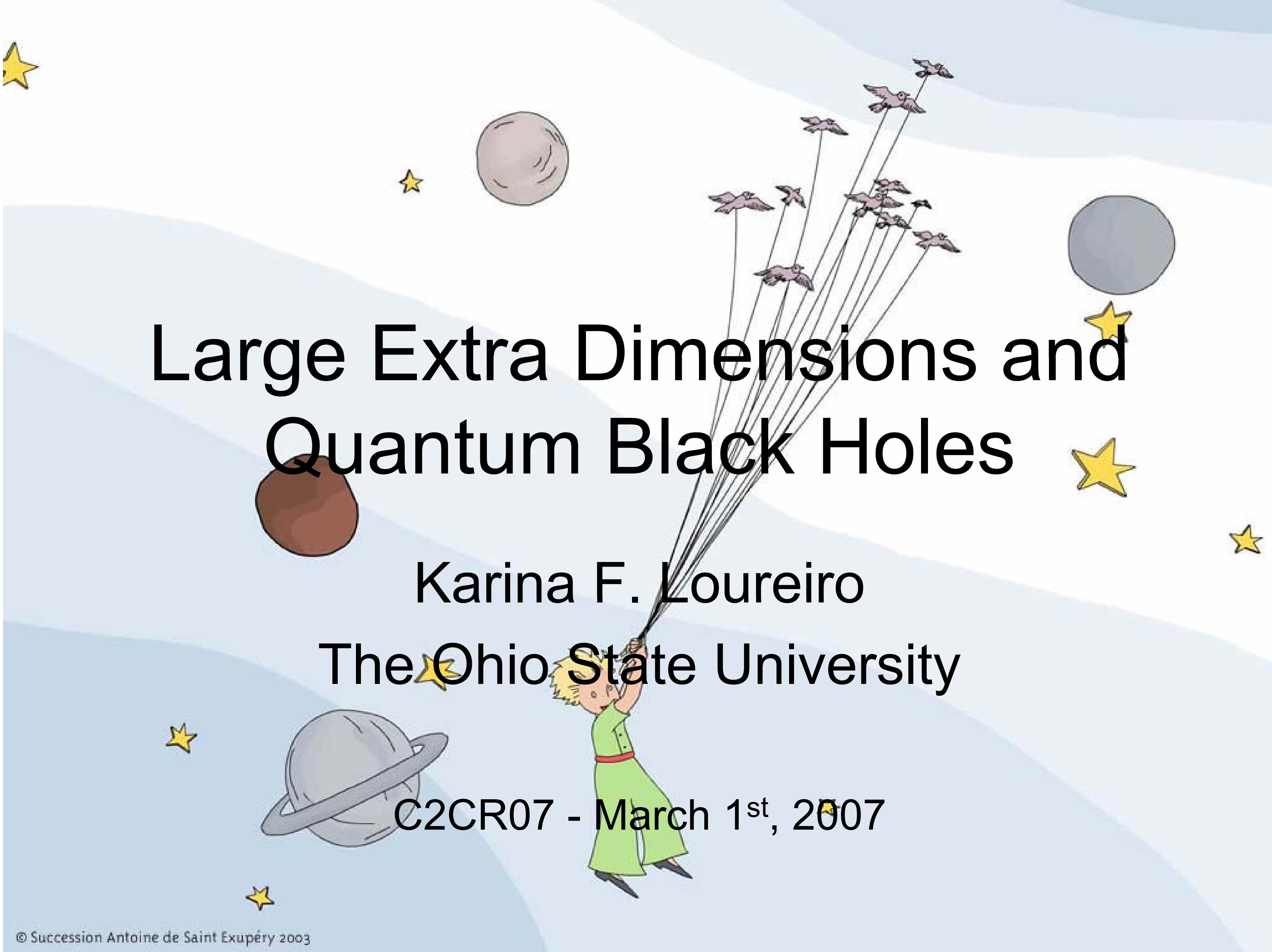

Large Extra Dimensions and Quantum Black Holes

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C2CR07 - March 1st, 2007

Outline

- Motivation
- “Large” Extra Dimensions
  - Some history is always nice…
  - Newtonian gravity and ED (Inverse Square Law Test)
  - Models for ED
    - Arkani-Hamed, Dimopoulos, Dvali (and others)
    - Randall-Sundrum
- Black Holes
  - Black Holes in astronomy
  - Black Holes in accelerators
  - Black Holes from cosmic rays
- Experimental Bounds on the Planck Scale
- Conclusions

Motivation:

A quantum theory of gravity?

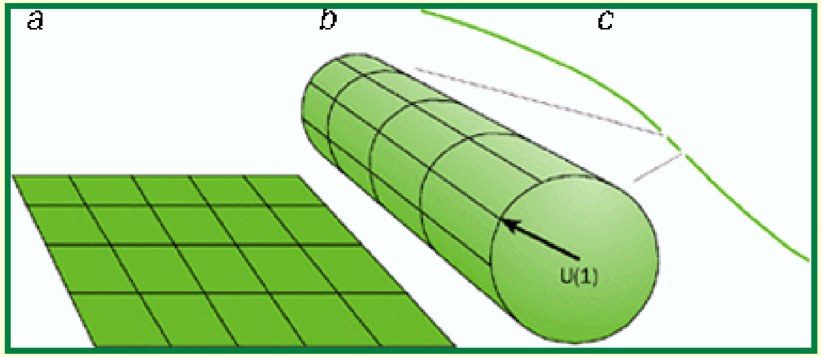
- Two major problems have not been resolved yet:
  - The hierarchy problem
  - The cosmological constant problem
- The existence of new dimensions can help in the resolution of these two conundrums and might (dis)prove the fact that gravity becomes strong at sub-millimeter distances (ADD and RS)
- New physics phenomena can be brought to light if we consider that the fundamental Planck scale could be as low as 1TeV for “n > 1” (ADD)
- If $M_{Pl} \sim m_{EW}$, black hole production and evaporation could be observed in collisions of elementary particles

Large Extra Dimensions

Where are they?

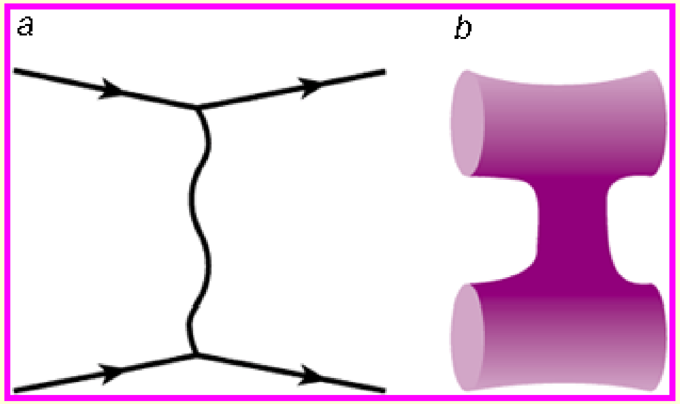
A bit of history…

- Once upon a time (1921), Theodor Kaluza in the hope of unifying gravitation and electromagnetism extended general relativity by including the U(1) symmetry of electromagnetism by adding a 4th spatial dimension.
- In 1926, Oskar Klein proposed that the fourth spatial dimension is curled up (compactified) in a circle of very small radius "R", therefore a particle moving a short distance along that axis would return where it began.



Source: PhysicsWorld

- In the 1970's and 1980's there's been renewed interest in (multiple) extra dimensions: SUSY and string theory.
- From 1998 onwards, new models have surfaced (ADD, RS, etc.) which address the hierarchy problem by exploiting the geometry of spacetime.



Source: PhysicsWorld

Gravity is automatically included in string theory; there is a vibration mode with the properties of the graviton.

Extra Dimensions in Newtonian Gravity

The idea is to know how gravity behaves at distances < 1mm, does it still abide by the r^{-2} law or does it change because of the presence of extra compactified dimensions (r^{1-D})?

- If the extra dimensions were non-compact, they would change the law of gravity away from being r^{-2} and the equations of motion of Newtonian gravity would not longer predict stable orbits.

$$dl^2 = g_{ij} dx^i dx^j = dr^2 + r^2 d\Omega_{D-1}$$

$$\nabla^2 \Phi = \partial_i (\sqrt{g} g^{ij} \partial_j \Phi) \sim \partial_r (r^{D-1} \partial_r \Phi)$$

$$\nabla^2 \Phi = 0 \Rightarrow F = -m \partial_r \Phi \sim \frac{G_D}{r^{D-1}}$$

- If the extra dimensions were compact, the force law would still remain as the inverse square law and we could set a lower bound on the Planck Scale.

$$dl^2 = g_{ij} dx^i dx^j$$

$$dl^2 = dr^2 + r^2 d\Omega_{D-2} + R^2 d\alpha^2$$

$$\sqrt{g} \sim R r^{D-2}$$

$$F \sim \frac{G_D}{2\pi R r^{D-2}} = \frac{G_{\hat{D}}}{r^{\hat{D}-1}}$$

$$\hat{D} \equiv D-1, \quad G_{\hat{D}} \equiv \frac{G_D}{2\pi R}$$

Eöt-Wash Experiment: Sub-mm Tests of Inverse Square Law (ISL)

