Probing Large Extra Dimensions in Collider Experiments

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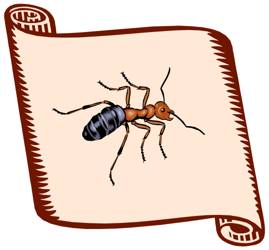
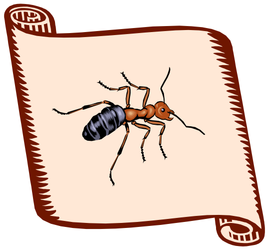


Outline

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



Standard Model: Beauty and the Beast

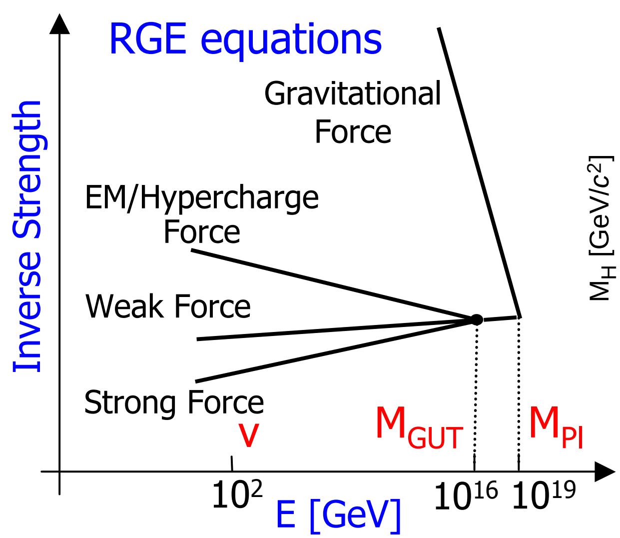
- ...beauty:

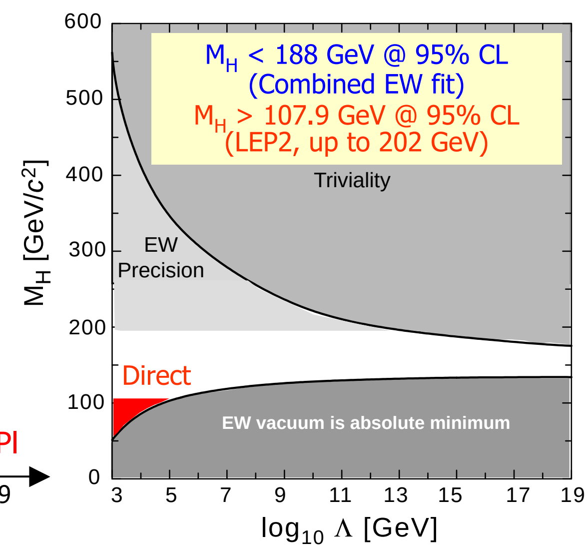
Moriond 2000

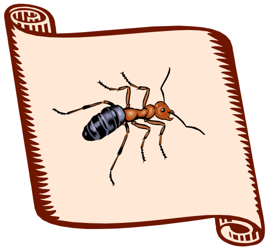
	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.07
Γ_Z [GeV]	2.4944 ± 0.0024	-.62
σ^0_{hadr} [nb]	41.544 ± 0.037	1.72
R_e	20.768 ± 0.024	1.19
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.70
A_e	0.1483 ± 0.0051	.13
A_τ	0.1425 ± 0.0044	-1.16
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.65
m_W [GeV]	80.401 ± 0.048	.15
R_b	0.21642 ± 0.00073	.85
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.34
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.29
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.47
$\sin^2\theta^{lept}_{eff}$	0.23096 ± 0.00026	-1.87
$\sin^2\theta_W$	0.2255 ± 0.0021	1.17
m_W [GeV]	80.448 ± 0.062	.88
m_t [GeV]	174.3 ± 5.1	.11
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.20

Pull: -3 -2 -1 0 1 2 3

- ...and the beast:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses
  - Higgs self-coupling is positive, which leads to a triviality problem that bounds m_H from above
  - The natural m_H value is Λ, where Λ is the scale of new physics; if SM is the ultimate theory up to GUT scale, an extremely precise ($\sim(v/m_{GUT})^2$) fine-tuning is required







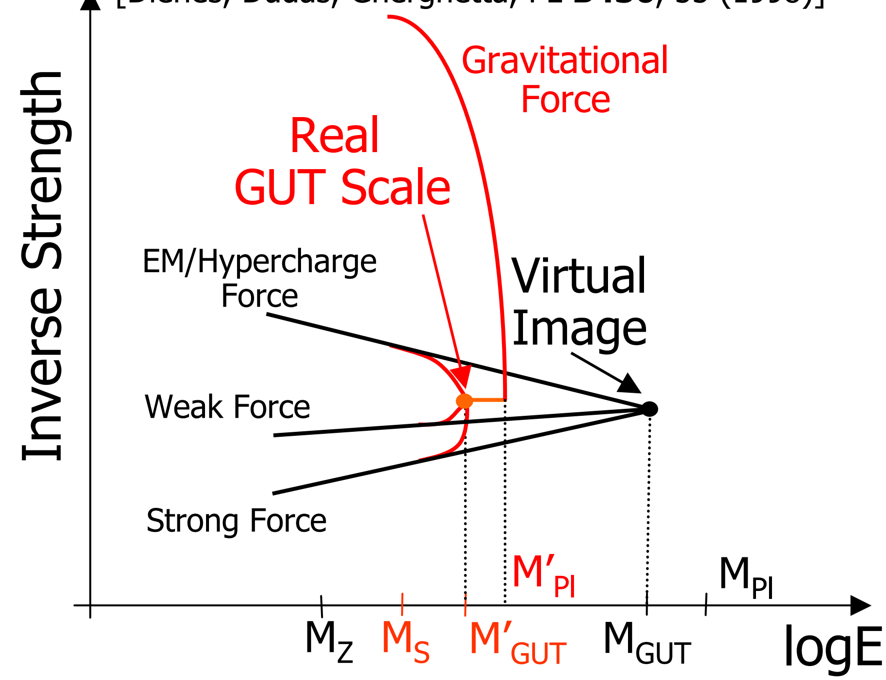
Life Beyond the Standard Model

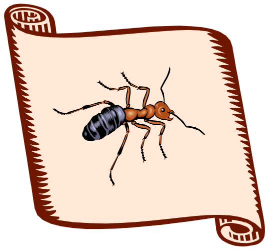
- We conclude that the SM is just an effective theory, a low-energy approximation of a more complete model that explains things postulated in the SM
- This new theory takes over at the scale Λ, comparable with the Higgs mass, i.e. $\Lambda \sim 1$ TeV
- Two main candidates for such a theory are:
  - SUSY (SUGRA, GMSB, AMSB)
  - Strong Dynamics (TC, ETS, topcolor, top see-saw, …)
- 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?!!

RGE Equations in Presence of Extra Spatial Dimensions

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



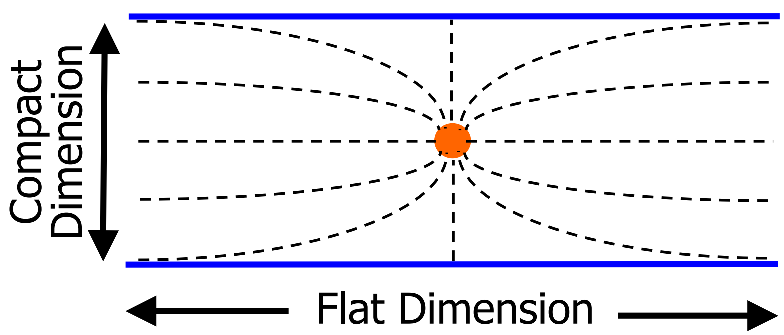


Crazy Idea? – But it Works!

- 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:



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

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

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

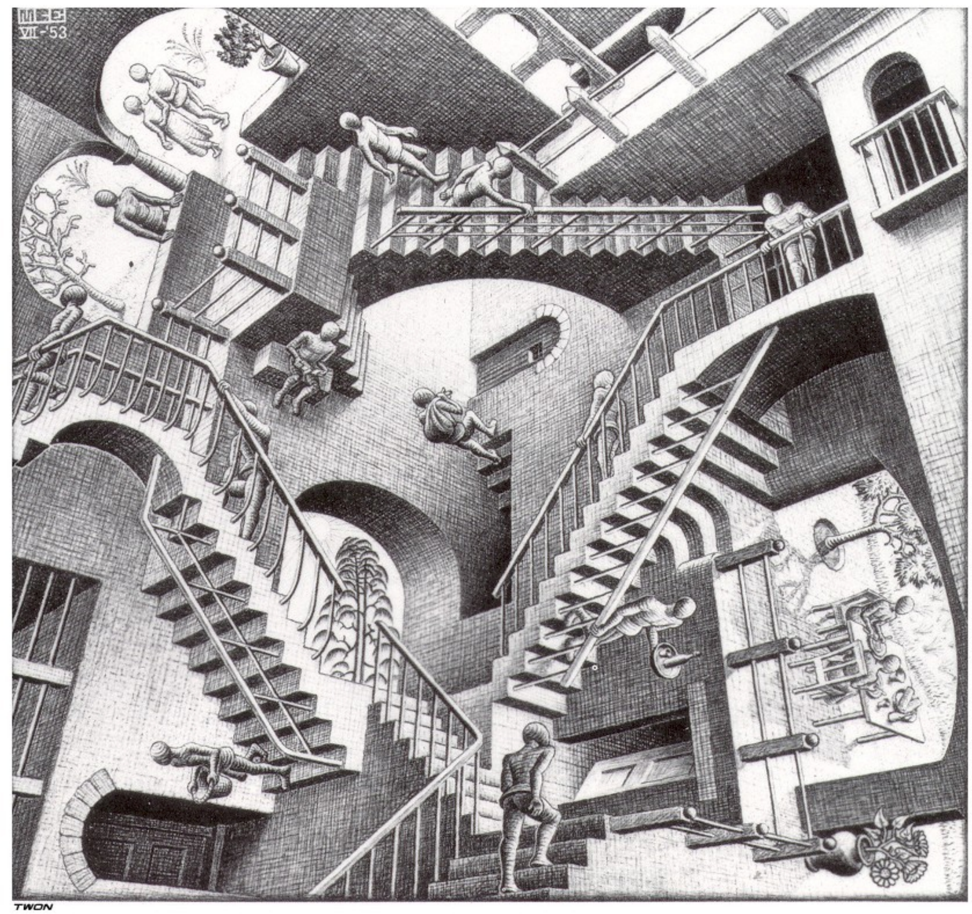
- More precisely, from Gauss's law:

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

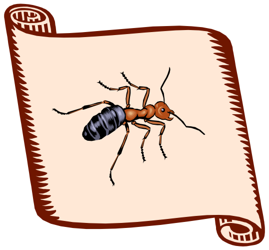
- Amazing as it is, but no one has tested Newton's law to distances less than ~ 1mm
- Therefore, large spatial extra dimensions compactified at a sub-millimeter scale are, in principle, allowed!

