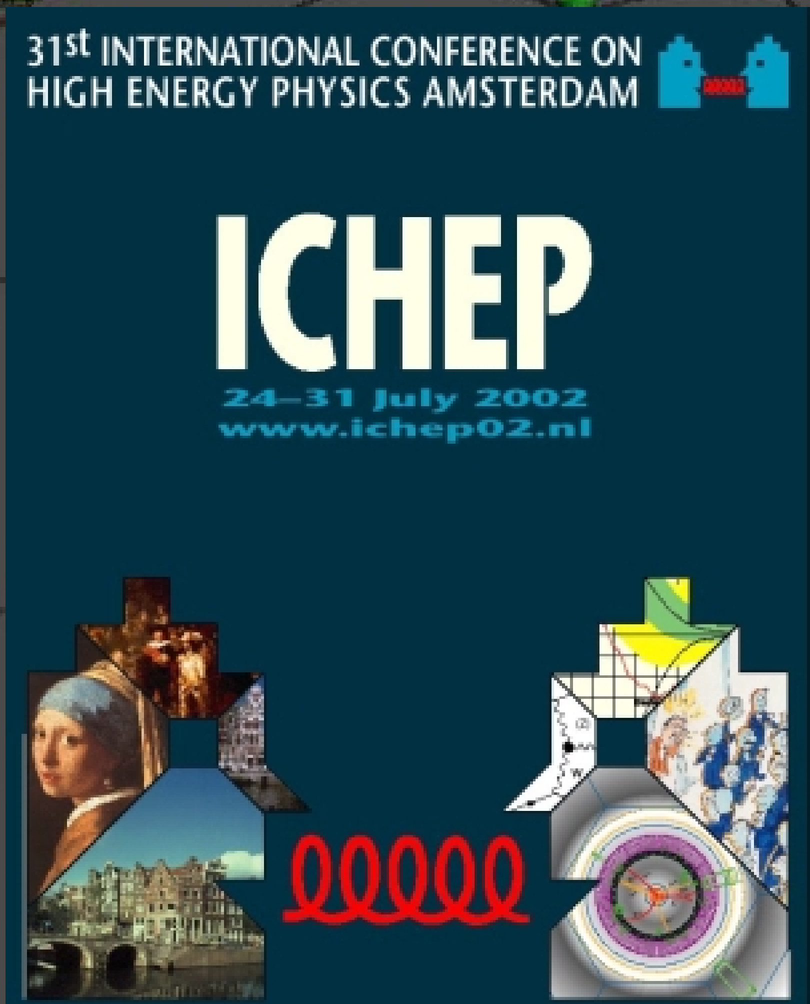

BLACK HOLES AT FUTURE COLLIDERS

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Outline

- Black holes in General Relativity
- 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
- 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 the famous metric with a singularity at a *Schwarzschild radius* $r = R_S \equiv 2MG_N/c^2$:

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

- If the radius of the object is less than R_S, a *black hole* with the event horizon at the Schwarzschild radius is formed
- The term, "Black Hole," was coined only half-a-century after Schwarzschild by John Wheeler (in 1967); previously often referred to as *frozen stars*
- Stephen Hawking showed (1971) that the black holes can evaporate via black body radiation with characteristic temperature $\sim 1/R_S$

Black Holes at Future Colliders?

