Collider Searches for Black Holes (particularly at CMS)

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Hengstberger Symposium "Extra Dimensions and Mini Black Holes"

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Outline

- Extra Dimensions: Recap
- Black Hole Production and Decay
- Randall-Sundrum Black Holes
- New Physics in Black Hole Decays
- Jet Suppression
- Conclusions

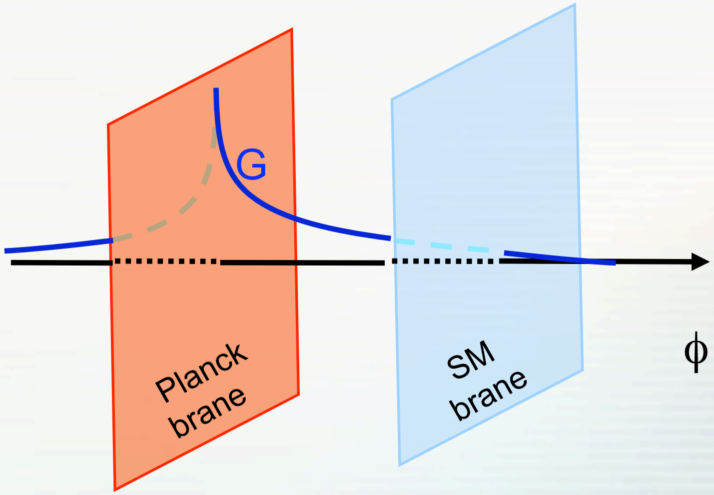
Extra Dimensions: a Brief Recap

ADD Paradigm:

- Pro: "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the "bulk" space
- Size of ED's (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- Con: Doesn't explain why ED are so large

RS Model:

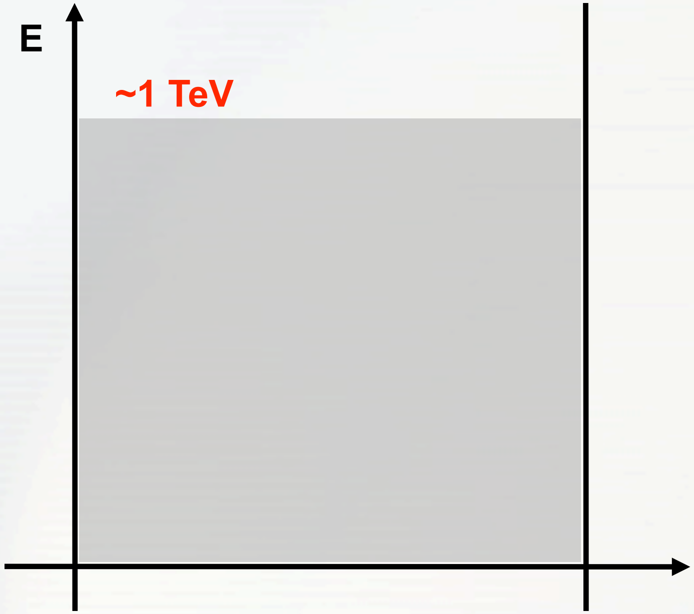
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

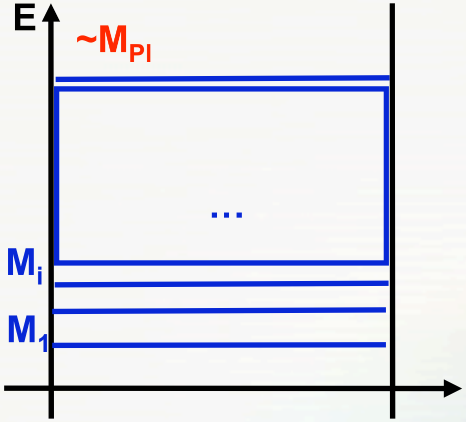
ADD Paradigm:

- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can’t resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by the large number of modes



RS Model:

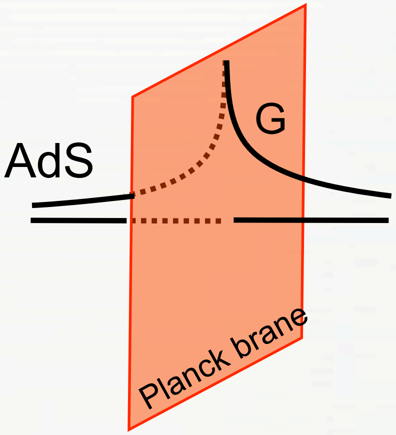
- “Particle in a box” with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for the zero mode; $1/\Lambda_\pi^2$ for the others



$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - –One + brane – no low energy effects
  - –Two + and – branes – TeV Kaluza-Klein modes of graviton
  - –Low energy effects on SM brane are given by Λ_π; for kr ~ 10, Λ_π ~ 1 TeV and the hierarchy problem is solved naturally



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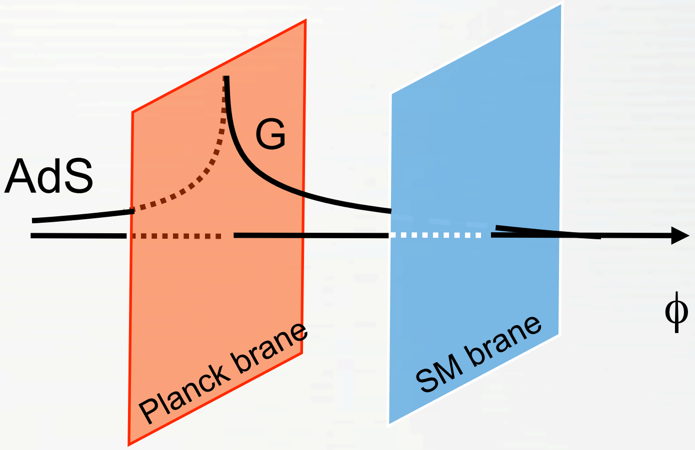

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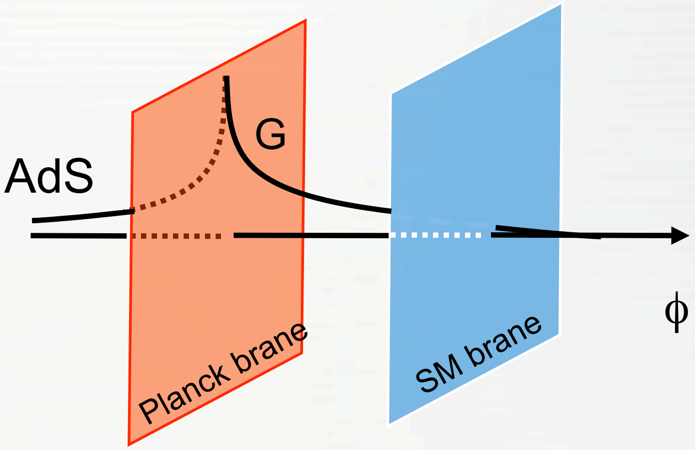
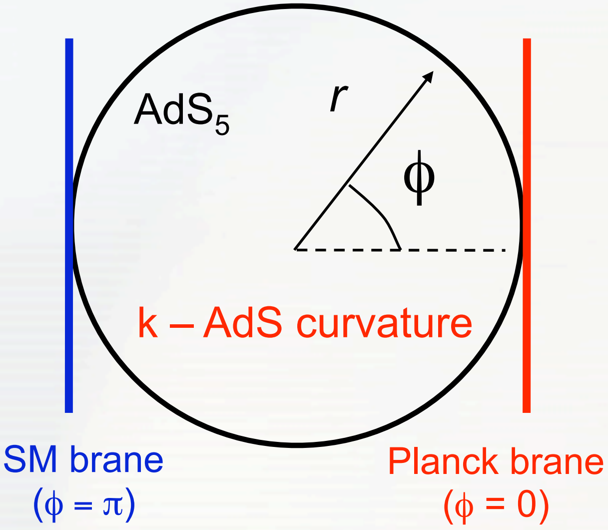




Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

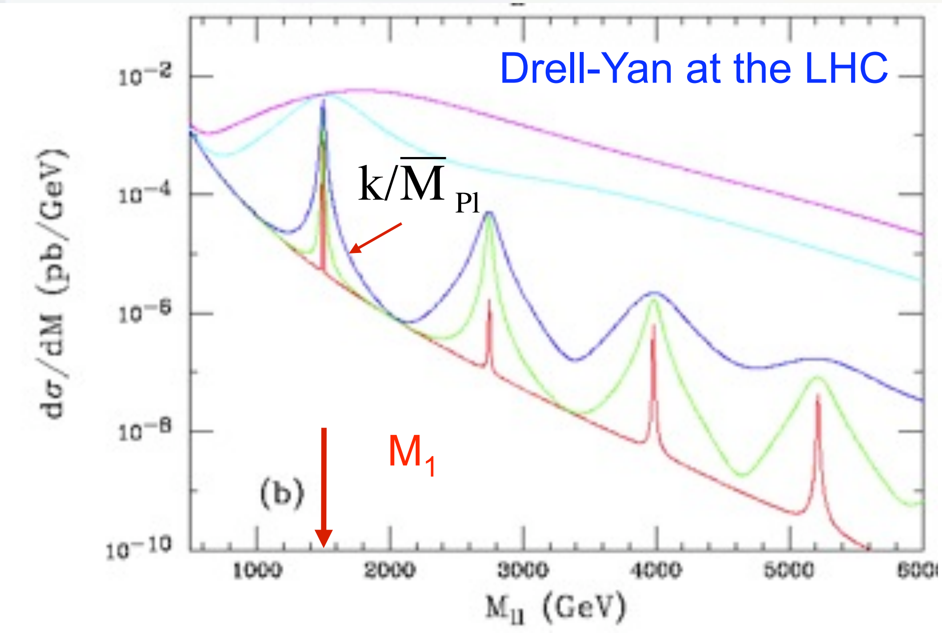
$$\Lambda_\pi = \overline{M}_{\mathrm{Pl}} e^{-kr\pi}$$

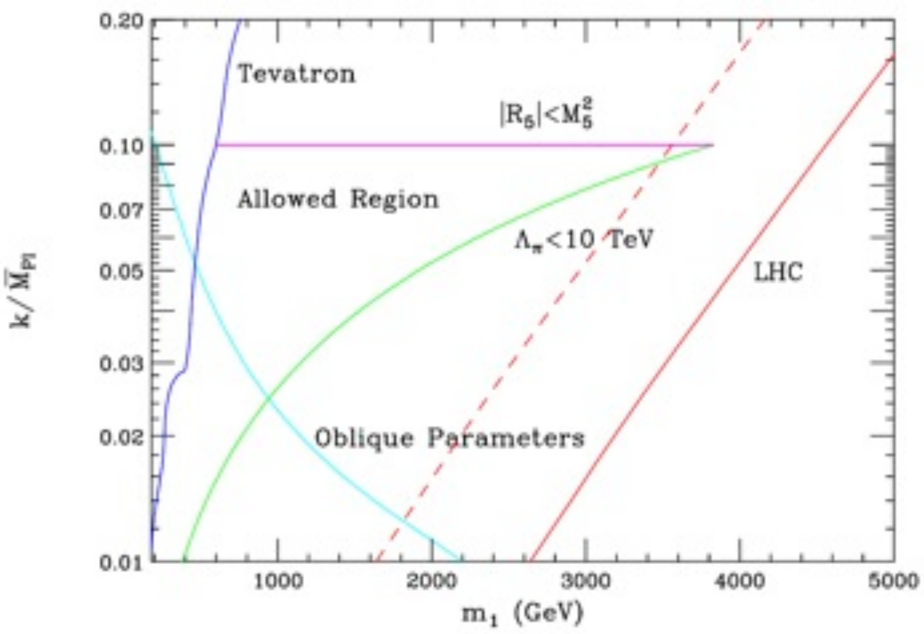
Reduced Planck mass:

$$\boxed{\overline{M}_{\mathrm{Pl}} \equiv M_{\mathrm{Pl}}/\sqrt{8\pi}}$$

Randall-Sundrum Model Observables

- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{\rm Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{\rm Pl} \leq 0.10$ is the expected range
- Gravitons are narrow

