Search for Exotics and Extra Dimensions at LEP

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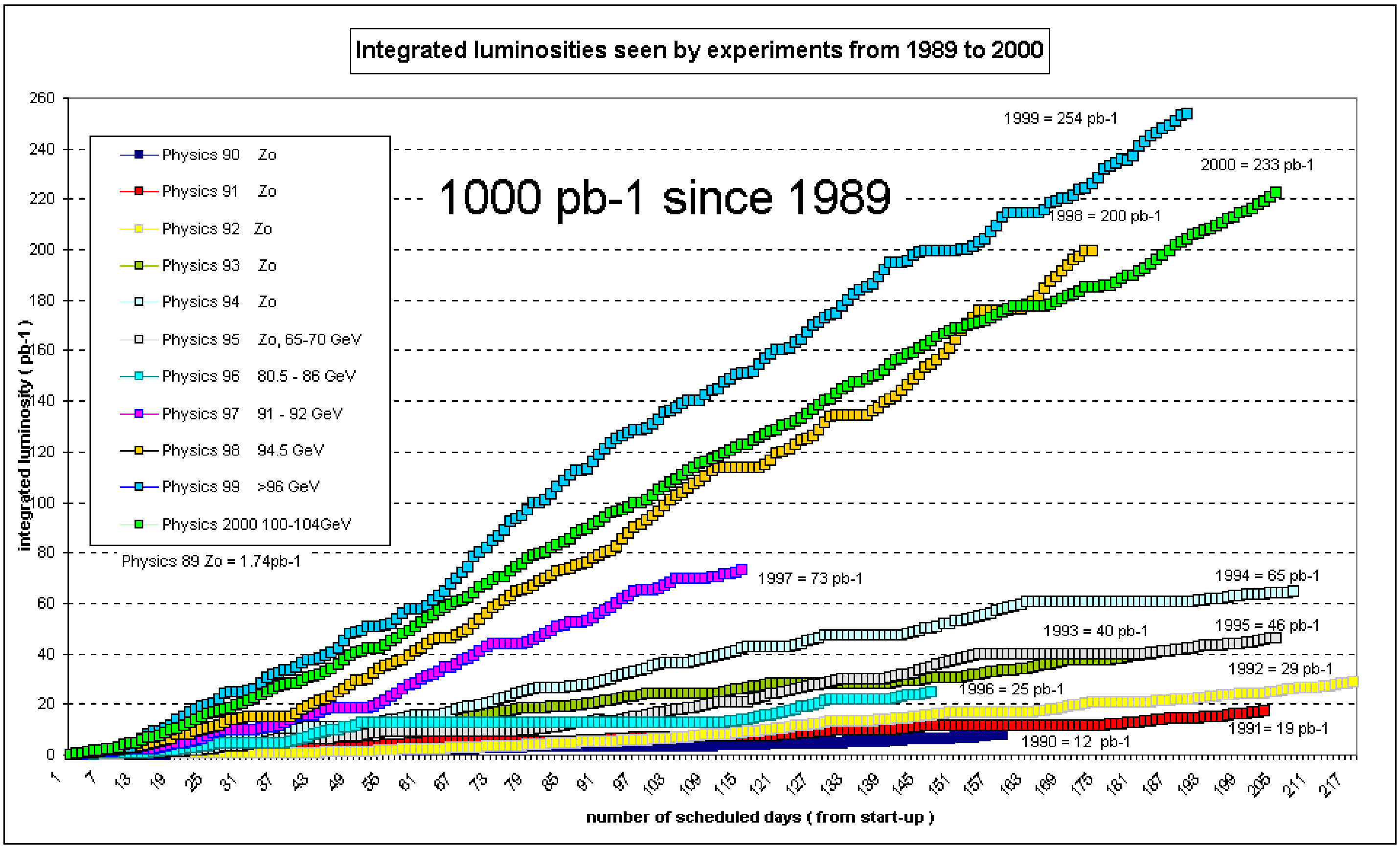
OUTLINE

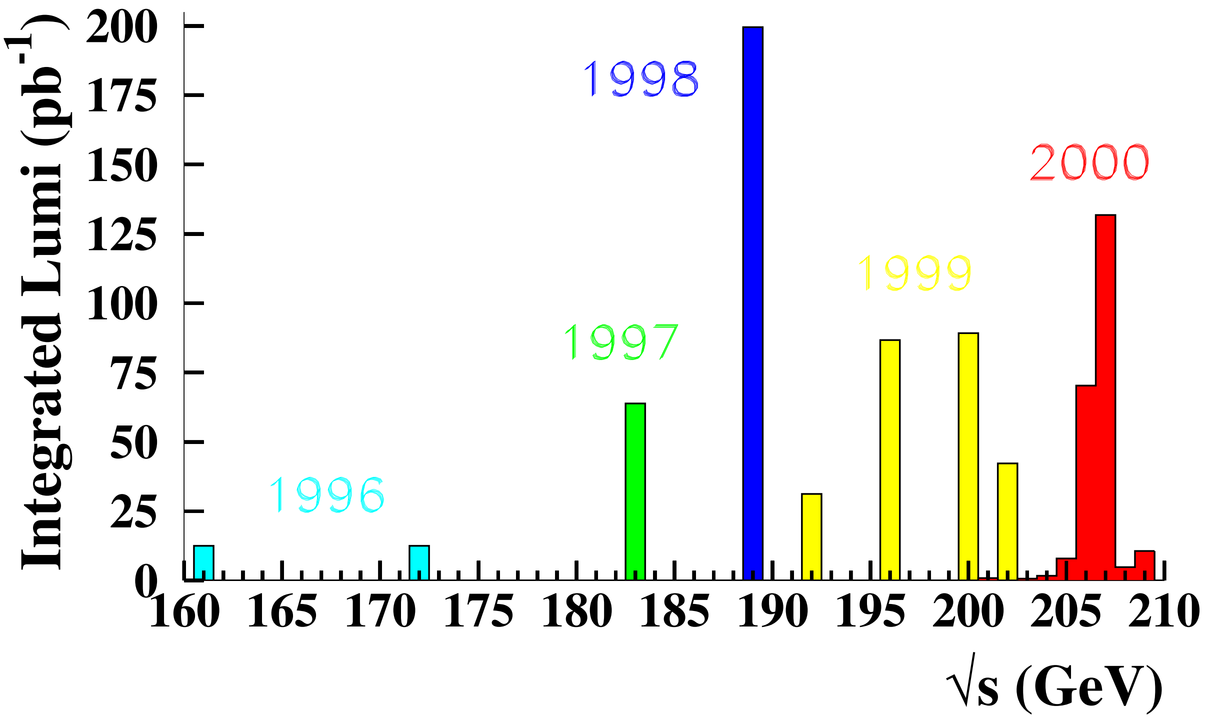
- Four-fermion Contact Interactions
- Z' boson
- Leptoquarks
- Excited leptons
- Technicolor
- Low-scale Gravity in Extra Dimensions

All limits at 95% C.L.

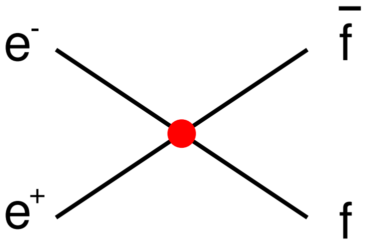
LEP data set



More than 600 pb^{-1}/expt. recorded at LEP2



Four-Fermion Contact Interactions



General framework for describing interactions beyond the SM

- Gauge invariant
- Conserve chirality and flavor

Set $g^2/4\pi = 1$

$$\mathcal{L}_{\rm contact} = \frac{g^2}{(1+\delta)\Lambda^2} \sum_{ij=\rm L,R} \eta_{ij} (\bar{\rm e}_{\rm i}\gamma^\mu {\rm e}_{\rm i})(\bar{\rm f}_{\rm j}\gamma_\mu {\rm f}_{\rm j})$$

