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Probing Strong Electroweak Symmetry Breaking in $W^+W^- \to t\bar{t}$

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ABSTRACT

We study the process $W^+W^- \to t\bar{t}$ in several models of strong interaction electroweak symmetry breaking. We calculate the signals that can be expected by observing the reaction $e^+e^- \to \nu\bar{\nu}t\bar{t}$ at an e^+e^- linear collider with 1.5 TeV center of mass energy. We also discuss how the lowest-lying resonances predicted by these models could be identified using top polarization observables.

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PROBING STRONG ELECTROWEAK SYMMETRY BREAKING IN $W^+W^- \to t\bar{t}$

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1 The reaction $W^+W^- \to t\bar{t}$ in strong-interaction Higgs sectors

Vector boson scattering experiments form the core of the program to probe the Higgs mechanism in models with strong interaction electroweak symmetry breaking at TeV energies. It was pointed out by Barklow [1] that the related process $W^+W^- \to t\bar{t}$ could also be used to probe how the Higgs sector couples to fermions. Although QCD backgrounds make this process very difficult to observe at hadron colliders, he showed that, at an e^+e^- linear collider (LC) with $\sqrt{s} = 1.5$ TeV, the signal of a Standard Model (SM) Higgs sector could be established with good statistical significance. We have studied the sensitivity of the reaction $W^+W^- \to t\bar{t}$ to more general models of strong interaction electroweak symmetry breaking. [2] Our aim is to explore whether this process allows us to test experimentally the nature of the Higgs sector and the role played by the top quark in the dynamics of the symmetry breaking.

The new strong interactions are expected to give the dominant contributions in scattering amplitudes with longitudinally polarized W bosons. By the Equivalence Theorem, these are given by Goldstone boson scattering amplitudes $\pi^+\pi^- \to t\bar{t}$. For $\sqrt{s} >> m_t$, the low energy theorem (LET) gives

$$\mathcal{M}(\pi^+\pi^- \to t_R\bar{t}_L) = -\frac{2m_t^2}{v^2}\frac{\sin\theta}{1-\cos\theta}, \qquad \mathcal{M}(\pi^+\pi^- \to t_L\bar{t}_R) = 0,$$
$$\mathcal{M}(\pi^+\pi^- \to t_L\bar{t}_L) = \mathcal{M}(\pi^+\pi^- \to t_R\bar{t}_R) = -\frac{m_t\sqrt{s}}{v^2}. \qquad (1)$$

The helicity-flip amplitudes violate the $I = 0$ partial wave unitarity bound

at $\sqrt{s} \approx 10$ TeV.[3] The new physics of the symmetry breaking must therefore appear below this scale. We expect, as in vector boson scattering, that the new resonances predicted in strong interaction models will play a role in the unitarization. Depending on the model, these may be the same resonances that contribute to W^+W^- scattering or new ones related to the mechanism of top mass generation. In the first case, illustrated by the SM, the top quark and W boson couplings to the scalar should be proportional to the masses that they acquire by the Higgs mechanism, and Eq.(1) become

$$\mathcal{M}(\pi^+\pi^- \to t_L\bar{t}_L) = \mathcal{M}(\pi^+\pi^- \to t_R\bar{t}_R) = \frac{m_t\sqrt{s}}{v^2}\frac{M_S^2}{s - M_S^2}\,. \qquad (2)$$

The second possibility is illustrated by topcolor-assisted technicolor models. These models have an additional scalar (the top-Higgs) with an enhanced coupling to $t\bar{t}$ and a suppressed coupling to WW. While the top-Higgs contribution to WW scattering is negligible, its effect in $W^+W^- \to t\bar{t}$ is comparable to that of a SM Higgs boson of the same mass.

