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Limits on an Additional Heavy Gauge Boson Z′ from the L3 Experiment

The L3 Collaboration

Abstract

Results on total cross sections and asymmetries of fermion pair production in e^+e^- annihilation obtained with the L3 detector at LEP are used to determine limits on the mass of a heavy gauge boson Z′ and the Z-Z′ mixing angle, θ_M. For most of the usual Z′ models we find

$$-0.007 < \theta_M < 0.005.$$

Assuming lepton universality, model-independent Z′ studies show that Z′ couplings to leptons are shrinked:

$$\begin{aligned} |g'a'_l| &< 0.303\frac{(m_{\mathrm{Z}'}^2/\mathrm{GeV}^2 - 156^2)^{1/2}}{156} \\ |g'v'_l| &< 0.336\frac{(m_{\mathrm{Z}'}^2/\mathrm{GeV}^2 - 156^2)^{1/2}}{156} \\ |\theta_M| &< 0.058\left(1 - \frac{m_{\mathrm{Z}}^2}{m_{\mathrm{Z}'}^2}\right)^{1/2} \end{aligned}$$

Introduction

Although the Standard Model describes the experimental data almost perfectly, the search for new phenomena based on a more fundamental theory is going on enthusiastically. Most Grand Unified Theories predict additional particles which could also affect the $\mathcal{O}$(TeV) energy range. Here, we study the compatibility of the L3 measurements of cross sections and asymmetries with the existence of an additional heavy neutral gauge boson Z′. A light Z′ leads to small deviations of the data from their Standard Model predictions. The earlier analysis [1] with L3 measurements in 1990/1991 is updated including published and preliminary results of the LEP runs in 1992 – 1996 [2–4]. Since 1990 a total luminosity of 117.8 pb^{-1} has been collected at different centre-of-mass energy points around the Z resonance. In November 1995 LEP was operated at centre-of-mass energies between 130 GeV and 140 GeV and a total integrated luminosity of 5.0 pb^{-1} was recorded. In 1996 about 20 pb^{-1} were collected above the W threshold. These cross section and asymmetry measurements are also sensitive to effects of a Z′ which is not too heavy. If no signal of a Z′ is found, limits on Z′ parameters can be derived.

In the first part of this paper we summarize the results of a Z′ search based on usual Z′ models. In the second part, we present the procedure and the results of a model-independent Z′ search.

Lineshape Analysis with Z and Z′

An extra gauge boson extends the neutral current Lagrangian by an additional contribution,

$$\mathcal{L} = eA_\mu J^\mu_\gamma + gZ_\mu J^\mu_Z + g'Z'_\mu J^\mu_{Z'}. \tag{1}$$

The Z′ contributions are described by the Z′ mass, $m_{Z'}$, the Z-Z′ mixing, θ_M, and the Z′ couplings to fermions, a'_f and v'_f. If θ_M is not zero, observables on the Z resonance are influenced by the Z-Z′ mixing. For the Z width, Γ_Z,

$$\Gamma_Z \sim \sum_f m_Z^3\ \rho_f\ ({v_Z^f}^2 + {a_Z^f}^2) \tag{2}$$

the ρ–parameter is modified,

$$\rho_f \quad\longrightarrow\quad \rho_f + \Delta\rho^f_{Z'} \quad=\quad \rho_f\left(1 + \frac{m^2_{Z'}}{m^2_Z}\sin^2\theta_M\right), \tag{3}$$

and the couplings change to

$$\begin{aligned} a_f &= \cos\theta_M \cdot a^f_{\mathrm{Z}} + \sin\theta_M \cdot a^f_{\mathrm{Z}'} \cdot \frac{g'}{g}, & a'_f &= \cos\theta_M \cdot a^f_{\mathrm{Z}} + \sin\theta_M \cdot a^f_{\mathrm{Z}'} \cdot \frac{g}{g'}, \\ v_f &= \cos\theta_M \cdot v^f_{\mathrm{Z}'} - \sin\theta_M \cdot v^f_{\mathrm{Z}} \cdot \frac{g'}{g}, & v'_f &= \cos\theta_M \cdot v^f_{\mathrm{Z}'} - \sin\theta_M \cdot v^f_{\mathrm{Z}} \cdot \frac{g}{g'}. \end{aligned}$$

