Mini-Review on Extra Dimensions

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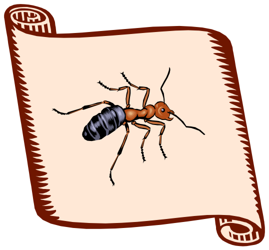
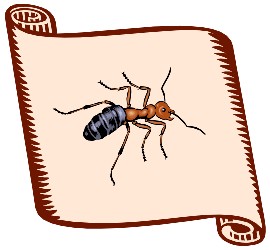


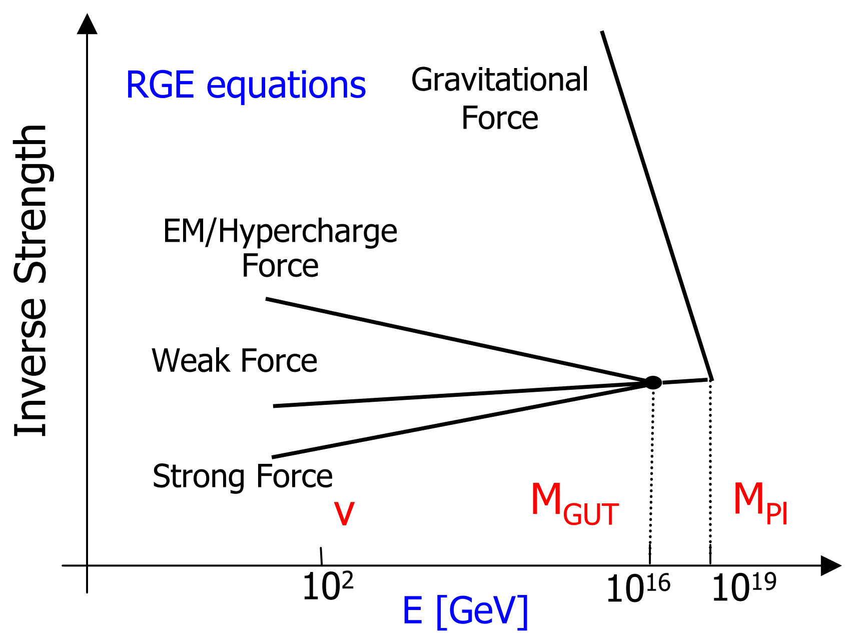
Outline

- Theory of Large Extra Dimensions
- Current Limits on Large Extra Dimensions
  - Cosmological Constraints
  - Gravity at Short Distances
  - LEP2 Searches for Large Extra Dimensions
    - Direct Graviton Emission
    - Virtual Graviton Effects
  - HERA Searches for Large Extra Dimensions
  - Tevatron Searches for Large Extra Dimensions
    - DØ Search for virtual graviton effects
    - Looking for direct graviton emission
- Unusual Signatures for Extra Dimensions
- Conclusions

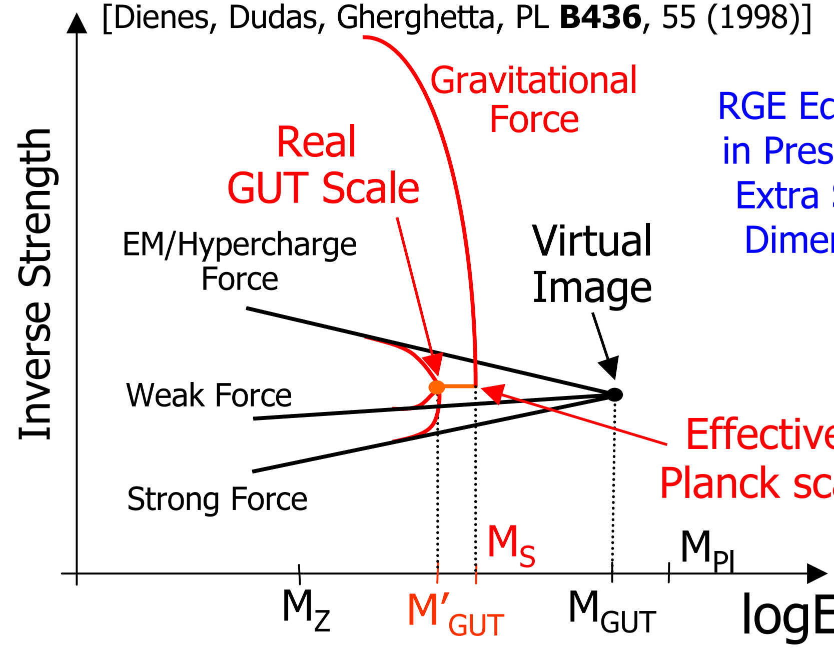


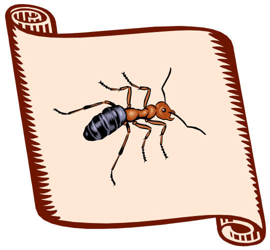
Life Beyond the Standard Model

- The SM, despite its tremendous success, accommodates, but fails to explain:
  - EWSB
  - Origin of fermion masses
  - CP-violation and baryon asymmetry
- It also suffers from quadratic divergencies which call for new physics at a scale of the order of Higgs mass, i.e. ~1 TeV
- But: what if there is no other scale, and the SM model is correct up to the Planck scale?
- Arkani-Hamed, Dimopoulos, Dvali (ADD) (1998): what if the Planck scale is ~ 1 TeV?!!
- What about GUT?



[Dienes, Dudas, Gherghetta, PL **B436**, 55 (1998)]



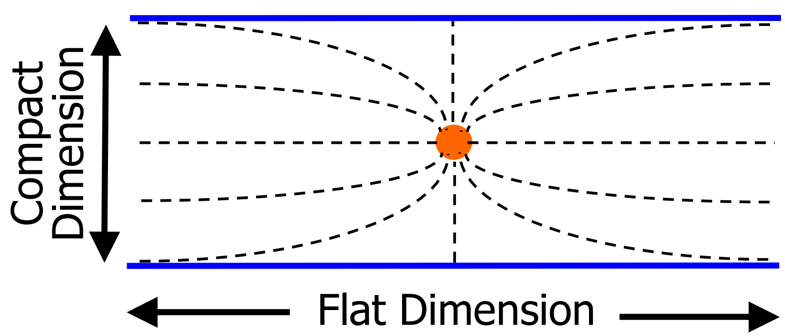


A Crazy Idea? – But it Works!

- What about Newton's law?

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

- Ruled out for flat extra dimensions, but has not been ruled out for sufficiently small compactified extra dimensions:



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \text{ for } r >> R$$

M_S – effective Planck Scale

- But: how to make gravity strong?
- $G'_N = 1/M_S^2 \sim G_F \Rightarrow M_S \sim 1$ TeV

$$M_S^{n+2} \propto M_{Pl}^2 / R^n$$

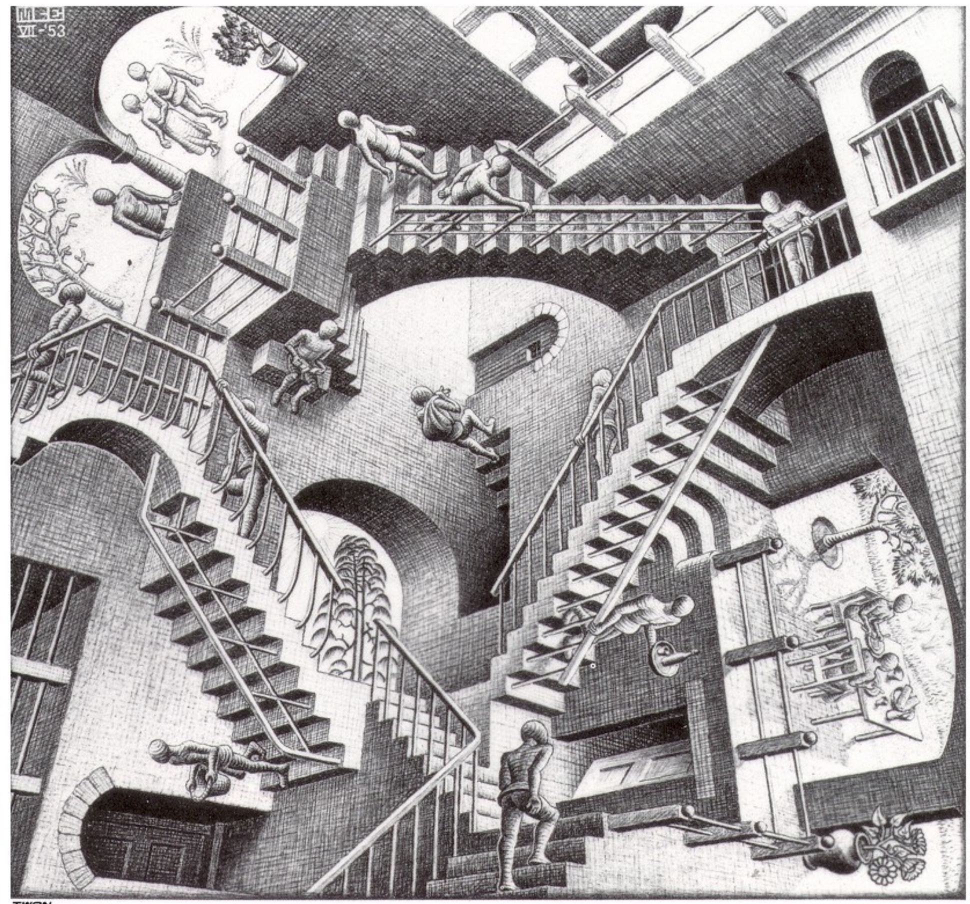
- More precisely, from Gauss's law:

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

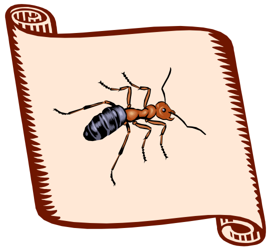
- Amazing as it is, but no one has tested Newton's law to distances less than ~ 1mm
- Therefore, large spatial extra dimensions compactified at a sub-millimeter scale are, in principle, allowed!

