Phenomenology of an Additional Neutral Boson Which Interacts Only with Third-Family Fermions

A. A. Andrianov[1], P. Osland[2], A. A. Pankov[3], N. V. Romanenko[4]

[1] Institute of Physics, University of Sanct-Petersburg, 198904 Sanct-Petersburg, Russia,
[2] University of Bergen, Allégt. 55, N-5007 Bergen, Norway,
[3] Gomel Polytechnical Institute, Gomel, 246746 Belarus,
[4] Department of Neutron Research, Petersburg Nuclear Physics Institute, 188350, Gatchina, Russia

Abstract

The phenomenology of an additional $U(1)$ neutral gauge boson Z' coupled to the third family of fermions is discussed. One might expect such a particle to contribute to processes where taus, b and t quarks are produced. We find that it could not be observed, neither at the Tevatron nor at the LHC because the corresponding cross sections are many orders of magnitude below the QCD background. The possibility to find such a Z' at future e^+e^- colliders is more encouraging, but still difficult.

1 Introduction

We discuss a model for the breaking of universality in weak interactions. Particular attention is paid to the signatures of new heavy elementary vector (spin-1) particles (Z' bosons) which can be detected at the present or future high–energy accelerators. As the quarks of the third family (t and b) are significantly heavier than those of the two other families, one may speculate that such a boson may be involved in the formation of this difference, and thereby interact directly with the t and b quarks (as well as the τ and ν_τ) and only much more weakly with the lighter quarks and leptons, solely due to radiatively-created mixings.

A theoretical extension of the Standard Model adopting a new heavy Z' boson may need to include more unknown heavy fermions and scalar Higgs bosons. Otherwise the quantum anomalies break the unitarity and the mass pattern for heavy fermions will violate experimental bounds on deviations from the Standard Model in the low energy data. There can be a variety of possible models depending on the strength of the vector and axial-vector couplings of the Z' to quarks and leptons. First of all, additional bosons naturally appear in Grand Unification theories [1]. The Left-Right-symmetric model also contains at least one Z' boson [2].

Usually these Z' bosons interact universally with the fermions of all families, the phenomenology of such particles was considered by Leike and others [3, 4]. There exists a scheme in which Grand Unification symmetry breaking leads to the formation of a so-called "leptophobic" and "hadrophilic" Z' boson, which interacts only with hadrons. The phenomenology of such bosons was considered by several authors [1, 5]. A related idea has been advanced by Okun and collaborators, who consider a 'leptonic' photon [6].

A scheme with the breaking of universality in weak interactions has been studied by Dyatlov [7] in connection with the problem of the fermion mass hierarchy. It was shown that a neutral gauge boson interacting differently with the heaviest fermions naturally leads to a realistic mass hierarchy and Kobayashi-Maskawa mixing matrix. The phenomenology of a Z' interacting only with the quarks of the third family was considered recently by Holdom [8], by Frampton, Wise and Wright [9], and by Muller and Nandi [10].

2 Model parameters and experimental input

In our model [11] we assume that the Z' interacts only with fermions of the third family. Then the neutral current Lagrangian is of the form [1]:

$$-\mathcal{L}_{\rm NC} = eJ^\mu_{\rm em}A_\mu + g_Z J^\mu Z_\mu + g_{Z'} J'^\mu Z'_\mu, \tag{1}$$

where the first two terms are just those of the SM and J'^μ involves only the third-family fermions, t, b, τ and ν_τ. This form of $\mathcal{L}_{\rm NC}$ corresponds to the case where the new $U(1)$ neutral gauge particle is not mixed with the photon [12].

In the usual notations of the SM one has $g_Z = g/\cos\theta_{\rm W}$, while $g_{Z'}$ is a phenomenologically free parameter. However, in more complete theories involving Z' (*i.e.*, GUT, or LR-models), the value of $g_{Z'}$ is tightly connected to g_Z [1]:

$$g_{Z'} = \sqrt{\frac{5}{3}} \sin\theta_{\rm W} \sqrt{\lambda}\, g_Z, \tag{2}$$

where λ is usually in the range 2/3 to 1 [1]. This means that

$$g_{Z'}/g_Z \approx 0.62. \tag{3}$$

We shall use this constraint in the numerical work that is presented here.

