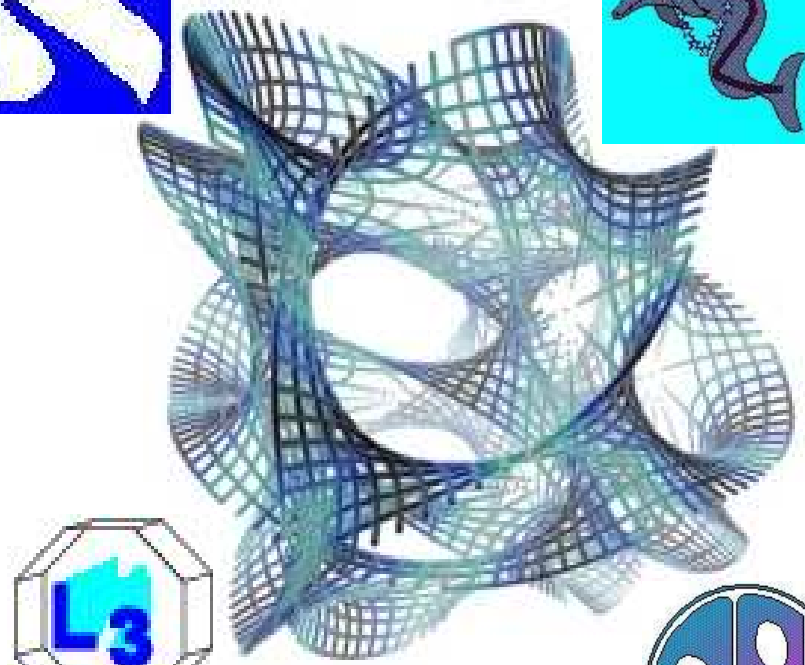
Extra Dimension Search at LEP

ALEPH

DELPHI



L3

OPAL

Stefan Ask (Lund University / DELPHI)

On behalf of the LEP collaborations

ICHEP 2004 Beijing

LEP Studies

- Graviton Emission
- Virtual Graviton Exchange
- TeV String Search
- Branon Search
- Radion Search

Outline

Introduction

The theoretical scenarios studied at LEP

Graviton Emission

ADD Scenario

- ALEPH DELPHI L3 Final Results
- **ADL Combined Results**

Graviton Exchange

ADD Scenario

- ADLO Combined Results

→ TeV String Search

(ADD Scenario)

- L3 Results

Branon Search

ADD Scenario

- L3 Results

Radion Search

RS Scenario

- OPAL Results

Conclusions

e^+ Data Set e^-

Results based mainly on year 1998 – 2000 data

$E_{CM} = 189 - 209\ GeV$

$\mathscr{L} = 0.6\ fb^{-1} / Exp.$

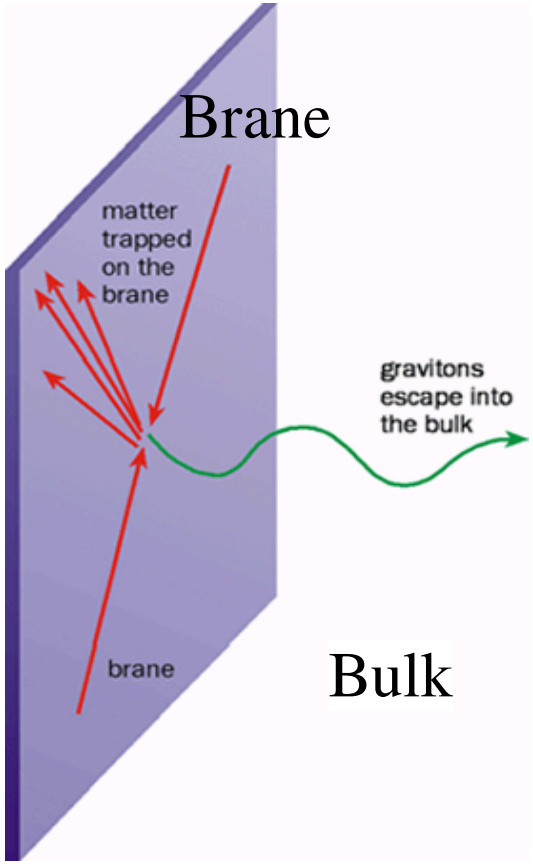
Earlier LEP2 data used in some cases

$E_{CM} = 130 - 184\ GeV$

$\mathscr{L} < 70\ pb^{-1} / Exp.$

All Limits Computed at 95 % CL

Extra Dimensions and Branes



Two Brane Scenarios Studied at LEP

- The ADD Scenario
- The Randall-Sundrum scenario (RS1)

Brane with 3 Spatial Dimensions in Bulk with D-3 Additional (Extra) Dimensions

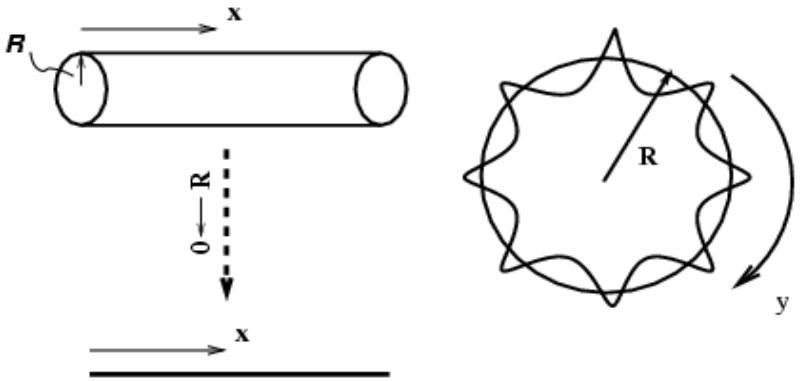
- Brane picture suggested by several String Models
- Gravity weak on the brane since it acts in a more extended space than the brane
- Gravity Phenomena appear at, $M = [M_D, \Lambda_w] \sim 1\,TeV$

  → $M \ll M_P$ "Solves" the hierarchy problem

- SM particles confined to the brane
- Gravity propagates in whole D-dim space

Phenomena in 4-dim (on the brane)

Compactified Extra Dimensions



Finite Size + Escaping momentum appearing as mass on the brane

Graviton Kaluza-Klein Modes (KK-tower)

$$m_{KK}^2 = \sum_d p_d^2 \ , d = 4, \ldots, D$$

Effective 4-dim Theory below M_D

- Massive KK spin-2 gravitons, $G_{\mu\nu}^{(n)}$
- Massive KK scalar gravitons, $H^{(n)}$
  Including the Radion (n=0)
- Massive scalar branons, $\tilde{\pi}$
  Possible particles related to the brane dynamics