Examples of Compactified Spatial Dimensions

M.C.Escher, Mobius Strip II (1963)

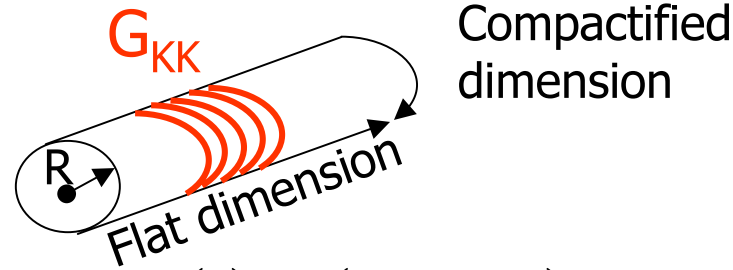


M.C.Escher, Relativity (1953)



An Importance of Being Compact

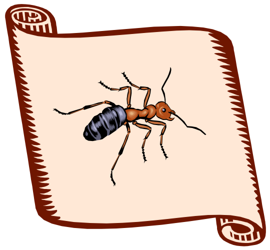
- Compactified dimensions offer a way to increase tremendously gravitational interaction due to a large number of the available "winding" modes
- This tower of excitations is known as Kaluza-Klein modes, and such gravitons propagating in the compactified extra dimensions are called Kaluza-Klein gravitons, G_{KK}
- From the point of view of a 3+1-dimensional space time, the Kaluza-Klein graviton modes are massive, with the mass per excitation more ~ 1/R
- Since the mass per excitation mode is so small (e.g. 400 eV for n = 3, or 0.2 MeV for n = 4), a very large number of modes can be excited at high energies



$$\phi(x) = \phi(x + 2\pi kR), \ k = 0,1,2\cdots$$

$$M(G_{KK}) = \sqrt{P_x^2} = 2\pi k/R$$

- Each Kaluza-Klein graviton mode couples with the gravitational strength
- For a large number of modes, accessible at high energies, gravitational coupling is therefore enhanced drastically
- Low energy precision measurements are not sensitive to the ADD effects

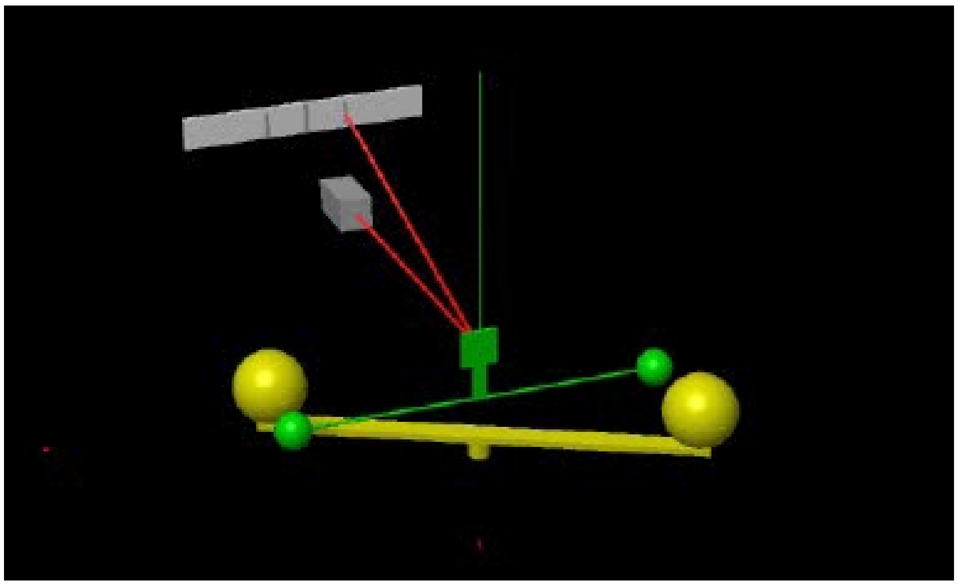


Cosmological Limits on Large Extra Dimensions

- Supernova cooling due to the graviton emission
  - Any new cooling mechanism would decrease the thought-to-be dominant cooling by the neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by the Kamiokande and IMB
  - Application to the ADD scenario [Cullen, Perelstein, PRL **83**, 268 (1999)]:
    - M_S > 30 TeV (n=2)
    - M_S > 4 TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \to \gamma\gamma$ decays
  - Best CDG measurement come from the COMPTEL instrument in the 800 KeV - 30 MeV range
  - Application to the ADD scenario [Hall, Smith, PRD 60, 085008 (1999)]:
    - M_S > 100 TeV (n=2)
    - M_S > 5 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 seems to be excluded

Current Limits from Gravitational Experiments

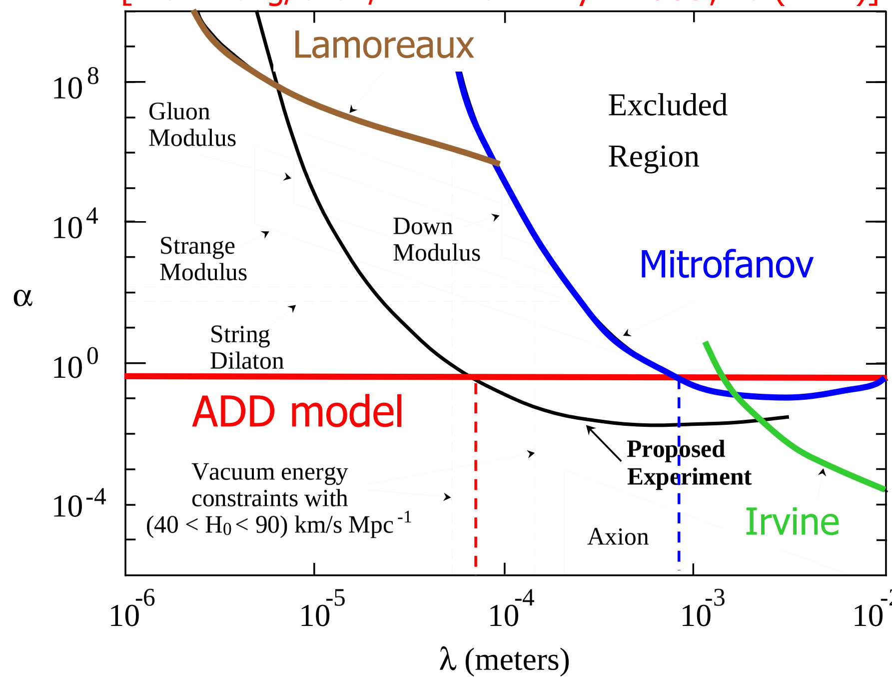
- 1798: Cavendish experiment (torsion balance)



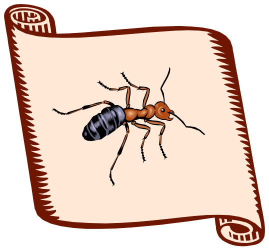
- Mid-1970-ies: a number of Cavendish-type experiments searching for the "fifth forth" via deviations from Newton's law
- Sensitivity vanishes quickly for distances less than 1 mm
- Major background: Van der Waals and Casimir forces

Status of short-range gravity experiments

[From Long/Chan/Price Nucl. Phys. **B539**, 23 (1999)]



- Best sub-millimeter results are from 1997 Lamoreaux experiment [PRL **78**, 5 (1997)] to measure the Casimir force
- New preliminary result from Adelberger et al. (APS 2000 Meeting) indicates that n=2 is ruled out

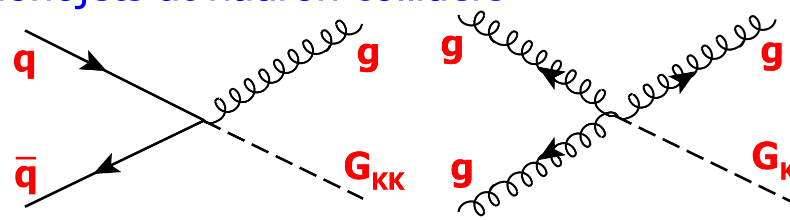


Collider Signatures for Large Extra Dimensions

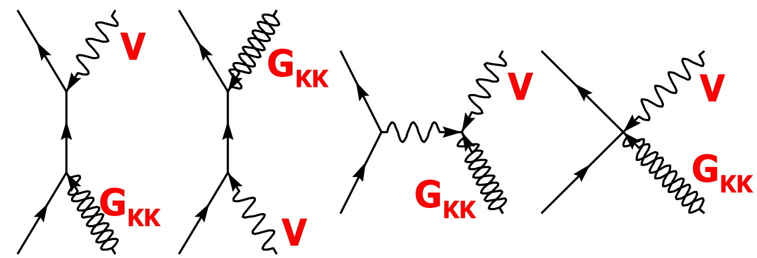
- Kaluza-Klein gravitons couple to the momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- Since the spin 2 graviton in generally has a bulk momentum component, its spin from the point of view of our brane can appear as 0, 1, or 2
- Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing E_T or fermion/vector boson pair production

