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Limit on parity violating couplings between massive vector bosons

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Abstract: The most general Lorentz invariant triple boson coupling between W and Z bosons allows a parity violating coupling. Based on results from the LEP measurements of the coupling Δg_1^Z, we obtain constraints on the parity violating coupling z_Z.

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Contents

1. Introduction

From the precision measurements at LEP I, we know the Z bosons produced by e^+e^- annihilation have an average polarization of 13%.[1] Interestingly, for W pair production through the s channel, $e^+e^- \to Z/\gamma \to W^+W^-$, the standard model implies that the coupling of the Z to the W pair does not depend on the Z helicity. Although this is a well known feature of the standard model, it seems odd that the massive gauge bosons, which violate parity conservation in their interactions with fermions, do not violate parity when they interact with each other.

Setting the standard model aside, this note intends to investigate the possible magnitude of parity violation in the WWZ interaction based on current measurements. The next section gives the general framework and the result. The conclusions are given in section 3.

2. Framework

At LEP II energies, W pair production proceeds primarily through the three CC03 diagrams: s channel via γ or Z and t channel neutrino exchange. Non-resonant diagrams also contribute, but are not significant for this analysis. In the following, the e^- and e^+ helicities are given by $\sigma/2$ and $-\sigma/2$, and those of the W^- and W^+ by λ and $\overline{\lambda}$, as in [1]. Since the γ or Z in the s channel is spin 1, the W pair in the final state must be in a $|\lambda - \overline{\lambda}| = 0, 1$ helicity state. Helicity states with $|\lambda - \overline{\lambda}| = 2$ may only be produced from the t channel process. Also, the t channel couples only to the $\sigma = -1$ initial state owing to the V$-$A interaction at each eνW vertex.

[1] Helicity conservation at high energy implies the Z bosons are produced in the $m = \pm 1$ helicity state or, using the older expression, with 100% alignment.

Considering the s channel processes as quantum mechanical rotations in the interaction plane, the amplitudes of each of the W pair helicity states are

$$\mathcal{M}_{Z/\gamma}(\lambda - \overline{\lambda} = -1) = \mathcal{A}_{-} \left(\frac{1 - \cos\theta}{2} \right), \tag{2.1}$$

$$\mathcal{M}_{Z/\gamma}(\lambda - \overline{\lambda} = 0) = \mathcal{A}_{0} \left(\frac{\sin\theta}{\sqrt{2}} \right), \tag{2.2}$$

$$\mathcal{M}_{Z/\gamma}(\lambda - \overline{\lambda} = +1) = \mathcal{A}_{+} \left(\frac{1 + \cos\theta}{2} \right), \tag{2.3}$$

where θ denotes the angle of the W^- with the electron beam. Parity violation occurs in the WWZ interaction if amplitude (2.1) is not equal to amplitude (2.3), i.e. if $\mathcal{A}_+ \neq \mathcal{A}_-$, there is a forward-backward asymmetry in the $e^+e^- \to Z/\gamma \to W^+W^-$ production angular distribution $A_{fb} = (N_{\cos\theta>0} - N_{\cos\theta<0})/N_{total}$. The direct determination of A_{fb} is complicated by the interference with the strongly forward peaked t channel contribution.

The differential cross section for the full $e^+e^- \to W^+W^-$ process is given in [1, eq. 12]:

$$\begin{aligned}\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta}{4s}\Bigg\{\Sigma_{\sigma=\pm}\Bigg[& \frac{\sin^2\theta}{2}\left(|\mathcal{M}_{\sigma,++}|^2 + |\mathcal{M}_{\sigma,00}|^2 + |\mathcal{M}_{\sigma,--}|^2\right) + \\ & + \frac{(1+\sigma\cos\theta)^2}{4}\left(|\mathcal{M}_{\sigma,+0}|^2 + |\mathcal{M}_{\sigma,0-}|^2\right) + \\ & + \frac{(1-\sigma\cos\theta)^2}{4}\left(|\mathcal{M}_{\sigma,0+}|^2 + |\mathcal{M}_{\sigma,-0}|^2\right)\Bigg] + \\ & + \frac{1}{2}(1+\cos^2\theta)\sin^2\theta\frac{2}{\sin^4\theta_W}\frac{1}{(1+\beta^2-2\beta\cos\theta)^2}\Bigg\},\end{aligned}$$