Particles Searches at LEP

- The ADD Scenario
  - → Spin-2 graviton (Rigid brane)
  - → Branons (Flexible brane)
- The Randall-Sundrum scenario (RS1)
  - → Radion

The ADD Scenario (Large Extra Dimensions)

(* N. Arkani-Hamed, S. Dimopoulos, G. Dvali)

Model

Extra dimensions are
- **Compactified**
  (normally assumed on a torus and with equal radii, R)
- **Large**
  (R up to about 1mm)

→
- **No hierarchy due to large volume of the compactified space**
- **Dense KK-tower**

Assumed torus shape

$M_P^2 = 8\pi R^n M_D^{n+2}$

$M_D \sim 1\,TeV$

$\Delta m_{KK} \propto 1/R$

Bounds

Gravity Experiment, Cosmology and Astrophysical Constraints

→
- 1-dim, Newton's law would be changed at solar system distances
- 2-dim, Strong bounds
- > 2-dim, **Relatively weak bounds**

Processes at LEP

Rigid Brane

$f \gg M_D$

Graviton Emisson:

$e^+ e^- \to G + \gamma$

Graviton Exchange:

$e^+ e^- \to G^* \to ff/\gamma\gamma$

Brane tension →

Flexible Brane

$f \ll M_D$

Branon Production:

$e^+ e^- \to \tilde{\pi}\tilde{\pi} + \gamma/Z$

Graviton processes exponentially suppressed, $e^{\frac{-M_D^2 s(1-x)}{f^4 (2\pi)^2}}$

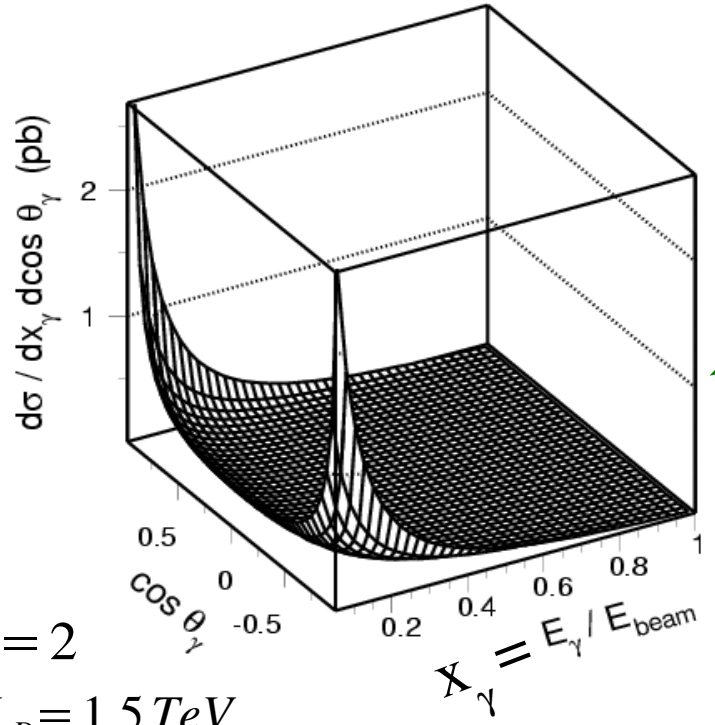
The Possible Signals at LEP (ADD)

$e^+ e^- \rightarrow G + \gamma$

(* G.F. Giudice, R. Rattazzi and J.D. Wells;
E.A. Mirabelli, M. Perelstein and M.E. Peskin)

$$\frac{d^2\sigma}{dx_\gamma\, d\cos(\theta_\gamma)} = \left(\frac{\sqrt{s^n}}{M_D^{n+2}}\right) F(n, x_\gamma, \theta_\gamma)$$

Single photon process directly sensitive to the fundamental scale of gravity (M_D) and the number of dimensions (n).



$n = 2$

$M_D = 1.5\,TeV$

$e^+ e^- \rightarrow G^* \rightarrow ff / \gamma\gamma$

(* J. Hewett ; K. Agashe and N.G. Deshpande)

$$\frac{d\sigma}{dcos(\theta)} = F(\lambda / M_H^4)$$

Fermion and photon pair process sensitive to cut-off mass scale (M_H) and the coupling (λ).

$\lambda = \pm 1$ Used in the analysis

$e^+ e^- \rightarrow \tilde{\pi}\,\tilde{\pi} + \gamma / Z$

(* J. Alcaraz, J.A.R. Cembranos, A. Dobado and A.L. Maroto)

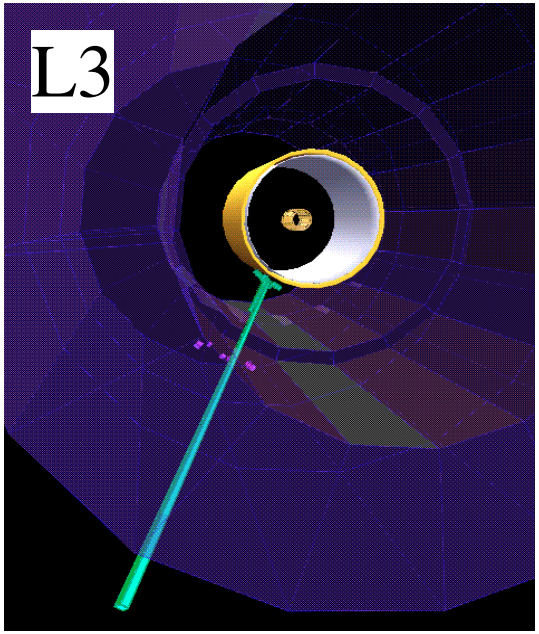
- Photon distributions similar to Graviton emission process

$$\frac{d^2\sigma}{dx_\gamma\, dcos(\theta_\gamma)} = \frac{n_b}{f^8} F(M_b, x_\gamma, s) G(x_\gamma, \theta_\gamma)$$