2006

Yukawa addition

$$V(r) = -G\frac{m_1 m_2}{r}\left[1 + \alpha e^{-r/\lambda}\right]$$

$r \geq R$: experimentally relevant

$\alpha = 8n/3$: dimensionless strength parameter

λ : length scale

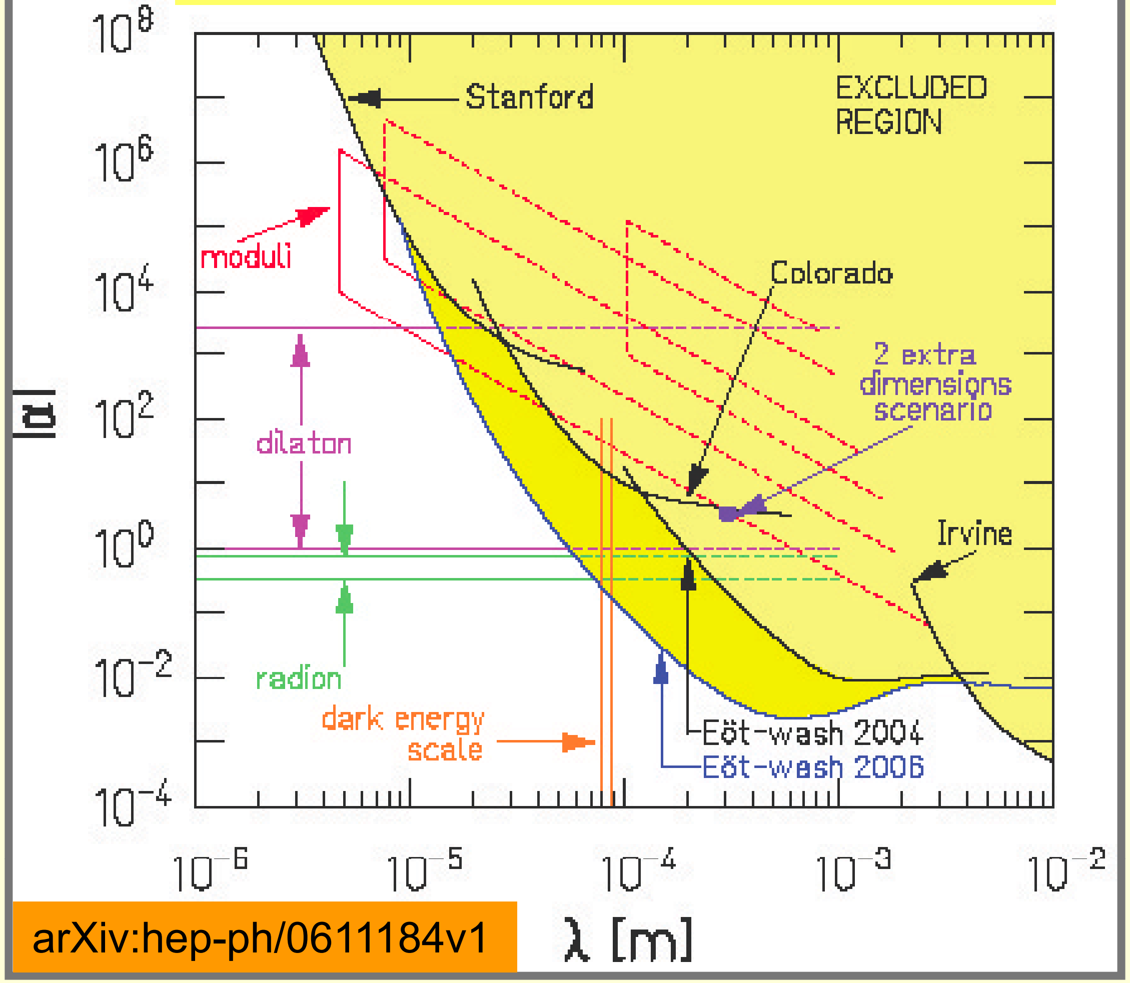
Maximum size of ED ($r_1 >> r_{i=2,\dots,n}$)
EDs are compactified in a torus

Any $|\alpha| \leq 1$ must have $\lambda \leq 56\ \mu m$

Largest ED:
n=1 , R ≤ 44 μm

$M_{D\ (n=2)} \geq 3.2\ TeV/c^2$

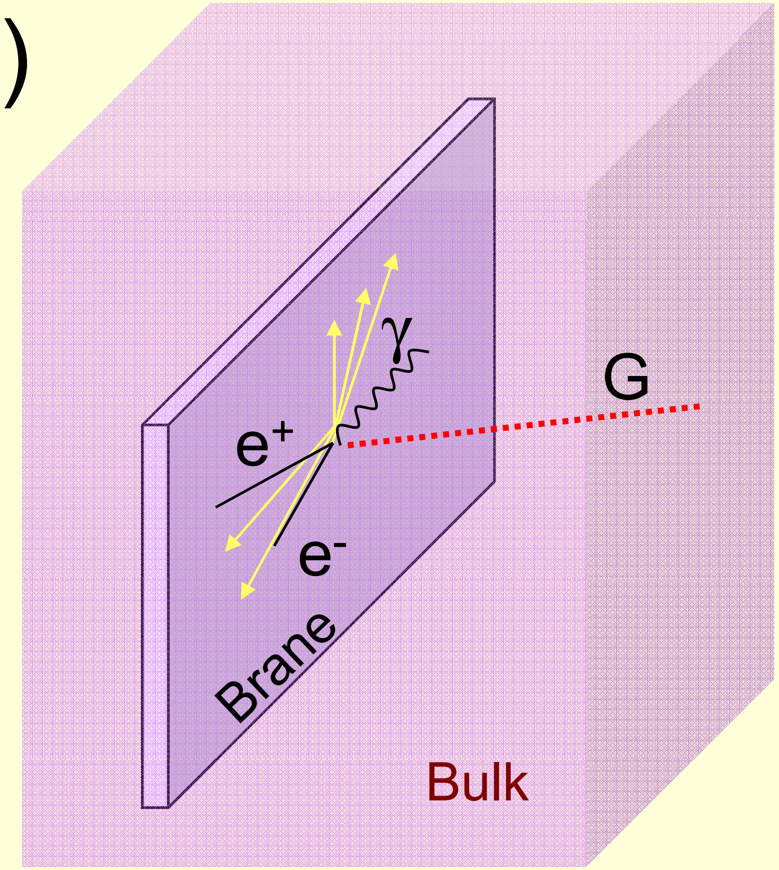
95% C.L. constraints on Yukawa violation of ISL



arXiv:hep-ph/0611184v1

The New Models for ED: Arkani-Hamed Dimopoulos-Dvali (ADD)

- We live in a 3+1 dimensional subspace called a 3-brane embedded in a D=(3+n+1) dimensional spacetime: the "bulk."
- The "n" dimensions transverse to the 3-brane have a common size R.
- Depending on theory : only gravity and other non-SM fields propagate in the full (4+n)-dimensional spacetime; all SM fields are confined to a 3-brane extended in the non-compact dimensions.
- Assume that gravity is unmodified over the 33 orders of magnitude between 1cm down to the Planck length~10^{-33} cm. What are the "supposed" effects on Newtonian gravity?



$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \Rightarrow \frac{1}{M_{Pl(3+n)}^{(n+2)}}\frac{m_1 m_2}{r^{n+1}} \quad \text{for r} \ll \text{R}$$

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \Rightarrow \frac{m_1 m_2}{M_{Pl(3+n)}^{(n+2)} R^n}\frac{1}{r} \quad \text{for r} \gg \text{R}$$

$$G_N = \frac{1}{(M_{PL(4+n)})^2} \equiv 1/M_D^2$$

$$M_D \sim 1TeV$$

$$M_D^2 = M_{Pl(4+n)}^{2+n} R^n$$

ADD (II)

Physics Letters B 429 (1998) 263-272
Physics Letters B 436 (1998) 257-263
Physics Letters B 441 (1998) 96-104

- Assuming $M_{Pl(4+n)} \sim m_{EW}$, with m_{EW} being the only short distance scale in theory, and following the gravitational potential given by Gauss' law in (4+n) dimensions we obtain that the size of the extra dimensions is:

$$R \sim 10^{\frac{30}{n}-17} cm \times \left(\frac{1TeV}{m_{EW}}\right)^{1+\frac{2}{n}}$$

Radius of Compactified Dimensions

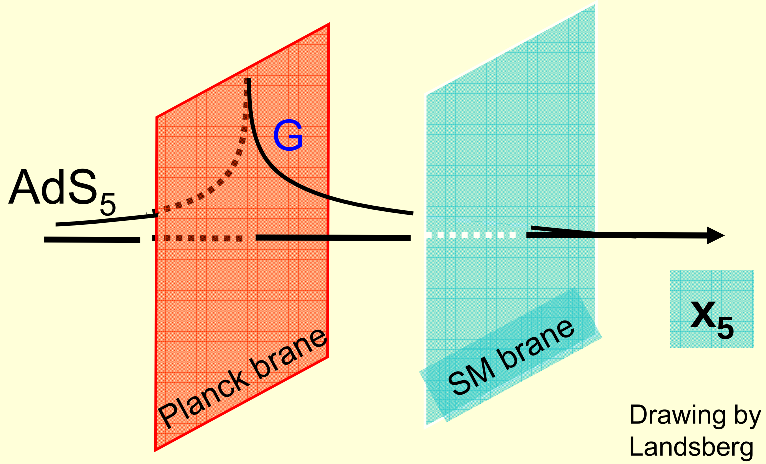
Number of ED

- For n=1 $R \sim 10^{13}$ cm: deviations of Newtonian gravity over solar system distances; empirically excluded.
- For n>2, gravity modified noticeable at distances smaller than currently probed experimentally.
- For n=2 (R~ 100μm - 1mm) rather R < 44μm; experimental evidence is within our reach.
- A (4+n) dimensional graviton and other non SM fields will propagate into the bulk.
- SM fields remain localized* within the thickness of the 3-brane.

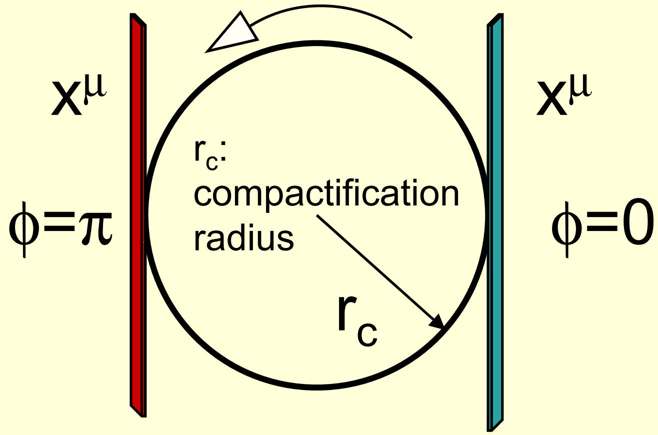
The New Models for ED: Randall-Sundrum (RS)

- Though ADD eliminates the hierarchy problem between M_{Pl} and m_{EW}, it introduces a new hierarchy between m_{EW} and the compactification scale $\mu_c \sim 1/R$.
- RS propose a non-factorizable 4D-metric multiplied by a “warp” factor $e^{-2kr_c\phi}$, which changes rapidly as a function of an additional dimension.
- This metric is a solution to Einstein’s equations with two 3-branes.
- Coupling constant of an individual KK excitation to matter or other gravitational modes is set by m_{EW}.
- Properties of this model determined by the mass of the graviton and the ratio k/M_{Pl}.

Phys. Rev. Lett. **83**, 17 (1999)



Drawing by G. Landsberg



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

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

The New Models for ED: Experimental Signatures

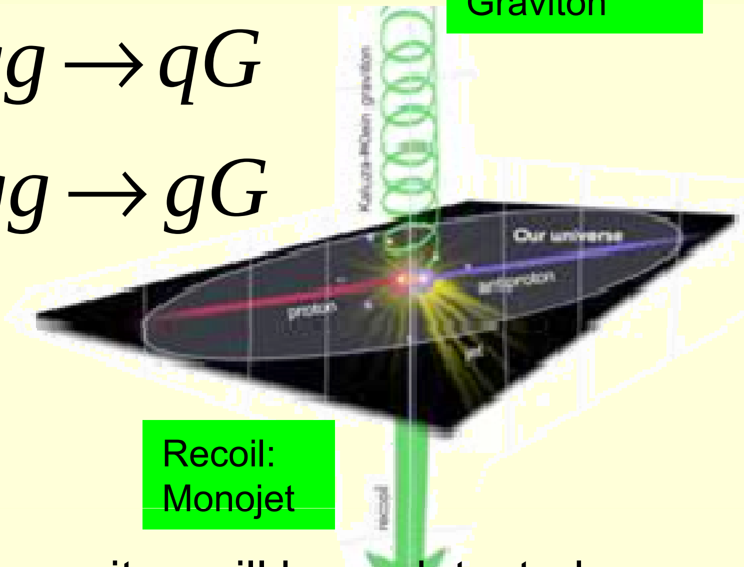
ADD

$$q\bar{q} \to gG$$

$$qg \to qG$$

$$gg \to gG$$

Kaluza-Klein Graviton

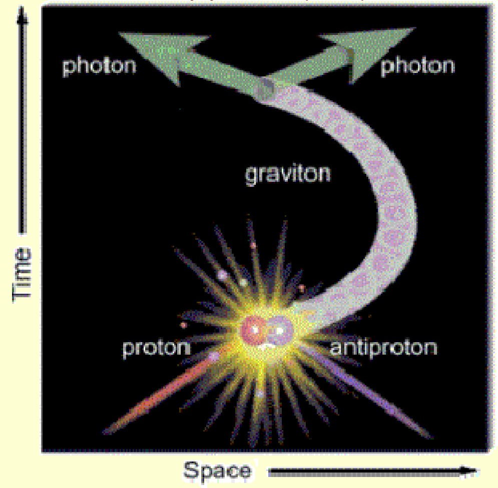


Recoil: Monojet

The graviton will be undetected leaving the final state gluon or quark to produce a single jet : jet + missing E_T.