Examples of Compactified Spatial Dimensions

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

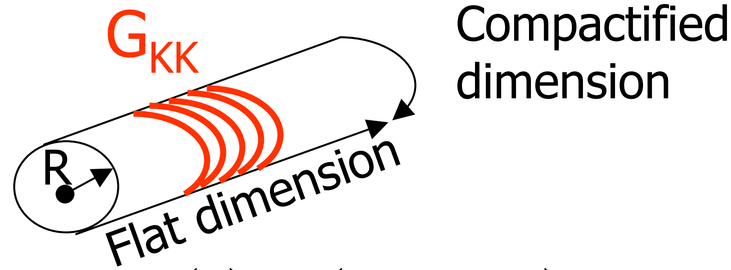


M.C.Escher, Relativity (1953)



An Importance of Being Compact

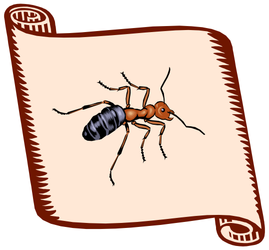
- Compactified dimensions offer a way to increase tremendously gravitational interaction due to a large number of the available “winding” modes
- This tower of excitations is known as Kaluza-Klein modes, and such gravitons propagating in the compactified extra dimensions are called Kaluza-Klein gravitons, 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



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

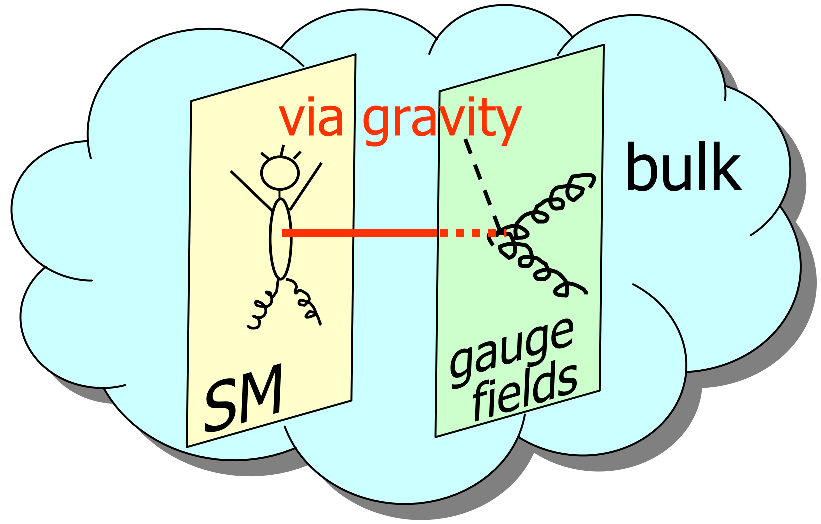
$$M(G_{KK}) = \sqrt{P_x^2} = 2\pi k/R$$

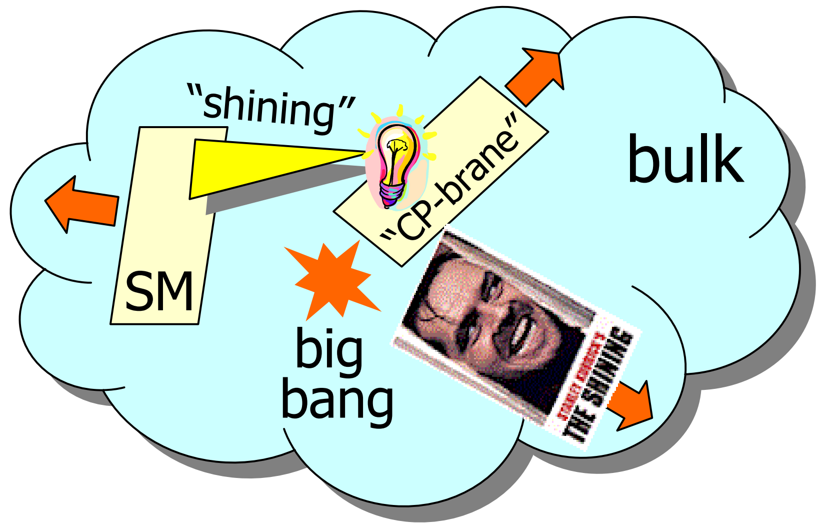
- Each Kaluza-Klein graviton mode couples with the gravitational strength
- For a large number of modes, accessible at high energies, gravitational coupling is therefore enhanced drastically
- Low energy precision measurements are not sensitive to the ADD effects

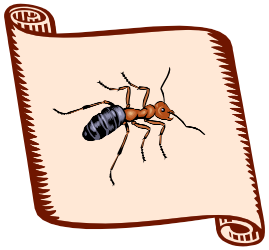


Phenomenology of Large Extra Dimensions

- New idea, inspired by the string theory, with direct connection to the observables
  - Since large extra dimensions bring the GUT and gravity scales right at the EWSB scale, they solve the hierarchy problem
  - There are multiple mechanisms that allow gauge fields in the bulk to communicate symmetry breaking to our brane
- A new mechanism, "shining" is a powerful way of introducing a small parameter into the theory, and explain many yet unsolved phenomena, such as CP violation, etc.
- New framework, possibly explaining neutrino masses, EWSB mechanism, and other puzzling phenomena
- First alternative to the "established" EWSB candidates in 25 years! – What took us so long?
- A significant theoretical interest to the subject ensures rapid development of this field
- Close to 300 theoretical papers on this subject over the past two years – truly a topic du jour





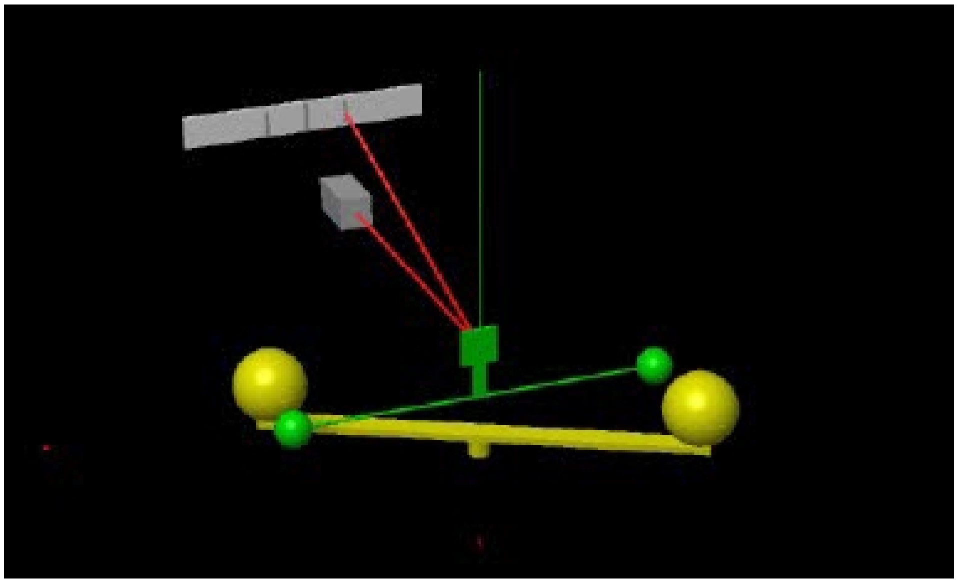


Cosmological Limits on Large Extra Dimensions

- 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

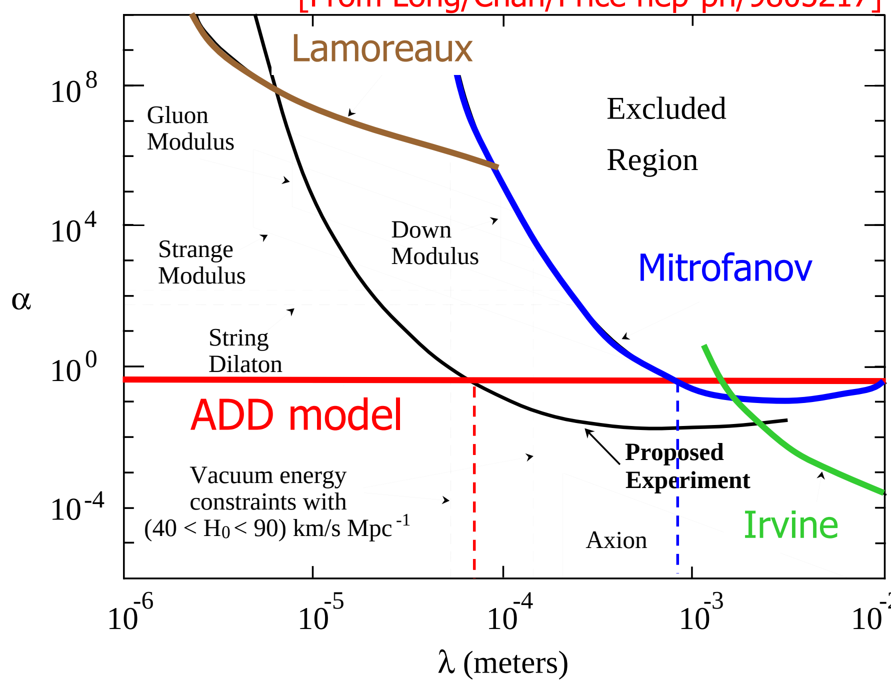
- 1798: Cavendish experiment (torsion balance)



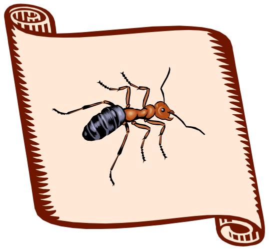
- Mid-1970-ies: a number of Cavendish-type experiments searching for the "fifth forth" via deviations from Newton's law
- Sensitivity vanishes quickly for distances less than 1 mm
- Major background: Van der Waals and Casimir forces

