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

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CERN Experimental Seminar

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Outline

- Theory and Phenomenology 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
- Sensitivity of Future Collider Experiments
- New Ripples in Extra Dimensions
- Conclusions

Life Within the Standard Model

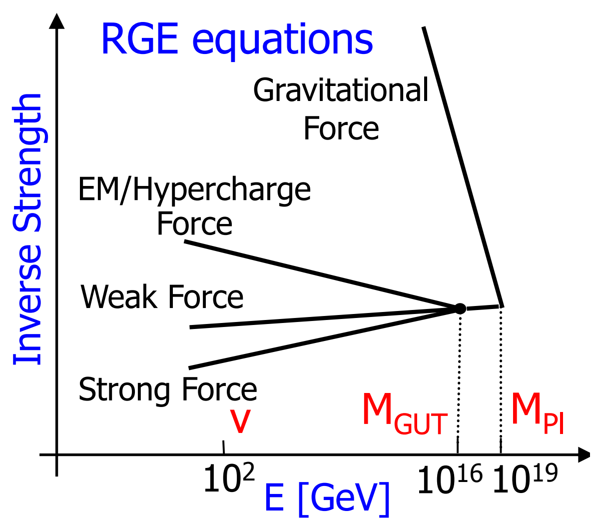
- ...is boringly precise:

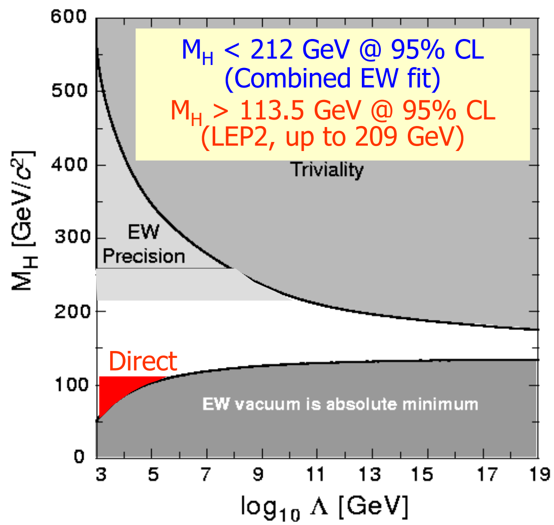
Winter 2001

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.04
Γ_Z [GeV]	2.4952 ± 0.0023	-.46
σ^0_{hadr} [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.09
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.79
A_e	0.1498 ± 0.0048	.41
A_τ	0.1439 ± 0.0041	-.96
$\sin^2\theta^{lept}_{eff}$	0.2322 ± 0.0010	.78
m_W [GeV]	80.446 ± 0.040	1.32
R_b	0.21664 ± 0.00068	1.32
R_c	0.1729 ± 0.0032	.20
$A^{0,b}_{fb}$	0.0982 ± 0.0017	-3.20
$A^{0,c}_{fb}$	0.0689 ± 0.0035	-1.48
A_b	0.921 ± 0.020	-.68
A_c	0.667 ± 0.026	-.05
A_l	0.1513 ± 0.0021	1.68
$\sin^2\theta_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.95
m_t [GeV]	174.3 ± 5.1	-.27
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.36

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

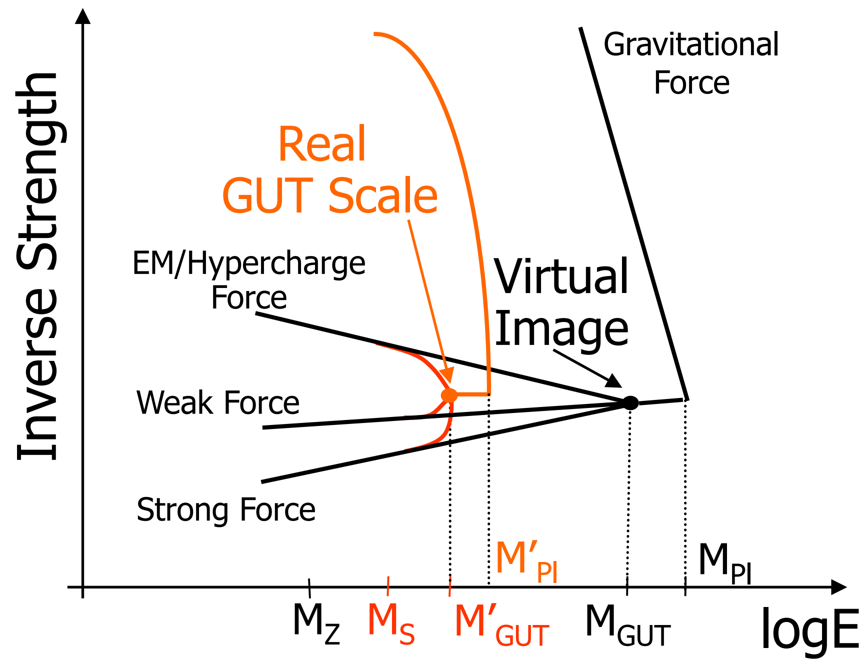
- ...but not at all boring:
  - Standard Model accommodates, but does not explain:
    - EWSB
    - CP-violation
    - Fermion masses
  - Higgs self-coupling is positive, which leads to a triviality problem that bounds m_H from above
  - The natural m_H value is Λ, where Λ is the scale of new physics; 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 have to 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 a scale Λ comparable to the mass of the Higgs boson, i.e. $\Lambda \sim 1$ TeV
- Two main candidates for such a theory are:
  - SUSY (SUGRA, GMSB, AMSB)
  - Strong Dynamics (TC, ETC, 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 fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of extra spatial dimensions where only gravity propagates
- SM particles are confined to a 3D “brane”
- Low energy GUT unification is also possible with extra dimensions: Dienes, Dudas, Ghergetta (1998)

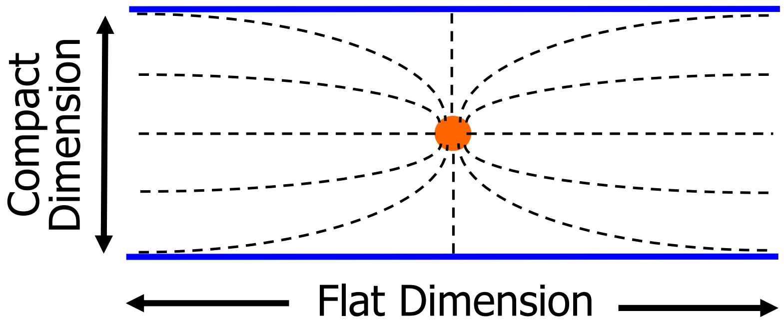


A Crazy Idea? – But it Could Work!

- 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 (as of 1998)
- Therefore, large spatial extra dimensions compactified at a sub-millimeter scale are, in principle, allowed!

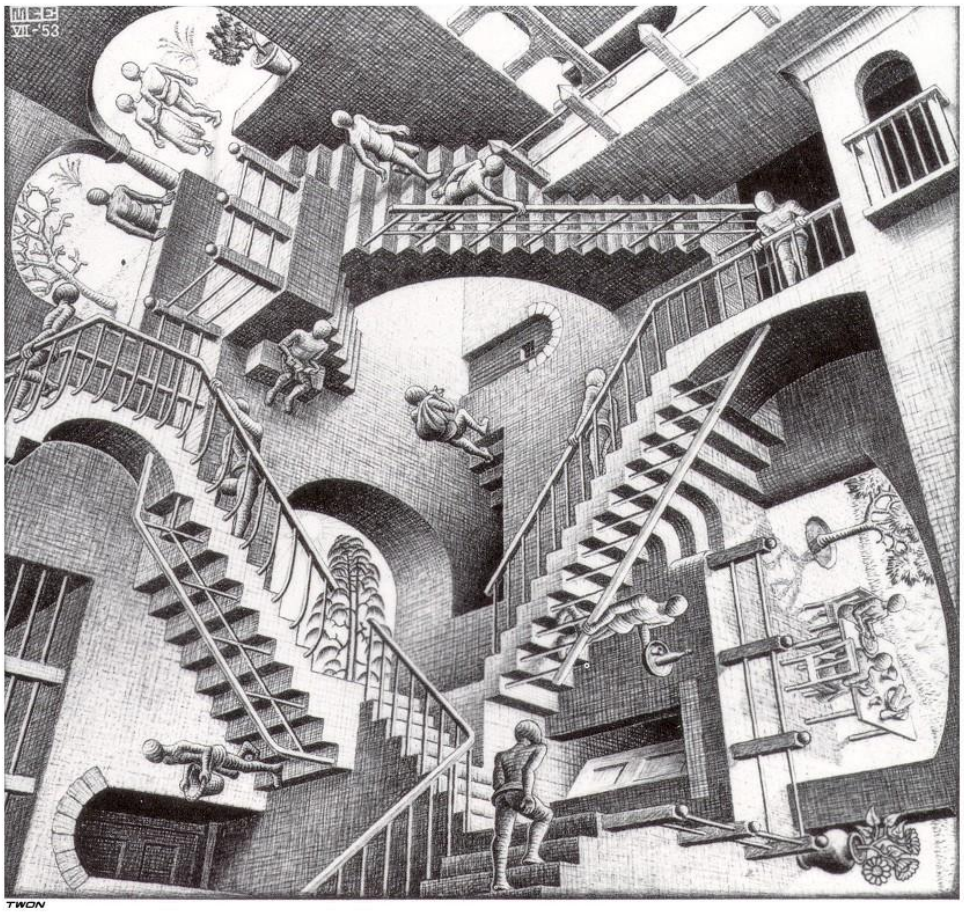
Shakespeare on Compact Dimensions

"…Why bastard? wherefore base?
When my dimensions are as well compact,
My mind as generous, and my shape as true,
As honest madam's issue?"

(Edmund, bastard son to Gloucester)
Shakespeare, King Lear, Act 1, Scene 2

Examples of Compactified Spatial Dimensions

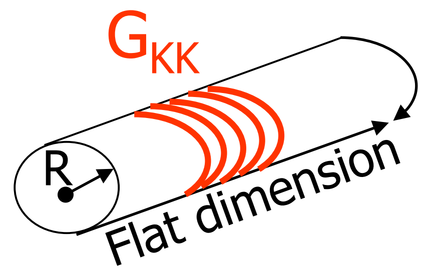
M.C.Escher, Mobius Strip II (1963)



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



Compactified dimension

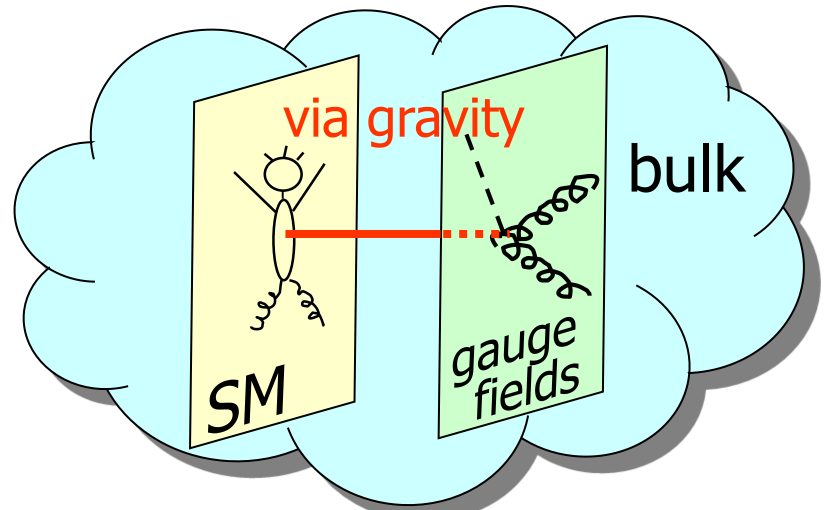
$$\phi(x) = \phi(x + 2\pi kR),\ k = 0, 1, 2\ldots$$

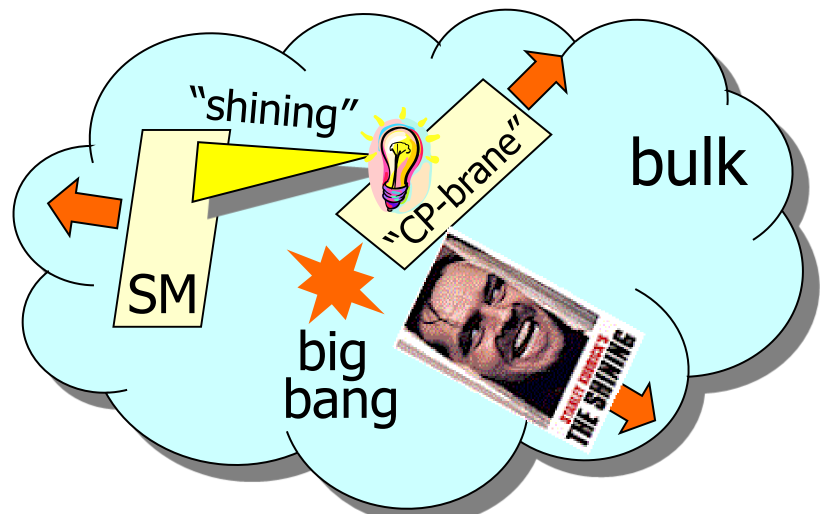
$$M(G_{KK}) = \sqrt{P_x^2} = 2\pi k/R$$

- 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, flavor physics, 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
- Over 700 theoretical papers on this subject over the past 2.5 years – truly a topic du jour





