Title: Out-of-this-World Physics: Probing Quantum Gravity in the Lab

Date: Nov 06, 2007 02:30 PM

URL: http://pirsa.org/07110045

Abstract: I\'ll give a broad review of various ways of looking for large, small, and warped extra dimensions and will give only a brief review of the black-hole business, particularly an introduction based on the original paper we wrote and recent work on Randall-Sundrum black holes.

Large Hierarchies Tend to Collapse...

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More Large Hierarchies

Collapse of the Soviet Union

The nineties…

Large Hierarchies Tend to Collapse...

Gravitational Hierarchy Collapse

With thanks to Chris Quigg and the B44 restaurant in San Francisco

- Human Castles in Catalonia

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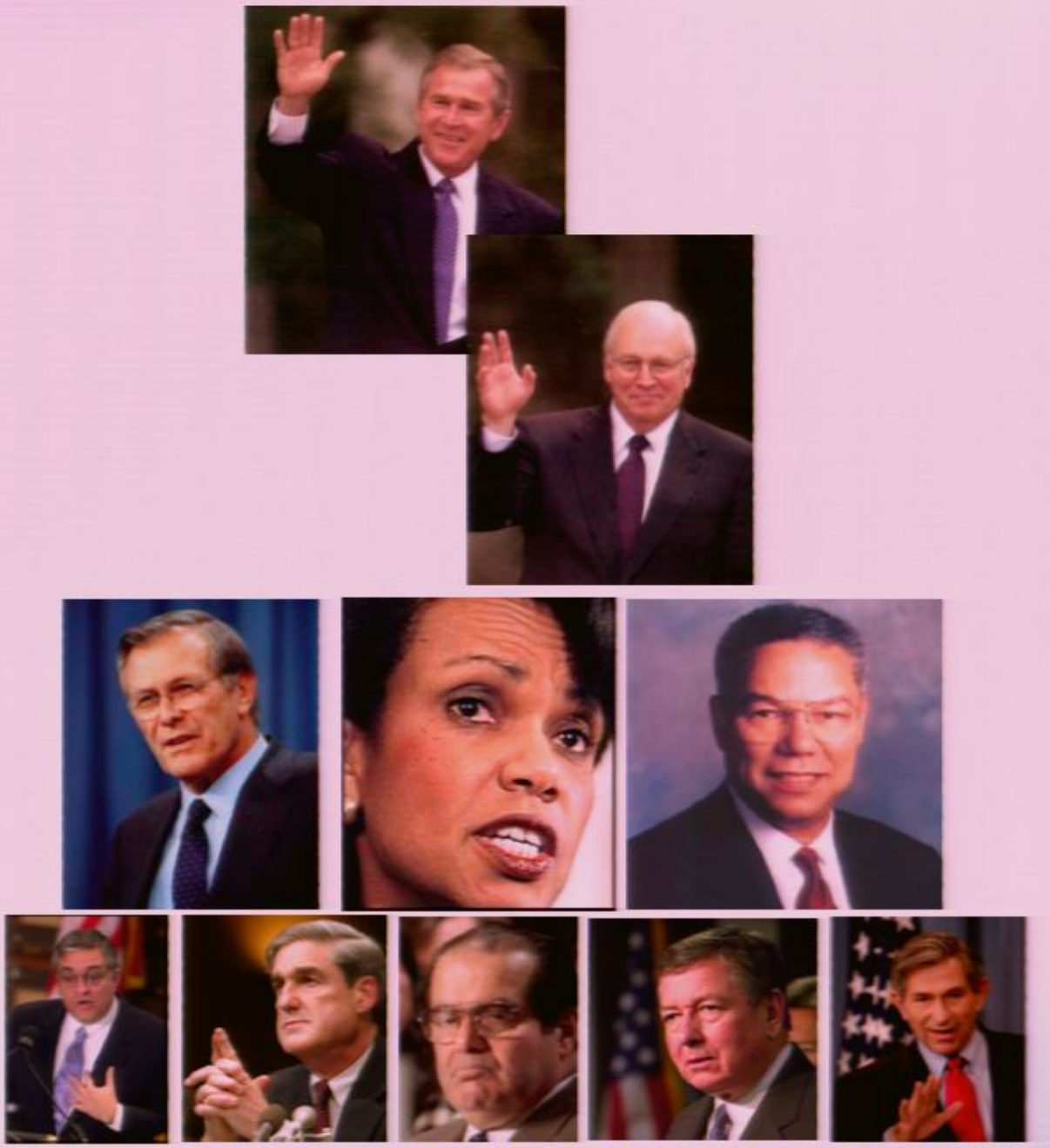
Note: Some Hierarchies are ...



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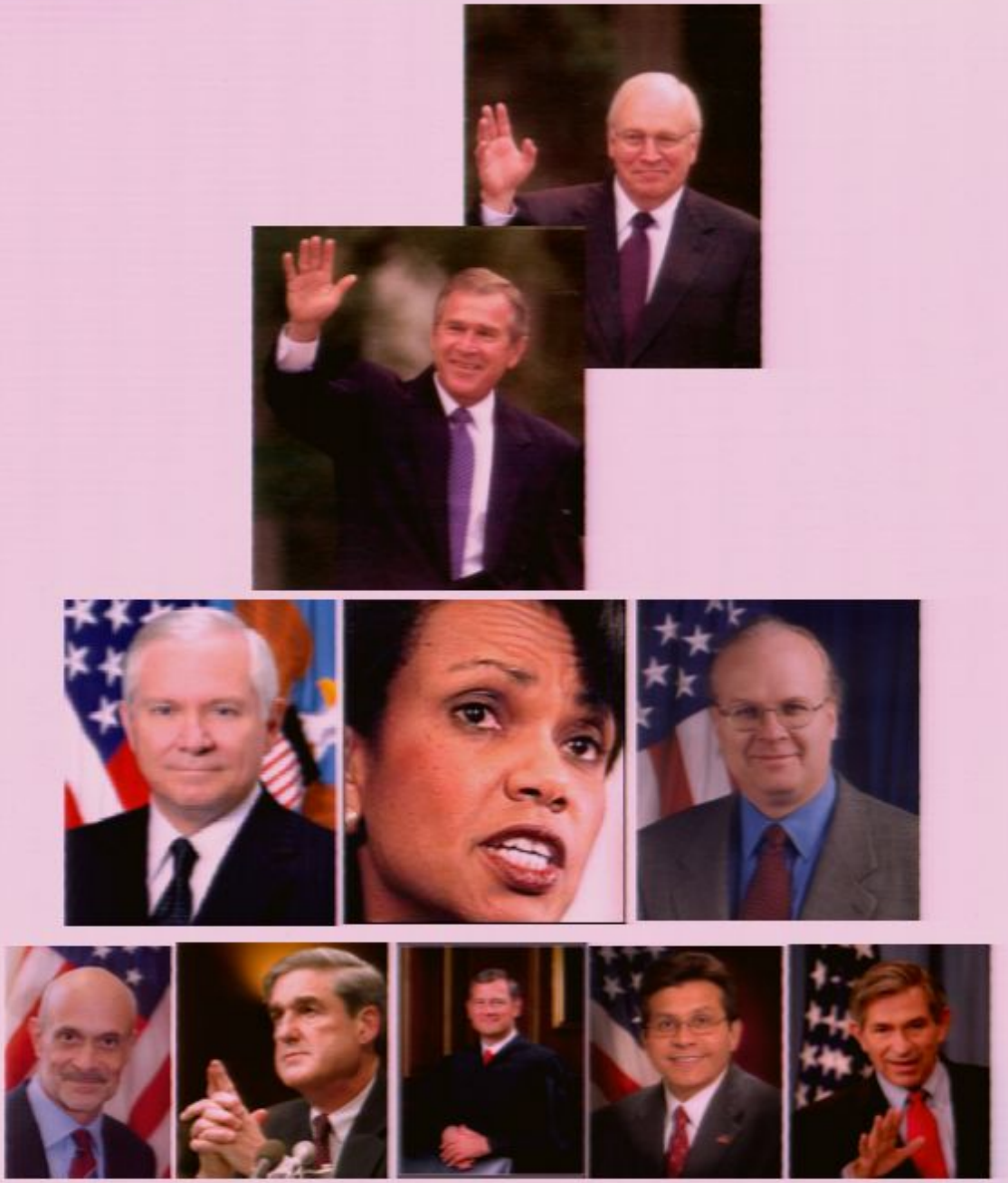

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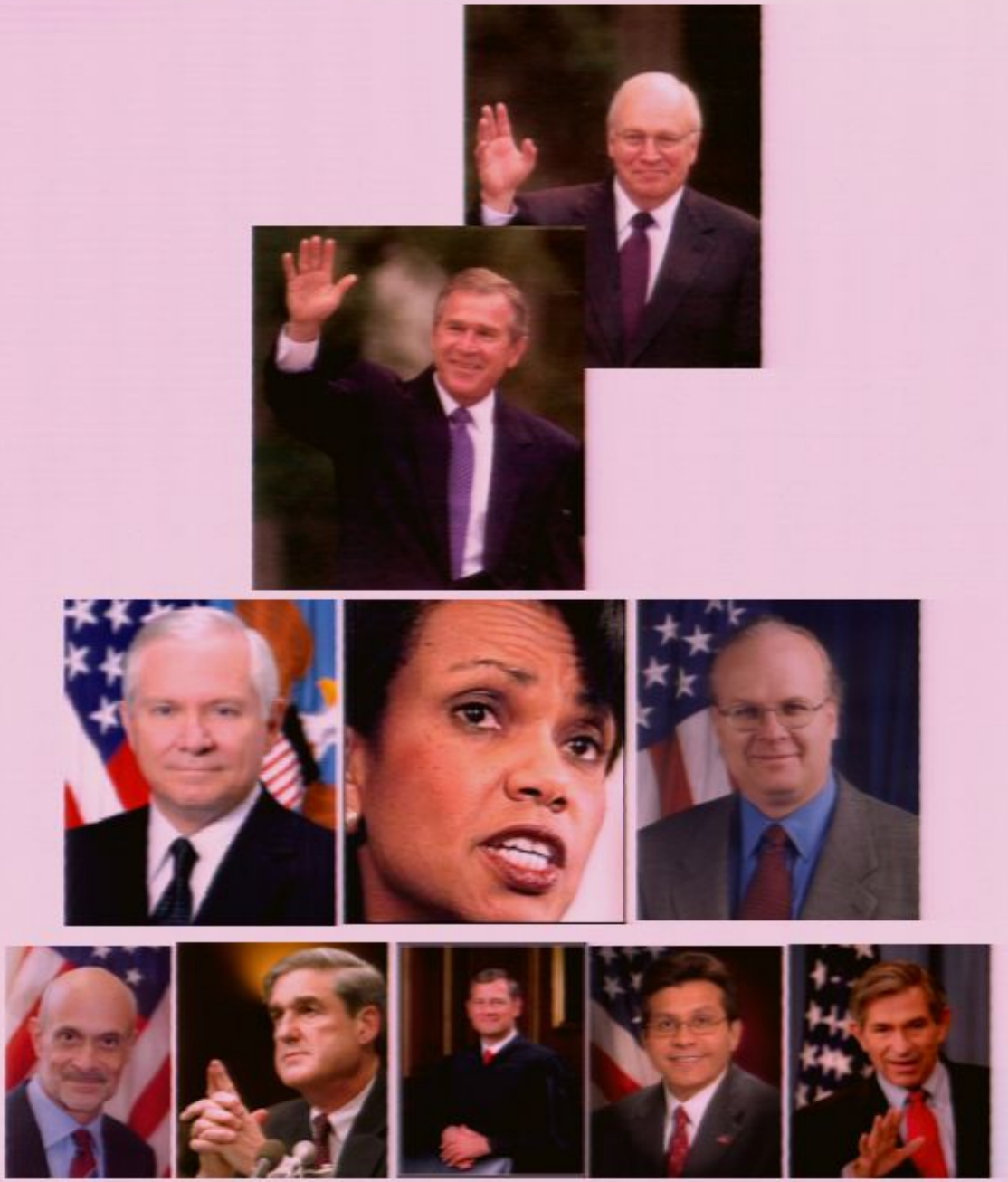

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- Alternative: the *anthropic principle*
  - Properties of the universe are so special because we happen to exist and be able to ask these very questions
  - Not covered in this talk

1998: Large Extra Dimensions

- But: what if there is no other scale, and SM model is correct up to M_{Pl}?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of *large* (r ~ 1mm – 1fm) extra spatial dimensions:
  - –SM particles are confined to a 3D "brane"
  - –Gravity is the only force that permeates "bulk" space
- What about Newton's law?

$$V(\rho) = \frac{1}{M_{\rm Pl}^2}\frac{m_1 m_2}{\rho^{n+1}} \to \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{\rho^{n+1}}$$

- Ruled out for infinite ED, but does not apply for compact ones:

$$V(\rho) \approx \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^n \rho}, \text{for} \rho \gg r$$

- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space $G'_N = 1/(M_{\rm Pl}^{[3+n]})^2$ = $1/M_D^2$; M_D ~ 1 TeV

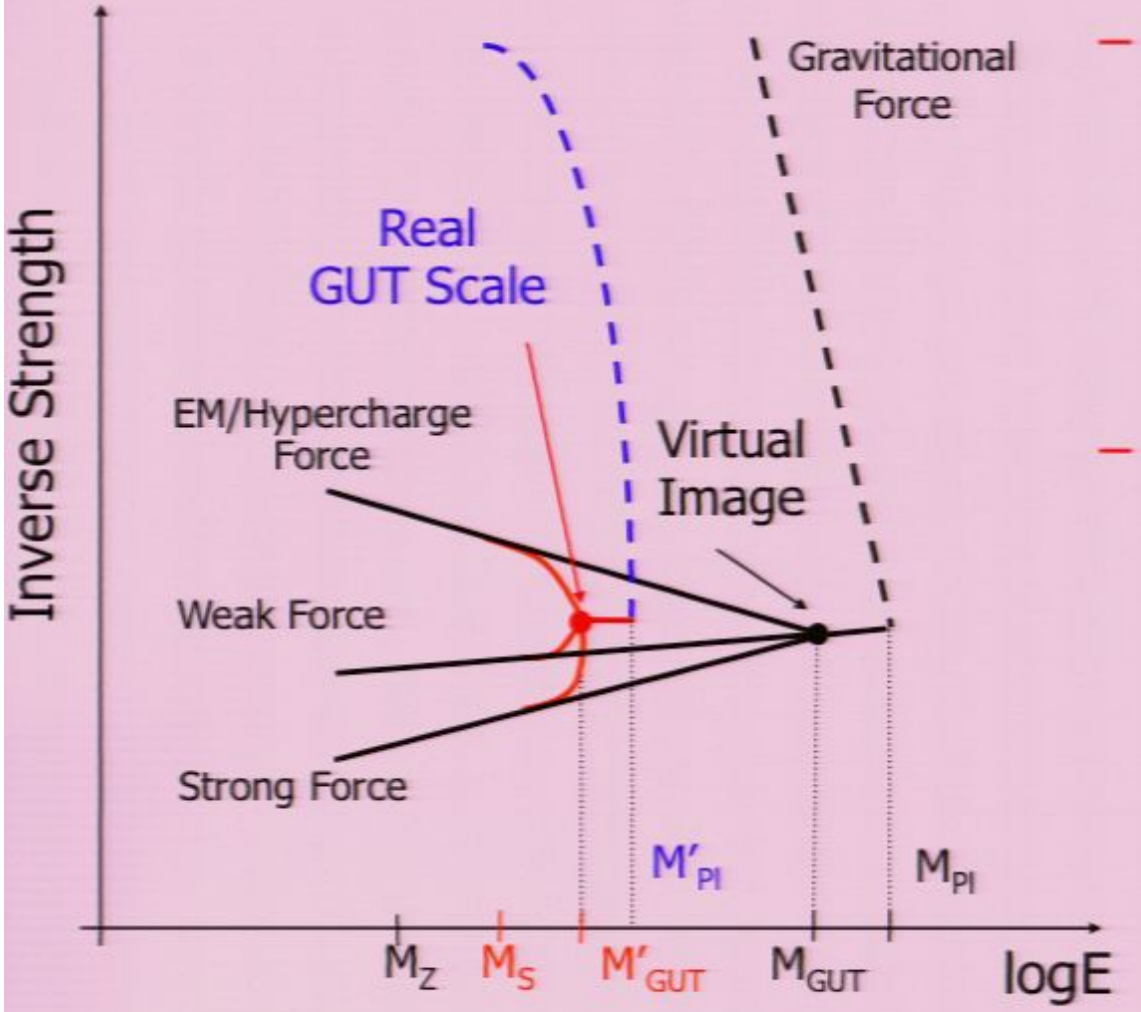
$$M_D^{n+2} \sim M_{\rm Pl}^2/r^n$$

- More precisely, from Gauss's law:

$$r = \frac{1}{\sqrt{4\pi}M_D}\left(\frac{M_{\rm Pl}}{M_D}\right)^{2/n} \sim \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7 mm, & n=2 \\ 3 nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}$$

- Amazing as it is, but as of 1998 no one has tested Newton's law to distances less than ~ 1mm!
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

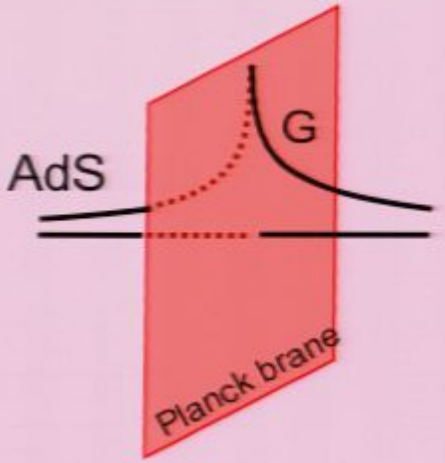
1998: TeV^{-1} Extra Dimensions



- Simultaneously, another idea has appeared:
  - Explore modification of force behavior in (3+n)-dimensions to achieve low-energy grand unification [Dienes, Dudas, Gherghetta, PL **B436**, 55 (1998)]
  - To achieve that, allow other force carriers (g, γ, W, and Z) to propagate in an extra dimension, which is "longitudinal" to the SM brane and compactified on a "natural" EW scale:
    - $R \sim 1\ \text{TeV}^{-1} \sim 10^{-19}$ m

1999: 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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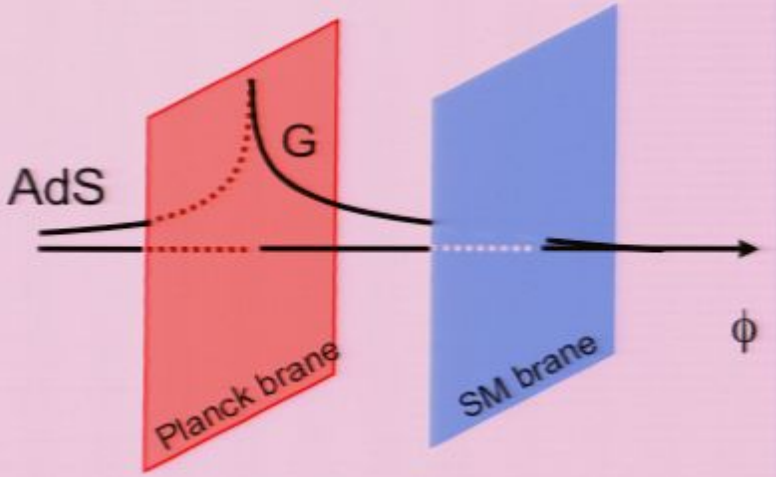

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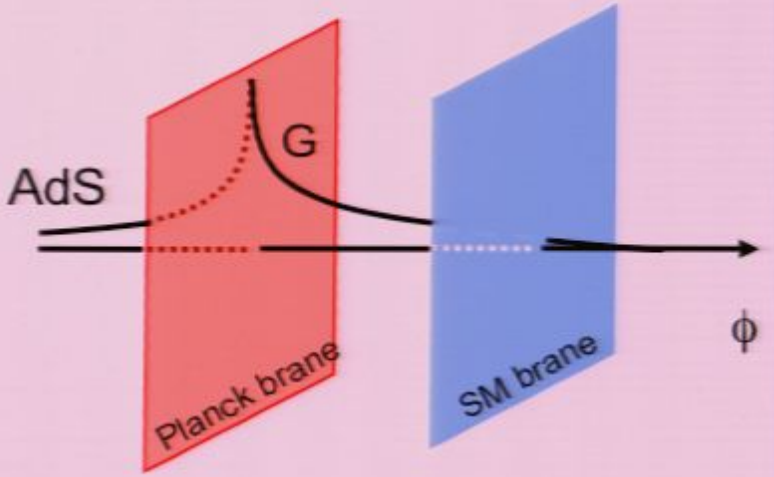
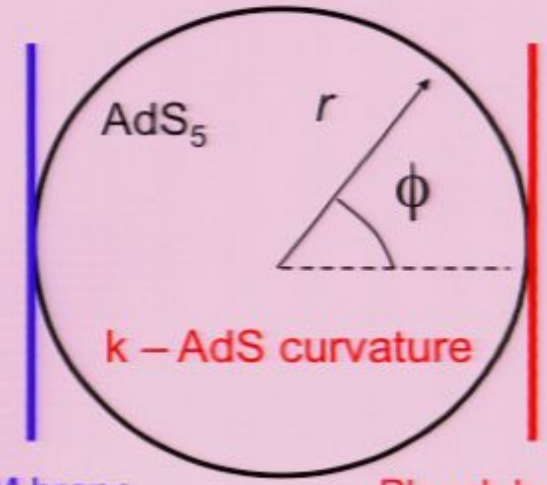




Anti-deSitter space-time metric:

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

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

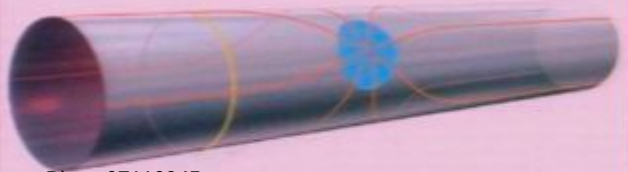
Reduced Planck mass:

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

Extra Dimensions: a Brief Recap

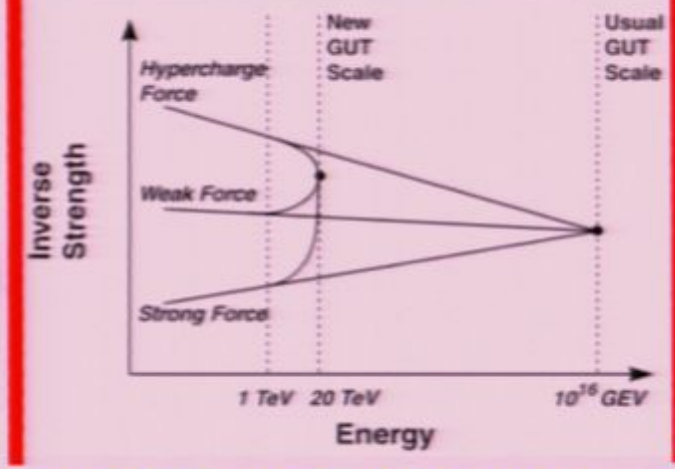
ADD Paradigm:

- 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



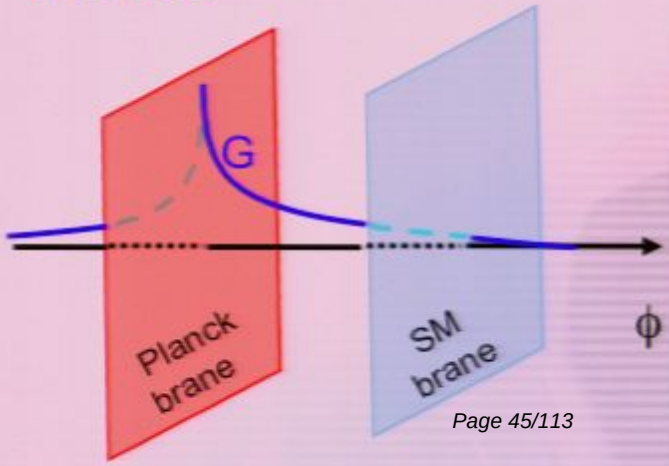
TeV^{-1} Scenario:

- Pro: Lowers GUT scale by changing the running of couplings
- Only gauge bosons (g/γ/W/Z) "live" in ED's
- Size of ED's ~1 TeV^{-1} or ~10^{-19} m – i.e., natural EWSB size
- Con: Gravity is not in the picture



RS Model:

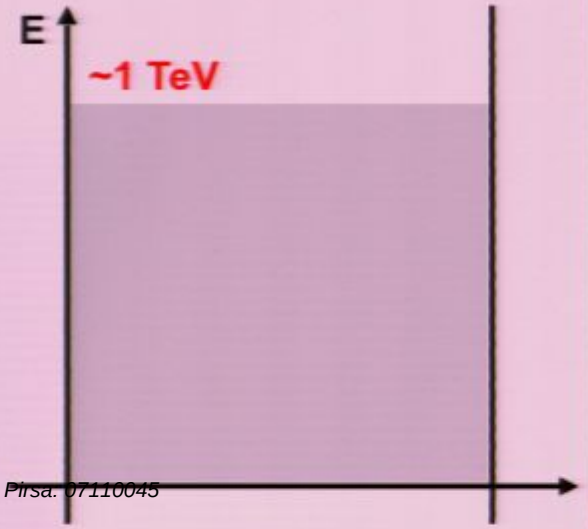
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

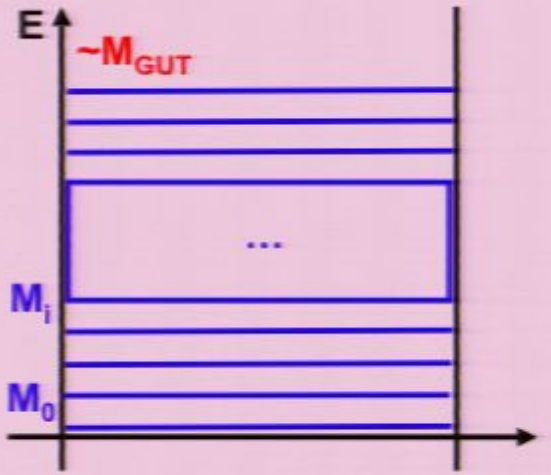
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

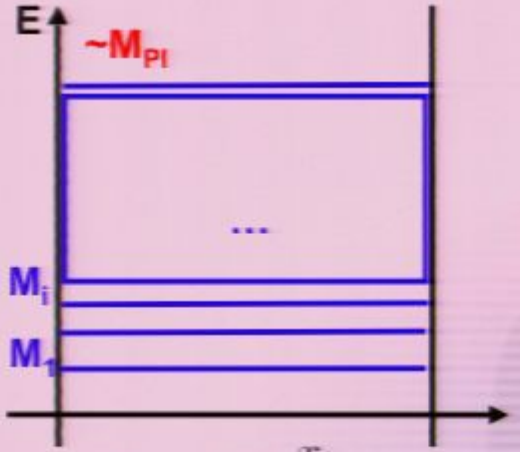
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_w per mode

$$M_i = \sqrt{M_0^2 + i^2/r^2}$$



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

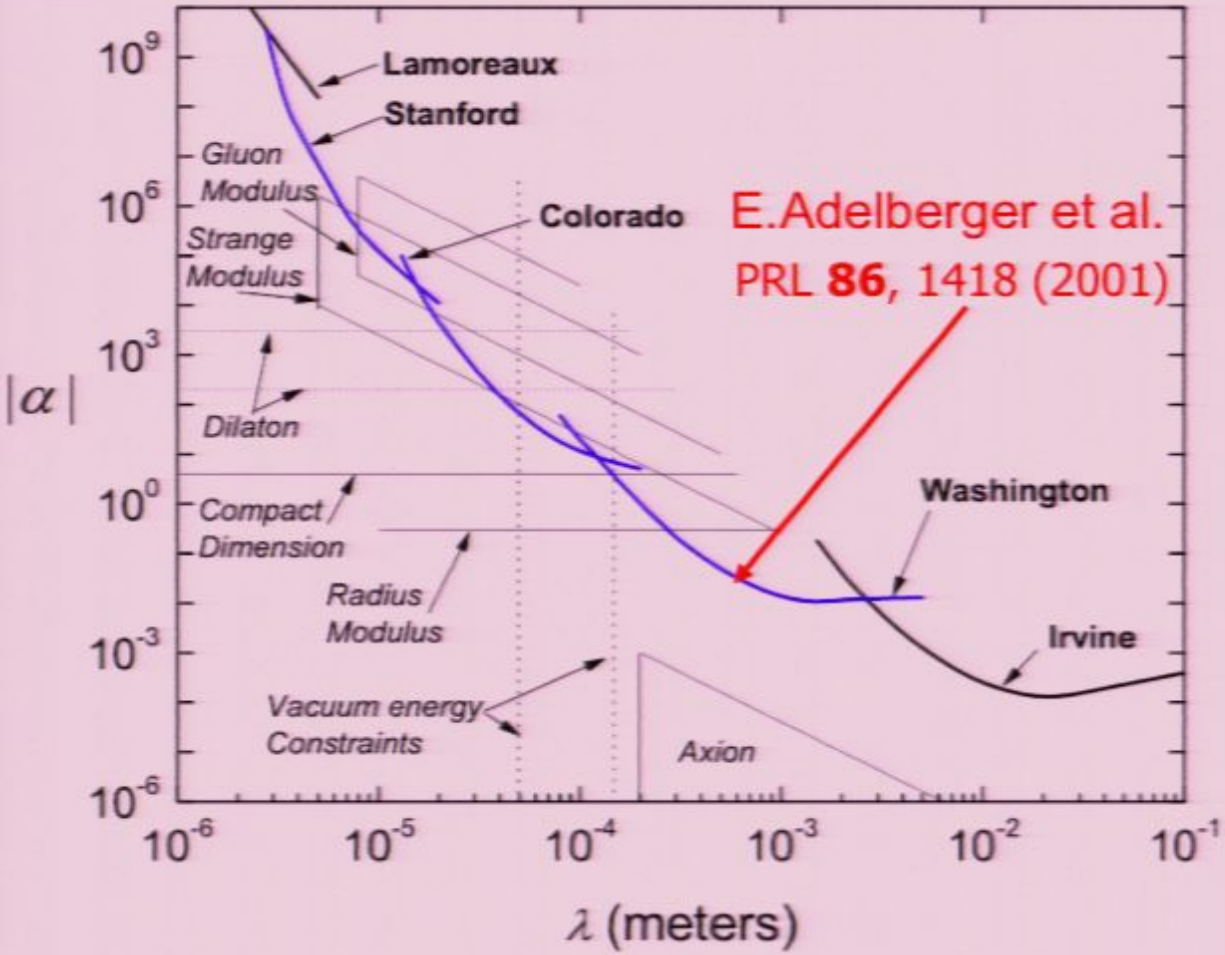


$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx$$

$$M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

Large ED: Gravity at Short Distances

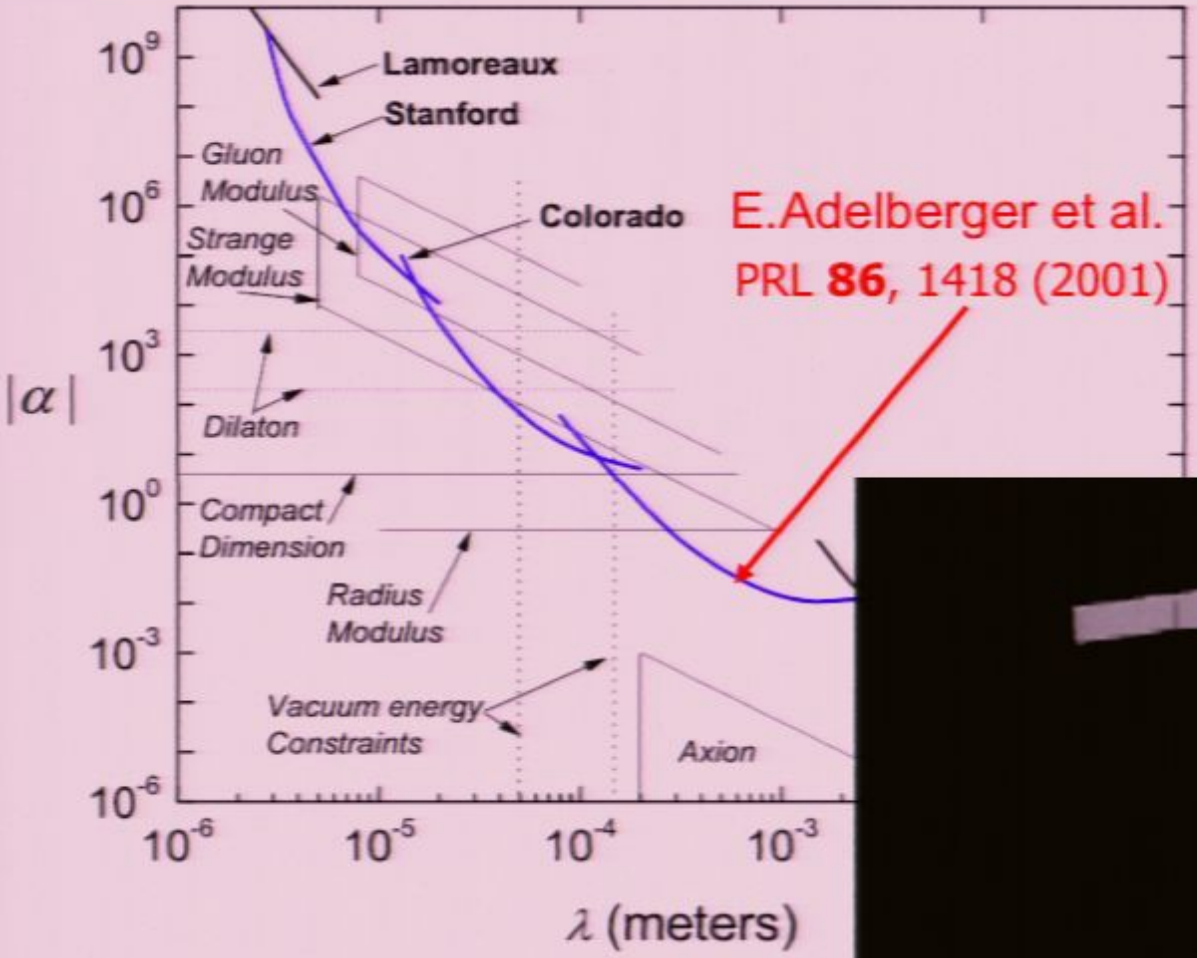
[J. Long, J. Price, hep-ph/0303057]