Real Graviton Emission

Monojets at hadron colliders

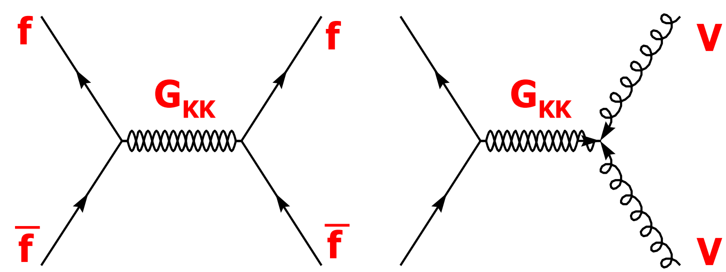


Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission

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

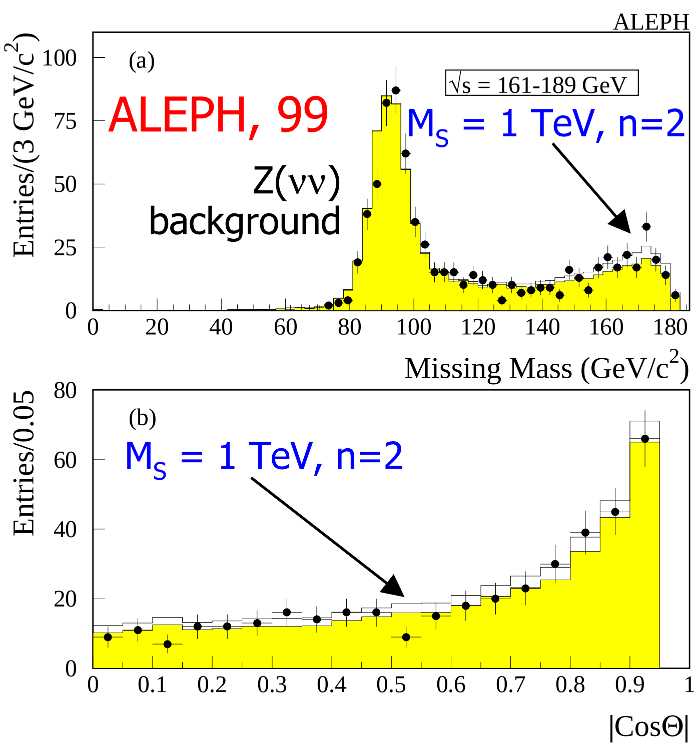


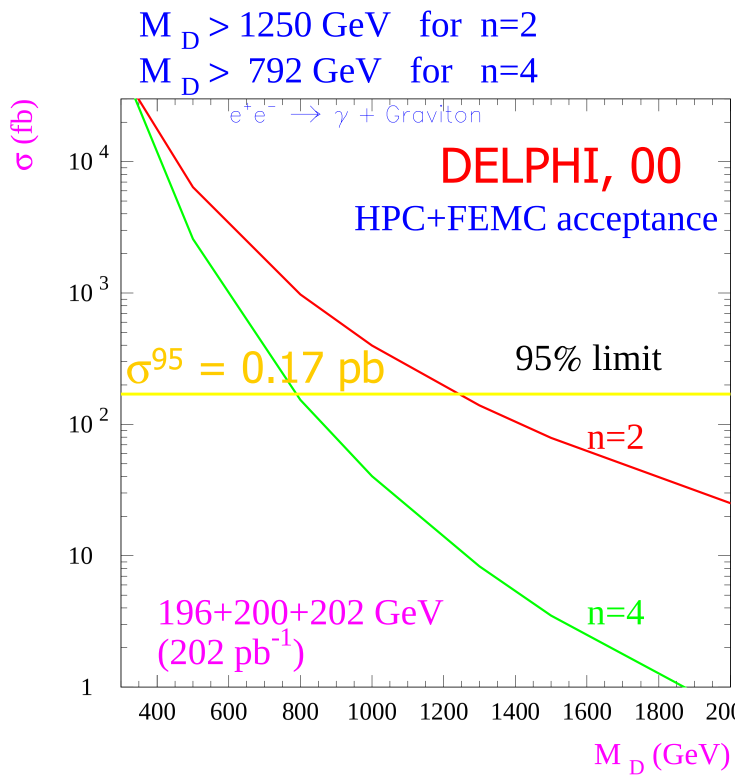
LEP2 Searches for Direct Graviton Emission - I

- $e^+e^- \to \gamma G_{KK}$
  - Photon + ME_T signature
  - "Recycling" of the GMSB analyses
  - ALEPH (2D-fit), DELPHI, L3 (x), OPAL (event counting)

$$\frac{d^2\sigma}{dxdz} = \frac{\alpha}{32s}\frac{\pi^{\frac{n}{2}}}{\Gamma\left(\frac{n}{2}\right)}\left(\frac{\sqrt{s}}{M_S}\right)^{n+2} f(x,z),\quad x = \frac{2E_\gamma}{\sqrt{s}},\quad z = \cos\theta$$

$$f(x,z) = \frac{2(1-x)^{\frac{n}{2}-1}}{x(1-z^2)}\left[(2-x)^2(1-x+x^2) - 3x^2(1-x)z^2 - x^4z^4\right]$$





Theory:

[Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999) and corrected version: hep-ph/9811291]

Experiment:

ALEPH-CONF-2000-005

DELPHI 2000 CONF 344

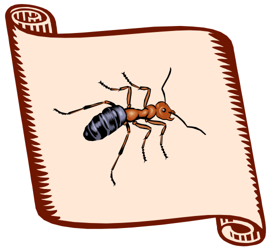
L3: Phys. Lett. **B470**, 268 (1999)

OPAL: CERN-EP-2000-050, submitted to Eur. Phys. J **C**

Results:

M_S > 1.3-0.6 TeV for n=2-6 (DELPHI)

ALEPH, L3, OPAL – slightly worse

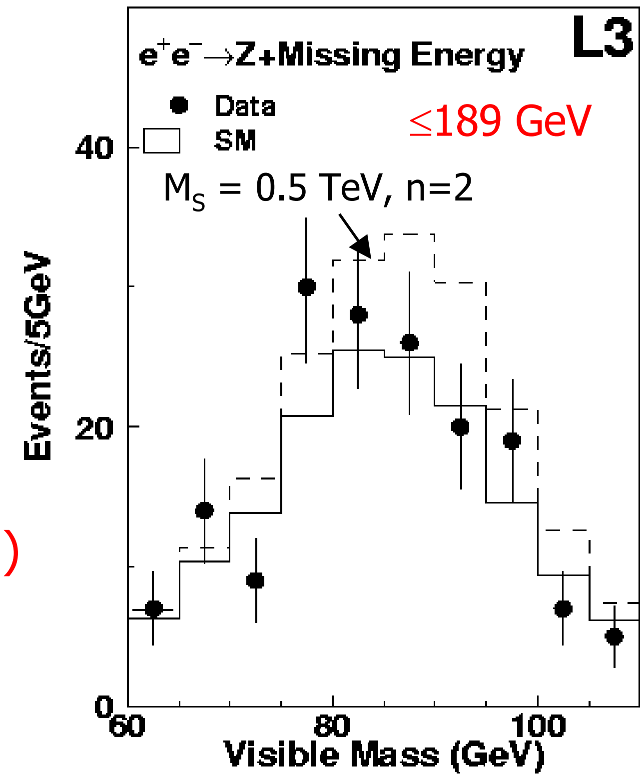


LEP2 Searches for Direct Graviton Emission - II

- $e^+e^- \to ZG_{KK}$
  - Z(jj) + ME_T signature
  - "Recycling" of the invisible Higgs analyses
  - ALEPH: Z(jj)G, 184 GeV, total cross section method
  - L3: Z(jj)G, 189 GeV, increased sensitivity via analysis of the visible mass distribution
  - OPAL: 189 GeV
  - M_S > 0.35-0.12 TeV (ALEPH) for n = 2-6
  - M_S > 0.60-0.21 TeV (L3) for n = 2-6

$$\frac{\Gamma(Z \to f\bar{f}\,G)}{\Gamma(Z \to f\bar{f})} = \frac{1}{4\pi}\frac{1}{3(n+2)}\left(\frac{M_Z}{M_S}\right)^{n+2} I$$

$$I = \frac{\pi^{\frac{n-2}{2}}}{\Gamma(\frac{n}{2})}\int_0^1 dx \int_0^{(1-\sqrt{x})^2} dy\, \frac{y^{\frac{n-2}{2}}(12x+A)\sqrt{A}}{6(1-x)^2},\quad A = (1-x-y)^2 - 4xy$$



Theory:

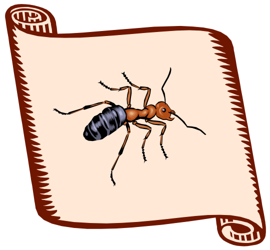
[Balazs, Dicus, He, Repko, Yuan, Phys. Rev. Lett. **83**, 2112 (1999) – width ratio]

[Cheung, Keung, Phys. Rev. **D60**, 112003 (1999) – mass distribution]

Experiment:

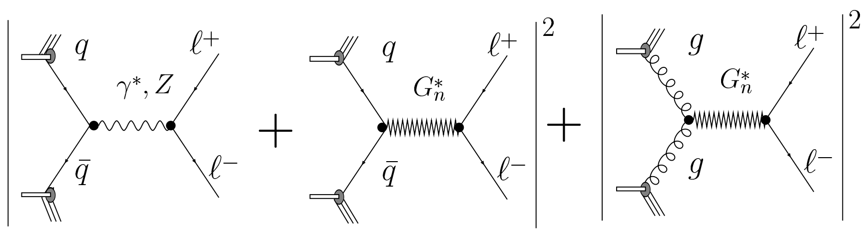
ALEPH-CONF-99-027

L3: Phys. Lett. **B470**, 281 (1999)