RS

- Narrow G (high mass) resonance:
  - Width of the resonance determined by k/M_{Pl},
  - Two parameters needed to define the model (k and r_c)
  - Graviton detected when it decays into e^+e^-, $\gamma\gamma$, or $\mu^+\mu^-$



The New Models for ED: Experimental Backgrounds

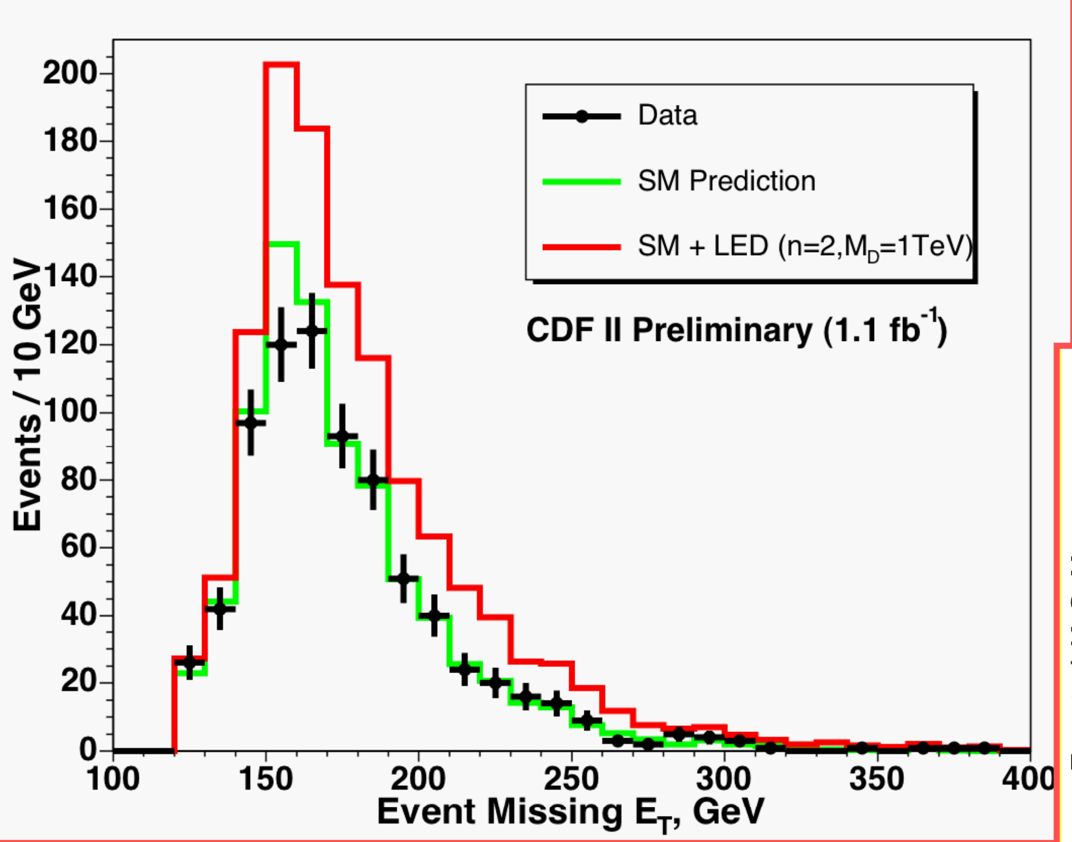
ADD

- The most important backgrounds are:
  - Electroweak:
    - 1-jet + $Z \rightarrow \nu\nu$ and $W \rightarrow l\nu$: where l is lost
  - QCD:
    - Jets mismeasured: 6% of the total background

RS

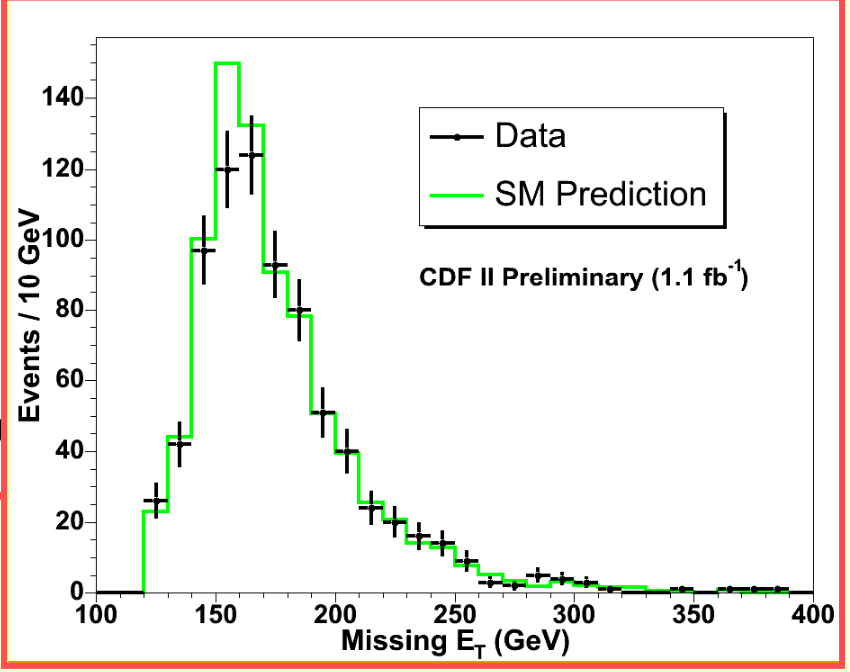
- Based on channel search strategy:
  - Dilepton signal:
    - SM Drell-Yan
    - QCD and W+jets
    - Higher order EW processes
    - W+γ and $\gamma\gamma$ (for dielectron channel)
    - Cosmic rays (for dimuon channel)
  - Diphoton signal:
    - SM diphoton production
    - Single γ + jet faking γ (π^0)

The New Models for ED: Experimental Limits on Monojet Search - ADD



Comparison of the event missing E_T distribution in candidate sample with hypothetical signal from SM + LED.

Comparison of event missing E_T with SM distribution.



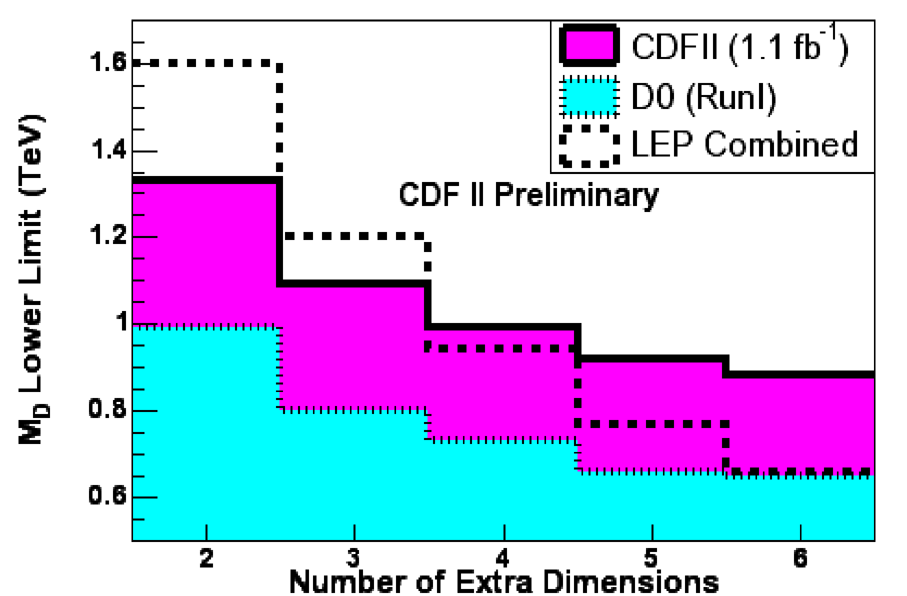
http://www-cdf.fnal.gov/physics/exotic/r2a/20050901.LED_JetMet/1fb/

The New Models for ED: Experimental Limits on Monojet Search - ADD

95%CL Limits on M_D for Run II in TeV for n=2-6 compared with limits from Run I.

Limit comparison on number of EDs for LEP, DØ-Run I and CDFII.

n	M_D (TeV/c²) 368 pb^{-1}	M_D (TeV/c²) 1.1 fb^{-1}	R(mm) 368 pb^{-1}	R(mm) 1.1 fb^{-1}
2	1.16	1.33	0.36	0.27
3	0.98	1.09	3.7×10^{-6}	3.1×10^{-6}
4	0.90	0.99	1.1×10^{-8}	9.9×10^{-9}
5	0.85	0.92	3.5×10^{-10}	3.2×10^{-10}
6	0.83	0.88	3.4×10^{-11}	3.1×10^{-11}

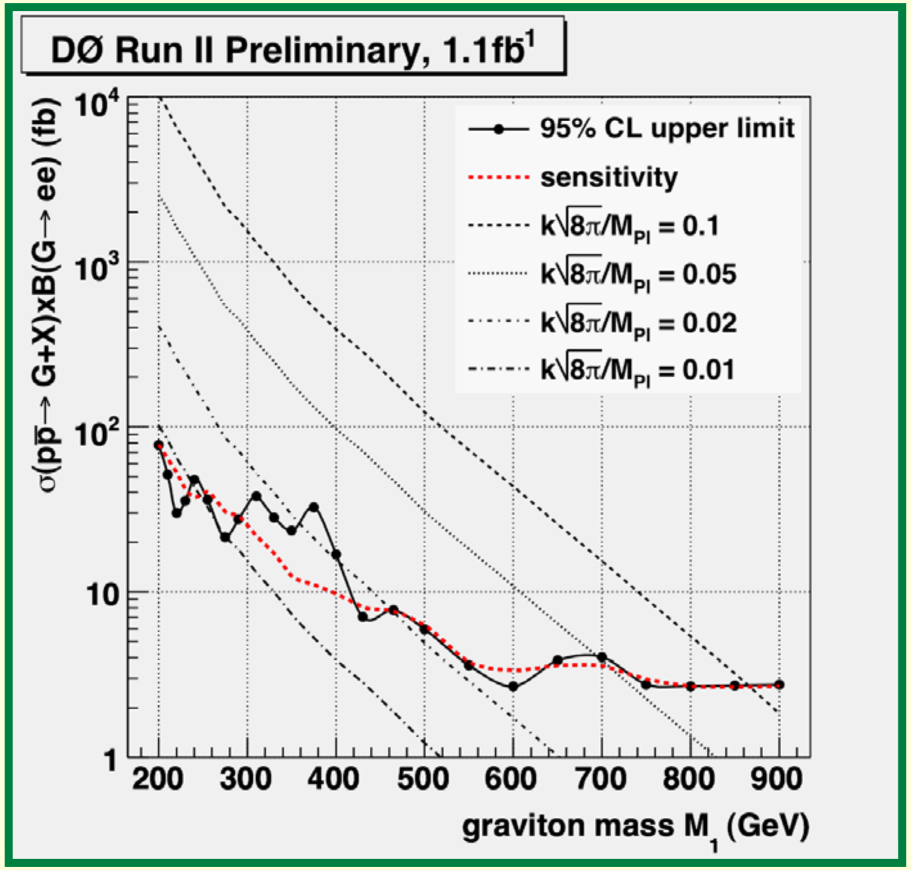


CDF note 7896
http://www-cdf.fnal.gov/physics/exotic/r2a/20050901.LED_JetMet/1fb/

