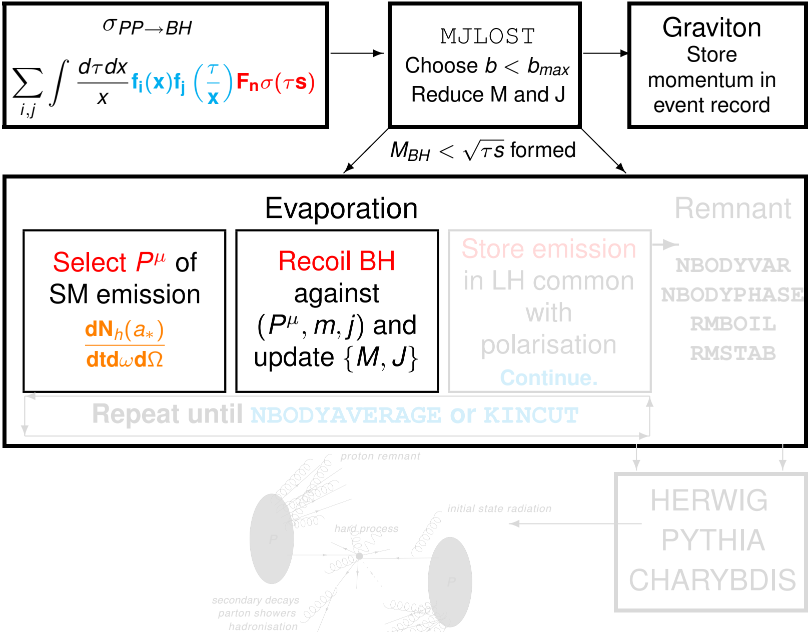

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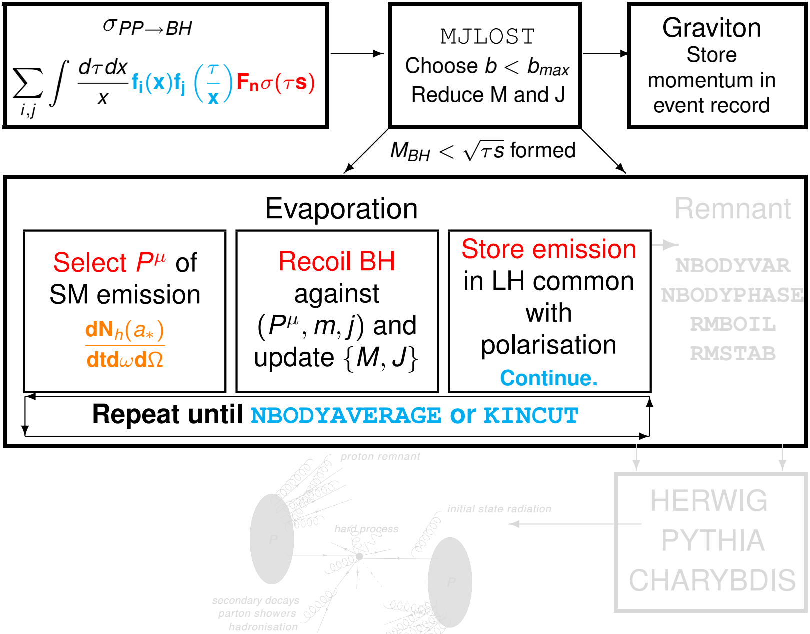

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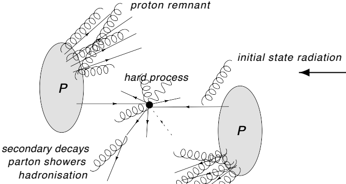

Outline

BH event generators

$J = 0$ **generators**

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  S. Dimopoulos et al. hep-ph/0106295
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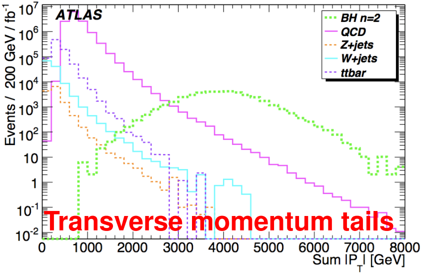

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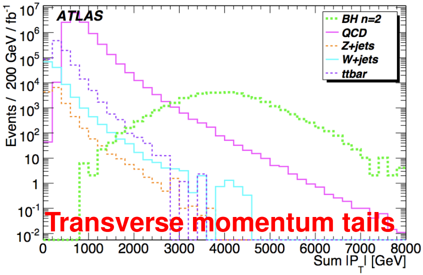