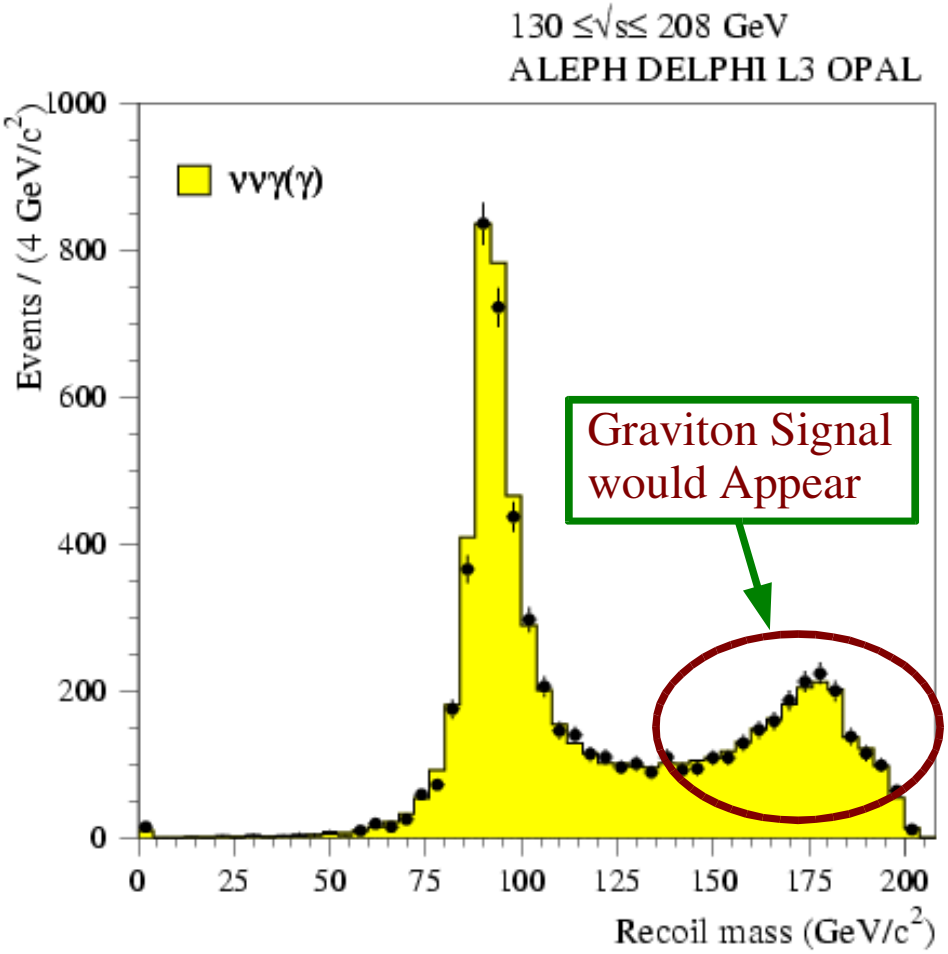
Branon process sensitive to number of branons (n_b), branon mass (M_b) and brane tension (f).

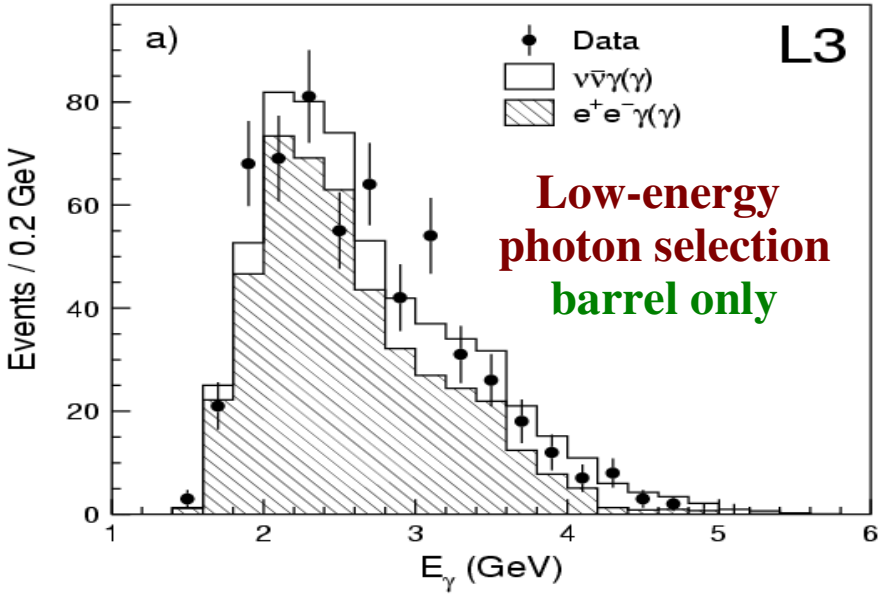
$n_b = 1$ Used in the analysis

ADLO : Graviton + γ Production



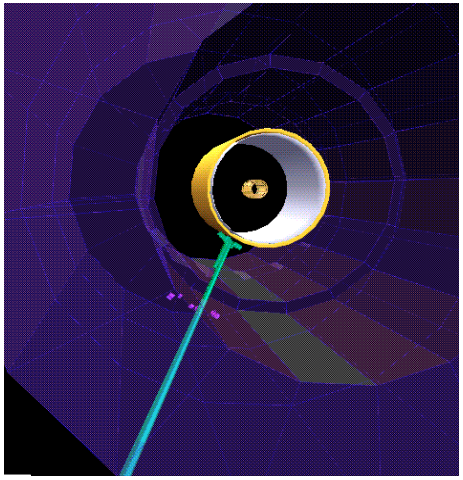
Results using year 2000 & 1999 data not available yet.



