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.

"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)
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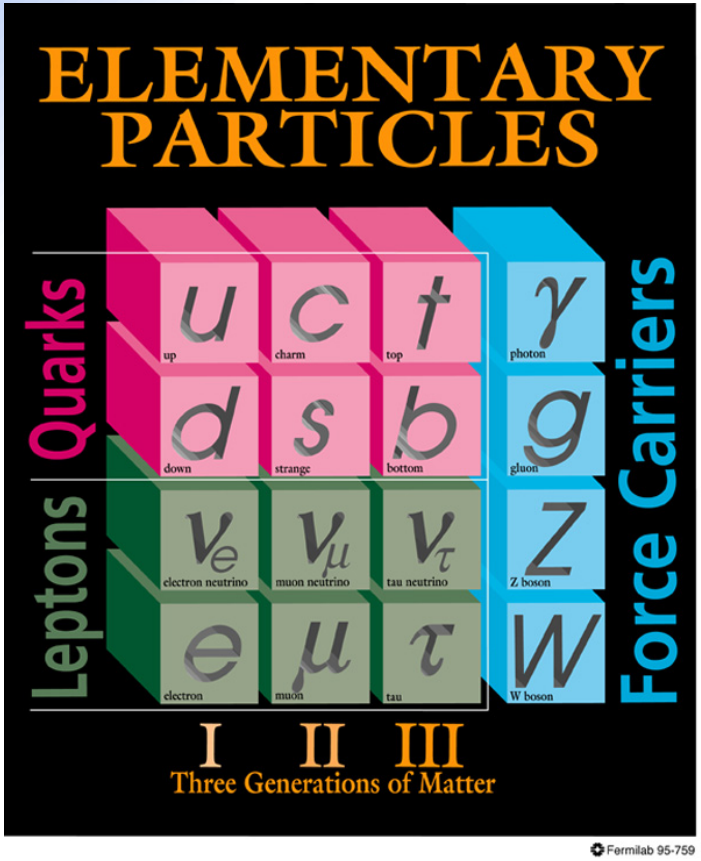
- Piero Nicolini (FIAS, Germany)
- Martin Sprenger (DESY, Germany)
- Sabine Hossenfelder (NORDITA, Stockholm)
- Stefan Hofmann (LMU Munich, Germany)

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

Outline

- Is gravity weak?
- Extra dimensions: Why and how
- Black holes at colliders
- Update on experimental constraints
- Conclusions

The Standard Model



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

What is the problem?

Many problems, but one is obvious:

Where is gravity?

1. No quantum theory of gravity.
2. Gravity is extraordinarily weak.
   It is only important in everyday life, because it is always attractive and masses are huge.

The hierarchy problem

- Example:

$$F_{\text{EM}} = \frac{q_1 q_2}{r^2} \qquad F_{\text{gravity}} = G_N \frac{m_1 m_2}{r^2}$$

Even for the heaviest elementary particles (e.g., *W* bosons, top quarks)

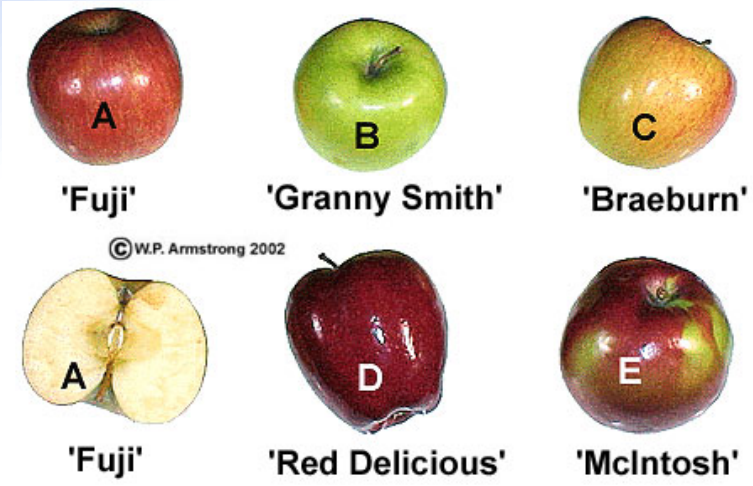
$$F_{\text{gravity}} \sim 10^{-32}\, F_{\text{EM}}$$

- Gravity is comparable for masses (or energies) ~ 10^{15} TeV, far beyond experiment (M_{weak} ~ 1 TeV).

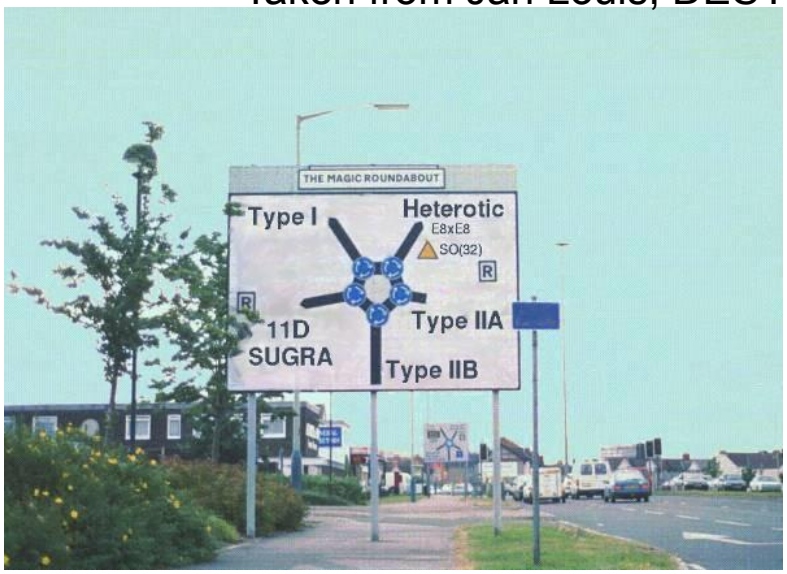
- The Hierarchy Problem: Why is gravity so weak?

Possible Solutions…

- String theory



Taken from Jan Louis, DESY



- Essential result: - More dimensions
  - Noncommutative space

Noncommutativity

Space-time noncommutativity is an extension of quantum mechanics:

Heisenberg algebra:

$$[\hat{x}^i, p^j] = i\hbar\delta^{ij}$$

$$[p^i, p^j] = 0$$

is extended with new noncommutative (NC) relations:

$$[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$$

that lead to new uncertainty relations:

$$\Delta x^\mu \Delta x^\nu \geq \frac{1}{2}|\theta^{\mu\nu}|$$

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)

Idea(l): large extra dimensions

- Randall & Sundrum (1999)
  → one large extra dimension R~10 l_{Planck}
  → warped dimensions

$$\mathrm{d}s^2 = \mathrm{e}^{-2kR|\phi|}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + R^2\mathrm{d}\phi^2$$

with $\phi := y/R$

Warp factor leads to exponential mass scale suppression (kR~12)

$$m = \mathrm{e}^{-kR\pi} m_0$$

➔ TeV scale physics
➔ Collider signatures

Idea (II): large 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

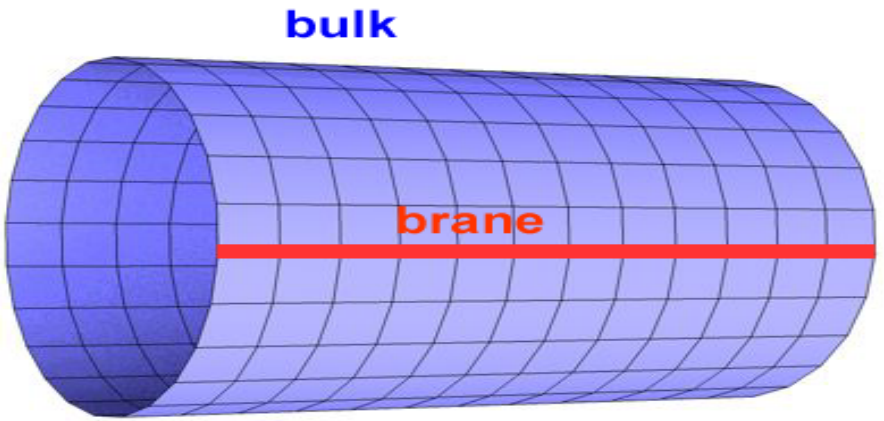
$$(x_0, x_1, x_2, x_3, y_1, \ldots y_d) =: (x, y)$$

$$\mathrm{d}s^2 = -(\mathrm{d}x^0)^2 + \sum_\nu (\mathrm{d}x^\nu)^2 + \sum_i (\mathrm{d}y^i)^2$$

The ADD model

- 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)

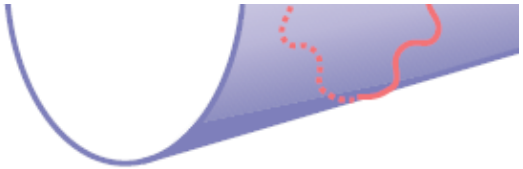
$$
\begin{aligned}
{}^{(5)}\Box\Phi &= 0 \\
\Leftrightarrow \quad \left({}^{(4)}\Box + \partial_5^2\right)\Phi &= 0 \\
\Leftrightarrow \quad \left({}^{(4)}\Box - \frac{n^2}{R^2}\right)\Phi &= 0
\end{aligned}
$$