Some models of strong symmetry breaking, like technicolor, can also give contributions coming from the s-channel exchange of vector resonances. The extended technicolor interactions that give rise to the top mass also generate an effective coupling of the techni-rho (ρ_T) to the $t\bar{t}$ pairs. The ρ_T exchange contributes to the helicity-conserving amplitudes with

$$\mathcal{M}(\pi^+\pi^- \to t_L\bar{t}_R, t_R\bar{t}_L) = -\eta_{L,R}\frac{m_t}{v}\frac{m_\rho\sqrt{N/2}}{v}\frac{s}{s - m_\rho^2}\sin\theta, \qquad (3)$$

where N is the number of technifermion doublets and $\eta_{L,R}$ are model-dependent dimensionless parameters of order one. This helicity-preserving contribution from a ρ_T resonance is comparable to the helicity-violating contribution from the scalar exchange and can be the most important contribution in technicolor models. Given this sensitivity to models, we investigate their experimental signals in the next two sections.

2 Signals in $e^+e^- \to \nu\bar{\nu}t\bar{t}$

The production of $t\bar{t}$ pairs from W^+W^- fusion can be studied in a high energy e^+e^- LC by analyzing the reaction $e^+e^- \to \nu\bar{\nu}t\bar{t}$. We consider only fusion diagrams, which are expected to dominate the production of $t\bar{t}$ pairs with high invariant mass. We use the effective-W approximation with helicity-dependent structure functions [4,2] of the W bosons. As we have seen in Sec.1, at extreme energies these cross sections have a strong dependence on polarization,

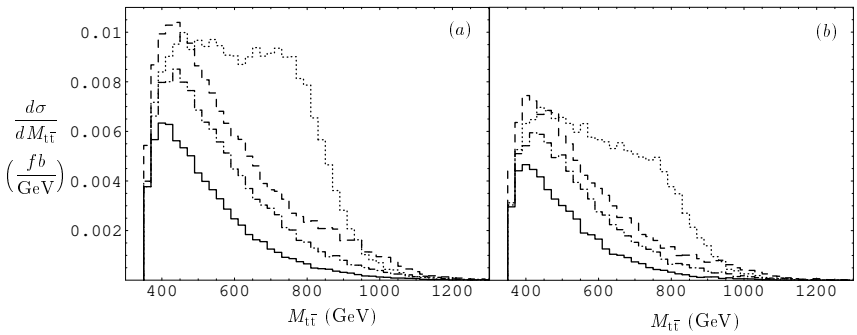

Figure 1: (a) Differential cross section for $e^+e^- \to \nu\bar{\nu}t\bar{t}$ as a function of the $t\bar{t}$ invariant mass, for a LC with $\sqrt{s} = 1.5$ TeV. The curves correspond to the SM with a Higgs mass of 100 GeV (solid) and 800 GeV (dots), the technicolor model described in the text with $m_\rho = 1$ TeV (dash) and the LET limit (dot-dash). (b) Same as (a) including ISR and beamstrahlung.

so we have taken care to keep the helicity dependence in every stage of the calculation. We use full helicity amplitudes for the process $W^+W^- \to t\bar{t}$ and polarized top decay amplitudes to build up polarization observables.

In our analysis, we have neglected the transverse momentum of the W's, expected to be of order M_W. Although this is a reasonable approximation for computing the signal cross sections, the system of cuts which separate the $W^+W^- \to t\bar{t}$ events from the important backgrounds due to $\gamma\gamma \to t\bar{t}$ and $e^+e^- \to t\bar{t}$ involves the total transverse momenta of the $t\bar{t}$ system. [1] Thus, we do not address the backgrounds here.

In Figure 1(a), we show the $t\bar{t}$ invariant mass distributions in $e^+e^- \to \nu\bar{\nu}t\bar{t}$ at $\sqrt{s} = 1.5$ TeV predicted by the models described in Sec.1. The SM distribution with a Higgs boson mass of 800 GeV is compared with a Higgs boson of 100 GeV, and the LET predictions. We have also chosen a technicolor model with $N_{\mathrm{TC}} = 4$ and three effective techniquark doublets. The ρ_T mass is 1 TeV with a width of 45 GeV. The η_L, η_R satisfy the bounds imposed by R_b measurements. In Figure 1(b) we show the effect of including initial state radiation (ISR) and beamstrahlung (BS), using a 1.5 TeV NLC parameter set. [5,6] Beamstrahlung is responsible for roughly 80% of the damping of the signal, being more important at high values of $M_{t\bar{t}}$. This is precisely the region of interest for strong-interaction physics, and so it is gratifying that a clear signal over the SM prediction with a Higgs of 100 GeV can still be seen in all cases.

