

Search For Large Extra Dimensions at DØ

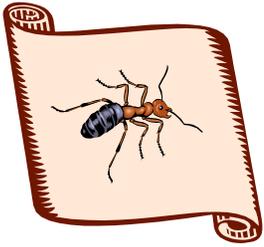
Greg Landsberg



(for the DØ Collaboration)

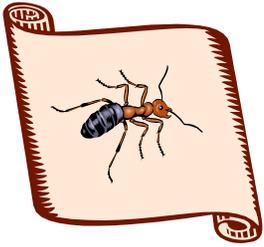
Fermilab Wine & Cheese Seminar

April 21, 2000



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
- + DØ Run I Search for Virtual Graviton Effects
 - + Method
 - + Data Selection
 - + Results
- + Projections for Run II and Future Colliders
- + Unusual Signatures for Extra Dimensions (Black Holes)
- + Conclusions



Life With the Standard Model

✚ ...is boringly precise:

Moriond 2000

	Measurement	Pull	Pull
			-3 -2 -1 0 1 2 3
m_Z [GeV]	91.1871 ± 0.0021	.07	
Γ_Z [GeV]	2.4944 ± 0.0024	-.62	
σ_{had}^0 [nb]	41.544 ± 0.037	1.72	
R_e	20.768 ± 0.024	1.19	
$A_{\text{fb}}^{0,e}$	0.01701 ± 0.00095	.70	
A_e	0.1483 ± 0.0051	.13	
A_τ	0.1425 ± 0.0044	-1.16	
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	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	
$A_{\text{fb}}^{0,b}$	0.0988 ± 0.0020	-2.34	
$A_{\text{fb}}^{0,c}$	0.0692 ± 0.0037	-1.29	
A_b	0.911 ± 0.025	-.95	
A_c	0.630 ± 0.026	-1.47	
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	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	
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02804 ± 0.00065	-.20	

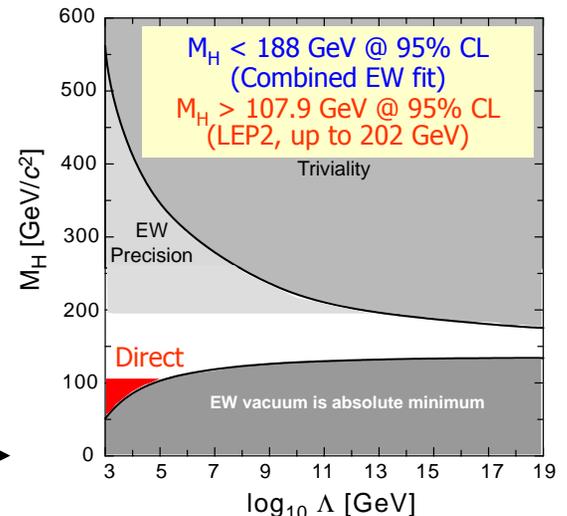
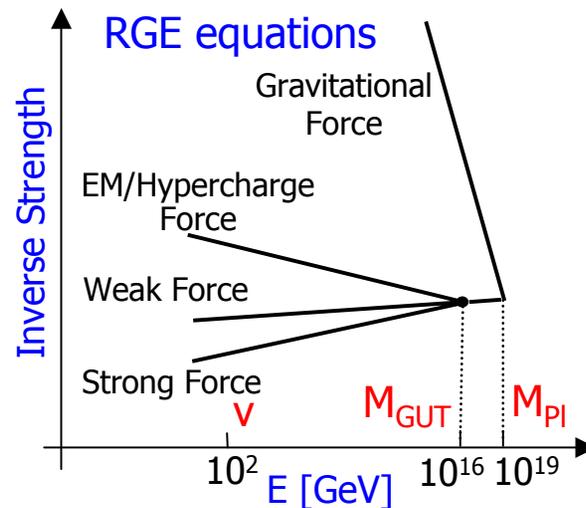
✚ ...but not at all boring:

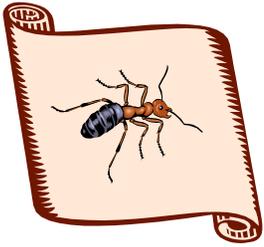
✚ Standard Model accommodates, but does not explain:

- ✚ 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 $\sim (\nu/m_{\text{GUT}})^2$ fine-tuning is required

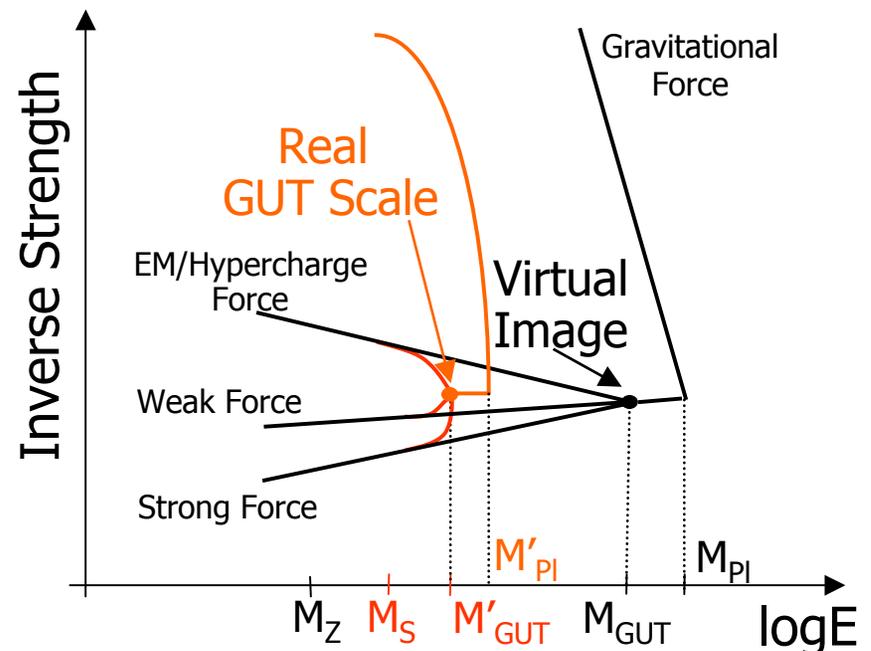


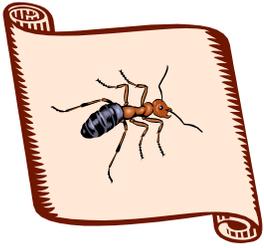


Life Beyond the Standard Model

- ✚ 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. $\Lambda \sim 1 \text{ TeV}$
- ✚ 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 $\sim 1 \text{ TeV}$?!?**
- ✚ **Low energy GUT unification** is also possible with extra dimensions: **Dienes, Dudas, Ghergetta (1998)**



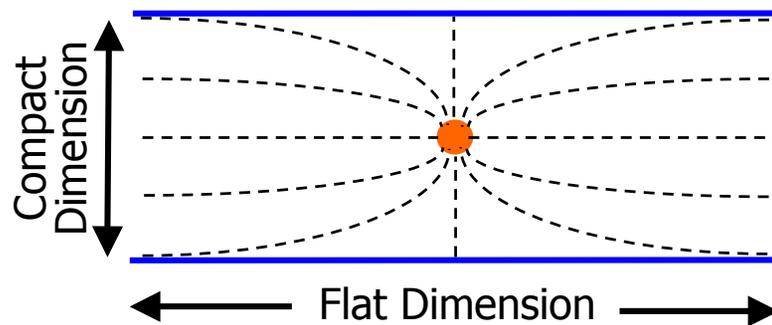


Crazy Idea? – But it Works!

- What about **Newton's law**?

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

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



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

↖ M_S – effective Planck Scale

- But: how to make **gravity strong**?

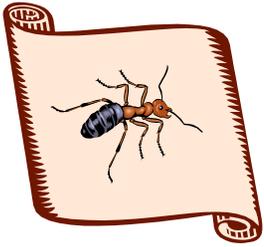
$$G'_N = 1/M_S^2 \sim G_F \Rightarrow M_S \sim 1 \text{ TeV}$$

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

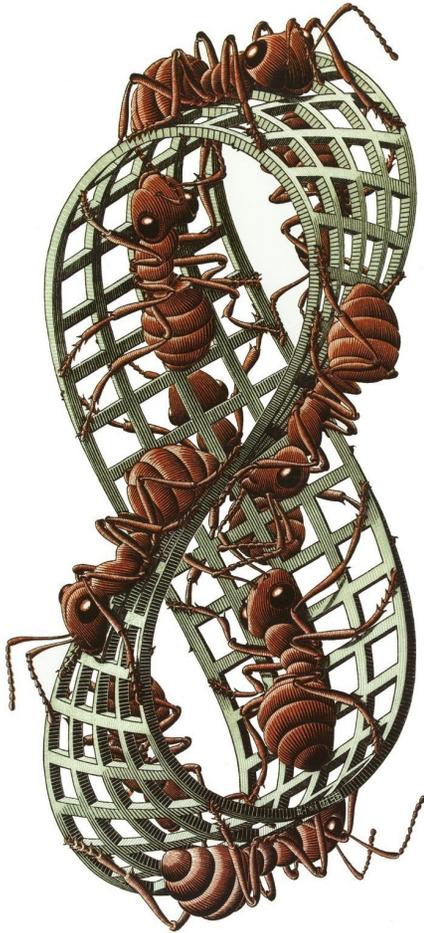
- More precisely, from Gauss's law:

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

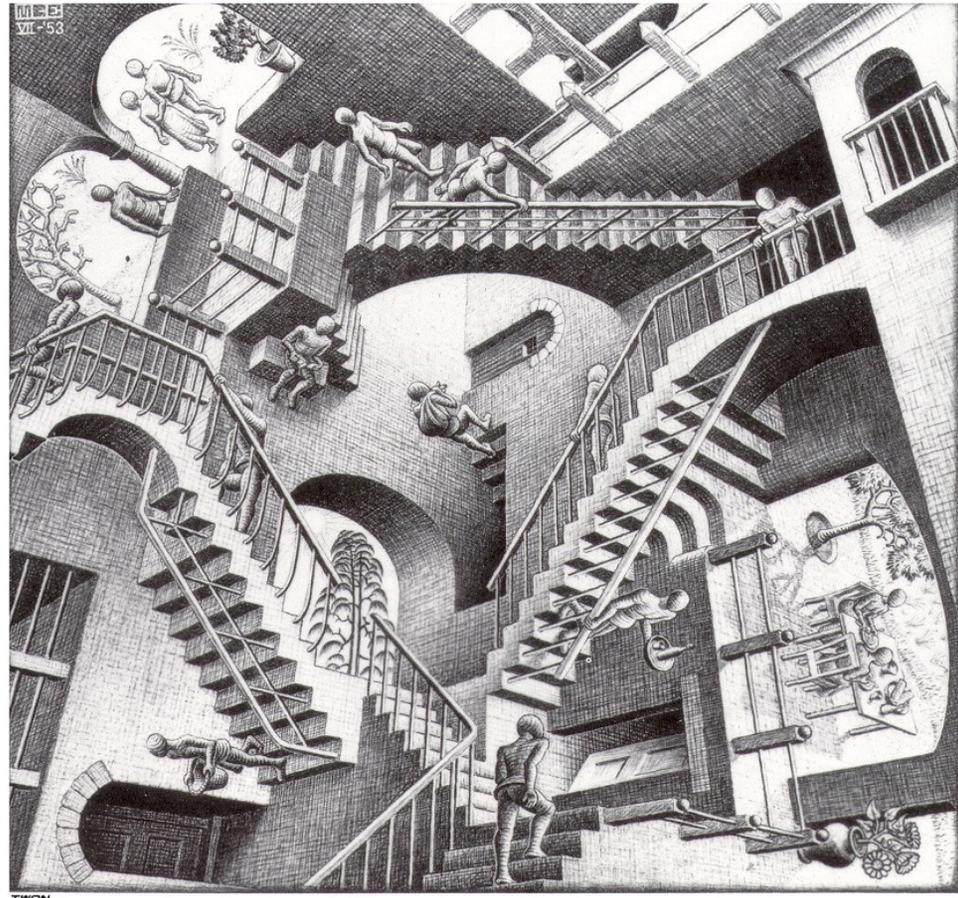
- Amazing as it is, but **no one has tested Newton's law to distances less than ~ 1mm**
- Therefore, **large spatial extra dimensions** compactified at a sub-millimeter scale are, in principle, allowed!



Examples of Compactified Spatial Dimensions



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

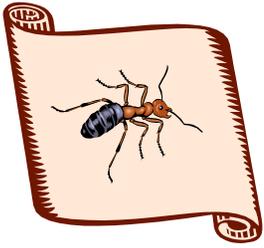


M.C. Escher, Relativity (1953)

[All M.C. Escher works and texts copyright © Cordon Art B.V., P.O. Box 101, 3740 AC The Netherlands. Used by permission.]