a^f_{Z}, v^f_{Z} and $a^f_{\mathrm{Z}'}$, $v^f_{\mathrm{Z}'}$ are the Z and Z′ couplings to fermions without Z-Z′ mixing. Measurements on the Z peak allow a precise determination of θ_M. Contributions proportional to the Z′ propagator become important only off the Z peak. They are sensitive to the mass and the couplings of a potential Z$'$,

$$
\begin{aligned}
\sigma^f_{\gamma Z'} &\sim \frac{v'_e v'_f}{s - M^2_{Z'}} \\
\sigma^f_{ZZ'} &\sim \frac{(a_e a'_e + v_e v'_e)\left(a_f a'_f + v_f v'_f\right)}{(s - M^2_Z)\,(s - M^2_{Z'})} \\
\sigma^f_{Z'Z'} &\sim \frac{\left(v'^2_e + a'^2_e\right)\left(v'^2_f + a'^2_f\right)}{(s - M^2_{Z'})^2}
\end{aligned}
\tag{4}
$$

with

$$M^2_{Z'} = m^2_{Z'} - i\Gamma_{Z'} m_{Z'}. \tag{5}$$

In dependence on the centre-of-mass energy and the Z$'$f$\bar{\text{f}}$ couplings the γZ$'$, ZZ$'$ and Z$'$Z$'$ contributions to cross sections and asymmetries could dominate the γZ and ZZ contributions.

Symmetry breaking of GUTs leads to special Z$'$ models with well defined Z$'$f$\bar{\text{f}}$ couplings. Popular models result from E$_6$ GUT or left-right symmetries [5, 6],

$$J^\mu_{Z'} = J^\mu_\chi \cos\Theta_6 + J^\mu_\psi \sin\Theta_6 \ ; \qquad J^\mu_{Z'} = \alpha_{LR} J^\mu_{3R} - \frac{1}{2\alpha_{LR}} J^\mu_{B-L}. \tag{6}$$

Specified cases are the χ, ψ and η model ($\Theta_6 = 0; \pi/2; -\arctan\sqrt{5/3}$) and Left-Right models ($\sqrt{2/3} \leq \alpha_{LR} \leq \sqrt{\cot^2\theta_W - 1}$).

If no indication for the existence of a Z$'$ is found bounds on the Z$'$ mass and the Z-Z$'$ mixing are determined for special Z$'$ models.

A more general approach does not fix the Z$'$ model, i.e. the Z$'$f$\bar{\text{f}}$ couplings. With this model-blind method the Z$'$f$\bar{\text{f}}$ couplings cannot be determined independently on the Z$'$ mass because the measurements are only sensitive to normalized couplings, a^N_f, v^N_f,

$$a^N_f = g' a'_f \sqrt{s/(M^2_{Z'} - s)} \tag{7}$$

(see also [7] and equation 4).

The disadvantage of model-independent studies is the large number of free Z$'$ couplings. But good limits on Z$'$l$\bar{\text{l}}$ couplings are expected assuming lepton universality and considering only lepton pair production.

We perform the Z$'$ search using all observables measured on the Z resonance and at higher centre-of-mass energies: hadronic and leptonic cross sections, leptonic forward-backward asymmetries, τ polarization, b-quark forward-backward asymmetry and the partial decay width of the Z boson to b-quarks [2–4, 8–10] In contrast to cross section data on the peak, at higher energies a radiative return to the Z peak has to be avoided in order to be sensitive to Z$'$ propagator effects. Thus, we use the high energy cross sections and asymmetries in our analysis. Systematic errors and the LEP energy error are taken into account as described in [2–4, 11].