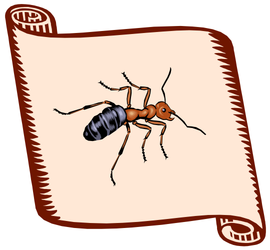
Virtual Graviton Effects

- In the case of pair production via virtual graviton, gravity effects interfere with the SM (e.g., l^+l^- at hadron colliders):



- Therefore, production cross section has three terms: SM, interference, and direct gravity effects
- The sum in KK states is divergent in the effective theory, so in order to calculate the cross sections, an explicit cut-off is required
- An expected value of the cut-off is ≈ M_S, as this is the scale at which the effective theory breaks down, and the string theory needs to be used to calculate production
- Unfortunately, a number of similar papers calculating the virtual graviton effects appeared simultaneously
- Hence, there are three major conventions on how to write the effective Lagrangian:
  - Hewett, Phys. Rev. Lett. **82**, 4765 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999); revised version, hep-ph/9811291
  - Han, Lykken, Zhang, Phys. Rev. **D59**, 105006 (1999); revised version, hep-ph/9811350
- Fortunately (after a lot of discussions and revisions) all three conventions turned out to be completely equivalent and only the definitions of M_S are different:

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



Hewett, GRW, and HLZ Formalisms

- Hewett: neither sign of the interference nor the dependence on the number of extra dimensions is known; therefore the interference term is $\sim\lambda/M_S^4$(Hewett), where λ is of order 1; numerically uses $\lambda = \pm 1$
- GRW: sign of the interference is fixed, but the dependence on the number of extra dimensions is unknown; therefore the interference term is $\sim 1/\Lambda_T^4$ (where Λ_T is their notation for M_S)
- HLZ: not only the sign of interference is fixed, but the n-dependence can be calculated in the effective theory; thus the interference term is $\sim F/M_S^4$(HLZ), where F reflects the dependence on the number of extra dimensions:

$$F = \begin{cases} \log\left(\frac{M_S^2}{s}\right), n = 2 \\ \frac{2}{n-2}, n > 2 \end{cases}$$

- Correspondence between the three formalisms:

$$M_S(\mathbf{Hewett})\big|_{\lambda=+1} \equiv \sqrt[4]{\frac{2}{\pi}}\Lambda_T(\mathbf{GRW})$$

$$\frac{\lambda}{M_S^4(\mathbf{Hewett})} = \frac{\pi}{2}\frac{F}{M_S^4(\mathbf{HLZ})}$$

$$\frac{1}{\Lambda_T^4(\mathbf{GRW})} = \frac{F}{M_S^4(\mathbf{HLZ})}$$

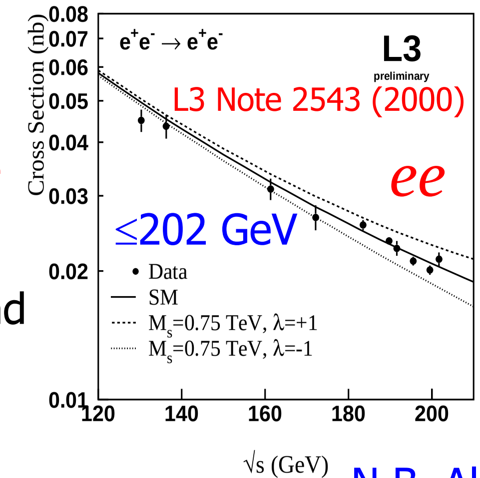
- Rule of thumb:

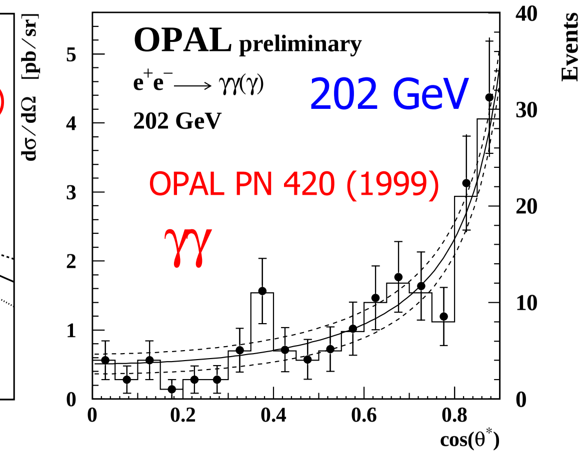
$$M_S(\mathbf{Hewett})\big|_{\lambda=+1} \approx M_S(\mathbf{HLZ})\big|_{n=5}$$

$$\Lambda_T(\mathbf{GRW}) = M_S(\mathbf{HLZ})\big|_{n=4}$$

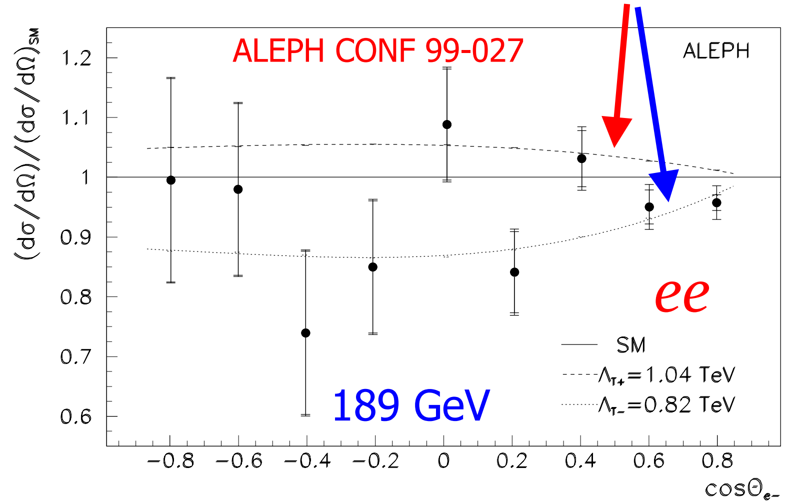
LEP2 Searches for Virtual Graviton Effects

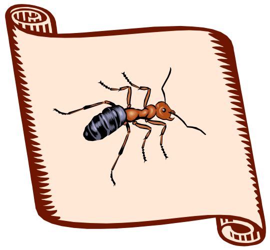
- LEP2 Collaborations looked at difermion and diboson production due to the G_{KK} exchange
- Unfortunately, different formalisms were used by different collaborations, and sometimes even within a collaboration, which makes results hard to compare and combine
- Internal inconsistency could affect some of the combined limits
- Most sensitive channels are:
  - Dielectron s-channel production and Bhabha scattering
  - Diphoton production
- Limits on M_S(Hewett) ~ 0.8-1.2 TeV
- Bibliography:
  - ALEPH: CONF 99-027, 2000-005, 2000-030
  - DELPHI: CONF 355, 363 (2000)
  - L3: PL **B464**, 135; **B470**, 281 (1999); Notes 2543, 2590 (2000)
  - OPAL: CERN-EP/99-097, PN 420 (1999)





N.B. All LEP Collaborations considered both interference signs





LEP2 Searches for Virtual Graviton Effects - VV

- $e^+e^- \to WW/ZZ$
  - Recycle WW cross section and anomalous ZZγ couplings analyses
  - L3 used angular distributions (WW) and mass variables (ZZ) to set limits

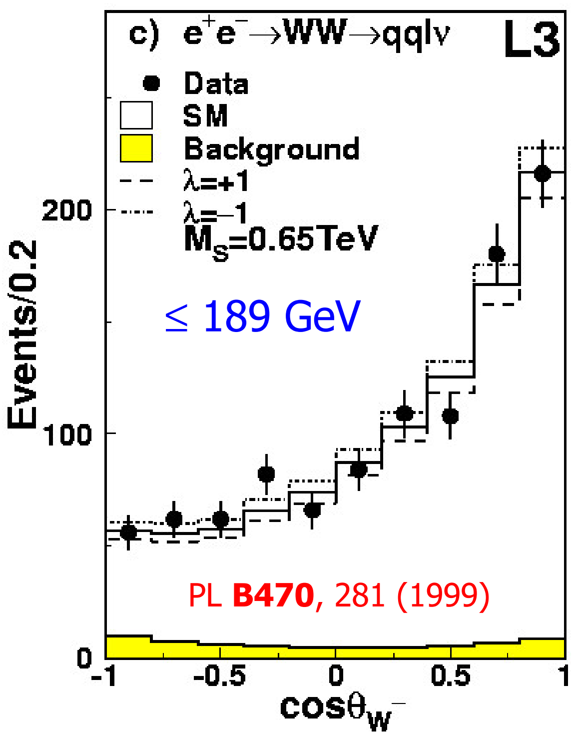
Theory:

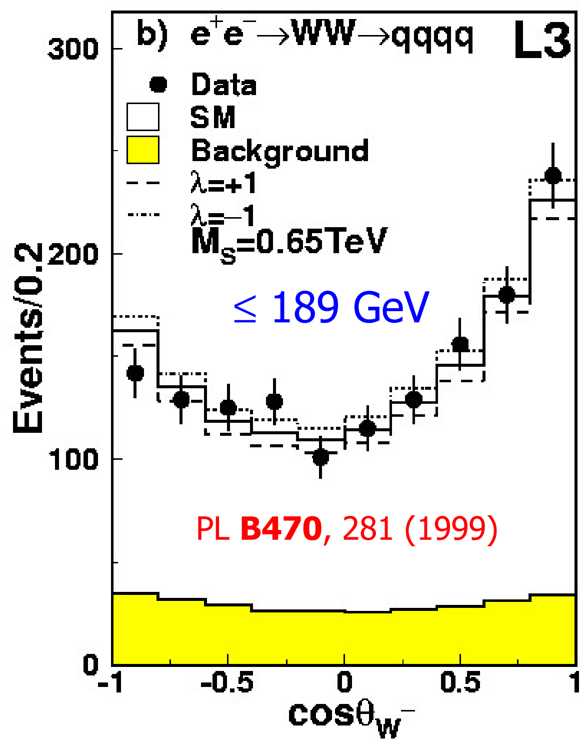
[Agashe, Deshpande, Phys. Lett. **B456**, 60 (1999)]