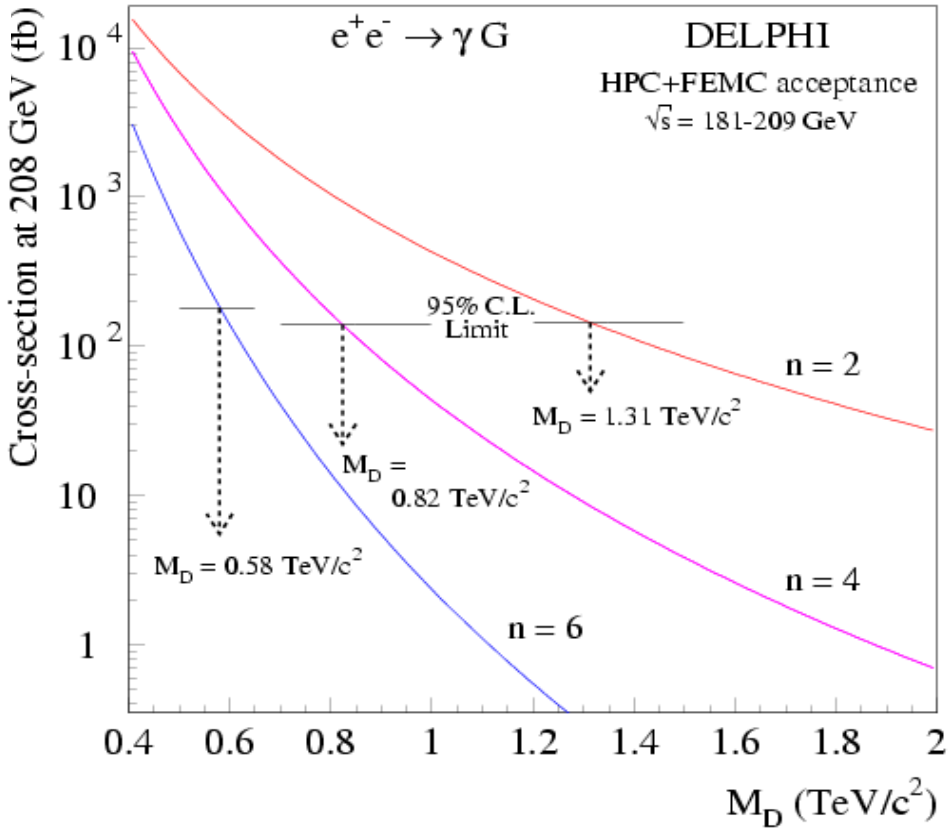


Good Agreement between Data and SM Expectation for ALEPH, DELPHI, L3 and OPAL

ADLO: Graviton + γ Production



No Indications of a Signal



Final M_D Limits (TeV) [Obt. (Exp.)]

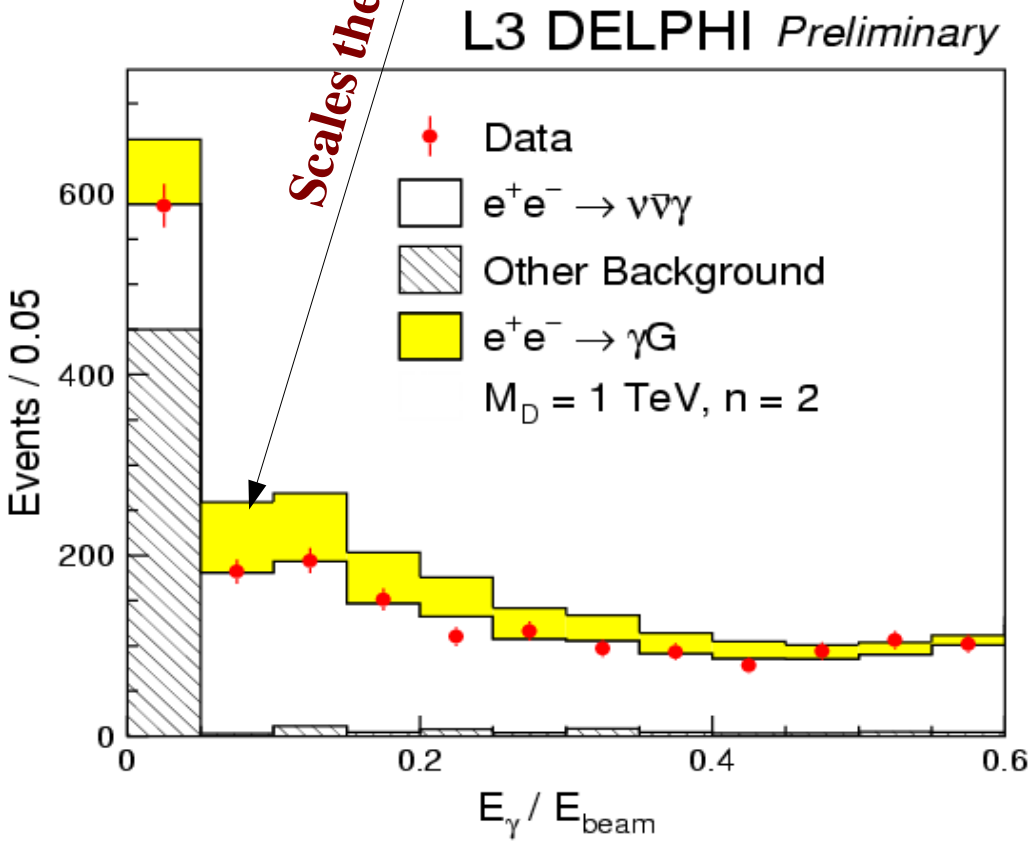
n	ALEPH	DELPHI	L3
2	1.26	1.31 (1.27)	1.50 (1.49)
3	0.95	1.02 (0.98)	1.14 (1.12)
4	0.77	0.82 (0.80)	0.91 (0.89)
5	0.65	0.67 (0.67)	0.76 (0.75)
6	0.57	0.58 (0.58)	0.65 (0.64)
7	---	---	0.57 (0.56)
8	---	---	0.51 (0.51)

ALEPH and DELPHI show a similar sensitivity whereas that of L3 is higher

Combined: Graviton + γ

Measurement of scaling factor, $x = 1/(M_D)^{n+2}$

Scales the signal



Combined Likelihood

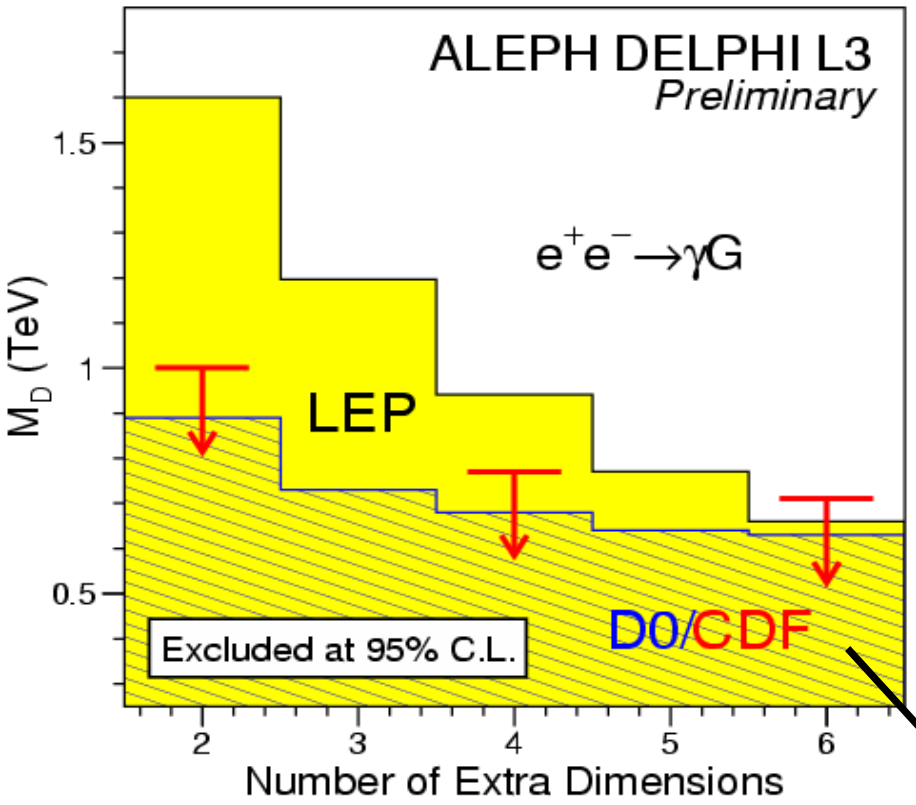
$$\mathscr{L}(x) = \mathscr{L}(x)^{ALEPH} \times \mathscr{L}(x)^{DELPHI} \times \mathscr{L}(x)^{L3}$$