Using the Extra Dimension Paradigm

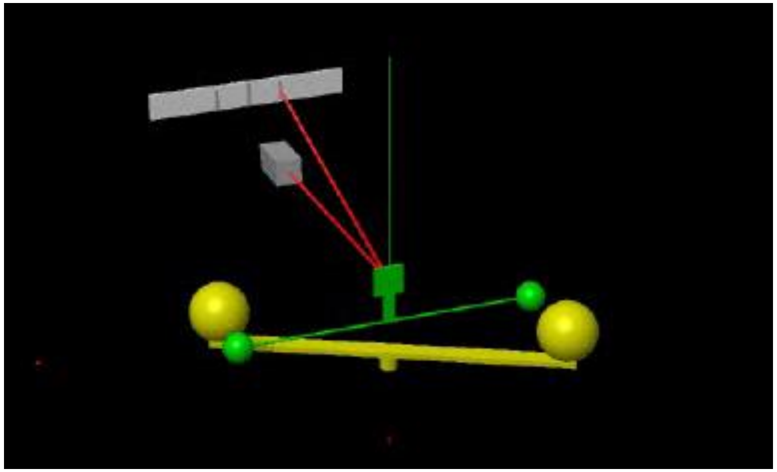
- EWSB from extra dimensions:
  - Hall, Kolda, PL **B459**, 213 (1999) (lifted Higgs mass constraints)
  - Antoniadis, Benakli, Quiros, NP **B583**, 35 (2000) (EWSB from strings in ED)
  - Cheng, Dobrescu, Hill, NP **B589**, 249 (2000) (strong dynamics from ED)
  - Mirabelli, Schmaltz, PR **D61**, 113011 (2000) (Yukawa couplings from split left- and right-handed fermions in ED)
  - Barbieri, Hall, Namura, hep-ph/0011311 (radiative EWSB via t-quark in the bulk)
- Flavor/CP physics from ED:
  - Arkani-Hamed, Hall, Smith, Weiner, PR **D61**, 116003 (2000) (flavor/CP breaking fields on distant branes in ED)
  - Huang, Li, Wei, Yan, hep-ph/0101002 (CP-violating phases from moduli fields in ED)
- Neutrino masses and oscillations from ED:
  - Arkani-Hamed, Dimopoulos, Dvali, March-Russell, hep-ph/9811448 (light Dirac neutrinos from right-handed neutrinos in the bulk or light Majorana neutrinos from lepton number breaking on distant branes)
  - Dienes, Dudas, Gherghetta, NP **B557**, 25 (1999) (light neutrinos from right-handed neutrinos in ED or ED see-saw mechanism)
  - Lukas, Ramon, Romanino, Ross, PL **B495**, 136 (2000)**;** hep-ph/0011295 (sterile neutrinos from bulk; oscillations into bulk KK states)
- Many other topics from Higgs to dark matter

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 and Perelstein, PRL **83**, 268 (1999)]:
    - M_S > 30 TeV (n=2)
    - M_S > 4 TeV (n=3)
  - NLO calculations for G_{KK} and dilaton emission [Hanhart, Phillips, Reddy, and Savage, nucl-th/0007016]:
    - M_S > 25 TeV (n=2)
    - M_S > 1.7 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 and 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

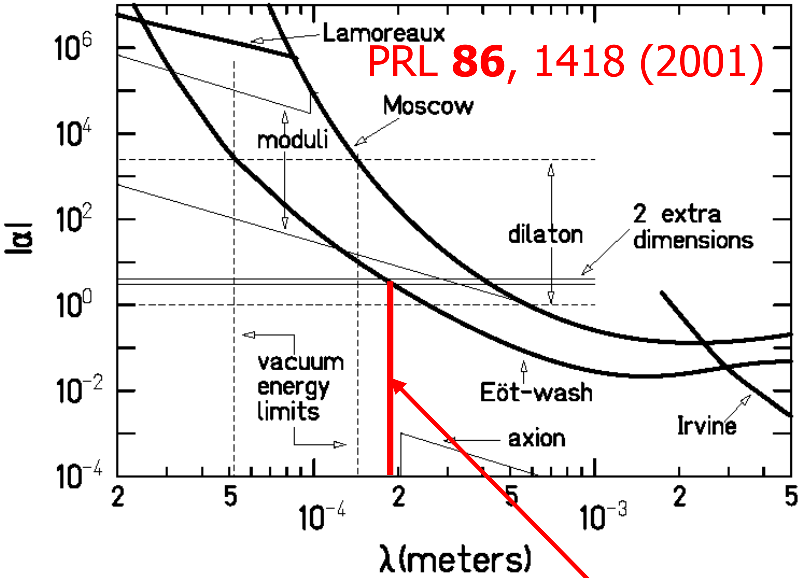
Current Limits from Gravity Experiments

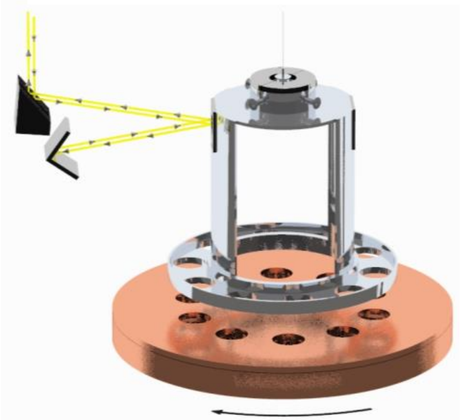
- 1798: Cavendish experiment (torsion balance)



- 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
- High-energy colliders are the only means to probe gravity at shorter (sub-micron) distances

E.Adelberger et al.





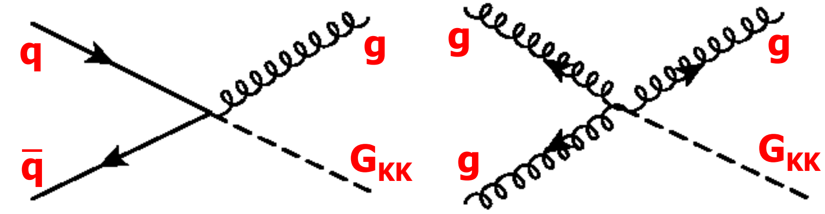
The Eöt-Wash results rule out n=2 extra dimensions for R > 0.19 mm (or M_S < 1.9 TeV)

Collider Signatures for Large Extra Dimensions

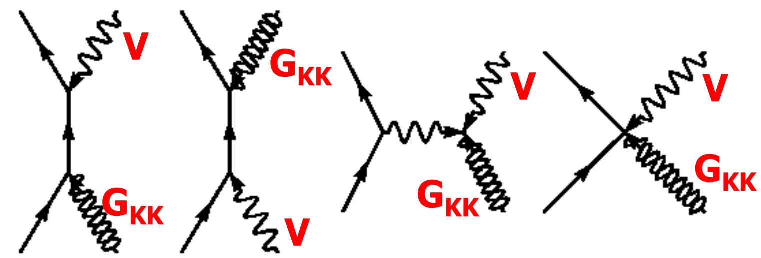
- Kaluza-Klein gravitons couple to the momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy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

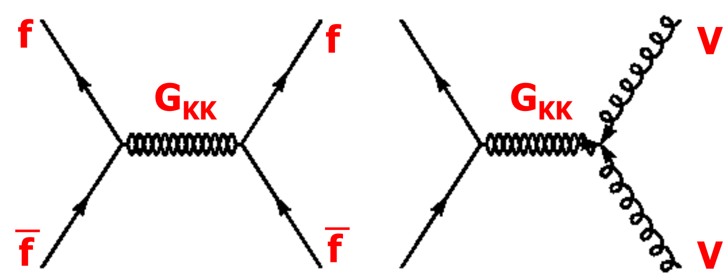


Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission

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

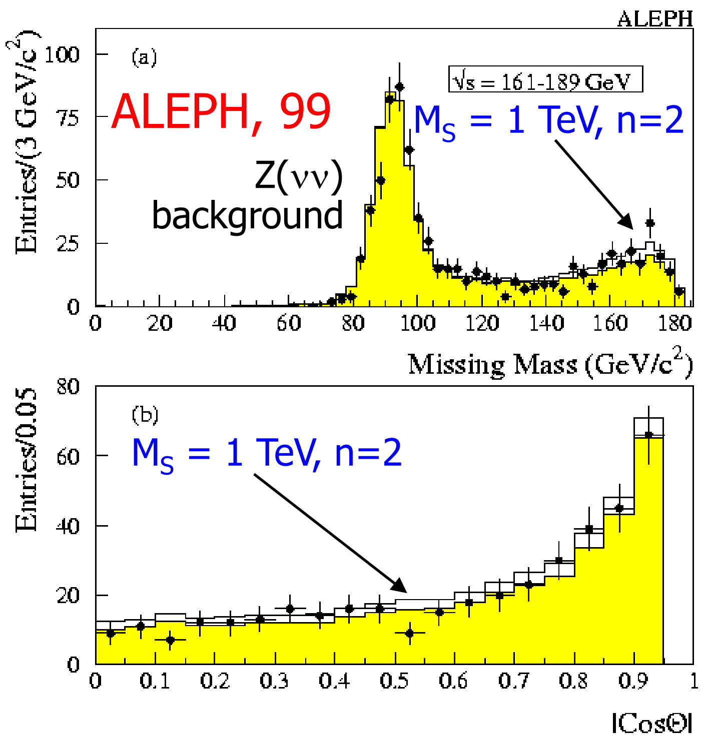


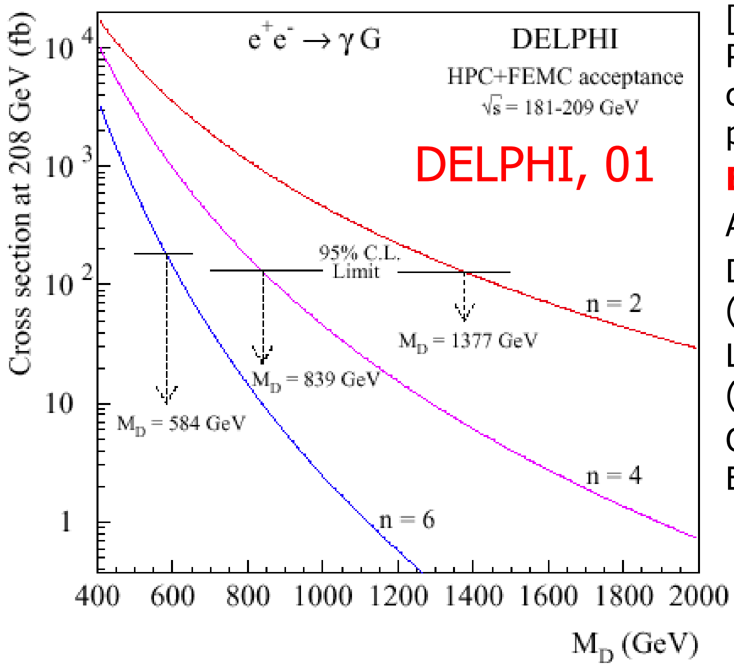
LEP2 Searches for Direct Graviton Emission - I

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

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

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





Theory:

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

Experiment:

ALEPH-CONF-2001-011

DELPHI Eur. Phys. J **C17**, 53 (2000); CONF 452 (2001)

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

OPAL: CERN-EP-2000-050, Eur. Phys. J. **C18**, 253 (2000)

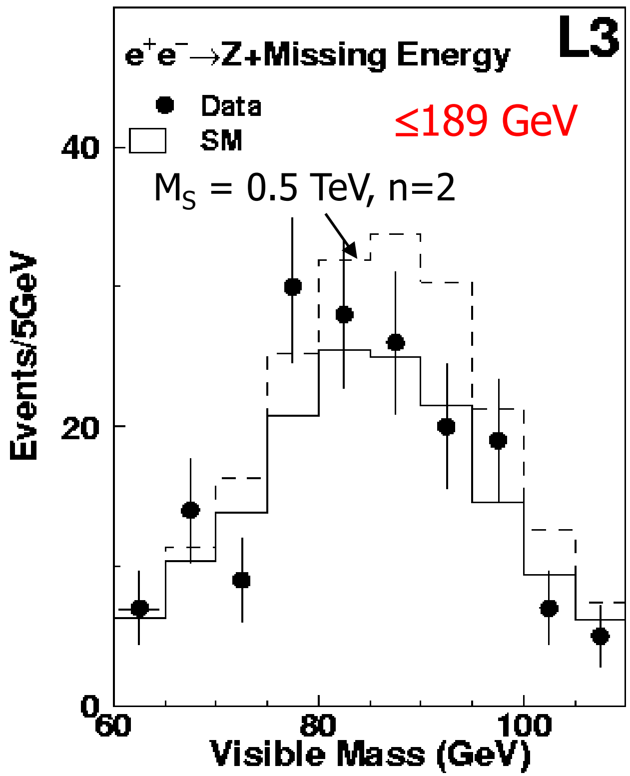
Results:
M_S > 1.3-0.6 TeV for n=2-6 (DELPHI)
ALEPH, L3, OPAL – slightly worse

LEP2 Searches for Direct Graviton Emission - II

- $e^+e^- \to ZG_{KK}$
  - Z(jj) + ME_T signature
  - "Recycling" of the invisible Higgs analyses
  - ALEPH: BR(Z → Z*(jj)G), 184 GeV
  - L3: Z(jj)G_{KK}, 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]

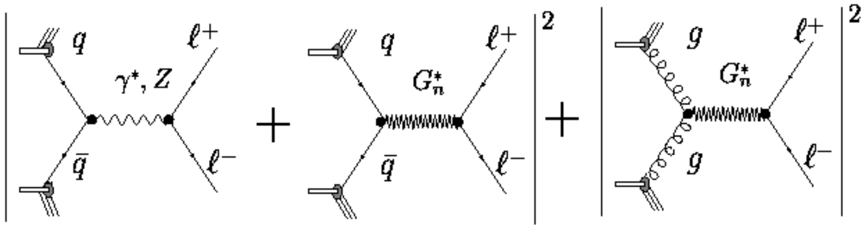
Experiment:

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 $\approx M_S$, 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 $\sim\mathcal{F}/M_S^4$(HLZ), where $\mathcal{F}$ reflects the dependence on the number of extra dimensions:

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

- Correspondence between the three formalisms:

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

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

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

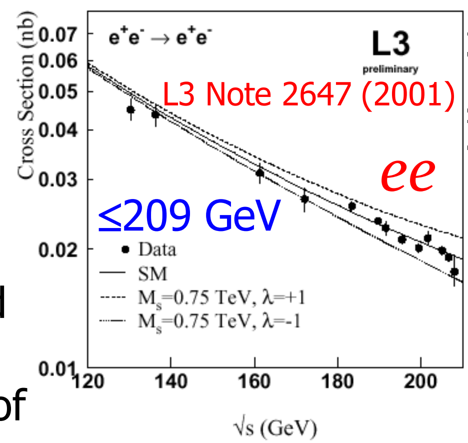
- Rule of thumb:

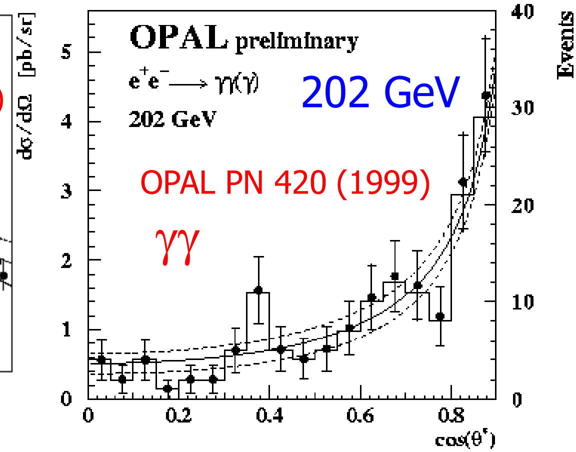
$$M_S(\mathbf{Hewett})\big|_{\lambda=+1} \approx M_S(\mathbf{HLZ})\big|_{n=5}$$