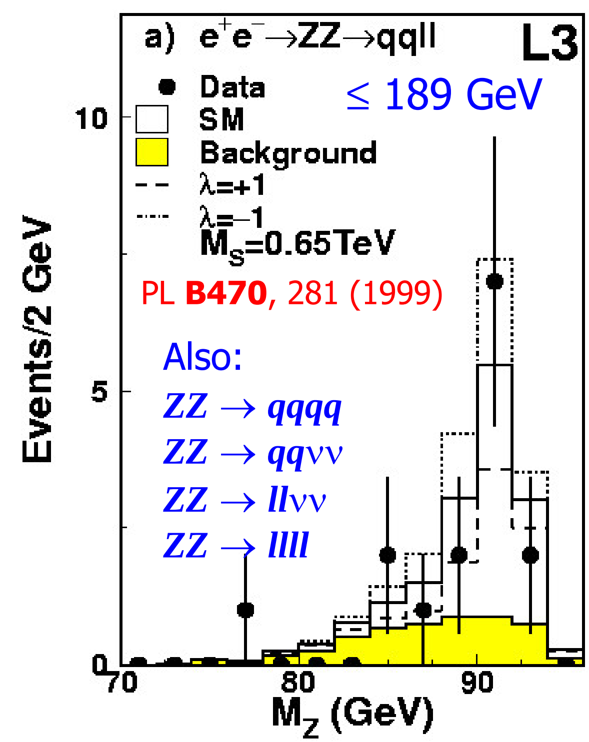
$$M_S^{AD}\Big|_{\lambda=-1} \equiv M_S^{Hewett}\Big|_{\lambda=+1}$$

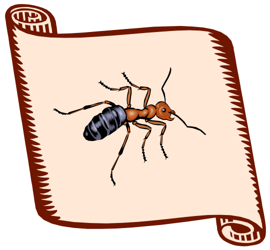
AD convention is equivalent to Hewett's with a flipped sign of λ

M_S > 520-650 GeV (WW); M_S > 460-470 GeV (ZZ)









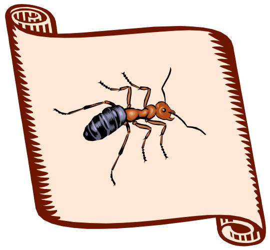
LEP2 Lower 95% CL M_S(Hewett) Limits (TeV)

Experiment	$e^+e^- \to \gamma G$ n=2	n=3	n=4	n=5	n=6	$e^+e^- \to ZG$ n=2	n=3	n=4	n=5	n=6
ALEPH	1.10	0.86	0.70	0.60	0.52	0.35	0.22	0.17	0.14	0.12
DELPHI	1.25	**0.97**	0.79	**0.68**	**0.59**					
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	**0.24**	**0.21**
OPAL	1.09	0.86	0.71	0.61	0.53					

Color coding
≤184 GeV
≤189 GeV
≤202 GeV
λ=-1 λ=+1 GL

Virtual Graviton Exchange

Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	Combined
ALEPH (Λ_T)	1.17 0.91	0.73 0.75	0.67 0.69	0.59/0.64 0.55/0.55 (bb)	1.17 0.94	0.91 0.92			0.84/1.12 (<189) **M_S >** 0.75/1.00
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.69 0.71			0.60/0.76 (ff) (<202)
L3	0.91 0.99	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.80 0.79	0.68 0.79	1.2 1.2	1.3/1.2 (<202)
OPAL		0.63 0.60	0.50 0.63		0.61 0.68	0.63 0.64			0.61/0.68 (ff) (<189)



HERA Search for Virtual Graviton Effects

- $e^{\pm}p \to e^{\pm}p$
  - t-channel exchange, similar to Bhabha scattering diagrams; based on the GRW formalism (set limits on Λ_T, but call it M_S)
  - Usual SM, Z/γ^* interference, and direct G_{KK} terms
  - Analysis method: fit to the $d\sigma/dQ^2$ distribution (H1)
  - Current combined limits: $\Lambda_T > 0.67/0.73$ TeV ($M_S > 0.60/0.65$ TeV)
  - Expected sensitivity up to 1 TeV with the ultimate HERA data set

$$\frac{d\sigma(e^{\pm}q \to e^{\pm}q)}{dt} = \frac{d\sigma_{SM}}{dt} + \frac{d\sigma_G}{dt} + \frac{d\sigma_{\gamma G}}{dt} + \frac{d\sigma_{ZG}}{dt},$$

$$\frac{d\sigma_G}{dt} = \frac{\pi}{32}\frac{\lambda^2}{M_S^8}\frac{1}{s^2}\left(32u^4 + 64u^3t + 42u^2t^2 + 10ut^3 + t^4\right),$$

$$\frac{d\sigma_{\gamma G}}{dt} = \mp\frac{\pi}{2}\frac{\lambda}{M_S^4}\frac{\alpha e_q}{s^2}\frac{(2u+t)^3}{t},$$

$$\frac{d\sigma_{ZG}}{dt} = \frac{\pi}{2}\frac{\lambda}{M_S^4}\frac{\alpha}{s^2\sin^2 2\theta_W}\left(v_e v_q \frac{(2u+t)^3}{t - m_Z^2} - a_e a_q \frac{t(6u^2 + 6ut + t^2)}{t - m_Z^2}\right),$$

$$\frac{d\sigma(e^{\pm}g \to e^{\pm}g)}{dt} = \frac{\pi}{8}\frac{\lambda^2}{M_S^8}\frac{u}{s^2}\left(2u^3 + 4u^2t + 3ut^2 + t^3\right)$$

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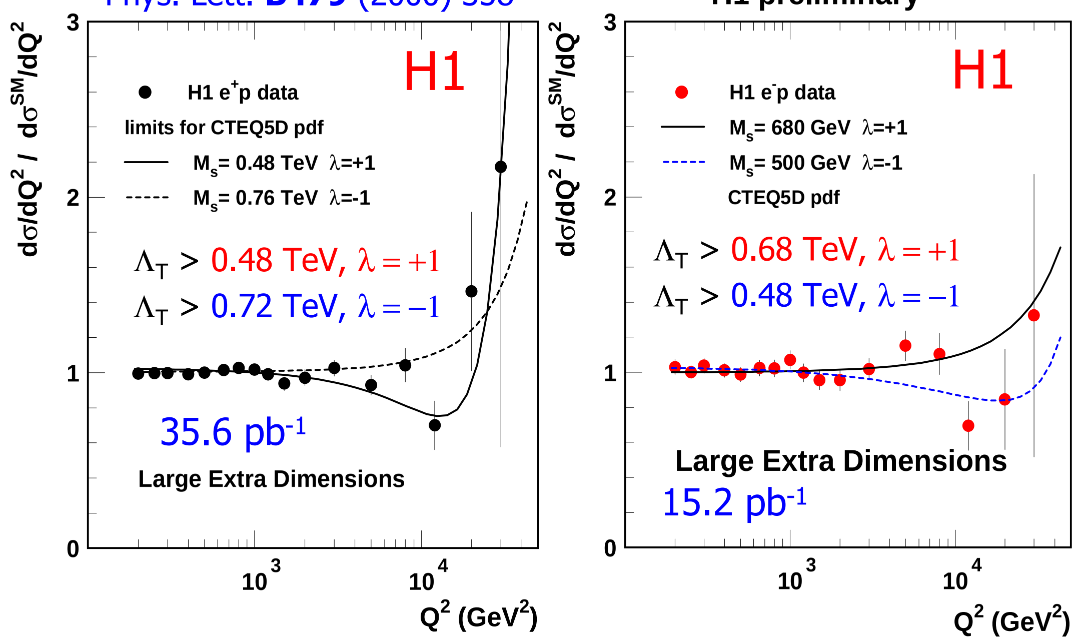
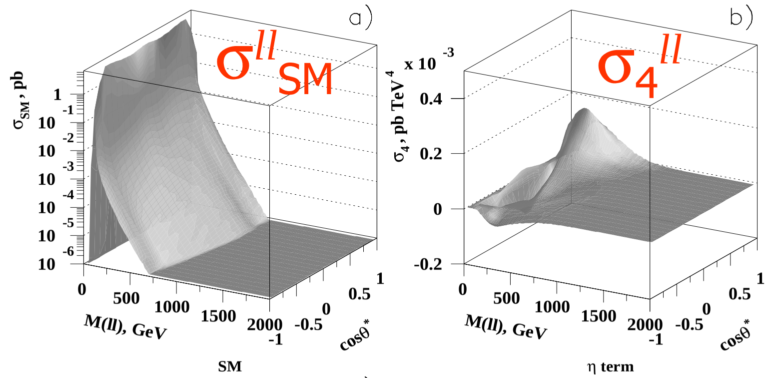
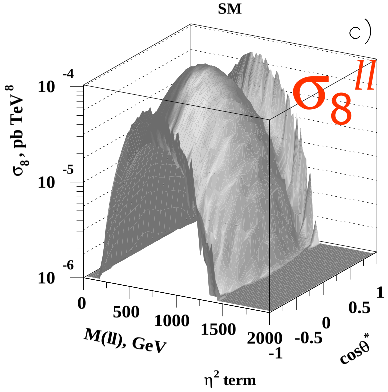
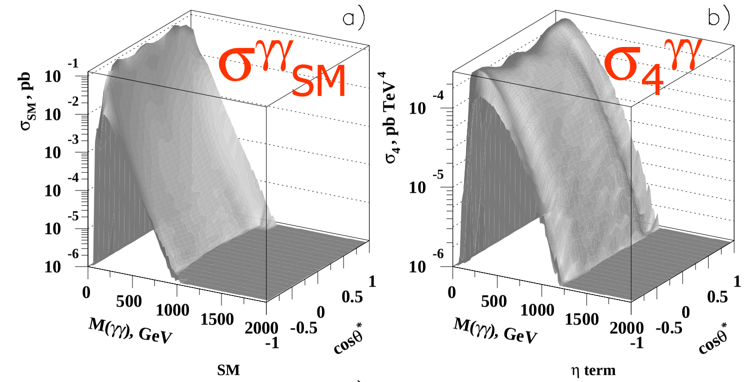