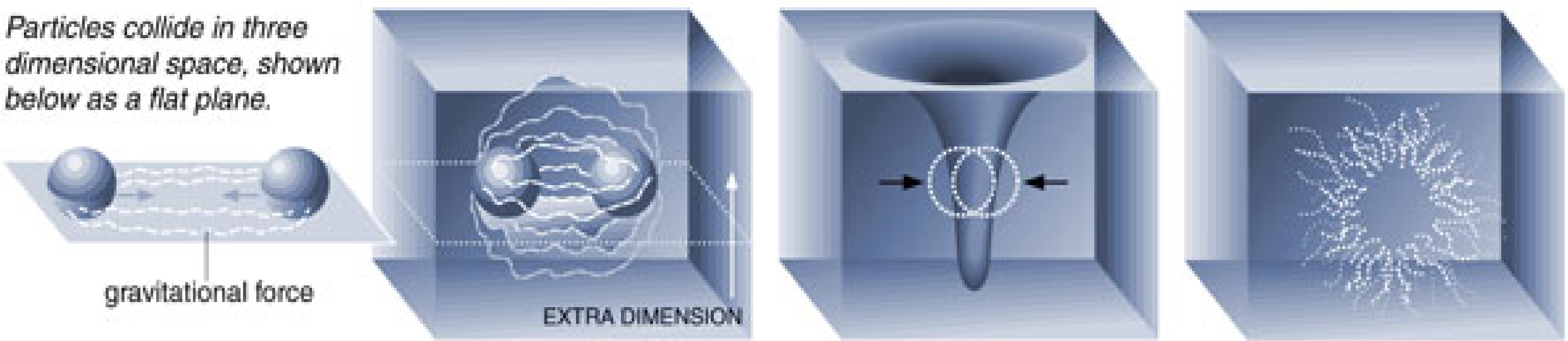
- In the models with large extra spatial dimensions (ADD), gravity is ~10^{38} times stronger than conventionally thought, and will exhibit its full strength at the distances less than the size of extra dimensions (~1 nm, n=3 to ~1 fm, n=7)

Black Holes on Demand

NYT, September 11, 2001

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:



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.

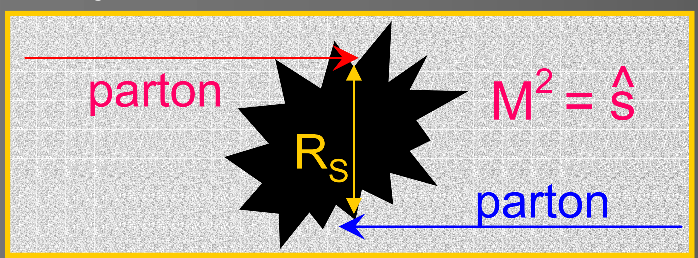
Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Our Approach & Assumptions

- Based on the work done with Savas Dimopoulos [PRL **87**, 161602 (2001)] within the ADD model
- See also Giddings/Thomas [PRD **65,** 056010 (2002)]
- Extends earlier theoretical studies by Argyres/ Dimopoulos/March-Russell [PL **B441, 96** (1998)]

  and Banks/Fischler [hep-th/9906038] to collider phenomenology
- Main idea: when the c.o.m. energy reaches the fundamental Planck scale ~1 TeV, a BH is formed
- Big surprise: BH production is not an exotic remote possibility, but the dominant effect!
- Cross section is given by the black disk approximation:

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



- Early follow-up papers by Voloshin argued exponential suppression; proved to be wrong by Eardley/Giddings [gr-qc/0201034], Jevicki/Thaler [hep-th/0203172] and others
- Giddings [hep-th/0203004]: strong gravity processes, e.g. BH formation, are important in the AdS/CFT duality approach and result in $\sigma \sim \log^2 s$ for high energy QCD scattering (saturating the Froissart bound), in agreement with the Pomeron amplitude analyses by Kang/ Nicolescu [PRD **11**, 2461 (1975)] and COMPETE Coll. [PRD **65**, 074024 (2001)]
- 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., [PL **B441**, 96 (1998)] (after Myers/Perry [Ann. Phys. **172**, 304 (1986)]) it leads to:

