Z' Bosons – Present and Future Limits at e^+e^- Colliders

The L3 Collaboration

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Beyond the Standard Model V, 1997

- Physics of Z'
- Z' models
- Sensitivity for Z' effects
- Analysis & Results
  - Z' mass bounds
  - ZZ' mixing
  - Model-independent Z' Studies
- Model-independent Z' Studies at NLC
- Summary

Indirect Z′ Search

$$\mathcal{L} = eA_\mu J^\mu_\gamma + gZ^0_\mu J^\mu_{Z^0} + g'Z'^0_\mu J^\mu_{Z'^0}$$

Idea:

- Z′ with $m_{Z'} > \sqrt{s}$ leads to deviations of observables (σ, A_{FB} etc.) from the Standard Model predictions.
- If no significant hint for the existence of a Z′ can be found
  $\rightarrow$ place limits on Z′ parameters

Z′ parameters:

- mass, $m_{Z'}$
- ZZ′ mixing angle, θ_M,
  $$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M \end{pmatrix} \begin{pmatrix} Z^0 \\ Z^{0\prime} \end{pmatrix}$$
- Z′ couplings to fermions:
  1. defined by GUT models (model-dependent Z′ search)
  2. model-blind Z′ search

E_6 Models

$$J^{\mu}_{Z'} = J^{\mu}_{\chi}\cos\theta_6 + J^{\mu}_{\psi}\sin\theta_6$$

Special cases:

- χ model: $\theta_6 = 0$
- ψ model: $\theta_6 = \pi/2$
- η model: $\theta_6 = -\arctan\sqrt{5/3}$

Left-Right Symmetric Models

$$J_{LR} = \alpha_{LR} J^{\mu}_{3R} - \frac{1}{2\alpha_{LR}} J^{\mu}_{B-L}$$

with

$$\alpha_{LR} = \left[\frac{1-\left(1+g_L^2/g_R^2\right)\sin^2\theta_W}{\left(g_L^2/g_R^2\right)\sin^2\theta_W}\right]^{1/2}$$

Special case: LR model,

$$g_L = g_R \quad \alpha_{LR} = 1.53$$

Sequential Standard Model

Z′ ≡ Z, only heavier (SSM)

On the Z resonance

ZZ′ mixing:

$$\tan\theta_M = \frac{m_o^2 - m_Z^2}{m_{Z'}^2 - m_o^2}; \qquad m_o = \frac{m_W}{\rho\cos\theta_W}$$

and

$$a_f(\mathrm{Z}) \;=\; \cos\theta_M a_f + \frac{g'}{g}\sin\theta_M a'_f$$

Precise measurement of Z observables allows determination of ZZ′ mixing.

