Mini-Review on Mini-Black Holes from the Mini-Big Bang

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RHIC

relativistic heavy ion collider

Statement on Committee Review of Speculative "Disaster Scenarios" at Brookhaven Lab's RHIC

October 6, 1999

Brookhaven National Laboratory has posted on its Web site a report by expert physicists who recently reviewed speculative disaster scenarios at the Relativistic Heavy Ion Collider.

The report summarizes technical discussions that conclude there is no danger of a "disaster" at RHIC.

In July 1999, Brookhaven Lab Director John Marburger convened a committee of distinguished physicists to write a comprehensive report on the arguments that address the safety of each of the speculative disaster scenarios at RHIC. The scenarios are:

- Creation of a black hole that would "eat" ordinary matter.
- Initiation of a transition to a new, more stable universe.
- Formation of a "strangelet" that would convert ordinary matter to a new form.

→ triggered more than 1000 papers (and a couple of lawsuits)

"We conclude that there are no credible mechanisms for catastrophic scenarios at RHIC," said committee chair Robert Jaffe, Professor of Physics and Director, Center for Theoretical Physics at Massachusetts Institute of Technology. "Accordingly, we see no reason to delay RHIC operation."

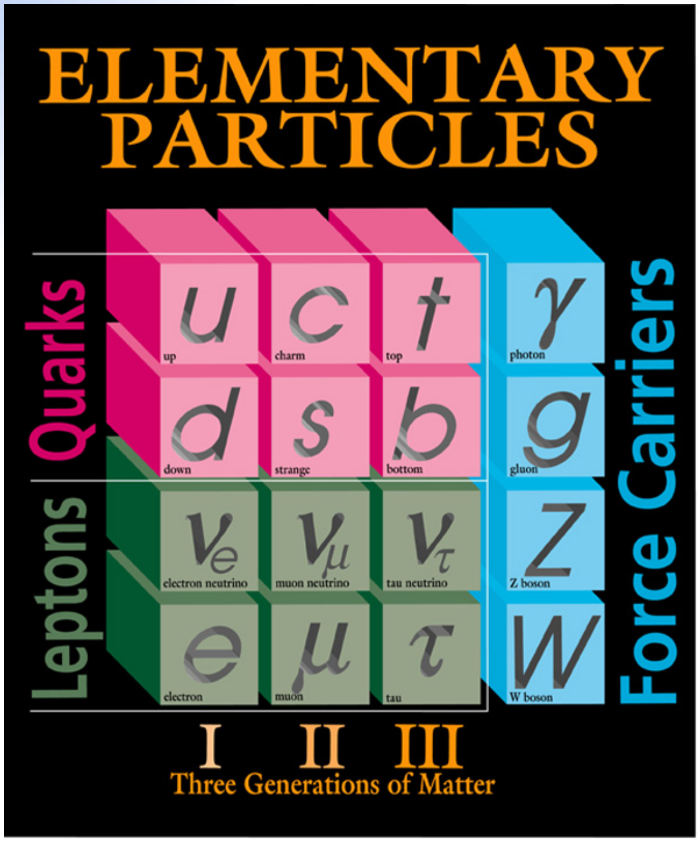
Thanks to

- Ben Koch (ITP, Germany)
- Ulrich Harbach (→ Patent lawyer)
- Christoph Rahmede (Sissa, Italy)
- Piero Nicolini (FIAS, Germany)
- Martin Sprenger (DESY, Germany)
- Sabine Hossenfelder (NORDITA, Stockholm)
- Stefan Hofmann (LMU Munich, Germany)

Based on: Phys.Rev.D66:101502,2002, **Phys.Lett.B548:73-76,2002, J.Phys.G28:1657-1665,2002**, **Phys.Lett.B566:233-239,2003**, **Int.J.Mod.Phys.D13:1453-1460,2004**, **JHEP 0510:053,2005**

Happy Birthday Takeshi!

The Standard Model



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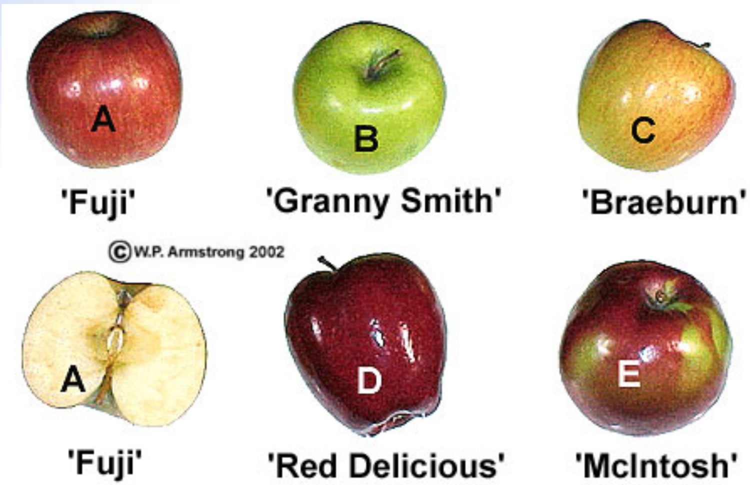
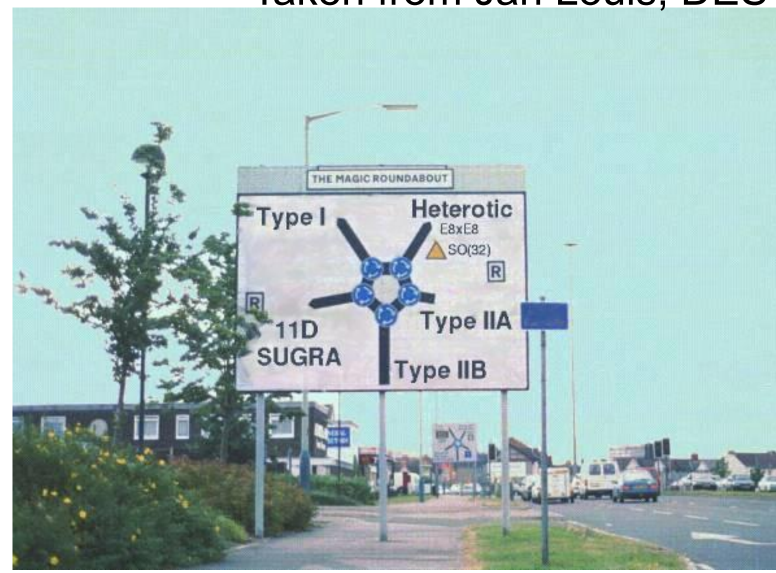
Carrier	Force	Group
γ photon	E&M	U(1)
g gluon	Strong	SU(3)
Z *W*	Weak	SU(2)

How to include gravity?

- String theory

Taken from Jan Louis, DESY





- Essential result: - More dimensions
  - Noncommutative space

Motivation for extra dimensions

- Kaluza-Klein (last century 1920ies)
- String theory/M-theory/SUGRA
  →10/11 dimensions
- Hierarchy problem can be solved
  (why is the Planck scale so much
  different from the electro-weak scale?!)
- Usually compactified extra-dimensions on
  radii $R \sim 1/M_{Planck}$ (hard to observe)

Extra dimensions

- Arkani-Hamed, Dvali, Dimopoulos (1998)
  → 1-7 large extra dimensions
  → only for gravity
  → R~ fm … mm (y_i are compactified)
  → new fundamental scale M_f~TeV

$$(x_0, x_1, x_2, x_3, y_1, \dots y_d) =: (x, y)$$

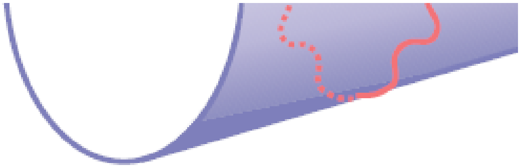
$$ds^2 = -(dx^0)^2 + \sum_\nu (dx^\nu)^2 + \sum_i (dy^i)^2$$

N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, PLB **429**, 263 (1998);

See also RS model → 1 warped extra dim. R~10 l_Planck

Einstein-Hilbert action

- Expansion of the metric (KK-towers)
- Integration of the d spatial dimensions



$$S_{d+4} = M_f^{d+2} \int R\sqrt{g}\,\mathrm{d}^4x\,\mathrm{d}^dy$$

$$= L^d M_f^{d+2} \int {}^{(4)}R\sqrt{{}^{(4)}g}\,\mathrm{d}^4x + \sum_{n>0}(\ldots)$$

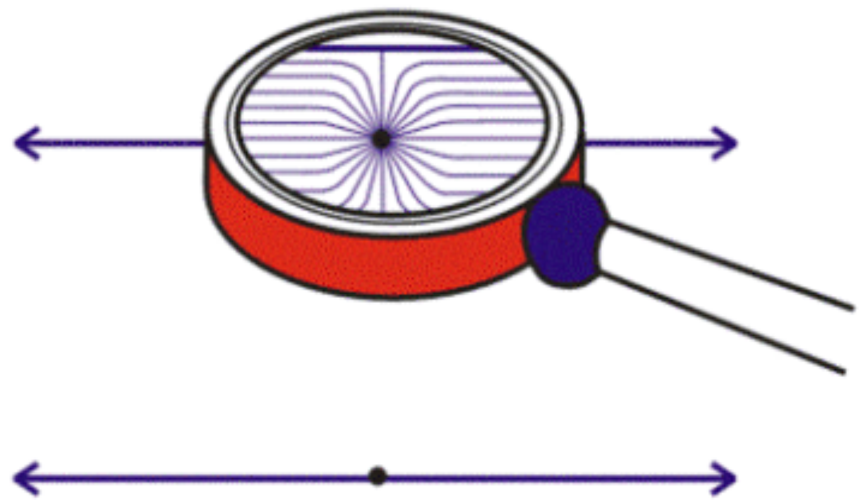
$$\Rightarrow m_p^2 = M_f^{d+2} L^d$$

Matching Newton 's law

Newton with **LXDs**:

r < R: $$\frac{V}{m} = \frac{1}{M_f^{d+2}} \frac{M}{r^{d+1}}$$

r > R: $$\frac{V}{m} \sim \frac{1}{M_f^{d+2} R^d} \frac{M}{r}$$



Newton as we know him:

$$\frac{V}{m} = \frac{1}{M_P^2} \frac{M}{r^1}$$

Matching:

$$M_p^2 = M_f^{2+d} R^d$$

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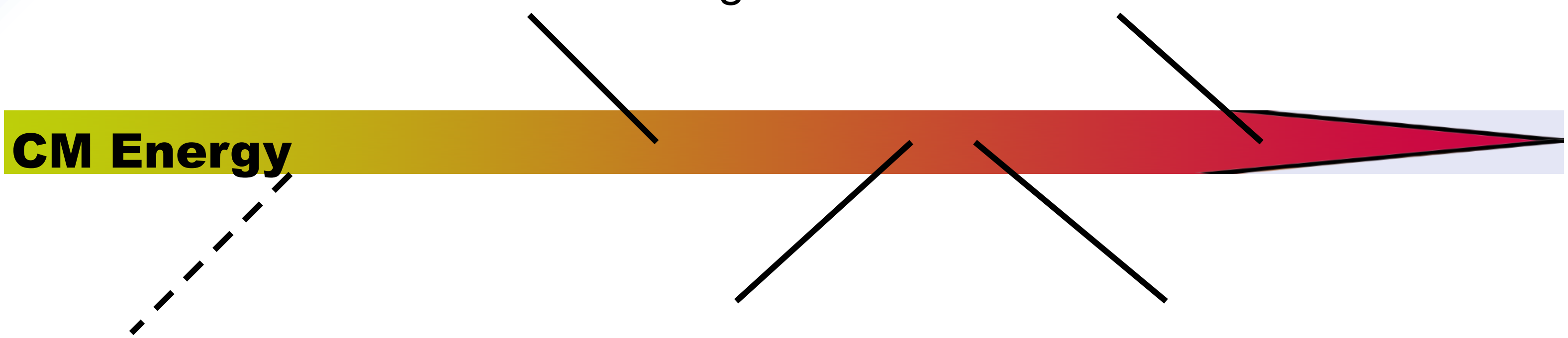
Observables of LXDs