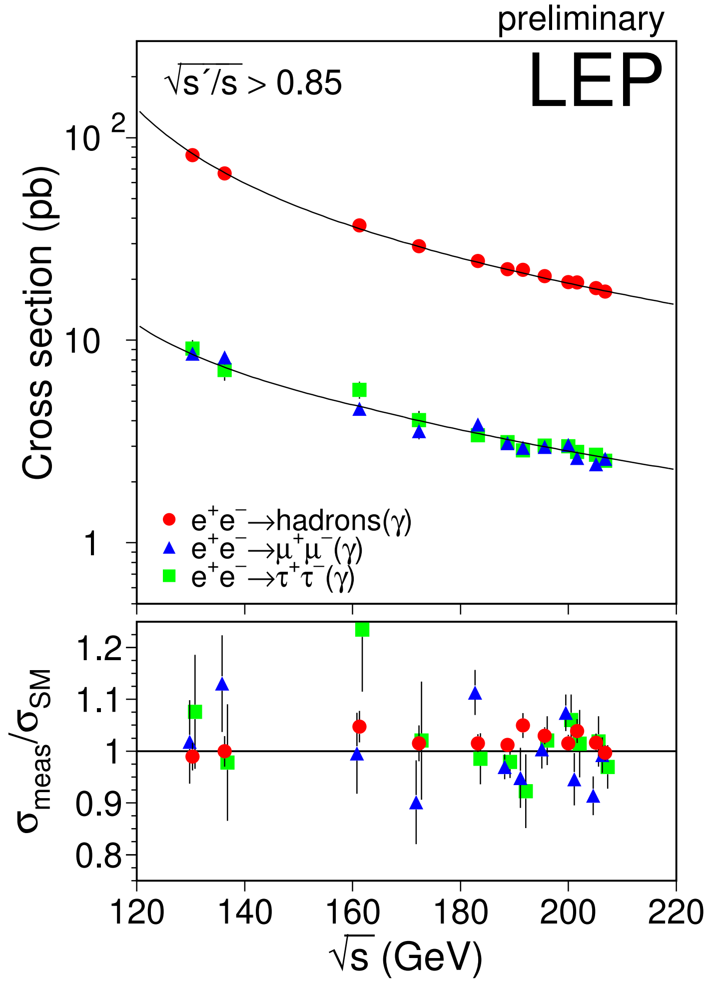
Energy scale

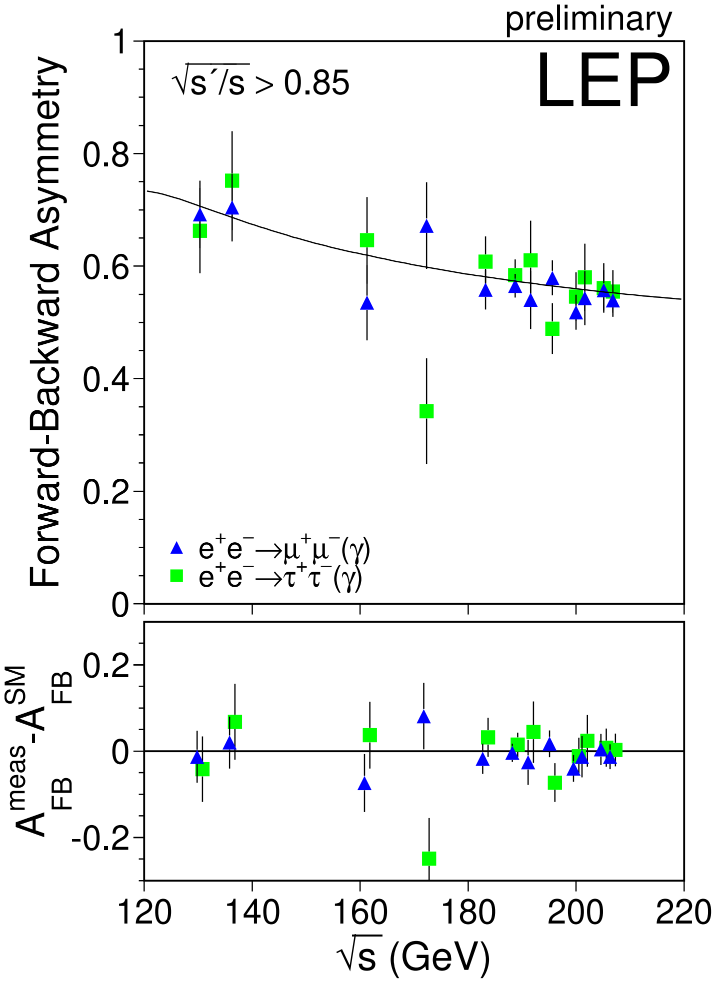
Choose helicity

Model	$\eta_{\rm LL}$	$\eta_{\rm RR}$	$\eta_{\rm LR}$	$\eta_{\rm RL}$
LL	±1	0	0	0
RR	0	±1	0	0
LR	0	0	±1	0
RL	0	0	0	±1
AA	±1	±1	∓1	∓1
VV	±1	±1	±1	±1
V0	±1	±1	0	0
A0	0	0	±1	±1

Contact Interactions

- Fit cross-section and asymmetries
- assume lepton universality



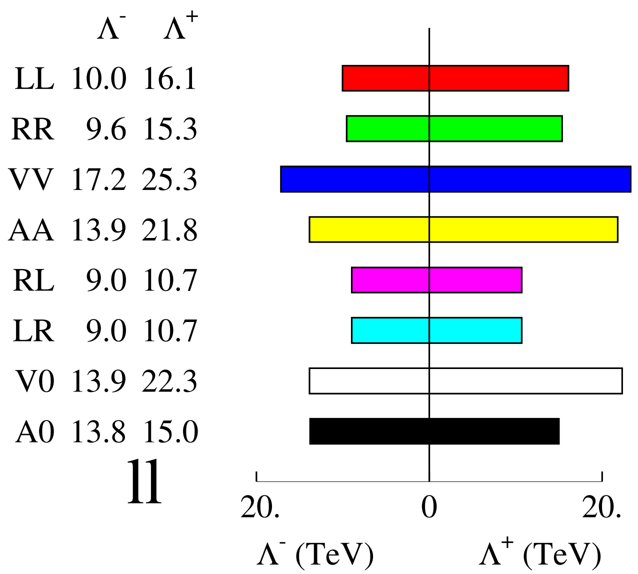


Contact Interactions - Results

Interactions $ee\ell\ell$, $eebb$, $eecc$ only accessible at LEP

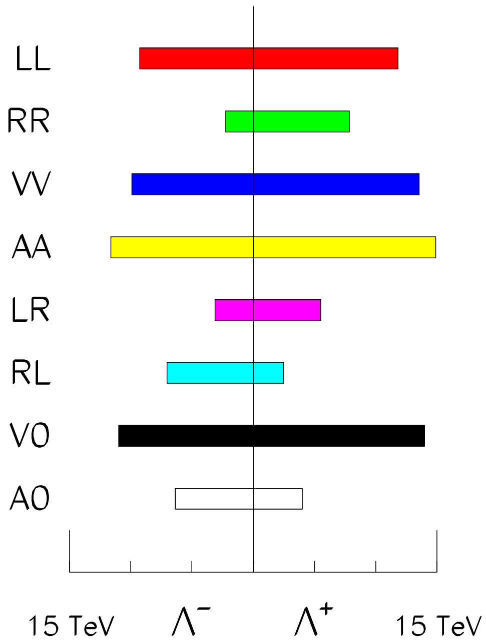
$$e^+e^- \to \ell\ell$$

LEP Combined Preliminary



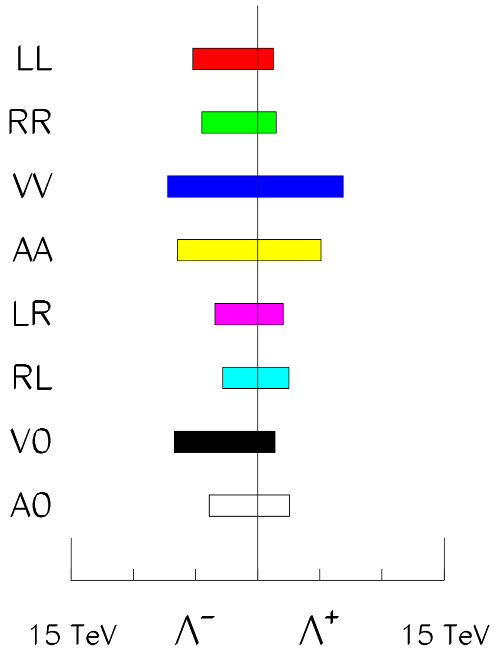
$$e^+e^- \to b\bar{b}$$

bb - LEP Combined preliminary



$$e^+e^- \to c\bar{c}$$

cc - LEP Combined Preliminary



Z' boson

Additional heavy gauge boson predicted by many theories

$$\mathcal{L}_{\mathrm{NC}} = eA_\beta J_\gamma^\beta + gZ_\beta^0 J_{Z^0}^\beta + g' Z_\beta^{0'} J_{Z^{0'}}^\beta$$

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\theta_{ZZ'} & \sin\theta_{ZZ'} \\ -\sin\theta_{ZZ'} & \cos\theta_{ZZ'} \end{pmatrix} \begin{pmatrix} Z^0 \\ Z^{0'} \end{pmatrix}$$

mass eigenstates

gauge eigenstates

E_6 GUT

SM embedded in E(6) group

$\mathrm{Z}^{0'} = \mathrm{Z}_\psi \sin\theta_{\mathrm{E6}} + \mathrm{Z}_\chi \cos\theta_{\mathrm{E6}}$

χ model $\quad \theta_{\mathrm{E6}} = 0$

ψ model $\quad \theta_{\mathrm{E6}} = \pi/2$

η model $\quad \theta_{\mathrm{E6}} = -\arctan\sqrt{5/3}$

Sequential SM

$\mathrm{Z}^{0'}$ with SM couplings

Left-Right Models

introduce symmetry group $\mathrm{SU}(2)_{\mathrm{R}}$

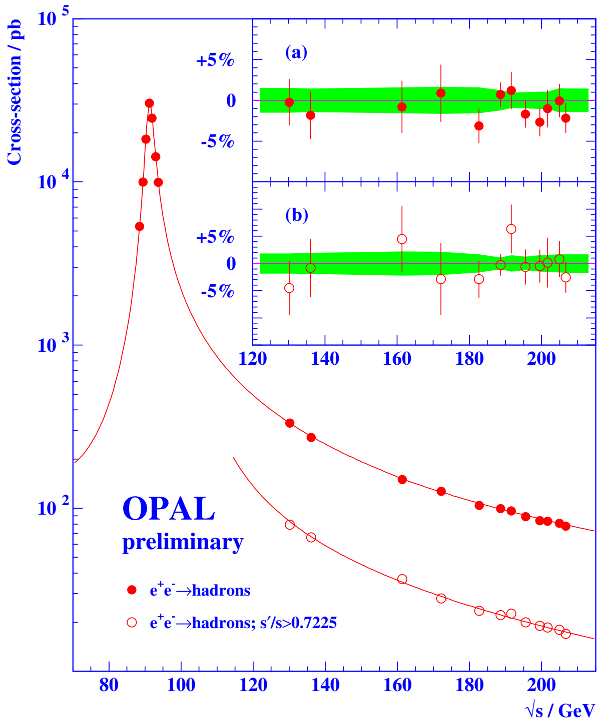
3 new vector bosons couple to right-handed fermions

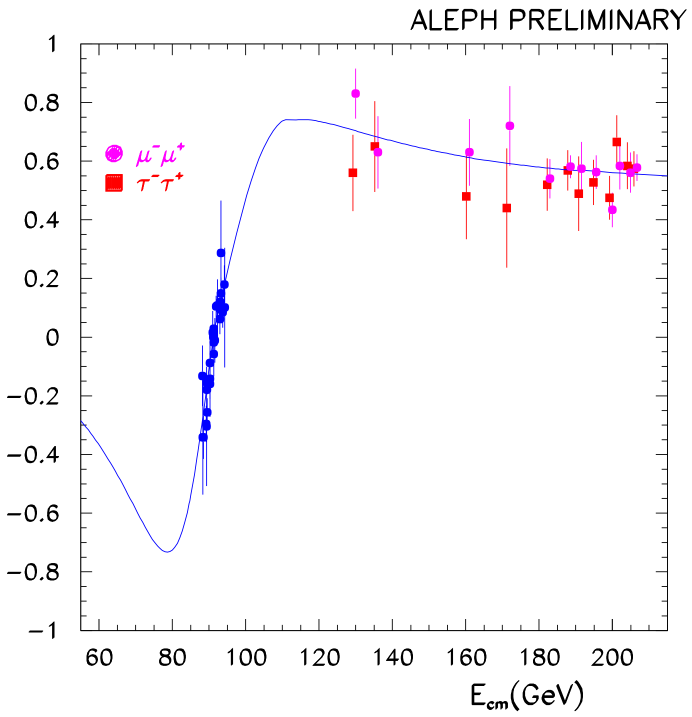
$$\alpha_{\mathrm{LR}} = \sqrt{\frac{\cos^2\theta_{\mathrm{W}}}{\sin^2\theta_{\mathrm{W}}}\frac{g_{\mathrm{R}}^2}{g_{\mathrm{L}}^2} - 1}$$

Consider LR Symmetric Model $\Rightarrow \mathrm{g}_{\mathrm{L}} = \mathrm{g}_{\mathrm{R}}$

