A NEW VECTOR RESONANCE PRODUCTION AT FUTURE e^+e^- COLLIDERS. [1]

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Submitted August 15, 2005

We study the possible production, at future e^+e^- colliders, of new vector resonances associated with new strong physics that could be responsible for electroweak symmetry breaking. Since the new resonances exhibit enhanced couplings to the W and Z bosons as well as to the top quark we concentrate on the processes $e^+e^- \to t\bar{t}$ and $e^+e^- \to \nu_e\bar{\nu}_e t\bar{t}$. We calculate the cross sections of these processes as well as of the relevant backgrounds.

PACS: 12.60.Fr, 12.15.Ji

1 Introduction

The mechanism of electroweak symmetry breaking (ESB), responsible for the masses of gauge bosons, and perhaps fermions, remains an unsolved mystery. ESB gives rise to the massless Goldstone bosons which, through the Higgs mechanism, become longitudinal components of originally massless $W^\pm$ and Z bosons. If the coming experiments, LC and LHC, exclude the existence of the Standard Model (SM) Higgs boson and a light Higgs, a mechanism for ESB alternative to the SM and supersymmetry could be a strongly interacting new physics sector, a scaled-up analogy of the QCD. In the absence of the SM Higgs boson, scattering amplitudes of such processes as $WW \to WW$ violate a tree-level S-matrix unitarity at a TeV scale. In models of strong ESB (SESB) new composite resonances are expected to appear to unitarize the scattering amplitudes. Many studies have concentrated on the production and signatures of the resonances in $W_LW_L \to W_LW_L$ scattering at future lepton and hadron colliders [1].

In our paper we study the $W_LW_L \to t\bar{t}$ scattering as a subprocess of $e^+e^- \to \nu_e\bar{\nu}_e t\bar{t}$ as well as the direct production of the vector resonance in $e^+e^- \to t\bar{t}$. The main appeal of the processes lies in the possibility to test the role of the top quark in ESB [1–3].

To unitarize the VV scattering amplitudes ($V = W, Z$) the simpliest solution would be to introduce either a scalar isoscalar SU(2)$_V$ resonance (S), or a vector isovector resonance (ρ). While we have studied the S-resonance case elsewhere [4], in this paper we focus on the ρ-resonance which is introduced as a new gauge boson triplet following the BESS (Breaking Electroweak Symmetry Strongly) model [5] approach.

[1] Presented at 15-th Conference of Czech and Slovak Physicists, Košice, Slovakia, September 5-8, 2005

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2 ρ-resonance model

In the original version of the BESS model [5] it is assumed that all fermion generations of the same chirality couple to the vector resonance with the same strength. This leads to stringent limits on the ρ-to-fermion couplings from the existing measurements of the SM parameters. In our modification [4] of the BESS model we break this universality and assume that only the top quarks and the left-handed bottom quark b_L couple directly and possibly strongly to the ρ-resonance. However, the symmetries of the model require b_L to couple to ρ with the same strength b_1 as the left-handed top quark t_L and, as a consequence, b_1 is constrained to relatively small values (see the next session) as follows from the low energy measurements of the $Zb\bar{b}$ vertex [4]. On the other hand b_R field can be chosen not to interact directly with ρ at all which protects the right-handed ρ-to-t_R coupling b_2 from the $Zb\bar{b}$ constraint.

Our model is based on the non-linear sigma model which is SU(2)$_L\times$U(1)$_Y$ gauged. The corresponding effective Lagrangian is discussed in detail in our previous paper [4]. Here we show only the fermion part of the model which describes the interaction of the ρ-resonance vector field $\vec{\rho}_\mu$ with the third generation of quarks $\psi = (t, b)$

$$\begin{aligned} L_\rho^f &= b_1\bar{\psi}_L\xi^\dagger i\gamma^\mu[\partial_\mu - ig''\vec{\rho}_\mu\vec{\tau} + ig'/6B_\mu]\xi\psi_L \\ &+b_2\bar{\psi}_R P\xi i\gamma^\mu[\partial_\mu - ig''\vec{\rho}_\mu\vec{\tau} + ig'/6B_\mu]\xi^\dagger P\psi_R - (\bar{\psi}_L U^\dagger M\psi_R + h.c.) \\ &-\lambda_1\bar{\psi}_L i\gamma^\mu(\xi^\dagger\mathcal{A}_\mu\xi)\psi_L + \lambda_2\bar{\psi}_R P i\gamma^\mu(\xi\mathcal{A}_\mu\xi^\dagger)P\psi_R\ , \end{aligned} \tag{1}$$