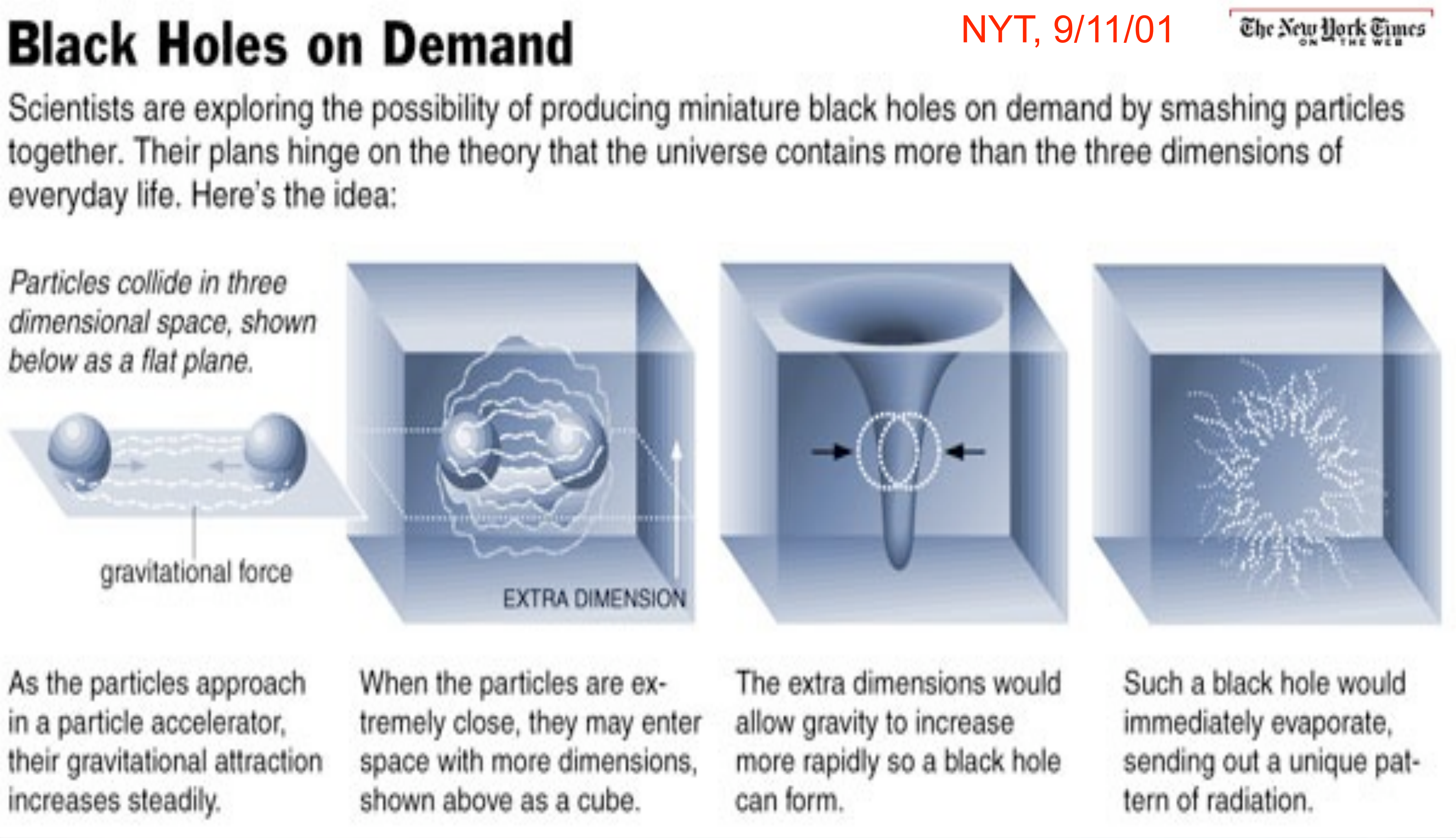




Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

Black Holes at the LHC?

Black Holes on Demand



NYT, 9/11/01

The New York Times ON THE WEB

Black Holes on Demand

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.

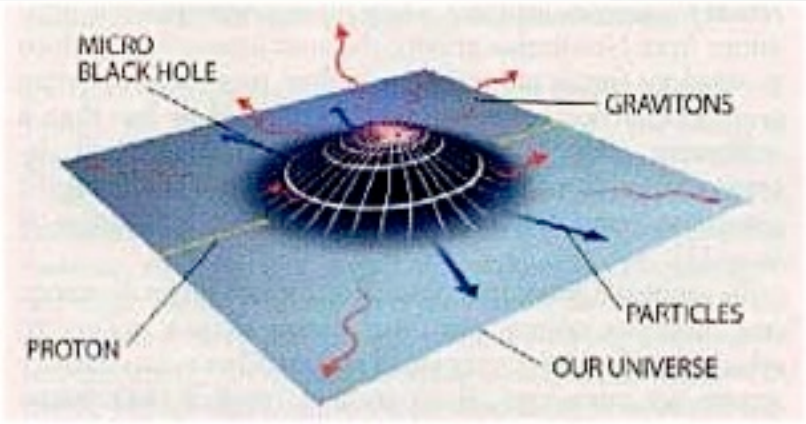
The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

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

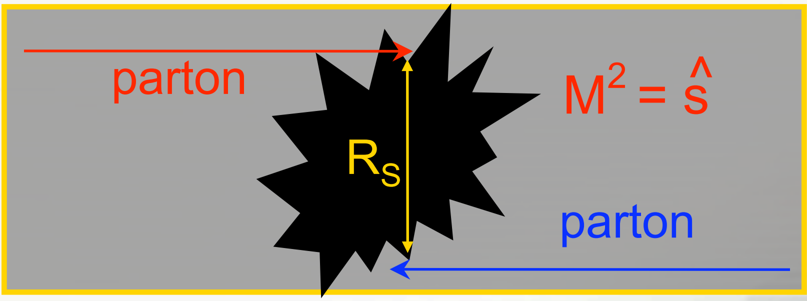
BH at LHC: Theoretical Framework

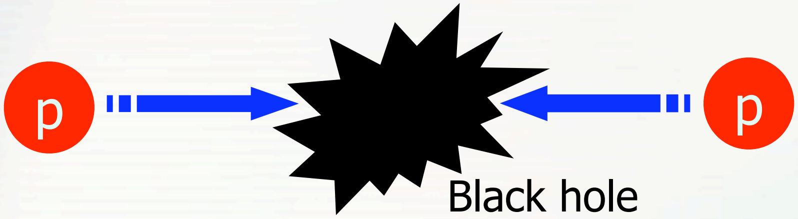
- Based on the work done with Dimopoulos a few years ago [PRL **87**, 161602 (2001)] and a related study by Giddings/Thomas [PRD **65,** 056010 (2002)]
- Extends previous, more theoretical studies by Argyres/Dimopoulos/March-Russell [PL **B441**, 96 (1998)], Banks/Fischler [JHEP, **9906**, 014 (1999)], Emparan/ Horowitz/Myers [PRL **85**, 499 (2000)] 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!
- Also true in the RS models where Λ_π is the characteristic scale

Artist's view:



Cross section is given by a black disk approximation:





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

Comparable with that of the top-quark pair production!

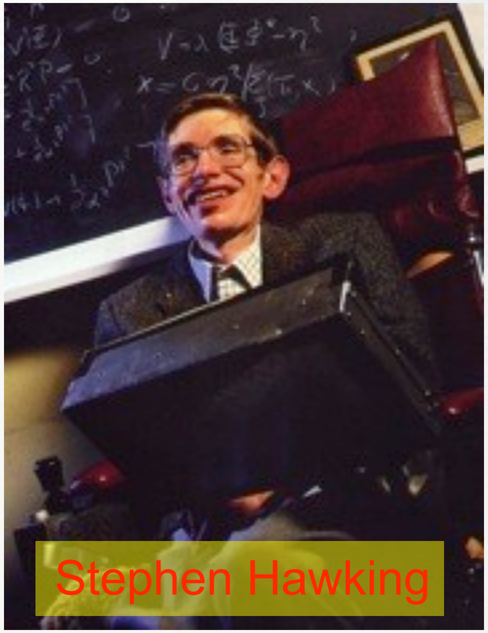
Assumptions and Approximations

- 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
- Many subsequent publications studied those, but it's not really strict science due to unknown quantum gravity (QG) corrections
- 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 $M_{BH} \gg M_{Pl}$; only consider $M_{BH} > M_{Pl}$
- Clearly, these are important limitations, but there is no way around them without the knowledge of QG

Black Hole Evolution

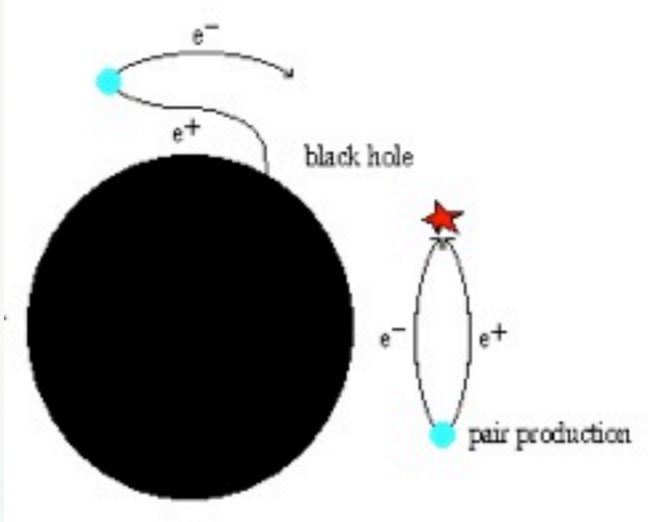
- Naïvely, black holes would only grow once they are formed
- In 1975 Steven Hawking showed that this is not true [Commun. Math. Phys. **43**, 199 (1975)], as the black hole can evaporate by emitting pairs of virtual photons at the event horizon, with one of the pair escaping the BH gravity
- These photons have a perfect black-body spectrum with the *Hawking temperature*:

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



Stephen Hawking

- In natural units ($\hbar = c = k_B = 1$), one has the following fundamental relationship: $R_S T_H = (4\pi)^{-1}$
- If T_H is high enough, massive particles can also be produced in evaporation
- 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 model of quantum gravity we know of: string theory



Black Hole Evaporation

- As the BH evaporates, its mass becomes smaller, R_S decreases, and Hawking temperature increases
- Consequently, as the BH evolves, the radiation spectrum becomes harder and harder, until the BH evaporates completely in a giant flash of light
- Ergo, the BH spends most of its time at the lowest temperature, when the radiation is soft