Z' boson

- Fit to hadronic/leptonic cross-section, leptonic asymmetries
- Use both LEP1 and LEP2 data





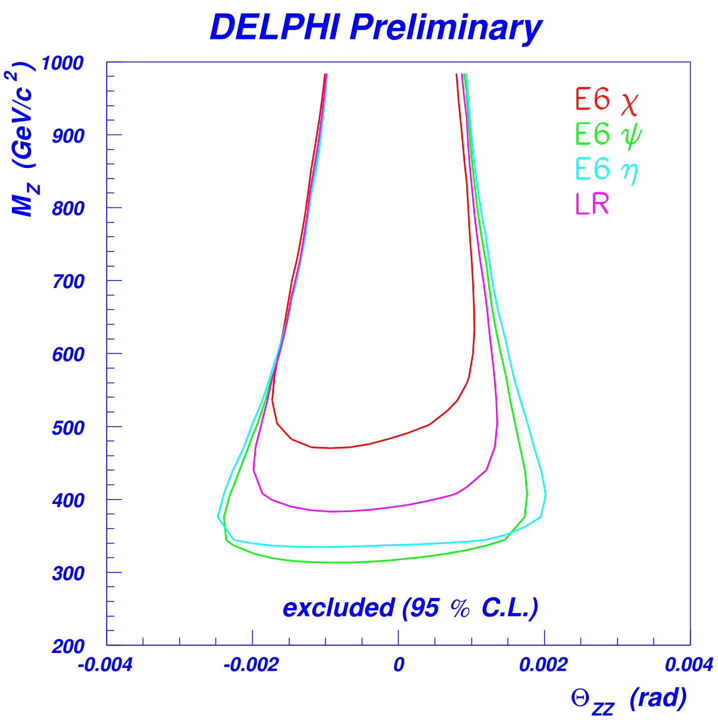
- Lower mass limits on $\mathrm{M}_{Z'}$ assuming $\theta_{ZZ'}$ = 0

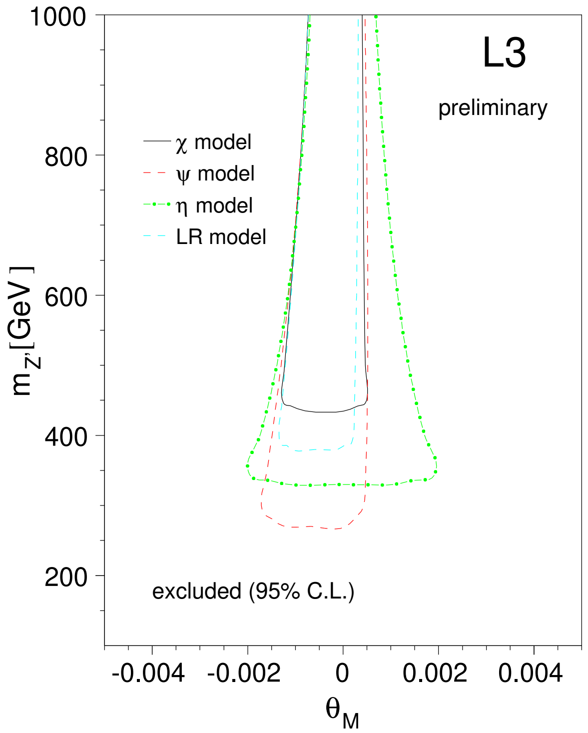
	95% CL lower limit on $\mathrm{M}_{Z'}$ (GeV)				
	ALEPH*	DELPHI	L3	OPAL	LEP
χ	680	503	460	684	715
ψ	410	336	275	334	478
η	350	353	330	451	454
LRS	600	412	450	469	862
SSM	—	—	1280	—	2090

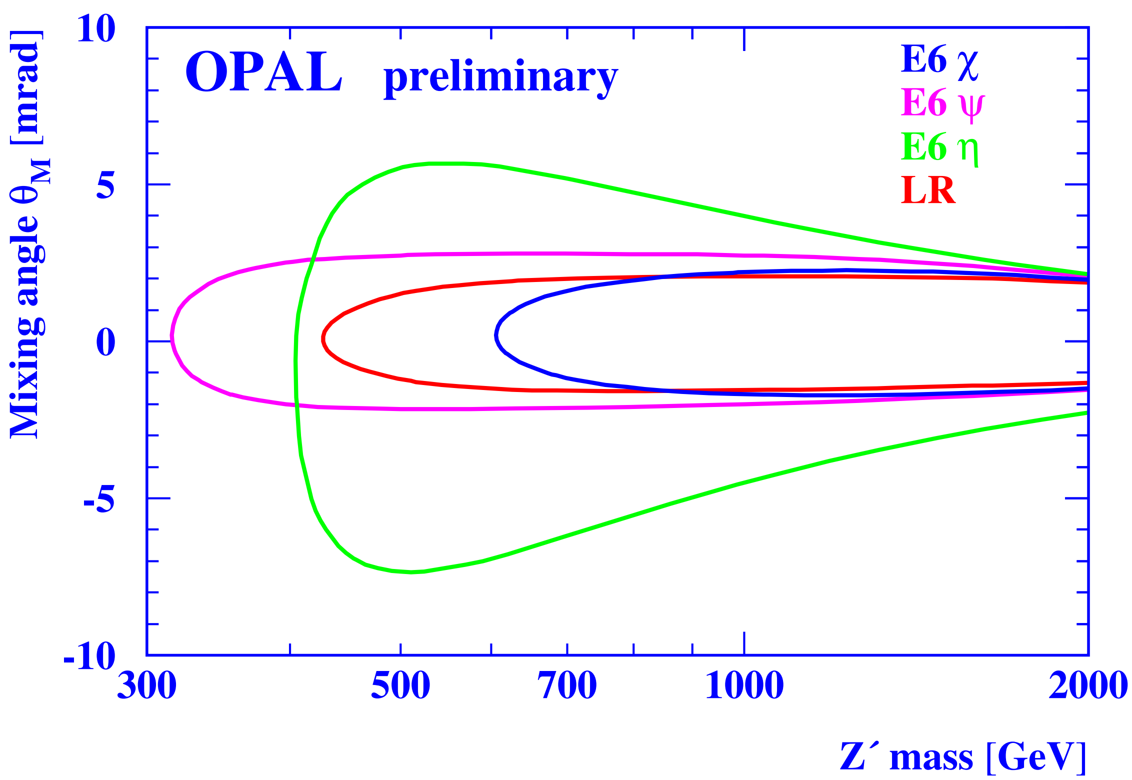
* $\sqrt{s}$ up to 202 GeV

Z' boson - Results

95% CL exclusion contour in the $M_{Z'}$ vs $\theta_{ZZ'}$ plane



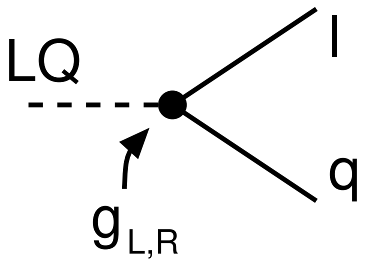


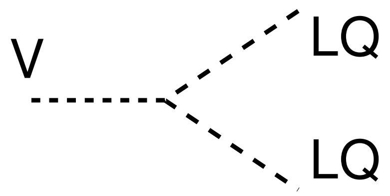


Leptoquarks

Particles carrying both baryon and lepton number and mediating interaction between quarks and leptons.

Assume LQ interaction $\left\{ \begin{array}{l} \text{dimensionless} \\ \text{SU(3)xSU(2)xU(1)} \\ \text{B and L conservation} \end{array} \right\} \Rightarrow$ $\boxed{\begin{array}{c}\text{9 scalars} \\ \text{and} \\ \text{9 vectors}\end{array}}$





uniquely determined from Q and I_3

Free parameters $\boxed{M_{LQ}, g_{L,R}}$

Direct Search: $e^+e^- \rightarrow eq\ LQ$ $\qquad M_{LQ} < \sqrt{s}$

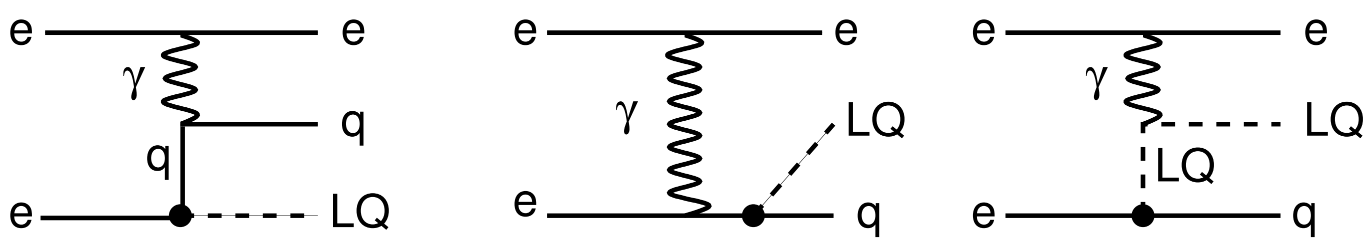
$e^+e^- \rightarrow LQ\ LQ$ $\qquad M_{LQ} < \sqrt{s}/2$