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

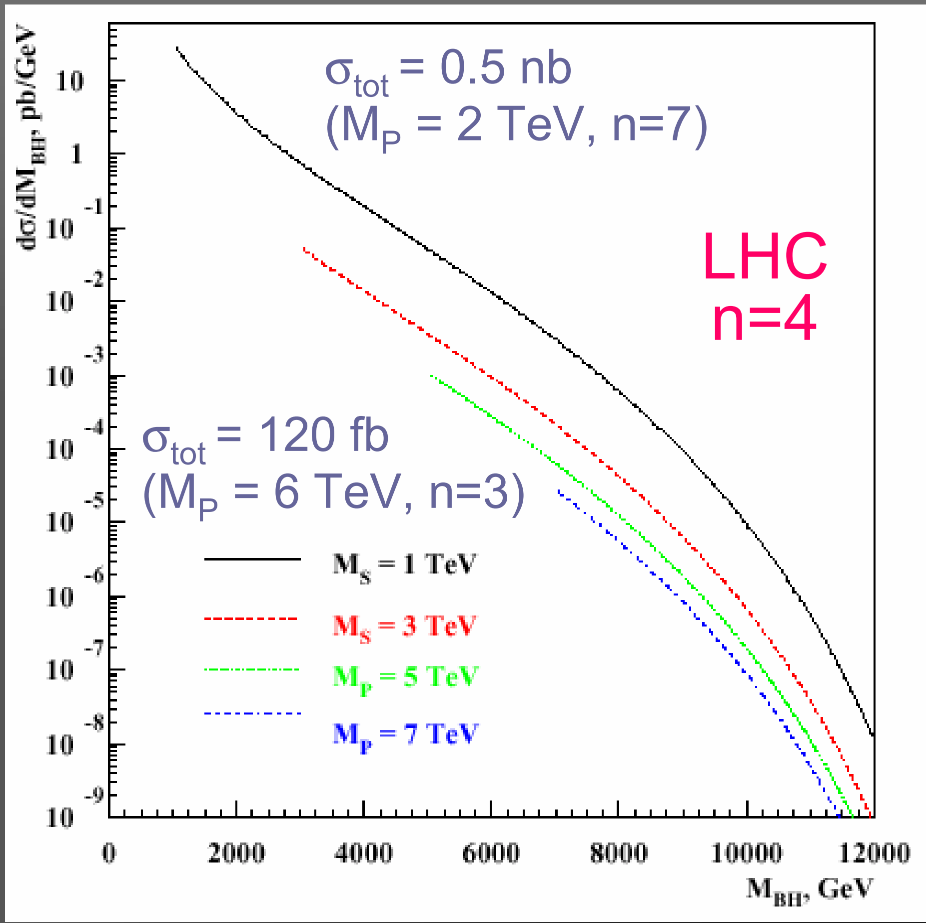
- Hadron colliders: use parton luminosity w/ MRSD-' PDF (valid up to the VLHC energies)

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

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

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from qq' interactions, and not from the gg!
- e^+e^- colliders: accounts for beamsstrahlung