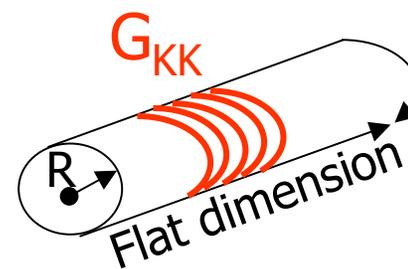
Fermilab W&C, 4/21/2000

Greg Landsberg, Searches for Large Extra Dimensions at D0



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 $\sim 1/R$
- + 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

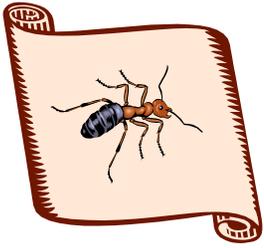


Compactified dimension

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

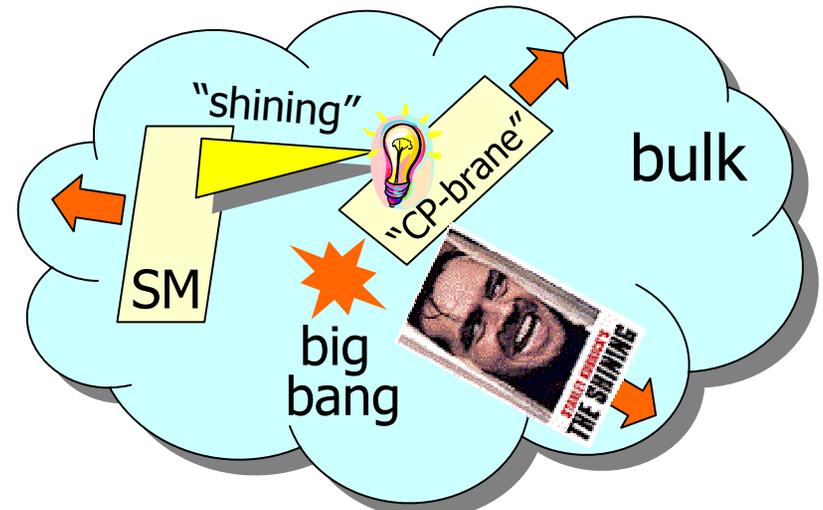
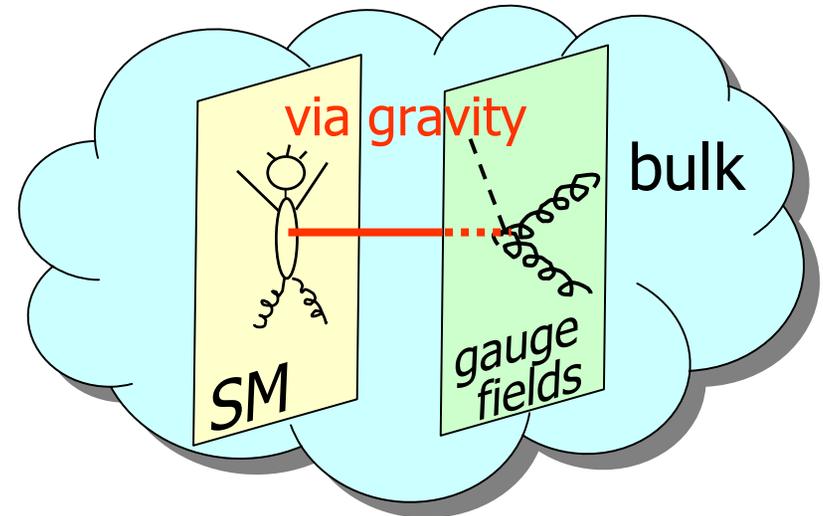
$$M(G_{KK}) = \sqrt{P_x^2} = 2\pi k/R$$

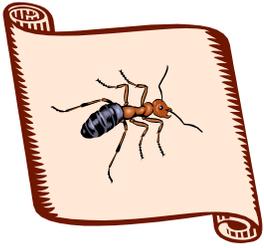
- + Each **Kaluza-Klein graviton mode couples with the gravitational strength**
- + For a large number of modes, accessible **at high energies**, **gravitational coupling is therefore enhanced** drastically
- + **Low energy** precision measurements are **not sensitive** to the ADD effects



Phenomenology of Large Extra Dimensions

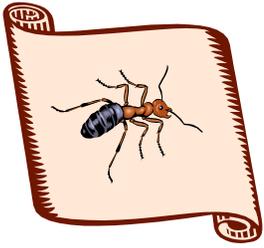
- ✦ **New idea**, inspired by the string theory, with direct connection to the observables
 - ✦ Since large extra dimensions **bring the GUT and gravity scales right at the EWSB scale**, they **solve the hierarchy problem**
 - ✦ There are **multiple mechanisms** that **allow gauge fields in the bulk 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
- ✦ Over **150** theoretical **papers** on this subject over the past two years – truly a **topic du jour**





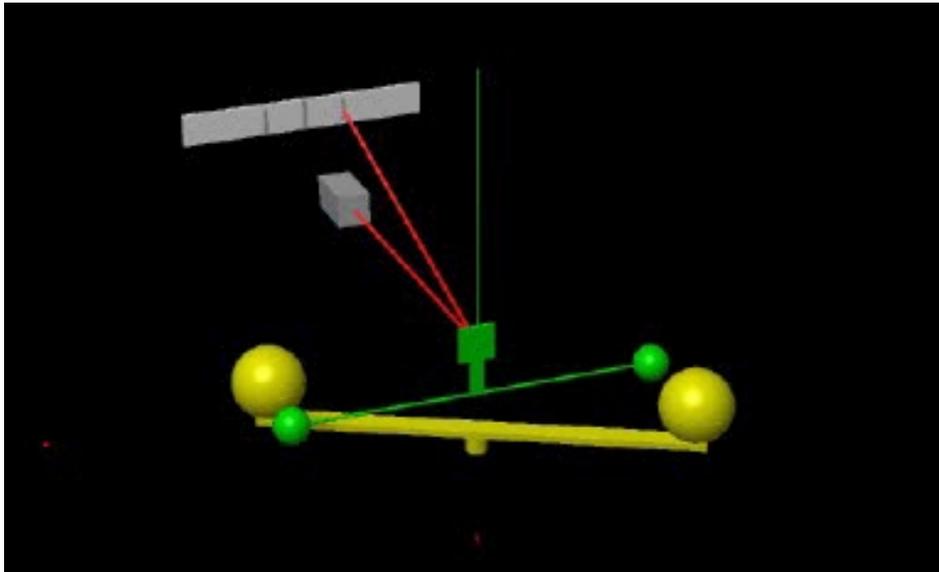
Cosmological Limits on Large Extra Dimensions

- ✚ 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)]:
 - ✚ $M_S > 30 \text{ TeV}$ (n=2)
 - ✚ $M_S > 4 \text{ TeV}$ (n=3)
- ✚ Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \rightarrow \gamma\gamma$ decays
 - ✚ Best CDG measurement come from the COMPTTEL instrument in the 800 KeV - 30 MeV range
 - ✚ Application to the ADD scenario [Hall, Smith, PRD **60**, 085008 (1999)]:
 - ✚ $M_S > 100 \text{ TeV}$ (n=2)
 - ✚ $M_S > 5 \text{ TeV}$ (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



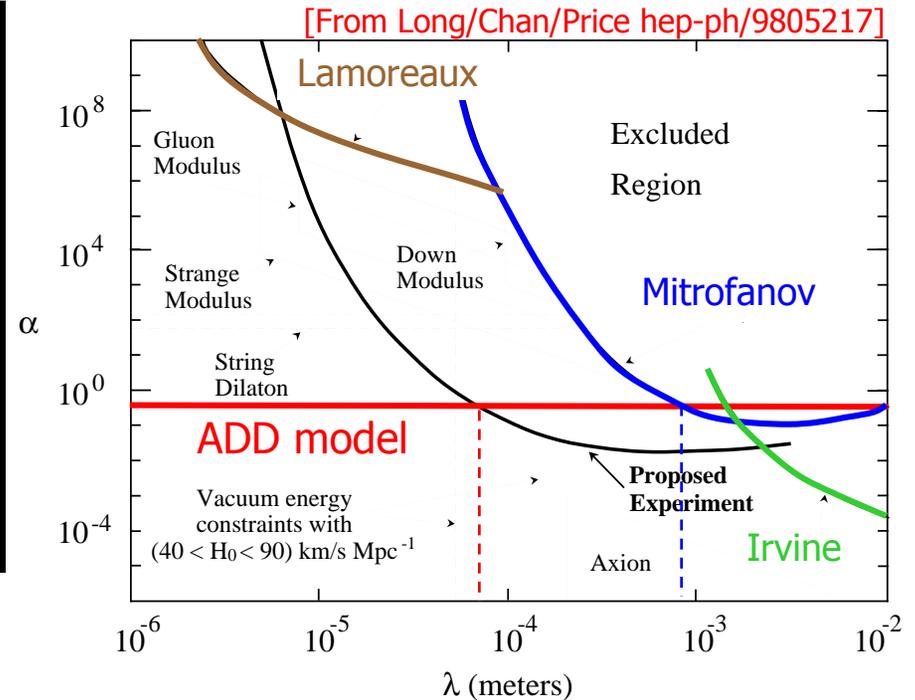
Current Limits from Gravitational Experiments

- 1798: Cavendish experiment (torsion balance)

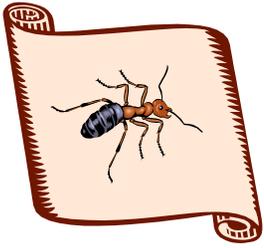


- Mid-1970-ies: a number of Cavendish-type experiments searching for the "fifth forth" via deviations from Newton's law
- Sensitivity vanishes quickly for distances less than 1 mm
- Major background: Van der Waals and Casimir forces

Status of short-range gravity experiments

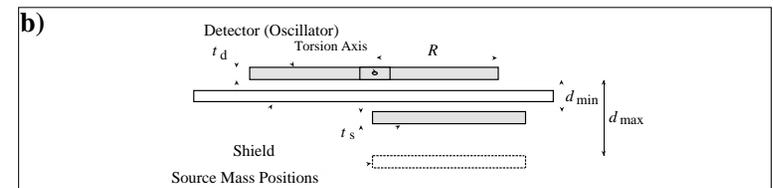
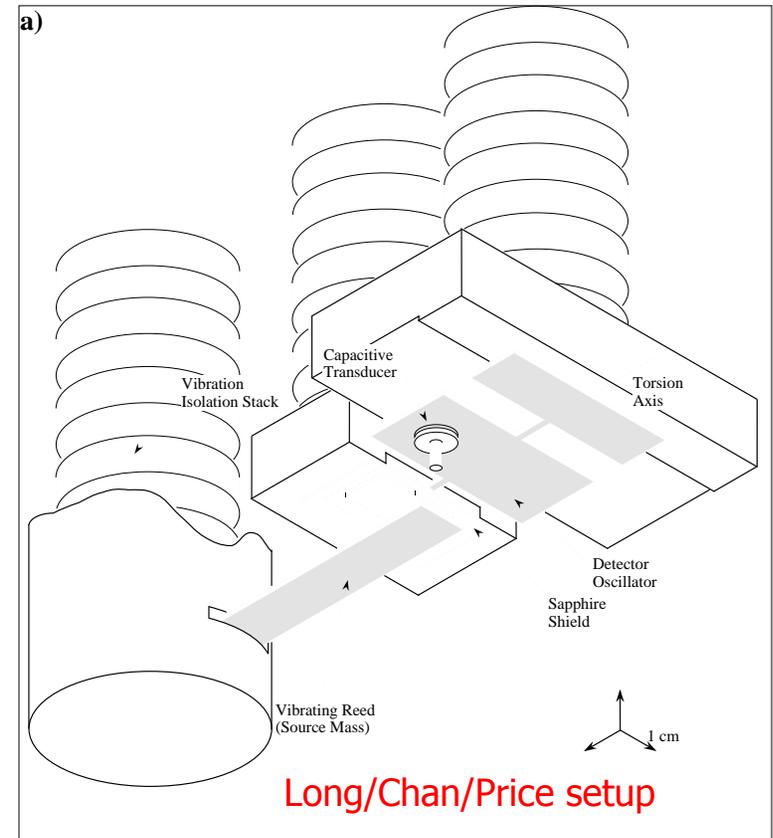


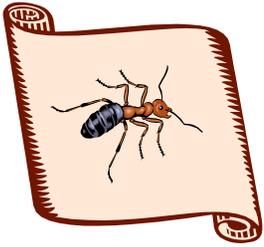
- Best sub-millimeter results are from 1997 Lamoreaux experiment [PRL **78**, 5 (1997)] to measure the Casimir force
- Sensitivity is many orders of magnitude lower than needed to test ADD theory



New Generation of Gravitational Experiments

- ✚ **New generation** of precision experiments to measure gravity at short distances (100 μm or less) is being built:
 - ✚ Long/Chan/Price @ Colorado
 - ✚ Kapitulnik/Kenny @ Stanford
- ✚ **Colorado setup:**
 - ✚ Use **low temperatures** and **SQUID** resonance pickup (~ 1 KHz) to increase the sensitivity and diminish seismic and vibrational effects
 - ✚ Gold-foil **shield against the Van der Waals force** (Casimir force is small for distances > 1 μm)
 - ✚ Plan to **measure** gravity at the distances **between 100 μm and 1 mm**; to a precision necessary to test the ADD model
 - ✚ **Future LHe experiment** will be able to probe gravity at even shorter distances ~ 10 μm
- ✚ **First results** from both experiments are expected **this Spring**; will be able to **test $n=2$** , but can not probe higher number of dimensions
- ✚ One needs **particle accelerators** to probe gravity at **sub-micrometer** distances

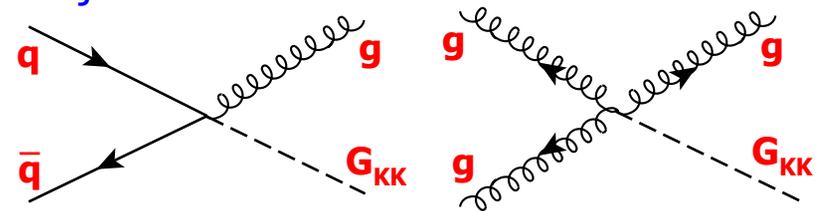




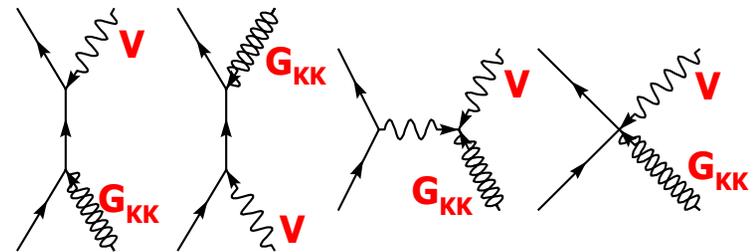
Collider Signatures for Large Extra Dimensions

- ✚ 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 general 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