The determination of limits on Z$'$ parameters is done using the programs ZFITTER 5.0 [12] and ZEFIT 5.0 [13].

Model-dependent Z$'$ search

In general, the models considered depend on the following parameters: m_{Z}, $m_{\mathrm{Z}'}$, θ_M, m_{t}, m_{H}, α_s and Z$'$ model parameters such as Θ_6 or α_{LR}. We fix the Z$'$ model (Θ_6 or α_{LR}) and the

Higgs mass, $m_{\rm H} = 150$ GeV, and constrain the top mass by the combined results of CDF and D0 [14], $m_{\rm t} = 175 \pm 6$ GeV, and α_s to the world average, $\alpha_s = 0.118 \pm 0.003$ [15]. A variation of the Higgs mass influences only slightly the results for the Z′ parameters (see [1]). We use $m_{\rm Z} = 91.1883 \pm 0.0029$ GeV (see results in [2]).

First, all observables are compared with the predictions of the E_6 models χ, ψ and η as well as the LR model. In order to determine the allowed regions for the parameters θ_M and $m_{Z'}$ within a particular model we perform a χ^2 fit using MINUIT [16] and require $\chi^2 \leq \chi^2_{min} + 11.07$, corresponding to the 95% confidence limit for five free parameters. The results are shown in Figure 1 for the χ, ψ, η and LR model. The Z-Z′ mixing angle is compatible with zero. No hint for a Z′ is found.

If we assume in agreement with [17] that the Z′ mass is $m_{Z'} > 600$GeV we derive for all E_6 and LR models the 95% CL allowed values for the Z-Z′ mixing as shown in figure 2.

Lower bounds on the Z′ mass are derived assuming $\theta_M = 0$. Figure 3 shows the minimal values for the Z′ mass, $m_{Z'}^{lim}$, which cannot be excluded at 95% CL by the L3 data in case of E_6 and Left-Right models. Assuming a Z′ with Standard Model couplings to fermions we find $m_{Z'} > 550$ GeV. The corresponding limit from direct Z′ searches given by the CDF collaboration is 690 GeV [17].

Model-independent Z′ Search

The models considered above are only a small choice of possible Z′ models. Thus, one should search for a Z′ model-independently.

First, we study the process $e^+e^- \to l\bar{l}$ and assume lepton universality. We use $m_{\rm Z} = 91.1883 \pm 0.0029$ GeV and fix $m_t = 175$ GeV, $m_{\rm H} = 150$ GeV and $\alpha_s = 0.118$ and derive Z′ couplings to leptons with respect to the Z-Z′ mixing angle.

As already mentioned in equation (7) the determination of Z′ couplings depends on the Z′ mass. Here, we fix $m_{Z'}$ to several values. The results are presented in figure 4 at the 95% CL and can be described by

$$
\begin{aligned}
|g' a'_l| &< 0.303 \frac{\left[m^2_{\rm Z'} - 156^2 {\rm GeV}^2\right]^{1/2}}{156{\rm GeV}} \\
|g' v'_l| &< 0.336 \frac{\left[m^2_{\rm Z'} - 156^2 {\rm GeV}^2\right]^{1/2}}{156{\rm GeV}}
\end{aligned}
\tag{8}
$$

Also the limits on the Z-Z′ mixing depend on the Z′ mass:

$$
|\theta_M| < 0.0582 \left(1 - \frac{m^2_{\rm Z}}{m^2_{\rm Z'}}\right)^{1/2} \tag{9}
$$

The allowed regions for a'_l, v'_l and θ_M are located symmetrically around the point $(a'_l;\ v'_l;\ \theta_M)$ = (0;0;0) which corresponds to the Standard Model.

It is more difficult to find analogous bounds on $Z'q\bar{q}$ couplings.

