Abstract: I will survey some of the physics of TeV-scale black hole production, as well as outstanding issues. I will also discuss some of the conceptual issues surrounding high-energy black hole production.
Black hole production at high energies

Steven B. Giddings

UC Santa Barbara

“Experimental search for quantum gravity”
Black hole production may be the most spectacular physics at future colliders ...
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Black hole production may be the most spectacular physics at future colliders ... perhaps even LHC.

Even if not, it raises profound and likely important theoretical issues. Will give a brief summary...

(Recent review: arXiv:0709.1107)
The basic idea: at collision energies 
\[ E \gtrsim M_P \]
can form black holes;
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Possible scenarios:

- Large extra dimensions
- Large warping

\[ ds^2 = e^{2A(y)} dx_4^2 + g_{mn} dy^m dy^n \]
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\[ M_4^2 = M_P^{2+n} \int d^n y \sqrt{g} e^{2A} \]
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+ brane world, to make gauge thy 4d

...many such scenarios being investigated, particularly in string theory
Focus on model independent features of black hole production;

Small expansion parameter: \( \frac{M_P}{E} \)
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Small expansion parameter: \( M_P/E \)

There are of course possible model dependent (and quantum gravity dependent) effects, in particular at \( E \sim M_P \).
The basic phenomenological scenario:

Trapped surface

... in higher-dimensional space
The basic phenomenological scenario:

**Formation**

1. Balding
2. Spindown
3. Schwarzschild
4. Planck

...in higher-dimensional space
The basic phenomenological scenario:

Formation

Decay
1. Balding
2. Spindown
3. Schwarzschild
4. Planck

Will summarize, indicating improvements in understanding and needs

Build on original results: SBG & Thomas hep-ph/0106219
Dimopoulos and Landsberg hep-ph/0106295
Formation

~ Classical \( (M_p/E) \)
Formation

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Aichelburg-Sexl shocks
Formation

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Trapped surface (aka black hole);
forms “before” collision

Penrose
SBG & Eardley
Yoshino & Nambu
Spacetime picture
Spacetime picture
Spacetime picture

Important point:

since trapped surface forms in flat region, can compute its size. This gives

1. Cross section
2. LB on mass of BH
Spacetime picture

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Recent improvements in computing size ...
Cross-section estimate (parton level)

\[ \sigma \approx \pi R_S (E_{CM})^2 \quad \text{and} \quad R_S \propto (G E_{CM})^{1/(D-3)} \]

3.09 in D=10

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(One possible caveat (Yoshino & Mann): charge effects -- reduce?? -- Improvement needed)
Spacetime picture

? flat flat

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flat  flat

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Spacetime picture

black hole

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Must fold with PDFs to get rate at LHC ... but first, discuss aspects of decay
Decay: 1. Balding

“Black hole has no hair”
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“Black hole has no hair”

- So black hole first sheds multipole moments of all fields (also, charge, color)

- Classical process, timescale \( t \sim R_s \)
Balding, cont’d
- Emit grav., EM, etc radiation
- Result: spinning (Kerr) BH
- Lower bd on area from \( A_{TS} \)

\[ M \sim 0.6E_{CM}, \quad D = 10 \]
Balding, cont’d
- Emit grav., EM, etc radiation
- Result: spinning (Kerr) BH
- Lower bd on area from $A_{TS}$

$M \sim 0.6E_{CM}$, $D = 10$

Possible future improvements: numerical study?
(essentially classical process) -- explicit description of formation
Decay: 2. Spindown

- Spinning black hole begins to Hawking radiate
- Preferentially sheds angular momentum
- Time scale: \( t \sim E^{D-1/D-3} \)
- Must calculate higher-D Hawking emission rates
- HARD PROBLEM! (~thermal, +gray body)
- Initial estimates based on extrapolation from 4d: SBG & Thomas
Spindown, cont’d

Much ongoing work:

Casals, Creek, Dolan, Kanti, Winstanley

Ida, Oda, & Park + others ...
Spindown, cont'd

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Indeed, a recent claim (Ida, Oda, & Park), based on gray body factors and numerical evolution:

> 50% of mass lost during spindown.
Spindown, cont’d

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Indeed, a recent claim (Ida, Oda, & Park), based on gray body factors and numerical evolution:

> 50% of mass lost during spindown.