MeV region
supernova and
neutron star cooling

400 TeV ultra high
energetic cosmic rays



Measuring
Newtons law

More than 2 XD
Newton checked to μm
range

TeV region todays
colliders

14 TeV Large
Hadron Collider LHC

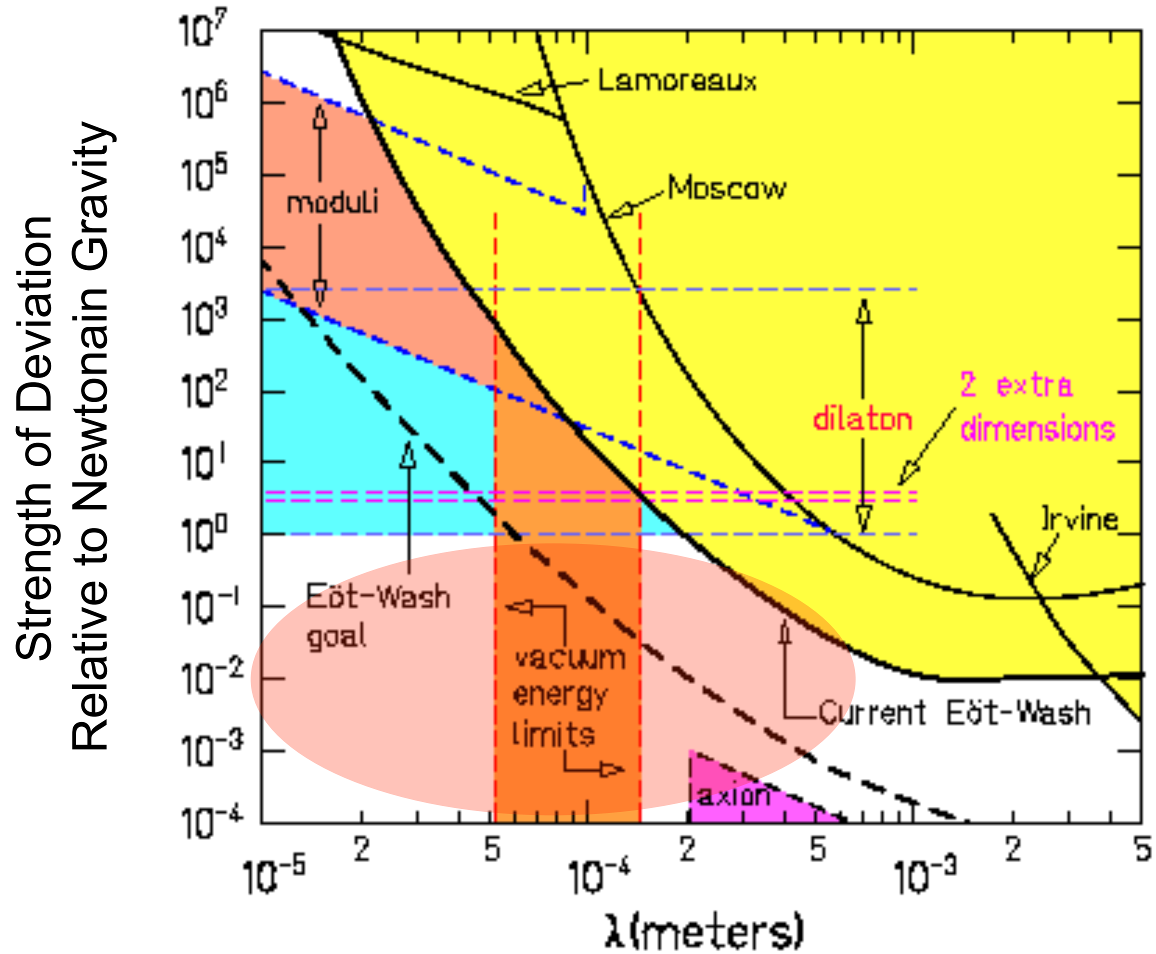
Possible observables:
- microscopic black holes

- graviton production-modified cross sections missing E_T

Tests of Newtonian Gravity

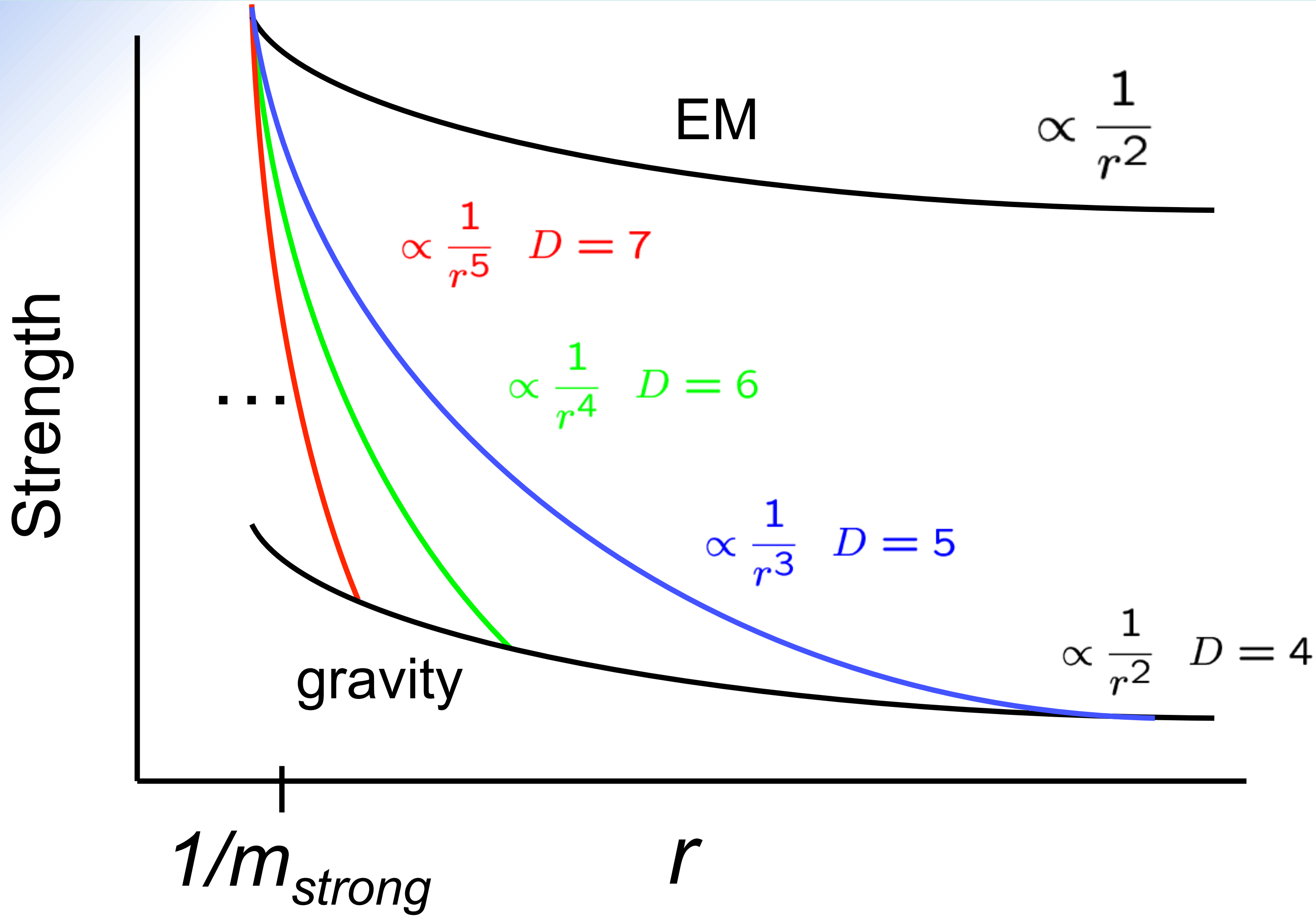
$L \sim 10^{\frac{32}{n}-19}$ m

n	L
~~1~~	~~10^{13} m~~
~~2~~	~~mm~~
3	10 nm
4	10^{-11} m
6	10 fm



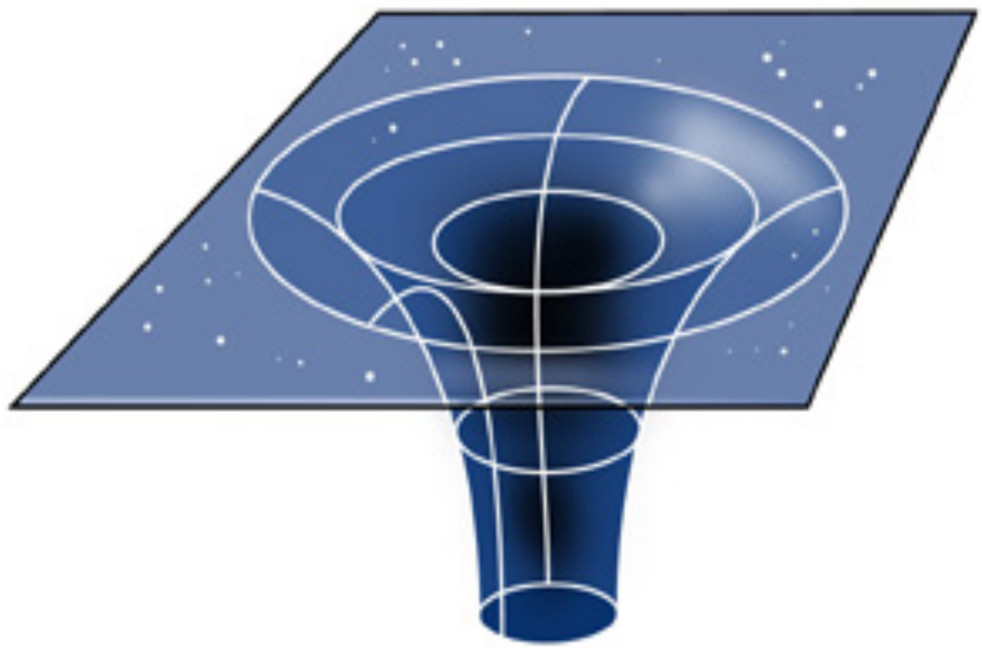
Long *et al.*, *Nature* (2003)

Gravity in Extra Dimensions



Black Holes

- Solutions to Einstein's equations
- Schwarzschild radius $r_s \sim GM_{\mathrm{BH}}$ – requires large mass/energy in small volume
- Light and other particles do not escape; classically, BHs are stable



The Schwarzschild radius

$$ds^2 = -\alpha_{(d+3)}(r,t)\mathrm{d}t^2 + \beta_{(d+3)}(r,t)\mathrm{d}r^2 + r^2\mathrm{d}\Omega_{(d+3)}$$