First of all, the Z′ couplings to leptons should be known in order to determine $Z'q\bar{q}$ couplings from e^+e^- annihilation. If they are assumed to be zero $Z'q\bar{q}$ couplings can only be obtained if the Z-Z′ mixing is $\theta_M \neq 0$. It is evident from figure 4 that these conditions are not met. Following, there is no sensitivity for $Z'q\bar{q}$ couplings at the moment.

Conclusions

There is no indication for the existence of a Z′ predicted by E_6 or Left-Right models. The fitted Z-Z′ mixing angle θ_M is compatible with zero for the models considered and in model-blind analyses. For usual E_6 and LR models the allowed values for θ_M are typically between -0.007 and 0.005 at the 95% CL. With the data of the high energy run of LEP at c.m. energies a Z′ with a mass less than about 250 GeV is excluded at 95% CL for these models.

The high energy runs of LEP enable a model-independent determination of Z′ couplings to leptons. The results depend on the Z′ and can be expressed by formulae (8,9).

Restrictions to $Z'q\bar{q}$ couplings are impossible as long as a_l', v_l' and θ_M could be zero.

At the end of LEP2 running the indirect limits on the Z′ mass and on the $Z'l\bar{l}$ will be substiantielly improved.

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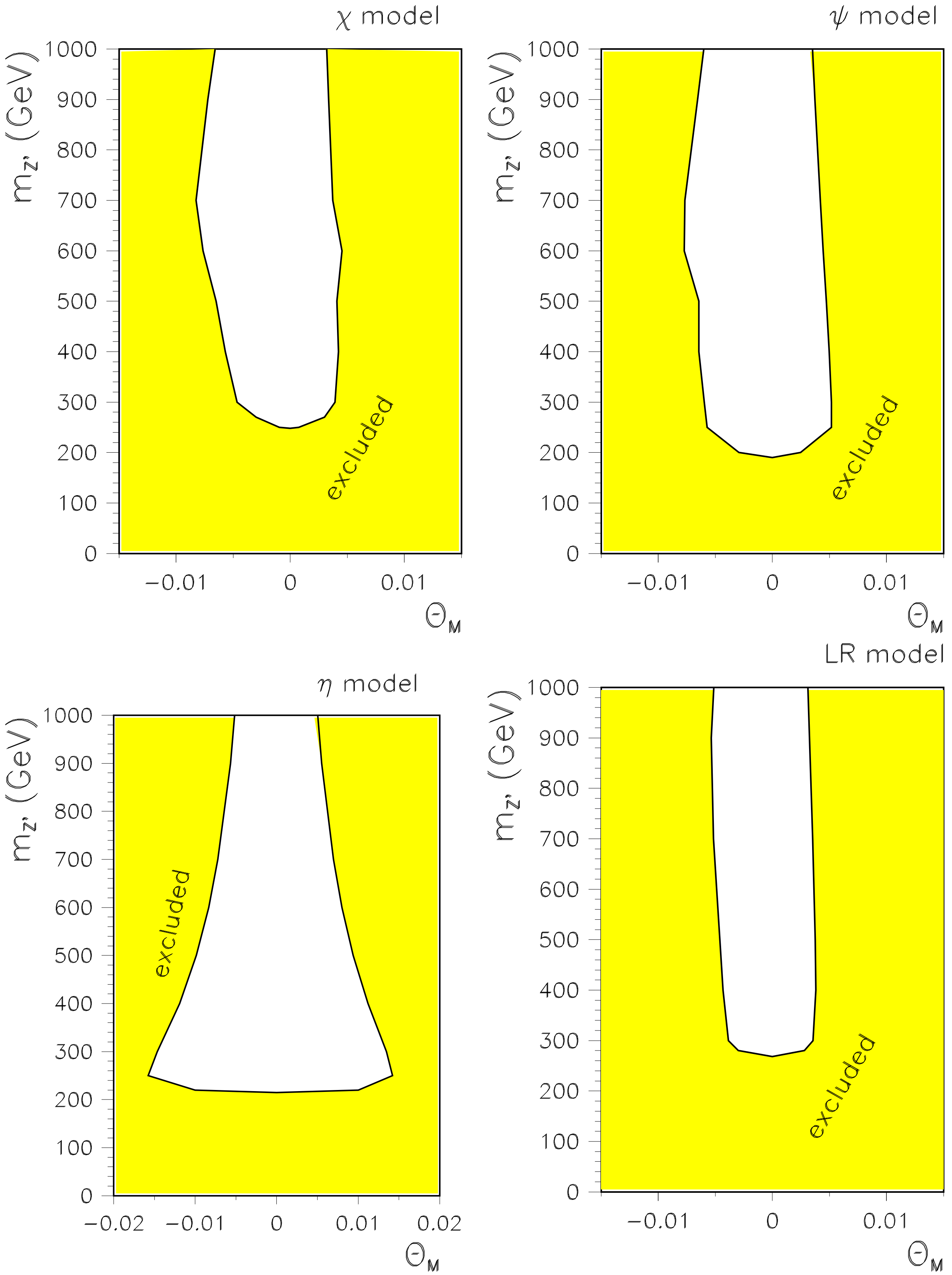

