BLACK HOLES AT FUTURE

COLLIDERS AND BEYOND

Greg Landsberg

BROWN UNIVERSITY

SUSY 2002

June 23, 2002

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* $r = R_S \equiv 2MG_N/c^2$:

$$g_{\mu\nu} = \begin{pmatrix} 1 - \dfrac{2MG_N}{rc^2} & 0 & 0 & 0 \\ 0 & -\left(1 - \dfrac{2MG_N}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2\sin\theta \end{pmatrix} \left.\begin{matrix} \\ \end{matrix}\right\} \text{time} \quad \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \text{space}$$

- 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, $v_{esc} = (2G_N M/R_S)^{1/2}$ 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: $R_S T_H = (4\pi)^{-1}$
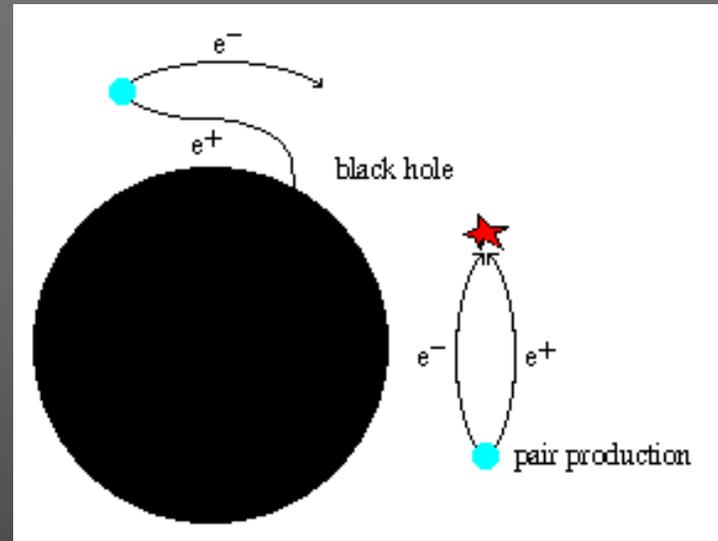
- Information paradox: if we throw an encyclopedia in a black hole, and watch it evaporating, where would the information disappear?

- 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 (~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 ~ 50 nK, λ ~ 300 km, P ~ 20 kW!)
- 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

"It's black, and it looks like a hole. I'd say it's a Black Hole."

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

Cygnus X-1

HDE 226868

Chandra X-ray Spectrum

Circinus galaxy
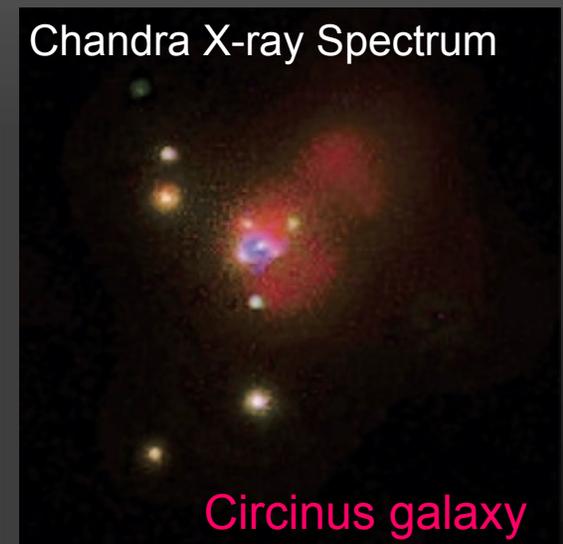
Large Extra Dimensions

- Arkani-Hamed, Dimopoulos, Dvali (1998): there could be large extra dimensions that only gravity feels!
- What about *Newton's law*?

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \rightarrow \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$

- Ruled out for flat extra dimensions, but has not been ruled out for compactified extra dimensions:

Compact Dimension

Flat Dimension
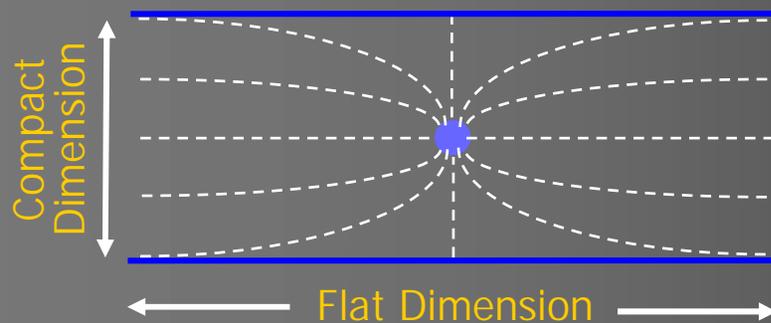
$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \text{ for } r \gg R$$

M_P – fundamental Planck Scale

- But: how to make gravity strong?
- $G'_N = 1/M_P^2 \sim G_F \Rightarrow M_P \sim 1$ TeV

$$M_P^{n+2} \propto M_{Pl}^2 \big/ R^n$$

- More precisely, from Gauss's law:

$$R = \frac{1}{2\sqrt{\pi}M_S}\left(\frac{M_{Pl}}{M_S}\right)^{2/n} \propto \begin{cases} 8\times10^{12}m, & n=1 \\ 0.7\,mm, & n=2 \\ 3\,nm, & n=3 \\ 6\times10^{-12}m, & n=4 \end{cases}$$

- Amazing as it is, but no one has tested Newton's law to distances less than ~1 mm (as of 1998) or 0.15 mm (2002)
- Therefore, large spatial extra dimensions compactified at a sub-millimeter scale are, in principle, allowed!
- If this is the case, gravity can be ~10[38] times stronger than what we think!

