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On the search for 50 GeV neutrinos

V.A. Ilyin [a], M. Maltoni [b], V.A. Novikov [c], L.B. Okun [c], A.N. Rozanov [d], M.I. Vysotsky [e]

[a] *SINP MSU, 119899 Moscow, Russia*
[b] *Instituto de Física Corpuscular – C.S.I.C., Departament de Física Teòrica, Universitat de València, Edificio Institutos de Paterna, Apt. 22085, E-46071 Valencia, Spain*
[c] *ITEP, 117218 Moscow, Russia*
[d] *ITEP and CPPM, IN2P3-CNRS, Univ. Méditerranée, F-13288, Marseilles, France*
[e] *ITEP, 117218 Moscow, Russia*

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Abstract

Using the computer code CompHEP we estimate the number of events and the background, at LEP II and TESLA, for the reaction $e^+e^- \to N\overline{N}\gamma$, where N is a hypothetical Dirac neutrino with mass of the order of 50 GeV. © 2001 Published by Elsevier Science B.V.

1. Introduction

The precision measurements of "invisible width" of Z-bosons prove that there exist only three ordinary neutrinos: ν_e, ν_μ, ν_τ [1]. Precision measurements of other Z-observables when compared with calculations of radiative corrections exclude the existence of the fourth generation of fermions in the case when the fourth neutrino N is heavy ($M_N \gtrsim 100$ GeV) [2]. However, as was shown recently [3], the radiative corrections become small if $m_N \sim m_Z/2$. Thus the existence of fourth generation with charged lepton and quarks being heavy ($M \gtrsim 100$ GeV) but with neutrino being "light" ($M_N \sim 50$ GeV) is still an open possibility.

As was proposed a long time ago [4], the cross section of e^+e^--annihilation into an invisible final state can be inferred from observation of initial state bremsstrahlung. In LEP II experiments [5–8] the production of final states involving one energetic photon,

$$e^+e^- \to \gamma + \text{“nothing”}, \tag{1}$$

was studied at centre-of-mass energies up to 202 GeV. In context of our discussion "nothing" means: (a) $\nu_\mu\bar{\nu}_\mu$ and $\nu_\tau\bar{\nu}_\tau$ produced in decays of real and virtual Z bosons, (b) $\nu_e\bar{\nu}_e$, where two mechanisms contribute, through s-channel Z boson and from t-channel exchange of W boson, and (c) $N\overline{N}$ pair from virtual Z bosons.

The aim of this note is to present results of calculation of the differential cross sections of the reaction (1) for various values of m_N and of $\sqrt{s_{e^+e^-}}$, and perform

E-mail addresses: ilyin@theory.npi.msu.su (V.A. Ilyin), maltoni@ific.uv.es (M. Maltoni), novikov@heron.itep.ru (V.A. Novikov), okun@heron.itep.ru (L.B. Okun), rozanov@cppm.in2p3.fr (A.N. Rozanov), vysotsky@heron.itep.ru (M.I. Vysotsky).

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the *Signal/Background* (S/B) analysis for the search for "50 GeV neutrino" at LEP II and future linear collider TESLA [9]. The calculation has been performed using the computer code CompHEP [10].

The fourth generation leptons were introduced in the Standard Model Lagrangian as an isodoublet for left-handed components of massive fermions (including neutrino) and isosinglet for right-handed states. Then, we assume vanishing mixing with the fourth generation — mixing angle between the fourth generation neutrino and those of first three generations should be less than 10^{-6} [11].

Higher order QED corrections connected with radiation from initial electron and positron states were taken into account by using the "structure function" technique: the squared matrix elements in the Born approximation were convoluted with the *Initial State Radiation* (ISR) structure function [12] at the scale parameter $Q = \sqrt{s}$. We found that ISR enlarges the signal cross sections by about 8–3% for $M_N = 46$–50 GeV, while background is not changed or slightly decreased for these values of neutrino mass because of opposite effect in $\nu_e\bar{\nu}_e$ and two other (muonic an tauonic) channels. Note, that on the Z-peak shoulder this enhancement is much higher, about 20–30% both for the signal and background.