Status of short-range gravity experiments

[From Long/Chan/Price hep-ph/9805217]



- Best sub-millimeter results are from 1997 Lamoreaux experiment [PRL **78**, 5 (1997)] to measure the Casimir force
- Sensitivity is many orders of magnitude lower than needed to test ADD theory

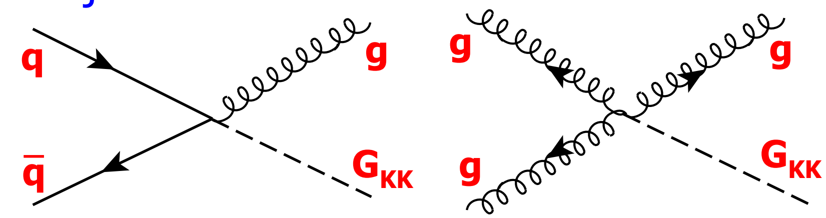


Collider Signatures for Large Extra Dimensions

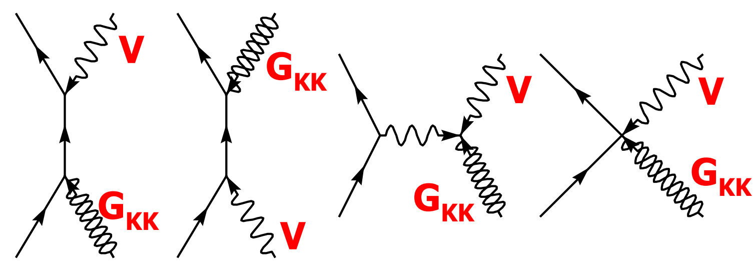
- Kaluza-Klein gravitons couple to the momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy 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

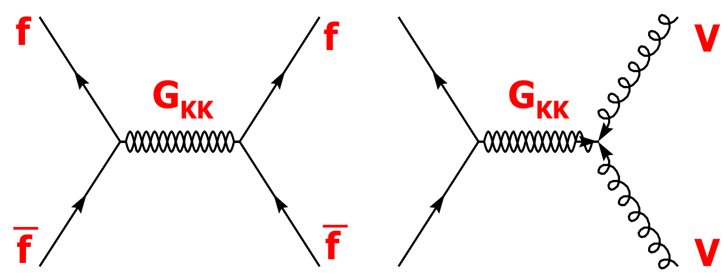


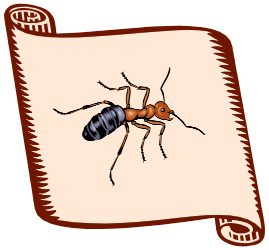
Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission

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



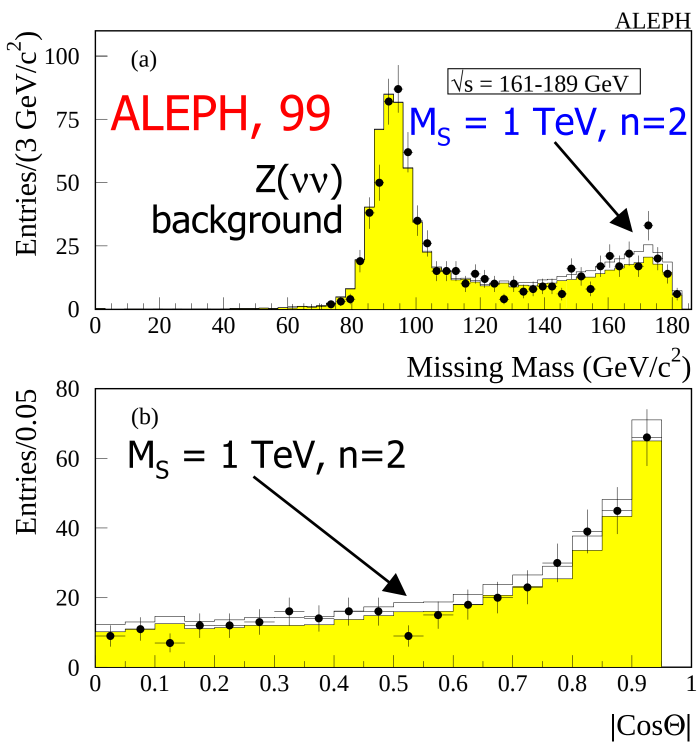


LEP2 Searches for Direct Graviton Emission - I

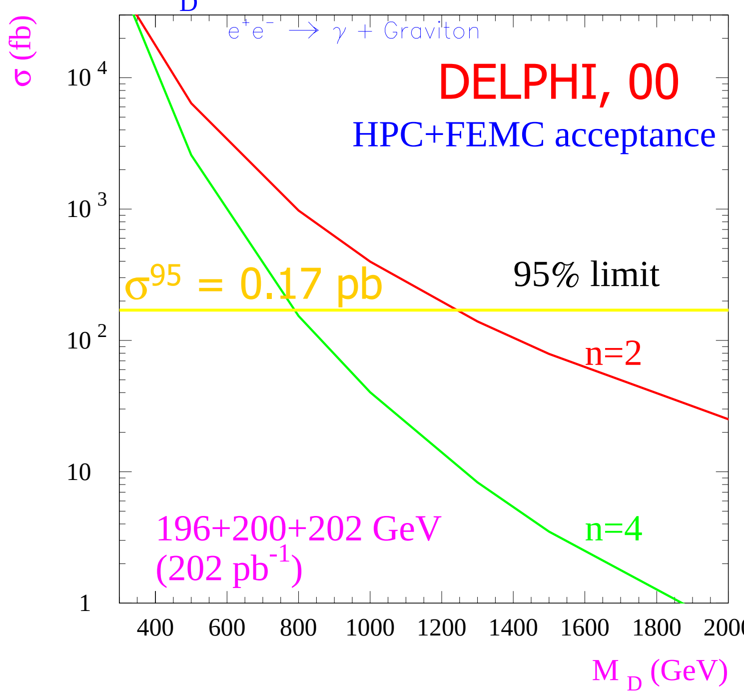
- $e^+e^- \to \gamma G_{KK}$
  - Photon + ME_T signature
  - "Recycling" of the GMSB analyses
  - ALEPH (2D-fit), DELPHI, L3 (x), OPAL (event counting)

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

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



M_D > 1250 GeV for n=2
M_D > 792 GeV for n=4



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)

Results:

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

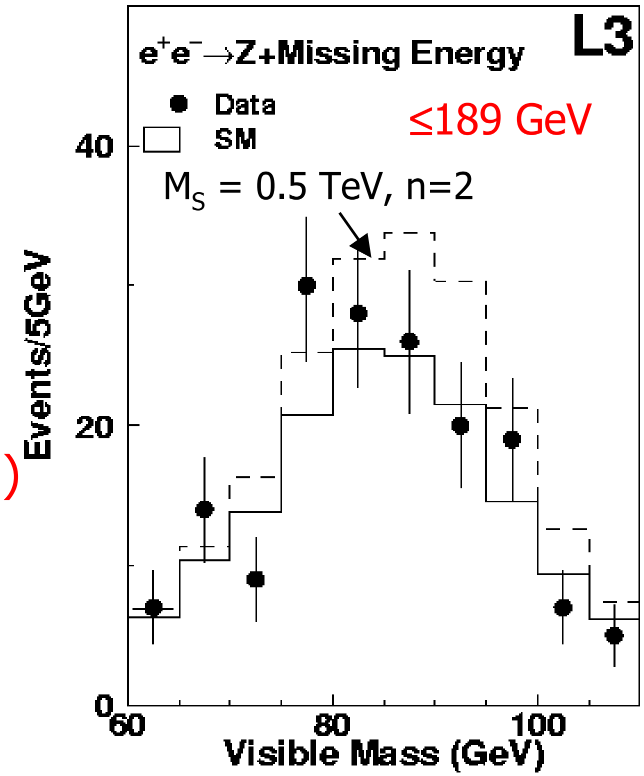
ALEPH, L3, OPAL – slightly worse

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
  - M_S > 0.35-0.12 TeV (ALEPH) for n = 2-6
  - M_S > 0.60-0.21 TeV (L3) for n = 2-6

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

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



Theory:

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

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

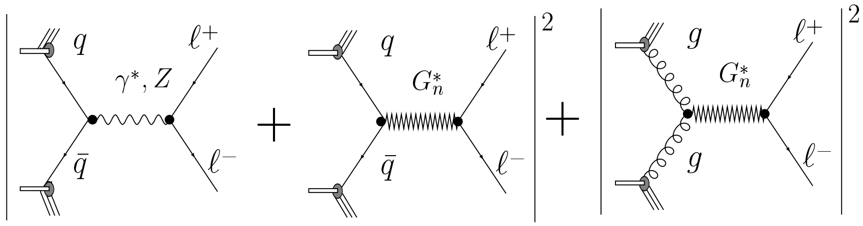
Experiment:

ALEPH-CONF-99-027

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

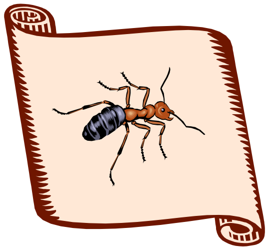
Virtual Graviton Effects

- 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 $\sim\lambda/M_S^4(\text{Hewett})$, 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 $\sim F/M_S^4(\text{HLZ})$, 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:

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

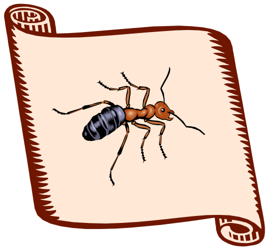
$$\frac{\lambda}{M_S^4(\mathbf{Hewett})} = \frac{\pi}{2}\frac{F}{M_S^4(\mathbf{HLZ})}$$

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

- Rule of thumb:

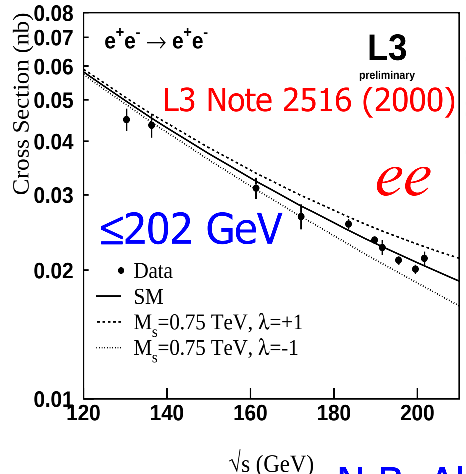
$$M_S(\mathbf{Hewett})\Big|_{\lambda=1} \approx M_S(\mathbf{HLZ})\Big|_{n=5}$$

