Strong Symmetry Breaking Signals in $e^+e^- \to W^+W^-$ at $\sqrt{s} = 800$ GeV

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Abstract. The sensitivity of e^+e^- linear colliders to strong W^+W^- scattering effects in $e^+e^- \to W^+W^-$ is examined. Past studies have concentrated on e^+e^- linear colliders with center-of-mass energies of more than 1 TeV and integrated luminosities of less than 200 fb^{-1}. Here we review the strong symmetry breaking signals that can be observed with center-of-mass energies of $0.5 - 0.8$ TeV and luminosities of $300 - 500$ fb^{-1}.

INTRODUCTION

Until a Higgs boson resonance is observed it is important to continue to ask how a collider with TeV scale parton–parton interactions will study electroweak symmetry breaking in the absence of such a resonance. If there is no Higgs boson resonance then W^+W^- scattering becomes strong above 1 TeV in the W^+W^- center-of-mass system. At an e^+e^- linear collider one would directly study W^+W^- scattering in reactions such as $e^+e^- \to \nu\overline{\nu}W^+W^-$ [1–3] and $e^+e^- \to \nu\overline{\nu}t\overline{t}$ [4,5].

One can also observe strong symmetry breaking effects in the reaction $e^+e^- \to W^+W^-$. Previous studies of this reaction have focused on e^+e^- colliders with center-of-mass energies greater than 1 TeV and integrated luminosities of no more than 200 fb^{-1} [6,7]. In this paper we examine how well one can study strong symmetry breaking in $e^+e^- \to W^+W^-$ if the center-of-mass energy is lowered to $0.5 - 0.8$ TeV and the integrated luminosity is raised to $300 - 500$ fb^{-1}.

The reaction $e^+e^- \to W^+W^-$ is affected in two ways by strong symmetry breaking. First, anomalous triple gauge boson couplings (TGC's) are induced by the strongly coupled physics responsible for electroweak symmetry breaking. Second, the amplitude for longitudinal W boson pair production, $e^+e^- \to W_{\rm L}W_{\rm L}$, is modified by strongly interacting W bosons, just as the amplitude for $e^+e^- \to \pi^+\pi^-$ is modified relative to pointlike charged scalar production by the QCD strong interactions of the pions [8].

TRIPLE GAUGE COUPLINGS

The interactions of the Standard Model gauge boson fields are described by an effective chiral Lagrangian if the electroweak symmetry breaking sector is strongly interacting:

$$\mathcal{L}_{SB} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \cdots$$

where

$$\begin{aligned}
\mathcal{L}^{(2)} &= \frac{1}{4} v^2 \mathrm{Tr} D^\mu \Sigma^\dagger D_\mu \Sigma, \\
\mathcal{L}^{(4)} &= \frac{L_1}{16\pi^2}\Big[\mathrm{Tr}\Big(D^\mu \Sigma^\dagger D_\mu \Sigma\Big)\Big]^2 + \frac{L_2}{16\pi^2}\mathrm{Tr}\Big(D_\mu \Sigma^\dagger D_\nu \Sigma\Big)\mathrm{Tr}\Big(D^\mu \Sigma^\dagger D^\nu \Sigma\Big) \\
&\quad -ig\frac{L_{9L}}{16\pi^2}\mathrm{Tr}\Big(W^{\mu\nu} D_\mu \Sigma D_\mu \Sigma^\dagger\Big) - ig'\frac{L_{9R}}{16\pi^2}\mathrm{Tr}\Big(B^{\mu\nu} D_\mu \Sigma^\dagger D_\nu \Sigma\Big) \\
&\quad +gg'\frac{L_{10}}{16\pi^2}\mathrm{Tr}\Big(\Sigma B^{\mu\nu}\Sigma^\dagger W_{\mu\nu}\Big) \quad .
\end{aligned}$$

Here W^i and B are the gauge fields and Σ is composed of the Goldstone boson fields w^i:

$$\Sigma = \exp\left(\frac{i w^i \tau^i}{v}\right) .$$

The terms with coefficients L_{9L}, L_{9R} induce anomalous triple gauge boson couplings:

$$\begin{aligned}
\kappa_\gamma &= 1 + \frac{e^2}{32\pi^2 s_w^2}(L_{9L} + L_{9R}) \\
\kappa_Z &= 1 + \frac{e^2}{32\pi^2 s_w^2}(L_{9L} - \frac{s_w^2}{c_w^2} L_{9R}) \\
g_1^Z &= 1 + \frac{e^2}{32\pi^2 s_w^2}\frac{L_{9L}}{c_w^2} \ .
\end{aligned}$$