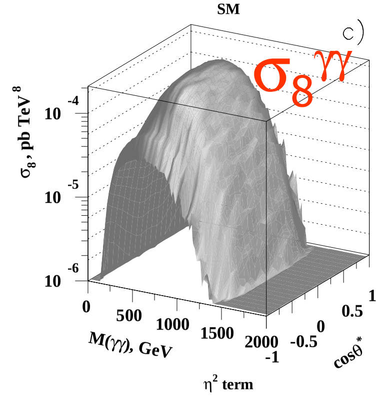
Tevatron Searches for Virtual Graviton Effects





$$\sigma^{ll}_{\eta} = \sigma^{ll}_{SM} + \sigma^{ll}_4\eta + \sigma^{ll}_8\eta^2$$





$$\sigma^{\gamma\gamma}_{\eta} = \sigma^{\gamma\gamma}_{SM} + \sigma^{\gamma\gamma}_4\eta + \sigma^{\gamma\gamma}_8\eta^2$$

$$\eta = \frac{F}{M_S^4}$$

$$F = \begin{cases} \log\left(\frac{M_S^2}{s}\right), n = 2 \\ \frac{2}{n-2}, n > 2 \end{cases}$$

$[\eta]$ = TeV^{-4}

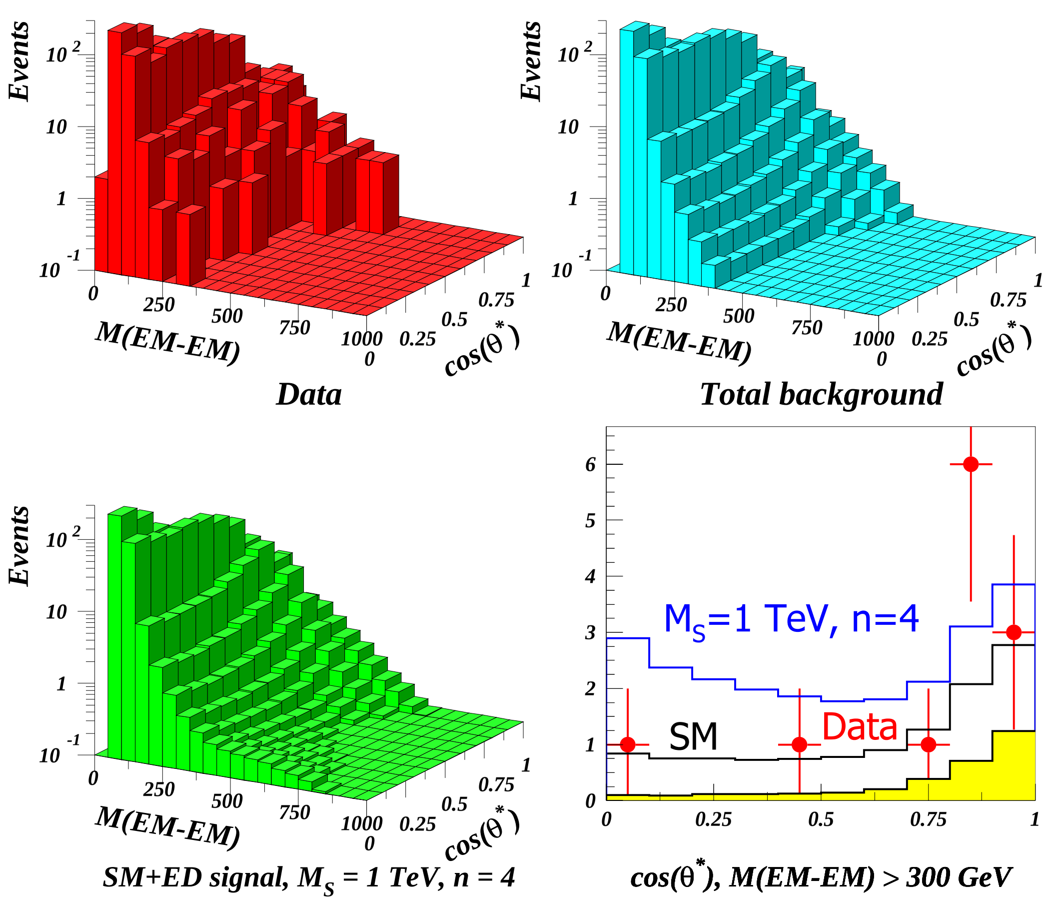
[Cheung, GL – hep-ph/9909218, to appear in PRD]

- Use invariant mass and scattering angle in the c.o.m. frame to maximize sensitivity
- Parameterize cross section as a bilinear form in scale η (works for any n>2)
- Note the asymmetry of the interference term, σ_4, for *ll* production
- Use Bayesian fit to the data (real one or MC one) to get the best estimate of η
- Diphoton channel is considerably more sensitive than the dilepton one

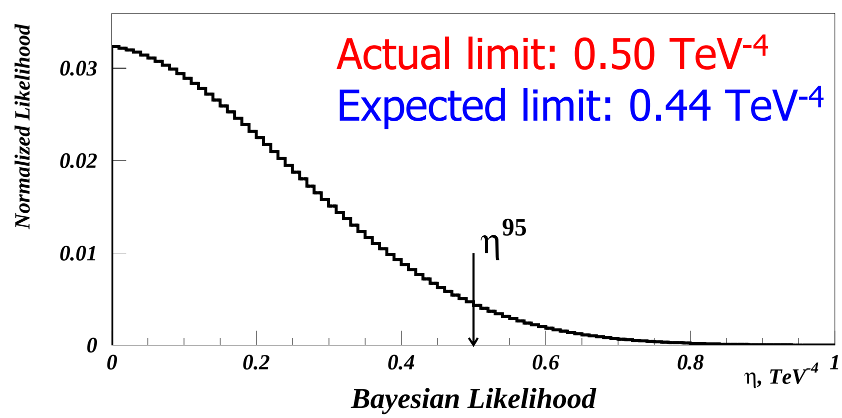
DØ Search Using Dielectrons and Diphotons

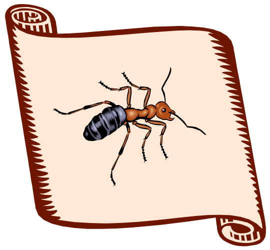
Comparison of the data and the SM predictions