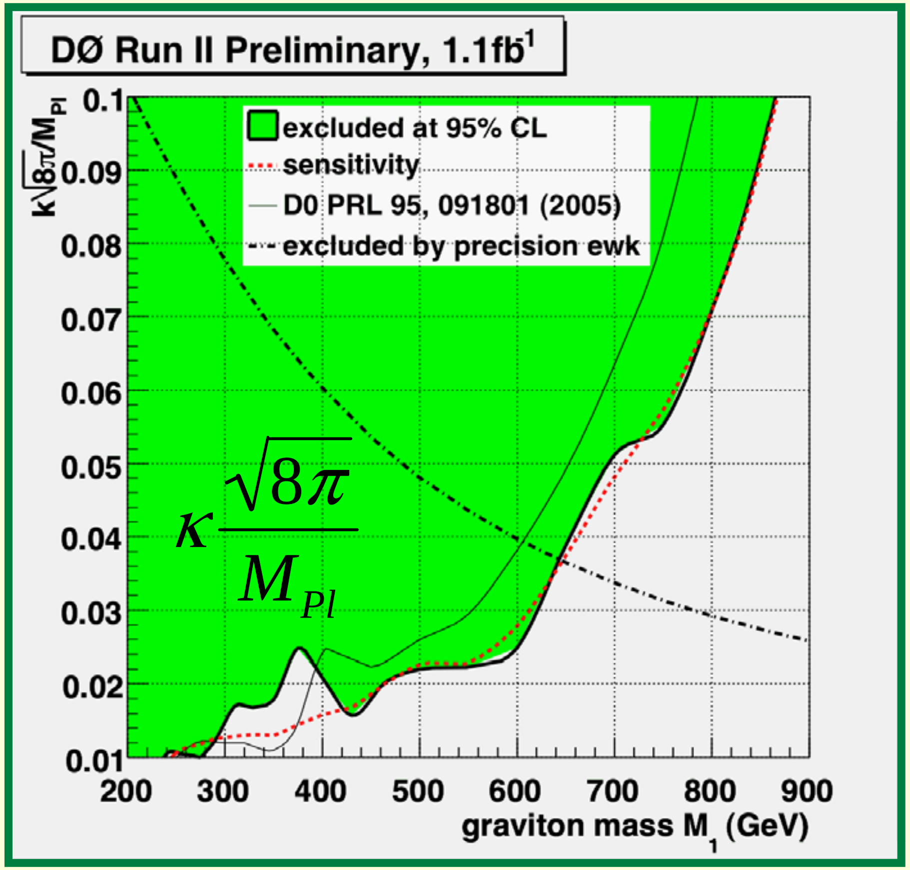
The New Models for ED: Experimental Limits on Diphoton/Dielectron Search - RS

95% Confidence Level Upper Limit with assumed fixed K-factor=1.34

DØnote 5195-CONF



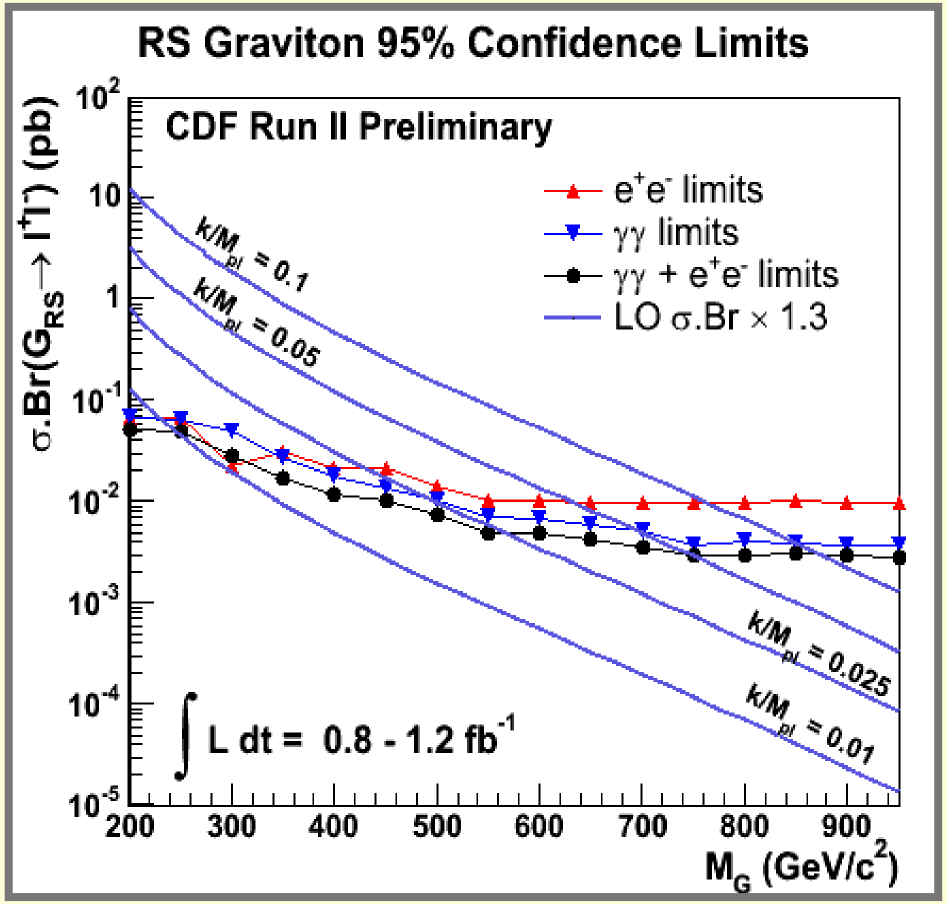
$$\sigma(p\bar{p} \to G + X) \times B(G \to e^+e^-)$$

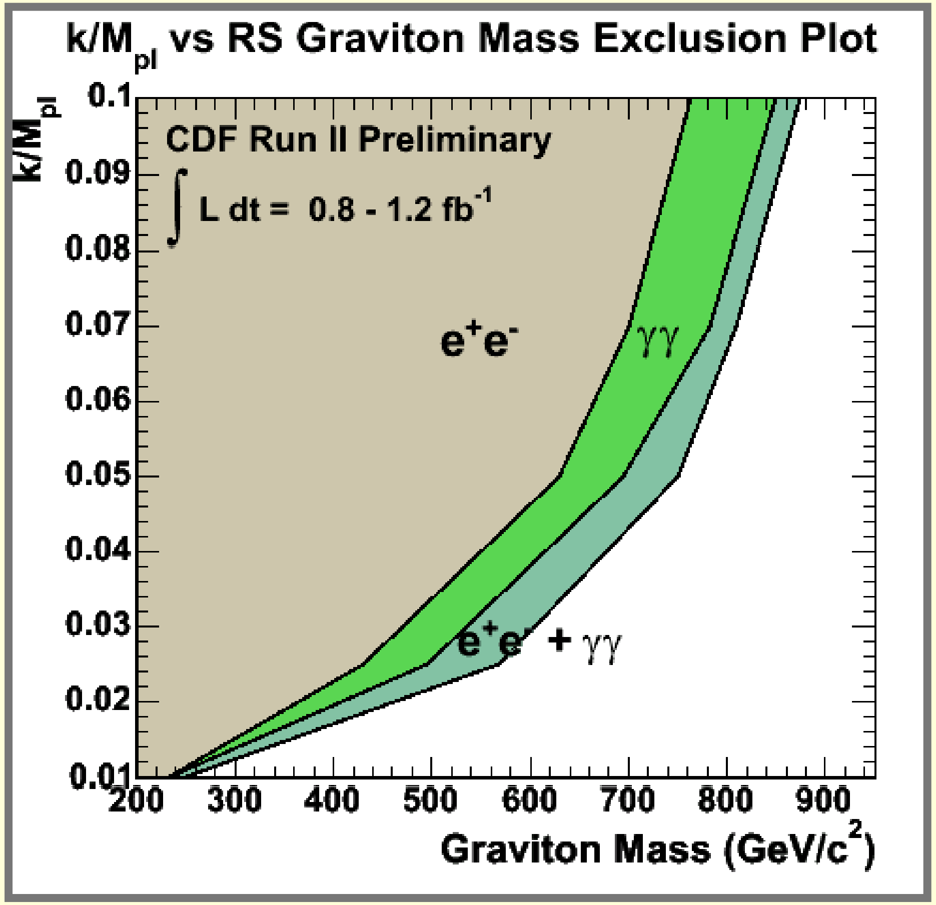


$$M_1 < 865 GeV \text{ for } \kappa\sqrt{8\pi}/M_{Pl} = 0.1$$

$$M_1 < 240 GeV \text{ for } \kappa\sqrt{8\pi}/M_{Pl} = 0.01$$

The New Models for ED: Experimental Limits on Diphoton/Dielectron Search - RS

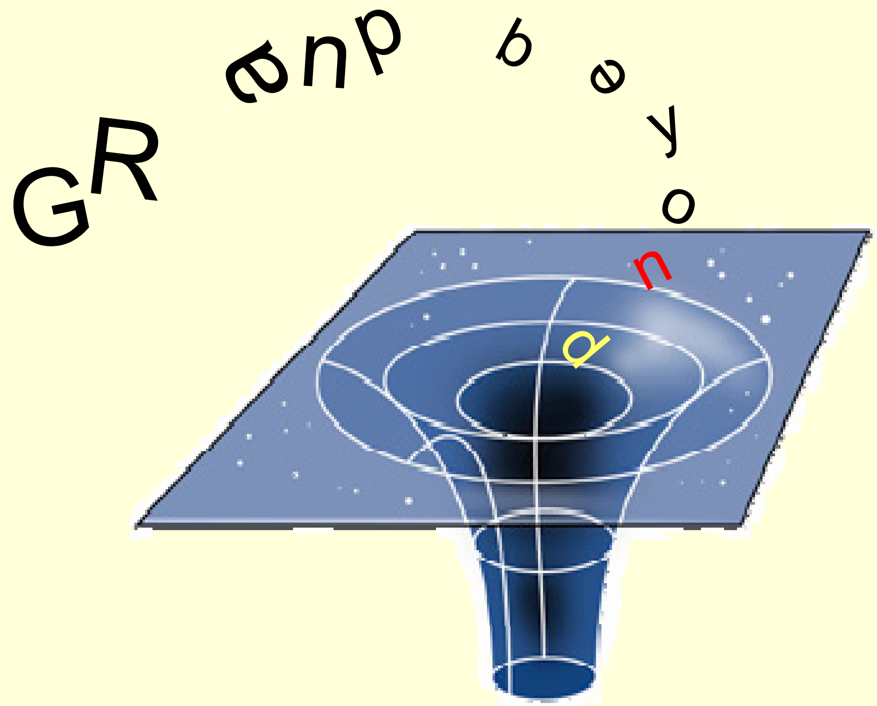




The combination of both dilepton and diphoton RS Graviton decay channels increases the exclusion region to masses below 875 (244) GeV/c^2 for k/M_{Pl}=0.1 (0.01).