Let us write down the Lagrangian for interactions of the Z and Z' with the fermions of the third family:

$$-\mathcal{L}_{\rm ZZ'} = g_Z Z_\mu \sum_{f=tb\tau\nu_\tau} \bar{\psi}_f \gamma^\mu \left(v_f - a_f\gamma_5\right) \psi_f + g_{Z'} Z'_\mu \sum_{f=tb\tau\nu_\tau} \bar{\psi}_f \gamma^\mu \left(v'_f - a'_f\gamma_5\right) \psi_f. \tag{4}$$

The parameters v_f and a_f are defined in the SM as follows:

$$v_f = \tfrac{1}{2} T_{\rm 3L} - \sin^2\theta_{\rm W} Q, \qquad a_f = \tfrac{1}{2} T_{3L}, \tag{5}$$

where T_3 and Q are the third component of weak isospin and electric charge, respectively (we suppress their flavor indices). The parameters v'_f and a'_f represent the chiral properties of the Z' interactions with fermions and the relative strengths of these interactions. One of all these parameters for all fermions can be absorbed into $g_{Z'}$, and in order to avoid this we normalize ${v'_\tau}^2 + {a'_\tau}^2 = \frac{1}{2}$, this normalization was used in [1] when obtaining Eq. (2). However, in our model the quantity ${v'_f}^2 + {a'_f}^2$ may vary from fermion to fermion.

The weak eigenstates Z_μ and Z'_μ may be mixed so that the mass eigenstates are:

$$(\,Z_1 Z_2) = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} (\,Z Z') \tag{6}$$

Then the well-known value of the SM Z-boson mass corresponds in this model to the Z_1 mass (M_1), while the mass of the Z_2 boson (M_2) is, of course, unknown.

In the extended model the mass of the weak eigenstate M_Z (*i.e.*, the matrix element of the mass operator) is unknown, it is related to the mass values M_1 and M_2, and the mixing ξ, as follows:

$$\tan^2\xi = \frac{M_Z^2 - M_1^2}{M_2^2 - M_Z^2}. \tag{7}$$

As a result, *for non-zero mixing angles one has corrections to the Weinberg angle $\theta_{\rm W}$ and gauge couplings g and g'*. They acquire dependence now not only from the standard electroweak input, but *from the parameters of the extended model (ξ, M_2) as well.* This means that the results of measurement of other electroweak quantities may be used to restrict these parameters.

3 Main Numerical Results

Irrespectively of the scheme of the Z' boson embedding into an extended electroweak theory one should know the feasibility to detect such a particle at a particular accelerator. Various high-energy colliders have been examined for that purpose: proton-antiproton ($p\bar{p}$) colliders (Tevatron or Upgraded Tevatron at the Fermilab), proton-proton (pp) collider (the LHC at CERN), and future electron-positron (e^+e^-) colliders.

For $p\bar{p}$ and pp colliders the main production mechanisms are the following: $b\bar{b}$-quark annihilation (from the small sea contribution in protons) near the Z' peak, quark-antiquark annihilation into a Z with conversion of the Z into a Z' due to small (radiative) mixing and also gluon-gluon fusion, which contributes to Z' production through b and t quark triangle diagrams [11]. The Z' boson is assumed detected through an excess of $b\bar{b}$ or $t\bar{t}$ hadronic jets. Other processes are suppressed by the kinematics and due to small coupling constants. Numerical estimates have been made whether the Z' signal can compete with the two-jet background originating from non-resonant processes. The conclusion is that the direct observation of a heavy Z' (heavier than the Z) with moderate coupling constants to b and t quarks is impossible at the $p\bar{p}$ Tevatron collider and unlikely even at the LHC.

The most interesting possibility is to investigate the feasibility of Z' discovery at the next generation of e^+e^- colliders whose design is now intensively discussed [13]. We have found that the process $e^+e^- \to b\bar{b}$ gives the the most restrictive bounds on the Z_2 mass and $Z - Z'$ mixing angle.

The cross section is given by the expression

$$\begin{aligned}\sigma_{b\bar{b}} \quad = \quad & \frac{4\pi\alpha^2}{3s}\Big[Q_e^2Q_b^2 + 2Q_e\bar{v}_{e1}Q_b\bar{v}_{b1}\mathrm{Re}\chi_1 + (\bar{v}_{e1}^2 + \bar{a}_{e1}^2)(\bar{v}_{b1}^2 + \bar{a}_{b1}^2)|\chi_1|^2 \\ & + 2Q_e\bar{v}_{e2}Q_b\bar{v}_{b2}\mathrm{Re}\chi_2 + (\bar{v}_{e2}^2 + \bar{a}_{e2}^2)(\bar{v}_{b2}^2 + \bar{a}_{b2}^2)|\chi_2|^2 \\ & + 2(\bar{v}_{e1}\bar{v}_{e2} + \bar{a}_{e1}\bar{a}_{e2})(\bar{v}_{b1}\bar{v}_{b2} + \bar{a}_{b1}\bar{a}_{b2})\mathrm{Re}\chi_1{\chi_2}^*\Big], \end{aligned} \tag{8}$$

with

$$\chi_i = \frac{s}{s - M_i^2 + iM_i\Gamma_i}, \tag{9}$$

and

$$\bar{v}_i = \frac{g_Z}{e}\,v_i, \qquad \bar{a}_i = \frac{g_Z}{e}\,a_i\,. \tag{10}$$

We show the contours of relative deviations from the SM cross sections at the 5% and 10% level for this process at the center-of-mass energy $\sqrt{s} = 190$ and 500 GeV in Figs. 1 and 2, respectively. The four parts refer to different chiralities of these couplings, as indicated. More detailed discussion (including other physical processes) can be found in [11].