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

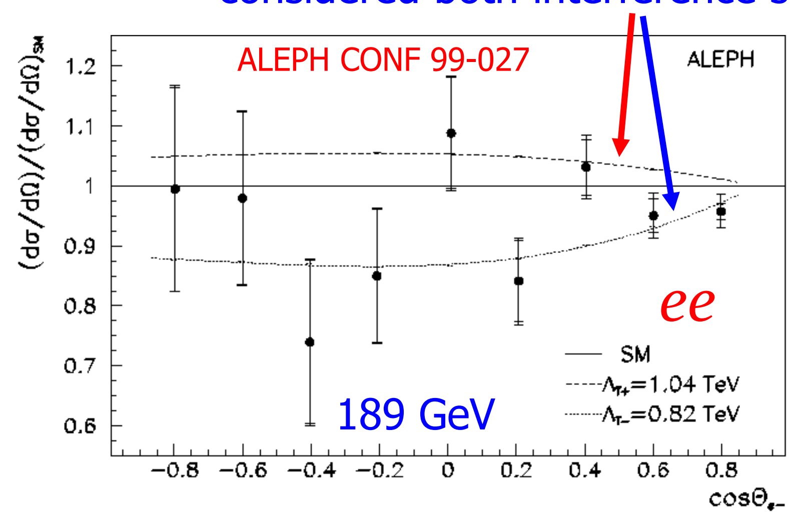
LEP2 Search for Virtual Graviton Effects – ff/γγ

- 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- and t-channel production
  - 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, 427, 430 (2000); 464 (2001); PL **B491**, 67 (2000)
  - L3: PL **B464**, 135; **B470**, 281 (1999); Notes 2647, 2648 (2001)
  - OPAL: EPJ **C13,** 553, *ibid.* **C18,** 253 (2000); Notes PN 420 (1999), PN 469, 471 (2001)





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
  - OPAL used angular distribution (ZZ)

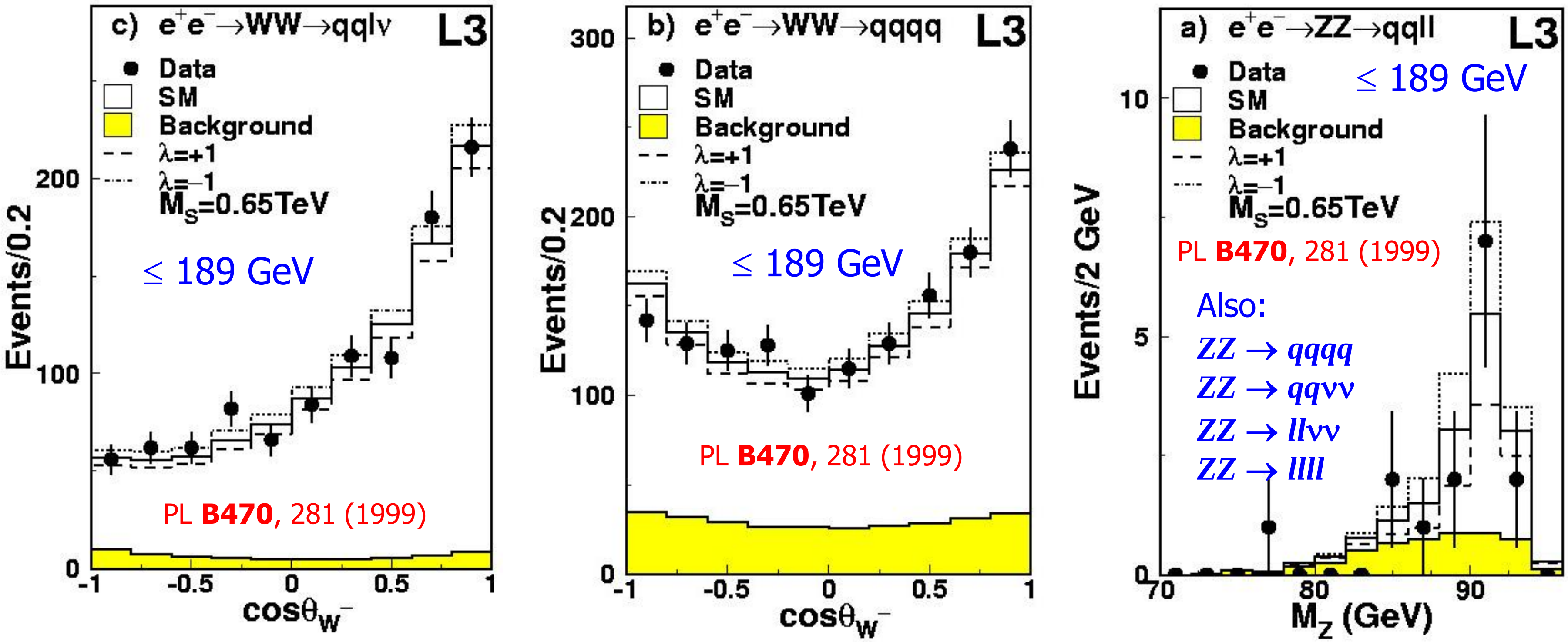
Theory:

[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 > 1.2 TeV (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	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58					
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
>200 GeV
λ=-1 λ=+1 GL

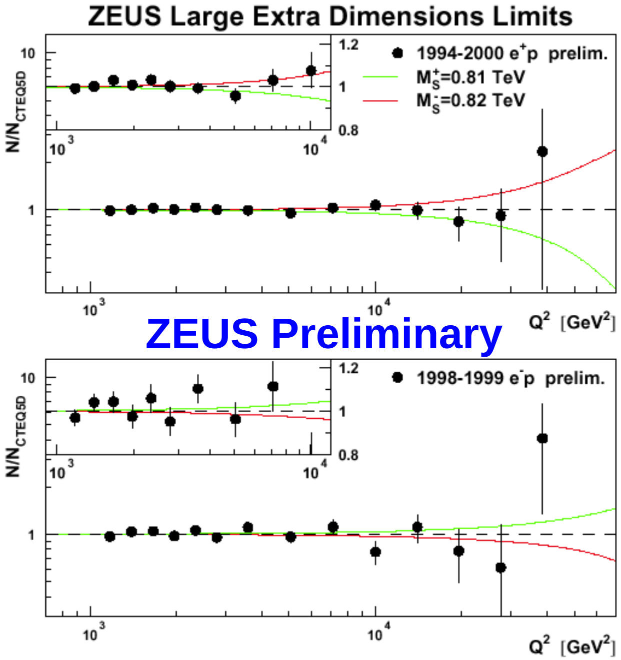
Virtual Graviton Exchange

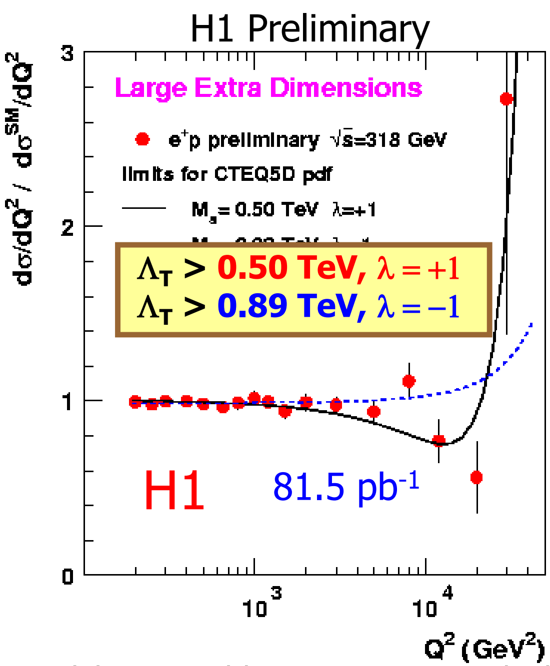
Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	Combined
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.49/0.49 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.70 0.77			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79	1.2 ? 1.2 ?	1.3/1.2 (<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)

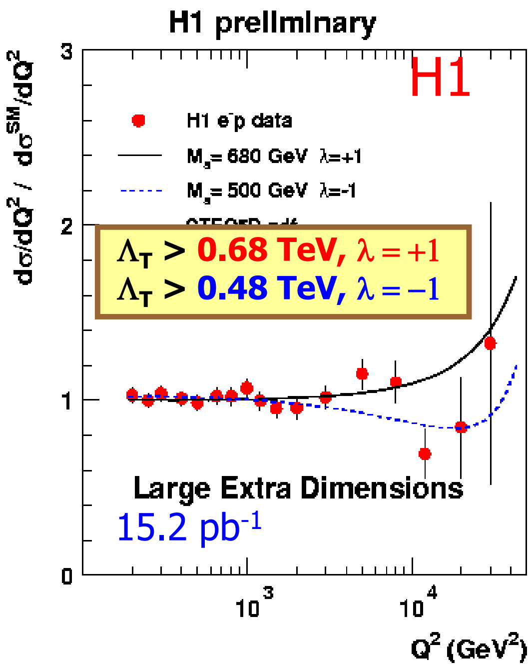
HERA Search for Virtual Graviton Effects

- $e^{\pm}p \rightarrow e^{\pm}p$
  - t-channel exchange, similar to Bhabha scattering diagrams; based on the GRW formalism (H1, set limits on Λ_T, but call it M_S) or Hewett's formalism (ZEUS)
  - Usual SM, Z/γ^* interference, and direct G_{KK} terms
  - Analysis method: fit to the $d\sigma/dQ^2$ distribution
  - Current H1 limits: Λ_T > 0.63/0.93 TeV (M_S > 0.56/0.83 TeV)
  - Current ZEUS limits: M_S > 0.81/0.82 TeV
  - Expected sensitivity up to 1 TeV with the ultimate HERA data set

Phys. Lett. **B479**, 358 (2000) – e^+p, 35.6 pb^{-1}







Virtual Graviton Exchange at the Tevatron

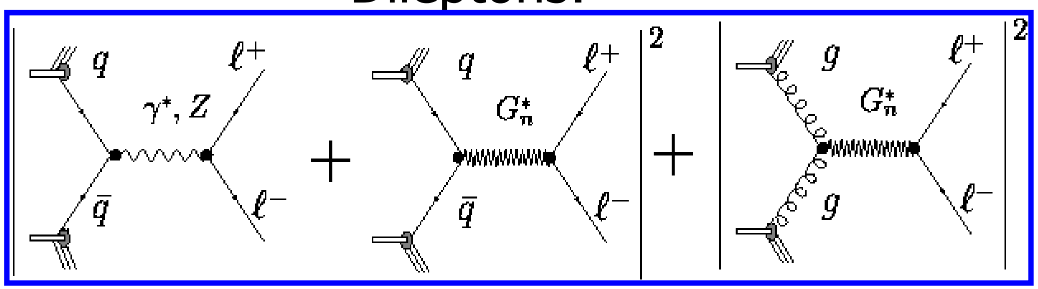
- Virtual graviton Drell-Yan and diphoton production
  - Mass spectrum has been looked at [Gupta, Mondal, Raychaudhuri, hep-ph/9904234; Cheung, Phys. Rev. **D61**, 015005 (2000), Phys. Lett. **B460**, 383 (1999),…]
  - Key improvement [Cheung, GL, PRD **62**, 076003 (2000)]: simultaneous analysis of 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

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

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

Dileptons:



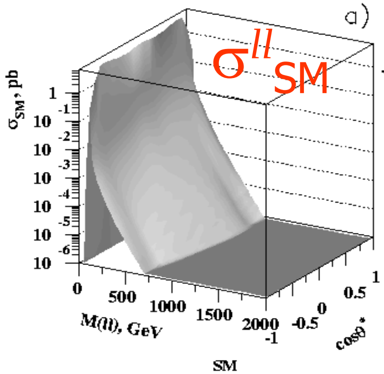
[For cross section formula see PRD **62**, 076003 (2000)]

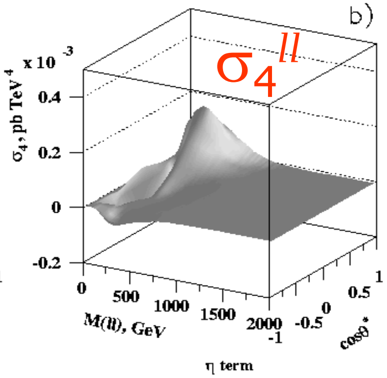
Diphotons:

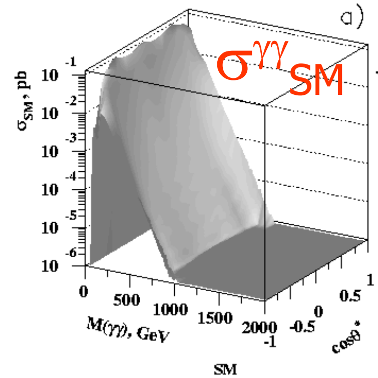
$$\frac{d^2\sigma}{dz\,dM_{\gamma\gamma}} = \sum_q \iint dx_1 dx_2 f_q(x_1) f_q(x_2) \frac{K(1+z^2)}{96\pi M_{\gamma\gamma}^2} \times \left[\underbrace{\frac{2e^4 Q_q^4}{1-z^2}}_{\text{SM}} + \underbrace{2\pi e^2 Q_q^2 \eta M_{\gamma\gamma}^4}_{\text{interference term}} + \underbrace{\frac{\pi^2}{2}(1-z^2)\eta^2 M_{\gamma\gamma}^8}_{G_{KK}\text{ term}} \right] +$$

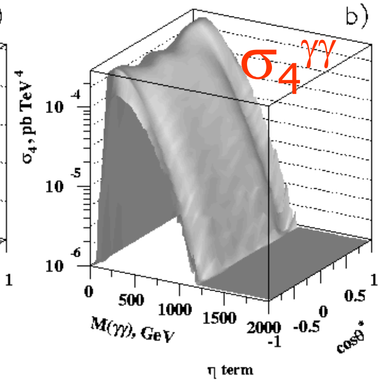
$$\iint dx_1 dx_2 f_g(x_1) f_q(x_2) \underbrace{\frac{K(1+6z^2+z^4)}{512 M_{\gamma\gamma}^2}\eta^2 M_{\gamma\gamma}^8}_{G_{KK}\text{ term}}$$

