STRONGLY-INTERACTING ELECTROWEAK SECTOR
AT $e^-e^-$ COLLIDERS*

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We study the possible experimental signatures resulting from a strongly-interacting electroweak sector at $e^-e^-$ colliders, emphasizing the signal enhancement by high beam polarization. We also discuss the unique role for operating the collider in $e^-\gamma$ mode to produce a heavy isosinglet vector state $\omega_T$.

1. Introduction

It has been pointed out that a TeV $e^-e^-$ linear collider may be unique in probing new physics in the weak isospin $I = 2$ channel for the longitudinal $WW$ scattering. Even if there is no resonance in this channel, a strongly-interacting electroweak sector (SEWS) may still yield a sufficiently large signal rate. However, the continuum standard model (SM) backgrounds are substantial and sophisticated kinematical cuts are needed to isolate the signal. On the other hand, as anticipated, an $e^-e^-$ linear collider may achieve high polarization for the $e^-$ beams. This will lead to significant improvement for the signal since not only the signal rate will be enhanced but also some background processes can be suppressed by properly choosing the beam polarization. We study this question quantitatively in Sec. 2.

Another attraction for an $e^-e^-$ collider is the possibility of operating it in $e^-\gamma$ mode by the back-scattering of a low-energy laser beam. This may provide a unique opportunity to produce a heavy isosinglet vector state $\omega_T$ in a strongly-interacting electroweak sector. We study the $\omega_T$ signal and corresponding backgrounds in Sec. 3. We summarize our discussions in Sec. 4.

2. SEWS Signal at $e^-e^-$ Colliders with High Beam Polarization

If no light Higgs boson is found for $m_H$ to be less than about 800 GeV, one would anticipate that the interactions among longitudinal vector bosons become strong. Without knowing the underlying dynamics for the strongly-interacting electroweak sector...
sector (SEWS), we will have to parametrize the physics by an effective theory, with possible low-lying resonant states. 6

The simplest model for a strongly-interacting \( W_L^- W_L^- \) sector is the exchange of a heavy scalar (Higgs) boson. This results in an enhancement of the \( e^- e^- \rightarrow \nu \nu W^- W^- \) production cross section compared to that expected from the exchange of a light Higgs boson in the SM. This enhancement due to a Higgs boson of mass 1 TeV can be defined as the difference of the \( W_L^- W_L^- \rightarrow W_L^- W_L^- \) fusion contributions

\[
\Delta \sigma_H = \sigma(m_H = 1 \text{ TeV}) - \sigma(m_H = 0.1 \text{ TeV})
\]

to \( e^- e^- \rightarrow \nu \nu W^- W^- \) production. There is no appreciable numerical change between the choices \( m_H = 0.1 \text{ TeV} \) and \( m_H = 0 \) for the light Higgs boson reference mass. We find the values \( \Delta \sigma_H \approx \begin{cases} 53.6 - 50.9 = 2.7 \text{ fb} & \text{at } \sqrt{s} = 1.5 \text{ TeV}; \\ 86.5 - 82.0 = 4.5 \text{ fb} & \text{at } \sqrt{s} = 2 \text{ TeV}. \end{cases} \)

This implies that the signal rate at a high luminosity collider with 100-200 fb\(^{-1}/yr\) is quite sizeable. However, the total cross section for \( e^- e^- \rightarrow \nu \nu W^- W^- \) from all Standard-Model diagrams (dominantly from the transversely polarized gauge bosons \( W_T^- W_T^- \)) is about 20 times larger than \( \Delta \sigma_H \). Hence the background contributions associated with \( W_T^- W_T^- \), \( W_T^- W_L^- \) must somehow be selectively reduced if we are to observe the strongly-interacting \( W_L^- W_L^- \) signal. Moreover, when considering the \( W \) hadronic decay, processes such as \( e^- e^- \rightarrow e^- e^- W^+ W^- \) and \( e^- e^- \rightarrow e^- \nu W^- Z \) would also become potential backgrounds, and one will have to scrutinize the backgrounds carefully. There are several ways to accomplish the substantial background suppression. We first present the implementation of selective kinematical cuts to isolate the signal. We then study the improvement by employing beam polarization.