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

Einstein-Hilbert action

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



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

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

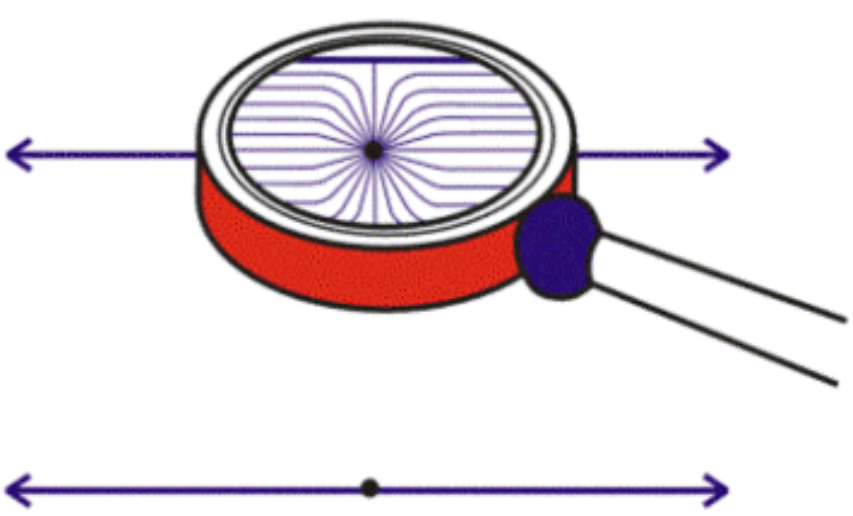
$$\Rightarrow m_p^2 = M_f^{d+2} L^d$$

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



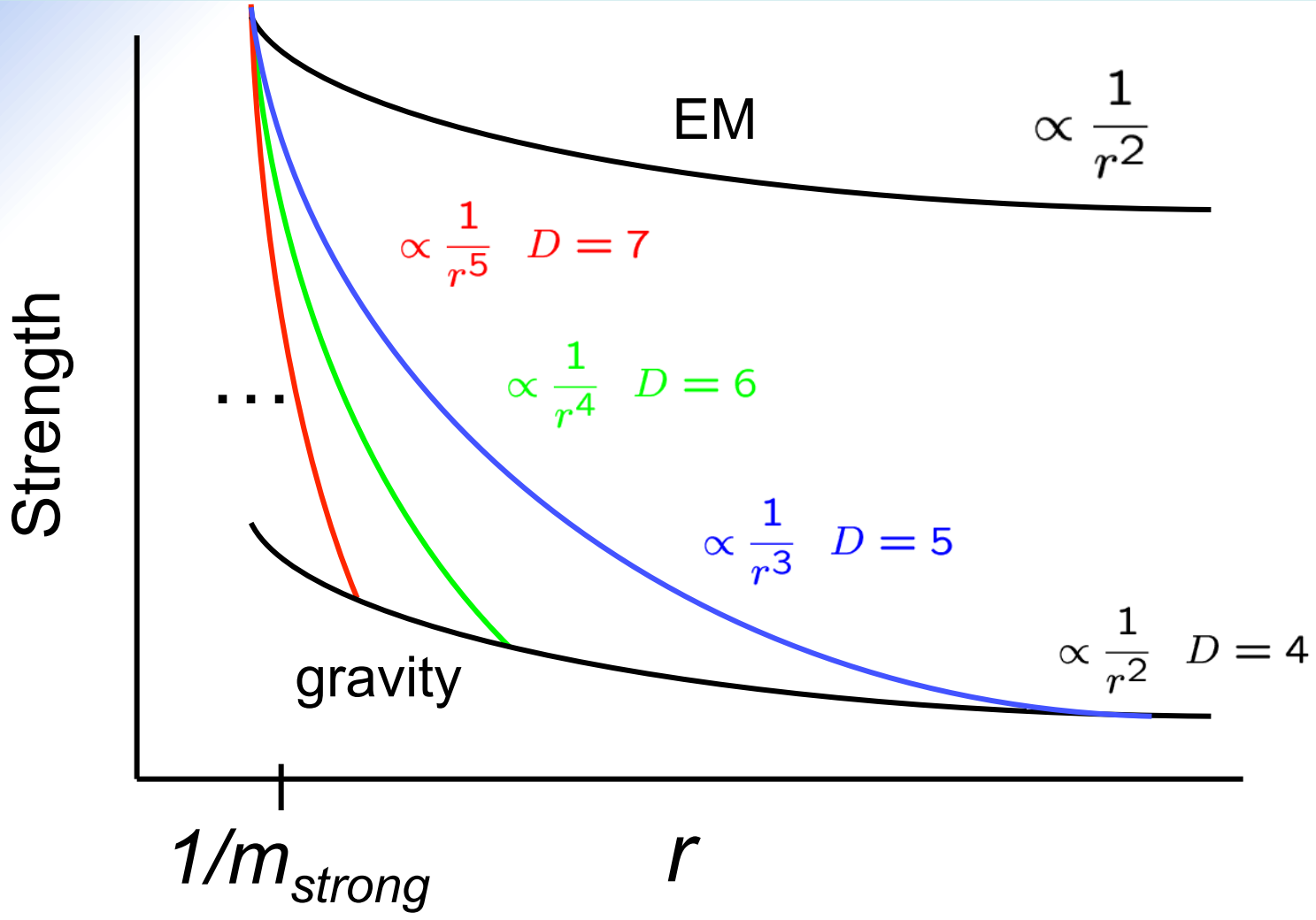
Newton as we know him:

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

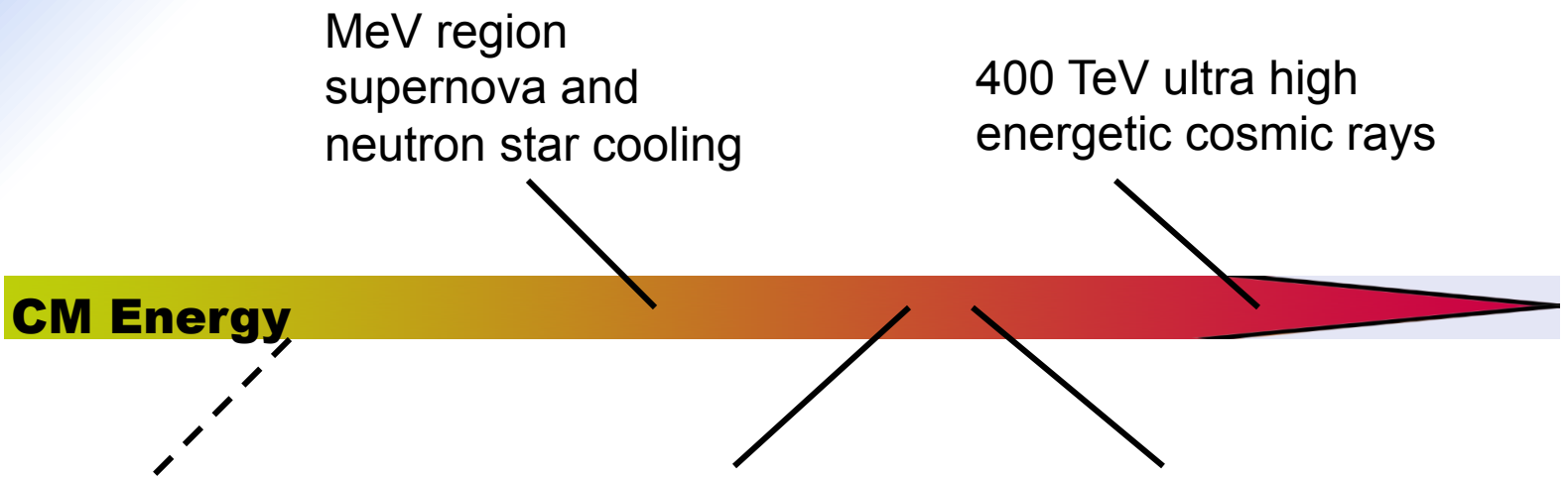
Matching:

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

Gravity in Extra Dimensions



Observables of LXDs



More than 2 XD
Newton checked to μm
range

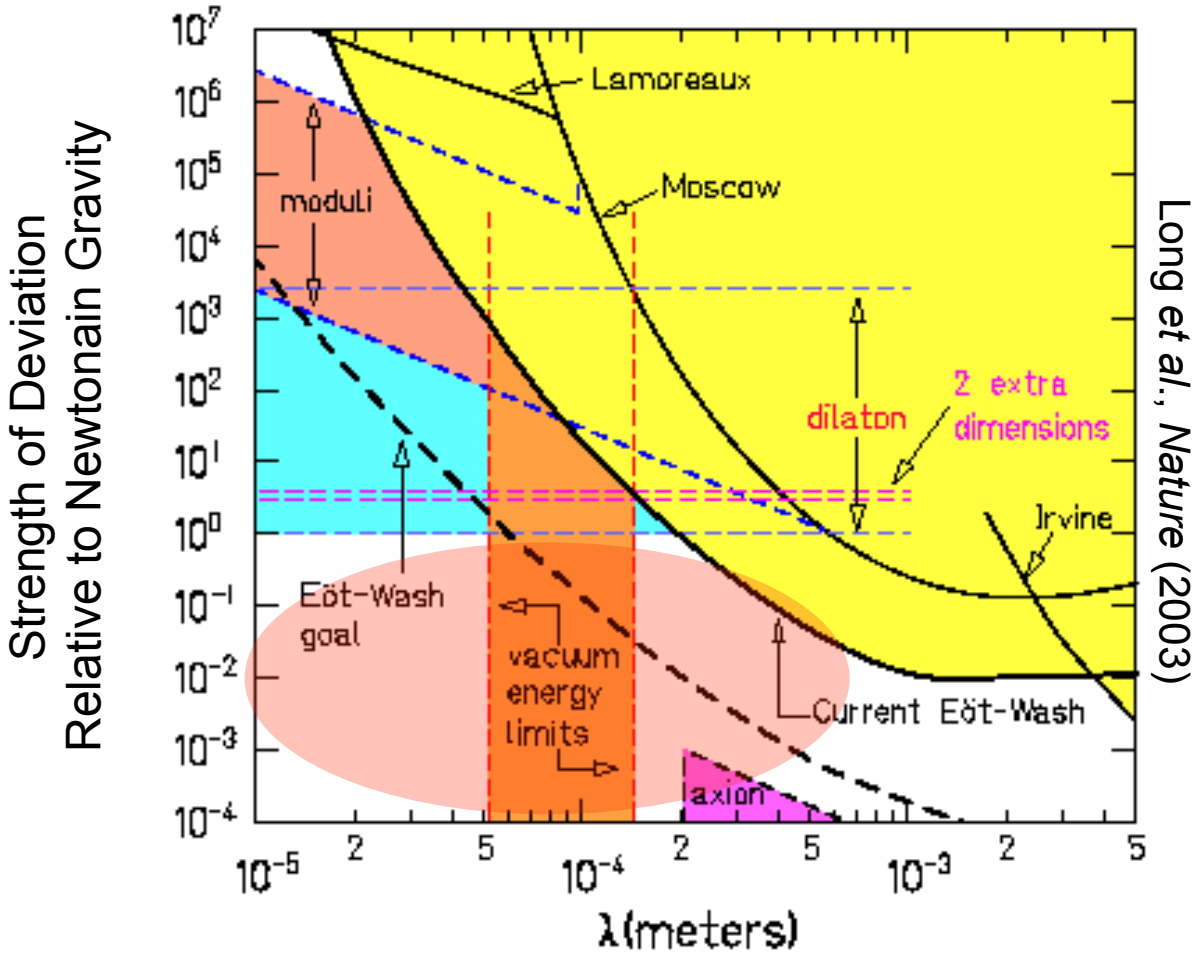
Possible observables:
- microscopic black holes

- 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

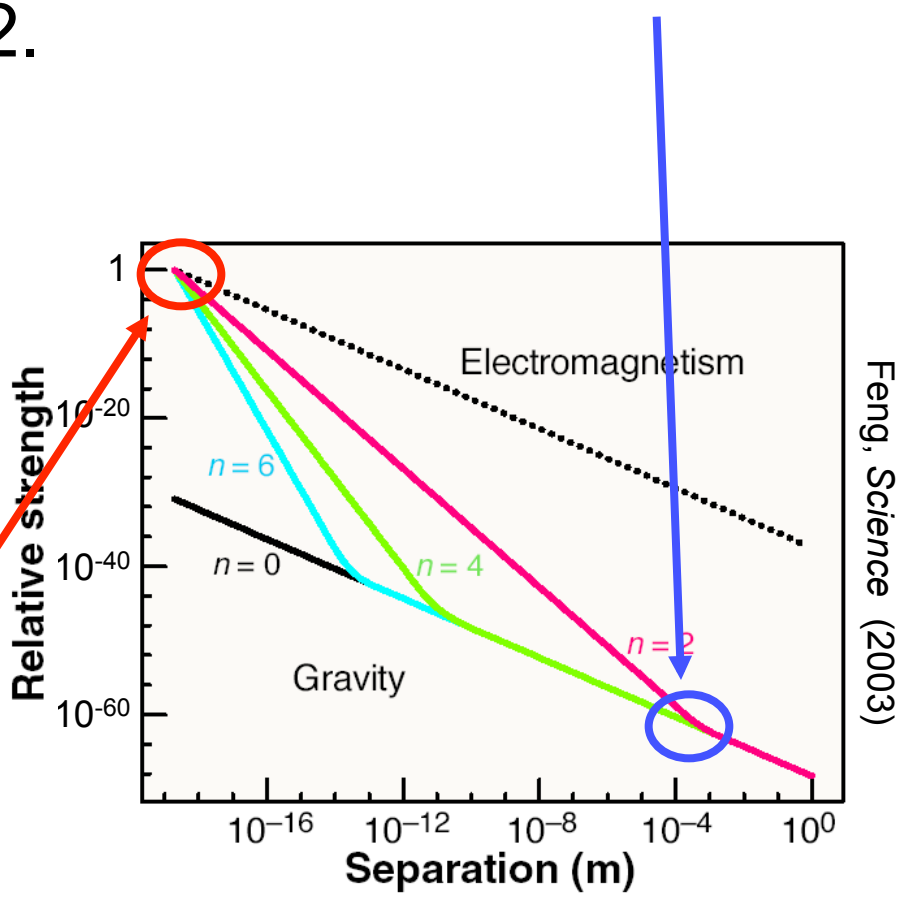


Constraints

- Tests of Newtonian gravity eliminate n = 1,2, but are ineffective for n >2.

