

# *BLACK HOLES AT FUTURE COLLIDERS AND BEYOND*

Greg Landsberg



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# Outline

- Black holes in General Relativity
- Astronomical Black Holes
- Production of Black Holes at Future Colliders
  - Basic Idea
  - Production and Decay
  - Test of Wien's Law
  - Discovering New Physics in the Black Hole Decays
- ... and beyond
  - String Balls
  - Black Holes in Cosmic Rays
- Conclusions

# Black Holes in General Relativity

- Black Holes are **direct prediction of Einstein's general relativity** theory, established in 1915 (although they were never quite accepted by Einstein!)
- In **1916 Karl Schwarzschild applied GR to a static non-spinning massive object** and derived famous metric with a singularity at a **Schwarzschild radius**  $r = R_S \equiv 2MG_N/c^2$  :

$$g_{\mu\nu} = \left( \begin{array}{cccc} 1 - \frac{2MG_N}{rc^2} & 0 & 0 & 0 \\ 0 & -\left(1 - \frac{2MG_N}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2 \theta \end{array} \right) \left. \begin{array}{l} \text{time} \\ \\ \\ \text{space} \end{array} \right\}$$

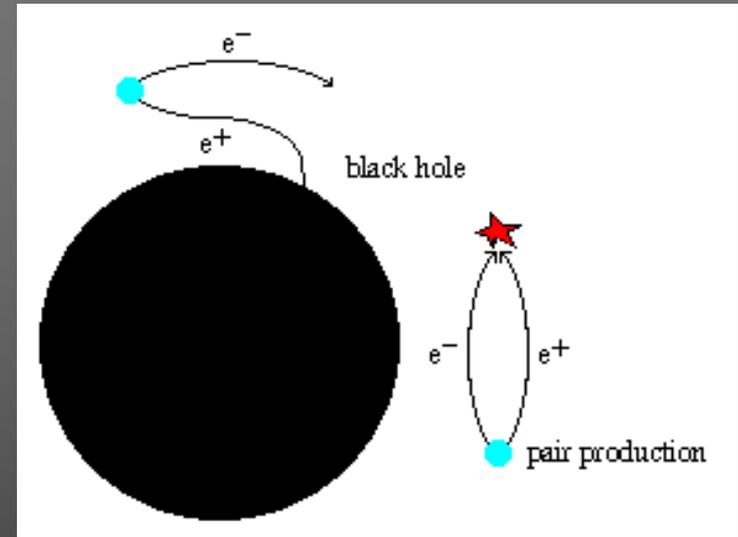
- If the **radius** of the object is less than  $R_S$ , a **black hole** with the event horizon at the Schwarzschild radius **is formed**
- Note, that  $R_S$  can be derived from Newtonian gravity by taking the escape velocity,  $v_{\text{esc}} = (2G_N M/R_S)^{1/2}$  to be equal to  $c$  – first **noticed by Laplace** in 1796; independently, **John Michell** presented similar qualitative idea to the Royal Society in 1783
- The term, “**Black Hole**,” was coined only half-a-century after Schwarzschild by **John Wheeler** (in 1967)
- Previously these objects were often referred to as “**frozen stars**” due to the time dilation at the event horizon

# Black Hole Evolution

- Naïvely, black holes would only grow once they are formed
- In 1975 **Steven Hawking** showed that this is not true, as the black hole can evaporate by emitting pairs of virtual photons at the event horizon, with one of the pair escaping the BH gravity
- These photons have a black-body spectrum with the *Hawking temperature*:

$$T_H = \frac{\hbar c}{4\pi k R_S}$$

- In natural units ( $\hbar = c = k = 1$ ), one has the following fundamental relationship:  $R_S T_H = (4\pi)^{-1}$



- Information paradox**: if we throw an encyclopedia in a black hole, and watch it evaporating, where would the information disappear?
- This paradox is **possibly solved** in the only quantum theory of gravity we know of: **string theory**

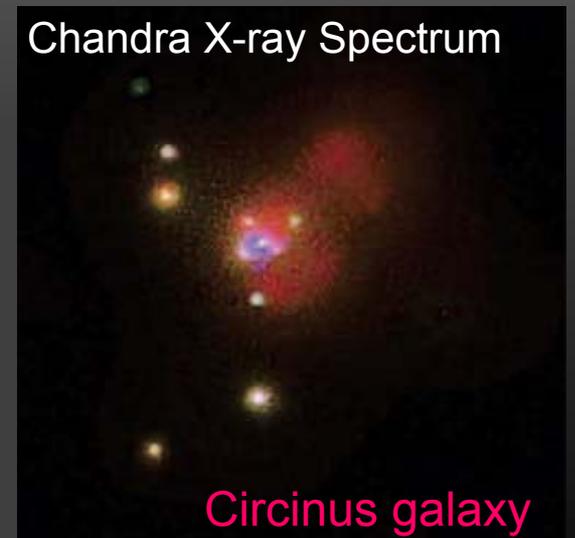
# Looking for Black Holes

- While there is **little doubt that BHs exist**, **we don't have** an unambiguous **evidence** for their existence so far
- Many astronomers believe that **quasars are powered by a BH** (from slightly above the Chandrasekhar limit of  $1.5 M_{\odot}$  to millions of  $M_{\odot}$ ), and that there are **supermassive** ( $\sim 10^6 M_{\odot}$ ) **black holes in the centers of many galaxies**, including our own
- The most crucial evidence, **Hawking radiation**, **has not been observed** ( $T_H \sim 100$  nK,  $\lambda \sim 100$  km,  $P \sim 10^{-27}$  W!,  $\sim 10^{14}$  years for a single  $\gamma$  to reach us!)
- The best indirect evidence we have is **matter accretion in binary systems**
- Astronomers are also looking for **"flares"** of large objects falling into supermassive black holes
- LIGO/VIRGO hope to observe **gravitational waves from black hole collisions**



# Some Black Hole Candidates

Name of Binary System	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass (Solar Units)
Cygnus X-1	B supergiant	5.6	6-15
LMC X-3	B main sequence	1.7	4-11
A0620-00 (V616 Mon)	K main sequence	7.8	4-9
GS2023+338 (V404 Cyg)	K main sequence	6.5	> 6
GS2000+25 (QZ Vul)	K main sequence	0.35	5-14
GS1124-683 (Nova Mus 1991)	K main sequence	0.43	4-6
GRO J1655-40 (Nova Sco 1994)	F main sequence	2.4	4-5
H1705-250 (Nova Oph 1977)	K main sequence	0.52	> 4