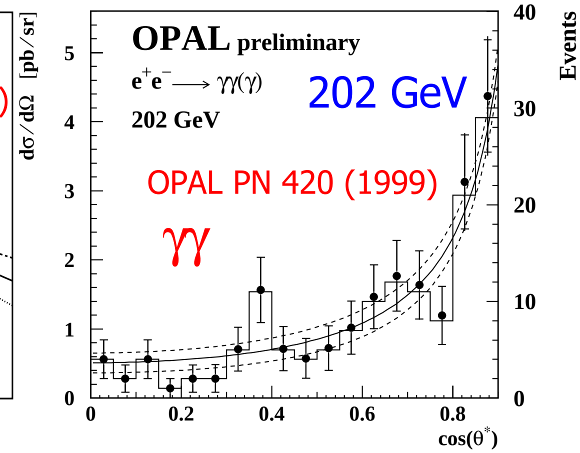
$$\Lambda_T(\mathbf{GRW}) = M_S(\mathbf{HLZ})\Big|_{n=4}$$



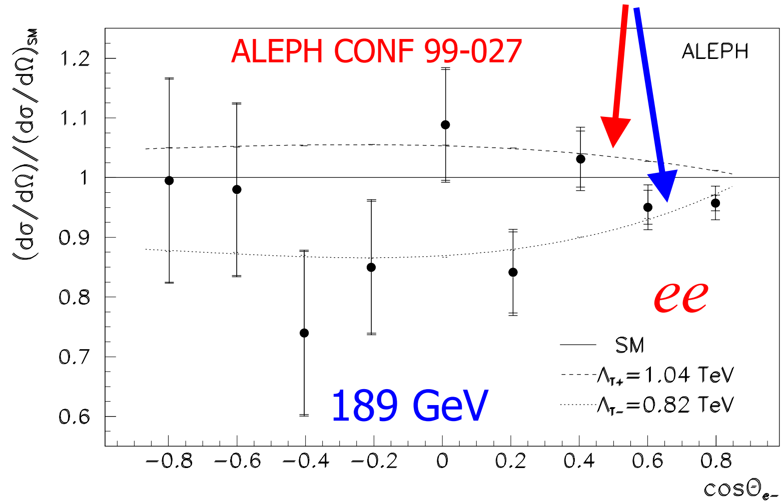
LEP2 Searches for Virtual Graviton Effects

- 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) ~ 0.8-1.0 TeV
- Bibliography:
  - ALEPH: CONF 99-027, 2000-005
  - DELPHI: CONF 355, 363 (2000)
  - L3: PL **B464**, 135; **B470**, 281 (1999)
  - 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 $ZZ\gamma$ couplings analyses
  - L3 used angular distributions (WW) and mass variables (ZZ) to set limits

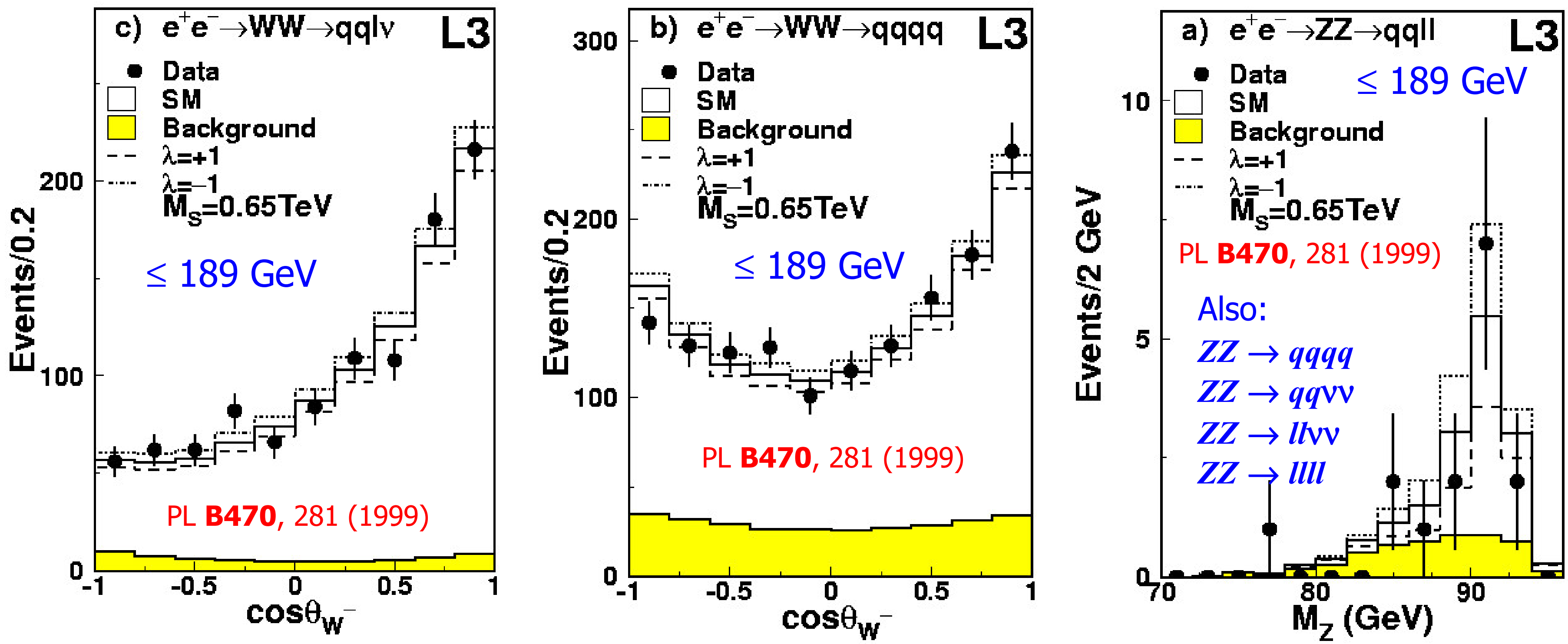
Theory:

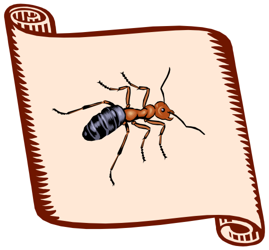
[Agashe, Deshpande, Phys. Lett. **B456**, 60 (1999)]

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

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)





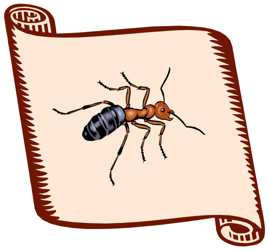
LEP2 Lower 95% CL M_S(Hewett) Limits (TeV)

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)	0.80 1.03	0.63 0.68	0.57 0.59	0.66/0.61 0.55/0.55 (bb)	0.82 1.04	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	0.76 0.77	0.87/1.07 (<189) ??? 0.82/0.89 (VV)
OPAL		0.63 0.60	0.50 0.63		0.61 0.68	0.63 0.64			0.61/0.68 (ff) (<189) **???**



Virtual Graviton Exchange at the Tevatron

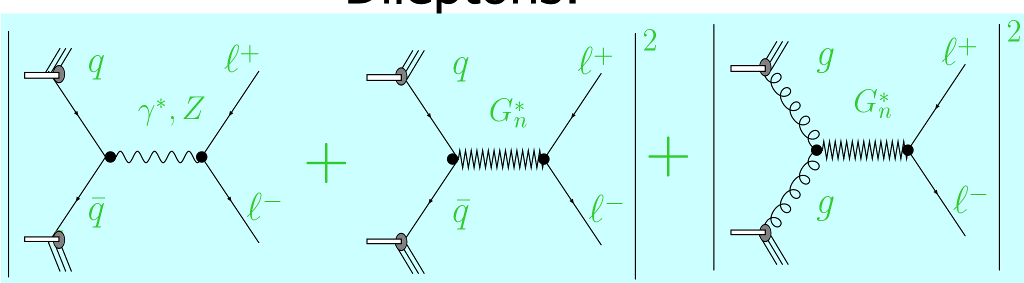
- Virtual graviton Drell-Yan and diphoton production
  - Mass spectrum has been looked at [Gupta, Mondal, Raychaudhuri, hep-ph/9904234; Cheung, Phys. Rev. **D61**, 015005 (2000), Phys. Lett. **B460**, 383 (1999),…]
  - Key improvement [Cheung, GL, hep-ph/9909218, to appear in PRD]: simultaneous analysis of the mass and angular distributions, as a spin 2 graviton would result in different angular distributions compared to the SM backgrounds; no other cuts!
  - There are three terms: SM, interference, and direct graviton contribution
  - Use Han/Lykken/Zhang formalism:

NLO corrections accounted for via a constant K-factor

$$\eta = \frac{F}{M_S^4(\mathbf{HLZ})}, \quad z \equiv \cos\theta^*$$

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

Dileptons:

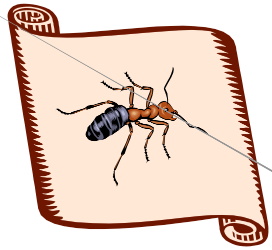


[For cross section formula see hep-ph/9909218]