where $g'', b_{1,2}, \lambda_{1,2}$ are free parameters, M=diag(m_t, m_b) and P =diag(1,0). The Goldstone bosons triplet $\vec{\pi}$ enters L_ρ^f through $\xi = \exp(i\pi_k\tau_k/v)$, $U = \xi\xi$ and $\mathcal{A}_\mu = \xi^\dagger(D_\mu U)\xi^\dagger/2$. The relevant parts of the effective chiral Lagrangian can be cast into a very simple form

$$L = ig_\pi M_\rho/v(\pi^-\partial^\mu\pi^+ - \pi^+\partial^\mu\pi^-)\rho_\mu^0 + g_V\bar{t}\gamma^\mu t\rho_\mu^0 + g_A\bar{t}\gamma^\mu\gamma^5 t\rho_\mu^0\ , \tag{2}$$

where $g_\pi = M_\rho/(2vg'')$, $g_V = g''b_2/(4(1+b_2)) + \mathcal{O}((g/g'')^2)$ are coupling constants of $\rho W_L W_L$ and $\rho t\bar{t}$ interactions. Partial wave unitarity limits for $M_\rho = 700$ GeV are $g_\pi \leq 1.75$ and $g_V \leq 1.7$. There are six new parameters – g'', b_1, b_2, λ_1, λ_2 and the ρ mass, M_ρ. We do not have any experimental constraints on M_ρ — the theoretical expectation is around 1–3 TeV. We do have, however, constraints on g'', b_1, b_2 and λ_1, λ_2. These are due to the corrections that g'', b_1, b_2, λ_1, λ_2 induce in the SM couplings of the Z and W to fermions at low energies ($\sim$90 GeV). The constraints are $g'' \gtrsim 10$, $|b_1 - \lambda_1| \lesssim 0.01$, and $-0.03 \lesssim b_2 - \lambda_2 \lesssim 0.04$. Below we assume $b_1 = \lambda_1 = 0$. Our results are almost independent of λ_2, leaving M_ρ, g'' and b_2 as free parameters.

3 Signal and background analysis

3.1 $e^+e^- \to \nu_e\bar{\nu}_e t\bar{t}$

In our calculations of the cross-sections we used two programs – CompHEP and Pythia. As an example we give the total cross-section for the signal process with parameters $M_\rho = 700$ GeV, $\Gamma_\rho = 12.5$ GeV, b_2=0.08, g''=20, calculated with no cuts: for three different energies of collision, $\sqrt{s} = 0.8, 1.0, 1.5$ TeV, we get $\sigma(e^+e^- \to \nu_e\bar{\nu}_e t\bar{t}) = 0.66, 1.16, 3.33$ fb, respectively.

We calculated the cross-sections of two major background processes: $e^+e^- \to t\bar{t}\gamma$ and $e^+e^- \to e^+e^-t\bar{t}$ (Pythia). The irreducible background is represented by the "No resonance" model (CompHEP). At the energy $\sqrt{s} = 0.8$ TeV we imposed the following set of cuts

$$\begin{aligned}
&500 < m_{t\bar{t}} < 750 \text{ GeV}, \quad -0.8 < \cos\theta_t, \cos\theta_{\bar{t}} < 0.8, \\
&0 < E_t, E_{\bar{t}} < 380 \text{ GeV}, \quad 15 < p_T(t\bar{t}) < 300 \text{ GeV}, \\
&20 < p_T(t), p_T(\bar{t}) < 330 \text{ GeV}, \quad 50 < M_{\nu\bar{\nu}} < 800 \text{ GeV}, \\
&90 \text{ GeV} < E_{miss}, \quad -0.96 < \cos\theta_{pmiss} < 0.96.
\end{aligned} \tag{3}$$

