$e^+e^- \to \gamma + X$ IN MAJORON MODELS

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Received 9 October 1989

We examine the reaction $e^+e^- \to \gamma$ + missing momentum in various majoron models that predict the existence of very light scalars coupled to the Z. The relevant features for neutrino counting experiments are obtained.

1. Introduction

In trying to extend the standard model one has to introduce extra parameters (such as couplings and masses) that are allowed to vary in a more or less broad range. However, in some cases, there exists enough experimental information to restrict severely the parameters' bounds or even to rule out a particular model. In the known Gelmini–Roncadelli [1] (GR) model, where a Higgs triplet (carrying lepton number) is introduced in order to provide Majorana masses for the neutrinos, the triplet vacuum expectation value is restricted to be much smaller than the doublet VEV; this is due to the known limits on the ρ parameter and to the stellar production of majorons [2]. This situation leads to the existence of a massless Goldstone boson (the majoron J) and a light Higgs boson ρ_L (with a mass several orders of magnitude below the electroweak scale) which have a gauge coupling with the Z boson; this coupling increases the Z width by the same amount that two extra massless neutrino generations would.

The other model [3] is inspired by the minimal supergravity model and has spontaneous R-parity violation, achieved through a nonzero VEV for the scalar tau neutrino. This model also predicts similar neutral scalars J and ρ_L, although it is more difficult to rule out (or confirm) because the contribution to the Z width is now one half of that of an extra neutrino; but since LEP is expected to provide a resolution of about 0.2 families, both these models may be (dis)proved in a short time.

Though the effect on the Z width has long been known, the same is not true for scattering processes: a priori, one expects an intricate interference of diagrams. Also, the single photon process has certainly advantages over the simple knowledge of the Z width, because one may test for energy dependent effects or, even more important, for polarization effects which are a possible key to the identification of invisible neutrals [4].

The problem (or maybe virtue) of these models is expected to be rather common among the class of models in which an enlarged Higgs structure provides massive neutrinos. We have recently learnt of a model [5] where the coupling $ZJ\rho_L$ is avoided by a careful choice of the scalar fields quantum numbers, although it requires some additional tunings in the Higgs potential.

Here we analyse (for these models) the single photon production in e^+e^- colliders, and compare with the standard model results.

2. $e^+e^- \to \gamma + X$ in the Gelmini–Roncadelli model

The cross section for $e^+e^- \to \gamma\nu\bar{\nu}$, computed in the standard model context [6,7], will be taken as a basis for the following discussion. In that case there are five relevant diagrams, which are drawn in fig. 1; for μ and τ neutrinos one has only the diagrams with neutral currents. We will often express the cross section for $e^+e^- \to \gamma + X$ in terms of the number of extra neutrinos $\Delta N_\nu = N_\nu - 3$ (not necessarily integer) required

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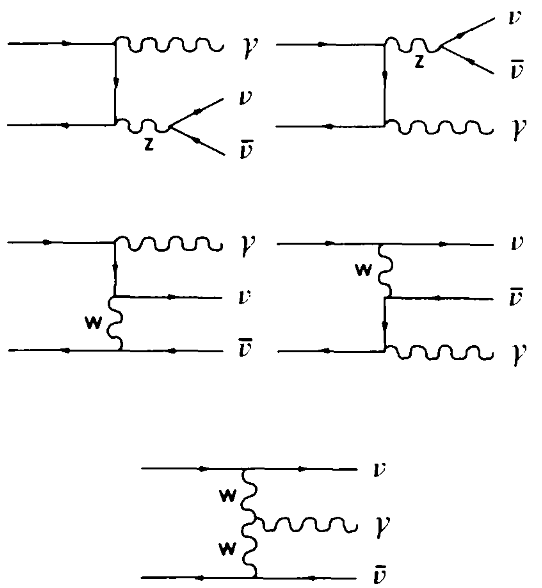

Fig. 1. Tree level diagrams for $e^+e^- \to \gamma\nu\bar{\nu}$ in the standard model. Only for the electron neutrino one has charged current diagrams.

to reproduce that quantity, that is, one compares a given result with the standard model result (with three generations) and computes the "number" of neutrinos one would have to add to the standard model to get the same value.