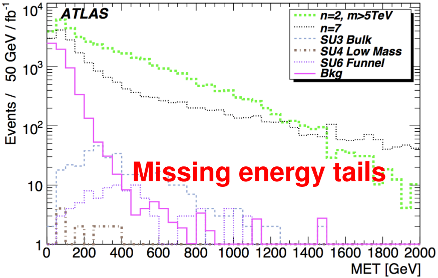

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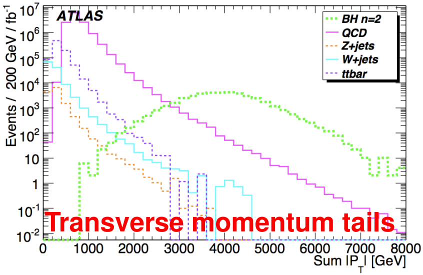

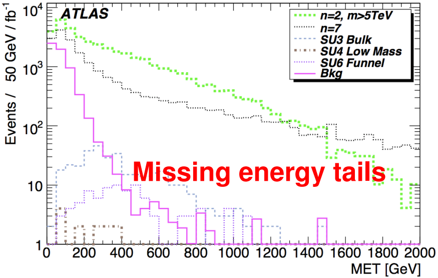

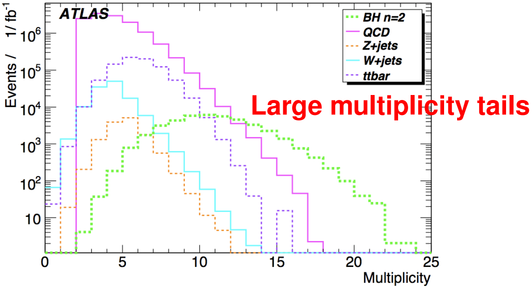

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- **High multiplicity events with large number or jets.** In the SM, SUSY and other BSM models this is usually suppressed. Even more if also leptons are present.
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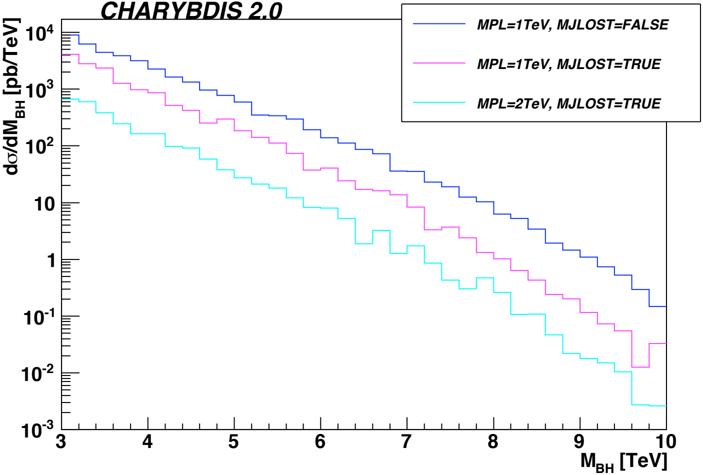

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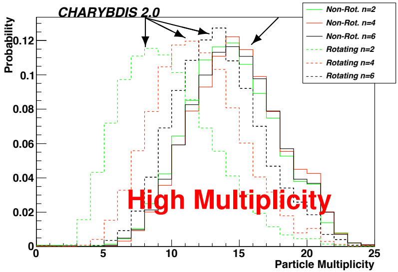

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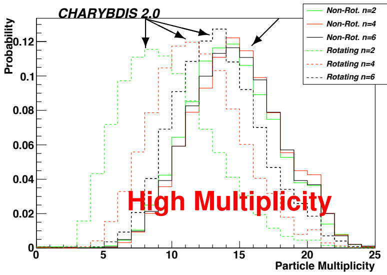

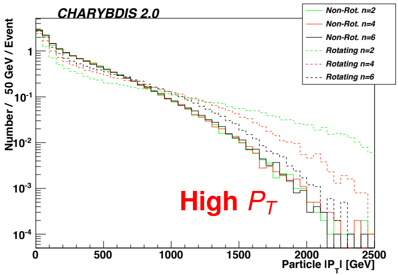

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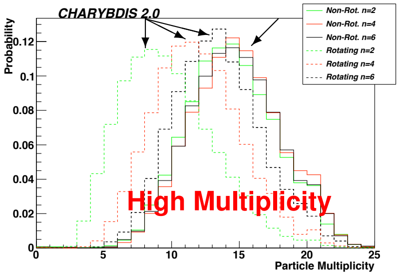