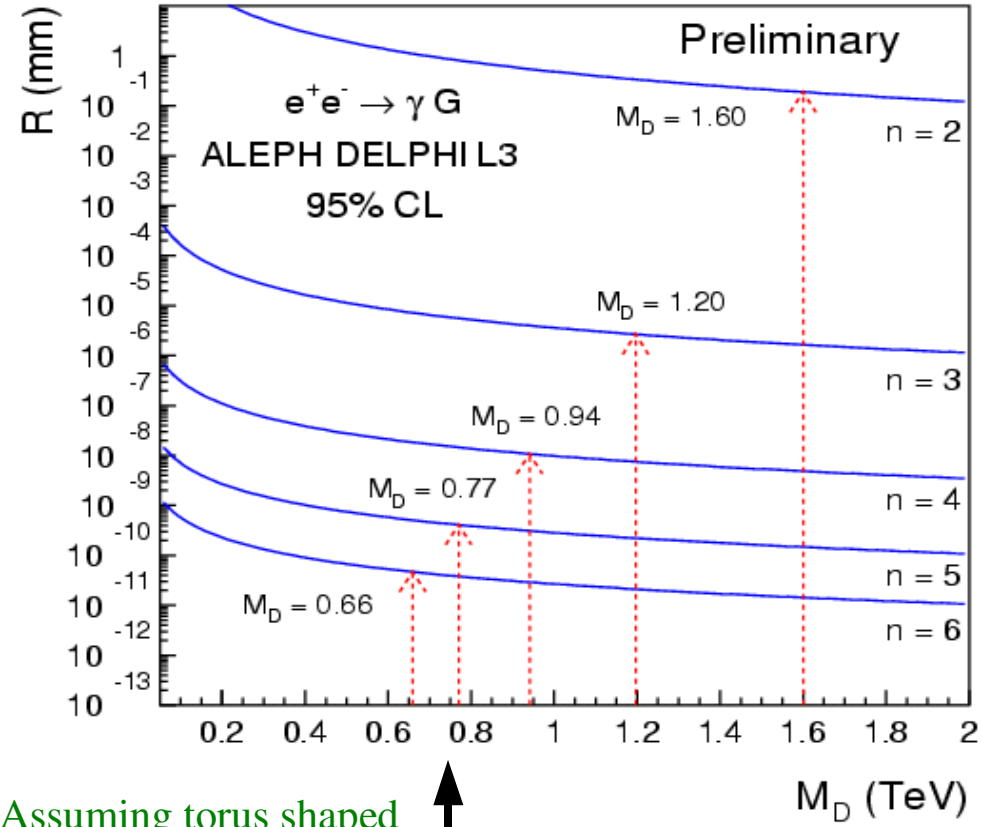
$$CL = \frac{\int_0^{x_{95}} \mathscr{L}(x)\,dx}{\int_0^{\infty} \mathscr{L}(x')\,dx'} = 0.95$$

ADL Combined Limit

n	$1/(M_D)^{n+2}$	M_D (TeV)
2	-0.02 +/- 0.08	> 1.60
3	-0.09 +/- 0.22	> 1.20
4	-0.3 +/- 0.8	> 0.94
5	-0.9 +/- 3.3	> 0.77
6	-4.8 +/- 15.2	> 0.66

Combined: Graviton + γ





Assuming torus shaped extra dimensions

$$G_N^{-1} = 8\pi\, R^n\, M_D^{n+2}$$

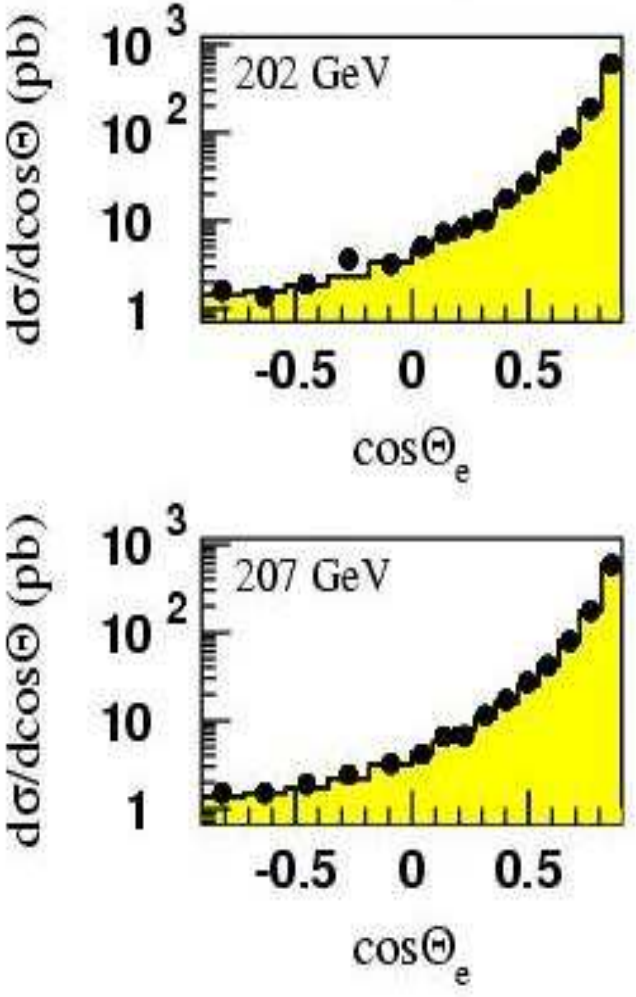
n	$R\ (mm)$
2	< 0.19
3	$< 2.6\text{x}10^{-6}$
4	$< 1.1\text{x}10^{-8}$
5	$< 4.1\text{x}10^{-10}$
6	$< 4.6\text{x}10^{-11}$