We have to consider the contribution of new particles both to $\gamma\nu\bar{\nu}$ and $\gamma J\rho_L$ production. An important criterium is that the diagrams which have a scalar to lepton coupling are highly suppressed relatively to other diagrams which have only gauge couplings. The reason is the following: the scalar to lepton couplings are either proportional to m_ℓ/M_W or to m_ν/v (where v is the triplet VEV, m_ℓ a charged lepton mass and m_ν a neutrino mass). The ratio m_ν/v is given an upper bound by looking at charged π and K leptonic decays, where the majoron coupling to neutrinos would give rise to a three body decay with a single charged lepton being detected. Compared with the fermion-gauge-boson couplings, the first ratio is ridiculously small and the second is small enough (it is less than 10^{-2}, according to ref. [8], at least for electron and muon neutrinos) to be neglected in this discussion (a detailed list of Feynman rules can be found in ref. [9]). Since the GR model has no extra gauge bosons, only extra scalars, we conclude that no relevant con-

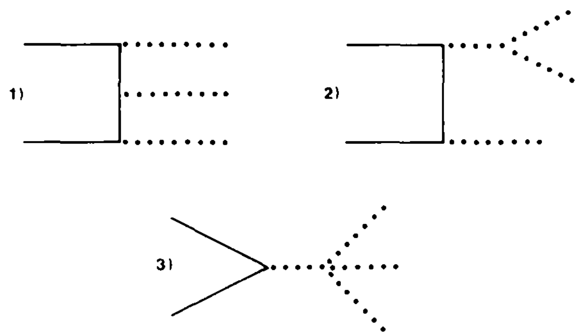

Fig. 2. Schematic diagram structure for $e^+e^- \to \gamma J\rho_L$. Solid lines denote charged fermions while dotted lines stand for neutral bosons.

tributions should be expected for the standard $e^+e^- \to \gamma\nu\bar{\nu}$. For the case $e^+e^- \to \gamma J\rho_L$ we show in fig. 2 the possible diagram structures: the solid lines stand for charged fermions (the input particles are e^+ and e^-) while the dotted lines denote neutral bosons. It is clear that structure 1 must have Yukawa couplings, and so it is discarded; structure 3 does not lead to any diagram since quartic vertices with photon legs are proportional to electric charge; and structure 2 gives two possible diagrams (shown in fig. 3 together with some examples of suppressed diagrams). Now it turns out that the structure of these diagrams leads to a differential cross section for $\gamma J\rho_L$ which is exactly twice the one for $\gamma\nu_\mu\bar{\nu}_\mu$ (the factor 2 is exactly the same as that which comes from the Z width). Let us denote by q, p_1 and p_2 the photon, majoron and light Higgs (or the photon, neutrino and antineutrino) 4-mo-

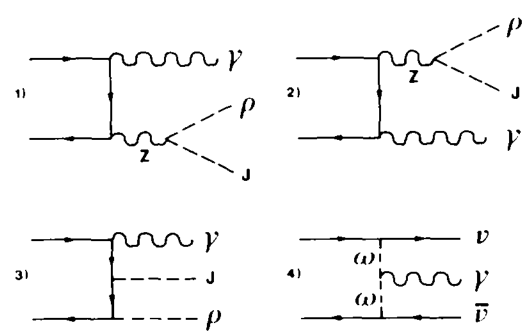

Fig. 3. Dominant diagrams for $e^+e^- \to \gamma J\rho_L$ (1 and 2), together with some suppressed diagrams for single photon production (3 and 4).

menta, respectively; since the $Z^\alpha J\rho_L$ vertex rule is

$$\frac{2e}{\sin 2\theta_w}(p_2-p_1)^\alpha, \tag{1}$$

we may write the relevant amplitudes as

$$T_{\gamma\nu\nu}=X_\alpha \bar{u}(p_2)\gamma^\alpha\gamma_L u(p_1),$$
$$T_{\gamma J\rho}=2iX_\alpha(p_1-p_2)^\alpha, \tag{2}$$

where X_α is the same quantity in both cases and does not depend at all on the invisible neutrals. In our notation $T_{\gamma\nu\nu}$ refers only to the amplitude for the neutral current diagrams shown in fig. 1 and $T_{\gamma J\rho}$ to the same type of diagrams shown in fig. 3. Since the differential cross section is

$$\mathrm{d}\sigma(\theta_\gamma, E_\gamma, \Omega^*_\rho) = \frac{E_\gamma|T|^2}{128(2\pi)^4 s}\,\mathrm{d}(\cos\theta_\gamma)\,\mathrm{d}E_\gamma\,\mathrm{d}\Omega^*_\rho, \tag{3}$$

performing an integration over the angular coordinates of these two particles in the rest frame of $p_\mu=p_{1\mu}+p_{2\mu}$ gives the result

$$2\int \mathrm{d}\Omega^*_\rho\,|T_{\gamma\nu\nu}|^2=\int \mathrm{d}\Omega^*_\rho\,|T_{\gamma J\rho}|^2 = \tfrac{16}{3}\pi(p_\alpha p_\beta - p^2 g_{\alpha\beta})X^\alpha X^\beta. \tag{4}$$

This proves the above claim. For more details on the evaluation of the neutrino cross section and for an explicit expression for X_α we refer to ref. [7] where the cross section for $e^+e^-\to\gamma\nu\bar{\nu}$ was evaluated for the first time without approximations.