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

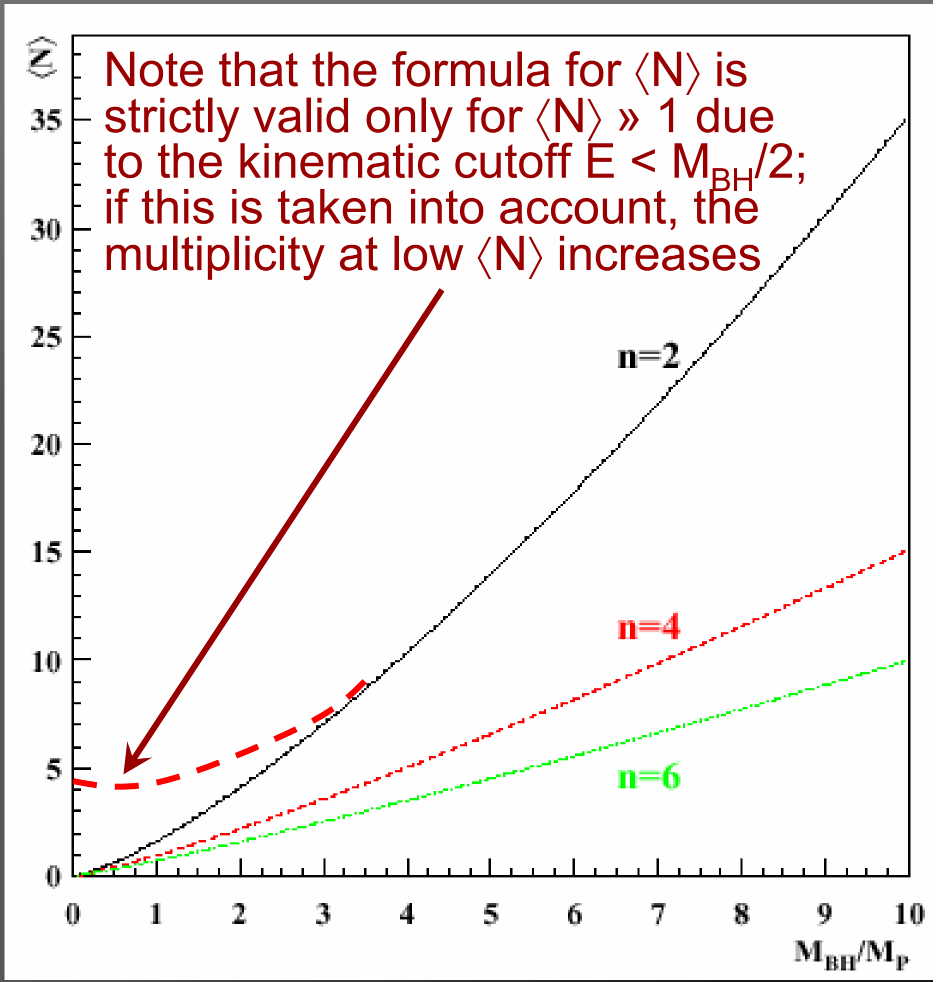


Black Hole Decay

- Once formed, the BH rapidly evaporates at the Hawking temperature: $T_H = (n+1)/4\pi R_S$ (in natural units: $\hbar = c = k = 1$)
- Stefan's law: $\tau \sim 10^{-26}$ s
- Emparan/Horowitz/Myers [PRL **85**, 499 (2000)]: BH radiates mainly on the brane
  - $\lambda \sim 2\pi/T_H > R_S$; 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, with 75% of energy in quarks/gluons (i.e., jets)
- Averaging over the BB spectrum gives average multiplicity of decay products:

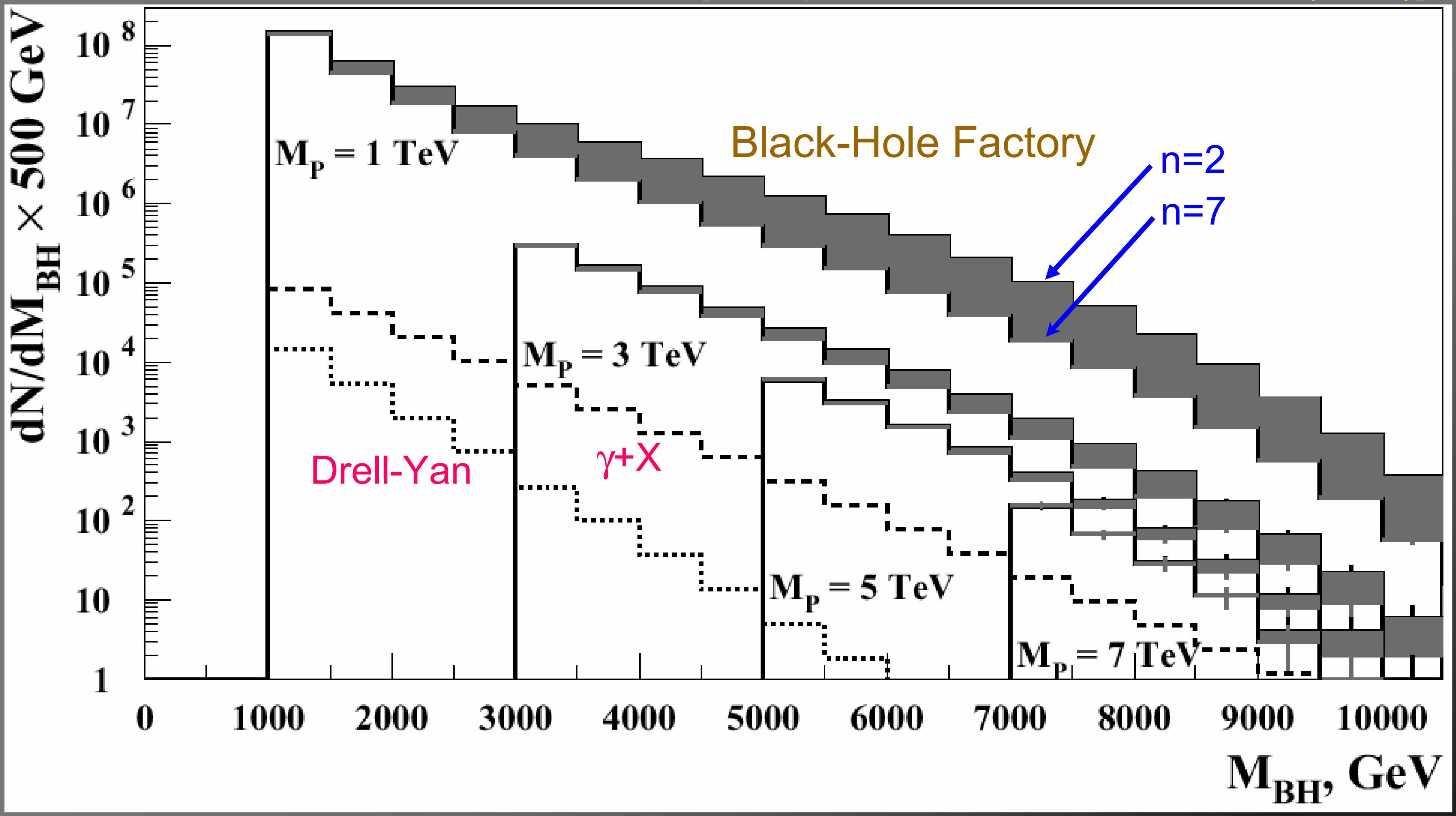
$$\boxed{\langle N \rangle \approx \frac{M_{BH}}{2T_H}}$$