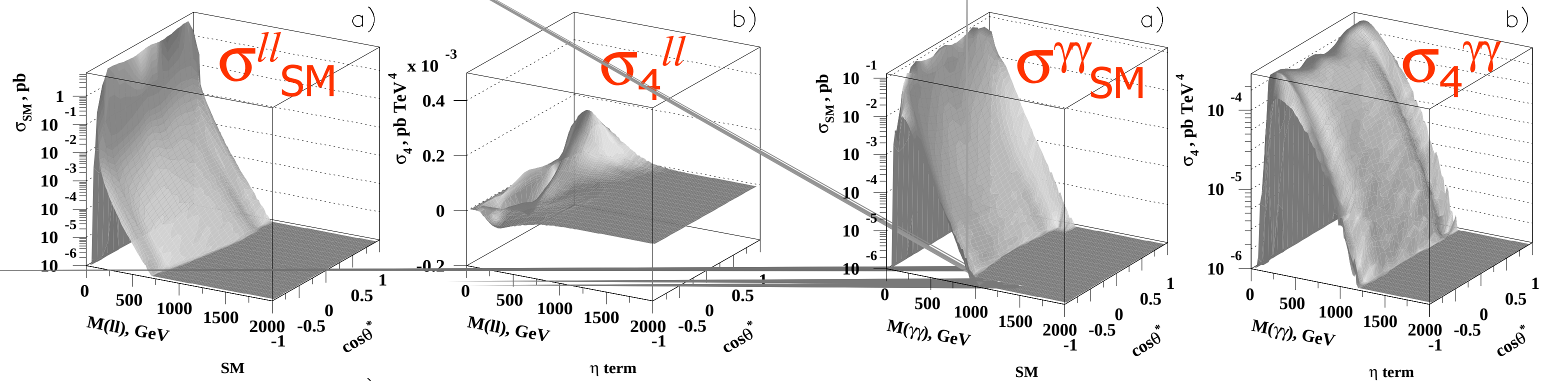
Diphotons:

$$\frac{d^2\sigma}{dz\,dM_{\gamma\gamma}} = \sum_q \iint dx_1 dx_2 f_q(x_1) f_q(x_2) \frac{K(1+z^2)}{96\pi M_{\gamma\gamma}^2} \times \left[\frac{2e^4Q_q^4}{1-z^2} + 2\pi e^2 Q_q^2 \eta M_{\gamma\gamma}^4 + \frac{\pi^2}{2}(1-z^2)\eta^2 M_{\gamma\gamma}^8\right] + \iint dx_1 dx_2 f_g(x_1) f_q(x_2) \frac{K(1+6z^2+z^4)}{512 M_{\gamma\gamma}^2}\eta^2 M_{\gamma\gamma}^8$$

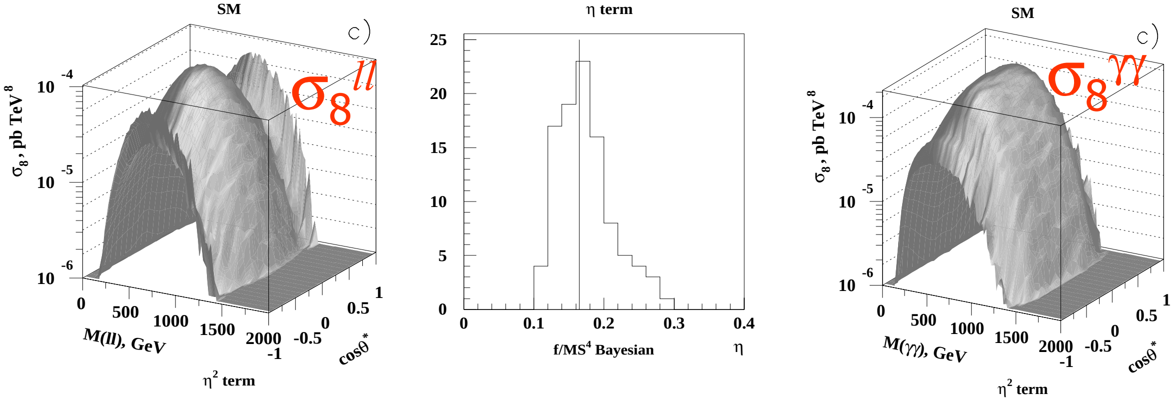
SM; interference term; G_{KK} term; G_{KK} term



Two-Dimensional Analysis



[η] = TeV^{-4}

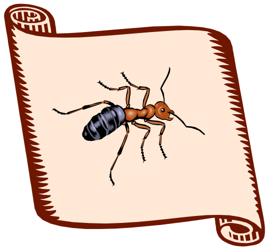


$$\sigma_\eta^{ll} = \sigma_{SM}^{ll} + \sigma_4^{ll}\eta + \sigma_8^{ll}\eta^2$$

$$\sigma_\eta^{\gamma\gamma} = \sigma_{SM}^{\gamma\gamma} + \sigma_4^{\gamma\gamma}\eta + \sigma_8^{\gamma\gamma}\eta^2$$

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

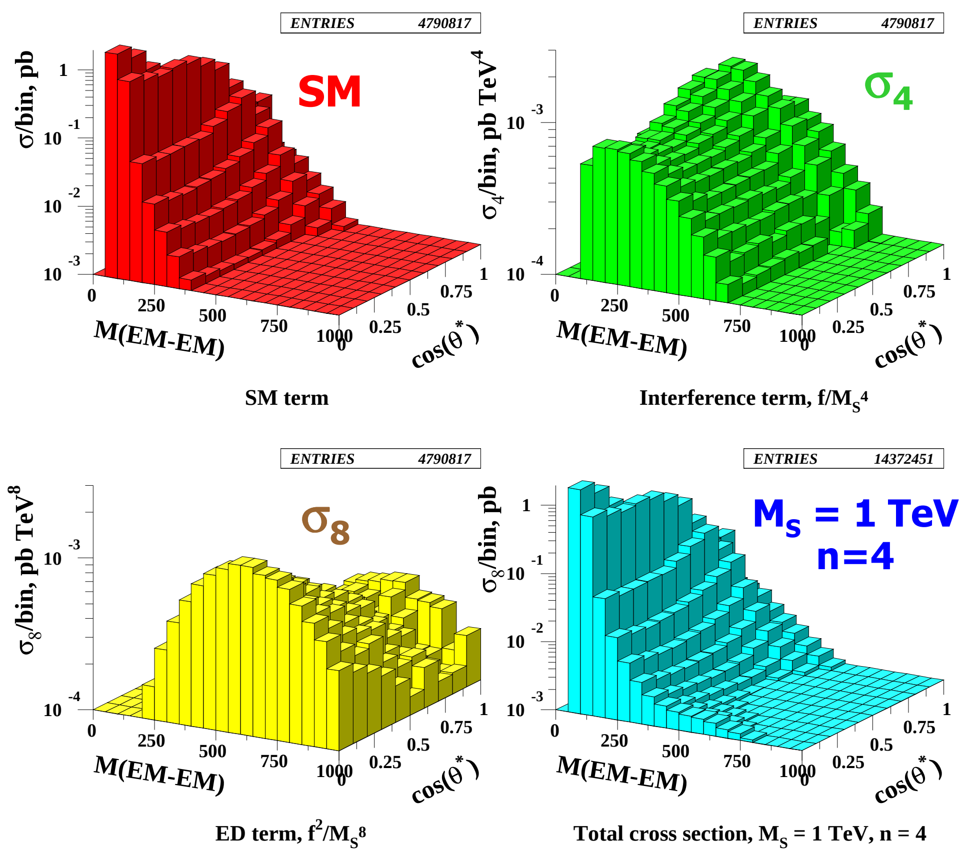
- Parameterize cross section as a bilinear form in scale η (works for any n>2)
- Note the asymmetry of the interference term, σ_4, for *ll* production
- Use Bayesian fit to the data (real one or MC one) to get the best estimate of η
- Repeat MC experiment many times and use the median as a measure of sensitivity
- Sensitivity is 20-30% (in terms of ∫Ldt) higher than that in 1-dimensional analysis
- Diphoton channel is considerably more sensitive than the dilepton one



DØ Search for Virtual Graviton Effects

- Basic idea: combine dielectron and diphoton channels to increase efficiency, and hence, sensitivity:
  - 2 EM clusters w/ E_T > 45 GeV, $|\eta|<1.1$ or $1.5<|\eta|<2.5$
  - $\varepsilon \approx 80\%$
  - $\int Ldt = 127\ pb^{-1}$ – entire Run I statistics
- Adding theoretical cross sections is OK, since at LO the relative contribution of each channel is known precisely
- NLO corrections are modeled via a constant K-factor of 1.3 ± 0.1

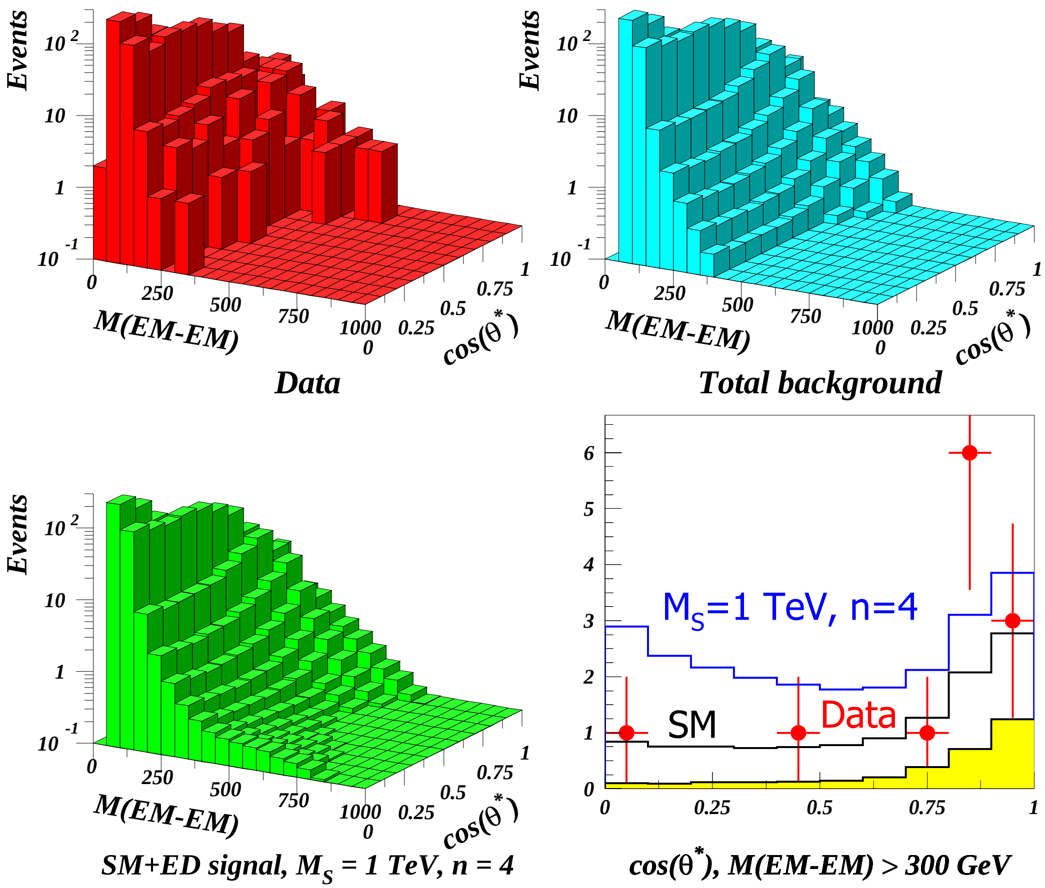
MC Simulation of the ED signatures



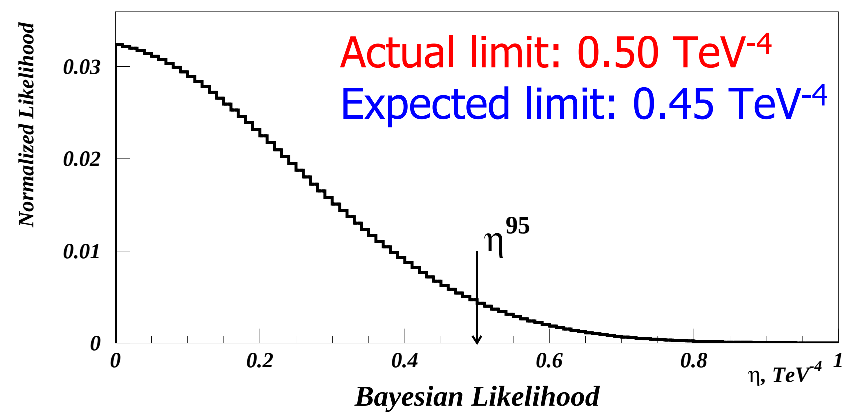
Expected Signal

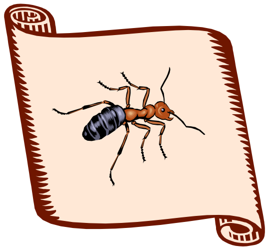
Comparison of the data and the SM predictions