Tevatron Searches for Virtual Graviton Effects





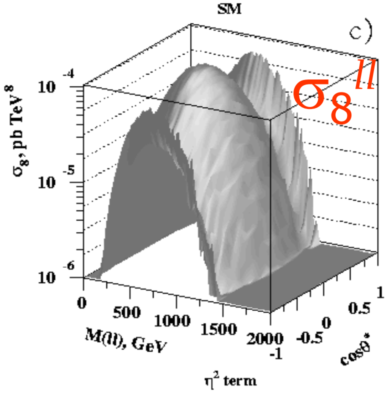




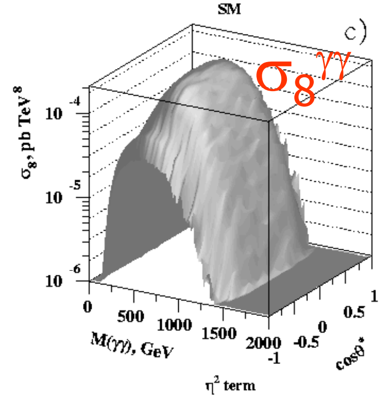
$$\eta = \frac{\mathcal{F}}{M_S^4}$$

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

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



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



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

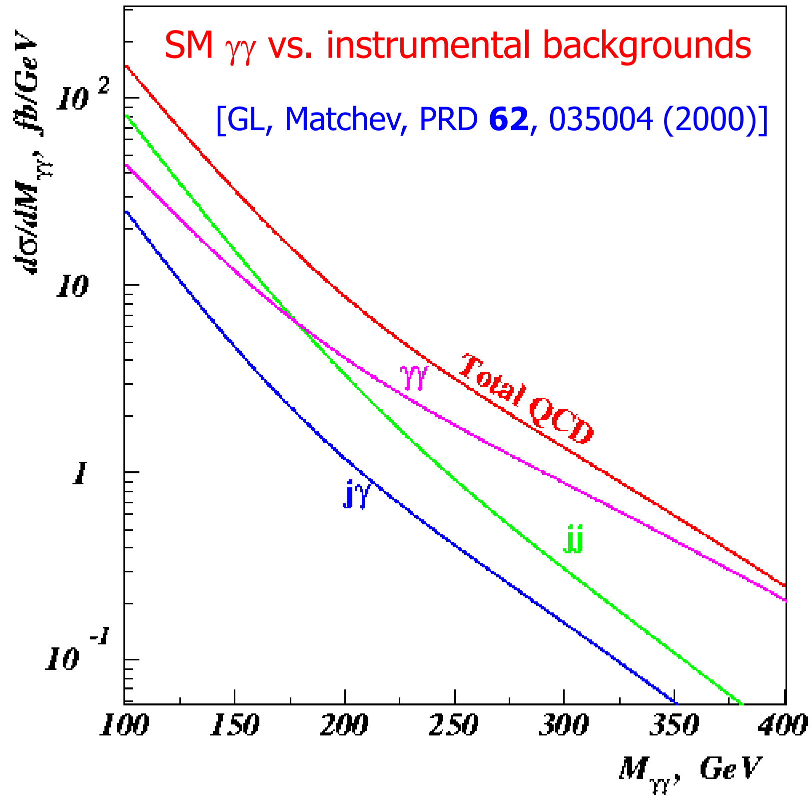
[Cheung, GL, PRD **62**, 076003 (2000)]

- 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 for Large Extra Dimensions

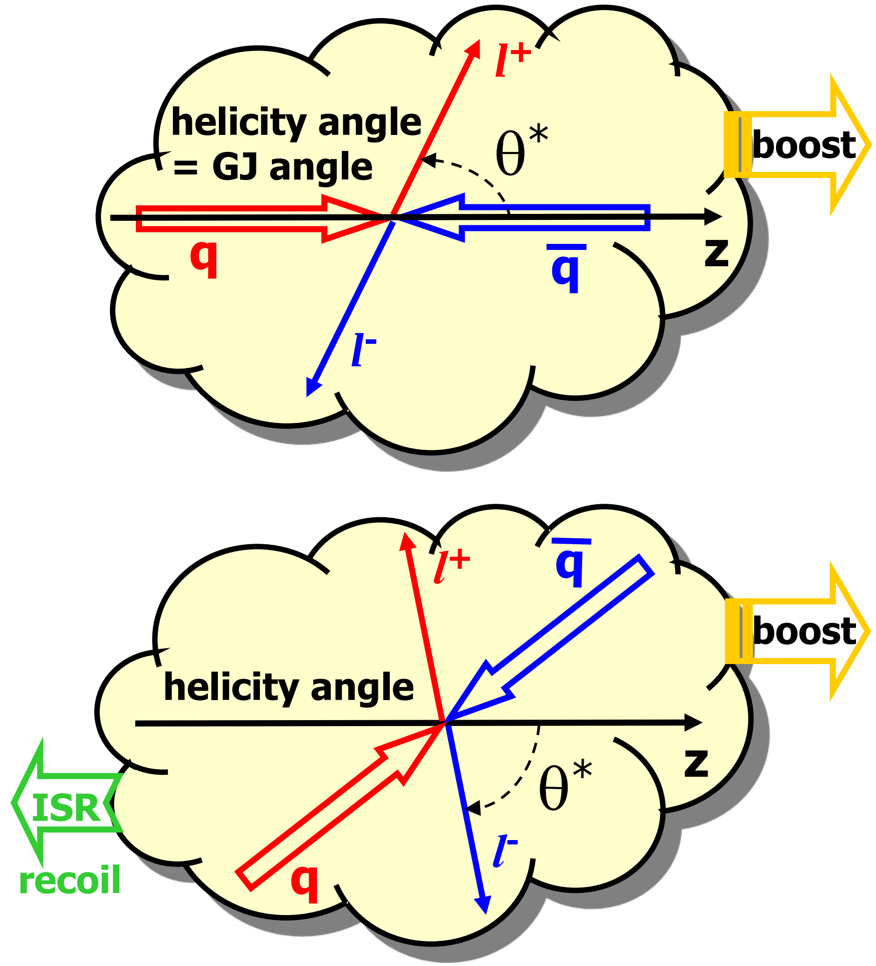
- First designated search for extra dimensions at hadron colliders
- Based on Cheung/GL method with a few important modifications:
  - DØ detector does not have central magnetic field, so the sign of $\cos\theta^*$ is not measured for dielectrons $\Rightarrow$ use $|\cos\theta^*|$
  - Dimuon mass resolution at high masses is poor $\Rightarrow$ do not use dimuons
  - Dielectron and diphoton efficiencies are moderate (~50%) due to tracking inefficiency (electrons) and conversions & random track overlap (photons) $\Rightarrow$ maximize the DØ discovery potential by combining dielectrons and diphotons (essentially ignore tracking information), i.e. use di-EM signature!
  - Instrumental background is not expected to be important at high masses $\Rightarrow$ open up the ID cuts to maximize the efficiency



- Use EM cluster shape information to pick the hard-scattering vertex, thus improving mass and $\cos\theta^*$ resolution

Next-to-Leading Order Corrections

- Angle θ^* in the parton level cross sections is defined as the angle between the incoming parton from p and the l^+, i.e. in the Gottfried-Jackson frame
- In the presence of the ISR this frame is no longer usable
- We use the helicity frame instead, and define θ^* as the angle between the direction of the boost and the parton which follows this direction, i.e. $\cos\theta^* \geq 0$
- ISR-induced "smearing", i.e. the difference between the $\cos\theta^*$ in the GJ and helicity frames is small (~0.05)
- The ISR effect is properly modeled in the signal MC
- Since NLO corrections for diphoton and dielectron production cross section are close, there is no theoretical "overhead" related to adding two channels; we use $K = 1.3 \pm 0.1$
- There is no QCD FSR in the di-EM final states



Data Selection and Efficiency

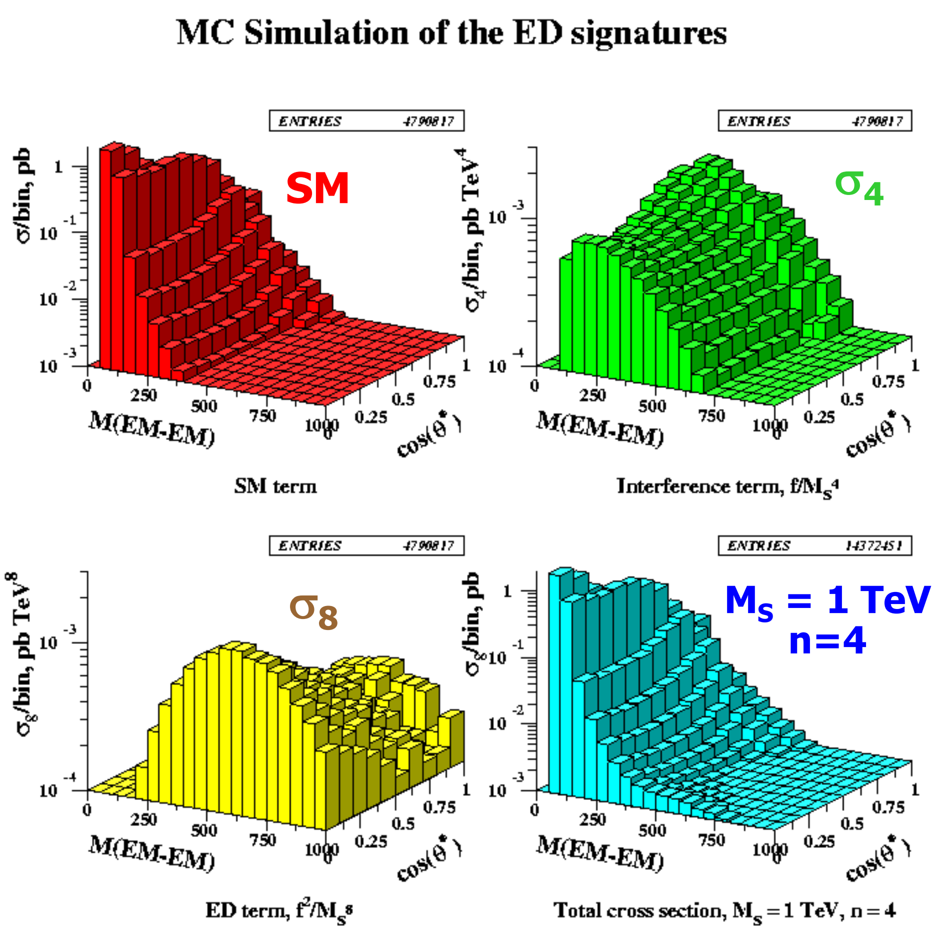
- Use entire Run I statistics from full luminosity, low-threshold di-EM triggers, $\int L dt = 127 \pm 6$ pb^{-1}
- Offline cuts are determined by the availability of background triggers:
  - Exactly 2 EM clusters w/ $E_T > 45$ GeV, $|\eta|<1.1$ or $1.5<|\eta|<2.5$ passing basic ID criteria:
    - EMF > 0.95
    - ISO < 0.10
    - $\chi^2 < 100$
  - $ME_T < 25$ GeV
  - No other kinematic cuts in the analysis, as the M/cosθ^* space completely defines the process
- Resulting data sample contains 1250 events
- Efficiency of the ID cuts is determined from the Z-peak data obtained with the same triggers by lowering the E_T(EM) cut

Cut	# of events
Starting sample	87,542
Quality cuts	82,947
≥2 EM	82.927
=2 EM	82,425
$E_T > 25$ GeV	36,409
Acceptance	30,585
EM ID	10,711
ET > 45 GeV	1,250

Cut	Efficiency
EM ID	$(87 \pm 2)\%$
MET < 25 GeV	$(98 \pm 1)\%$
Event quality	$(99.8 \pm 0.1)\%$
Overall, per event	$(79 \pm 2)\%$

Signal and SM Background Monte Carlo

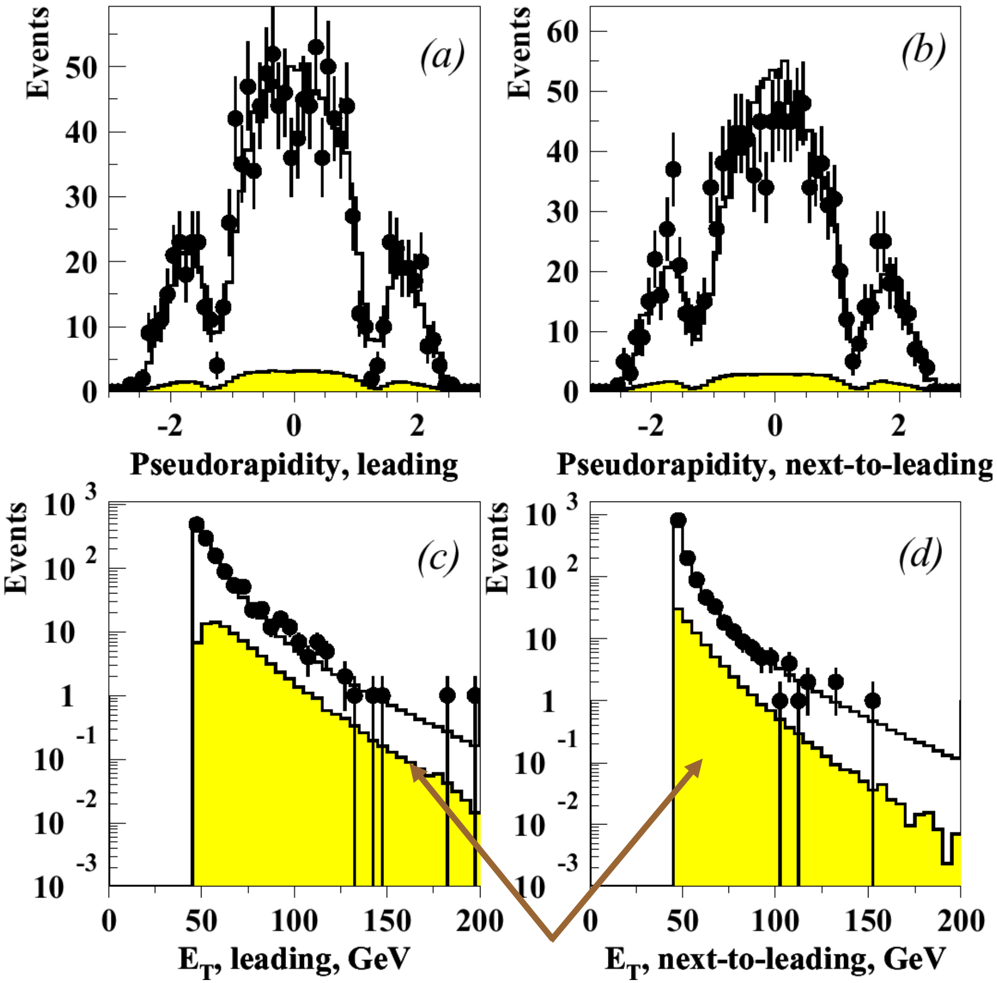
- Based on Cheung/GL LO parton level generator [PRD **62**, 076003 (2000)] that produces weighted events
- Augmented w/ fast parametric DØ detector simulation that properly models:
  - DØ detector acceptance and resolutions
  - Primary vertex smearing and resolution
  - Effects of additional vertices from multiple interactions in the event
  - Transverse kick of the di-EM system to account for ISR effects
  - Integration over parton distribution functions (CTEQ4LO and other modern p.d.f.)
  - K-factor correction to the cross sections
  - Both SM and gravity effects