3. $e^+e^-\to\gamma+X$ in the supersymmetric majoron model

Let us deal with supersymmetric particles first; in case of R-parity conservation, it is clear that s-particles cannot be present in the tree level diagrams for the majoron production; now if R-parity is broken spontaneously by a nonzero VEV for the scalar tau neutrino [3], there is a mixing of the τ with the charginos, and of the ν_τ with the neutralinos. Since none of these particles was contributing before the R-parity breaking, it is clear that they also cannot do it afterwards. Thus, only "ordinary" particles remain. And similarly to the GR model, constraints on the scalar to lepton couplings eliminate a large number of diagrams.

These considerations leave us the same two diagrams of the previous section, and the only difference is a factor $\frac{1}{2}$ in the $ZJ\rho_L$ coupling since in this case the scalars belong to doublets; consequently, the cross section is now four times smaller.

4. Results and conclusions

There are several candidates for a possible fractional contribution to ΔN_ν. We have studied these models in order to identify the characteristic majoron effects [#1]. We have shown that the ratio

$$R=\frac{\sigma(e^+e^-\to\gamma J\rho_L)}{\sigma(e^+e^-\to\gamma\nu_\mu\bar{\nu}_\mu)} \tag{5}$$

is always 2 ($\frac{1}{2}$) in the GR (supersymmetric majoron) model, regardless of the cuts imposed on the photon or of the beam energy. This also has the consequence that if one uses polarized beams the majoron effects on the asymmetries are not different from the neutrino ones [4]. Of course, in the actual experiment, one does not distinguish among the different neutrino species and the factor 2 (or $\frac{1}{2}$) only appears after a careful comparison with the standard model. To see this we shown in table 1, for the case of the GR model, the values of both cross sections, as well as their ratio Q, for a particular cut in the photon energy and scattering angle. Notice that the pole in the

[#1] Recent results from SLC [10] already rule out the Gelmini–Roncadelli model.

Table 1
Typical values of the integrated cross section (picobarn) both for $\gamma\nu\nu$ production in the standard model and $\gamma J\rho_L$ production in the GR model, for different $\sqrt{s}$ (GeV); Q is the ratio of the given cross sections. The photon cuts are $E_\gamma\geq 0.1\times\sqrt{s}$ and $\cos\theta_\gamma<0.94$. For the s-model Q is four times smaller.

$\sqrt{s}$	$\sigma(e^+e^-\to\gamma J\rho_L)$	$\sigma(e^+e^-\to\gamma\nu\bar{\nu}$	Q
50	2.37×10^{-2}	5.15×10^{-2}	0.46
75	7.93×10^{-2}	1.61×10^{-1}	0.49
90	4.31×10^{-1}	5.43×10^{-1}	0.80
100	3.21×10^{0}	4.33×10^{0}	0.74
110	1.53×10^{1}	2.33×10^{1}	0.66
115	1.16×10^{1}	1.81×10^{1}	0.64

Z propagator is displaced due to the photon energy. For the cut we have chosen, the pole occurs for $\sqrt{s} \approx 110$ GeV. It is only near to this value that the W exchange diagrams are negligible and the ratio Q gets close to $\frac{2}{3}$. We should stress that away from the pole an exact calculation of the W exchange diagrams is necessary [7]. In the supersymmetric majoron model there are other processes that can contribute to $e^+e^- \to \gamma + X$ (like $e^+e^- \to \gamma\chi^0\chi^0$ or $\gamma\tilde{\nu}\tilde{\nu}$), but that could only render the process more visible, increasing ΔN_ν; and one should note that this increment is largely dependent on the s-particle masses [4,10].

Perhaps one should remark that the contribution of scalar particles does not need to be always very suppressed; for example, if there are scalar n-plets with no neutral field then the bound quoted before does not apply to all scalar to fermion couplings, one such example is given in ref. [5]. Of course, that kind of model cannot be considered to be minimal, and even if there are other diagrams to be taken into account this does not necessarily mean that the cross section for this process may be lowered significantly (it might very well increase).

Finally, one should mention the doublet majoron model [11], in which one expects a contribution one-half of that of a new neutrino pair, just like in the SUSY model. This is due to the fact that the $ZJ\rho_L$ vertex is proportional to the scalar multiplet hypercharge, and in this one has doublets instead of a triplet.

Acknowledgement

We thank J. Valle for discussions during the first stages of this work.

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