# BH at Accelerators: Basic Idea

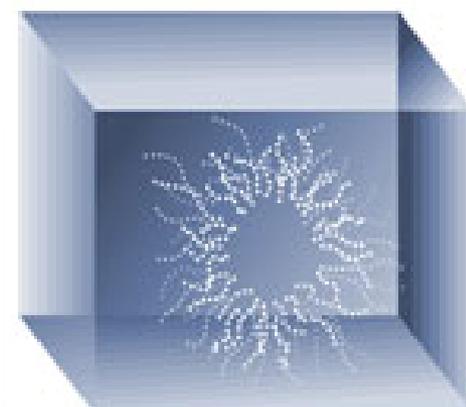
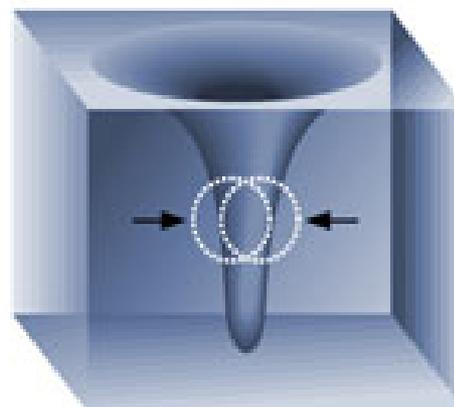
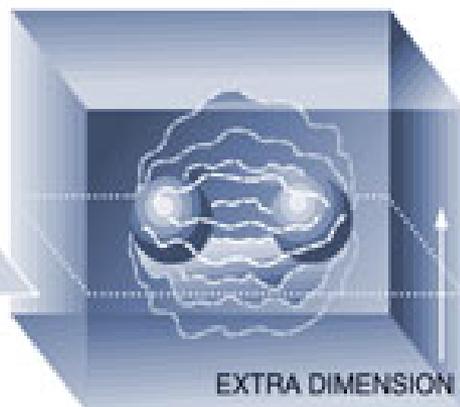
## Black Holes on Demand

NYT, 9/11/01

The New York Times  
ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

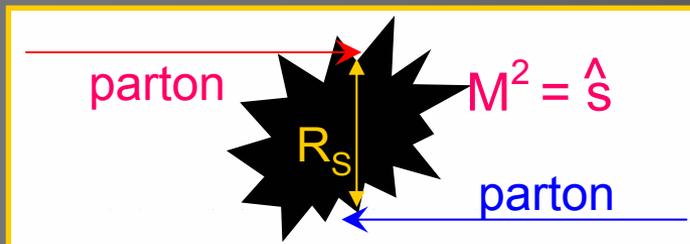
The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

# Our Approach & Assumptions

- Based on the work done with Savas Dimopoulos last summer [PRL **87**, 161602 (2001)]
- A related study by Giddings/Thomas [PRD **65**, 056010 (2002)]
- Extends previous theoretical studies to collider phenomenology
- Big surprise: BH production is not an exotic remote possibility, but the dominant effect!
- Main idea: when the c.o.m. energy reaches the fundamental Planck scale, a BH is formed; cross section is given by the black disk approximation:

$$\sigma \sim \pi R_S^2 \sim 1 \text{ TeV}^{-2} \sim 10^{-38} \text{ m}^2 \sim 100 \text{ pb}$$



- Fundamental limitation: our lack of knowledge of quantum gravity effects close to the Planck scale
- Consequently, in the original paper we made no attempts for partial improvement of the results, e.g.:
  - Grey body factors (see Chris's talk)
  - BH spin, charge, color hair (see Kin-ya's talk)
  - Relativistic effects and time-dependence
  - These effects were studied in many of the follow-up papers in certain approximations
- The underlying assumptions rely on two simple qualitative properties:
  - The absence of small couplings;
  - The "democratic" nature of BH decays
- We expect these features to survive for light BH
- Use semi-classical approach strictly valid only for  $M_{\text{BH}} \gg M_{\text{P}}$ ; only consider  $M_{\text{BH}} > M_{\text{P}}$

# Voloshin Suppression etc.

- Black hole production by man-made and natural beams is **an exploding topic**; this led to a number of speculative papers
- An exponential suppression claimed by Voloshin [PL **B518**, 137 (2001) and PL **B524**, 376 (2002)] is one of the examples: the conclusions have been disputed:
  - Dimopoulos/Emparan – string theory calculations [PL **B526**, 393 (2002)]
  - Eardley/Giddings – full GR calculations for high-energy collisions with an impact parameter [PRD **66**, 044011 (2002)]; extends earlier d'Eath and Payne work
  - An extension of Eardley-Giddings calculations **into many dimensions** by Yoshina/Nambu: [PRD **67**, 024009 (2003)]
  - Hsu – path integral approach w/ quantum corrections [hep-ph/0203154]
  - Jevicki/Thaler – Gibbons-Hawking action used in Voloshin's paper is incorrect, as the black hole is not formed yet! Correct Hamiltonian was derived:  $H = p(r^2 - M) \rightarrow \sim p(r^2 - H)$ , which leads to a logarithmic, and not a power-law divergence in the action integral. Hence, there is no exponential suppression [hep-th/0203172]
- **By now it's been generally agreed that the cross section can be approximated reliably via geometrical approach**

# Black Hole Production

Schwarzschild radius is given by Argyres et al., hep-th/9808138 [after Myers/Perry, Ann. Phys. 172 (1986) 304]; it leads to:

$$\sigma(\hat{s} = M_{BH}^2) = \pi R_S^2 = \frac{1}{M_P^2} \left[ \frac{M_{BH}}{M_P} \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{\frac{2}{n+1}}$$