SM parameters were set in calculations as $M_Z = 91.1884$ GeV, $\Gamma_Z = 2.45$ GeV, $M_W = 80.343$ GeV. Couplings at electroweak vertices were normalized to $\alpha(m_e) \cdot \alpha(M_Z)^2 = (1/137) \cdot (1/128)^2$, thus taking W and Z couplings at the electroweak scale while the photon emission vertex is kept in the classical limit.

2. 50 GeV neutrinos at LEP II

As we have mentioned already, the single photon final states were analyzed by all LEP II experiments [5–8] and no deviations from SM predictions were observed. There were established limits on additional photon production in the context of different "new physics" hypotheses, in particular in SUSY models and low scale gravity models with extra dimensions. It is clear, that these data can be used also to establish the limits on the mass of the fourth generation (Dirac) neutrino in the discussed mass range $m_N \sim 50$ GeV, what was not done yet as we know. In this section we make a phenomenological analysis of possible limits on m_N taking into account LEP II data, being collected already [5–8],

$$1997\text{–}1998 \quad \sqrt{s} = 182, 189\ \text{GeV},$$
$$\sim 226\ \text{pb}^{-1}/\text{Coll.}, \quad \mathcal{L}_{\text{tot}} = 904.2\ \text{pb}^{-1};$$
$$1999 \quad \sqrt{s} = 192\text{–}202\ \text{GeV},$$
$$\sim 230\ \text{pb}^{-1}/\text{Coll.}, \quad \mathcal{L}_{\text{tot}} = 923\ \text{pb}^{-1},$$

and data from current (final) run with collision energies 199.9–208.7 GeV (average energy 205 GeV). From LEPII schedule one can expect that it will be delivered about 200 pb^{-1} during the 2000 run. Thus, four experiments will accumulate in total 800 pb^{-1} additional data.

In Fig. 1 (upper left side plot) the distribution on "invisible" mass M_{inv} (invariant mass of the neutrino pair) [1] is represented for SM background and the $N\overline{N}$ signal for $\sqrt{s} = 200$ GeV and different values of N masses, $M_N = 46$–100 GeV. Here we applied kinematical cuts on the photon polar angle and transverse momentum, $|\cos\vartheta_\gamma| < 0.95$ and $p_T^\gamma > 0.0375\sqrt{s}$, being the ALEPH selection criteria [5]. Other experiments tried to include in the analysis also events with smaller photon polar angles and lower transverse momenta. E.g., DELPHI collected events with photon emmited at angles up to 3.8°.

One can see that the S/B ratio is better on the Z-peak shoulder. However, for higher significance of the $N\overline{N}$ signal, evaluated as $N_{\text{S}}/\sqrt{N_{\text{B}}}$, one should include whole interval on M_{inv} allowed kinematically. For example, for statistics 230 pb^{-1} the signal significance is 0.72 for $m_N = 48$ GeV, see Table 1 for details. In this case SM predicts about 212 events per experiment with only 9 events with massive neutrino pair. Here we have taken into account the photon detection efficiency — in the ALEPH Monte-Carlo analysis [5] it was estimated at the level 74%. For other experiments the photon detection efficiency is lower, but they used wider selection criteria.

Let us now look how the $N\overline{N}$ signal significance depends on angular and transverse momentum cuts. In the Table 2 the cross sections for SM background and $N\overline{N}$ signal (with $m_N = 48$ GeV) are given for three

[1] M_{inv} is directly connected with another variable frequently used, $x_\gamma \equiv E_\gamma/E_{\text{beam}} = 1 - M_{\text{inv}}^2/s$.