In summary, we have extended the more exploratory analysis of ref. [9], and found that a Z' boson coupled only to the third family fermions is rather difficult to discover, even for powerful colliders.

For the hadronic colliders such as the Tevatron or the LHC this Z' is invisible because of the QCD background which is many orders of magnitude greater than the exotic cross sections involving the Z'. For the e^+e^- colliders the effects can be observed only through $Z-Z'$ mixing (which may be the effective mixing coming from one-loop diagrams) and are also rather small.

It seems that some additional progress may be achieved if one investigates not the full cross-sections of processes involving the Z', but their dependence from the $b\bar{b}$ ($t\bar{t}$, $\tau\bar{\tau}$) invariant mass. We hope to return to this question in future work.

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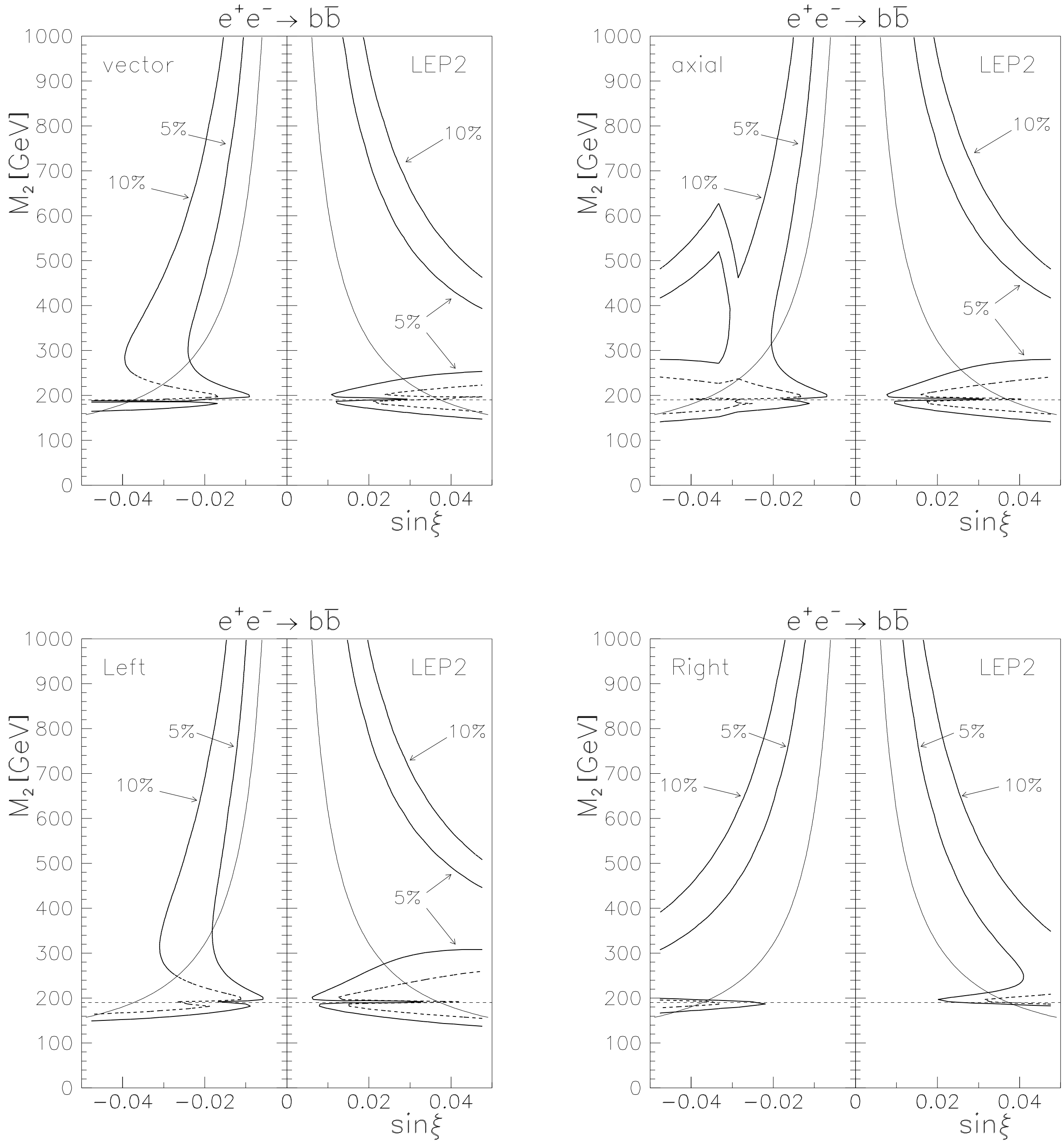

Figure 1. Modification of the $e^+e^- \to b\bar{b}$ cross section and limitations on the strength of the mixing due to the ρ parameter.