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.

gravitational force
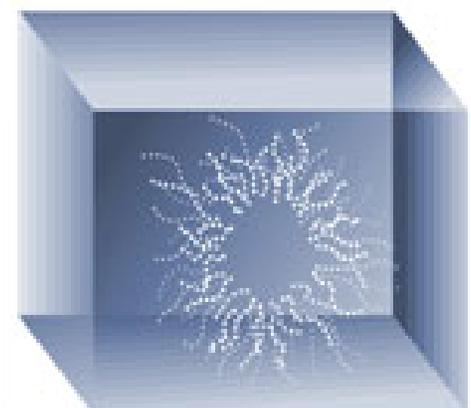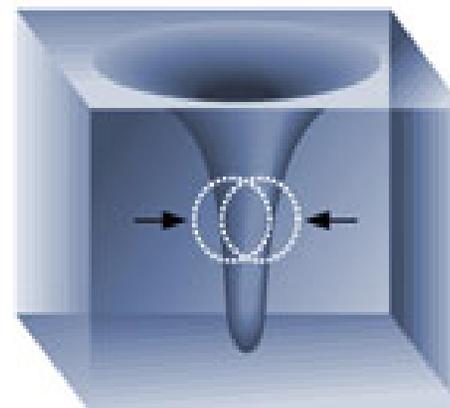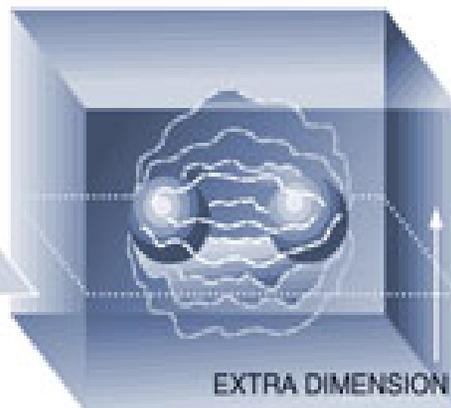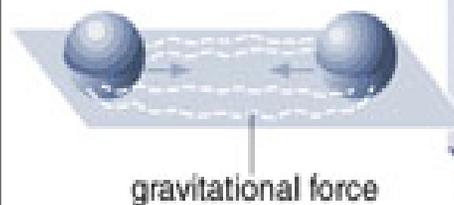
EXTRA DIMENSION

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:

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

parton $M^2 = \hat{s}$

R_S

parton
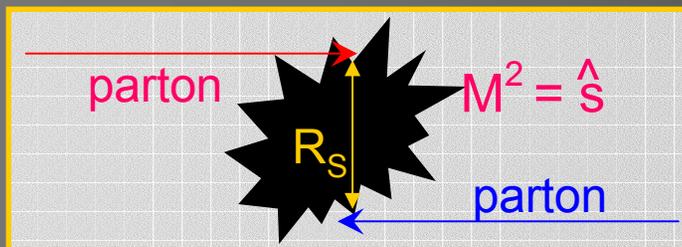
- Fundamental limitation: our lack of knowledge of quantum gravity effects close to the Planck scale

- Consequently, no attempts for partial improvement of the results, e.g.:
  - Grey body factors
  - BH spin, charge, color hair
  - Relativistic effects and time-dependence

- 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 $M_{BH} \gg M_P$; only consider $M_{BH} > M_P$

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:

$$\sigma(\hat{s} = M_{BH}^2) = \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$
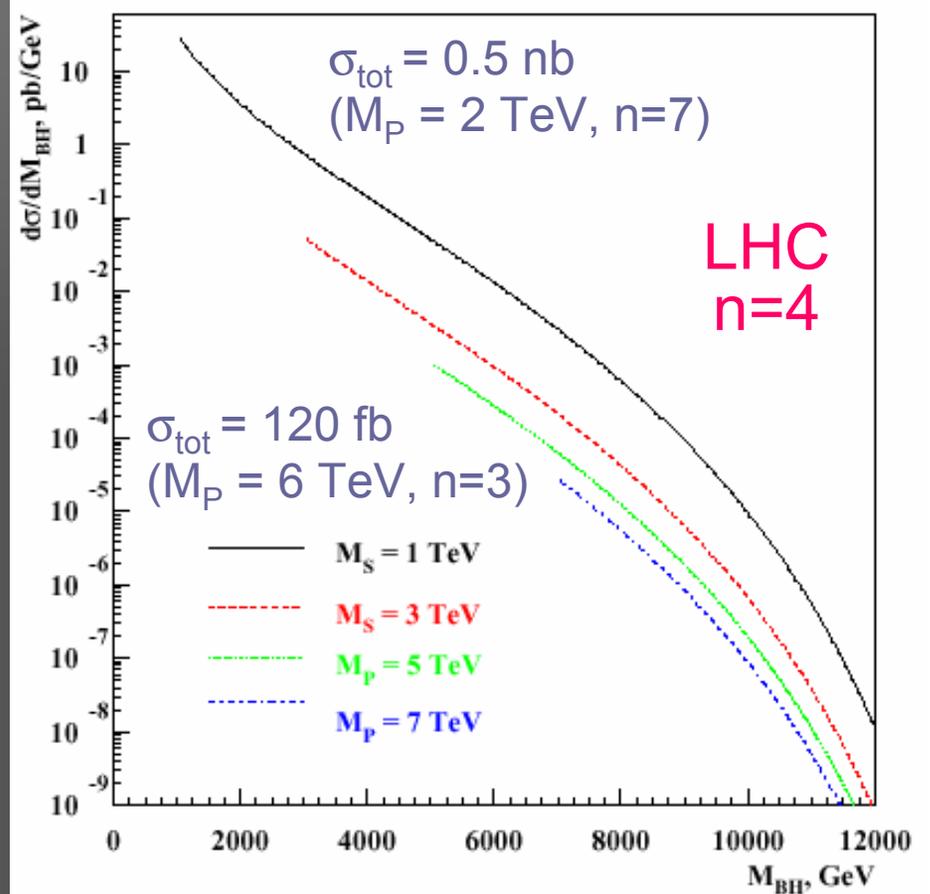
- Hadron colliders: use parton luminosity w/ MRSD-′ PDF (valid up to the VLHC energies)