DØ Preliminary, Run I, 127 pb^{-1}

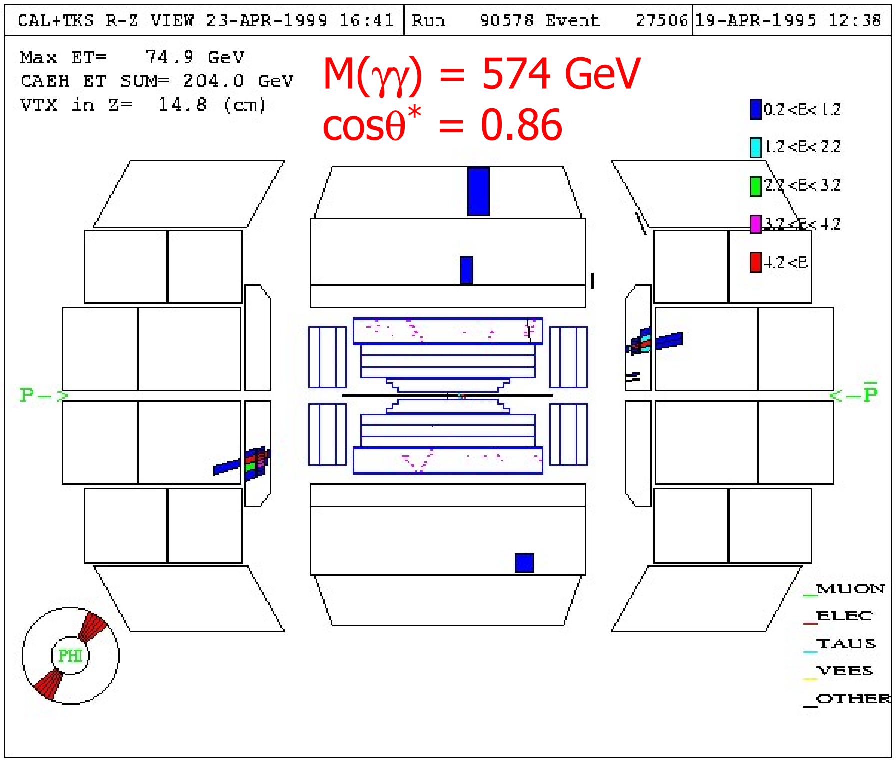


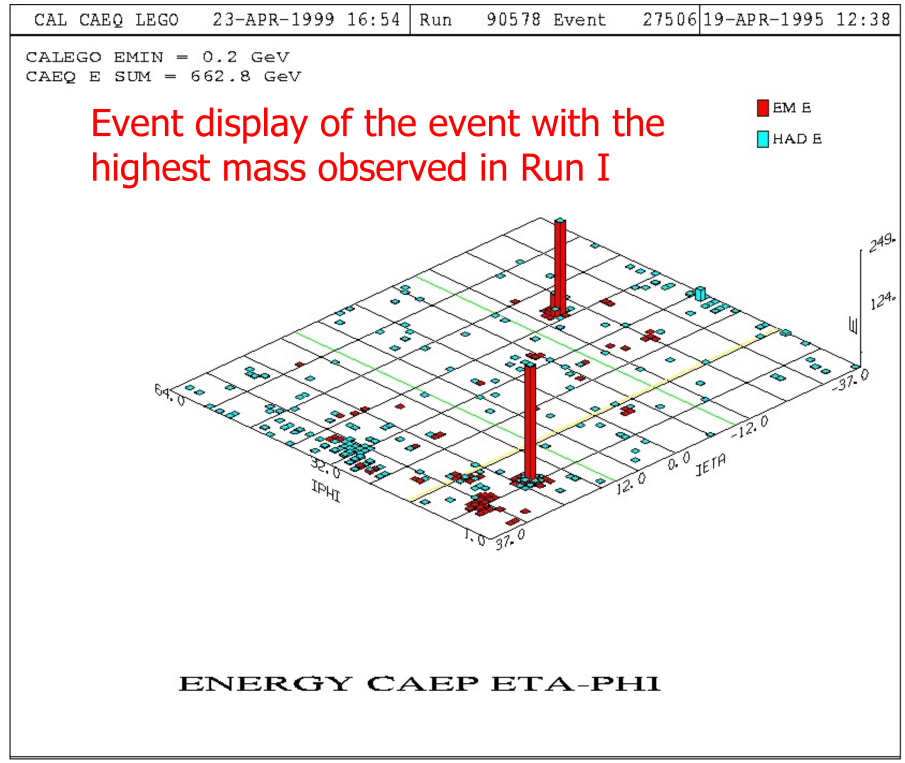
- Combine dielectron and diphoton events to avoid inefficiency due to tracking and conversions
- Since the dominant background is irreducible DY and diphoton production, release ID cuts to maximize sensitivity
- No excess of events is seen at high masses and low scattering angles, where the signal is expected to exhibit itself





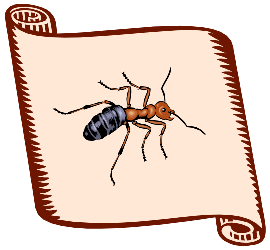
High-Mass Candidate Events



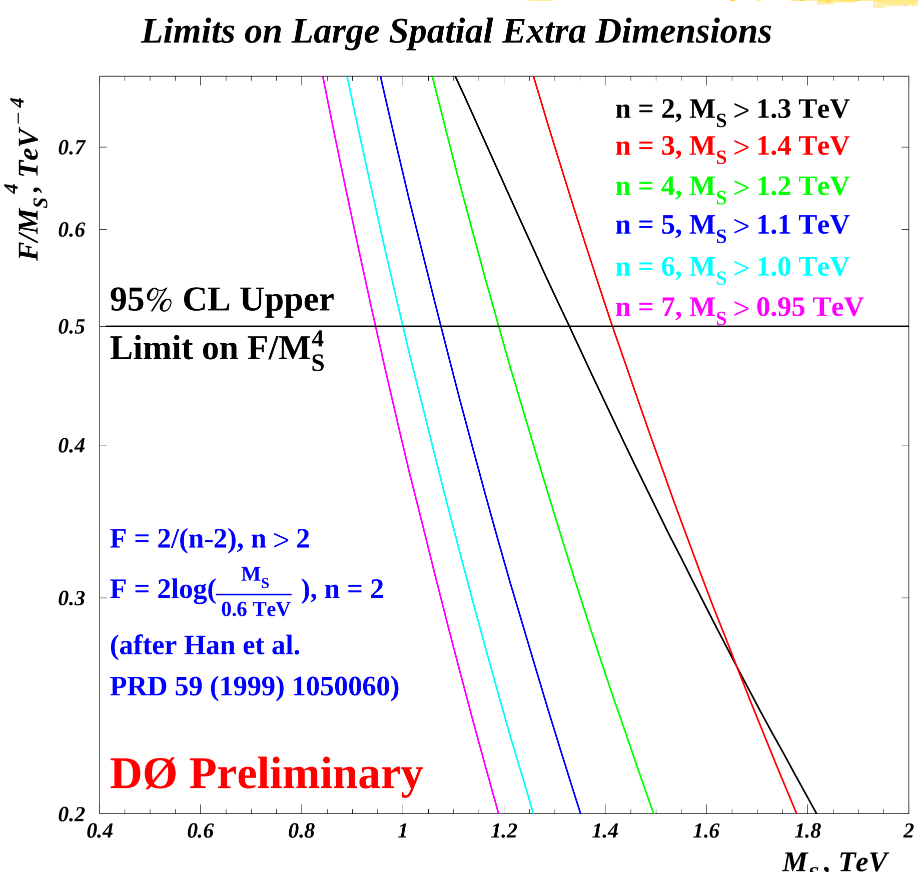


- Parameters of the two high-mass candidate events:

Run	Event	Z_{vtx}	ME_T	Type	E_T^1	E_T^2	η_1	η_2	M	$\cos\theta^*$	N_{jet}	P_T-kick
90578	27506	3.6 cm	15 GeV	$\gamma\gamma$	81 GeV	81 GeV	1.98	-1.91	575 GeV	0.86	0	11.7 GeV
84582	11674	-34 cm	15 GeV	ee	134 GeV	132 GeV	0.99	-1.59	520 GeV	0.84	0	18.8 GeV

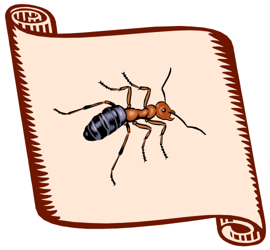


DØ Limits on Large Extra Dimensions



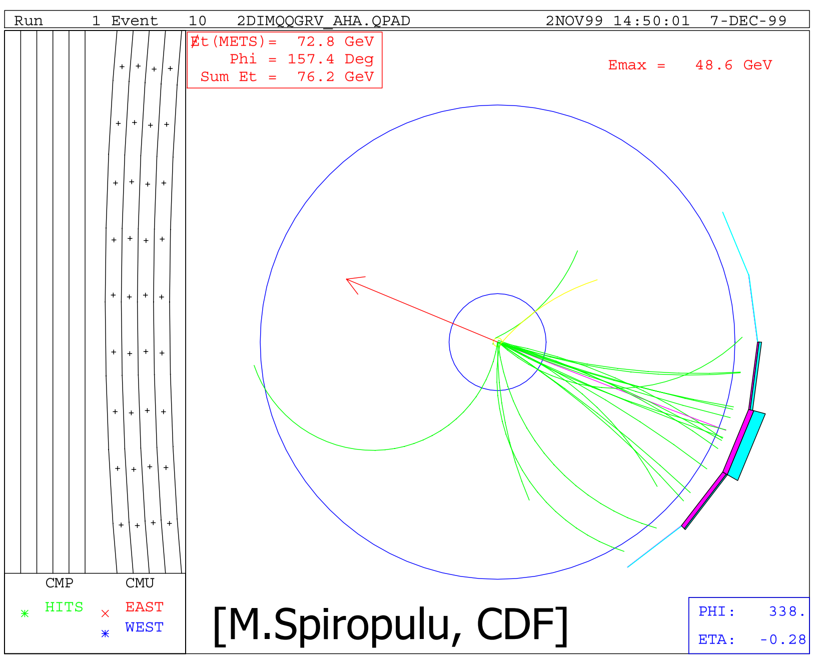
- Sensitivity is limited by statistics; it will double (in terms of M_S) in Run IIA (2 fb^{-1}), and triple in Run IIB (20 fb^{-1})

- For n > 2 M_S limits can be obtained directly from η limits
- For n = 2, use average s for gravity contribution ($\langle \hat{s} \rangle$ = 0.36 TeV^2, see hep-ph/9909218)
- Translate limits in the Hewett and GRW frameworks for easy comparison with other experiments:
  - M_S(Hewett) > 1.1 TeV and 1.0 TeV ($\lambda = -1$)
  - Λ_T(GRW) > 1.2 TeV
- This limits are comparable with the latest limits from LEP2
- They are complementary to those from LEP2, as they probe different range of energies
- Looking forward for limits from the CDF DY analysis (M_S ~ 0.9-1.0 TeV), utilizing the same technique
- Significant improvement is expected by combining the results of the two Tevatron experiments



Tevatron: Real Graviton Emission

- $q\bar{q} \to gG_{KK}$ (dominant channel)
  - jets + ME_T final state
  - $Z(\nu\nu)$+jets is irreducible background
  - Important instrumental backgrounds from jet mismeasurement, cosmics, etc.
  - Both CDF and DØ are pursuing this search



[M.Spiropulu, CDF]

Theory:

[Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999) and corrected version, hep-ph/9811291]

[Mirabelli, Perelstein, Peskin, PRL **82**, 2236 (1999)]

$$\frac{d\sigma}{dt}(q\bar{q} \to gG) = \frac{\alpha_S}{36}\frac{1}{sM_S^2}F_1\left(\frac{t}{s}, \frac{m^2}{s}\right)$$

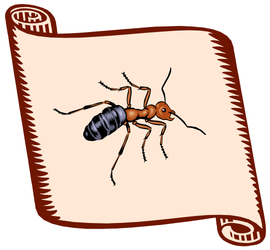
$$F_1(x,y) = \frac{1}{x(y-1-x)}\left[-4x(1+x)(1+2x+2x^2) + y(1+6x+18x^2+16x^3) - 6y^2x(1+2x) + y^3(1+4x)\right]$$