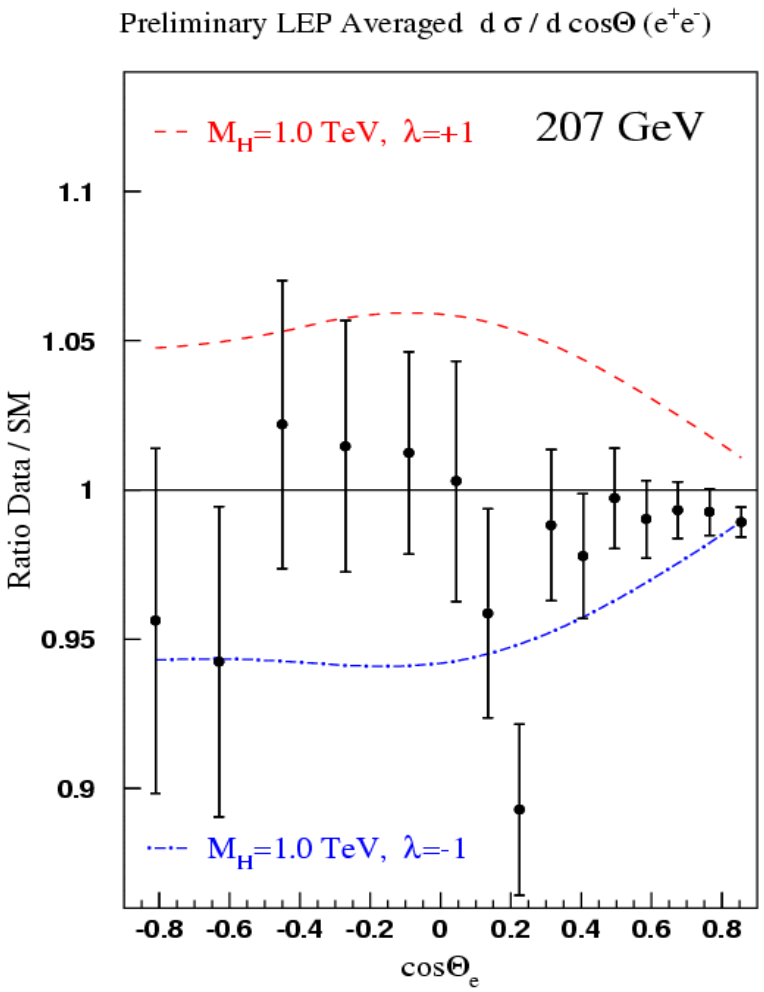
- LEP limits increasingly stringent with lower number of extra dimensions compared to the D0/CDF results

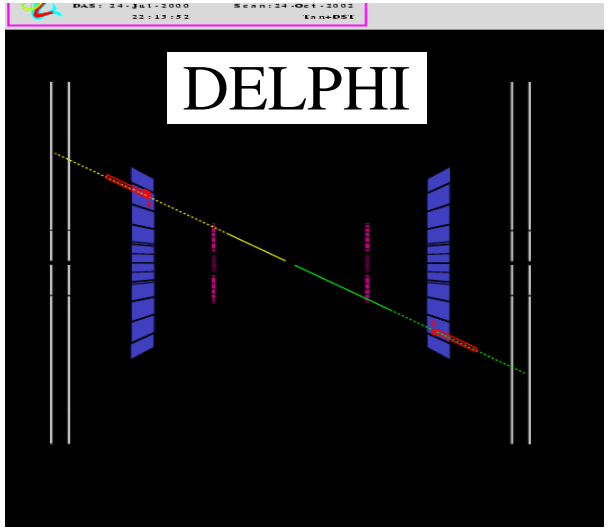
(D0/CDF results are based on Run I data only)

Virtual Graviton Exchange

Fit to LEP combination of the differential Bhabha and photon pair cross section (Fit-Parameter, $x_H = \frac{\lambda}{M_H^4}$)







$$e^+ e^- \to e^+ e^-$$

$M_H > 1.20\,TeV\ (\lambda = +1)$

$M_H > 1.09\,TeV\ (\lambda = -1)$

$$e^+ e^- \to \gamma\gamma$$

$M_H > 0.93\,TeV\ (\lambda = +1)$

$M_H > 1.01\,TeV\ (\lambda = -1)$

TeV String Search

String model with ADD extra dimensions

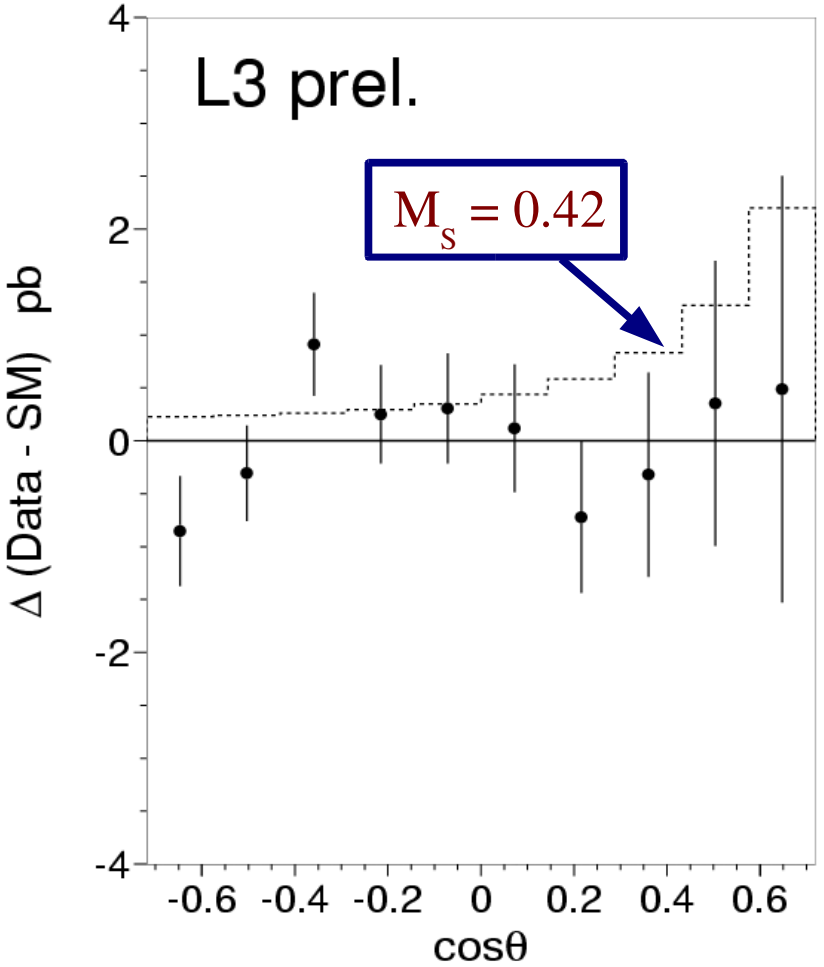
(* S. Cullen, M. Perelstein and M. Peskin ;
E.Accomando, I. Antoniadis and K. Benakli)