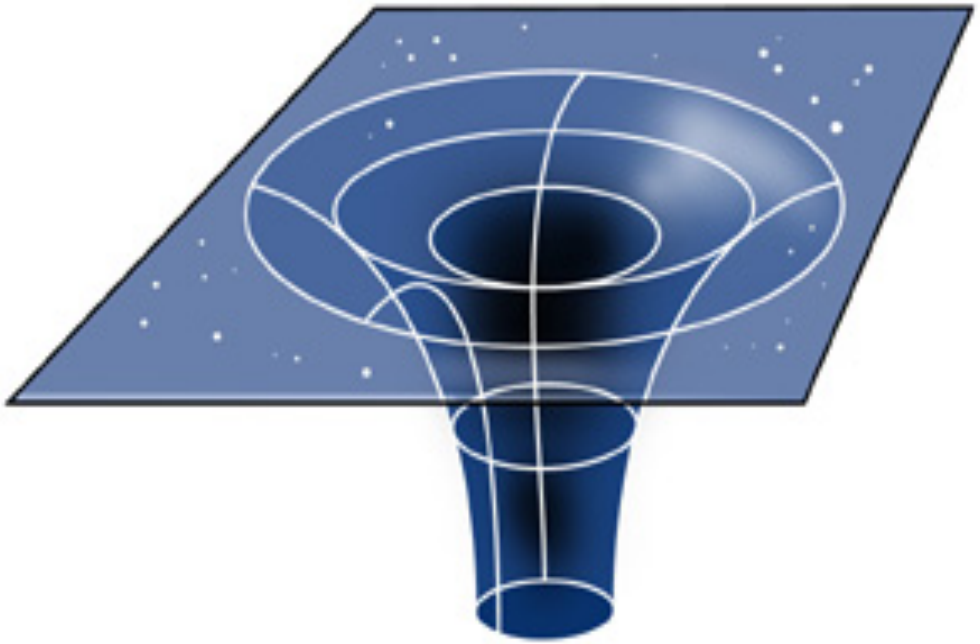
- Astrophysical probes (supernova cooling) provide even more stringent constraints, eliminate n = 2,3,4, but are ineffective for n >4.

- A better strategy: probe small distances, high energies.



Black Holes

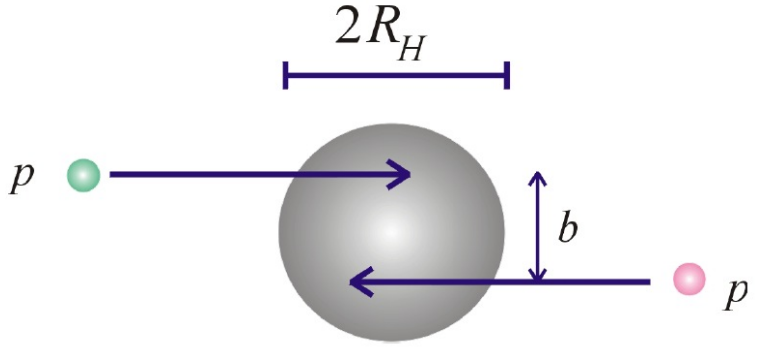
- Solutions to Einstein's equations
- Schwarzschild radius $r_s \sim GM_{BH}$ – requires large mass/energy in small volume
- Light and other particles do not escape; classically, BHs are stable



BHs from Particle Collisions

- BH creation requires

  $E_{COM} > m_{grav}$

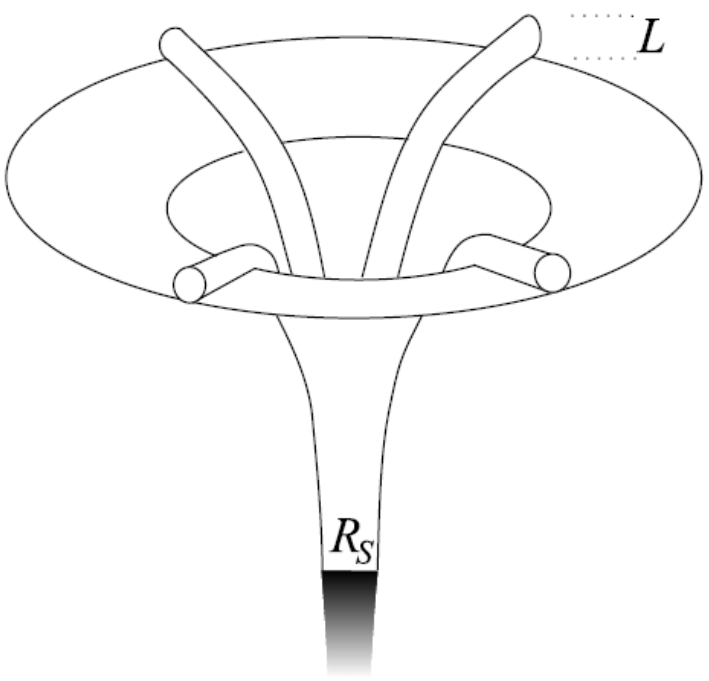


Penrose (1974)
Banks, Fischler (1999)
Bleicher, Hossenfelder (2001)

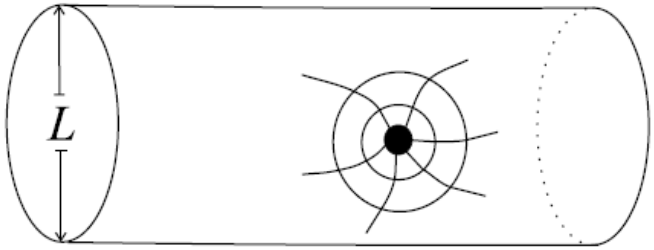
- In 4D, $m_{grav} \sim 10^{15}$ TeV,
  far above accessible energies ~ TeV

- But with extra dimensions, $m_{grav} \sim$ TeV is possible, can create micro black holes in particle collisions!

Which setting is relevant?



- Typical collider black holes are small than the diameter of the extra dimensions in ADD



→ Allows to neglect boundary conditions

- First papers on black hole production at LHC:
- Argyres, Dimopoulos, March-Russel, Phys.Lett.B441:96-104,1998
- Banks and Fishler, hep-th/9906038
- Dimopoulos, Landsberg, Phys.Rev.Lett.87:161602,2001, “Black holes at the LHC”
- Giddings and Thomas, Phys.Rev.D65:056010,2002, “High energy colliders as black holes factories”

The Schwarzschild radius

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

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

Why do LXD make a difference?

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

Thornes hoop conjecture

- BH cross section is $\sigma(XX \to \text{BH}) = \pi R_S^2$

→ $\sigma(p_1p_2 \to \text{BH}) \sim 400$ pb

Still vital discussion of this (classical) cross sections

- S. Dimopoulos and G. Landsberg Phys. Rev. Lett. **87**, 161602 (2001).
- M. B. Voloshin, Phys. Lett. B **518**, 137 (2001); Phys. Lett. B **524**, 376 (2002).
- S. B. Giddings, ed. N. Graf, eConf **C010630**, P328 (2001).
- S. N. Solodukhin, Phys. Lett. B **533**, 153 (2002).
- H. Yoshino and V. S. Rychkov, Phys. Rev. D **71** (2005) 104028 ...

Consens 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

Black Holes at Colliders

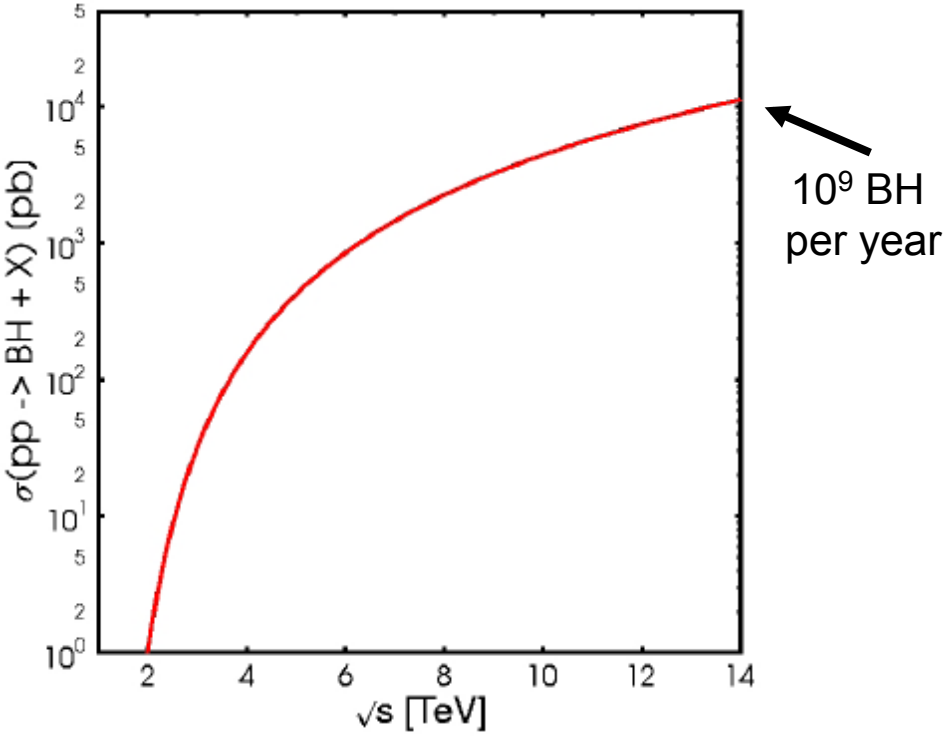
- BH created when two particles of high enough energy pass within ~ r_s .

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

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

- Large Hadron Collider:
  E_{COM} = 14 TeV
  $pp \rightarrow$ BH + X

- LHC prediction: 100 black holes per second



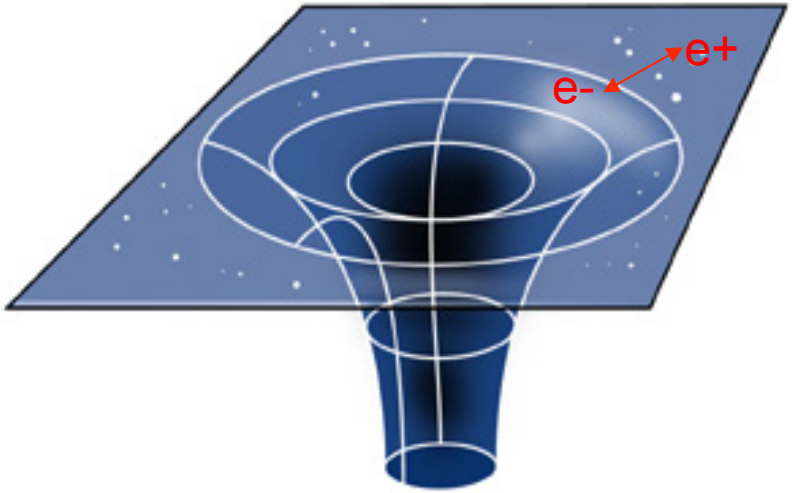
LHC: S. Hossenfelder, M.B., et al., PRD 66 (2002)
Tevatron: M. Bleicher et al., PLB548 (2002)

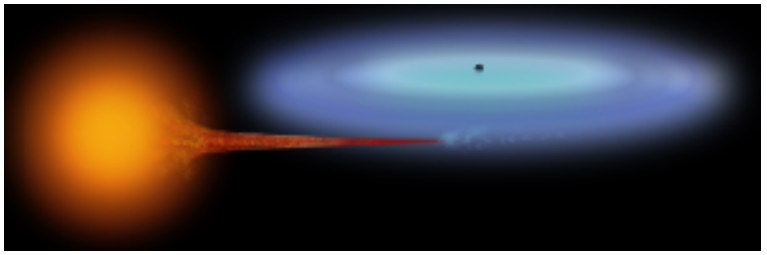
Black Hole Evaporation

- 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





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

  - Y. B. Zel'dovich, in: "Proc. 2nd Seminar in Quantum Gravity", edited by M. A. Markov and P. C. West, Plenum, New York (1984).
  - R. J. Adler, P. Chen and D. I. Santiago, Gen. Rel. Grav. **33**, 2101 (2001)
  - J. D. Barrow, E. J. Copeland and A. R. Liddle, Phys. Rev. **D 46**, 645 (1992).
  - S. Coleman, J. Preskill and F. Wilczek, Mod. Phys. Lett. **A6** 1631 (1991).
  - S. Hossenfelder, M. Bleicher, S. Hofmann, H. Stocker and A. Kotwal, Phys. Lett. B **566**, 233 (2002)
  - M. Bonanno, M. Reuter, Phys. Rev. D 73 (2006)

Signatures

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

Event Characteristics

Decay Signature

Average of ~ 6 particles for each decay, emitted spherically

~120 Particle degrees of freedom

→ ~ 1% chance for each.