Myers, Perry 1984

D-dimensional Einstein Eq. gives the **Schwarzschild radius** for a D-dimensional Black Hole

$$R_S^{d+1} = \frac{2}{d+1}\left(\frac{1}{M_f}\right)^{d+1}\frac{M}{M_f}$$

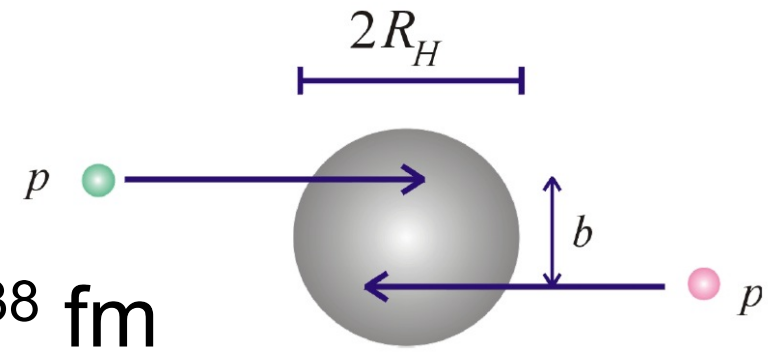
Surface gravity:

$$\kappa_D = \frac{1+d}{2}\frac{1}{R_S}$$

I.e. $R_s \sim M/m^2_{grav}$

Reduction of m_{grav} ➔ increase in R_s

BHs from Particle Collisions



Penrose (1974)
Banks, Fischler (1999)
Bleicher, Hossenfelder (2001)

- Effect: $R_s^{4d}(1\ \text{TeV}) \sim 10^{-38}$ fm
  $R_s^{lxd}(1\ \text{TeV}) \sim 10^{-4}$ fm

- BH cross section is

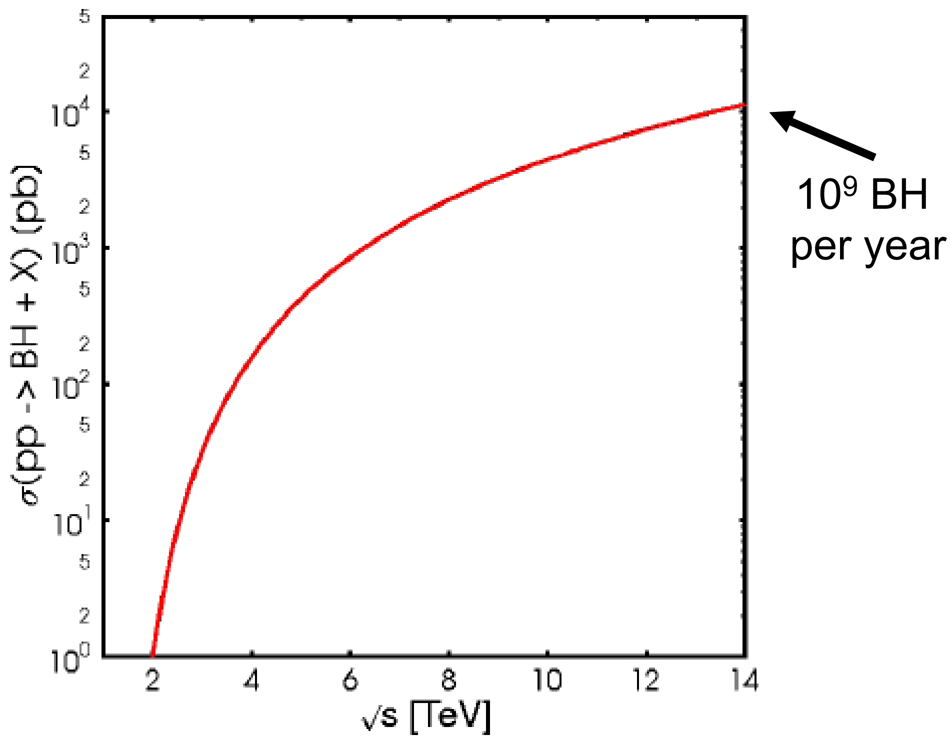
→ $\sigma(p_1 p_2 \rightarrow BH) \sim 400$ pb

Black Holes at Colliders

- BH created when two particles of high enough energy pass within ~ r_s .

Eardley, Giddings, PRD (2002)
Yoshino, Nambu, PRD (2003)
Dimopoulos, Landsberg, PRL (2001)

$$\frac{d\sigma}{dM} = \sum_{A_1,B_2} \int_0^1 dx_1 \frac{2\sqrt{\hat{s}}}{x_1 s} f_A(x_1,\hat{s}) f_B(y_2,\hat{s}) \sigma(\hat{s},d)$$



- Large Hadron Collider:
  E_{COM} = 14 TeV
  pp → BH + *X*

- LHC prediction: 100 black holes per second

LHC: S. Hossenfelder, M.B., et al., PRD 66 (2002)
Tevatron: M. Bleicher et al., PLB548 (2002)

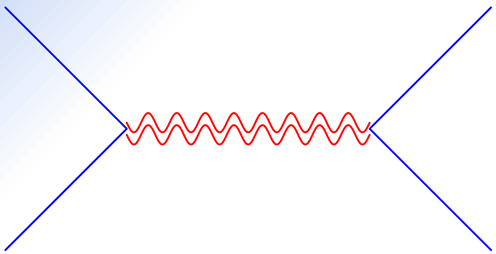
Signatures

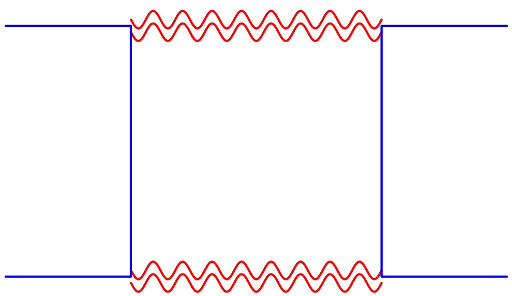
- Event shapes (thermal emission)
- Modifies hadron spectra
- Exotic particle production
- Cut-off in pT spectra
- Remnants?

Constraints from LHC

- Exotic particle search
- Constraints on the exchange of gravitons
- Kaluza-Klein excitations
- Direct searches for black holes

Graviton exchange





Experiment	Process	+	−
LEP [7]	$e^+e^- \to \gamma\gamma$	0.93 TeV	1.01 TeV
LEP [8–11]	$e^+e^- \to e^+e^-$	1.18 TeV	1.17 TeV
H1 [12]	e^+p and e^-p	0.74 TeV	0.71 TeV
ZEUS [13]	e^+p and e^-p	0.72 TeV	0.73 TeV
CDF [14]	$p\bar{p} \to e^+e^-, \gamma\gamma$	0.99 TeV	0.96 TeV
DØ [14]	$p\bar{p} \to e^+e^-, \gamma\gamma$	1.28 TeV	1.14 TeV
DØ [15]	$p\bar{p} \to jj$	1.48 TeV	1.48 TeV
CMS at 7 TeV with 40/pb [16]	$pp \to \mu^-\mu^+$	1.6 TeV	1.6 TeV
CMS at 7 TeV with 36/pb [30]	$pp \to \gamma\gamma$	1.74 TeV	1.71 TeV
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	2.2 TeV	2.1 TeV
ATLAS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.2 TeV
CMS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.4 TeV

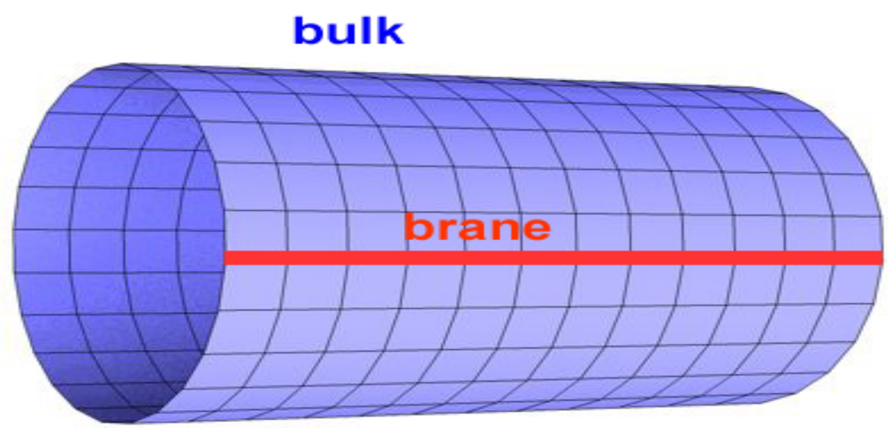
Limits on the tree level exchange

from R.Franceschini et al, JHEP05(2011)092

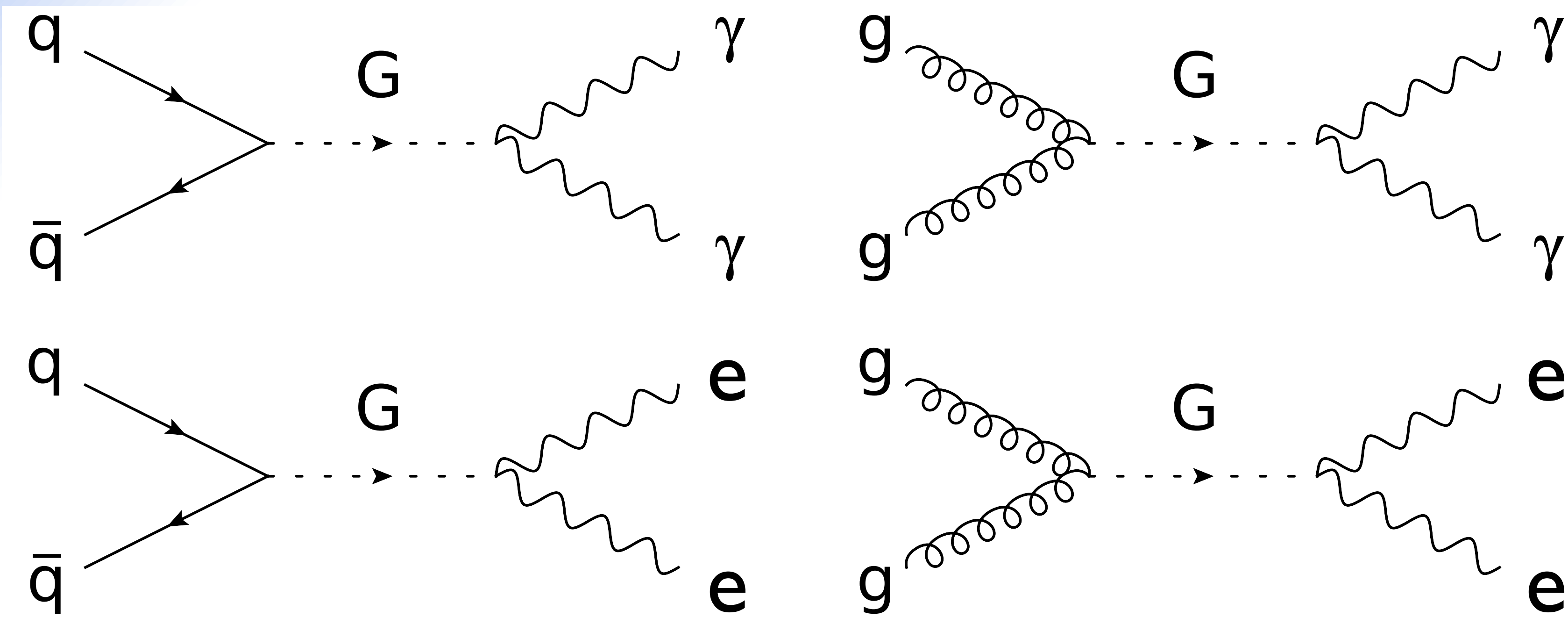
Kaluza-Klein excitations

- 3+d space like dimensions
- d dimensions on d-torus with radii R
- only gravity propagates in all dimensions (bulk)
- all other in 4-dim. space time (brane)

$$\begin{aligned} {}^{(5)}\Box\Phi &= 0 \\ \Leftrightarrow \quad \left({}^{(4)}\Box + \partial_5^2\right)\Phi &= 0 \\ \Leftrightarrow \quad \left({}^{(4)}\Box - \frac{n^2}{R^2}\right)\Phi &= 0 \end{aligned}$$