CDF/ANAL/EXOTIC/PUBLIC/8421

Black Holes



Astrophysical Black Holes (I)

- Direct prediction of Einstein's General Relativity
- BHs are described exactly by the Kerr metric with the Schwarzschild metric as a special case (set a=0)

$$ds^2 = \frac{(\Delta - a^2 \sin^2\theta)}{\rho^2} c^2 dt^2 + \frac{4GMa}{c\rho^2} r \sin^2\theta d\phi dt - \frac{\rho^2}{\Delta} dr^2 - \rho^2 d\theta^2 - A\frac{\sin^2\theta}{\rho^2} d\phi^2$$

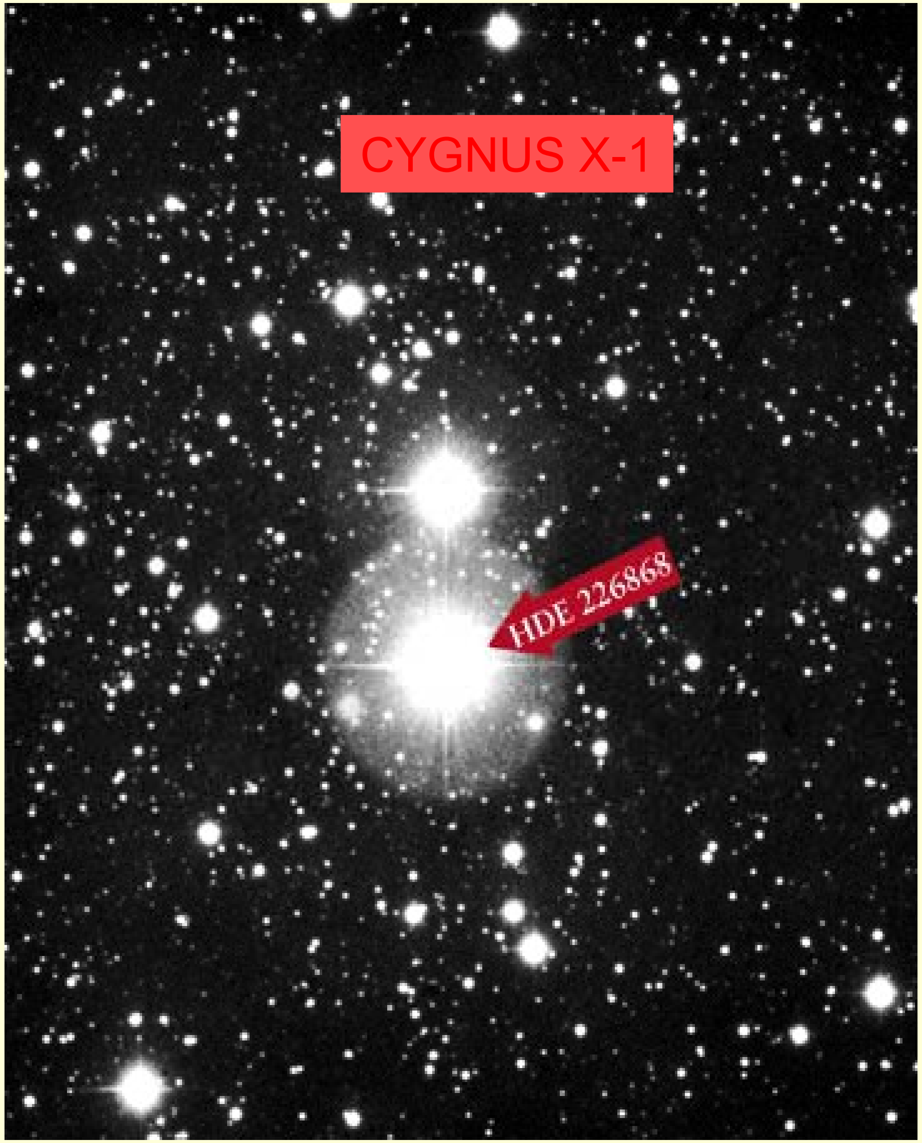
$$\Delta = r^2 - \frac{2GM}{c^2} r + a^2$$

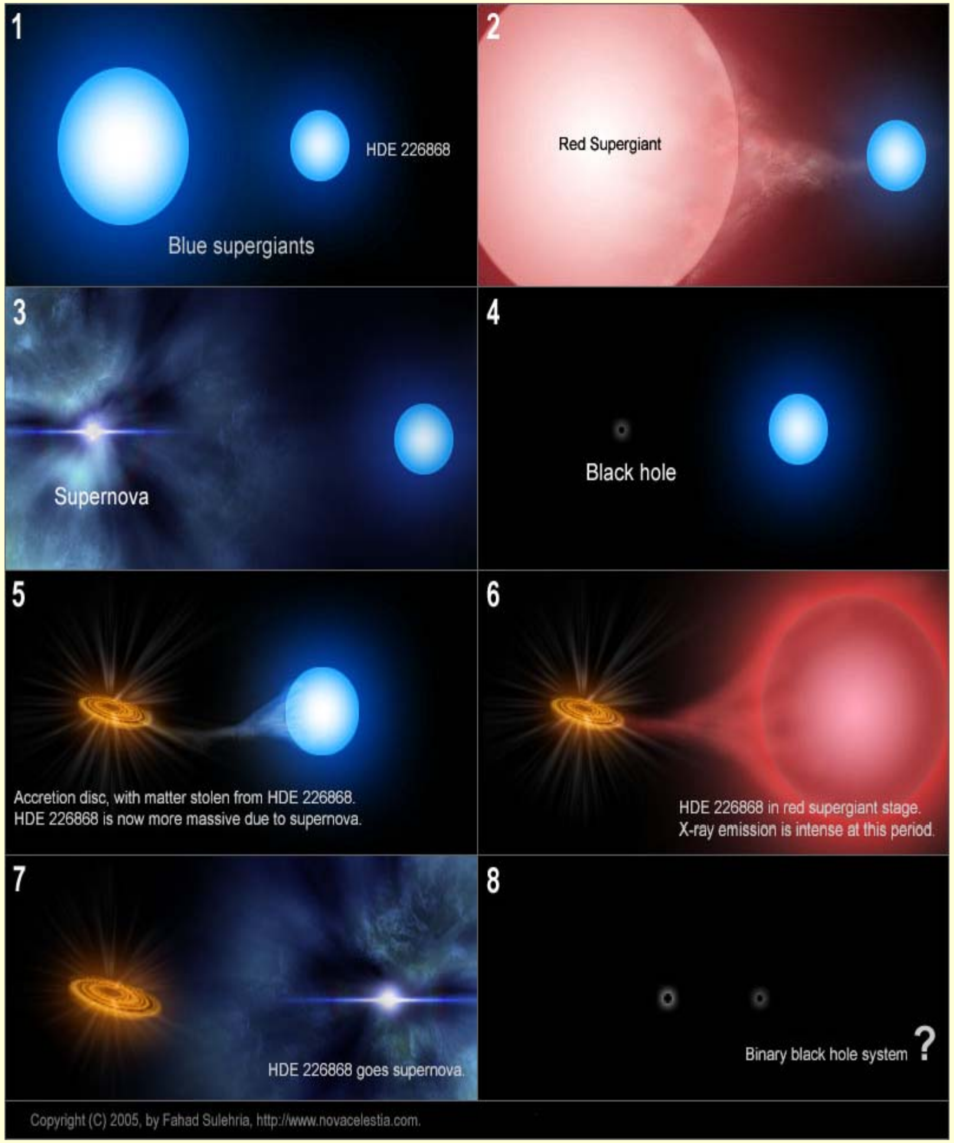
$$\rho^2 = r^2 + a^2 \cos^2\theta$$

$$A = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta$$

- The existence of a BH is proven when a horizon is found
  1. Binary star systems or double neutron star binary system
  2. Stellar mass black holes
  3. Super massive BHs located at the center of galaxies

Astrophysical Black Holes (II)

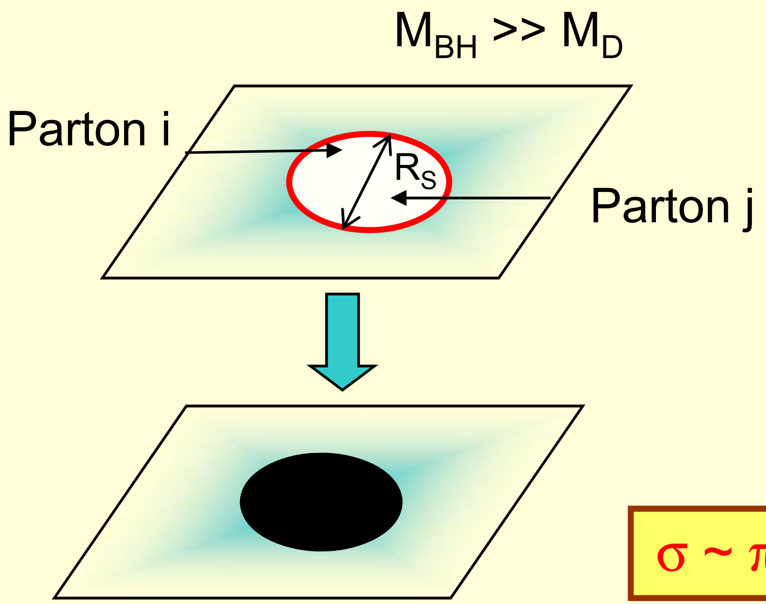




Particle Collider Black Holes (I)

Phys. Lett. B 441, 96 (1998)

- *Formation:* By semi-classical arguments if the impact parameter of a head-on collision between two partons is less than the Schwarzschild radius R_s corresponding to the center-of-mass energy $\sqrt{s}$, then a black hole with mass M_{BH} is formed.