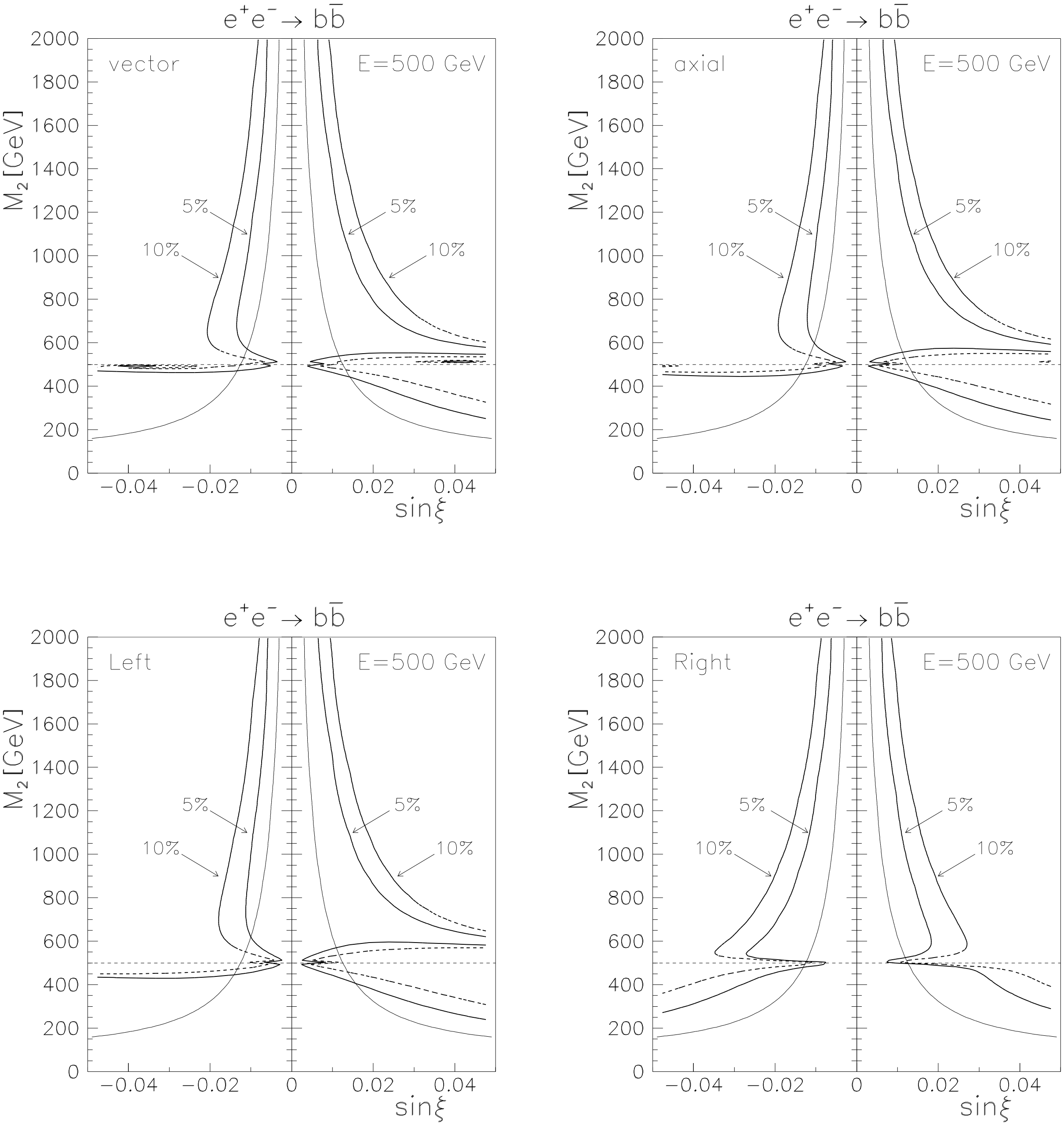

Figure 2. Modification of the $e^+e^- \to b\bar{b}$ cross section and limitations on the strength of the mixing due to the ρ parameter.