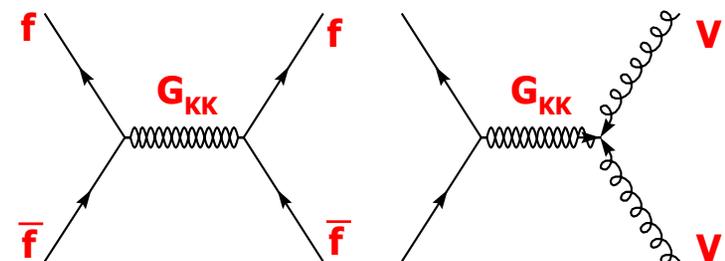
Real Graviton Emission Monojets at hadron colliders

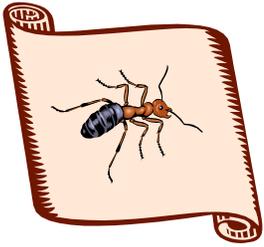


Single VB at hadron or e^+e^- colliders



Virtual Graviton Emission Fermion or VB pairs at hadron or e^+e^- colliders





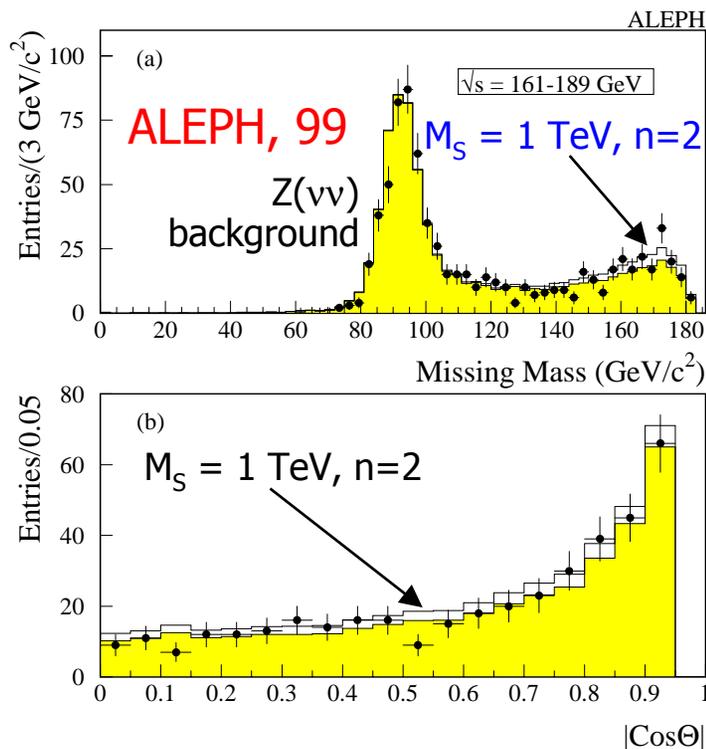
LEP2 Searches for Direct Graviton Emission - I

$$e^+e^- \rightarrow \gamma G_{KK}$$

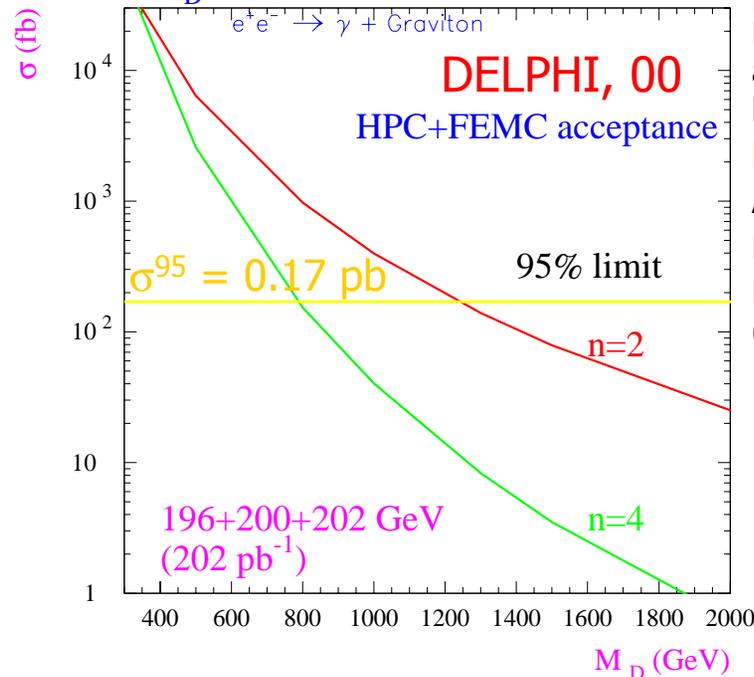
- Photon + M_{E_T} signature
- "Recycling" of the GMSB analyses
- ALEPH (2D-fit), DELPHI, L3 (x)

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

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



$M_D > 1250 \text{ GeV}$ for $n=2$
 $M_D > 792 \text{ GeV}$ for $n=4$



Theory:

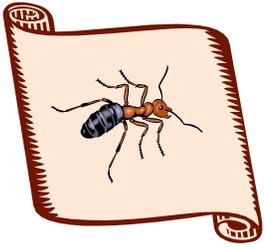
[Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999) and corrected version: hep-ph/9811291]

Experiment:

ALEPH-CONF-2000-005
 DELPHI 2000 CONF 344
 L3: Phys. Lett. **B470**, 268 (1999)

Results:

$M_S > 1.3-0.6 \text{ TeV}$ for $n=2-6$ (DELPHI)
 ALEPH, L3 – slightly worse



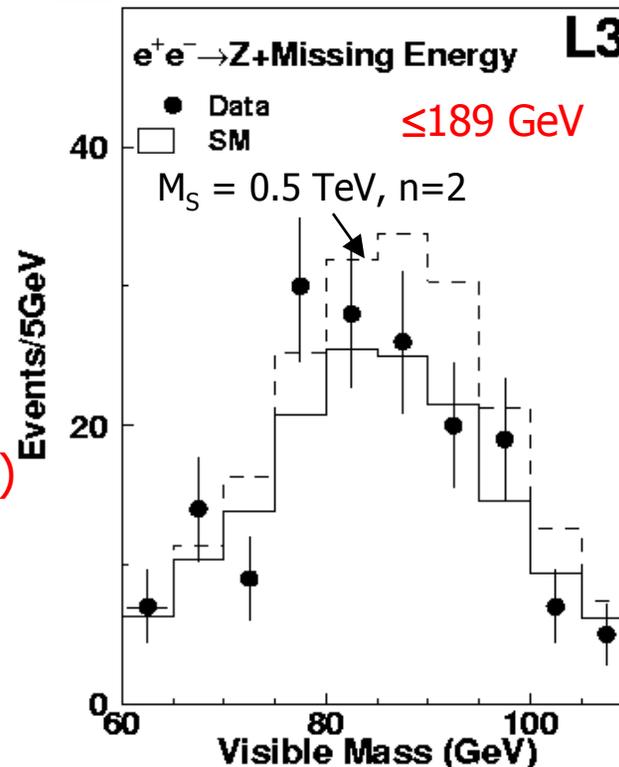
LEP2 Searches for Direct Graviton Emission - II

$$e^+e^- \rightarrow ZG_{KK}$$

- ✚ 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 $n = 2-6$

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

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

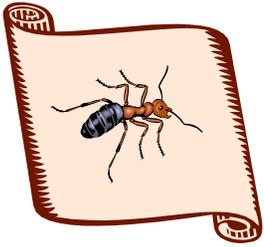


Theory:

[Balazs, Dicus, He, Repko, Yuan, Phys. Rev. Lett. **83**, 2112 (1999) – width ratio]
 [Cheung, Keung, Phys. Rev. **D60**, 112003 (1999) – mass distribution]

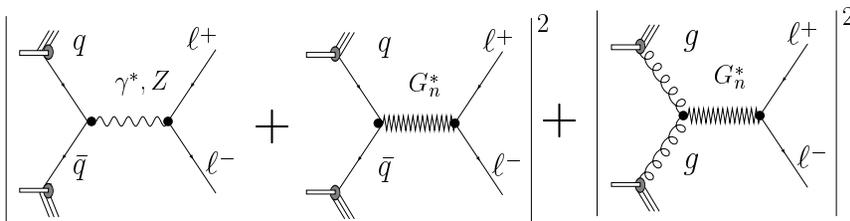
Experiment:

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 $\approx M_S$** , as this is the scale at which the effective theory breaks down, and the string theory needs to be used to calculate production

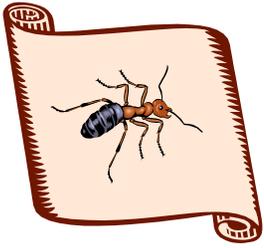
- Unfortunately, **a number of similar papers** calculating the virtual graviton effects appeared simultaneously

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

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

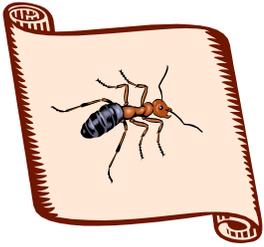
$$\frac{\lambda}{M_S^4(\text{Hewett})} = \frac{\pi}{2} \frac{F}{M_S^4(\text{HLZ})}$$

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

- Rule of thumb**:

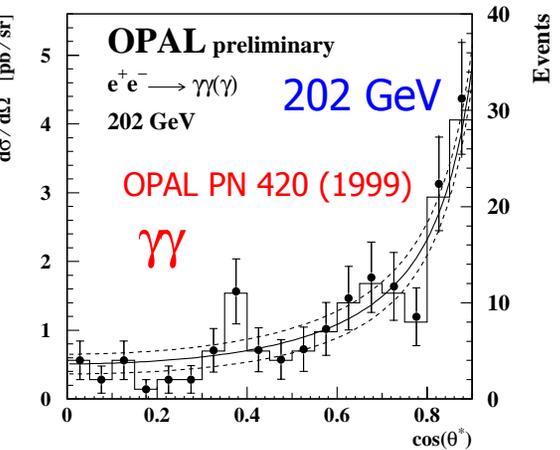
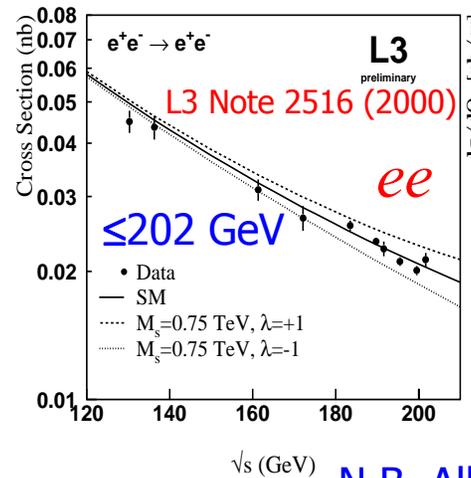
$$M_S(\text{Hewett})|_{\lambda=1} \approx M_S(\text{HLZ})|_{n=5}$$

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

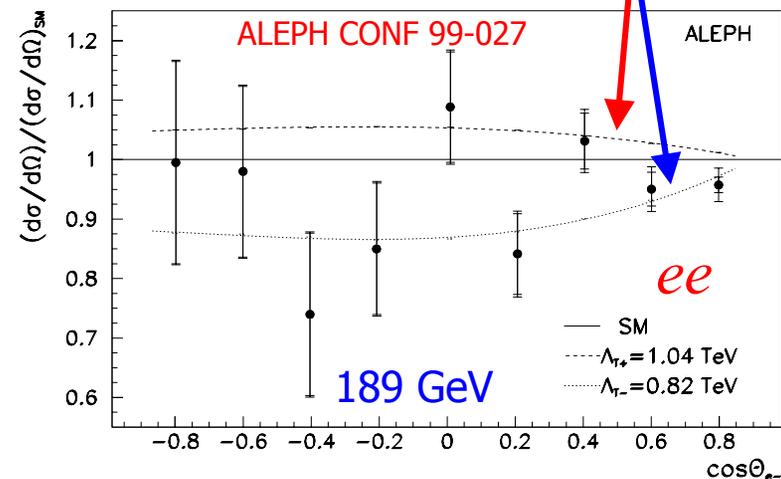


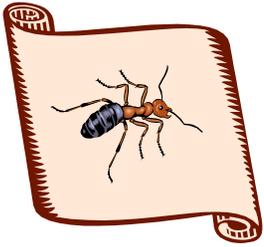
LEP2 Searches for Virtual Graviton Effects

- ✚ 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) \sim **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



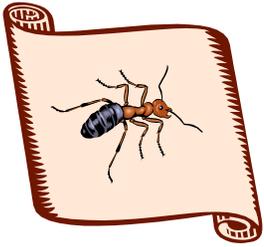


LEP2 Lower 95% CL M_S (Hewett) Limits (TeV)

Experiment	$e^+e^- \rightarrow \gamma G$					$e^+e^- \rightarrow ZG$					Color coding
	n=2	n=3	n=4	n=5	n=6	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	≤184 GeV
DELPHI	1.25	0.97	0.79	0.68	0.59						≤189 GeV
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	0.24	0.21	≤202 GeV
OPAL											$\lambda=-1$ $\lambda=+1$ 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) M_S for $\gamma\gamma$ is wrong?
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) M_S for $\gamma\gamma$ is wrong?