Assuming QCD values for L_{9L} and L_{9R}, κ_γ is shifted by $\Delta\kappa_\gamma \sim -3 \times 10^{-3}$. This shift is almost an order of magnitude larger than the 4×10^{-4} measurement precision expected for $\Delta\kappa_\gamma$ at an e^+e^- collider at $\sqrt{s} = 500$ GeV with 300 fb^{-1} [9].

MEASURING THE AMPLITUDE $e^+e^- \to W_\mathrm{L} W_\mathrm{L}$

The amplitude for $e^+e^- \to W_\mathrm{L} W_\mathrm{L}$ will develop a complex form factor F_T if the longitudinal W bosons are strongly interacting. We use the following expression for this form factor:

$$F_T = \exp[\frac{1}{\pi}\int_0^\infty ds' \delta(s', M_\rho, \Gamma_\rho)\{\frac{1}{s' - s - i\epsilon} - \frac{1}{s'}\}]$$

where

$$\delta(s) = \frac{1}{96\pi}\frac{s}{v^2} + \frac{3\pi}{8}\left[tanh(\frac{s-M_\rho^2}{M_\rho\Gamma_\rho}) + 1 \right] .$$

Here M_ρ, Γ_ρ are the mass and width respectively of a vector resonance in $W_{\rm L}W_{\rm L}$ scattering. The term

$$\delta(s) = \frac{1}{96\pi}\frac{s}{v^2}$$

is the Low Energy Theorem (LET) amplitude for $W_{\rm L}W_{\rm L}$ scattering at energies below a resonance. The following unitarization scheme is used for the LET amplitude:

$$\delta(s) = \begin{cases} \frac{1}{96\pi}\frac{s}{v^2} & \text{if } s < s^0 \\ \\ \frac{1}{96\pi}\frac{s^0}{v^2} & \text{if } s \geq s^0 \end{cases}$$

where $s^0 = (2.8 \text{ TeV})^2$. This scheme produces values for F_T which are similar to those obtained with the K-matrix unitarization scheme in the LET limit of $M_\rho \to \infty$.

The real and imaginary parts of F_T are determined experimentally with a maximum likelihood fit. The inputs to this fit are the W^- production angle and the four W^+W^- decay angles. This type of analysis is commonly used at LEP2 to measure TGC's. We assume 80/0% e^-/e^+ beam polarization where the e^- beam is all left-handed. We analyze the $e\nu q\overline{q}$ and $\mu\nu q\overline{q}$ channels assuming a solid angle coverage of $|\cos\Theta| < 0.9$.

To improve our sensitivity we assume that charm jets can be tagged with 100% purity and 65% efficiency. Such a purity/efficiency combination is not out of the question given that b jet contamination is not a factor in the $e\nu q\overline{q}$ and $\mu\nu q\overline{q}$ channels. Charm tagging provides an improvement in the LET signal which is equivalent to a 50% increase in luminosity.

We use statistical errors only. In practice, one will also have to consider various sources of systematic errors. However, these are fairly small in the $e\nu q\overline{q}$ and $\mu\nu q\overline{q}$ channels, and in any event they will be offset by an increase in statistical precision when other W^+W^- decay channels, such as $\tau\nu q\overline{q}$ and $q\overline{q}q\overline{q}$, are included.

The expected 95% confidence level limits for F_T for $\sqrt{s} = 800$ GeV and a luminosity of 500 fb^{-1} are show in Figure 1. The following sets of vector resonance masses and widths were used to calculate the predictions for F_T shown in Figure 1:

$$(M_\rho, \Gamma_\rho) \;=\; (1.234, 0.104),\; (1.600, 0.224),\; (2.500, 0.844) \text{ TeV} .$$

Table 1 summarizes the signal signifcance for various vector resonances and for the LET limit. The significances from e^+e^- linear colliders of different energies and luminositities are displayed along with the significances expected from the LHC [10].