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

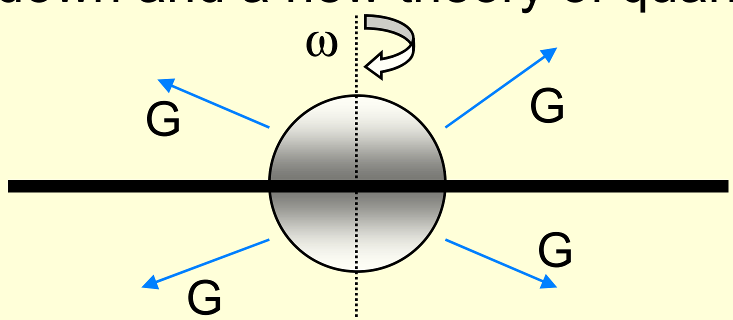
$$R_S(M_{BH}) = \frac{1}{\sqrt{\pi}M_D}\left[\frac{M_{BH}}{M_D}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{n+1}}$$

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

Particle Collider Black Holes (II)

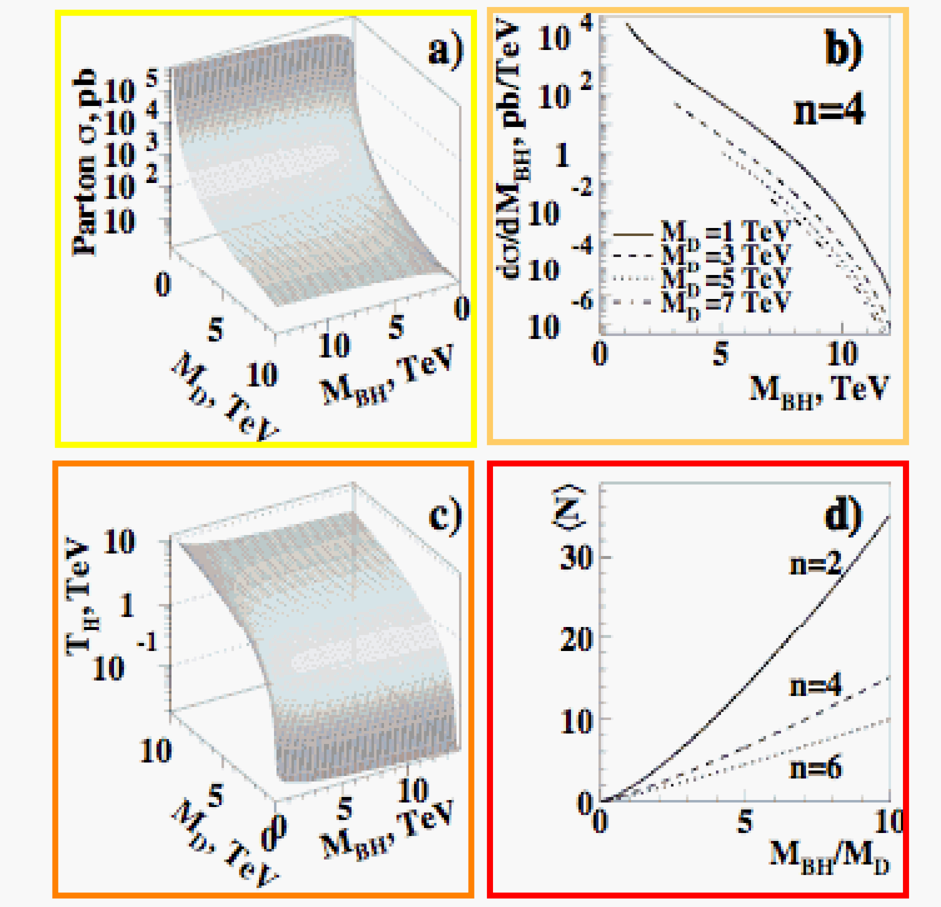
- BHs evaporate semi-classically in a time $\tau \sim 10^{-27}$ sec (τ is estimated using Stefan's law of thermal radiation)
- *Evaporation:*
  - Balding Phase: BH sheds the hair associated with multipole momenta by emitting gauge radiation (SM fields in the brane and G in the bulk) until it reaches the Kerr solution for a spinning BH (15%)
  - Spin-down: BH loses residual angular momentum and becomes a Schwarzschild BH.
  - Hawking evaporation "ends"* when the mass of the BH approaches M_D via emission of black-body radiation with a characteristic Hawking temperature - T_H. [semi-classical argument breaks down and a new theory of quantum gravity is needed]

$$T_H = \frac{n+1}{4\pi R_S}$$



BHs @ The LHC

Phys. Rev. Lett. **87**, 161602 (2001)



a) Parton-level production cross section
b) Differential production cross section
c) Hawking temperature
d) Average particle multiplicity in BH decays

Parton luminosity approach is used to obtain the production cross section. The sum dL/dM_{BH} is over all types of initial partons.

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

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

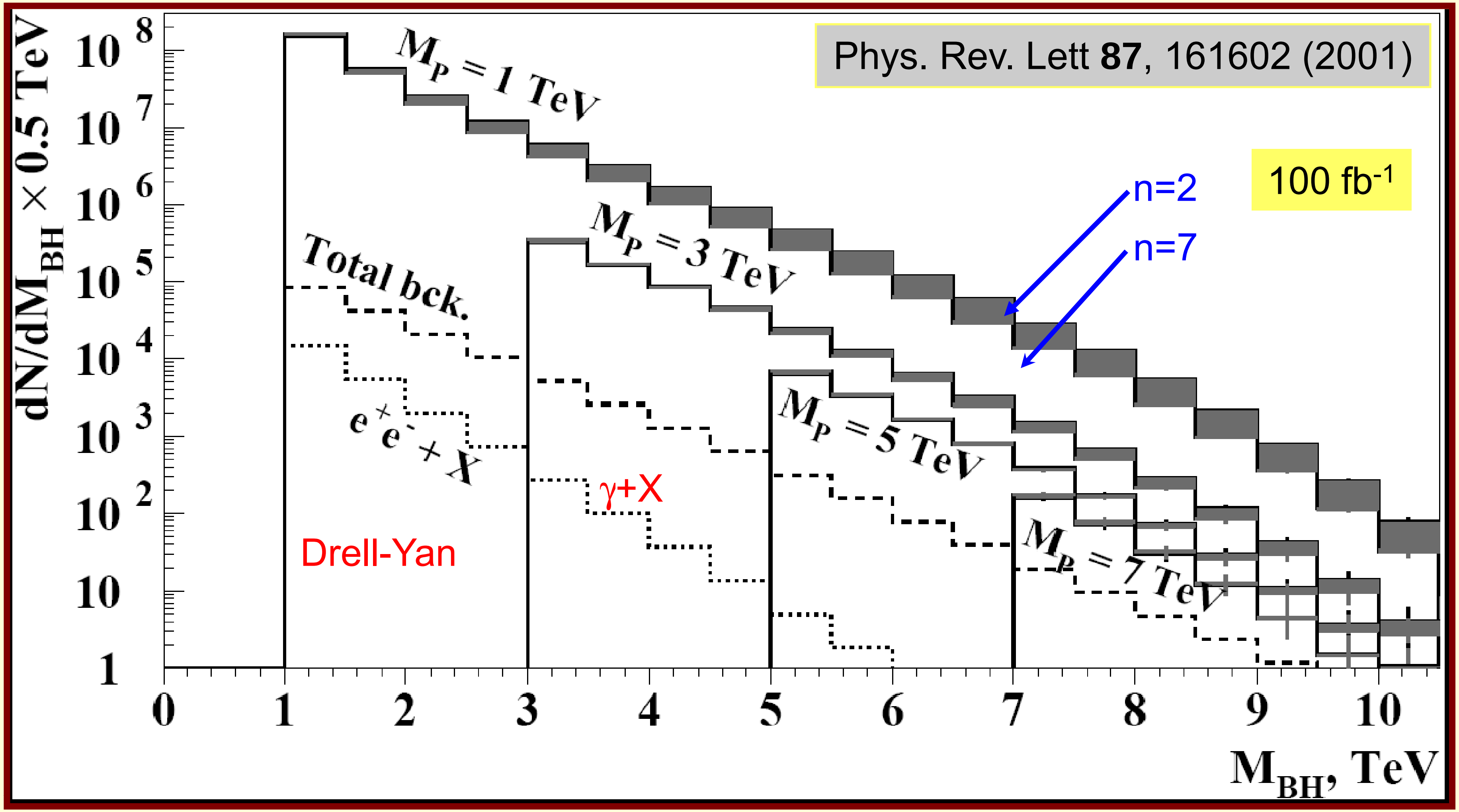
Valid up to ~100TeV (VLHC)

$$T_H = M_{Pl}\left(\frac{M_{Pl}}{M_{BH}} \frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)}\right)^{1/(n+1)} \frac{n+1}{4\sqrt{\pi}} = \frac{n+1}{4\pi R_S}$$

$$\langle N \rangle \approx \frac{2\sqrt{\pi}}{n+1}\left(\frac{M_{BH}}{M_{Pl}}\right)^{\frac{n+2}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)^{\frac{1}{n+1}}$$

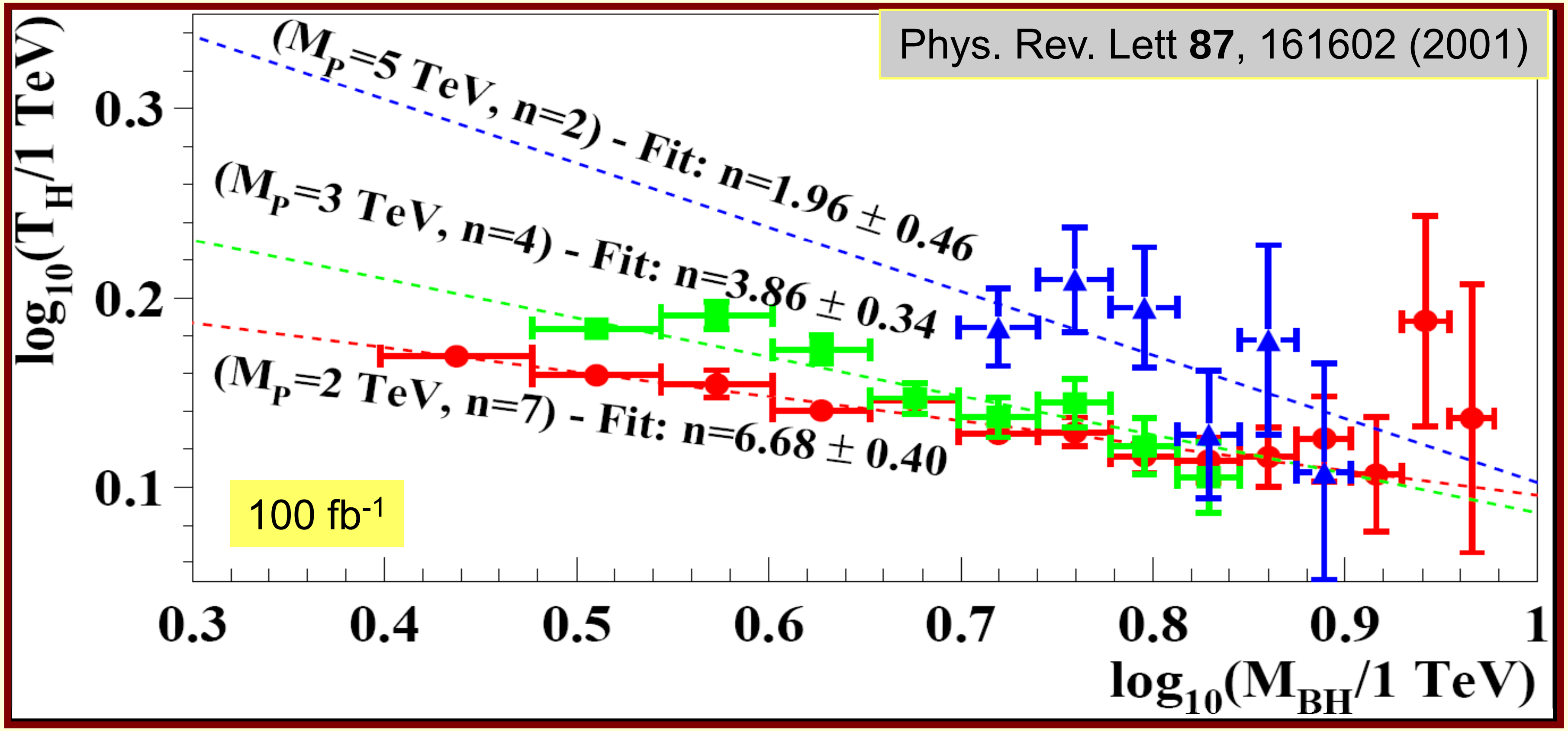
Holds for $M_{BH} >> T_H$ ($N >> 1$)