Indirect Search: Look for deviation in $e^+e^- \rightarrow q\bar{q}$

$$M_{LQ} > \sqrt{s}$$

LQ - Single Production

Single production $e^+e^- \rightarrow eq\,LQ$



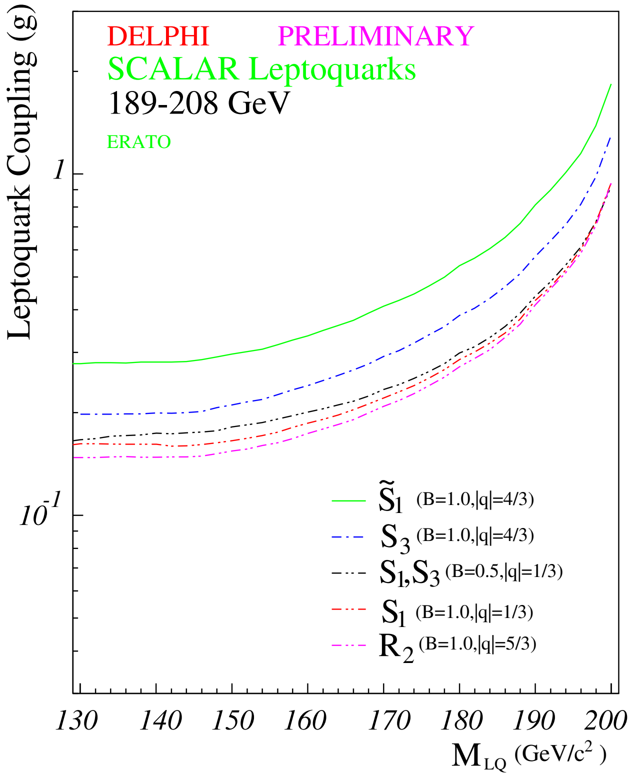
Charged decay mode: $LQ \rightarrow eq$

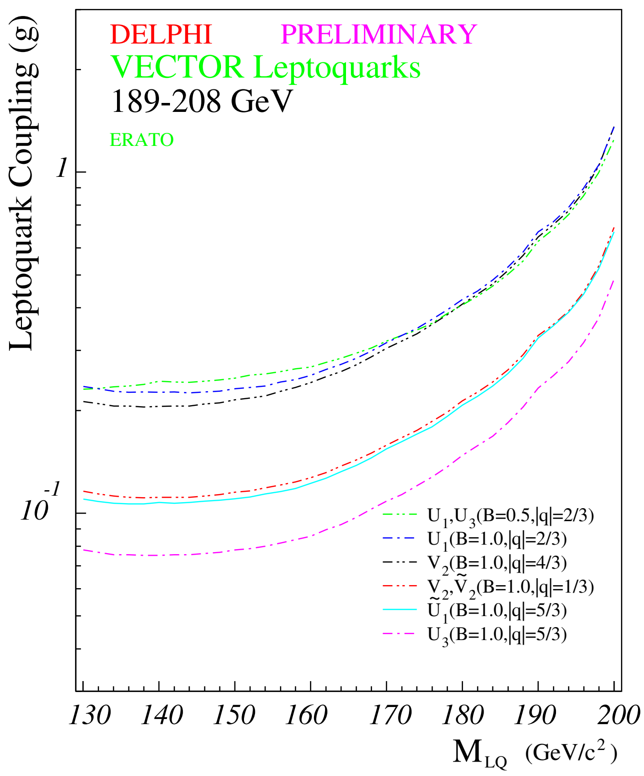
- monojet + isolated electron
- bkg: 4-f and 2-γ

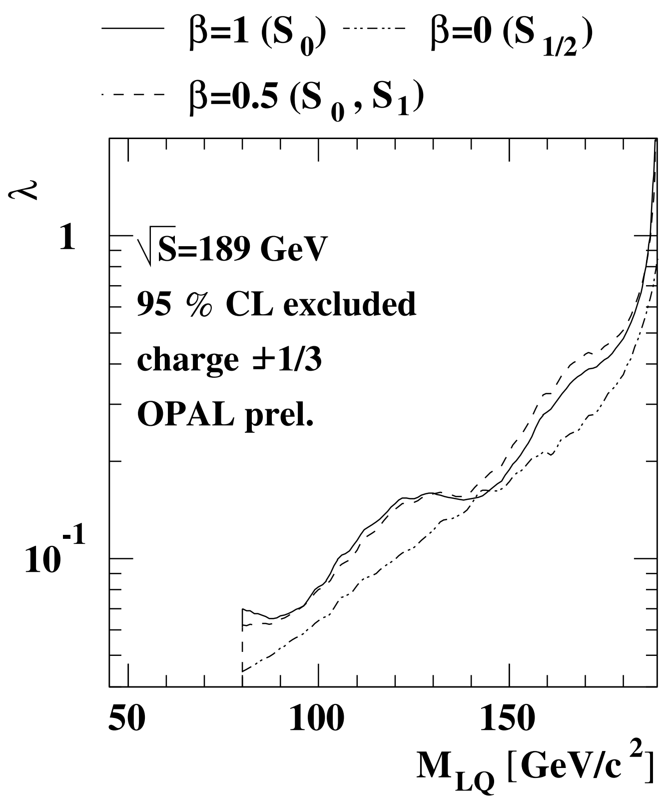
Neutral decay mode: $LQ \rightarrow \nu q$

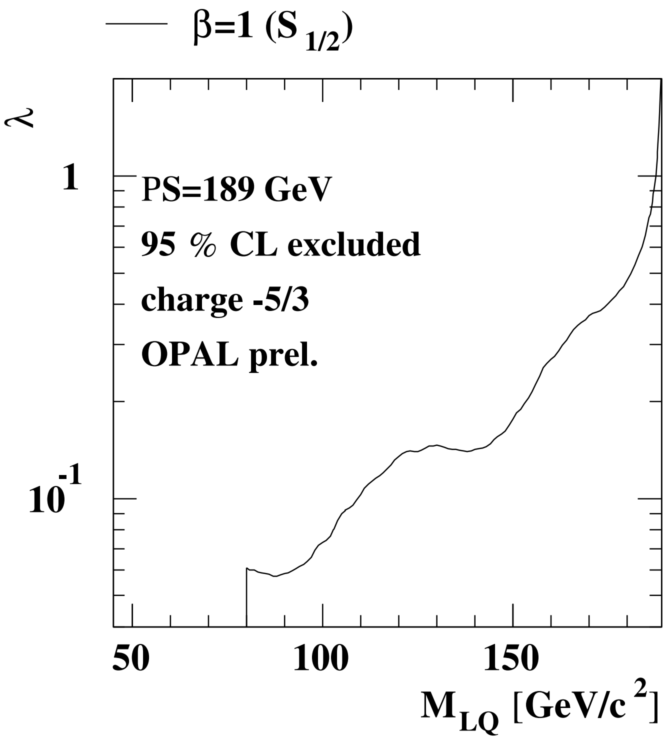
- monojet
- bkg: 4-f and 2-γ (CC DIS)

LQ - Single Production - Results

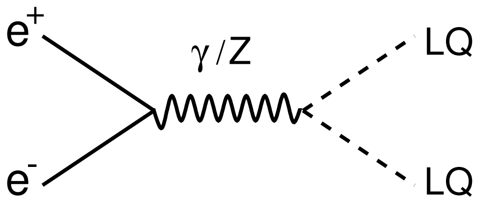




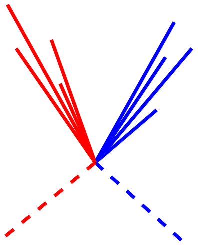




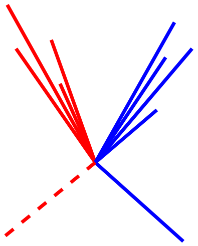
LQ - Pair Production



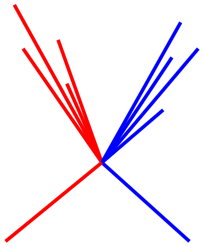
- Independent of $g_{R,L}$
- All LQ generations
- LQ with large coupling to neutrinos can be studied



$qq\nu\nu$



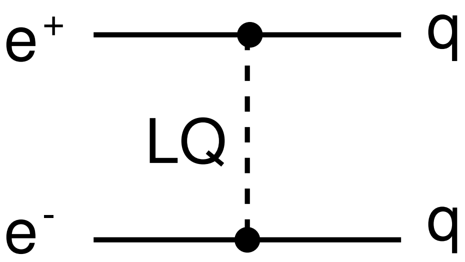
$ql\nu$



$qqll$

		OPAL 200-209 GeV Mass limits (GeV)		
LQ	Q_{em}	1^{st}	2^{nd}	3^{rd}
$\tilde{S}_0$	-4/3	97.6	100.3	98.2
$S_{\frac{1}{2}}$	-2/3	90.9	90.4	87.2
	-5/3	98.7	100.8	99.2
$\tilde{S}_{\frac{1}{2}}$	+1/3	76.5	76.5	76.5
	-2/3	93.9	98.6	94.9
S_1	+2/3	94.7	94.7	94.7
	-4/3	99.2	101.1	99.6
V_0	-2/3	98.7	98.7	96.5
$\tilde{V}_0$	-5/3	101.7	$>$ 102	101.8
$V_{\frac{1}{2}}$	-1/3	98.9	98.7	98.2
	-4/3	101.3	$>$ 102	101.5
$\tilde{V}_{\frac{1}{2}}$	+2/3	98.3	98.3	98.3
	-1/3	99.9	101.4	100.3
V_1	+1/3	100.7	100.7	100.7
	-2/3	98.7	98.7	96.5
	-5/3	101.9	$>$ 102	$>$ 102

LQ - Indirect Search



- Fit $\sigma(e^+e^- \to q\bar{q})$
- Take g_L or $g_R \neq 0$
- Set $g_{L,R} = \sqrt{4\pi\alpha_{em}}$
- Assume flavour diagonal coupling

ALEPH+DELPHI+L3+OPAL
130-209 GeV

Scalar LQ		M_{LQ} (GeV)
S_0	$\to e_L u$	789
	$\to e_R u$	639
$\tilde{S}_0$	$\to e_R u$	210
$S_{\frac{1}{2}}$	$\to e_L \bar{u}$	189
	$\to e_R \bar{u}, e_R \bar{d}$	240
$\tilde{S}_{\frac{1}{2}}$	$\to e_L \bar{d}$	–
S_1	$\to e_L u, e_L d$	364

Vector LQ		M_{LQ} (GeV)
V_0	$\to e_L \bar{d}$	1070
	$\to e_R \bar{d}$	167
$\tilde{V}_0$	$\to e_R \bar{u}$	497
$V_{\frac{1}{2}}$	$\to e_L d$	305
	$\to e_R u, e_R d$	227
$\tilde{V}_{\frac{1}{2}}$	$\to e_L u$	176
V_1	$\to e_L \bar{u}, e_L \bar{d}$	664

Excited Leptons

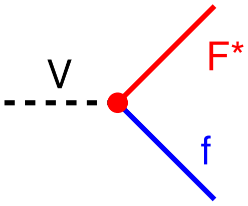
Composite leptons $\Rightarrow$ excited states ℓ^*, ν^*

Stringent constraints from g-2 precision measurements

$\Downarrow$

Assume chiral coupling to avoid large contributions to anomalous magnetic moment

$\Downarrow$



$$\mathcal{L} = \frac{1}{2\Lambda}\bar{F}^*\sigma^{\mu\nu}\left[g\,f\,\frac{\boldsymbol{\tau}}{2}\mathbf{W}_{\mu\nu} + g'\,f'\,\frac{Y}{2}B_{\mu\nu}\right] f_{\mathrm{L}}$$

compositeness scale

weight factors

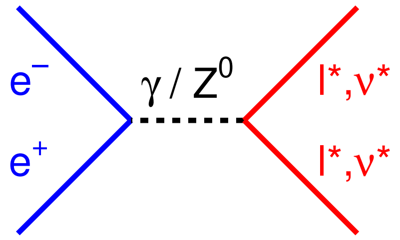
Branching ratio, efficiencies, topologies,.. depend on f, f'

Common settings $\begin{cases} f = f' & (\cancel{\nu^* \to \nu\gamma}) \\ f = -f' & (\cancel{\ell^* \to \ell\gamma}) \end{cases}$