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

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

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from qq′ interactions
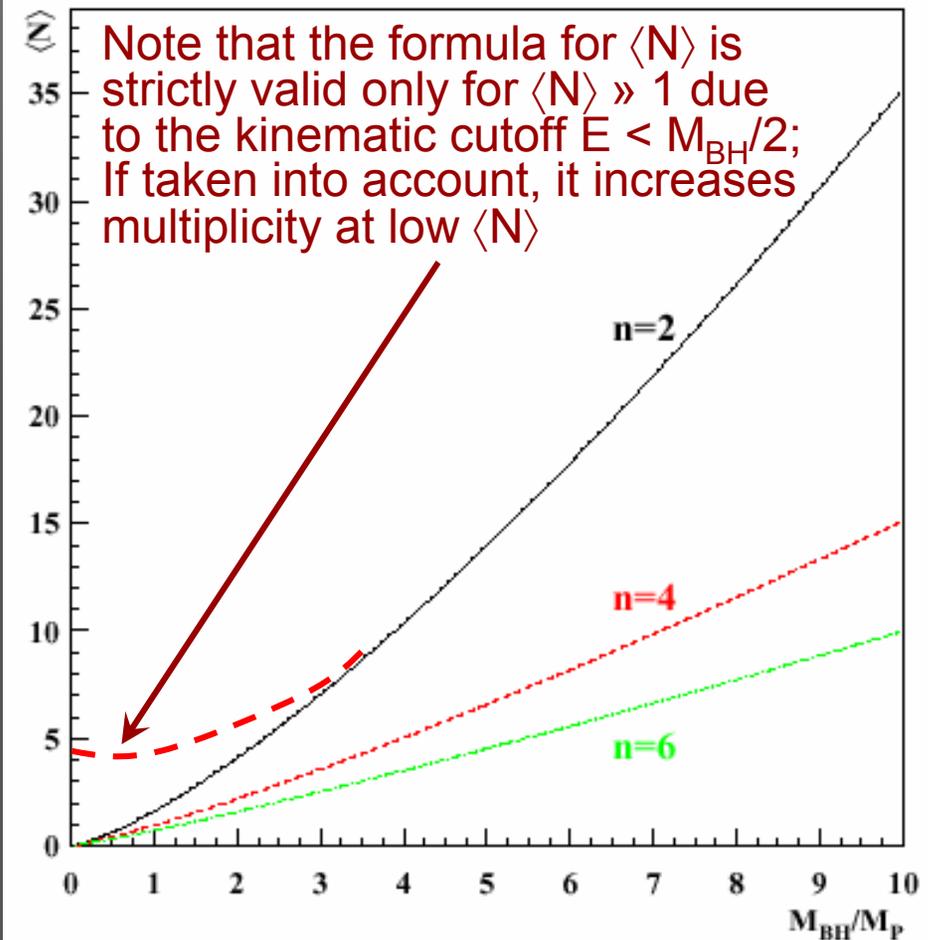
[Dimopoulos, GL, PRL **87**, 161602 (2001)]

σ_{tot} = 0.5 nb
(M_P = 2 TeV, n=7)

LHC
n=4

σ_{tot} = 120 fb
(M_P = 6 TeV, n=3)

M_S = 1 TeV
M_S = 3 TeV
M_P = 5 TeV
M_P = 7 TeV

dσ/dM_{BH}, pb/GeV — M_{BH}, GeV

Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$ [Dimopoulos, GL, PRL **87**, 161602 (2001)]

- 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 ~120 SM d.o.f. yield probability of Hawking evaporation into γ, $l^{\pm}$, and ν ~2%, 10%, and 5% respectively