In Table 1, we present the event yields for an integrated luminosity of 200 fb^{-1} and unpolarized beams, first without and then with effects of ISR and beamstrahlung. In models with heavy resonances, we have also considered the effect of applying the cuts ($M_{t\bar{t}} > 500$ GeV, $\cos\theta_{\mathrm{CM}} < 0.5$) to enhance the strong-interaction signal. In the second part of Table 1, we compare the

Table 1: Number of $e^+e^- \to \nu\bar{\nu}t\bar{t}$ events in a LC with $\sqrt{s} = 1.5$ TeV and $\mathcal{L} = 200 fb^{-1}$, for the models described in the text. Event numbers including ISR, beamstrahlung, and cuts are also shown separately. The estimated significance of the signal is given in brackets.

Model	Events	w. ISR+B		w. Cuts	w. Cuts ISR+B	
SM, $m_H = 100$ GeV	300	200	(—)	35	22	(—)
SM, $m_H = 800$ GeV	934	571	(26)	449	257	(50)
TC, $m_\rho = 1$ TeV	661	419	(15)	233	133	(23)
LET	487	316	(8)	139	82	(13)
SM, $m_H = 400$ GeV	1538	1092	(63)			
Top-C, $m_{H_t} = 400$ GeV	974	668	(33)			

signal of a topcolor-assisted technicolor model with $f_t/f_T = 1/4$ and a top-Higgs mass of 400 GeV, with the signal of a 400 GeV SM Higgs boson. Both models give an increase of events at the same value of $M_{t\bar{t}}$ over the light-Higgs expectations, but the top-Higgs signal is clearly smaller. Finally, we give in parentheses an estimate of the significance of the excess of events expected in each strong-interaction model over the number of events expected in the SM with a Higgs of 100 GeV, which is taken as background. Although this is a highly idealized estimate of the real significance of the signal, these numbers are comparable to those found by Barklow using a complete Standard Model analysis.

3 Top quark polarization observables

Since scalar resonances couple to helicity-flip amplitudes and vector resonances to helicity-conserving ones, a scalar resonance produces a strong anti-correlation in the helicities of the final t and $\bar{t}$ quarks while vector resonance exchange tends to correlate the t and $\bar{t}$ helicities. Define the helicity correlation asymmetry [7] C of the final $t\bar{t}$ pairs produced in $e^+e^- \to \nu\bar{\nu}t\bar{t}$:

$$C = [\sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_R) - \sigma(t_L\bar{t}_R) - \sigma(t_R\bar{t}_L)] \ /\sigma(\text{unpolarized}). \qquad (4)$$

We find that this quantity has a strong dependence on the type of model. In the SM with M_H=100 GeV, $t\bar{t}$ pairs are predominantly produced in the RL configuration and $C = -0.42$. If the Higgs mass is increased over the $t\bar{t}$ threshold, the number of LL and RR pairs is dramatically enhanced and C takes a positive value. For a Higgs mass of 800 GeV we find $C = +0.51$. In technicolor models, the combined effects of saturation in the $J = 0$ channel

and techni-rho exchange in the $J = 1$ channel compete to give a small value of C. In the model described in Section 2 we find $C = -0.12$. These values of C correspond to a 1.5 TeV LC and include ISR and beamstrahlung effects.

However, to extract this spin correlation asymmetry from the expected sample of events will not be easy. Since the $t\bar{t}$ system is produced with smaller $M_{t\bar{t}}$ than the collider energy and a substantial transverse momenta, we have to rely on fully reconstructed events. We will use for this analysis 6-jet and 4-jets+lepton decay modes, assuming an overall reconstruction efficiency (including b-tagging) of $\epsilon_{\rm rec} = 30\%$. We assume that leptons can be identified with efficiency $\epsilon_{\rm l} = 100\%$. Jet flavor identification is needed in hadronic decays; to obtain this information, we assume that it will be possible to tag c quarks with efficiency $\epsilon_{\rm c-tag}$= 50%.