There are characteristic kinematical features for the signal events in \( W_L^- W_L^- \) scattering.\( ^7, ^6, ^1 \) For instance:

- The signal gives large \( M(W^- W^-) \) of order 1 TeV with centrally-produced \( W^- \) having large \( p_T(W) \). The two \( W_L^- \)’s in the final state are largely back-to-back, resulting in large transverse momentum difference \( \Delta p_T(W) = |p_T(W_1) - p_T(W_2)| \).
- The \( p_T(WW) \) spectrum of the signal is peaked around \( M_W \) and falls off rapidly at high \( p_T \) like \( 1/p_T^2 \).
- Rejecting energetic electrons in the final state will help remove the potentially large background processes such as \( e^- e^- \rightarrow e^- e^- W^+ W^- \) and \( e^- e^- \rightarrow e^- \nu W^- Z \), which are especially dangerous when identifying \( W_L^- \)’s via the hadronic mode.
- When including the finite jet-energy resolution in considering the \( W \) hadronic decay \( W \rightarrow jj \), we adopt the energy smearing \( \delta E_j / E_j = 0.50 / \sqrt{E_j} + 0.02 \).
Table 1. Kinematical cuts and hadronic W identification.

| kinematical variable | selective cut |
|----------------------|---------------|
| $M_{WW}^{min}$       | 500 GeV       |
| $p_{T}^{min}(W)$     | 150 GeV       |
| $|\cos \theta_W^{max}|$ | 0.8           |
| $\Delta p_{T}^{min}(WW)$ | 400 GeV   |
| $p_{T}(WW)$          | 50–300 GeV    |
| electron veto in the range | $E_e > 50$ GeV |
| $M(W \rightarrow jj)$ | $0.85 M_W$, $\frac{1}{2}(M_W + M_Z)$ |
| $M(Z \rightarrow jj)$ | $\frac{1}{2}(M_W + M_Z)$, $1.15M_Z$ |

It turns out to be feasible to discriminate the $W$ from $Z$ in the di-jet mode by their mass difference.

We summarize our acceptance cuts in Table 1. Before including the hadronic decay branching fraction and the $M(W \rightarrow jj)$ reconstruction, the signal rate with the cuts becomes about 1.0 fb at $\sqrt{s} = 2$ TeV, where the remaining backgrounds are 2.8 fb for $e^- e^- \rightarrow \nu \nu W^- W^-$, 4.4 fb for $e^- e^- \rightarrow e^- e^- W^- W^+$ and 4.7 fb for $e^- e^- \rightarrow e^- e^- W^- Z$. At $\sqrt{s} = 1.5$ TeV, the signal rate is down to about 0.4 fb, making the signal observation more difficult. Including the $W/Z$ discrimination through the di-jet mass of their decay products improve the signal-to-background ratio significantly. Monte Carlo simulation indicates that true $WW$, $WZ$, $ZZ \rightarrow jjjj$ events will be interpreted statistically as follows:

- $WW \Rightarrow 73\% WW$, 17\% $WZ$, 1\% $ZZ$, 9\% reject
- $WZ \Rightarrow 19\% WW$, 66\% $WZ$, 7\% $ZZ$, 8\% reject
- $ZZ \Rightarrow 5\% WW$, 32\% $WZ$, 55\% $ZZ$, 8\% reject

By beating down the persistent $WZ$ background which escapes the “electron veto” cut, this helps improve the signal observability.

Applying the cuts and signal efficiency obtained from the above study based on the heavy scalar model, we can estimate the signal rates for other SEWS scenarios. We consider a chirally-coupled scalar boson ($m_S = 1$ TeV and $\Gamma_S = 350$ GeV), a chirally-coupled vector boson ($m_V = 1$ TeV and $\Gamma_V = 25$ GeV), and the low energy theorem amplitude. These calculations are carried out with the effective $W$-boson approximation, which is justified for the current application.