LHC Potential for BH Creation



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

BHs and ED @ the LHC

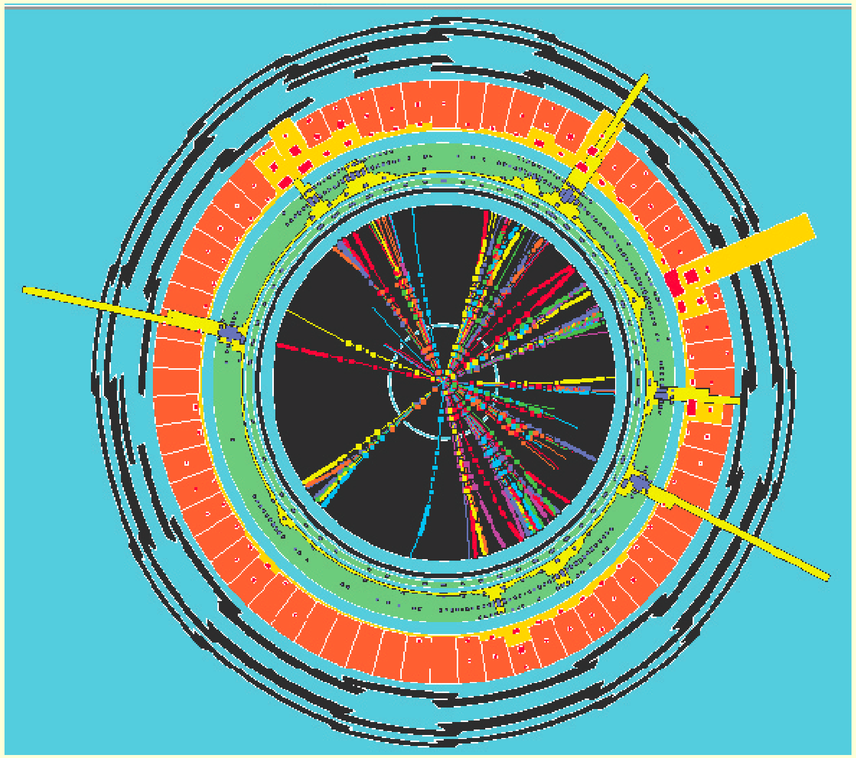


$$\log_{10}(T_H/1TeV) = -\frac{1}{n+1}\log_{10}(M_{BH}/1TeV) + const$$

Slope of straight line fit gives the dimensionality of space

BHs Signatures & Decay

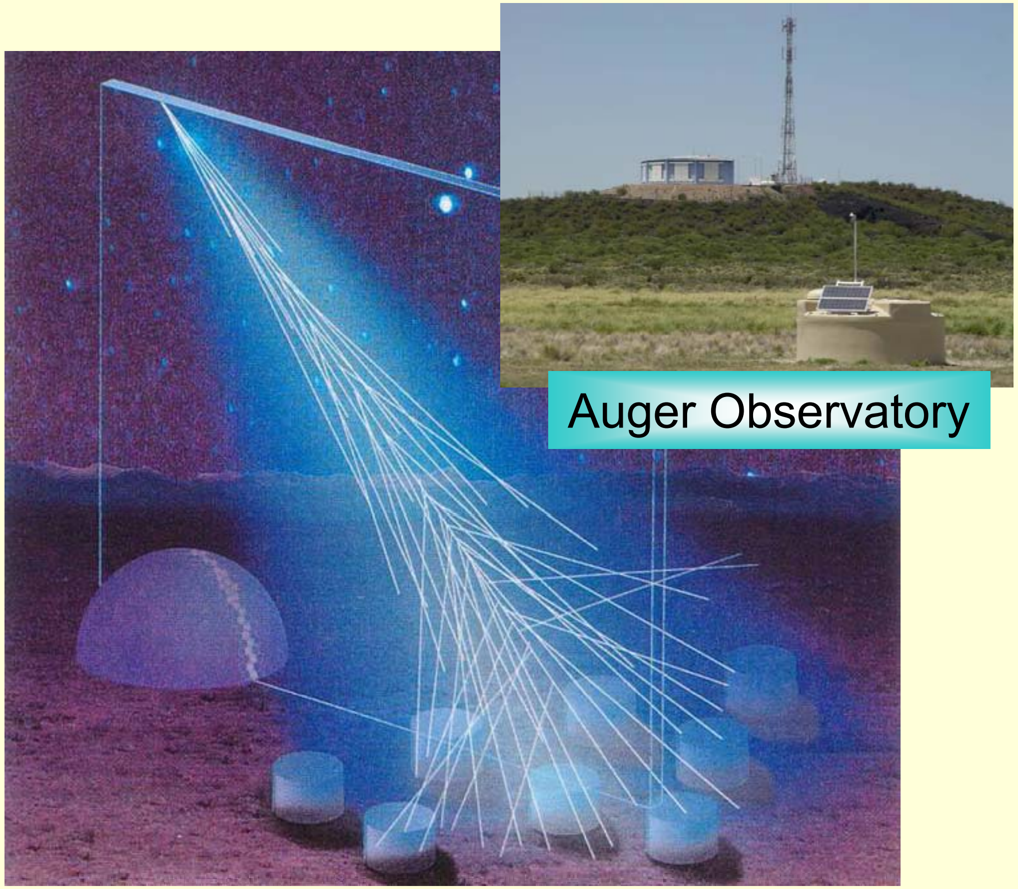
- BH decays equally to all modes without a large boost in the lab frame
- Hadronic to leptonic activity 5:1 (from the Hawking evaporation phase)
- Hadronic to photonic activity 100:1 (from the Hawking evaporation phase)
- High multiplicity
- High sphericity due to high multiplicity and moderate boost factor in the lab frame $\langle \gamma\beta \rangle \leq 1$
- Visible transverse energy of the order of 1/3 of the total energy
- Emission of a few hard visible quanta at the end of the evaporation phase
- Suppression of hard perturbative scattering processes



ATLAS - Atlantis Event Display

Cosmic Rays Black Holes (I)

- They occur when ultra-high energy cosmic rays (UHECR) interact with the Earth's atmosphere (e.g., cosmic neutrinos with $E_\nu > 10^6$ GeV).
- BH cross section uses the flat disk approximation and assumes $M_{BH} = \sqrt{s}$.
- BH production is not suppressed by perturbative couplings and it is enhanced by the sum over all partons.
- Since the interaction length of the neutrinos L, is 1.7×10^7 kmwe (pb/σ) is large compared to the Earth's atmospheric depths (0.36 kmwe), they produce black holes uniformly at all atmospheric depths.



Auger Observatory

Akeno Giant Air Shower Array (AGASA)

Cosmic Rays Black Holes (II)

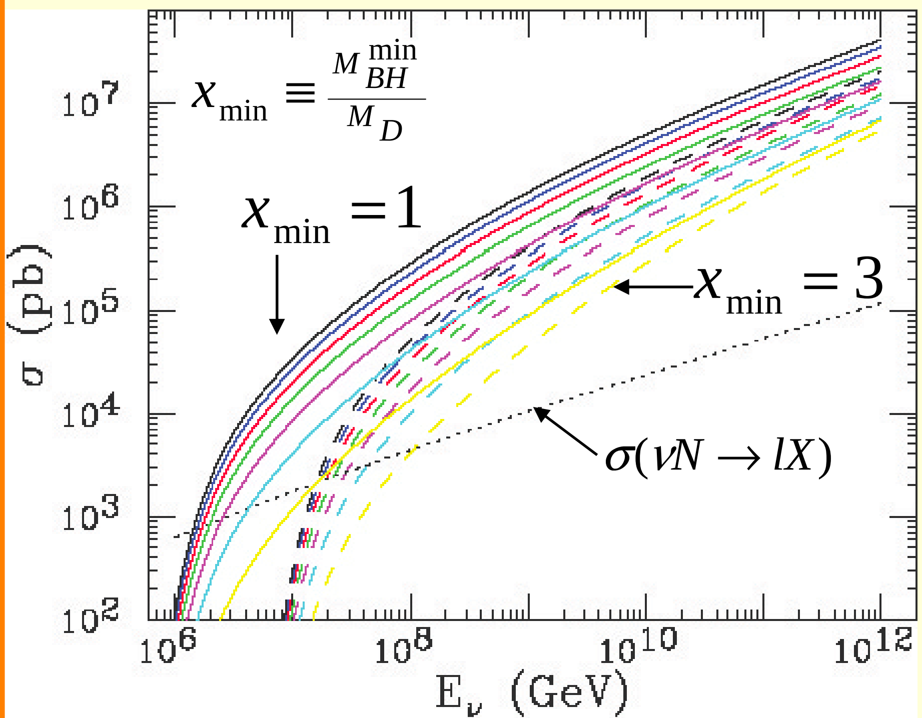
- For showers with large enough zenith angles, the likelihood of interaction is maximized and the background from hadronic cosmic rays eliminated.
- There is a minimum BH mass for which the cross section is valid, $x_{min} \equiv M_{BHmin}/M_D$

$$\sigma(\nu N \to BH) = \sum_i \int_{(M_{BH}^{Min})^2/s}^{1} dx\, \hat{\sigma}_i(\sqrt{xs})\, f_i(x,Q)$$

$$s = 2 m_N E_\nu$$

The sum is over all partons in the nucleon and the f_i's are the parton distribution functions