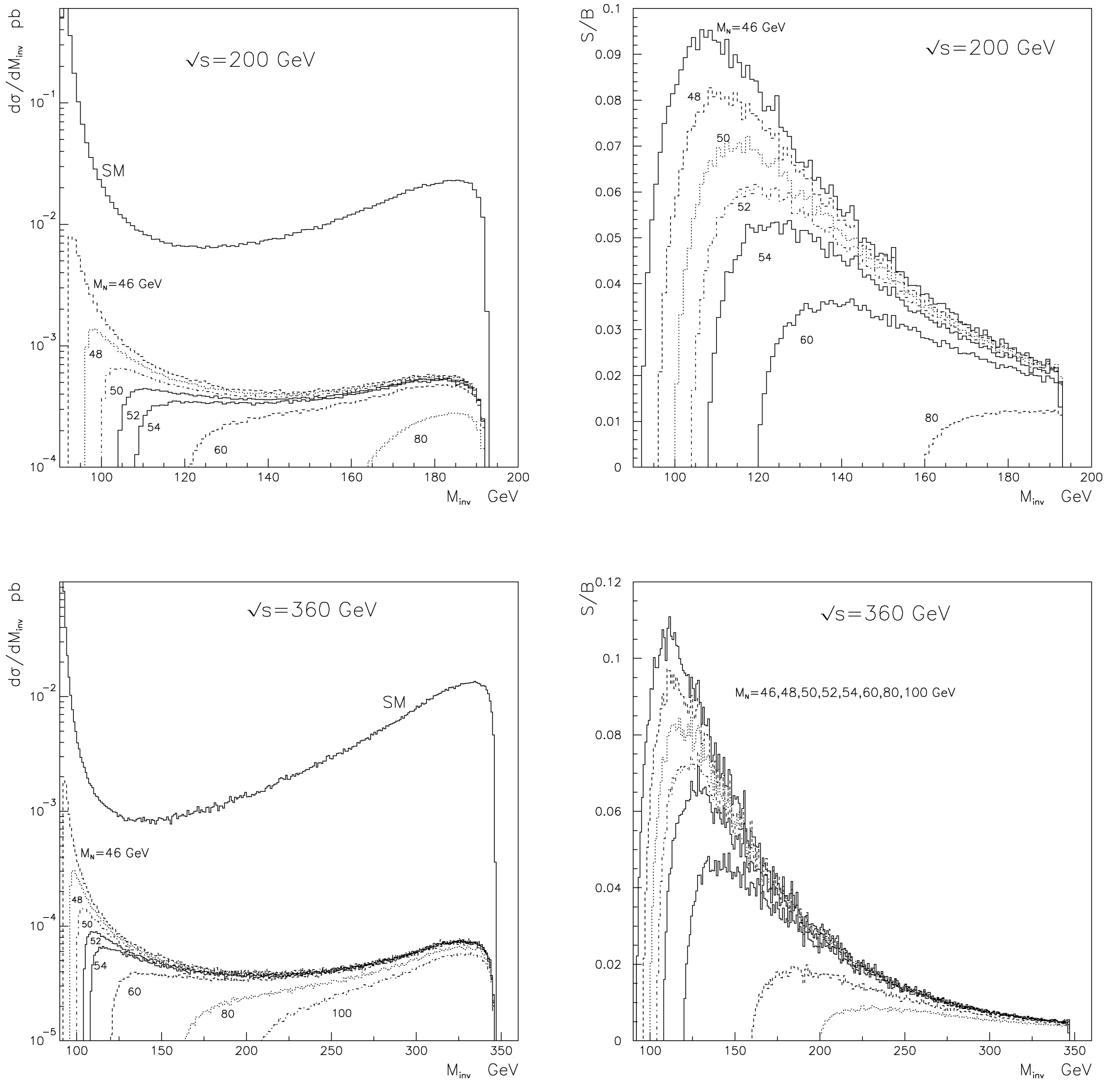

Fig. 1. The left side plots: $d\sigma/dM_{\text{inv}}$ (in pb) for Standard Model and for the different values of m_N. The right side plots: the Signal/Background ratio as a function of M_{inv}. Cuts applied: $|\cos\vartheta_\gamma| < 0.95$ and $p_T^\gamma > 0.0375\sqrt{s}$. The photon detection efficiency 74% is assumed.

values of the angular and p_T cuts. One can see that the signal significance is higher for weaker cuts.