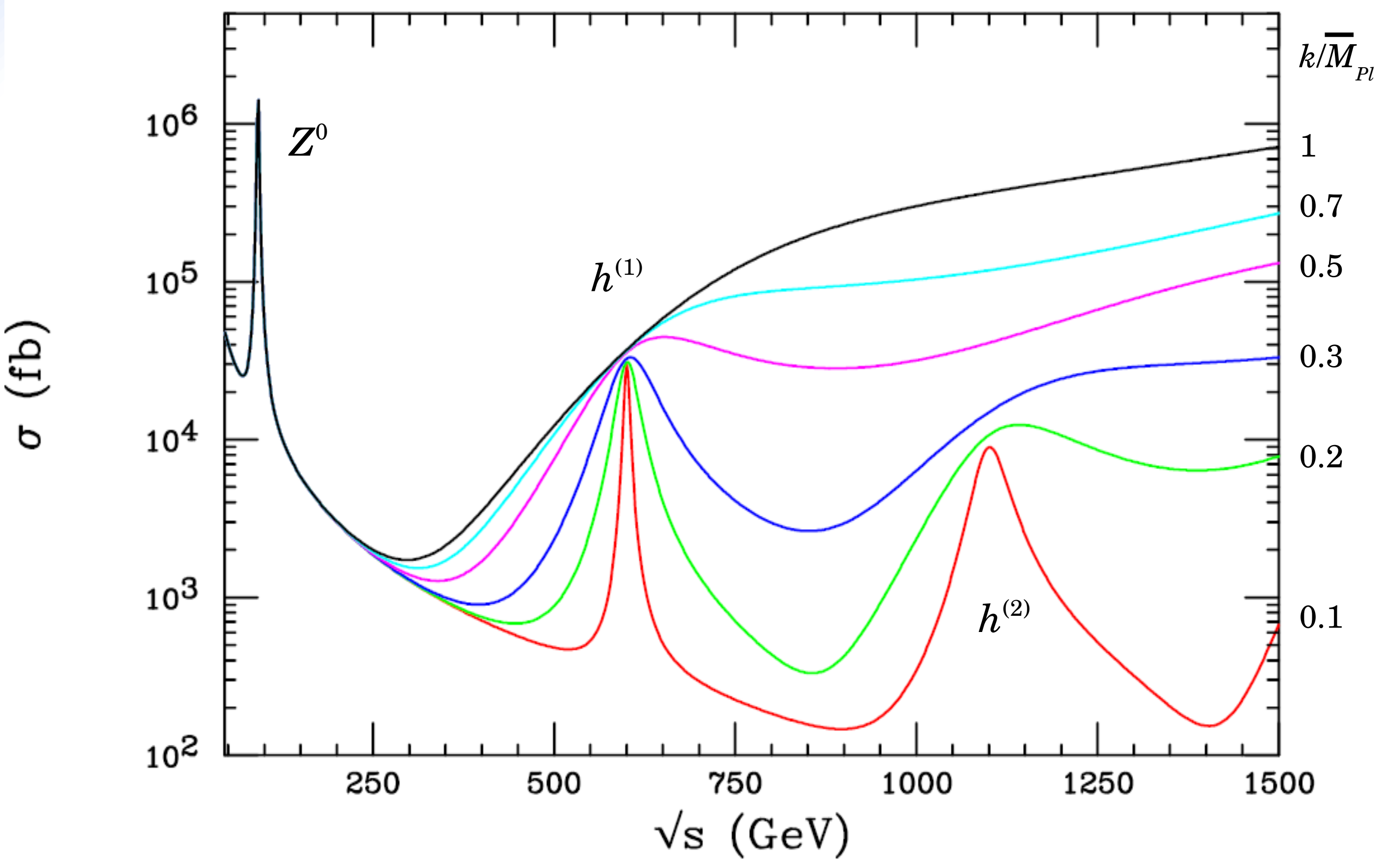
Randall-Sundrum KK (II)



from Evan Wulf (ATLAS)

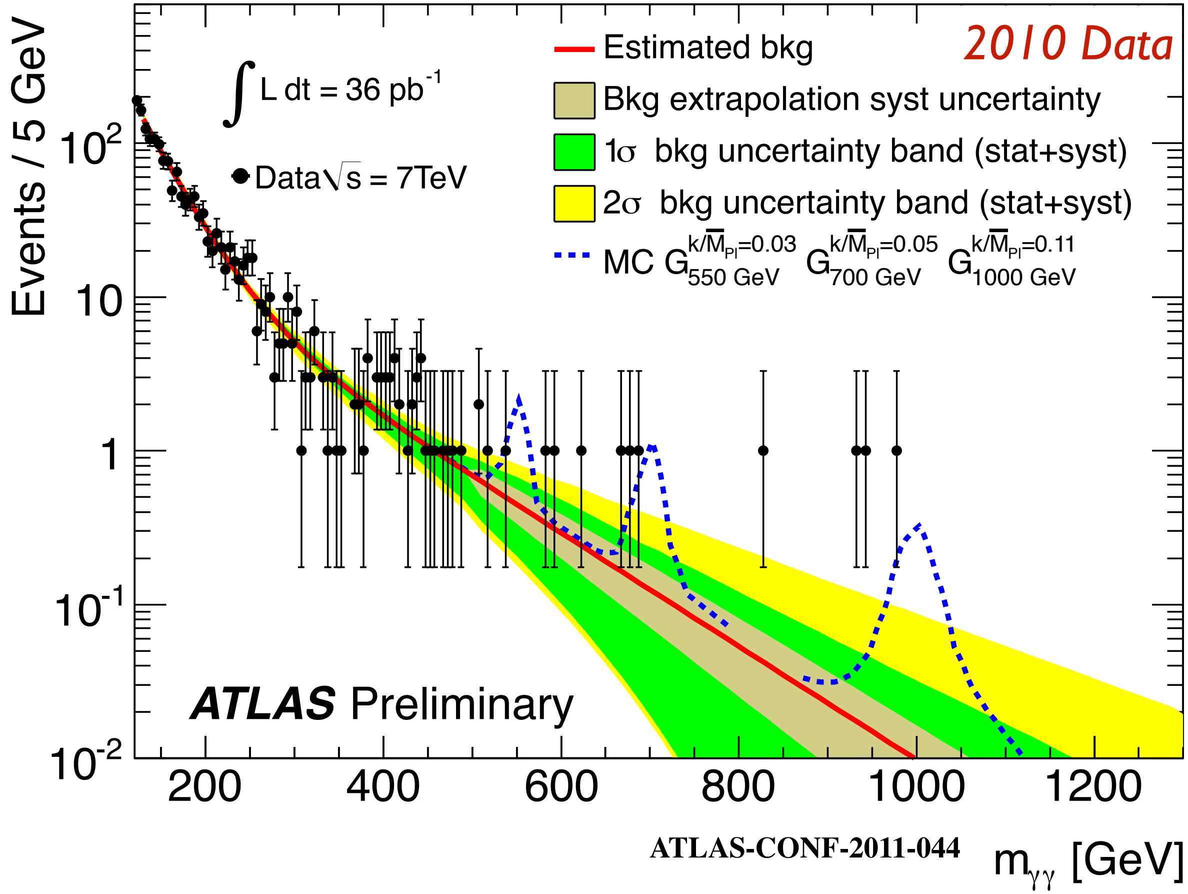
Randall-Sundrum KK (I)

arXiv:hep-ph/9909255v1



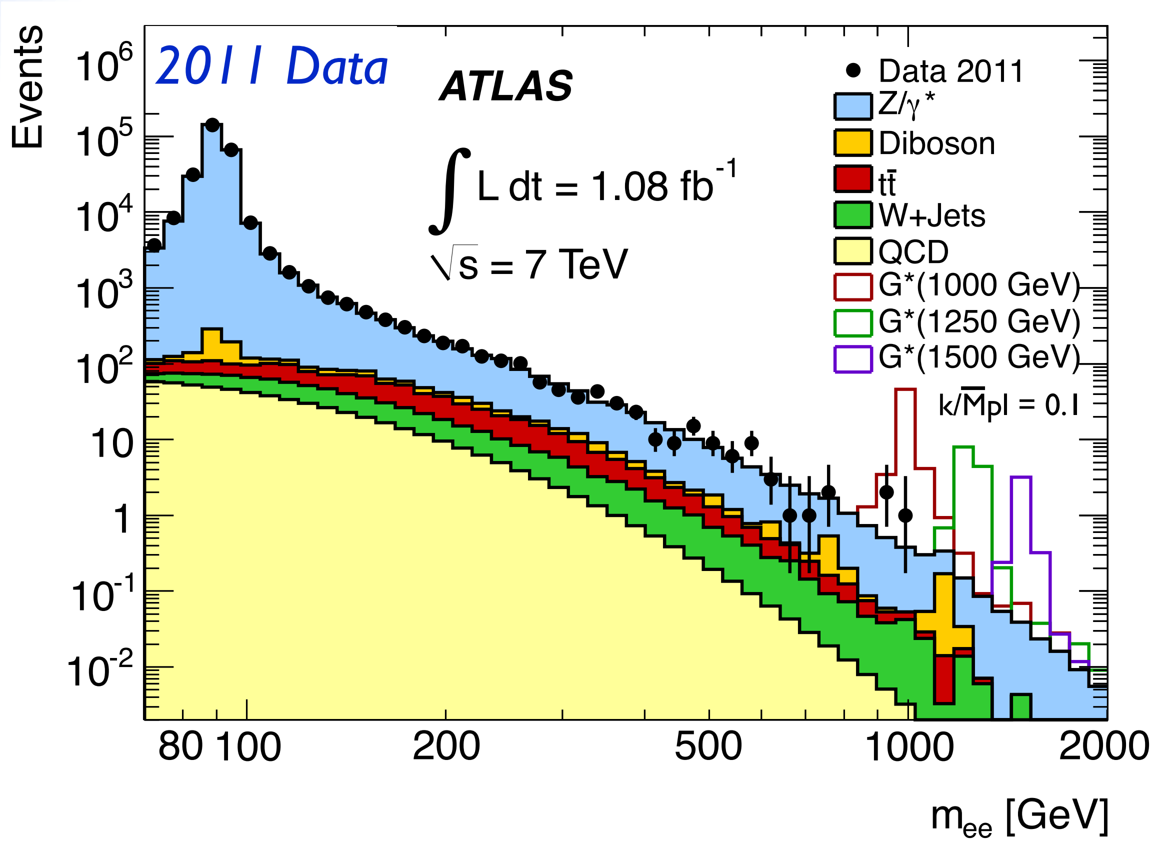
from Evan Wulf (ATLAS)

Randall-Sundrum KK (III)



ATLAS-CONF-2011-044

Randall-Sundrum KK (IV)



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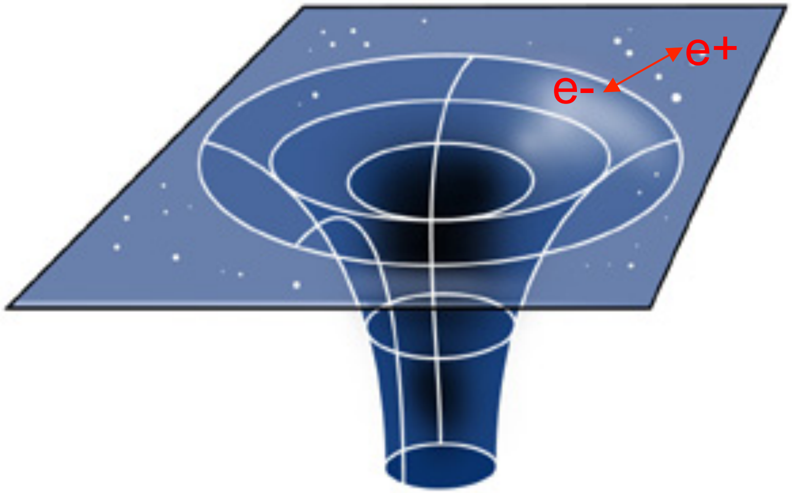
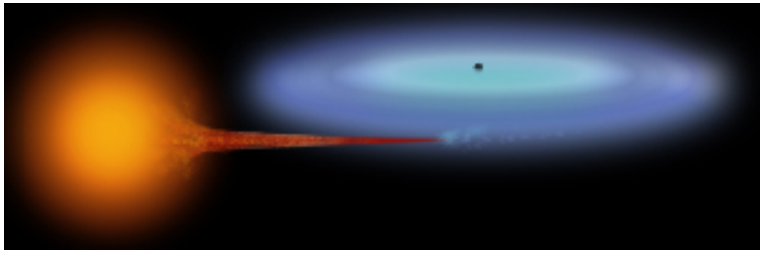
Black Hole Evaporation