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



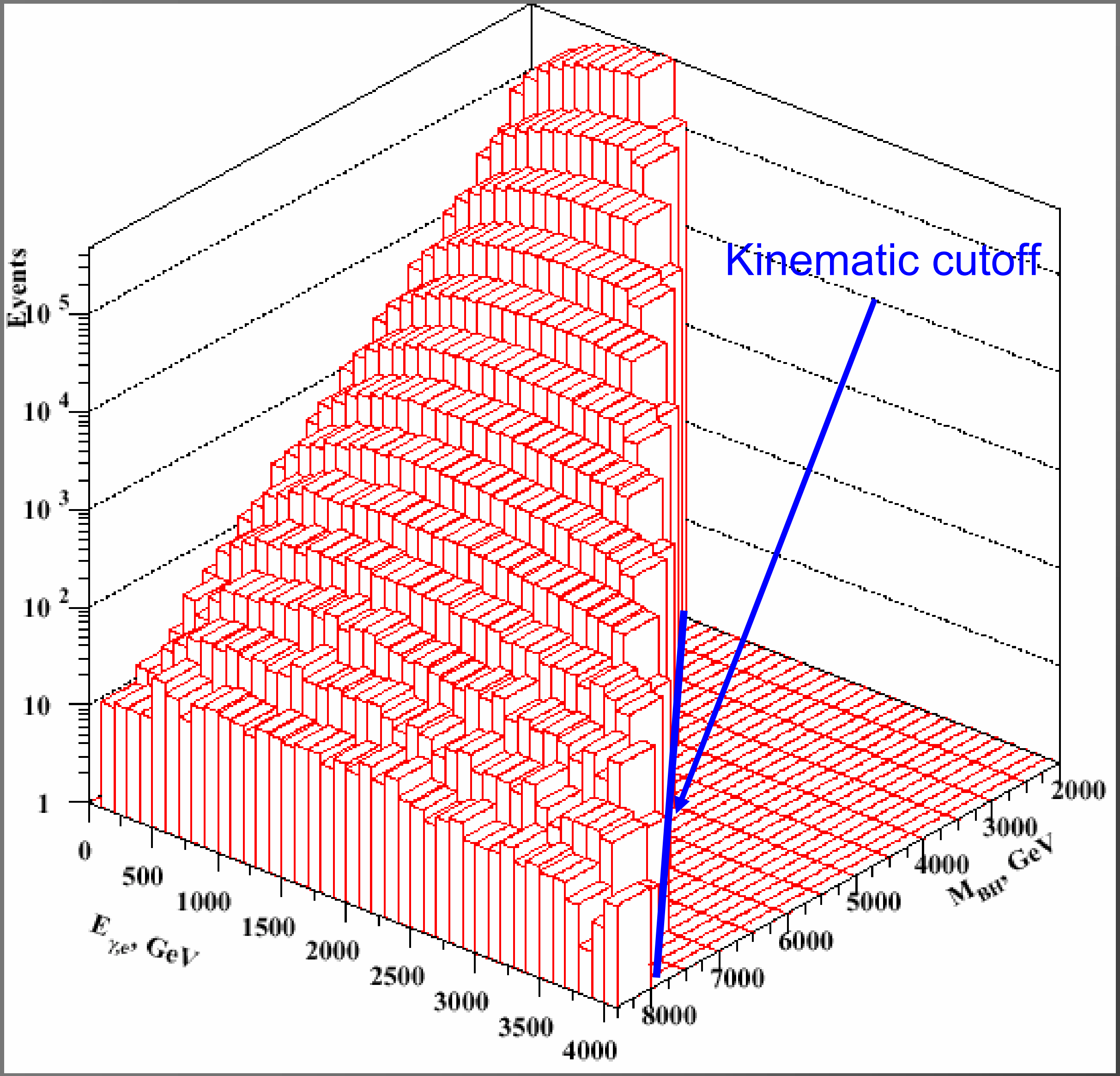
LHC as a Black Hole Factory

[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

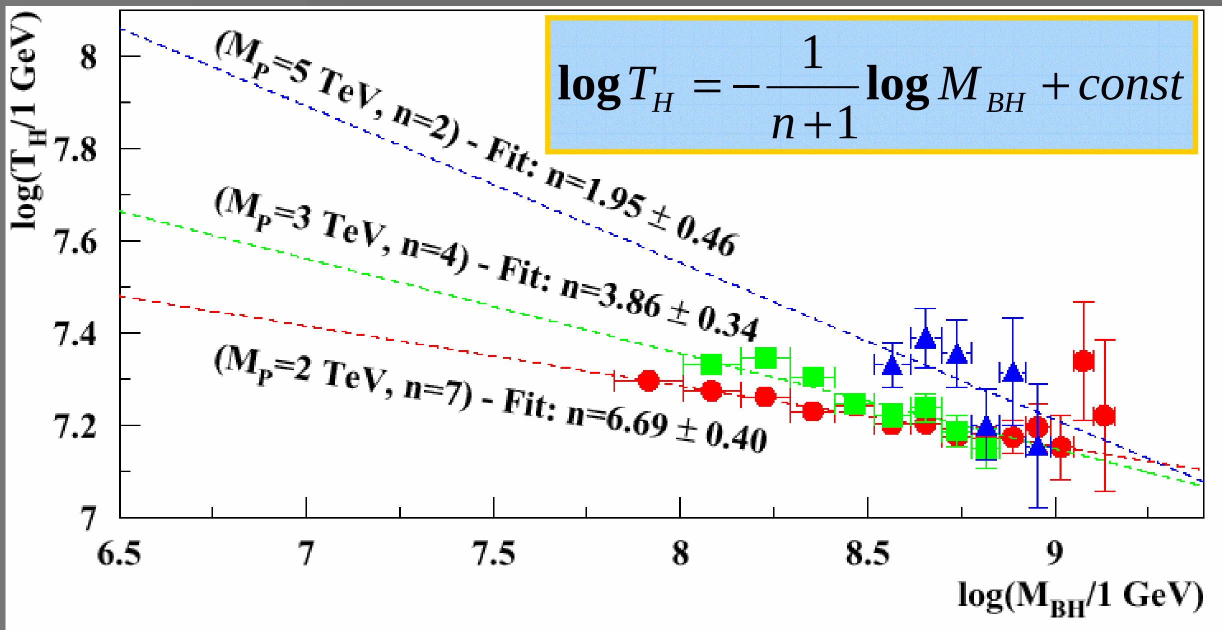
Wien's Law Test at the LHC