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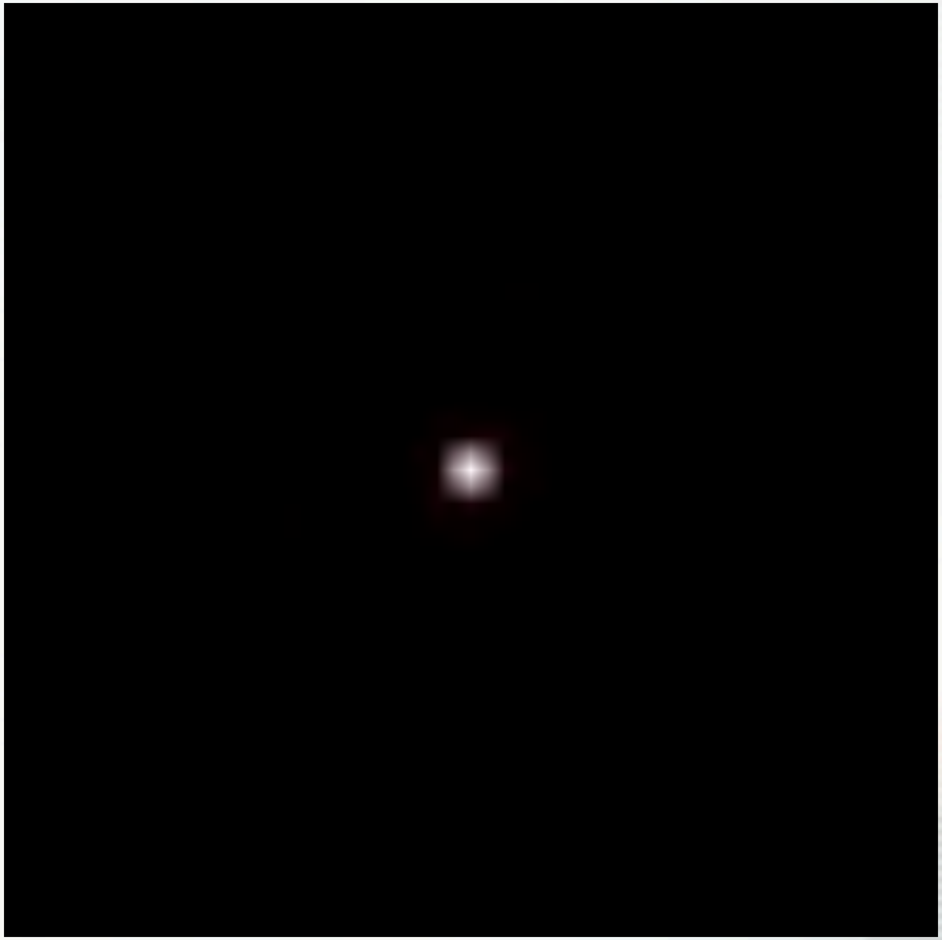

Looking for Black Holes

- 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 BH's (from slightly above the Oppenheimer-Volkov 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 ~ 100 nK, λ ~ 100 km, P ~ 10^{-27} W: ~10^{14} years for a single γ to reach us!)
- The best indirect evidence so far is spectrum/periodicity in binary systems
- Astronomers are also looking for "flares" of large objects falling into supermassive BH's
- LIGO/VIRGO hope to observe gravitational waves from black hole collisions

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

Black Hole Production

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

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

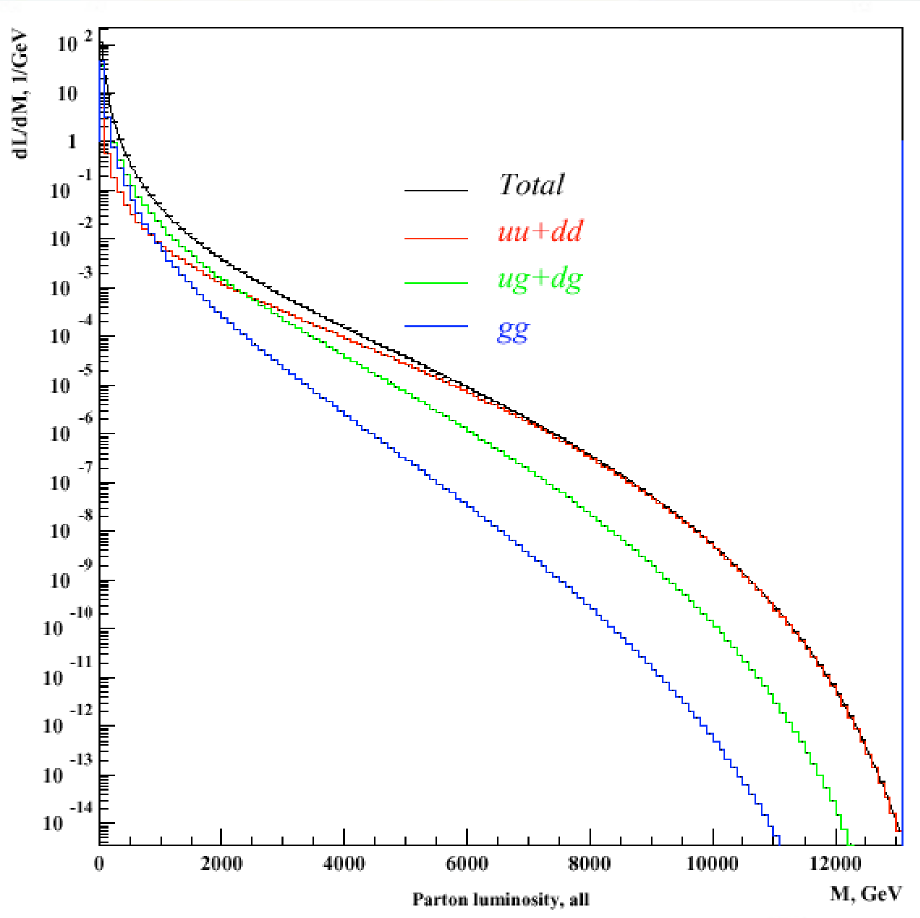
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

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

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

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from quark-quark interactions (BH w/ color, B ≠ 0)

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



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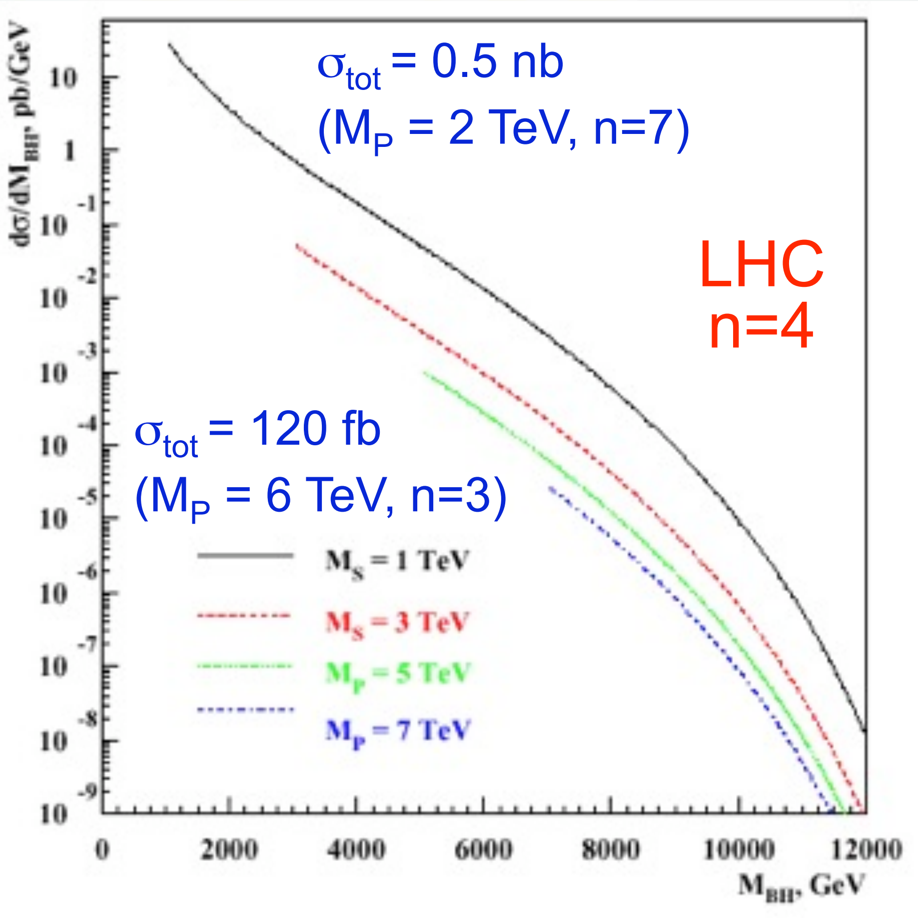


σ_{tot} = 0.5 nb
(M_P = 2 TeV, n=7)

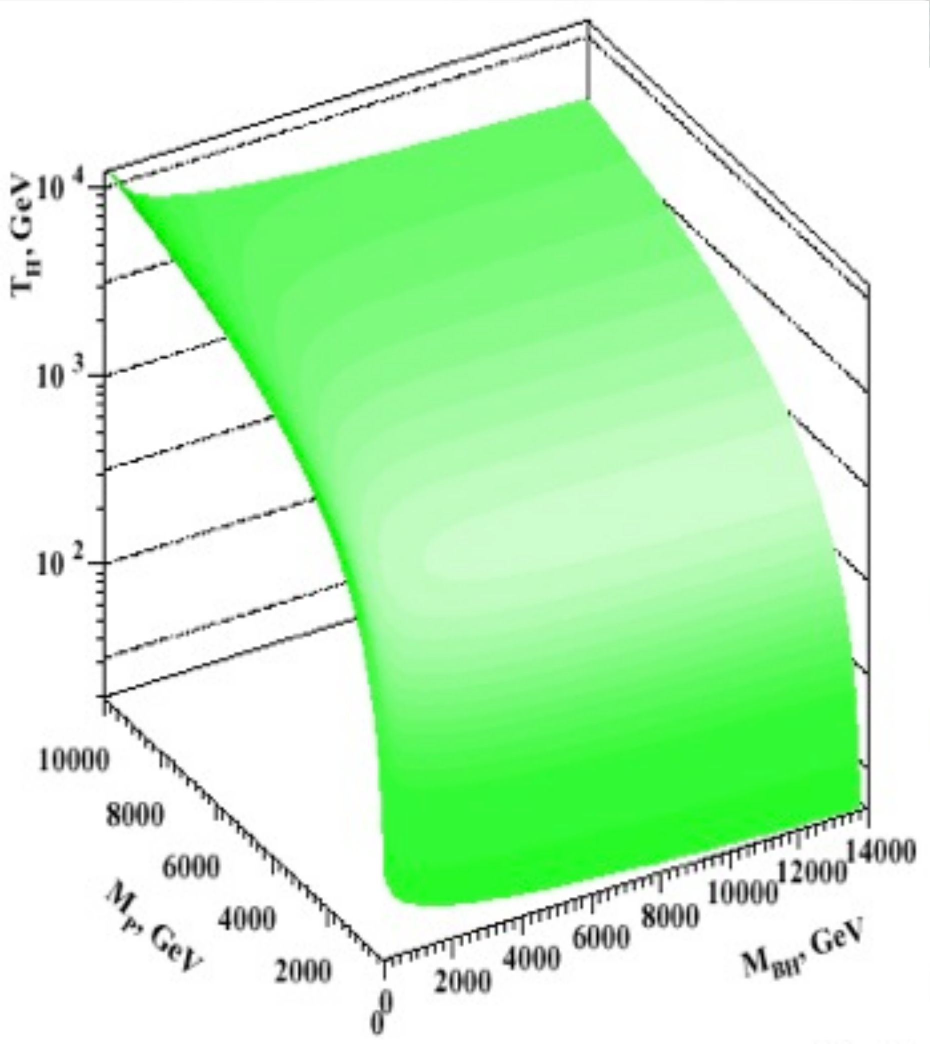
LHC
n=4

σ_{tot} = 120 fb
(M_P = 6 TeV, n=3)

Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$ (in natural units $\hbar = c = k = 1$)
- BH radiates mainly in our 3D world: Emparan/Horowitz/Myers [PRL **85**, 499 (2000)]
    - $\lambda \sim 2\pi/T_H > R_S$; 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, $\ell^\pm$, and ν ~2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

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



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

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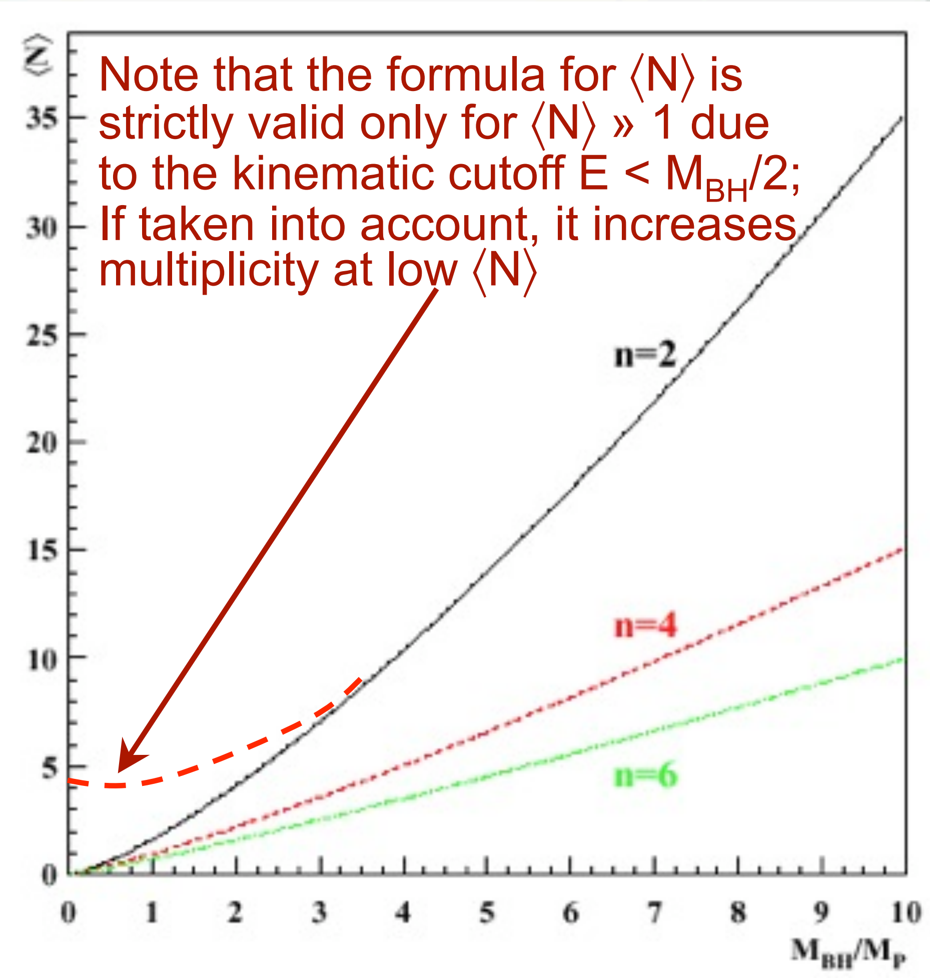
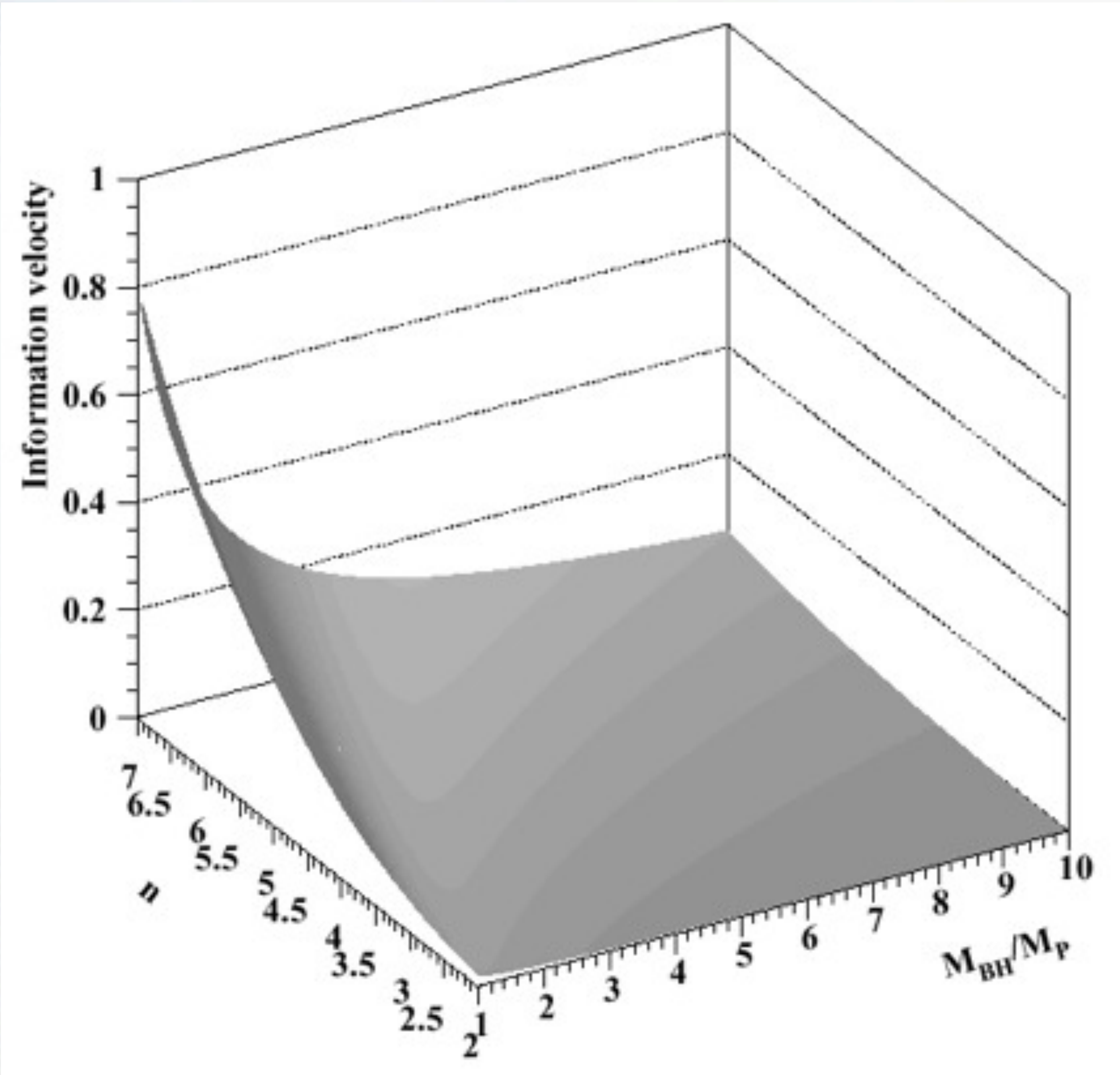
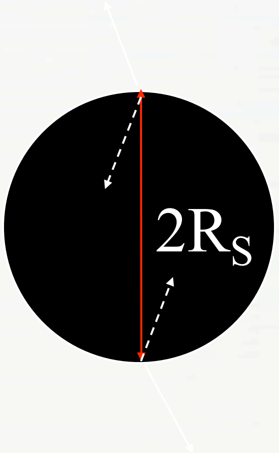


Note that the formula for $\langle N\rangle$ is strictly valid only for $\langle N\rangle \gg 1$ due to the kinematic cutoff $E < M_{BH}/2$; If taken into account, it increases multiplicity at low $\langle N\rangle$

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

Information Paradox?



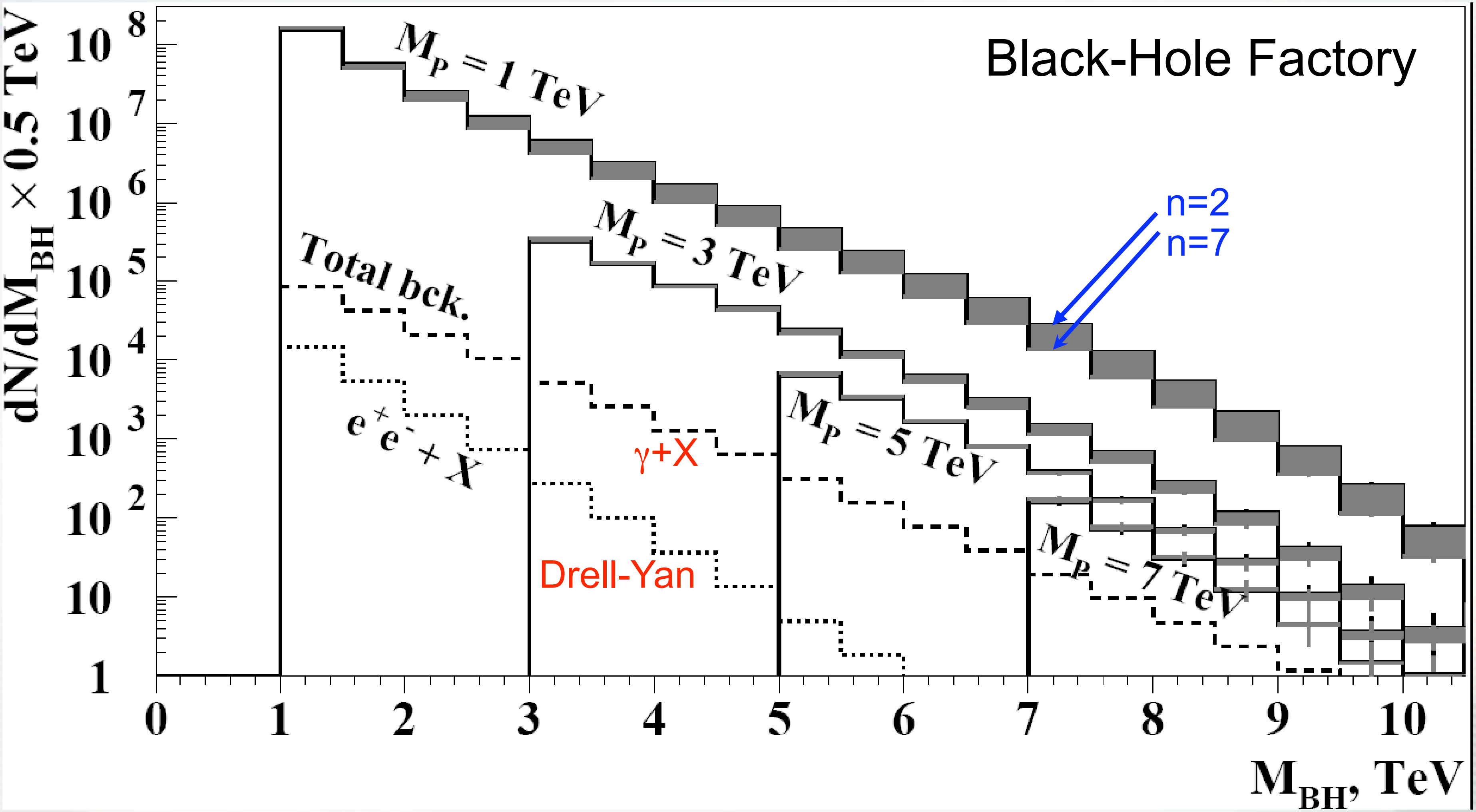


$\beta \sim 2R_S/\tau$

Necessary condition for solving the information paradox (semi-classically): $\beta < 1$