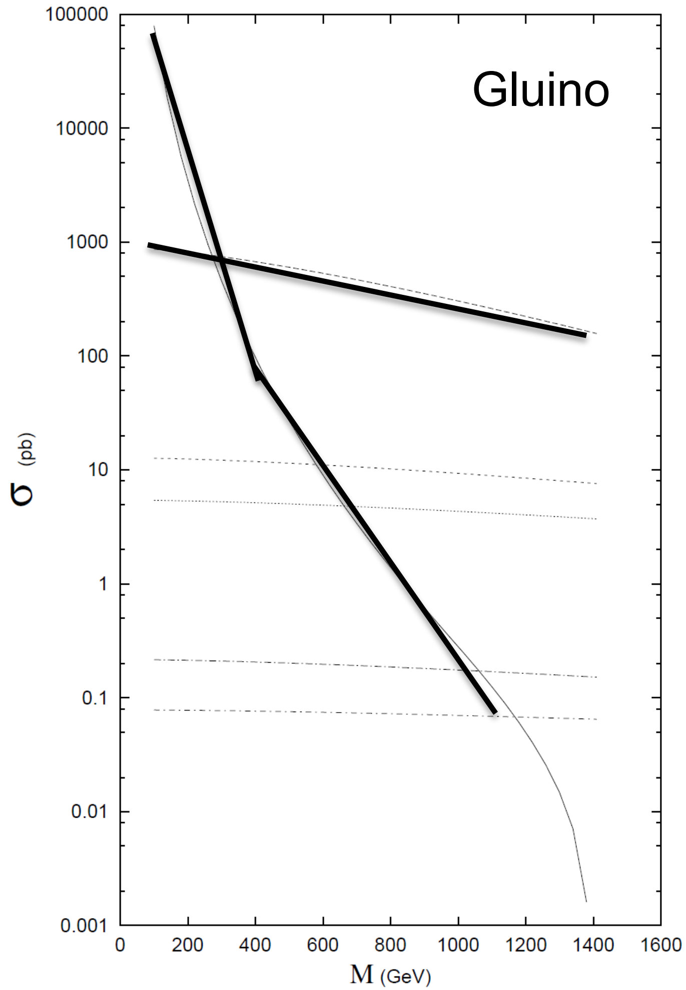
- Quantum mechanically, black holes are not stable – they emit Hawking radiation
- Temperature: $T_H \sim 1/R_s$
  Lifetime: $\tau \sim (M_{BH})^3$
- For $M_{BH} \sim M_{sun}$, $T_H \sim 0.01$ K. Astrophysical BHs emit only photons, live ~ forever

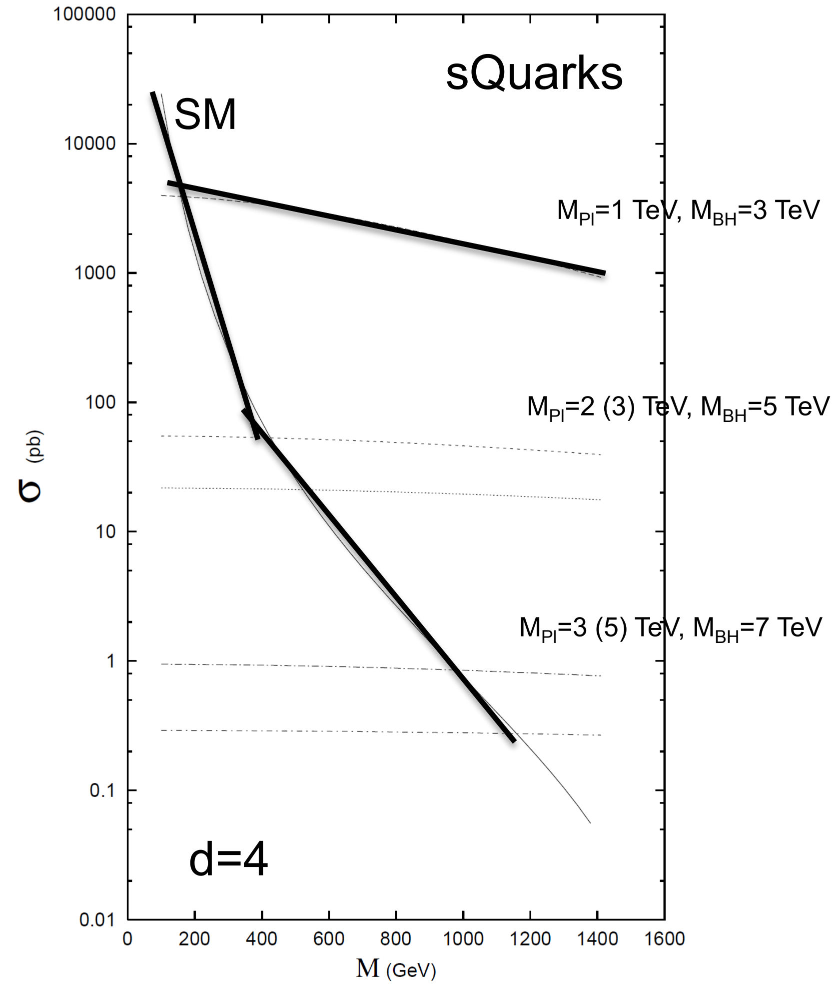




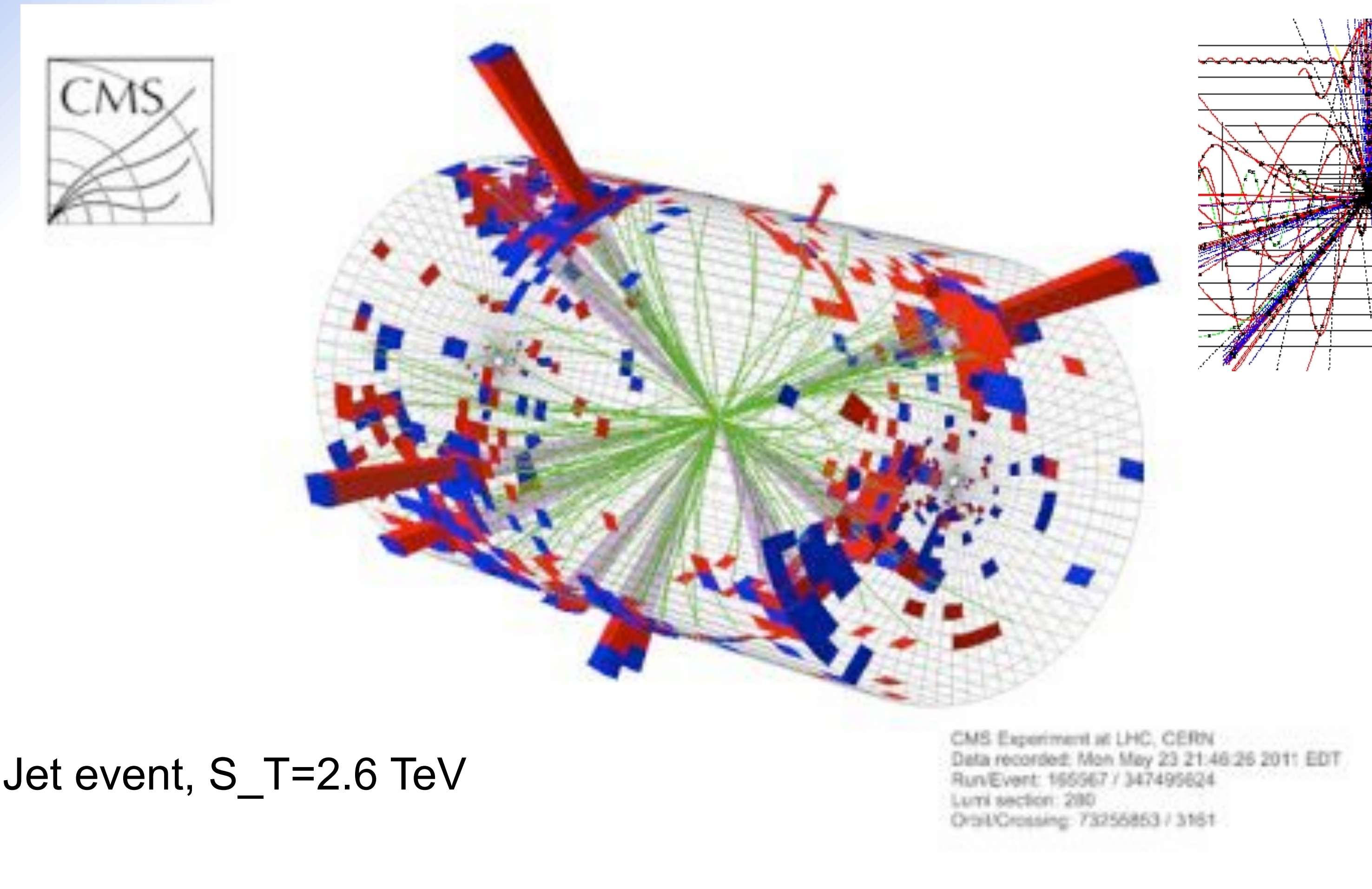
Exotic particle production

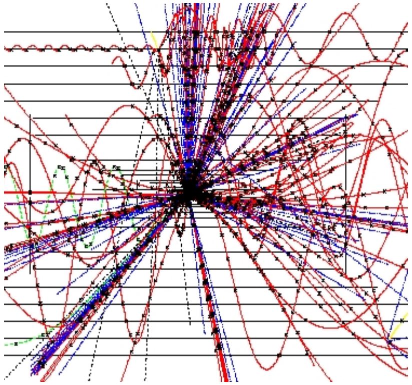
Chamblin, Cooper, Nayak PRD (2004)
see also Landsberg PRL (2002)