Summing over spin and color gives:

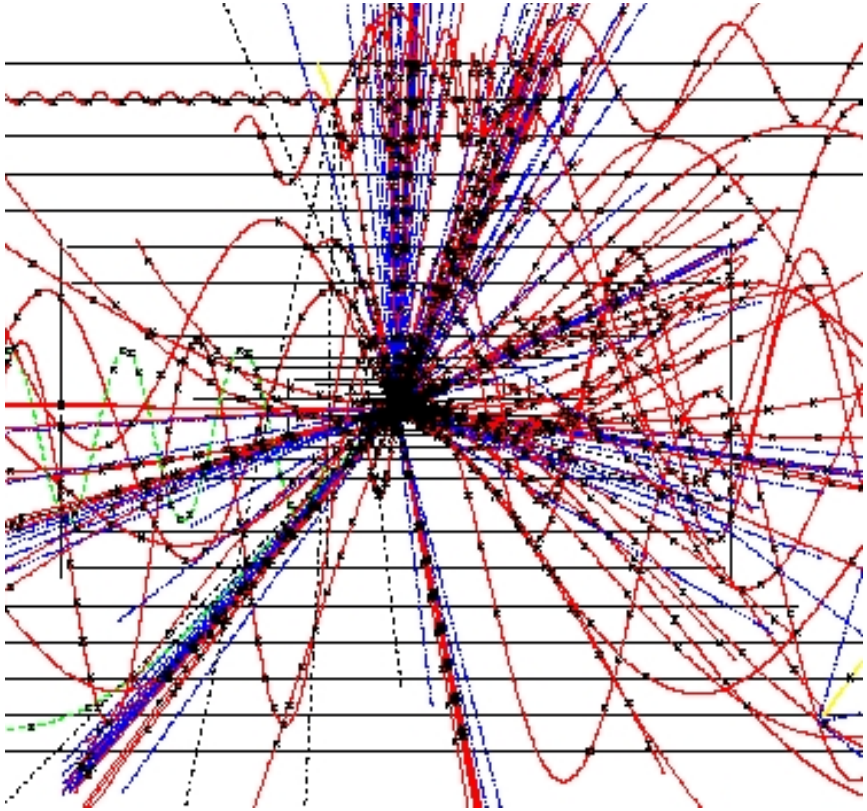
- 75 % quarks and gluons
- 10 % charged leptons
- 5 % neutrinos
- 5 % photons or W/Z bosons
- Also get new particles around 100GeV,

Small fraction of invisible neutrinos and gravitons

→ BH's easy to reconstruct

10% high PT leptons → trigger

S. Vahsen (2008)



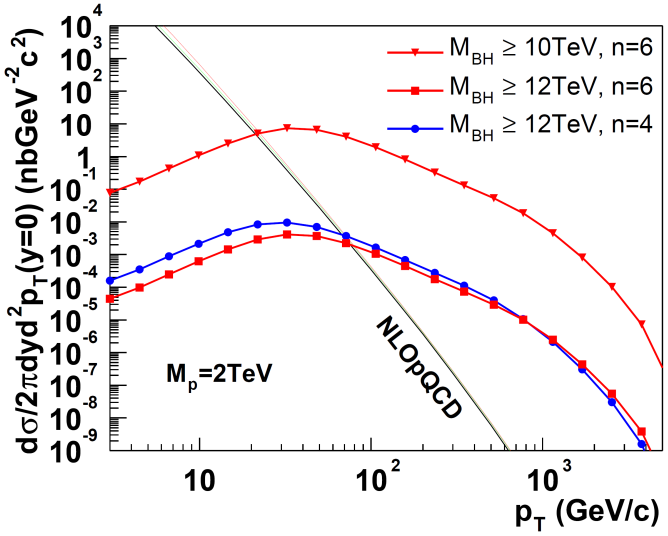
De Roeck (2002)

Hadron spectrum

- Get hadron spectrum from parton fragmentation

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

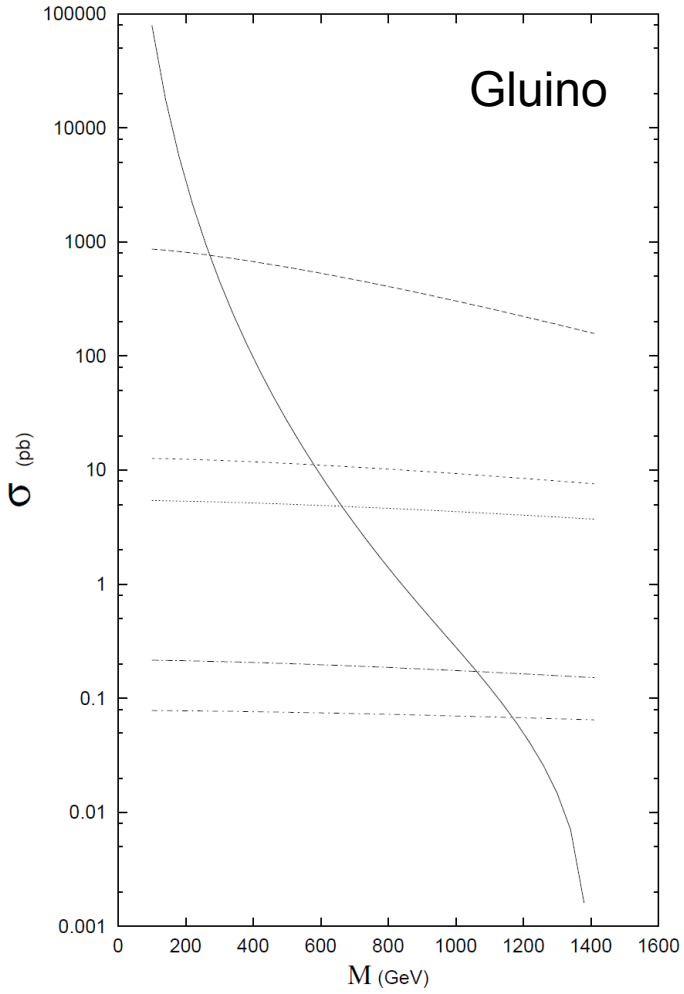
- Charged hadrons from BHs exceed pQCD at high pT
- Bump near Hawking temperature

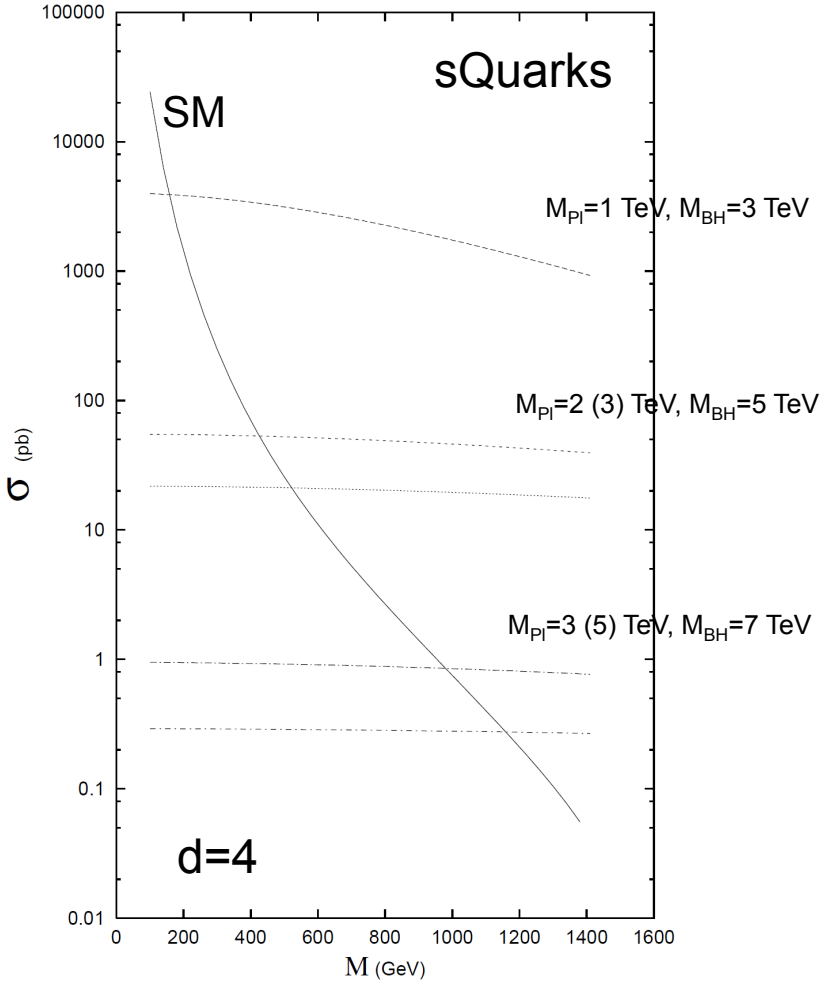


From I. Sarcevic et al (2007)

Exotic particle production

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

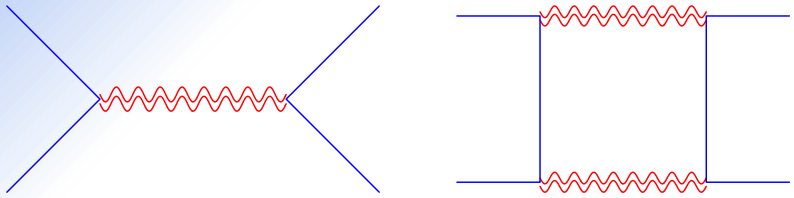




Constraints from LHC

- Exotic particle search
- Indirect constraints on the exchange of gravitons
- 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

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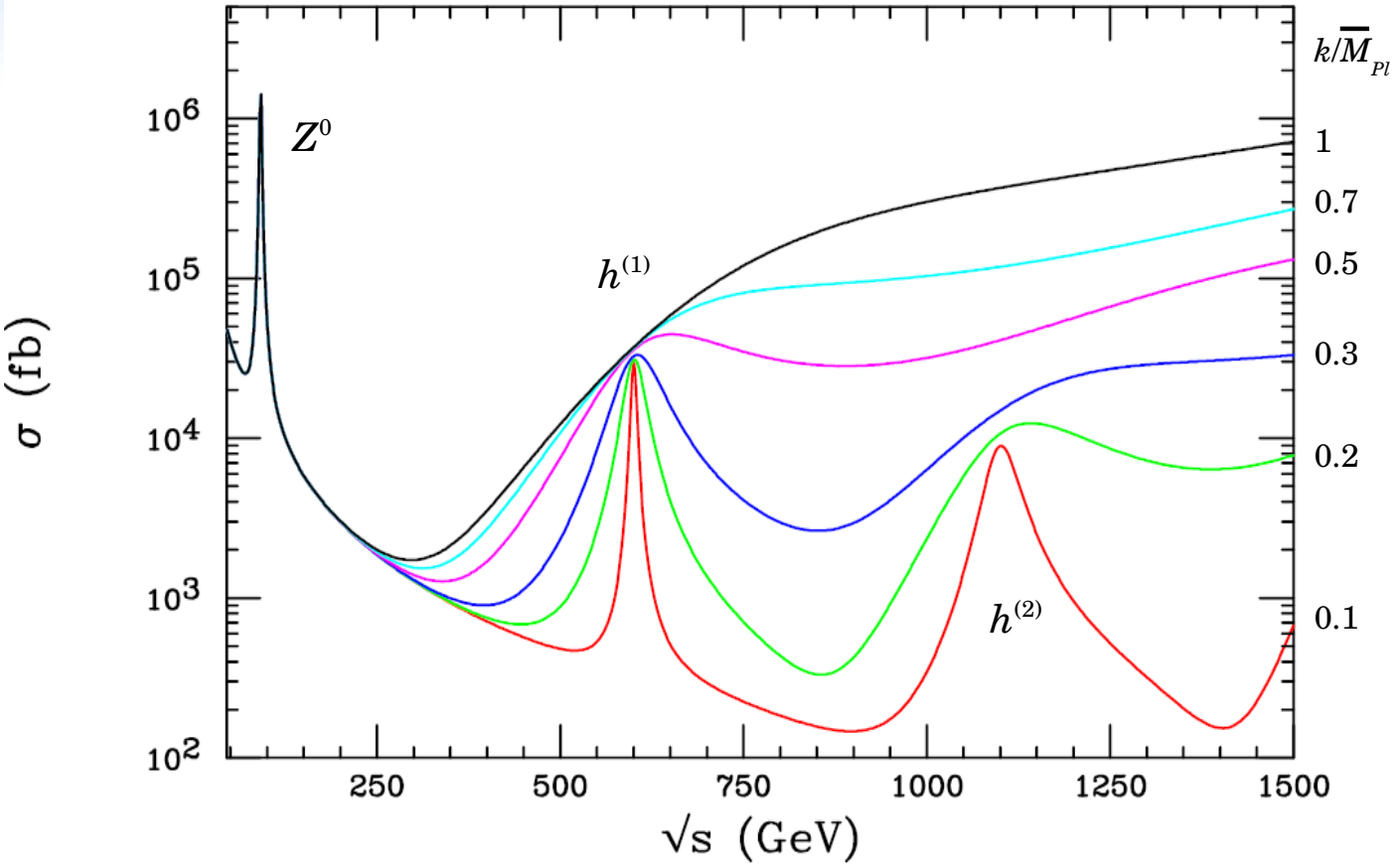
Limits on the loop level exchange