Virtual Graviton Exchange at the Tevatron

Virtual graviton Drell-Yan and diphoton production

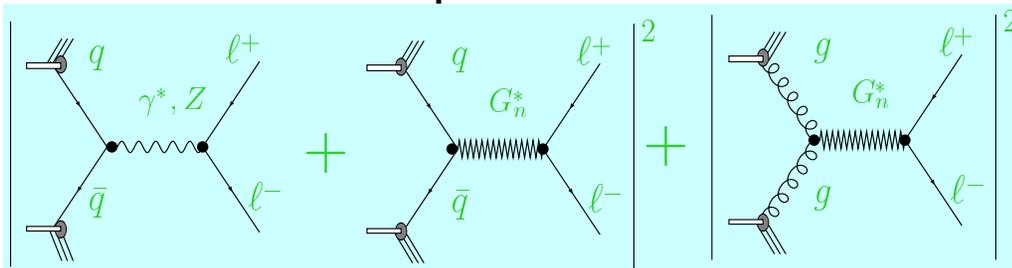
- Mass spectrum has been looked at [Gupta, Mondal, Raychaudhuri, hep-ph/9904234; Cheung, Phys. Rev. **D61**, 015005 (2000), Phys. Lett. **B460**, 383 (1999),...]
- Key improvement [Cheung, GL, hep-ph/9909218, to appear in PRD]: simultaneous analysis of the mass and angular distributions, as a spin 2 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

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

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

Dileptons:



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

Diphotons:

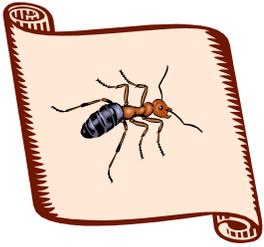
$$\frac{d^2\sigma}{dzdM_\gamma} = \sum_q \iint dx_1 dx_2 f_q(x_1) f_q(x_2) \frac{K(1+z^2)}{96\pi M_\gamma^2} \times$$

$$\left[\frac{2e^4 Q_q^4}{1-z^2} + 2\pi e^2 Q_q^2 \eta M_\gamma^4 + \frac{\pi^2}{2} (1-z^2) \eta^2 M_\gamma^8 \right] +$$

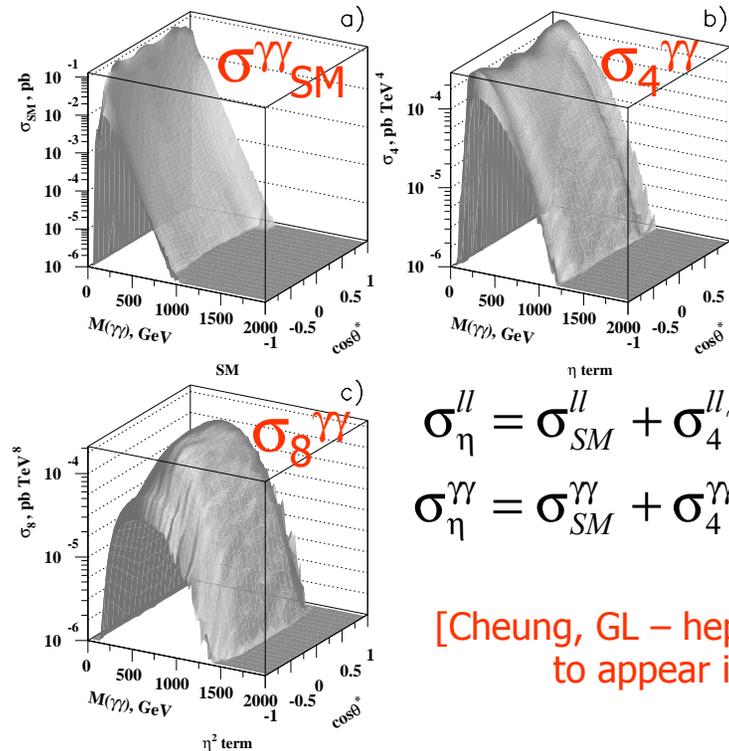
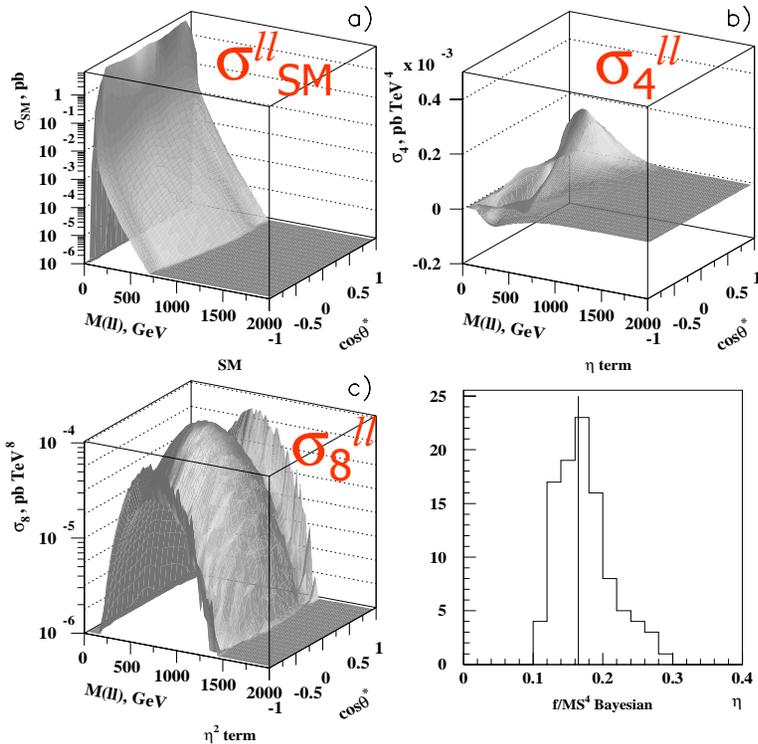
SM interference term G_{KK} term

$$\iint dx_1 dx_2 f_g(x_1) f_g(x_2) \frac{K(1+6z^2+z^4)}{512 M_\gamma^2} \eta^2 M_\gamma^8$$

G_{KK} term



Two-Dimensional Analysis



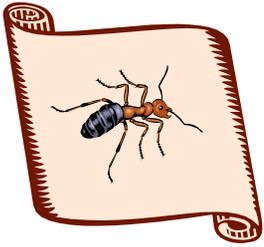
$$[\eta] = \text{TeV}^{-4}$$

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

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

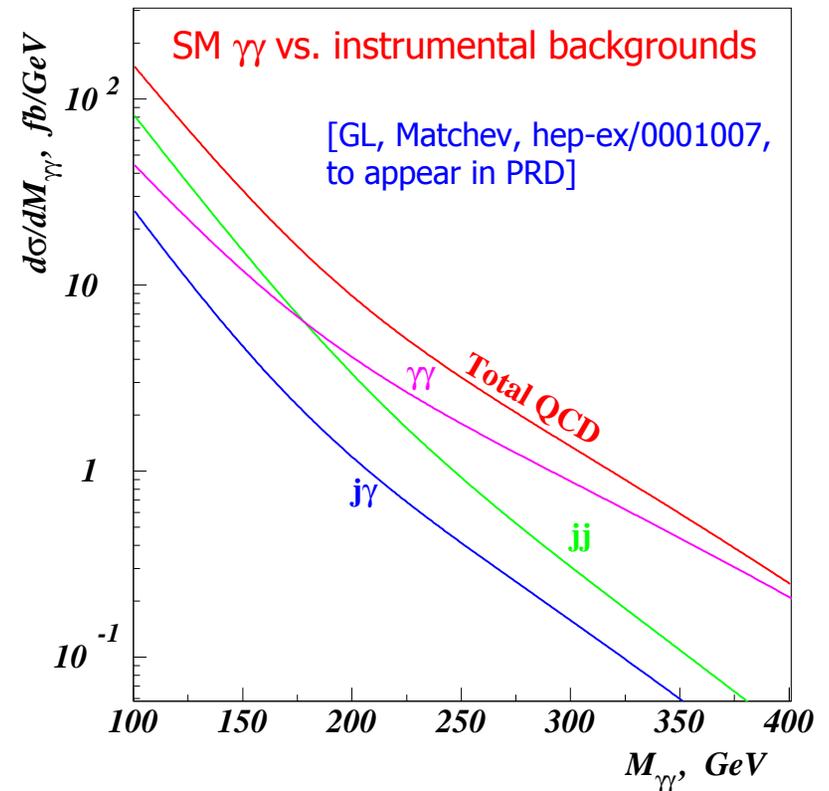
[Cheung, GL – hep-ph/9909218, to appear in PRD]

- 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 $\int L dt$) **higher** than that in 1-dimensional analysis
- Diphoton** channel is considerably **more sensitive** than the **dilepton** one

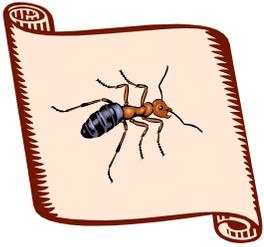


DØ Search for Large Extra Dimensions

- ✚ 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** ($\sim 50\%$) 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**

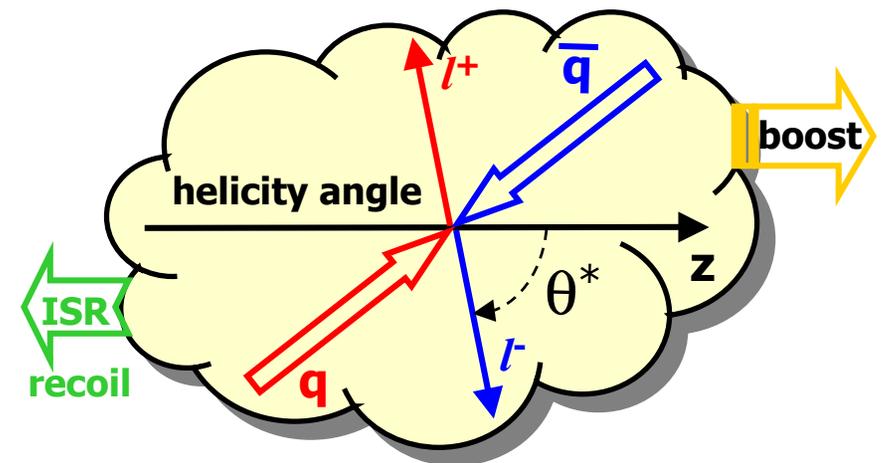
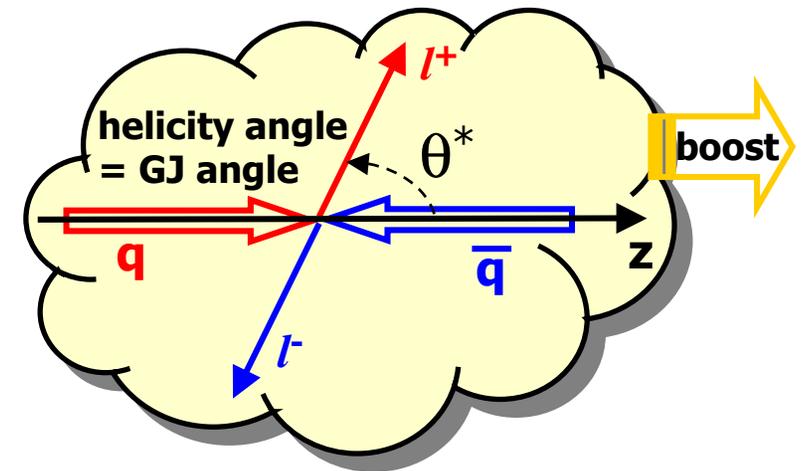


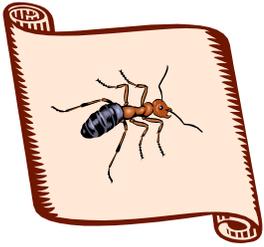
- ✚ Use **EM cluster shape information** to pick the hard-scattering vertex, thus improving mass and $\cos\theta^*$ resolution



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



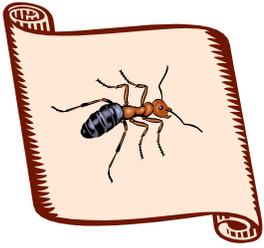


Data Selection and Efficiency

- ✚ Use **entire Run I statistics** from full luminosity, low-threshold di-EM triggers, $\int \mathcal{L} dt = 127 \pm 6 \text{ pb}^{-1}$
- ✚ **Offline cuts** are determined by the availability of background triggers:
 - ✚ Exactly 2 EM clusters w/ $E_T > 45 \text{ GeV}$, $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$ passing **basic ID** criteria:
 - ✚ $EMF > 0.95$
 - ✚ $ISO < 0.10$
 - ✚ $\chi^2 < 100$
 - ✚ $ME_T < 25 \text{ GeV}$
 - ✚ **No other kinematic cuts** in the analysis, as the $M/\cos\theta^*$ space completely defines the process
- ✚ Resulting data sample contains **1282 events**
- ✚ **Efficiency of the ID cuts** is determined from the **Z-peak** data obtained with the same triggers by lowering the $E_T(\text{EM})$ cut

Cut	# of events
Starting sample	86,013
Quality cuts	84,509
≥ 2 EM	84,490
$= 2$ EM	83,976
$E_T > 25 \text{ GeV}$	37,146
Acceptance	31,210
EM ID	10,945
$E_T > 45 \text{ GeV}$	1,282

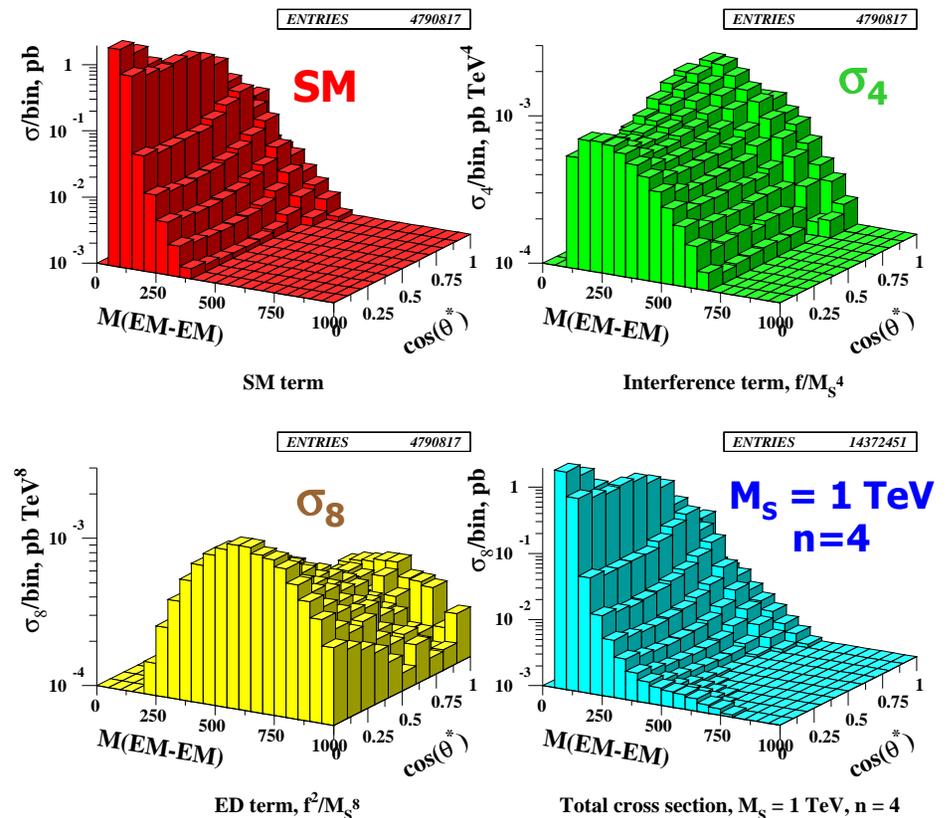
Cut	Efficiency
EM ID	$(88 \pm 2)\%$
$ME_T < 25 \text{ GeV}$	$(99.0 \pm 0.5)\%$
Event quality	$(99.4 \pm 0.5)\%$
Overall, per event	$(76 \pm 2)\%$