- Select events with high multiplicity ⟨N⟩>4, an electron or a photon, and low ME_T
- Reconstruct the BH mass (dominated by jet energy resolution, σ ~ 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

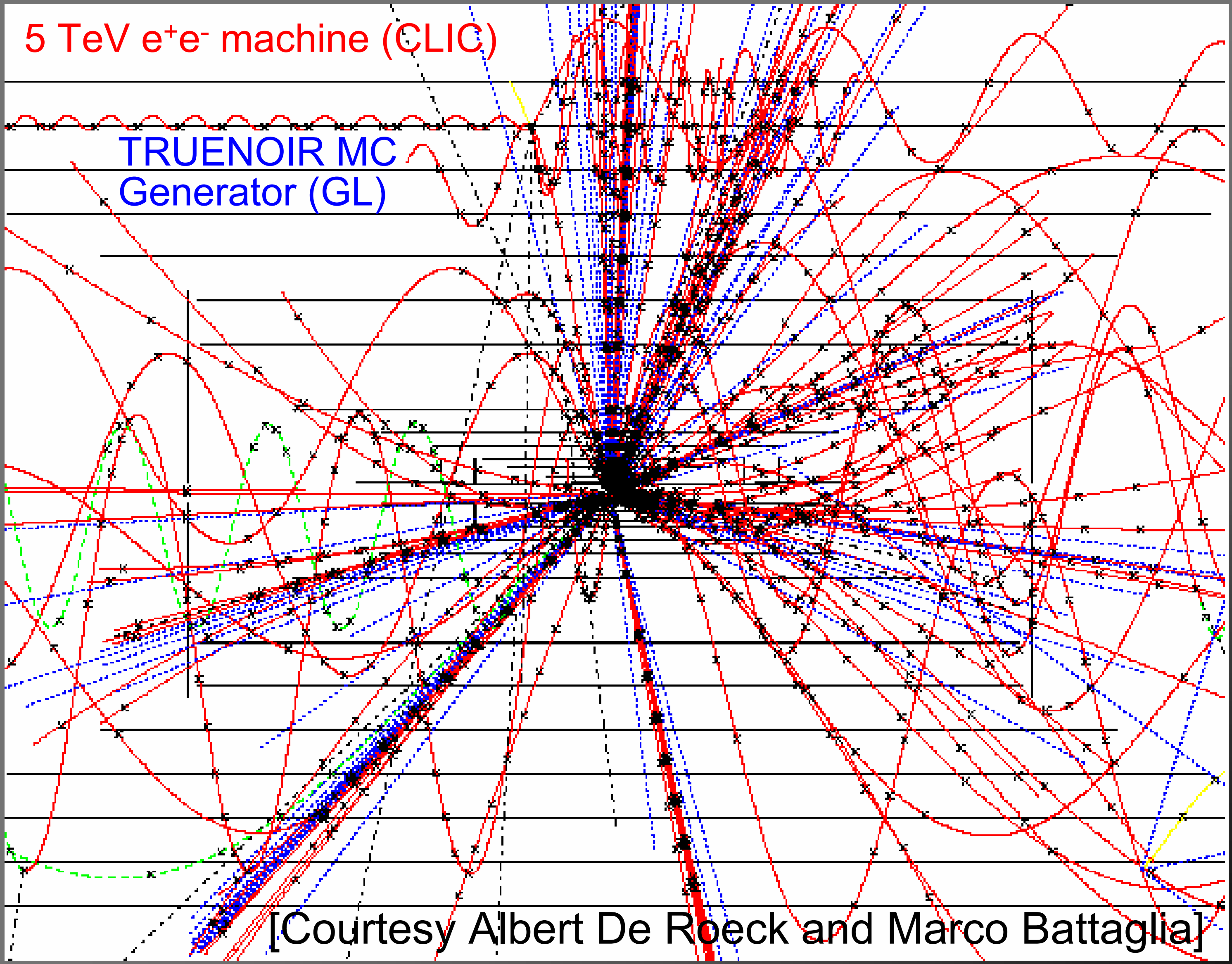
[Dimopoulos, GL, PRL **87**, 161602 (2001)]