where β is the $W^\pm$ velocity. The first term in the sum corresponds to the $|\lambda - \overline{\lambda}| = 0$ final state, the second and third to the $|\lambda - \overline{\lambda}| = \pm 1$ state, and the last term to the $|\lambda - \overline{\lambda}| = \pm 2$ state to which only the t channel process contributes. The matrix elements $\mathcal{M}_{\sigma,\lambda,\overline{\lambda}}$ can be written as a sum of the contributions from the different processes,

$$\mathcal{M}_{\sigma,\lambda,\overline{\lambda}} = \mathcal{M}_{\nu} + \mathcal{M}_{Z} + \mathcal{M}_{\gamma},$$

see [1, eq. 11 and table 2]. Parity violation shows up as a factor $g_5\beta$ in the $(\lambda, \overline{\lambda}) = (+,0)$ and $(0,-)$ helicity states and $-g_5\beta$ in the $(0,+)$ and $(-,0)$ states. A non-zero value of $g_5\beta$, or equivalently z_Z [2, 3] modifies the forward backward asymmetry, so a measurement of the forward-backward asymmetry measures the parity violation, assuming the other WWZ couplings are as predicted by the standard model.

In fact, such a forward-backward asymmetry measurement has already been conducted, albeit indirectly. Measurements of the WWZ Δg_1^Z coupling have been carried out by fitting to the total and differential cross sections for W boson pair production [4, 5, 6, 7] within the $SU(2) \times U(1)$ framework.

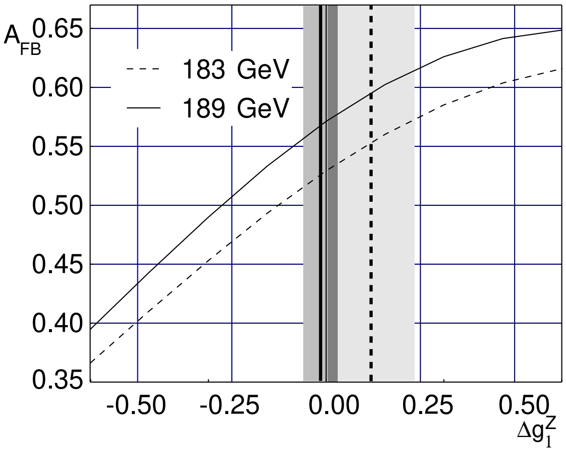

Figure 1: Dependence of A_{fb} on Δg_1^Z, for centre-of-mass collision energies 183 and 189 GeV. The bands represent the combined LEP experiment measurements of Δg_1^Z and their errors, for the two energies, as in table 1.

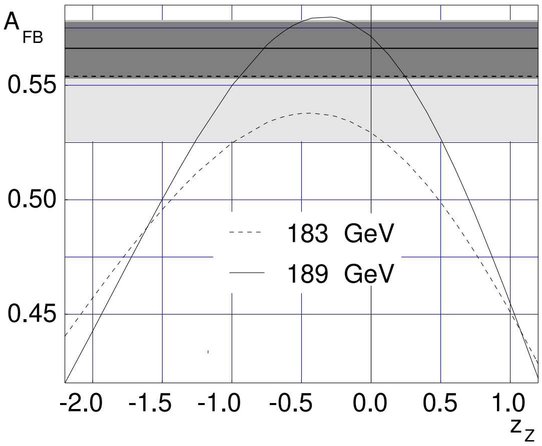

Figure 2: Dependence of A_{fb} on the parity violating coupling z_Z at collision energies of 183 and 189 GeV. The bands represent the central values and errors for A_{fb} derived from the z_Z dependence of A_{fb} as in fig. 1.

The dependence of the forward-backward asymmetry on Δg_1^Z as predicted by the GENTLE [3] program are shown in fig. 1. The uncertainties in the input values for the program have been taken into consideration. Combining this with the results for Δg_1^Z from the LEP experiments as given in table 1, one can obtain the following values for the forward-backward asymmetries, assuming standard model couplings for $e^+e^- \to W^+W^-$ except for the variation of Δg_1^Z: $A_{fb(183\text{ GeV})} = 0.554^{+0.024}_{-0.028}$ and $A_{fb(189\text{ GeV})} = 0.566^{+0.012}_{-0.013}$.