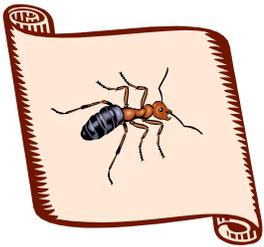


Signal and SM Background Monte Carlo

- Based on **Cheung/GL LO parton level generator** [hep-ph/9909218] 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** (CTEQ4L and other modern p.d.f.)
 - K-factor** correction to the cross sections
 - Both **SM** and **gravity** effects

MC Simulation of the ED signatures





Summary of the Backgrounds

SM backgrounds in the MC:

- Drell-Yan

- $\gamma\gamma$ ($gg \rightarrow \gamma\gamma$ is negligible \Rightarrow not included)

- Other SM backgrounds are mostly at low masses and are completely negligible:

- $W+j/\gamma$ < 0.4%

- WW < 0.1%

- top < 0.1%

- $Z \rightarrow \tau\tau$ < 0.1%

- $Z+\gamma$ < 0.01%

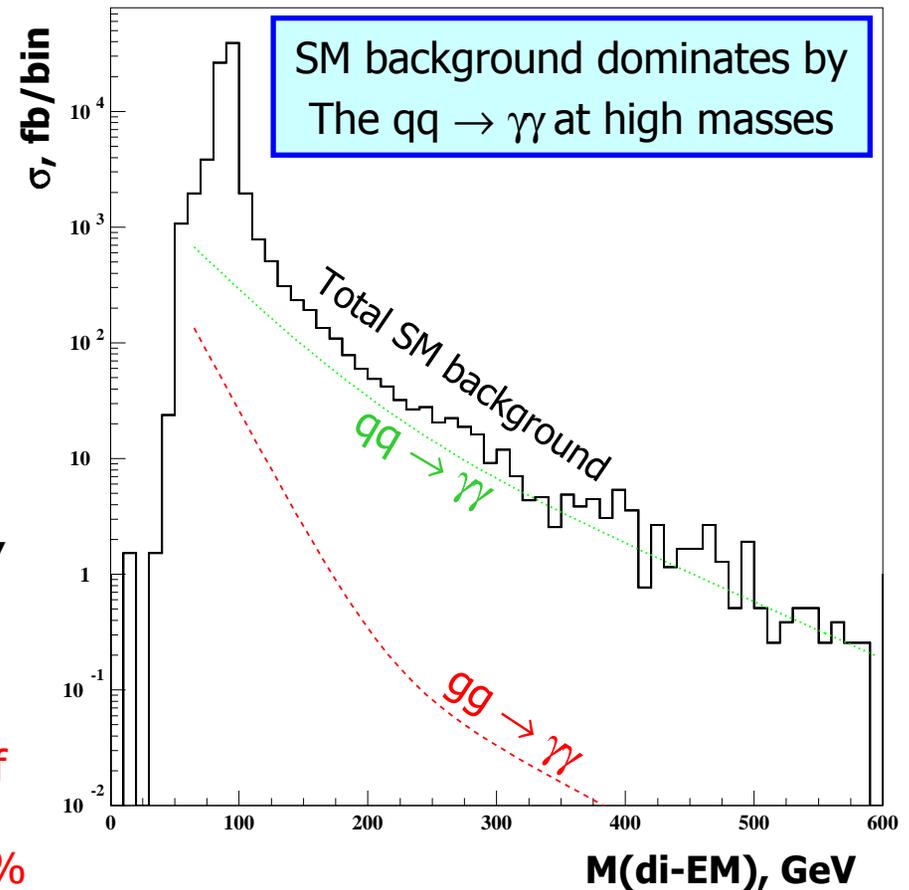
- Other < 0.01%

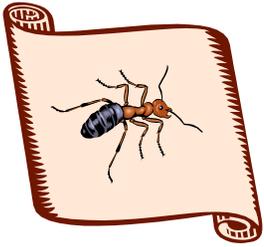
- Instrumental background from $jj/j\gamma \rightarrow \gamma\gamma$ due to jets fragmenting in a leading π^0

- 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 $\sim 7\%$

- Conservatively ignore small backgrounds





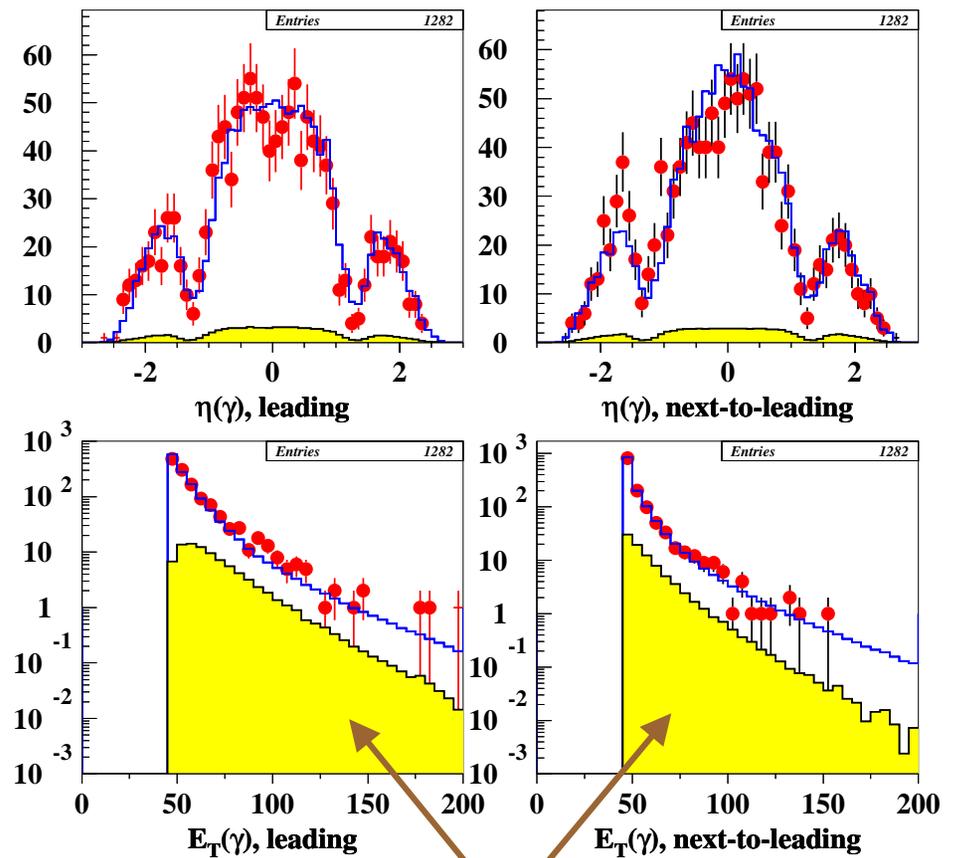
MC Description of the Data and Systematics

- 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:

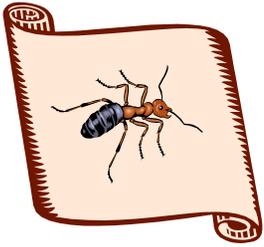
Source	Uncertainty
K-factor	10%
p.d.f. choice	5%
$\int L dt$	4%
Efficiency	3%
Normalization at low M	10%
Overall	16%

- Additional **10% conservative systematic error is assigned** to address a small normalization discrepancy for released E_T cuts (see cross-checks)

Agreement between the MC and the data



Instrumental background (25% uncertainty)



Fitting Procedure: Extracting Gravity Effects

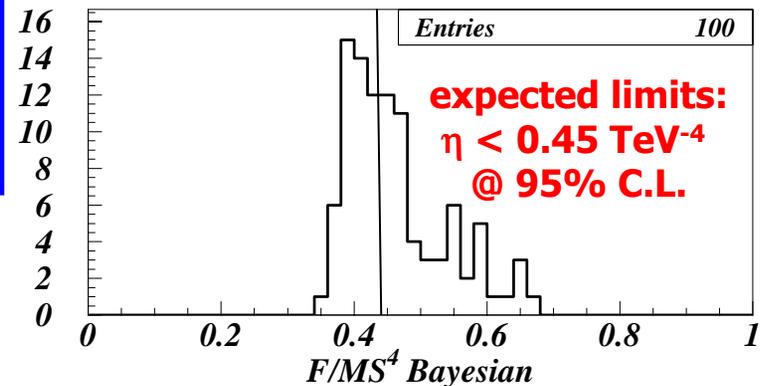
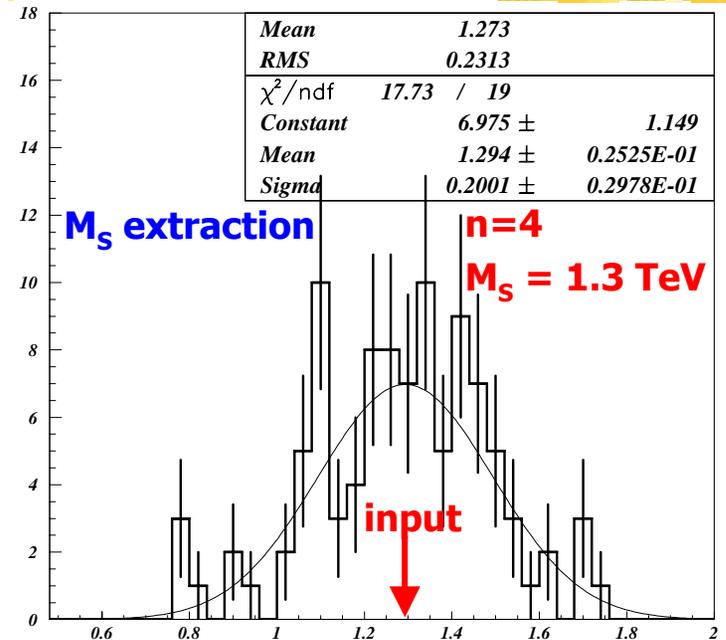
- Bin the data in a $M \times \cos\theta^*$ grid (up to 40×10 bins; $M \in [0, 2 \text{ TeV}]$, $\cos\theta^* \in [0, 1]$)
- Parameterize cross section in each bin as a bilinear form in η : $\sigma = \sigma_{SM} + \eta\sigma_4 + \eta^2\sigma_8$
- Use Bayesian fit with flat prior (in η) to extract the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

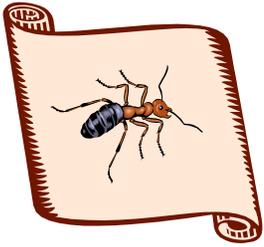
$$P(N | \eta, B) = \sum_{i,j} \frac{(S_{ij} + B_{ij})^{n_{ij}} e^{-(S_{ij} + B_{ij})}}{n_{ij}!}, \quad S_{ij} = \epsilon \sigma_{ij} \int L dt$$

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

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

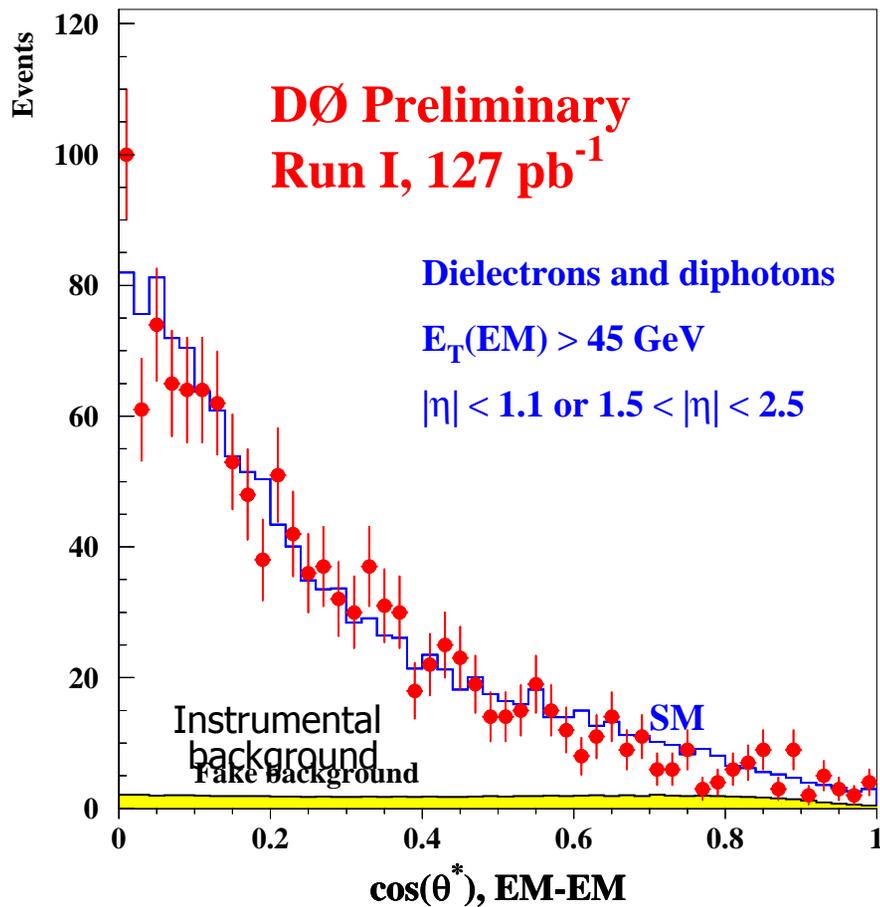
- Also cross-check with a simple maximum likelihood method