DØ Preliminary, Run I, 127 pb^{-1}

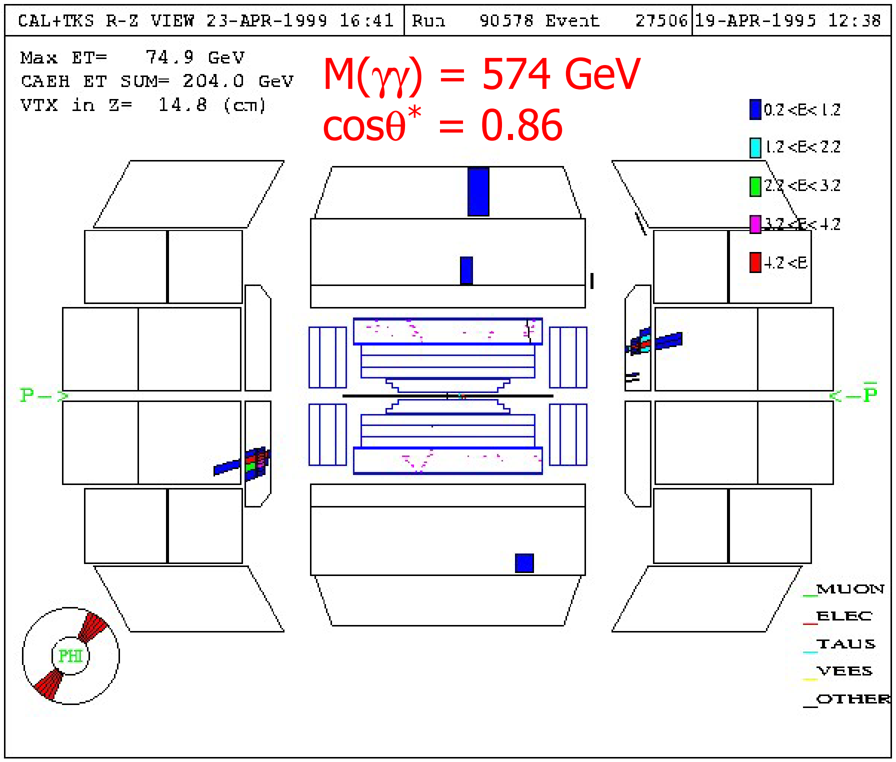


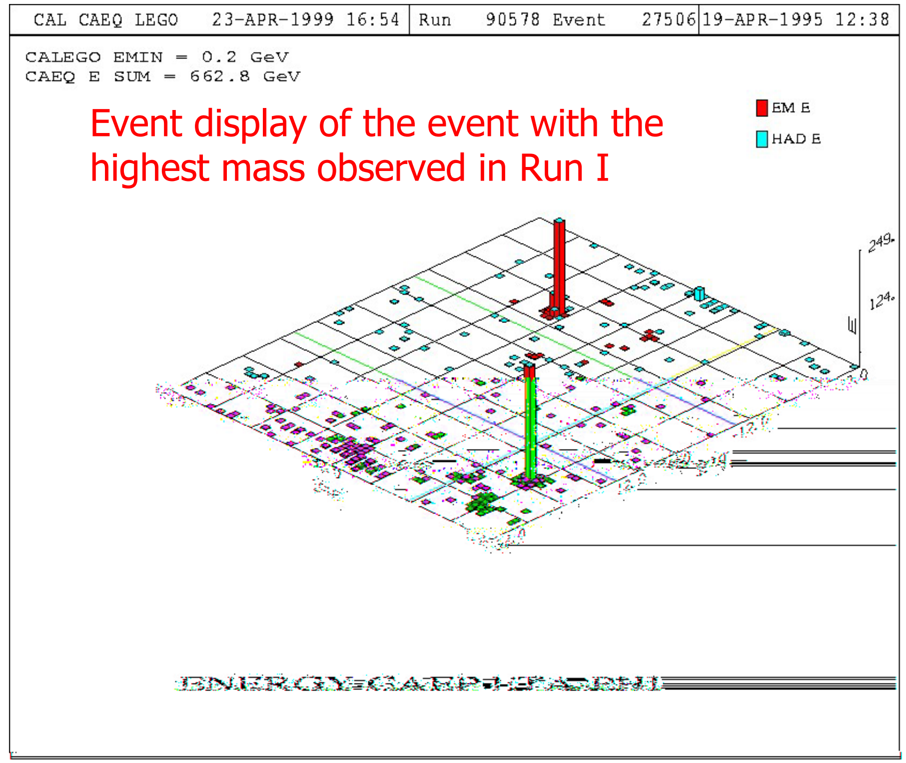
- Data do not support extra dimensions hypothesis
- No excess of events is seen at high masses and low scattering angles, where the signal is expected to exhibit itself
- In the absence of evidence for extra dimensions we proceed with setting limits on their size





High-Mass Candidate Events

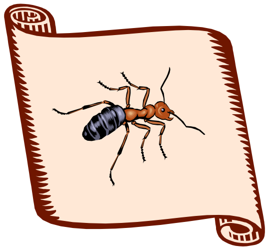


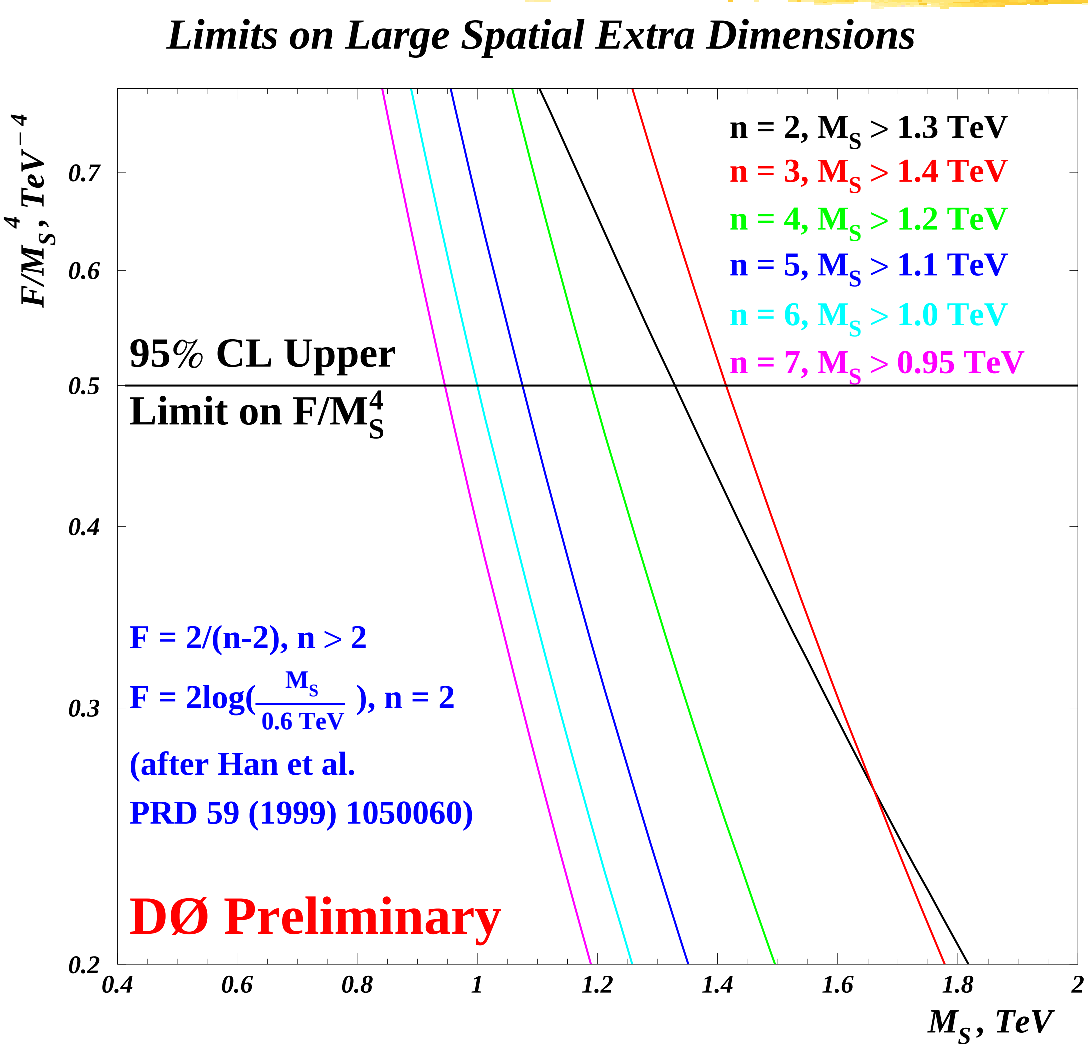


- Parameters of the two high-mass candidate events:

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	γγ	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