from Francheschini et al, JHEP05(2011)092

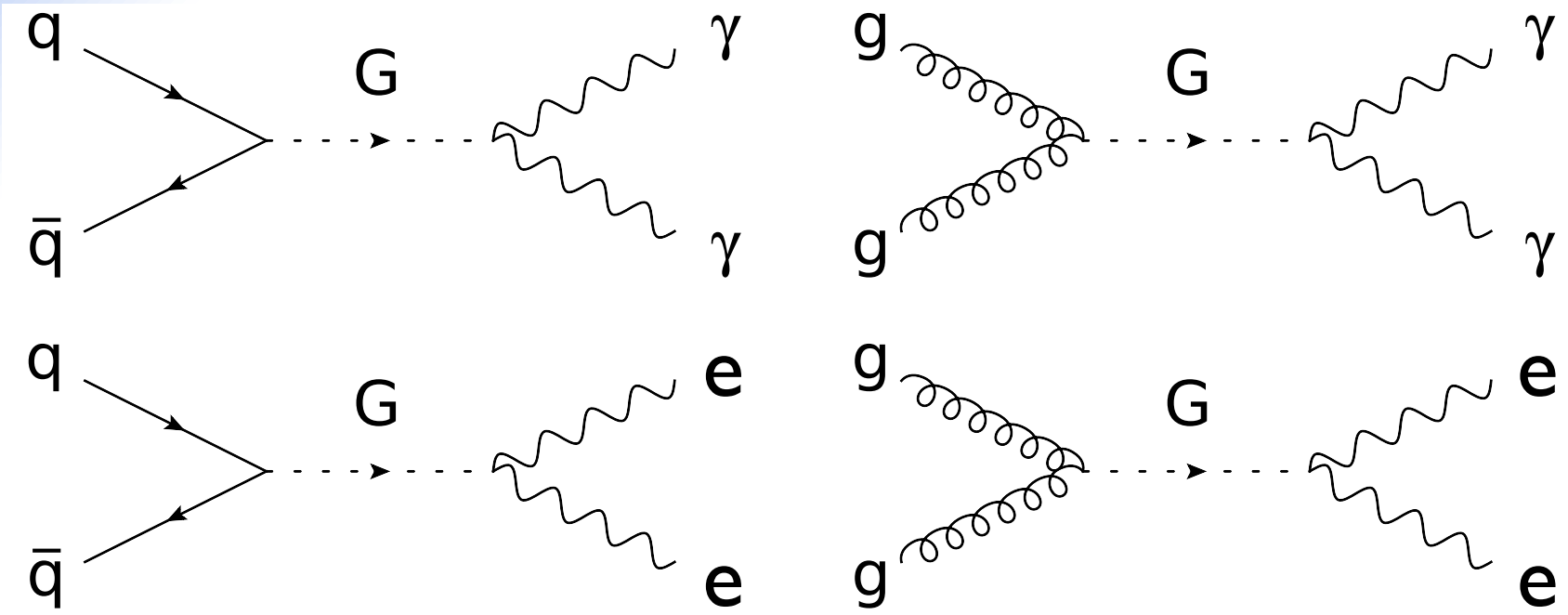
Randall-Sundrum KK (I)

arXiv:hep-ph/9909255v1



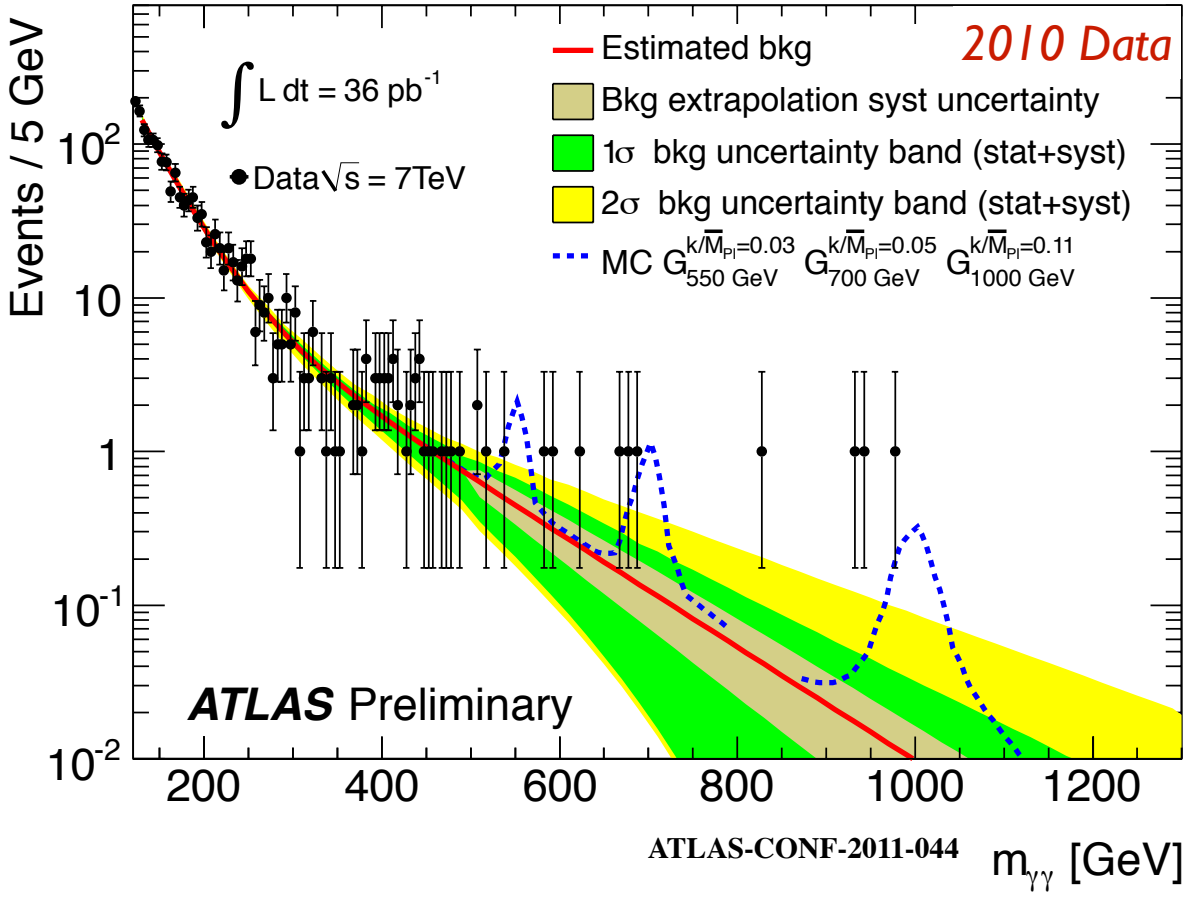
from Evan Wulf (ATLAS)

Randall-Sundrum KK (II)

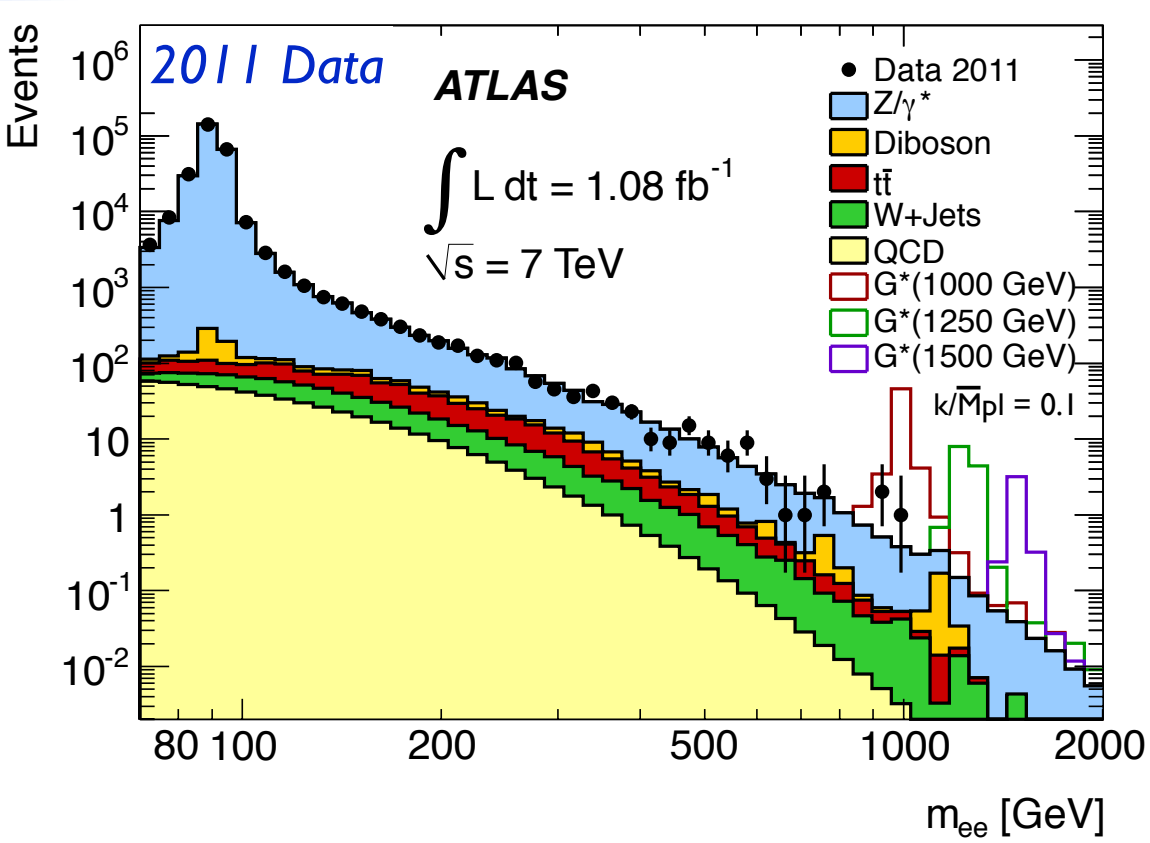


from Evan Wulf (ATLAS)