Figure 1: The 95% CL allowed regions (preliminary) in the $m_{Z'}$ vs θ_M plane for the models χ, ψ, The Z mass is $m_Z = 91.1883 \pm 0.0029$ GeV, the top mass and α_s are constrained to $m_t = 175 \pm 6$ GeV and $\alpha_s = 0.118 \pm 0.003$. The Higgs mass is fixed to $m_H = 150$ GeV.

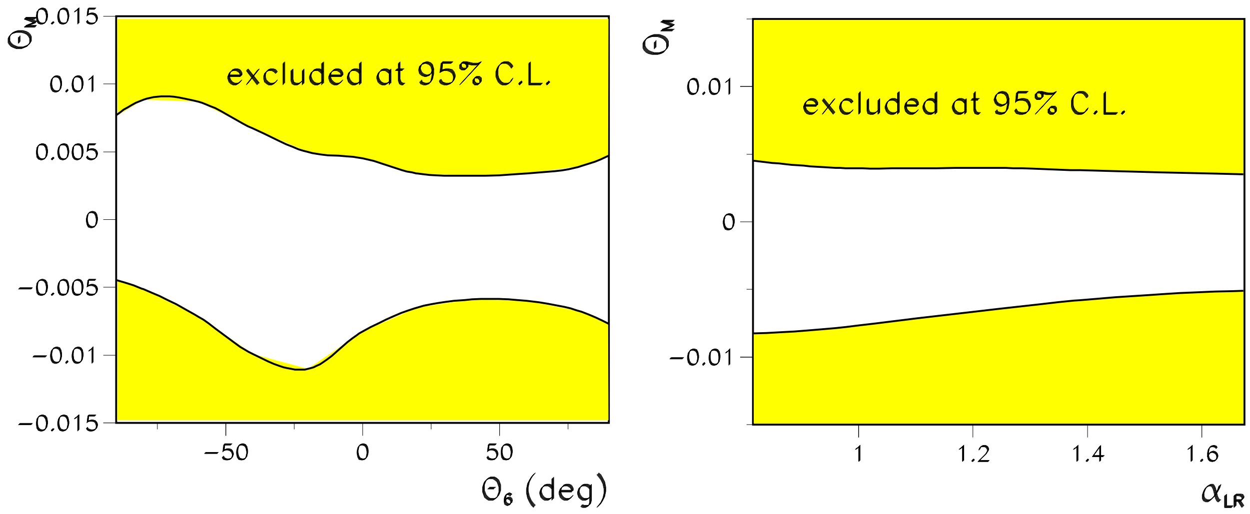

Figure 2: The 95% CL bounds (preliminary) on θ_M in dependence on the model parameter θ_6 and α_{LR} for $m_{Z'} > 600$ GeV. The Z mass is $m_Z = 91.1883 \pm 0.0029$ GeV, the top mass and α_s are constrained to $m_t = 175 \pm 6$ GeV and $\alpha_s = 0.118 \pm 0.003$. The Higgs mass is fixed to $m_H = 150$ GeV.