The predicted numbers of events with hadronic $W$ decay at $\sqrt{s} = 1.5$ TeV are presented in Table 2. Results are given with the cuts listed in Table 1 and for an integrated luminosity of 200 fb$^{-1}$. So far, we have ignored the $e^- e^-$-beam polarization and the corresponding results are in the first row of Table 1 ($P_e = 0$). We see that the statistical significance is rather poor for all models, barely reaching a $3\sigma$ effect for the best signal of the LET model.

However, high $e^- e^-$-beam polarizations seem achievable at the NLC and one would like to ask its implication on SEWS physics. If we denote the percentage of the
\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
$\sqrt{s} = 1.5$ TeV & $M_{WW}^{min}=0.5$ TeV & SM & Scalar & Vector & LET & Bckgnds \\
\hline
$P_e = 0$ & $S/\sqrt{B}$ & $m_H = 1$ TeV & $m_S = 1$ TeV & $m_V = 1$ TeV & \\
\hline
$P_e = -85\%$ & $S/\sqrt{B}$ & 93 & 121 & 123 & 144 & 620 \\
\hline
$P_e = -100\%$ & $S/\sqrt{B}$ & 109 & 141 & 144 & 168 & 713 \\
\hline
\end{tabular}
\caption{Same as Table 2, but with an integrated luminosity of 300 fb$^{-1}$.}
\end{table}

Table 3. Longitudinal beam polarization along the beam direction by $P_e$, with $P_e = -1(+1)$ for $e^-_L (e^-_R)$, we can express the scattering matrix element squared for a given physical process by

$$\sum |M_{tot}|^2 = \frac{1}{4} \Sigma_{\lambda_1, \lambda_2} |M(\lambda_1, \lambda_2)|^2$$

$$= \frac{1}{4^2} [(1 + P_{e_1})(1 + P_{e_2}) |M(+, +)|^2 + (1 + P_{e_1})(1 - P_{e_2}) |M(+, -)|^2 + (1 - P_{e_1})(1 + P_{e_2}) |M(-, +)|^2 + (1 - P_{e_1})(1 - P_{e_2}) |M(-, -)|^2 ] , \quad (3)$$

where $M(\lambda_1, \lambda_2)$ is the helicity amplitude with initial state electronic helicities $\lambda_1$ and $\lambda_2$. Since the $W^-_L W^-_L$ scattering signal is through purely left-handed currents in $M(\lambda, \lambda)$, while some dominant backgrounds such as $\gamma \gamma \rightarrow W^+ W^-$ and $W Z$ final state are non-chiral, one could significantly improve the signal observability by employing a left-handed longitudinally polarized $e^-$ beam. As an illustration, we...
consider $P_e = P_{e1} = P_{e2} = -85\%$. Then the matrix element squared becomes
\[ \sum |M_{tot}|^2 \approx 0.0056 |M(+, +)|^2 + 0.14 |M(+, -)|^2 + 0.86 |M(-, -)|^2. \] (4)

The numerical coefficients in front of the helicity amplitudes squared clearly demonstrate the advantage for choosing the left-handed beam polarizations. In the ideal case with $P_e = -100\%$, the signal cross section from $M(-, -)$ would be enhanced by a factor of 4 with respect to the unpolarized one, while the backgrounds involving $\epsilon_R$ would be eliminated. Our corresponding results are shown in Table 2, indicated by $P_e = -85\%$ and $P_e = -100\%$. We see that the signal statistical significance is essentially doubled by employing $-85\%$ beam polarizations. In Table 3, results for $300$ fb$^{-1}$ are shown.

3. $\omega_T$ Signal in eγ Collisions

In many dynamical electroweak symmetry breaking models, it is quite common that there exist other resonant states, besides an isotriplet vector ($\rho_T$) and an isosinglet scalar ($H$), such as an isosinglet vector $\omega_T$ and isotriplet axial vector $A_T$. In fact, it has been argued that to preserve good high energy behavior in a SEWS sector, it is necessary for all the above resonant states to coexist. It is therefore wise to keep an open mind and to include other characteristic resonant states in examining the SEWS physics at colliders.