Black Hole Factory

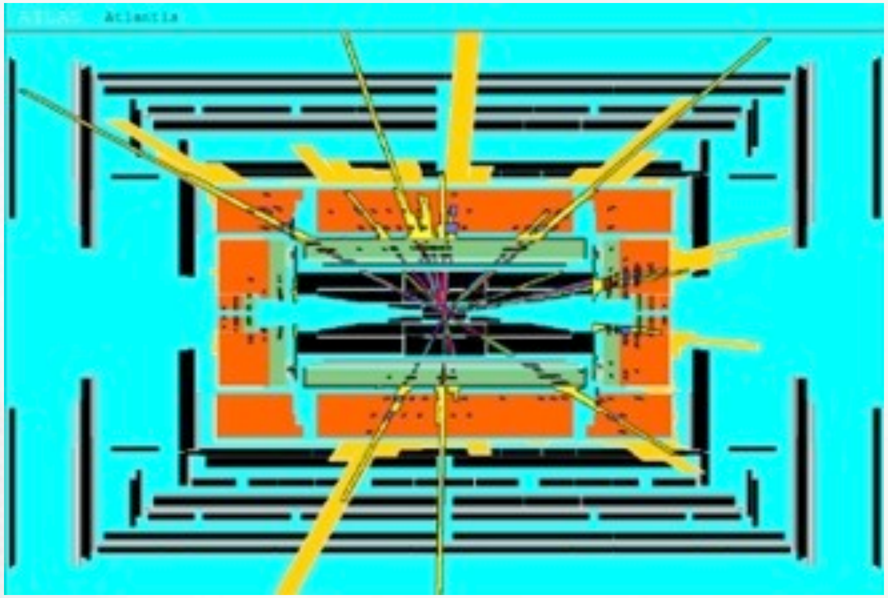
Dimopoulos, GL [PRL **87**, 161602 (2001)]



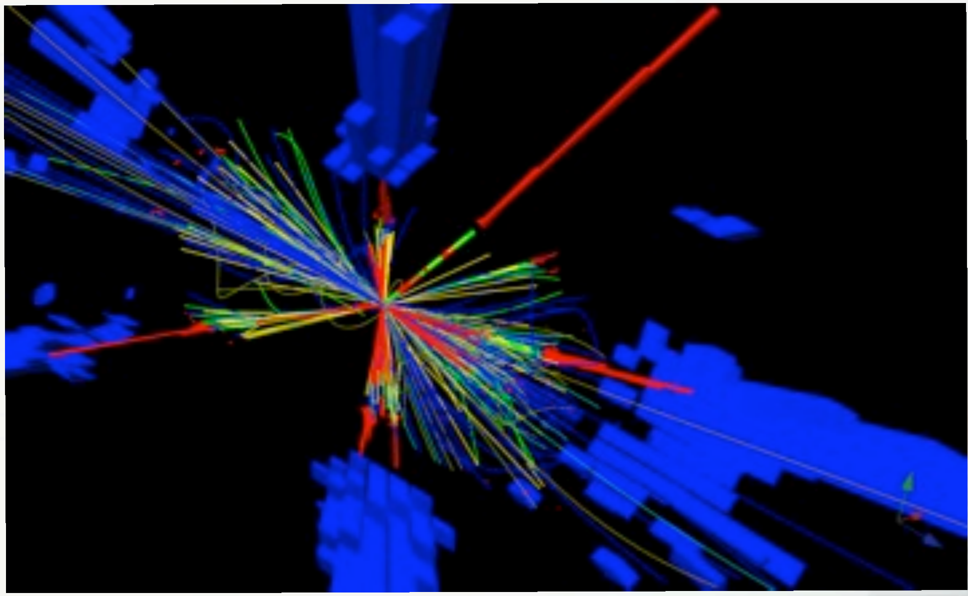
Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

Black Hole Events

- Detailed studies ongoing in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR (GL)/CHARYBDIS/CATFISH (Cavaglia) /BLACKMAX (Dai et al.)
  - The hunt is going on!



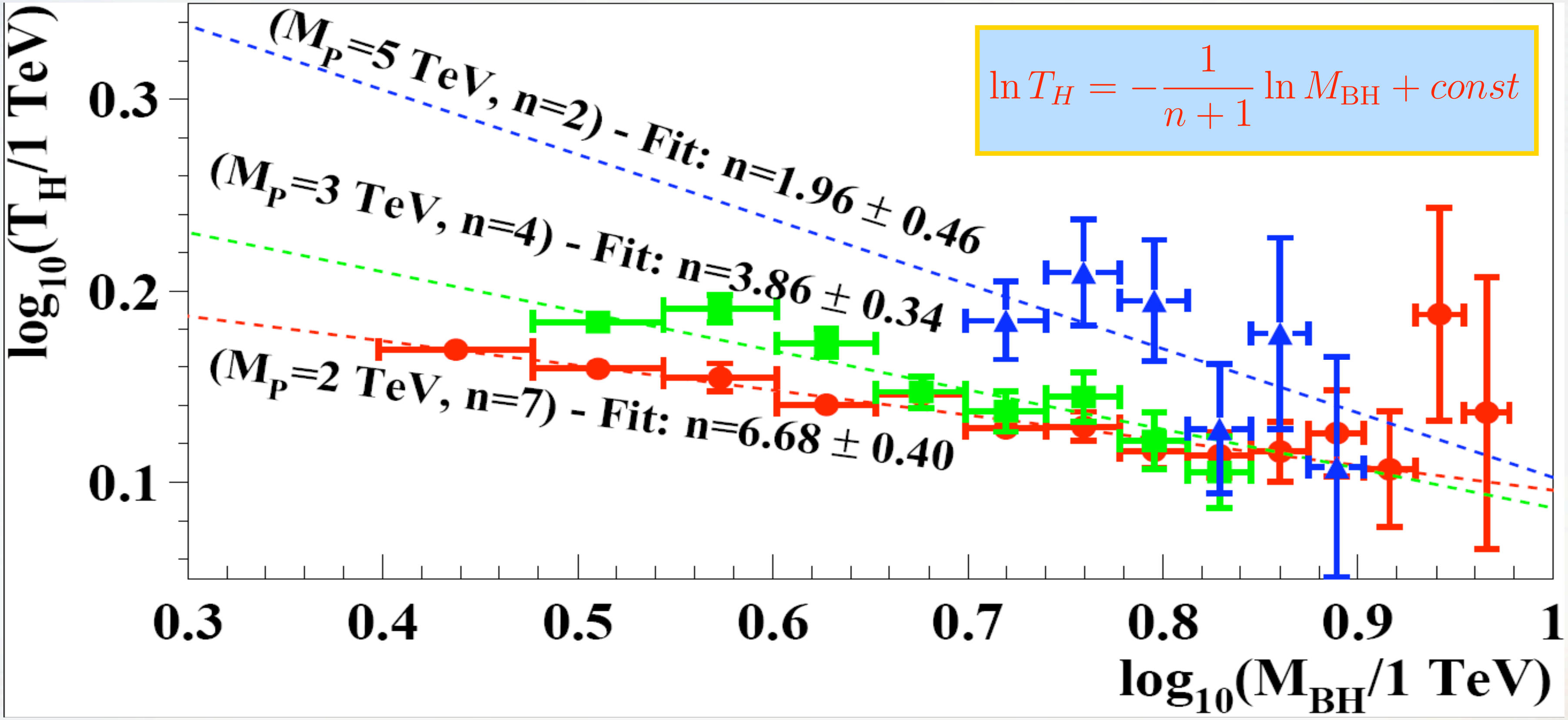
Simulated black hole event in the ATLAS detector



Simulated black hole event in the CMS detector

Shape of Gravity at the LHC

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



- 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

Randall-Sundrum Black Holes

- Not nearly as studied as BH in large ED
  - Originally suggested in Anchordoqui, Goldberg, Shapere [PRD **66**, 024033 (2002)]
  - A few authors extended work to various cases: Rizzo [JHEP **0501**, 28 (2005); hep-ph/0510420; hep-ph/0603242]; Stojkovic [PRL **94**, 011603 (2005)]
  - The event horizon has a pancake-like shape (squashed in the 5th dimension by $e^{-k\pi r}$)
- Nevertheless, the comparison with the ADD BH is trivial, GL [J. Phys. **G32**, R337 (2006)]
  - If $R_S e^{-k\pi r} << \pi r$ the BH is still "small" and can be treated as a 5D BH in flat space (ignoring the AdS curvature at the SM brane $\sim k^2 << 1$)
  - For BH production, Λ_π in the RS model plays the same role as the fundamental Planck scale M_D in the ADD model
  - Recent paper by Meade/Randall [arXiv:0708.3017] used a different characteristic scale: $\overline{M}_{\rm Pl} e^{-k\pi r}$, which resulted in a more conservative cross section estimate

RS to ADD Mapping

- Unlike the ADD, the 5D Planck scale, M, is of order of M_{Pl}:

$$M_{Pl}^2 = \frac{M^3}{k}\left(1 - e^{-2\pi k R_c}\right) \approx \frac{M^3}{k} \sim M^2$$

- The Schwarzschild radius: $R_S = \frac{1}{\pi M e^{-k\pi R_C}}\sqrt{\frac{M_{BH}}{3Me^{-k\pi R_C}}}$