- Sub-millimeter gravity measurements could probe *only* n=2 case *only* within the ADD model
  - The best sensitivity so far have been achieved in the U of Washington torsion balance experiment – a high-tech "remake" of the 1798 Cavendish experiment
    - $R \lesssim 0.16$ mm ($M_D \gtrsim 1.7$ TeV)
- Sensitivity vanishes quickly with the distance – can't push limits further down significantly
  - Started restricting ADD with 2 extra dimensions; can't probe any higher number
  - Ultimately push the sensitivity by a factor of two in terms of the distance
- No sensitivity to the TeV^{-1} and RS models

Large ED: Gravity at Short Distances

[J. Long, J. Price, hep-ph/0303057]



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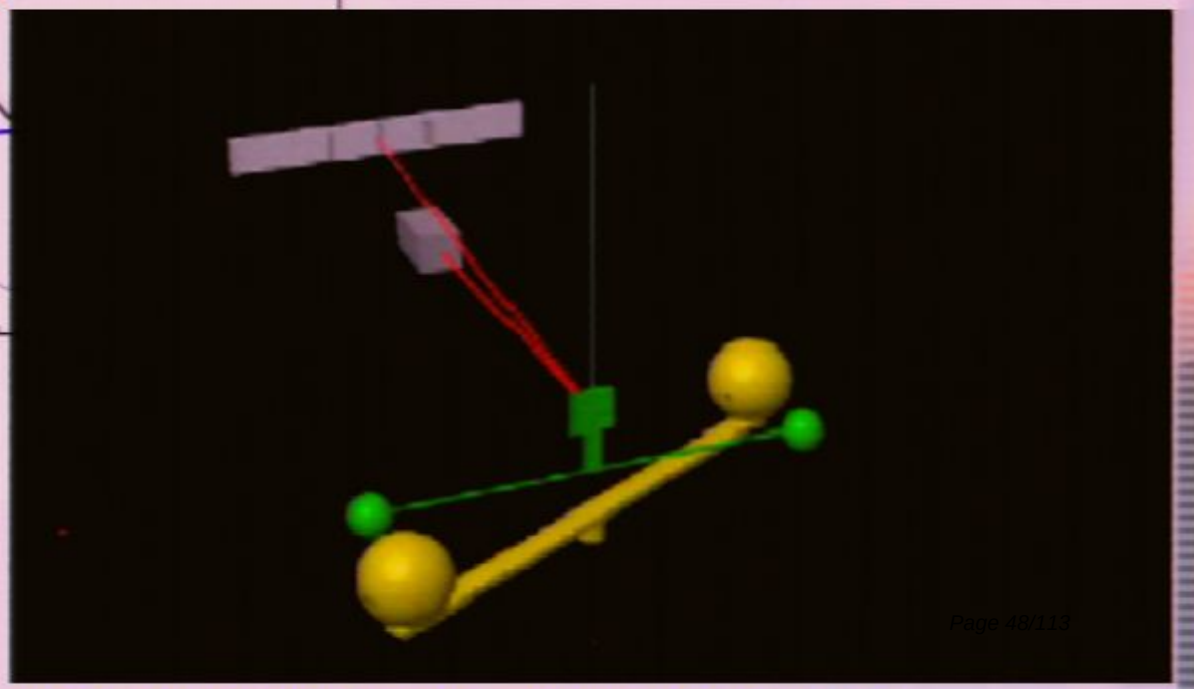

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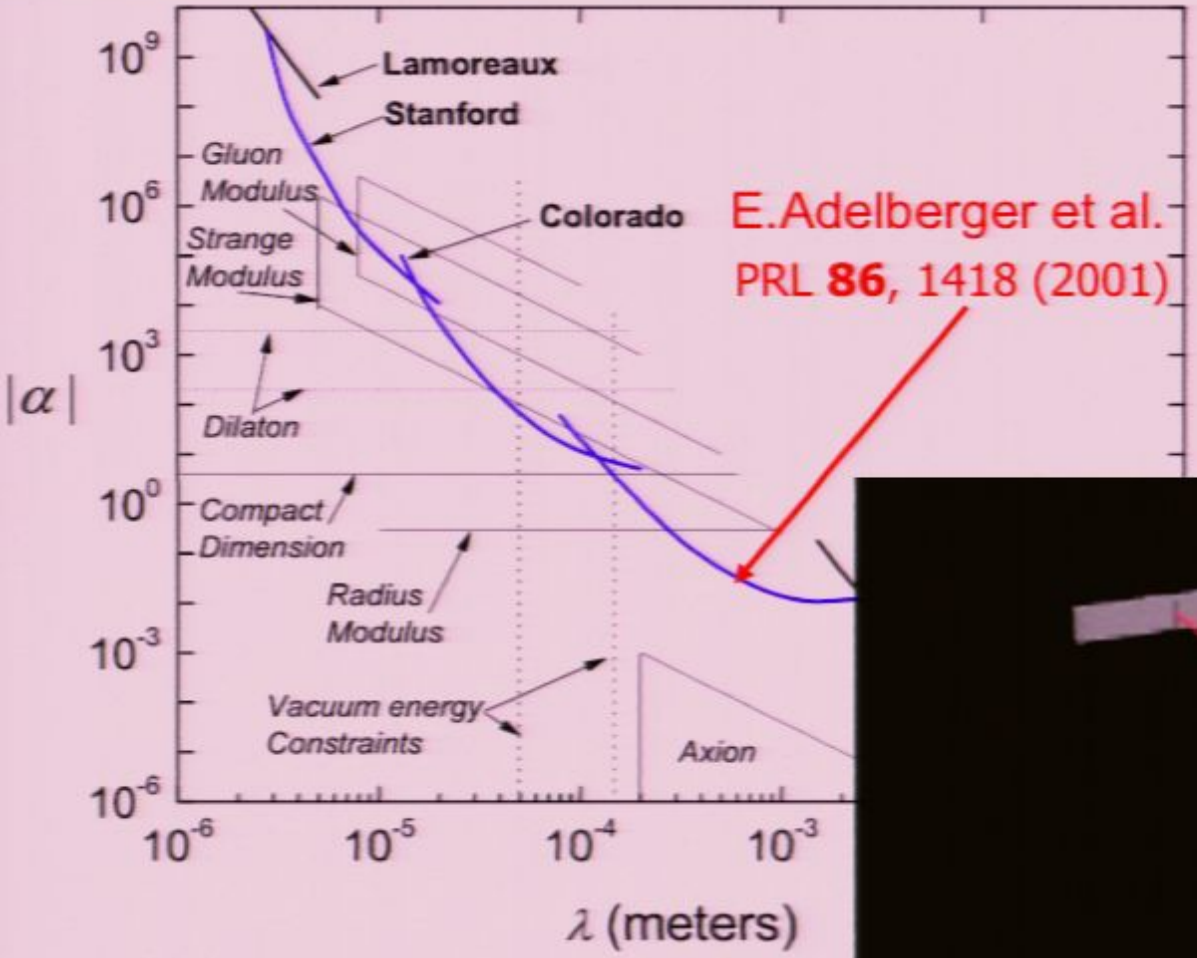

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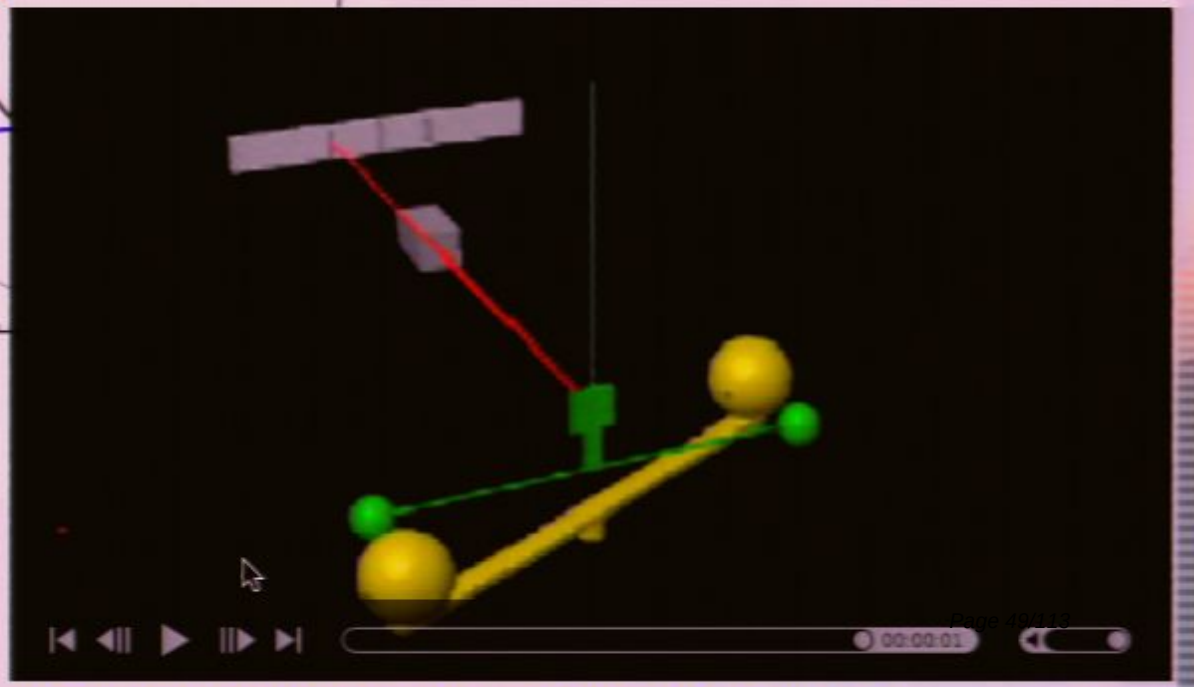

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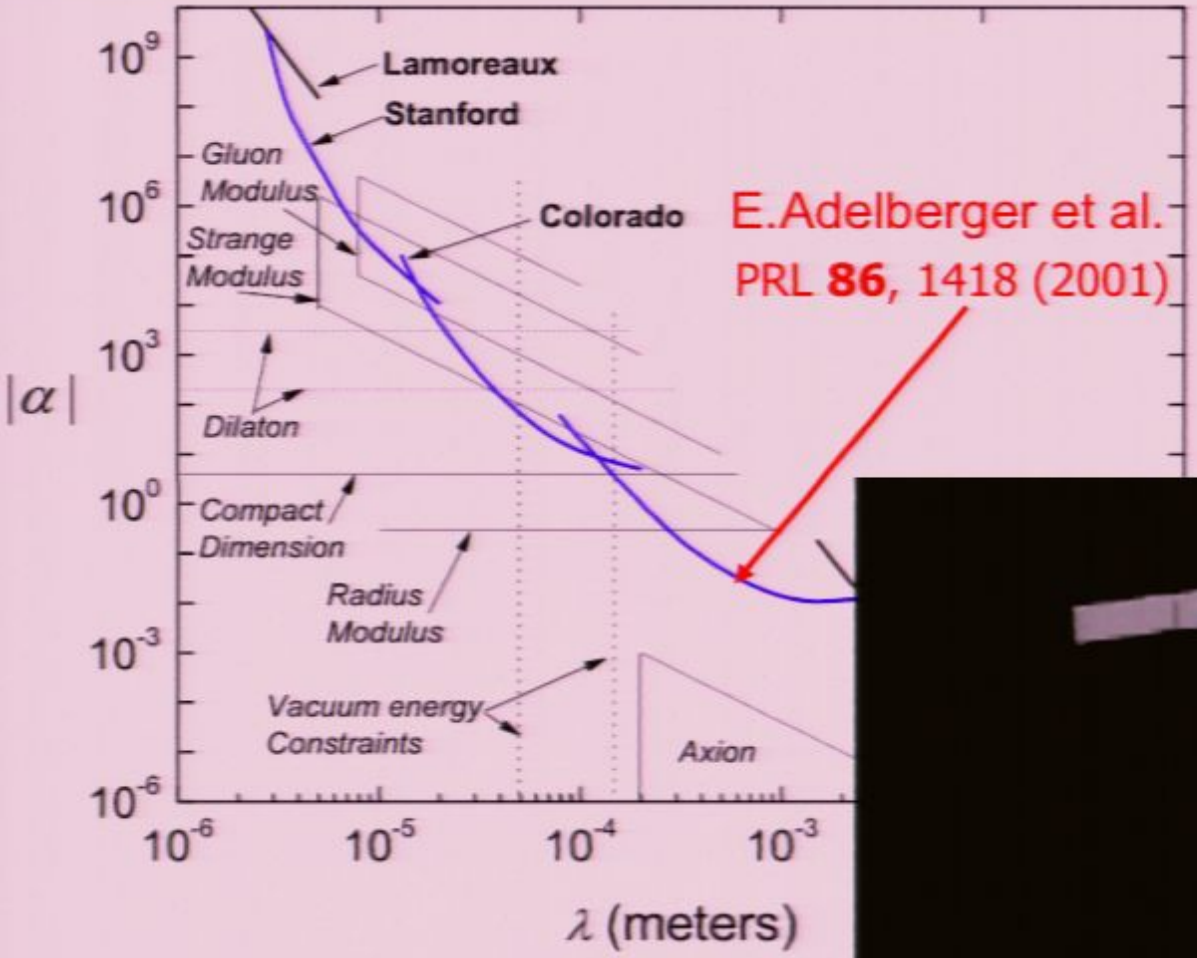

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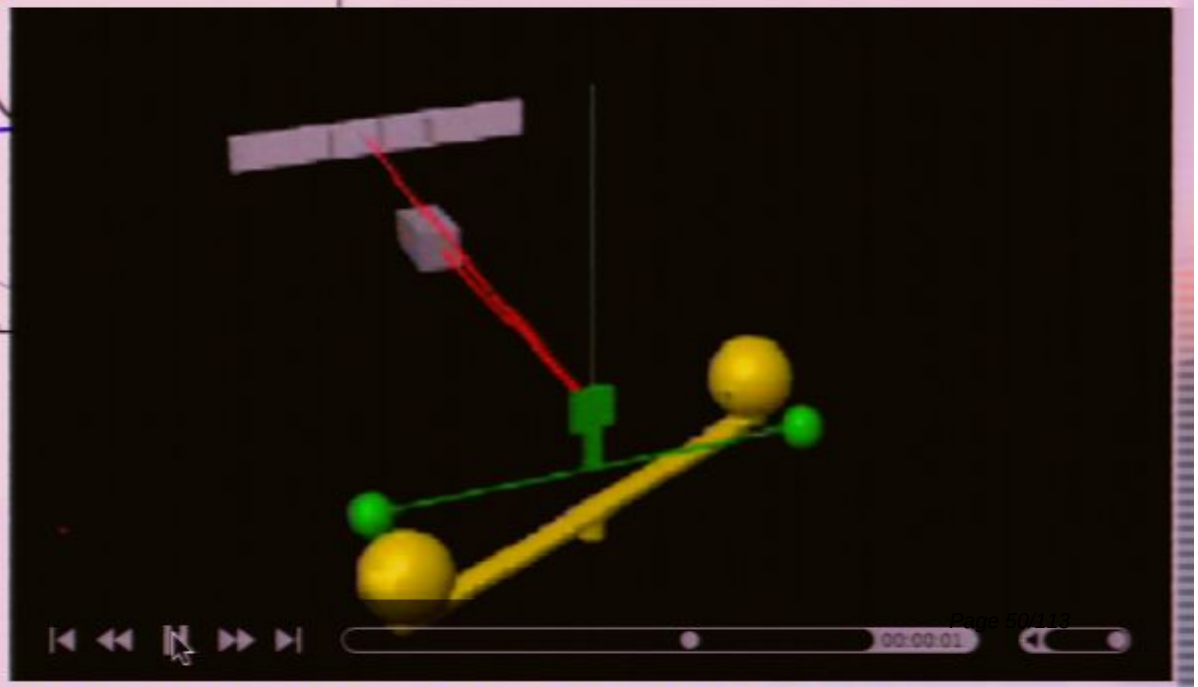

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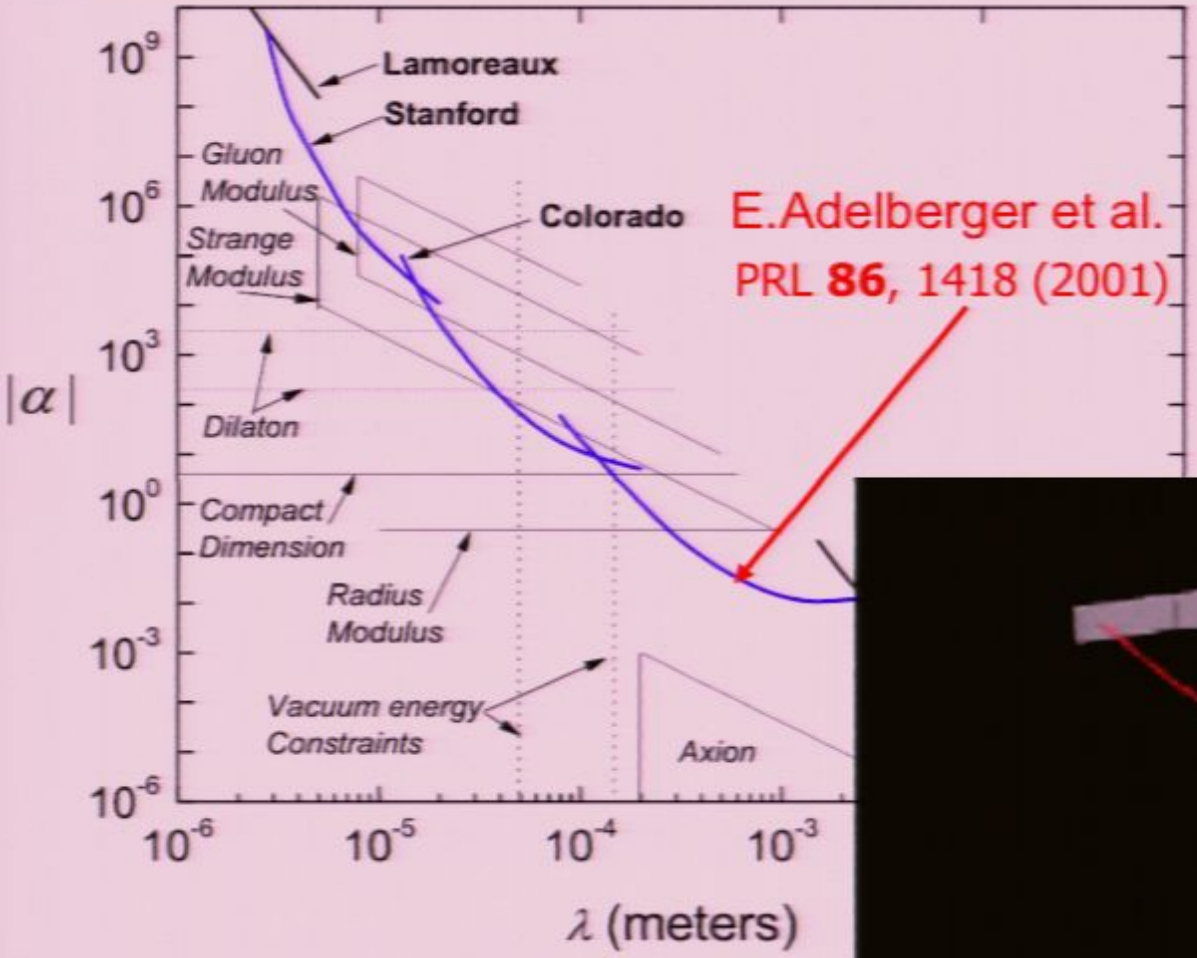

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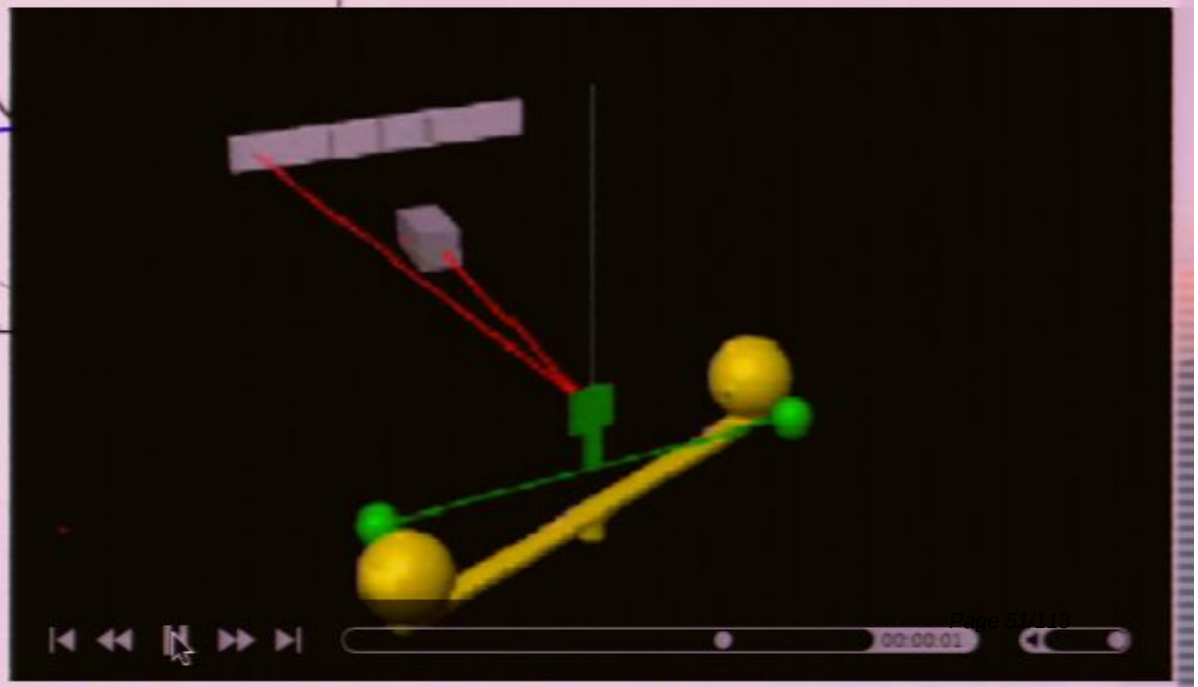

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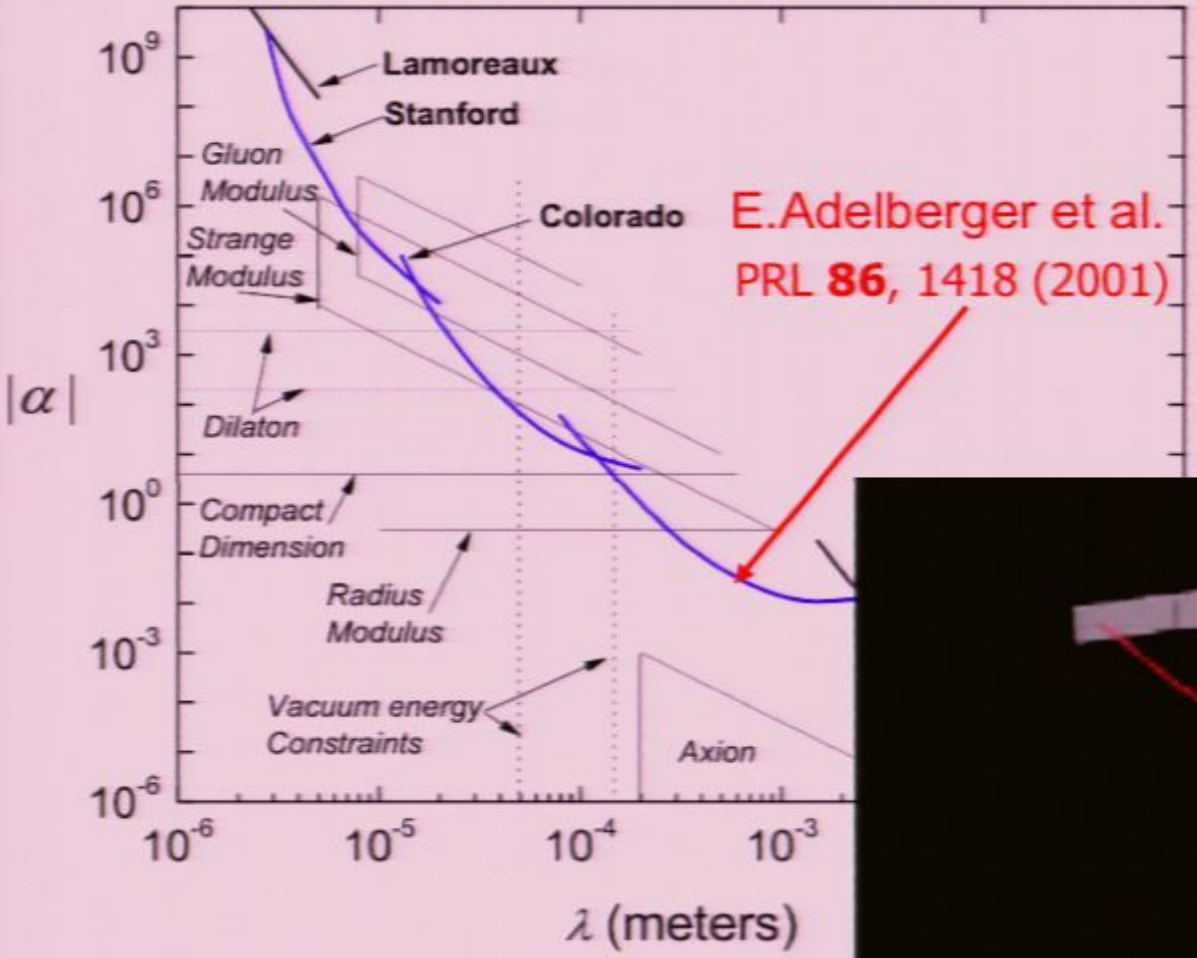

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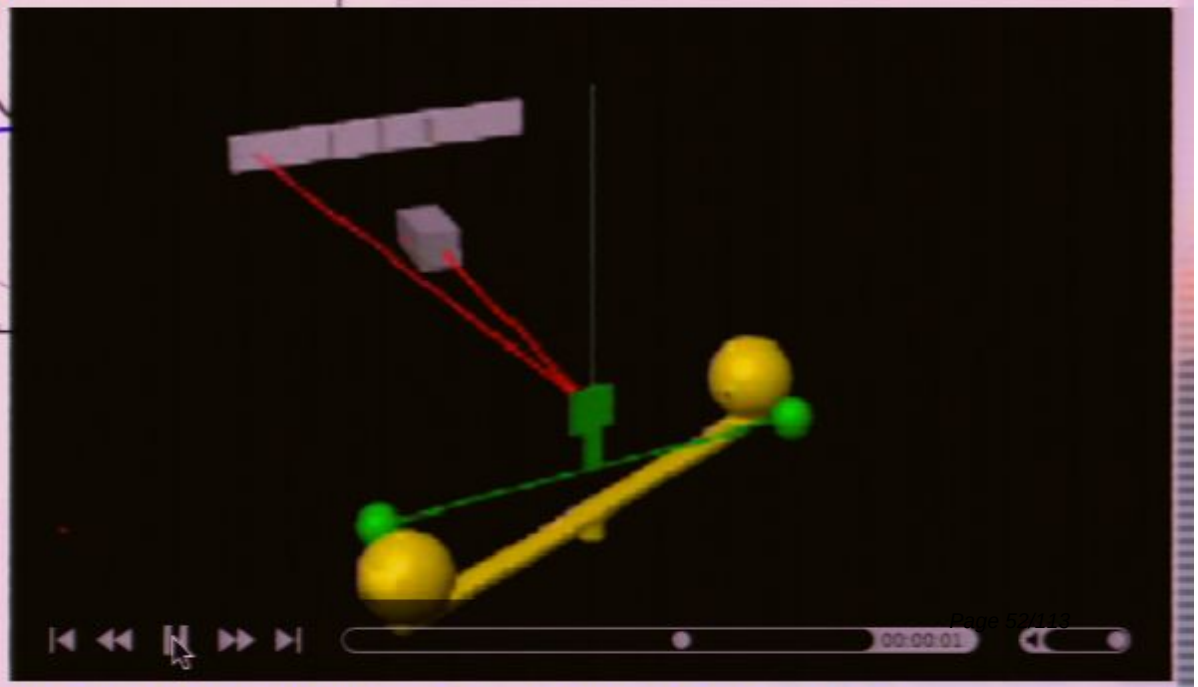