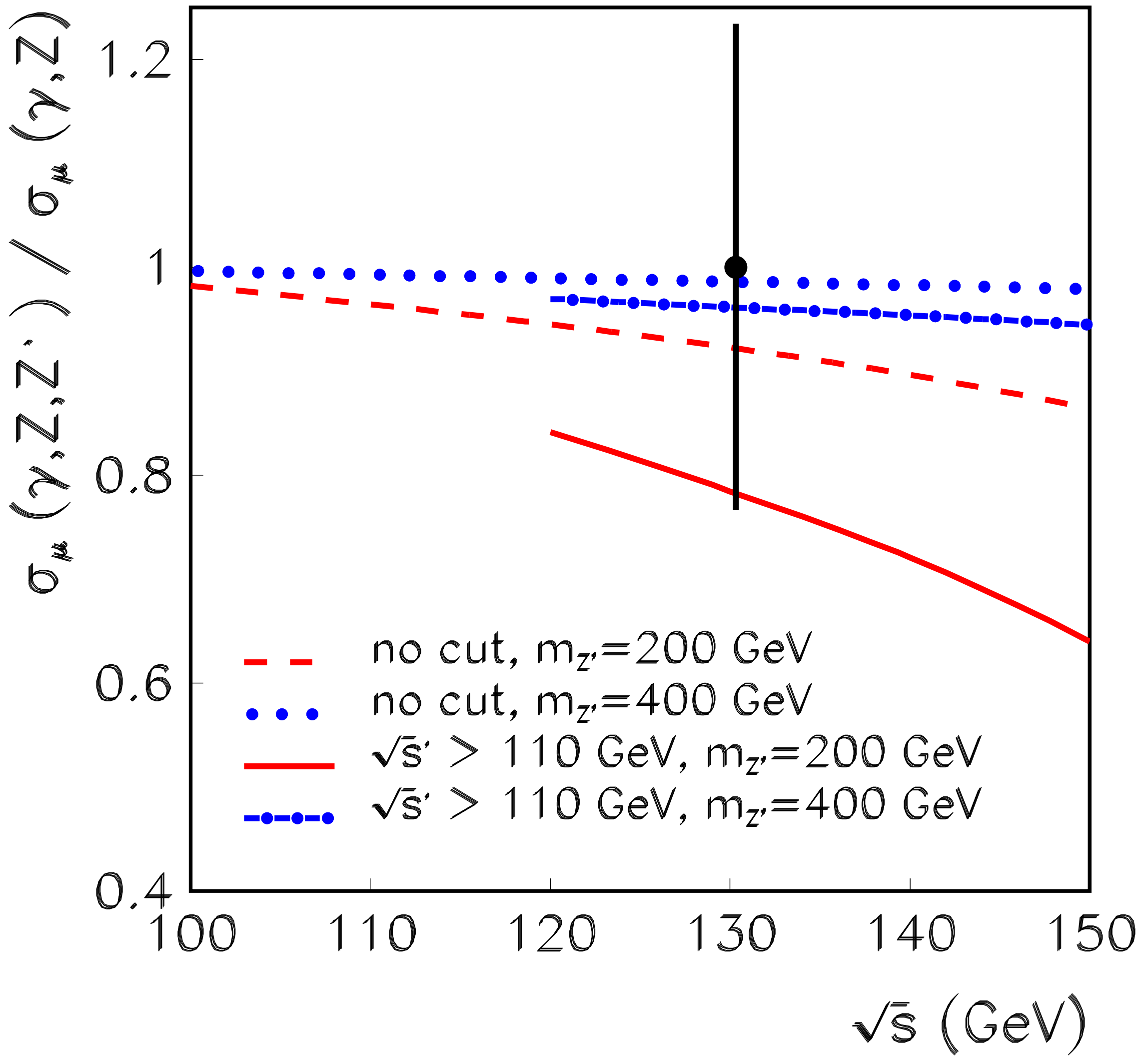
Above the Z Resonance

$$\sigma = \underbrace{\sigma_{\gamma\gamma} + \sigma_{\gamma Z} + \sigma_{ZZ}}_{\text{dominant}} + \underbrace{\sigma_{\gamma Z'} + \sigma_{ZZ'} + \sigma_{Z'Z'}}_{\sigma_{Z'}}$$

dominant $\qquad$ $\sigma_{Z'}$, can be competitive if $m_{Z'}$ is not too large

Clear Z′ signal:

Avoid radiative return to the Z peak!
(cut on energy of photon(s) emitted in the inital state)



Sensitivity for Z' signal with and without s' cut; $s'=(1\text{-}E_\gamma/E_{beam})s$

- include all leptonic and hadronic cross sections, asymmetries, τ polarization, R_b, R_c
  (L3: PLB 370(1996)126; L3 notes #2057, #2065 and references therein)
  LEP: LEPEWWG 97-01 (Winter Conferences 1997)

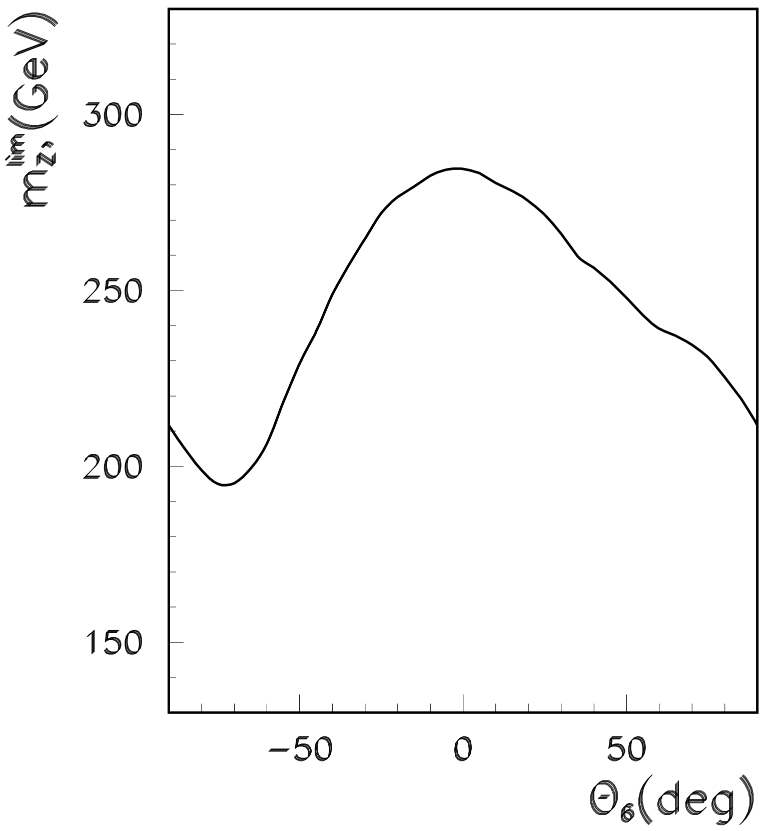
- above the Z resonance include the high energy data only

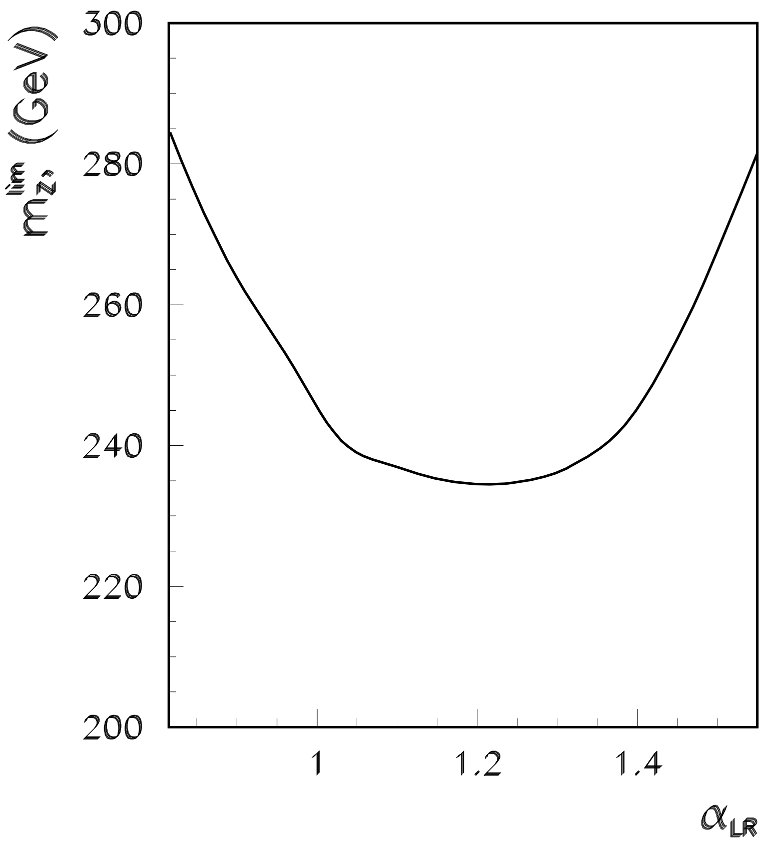
- use ZEFIT$\times$ZFITTER

- determine bounds on $\mathrm{m}_{Z'}$ and ZZ′ mixing, θ_M, in dependence on Z′ model

- is there a preference for a special Z′ model?