arXiv:hep-ph/0112247 v3 30 Apr 2002

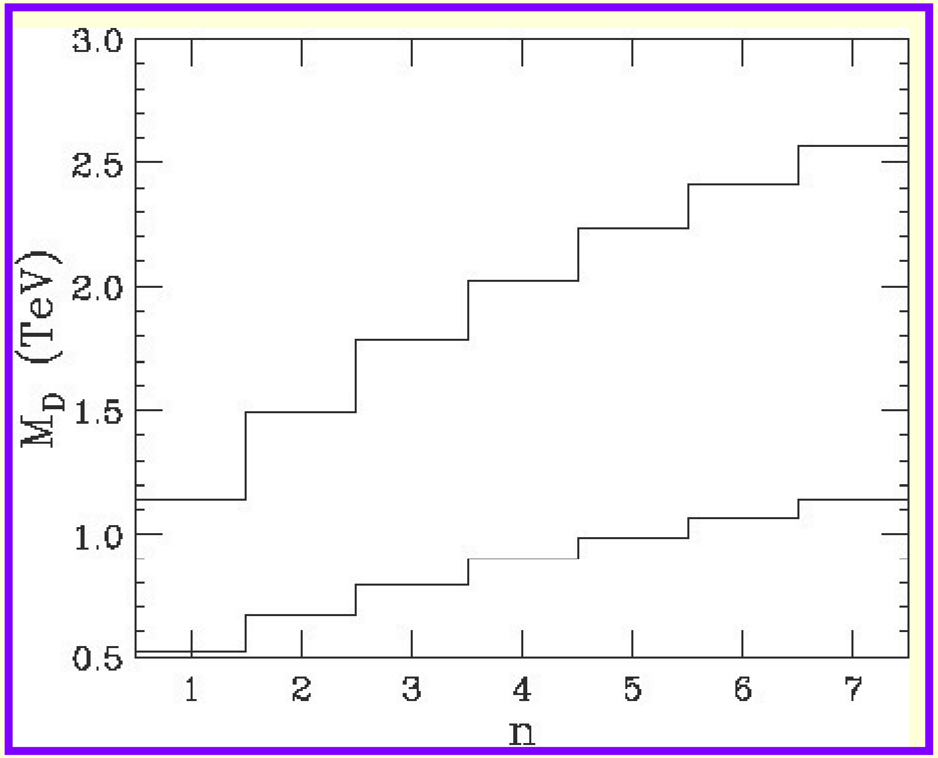


Cross sections for n=1,…,7 from below, M_D = 1 TeV.

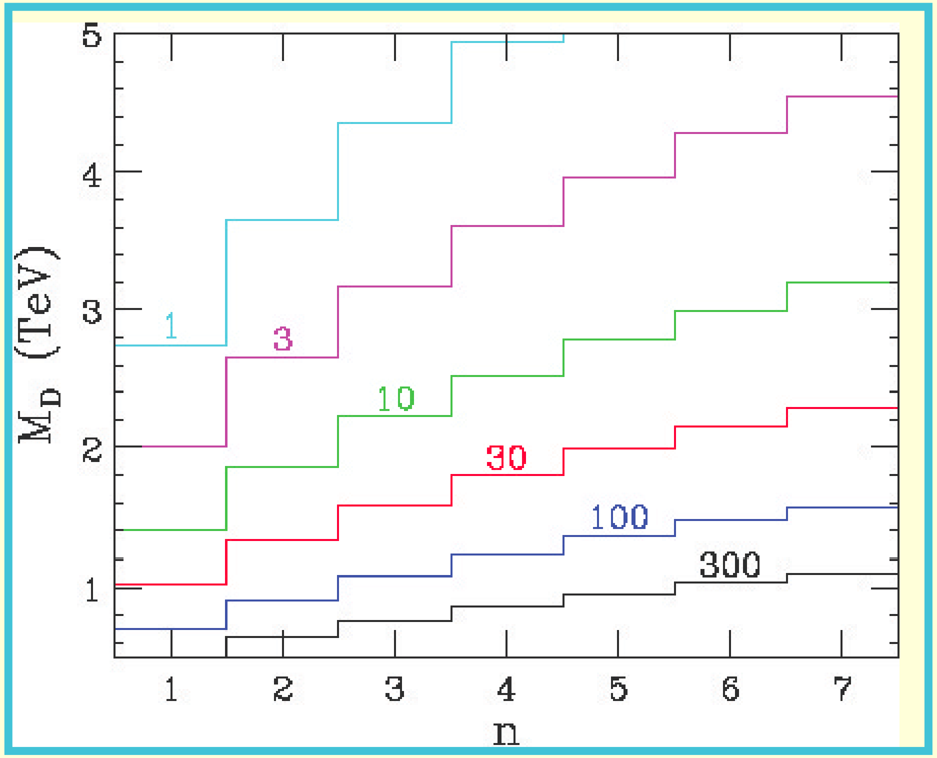
$$\sigma(\nu N \to BH) \propto \left[\frac{1}{M_D^2}\right]^{\frac{2+n}{1+n}}$$

Cosmic Rays Black Holes (III)

AGASA



AUGER



95% C.L. upper and lower bounds on M_D for various n, given 6 candidate events above a background of 1.72 events in 1710.5 live days (x_{min} = 1)

No. BHs detected by ground array in 5-Auger site years (x_{min} = 1).

arXiv:hep-ph/0112247 v3 30 Apr 2002

Experimental Bounds on M_D [TeV] at 95% CL

	AGASA		AUGER		D0 (ADD) [HLZ]	
n	xmin=1	xmin=3	xmin=1	EOT-WASH	DiMuon	DiElectron DiPhoton
2				3.2	1.09	1.67
3					1.27	1.70
4	> 1.3 - 1.5	> 1.0 - 1.1	3.0*		1.07	1.43
5					0.97	1.29
6			2.0		0.90	1.20
7	> 1.6 - 1.8	> 1.1 - 1.3			0.85	1.14
GRW					1.07	1.43
Hewett $\lambda=+-1$					0.96/0.93	1.28

	CDF (ADD)	LEP	LHC (ADD)			
n	(K=1.3)	(Avg.)	1 TeV	3 TeV	5 TeV	ASTROPHYS.
2	1.33	1.60	1 ± 1%	3 ± 3.3%	5 ± 40%	> 600 - 1800
3	1.09	1.20	1 ± 1%	3 ± 7.5%	5 ± 48%	> 10 - 100
4	0.99	0.94	1 ± 1%	3 ± 9.5%	5 ± 54%	
5	0.92	0.77	1 ± 1%	3 ± 17%		
6	0.88	0.66	1 ± 1%	3 ± 23%	Fit Fails	
7			1 ± 1%	3 ± 24%		

1. *For n ≥ 4
2. GRW: Giudice-Rattazzi-Wells
3. HLZ: Han-Lykken-Zhang

DØ Note 4336-Conf - FINAL Version 2/25/04
DØ Note 4349-Conf - Version 2.1 FINAL 3/17/04
arXiv:hep-ex/0506063 v2 16 Nov 2005

Summary & Conclusions

- Experimentally consistent lower limits on M_{Pl} have been set to the 95% C.L.
- Up to the present, no “direct” experimental evidence of the existence of the graviton has been unveiled.
- The number of extra dimensions and their characteristics (compactified or warped) is still undetermined.
- Gravity is either intrinsically weak or is strong but diluted in the extra dimensions.
- If gravity is strong at 1 TeV, extra dimensions could be discovered through black holes from particle colliders or cosmic ray experiments. If not, we go back to the drawing board.

Back-up Slides

Other References

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Eöt-Wash Experiment: Sub-mm Tests of Inverse Square Law (ISL)

2004 Results

Yukawa addition

$$V(r) = -G\frac{m_1 m_2}{r}\left[1 + \alpha e^{-r/\lambda}\right]$$

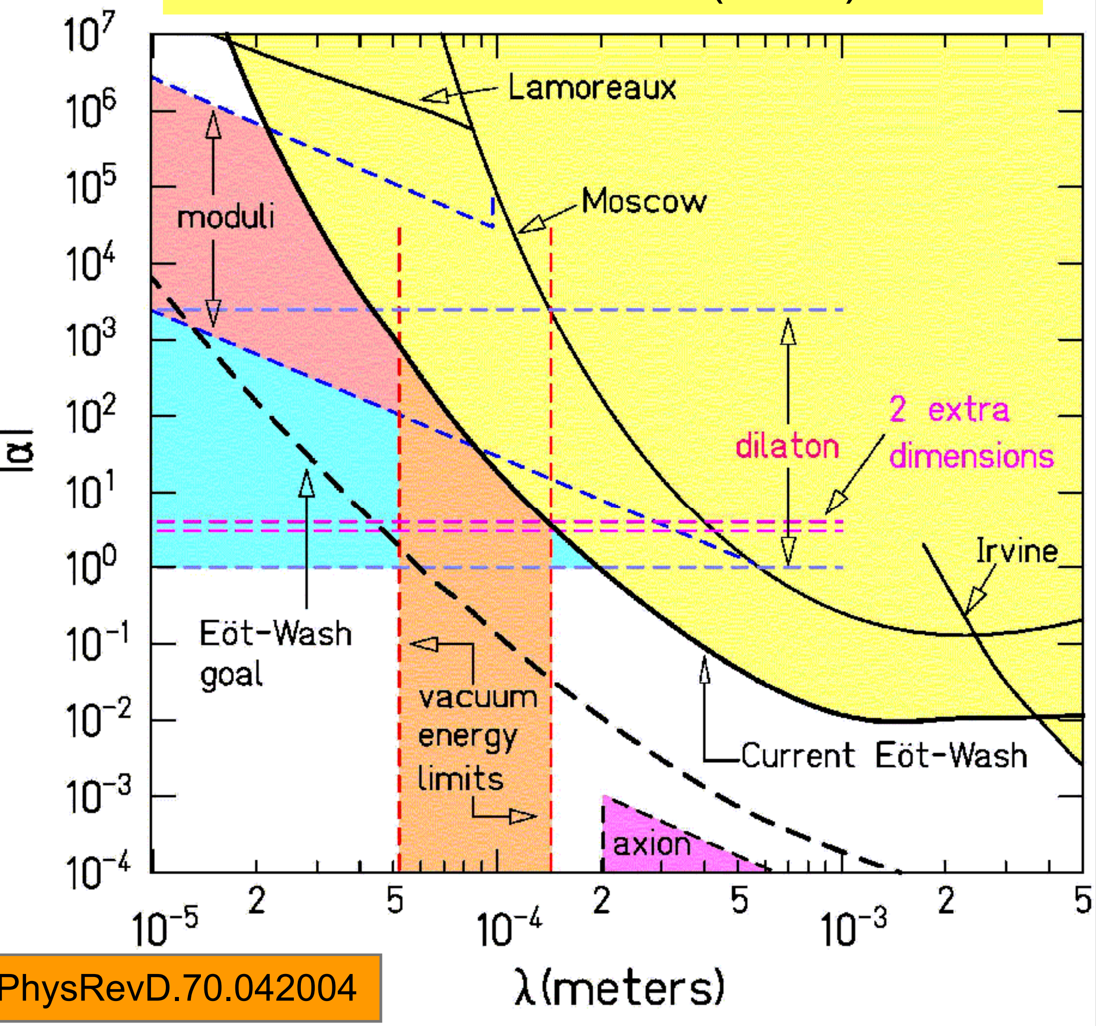
- $r \geq R$: experimentally relevant
- $\alpha = 8n/3$: dimensionless strength parameter
- $\lambda = R$: length scale

Maximum size of ED ($r_1 >> r_{i=2,\ldots,n}$)
EDs are compactified in a torus

Largest ED:
$n=1$, $R \leq 160\ \mu m$
Two EDs:
$n=2$, $R \leq 130\ \mu m$

$M_D \geq 1.7\ TeV/c^2$

95% C.L. constraints on Yukawa violation of ISL (2004)



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