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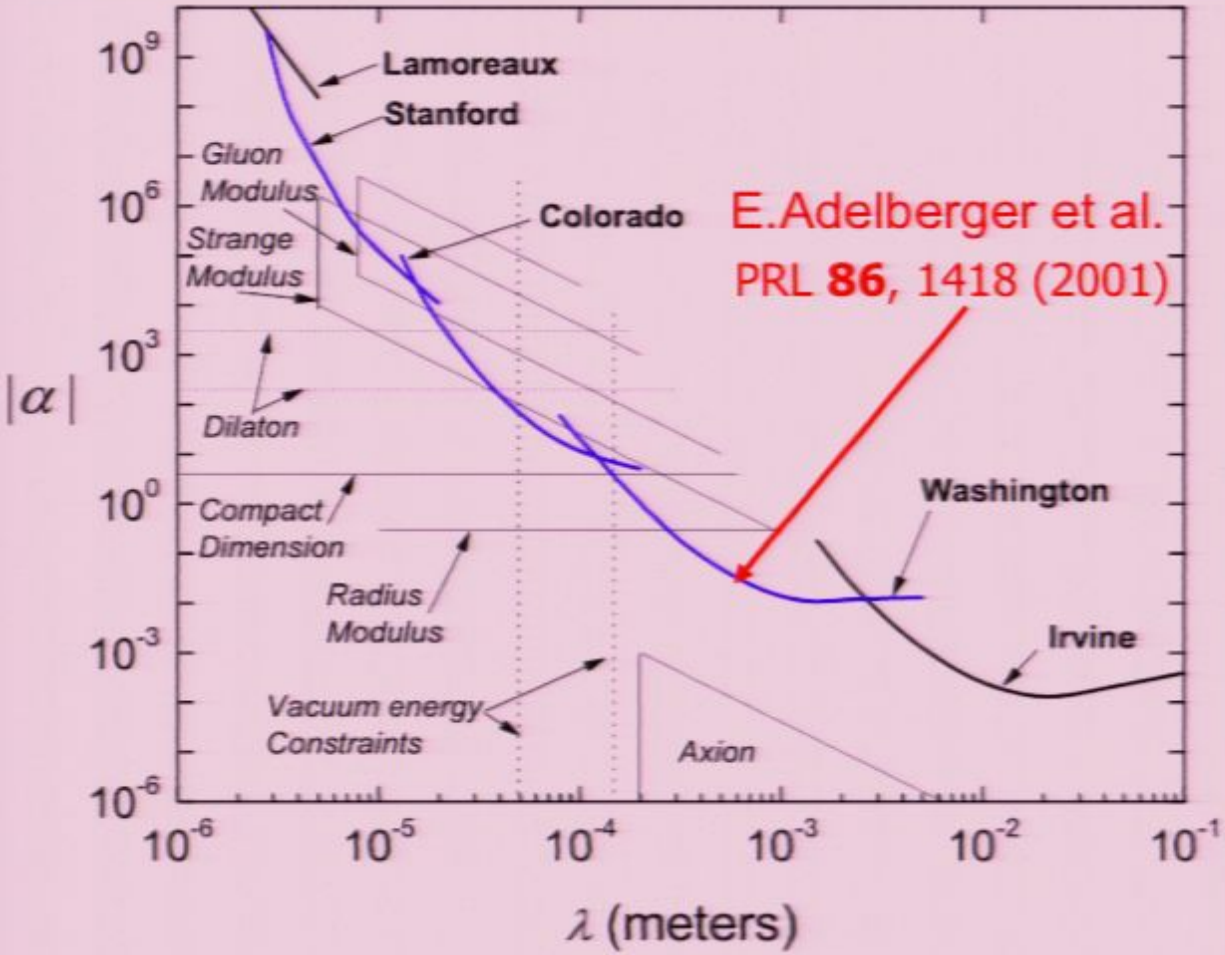

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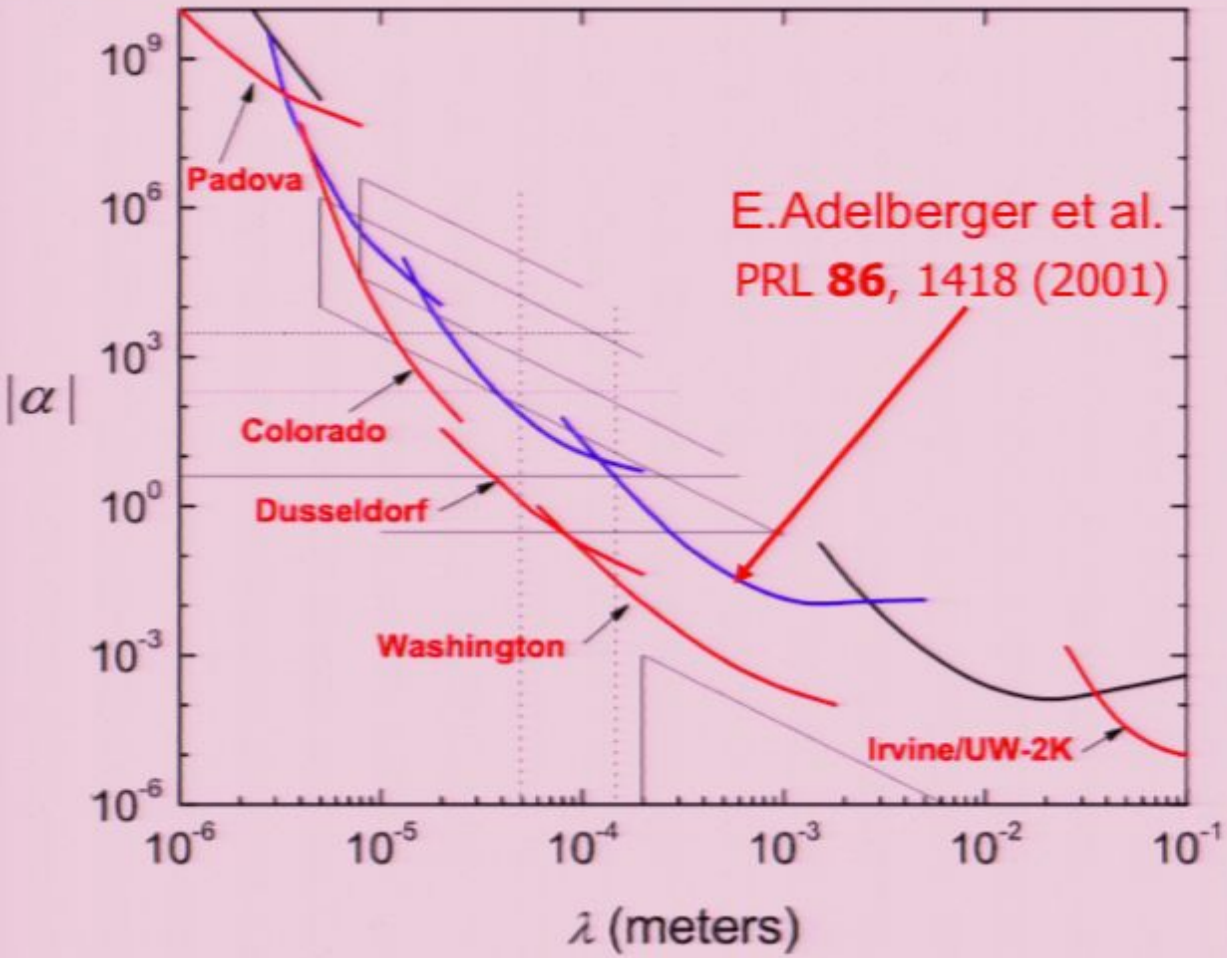
    - $R \lesssim 0.16$ mm ($M_D \gtrsim 1.7$ TeV)
- Sensitivity vanishes quickly with the distance – can't push limits further down significantly
  - Started restricting ADD with 2 extra dimensions; can't probe any higher number
  - Ultimately push the sensitivity by a factor of two in terms of the distance
- No sensitivity to the TeV^{-1} and RS models

Large ED: Gravity at Short Distances

[J. Long, J. Price, hep-ph/0303057]



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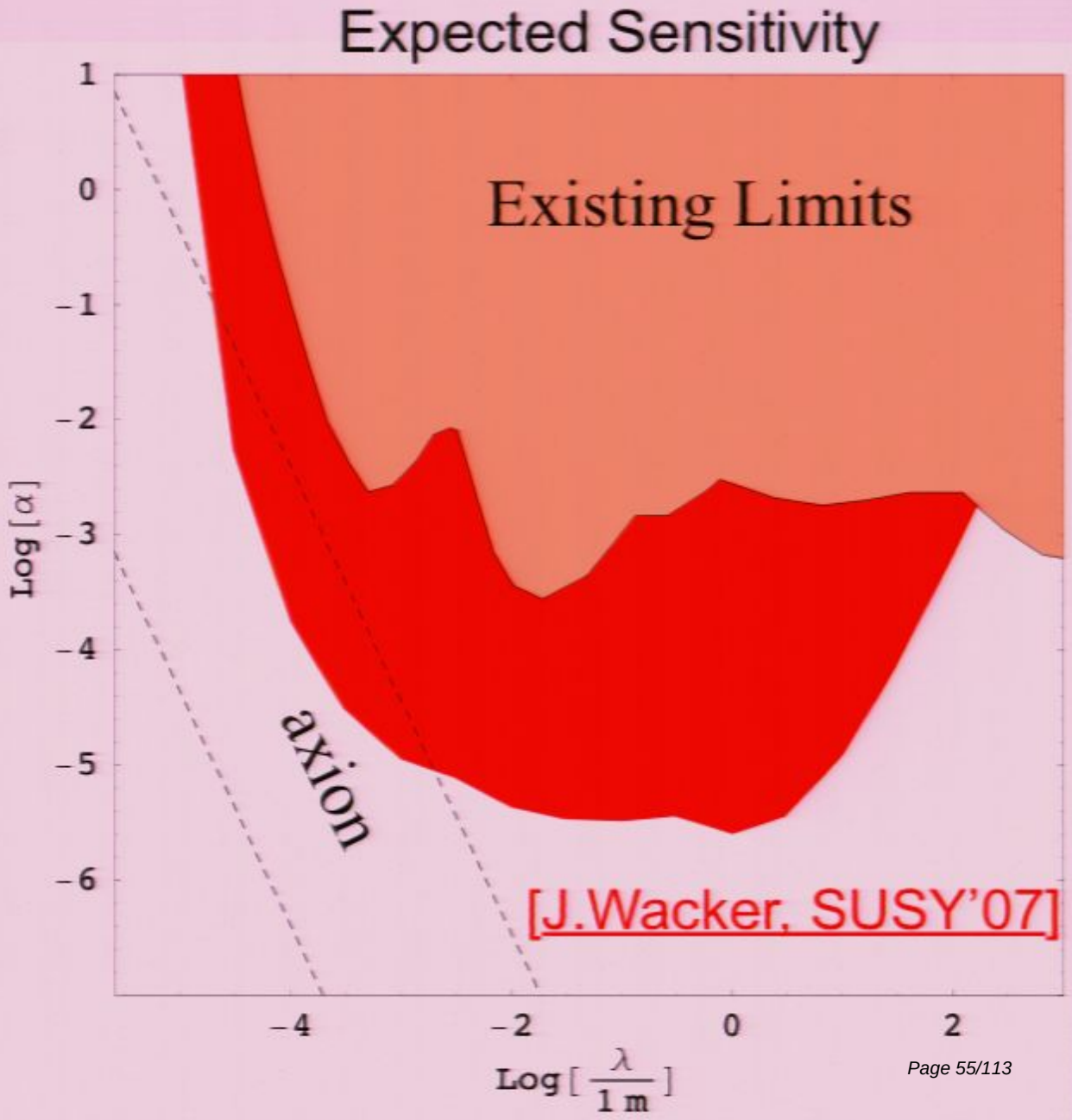
New Ideas in Gravity Measurements

- Use an atomic interferometer for precision measurement of acceleration
- Stanford experiment: 10m Mach-Zehnder space-time interferometer (Hogan)
- Measure phase shift in the presence of a test mass placed near the interferometer
- Several ideas in the pipeline on sensitivity increase; projected ultimate sensitivity



Large ED: Astro & Cosmo Constraints

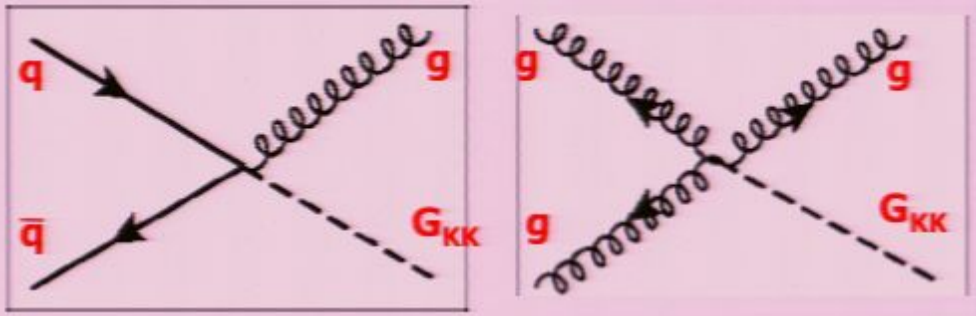
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant one via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by Kamiokande and IMB
  - Application to the ADD scenario: Cullen and Perelstein [PRL **83**, 268 (1999)]; Hanhart, Phillips, Reddy, and Savage [Nucl. Phys. **B595**, 335 (2001)]:
    - M_D > 25-30 TeV (n=2)
    - M_D > 2-4 TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \rightarrow \gamma\gamma$ decays: Hall and Smith [PRD **60**, 085008 (1999)]:
  - M_D > 100 TeV (n=2)
  - M_D > 5 TeV (n=3)
- Overclosure of the universe, matter dominance in the early universe, Fairbairn [Phys. Lett. **B508**, 335 (2001)]; Fairbairn, Griffiths [JHEP 0202, **024** (2002)]
  - M_D > 86 TeV (n=2)
  - M_D > 7.4 TeV (n=3)
- Neutron star γ-emission from radiative decays of the gravitons trapped during the supernova collapse, Hannestad and Raffelt [PRL **88**, 071301 (2002)]:
  - M_D > 1700 TeV (n=2)
  - M_D > 60 TeV (n=3)
- Caveat: there are many known (and unknown!) uncertainties, so the cosmological bounds are reliable only as an order of magnitude estimate
- Still, n=2 is largely disfavored

Collider Signatures for Large ED

- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang [PRD **59**, 105006 (1999)]
  - Giudice, Rattazzi, Wells [NP **B544**, 3 (1999)]
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be ~M_D (and likely < M_D)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders



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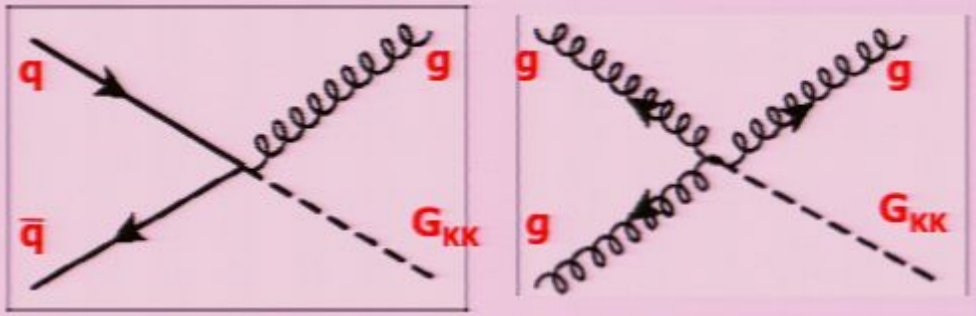
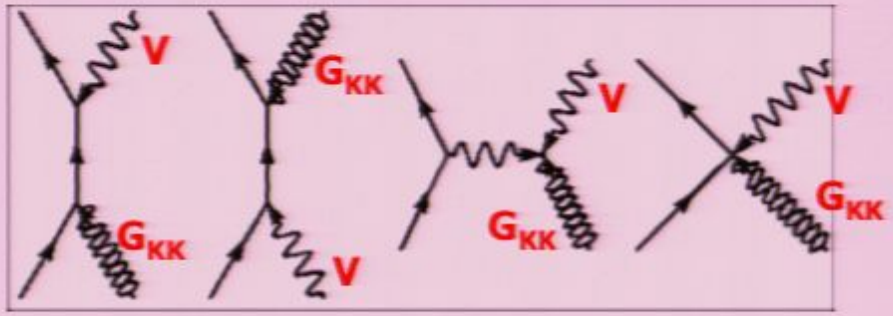


Single VB at hadron or e^+e^- colliders



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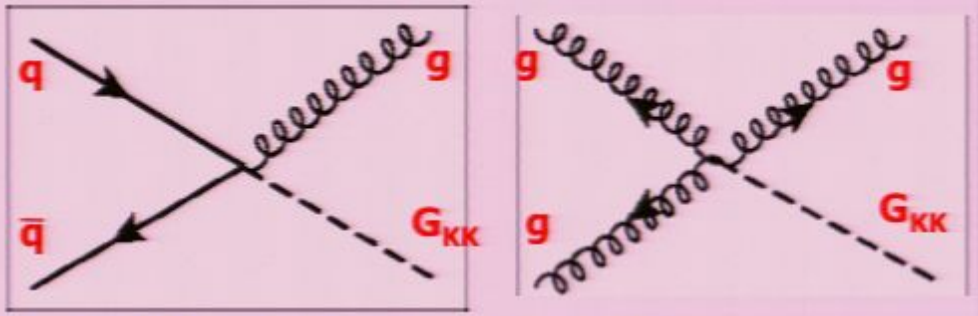

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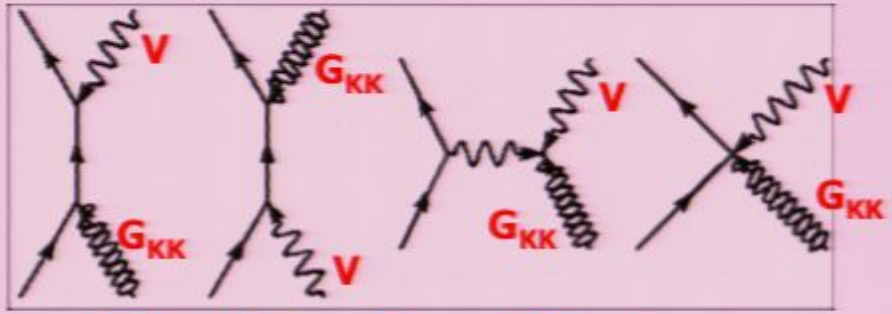
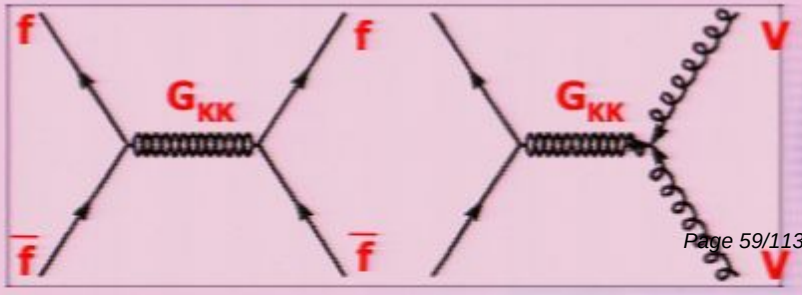


Virtual Graviton Effects

Fermion or VB pairs at hadron or e^+e^- colliders



L'EPilogue (Large ED)

Direct Graviton Emission

	$e^+e^- \to \gamma G$					$e^+e^- \to ZG$					
Experiment	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6	Color coding
ALEPH	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12	≤184 GeV
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58						≤189 GeV
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	**0.24**	**0.21**	>200 GeV
OPAL	1.09	0.86	0.71	0.61	0.53						λ=-1 λ=+1 GL

All limits are in TeV

Virtual Graviton Exchange

Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	Combined
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.46/0.46 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.83 0.91			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79		1.0/1.1 (<202)
OPAL	1.15 1.00	0.62 0.66			0.62 0.66	0.89 0.83		0.63 0.74	1.17/1.03 (<209)

LEP Combined: 1.2/1.1 TeV

Monojets: Tainted History

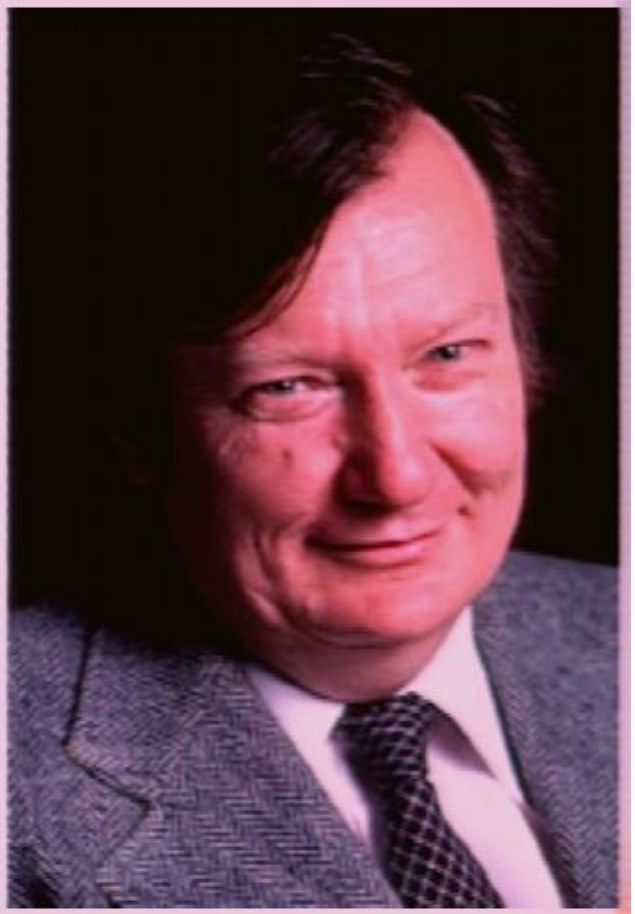
EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.



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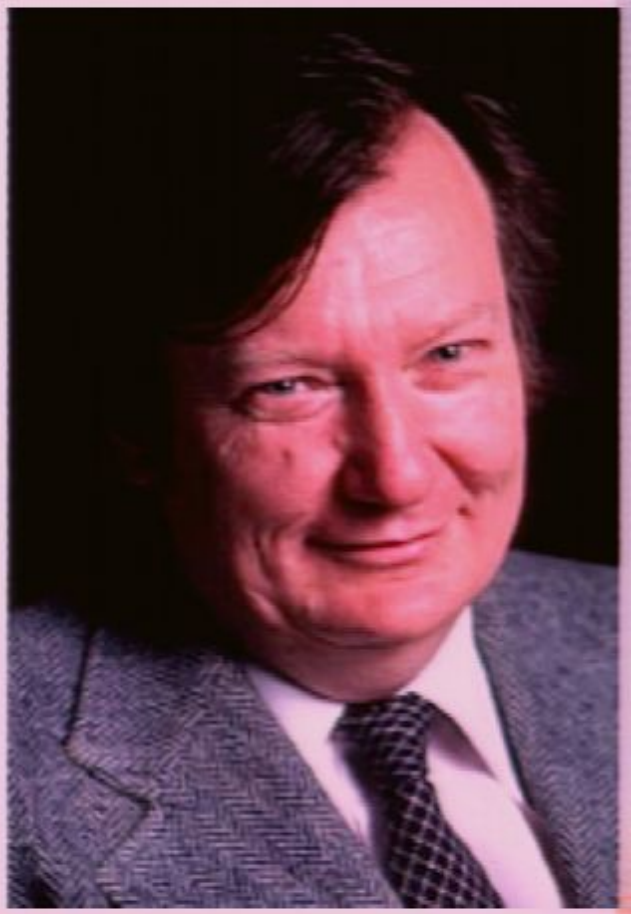

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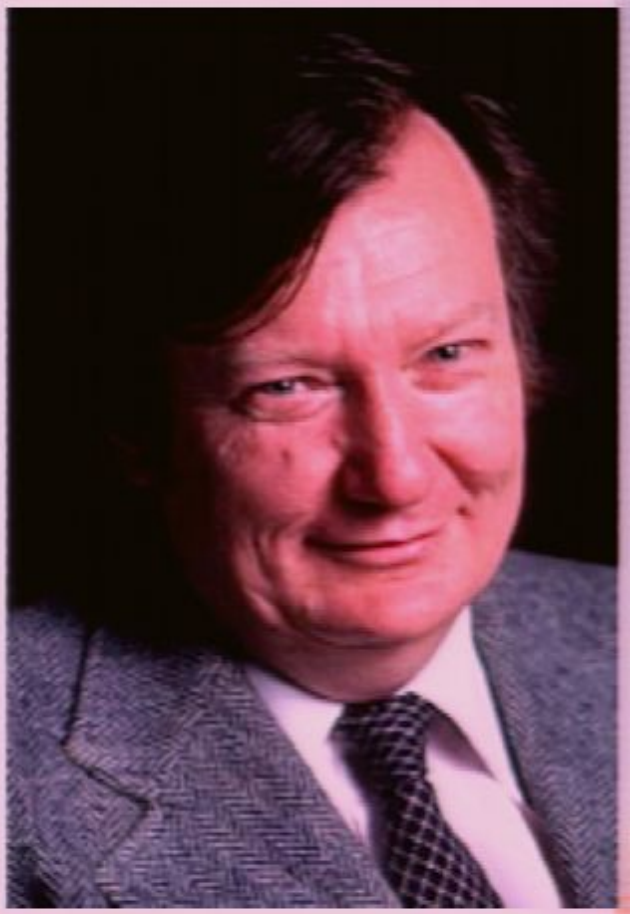
VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

Stephen F. King
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 26 November 1984)

The recent discovery of monojets by Arnison *et al.*[1] at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they cannot be explained by the minimal standard model.[2]



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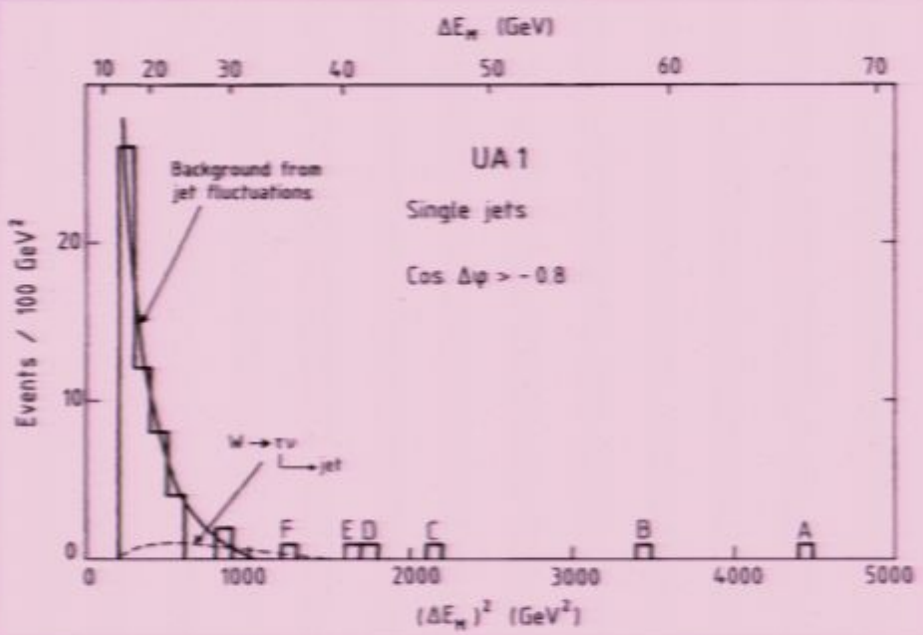
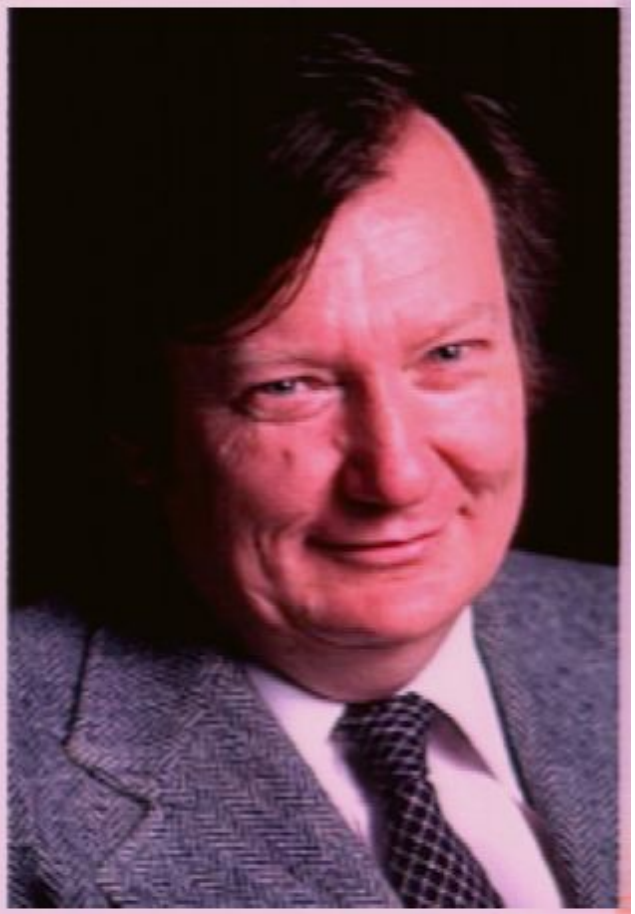
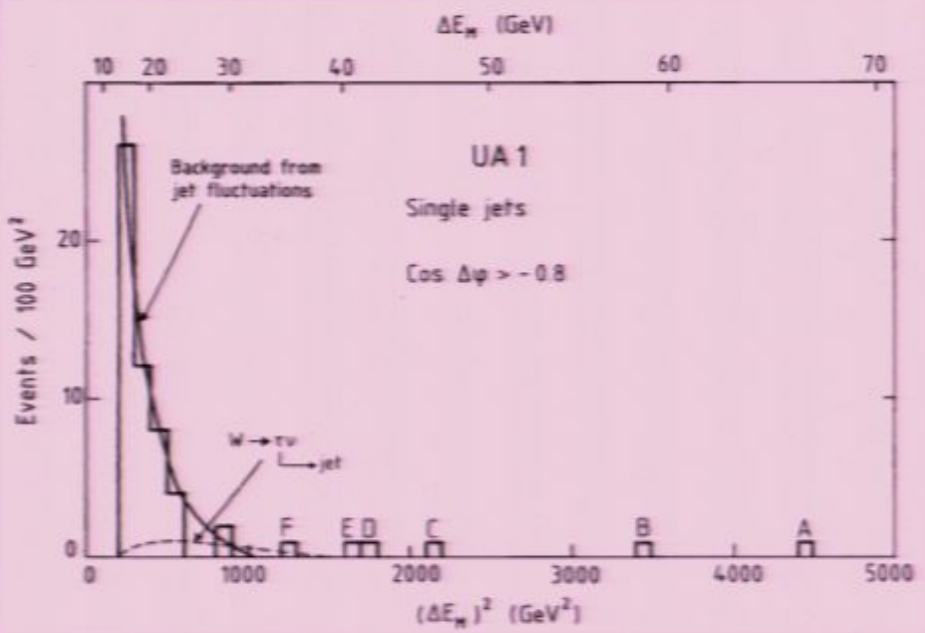
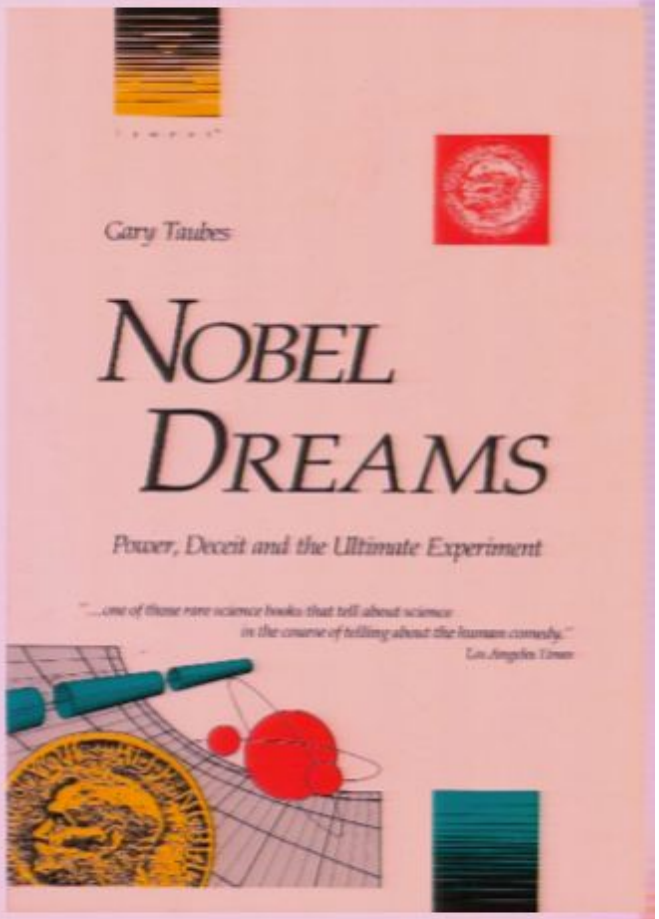




- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

Monojets: Tainted History





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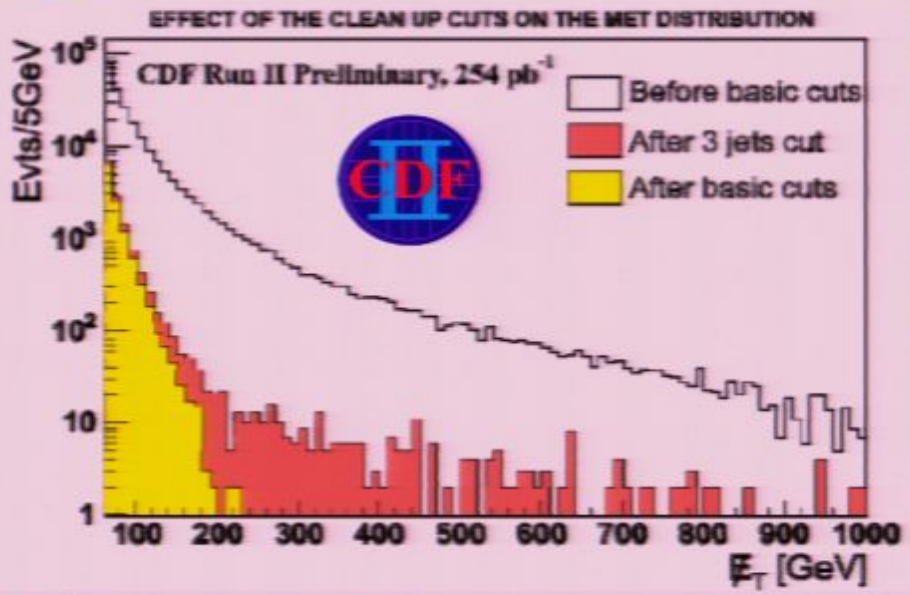
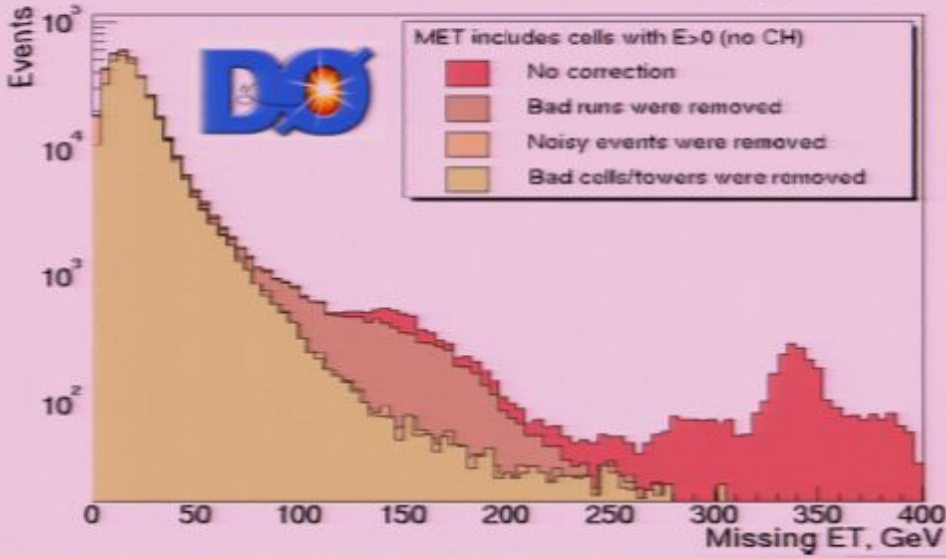
Why Jets+ME_T is Tough?

- Jets tend to fluctuate wildly:
  - Large shower fluctuation
  - Non-linear calorimeter response
  - Non-compensation (i.e., e/h ≠ 1)
  - Fluctuations in the e/h energy ratio
- Instrumental effects:
  - Dead or "hot" calorimeter cells
  - Cosmic rays
  - Poorly instrumented area of the detector
- Note that in Run II DØ showed the first results in this channel only in 2005 (4 years into the run); CDF made their results public and published them in 2006
- Likely not an early LHC running measurement!

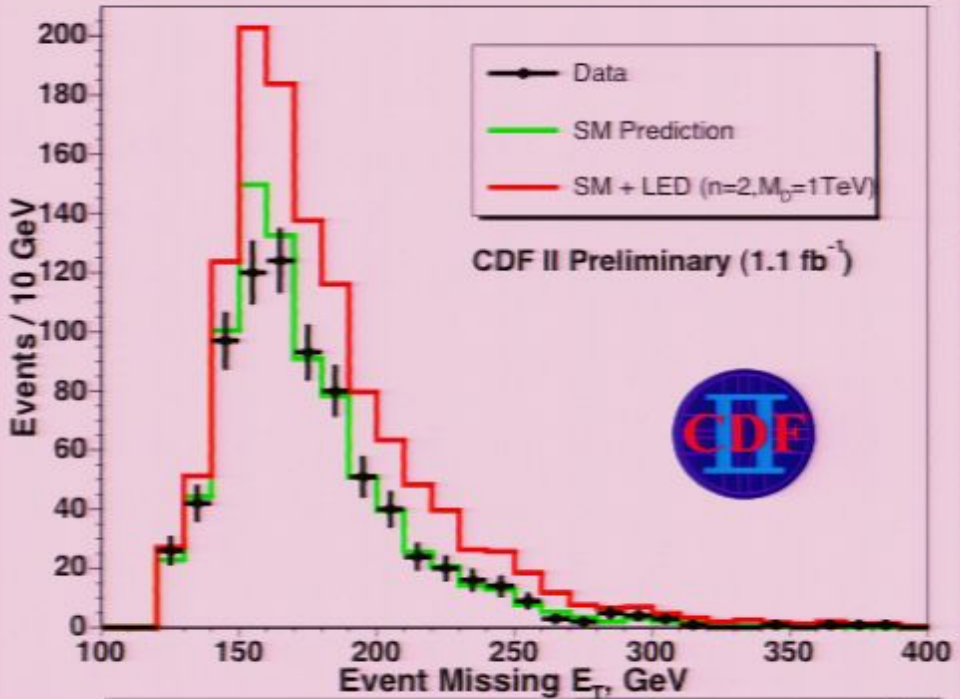


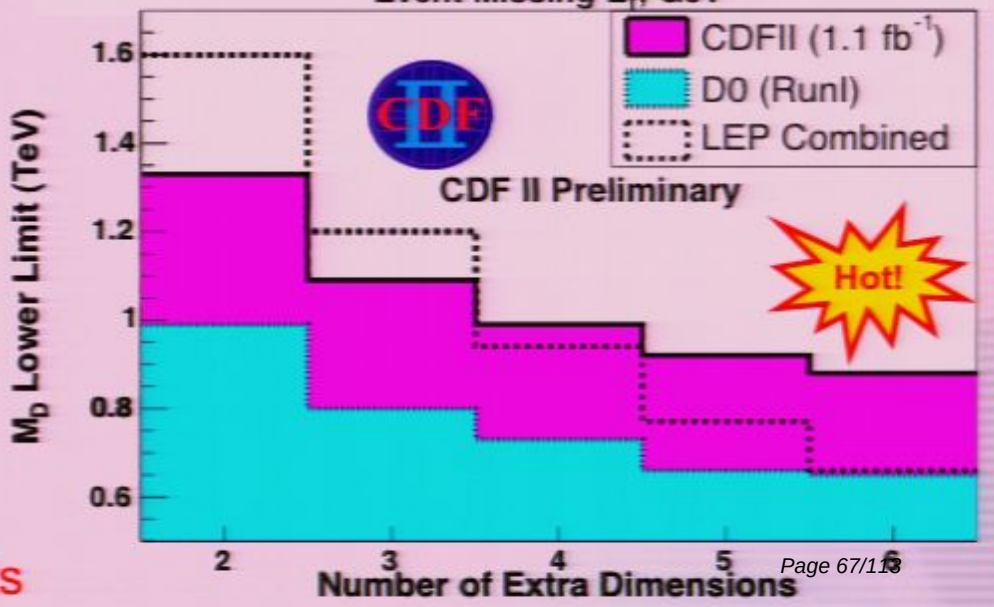


- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

Tevatron: Large ED Search via Monojets

- jets + ME_T final state
- Z(νν)+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
- DØ pioneered this search and set limits [PRL, **90** 251802 (2003)] M_P > 1.0-0.6 TeV for n=2…7
- New CDF analysis w/ 1.1 fb^{-1}
  - Central jet w/ E_T > 150 GeV
  - ME_T > 120 GeV
  - No other jets w/ E_T > 60 GeV
  - 779 events observed with 819 ± 71 expected (half comes from Z(νν)+j)
  - Set limits on the fundamental Planck scale between 0.88 and 1.33 TeV
  - Similar results with looser ME_T, E_T^j cuts

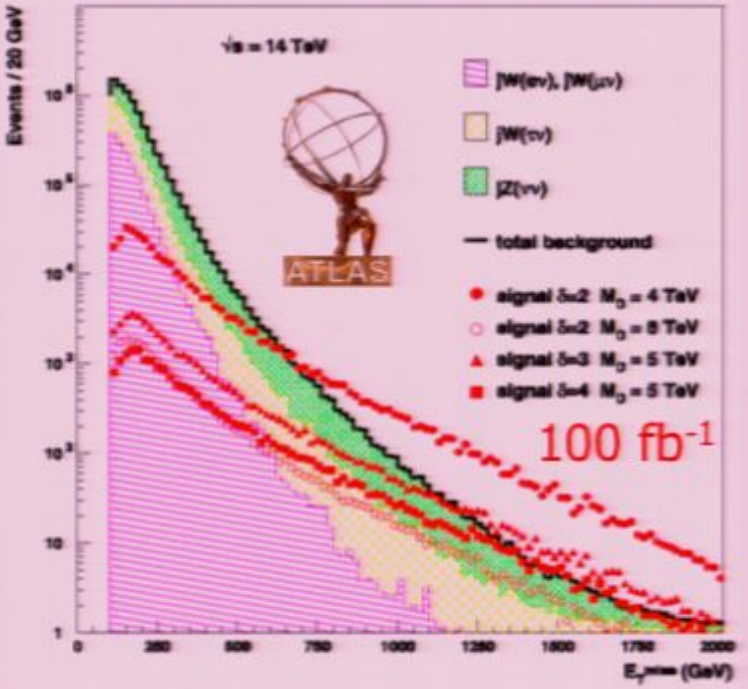




Expectations at the LHC

Monojets:

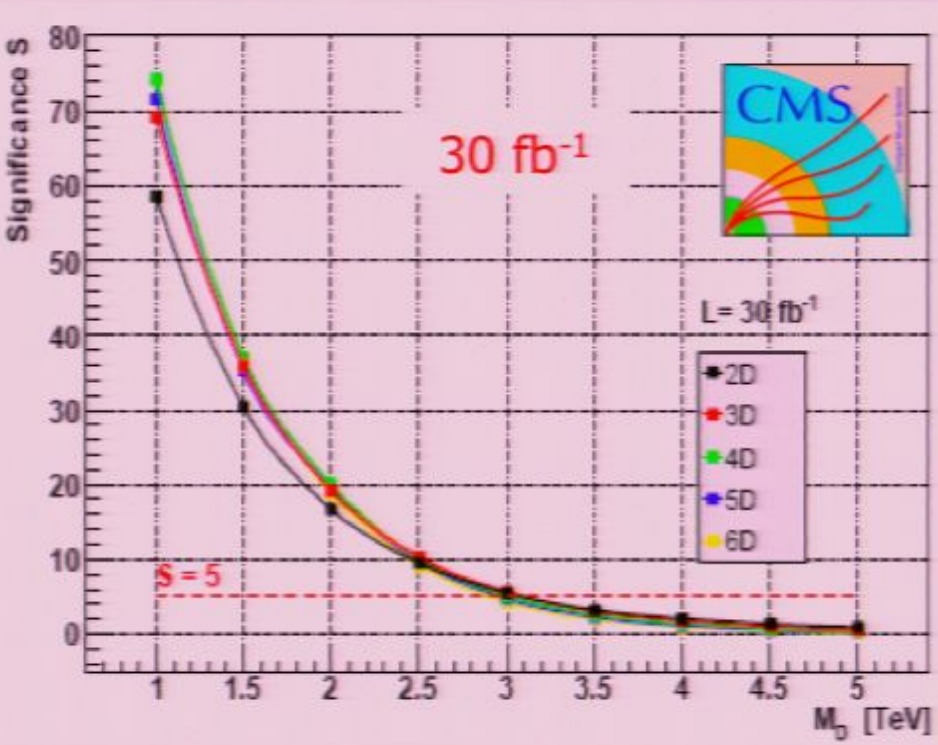
- ATLAS fast simulation for 30 and 100 fb^{-1} (caveat: no instrumental bckg. included)



δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

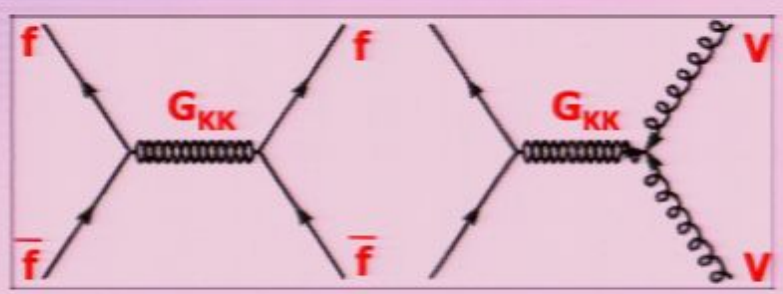
•Monophotons:

–ATLAS and CMS simulations for 100 fb^{-1} and 30 fb^{-1}, respectively



δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

Tevatron: Virtual Graviton Effects



- Expect an interference with the SM fermion or boson pair production

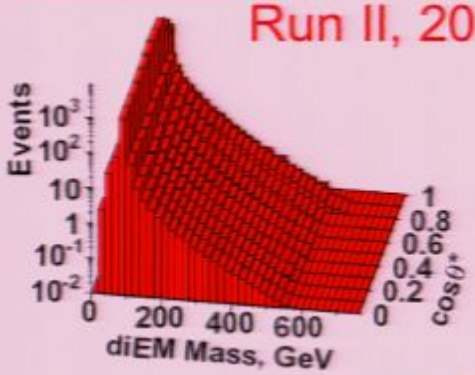
$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1(\cos\theta^*, M) + \frac{b(n)}{M_S^8} f_2(\cos\theta^*, M)$$

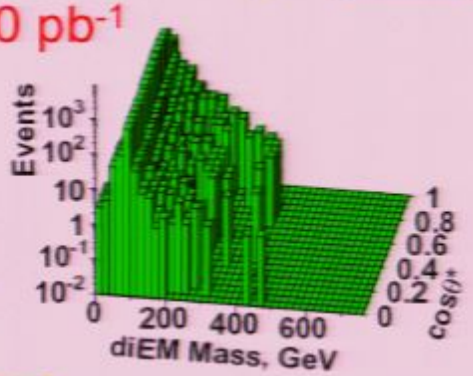
- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED Cheung, GL [PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from new DØ Run II data:
  - M_S > 1.1-1.6 TeV (n=2-7)
- Combined with the Run I DØ result:
  - M_S > 1.1-1.7 TeV – tightest to date
- Sensitivity in Run II and at the LHC:

	Run II, 2 fb^{-1}	LHC, 100 fb^{-1}
$e^+e^- + \mu^+\mu^-$	1.3-1.9 TeV	6.5-10 TeV
$\gamma\gamma$	1.5-2.4 TeV	7.5-12 TeV
$e^+e^- + \mu^+\mu^- + \gamma\gamma$	**1.5-2.5 TeV**	**7.9-13 TeV**

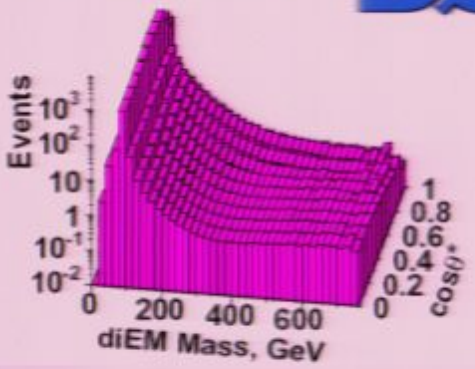
SM Prediction | DØ Run II Preliminary | **Data**

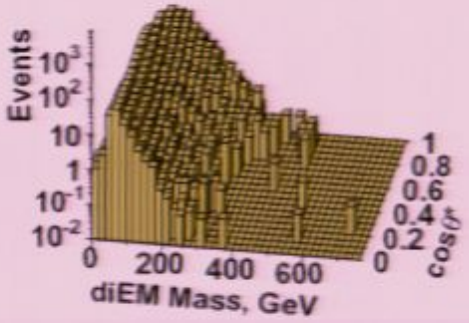
Run II, 200 pb^{-1}





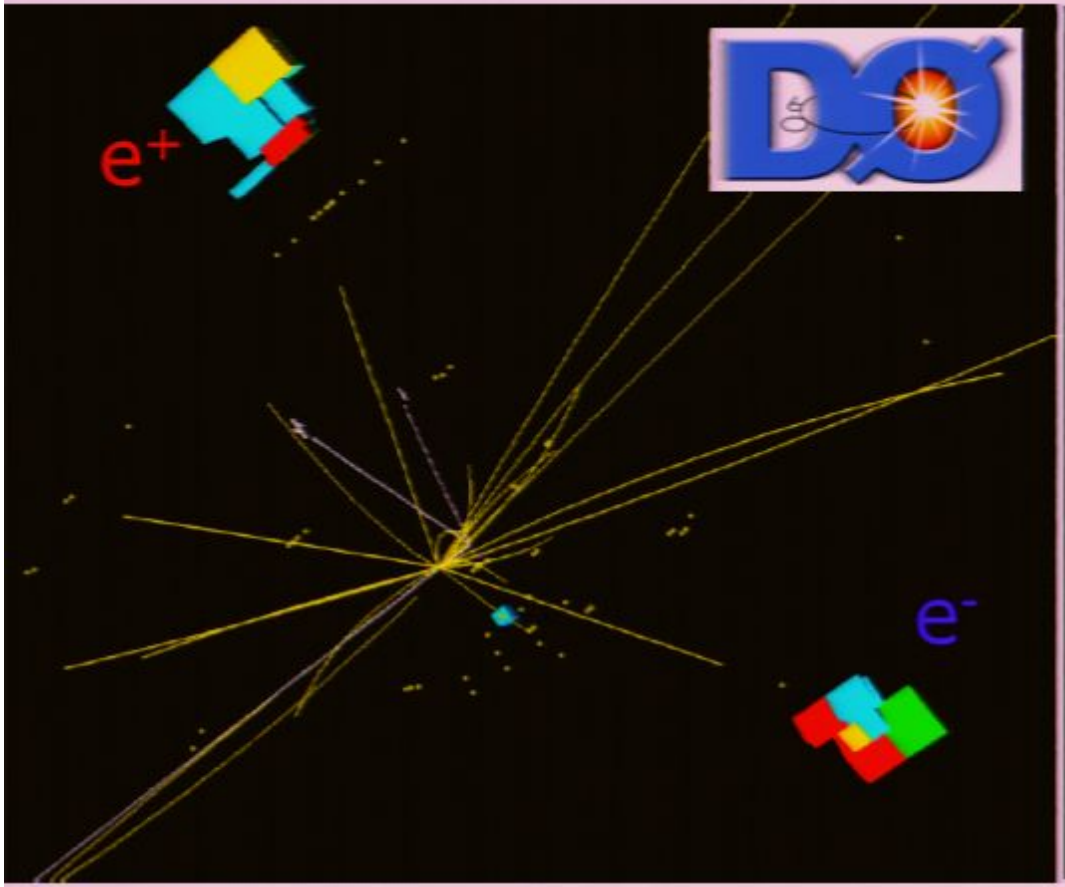
ED Signal | **QCD Background**

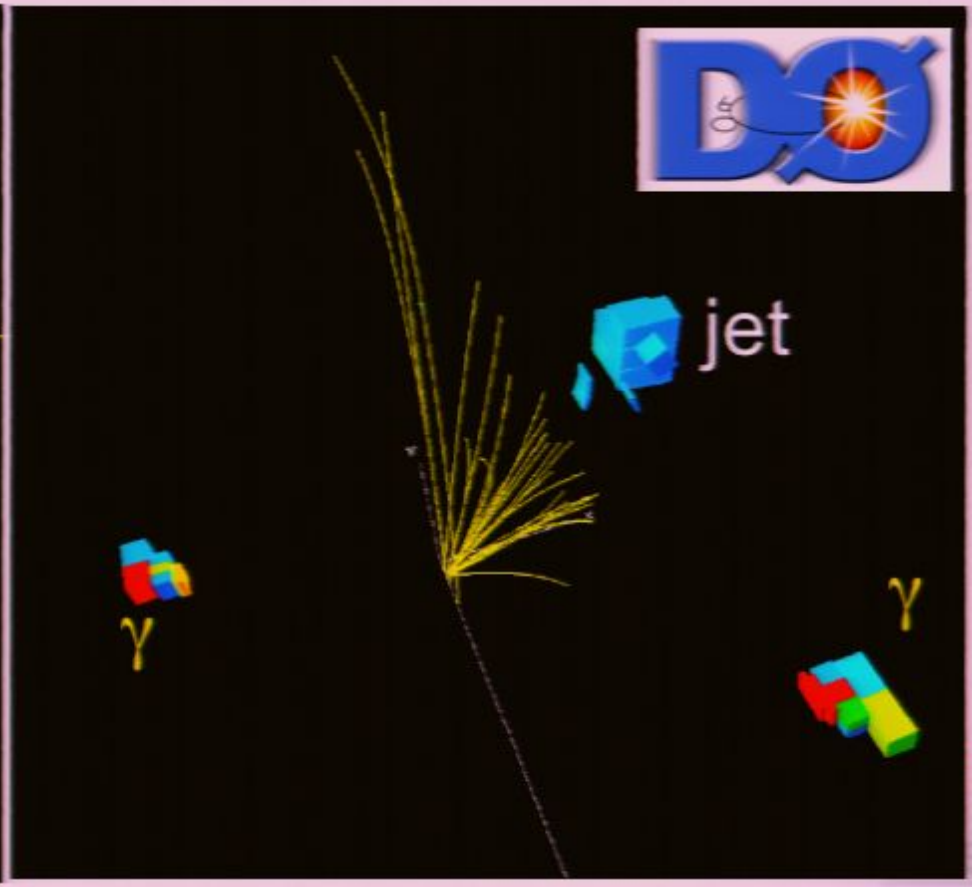




Interesting Candidate Events

- While the DØ data are consistent with the SM, the two highest-mass candidates have anomalously low value of $\cos\theta^*$ typical of ED signal:

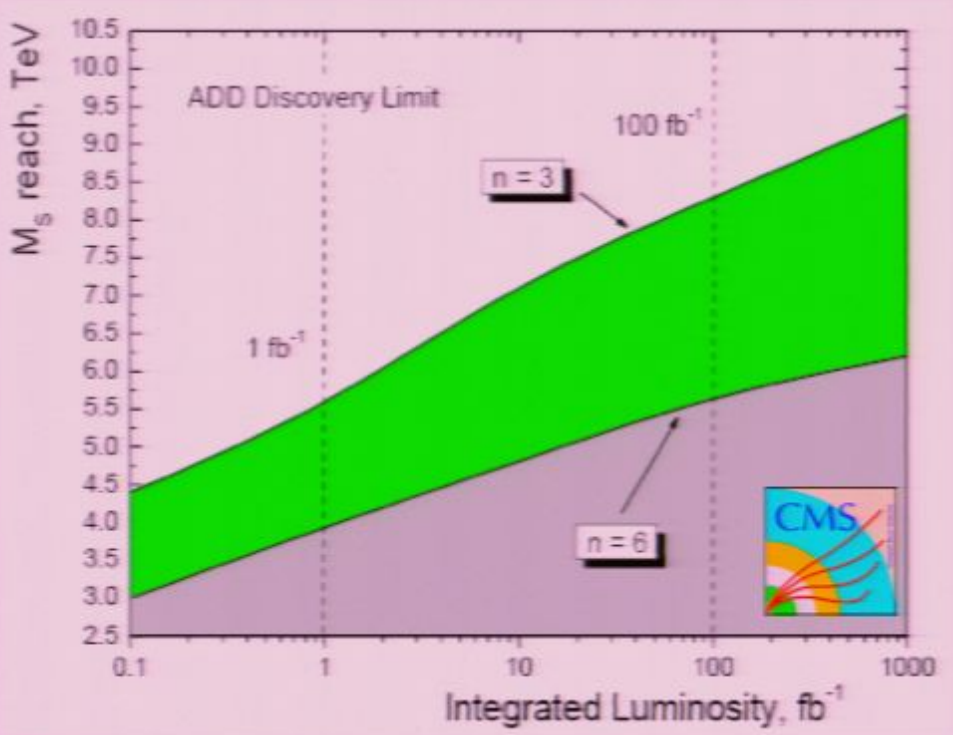




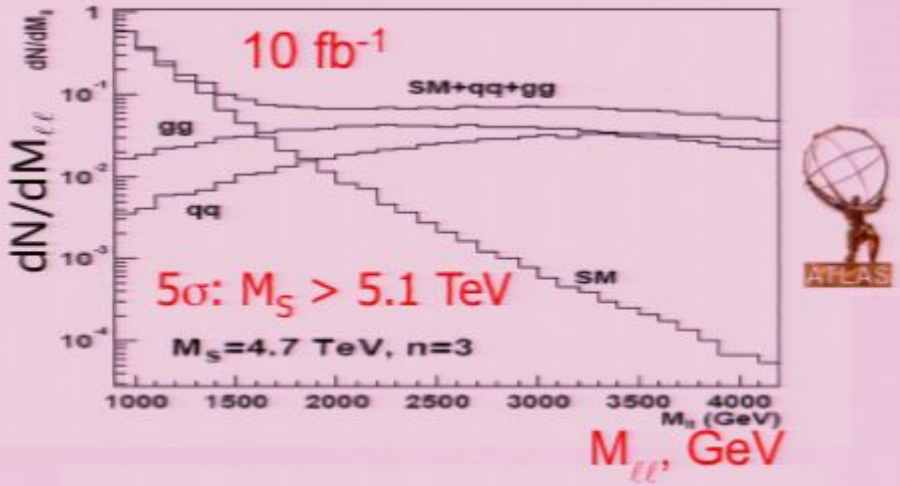
Event Callas: M_{ee} = 475 GeV, $\cos\eta^*$ = 0.01 Event Farrar: $M_{\gamma\gamma}$ = 436 GeV, $\cos\eta^*$ = 0.03

Virtual Graviton Effects at the LHC

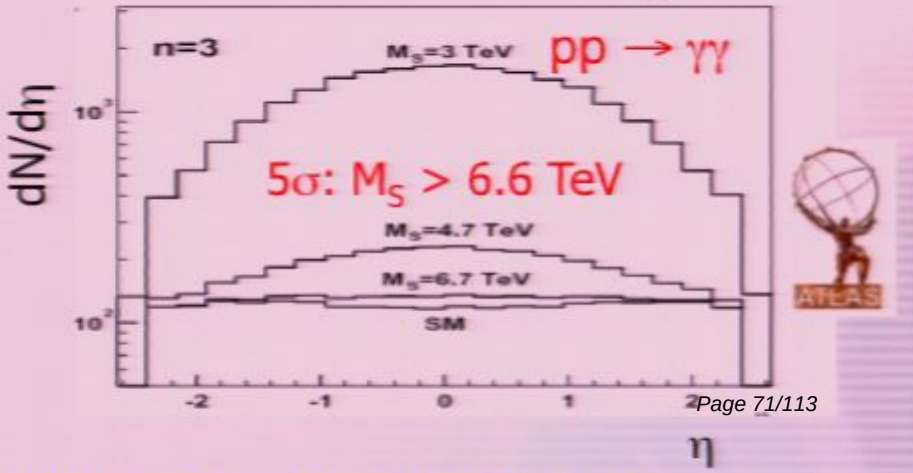
- Clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels:
  - Factor of ~3 gain over the Tevatron/Cosmic Ray limits in just 100 pb^{-1}
  - Will also probe generic compositeness models with similar increase in sensitivity compared to the existing limits