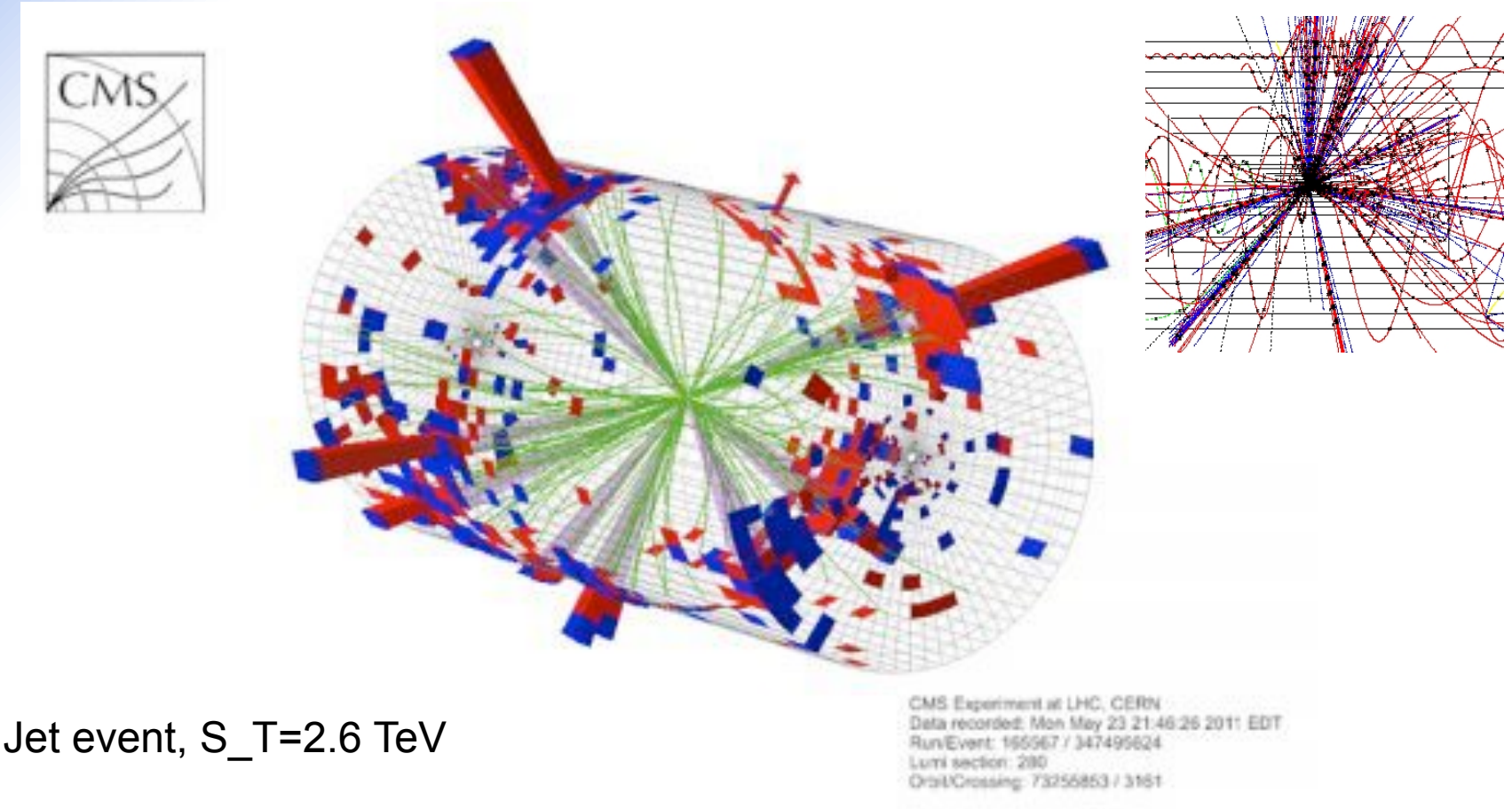
Randall-Sundrum KK (III)



Randall-Sundrum KK (IV)

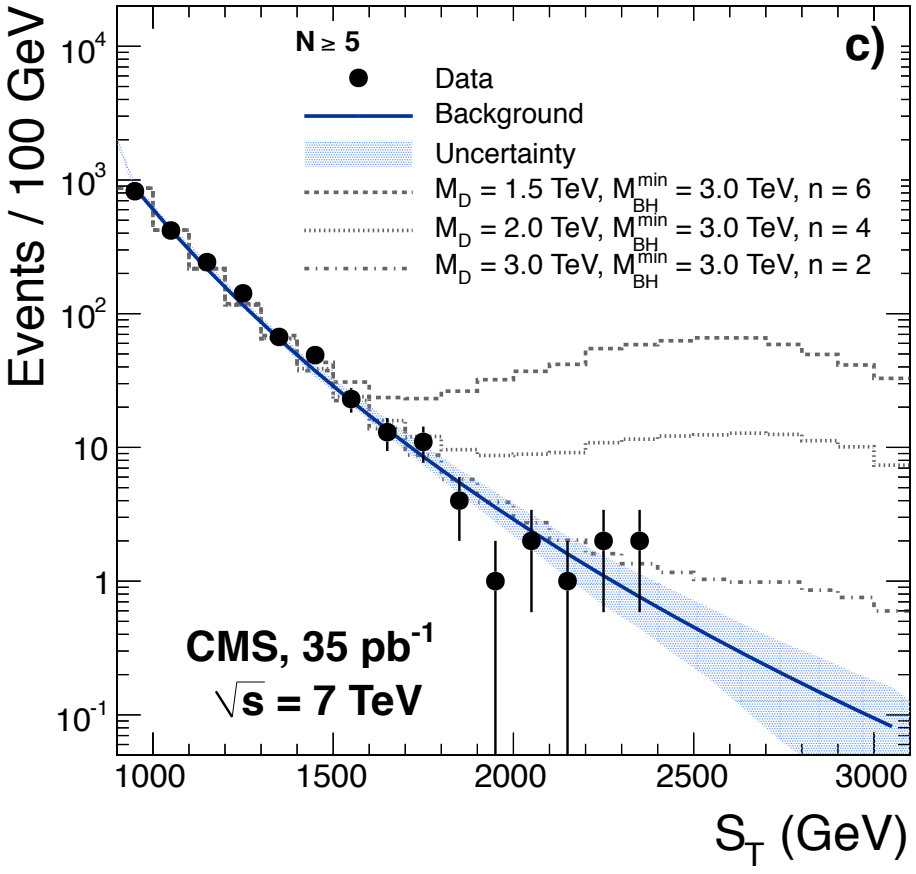


Direct black hole search

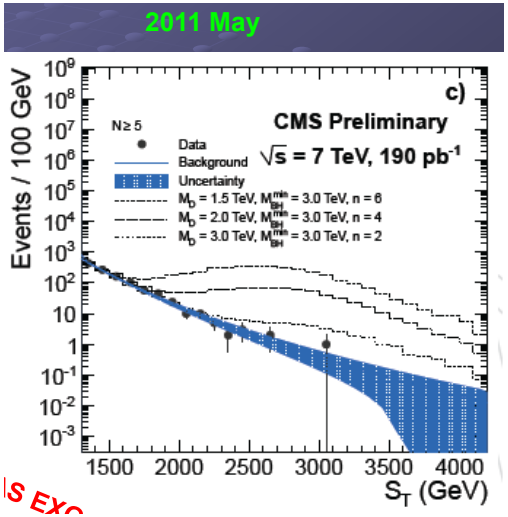


9 Jet event, S_T=2.6 TeV

Direct black hole search (I)



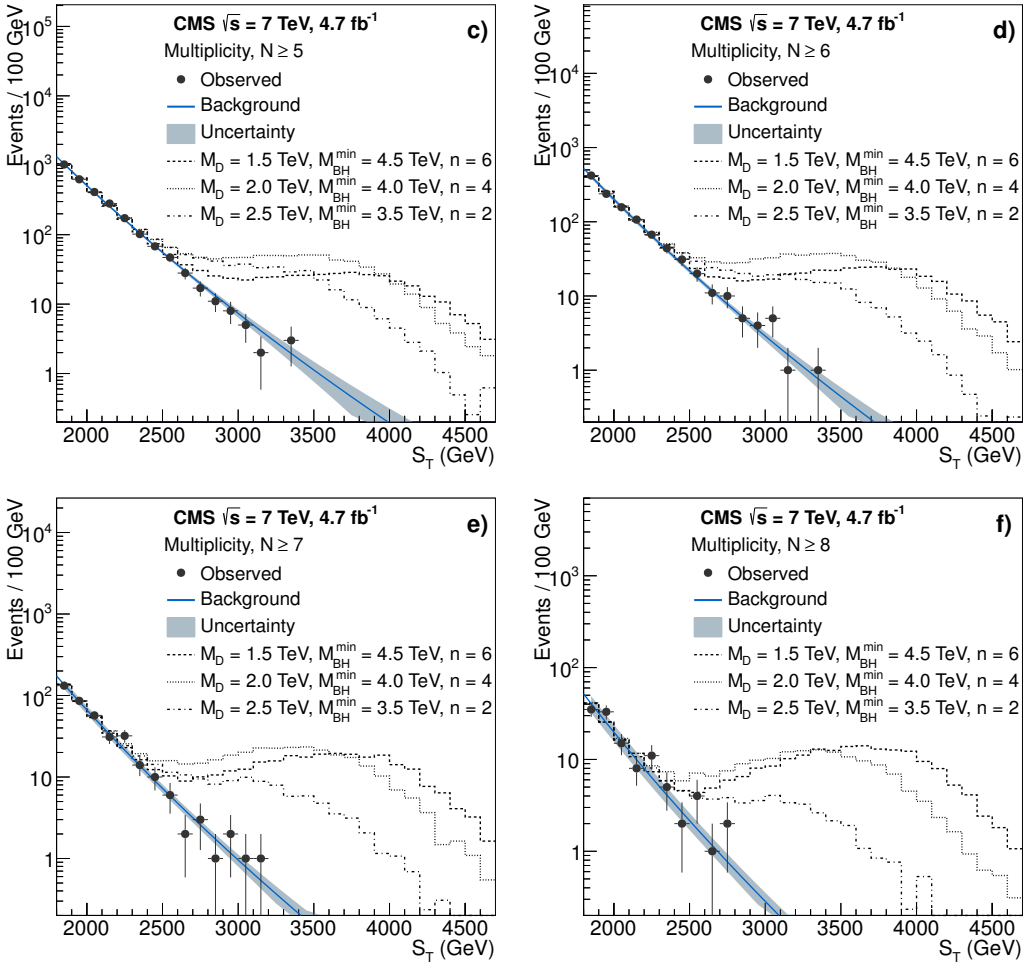
- Search for high E_T multi-particle final states
- Similar results for N>2 final state particles
- No deviations from Standard Model observed!



S_T is summed E_t is acceptance

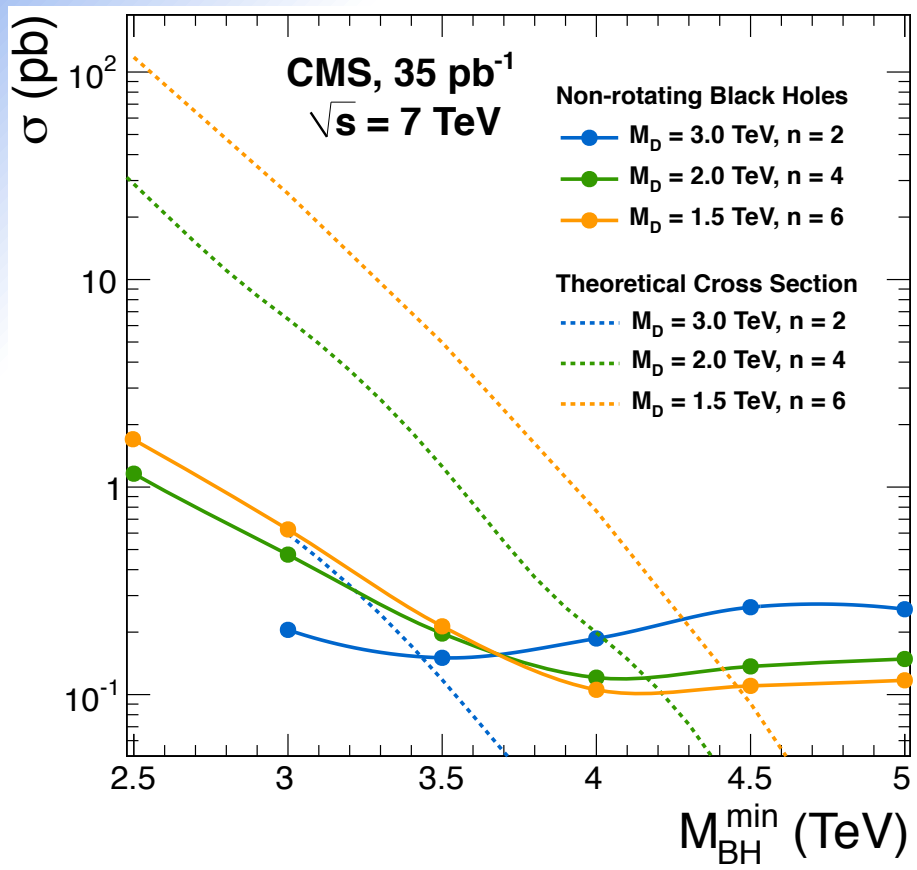
CMS, arxiv:1012.3375

Latest results

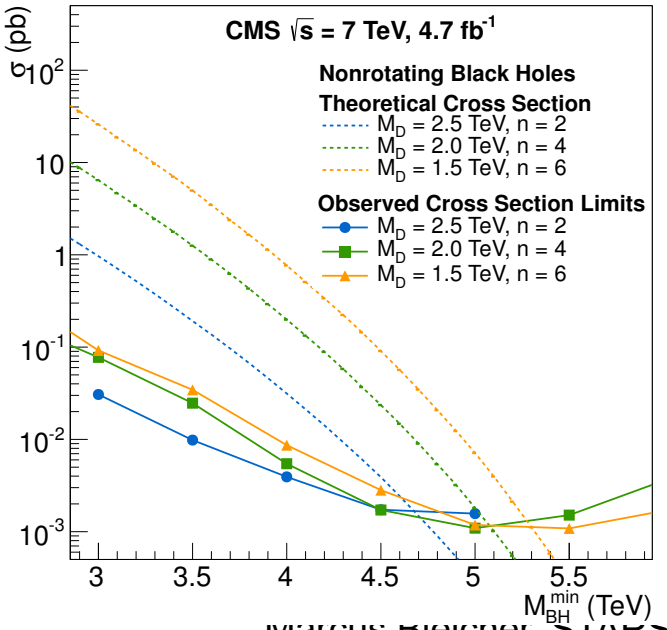


CMS, JHEP04 (2012)61

Direct black hole search (II)