- Averaging over the BB spectrum gives average multiplicity of decay products:
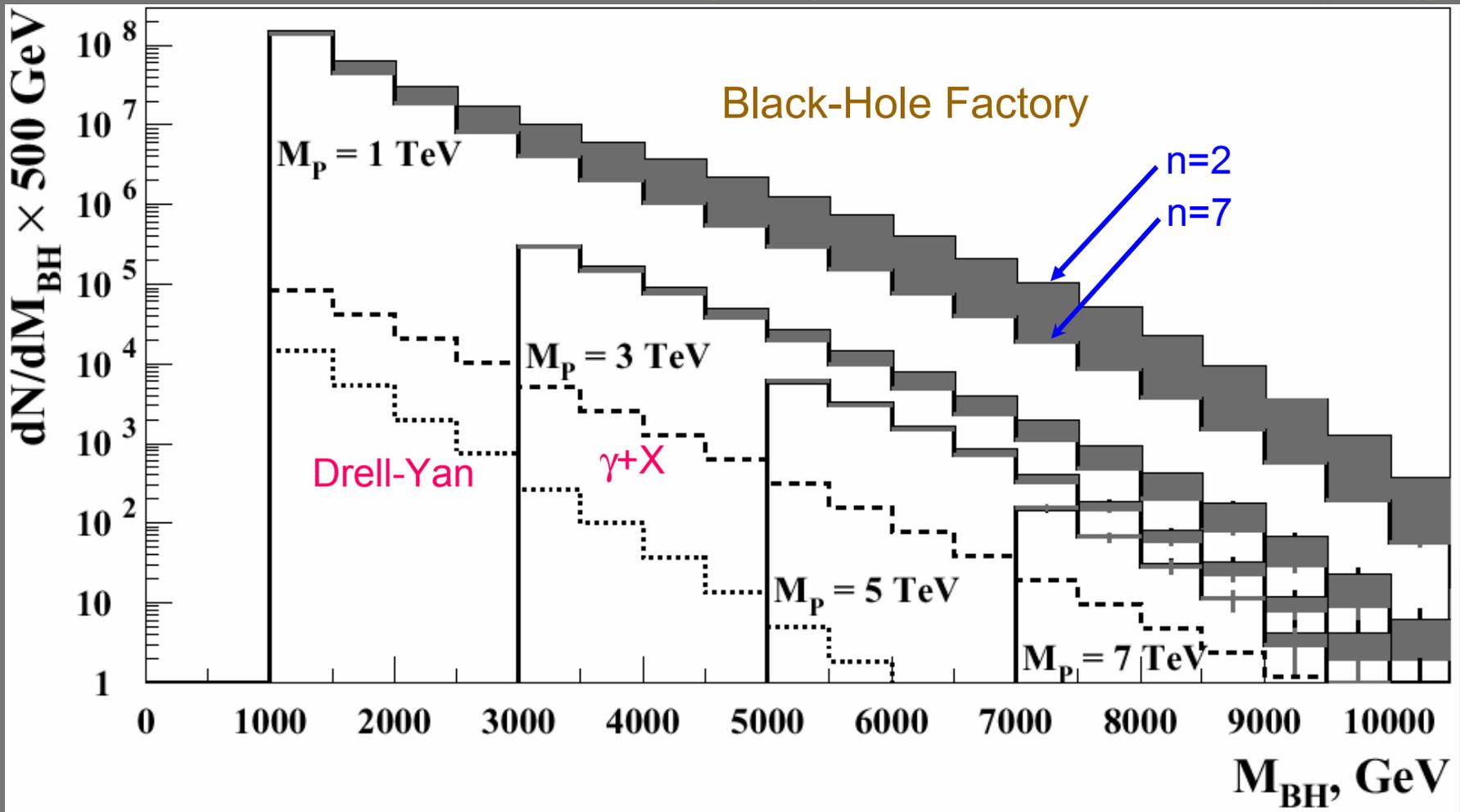
$$\langle N \rangle \approx \frac{M_{BH}}{2T_H}$$

Note that the formula for $\langle N \rangle$ is strictly valid only for $\langle N \rangle \gg 1$ due to the kinematic cutoff $E < M_{BH}/2$; If taken into account, it increases multiplicity at low $\langle N \rangle$