CMS reach for large ED in the dimuon channel



$M_{\ell\ell}$, GeV

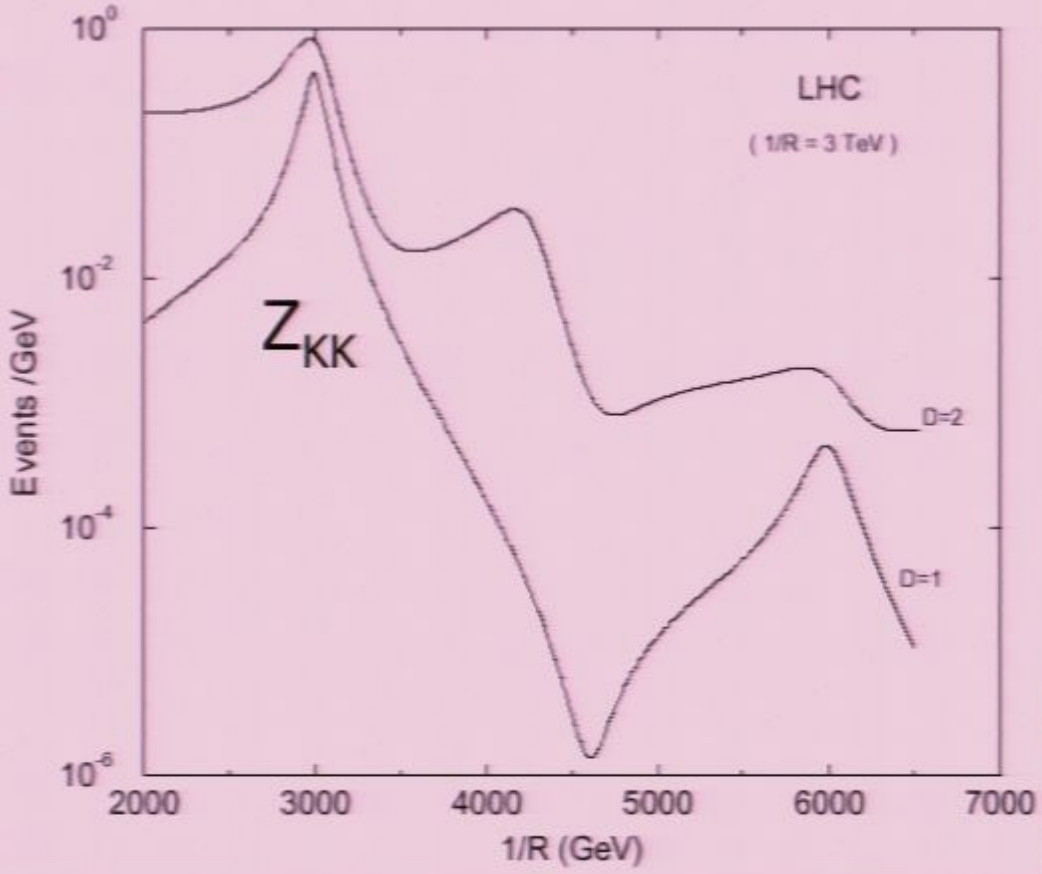


η

TeV^{-1} Extra Dimensions

- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by Antoniadis [PL **B246**, 377 (1990)] in the string theory context
- Used by Dienes, Dudas, and Gherghetta [PL **B436**, 55 (1998)] to allow for low-energy unification
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances at the LHC energies
  - At lower energies, can study effects of virtual exchange of the Kaluza-Klein modes of vector bosons
- Current indirect constraints come from precision EW measurements:
  - 1/r ~ 6 TeV

Antoniadis, Benaklis, and Quiros
[PL **B460**, 176 (1999)]

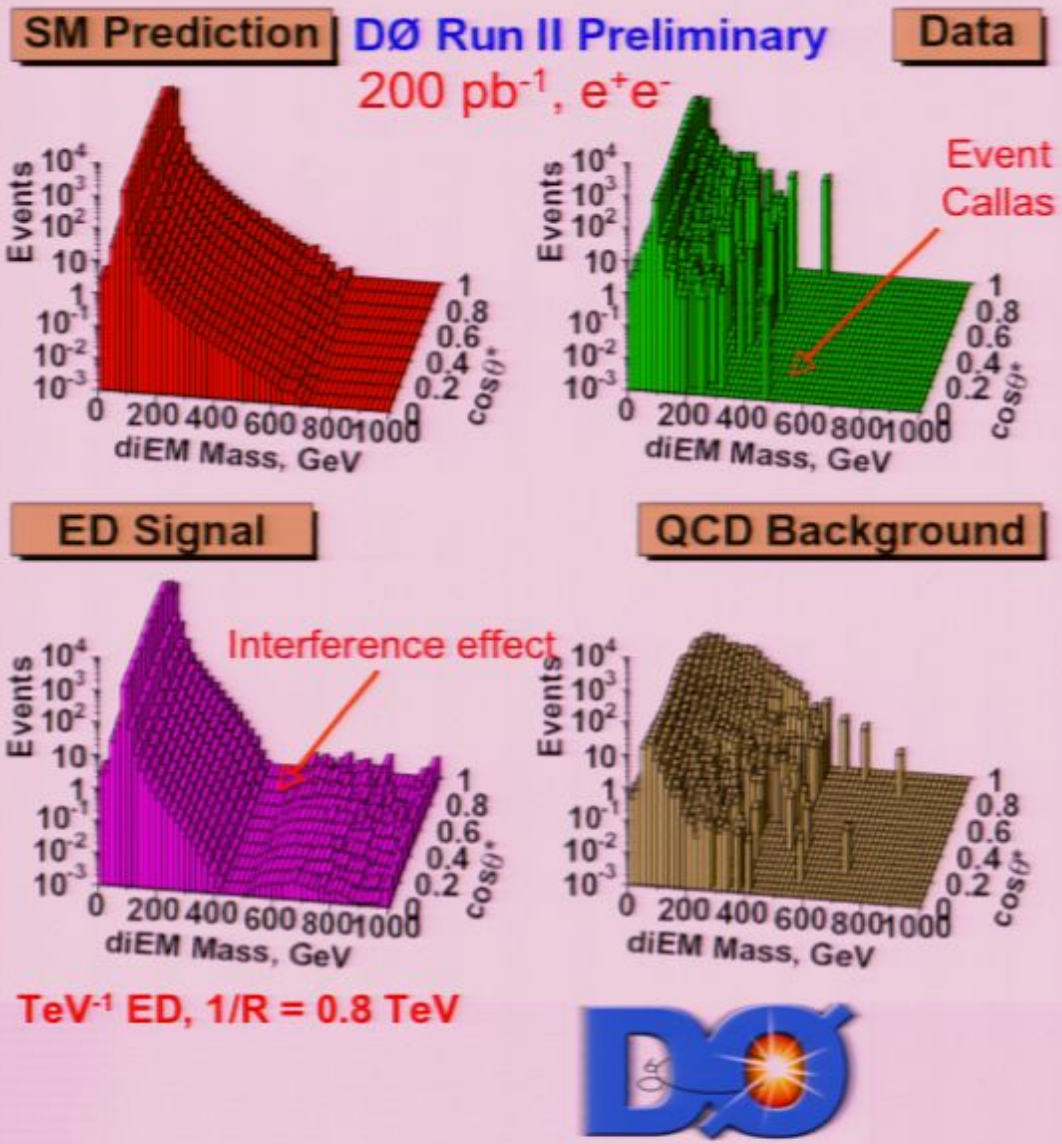


Current Limits on TeV^{-1} ED

From Cheung & GL [PRD **65**, 076003 (2002)]

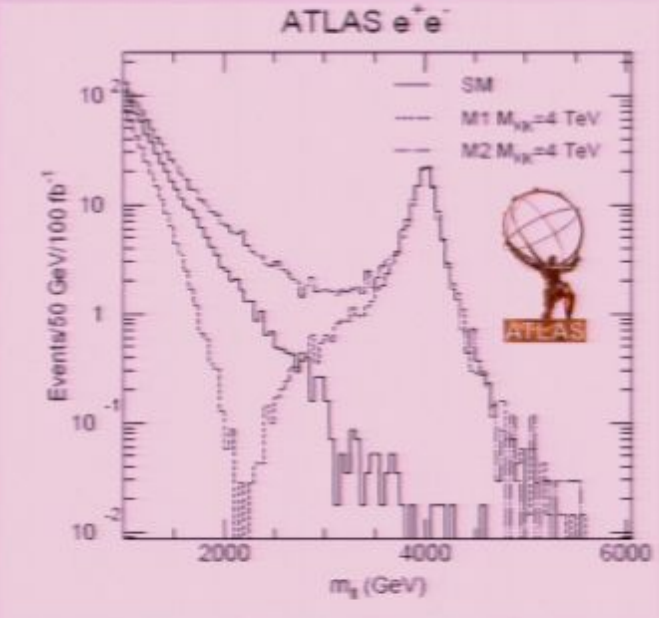
	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33\ ^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09\ ^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62\ ^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28\ ^{+0.092}_{-0.092}$	0.076	6.6
HERA:			
NC	$-2.74\ ^{+1.49}_{-1.51}$	1.59	1.4
CC	$-0.057\ ^{+1.28}_{-1.31}$	2.45	1.2
HERA combined	$-1.23\ ^{+0.98}_{-0.99}$	1.25	1.6
TEVATRON:			
Drell-yan	$-0.87\ ^{+1.12}_{-1.03}$	1.96	1.3
Tevatron dijet	$0.46\ ^{+0.37}_{-0.58}$	1.0	1.8
Tevatron top production	$-0.53\ ^{+0.51}_{-0.49}$	9.2	0.60
Tevatron combined	$-0.38\ ^{+0.52}_{-0.48}$	0.65	2.3
All combined	$-0.29\ ^{+0.090}_{-0.090}$	0.071	6.8

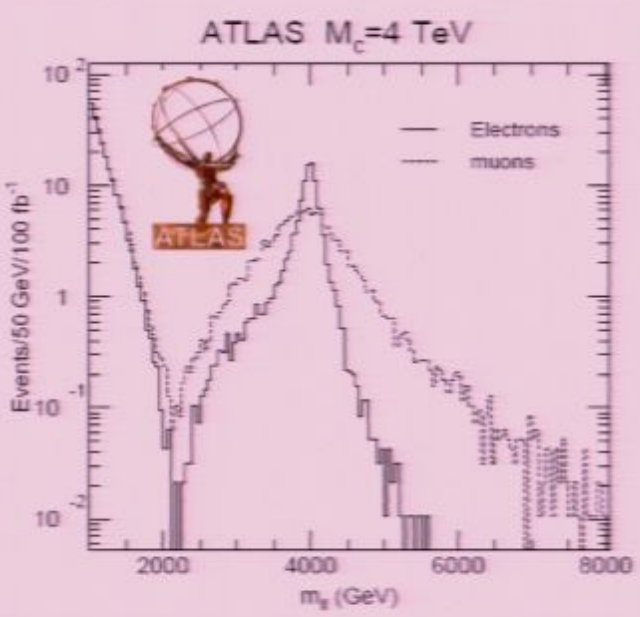
First Dedicated Search for TeV^{-1} ED

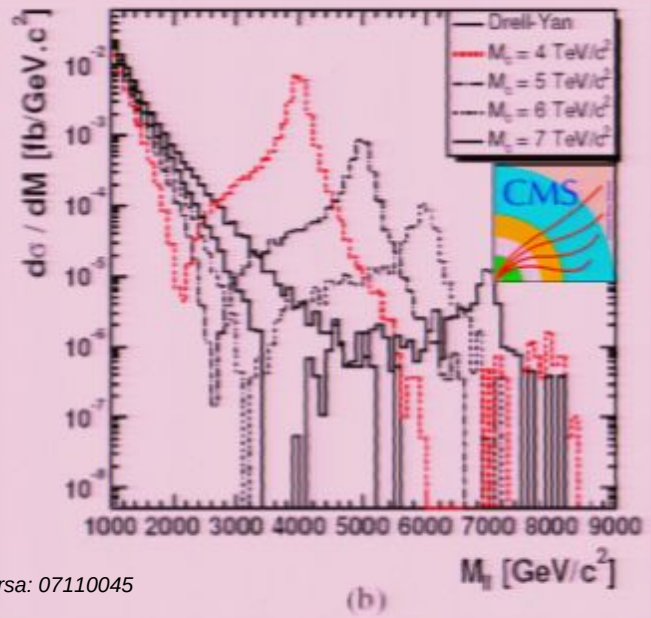


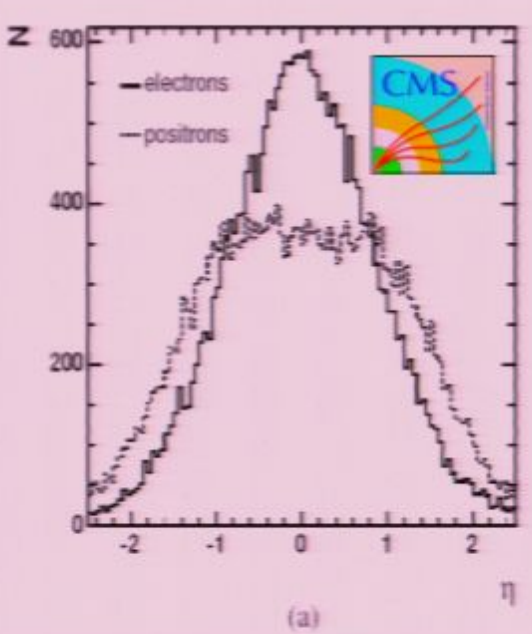
- While the Tevatron sensitivity is inferior to indirect limits, it explores the effects of virtual KK modes at higher energies, i.e. complementary to those in the EW data
- DØ has performed the first dedicated search of this kind in the dielectron channel based on 200 pb^{-1} of Run II data (Z_{KK}, $\gamma_{KK} \rightarrow e^+e^-$)
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity in the DY production Cheung, GL [PRD **65**, 076003 (2002)]
- Data agree with the SM predictions, which resulted in the following limit:
  - $1/r > 1.12$ TeV @ 95% CL
  - $r < 1.75 \times 10^{-19}$ m

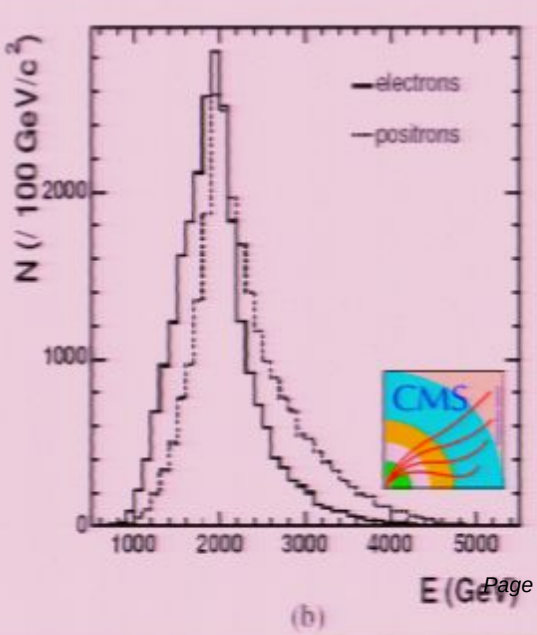
LHC: KK Excitations of the Z Boson





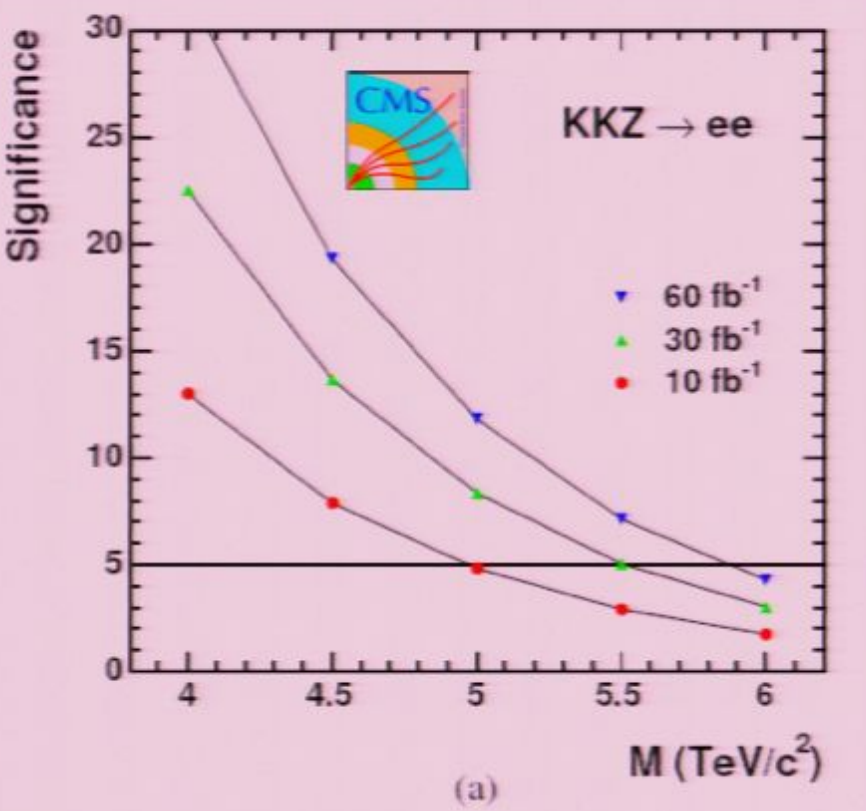


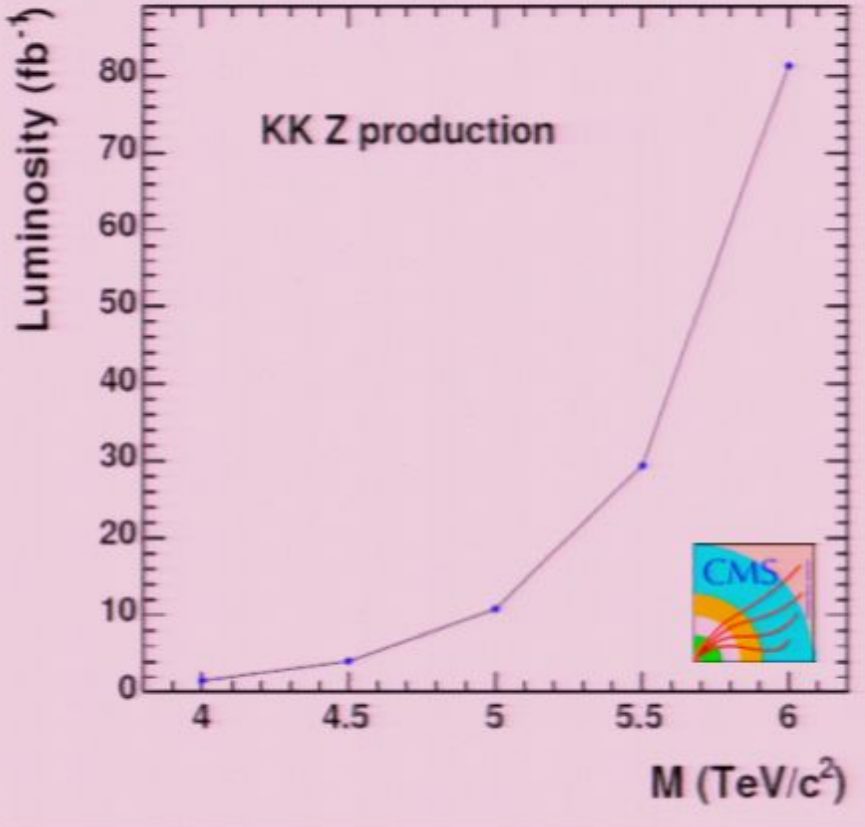




KK Resonance Reach at the LHC

- Dramatic reach even with ~1 fb^{-1}

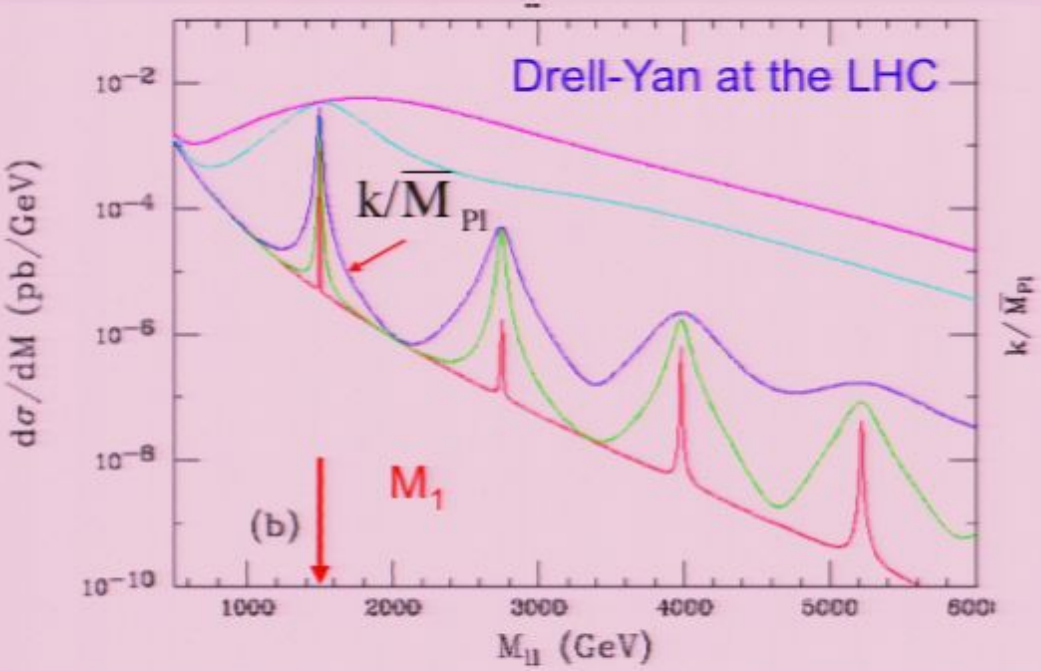


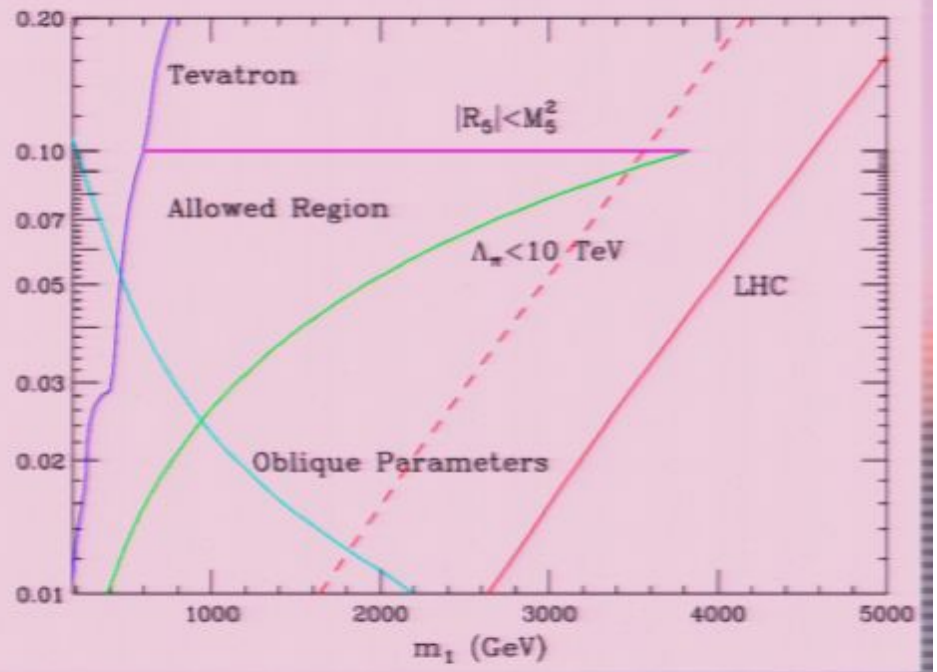


Randall-Sundrum Model Observables

- 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

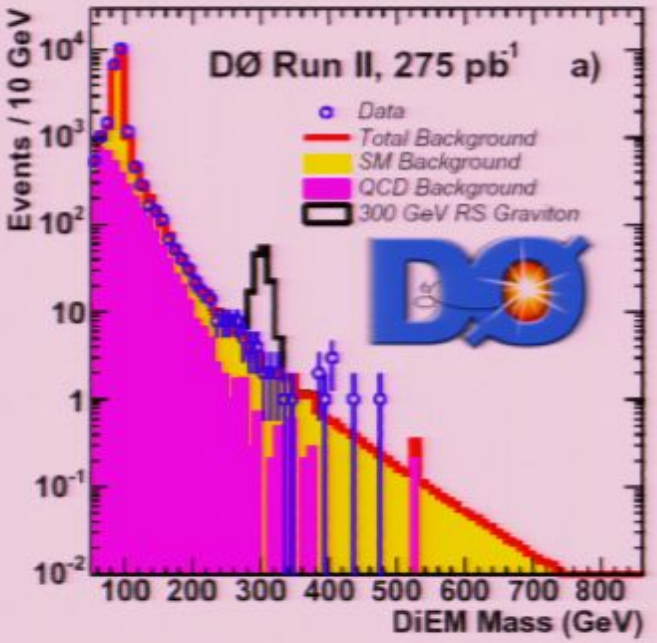
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{\rm Pl} \leq 0.10$ is the expected range
- Gravitons are narrow
- Similar observables for Z_{KK}/g_{KK} in TeV^{-1} models