MC Description of the Data and Systematics

- Kinematic distributions are well described with the sum of the SM and instrumental backgrounds
- The following systematic errors on the differential cross sections have been identified and taken in the account:

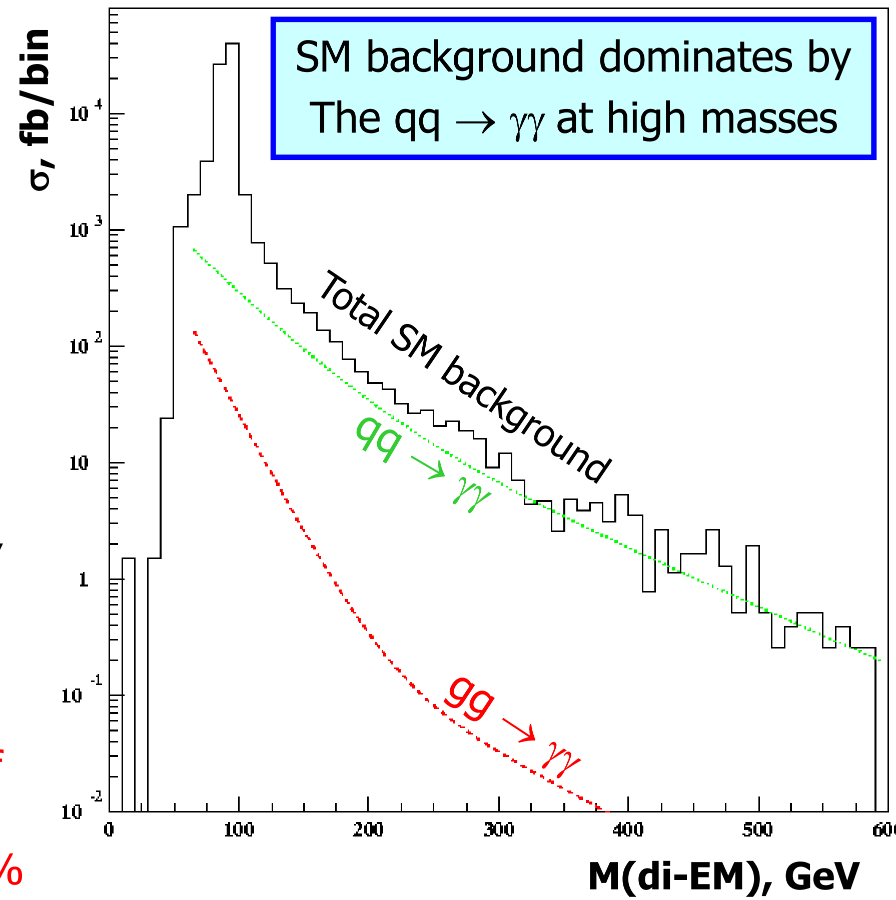
Source	Uncertainty
K-factor	10%
p.d.f. choice	5%
∫Ldt	4%
Efficiency	3%
Overall	12%



Instrumental background (25% uncertainty)

Summary of the Backgrounds

- SM backgrounds in the MC:
  - Drell-Yan
  - $\gamma\gamma$ ($gg \to \gamma\gamma$ is negligible $\Rightarrow$ not included)
- Other SM backgrounds are mostly at low masses and are completely negligible:
  - W+j/γ < 0.4%
  - WW < 0.1%
  - top < 0.1%
  - $Z \to \tau\tau$ < 0.1%
  - Z+γ < 0.01%
  - Other < 0.01%
- Instrumental background from $jj/j\gamma \to$ "$\gamma\gamma$" due to jets fragmenting in a leading π^0
  - Determined w/ the data from a single EM trigger with 40 GeV threshold by applying probability for a jet to fake an EM object of $(0.18 \pm 0.04)\%$, independent of E_T and η
  - Instrumental background (mostly jj) is ~7%
- Conservatively ignore small backgrounds



Fitting Procedure: Extracting Gravity Effects

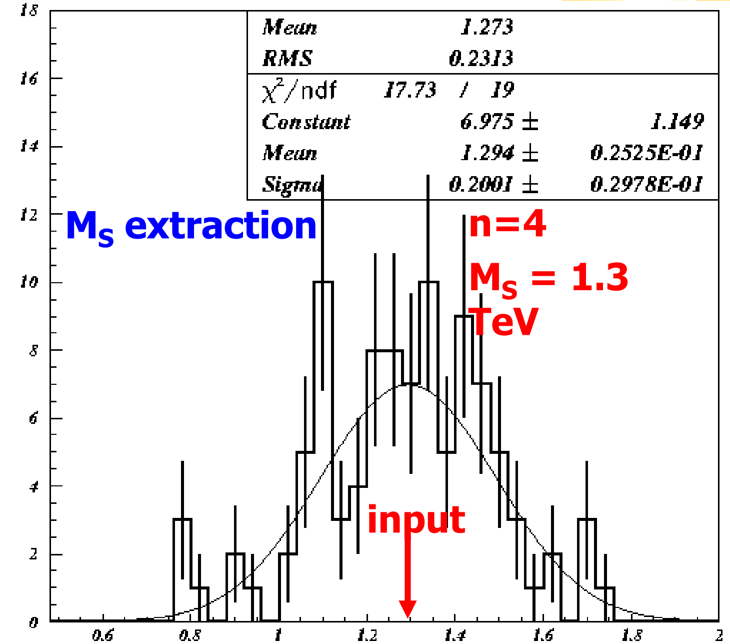
- Bin the data in a $M\times|\cos\theta^*|$ grid (up to 40×10 bins; $M\in[0,2\text{ TeV}]$, $|\cos\theta^*|\in[0,1]$)
- Parameterize cross section in each bin as a bilinear form in η: $\sigma = \sigma_{SM}+\eta\sigma_4+\eta^2\sigma_8$
- Use Bayesian fit with flat prior (in η) to extract the best value of η and 95% C.L. intervals:

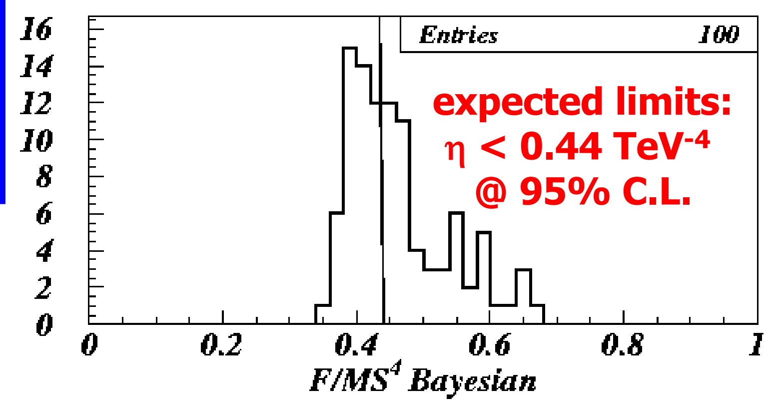
$$P(N\,|\,\eta,B)=\sum_{i,j}\frac{(S_{ij}+B_{ij})^{n_{ij}}e^{-(S_{ij}+B_{ij})}}{n_{ij}!},\quad S_{ij}=\varepsilon\sigma_{ij}\int L dt$$

$$P(\eta\,|\,N)=\frac{1}{A}\int db\exp\left(\frac{-(b-b_0)^2}{2\sigma_b^2}\right)\int dS\exp\left(\frac{-(S-S_0)^2}{2\sigma_S^2}\right)P(N\,|\,\eta,B)$$

$$\hat{\eta}\Rightarrow\max P(\eta\,|\,N);\quad\int_0^{\eta_{95}}d\eta P(\eta\,|\,N)=0.95$$

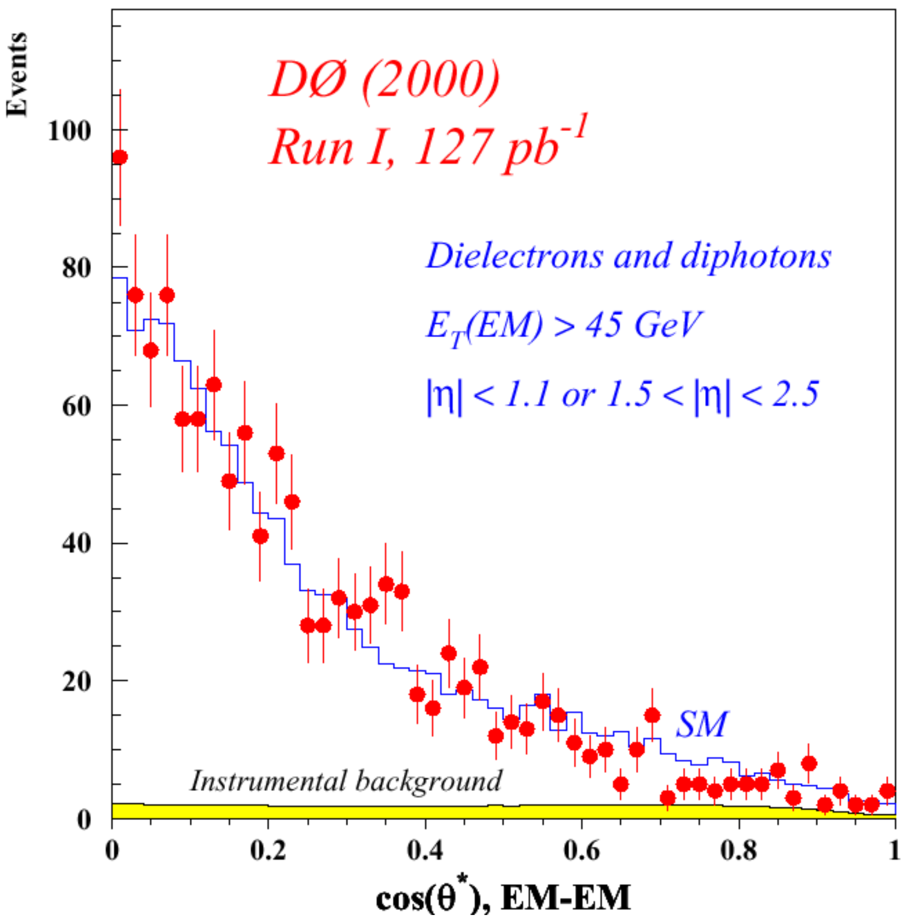
- Also cross-check with a simple maximum likelihood method





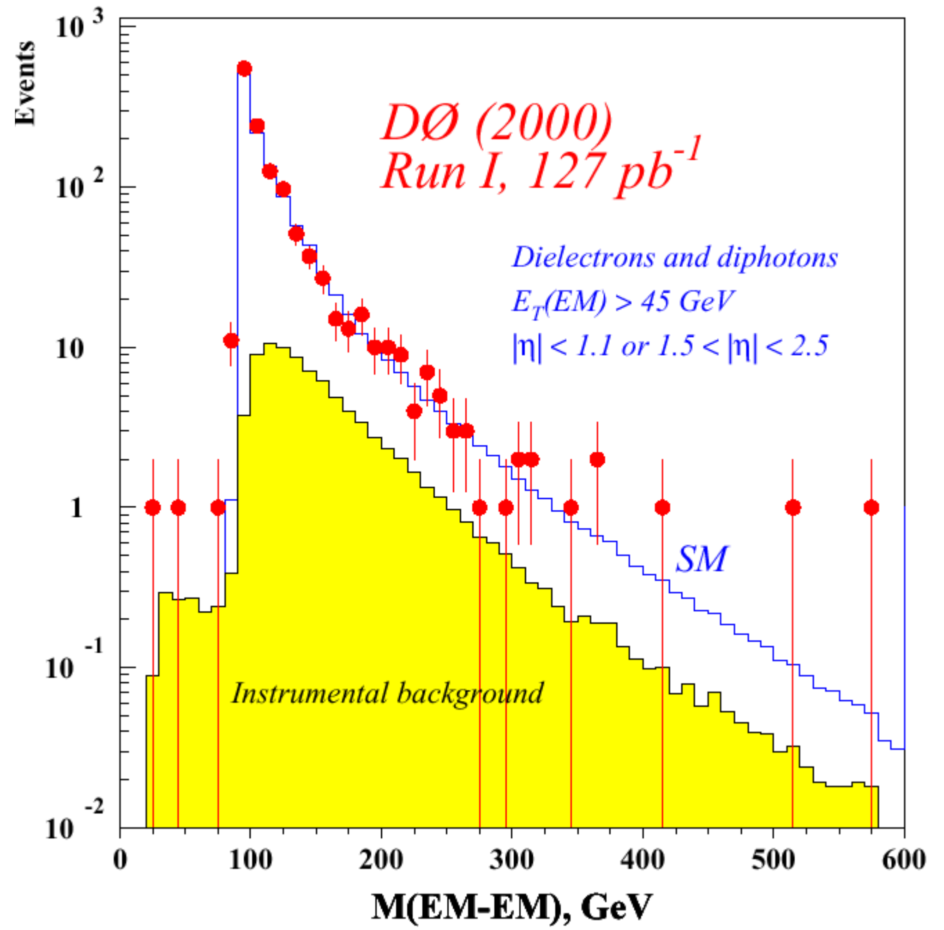
DØ Results: Mass and Angular Distributions