n=2

n=4

n=6

M_{BH}/M_P

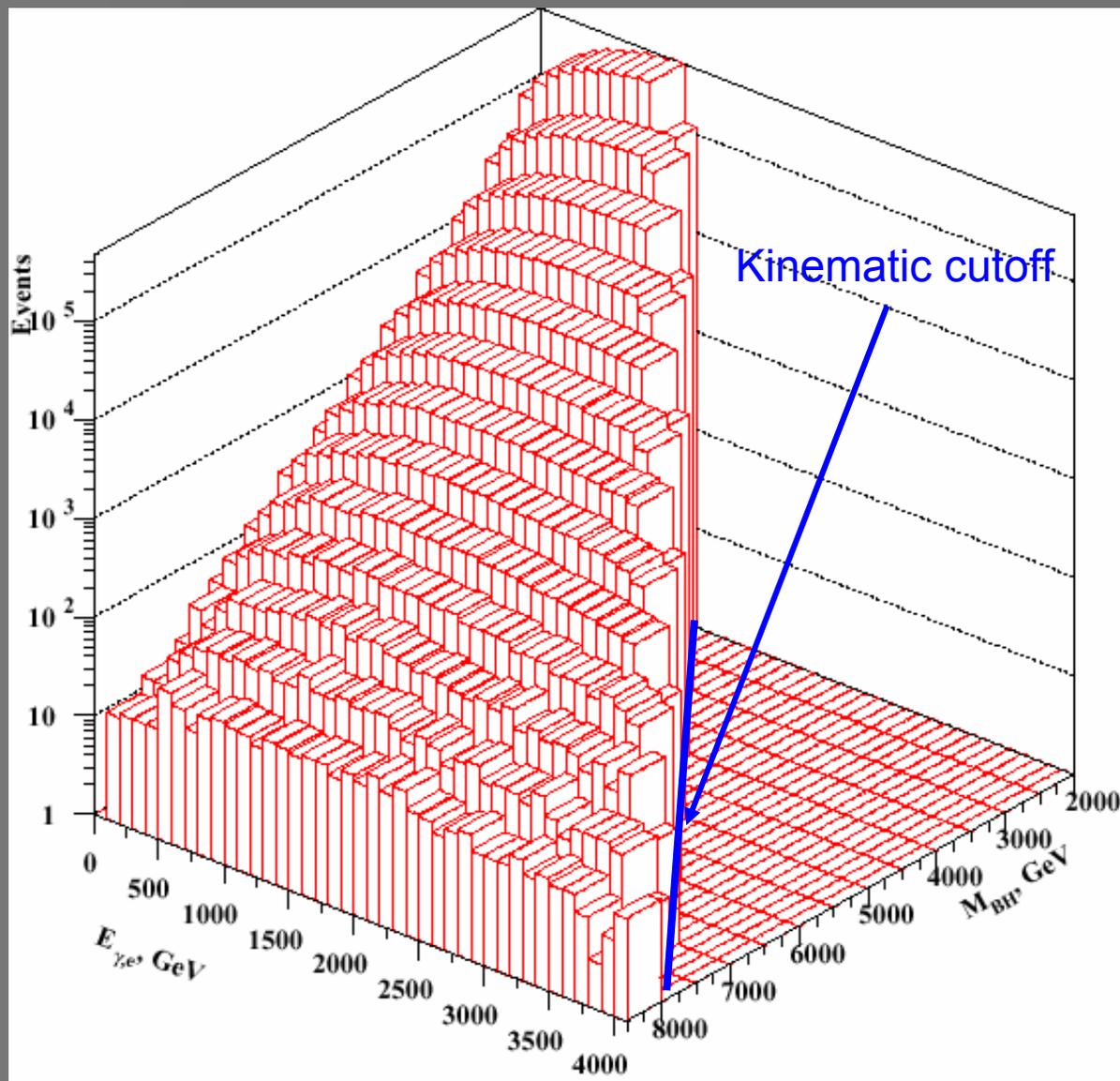- Stefan's law: $\tau \sim 10^{-26}$ s

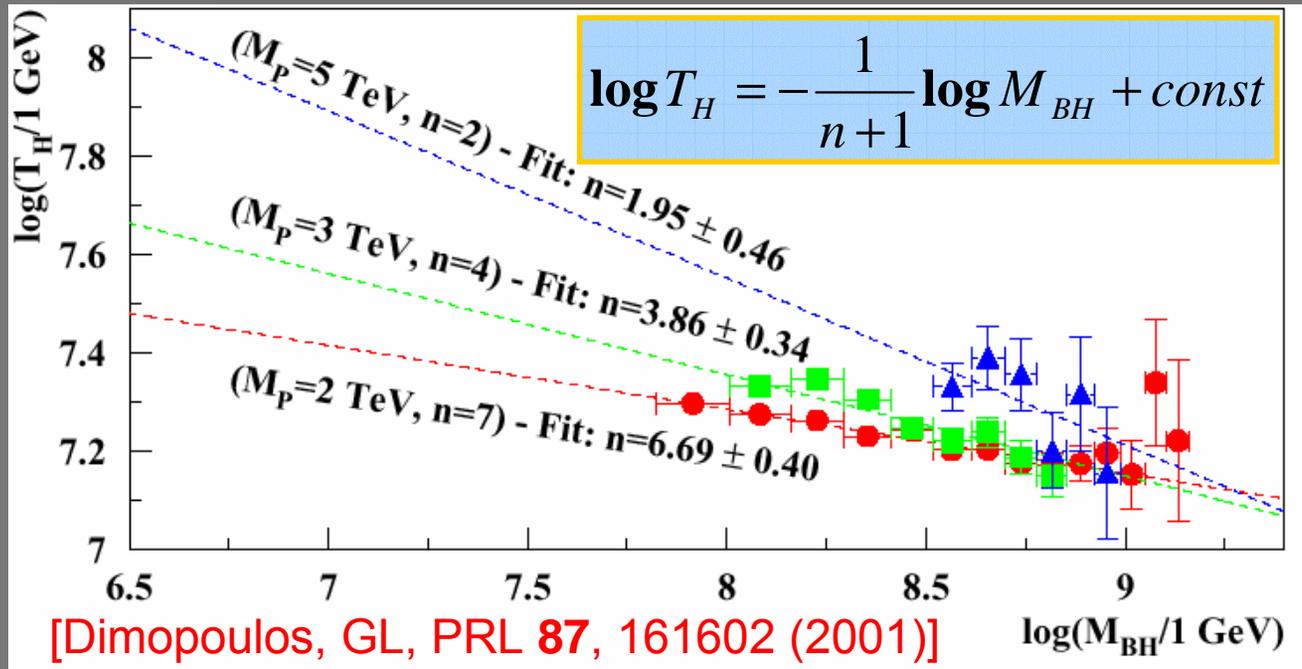# LHC as a Black Hole Factory

[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

Kinematic cutoff

- 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
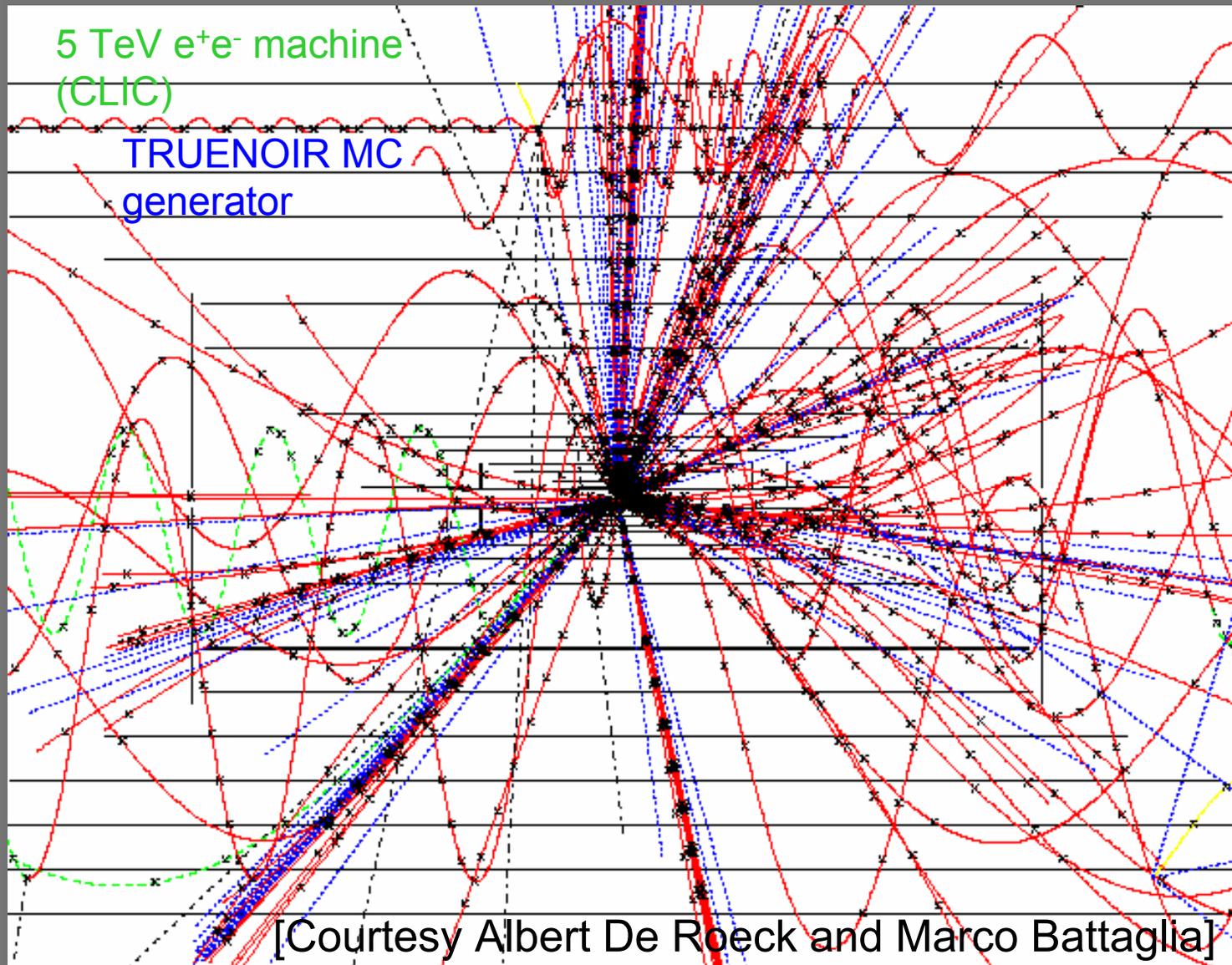- Correlation of the two gives a direct way to test the Hawking's law