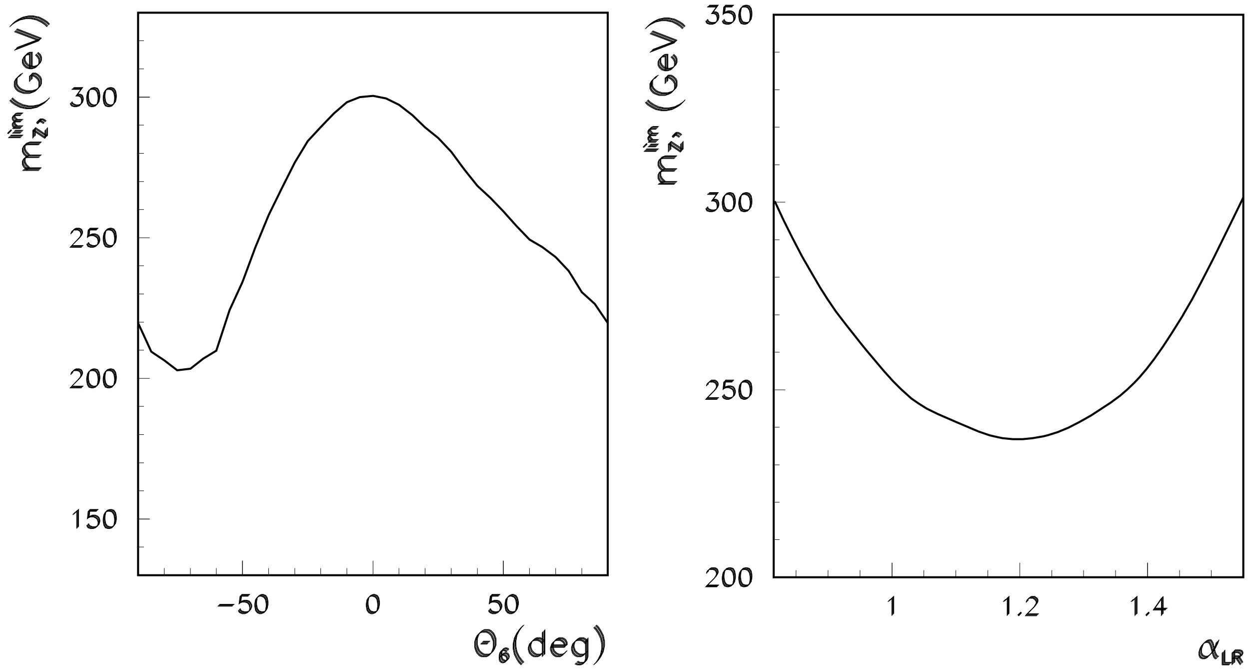

Figure 3: The 95% CL lower limits (preliminary) on $m_{Z'}$, $m_{Z'}^{lim}$, as a function of the model parameter Θ_6 for the E_6 model and α_{LR} for the left-right symmetric model. The Z mass, the top mass, α_s and the Higgs mass are fixed: $m_Z = 91.1883$ GeV, $m_t = 175$ GeV, $\alpha_s = 0.118$ and $m_H = 150$ GeV.