Pair production: $e^+e^- \to \ell^*\ell^*, \nu^*\nu^*$

Single production: $e^+e^- \to \ell^*\ell, \nu^*\nu$

Excited Leptons - Pair Production

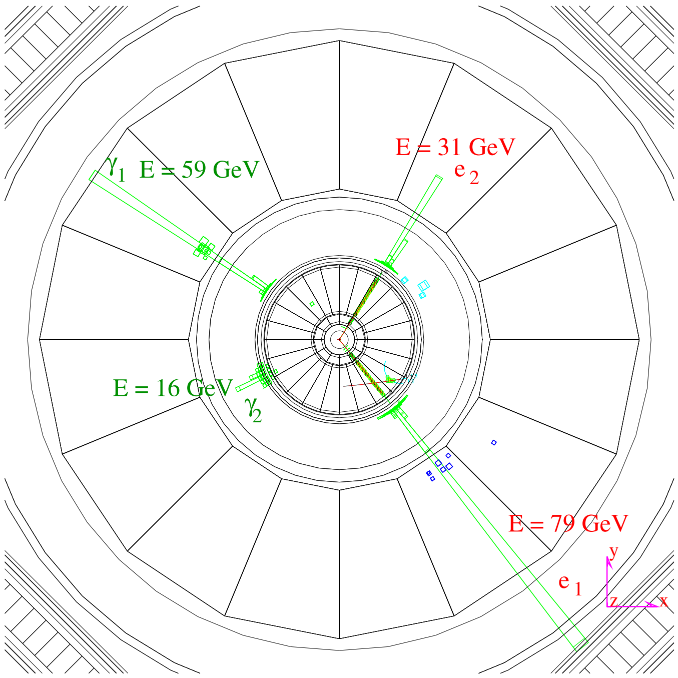


$$\ell^* \rightarrow \ell\gamma, \ell Z, \nu W$$
$$\nu^* \rightarrow \nu\gamma, \nu Z, \ell W$$

$$e^+e^- \rightarrow e^*e^* \rightarrow ee\gamma\gamma$$

m(e$_1$,γ$_2$) = 60 GeV   m(e$_2$,γ$_1$) = 59 GeV

Run # 772501 **Event #** 3103 Total Energy : 189.50 GeV

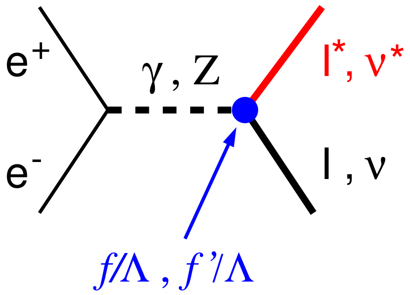


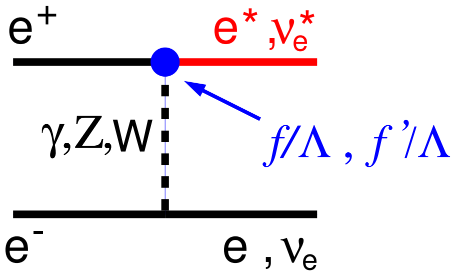
Transverse Imbalance : .0166		**Longitudinal Imbalance :** -.0202	
Thrust : .7979	**Major :** .2969	**Minor :** .2251	
Event DAQ Time : 990820 54953			

	95% CL Mass Limit (GeV)						
	$f = f'$				$f = -f'$		Coupl. Ind.
	DELPHI	**OPAL**	**L3**	**ALEPH**	**DELPHI**	**L3**	**L3**
e^*	103.0	102.9	100.1	94.3	98.0	96.2	96.0
μ^*	103.1	102.9	100.3	94.3	98.0	96.2	96.2
τ^*	102.2	102.8	99.9	94.3	98.0	96.2	94.9
ν_e^*	102.0	99.5	99.3	94.2	102.7	99.5	98.5
ν_μ^*	102.4	99.5	99.4	94.2	102.8	99.5	98.5
ν_τ^*	95.3	91.9	93.9	94.2	102.8	99.4	92.7

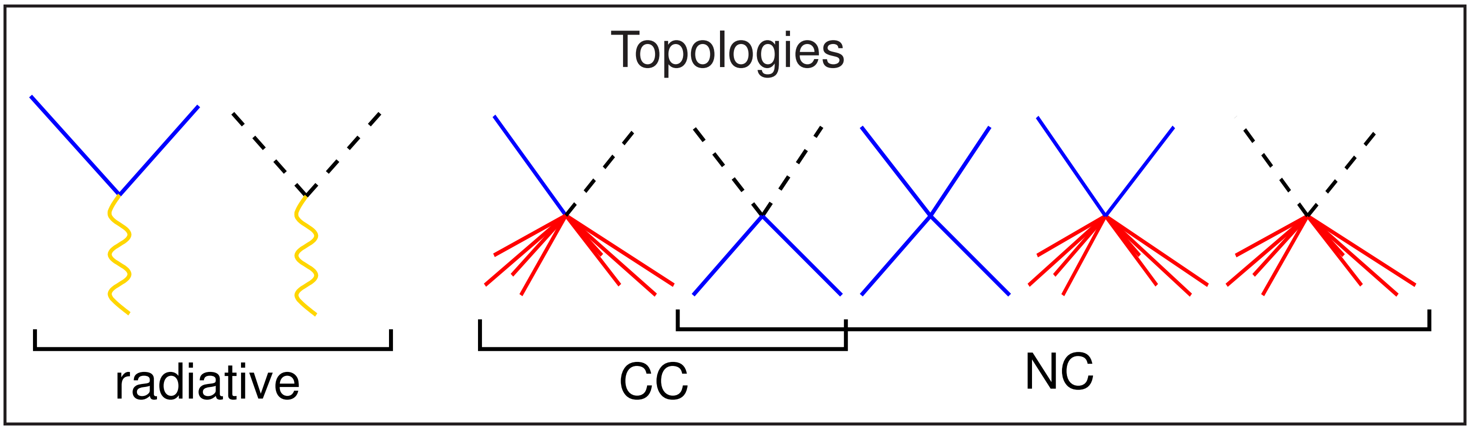
$\sqrt{s}$ = 189- 209 GeV ($\approx$170 pb^{-1})
$\sqrt{s}$ = 192-202 GeV
$\sqrt{s}$ = 189-208 GeV
$\sqrt{s}$ = 189 GeV