But bear in mind:

1) depends on rather arbitrary definition of end of spindown;

2) continued uncertainties over bulk emission
Spindown, cont’d

- This does suggest looking for characteristic radiation patterns, as proposed in SBG & Thomas

- Also, spindown/higher dim effects modify ratio vector:spinor:scalar; vectors and spinors dominate
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- Also, spindown/higher dim effects modify ratio vector:spinor:scalar; vectors and spinors dominate.

Future improvements:

Carefully check and bring this story to completion, specifically working out signatures.
Decay: 3. Schwarzschild
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- Possibly subdominant, <50%??

- Hawking emission (power spectrum, relative emission rates, ...) better understood

- Approx. thermal spectrum (w/ gray body modification) at $T_H \propto 1/R_S \propto M^{-1/D-3}$

- Multiplicities approx. thermal, but e.g. suppression of low-E gauge bosons, etc.
Future improvements needed:

Full study of evolution through spindown and Schwarzschild phases, properly incorporating gray body factors, and integrating over evolution, to determine

energy spectrum
relative multiplicities
event shapes (angular distribution, etc.)
Decay: 4. Planck

- When the BH reaches $M \sim M_P$, known physics breaks down

- The most interesting phase

- Expect: a few particles/strings w/ $E \sim M_P$ but who knows?
Experimental expectations:

Threshold for BH production
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Threshold for BH production

Large extra dimensions, warped compactifications:
still \( M_D \gtrsim 1 \text{TeV} \) (SUSY 2007; PDB conventions)

Thus \( M_{BH} \gtrsim 5 \text{TeV} \) \( (S_{BH} \sim 24) \)
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Thus \[ M_{BH} \gtrsim 5\text{TeV} \quad (S_{BH} \simeq 24) \]

Event rates originally estimated to approach 1 Hz ...
But greater inelasticity from higher $D$ can reduce ... 

\[
\begin{align*}
M/2\mu & \quad b/r_0 \\
0.7 & \quad 0.6 \\
0.5 & \quad 0.4 \\
0.3 & \quad 0.2 \\
0.1 & \quad 0.25 \quad 0.5 \quad 0.75 \quad 1 \quad 1.25 \quad 1.5
\end{align*}
\]

- represents a lower bound. E.g. in 4D, $lb$ is $.71E$; improved estimates (D’Eath): $.84E$
But greater inelasticity from higher D can reduce ...

- represents a lower bound. E.g. in 4D, \( b \) is \( .71E \); improved estimates (D’Eath): \( .84E \)

So: rough estimate:

(I): \[ M = .6E, b < .5R_S \quad ; \quad M = 0, b > .5R_S \]

(II): \[ M = .7E, b < .5R_S \quad ; \quad M = 0, b > .5R_S \]
Fold in PDFs (courtesy T. Rizzo), find:

\[(I) : \sigma = 1.8 \times 10^2 \text{ fb} \Rightarrow 1BH/10\text{min}\]

\[(II) : \sigma = 1.8 \times 10^3 \text{ fb} \Rightarrow 1BH/\text{min}\]

(At nominal LHC luminosity of $10^{34}/\text{cm}^2\text{s}$)
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... still very respectable!
Explicit signatures?

Event generators

TRUENOIR
CHARYBDIS
Catfish
Explicit signatures?

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TRUENOIR
CHARYBDIS
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... just Schwarzschild, not spindown

So, given importance of spindown, this suggests more work is needed for detailed quantitative predictions
Nonetheless, striking qualitative signatures can be inferred

- potentially large cross-section (0.02 Hz?)
- (increase of cross section w/ energy)
- relatively high sphericity
- high multiplicity of primaries
- hard transverse leptons and hard jets -- many
- ~thermally-determined ratios of species
- angular distributions characterizing spindown
- jet suppression

...
What about cosmic rays?