- Effect on Bhabha scattering of TeV scale strings

$$\frac{d\sigma}{d\cos\theta} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} |F(M_S)|^2$$

$$M_S = [\,String\ scale\,] = (1.6 - 3.0) \times M_D$$

- This TeV string effect would typically dominate over virtual graviton exchange



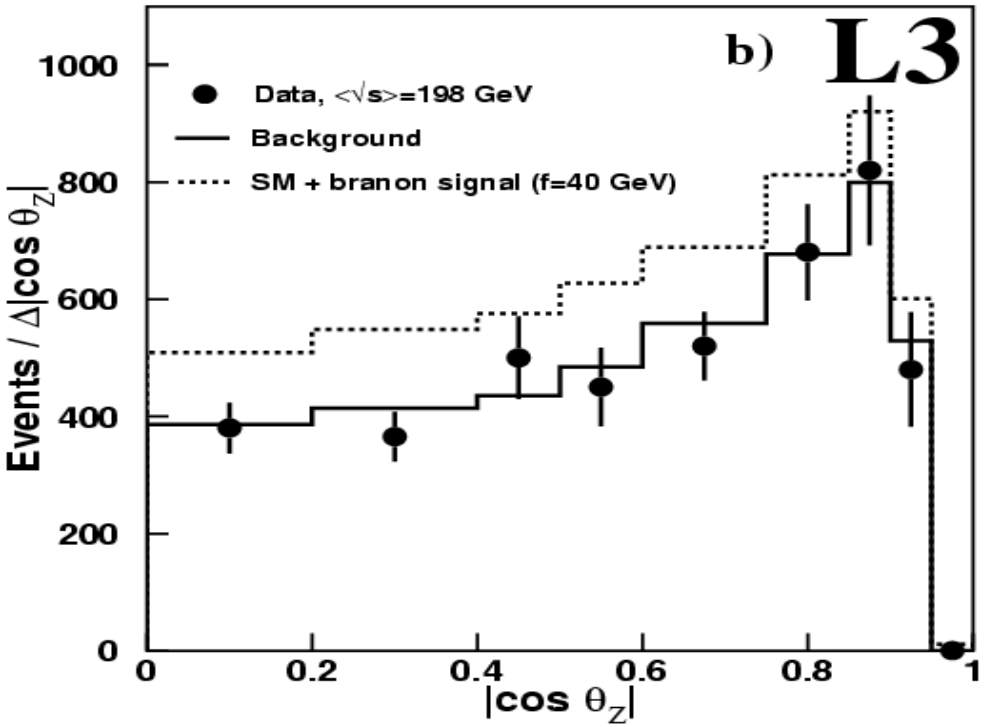
Obtained Limit

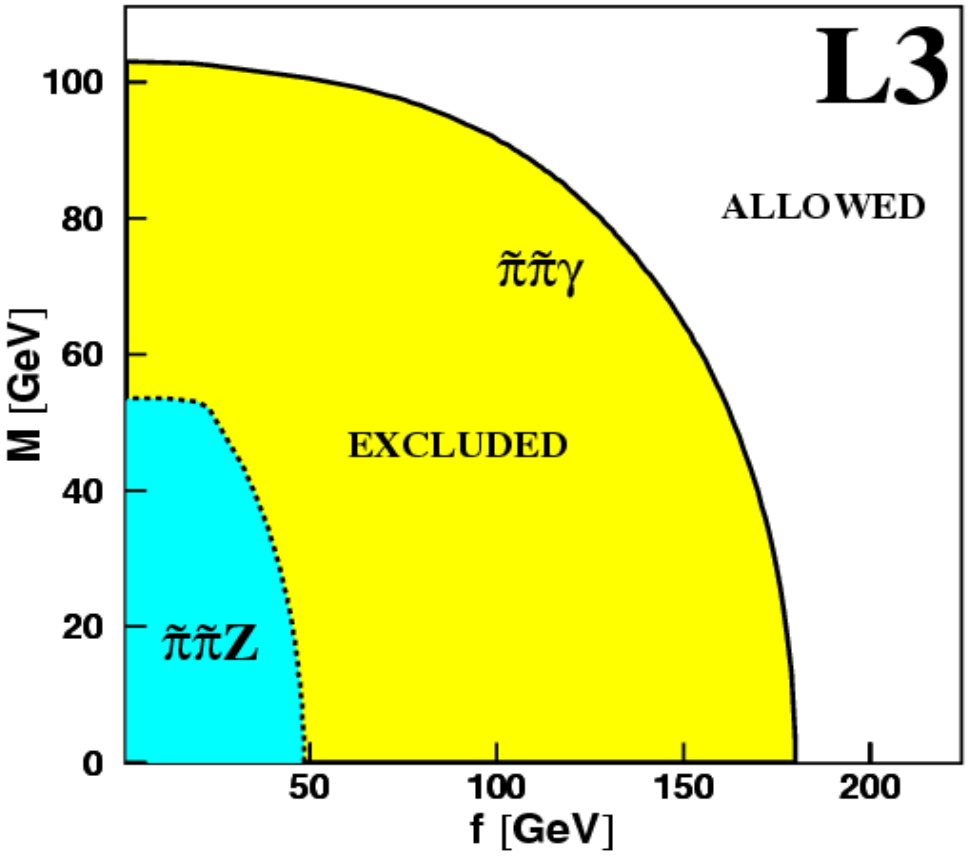
$M_S > 0.55\ TeV$

Branon Search

$$e^+ e^- \to \tilde{\pi}\,\tilde{\pi} + \gamma / Z$$

- Single photon events
  (as for the G+γ search)
- Single Z signature events
  (Unbalanced hadronic events with visible mass compatible with m_Z)





	$M_b = 0$	$f = 0$
$\tilde{\pi}\,\tilde{\pi}\,\gamma$:	$f > 180\,GeV$	$M_b > 103\,GeV$
$\tilde{\pi}\,\tilde{\pi}\,Z$:	$f > 47\,GeV$	$M_b > 54\,GeV$

The RS Scenario and LEP

(* L. Randall and R. Sundrum)

Two Branes:

- SM confined to one brane (SM-brane)
- Gravity concentrated to the other brane (Planck-brane, due to "warped" geometry)

One Extra Dimension: (between the branes)

- Gravity exponentially damped with increasing distance from the Planck brane

  Weak gravity on SM brane

- Local fluctuations of inter-brane distance

  The Radion, massive scalar

Radion have same Quantum Numbers as the Higgs

Higgs – Radion mixing, into one Higgs-like and one Radion-like state (h & r)