Single production of Excited Leptons

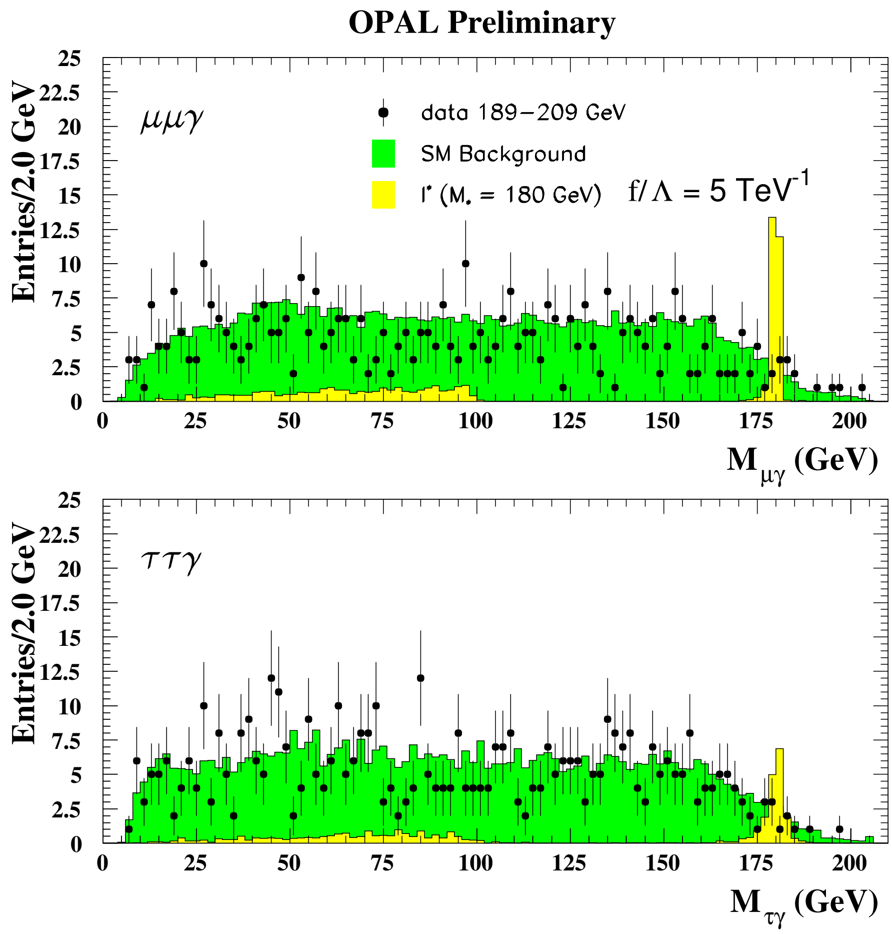




Discovery up to
$$M_* \sim \sqrt{s}$$



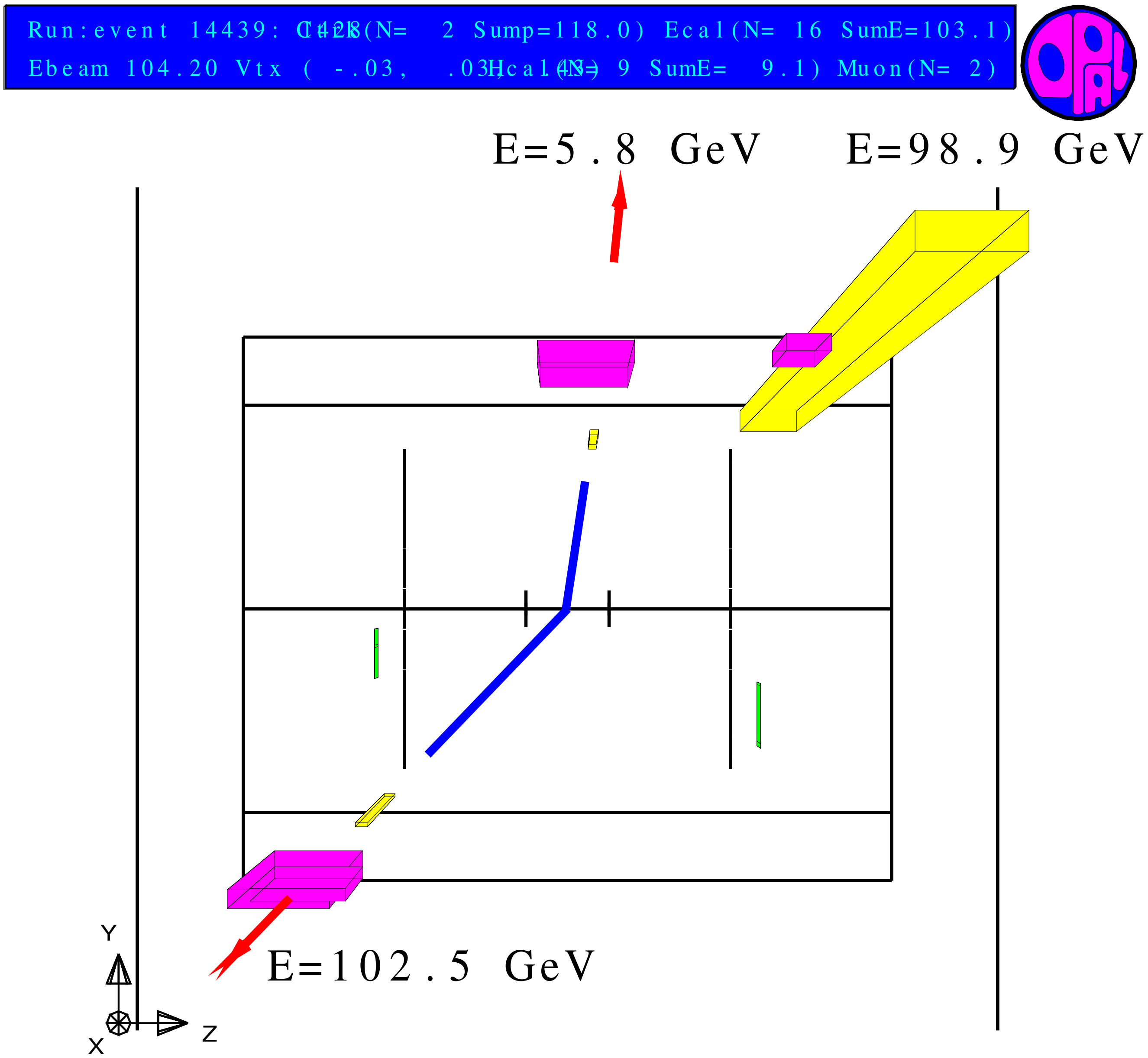
Look for peak in invariant mass



Excited Lepton Candidate event

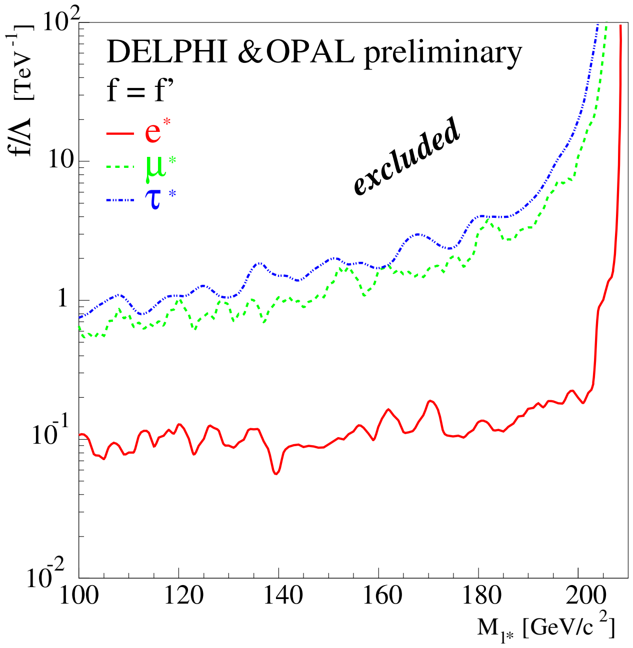
$$e^+e^- \to \mu^* \mu \to \mu\mu\gamma$$

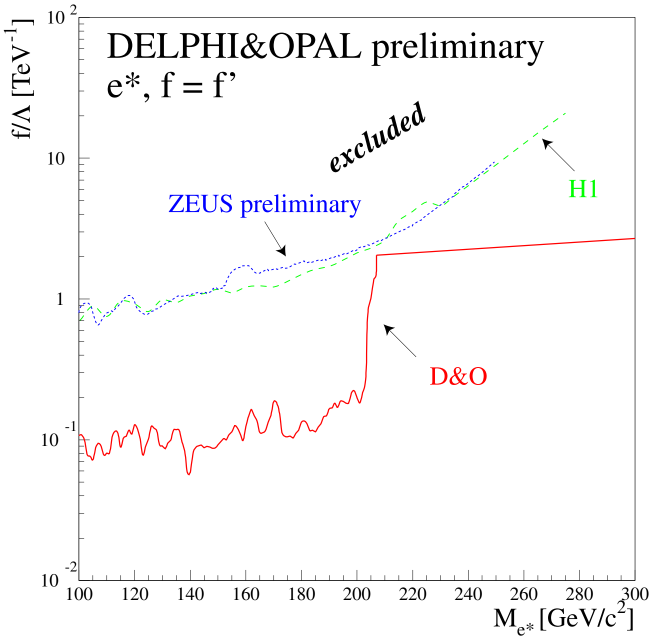
($\sqrt{s} = 208.4$ GeV, $M_{\mu\gamma} = 201.3$ GeV)

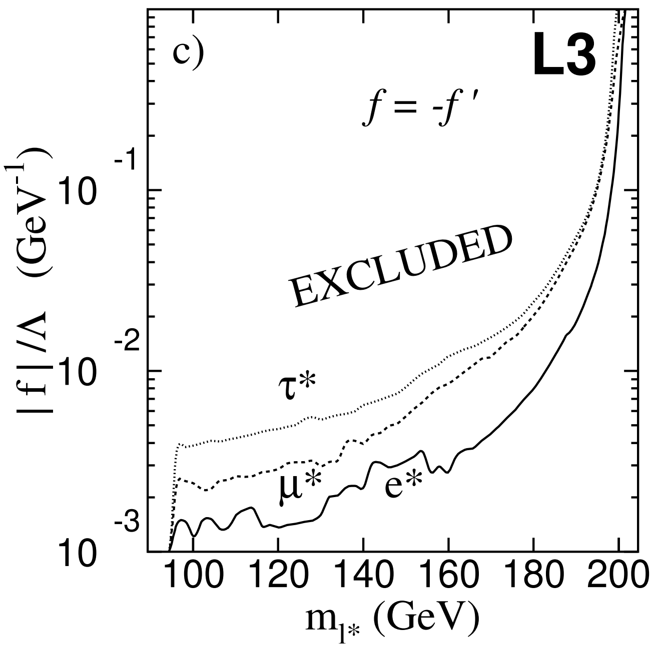


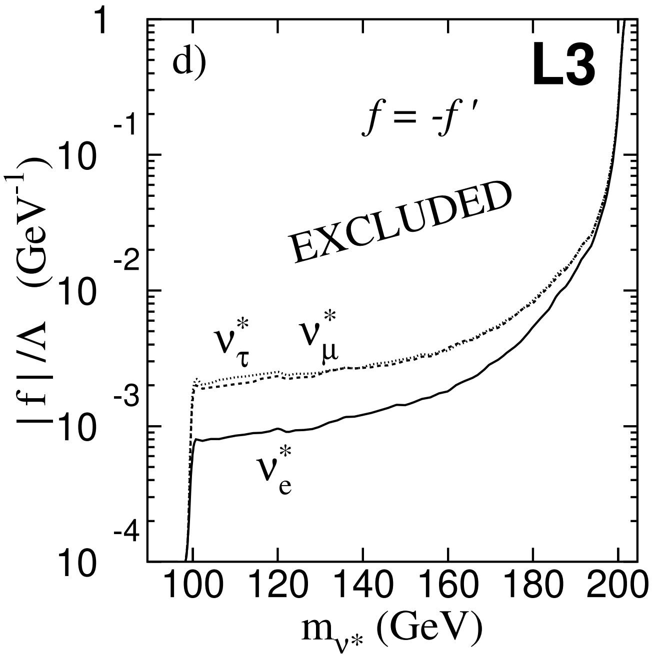
$$M_{\mu\mu} = 46.0 \text{ GeV}$$

Excited Leptons - Single production - Results









Technicolor

- New QCD-like (strong) interaction produce EWSB

$$\Lambda_{\rm TC} << \Lambda_{\rm QCD}$$

- W,Z are condensates of a new family of fermions

Technifermions

$$\text{BUT problems ...} \left\{ \begin{array}{c} \text{FCNC} \\ \mathrm{m_f} \\ \text{EW data} \end{array} \right\} \text{... Extended TC models}$$

Technicolor “straw-man” model

- low-scale TC
- Minimum number of free parameters
- Only consider lightest technifermions $(\mathrm{T_U}, \mathrm{T_D})$
- lightest bound states $\rho_{\rm T}^{\pm,0}, \omega_{\rm T}$ vector

  $\pi_{\rm T}^{\pm,0}, \pi_{\rm T}^{0'}$ pseudoscalar

$$\mathrm{M}_{\rho_{\rm T}}, \mathrm{M}_{\pi_{\rm T}}, \mathrm{N_D}, \mathrm{Q_U} + \mathrm{Q_D}, \mathrm{M_V}, \alpha_{\rho_{\rm T}}$$

Technicolor - Experimental signatures

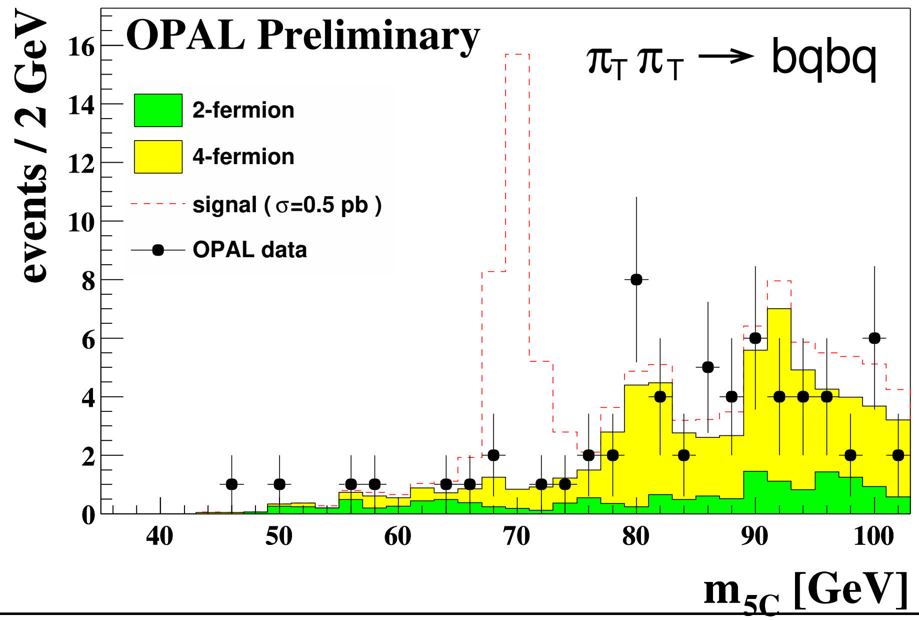
$$e^+e^- \to \rho_T^{(*)}(\gamma) \to \begin{cases} \pi_T^+\pi_T^- & \text{dominant } M_{\rho_T} > 2M_{\pi_T} \\ \pi_T^\pm W_L^\mp & \\ W_L^+ W_L^- & \\ \pi_T^0\gamma & \text{model dependent } (\rho_T/\omega_T) \\ f\bar{f} & \text{suppressed} \end{cases}$$