Then, we found that, in spite of the $N\overline{N}$ signal being due to s-channel diagrams, while large contribution to the SM background is due to t-channel W-exchange, the angular distributions have similar shape for signal and background; that is clearly seen on Fig. 2. Thus, it seems that there are no chances to improve the signal significance by using more complicated selection criteria, e.g., exploiting the correlation between photon polar angle and p_T.

The general conclusion from this analysis is that one should collect single photon events with the weakest kinematical cuts allowed by detector construction

Table 1
Cross sections and $N\overline{N}$ signal significance for different values of the $M_{\rm inv}$ cut. $\sqrt{s} = 200$ GeV and $m_N = 48$ GeV. Cuts applied: $|\cos\vartheta_\gamma| < 0.95$ and $p_T^\gamma > 0.0375\sqrt{s}$

max $M_{\rm inv}$ (GeV)	–	–	140	130	120	110
min $M_{\rm inv}$ (GeV)	$2m_N$	97.5	97.5	97.5	97.5	97.5
$\sigma_{\rm SM}$ (pb)	1.243	1.175	0.402	0.333	0.268	0.196
$\sigma_{N\overline{N}}$ (pb)	0.0529	0.0512	0.0269	0.0228	0.0182	0.0125
$N_{\rm S}/\sqrt{N_{\rm B}}$, 230 pb^{-1}	0.720	0.716	0.644	0.598	0.571	0.428

Table 2
Cross sections and $N\overline{N}$ signal significance for different values of the cuts on photon polar angle and transverse momentum. $\sqrt{s} = 200$ GeV, $m_N = 48$ GeV. The cut $M_{\rm inv} > 2m_N$ is applied

$\vartheta_\gamma >$ (deg)	3			18.2 ($|\cos\vartheta_\gamma| < 0.95$)			30		
$p_T^\gamma >$ (GeV)	1	7.5	15	1	7.5	15	1	7.5	15
$\sigma_{\rm SM}$ (pb)	6.089	2.731	1.682	3.620	1.947	1.410	2.668	1.458	1.082
$\sigma_{N\overline{N}}$ (pb)	0.153	0.0706	0.0436	0.0903	0.0527	0.0392	0.0668	0.0400	0.0304
$N_{\rm S}/\sqrt{N_{\rm B}}$, 230 pb^{-1}	0.942	0.648	0.509	0.720	0.573	0.501	0.620	0.502	0.443

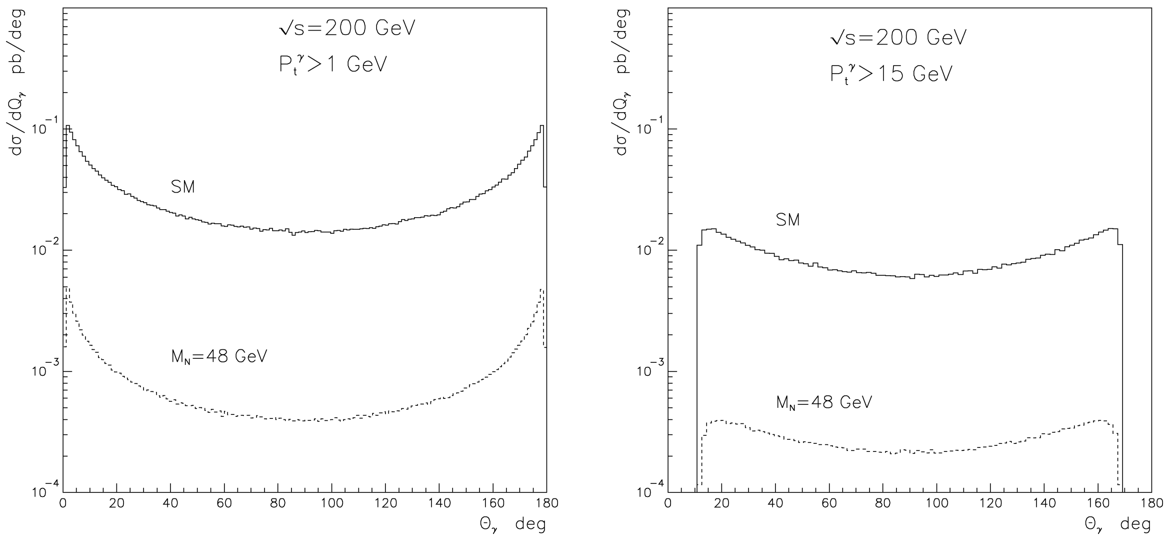

Fig. 2. Distribution on photon polar angle for the Standard Model and for the $N\overline{N}$ signal with $m_N = 48$ GeV. The cut $M_{\rm inv} > 2m_N$ is applied.