Lower Limits on Z′ mass, $m_{Z'}^{lim}$ (95% CL)





Comparison with results of direct Z′ mass measurements

(95% CL; in GeV):

(see: K.Maeshima, for CDF and D0, Warsaw 1996)

	$m_{Z'}^{lim}$ (GeV)	
Z′ model	direct	L3
χ	585	285
ψ	580	215
η	610	225
LR	555	275
SSM	690	520

Estimation for $m_{Z'}^{lim} < m_{Z'}$ from all 4 LEP experiments:

Use scaling law:

$$m_{Z'} > (s\mathcal{L}_{int})^{1/4}$$

(see A. Leike, ZPC 62(1994)265)

$\rightarrow$ $m_{Z'}^{lim}$ is enlarged by a factor 1.4

Future of indirect $m_{Z'}$ measurements

Expected lower Z′ mass bounds in GeV (95% CL):

	χ	ψ	η	LR	SSM
LEP2:					
500 pb^{-1}	940	540	580	760	1500
NLC:					
500 GeV					
50 fb^{-1}	3400	1850	2020	2720	4740
800 GeV					
200 fb^{-1}	5420	2510	2810	4510	7230
1.6 TeV					
800 fb^{-1}	11200	6260	6610	9040	15400

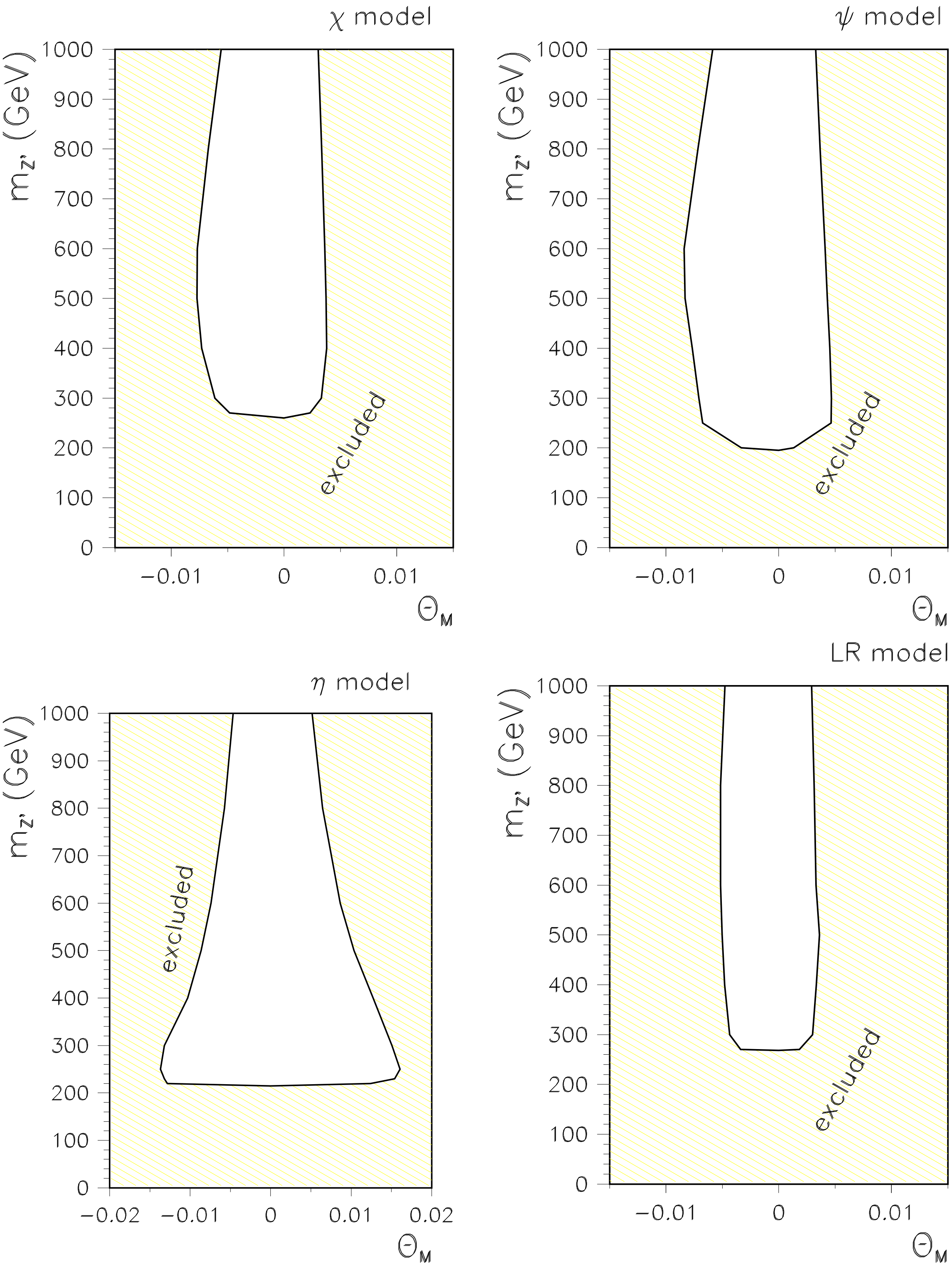
$$m_{Z'} > 4...7 \times \sqrt{s}$$

LHC (14TeV, 10 fb^{-1}): sensitiv to $m_{Z'} \leq$ 3...4 TeV

(see also S. Godfrey, PRD 51 (1995)1402)