To get a first indication on the significance with which the spin of a resonance could be probed, we work out the case of the SM with a Higgs mass of 800 GeV. To define observables correlated with the top quark helicity, we use the angular distributions of the top quark decay products

$$\frac{1}{\Gamma}\frac{d\Gamma_{t_{R,L}}}{d\cos\chi_i} = \frac{1 \ \pm a_i \cos\chi_i}{2}, \tag{5}$$

where χ_i is the angle of the decay product i with the top helicity axis, measured in the top rest frame. For the W^+ decay products, $a_l = 1$ for $l = (l^+, d, s)$ and $a_\nu = -0.31$ for $\nu = (\nu, u, c)$. For the b quark, $a_b = -0.41$. The signs of a_i are reversed for top anti-quarks. For each pair (i, j) of $(t, \bar{t})$ decay products and a particular model, we define $N_{ij}(+-)$ to be the excess in the number of events with $(cos\chi_i > 0$, $\cos\bar{\chi}_j < 0)$ over the SM expectations with a Higgs of 100 GeV, and similarly for the other sign combinations. Then, a scalar/vector asymmetry can be defined for different types of $(t, \bar{t})$ decay products

$$A_{ij}(S/V) = \frac{1}{a_i\bar{a}_j}\frac{N_{ij}(-+) + N_{ij}(+-) - N_{ij}(++) - N_{ij}(--)}{N_{ij}(\text{total})} \tag{6}$$

for a particular model and $A_{ij}(S/V) = 0$ by construction in the SM with a Higgs mass of 100 GeV. We will use the decay angle of leptons and s-quarks (identified by a c-tag), which have the stronger spin analyzing power ($a_l = 1$). The b quark can also be used with a cut in the W production angle $|\cos\chi_W| < 0.5$, which increases a_b to -0.6 but with an additional cost in efficiency $\epsilon_{\rm b-cut}$=50%. For $\mathcal{L} = 200 fb^{-1}$ including ISR and BS, data samples corresponding to three different values of the a_i should provide the asymmetry

measurements:

$$
\begin{array}{lllll}
A_{ll}(S/V) = 0.25 \pm 0.19: & (bl\nu)(bsc) & BR = 0.22, & \epsilon = \epsilon_{\rm rec} \cdot \epsilon_{\rm l} \cdot \epsilon_{\rm c-tag} \\
 & (bsc)(bsc) & BR = 0.11, & \epsilon = \epsilon_{\rm rec} \cdot \epsilon^2_{\rm c-tag} \\
A_{lb}(S/V) = 0.25 \pm 0.24: & (bl\nu)(bq\bar{q}) & BR = 0.44, & \epsilon = \epsilon_{\rm rec} \cdot \epsilon_{\rm l} \cdot \epsilon_{\rm b-cut} \\
 & (bsc)(bq\bar{q}) & BR = 0.22, & \epsilon = \epsilon_{\rm rec} \cdot \epsilon_{\rm c-tag} \cdot \epsilon_{\rm b-cut} \\
A_{bb}(S/V) = 0.25 \pm 0.63: & (bq\bar{q})(bq\bar{q}) & BR = 0.44, & \epsilon = \epsilon_{\rm rec} \cdot \epsilon^2_{\rm b-cut}
\end{array}
$$

which combined give an overall scalar/vector asymmetry $A(S/V) = 0.25 \pm 0.14$, a 1.8-σ effect. With a 100% left-handed polarized e^- beam, $A(S/V) = 0.25 \pm 0.10$, giving a statistical significance of the scalar nature of the resonance of approximately 2.5-σ.

4 Conclusions

If a light Higgs boson is not found at present collider experiments, it will be interesting to study the reaction $e^+e^- \to t\bar{t}\nu\bar{\nu}$ at a high energy e^+e^- LC. We have found good signals in the $M_{t\bar{t}}$ distributions for strong-interaction Higgs sectors with scalar/vector resonances in the TeV region. It may also be possible to probe the spin of these resonances by top quark polarization analysis.

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