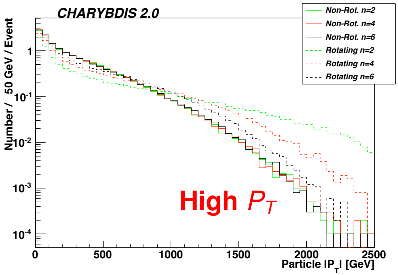

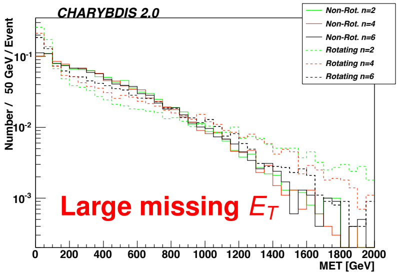

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- We have looked into some interesting **effects**/**models**:
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  2. The effect of rotation on energy and angular distributions;
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Future work will involve detailed studies of:

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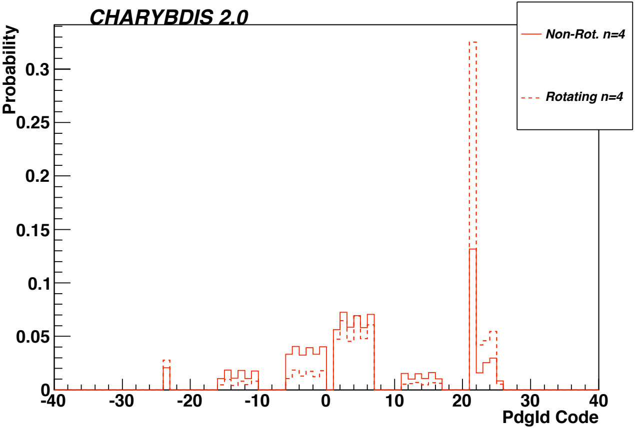
Thanks for your attention! Questions?

BACKUP

More effects of rotation – Species

Enhancement of Vector emission



The hierarchy problem: Higgs mass

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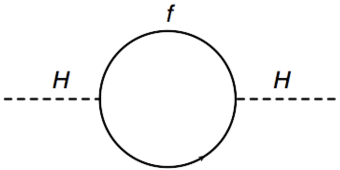

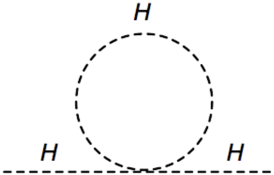

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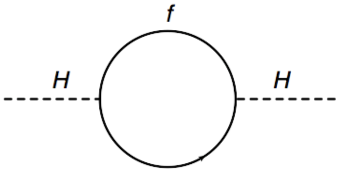

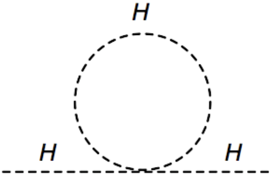

Higgs mass runs from high scale:

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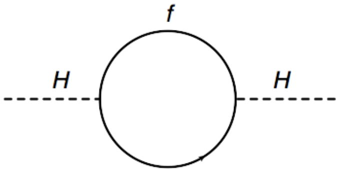

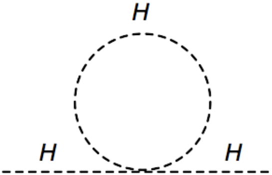

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If $\Lambda_{\mathrm{cutoff}} \sim M_4 \sim 10^{16}$ TeV $\Rightarrow$ **fine tuning** of $\sim 10^{-16}$

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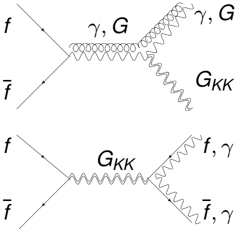
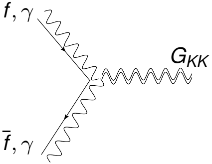
4. Etc...

Bounds on extra dimensions

$M_{Pl}^2 = R^n M_{(4+n)}^{2+n}$	R in μm ($n = 2$)	$M_{4+n} \sim 1$TeV OK
Deviations from r^{-2} in torsion-balance	$\lesssim 55$	$n > 1$
KK graviton production @ colliders	$\lesssim 800$	$n > 2$
KK graviton production in Supernovae	$\lesssim 5.1 \times 10^{-4}$	$n > 3$
KK gravitons early Universe production	$\lesssim 2.2 \times 10^{-5}$	$n > 3$





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Also quantum gravity approximations indicate small corrections:

T. Banks and W. Fischler, hep-th/9906038

S. N. Solodukhin, hep-ph/0201248

S. D. H. Hsu, hep-ph/0203154

Transient period

- During formation we should have an asymmetric BH with electric and gravitational multipole moments.