Comparison of the data with the SM predictions



Data agree well with the SM

Comparison of the data with the SM predictions



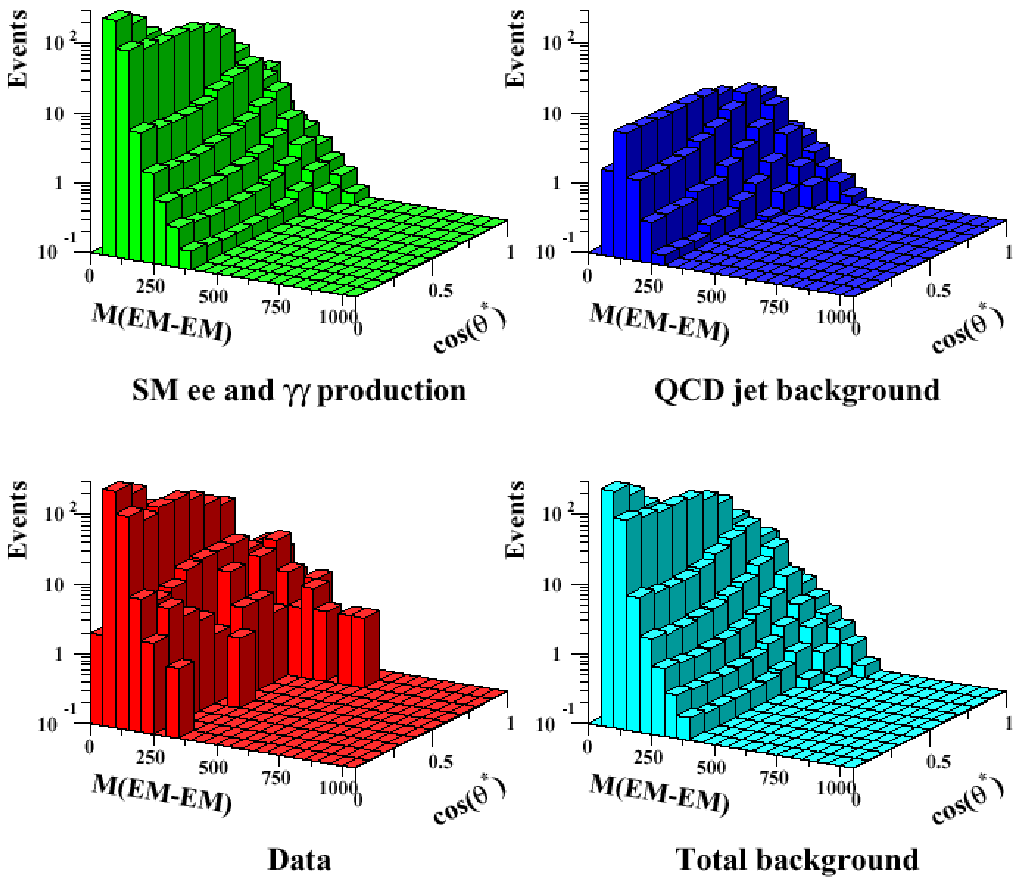
Note zero-events bins at high masses!

DØ Results: 2D-Spectra

- Data are in a good agreement with the SM predictions

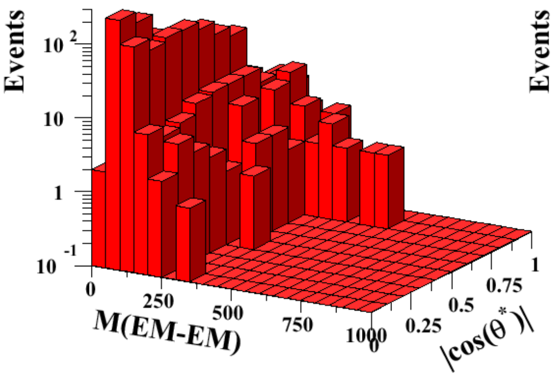
Mass cut	N	B	p
> 100 GeV	687	682	0.43
> 150 GeV	134	138	0.63
> 200 GeV	53	52.2	0.47
> 250 GeV	18	23.5	0.90
> 300 GeV	10	11.4	0.70
> 350 GeV	5	5.8	0.69
> 400 GeV	3	3.0	0.58
> 450 GeV	2	1.5	0.44
> 500 GeV	2	0.67	0.15
> 550 GeV	1	0.23	0.21
> 600 GeV	0	<0.1	1.00

Comparison of the data and the SM predictions

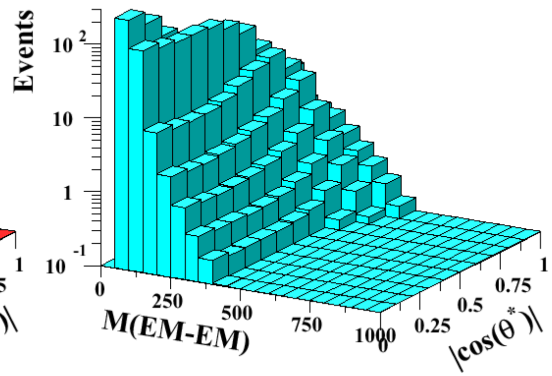


DØ Results in Dielectron and Diphoton Channels

DØ (2000), Run I, 127 pb^{-1}

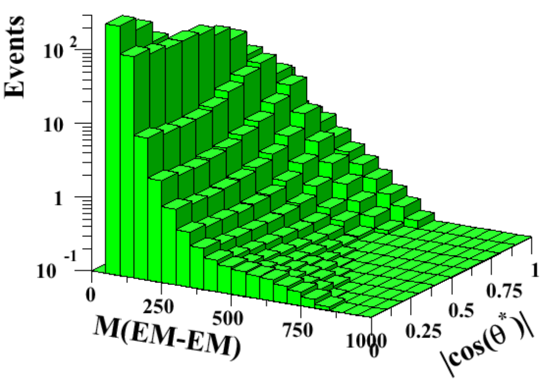


Data

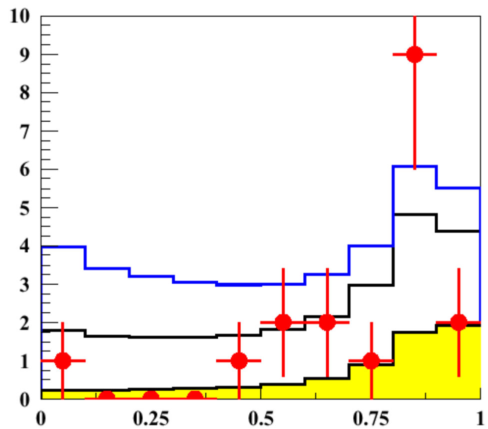


Total background

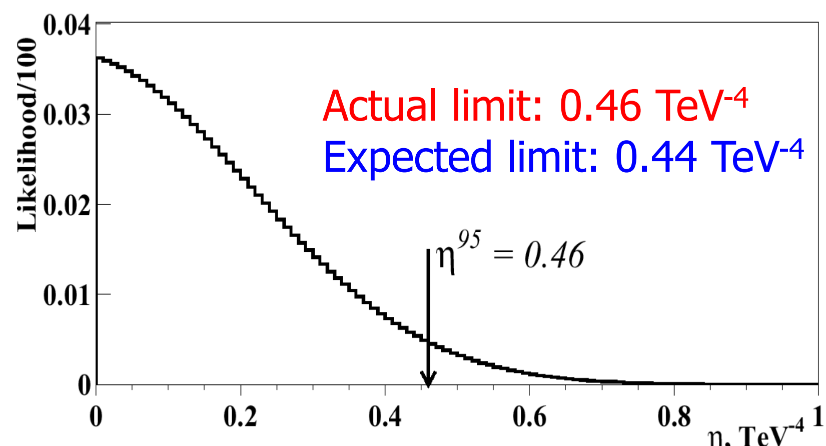
- High-mass, low $|\cos\theta|$ tail is a characteristic signature of LED
- 2-dimensional method resolves this tail from the high-mass, high $|\cos\theta|$ tail due to collinear divergencies in the SM diphoton production
- No excess of events is seen at high masses and low scattering angles, where the signal is expected to exhibit itself



SM+ED signal, M_S = 1 TeV, n = 4

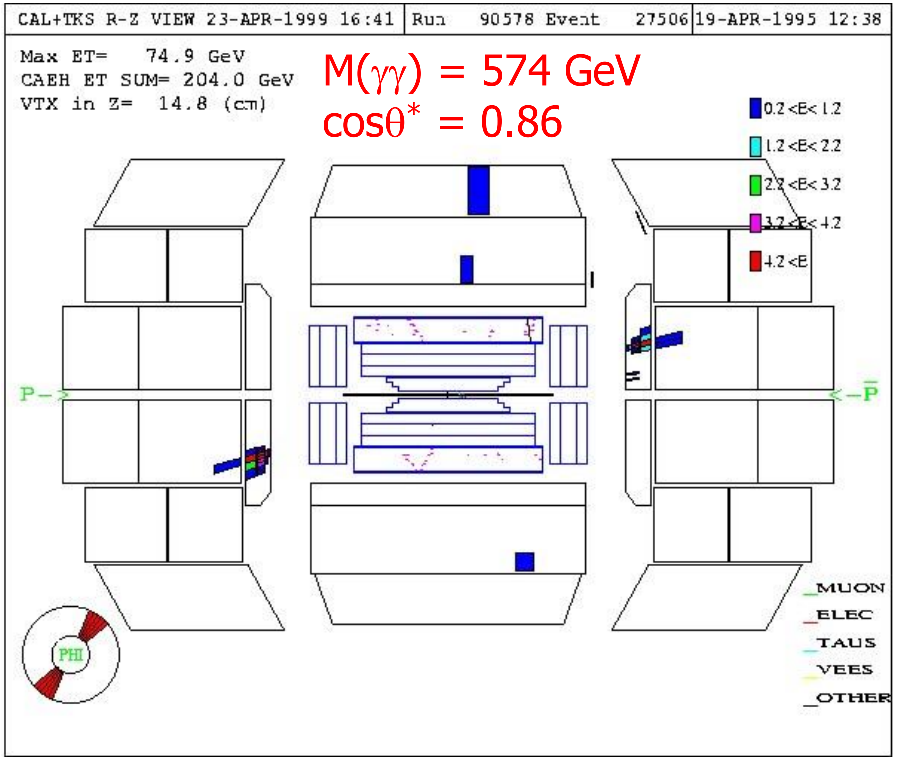


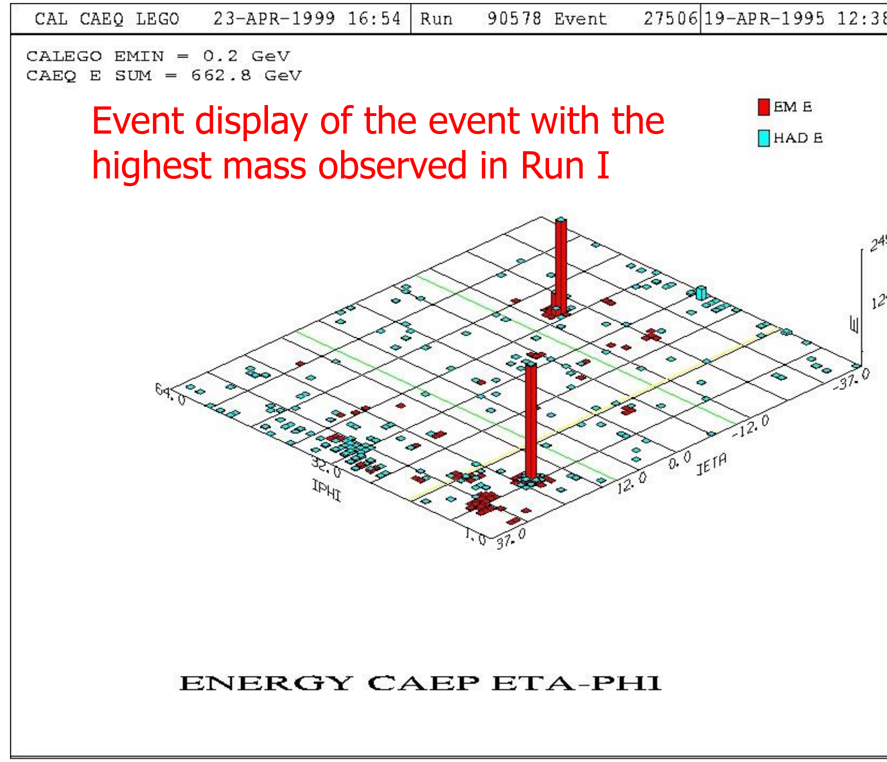
$|\cos(\theta^*)|$, M(EM-EM) > 250 GeV



Bayesian Likelihood

High-Mass Candidate Events

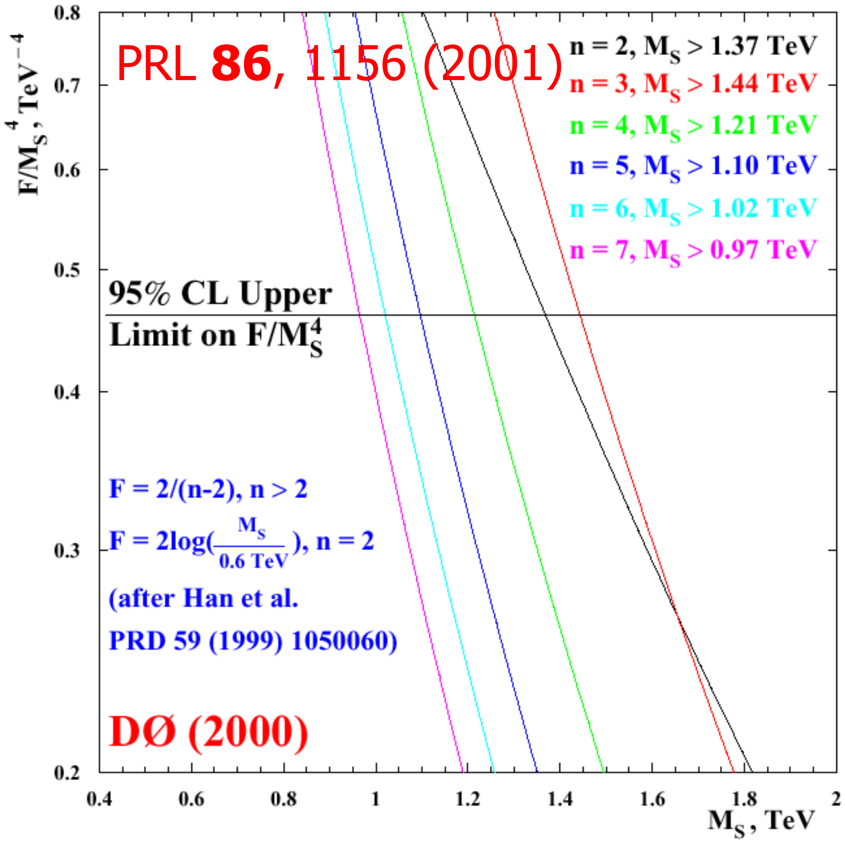




- Parameters of the two high-mass candidate events:

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

Limits on Large Extra Dimensions



	Run II, 2 fb^{-1}	Run II, 20 fb^{-1}	LHC, 100 fb^{-1}
$e^+e^- + \mu^+\mu^-$	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
$e^+e^- + \mu^+\mu^- + \gamma\gamma$	**1.5-2.5 TeV**	**2.1-3.5 TeV**	**7.9-13 TeV**

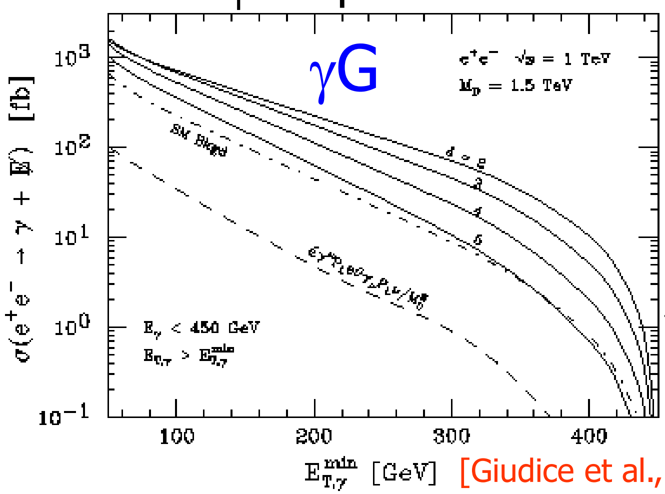
- For $n > 2$ M_S limits can be obtained directly from η limits
- For $n = 2$, use average $\hat{s}$ for gravity contribution ($\langle\hat{s}\rangle = 0.36$ TeV^2, [Cheung/GL, PRD **62**, 076003 (2000)])
- Translate limits in the Hewett and GRW frameworks for easy comparison with other experiments:
  - M_S(Hewett) > 1.1 TeV and 1.0 TeV ($\lambda = -1$)
  - Λ_T(GRW) > 1.2 TeV
- These limits are similar to the latest preliminary 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 and diphoton analyses ($M_S \sim$ 0.9-1.0 TeV), utilizing the same technique
- 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})

Real Graviton Emission at the NLC

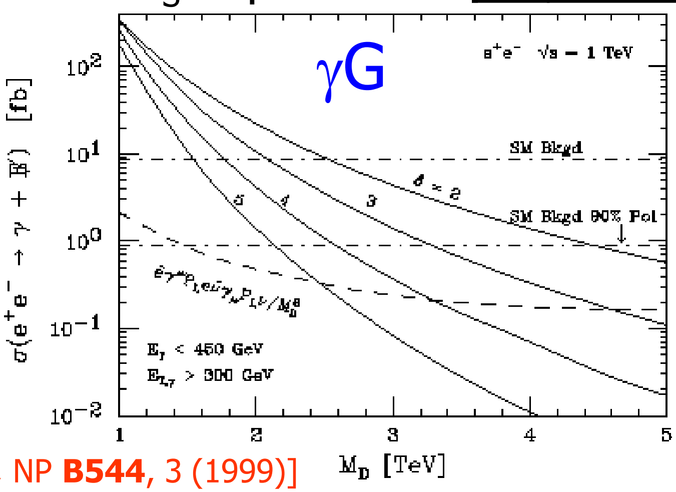
- $e^+e^- \rightarrow \gamma G/ZG$
  - Similar to LEP2 Studies
  - Polarization helps to reduce SM backgrounds
  - Low background gives an edge above LHC
  - Giudice, Rattazzi, Wells, NP **B544**, 3 (1999)
  - Mirabelli, Perelstein, Peskin, PRL **82**, 2236 (1999)
  - Cheung, Keung, PR **D60**, 112003 (1999)
  - Many others…

	M_S reach 200 fb^{-1} Giudice	M_S reach ? fb^{-1} Mirabelli	M_S reach 50 fb^{-1} Cheung
n	1 TeV, P = 90%, γG		1 TeV, P=0, γG/ZG
2	7.7 TeV	5.7 TeV	4.5 TeV 3.2-4.2 TeV
3		4.0 TeV	
4	4.5 TeV	3.0 TeV	
5		2.4 TeV	
6	3.1 TeV		

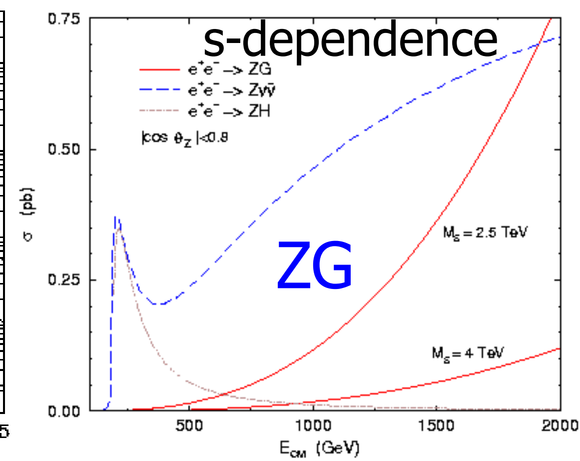
E_T^{min} spectrum



M_S dependence



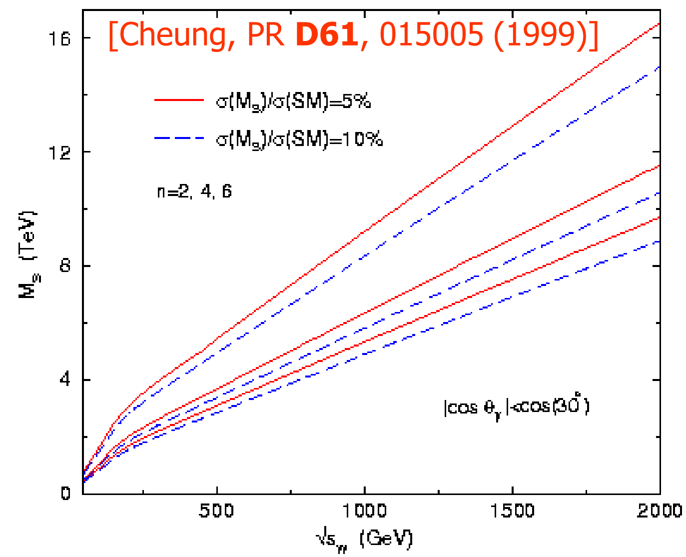
[Giudice et al., NP **B544**, 3 (1999)]



[Cheung et al., PR **D60**, 11203 (1999)]

Virtual Graviton Effects at the NLC

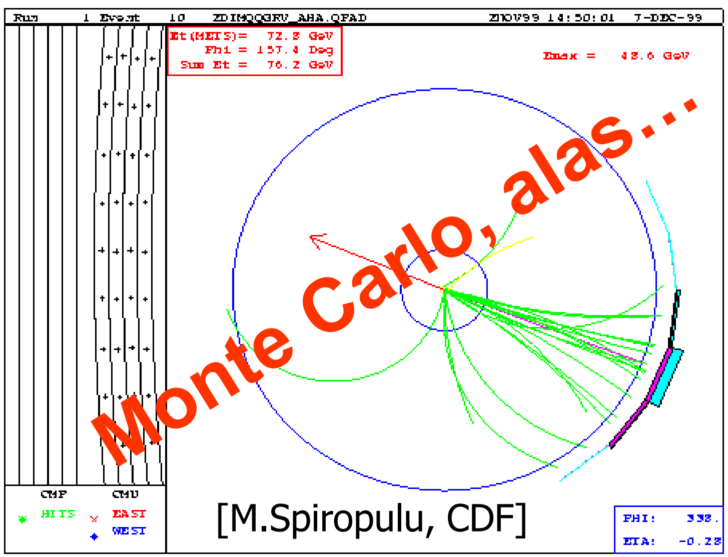
- $e^+e^- \to \gamma\gamma, ff, WW, ZZ$, etc.
  - Similar to LEP2 Studies
  - Polarization helps to reduce SM backgrounds
  - Sensitivity comparable to that at the LHC
  - Hewett, Phys. Rev. Lett. **82**, 4765 (1999)
  - Giudice, Rattazzi, Wells, NP **B544**, 3 (1999)
  - Rizzo, Phys. Rev. **D59**, 115010 (1999)
    - Cheung, Phys.Rev. **D61**, 015005 (2000)
    - Davoudiasl, Phys.Rev. **D61**, 044018 (2000)
    - Many others…



	Hewett	Giudice	Rizzo	Cheung	Davoudiasl
Luminosity	200 fb^{-1}	? fb^{-1}	100-500 fb^{-1}	10 fb^{-1}	200 fb^{-1}
$\gamma\gamma$		3.8 TeV		3.5-4.0 TeV	
ff	6.0-7.0 TeV		6.0-7.5 TeV		
$\gamma\gamma \to$ ff			3.5-4.5 TeV		
Compton					~ 6 TeV

Hadron Colliders: Real Graviton Emission

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



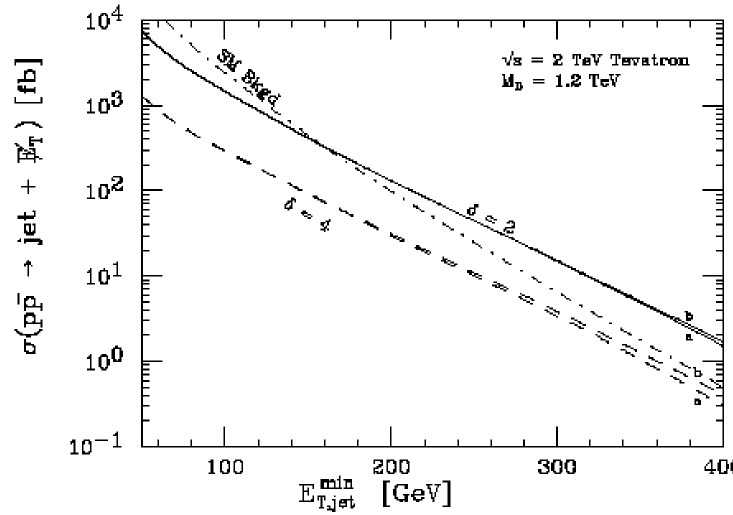
[M.Spiropulu, CDF]

Note that the sensitivity estimates are optimistic, as they ignore copious instrumental backgrounds.

Theory:

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

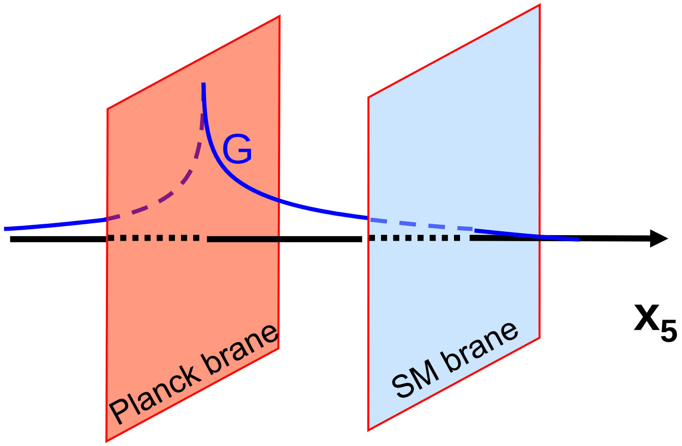
[Mirabelli, Perelstein, Peskin, PRL **82**, 2236 (1999)]

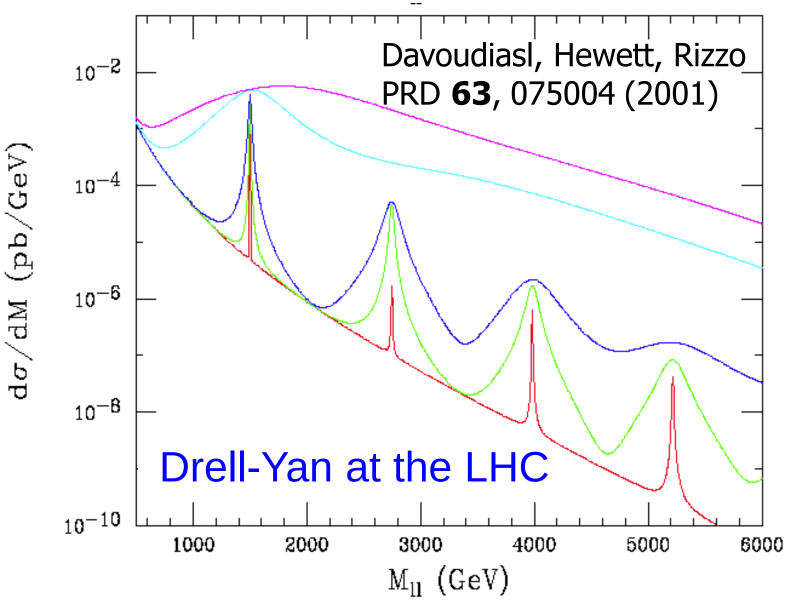


n	M_S reach, Run I	M_S reach, Run II	M_S reach, LHC 100 fb^{-1}
2	1100 GeV	1400 GeV	8.5 TeV
3	950 GeV	1150 GeV	6.8 TeV
4	850 GeV	1000 GeV	5.8 TeV
5	700 GeV	900 GeV	5.0 TeV