- Given $M^3 \approx kM_{Pl}{}^2 = \Lambda_\pi{}^2 k e^{2\pi k R_C}$, $R_S = \frac{1}{\sqrt{3}\pi\Lambda_\pi}\sqrt{\frac{M_{BH}}{\tilde{k}\Lambda_\pi}} \sim \frac{1}{\Lambda_\pi}$,

  where $\tilde{k} \equiv k / \overline{M}_{Pl}$

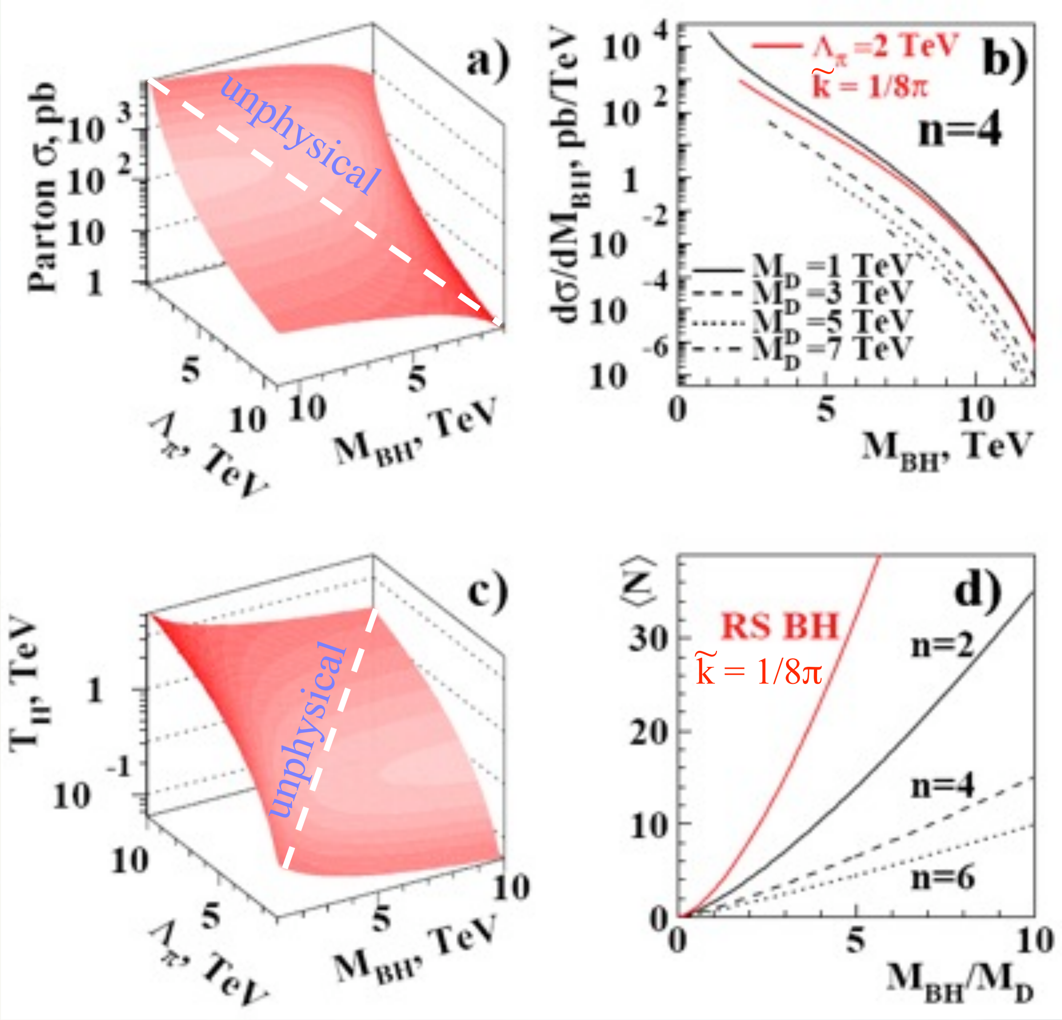
- Compare with: $R_S^{ADD}(5D) = \frac{1}{\sqrt{\pi} M_D}\sqrt{\frac{8M_{BH}}{3M_D}}$

- Then if one sets $\Lambda_\pi = M_D$ and $k = 1/8\pi \approx 0.04$, the RS formula turns into the ADD one! Thus, the two cases are equivalent within the approximations we used!

- $T_H = 1/(2\pi R_S)$ (ADD formula in 5D)

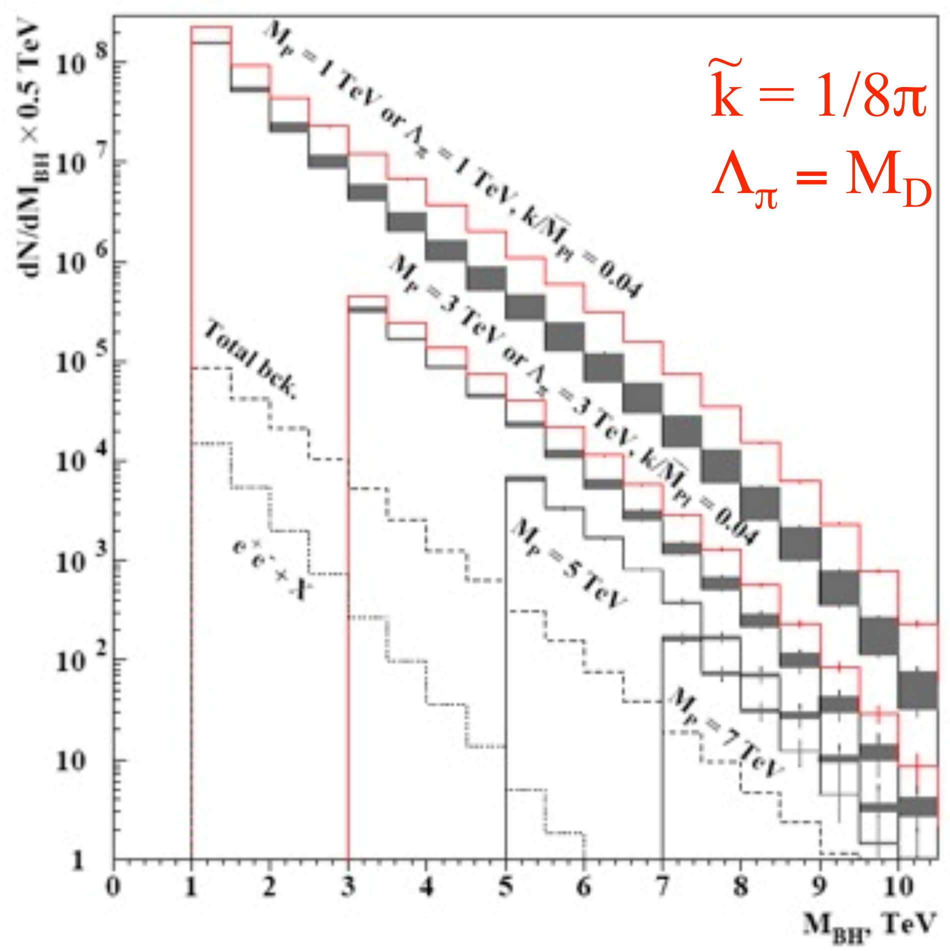
Searching for RS Black Holes

- More generally, the mapping between the ADD and RS parameters is as follows: $n = 1$, $M_D = \Lambda_\pi(8\pi\tilde{k})^{1/3}$
  - Note that generally, the BH production cutoff, if chosen equal to Λ_π, won't be equal to M_D
  - However, this parameter set is usable in the BH event generators to study arbitrary coupling values
- Cross section is somewhat higher for RS BH and they are colder than their ADD counterparts
- Consequently, the RS BH decay results in higher number of final state particles, making it easier to establish the signal