$\left.\right\}$ $M_{\rho_T}, M_{\pi_T}, N_D$

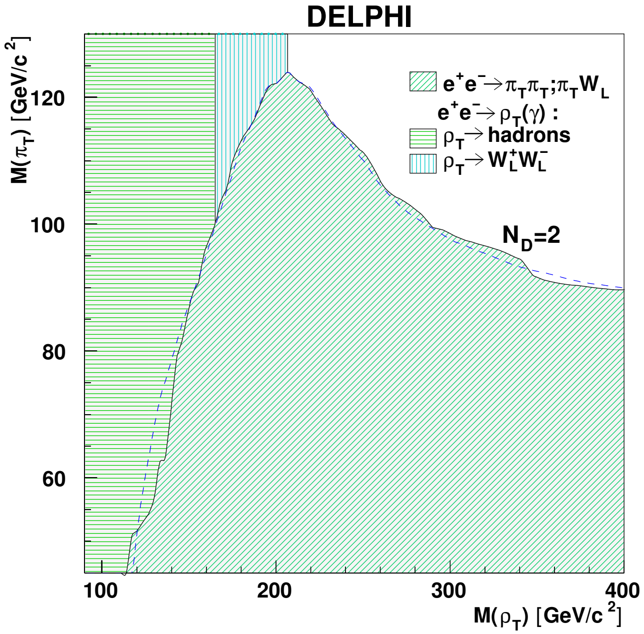
$M_V, \alpha_{\rho_T}, (Q_U+Q_D)$

$\Gamma(\pi_T \to f\bar{f}') \sim (m_f + m_{f'})^2$ ➡ $\sim$ 90% of π_T decays b-quark ➡ $\boxed{\text{b-tagging !}}$

- hadronic final states ($\geq$ 2 jets)
- b-jets
- WW-like
- look for peak in invariant mass $\Rightarrow$



Technicolor - Results

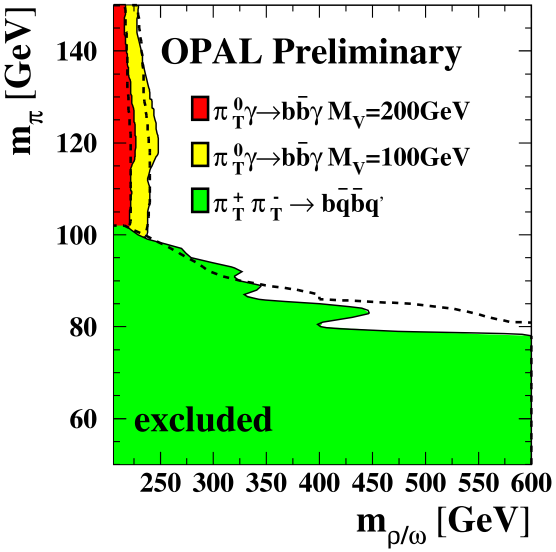


$\sqrt{s}$=192−209 GeV

$N_D=2$

$m_{\pi_T^\pm} > 79.8$ GeV ($N_D=2$)

$m_{\pi_T^\pm} > 89.1$ GeV ($N_D=9$)

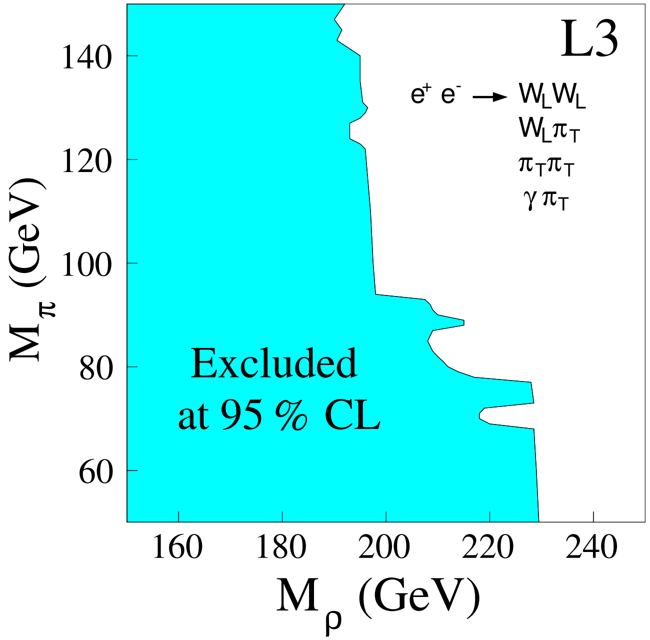


$\sqrt{s}$=200−209 GeV

$N_D=9, (Q_U+Q_D)=5/3$

$m_{\pi_T^\pm} > 62.0$ GeV ($N_D=2$)

$m_{\pi_T^\pm} > 77.0$ GeV ($N_D=9$)



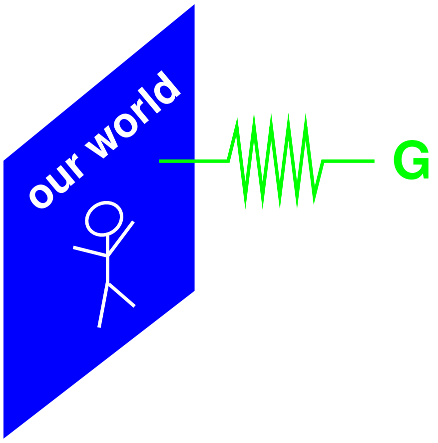
$\sqrt{s}$=189 GeV

All N_D

$(Q_U+Q_D)=-1,0,5/3$

Low-scale Gravity in Extra Dimensions

Why is gravity so weak?? $\mathrm{M_{Pl}} = \frac{1}{\sqrt{\mathrm{G_N}}} \sim 10^{19}$ GeV



Arkani-Hamed, Dimopoulos, Dvali (ADD)

- World confined to 4 dimensions
- Gravity propagates in extra dimensions

Planck Mass in 4-d

number of extra dimentions

$$M_{Pl}^2 = R^n M_D^{n+2}$$

radius of compactification of extra dimensions

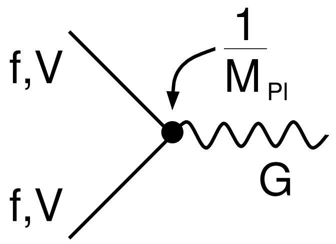
Planck Mass in D-dim

Choose $\mathrm{M_D} \sim \Lambda_{\mathrm{EW}} \Rightarrow$ $\boxed{\text{No Hierarchy problem!}}$

n	r	
1	10^{13} m	Excluded!
2	1 mm	stringent constraints from supernova
3	1 nm	
....		
7	1 fm	max in M-theory

Size of extra dimensions could be “large”
Within energy reach of present/future colliders

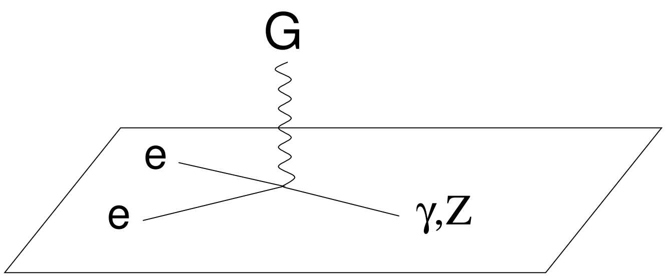
4+n dim		4 dim
massless spin 2	$\Leftrightarrow$	towers of massive gravitons $\Delta m \sim 1/R$



... but large number of states

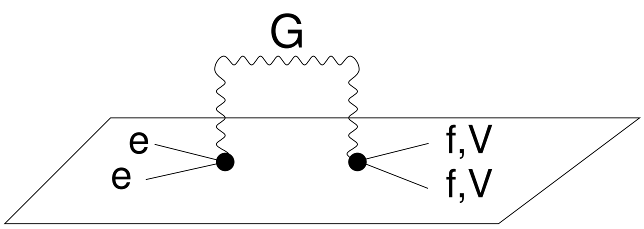
Massive, non-interacting, stable particle

Direct Searches



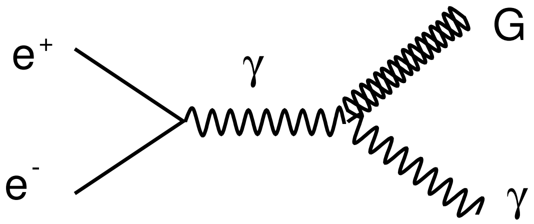
Missing energy

Indirect Searches



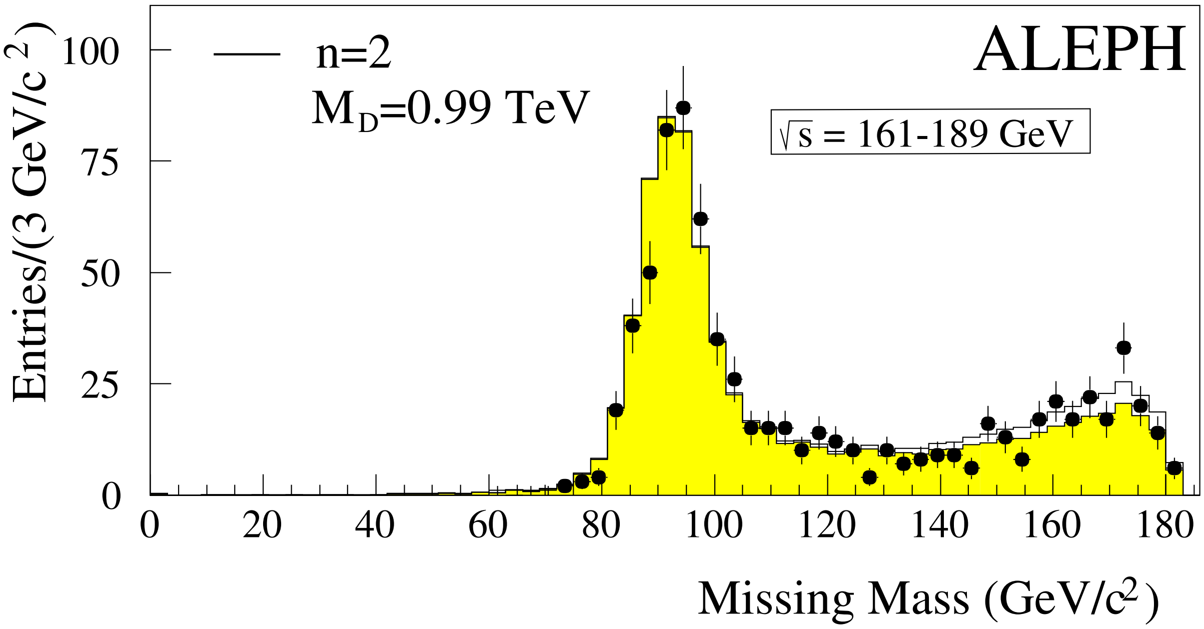
Look for deviations from $(d\sigma/d\Omega)_{\mathrm{SM}}$