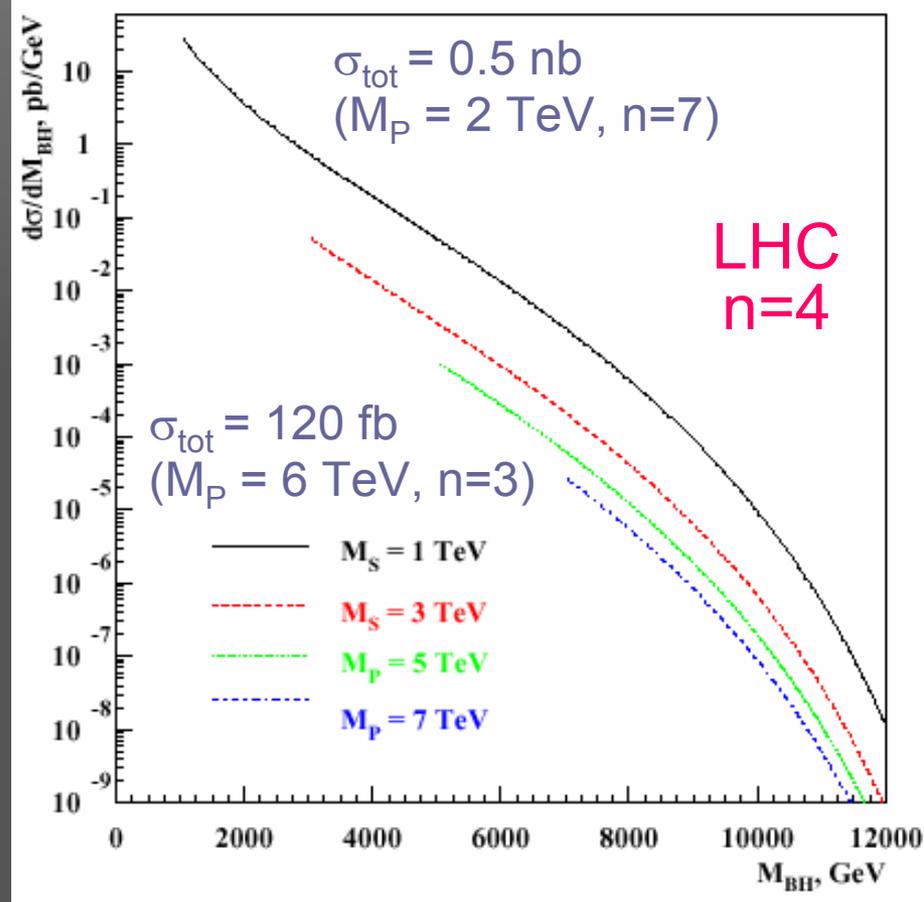
Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies)

$$\frac{d\sigma(pp \rightarrow BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}} \hat{\sigma}(ab \rightarrow BH) \Big|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{a,b} \int_{M_{BH}^2/s}^1 \frac{dx_a}{x_a} f_a(x_a) f_b\left(\frac{M_{BH}^2}{sx_a}\right)$$

Note: at c.o.m. energies  $\sim 1$  TeV the dominant contribution is from  $qq'$  interactions

[Dimopoulos, GL, PRL 87, 161602 (2001)]

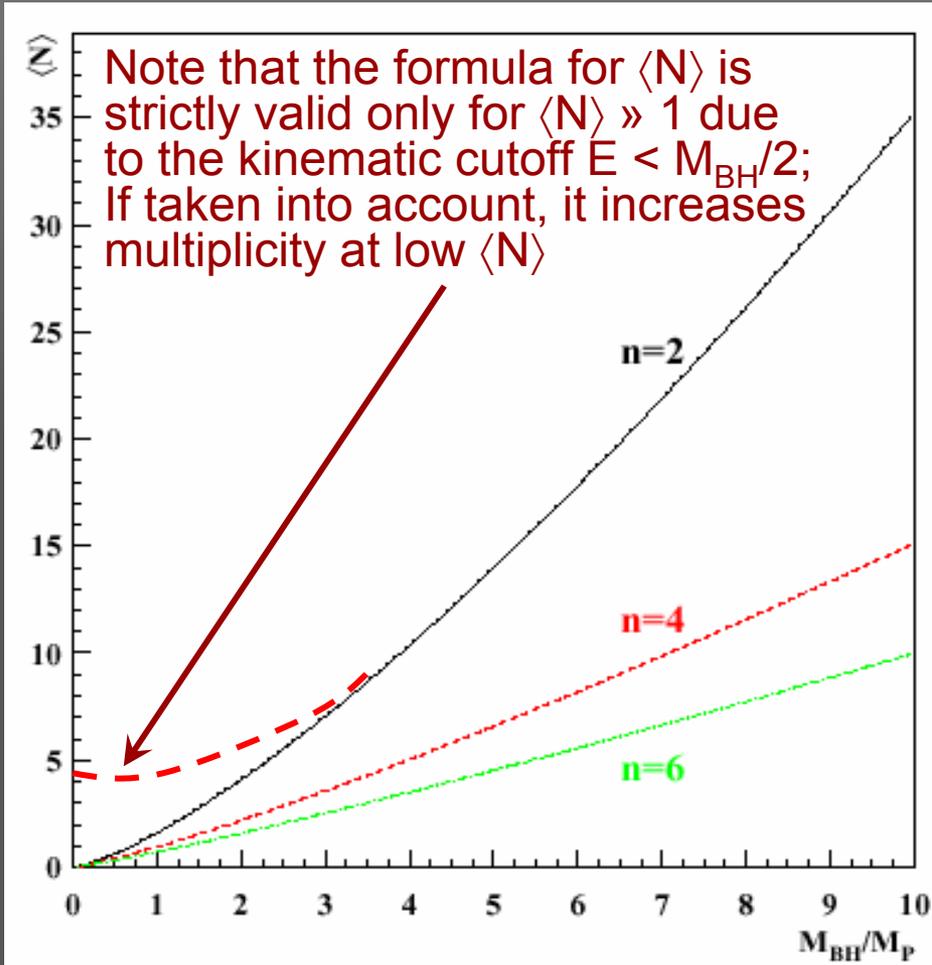


# Black Hole Decay

- Hawking temperature:  $R_S T_H = (n+1)/4\pi$
- BH radiates mainly on the brane [Emparan/Horowitz/Myers, hep-th/0003118]
  - $\lambda \sim 2\pi/T_H > R_S$ ; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
  - The decay into a particle on the brane and in the bulk is thus the same
  - Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed
- Democratic couplings to  $\sim 120$  SM d.o.f. yield probability of Hawking evaporation into  $\gamma$ ,  $l^\pm$ , and  $\nu \sim 2\%$ ,  $10\%$ , and  $5\%$  respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