Direct black hole search





9 Jet event, S_T=2.6 TeV

Event Characteristics

Decay Signature

Average of ~ 6 particles for each decay, emitted spherically

~120 Particle degrees of freedom

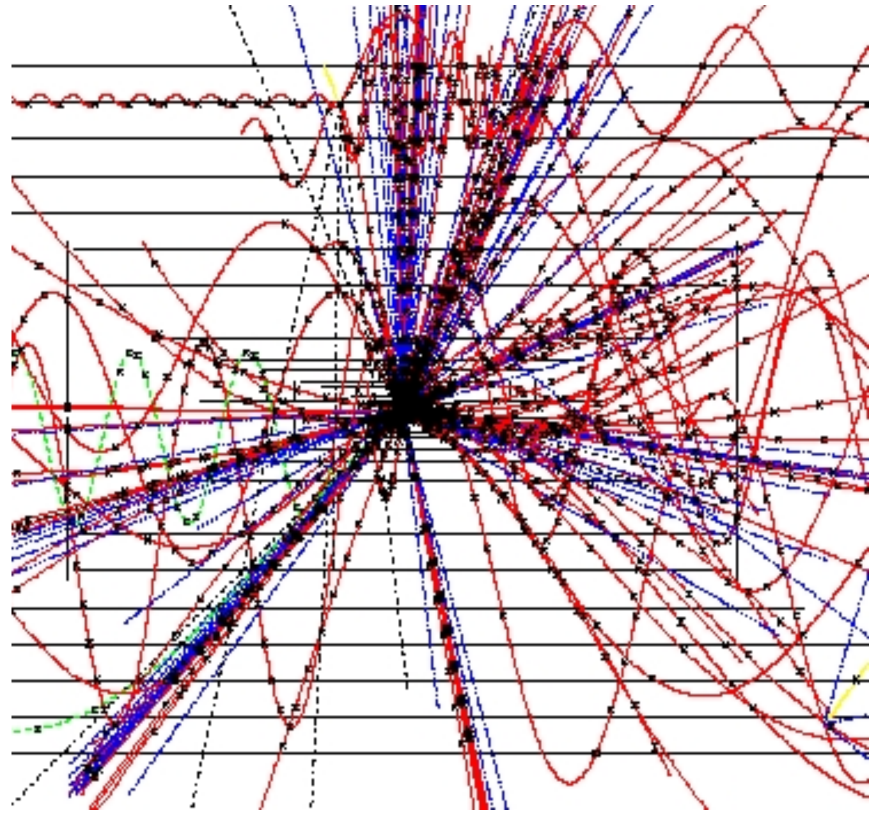
Summing over spin and color gives:

- 75 % quarks and gluons
- 10 % charged leptons
- 5 % neutrinos
- 5 % photons or W/Z bosons
- Also get new particles around 100-1000 GeV,

Small fraction of invisible neutrinos and gravitons

→ BH's easy to reconstruct

10% high PT leptons → trigger



De Roeck (2002)

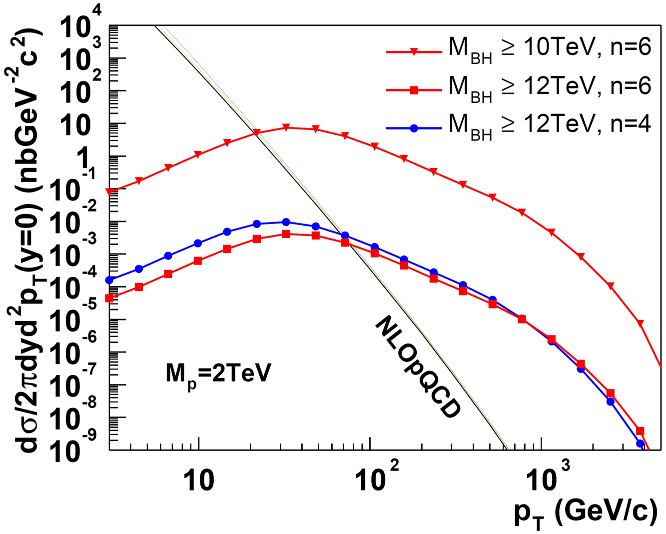
S. Vahsen (2008)

Hadron spectrum

- Get hadron spectrum from parton fragmentation

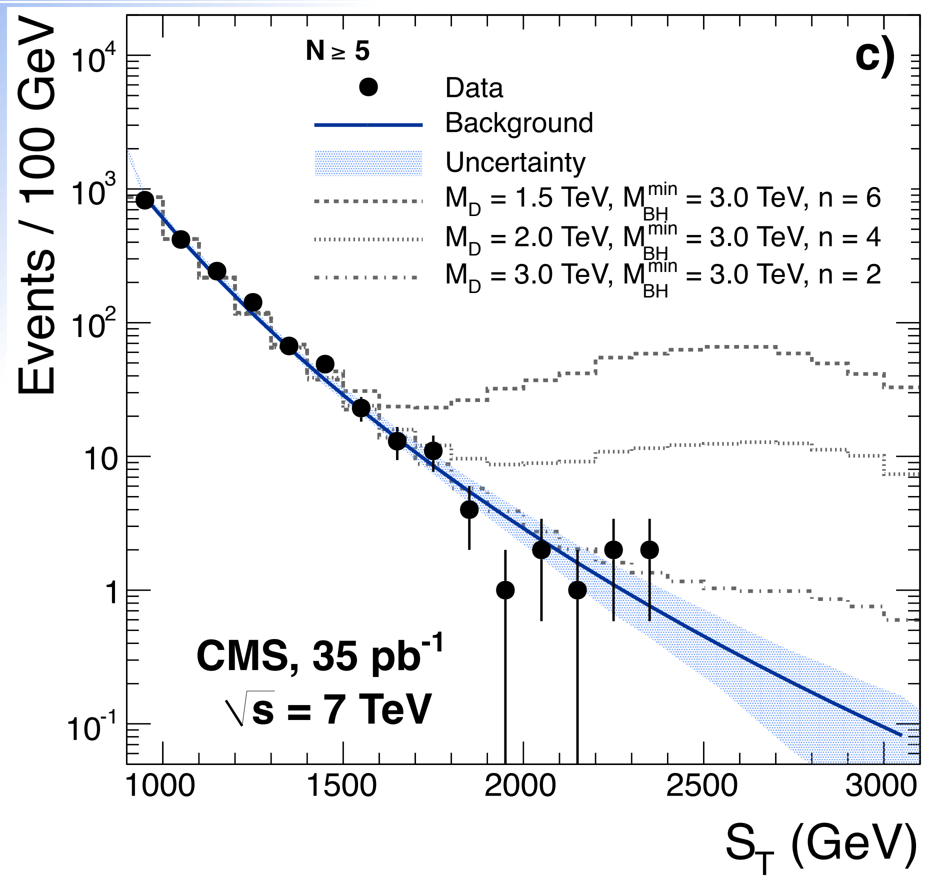
$$E\frac{d\sigma^h}{d^3p} = \frac{1}{s}\sum_{a,b,c}\int_{M^2_{BH,min}}^{s} dM^2_{BH}\int_{x_{1,min}}^{1}\frac{dx_1}{x_1}\int_{z_{min}}^{1}\frac{dz}{z^2} \times f_a(x_1,Q^2)\sigma_{BH}f_b(x_2,Q^2)E_c\frac{dN_c}{d^3p_c}D_c^h(z,Q_f^2),$$

- Charged hadrons from BHs exceed pQCD at high pT
- Bump near Hawking temperature



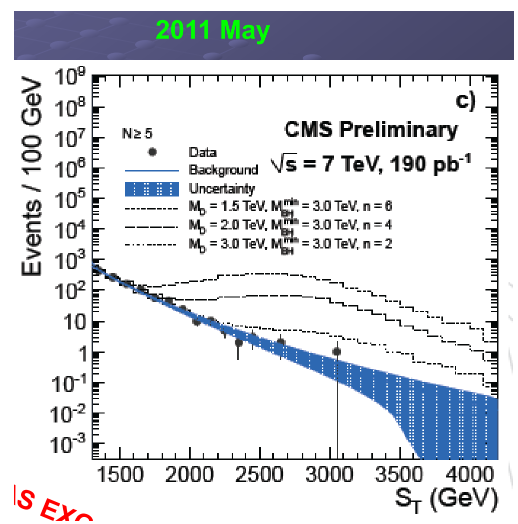
From I. Sarcevic et al (2007)

Direct black hole search (I)



S_T is summed E_t is acceptance

- Search for high E_T multi-particle final states
- Similar results for N>2 final state particles
- No deviations from Standard Model observed!



CMS, arxiv:1012.3375

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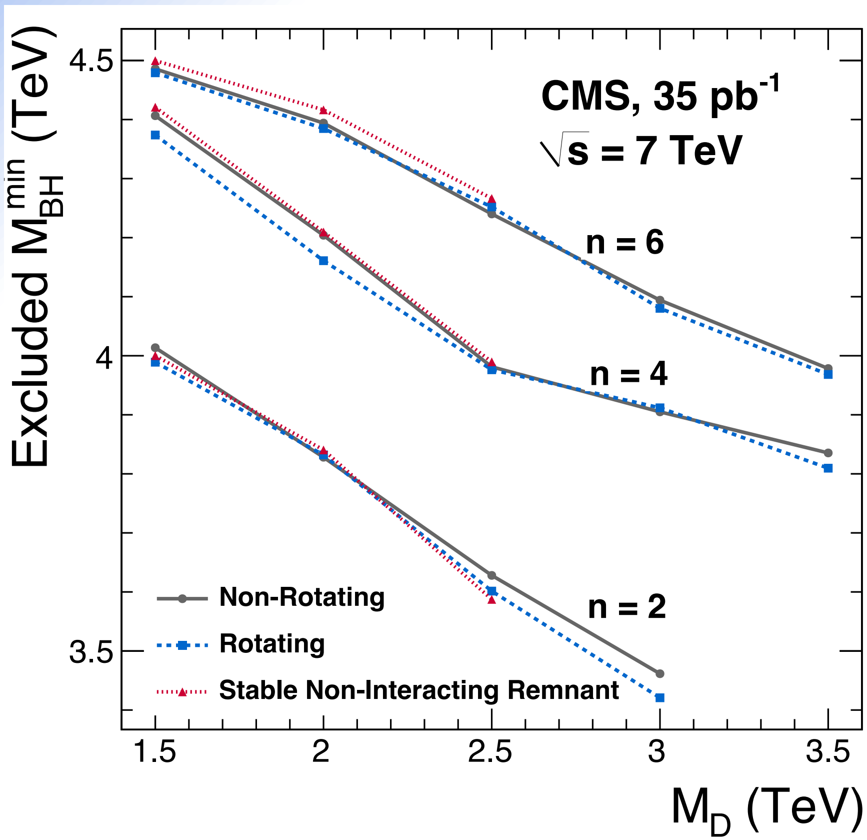
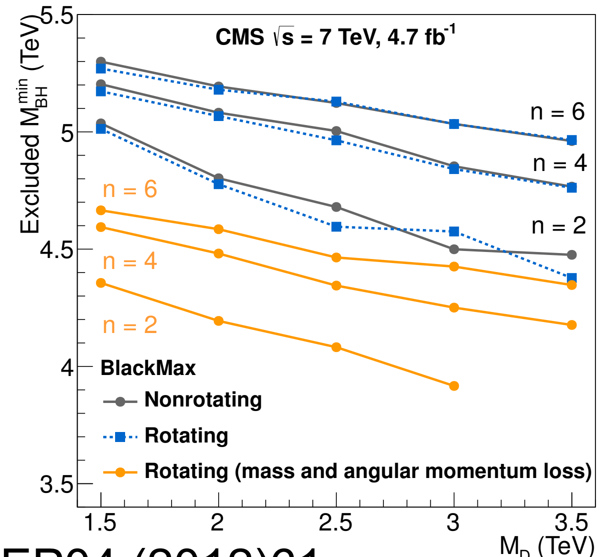
Direct black hole search (II)



- 95% percent exclusion limits
- All cases (rotating, non rotating, remnant formation) are strongly constrained