Shape of Gravity at the LHC

$$\log T_H = -\frac{1}{n+1} \log M_{BH} + const$$

$(M_P = 5\ TeV, n=2)$ - Fit: n=1.95 ± 0.46

$(M_P = 3\ TeV, n=4)$ - Fit: n=3.86 ± 0.34

$(M_P = 2\ TeV, n=7)$ - Fit: n=6.69 ± 0.40

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

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		

- 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

A Black Hole Event Display

5 TeV e⁺e⁻ machine (CLIC)

TRUENOIR MC generator
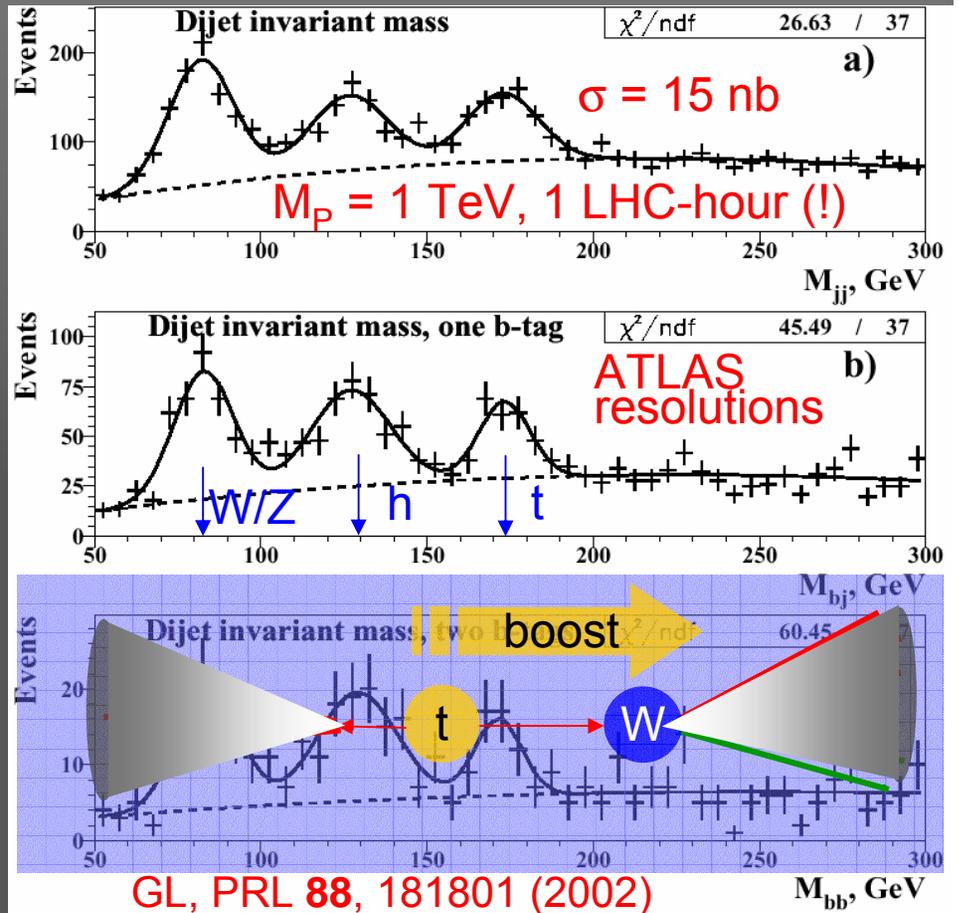
[Courtesy Albert De Roeck and Marco Battaglia]

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

"I've discovered what I believe to be the elementary basic particle: a small stone."

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!

σ = 15 nb

M_P = 1 TeV, 1 LHC-hour (!)