$$\langle N \rangle \approx \frac{M_{BH}}{2T_H}$$

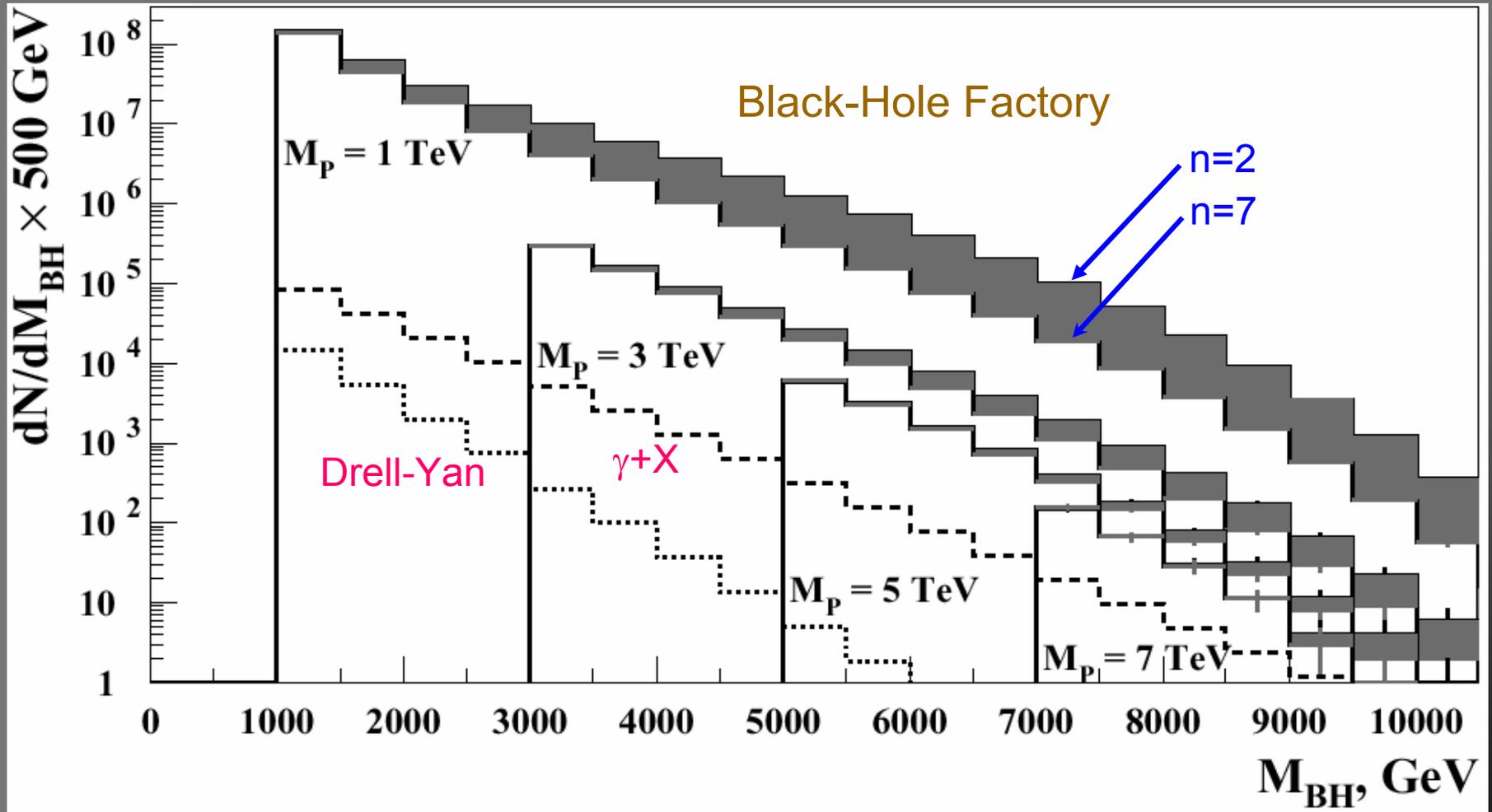
[Dimopoulos, GL, PRL 87, 161602 (2001)]



● Stefan's law:  $\tau \sim 10^{-26}$  s

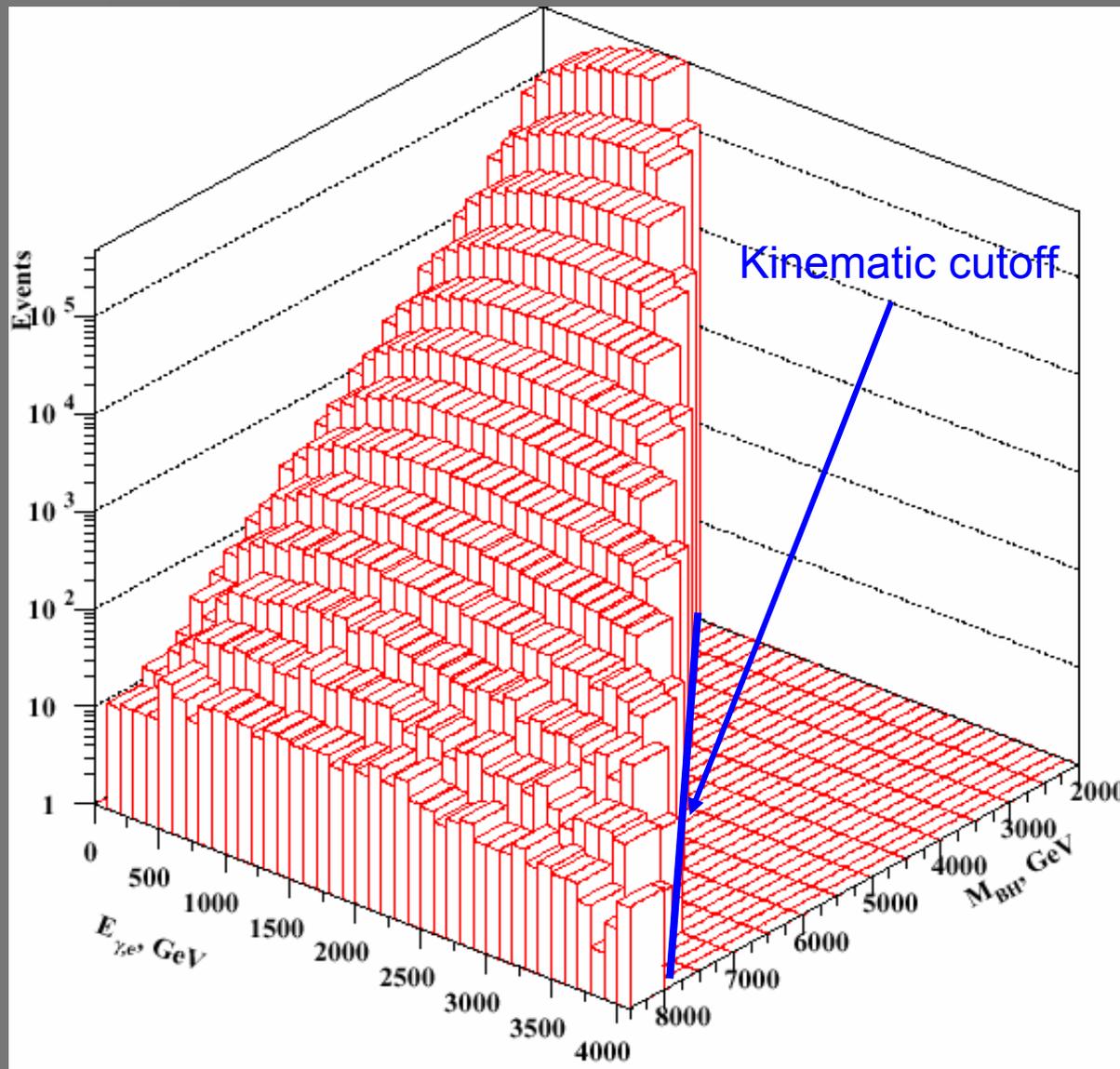
# LHC as a Black Hole Factory

[Dimopoulos, GL, PRL **87**, 161602 (2001)]