The total background was reduced from 301.6 fb to 0.13 fb and the signal decreased from 0.66 fb down to 0.2 fb. For the collision energy $\sqrt{s} = 1$ TeV we set:

$$\begin{aligned}
&500 < m_{t\bar{t}} < 900 \text{ GeV}, \quad -0.8 < \cos\theta_t, \cos\theta_{\bar{t}} < 0.8, \\
&0 < E_t, E_{\bar{t}} < 480 \text{ GeV}, \quad 15 < p_T(t\bar{t}) < 400 \text{ GeV}, \\
&20 < p_T(t), p_T(\bar{t}) < 400 \text{ GeV}, \quad 150 < M_{\nu\bar{\nu}} < 1000 \text{ GeV}, \\
&100 \text{ GeV} < E_{miss}, \quad -0.96 < \cos\theta_{pmiss} < 0.96.
\end{aligned} \tag{4}$$

The total background was reduced from 207.3 fb to 0.035 fb while the signal dropped from 1.16 fb down to 0.16 fb. Note that the variable θ_{pmiss} in (3) and (4) stands for the missing momentum angle.

The statistical sensitivity of the process to distinguish between the model with the vector resonance and "no-resonance" model (backgrounds included) is given by the following relation

$$R = \frac{|N(\rho) - N(\text{no-resonance})|}{\sqrt{N(t\bar{t}\gamma + e^+e^-t\bar{t}) + N(\text{no-resonance})}}, \tag{5}$$

where N denotes the number of events. In Fig. 1 we show R contours in the g'' - b_2 parametric space at the energy of 0.8 TeV and 1 TeV and the integrated luminosity of 200 fb^{-1}. Cuts (3) and (4) were imposed, respectively, with the exception of the first cut that was taken for both energies $670 < m_{t\bar{t}} < 730$ GeV. We should note, however, that to have a realistic measure of the statistical significance of the process we will have to extend our analysis further, *i. e.* we should include reconstruction efficiences and detector effects.

3.2 $e^+e^- \to t\bar{t}$

This process shows surprisingly good sensitivity to the presence of the ρ-resonance. While we expect ρ to couple strongly to the top quark and not to the electron, it turns out that the latter coupling (induced through ρ mixing with photon and Z-boson) is large enough to generate clear peak rising above continuum background.

In Fig 2 we show the total cross-sections in the region around the peaks of the vector resonances with a) $M_\rho = 0.7$ TeV and b) $M_\rho = 1.5$ TeV . The effects of initial state radiation (ISR) and beamstrahlung (BS) are taken into account. The calculation was performed without cuts. Note $R = 5$ line.

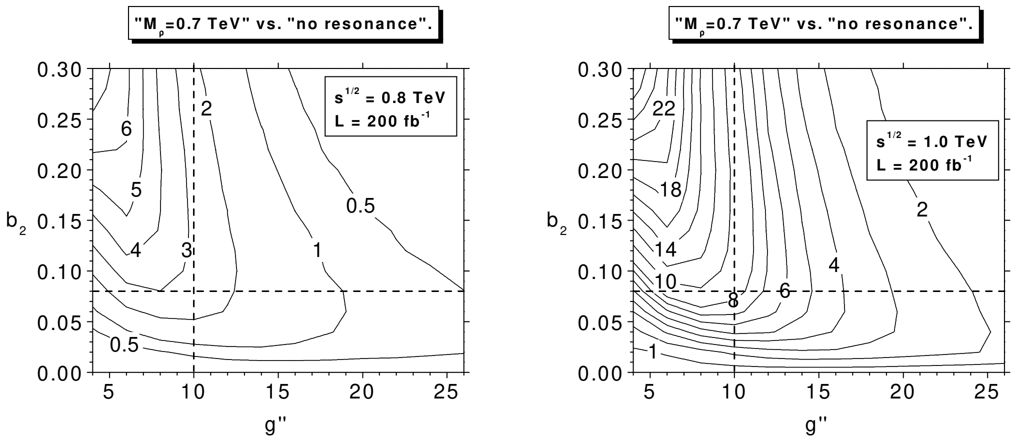

Fig. 1. Sensitivity contours (see Eq. (5)) in the g'' - b_2 parametric space at the energy of 0.8 and 1 TeV and the integrated luminosity of 200 fb^{-1}. The mass of the ρ-resonance is 0.7 TeV. The cuts (3) and (4) were used, respectively, except that the first cut in both cases was changed to $670 < m_{t\bar{t}} < 730$ GeV. The values of R are shown on the contours. The dashed lines are low-energy limits. The allowed regions are in the lower right corner.