We concentrate on the isosinglet vector $\omega_T$. It couples to three longitudinal gauge bosons (electroweak Goldstone bosons) strongly and to $Z\gamma$ electroweakly. The interactions can be parametrized effectively by two parameters $\chi$ and $g_\omega/\Lambda^2$, with $\chi, g_\omega$ naturally order of one and $\Lambda$ the new physics scale in the SEWS sector, typically $\Lambda \leq 4\pi v \approx 3$ TeV. More explicitly, we assume the couplings as those in Fig. 1. It is easy to see that one can trade the coupling parameters to the two partial widths $\Gamma(WWZ)$ and $\Gamma(Z\gamma)$. Including the mass $M_{\omega_T}$, there are three physical parameters in this sector.

The direct $\omega_T Z\gamma$ coupling in Fig. 1b implies that an $\omega_T$ can be effectively produced by $Z\gamma$ fusion in eγ collisions. This is indeed quite a unique feature for an

Figure 1: Effective interactions of $\omega_T$ with (a) $W^+_L W^-_L Z_L$ and (b) $Z\gamma$. 
Figure 2: Cross sections versus the $\sqrt{s_{e\gamma}}$ c.m. energy for the signal $e^-\gamma \rightarrow e^-\omega_T$ with $\omega_T \rightarrow W^+W^-Z$ and $Z\gamma$ (solid curves), and the SM backgrounds (dashes). Results for two mass values, $M_{\omega_T} = 0.8$ and 1.0 TeV, are presented.

As an exploratory study, we choose the parameters as follows

\[
\begin{array}{c|c|c|c}
M_{\omega_T} [\text{TeV}] & \Gamma(WWZ) [\text{GeV}] & \Gamma(Z\gamma) [\text{GeV}] \\
0.8 & 16 & 4 \\
1.0 & 20 & 5 \\
\end{array}
\]

In Fig. 2 we show the signal cross section versus the c.m. energy of an $e\gamma$ collider for both modes $\omega_T \rightarrow W^+W^-Z_L$ and $Z\gamma$ by the solid curves. The corresponding SM backgrounds are also presented by the dashed curves. For the WWZ channel, the energy dependence of the $\omega_T$ coupling to $W^+_LW^-_LZ_L$ gives the rise for the signal cross section at higher energies; while the contribution from $\gamma^* \rightarrow W^+W^-$ makes the SM background cross section for $e^-\gamma \rightarrow e^-ZW^+W^-$ increase with $\sqrt{s_{e\gamma}}$. The cross sections for $e^-\gamma \rightarrow e^-Z\gamma$ process (both signal and background) at a finite angle $\theta_e, \theta_\gamma > 10^\circ$ decrease at higher $\sqrt{s_{e\gamma}}$. It appears from the figure that the SM backgrounds are always at least as large as the signals in the total rate. However, we should notice that the signal is a resonant production and invariant mass spectra for the final states should reconstruct $M_{\omega_T}$. This is demonstrated in Fig. 3 where
the signal resonant peaks near $M_{\omega_T} = 0.8, 1.0$ TeV are clearly observable over the continuum SM backgrounds, where $\sqrt{s_{e\gamma}} = 1.5$ TeV is assumed. The signal rate near the peak is substantial, being more than a few hundred events per 100 fb$^{-1}$.

Further studies of related physics are in progress.

4. Summary

We discussed the possibility of observing a strong $W_L^+W_L^-$ scattering signal from a strongly-interacting electroweak sector (SEWS), which occurs through the weak isospin $I = 2$ channel and is unique for $e^-e^-$ collisions. We summarized the necessary kinematical cuts to significantly reduce the $W_T^+W_T^-, W_T^0W_L^-, W^+W^-$ and $W^-Z$ backgrounds to the $W_L^-W_L^-$ signal in hadronic $W$ decay mode. We quantified the effects of the beam polarizations and demonstrated the significant improvement for the signal observability by employing left-handed beam polarizations. We also pointed out the unique role for a TeV $e\gamma$ collider in producing other resonant states in SEWS, such as an isosinglet vector state $\omega_T$.

The interesting physics opportunity at a TeV $e^-e^-$ collider as well as $e\gamma$ and $\gamma\gamma$ colliders should be further explored.

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