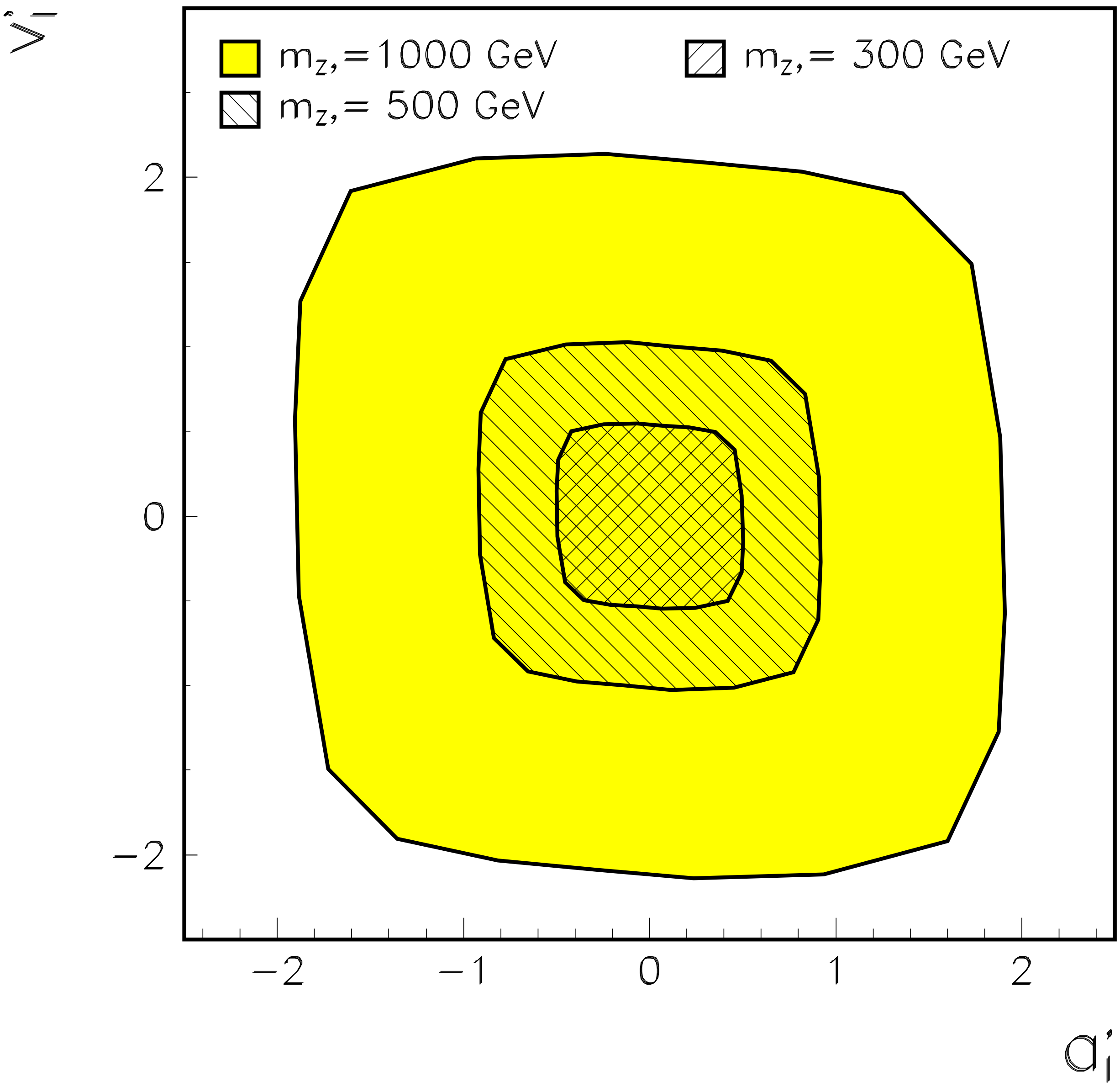

Figure 4: The 95% CL bounds (preliminary) on $Z'l\bar{l}$ couplings for $m_{Z'}$ = 300 GeV, 500 GeV and 1000 GeV. The Z mass, the top mass, α_s and the Higgs mass are fixed: $m_Z = 91.1883$ GeV, m_t = 175 GeV, $\alpha_s = 0.118$ and $m_H = 150$ GeV.