4 Conclusions

We have studied a new vector resonance from SESB in $e^+e^- \to \nu\bar{\nu}t\bar{t}$ and $e^+e^- \to t\bar{t}$ at future e^+e^- colliders operating at 1 TeV energy scale.

The first process contains $W_L W_L \to \rho \to t\bar{t}$ scattering as its subprocess and is potentially sensitive to the $\rho - t\bar{t}$ coupling g_V. The size of this coupling could hint on the mechanism of the top mass generation. We found (working at the level of undecayed top quarks) that statistical significance R is as large as 8 for M_ρ =700 GeV for certain regions of the parameter space allowed by the low energy constraints at 1 TeV collider.

While this process is generally sensitive to vector resonances which couple to the top quark and W boson, the second process, $e^+e^- \to t\bar{t}$ is sensitive only if the vector resonance coupling to the electron is not negligible. This is exactly the case of our model. In fact, it is the most promising process in this case. It requires that the collider be able to scan the whole energy scale up to the maximum energy to find the resonance peak. Our results show that it should be possible to discover ρ resonances with $b_2 = 0.08$ if the scanning luminosity is 1 fb^{-1}.

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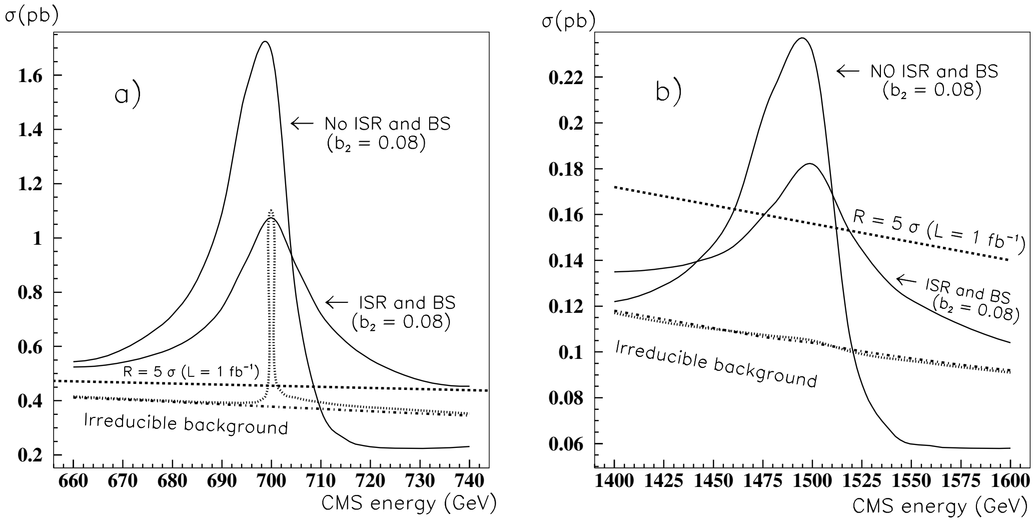

Fig. 2. **a)** $M_\rho = 700$ GeV. The solid curves show the total cross-section as a function of CMS energy without/with initial state radiation (ISR) and beamstrahlung (BS) corrections for a resonance with $b_2 = 0.08, g'' = 20, \Gamma = 12.5$ GeV. The dotted line (narrow peak) corresponds to a resonance with $b_2 = 0.003, g'' = 20, \Gamma = 0.25$ GeV(ISR & BS included). The dash-dotted straight line represents irreducible (continuum) background with ISR & BS. The dashed line shows the boundary at which the statistical significance $(S/\sqrt{B})$ equals 5 assuming the scanning luminosity $L_{scan} = 1$ fb^{-1}. **b)** Same as a), except that $M_\rho = 1500$ GeV and the width of the two resonances is changed accordingly to 40.9 GeV and 9.7 GeV. The latter resonance cross-section is almost identical with the irreducible background.

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