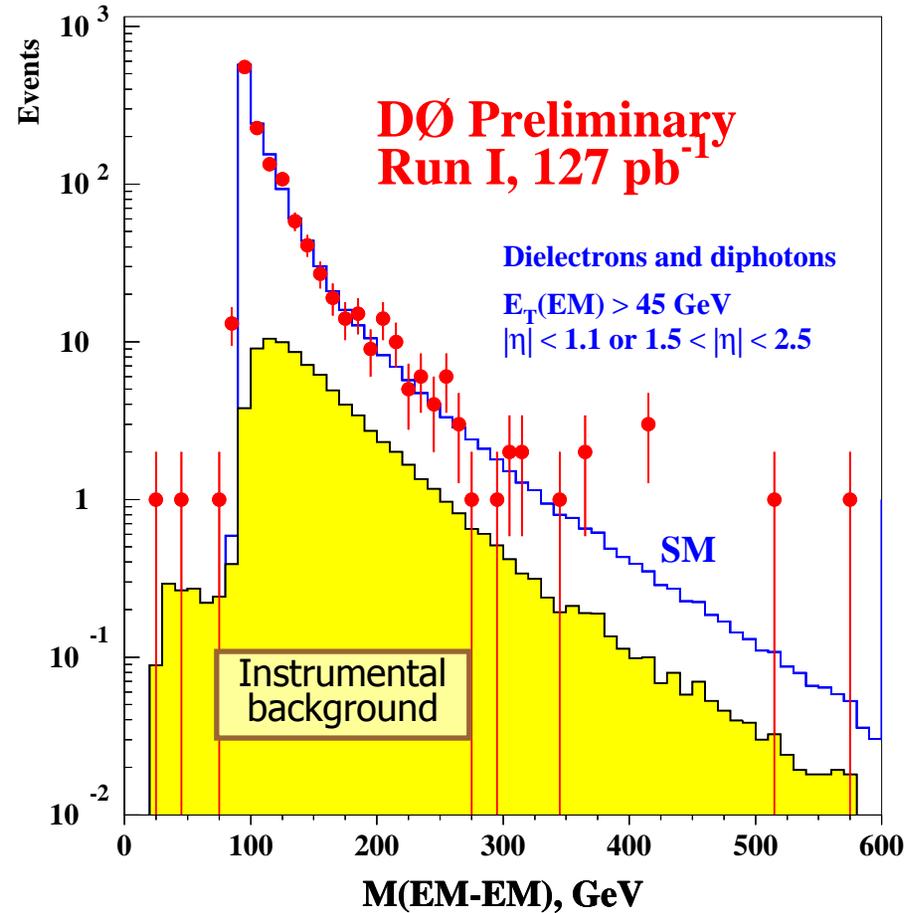


DØ Results - I

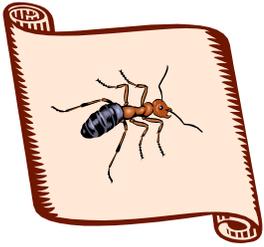
Comparison of the data with the SM predictions Comparison of the data with the SM predictions



Data agree well with the SM



Note zero-events bins at high masses!

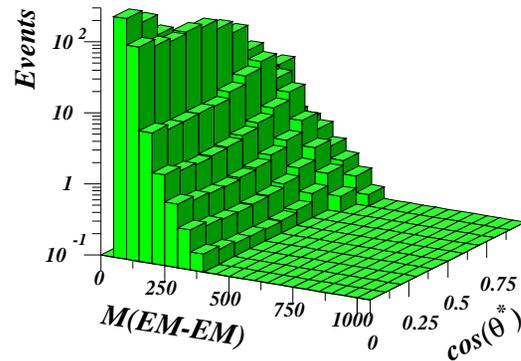


DØ Results - II

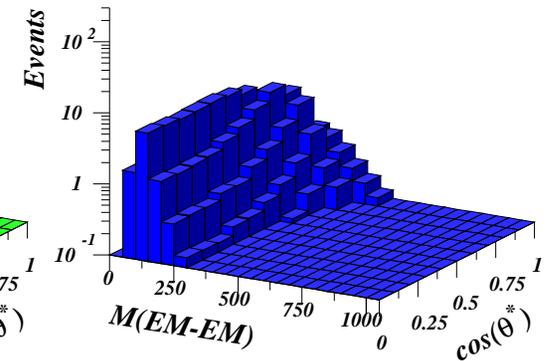
✚ Data are in a **good agreement** with the SM predictions

Comparison of the data and the SM predictions

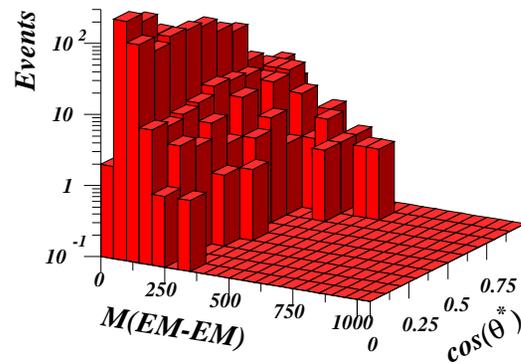
Mass cut	N	B	ρ
> 100 GeV	713	739	0.83
> 150 GeV	146	156	0.80
> 200 GeV	62	59.1	0.37
> 250 GeV	23	26.5	0.78
> 300 GeV	12	12.8	0.63
> 350 GeV	7	6.6	0.49
> 400 GeV	5	3.4	0.26
> 450 GeV	2	1.7	0.51
> 500 GeV	2	0.75	0.17
> 550 GeV	1	0.26	0.23
> 600 GeV	0	<0.1	1.00



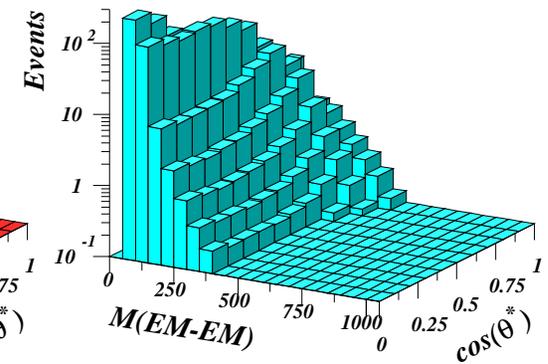
SM ee and $\gamma\gamma$ production



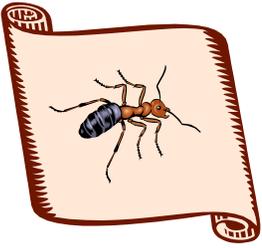
QCD jet background



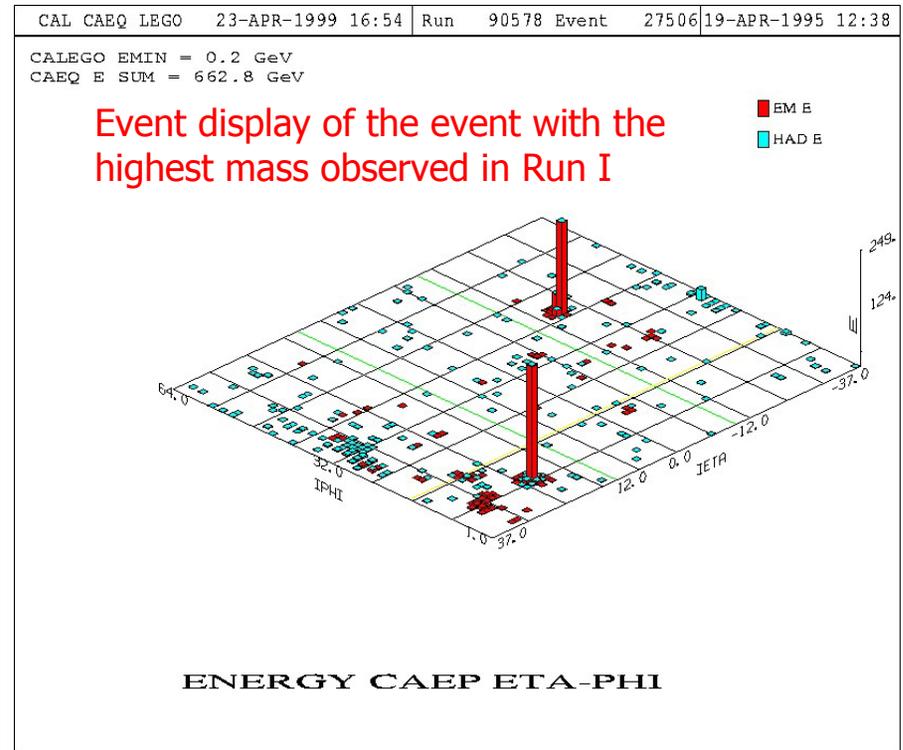
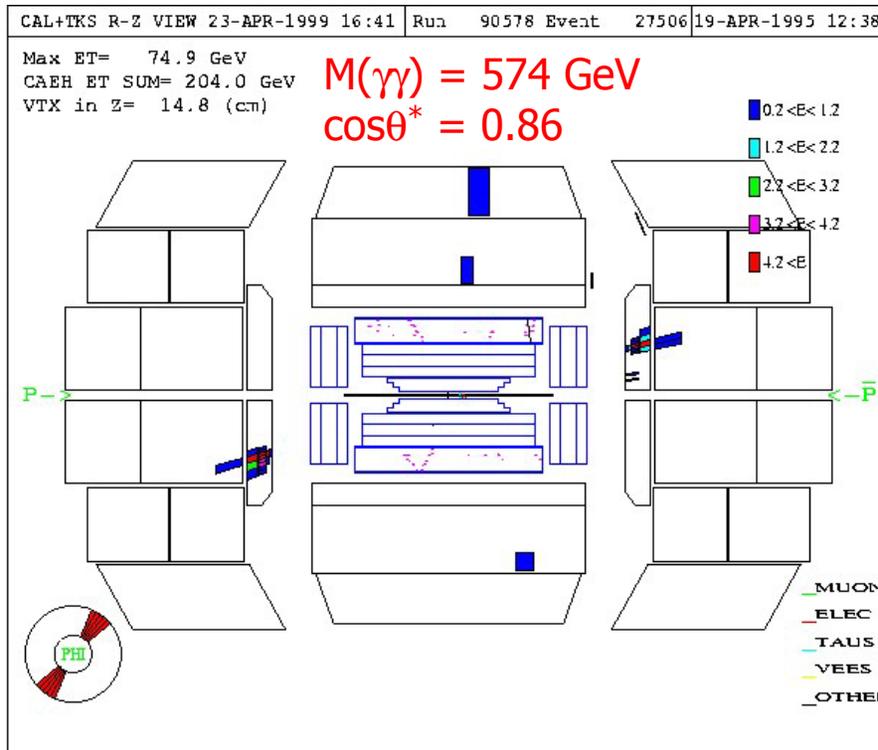
Data



Total background

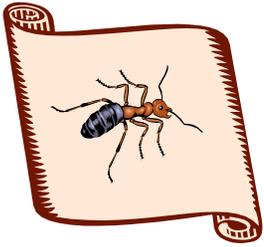


High-Mass Candidate Events



Parameters of the two high-mass candidate events:

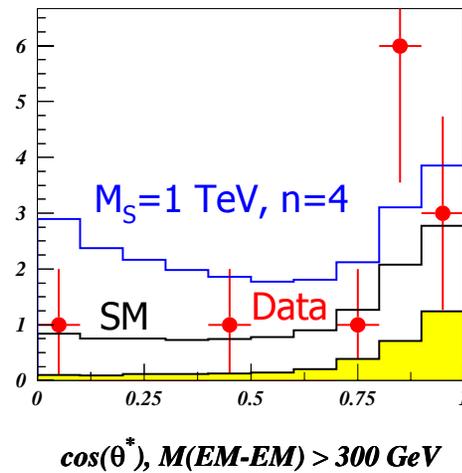
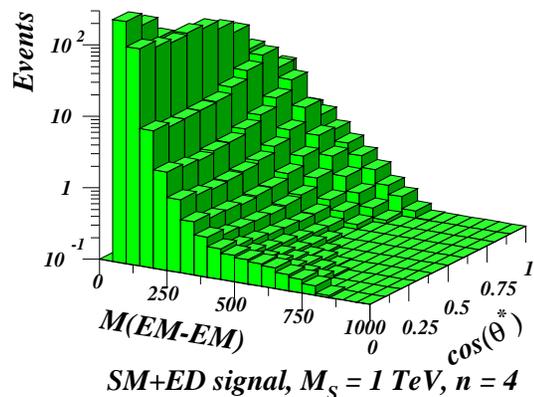
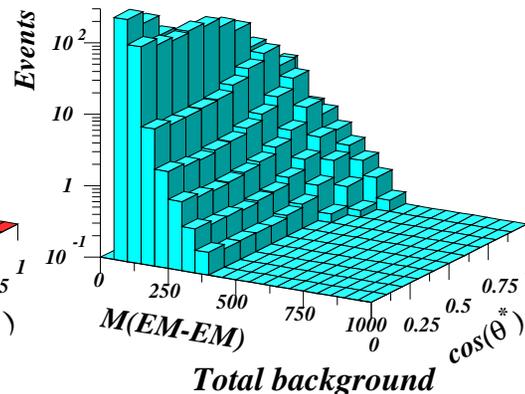
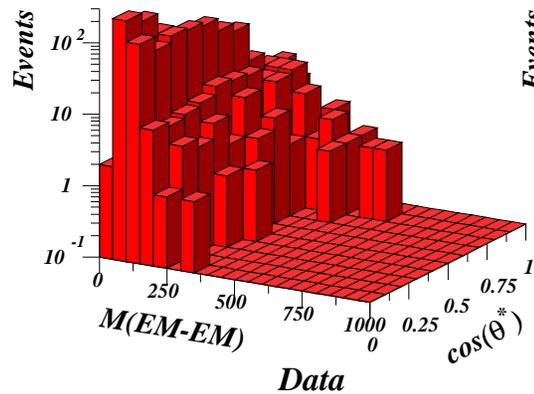
Run	Event	Z_{vtx}	ME_T	Type	E_T^1	E_T^2	η_1	η_2	M	$\cos\theta^*$	N_{jet}	$P_T\text{-kick}$
90578	27506	3.6 cm	15 GeV	$\gamma\gamma$	81 GeV	81 GeV	1.98	-1.91	575 GeV	0.86	0	11.7 GeV
84582	11674	-34 cm	15 GeV	ee	134 GeV	132 GeV	0.99	-1.59	520 GeV	0.84	0	18.8 GeV