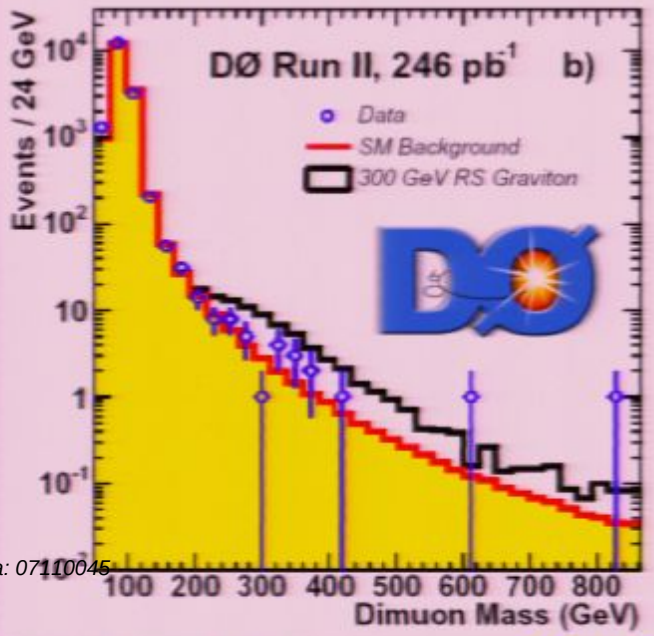


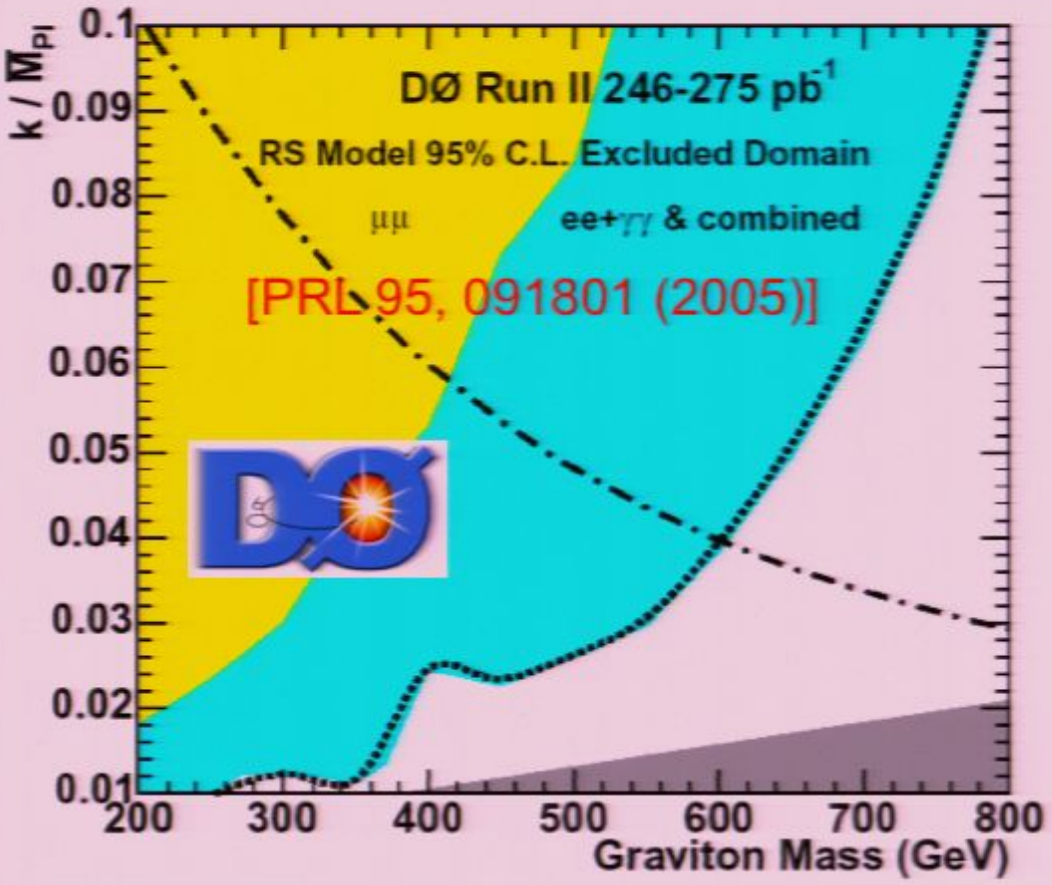


Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

First Search for RS Gravitons



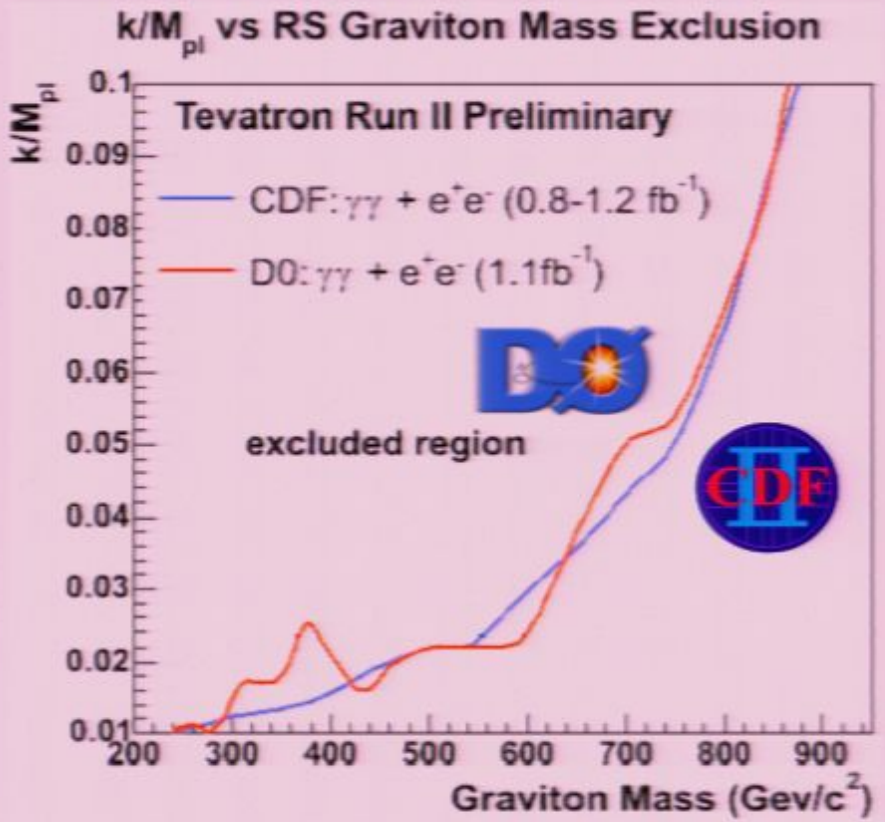


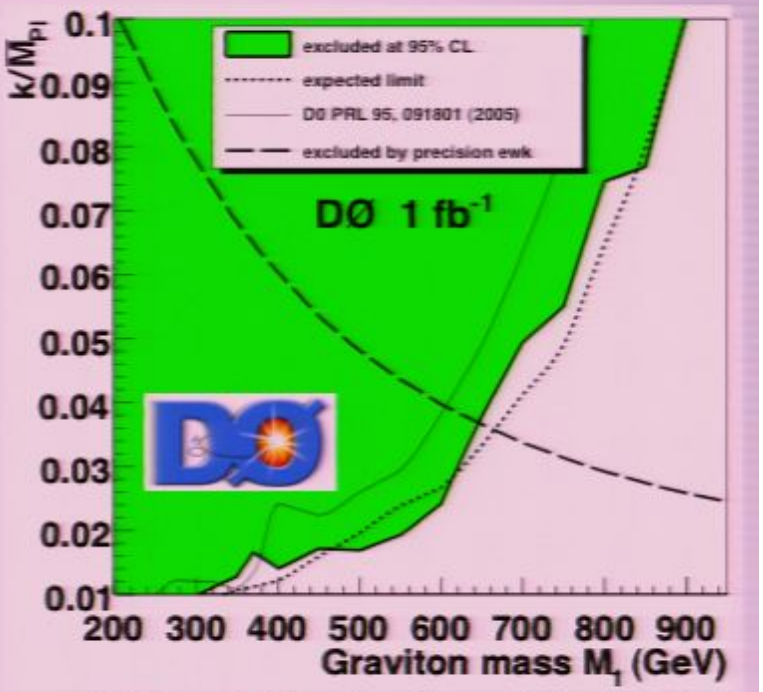


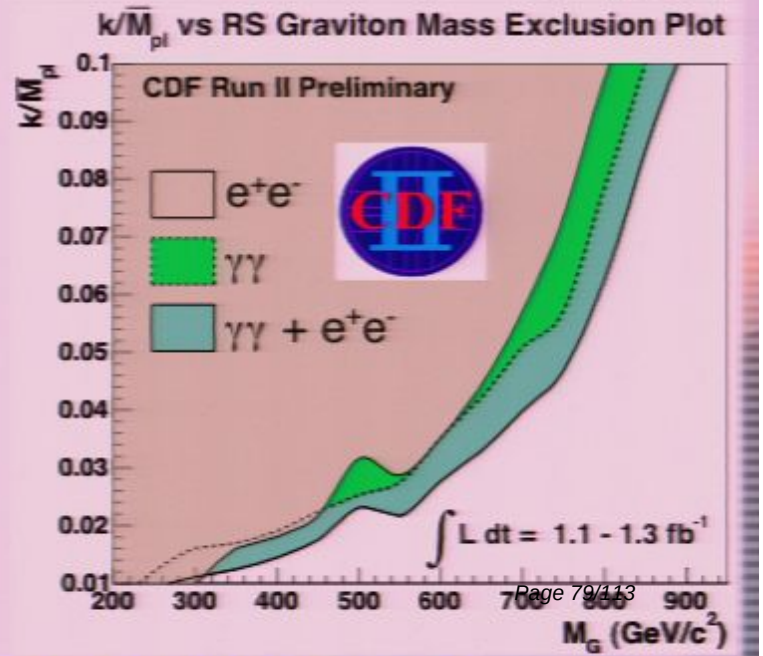
Assume a fixed K-factor of 1.3 for the signal

Most Recent Limits

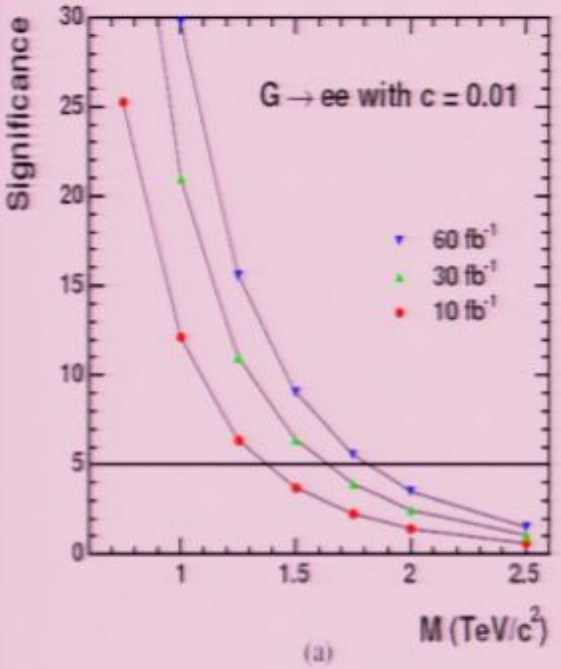
- Latest limits are 10% higher than the original ones despite 4x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!

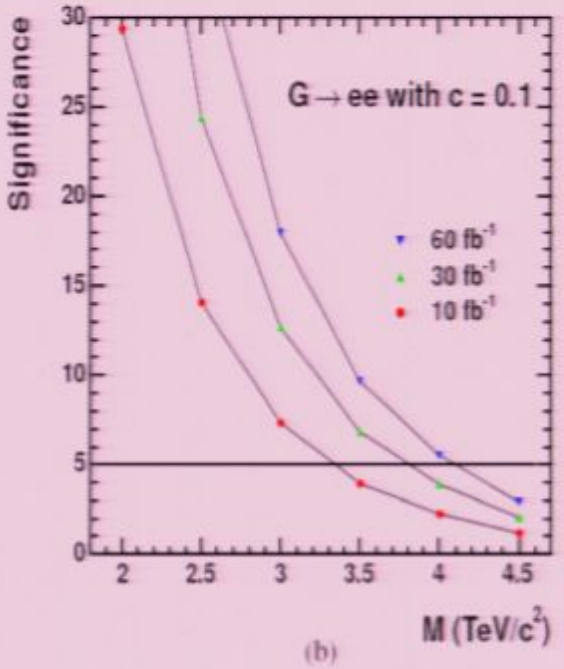


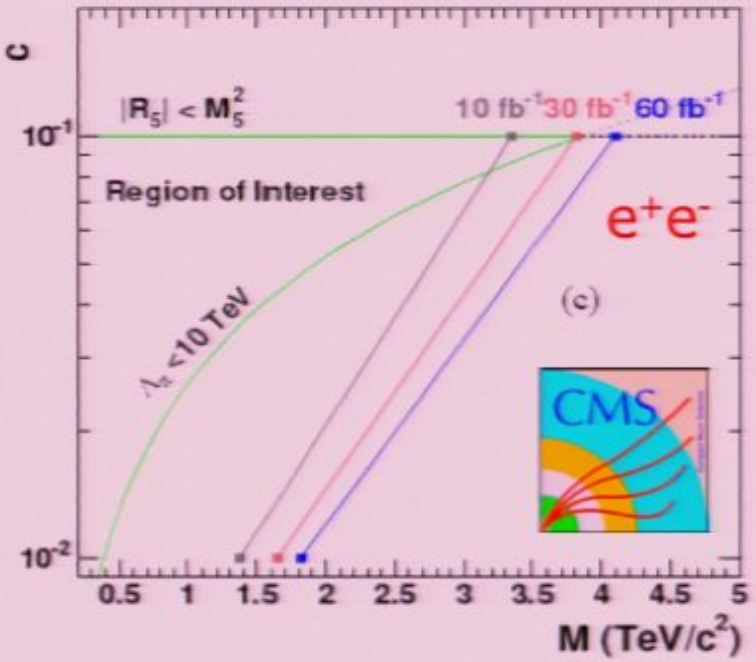


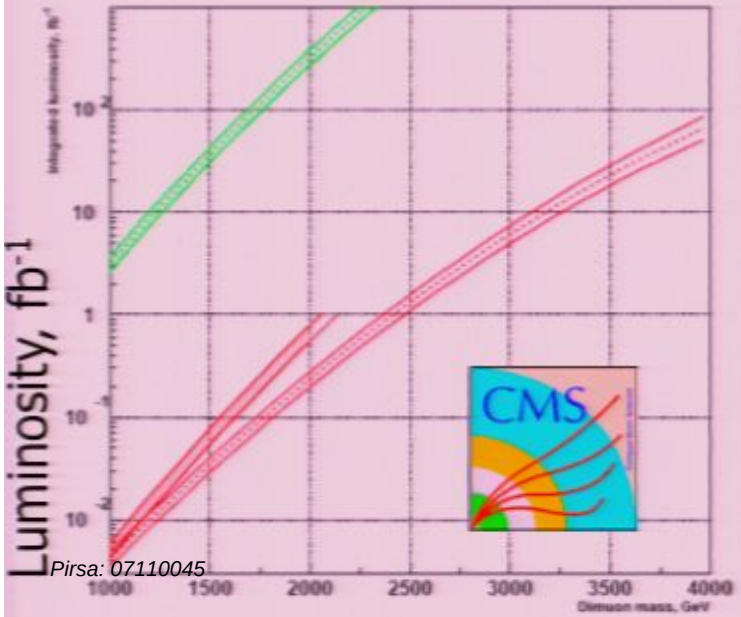


LHC: Randall-Sundrum Graviton Reach

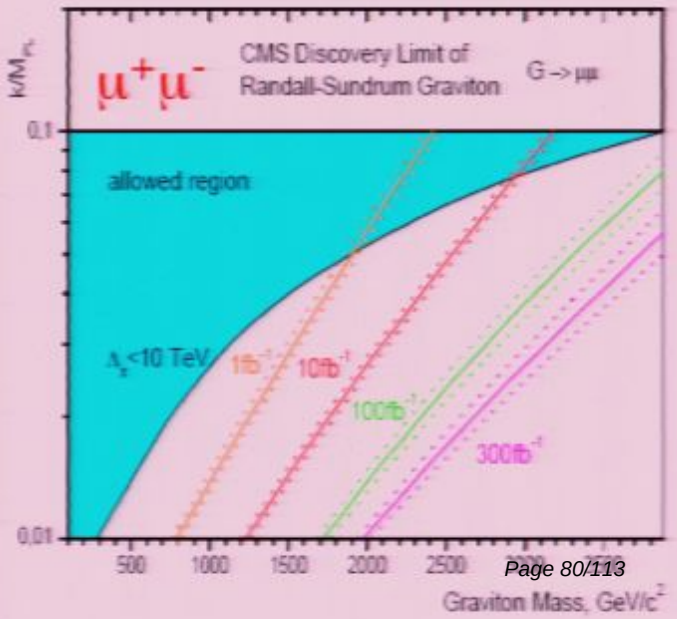








Coupling constant c	Estimator	1 fb^{-1}	10 fb^{-1}
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16



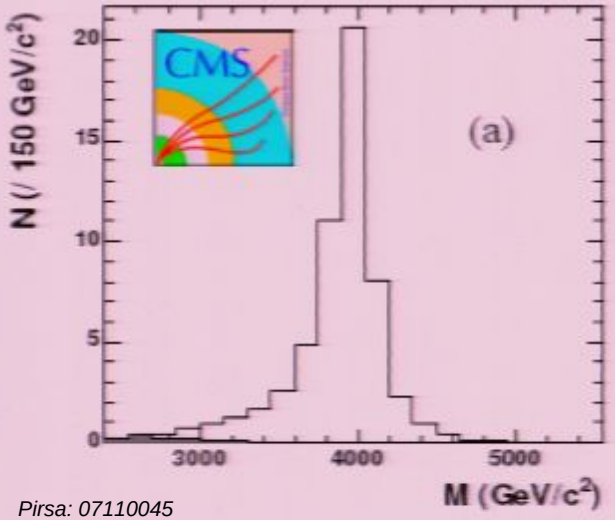
Dielectrons: Discovery Channel

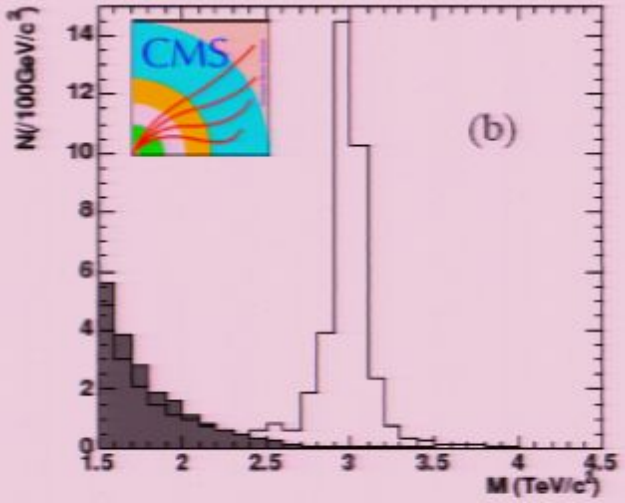
- Excellent resolution 5-10%/$\sqrt{E, GeV}$ (calorimeter based) and detection efficiency
- Low background above ~1 TeV

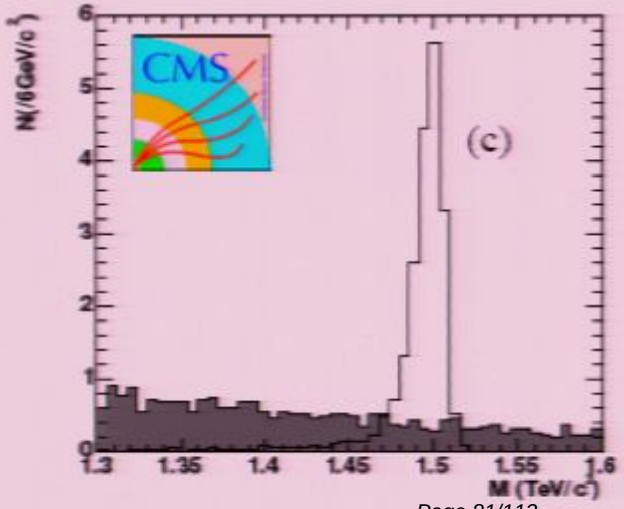
	KK Z		G, $c = 0.01$	G, $c = 0.1$	SSM Z'	
M	4.0	6.0	1.5	3.5	1.0	5.0
M_w	3.5-4.5	5.0-6.7	1.47-1.52	3.30-3.65	0.92-1.07	4.18-5.81
N_s	50.6	1.05	18.8	7.30	72020	0.58
N_b	0.13	0.005	4.16	0.121	85.5	0.025
S	22.5	3.0	6.39	6.83	225	1.63

CMS, 30 fb^{-1}

Z_{KK} production







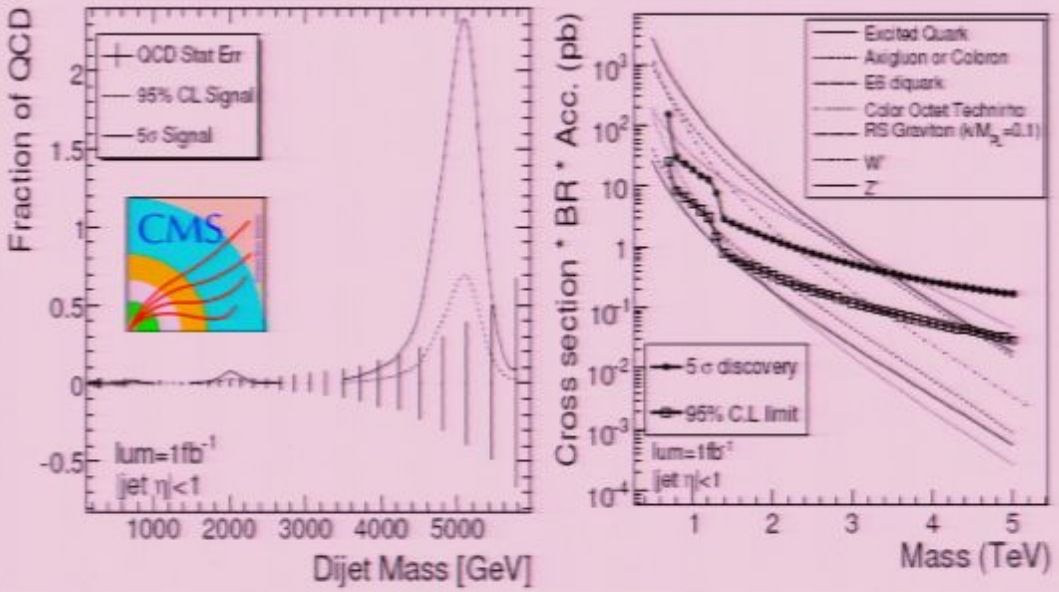
What about Dijets/Ditaus?

- If jet energy scale is fixed with early data, dijets channel is also sensitive to KK modes
  - CMS 0.1-10 fb^{-1} simulations
  - Caveat: PDF uncertainties are large: poor reach in the ADD scenario

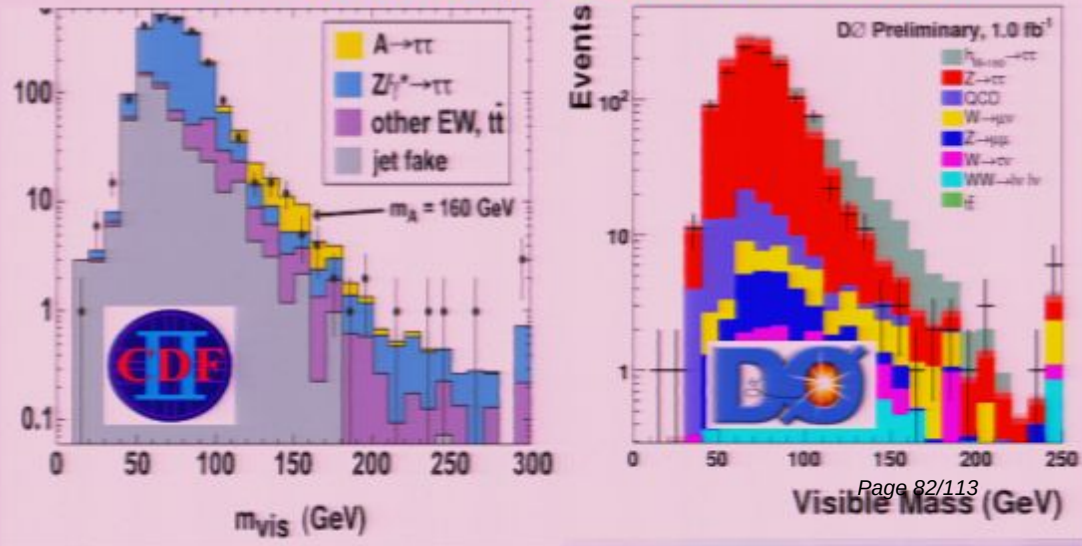
Resonance Model	95% CL Excluded Mass (TeV/c^2)			5σ Discovered Mass (TeV/c^2)		
	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}
Excited Quark	0.7 - 3.6	0.7 - 4.6	0.7 - 5.4	0.7 - 2.5	0.7 - 3.4	0.7 - 4.4
Axigluon or Colouron	0.7 - 3.5	0.7 - 4.5	0.7 - 5.3	0.7 - 2.2	0.7 - 3.3	0.7 - 4.3
E_6 diquarks	0.7 - 4.0	0.7 - 5.4	0.7 - 6.1	0.8 - 2.0	0.8 - 3.7	0.8 - 5.1
Colour Octet Technirho	0.7 - 2.4	0.7 - 3.3	0.7 - 4.3	0.7 - 1.5	0.7 - 2.2	0.7 - 3.1
Randall-Sundrum Graviton	0.7 - 1.1	0.7 - 1.1 1.3 - 1.6	0.7 - 1.1 1.3 - 1.6 2.1 - 2.3	N/A	N/A	N/A
W'	0.8 - 0.9	0.8 - 0.9 1.3 - 2.0	0.8 - 1.0 1.3 - 3.2	N/A	N/A	N/A
Z'	N/A	N/A	2.1 - 2.5	N/A	N/A	N/A

- Ditau channel is less studied for BSM discovery reach by the LHC collaborations, but still can be accessible for early physics
  - N.B. The first Tevatron Run II precision measurement paper was DØ Z($\tau\tau$) cross section determination
- Very interesting reach for MSSM Higgs and other resonances; could also be tricky?

Dijets at the LHC

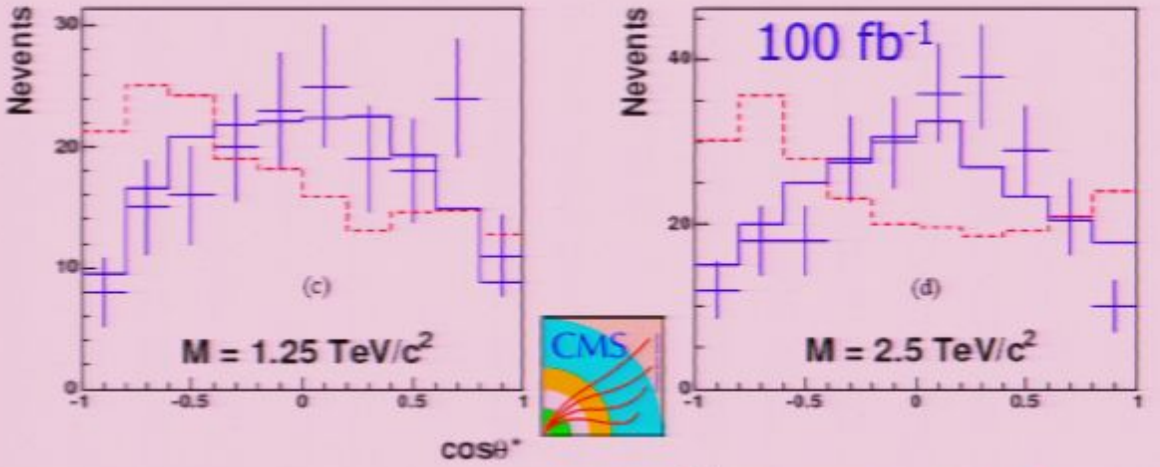


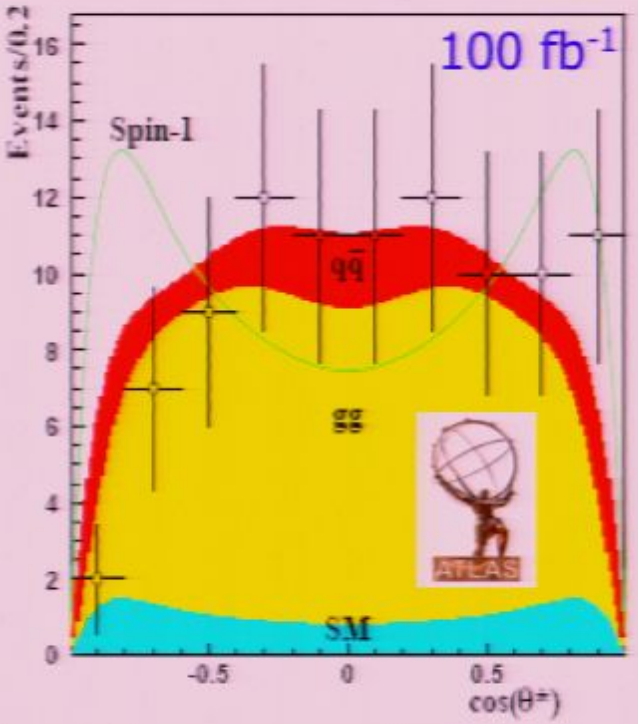
1 fb^{-1} ditau surprise at the Tevatron

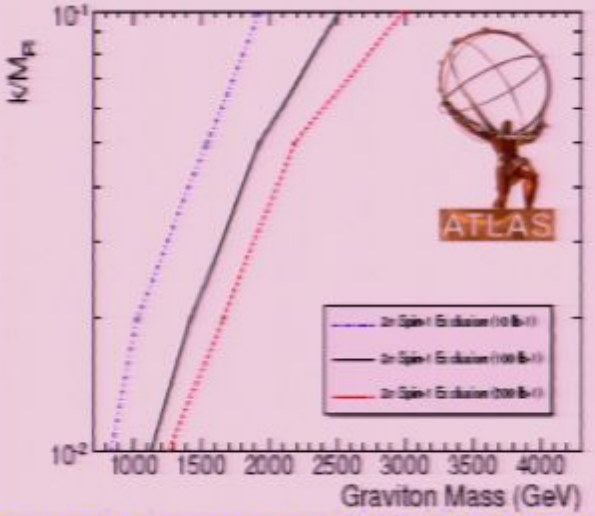


LHC: Graviton Spin?

- Not in the early running!
  - "One event – discovery; two events – cross section measurement; three events – angular distributions"

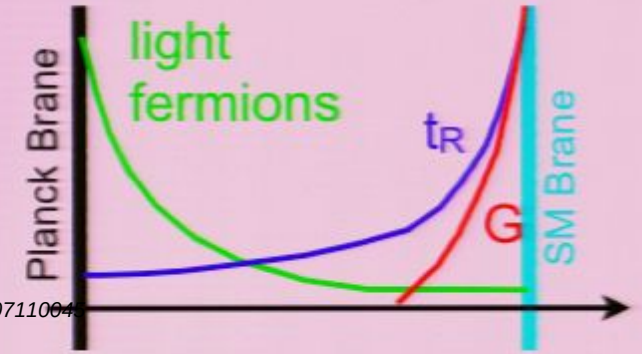




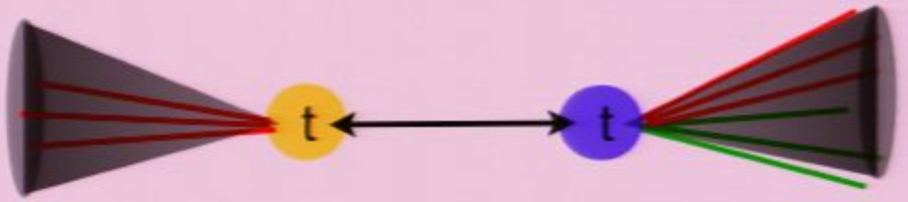


But: Life May be More Complicated!

- Simple RS model has many potential problems: FCNC, CP-violation
  - Those can be solved by putting fermions in the bulk
- Top quark is localized near the SM brane; light fermions are near the Planck brane
- Graviton mainly couples to the top quark, and thus the dominant decay mode is a pair of top quarks



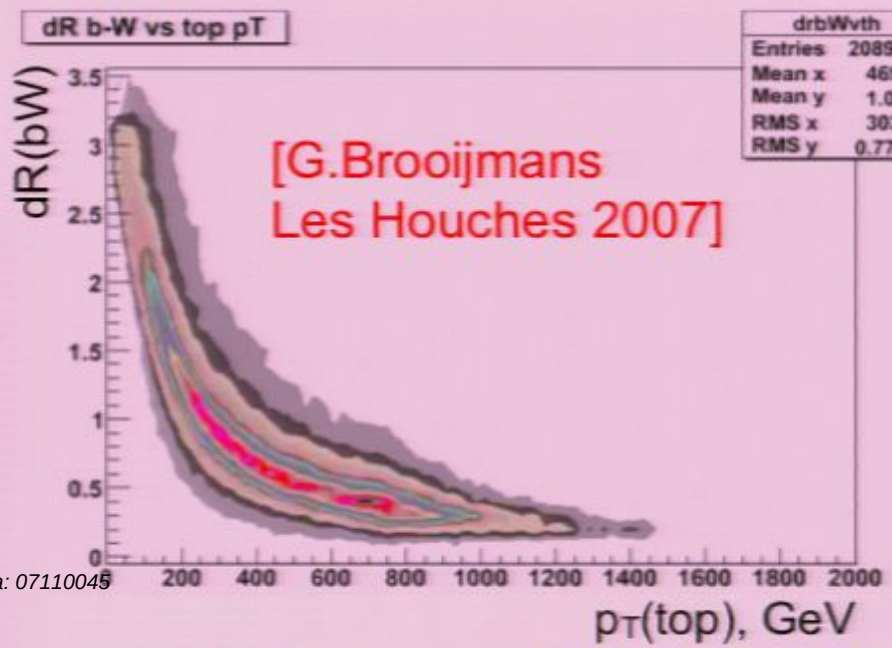
- For graviton masses ~2-3 TeV, top quarks emerge highly boosted, which makes it challenging to reconstruct them



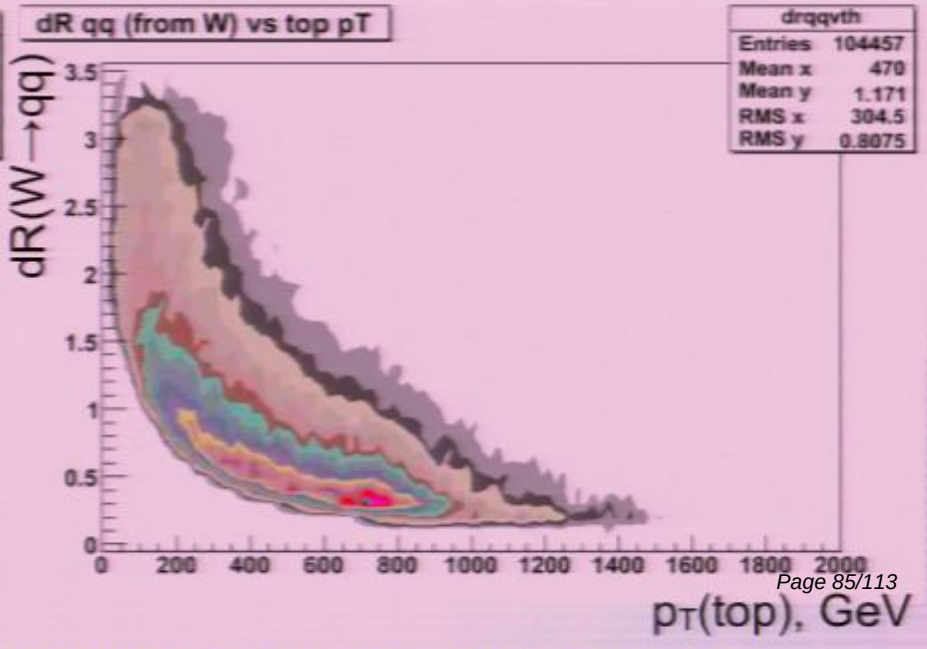
- Several challenges:
  - for 3-jet top decays jets are often merged in a single "fat" jet
  - b-tagging efficiency drops dramatically, as the opening angle between the tracks becomes small.