Both h and r are mainly produced in the "Higgs-strahlung" process

$$e^+ e^- \rightarrow Z + h/r$$

Which depends on the RS parameter space

$\xi = Mixing\ parameter$

$\Lambda_w = Mass\ scale\ on\ SM\ brane$

$m_h = Mass\ of\ Higgs-like\ state$

$m_r = Mass\ of\ Radion-like\ state$

(* C. Csaki, M.L. Graesser and G.D. Kribs)

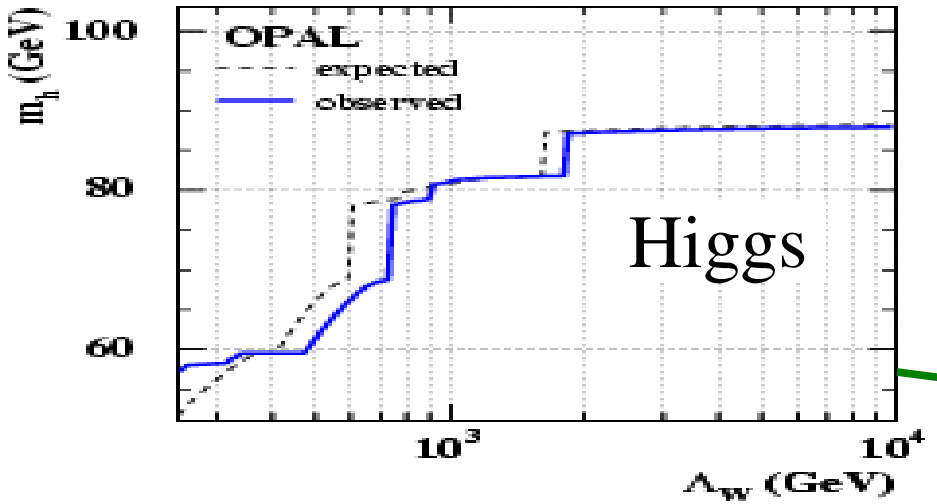
Radion Search

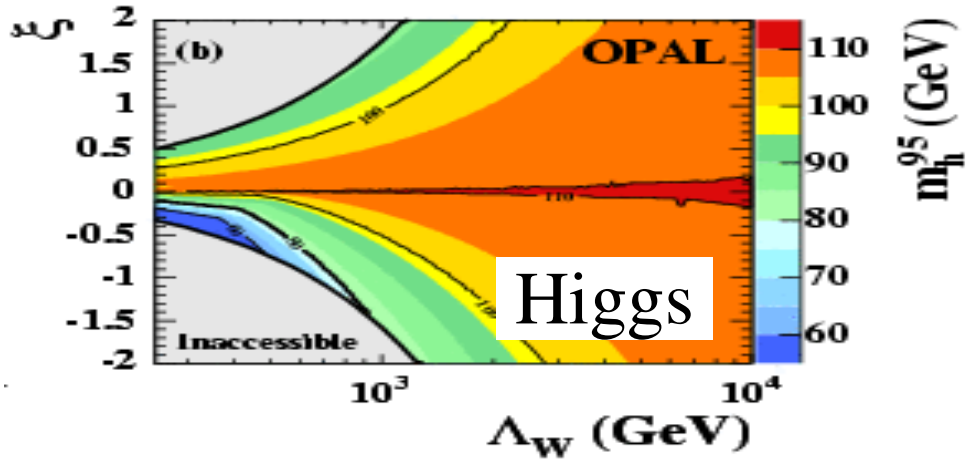
$e^+e^- \to Z + h/r$

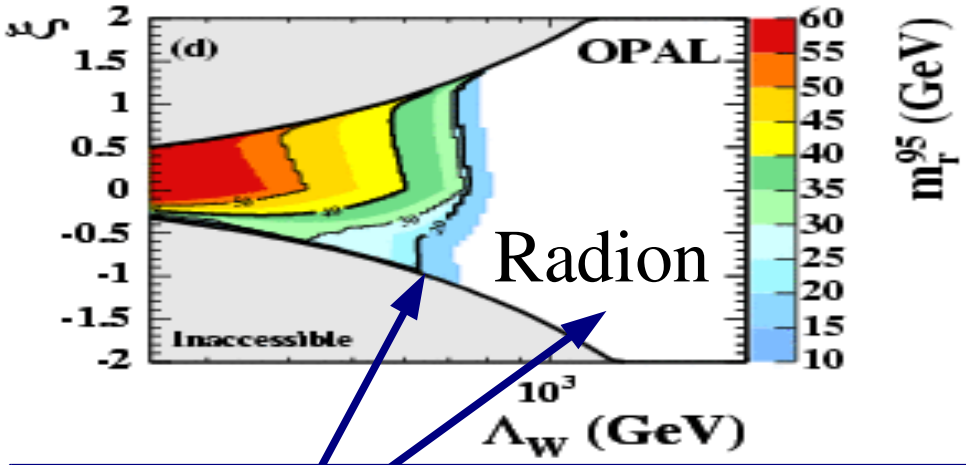
Searches used:

- *Standard Higgs search*
  $e^+e^- \to Zh, h \to bb$
- *Hadronically decaying Higgs search*
  $e^+e^- \to Zh, h \to qq/gg$
- *Decay mode independent Higgs search*
  $e^+e^- \to Zh, h \to xx$

- Excluded parameter space obtained by a parameter scan
- Point excluded if signal cross section exceeds the limit from any one of the three searches







Radion process suppressed with increasing Λ_w and at large negative mixing

Overall Higgs Limit

$m_h > 58\ GeV$

Conclusion

- Several extra dimension models have been investigated at LEP, but no indication of a signal has been observed

Exclusion Limits

ADD

$G + \gamma$

n	M_D (TeV)
2	> 1.60
3	> 1.20
4	> 0.94
5	> 0.77
6	> 0.66

$ff / \gamma\gamma$

$M_H > 1.20\ TeV\ (\lambda = +1)$

$M_H > 1.09\ TeV\ (\lambda = -1)$

$\tilde{\pi}\tilde{\pi} + \gamma / Z$

$f > 180\ GeV \quad (M_b = 0)$

$M_b > 103\ GeV \quad (f = 0)$

TeV String

$e^+ e^-$

$M_S > 0.55\ TeV$

RS

$Z + h / r$

$m_h > 58\ GeV$

- The LEP results give some of the most stringent constraints today on extra dimensions

Thanks to J.Timmermans, M.Gataullin, V.Hedberg, W.Adam, S.Mele and all who contributed
Also thanks to the organizers of ICHEP04 for the invitation and all their help