and conditions to suppress reducible background (e.g., Bhabha scattering). Of course, only a careful simulation can give answer what are the optimal selection criteria for the search for “50 GeV neutrino”. In what follows we use ALEPH selection criteria, $|\cos\vartheta_\gamma| < 0.95$ and $p_T^\gamma > 0.0375\sqrt{s}$, and apply cut $M_{\rm inv} > 2m_N$.

On Fig. 3 the signal and background cross sections and signal significances (for different samples of data) are represented as a function of m_N. One can derive that only the analysis based on combined data from all four experiments both from 1997–1999 runs ($\sqrt{s} =$ 182–202 GeV) and from the current run, in total

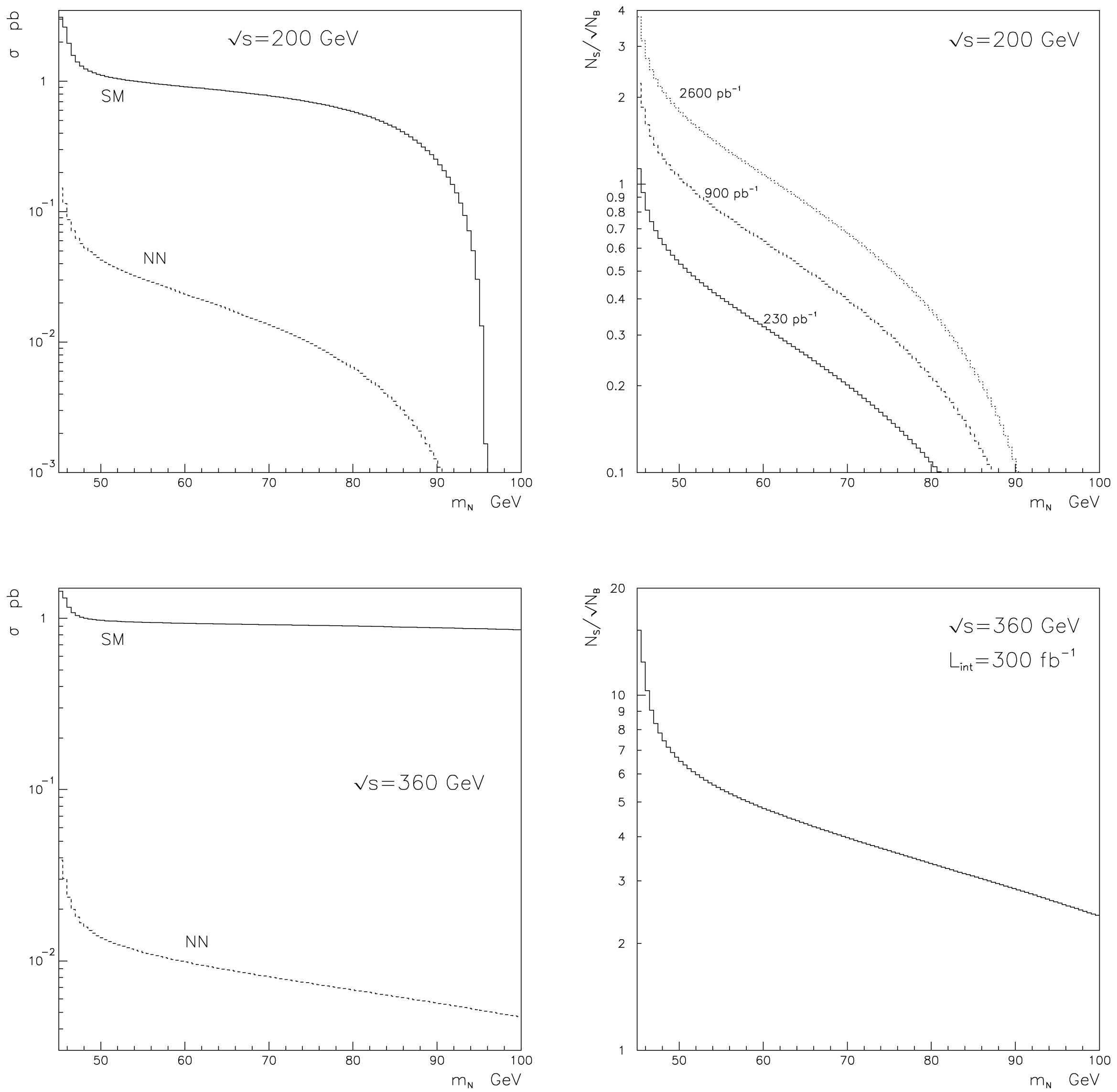

Fig. 3. Cross sections for the $N\overline{N}$ signal and SM background (left side plots) and $N\overline{N}$ signal significances at different statistics (right-side plots) as function of the neutrino mass. Cuts applied: $M_{\rm inv} > 2m_N$, $|\cos\vartheta_\gamma| < 0.95$ and $p_T^\gamma > 0.0375\sqrt{s}$. For the significance the photon detection efficiency 74% is assumed.

~ 2600 pb^{-1}, can exclude at 95% CL the interval of N mass up to ~ 50 GeV.

3. 50 GeV neutrinos at TESLA

From the point of view of expected cross sections the increase in energy leads to the decrease both of the signal and the background. This can be seen from comparing the left-side plots on Fig. 3. However, this decrease may be over compensated by the proposed increase of luminosity of the future linear e^+e^--collider. Thus for TESLA the expected year luminosity at the first stage ($\sqrt{s} = 360$ or 500 GeV) is 300 fb^{-1} [13].