Possible Remedies

- Several have been suggested:
  - Use of top-jet mass: poorly defined; depends on the jet algorithm and pile-up/underlying event; depends on the calorimeter granularity
  - 3D b-tagging
  - k_T algorithm with small D ~ 0.1-0.2 within the "fat" jet
- Requires serious experimental studies with realistic detector effects
  - Work started in Les Houches 2007 by the ATLAS and CMS members



[G.Brooijmans Les Houches 2007]



More Challenges: Universal ED

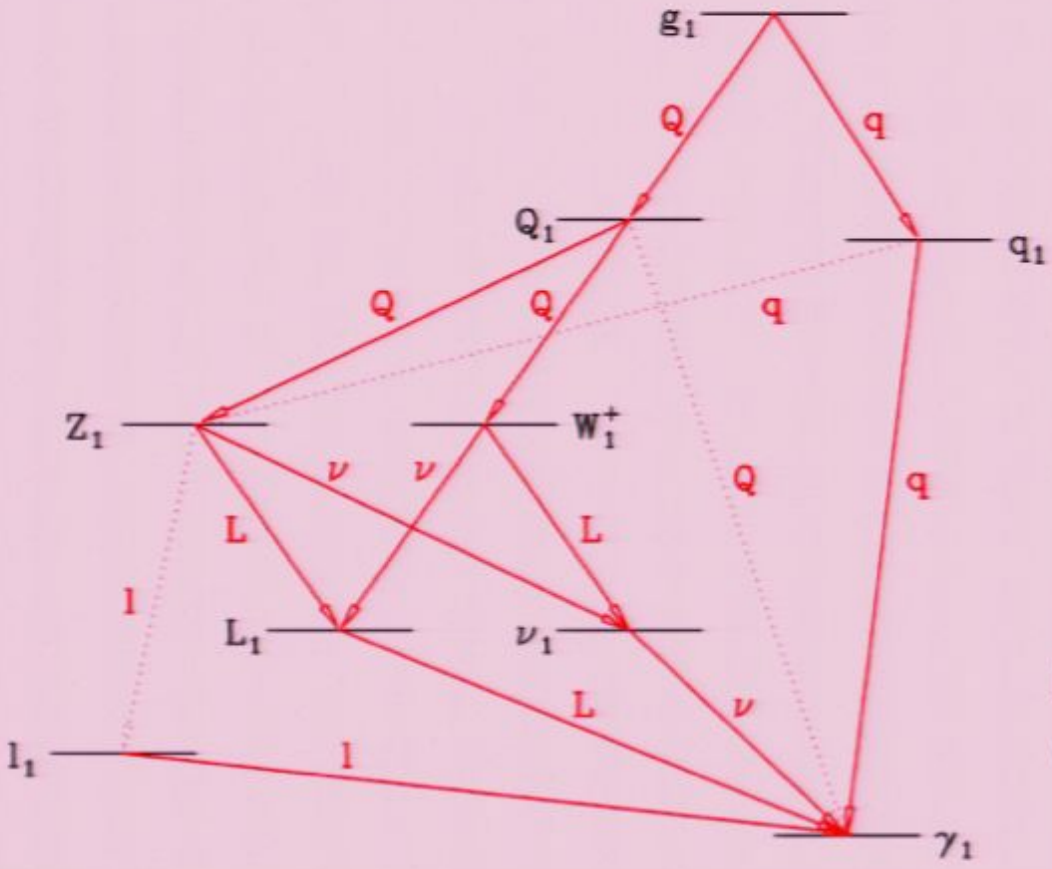
- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $r = 1/M_c \sim 1$ TeV^{-1} Appelquist, Cheng, Dobrescu [PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - Gravitational force is not included in this model
- The number of universal extra dimensions is not fixed:
  - it's feasible that there is just one (MUED)
  - the case of two extra dimensions is theoretically attractive, as it breaks down to the chiral Standard Model and has additional nice features, such as guaranteed proton stability, etc.
- Every particle acquires KK modes with the masses $M_n^2 = M_0^2 + M_c^2$, $n = 0, 1, 2, \ldots$
- Kaluza-Klein number (n) is conserved at tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode cold be stable (and is an excellent dark matter candidate Cheng, Feng, Matchev [PRL **89**, 211301 (2002)])
- Hence, first level KK-excitations are produced in pairs, similar to SUSY particles
- Consequently, current limits (dominated by precision electroweak measurements, particularly T-parameter) are sufficiently low ($M_c \sim 300$ GeV for one ED and of the same order, albeit more model-dependent for >1 ED)

Production Cross Section

Mass Spectrum and Decays

- First level KK-states spectroscopy

Cheng, Matchev, Schmaltz
[PRD **66**, 056006 (2002)]



Decay:

$B(g_1 \to Q_1 Q) \sim 50\%$

$B(g_1 \to q_1 q) \sim 50\%$

$B(q_1 \to q\gamma_1) \sim 100\%$

$B(t_1 \to W_1 b, H_1^+ b) \sim 100\%$

$B(Q_1 \to QZ_1 : W_1 : \gamma_1) \sim 33\% : 65\% : 2\%$

$B(W_1 \to \nu L_1 : \nu_1 L) = 1/6 : 1/6$ (per flavo

$B(Z_1 \to \nu\nu_1 : LL_1) \sim 1/6 : 1/6$ (per flavo

$B(L_1 \to \gamma_1 L) \sim 100\%$

$B(\nu_1 \to \gamma_1 \nu) \sim 100\%$

$B(H_1^{\pm} \to \gamma\gamma_1, H^{\pm}\gamma_1) \sim 100\%$

Production:

$q_1 q_1 + X \to ME_T$ + jets ($\sim\sigma_{had}/4$); bu

low ME_T

$Q_1 Q_1 + X \to V_1 V'_1$ + jets $\to$ 2-4 ℓ + M

($\sim\sigma_{had}/4$)

Before One Can Succeed in Searches

Sensitivity in the Four-Lepton Mode

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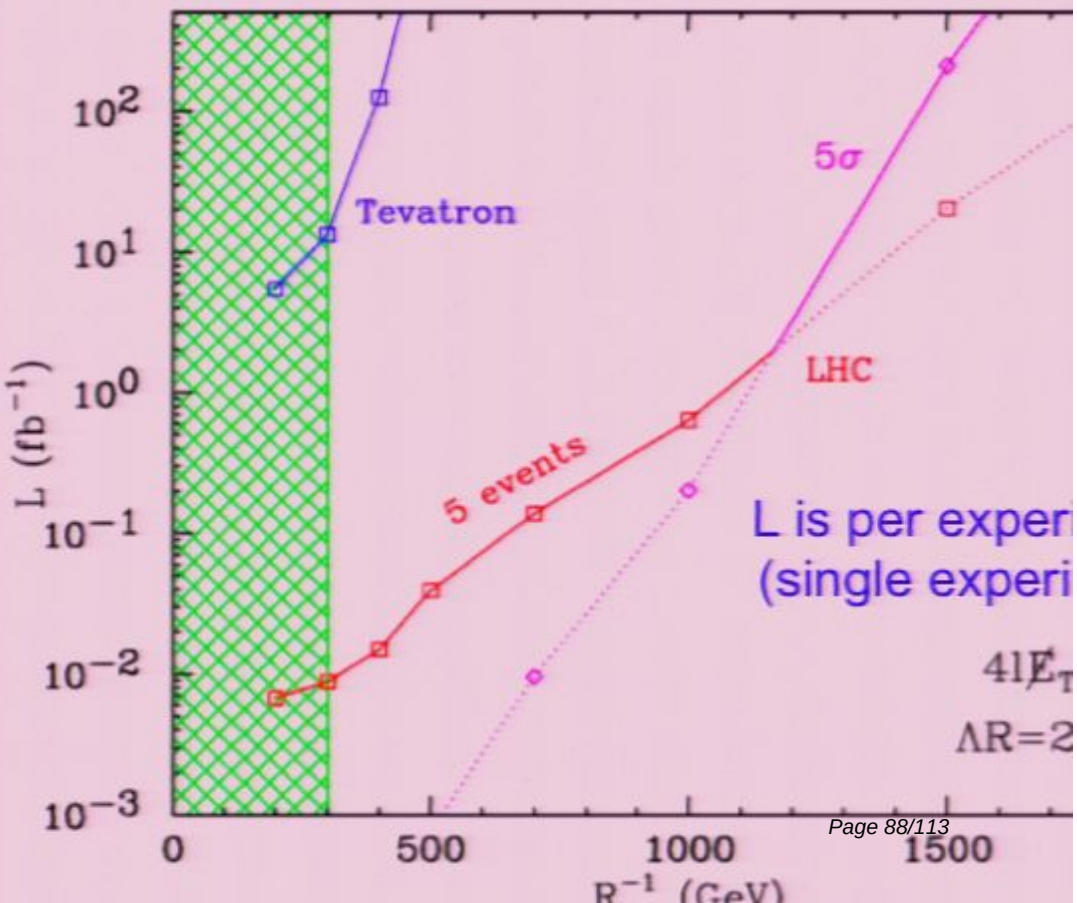
- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper
- Even at the Tevatron sensitivity can exceed current limits
- Much more promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
- Detailed simulations is required: CompHEP and PYTHIA implementations now exist

Cheng, Matchev, Schmaltz [PRD **66**, 056006



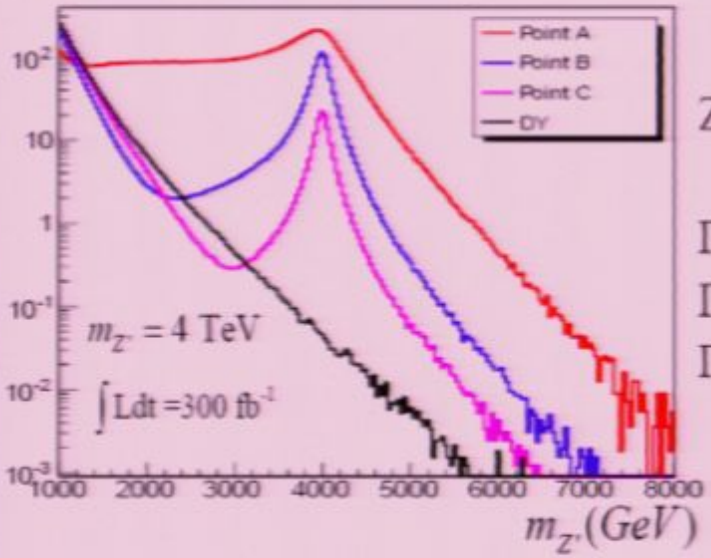
Before One Can Succeed in Searches

- Proper detector calibration, alignment, and detailed simulation is required
  - A daunting task, which easily takes several years
- Searches typically look for one event in a million; that means that the detector often has to be understood to the 10^{-6} level!
- Use calibration samples of well understood nature:
  - Test beams (initial calibration)
  - Cosmic runs (alignment, efficiency)
  - Minbias data (channel-by-channel calibration)
  - "Standard candles" – Z, W, top (efficiency, non-Gaussian tails in resolution, b-tagging)
  - Z(ee) and γ + jets (jet energy calibration and resolution)
  - High-p_T dijets (saturation, ME_T resolution and tails)
- Easily a subject for several dedicated talks; not covered here in detail:
- Note: while a few spectacular discoveries may happen as early as 2008, most would require two-three years of accelerator running and operating the detectors!
  - Gear up for a long(er) ride!

Challenges: General

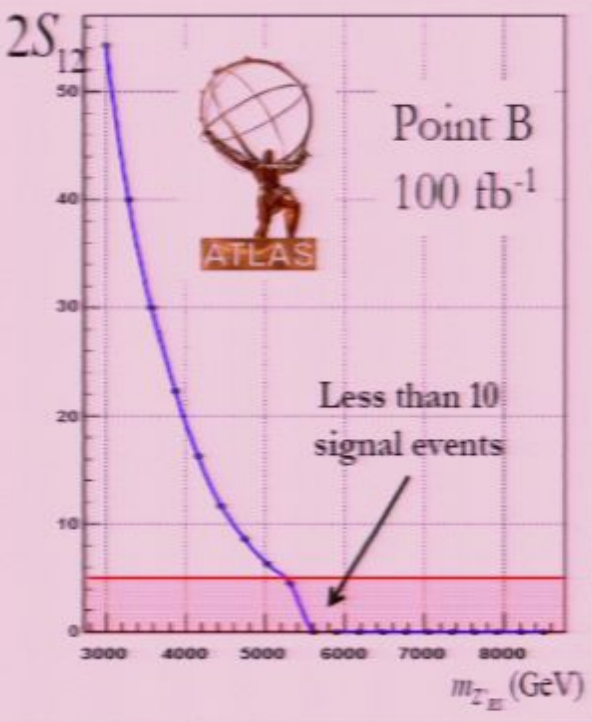
- Broad resonances are possible at high masses; signal starts looking like compositeness (or instrumental effect!)
- Reduces the reach; requires different optimization of the search

Example: bulk Z_{KK} in RS model



Z' Width @ $M_{Z'}$=4 TeV

Γ = 800 GeV for point A (0.2 $M_{Z'}$)
Γ = 200 GeV for point B (0.05 $M_{Z'}$)
Γ = 170 GeV for point C (0.04 $M_{Z'}$)

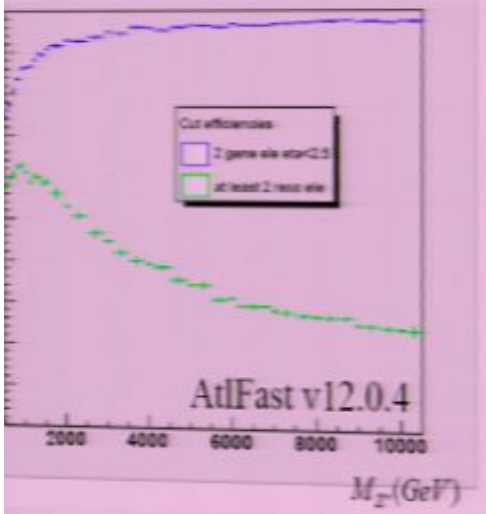


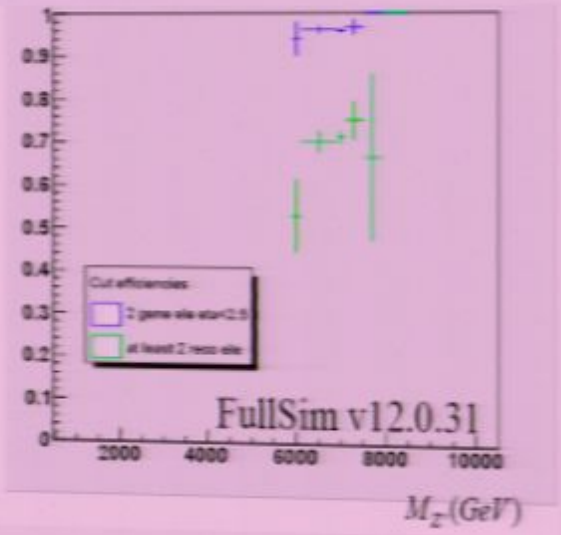
Challenges: ATLAS

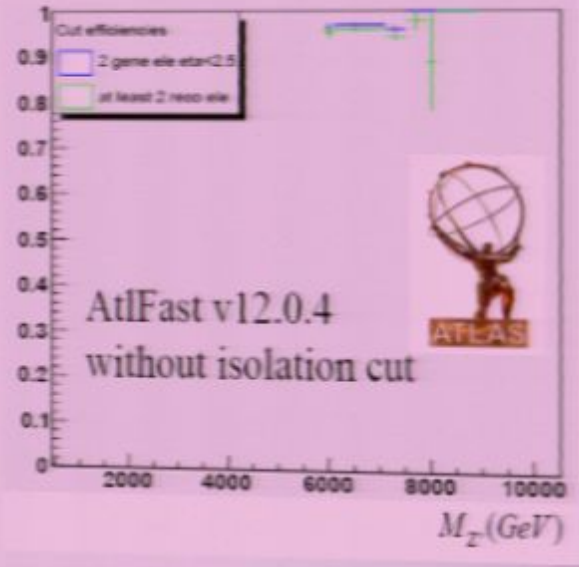
Electron efficiency drops fast with mass when "standard" isolation cut is used

- Loosely confirmed by full simulation

New set of isolation cuts is being developed to recover efficiency at high masses







Black Holes at the LHC?

Black Holes on Demand

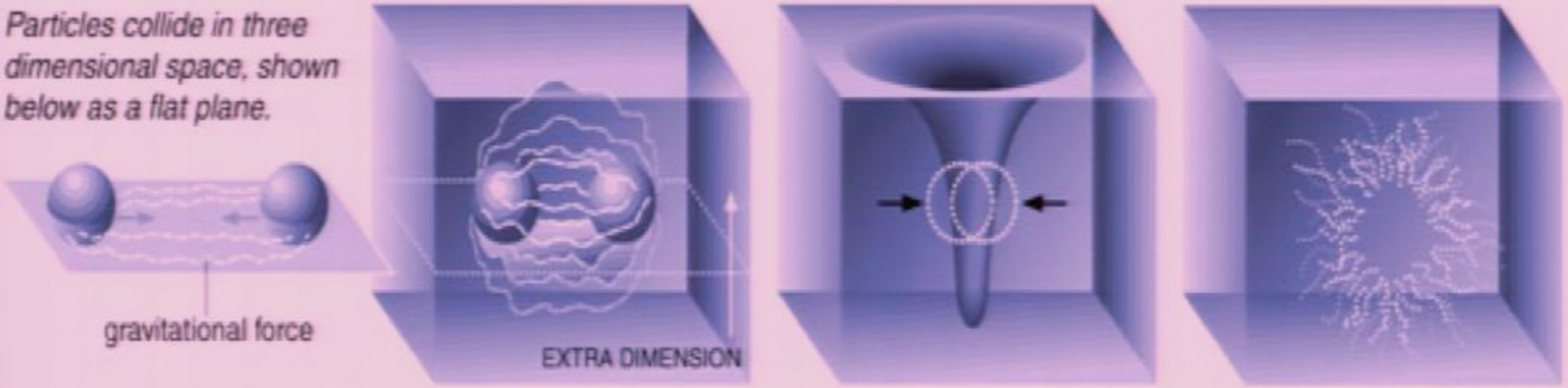
Black Holes on Demand

NYT, 9/11/01

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



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.

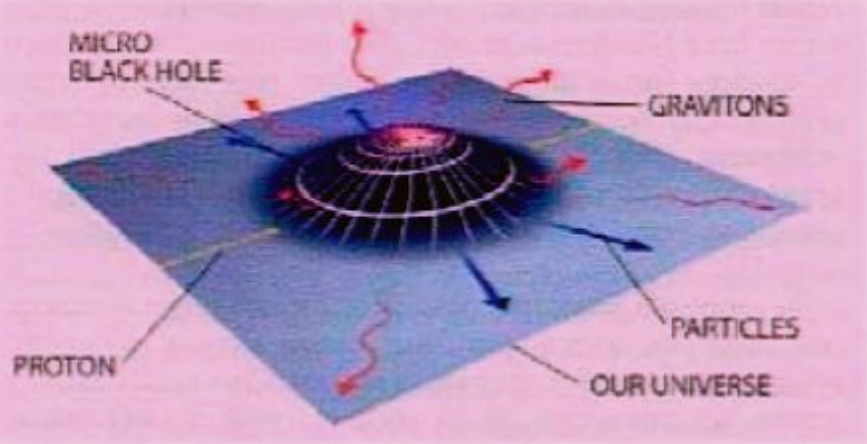
The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

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

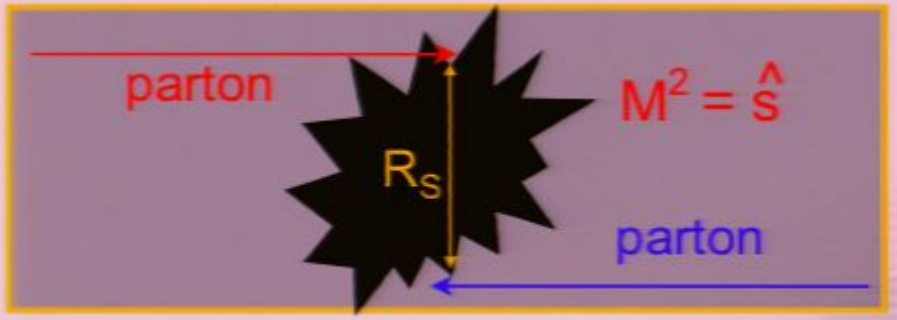
BH at LHC: Theoretical Framework

- 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
- The underlying assumptions rely on two simple qualitative properties:
  - The absence of small couplings;
  - The "democratic" nature of BH decays
- We expect these features to survive for light BH
- Use semi-classical approach strictly valid only for $M_{BH} \gg M_P$; only consider $M_{BH} > M_P$
- Clearly, these are important limitations, but there is no way around them without the knowledge of QG

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:

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

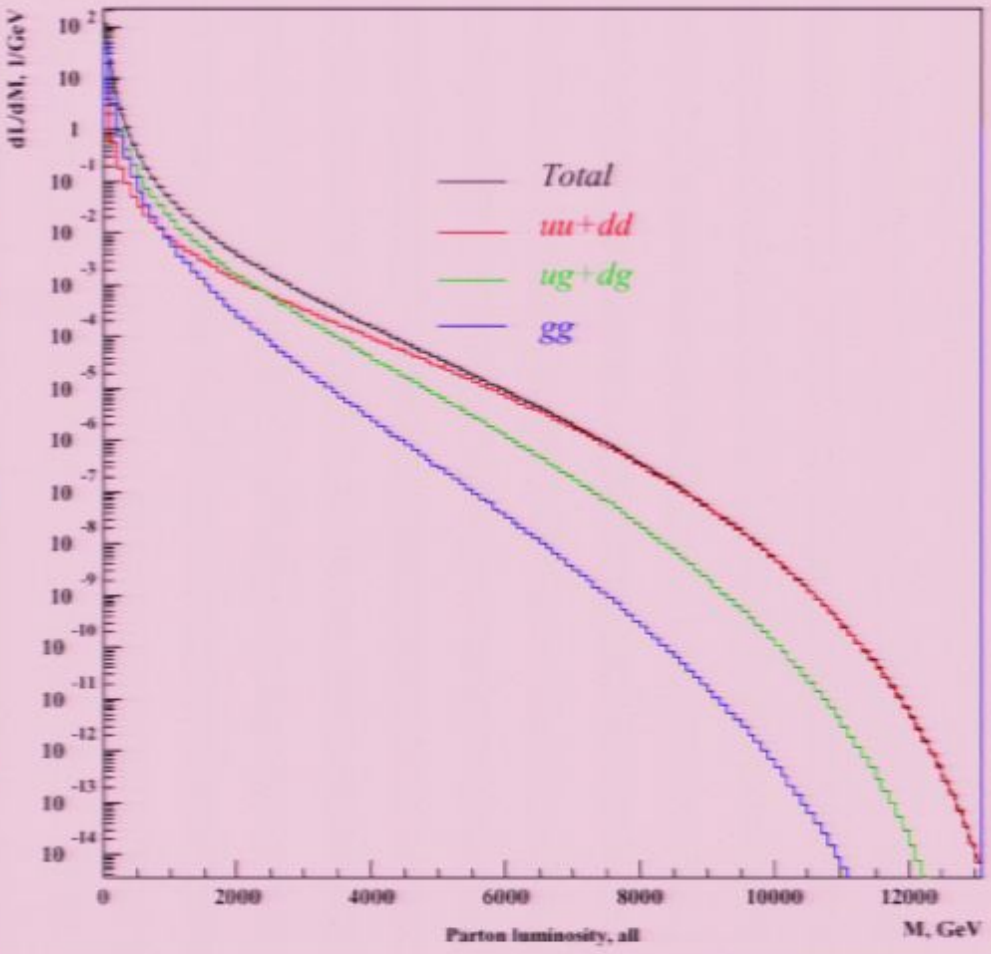
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

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

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

- 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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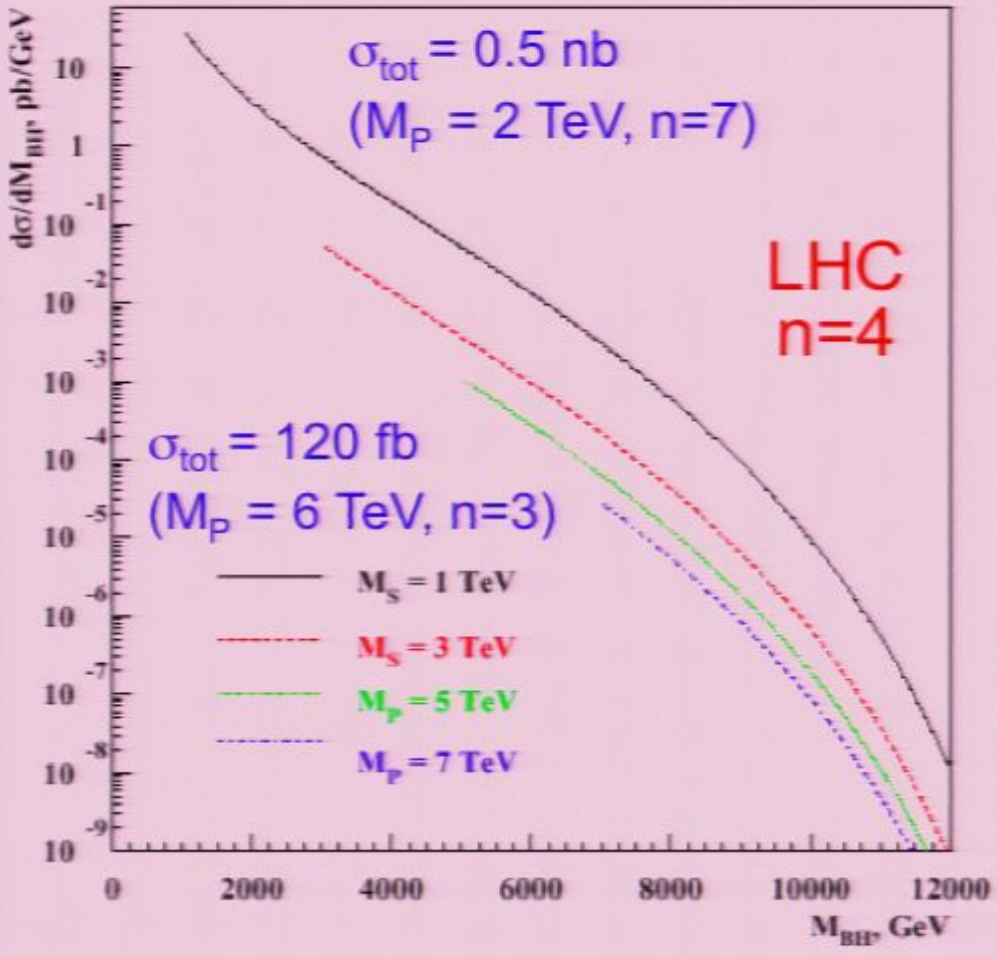
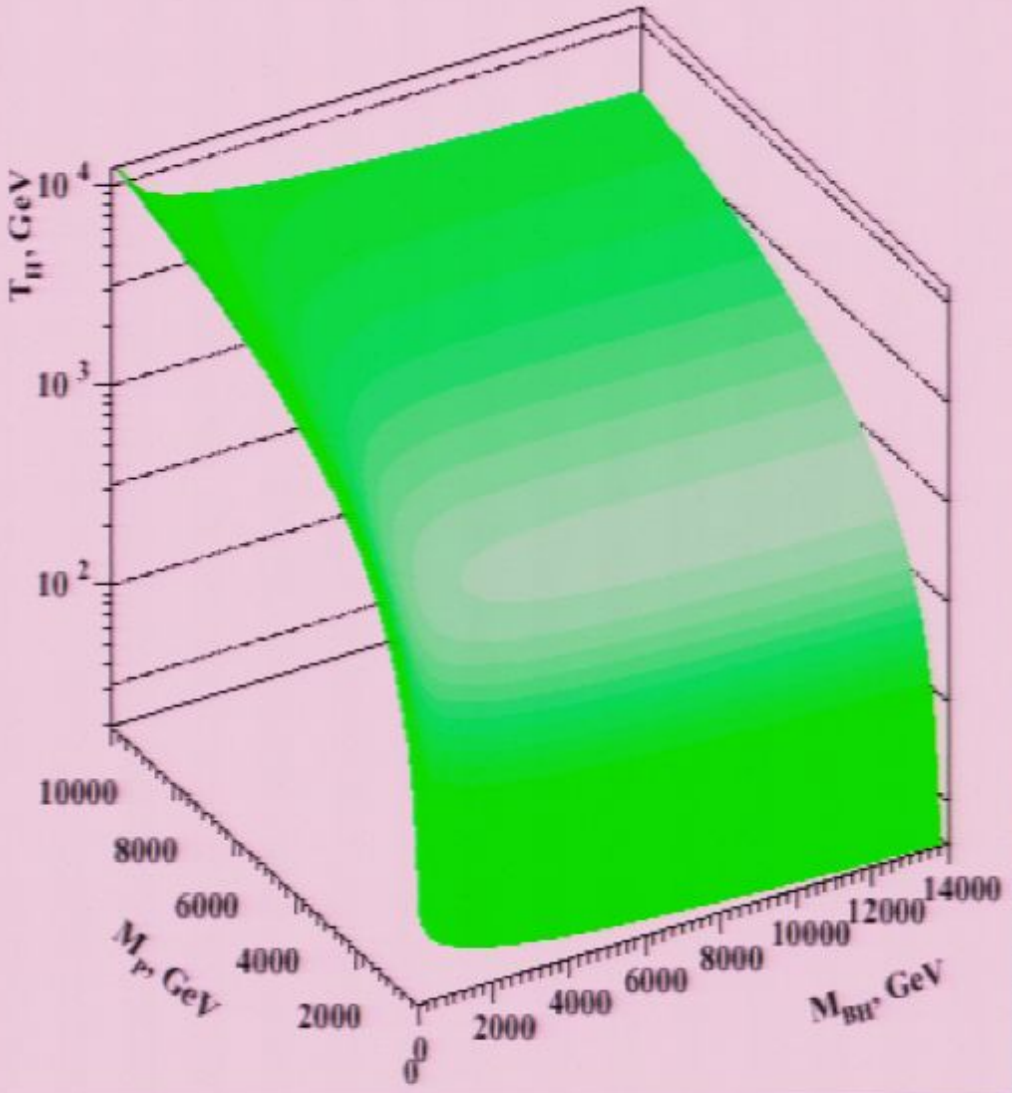