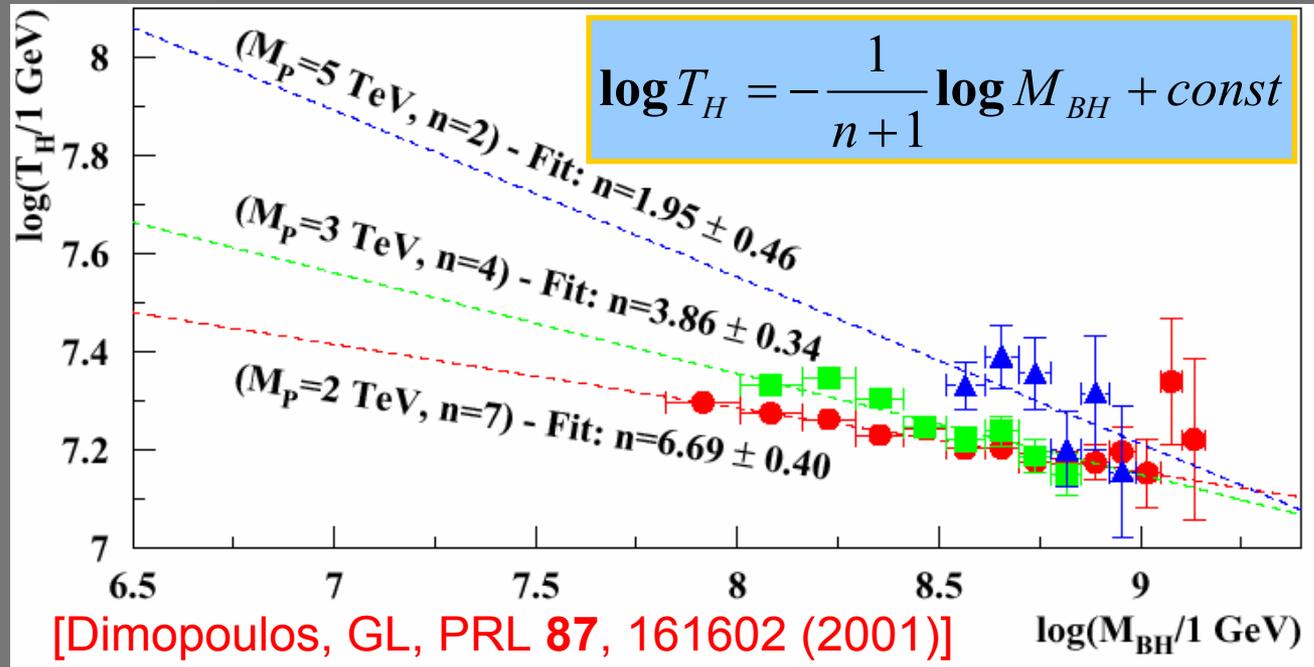
Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

# Wien's Law Test at the LHC



- Select events with high multiplicity  $\langle N \rangle > 4$ , an electron or a photon, and low  $ME_T$
- Reconstruct the BH mass (dominated by jet energy resolution,  $\sigma \sim 100$  GeV) on the event-by-event basis
- Reconstruct the collective black-body spectrum of electrons and photons in each BH mass bin
- Correlation of the two gives a direct way to test the Hawking's law

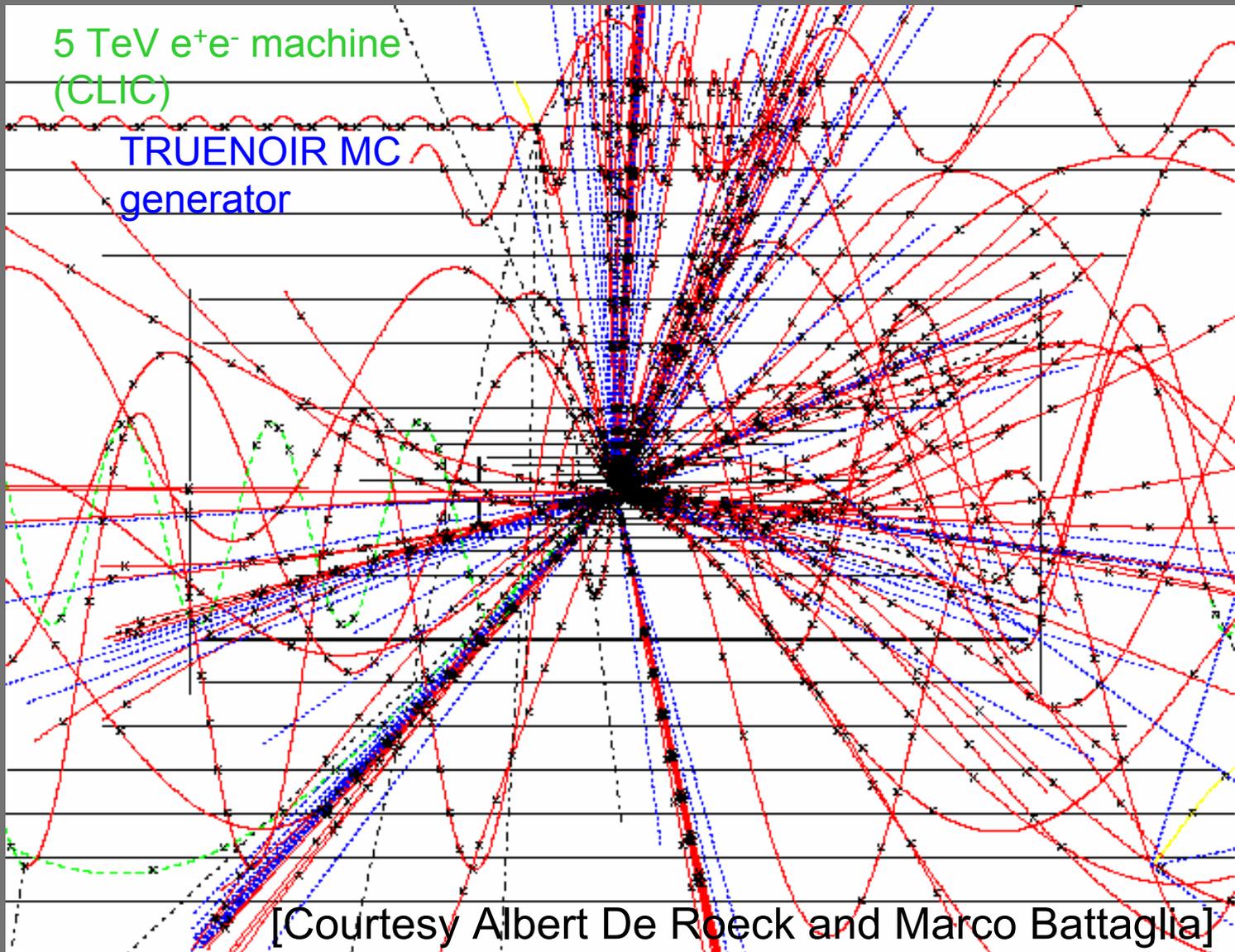
# Shape of Gravity at the LHC



- Relationship between  $\log T_H$  and  $\log M_{BH}$  allows to find the number of ED,
- This result is independent of their shape!
- This approach drastically differs from analyzing other collider signatures and would constitute a “smoking cannon” signature for a TeV Planck scale