New Ripples in Extra Dimensions

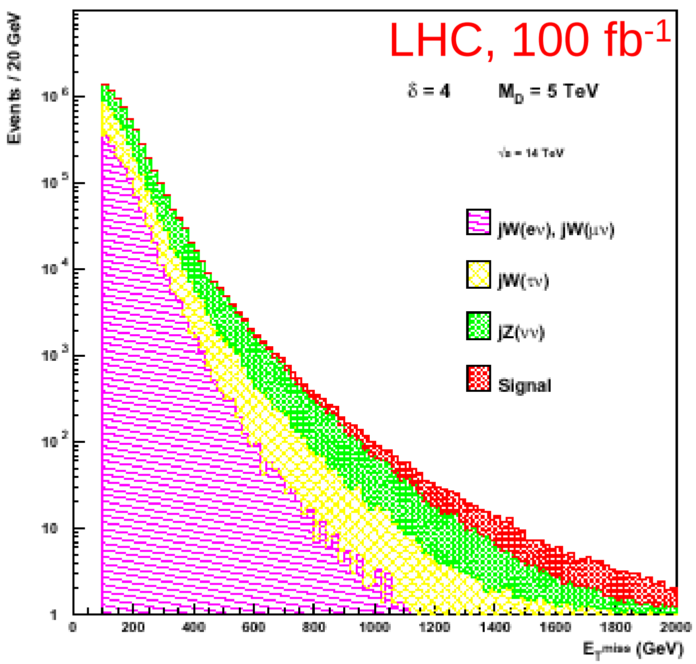
- Randall-Sundrum (RS) scenario
  [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - Gravity can be localized near a brane due to the non-factorizable geometry of a 5-dimensional space
  - \+ brane (RS) – no low energy effects
  - +− branes (RS) – TeV Kaluza-Klein modes of gauge bosons
  - ++ branes (Lykken-Randall) – low energy collider phenomenology, similar to ADD with n=6
  - −+− branes (Gregory-Rubakov-Sibiryakov) – infinite volume extra dimensions, possible cosmological effects
  - +−+ branes (Kogan et al.) – very light KK state, low energy collider phenomenology

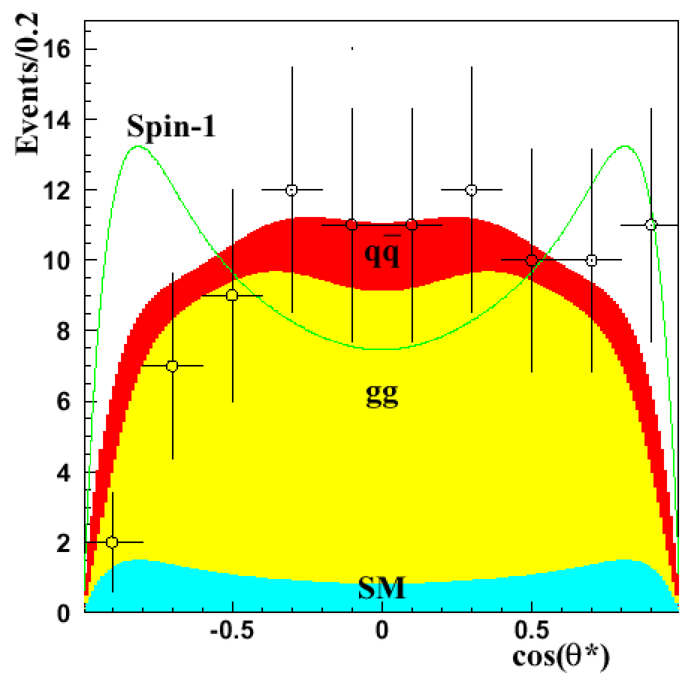




LHC: Designated Studies

- ADD ATLAS studies:
  Vacavant & Hinchliff [ATL-PHYS-2000-016]
  - M_S > 4-7.5 TeV (n=2)
  - M_S > 4.5-5.9 TeV (n=3)
  - M_S > 5 TeV (n=4)
  - In agreement with GRW/MPP predictions)
  - Similar sensitivity is achieved w/ monophotons
- RS ATLAS studies:
  Allanach/Odagiri/Parker/Webber
  [JHEP 09, 19 (2000)]
  - $G \to e^+e^-$
  - M_G > 2 TeV

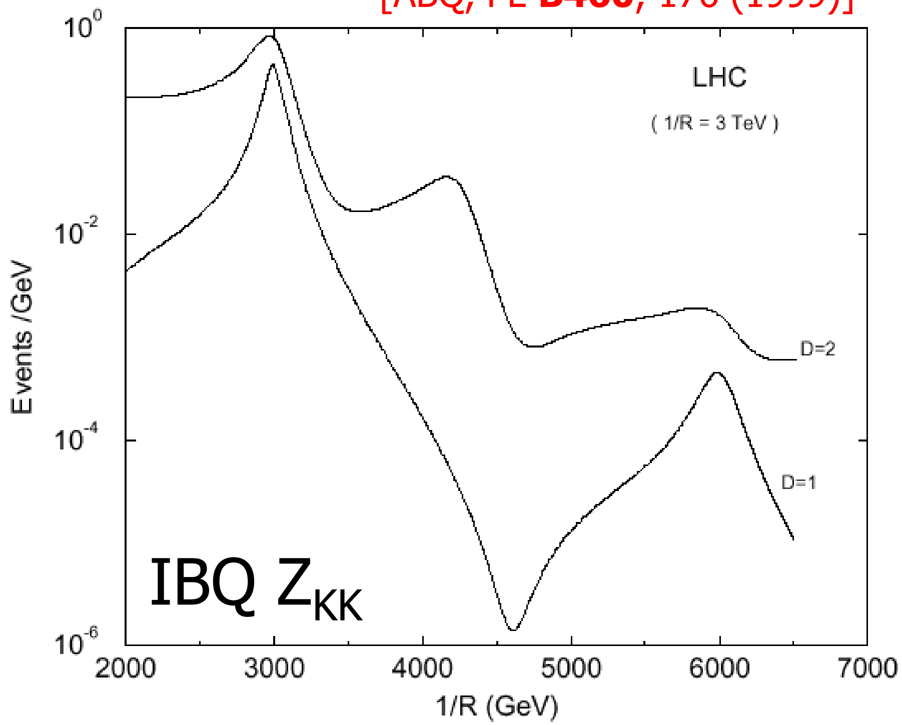




New Ripples in Extra Dimensions (cont'd)

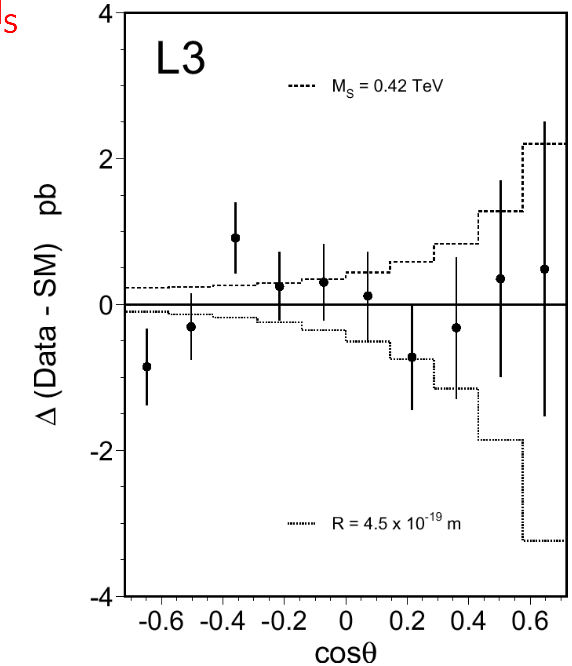
- Intermediate-size "longitudinal" extra dimensions with ~TeV^{-1} radius
  Antoniadis/Benaklis/Quiros
  [PL **B460**, 176 (1999)]
  - SM gauge bosons can propagate in these extra dimensions
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances
  - Effects also will be seen in the virtual exchange of the Kaluza-Klein modes of vector bosons at lower energies
- Time-like extra dimensions
  Dvali/Gabadadze/Senjanovic
  [hep-ph/9910207]
  - tachionic G_{KK}, possible to solve hierarchy problem, cosmological effects

[ABQ, PL **B460**, 176 (1999)]



Stringy Models

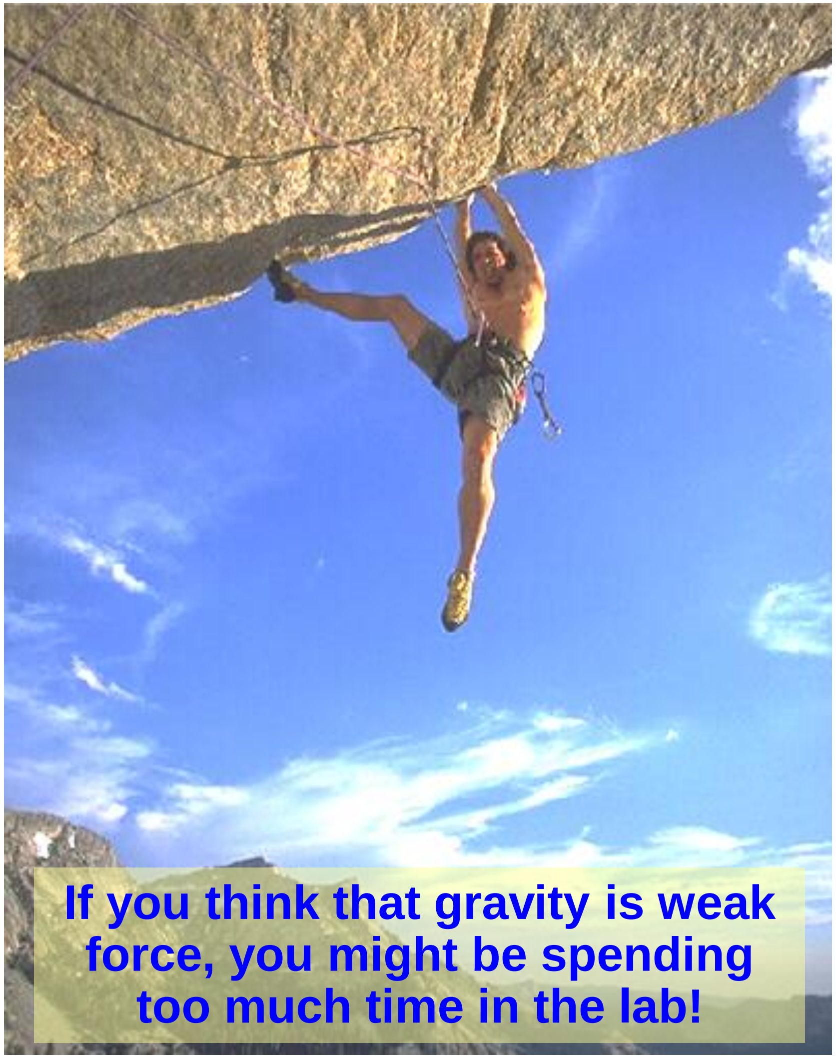
- Recent attempts to embed the idea of large extra dimensions in string models:
  - Shiu/Shrock/Tye [Phys. Lett. B **458**, 274 (1999)]
    - Type I string theory on a Z_n orbifold
    - Consider resulting twisted moduli fields which sit on the fixed points of the orbifolds and their effects on gg $\to$ gg scattering
    - These fields acquire mass ~1 TeV due to SUSY breaking, and their coupling with the bulk fields is suppressed by the volume factor
    - Since they couple to gravitons, these fields can produce bulk KK modes of the latter
    - Current sensitivity to the string scale, M_S, from CDF/DØ dijet data is ~1 TeV
- Cullen/Perelstein/Peskin, [Phys. Rev. D **62**, 055012 (2000)]
  - Embed QED into Type IIB string theory with n=6
  - Calculate corrections to $e^+e^- \to \gamma\gamma$ and Bhabha scattering due to string Regge excitations
  - L3 has set limit $M_S > 0.57$ TeV @ 95% CL
  - Also calculate $e^+e^-, gg \to \gamma G$ cross section
  - Another observable effect is a resonance in $q\bar{q} \to g^*$ at M_S



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 better established spatial dimensions
  - Unlikely due to the s-wave dominance [Emparan, Horowitz, Mayer, PRL **85**, 499 (2000)]
- 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)

Conclusions

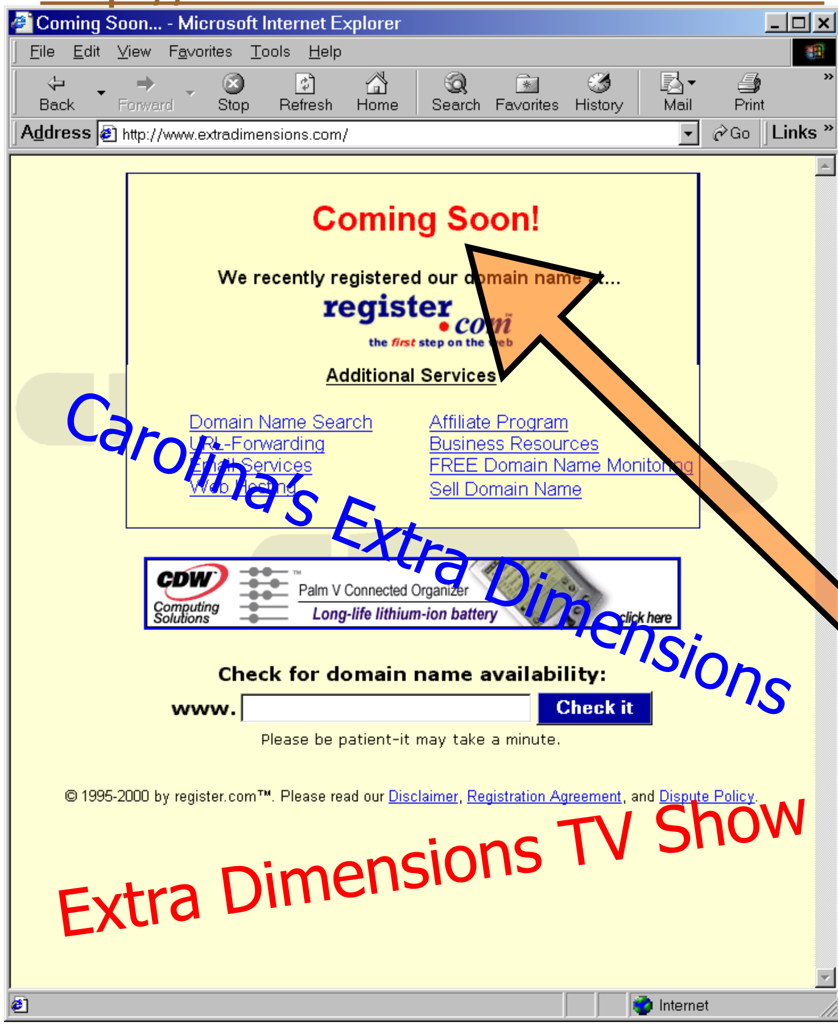


- "To be able to practice five things everywhere under heaven constitutes perfect virtue... [They are] gravity, generosity of soul, sincerity, earnestness, and kindness."

  Confucius, *The Confucian Analects*

Conclusions: Second Try

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!