Tevatron Run I/II reach, CDF+DØ [Giudice et al.]

n	M_S reach, Run I	M_S reach, Run II
2	1100 GeV	1400 GeV
3	950 GeV	1150 GeV
4	850 GeV	1000 GeV
5	700 GeV	900 GeV

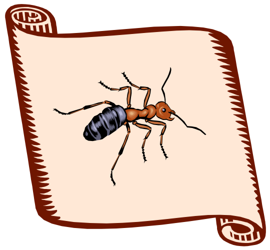
Note that non-perturbative effects could be important at high n

Note that this sensitivity estimate is probably optimistic, as it does not take into account copious instrumental backgrounds



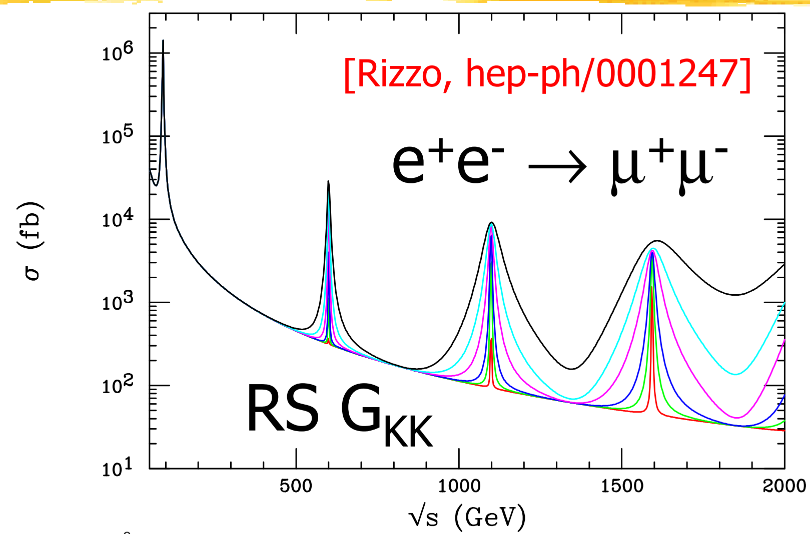
Black Hole Production

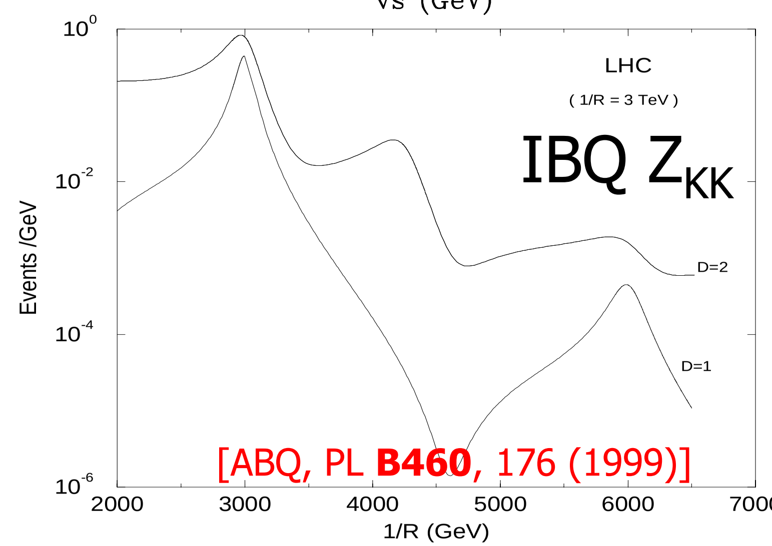
- Once the c.m. energy exceeds the compactification scale, M_S, a critical energy density is achieved and the black hole is formed
- Not to worry about the Earth being sucked into such a black hole; they should be constantly formed by cosmic rays
- The temperature of such a black hole is: $T = M_{Pl}^2/M \to M_S^2/M \times O(M/M_S) \sim M_S$
- For $M_S \sim T = 1$ TeV, the black body spectrum peaks at 250 GeV, and therefore the BH technically evaporates by emitting a single energetic photon – not quite a black body!
- Moreover, the lifetime of such a black hole is only $\sim 10^{-29}$ s
- The Scwartzchild radius of such a black hole is $\sim 1/M_S$, i.e. it's $\sim$ de Broglie wavelength; it's not clear of one could even consider such an object as a bound state
- Other possibility is evaporation in the bulk via G_{KK}, in which case the signature is a deficit of high-s events
  - At a hadron collider it's easy to tweak p.d.f. to account for such a deficit
  - At a lepton collider it's hard to establish that the beams have not missed each other in one of the better established spatial dimensions
- Interesting possibility for a black hole is to have a color 'hair' that holds it to our brane; if the color quantum number is conserved, the black hole could be metastable and live seconds or even days before it decays in a large number of hadrons
  - Look for events not in time with the accelerator clock with such a distinct signature (Dvali, GL, Matchev)

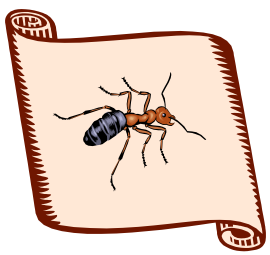


Gauge Boson Excitations

- New developments in theory of extra dimensions:
  - Randall-Sundrum two-brane model with gravity localized near the brane [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
    - Expect G_{KK} resonances in, e.g., $e^+e^- \to l^+l^-$ scattering
  - Antoniadis/Benaklis/Quiros intermediate 'longitudinal' extra dimensions with ~TeV^{-1} radius [PL **B460**, 176 (1999)]
    - Expect Z_{KK}, W_{KK}, g_{KK} resonances
    - Effects also will be seen in the virtual exchange of the Kaluza-Klein modes of vector bosons at lower energies

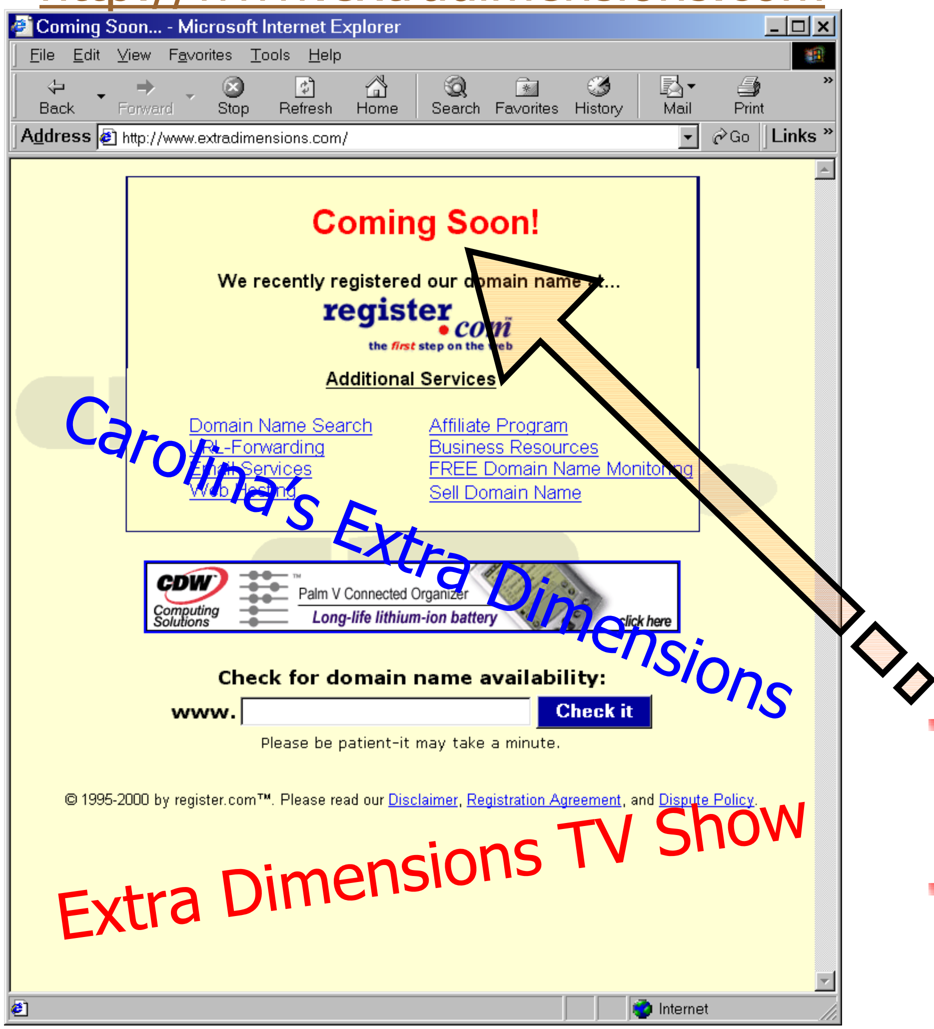






Conclusion: WWW Search for Extra Dimensions

http://www.extradimensions.com



On 2/15/00 patent 6,025,810 was issued to David Strom for a "hyper-light-speed antenna." The concept is deceptively simple: "The present invention takes a transmission of energy, and instead of sending it through normal time and space, it pokes a small hole into another dimension, thus sending the energy through a place which allows transmission of energy to exceed the speed of light." According to the patent, this portal "allows energy from another dimension to accelerate plant growth." - from the AIP's "What's New", 3/17/00

- Stay tuned – next generation of collider experiments has a good chance to solve the mystery of large extra dimensions!
- Ultimate test of this exciting theory will become possible at the LHC