$M_P$	1 TeV	2 TeV	3 TeV	4 TeV	5 TeV
$n = 2$	1%/0.01	1%/0.02	3.3%/0.10	16%/0.35	40%/0.46
$n = 3$	1%/0.01	1.4%/0.06	7.5%/0.22	30%/1.0	48%/1.2
$n = 4$	1%/0.01	2.3%/0.13	9.5%/0.34	35%/1.5	54%/2.0
$n = 5$	1%/0.02	3.2%/0.23	17%/1.1		
$n = 6$	1%/0.03	4.2%/0.34	23%/2.5	Fit fails	
$n = 7$	1%/0.07	4.5%/0.40	24%/3.8		

# A Black Hole Event Display



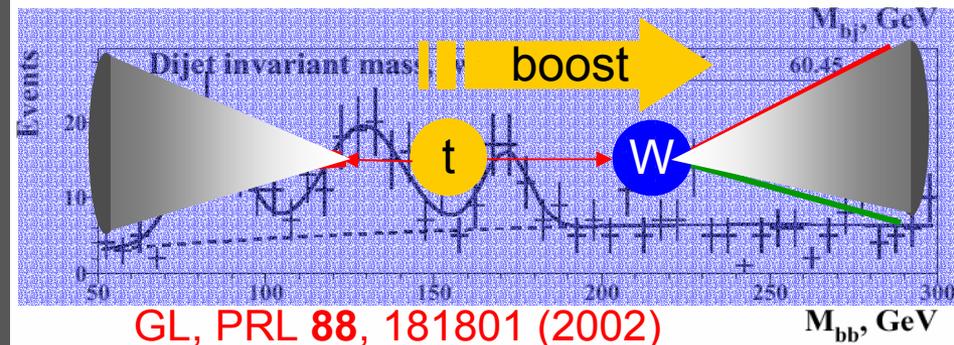
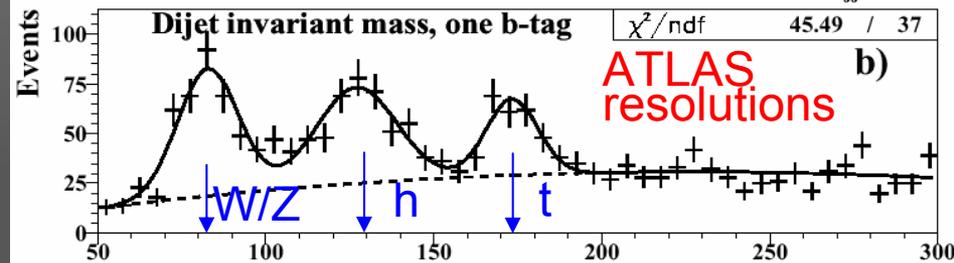
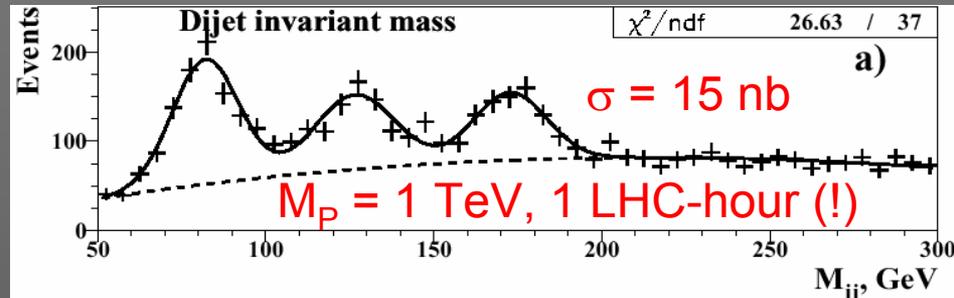
# Black Holes & New Physics

- The end of short-distance physics?
  - Naively – yes, as once the event horizon is larger than the size of the proton, all that a high-energy collider would produce is black holes!
  - But: black hole decays open a new window into new physics!
- Hence, rebirth of the short-distance physics!
- Gravity couples universally, so each new particle, which can appear in the BH decay would be produced with ~1% probability (if its mass is less than  $T_H \sim 100$  GeV)
- Moreover, spin zero (color) particle (SUSY!) production is enhanced by a factor of a few due to the s-wave function (color d.o.f.) enhancement
- Clean BH samples would make LHC a new physics factory as well



# Higgs Discovery in BH Decays

- Example: 130 GeV Higgs particle, which is tough to find either at the Tevatron or at the LHC
- Higgs with the mass of 130 GeV decays predominantly into a  $bb$ -pair
- Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results
- Time required for 5 sigma discovery:
  - $M_p = 1$  TeV – 1 hour
  - $M_p = 2$  TeV – 1 day
  - $M_p = 3$  TeV – 1 week
  - $M_p = 4$  TeV – 1 month
  - $M_p = 5$  TeV – 1 year
  - Standard method – 1 year w/ two calibrated detectors!



GL, PRL 88, 181801 (2002)

- An exciting prospect for discovery of other new particles w/ mass  $\sim 100$  GeV!