Black Hole Decay

- 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:

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



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

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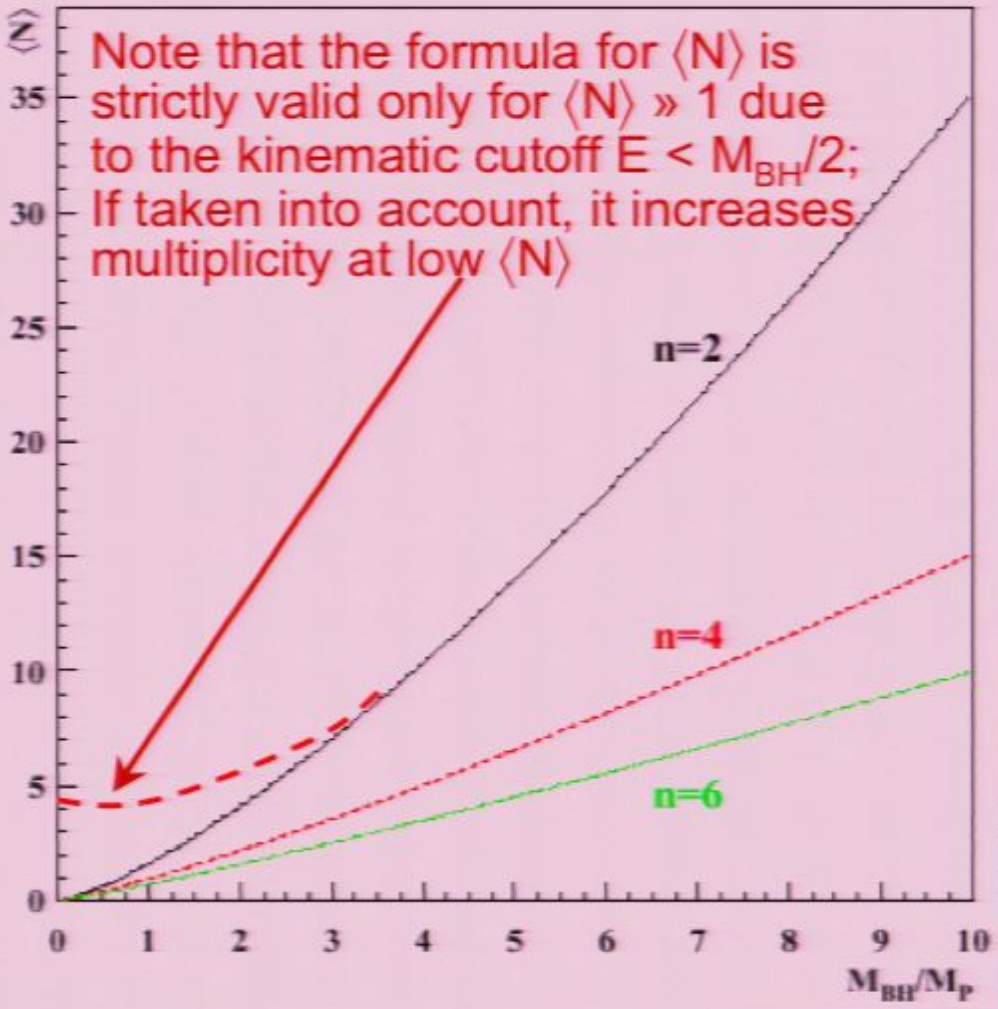

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Shape of gravity at the LHC

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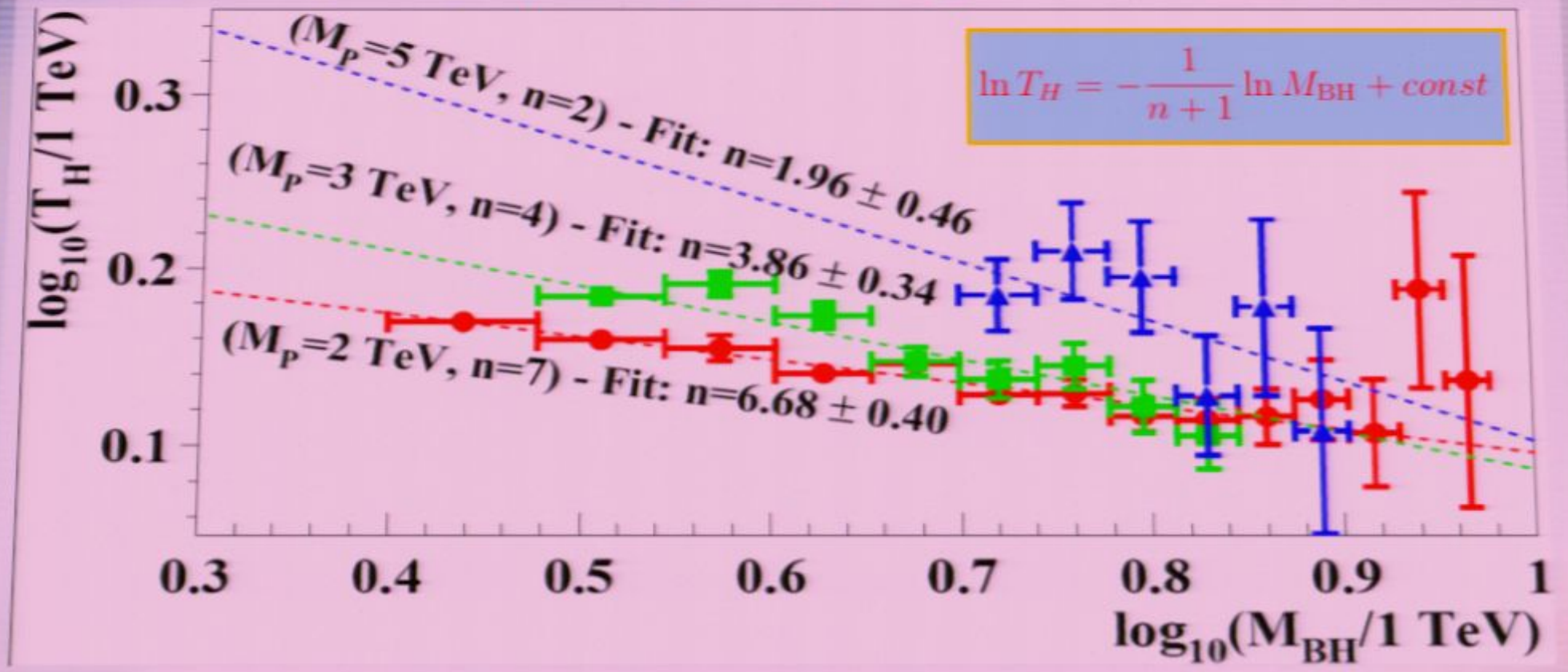

- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
  - This result is independent of their shape!
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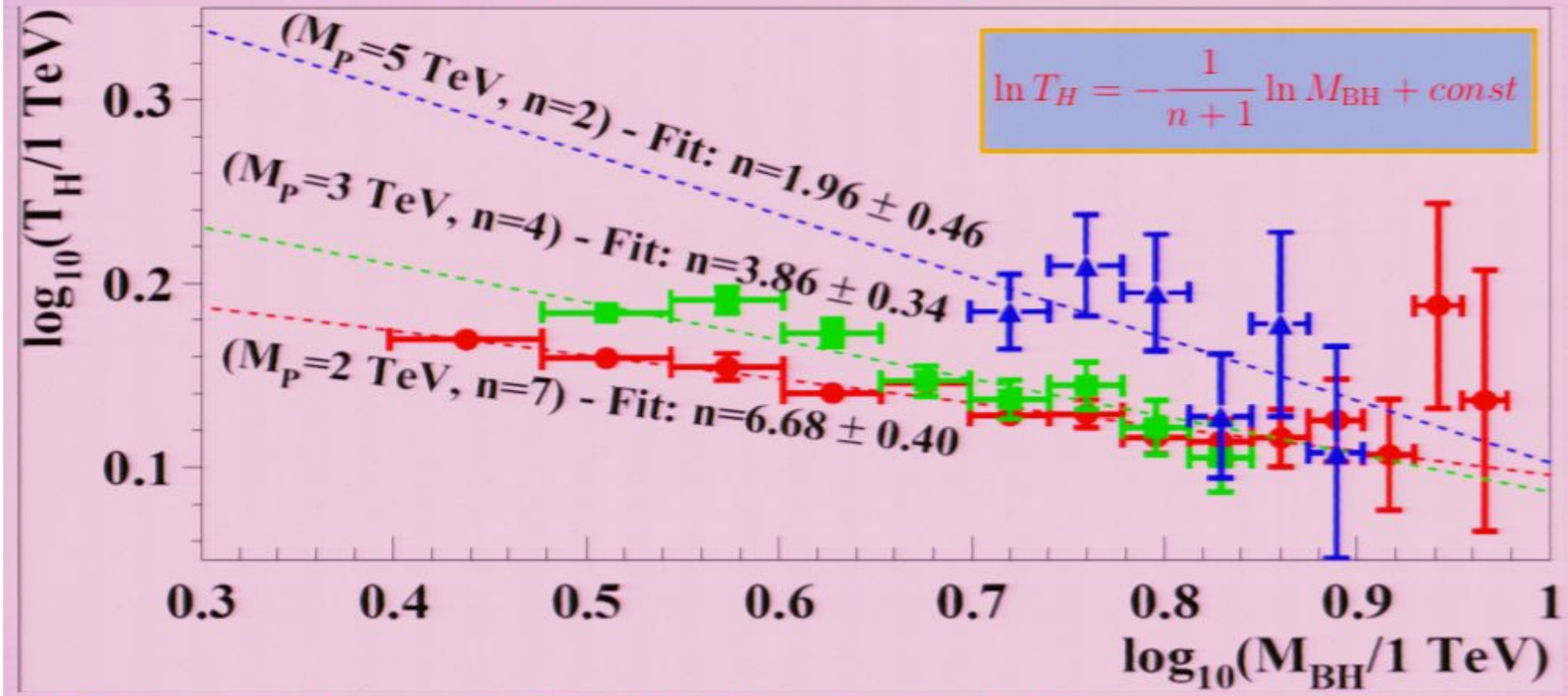

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Randall-Sundrum Black Holes

- 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: $\overline{M_{Pl}} e^{-k\pi r}$, which resulted in a more conservative cross section estimate

RS to ADD Mapping

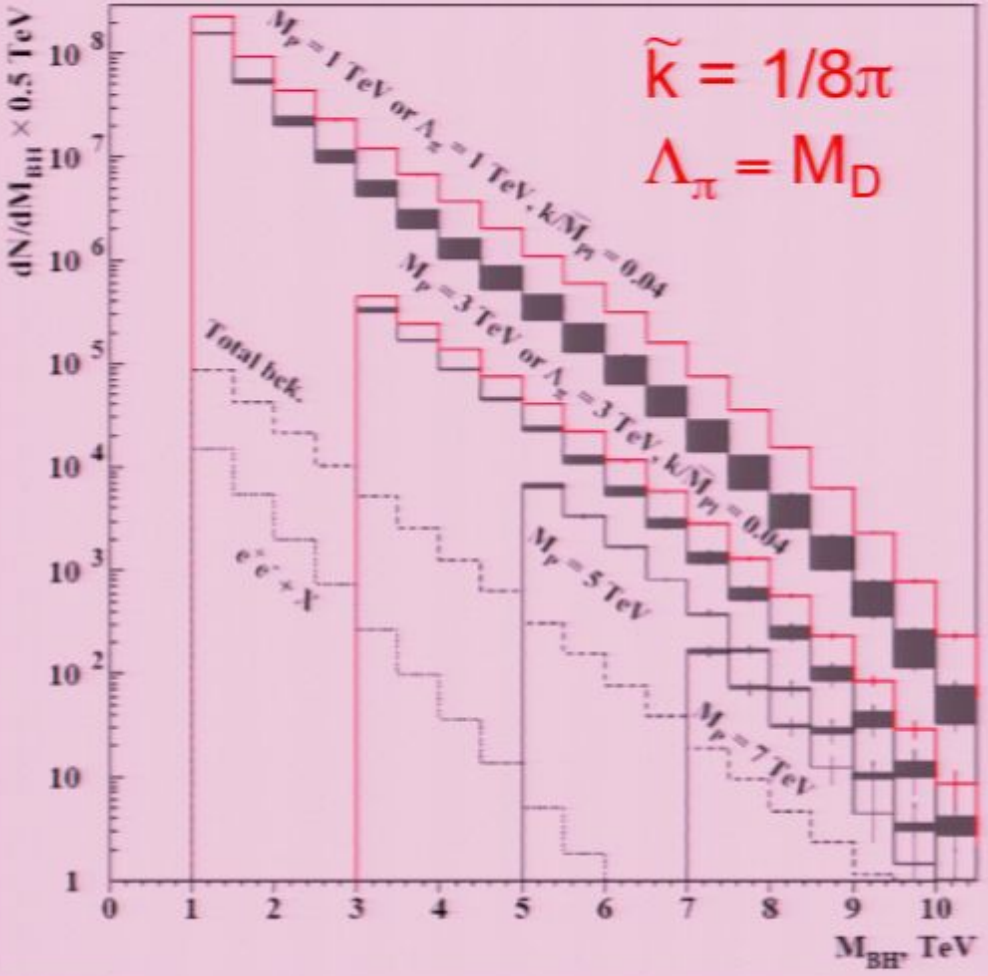
- Unlike the ADD, the 5D Planck scale, M, is of order of M_{Pl}:

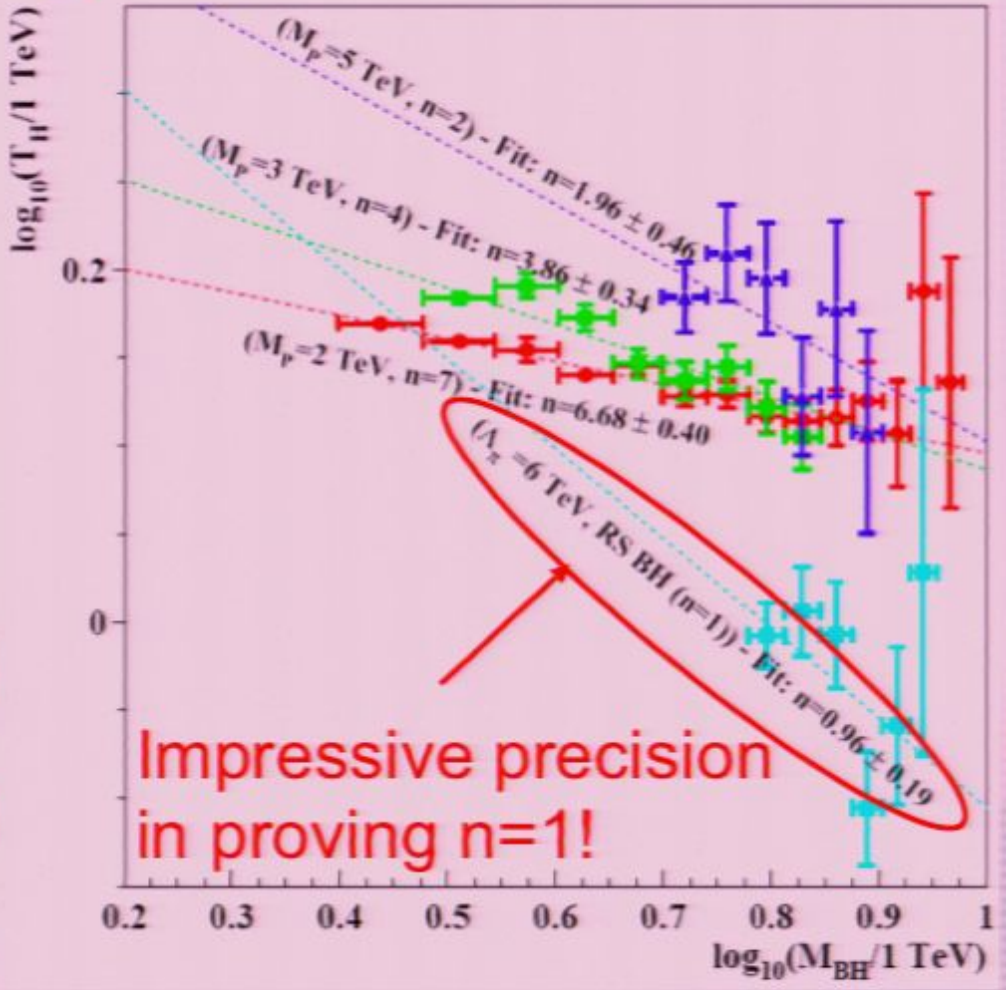
$$M_{\rm Pl}^2 = \frac{M^3}{k}\left(1 - e^{-2\pi kr}\right) \approx \frac{M^3}{k} \sim M^2$$

- The Schwarzschild radius: $R_s = \frac{1}{\pi M e^{-\pi kr}}\sqrt{\frac{M_{\rm BH}}{3Me^{-\pi kr}}}$
- Given $M^3 \approx kM_{Pl}^2 = \Lambda_\pi^2 k e^{2\pi kr}$, $R_s = \frac{1}{\sqrt{3}\pi\Lambda_\pi}\sqrt{\frac{M_{\rm BH}}{\tilde{k}\Lambda_\pi}} \sim \frac{1}{\Lambda_\pi}$
- Compare with: $R_S^{\rm ADD}(5D) = \frac{1}{\sqrt{\pi}M_D}\sqrt{\frac{8M_{\rm BH}}{3M_D}}$
- 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)

RS BH: Samples & Wien's Law

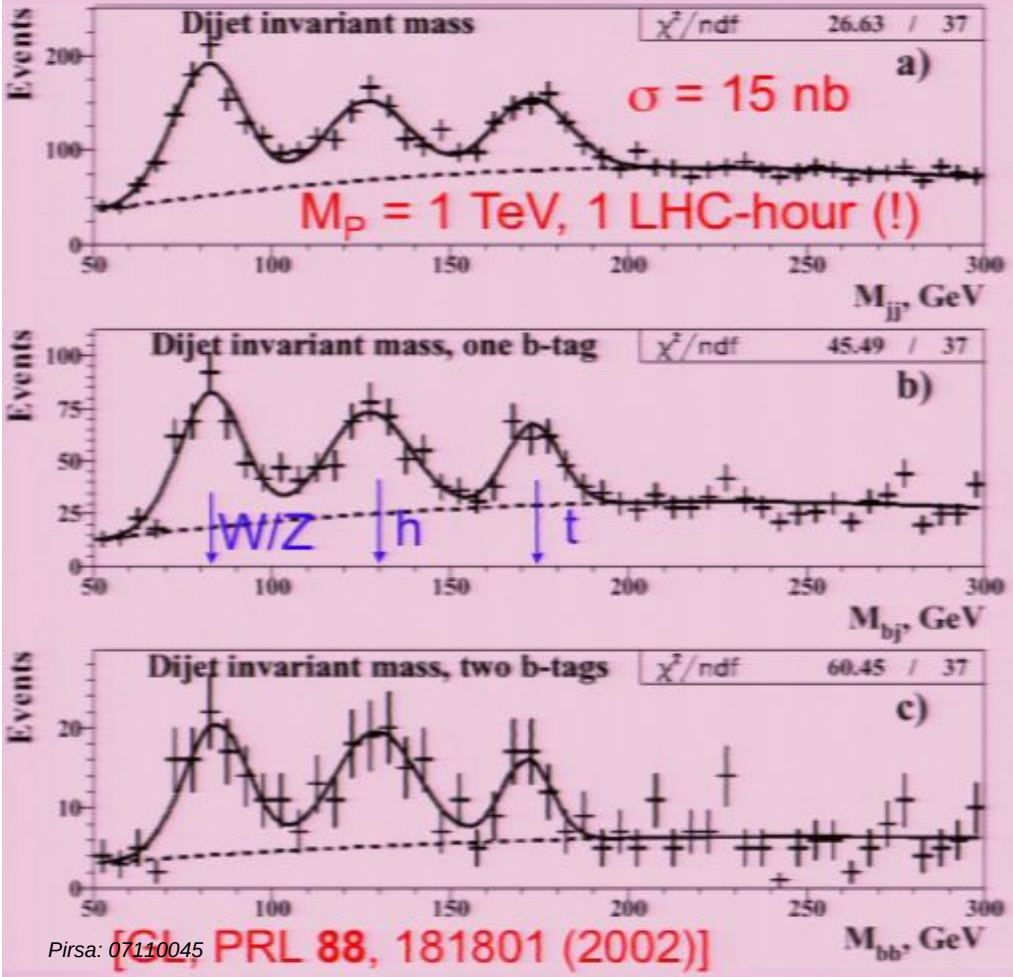
100 fb^{-1} @ the LHC





New Physics in BH Decays

- Example: Higgs with the mass of 130 GeV decays predominantly into $b\bar{b}$
  - Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use typical LHC detector response to obtain realistic results



[CL, PRL **88**, 181801 (2002)]

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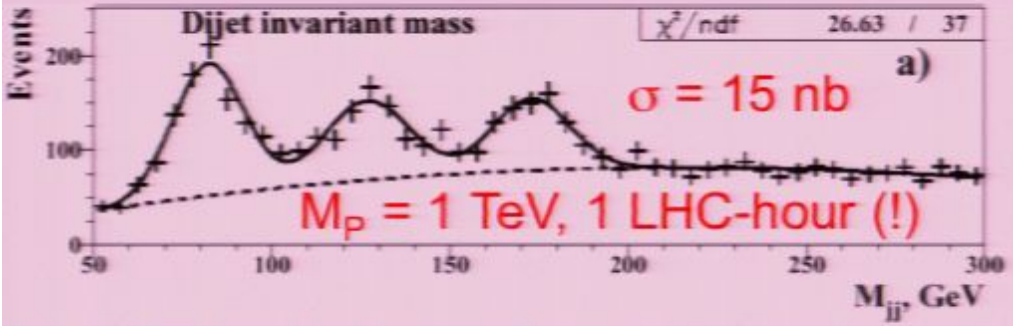

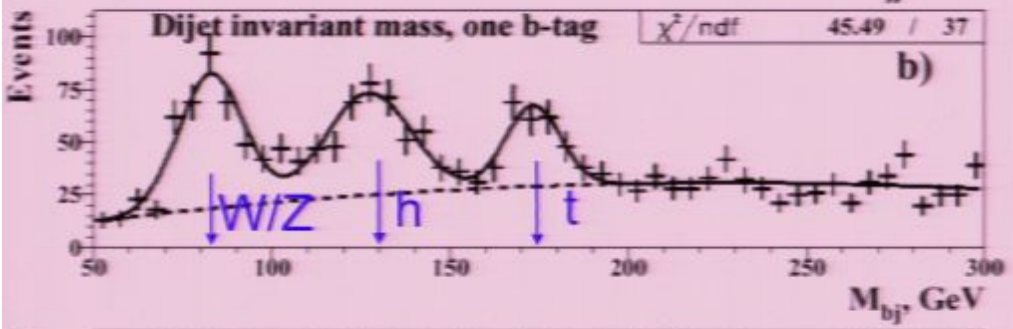

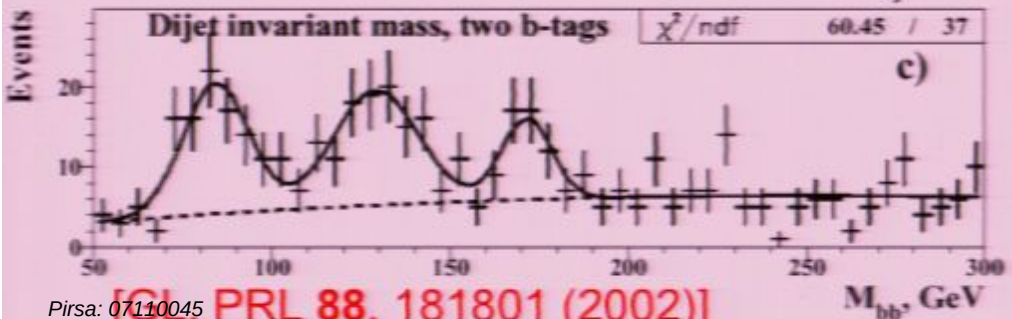

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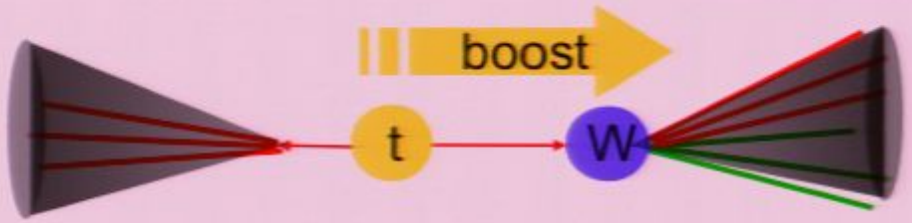
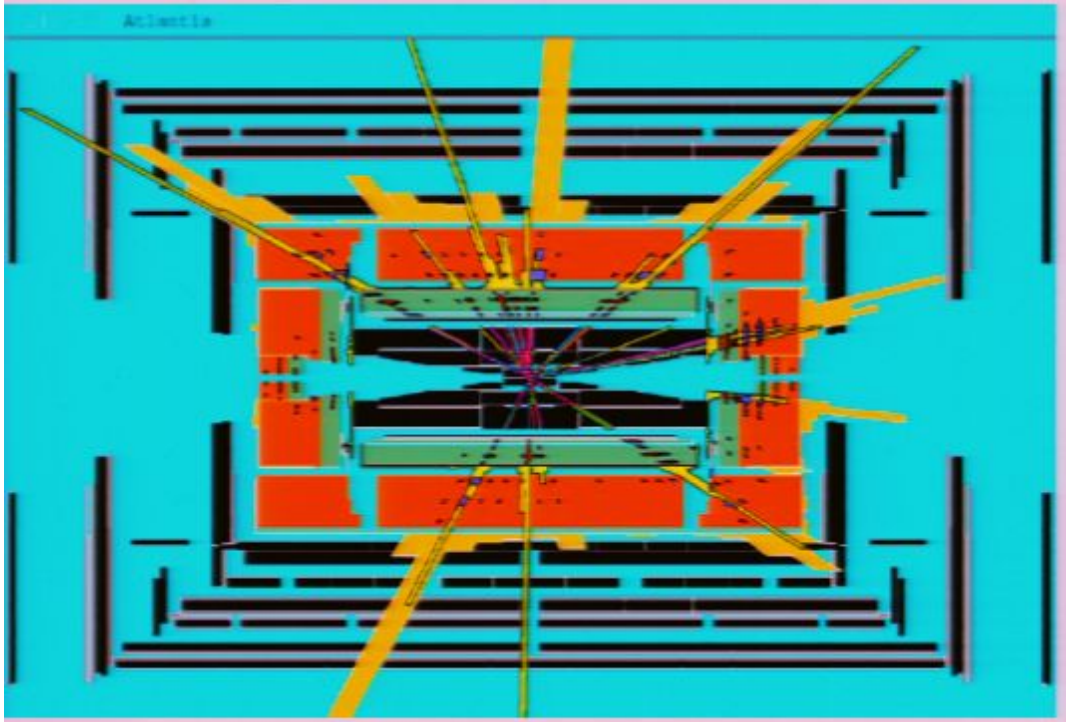


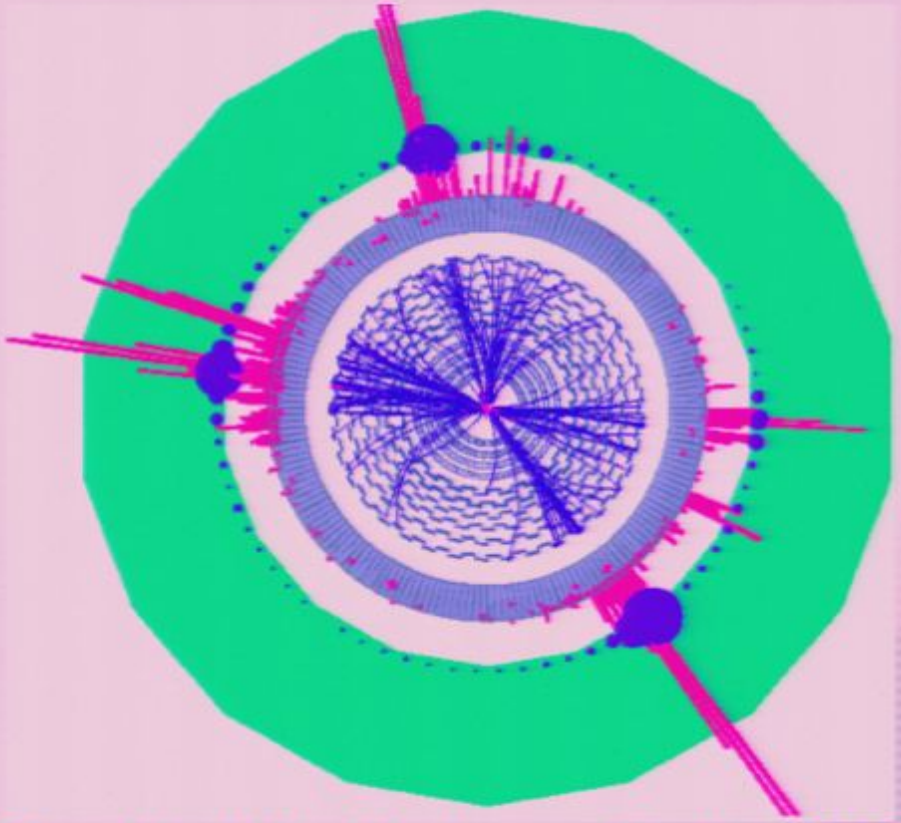
- Higgs observation in the black hole decays is possible at the LHC as early as in the first day of running even with the incomplete and poorly calibrated detectors!
- For M_P = 1, 2, 3, and 4 TeV one needs 1 day, 1 week, 1 month, or 1 year of running to find a 5σ signal
- Higgs is just an example – this applies to most of the new particles with the mass ~100 GeV

Black Hole Events

- Detailed studies already started in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR, GL/CHARYBDIS
- The hunt is going on!



Simulated black hole event in the ATLAS detector, from ATLAS-Japan Group



Simulated black hole event in the CMS detector, A. de Roeck & S. Wynhoff

Conclusions

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- If the scale of gravity is ~1 TeV, copious production of black holes at the LHC is likely to be an early and definitely most spectacular signature for extra dimensions

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- Spectacular signatures, large cross sections make these models extremely attractive for full exploration at the LHC
  - Some of the signatures may nevertheless be quite challenging!
- If the scale of gravity is ~1 TeV, copious production of black holes at the LHC is likely to be an early and definitely most spectacular signature for extra dimensions
- Such a possibility would fulfill our dreams for Grand Unification of an ultimate kind: that of particle physics, astrophysics, and cosmology!