ATLAS resolutions

W/Z   h   t

boost

GL, PRL **88**, 181801 (2002)

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

String Balls

String Balls at the LHC

- Dimopoulos/Emparan, [PL B**526**, 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:

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

- 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[3]
- 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

M_{BH} = 1 TeV, n=1-7

Auger, 5 years of running
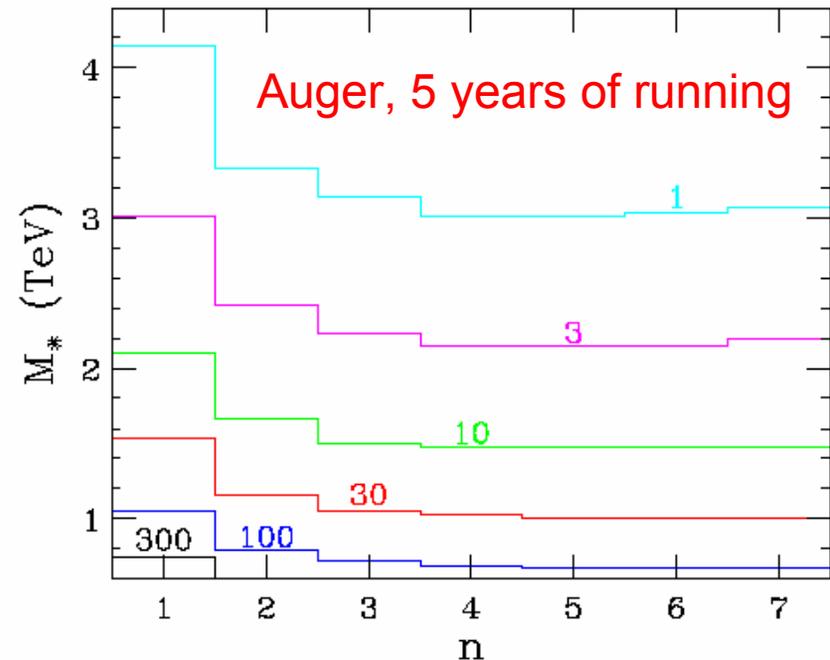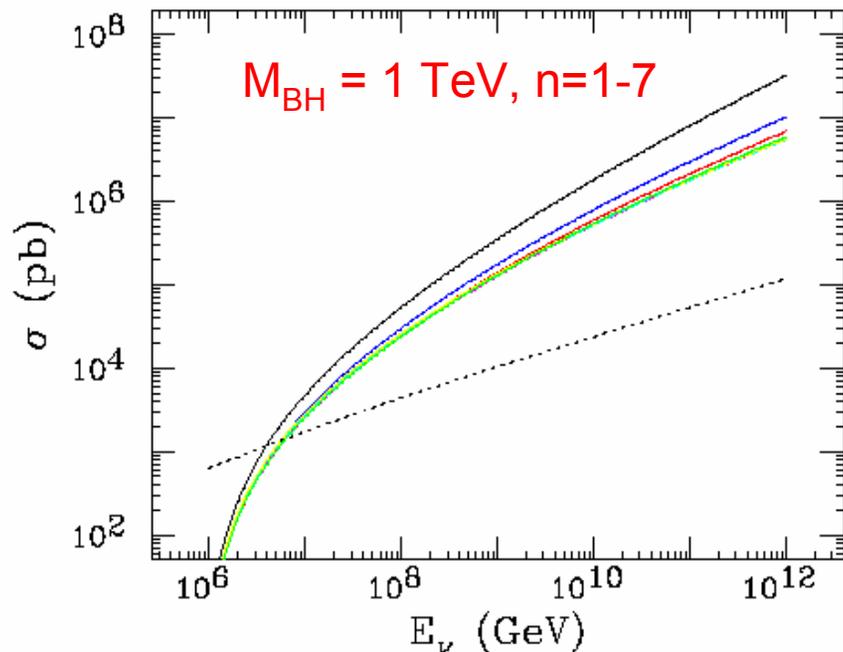
[Feng & Shapere, PRL **88** (2002) 021303]