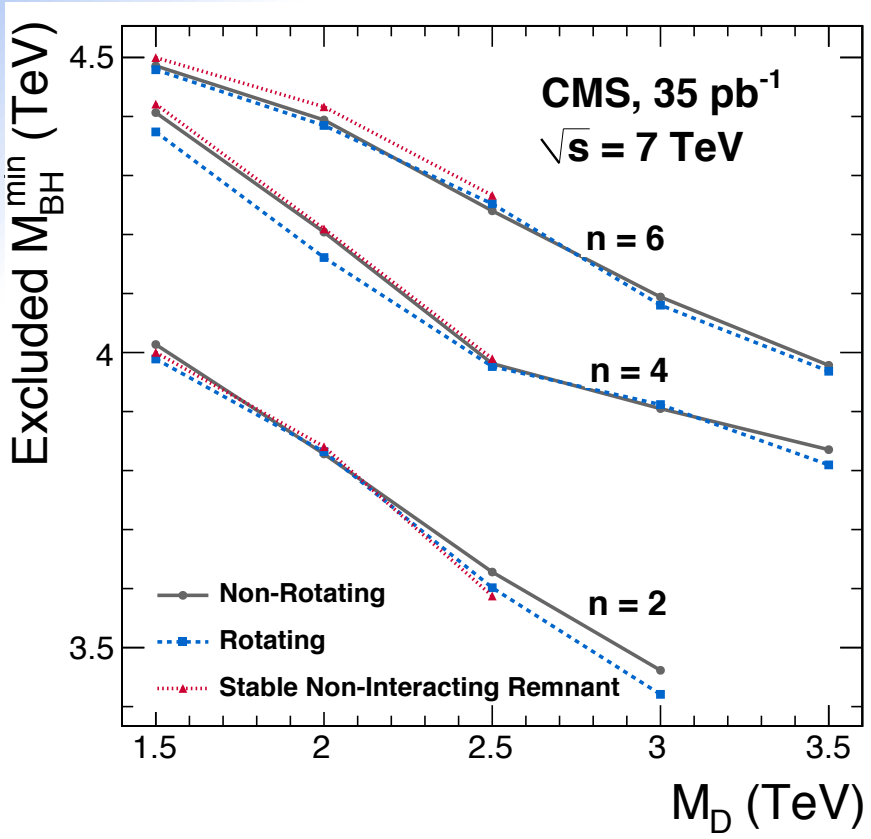
- Upper limits on the production cross section
- Stringent limit for M_BH<4.5-5 TeV



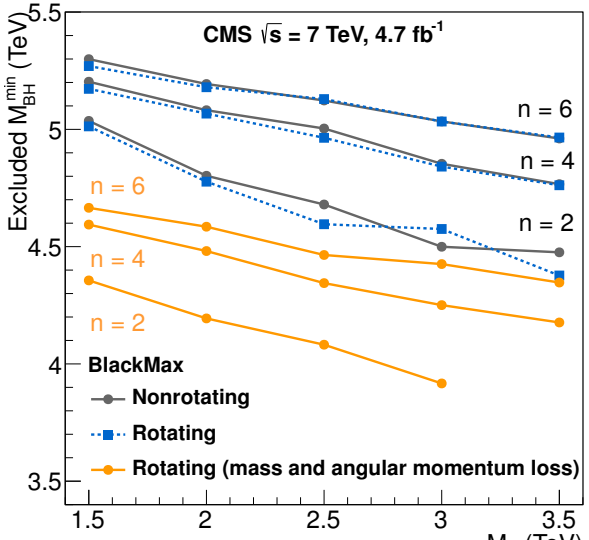
CMS, arxiv:1012.3375

CMS, JHEP04 (2012)61

Direct black hole search (III)



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



CMS, arxiv:1012.3375

CMS, JHEP04 (2012)61

Conclusion

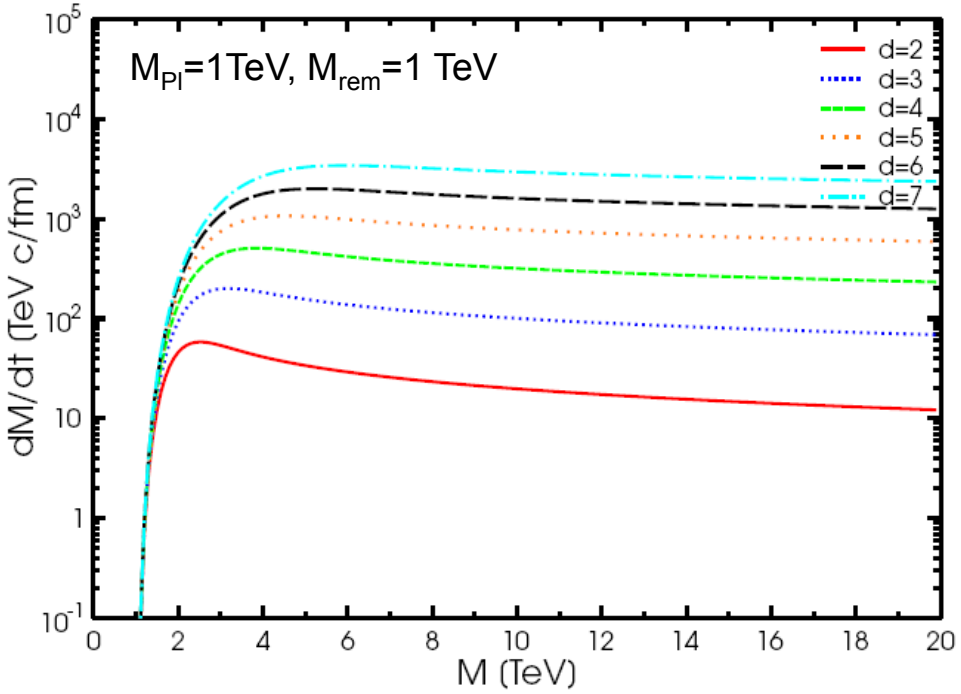
- Mini Black Holes, Gravitons, extra dimensions are still an interesting idea
- However:
  - No signals of BHs observed at LHC
  - Also no signal of Gravitons at LHC
  - Also no signal of non-commutativity

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)

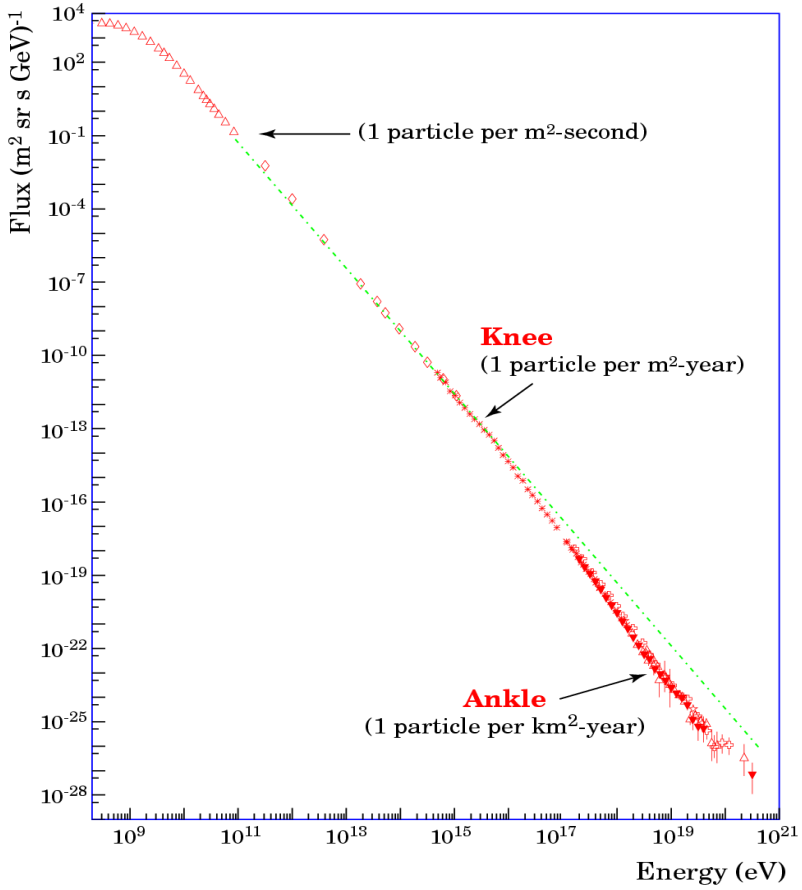
See also
Bonano, Reuter (Renormalized coupling constant) and Rizzo et al (Modified gravity)

→ Same effect, different origin

Black Holes from Cosmic Rays

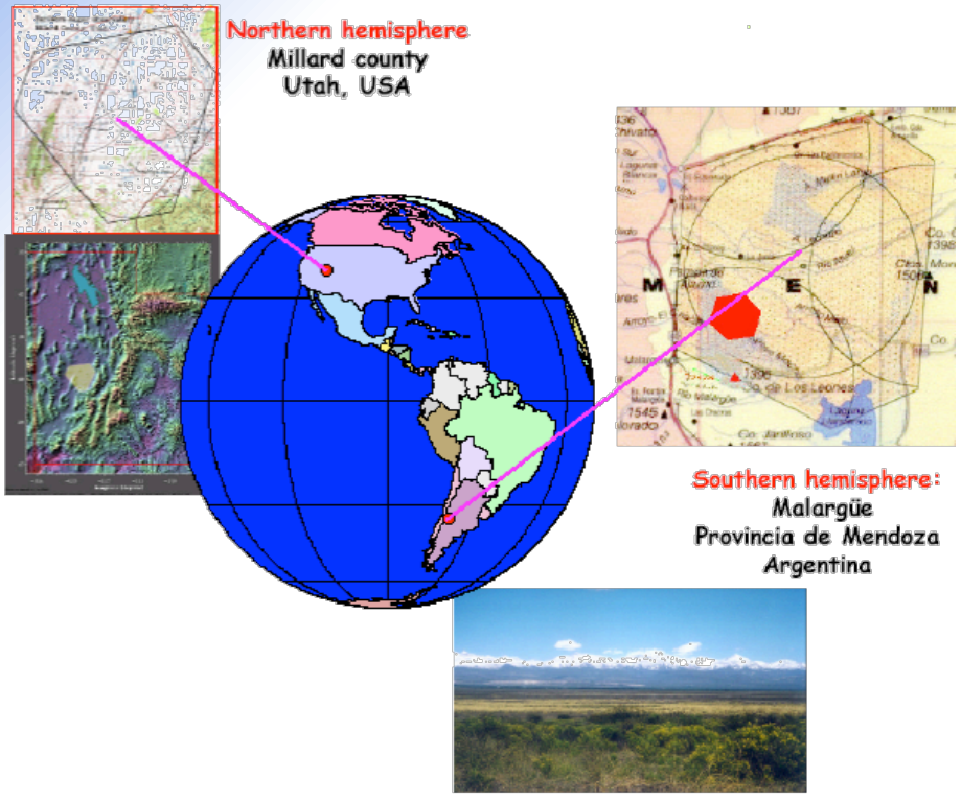
- Cosmic rays – Nature's free collider
- Observed events with 10^{20} eV produces

  E_{COM} ~ 500 TeV
- But meager fluxes. Can one use this energy?