Further advantage of the linear collider is the possibility to use polarized beams (80% circular polarization for electrons and 60% for positrons). This is important in suppressing the cross section of $e^+e^- \to \nu_e\bar{\nu}_e\gamma$ as this reaction goes mainly through the t-channel exchange of the W boson and gives substantial contribution to the background.[2] However, even without exploiting the beam polarization the advantage of TESLA in the total number of events is extremely important. Thus, Standard Model is expected to give approximately 0.3 million single photon events for $M_{\text{inv}} > 100$ GeV while the number of 50 GeV neutrino pairs would be about 4000. On Fig. 3 (lower plots) the signal and background cross sections, as well the significance, are represented for TESLA as a function of N mass. Here we applied cuts $|\cos\vartheta_\gamma| < 0.95$, $p_T^\gamma > 0.0375\sqrt{s}$ and $M_{\text{inv}} > 2m_N$, and assumed photon detection efficiency to be 74%, similarly to the LEP II case.

With such numbers, although the signal over background ratio is still small (2.3–0.5% for $m_N =$ 45–100 GeV correspondingly) the significance of the signal is excellent, higher than 2 for the whole interval of N neutrino mass under discussion. It means that fourth generation Dirac neutrino will be excluded at the 95% CL in TESLA experiment. However, if such a neutrino exists this new particle will be discovered with 5σ significance after one year of the TESLA operation at first stage if $m_N < 60$ GeV.

[2] For "light" neutrinos 45 GeV $< M_N <$ 50 GeV the ratio of s-channel to t-channel contributions is enhanced at the shoulder of Z-peak.

4. Conclusions

The total sample of single photon events from all four LEP II detectors can exclude the 50 GeV neutrinos at the 95% CL or show the evidences of their existence with only 2σ significance.

The future TESLA experiment at its first stage (with collision energy 360 or 500 GeV) will be able to exclude or discover fourth generation, if one combines TESLA results with the bounds from radiative corrections [2].

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