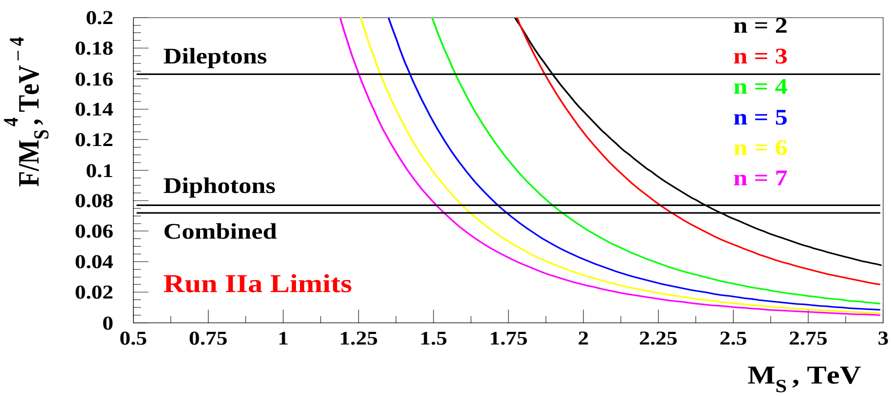


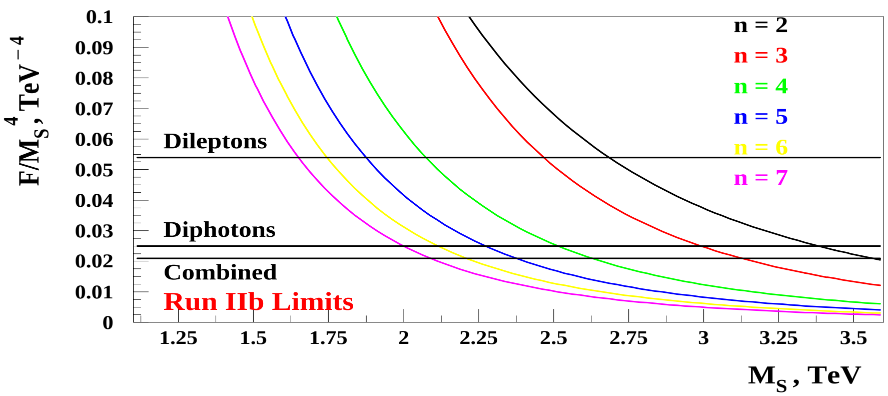
- For n > 2 M_S limits can be obtained directly from η limits
- For n = 2, use average $\hat{s}$ for gravity contribution ($\langle\hat{s}\rangle = 0.36$ TeV^2, see hep-ph/9909218)
- As n = 2 case has been ruled out by cosmological constraints, and is within the reach of the current gravity experiments
- Finally, translate limits in Hewett and GRW frameworks for easy comparison with other experiments:
  - M_S(Hewett) > 1.1 TeV
  - Λ_T(GRW) > 1.2 TeV
- This limits are comparable with the final limits expected from LEP2
- They are complementary to those from LEP2, as they probe much higher range of $\hat{s}$
- Looking forward for limits from CDF DY analysis (~0.9-1.0 TeV)

Run II and LHC Reach in Virtual Graviton Exchange

- Virtual exchange: expected sensitivity @95% CL

	Run IIA, 2 fb^{-1}	Run IIB, 20 fb^{-1}	LHC, 100 fb^{-1}
$l^+l^- + \mu^+\mu^-$	1.3-1.9 TeV	1.7-2.7 TeV	6.5-10 TeV
$\gamma\gamma$	1.5-2.4 TeV	2.0-3.4 TeV	7.5-12 TeV
$l^+l^- + \mu^+\mu^- + \gamma\gamma$	1.5-2.5 TeV	2.1-3.5 TeV	7.9-13 TeV





DØ Run I (preliminary): 1.0-1.3 TeV

- Dependence on the cut-off scale $\Lambda = cM_S$:

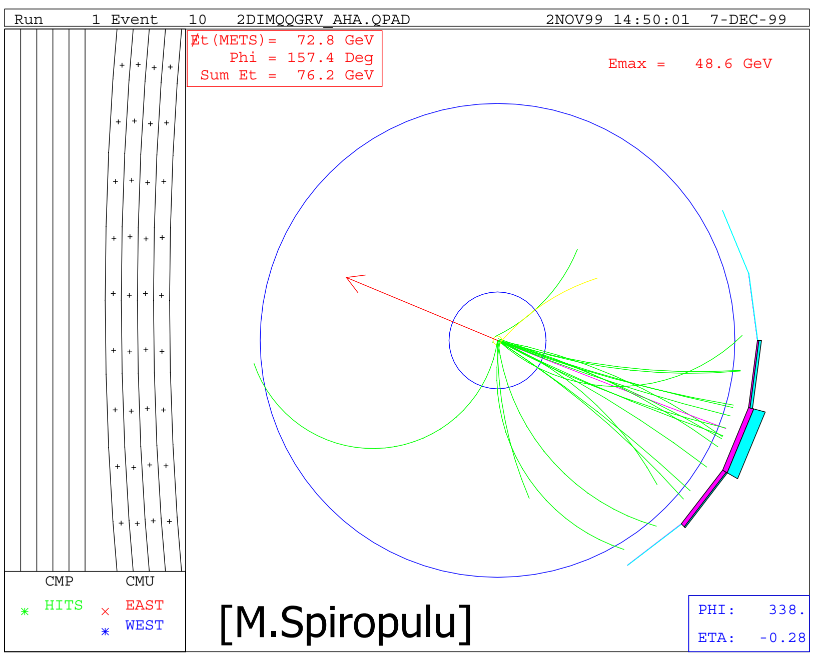
$$\eta = \frac{c^{n-2} f}{M_S^4}, \quad c = O(1)$$

$$f = \begin{cases} M_S^2/s, & n = 2 \\ 2/n-2, & n > 2 \end{cases}$$

- c=O(1) is natural in string theory (from exponential suppression of the G_{KK} couplings [Antoniadis et al, hep-ph/9904232] or from the brane tension [Bando et al, hep-ph/9906549])

Tevatron: Real Graviton Emission

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



[M.Spiropulu]

Theory:

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

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

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

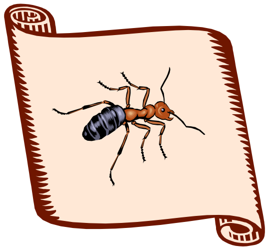
$$F_1(x, y) = \frac{1}{x(y-1-x)}\left[-4x(1+x)(1+2x+2x^2)+ y(1+6x+18x^2+16x^3)-6y^2x(1+2x)+y^3(1+4x)\right]$$

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

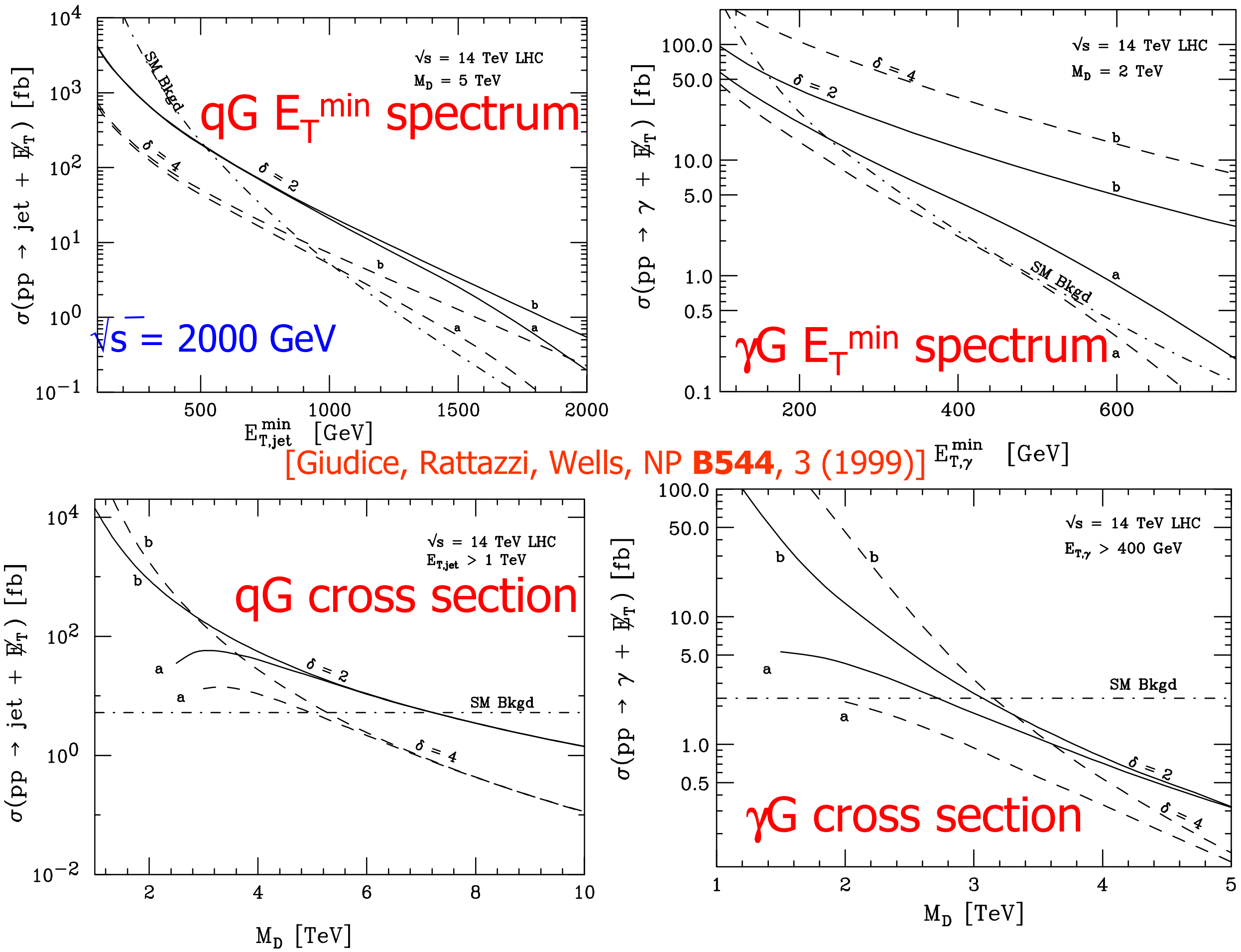
Note that non-perturbative effects could become important at high n