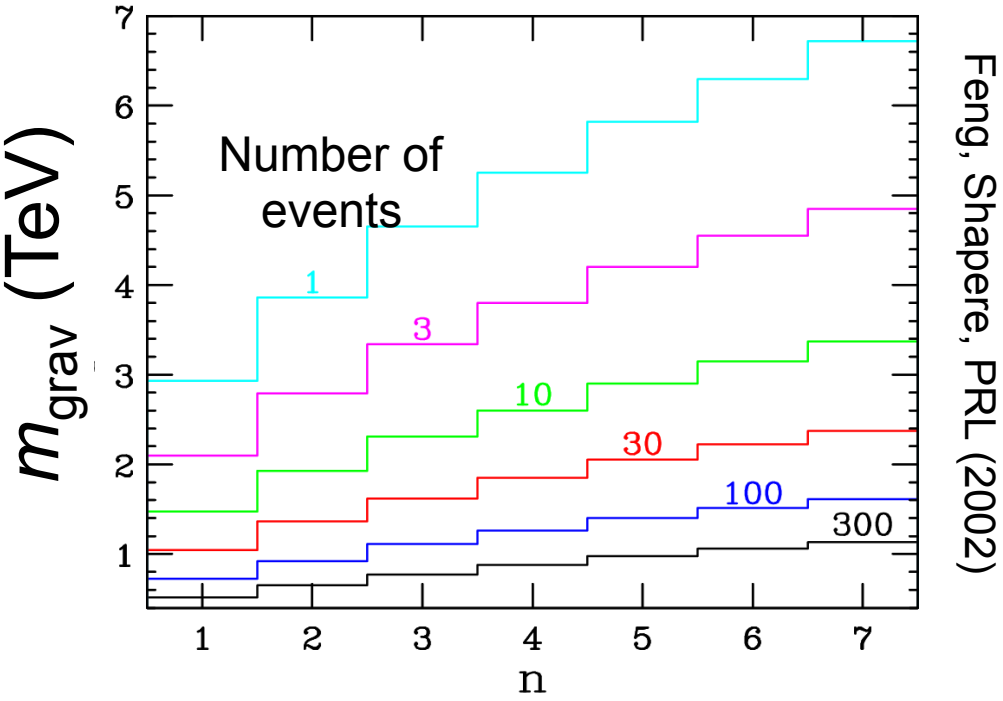
Kampert, Swordy (2001)

Auger Observatory

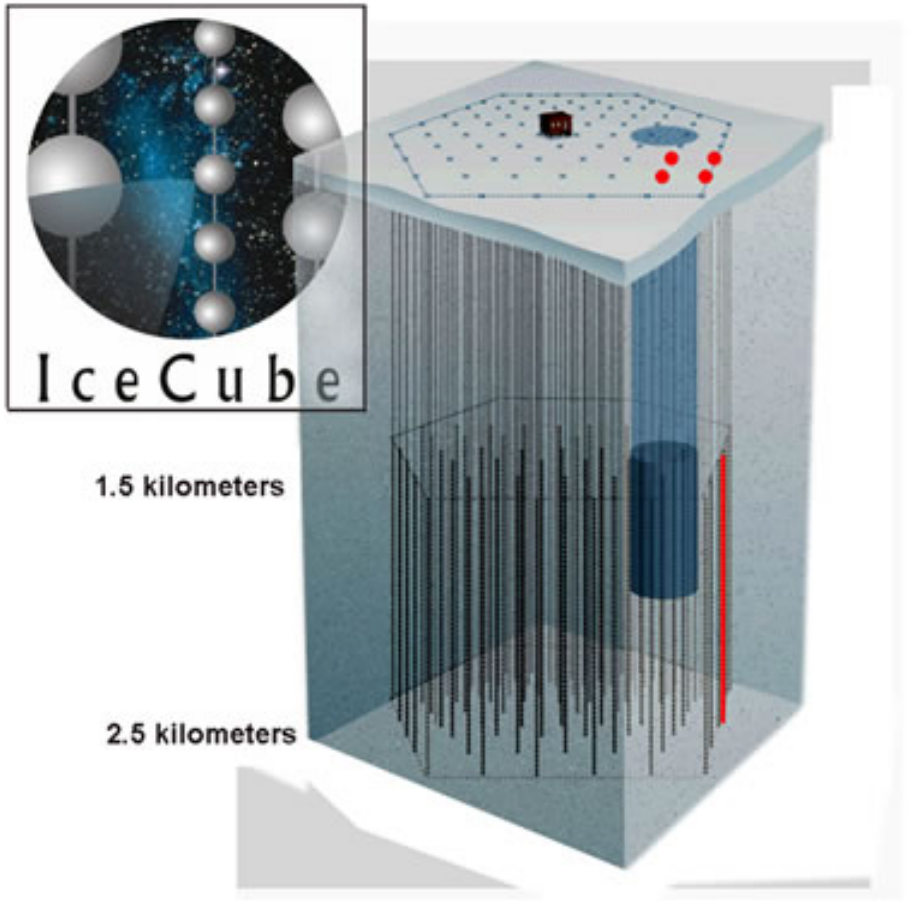


Black holes from cosmic neutrinos

- Currently no such events seen → stringent bound on extra dimensions.
- Auger can detect ~100 black holes in 3 years.



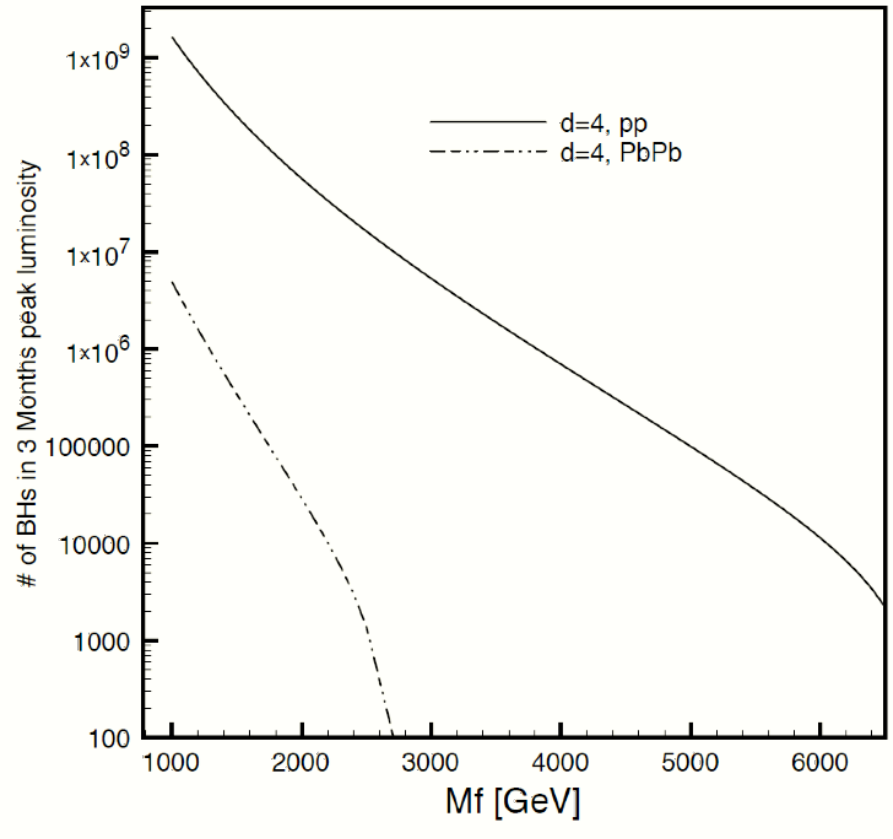
AMANDA/IceCube

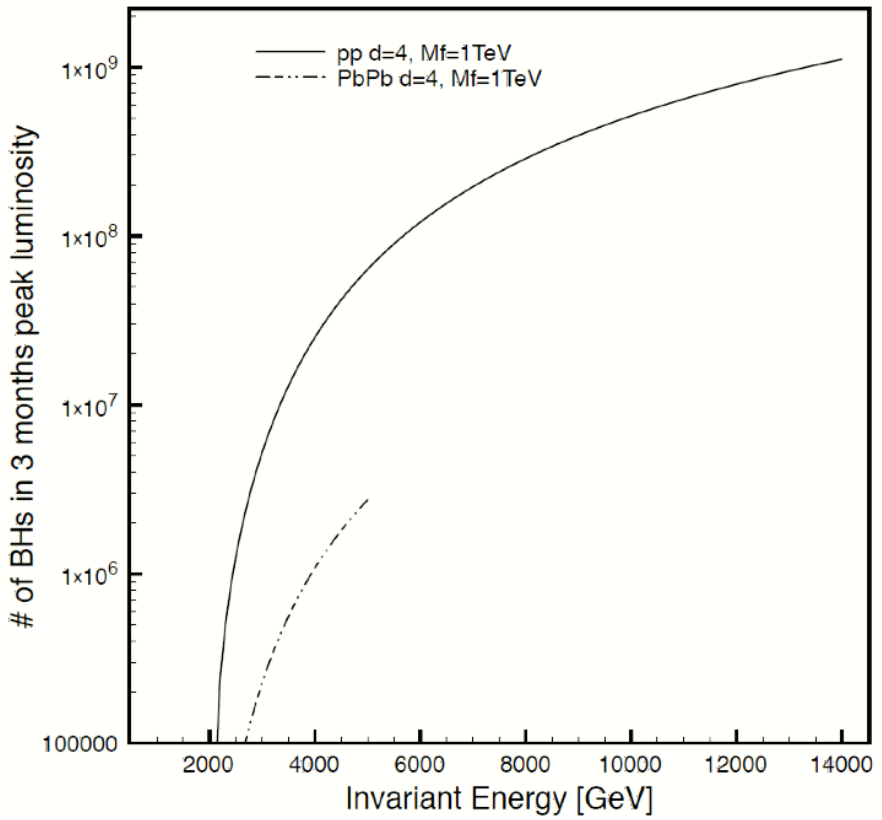


- Neutrino telescopes: promising BH detectors
- Similar rate: ~10 BH/year
- Complementary information
  - BH branching ratios (jets vs. muons)
  - Angular distributions

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

Pb+Pb vs pp

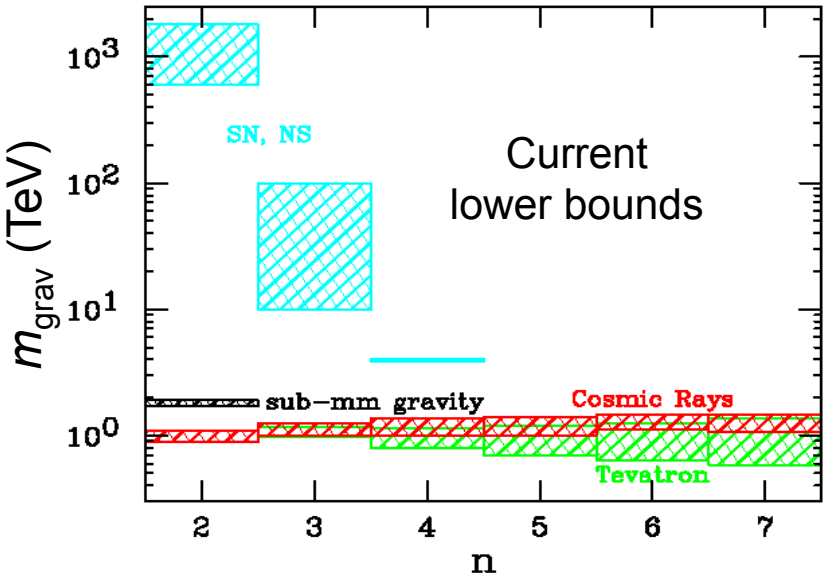




Luminosity difference: 10^{27} vs 10^{34} /cm/s

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!