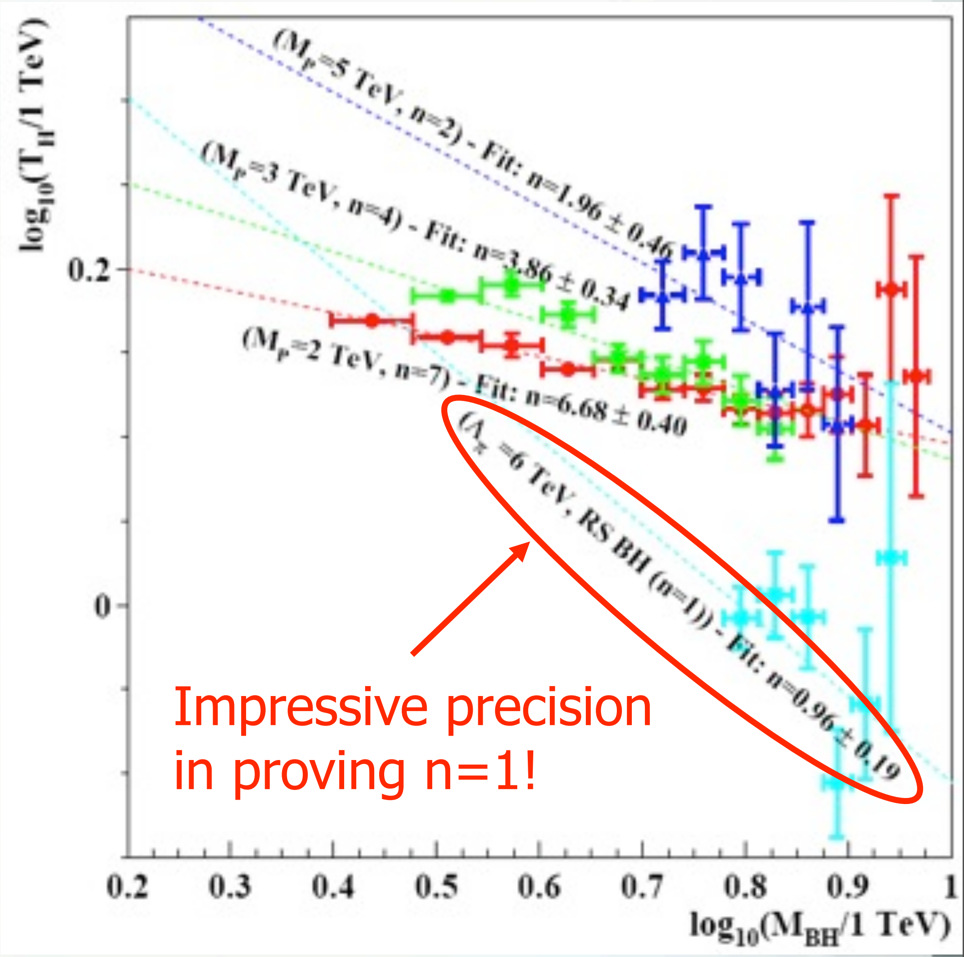
RS Black Holes: Wien's Law

100 fb^{-1} @ the LHC



$\tilde{k} = 1/8\pi$

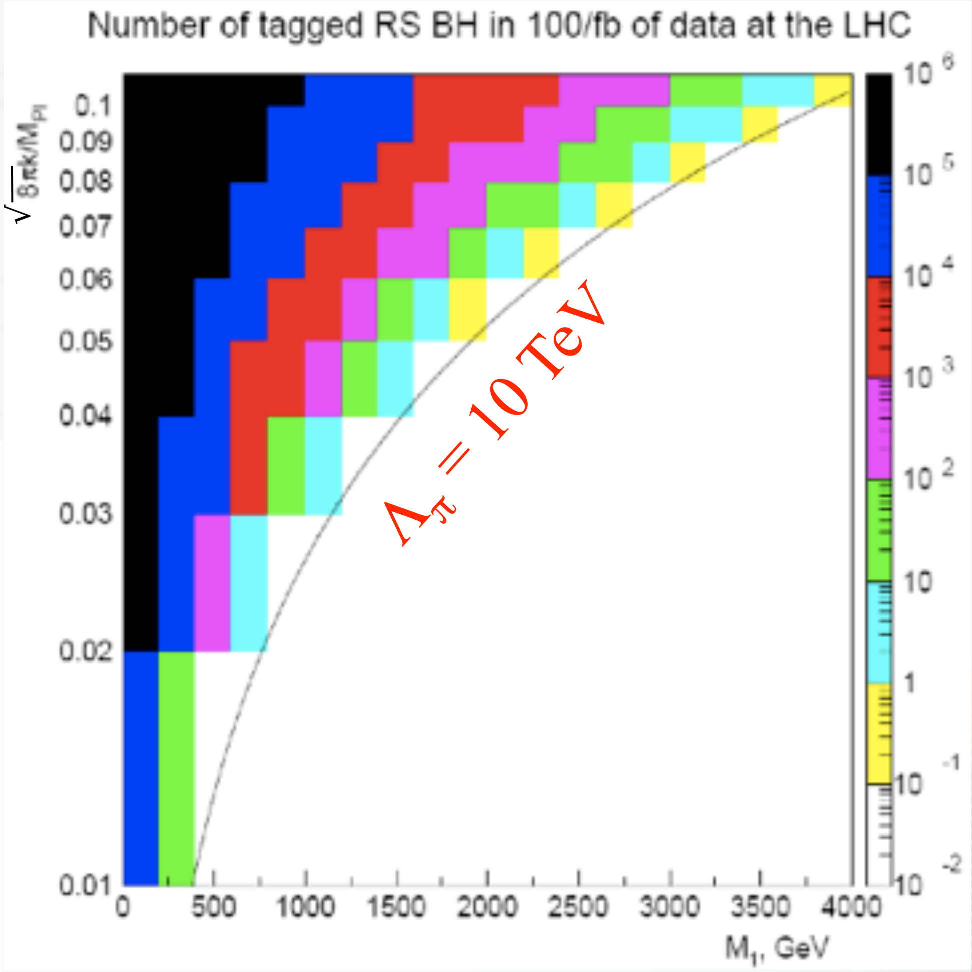
$\Lambda_\pi = M_D$

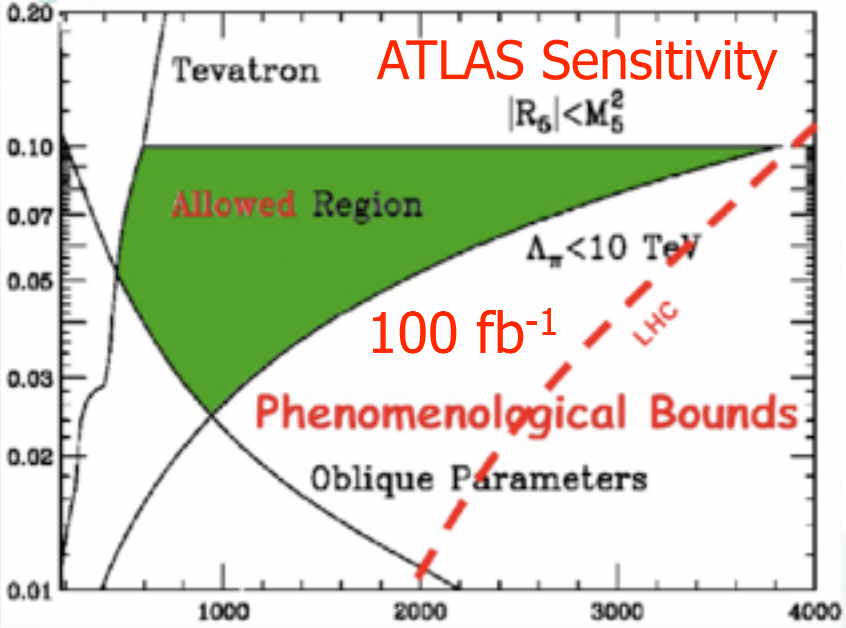


Impressive precision in proving n=1!

Probing Randall-Sundrum Model w/ BH

- In terms of probing $\tilde{k}$ vs. M_1, RS black holes would offer the entire allowed range to be probed with ~1 year at a nominal LHC luminosity
- Significant fraction of the allowed parameter space can be probed with just 1 fb^{-1} (up to M_1 ~ 3 TeV for $\tilde{k}$ = 0.1)
- The reach is fairly competitive with direct searches for RS gravitons in the dilepton/diphoton mode


Number of tagged RS BH in 100/fb of data at the LHC



Kerr Black Holes

- Black holes produced in particle collisions generally have a non-zero angular momentum:

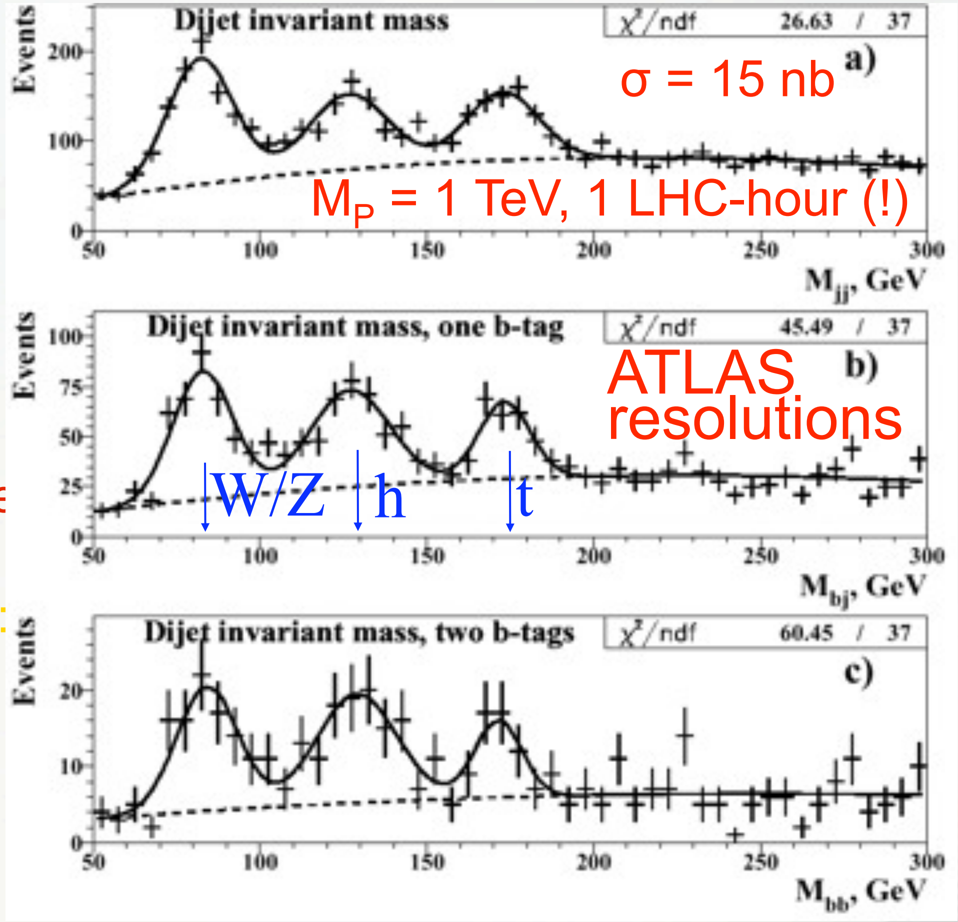
$$L = M_{\rm BH} R_S/2 = \frac{1}{2\sqrt{\pi}} \left[\frac{M_{\rm BH}}{M_{\rm Pl}}\right]^{\frac{n+2}{n=1}} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{n+1}}$$

- While L is small for $M_{BH} = M_{Pl}$, it grows with M_{BH} and can reach ~10 (in the units of $\hbar$), which is non-negligible
- Such a spinning black hole is described by the Kerr solution and has an enhanced emission of gravitons (super-radiance)
- Unfortunately, the grey-body factor for spin-2 particles for the case of Kerr black hole in d > 3 dimensions has not been calculated, so it’s hard to quantify the effect
- This is important for collider searches, as gravitons result in large missing transverse energy and reduced observable energy in the detector

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 $b\bar{b}$-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)]



σ = 15 nb

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

ATLAS resolutions

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

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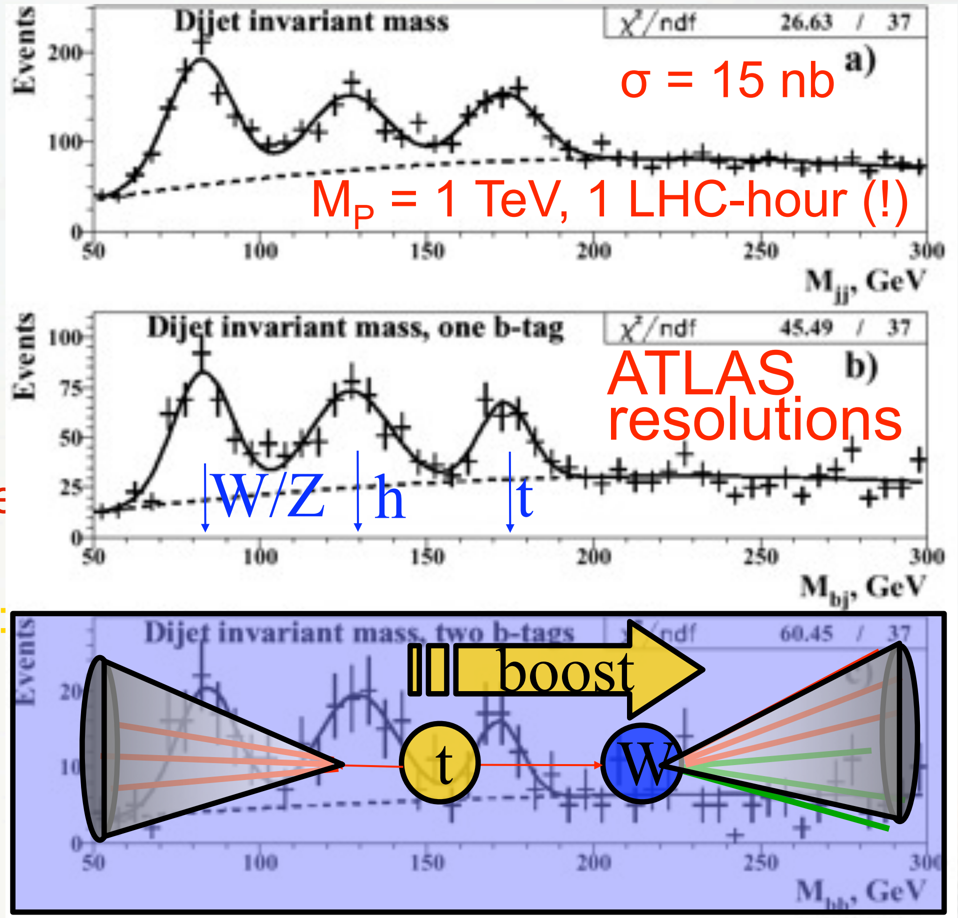