(SBG & Thomas; Feng & Shapere; Anchordoqui & Goldberg; Kowalski, Ringwald, & Tu; Alvarez-Muniz, Feng, Halzen, Han, Hooper, ...)

\[ \nu + N \rightarrow BH + X \]

\[ E_{CM} \text{ up to } \sim 100\text{TeV} \]
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could see (or rule out) at Auger, IceCube, ...?
Can rule out LHC production?
Anchordoqui, Feng, Goldberg, Shapere:

5 year Auger nonobservation can push to $M_P \sim 1 - 2 \, \text{TeV}$ ... so potential pressure
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Uncertainties/issues with this:

Stojkovic, Starkman, and Dai: $\nu p \rightarrow BH$

suppressed -- no $B$ decay in crossed diagrams
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Lykken, Mena, and Razzaque: cosmogenic \( \nu \)
flux suppressed through annih. w/ \( \bar{\nu} \)’s
Conclusion:

If we’re very lucky we might see some hints from Auger, otherwise will have to wait and see what LHC brings -- not long to wait!
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On the theory side: building detailed TeV-scale gravity models has been very challenging, but much progress and ongoing developments ...

warped/flux compactifications;
brane world constructions, etc.
At whatever scale it occurs, black hole production forces confrontation with profound theoretical issues. In fact

**Black hole information paradox**

**Basic statement:**
At whatever scale it occurs, black hole production forces confrontation with profound theoretical issues. In fact

Black hole information paradox

Basic statement:

Apparently must abandon a cherished principle of physics:

- unitarity and energy conservation (QM violated)
- stability (remnants)
- macroscopic locality (information escapes)
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...widespread belief
But, if nonlocality,
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1) What is the mechanism

2) How is Hawking’s argument evaded
But, if nonlocality,

1) What is the mechanism

2) How is Hawking’s argument evaded

3) Where does GR+local QFT fail?

- what is the correspondence limit for new physics?
Mechanism:

String extendedness?
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Investigate in high-energy scattering.
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Recent arguments:
hep-th/0604072;
arXiv:0705.1816, w. Gross and Maharana;

No evidence of a role for string extendedness
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... suggests intrinsically gravitational effect;

non-perturbative
Suggests correspondence boundary:

where does GR+LQFT break down?
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2 part. Fock sp.: \( \phi_x, p \phi_y, q |0\rangle \)

(min uncertainty wavepackets)
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\[ \phi_{x,p} \phi_{y,q} |0\rangle \]

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good description for \[ |x - y|^{D-3} > G |p + q| \]

where \[ G \sim G_{Newton} \]
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"the locality bound"

(extends off shell?)
Locality is a cornerstone of QFT -- can we believe this?
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How do we characterize locality?
1) Scattering behavior:

Local QFT

\[ \sigma_T \leq c(\ln E)^{D-2} \]

Froissart

\[ T(s, t) < E^N \]

Polynomial bddness -- fixed t
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Strong gravity/ black hole regime:

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(work w/ M. Srednicki, to appear)
2) Commutativity of local observables
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However:

- approximately local ("proto-local") observables can apparently be constructed
  
  SBG, Marolf & Hartle, hep-th/0512200,
  M. Gary & SBG hep-th/0612191

- but limitations on locality also from strong gravitational effects (locality bound, etc.)
Of course, there are other reasons to suspect nonlocality:

- ideas of holography (though haven’t yet sharply resolved info paradox)

- conundrums of cosmology: landscape, Boltzmann brains, etc.; possible resolution through breakdown of local QFT

SBG, hep-th/0703116
SBG & Marolf, arXiv:0705:1178
Still have the question of exactly how Hawking’s argument for information loss fails; indications of breakdown of perturbative gravity, thus role for non-perturbative gravity, which could well be fundamentally nonlocal.

Further discussion: SBG, hep-th/0703116
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Proposal: information escapes through such nonlocality of nonperturbative gravity; this becomes important on timescales $t \lesssim M^3$
Conclusions:

- If TeV-scale gravity is correct, BH production could be an spectacular effect.
- While more work needed to understand detailed signatures, semi-quantitative arguments indicate they should be prominent.
- Whether or not BH production is accessible in the near future, its possibility raises profound theoretical issues that may help guide the next revolution in quantum gravity.