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 one to measure 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 scale gravity

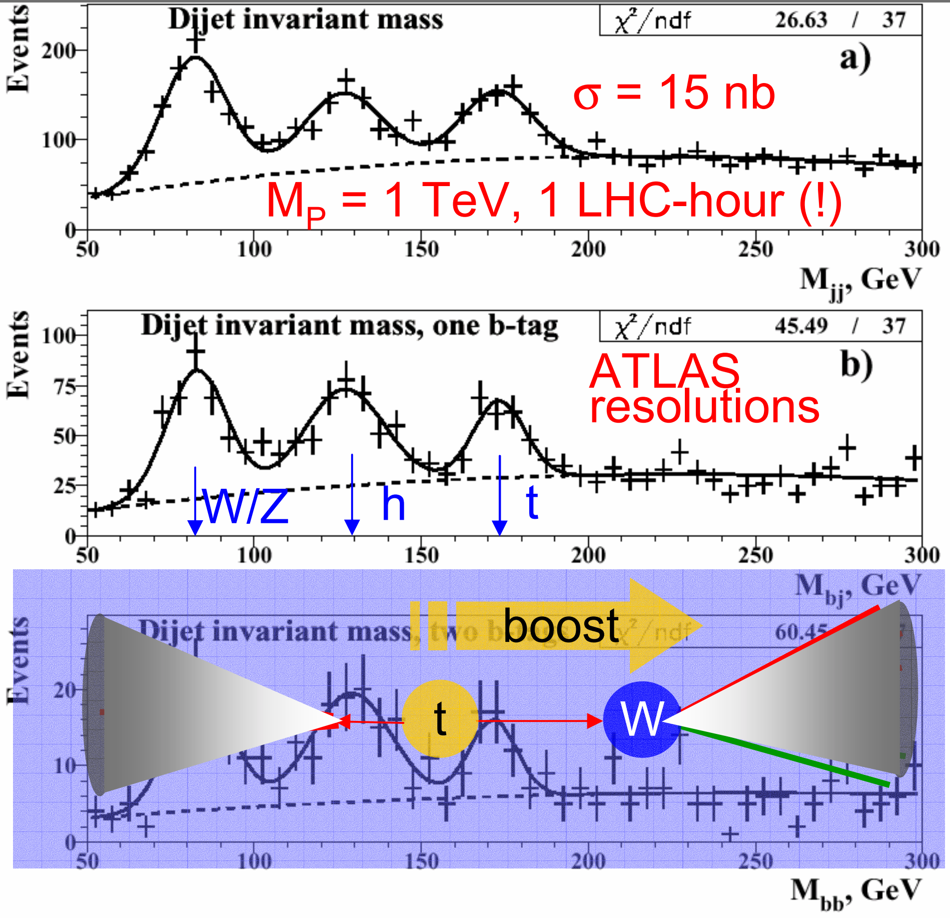
A Black Hole Event Display



New Physics 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 ~100 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