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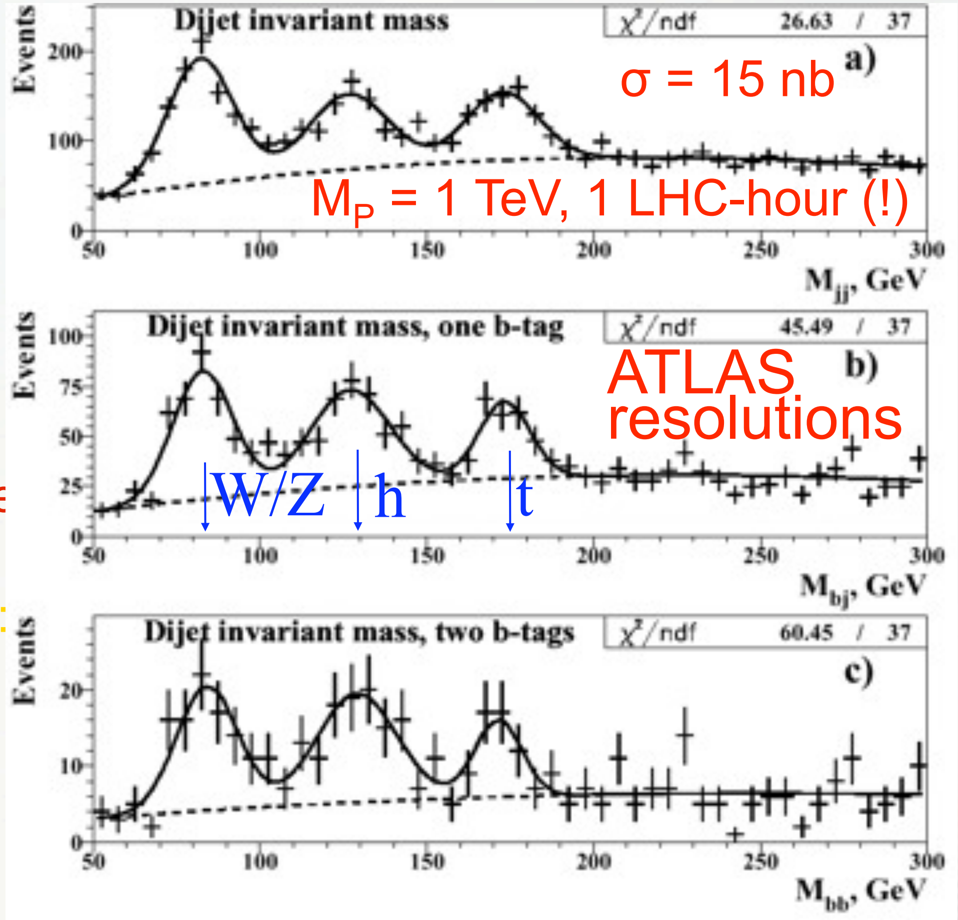

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ATLAS resolutions

W/Z

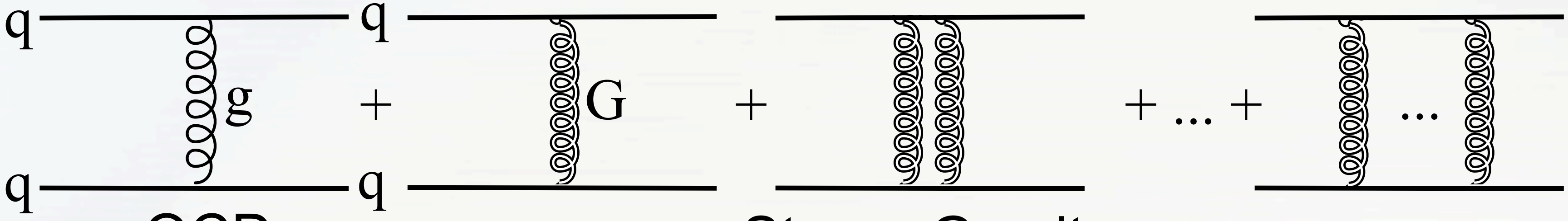
h

t

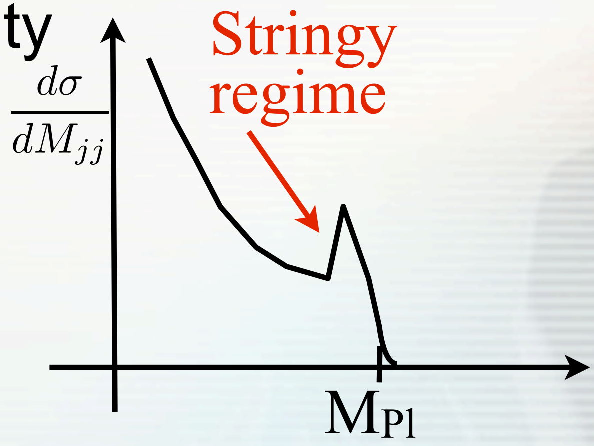
- An exciting prospect for discovery of other new particles w/ mass ~100 GeV!

Jet Production Suppression

- In the presence of black hole production, the dominant dijet production eventually will be suppressed [Banks & Fischler, hep-ph/9906038]
- Cross section argument: $\sigma \sim \frac{\alpha_S}{\hat{s}} \sim \frac{1}{M_{\rm Pl}^2}\left(\frac{\hat{s}}{M_{\rm Pl}^2}\right)^{\frac{1}{n+1}}$
  - Hence $\hat{s} \sim M_{\rm Pl}^2$
- Amplitude argument: dim. 6 $(\bar{\psi}\psi)^2\frac{g^2}{M^2}$ and 8 $(\bar{\psi}\partial\psi)^2\frac{g^2}{M_{Pl}^4}$

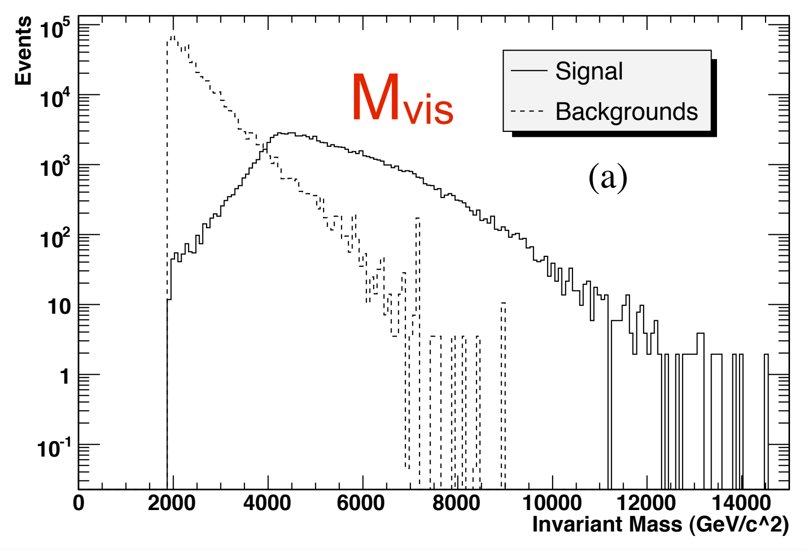


- Similar to generic compositeness, but compressed in energy due to the presence of dim-8 operators [GL, Strassler, work in progress]

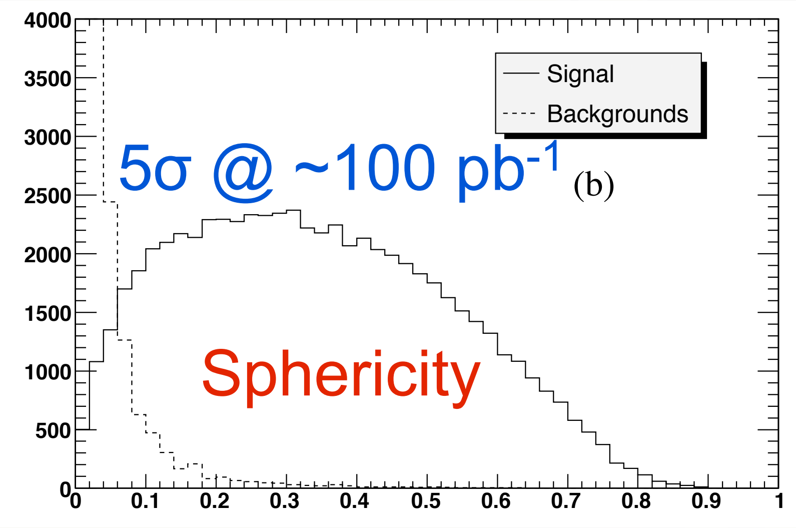


Black Holes in CMS

- Physics TDR (2006) 14 TeV study
- M_D = 2 TeV, M_{BH} > 4 TeV, n = 3
- Detailed 10 TeV studies are ongoing



M_{vis}

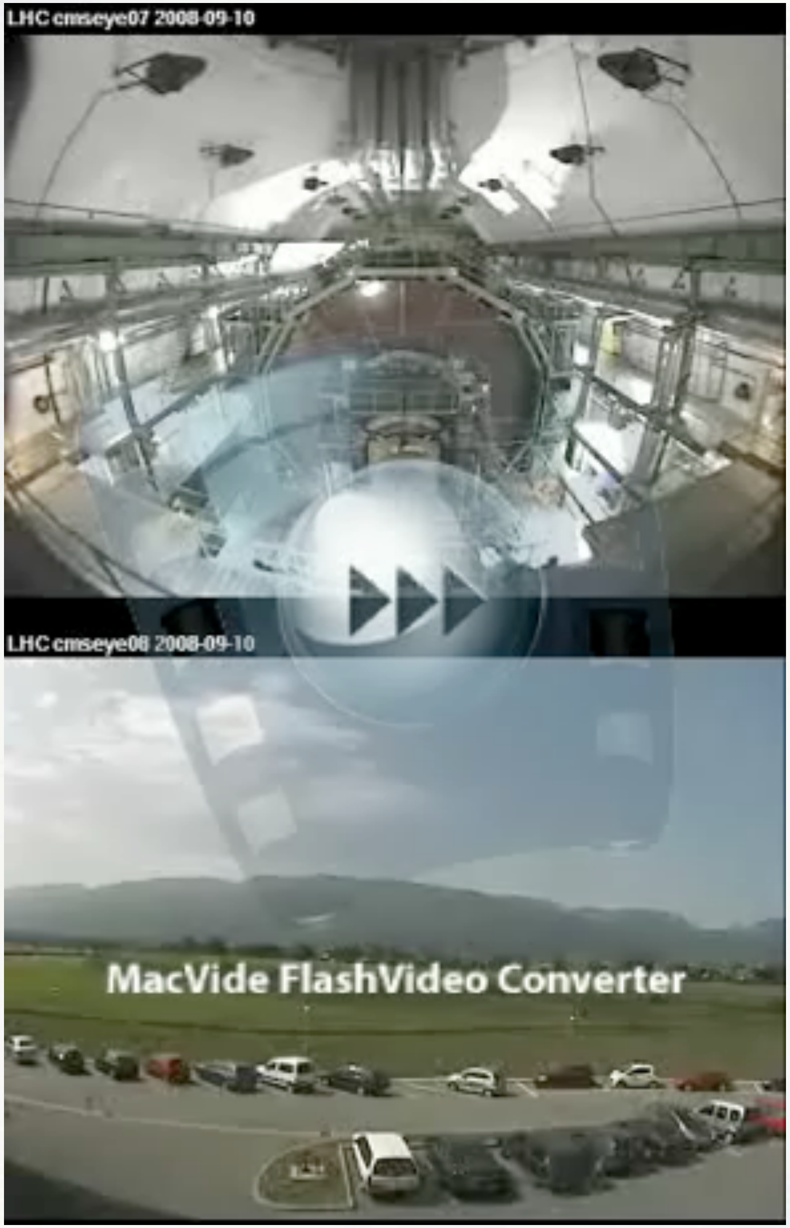


5σ @ ~100 pb^{-1}

Sphericity

Cut	Signal	tt+nJ	W+nj	Z+nJ	QCD Dijet	WW+nJ
Cross Section (pb)	18.85	371	896	781.84	33076.8	269.91
Events ($10\,fb^{-1}$)	188500	3.71×10^6	8.96×10^6	7.82×10^6	3.31×10^8	2.70×10^6
MInv > 2 TeV/c^2	18.71	13.29	6.53	3.85	2634.94	20.53
Tot. Multiplicity > 4	17.72	13.25	6.43	3.84	2613.18	20.42
Sphericity > 0.28	9.27	1.60	0.23	0.10	53.74	0.07
Final No.Events (10 fb-1)	92740	15990	2328	982	537391	740

More Black Holes in CMS



Thank You!