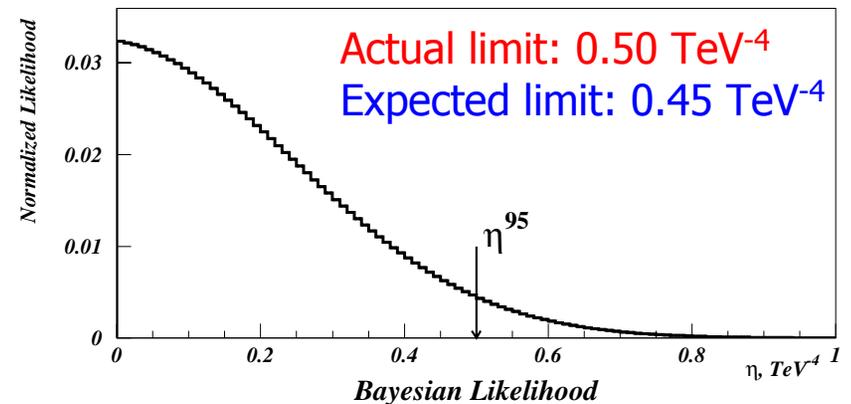
Expected Signal

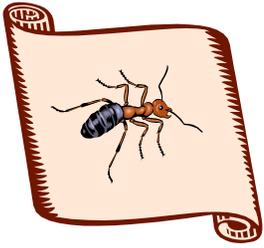
Comparison of the data and the SM predictions

DØ Preliminary, Run I, 127 pb⁻¹



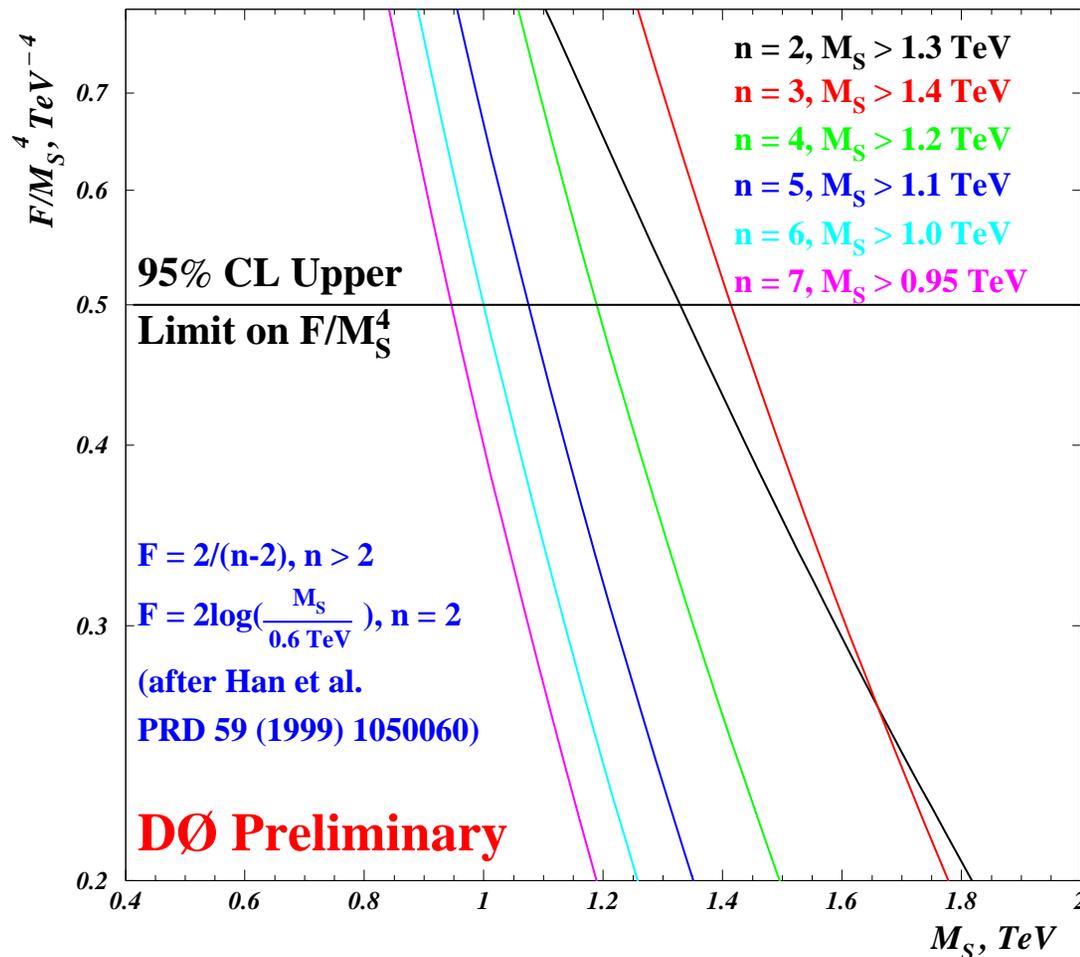
- ✚ Data **do not support** extra dimensions hypothesis
- ✚ **No excess of events is seen** at high masses and low scattering angles, where the signal is expected to exhibit itself
- ✚ In the absence of evidence for extra dimensions **we proceed with setting limits** on their size



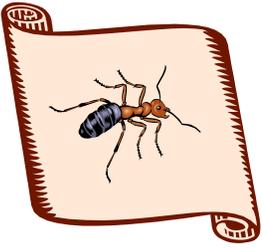


DØ Limits on Large Extra Dimensions

Limits on Large Spatial Extra Dimensions

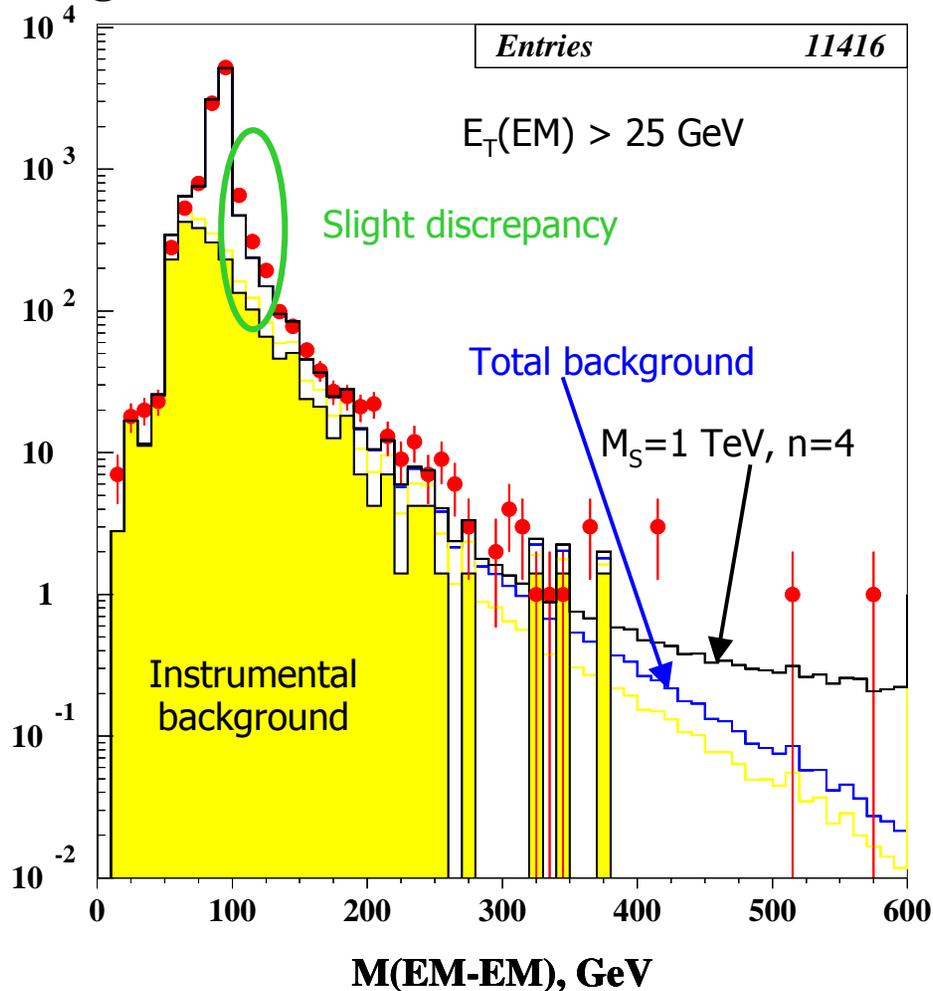


- For $n > 2$ M_S limits can be obtained directly from η limits
- For $n = 2$, use average \hat{s} for gravity contribution ($\langle \hat{s} \rangle = 0.36 \text{ TeV}^2$, see hep-ph/9909218)
- As $n = 2$ case has been ruled out by cosmological constraints, and is within the reach of the current gravity experiments, such an approximation is good enough
- Finally, translate limits in Hewett and GRW frameworks for easy comparison with other experiments:
 - $M_S(\text{Hewett}) > 1.1 \text{ TeV}$
 - $\Lambda_T(\text{GRW}) > 1.2 \text{ TeV}$
- These 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}

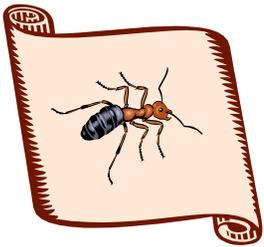


Cross-Checks: Lower $E_T(\text{EM})$ -Cut

Agreement between the MC and the data

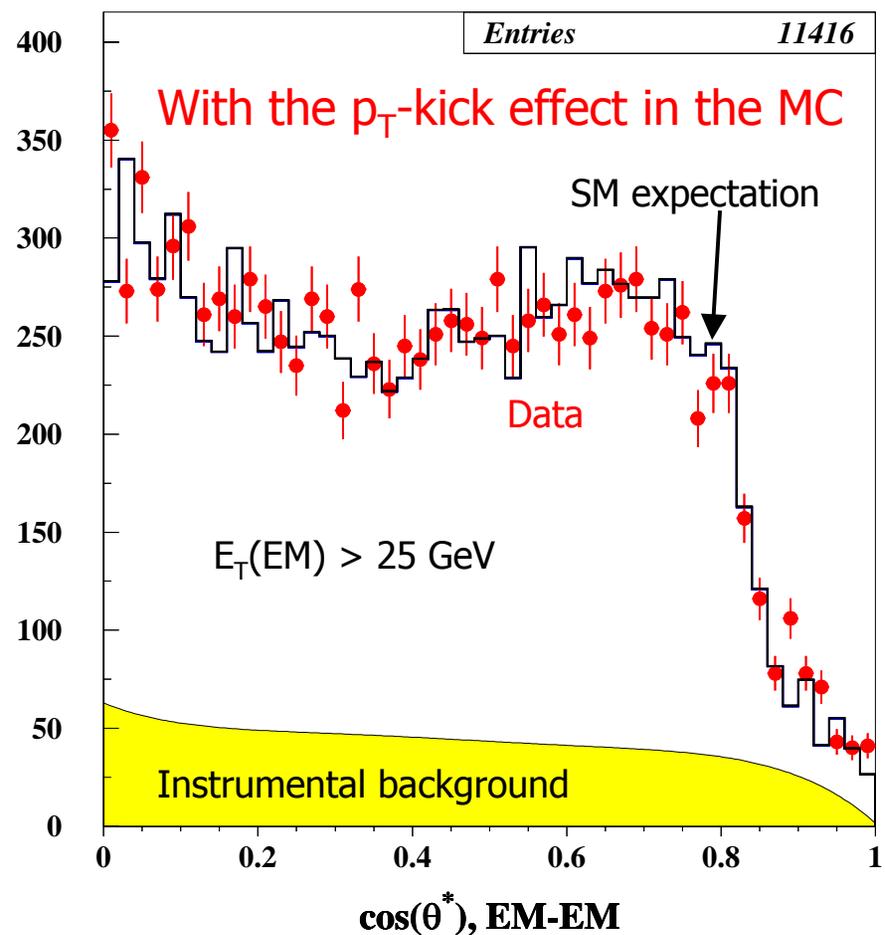
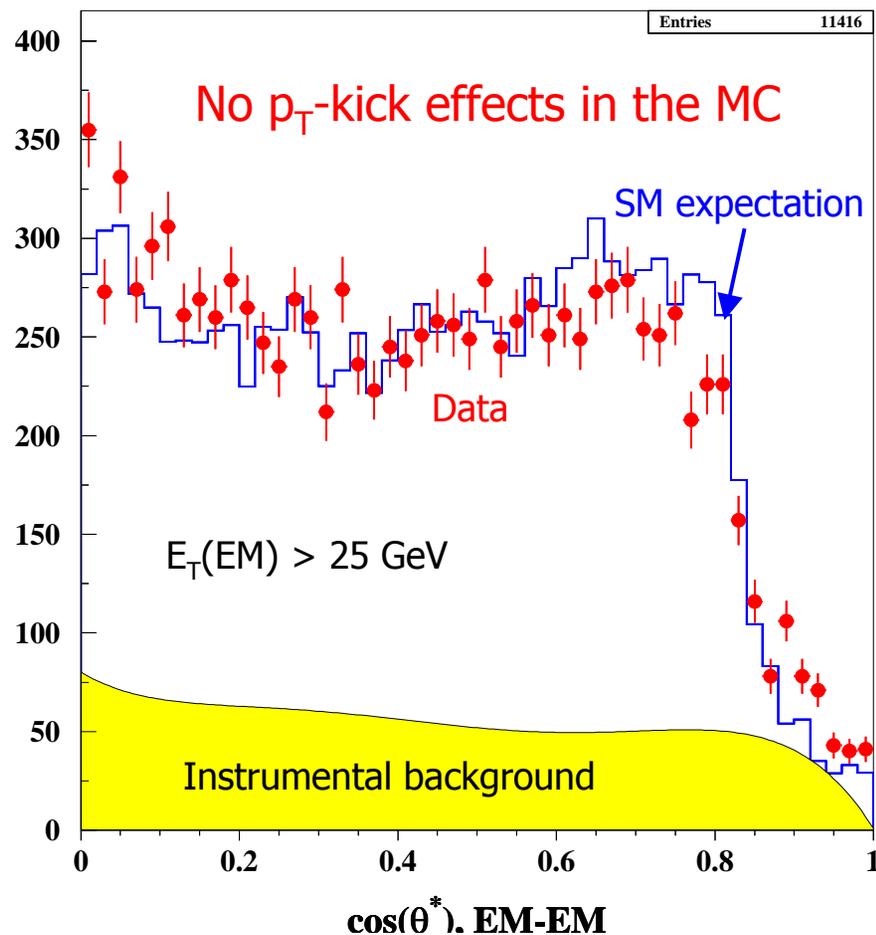