BH in Neutrino Telescopes

Ice[3] 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

Uehara, hep-ph/0110382v5

BH production

hep-ph/0201139

hep-ph/0202081
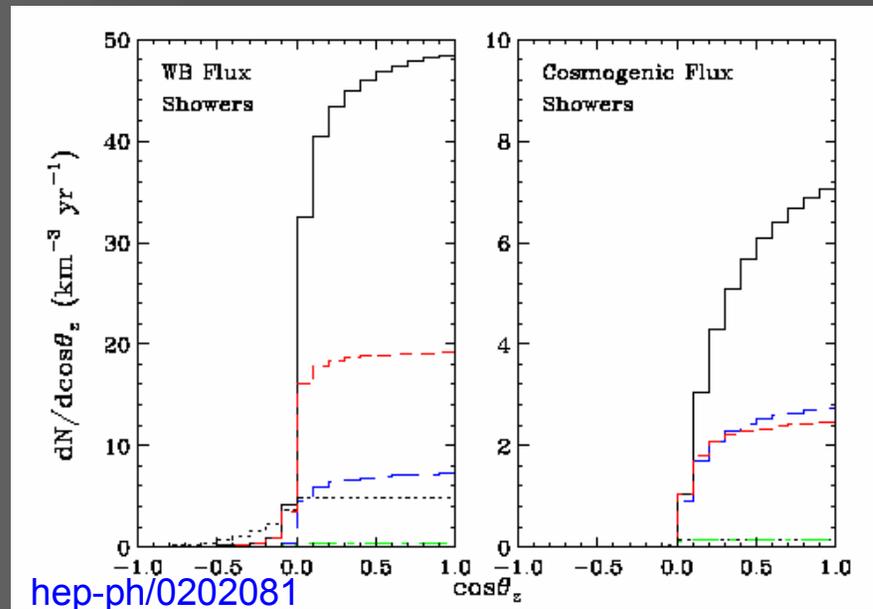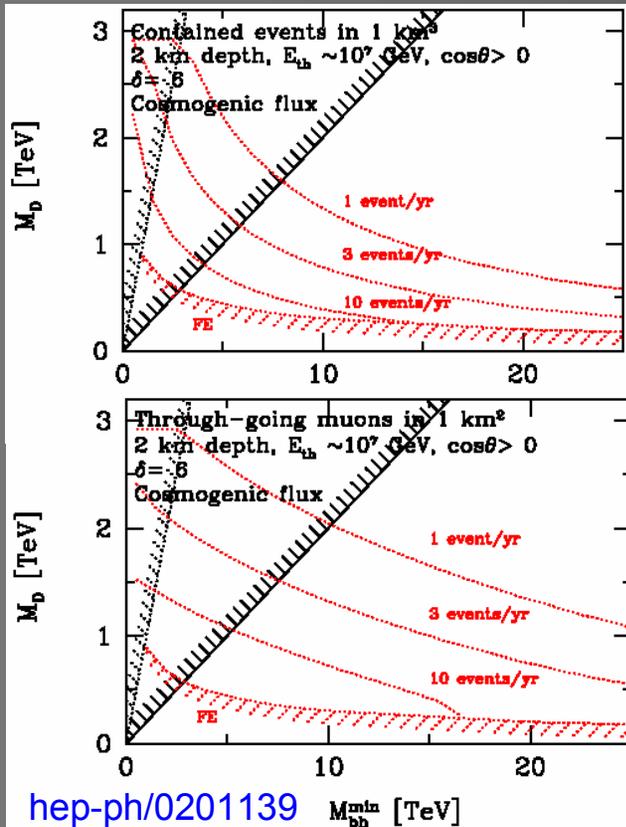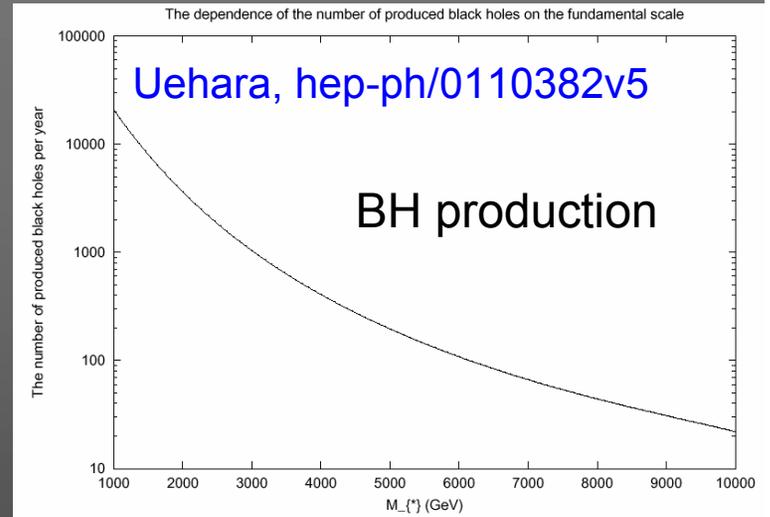
Reentering Black Holes

- An exciting BH phenomenology is possible in infinite-volume ED, where the fundamental Planck scale in the bulk could be very small ($M_* \sim 0.01$ 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 ~ 10 particles with the energy of $\sim 10^{18}$ GeV each

- Possible mechanism of UHECR production by cosmological accelerators

- Gia Dvali, GL – paper in preparation

$M_* \sim 0.01$ eV

$M_{BH} \ll M_P$

M_{BH} grows via accretion

$M_{BH} \sim M_P$

$E \sim 10^{18}$ GeV
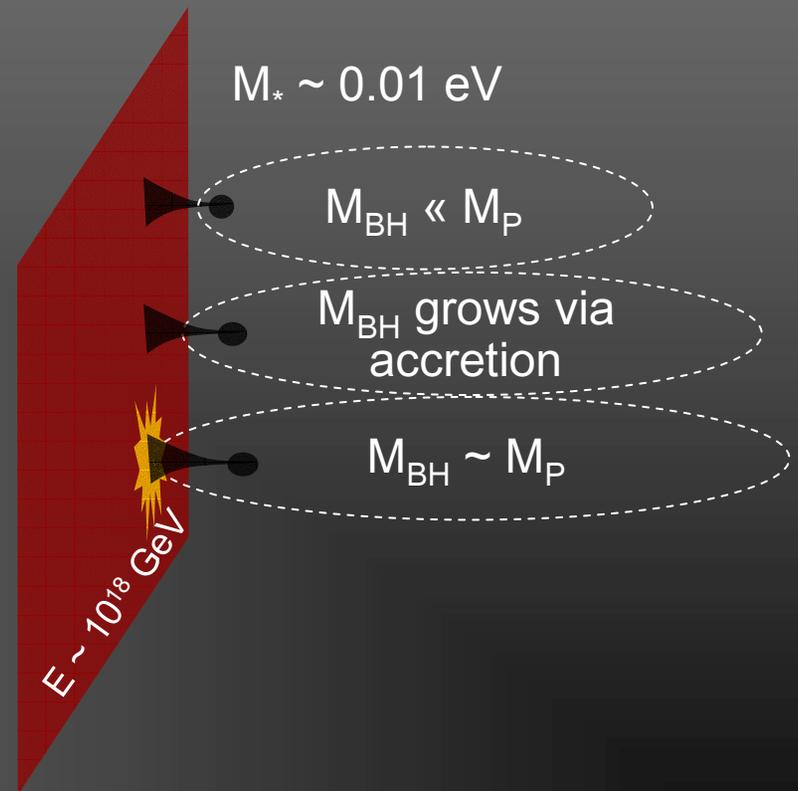
Conclusions

- 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 $M_{BH} \approx M_P$ black holes is essential to ensure fast progress on this exciting topic

- Nearly 100 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

Ice3   Voloshin   SB

Voloshin Suppression etc.

- Black hole production by man-made and natural beams is an exploding topic; this led to a number of speculative papers

- Exponential cross-section 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 B**526**, 393 (2002)]]
    - Eardley/Giddings – full GR calculations for high-energy collisions with an impact parameter [gr-qc/0201034]; extends earlier d'Eath and Payne work
    - 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) $\rightarrow$ ~ 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]