# String Balls at the LHC

- Dimopoulos/Empanan, [PL B526, 393 (2002)] – an attempt to account for stringy behavior for  $M_{BH} \sim M_S$
- GR is applicable only for  $M_{BH} > M_{min} \sim M_S/g_s^2$ , where  $g_s$  is the string coupling;  $M_P$  is typically  $< M_{min}$
- They show that for  $M_S < M < M_{min}$ , a *string ball*, which is a long jagged string, is formed
- Properties of a string-ball are similar to that of a BH: it evaporates at a Hagedorn temperature:

$$T_H = \frac{M_S}{2\sqrt{2}\pi}$$

in a similar mix of particles, with perhaps a larger bulk component

- Cross section of the string ball production is numerically similar to that of BH, due to the absence of a small coupling parameter:

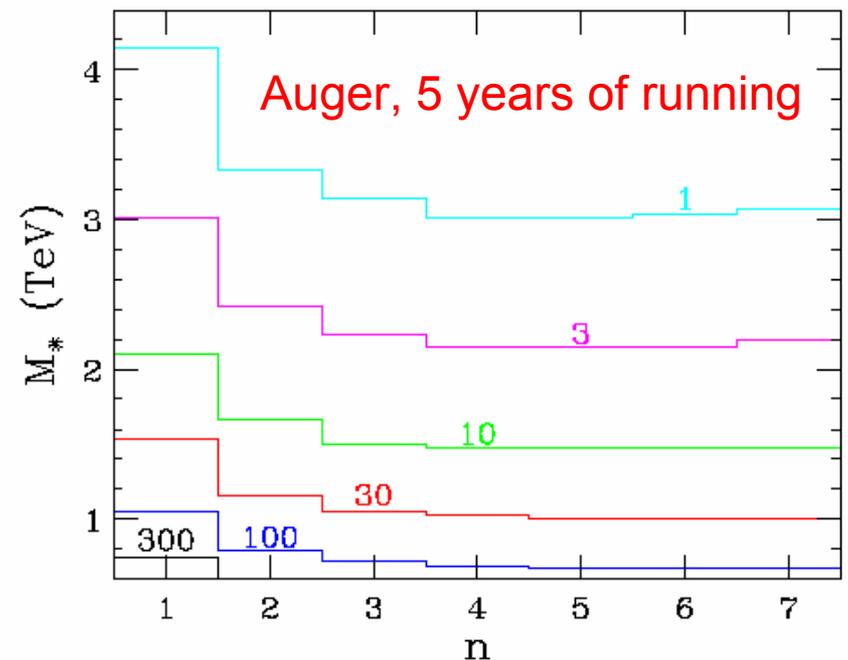
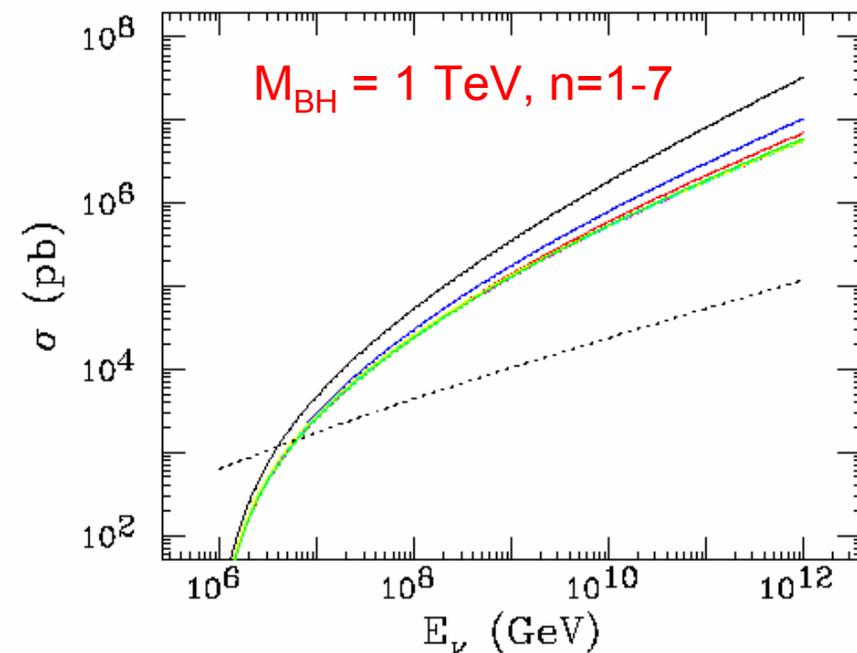
$$\sigma \sim \begin{cases} \frac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \leq M_s/g_s, \\ \frac{1}{M_s^2} & M_s/g_s < M_{SB} \leq M_s/g_s^2, \\ \frac{1}{M_P^2} \left(\frac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}. \end{cases}$$

- It might be possible to distinguish between the two cases by looking at the missing energy in the events, as well as at the production cross section dependence on the total mass of the object
- Very interesting idea; more studies of that kind to come!

# Black Holes in Cosmic Rays

- Recent studies by Feng/Shapere [PRL 88 (2002) 021303]; Anchordoqui/Goldberg [hep-ph/0109242]; Emparan/Massip/Rattazzi [hep-ph/0109287], ...
- Consider BH production deep in the atmosphere by UHE neutrinos

- Detect them, e.g. in the Pierre Auger fluorescence experiment, AGASSA, or Ice<sup>3</sup>
- Up to a few to a hundred BHs can be detected before the LHC turns on, if  $M_p < 3-4$  TeV
- Might be possible to establish uniqueness of the BH signature by comparing several neutrino-induced processes