CMS, arxiv:1012.3375

CMS, JHEP04 (2012)61

ner, RANP 2013

Conclusion

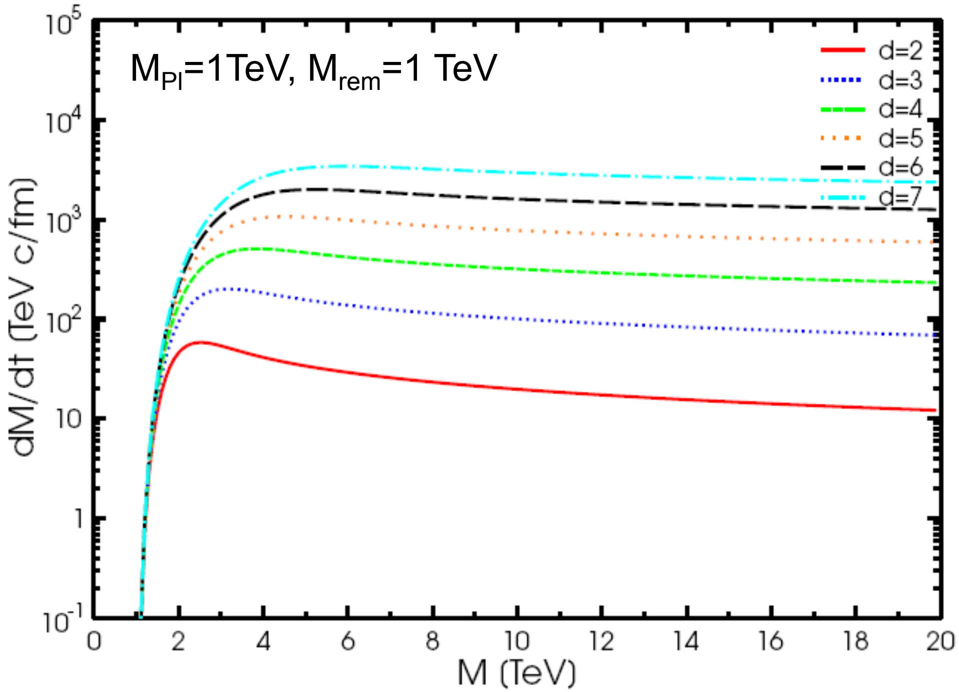
- Mini Black Holes, Gravitons, extra dimensions are still an interesting idea
- However:
  - No signals of BHs observed at LHC
  - Also no signal of Gravitons at LHC
  - (Also no signal of non-commutativity)

Backup

Remnants

- Include remnant in Charybdis by a modification of the emission spectrum
- Try direct measurement of heavy charged remnant

→ Ashes of the black hole



Koch, Hossenfelder, Bleicher (2007)

See also
Bonano, Reuter (Renormalized coupling constant) and Rizzo et al (Modified gravity)

→ Same effect, different origin

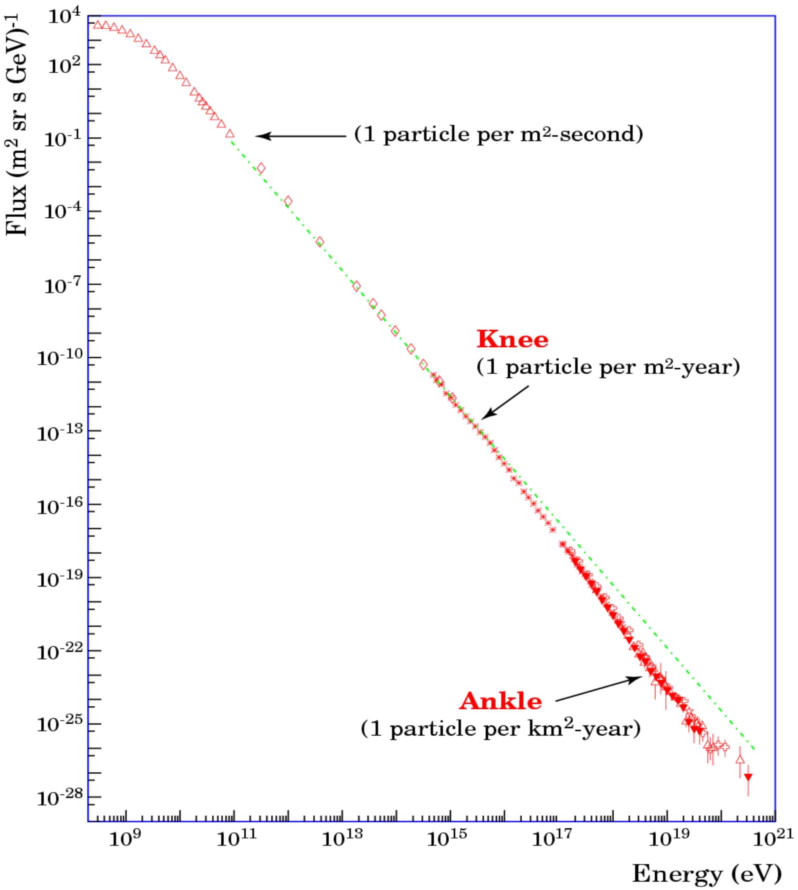
Black Holes from Cosmic Rays

- Cosmic rays –
  Nature's free collider

- Observed events with 10^{20} eV produces

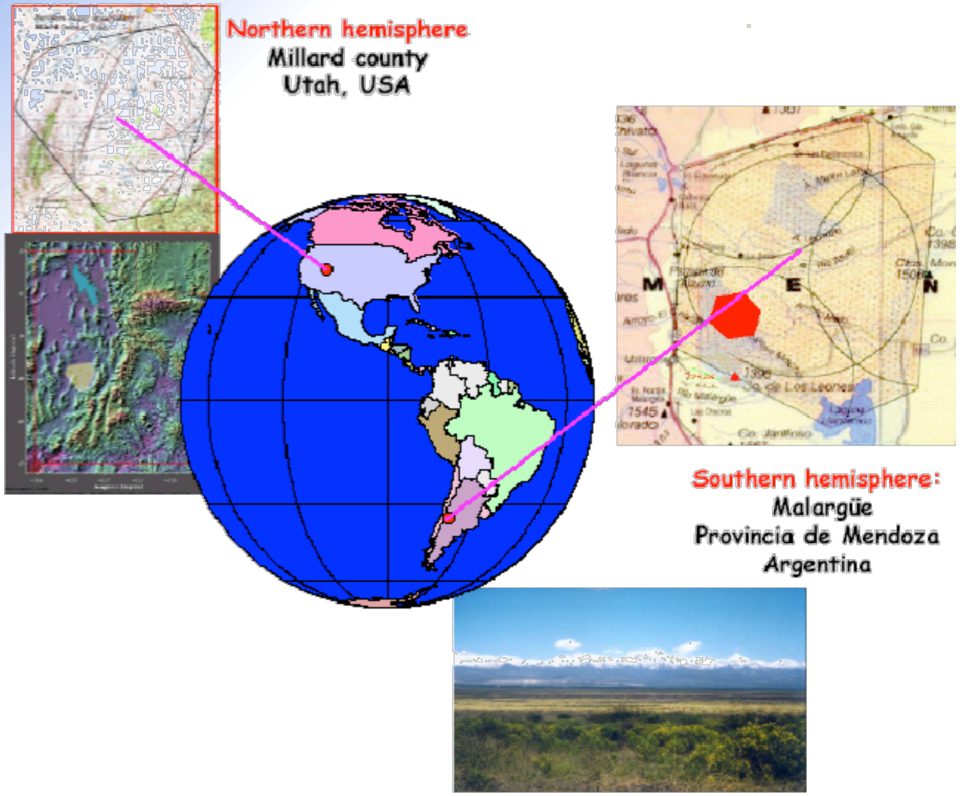
  $E_{COM} \sim 500$ TeV

- But meager fluxes. Can one use this energy?



Kampert, Swordy (2001)

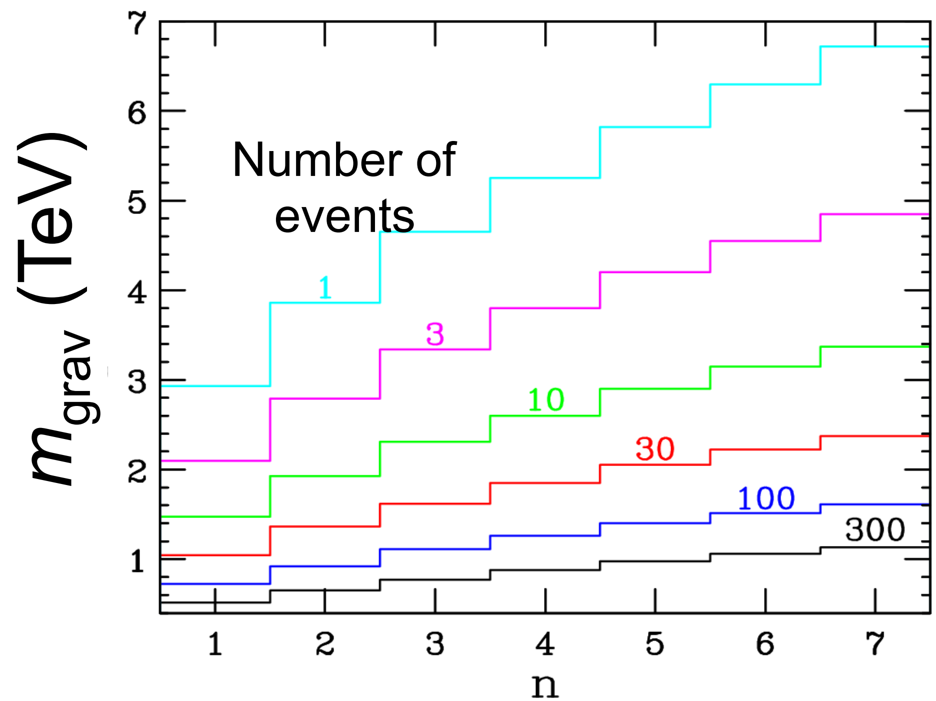
Auger Observatory



Black holes from cosmic neutrinos

- Currently no such events seen → stringent bound on extra dimensions.

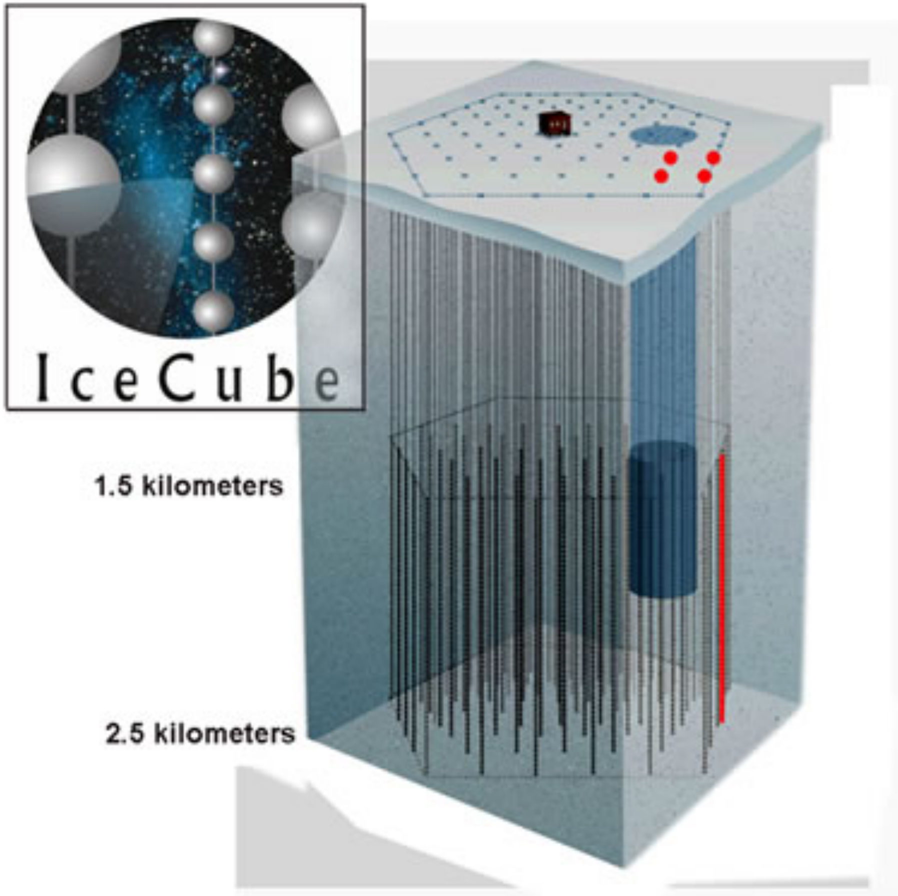
- Auger can detect ~100 black holes in 3 years.