m_H=150 GeV

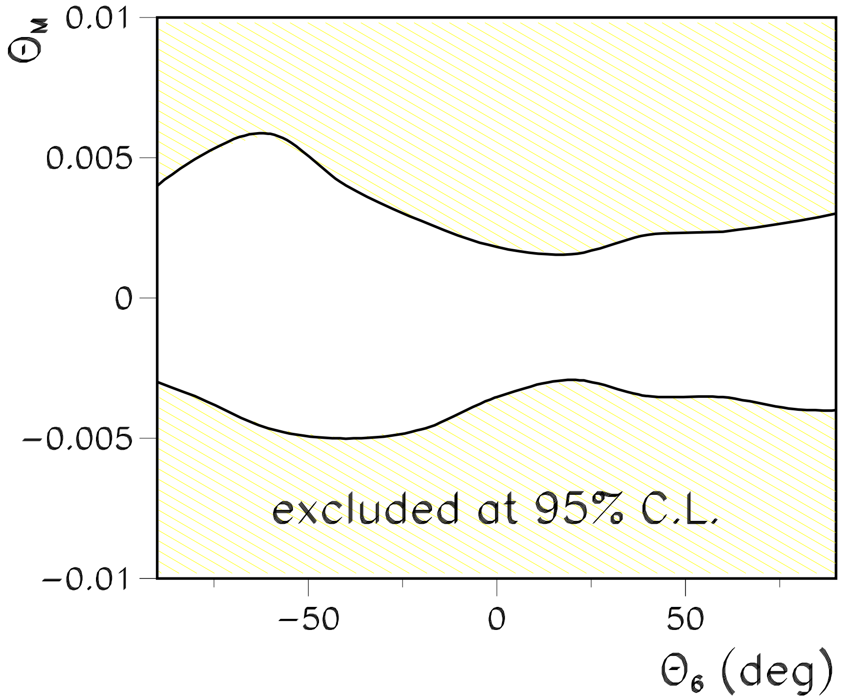
Constraints: m_t=175±6 GeV, $\alpha_s(m_Z)$=0.123±0.003

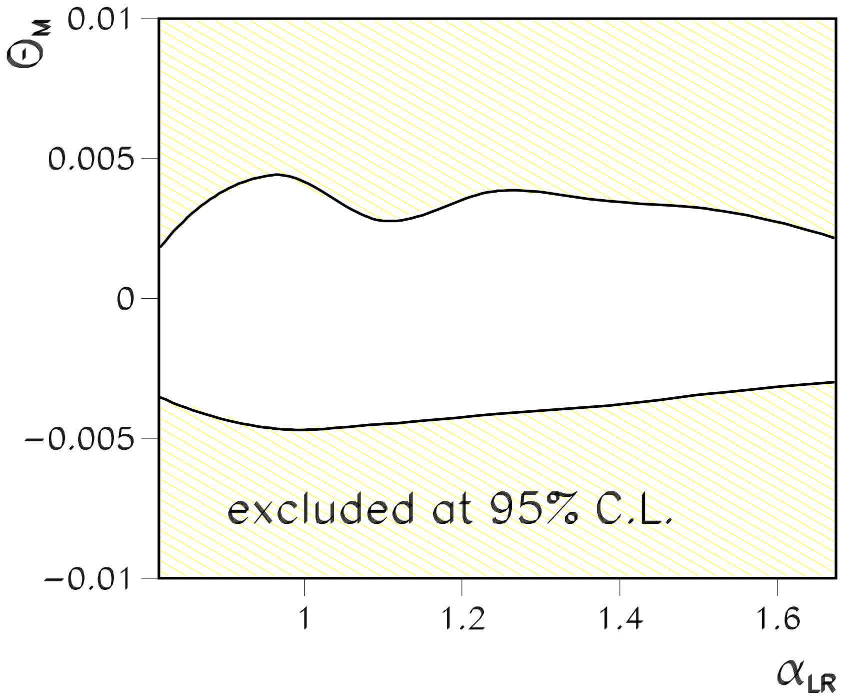


LEP results combined (LEPEWWG 97-01)

$m_{Z'} > 550$ GeV

Constraints: m_t=175±6 GeV $\alpha_s(m_Z)$=0.118±0.003





$$-0.007 < \theta_M < 0.005 \text{(L3)}$$

$$-0.003 < \theta_M < 0.003 \text{(LEP comb.)}$$

Model-independent Z′ Studies

a'_f, v'_f and $\theta_M, m_{Z'}$ are free parameters

Z and Z′ coupling to fermions:

$$\begin{aligned} a_f(\mathrm{Z}) &= \cos\theta_M a_f + \sin\theta_M \frac{g'}{g} a'_f \\ a_f(\mathrm{Z}') &= -\sin\theta_M \frac{g}{g'} a_f + \cos\theta_M a'_f \end{aligned}$$

- effective Z couplings are $a_f(\mathrm{Z}), v_f(\mathrm{Z})$
- Z′ couplings: We determine:
  $g' a_f(\mathrm{Z}') \equiv a'_f$
  $g' v_f(\mathrm{Z}') \equiv v'_f$

Disadvantage:

Many free parameters:

$\theta_M,\ m_{Z'}$
$a'_l, v'_l,\ a'_u, v'_u,\ a'_d, v'_d$

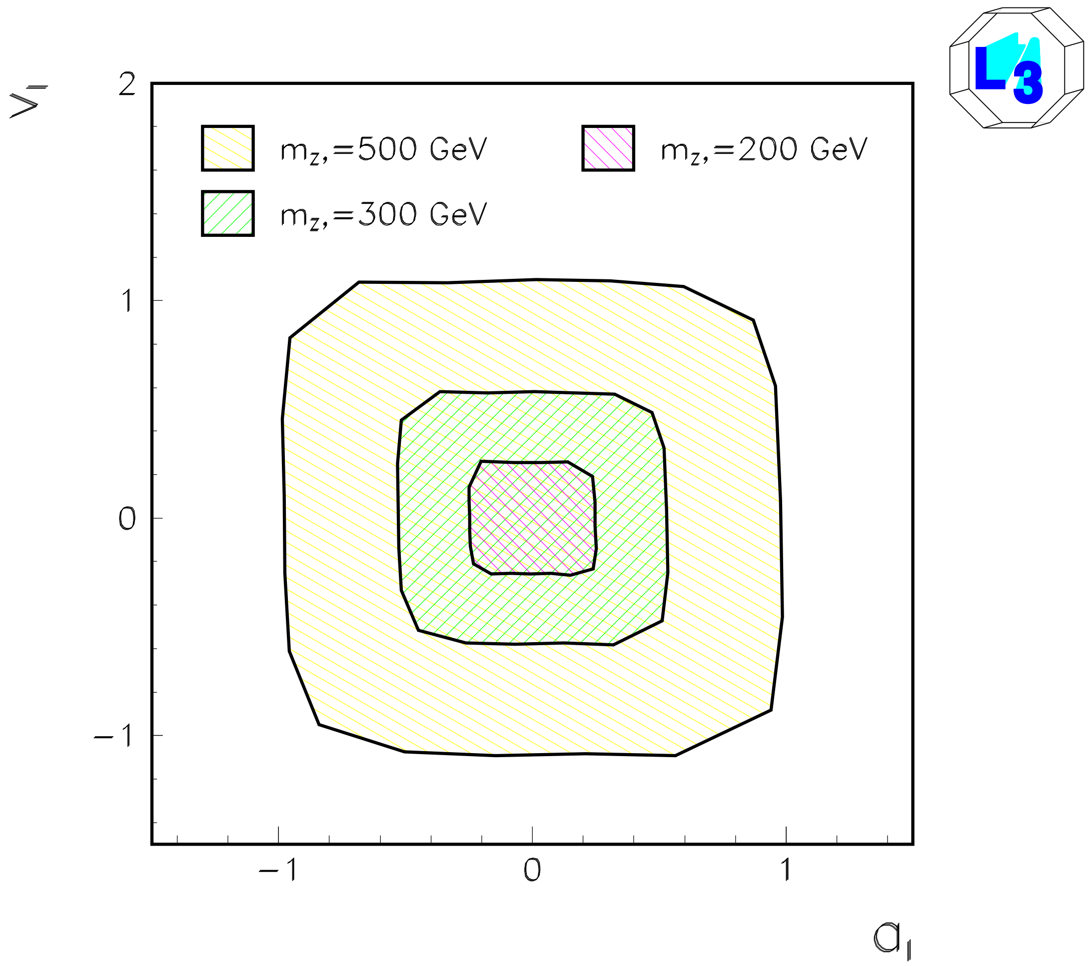
First Step: $Z'l\bar{l}$ couplings

with lepton universality:

$$\sigma_{Z'} \sim \frac{v_l' v_l'}{s - M_{Z'}^2} + \frac{(v_l v_l' + a_l a_l')^2}{(s - M_Z^2)(s - M_{Z'}^2)}$$

- $\Rightarrow$ Bounds on a_l', v_l'
- A Z′ with $a_q' \approx 0, v_q' \approx 0$ cannot be produced at $p\bar{p}$ colliders

Allowed regions for Z′l$\bar{l}$ couplings (95% CL)



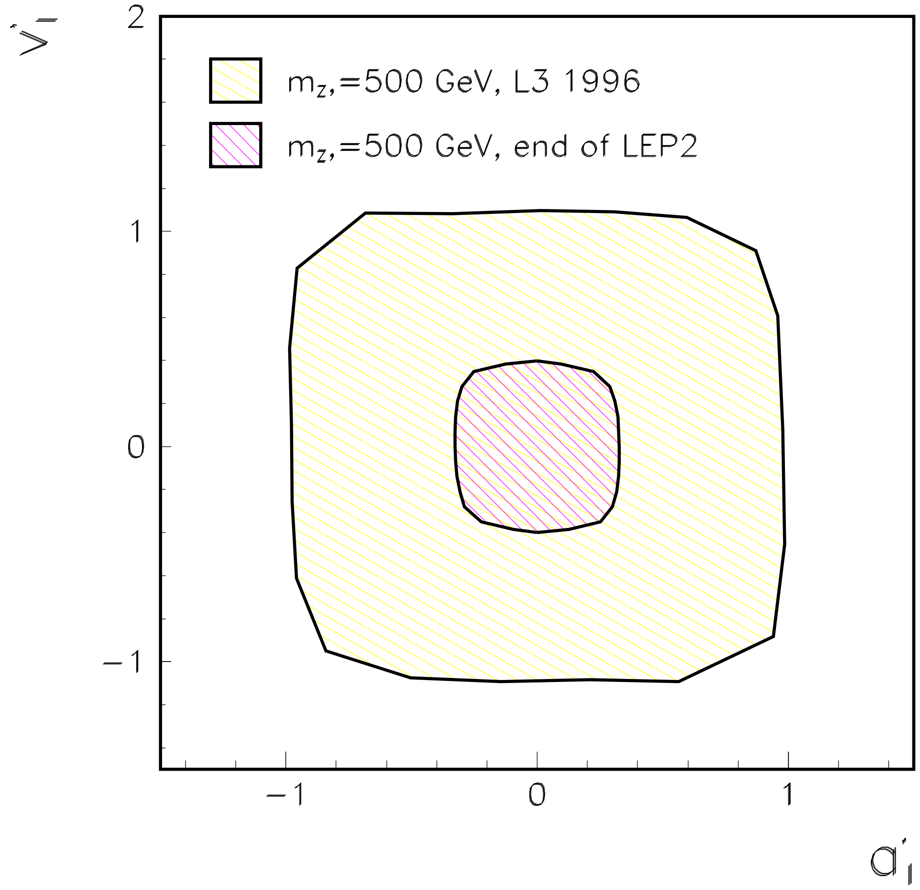
$$|a_l'| = g' a_l(\mathrm{Z}') \leq 0.36 \frac{\left[m_{\mathrm{Z}'}^2 - (170\mathrm{GeV})^2\right]^{1/2}}{170\mathrm{GeV}}$$

$$|v_l'| = g' v_l(\mathrm{Z}') \leq 0.40 \frac{\left[m_{\mathrm{Z}'}^2 - (170\mathrm{GeV})^2\right]^{1/2}}{170\mathrm{GeV}}$$

$$|\theta_M| \leq 0.056 \left[\frac{m_{\mathrm{Z}}^2}{m_{\mathrm{Z}'}^2 - m_{\mathrm{Z}}^2}\right]^{1/2}$$