Likewise GENTLE is used to calculate the forward-backward asymmetry as a function of the parity violating coupling z_Z, with the other couplings assuming their standard model values, fig. 2. The result for A_{fb} from Δg_1^Z can be combined with fig. 2 to determine z_Z. The resulting $-\log\mathcal{L}$ curves are shown in fig. 3 for 183 and 189 GeV, respectively.

	Δg_1^Z
ALEPH 183 GeV [4]	$0.23^{+0.17}_{-0.18}$
ALEPH 189 GeV [4]	$-0.02^{+0.06}_{-0.07}$
DELPHI 183 GeV [5]	$0.04^{+0.14}_{-0.14}$
DELPHI 189 GeV [6]	$0.00^{+0.07}_{-0.08}$
L3 189 GeV [7]	$-0.02^{+0.07}_{-0.07}$
Combination 183 GeV	0.12 ± 0.12
Combination 189 GeV	-0.02 ± 0.05

Table 1: LEP experiment measurements of Δg_1^Z for which separate results are available for the different centre-of-mass energies. The combinations shown are weighted means of these results, with error correlations estimated using the error subdivisions reported by ALEPH. The calculations in the present analysis are not sensitive to possible further refinements in the combination procedure.

JHEP10(1999)012

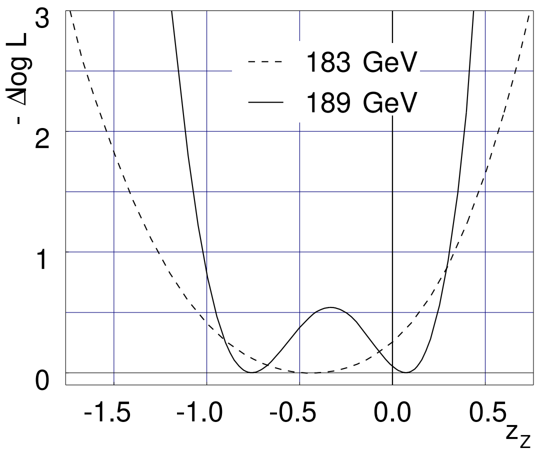

Figure 3: z_Z log likelihood distribution for 183 and 189 GeV centre of mass energies.

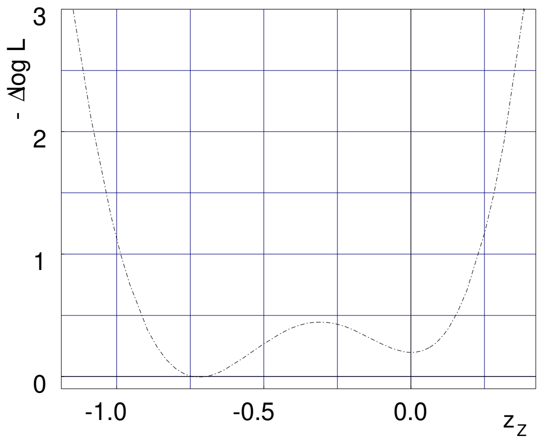

Figure 4: Combined z_Z log likelihood distribution from 183 and 189 GeV data.

The distributions obtained from measurements at the two collision centre-of-mass energies are combined, to obtain our final result shown in fig. 4. There exist two ambiguous solutions at -0.69 ± 0.21 and -0.04 ± 0.21, and we obtain at 95% CL, $-1.01 < z_Z < 0.25$.

3. Outlook

The first limits on z_Z from measurements of Δg_1^Z at LEP II have been presented. It appears there could be significant parity violation in the WWZ coupling, and z_Z should be included in future fits of the triple gauge couplings. The method outlined here would improve by a factor two by using the final LEP II limit on Δg_1^Z. Further improvements are possible by a direct fit of the data to measure z_Z, as is currently carried out for Δg_1^Z. This should be able to resolve between the two possible values that are allowed by z_Z according to this analysis.

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JHEP10(1999)012

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