Feng, Shapere, PRL (2002)

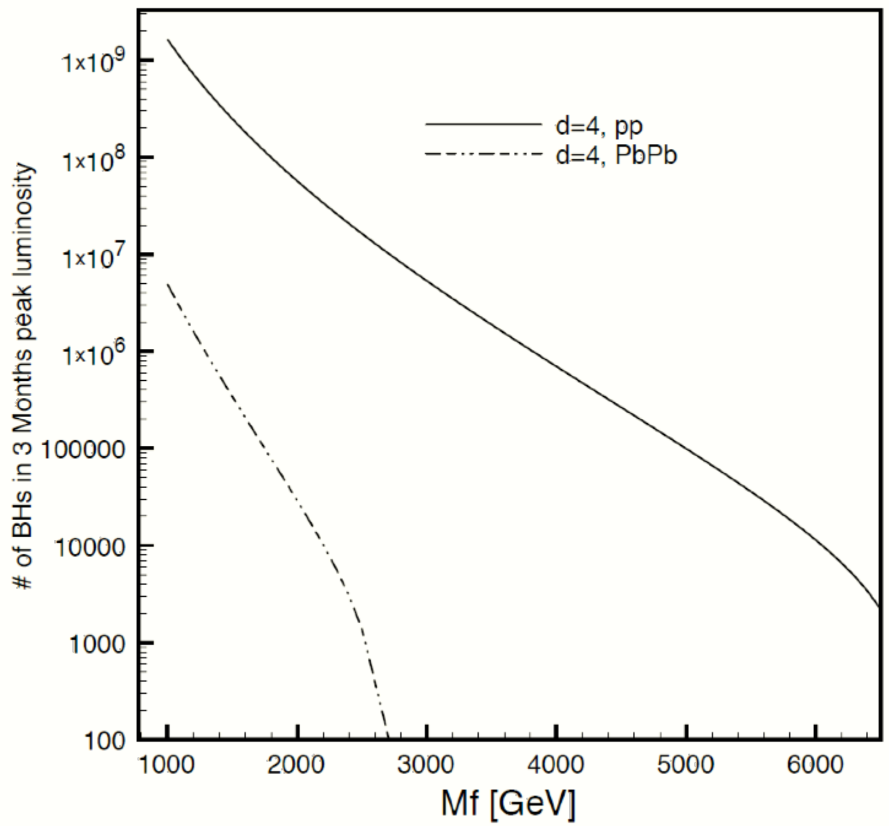
AMANDA/IceCube

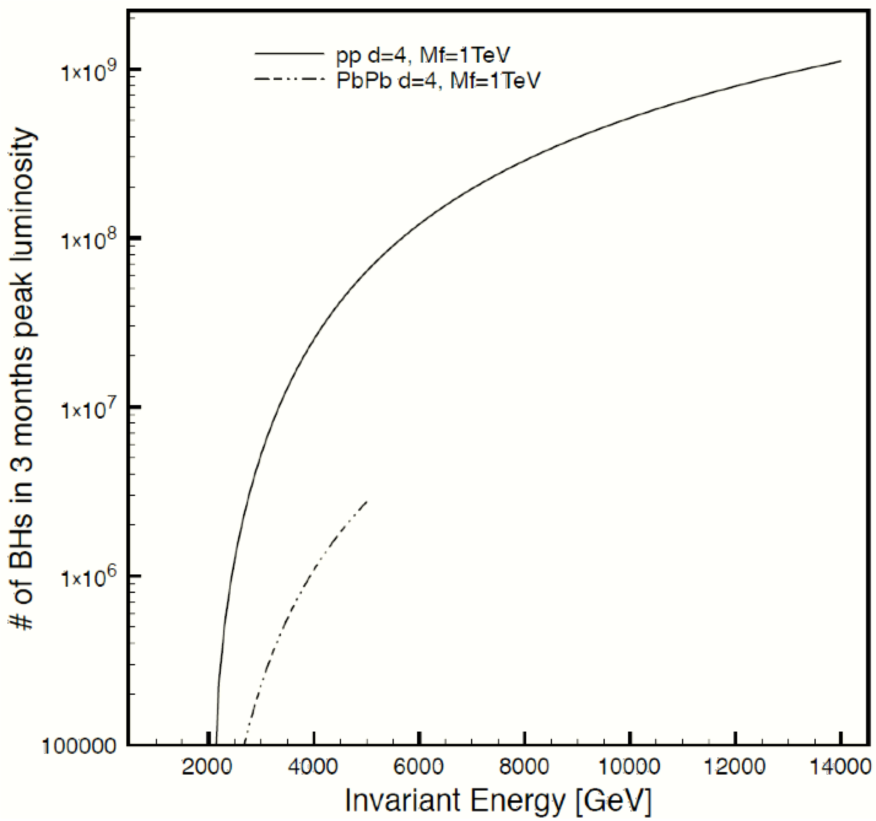
- Neutrino telescopes: promising BH detectors
- Similar rate: ~10 BH/year
- Complementary information
  - BH branching ratios (jets vs. muons)
  - Angular distributions



Kowalski, Ringwald, Tu, PLB (2002)
Alvarez-Muniz, Feng, Han, Hooper, Halzen, PRD (2002)
Harbach, Bleicher, subm. Astroparticle Phys.(2005)

Pb+Pb vs pp





Luminosity difference: 10^{27} vs 10^{34} /cm/s

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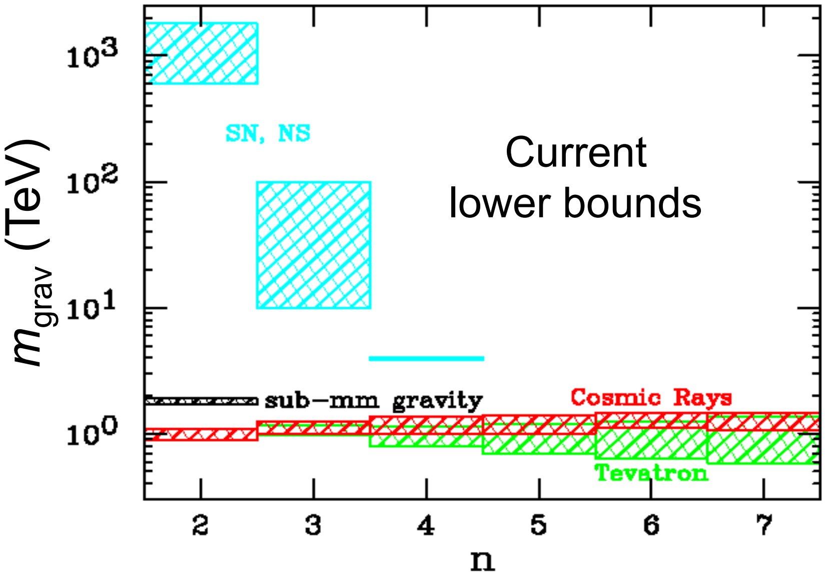
Conclusions

- Gravity is either weak or is strong but diluted by extra dimensions

- Black hole production is a leading test



- If gravity is strong at the TeV scale, we will find microscopic black holes at LHC!

Black Hole evaporation?

- **"Balding phase"**:BH gets rid of its hair
  mainly via gravitational radiation ->not visible in detector

- **Hawking phase**: decay
  mainly into standard-model particles.

  - R. Emparan, G. T. Horowitz and R. C. Myers Phys. Rev. Lett. **85**, 499 (2000)
  - S. B. Giddings and S. Thomas, Phys. Rev. **D 65** 056010 (2002).
  - C. M. Harris, M. J. Palmer, M. A. Parker, P. Richardson, A. Sabetfakhri and B. R. Webber, [arXiv:hep-ph/0411022]...

$$T_H = \frac{d+1}{4\pi R_s}$$

- **Final state**: Two possible scenarios
  - Hawking radiation continues until M_{BH}....M_f and then performes something like a final decay
  - Rapid decay slows down to form quasi-stable remnant

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Still vital discussion of this (classical) cross sections

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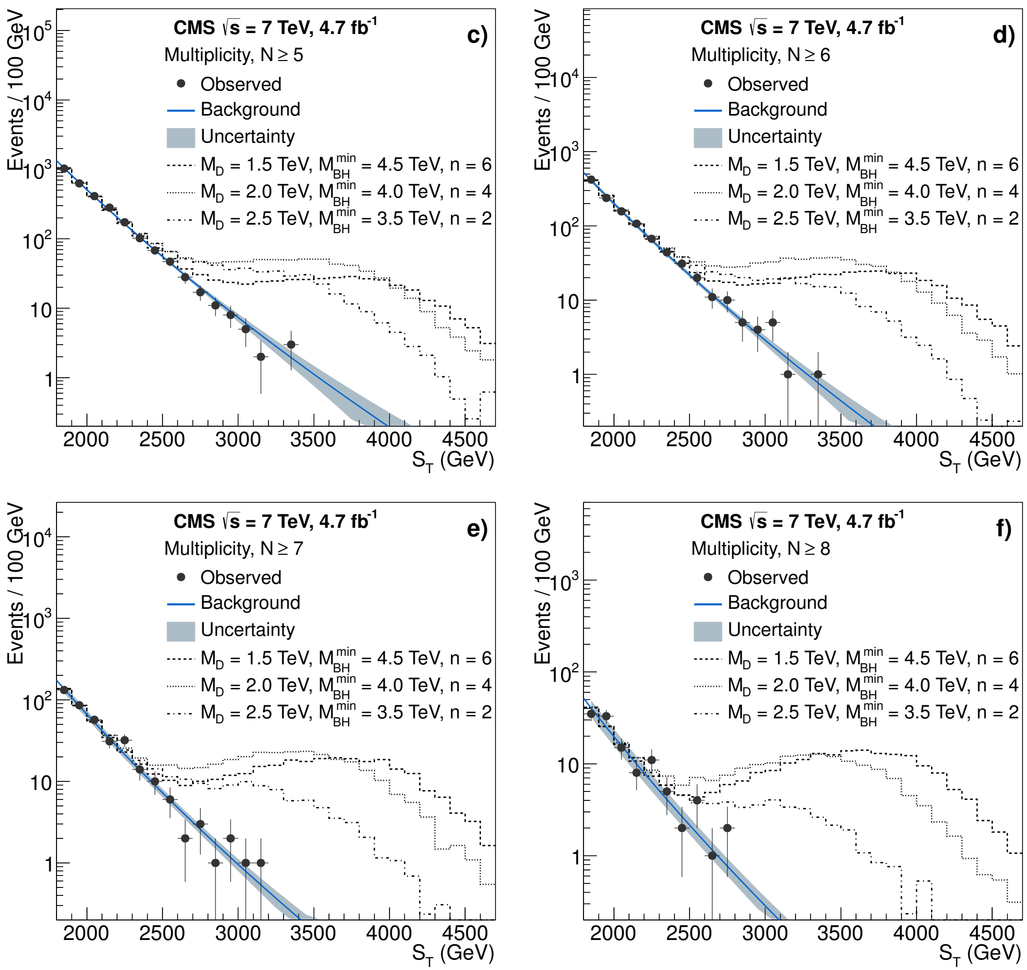
Consensus finally...
most calculations confirm the geometrical estimate of cross section;

$$\sigma(XX \to \mathrm{BH}) = \pi R_S^2$$

Graviton radiation, etc. that modify the cross sections are included in many new calculations

Latest results



CMS, JHEP04 (2012)61