LEP comb.: (a_l', v_l') bounds shrinked by factor 1.4

Allowed regions for $Z'l\bar{l}$ couplings (95% CL) expected after LEP2 running



see also: S.R., A. Leike, hep-ph/9607306
P. Osland, A. Pankov, hep-ph/9612314

Z′q$\bar{q}$ couplings

with lepton universality:

$$\Delta^{Z'}\sigma \sim \frac{v'_e v'_q}{s - M^2_{Z'}} + \frac{(v_e v'_e + a_e a'_e)(v_q v'_q + a_q a'_q)}{(s - M^2_Z)(s - M^2_{Z'})}$$

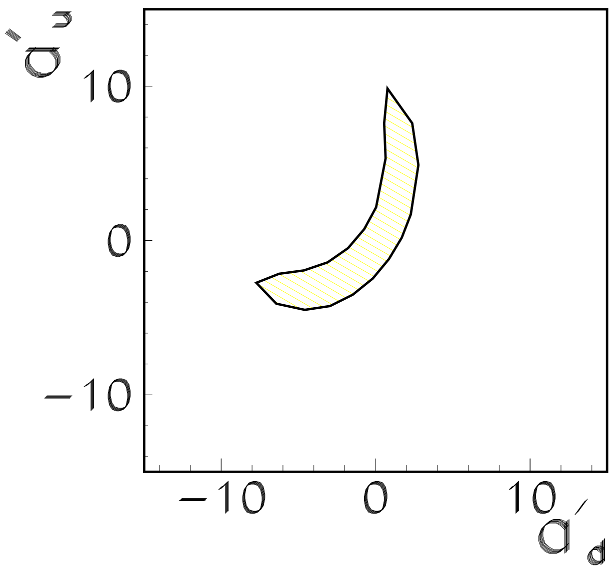
- Z′q$\bar{q}$ couplings depend strongly on Z′l$\bar{l}$ couplings
- on the peak R_b, $A_{FB}^{b\bar{b}} \ldots$ are measured, but there is no sensitivity to $\sigma_{Z'}$
- above the Z peak (LEP1.5, LEP2) only e$^+$e$^-$ $\rightarrow$ hadrons is measured:

$$\sigma_{Z'} \sim \sum_{u,d,c,s,b} \sigma_i(v'_l, a'_l, v'_q, a'_q)$$

- Z′q$\bar{q}$ bounds will be weaker than Z′l$\bar{l}$ bounds
- If $a'_l \approx 0$, $v'_l \approx 0$ and $\theta_M = 0$ is not excluded there is NO sensitivity to Z′q$\bar{q}$ couplings!

Small $Z'l\bar{l}$ couplings and large $Z'q\bar{q}$ couplings are compatible with LEP data.
Leptophobic Z' models have been studied. See also:

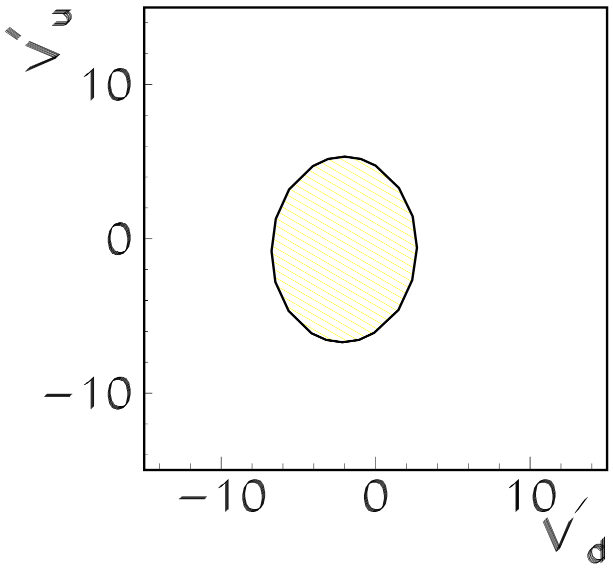
- K.S. Babu, C. Kolda, J. March-Russell; PRD54(1996)4635; hep-ph/9603212
- A.E. Faraggi, M. Masip; PLB388(1996)524; hep-ph/9604302
- J.L. Lopez, D.V. Nanopoulos; PRD55(1997)397; hep-ph/9605359
- M. Heyssler; PRD54(1996)5845; hep-ph/9605403
- C. Kolda; NP Proc.Suppl. 52A(1997)120; hep-ph/9606396
- J.L. Rosner; PLB387(1996)113; hep-ph/9607207
- H. Georgi, S.L. Glashow; PLB387(1996)341; hep-ph/9607202
- J.L. Lopez; NP Proc.Suppl. 52A(1997)284; hep-ph/9607231
- K.S. McFarland; hep-ph/9608312
- M.L. Mangano, G. Altarelli; hep-ph/9610469
- G. Altarelli et al.; PLB375(1996)292; hep-ph/9601324
- P. Chiappetta, J. Layssac, F.M. Renard,C. Verzegnassi; PRD54(1996)789; hep-ph/9601306



Fixed:

$$v'_u = v'_d = 0$$

$a'_l = -.475$ $v'_l = -.284$ $m_{Z'} = 500\text{GeV}$



Fixed:

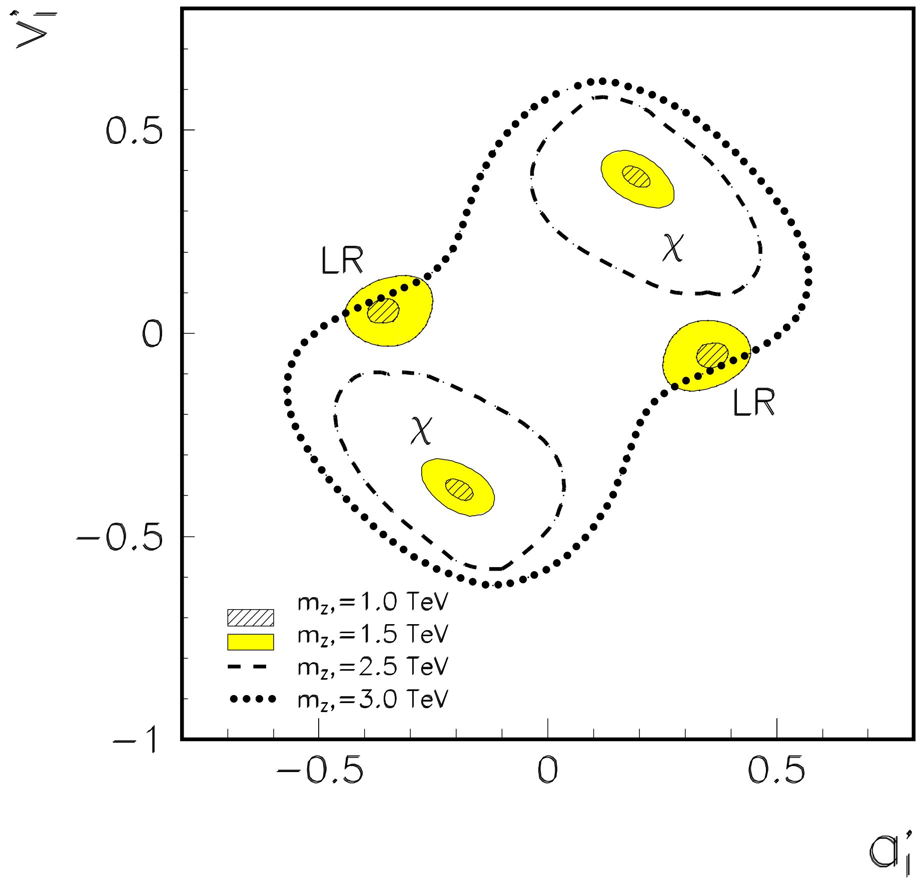
$$a'_u = a'_d = 0$$

$a'_l = -.516$ $v'_l = 0.200$ $m_{Z'} = 500\text{GeV}$

Are we able to identify the Z′ at NLC ?

Assume: Z′ mass is known (LHC)

Consider:	$\sqrt{s}$=500 GeV,	$\mathcal{L}_{int}$=50 fb^{-1}
	P$_{e^-}$=80%,	P$_{e^+}$=0
Input:	χ model (LR model)	
Determine:	Z′l$\bar{\text{l}}$ couplings	



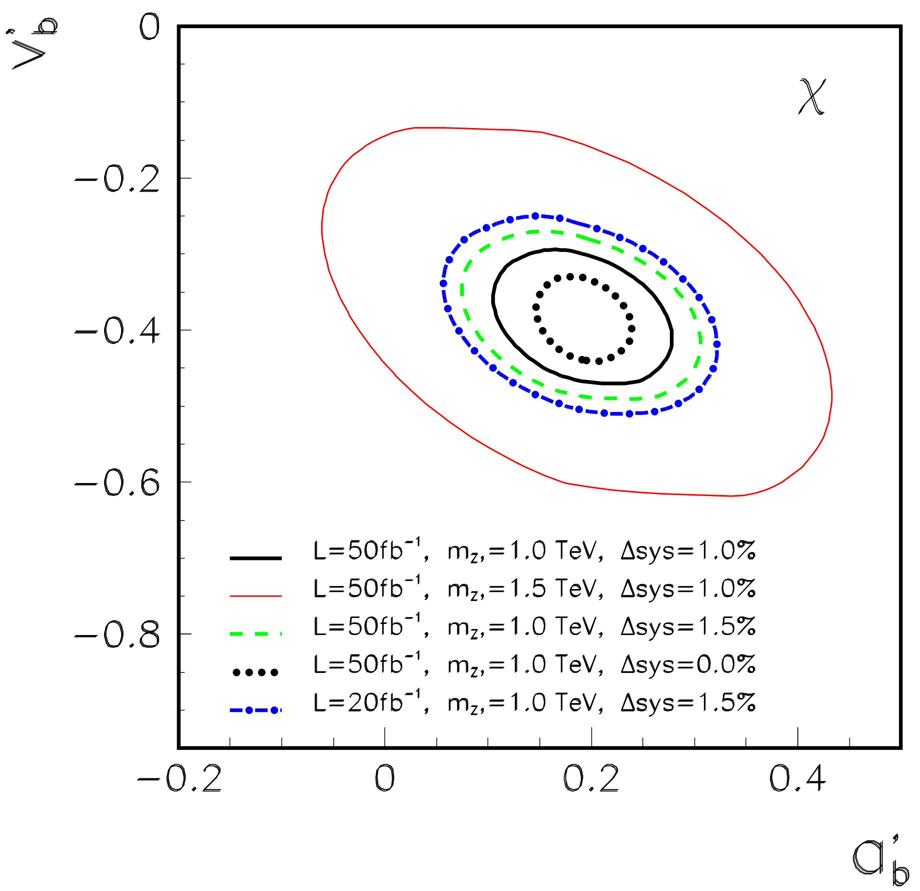
- Distinction between Z′ models possible for $m_{Z'} < 3\sqrt{s}$