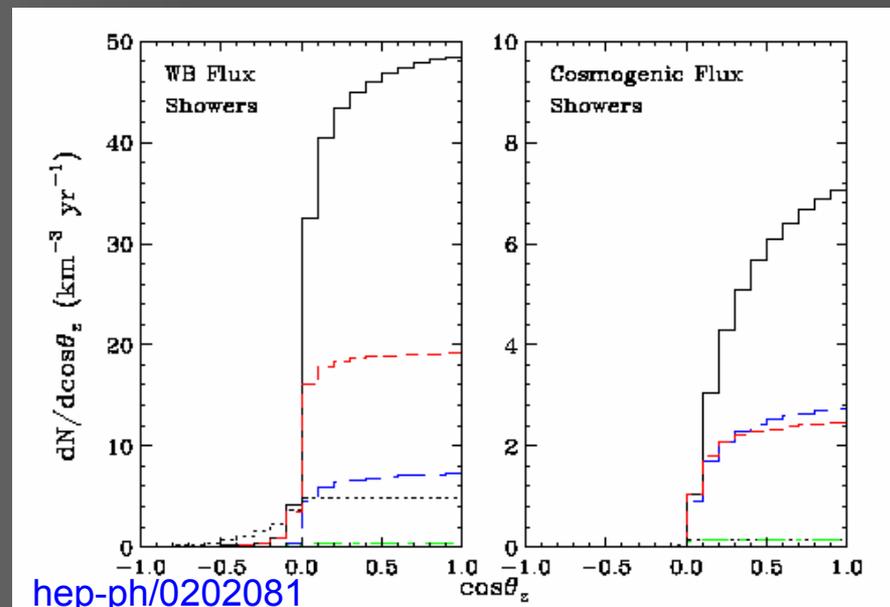
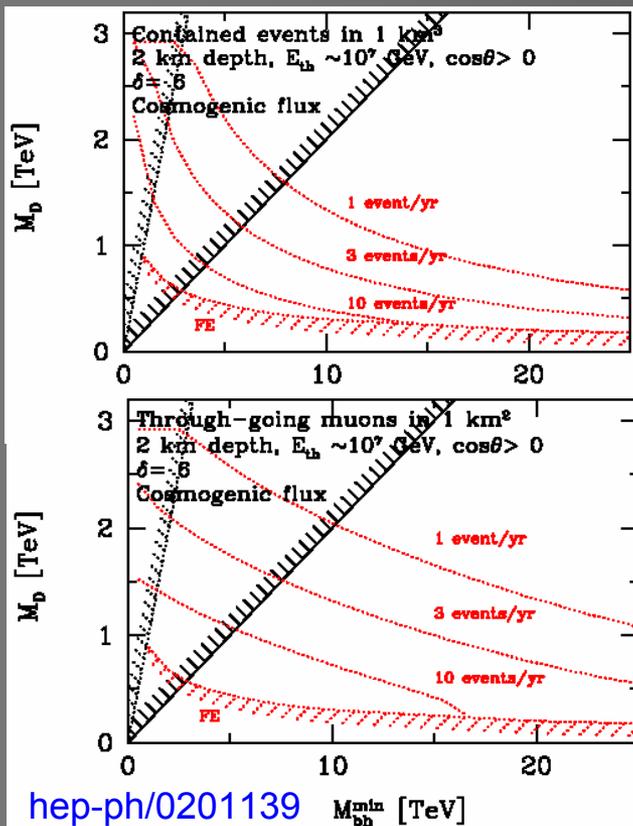
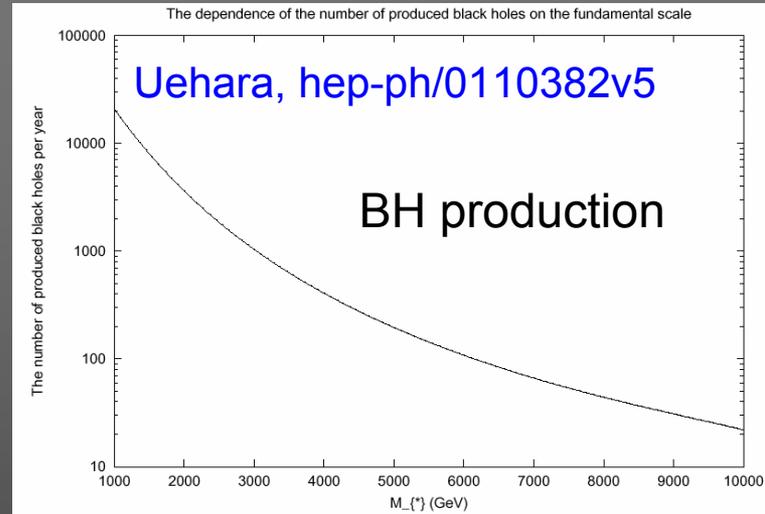


[Feng & Shapere, PRL 88 (2002) 021303]

# BH in Neutrino Telescopes

Ice<sup>3</sup> offers interesting possibilities of BH detection

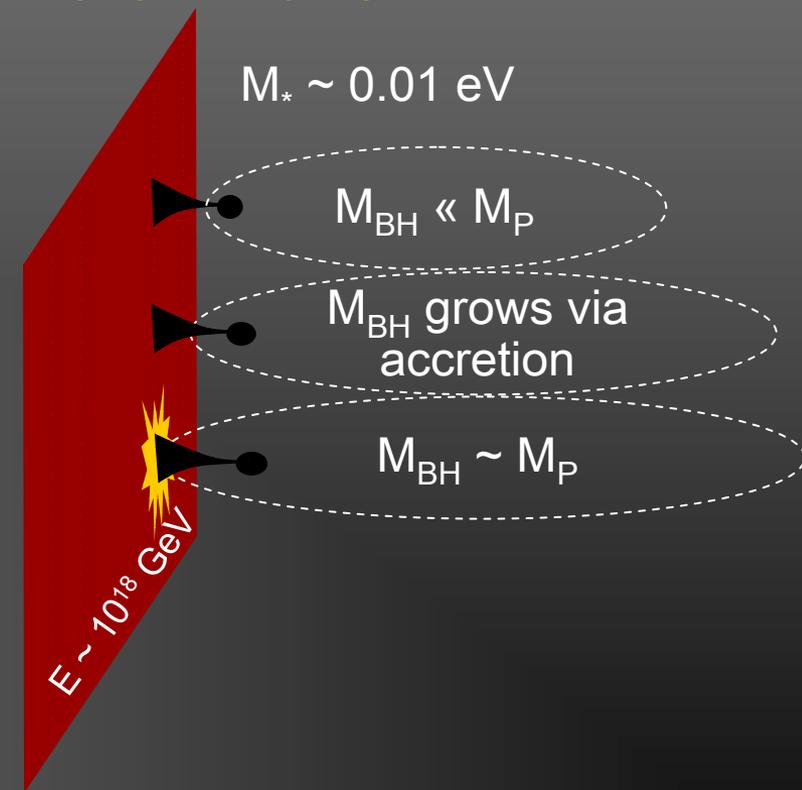
- Uehara, [hep-ph/0110382v5](#): event rate
- Kowalski/Ringwaldt/Tu, [hep-ph/0201139](#): contained and throughgoing events
- Alvarez-Muniz/Feng/Halzen/Han/Hooper, [hep-ph/0202081](#): zenith angle dependence



# Reentering Black Holes

- An exciting BH phenomenology is possible in **infinite-volume ED**, where the fundamental Planck scale in the bulk could be very small ( $M_* \sim 0.01 \text{ eV}$ )
- If this is the case, **an energetic particle** produced in a collision **could** move off the brane and **become a bulk BH**
- **It would then grow** by accreting graviton background radiation or the debris of other collisions, **until its mass reaches  $\sim M_P$**
- At this point **the bulk horizon would touch the brane**, and the bulk black hole evaporates with the emission of  **$\sim 10$  particles** with the energy of  **$\sim 10^{18} \text{ GeV}$**  each

- **Possible mechanism of UHECR production** by cosmological accelerators
- Gia Dvali, Gregory Gabadadze, GL – **a paper in preparation**



# Conclusions

- Black hole production at future colliders is **likely to be the first signature for quantum gravity** at a TeV
- **Large production cross section, low backgrounds, and little missing energy** would make BH production and decay a perfect laboratory to study strings and quantum gravity
- Precision **tests of Hawking radiation** may allow to determine the shape of extra dimensions
- **Theoretical** (string theory) **input for  $M_{\text{BH}} \approx M_{\text{P}}$  black holes is essential** to ensure fast progress on this exciting topic
- Nearly 150 follow-up articles to the original publication have already appeared – **expect more phenomenological studies to come!**
- A possibility of studying black holes at future colliders is **an exciting prospect of ultimate ‘unification’ of particle physics and cosmology**