Direct Search: $e^+e^- \rightarrow \mathrm{G}\gamma$



$$\sigma \sim \frac{\sqrt{s}^{\;n}}{\mathrm{M_D}^{\mathrm{n+2}}}$$

Varying amount of missing energy



95% lower limits on $\mathrm{M_D}$

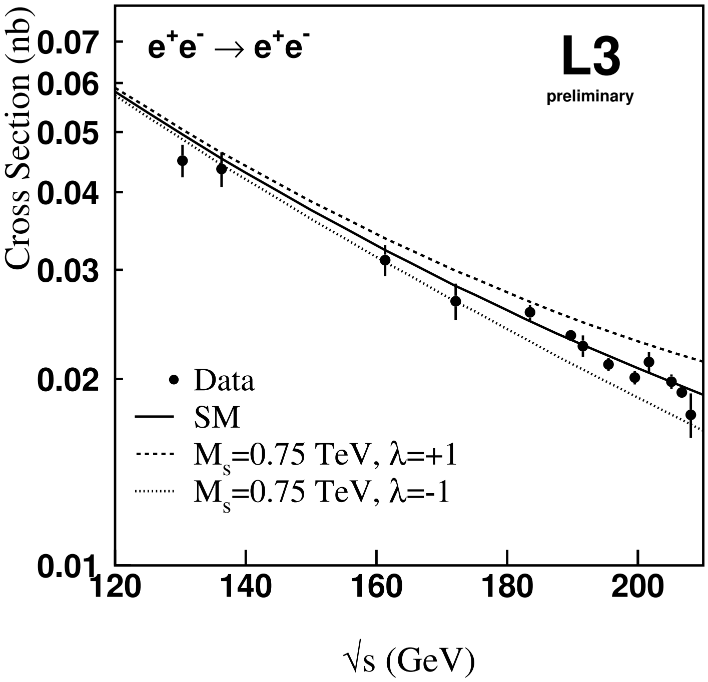
	Number of extra dimensions					
	2	3	4	5	6	7
ALEPH (189-209 GeV)	1.28	0.97	0.78	0.66	0.57	—
DELPHI (181-209 GeV)	1.38	—	0.84	—	0.58	—
L3 (189 GeV)	1.02	0.81	0.67	0.58	0.51	0.45
OPAL (189 GeV)	1.09	0.86	0.71	0.61	0.53	0.47

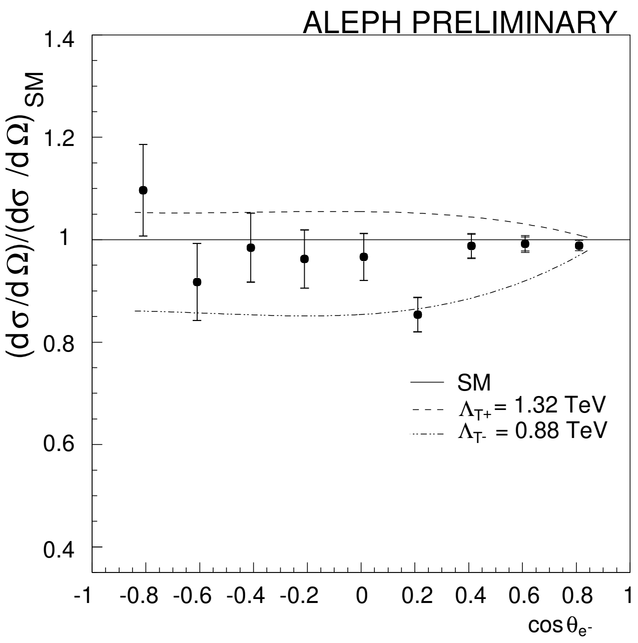
Indirect Search: $e^+e^- \to \mathrm{G}^* \to \mathrm{f\bar{f}}, \mathrm{VV}$

$$d\sigma/d\Omega = A(s,t) + \frac{\lambda}{\mathrm{M_s^4}} B(s,t) + \frac{\lambda^2}{\mathrm{M_s^8}} C(s,t)$$

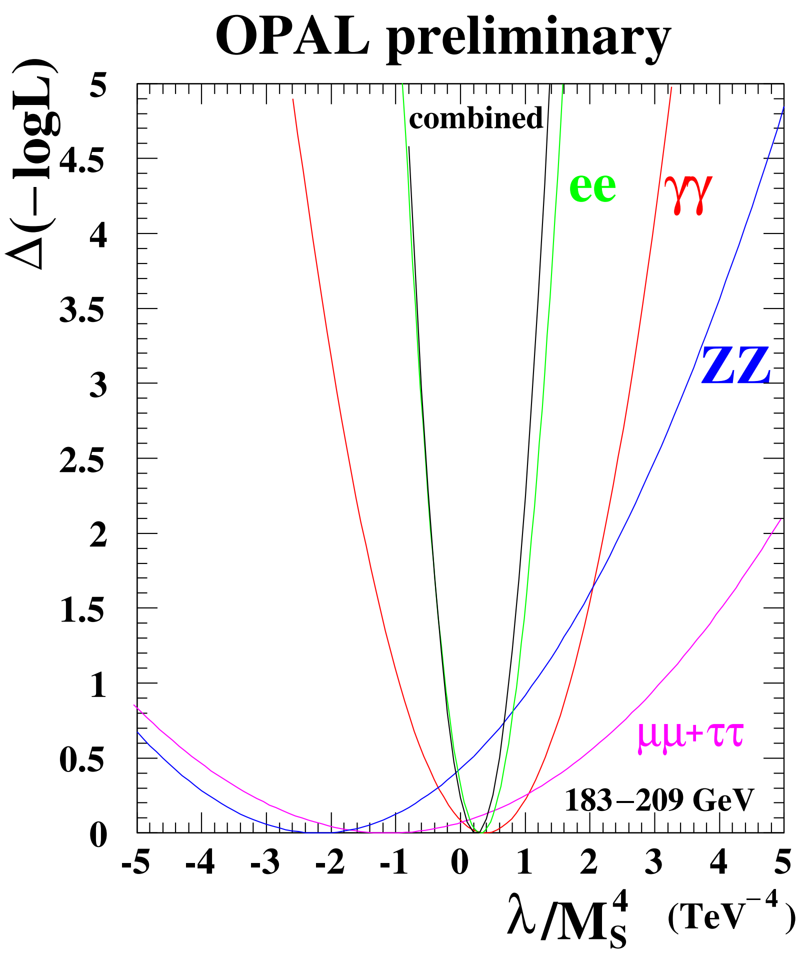
- λ depends on theory
- $\mathrm{M_s}$ UV cut-off set to string scale

$\mathrm{e^+e^-} \to \mathrm{e^+e^-}$ most sensitive channel





Indirect Search - Results



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

	M_s	
	$\lambda = -1$	$\lambda = +1$
L3	0.98	1.06
OPAL	1.00	1.15

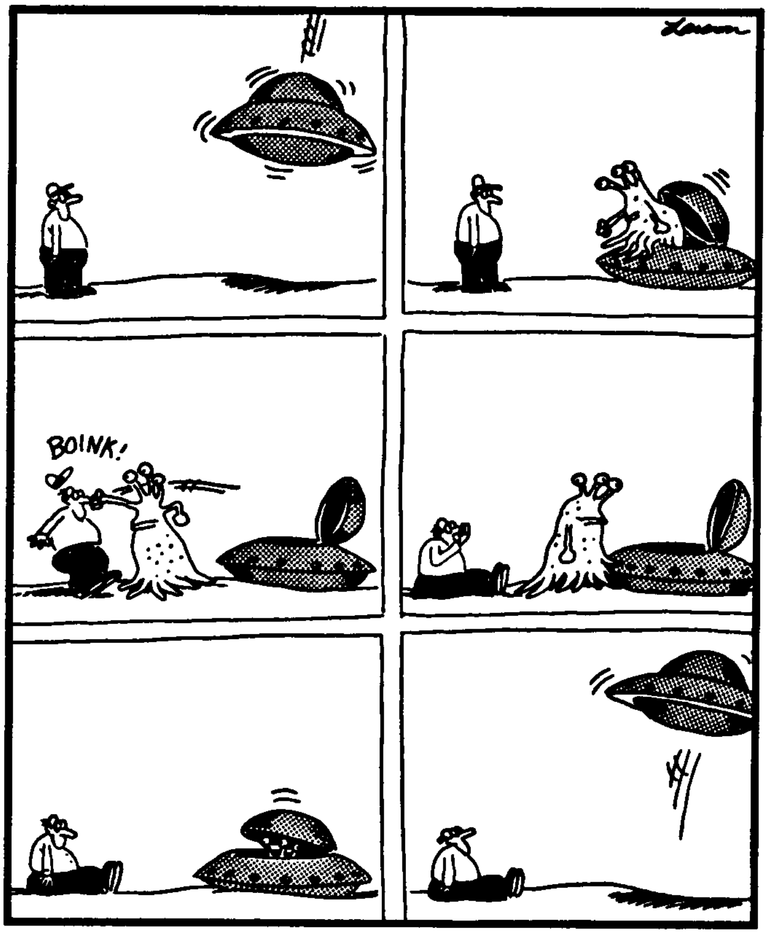
$e^+e^- \to \gamma\gamma$

	M_s	
	$\lambda = -1$	$\lambda = +1$
DELPHI	0.70	0.77
L3	0.99	0.84
OPAL	0.89	0.83

Summary

- Many “exotic” searches performed at LEP
- No hint of New Physics
- Lots of work remains to finalise analysis

http://alephwww.cern.ch/
http://delinfo.cern.ch/Delphi/
http://l3www.cern.ch/
http://opal.web.cern.ch/Opal/PPwelcome.html



Always be ready

for

anything ...