- 2-fold ambiguity

Uncertainty of $Z'f\bar{f}$ determination depends on

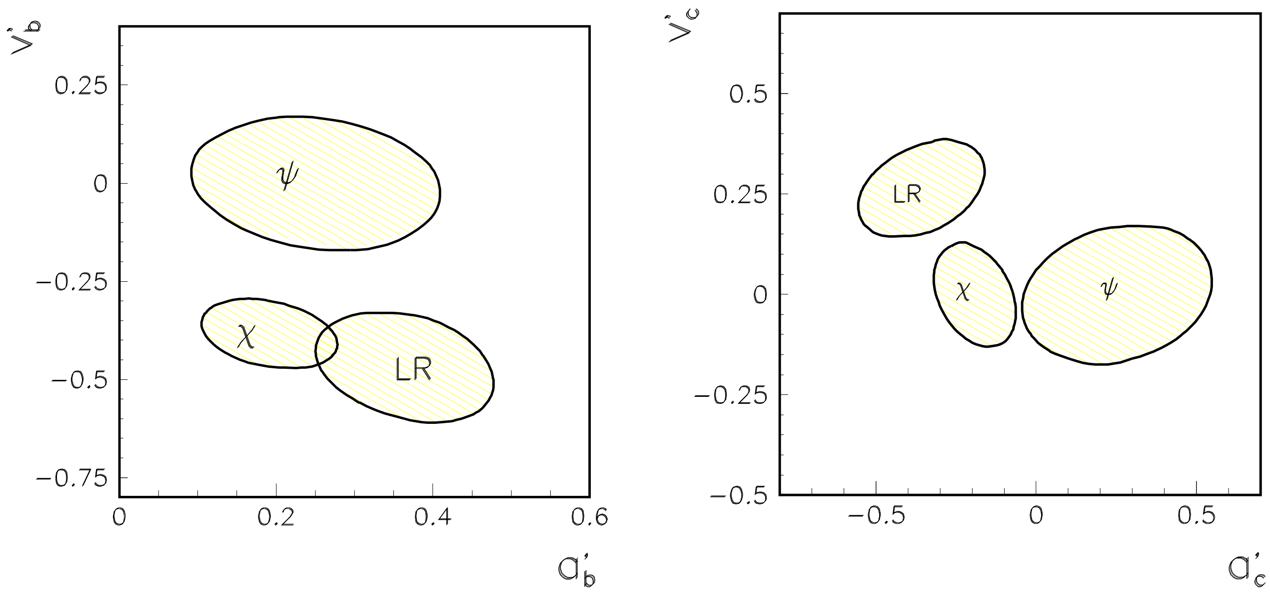
- $m_{Z'}$: $\Delta a'$, $\Delta v' \sim \sqrt{m_{Z'}^2 - s}$
- Δsys: $\Delta a'$, $\Delta v' \sim (\Delta sys^2 + \Delta stat^2)^{1/4}$; Δsys could dominate (heavy flavors)
- $\mathcal{L}_{int}$: $\Delta a'$, $\Delta v' \sim \mathcal{L}_{int}^{-1/4}$

Assume: Z′ exists (χ model),
$\sqrt{s}$=500 GeV, $m_{Z'}$ is known



Determine Z′q$\bar{q}$ couplings:

Assume: $m_{Z'}$=1000 GeV, $\sqrt{s}$=500 GeV
$\mathcal{L}_{int}$=50 fb^{-1}, P$_{e^-}$=80%
$\Delta^b sys$=1%, $\Delta^c sys$=1.5%



Distinction between Z′ models possible for
$m_{Z'} < 2\sqrt{s}$

Z′ exists, Z′ mass is unknown

- Bounds on Z′ couplings become weaker by a factor 5...10 depending on $m_{Z'}$, $\sqrt{s}$ and distribution of $\mathcal{L}$ on various $\sqrt{s}$ points
- more details see: T. Rizzo, Phys.Rev.D55(1997)5483, hep-ph/9612304 and references therein.

- No evidence of Z′

- Limits on ZZ′ mixing:
  -0.007 $\leq \theta_M \leq$ 0.004 (95% CL, L3)
  -0.003 $\leq \theta_M \leq$ 0.003 (95% CL, LEP comb.)
  for E_6 and LR models

- High energy LEP data improve the indirect limits on $m_{Z'}$. L3 gives $m_{Z'} >$ 350 GeV (95% CL)
  for E_6 and LR models. (SSM: $m_{Z'} >$ 520 GeV)
  Limits on Z′ mass are NOT competetive with direct limits.

- Model-independent analyses give bounds on Z′ couplings (95% CL, L3):

$$\begin{aligned}
|g' a'_l| &< 0.36 \frac{(m^2_{Z'} - 170^2)^{1/2}}{170} \\
|g' v'_l| &< 0.40 \frac{(m^2_{Z'} - 170^2)^{1/2}}{170} \\
|\theta_M| &< 0.056 \left(\frac{m^2_Z}{m^2_{Z'} - m^2_Z} \right)^{1/2}
\end{aligned}$$

- L3 data (LEP data) are compatible with large $Z'q\bar{q}$ couplings

Perspectives

- End of LEP2:
  - indirect limits on $m_{Z'}$ will be improved
  - Best accuracy for θ_M measurement from $e^+e^- \to f\bar{f}$ already reached. Further confirmation/improvement will be given by $e^+e^- \to W^+W^-$
    (see Paver, Pankov; PLB393(1996)437)
  - Bounds on Z′ couplings to leptons will be shrinked substantielly
- With an NLC a new era of Z′ search will start.
  - A Z′ can be discoverd up to $m_{Z'} < 6 \cdot \sqrt{s}$ for most Z′ models.
  - Z′ model identification will be possible if $m_{Z'} < 3 \cdot \sqrt{s}$
  - Determination of $Z'q\bar{q}$ couplings is limited by systematic errors.

Let's hope for surprises!