  $\rightarrow$**Distorted geometry.**

- The time for loss of multipoles is r_S (natural units).
- We will look next into the Hawking decay and realise that the typical timescale there is

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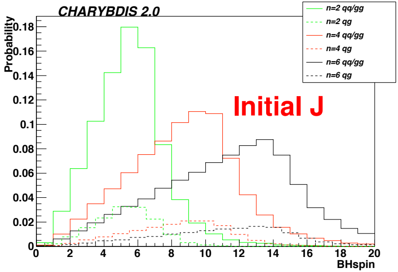

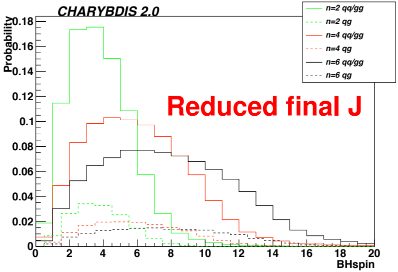

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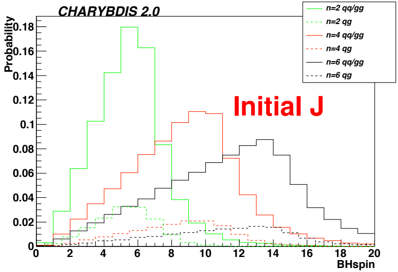

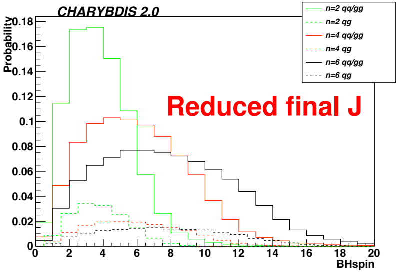

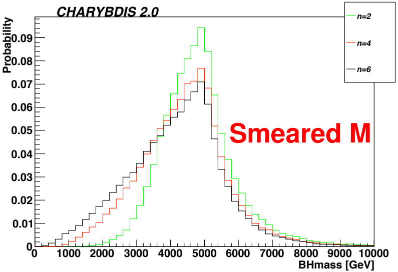

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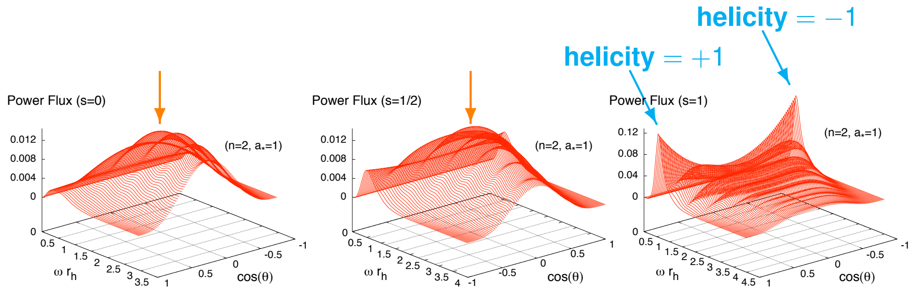
Hawking radiation – Angular spectrum

1. High rotation makes angular distributions **equatorial**.
2. However note lower energy vectors with **axial peaks!**:
   - Each peak comes from different polarisation contributions.
   - Study of **asymmetries in vector boson decays**.
   - Similar effect for fermions.



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

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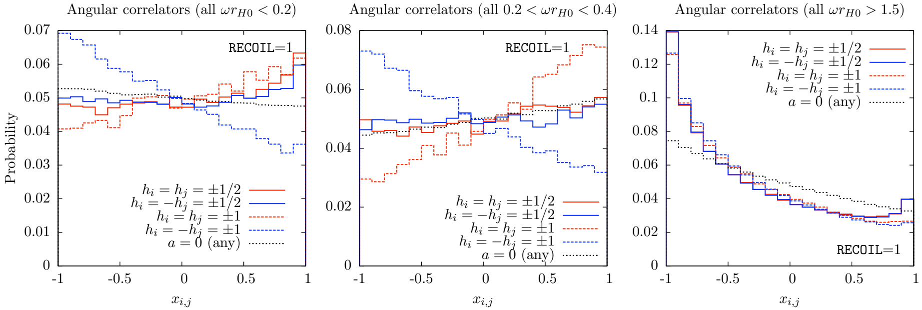

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- Mass **M** and angular momentum **J** as seen from infinity.

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- Spheroidal horizon with oblateness $\mathbf{a}_*$

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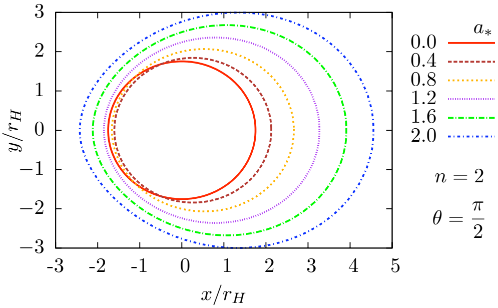

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Remnant models

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