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



LHC Reach in Direct Graviton Production

- $qg \to qG$ and $q\bar{q} \to \gamma G$ reach at the LHC



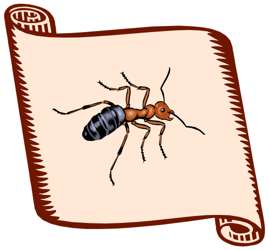
[Giudice, Rattazzi, Wells, NP **B544**, 3 (1999)]

Caveat: instrumental backgrounds are ignored

LHC reach in j+ME$_T$ channel for $\int Ldt = 100\ fb^{-1}$

n	M_S reach	Perturbativity
2	8.5 TeV	3.8 TeV
3	6.8 TeV	4.3 TeV
4	5.8 TeV	4.8 TeV
5	5.0 TeV	5.4 TeV

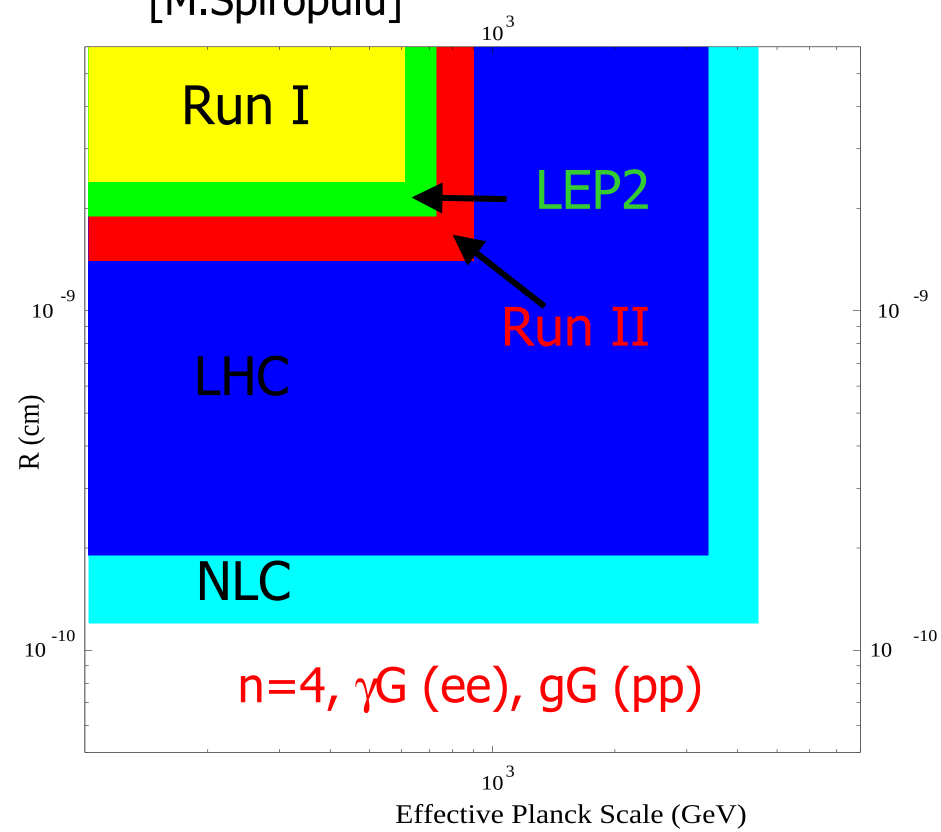
Note that non-perturbative effects could become important at high n



NLC Reach for Large Extra Dimensions

- If LED do exist, LHC is likely to discover them
- For real graviton emission NLC has an edge for low number of extra dimensions
- Phenomenology of LED could be very rich, and some effects (e.g., s-channel Kaluza-Klein resonances) could be studied only at NLC
- Polarized beams, a unique NLC capability, could be very helpful in studying the virtual graviton effects, and to suppress SM backgrounds to direct graviton emission

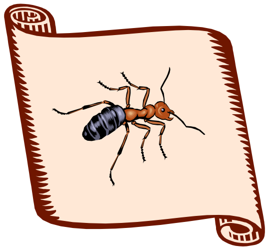
[M.Spiropulu]



Note that LHC reach exceeds that for NLC for n = 6, 7

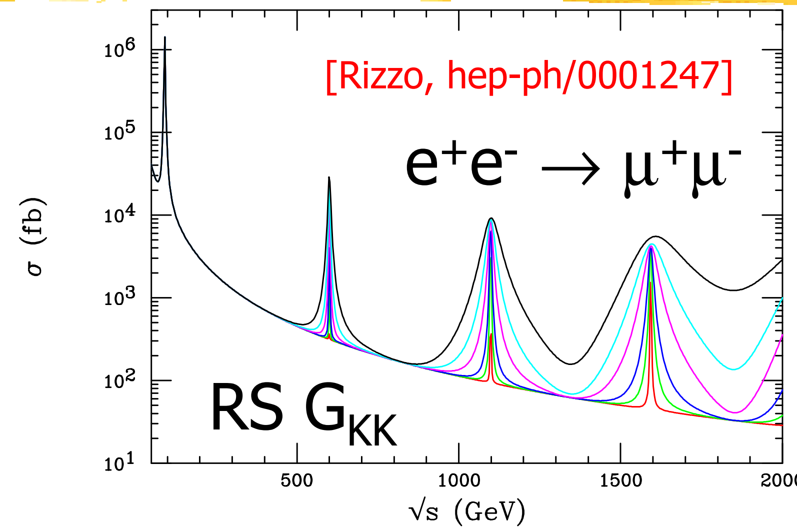
Black Hole Production

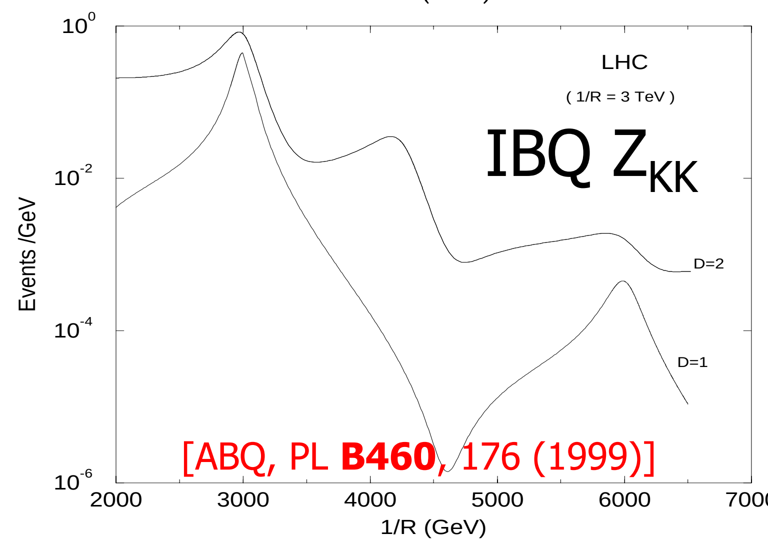
- Once the c.m. energy exceeds the compactification scale, M_S, a critical energy density is achieved and the black hole is formed
- Not to worry about the Earth being sucked into such a black hole; they should be constantly formed by cosmic rays
- The temperature of such a black hole is: $T = M_{Pl}^2/M \rightarrow M_S^2/M \times O(M/M_S) \sim M_S$
- 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 well-known 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)

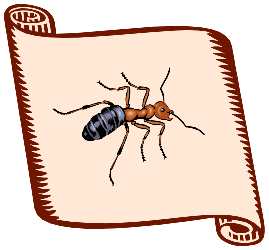


Gauge Boson Excitations

- New developments in 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 virtual resonance exchange at lower energies

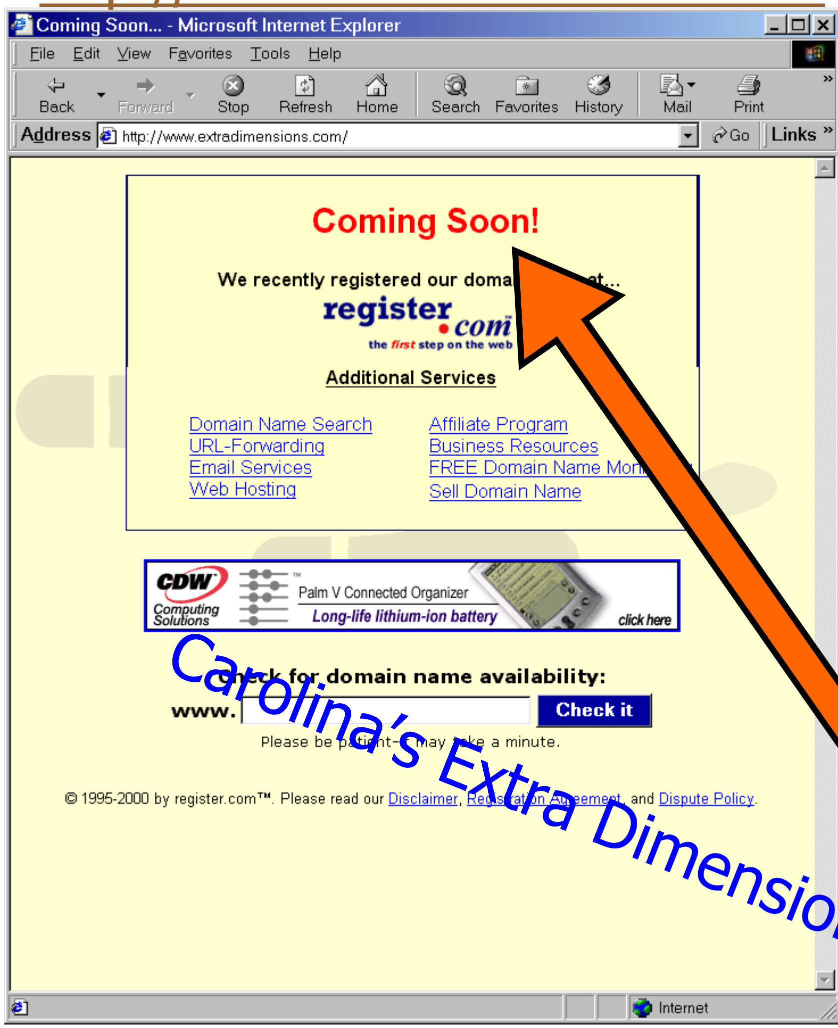






Conclusion: WWW Search for Extra Dimensions

http://www.extradimensions.com



Carolina's Extra Dimensions

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 APS "What's New", 3/17/00

Extra Dimensions TV Show

- Stay tuned – next generation of collider experiments has a good chance to solve the mystery of large extra dimensions!