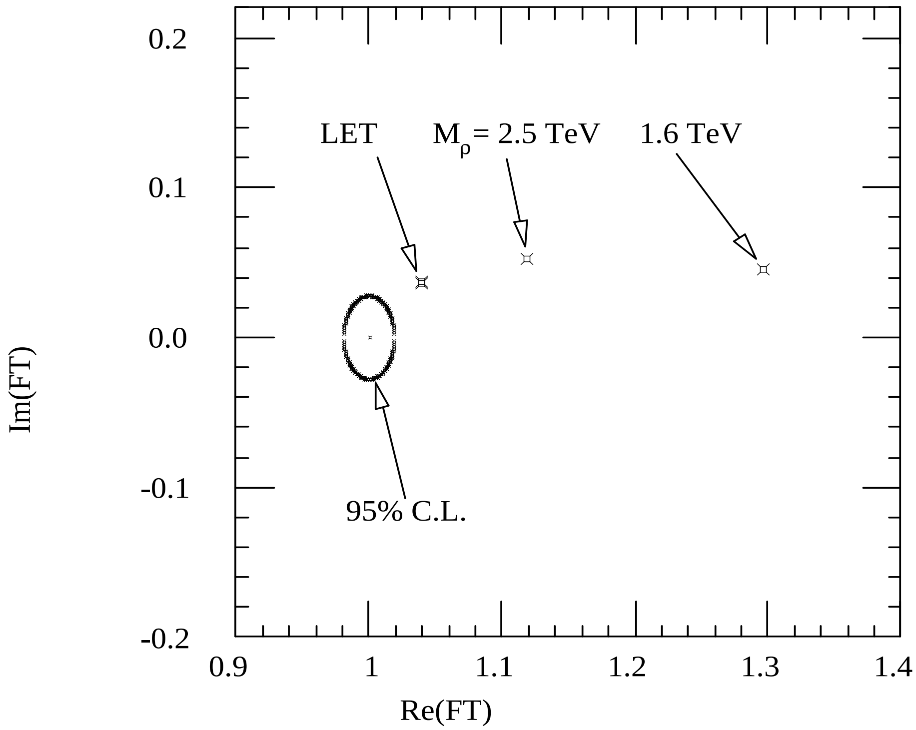

FIGURE 1. 95% C.L. contour for F_T for $\sqrt{s} = 800$ GeV and 500 fb^{-1}.

TABLE 1. Signal significance for various vector resonance masses.

	Final State	$\sqrt{s}$ TeV	$\mathcal{L}$ fb^{-1}	$M_\rho =$ 1.2 TeV	$M_\rho =$ 1.6 TeV	$M_\rho =$ 2.5 TeV	LET
LC	W^+W^-	0.5	300	27σ	16σ	7σ	3σ
LC	W^+W^-	0.8	500	73σ	38σ	16σ	6σ
LC	W^+W^-	1.5	200	114σ	204σ	24σ	5σ
LHC	qqW^+Z	14	100	8σ	6σ	–	–
LHC	qqW^+W^+	14	100	1σ	1σ	–	5σ

From Table 1 we see that e^+e^- linear colliders provide a significant enhancement over LHC in the study of vector resonance production in $W_\mathrm{L}W_\mathrm{L}$ scattering. Even at $\sqrt{s} = 500$ GeV an e^+e^- linear collider outperforms LHC in the study of 1.2, 1.6, and 2.5 TeV vector resonances.

The LET signal significance at the LHC and at the 0.8 and 1.5 TeV linear colliders are roughly the same. However, it is interesting that the LET significance at the 0.8 TeV linear collider is slightly better than the significance at the 1.5 TeV linear collider.

CONCLUSION

The reaction $e^+e^- \to W^+W^-$ will supply important information about a strong symmetry breaking sector which will complement the information obtained from other reactions at an e^+e^- linear collider and from the LHC. High precision measurements of triple gauge boson couplings will probe parameters of the effective chiral Lagrangian. The measurement of the form factor for $e^+e^- \to W_{\mathrm{L}}W_{\mathrm{L}}$ will significantly enhance our knowledege of the $I = J = 1$ channel in $W_{\mathrm{L}}W_{\mathrm{L}}$ scattering. Finally, in an interesting tradeoff of energy and luminosity, we observe that a linear collider with 500 fb^{-1} at $\sqrt{s} = 800$ GeV gives a larger LET signal than one with 200 fb^{-1} at $\sqrt{s} = 1500$ GeV.

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