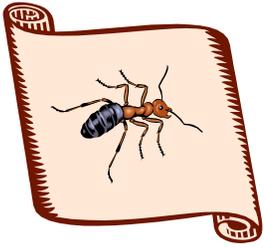
- ✚ We attempted to **lower the $E_T(\text{EM})$ cut to 25 GeV** for cross-checks
- ✚ There is **no** unrescaled background trigger available with such a low threshold, so the background statistics at high masses is very low
- ✚ There is a **slight discrepancy** observed in the upper tail of the Z-peak, **around 120 GeV**, which would have resulted in 10% normalization uncertainty, had the $E_T(\text{EM})$ cut been lower than it was set in the analysis
- ✚ In order to account for this slight discrepancy, a **conservative, 10% systematic error** has been assigned to account for this effect
- ✚ We are **working on addressing this slight discrepancy** which has to do with vertex mis-reconstruction



Cross-Checks: p_T -Kick

Agreement between the MC and the data Agreement between the MC and the data, p_T -kick



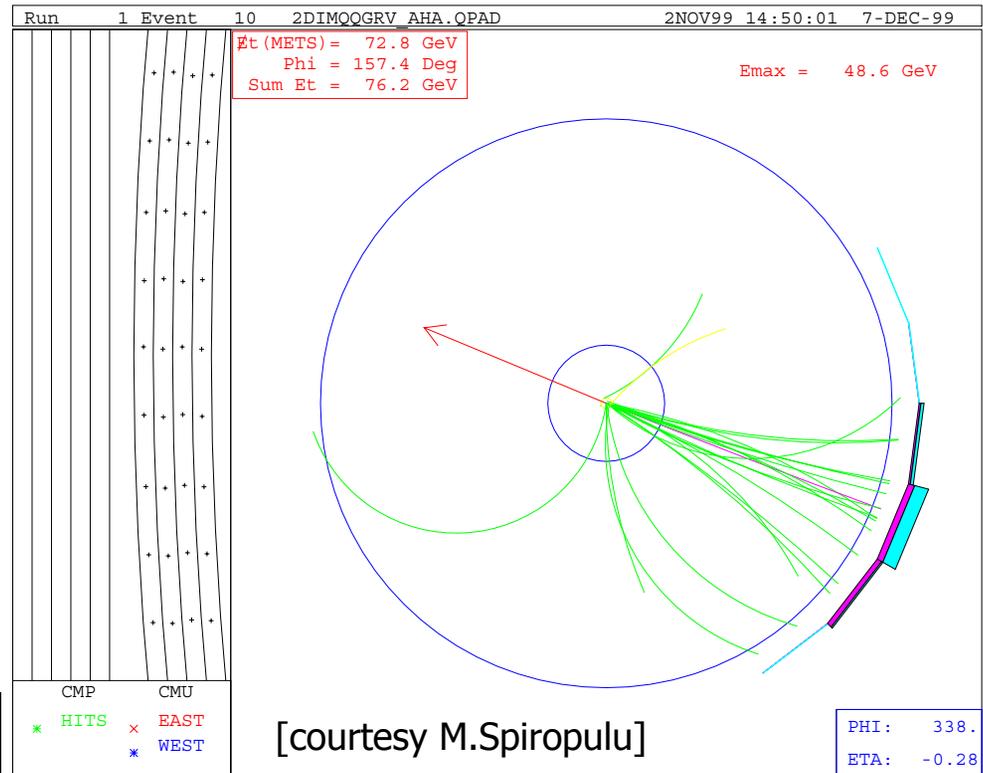


A Look in the Future

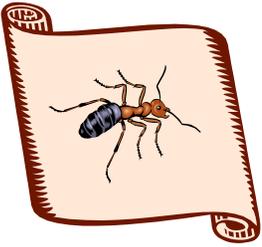
- ✚ The quest for extra dimensions is not over – it has just started
- ✚ We are looking forward to CDF results on the virtual graviton effects in DY production, which will allow us to combine our limits and further restrict the large extra dimensions theories
- ✚ Both CDF and DØ are pursuing the monojet signature – a complementary way of probing extra dimensions
- ✚ We just started to be sensitive to the interesting regions in the scale M_S , and Run IIA (IIB) data will allow us to double (triple) our reach (Cheung/GL, hep-ph/9909218):

	Run IIA, 2 fb^{-1}	Run IIB, 20 fb^{-1}
$l^+l^- + \mu^+\mu^-$	1.3-1.9 TeV	1.7-2.7 TeV
$\gamma\gamma$	1.5-2.4 TeV	2.0-3.4 TeV
$l^+l^- + \mu^+\mu^- + \gamma\gamma$	1.5-2.5 TeV	2.1-3.5 TeV

A monojet event as would have been seen by CDF

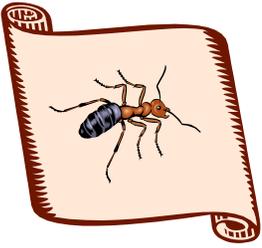


- ✚ Ultimate probe of extra dimensions will become available with the LHC and NLC (M_S up to 10 TeV)



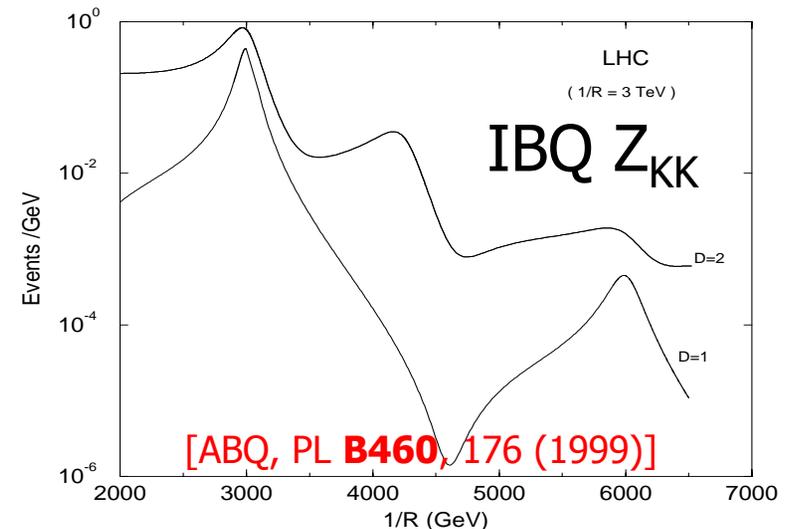
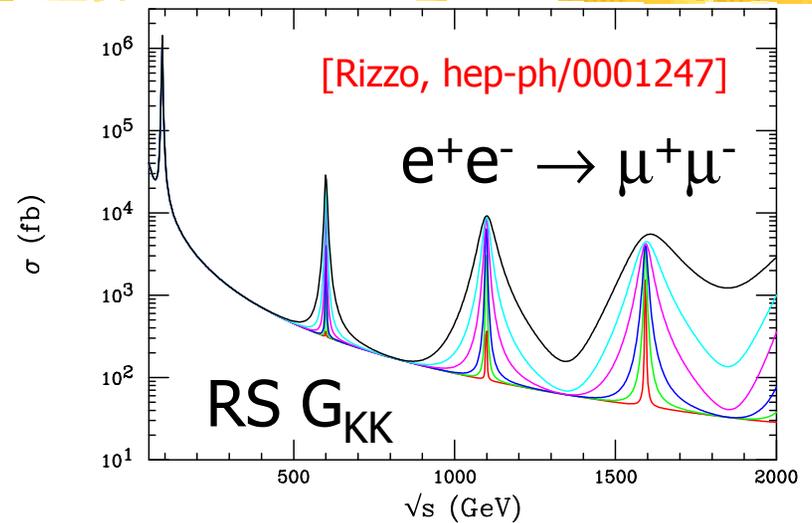
Black Hole Production

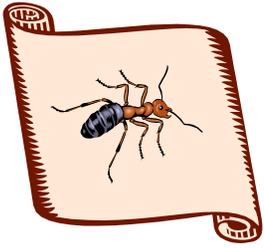
- ✦ Once the **c.m. energy exceeds the compactification scale**, M_S , a critical energy density is achieved and the black hole is formed
- ✦ **Not to worry** about the Earth being sucked into such a black hole; they should be constantly formed by cosmic rays
- ✦ The temperature of such a black hole is:
 $T = M_{\text{Pl}}^2/M \rightarrow M_S^2/M \times O(M/M_S) \sim M_S$
- ✦ For $M_S \sim T = 1 \text{ TeV}$, 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 $\sim 10^{-29} \text{ s}$
- ✦ 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 if 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

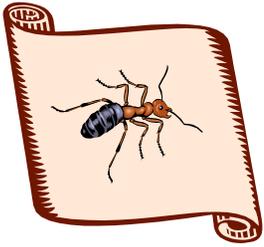
- ✚ New developments in extra dimensions:
 - ✚ **Randall-Sundrum** two-brane model with gravity localized near the brane [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
 - ✚ Expect G_{KK} resonances in, e.g., $e^+e^- \rightarrow l^+l^-$ scattering
 - ✚ **Antoniadis/Benaklis/Quiros** intermediate 'longitudinal' extra dimensions with $\sim \text{TeV}^{-1}$ 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





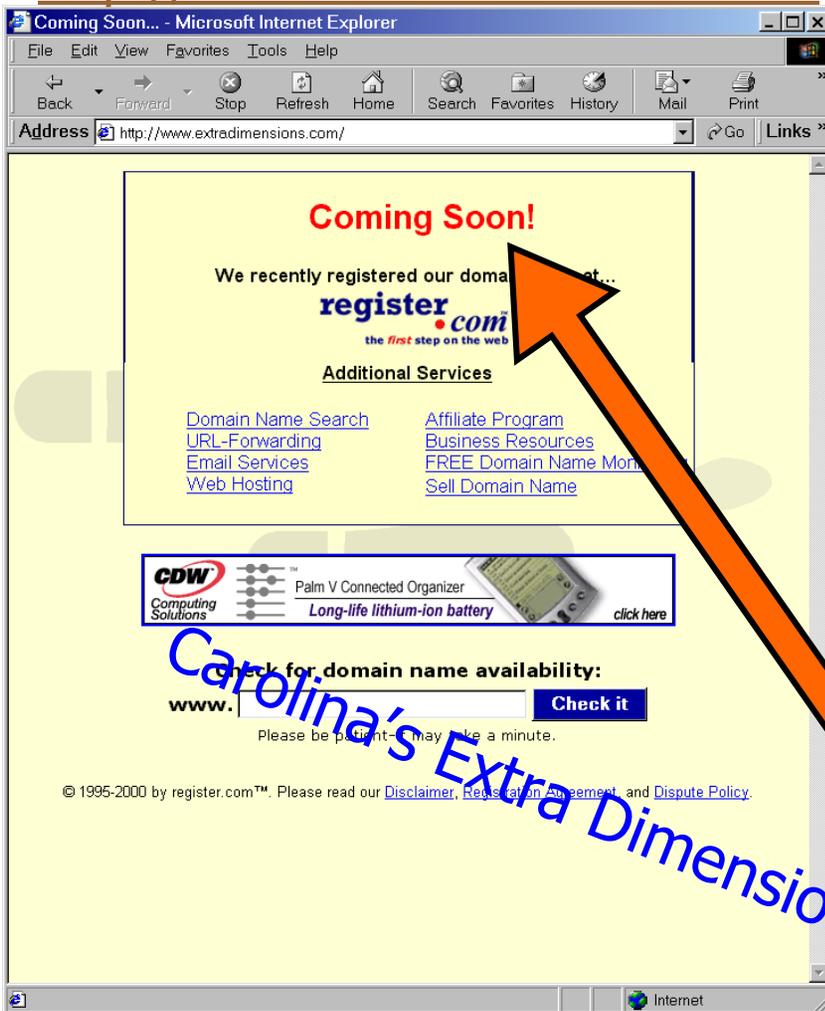
Summary

- ✚ DØ has completed a search for large extra dimensions via virtual graviton exchange in the diphoton and dielectron channel
- ✚ We see no evidence for the signal and set restrictive limits on the energy scale of extra dimensions between 1.0 and 1.3 TeV for the number of extra dimensions between 2 and 7
- ✚ These limits are comparable to the final limits expected from LEP2 and are complementary in nature
- ✚ Stay tuned for more results on Run I searches for extra dimensions from the CDF and DØ Collaborations in the next year
- ✚ Run II will offer further breakthrough in the reach for the quantum gravity scale, and we are looking forward to start it in just 10 months!
- ✚ We will have an excellent chance to discover extra dimensions in the next Run, or to rule them out up to the mass scales ~ 3 TeV



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 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!