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Search for R–Parity Breaking Sneutrino Exchange at LEP

The L3 Collaboration

Abstract

We report on a search for R–parity breaking effects due to supersymmetric tau–sneutrino exchange in the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ at centre–of–mass energies from 91 GeV to 172 GeV, using the L3 detector at LEP. No evidence for deviations from the Standard Model expectations of the measured cross sections and forward–backward asymmetries for these reactions is found. Upper limits for the couplings λ_{131} and λ_{232} for sneutrino masses up to $m_{\tilde{\nu}_\tau} \leq 190$ GeV are determined from an analysis of the expected effects due to tau sneutrino exchange.

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Introduction

Supersymmetric theories [1] are considered to be the most promising and natural extensions of the Standard Model (SM). The Minimal Supersymmetric Standard Model [2] conserves baryon number B and lepton number L, usually represented as the existence of a multiplicative discrete symmetry called R–parity [3]. R–parity conservation is not ensured by gauge invariance. The most general superpotential even for a minimal supersymmetric model contains interactions violating B and L.

The high–x, high–Q^2 events observed by the H1 [4] and ZEUS [5] collaborations at HERA have revived the interest in theories with broken R–parity. In this case the superpotential contains L–violating trilinear Yukawa couplings, $W_{\not R}^{lll}$, of two leptons to scalar sleptons [6, 7]:

$$W_{\not R}^{lll} = \lambda_{ijk} L_{\mathrm{L}}^i L_{\mathrm{L}}^j \bar{E}_{\mathrm{R}}^k \ , \tag{1}$$

where L stands for the left–handed doublets of leptons, E for the right–handed singlets of charged leptons, and ijk are generation indices. At least two different generations are coupled in the purely leptonic vertices, since $\lambda_{ijk} \neq 0$ only for $i < j$. Depending on the value of the couplings λ the effects due to sneutrino exchange in leptonic $\mathrm{e^+e^-}$ processes at LEP energies can be large [8].

The effects of sneutrino exchange manifest themselves as deviations from the Standard Model expectations of the measured cross sections, σ, and forward–backward asymmetries, A_{fb}, for $\mathrm{e^+e^-}$ and $\mu^+\mu^-$ final states:

$$\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}, \quad \mathrm{e^+e^-} \rightarrow \mu^+\mu^-. \tag{2}$$

Mass limits for sneutrinos within the Minimal Supersymmetric Standard Model have been derived from the measurement of the invisible width of the Z: $m_{\tilde{\nu}} > 41.8$ GeV, if three sneutrino generations are assumed, and $m_{\tilde{\nu}} > 37.1$ GeV, in case of one sneutrino generation [9]. The search for sneutrinos from models with broken R–parity is extended over the entire centre–of–mass energy range of LEP1 and LEP2.

Measurements of Lepton–Pair Production

Measurements of cross sections and forward–backward asymmetries for reactions (2) have been performed by the L3 experiment at centre–of–mass energies, $\sqrt{s}$, around the Z peak [10], at $\sqrt{s} =$ 130.3 and 136.3 GeV [11], and at $\sqrt{s} =$ 161.3, 170.3 and 172.3 GeV [12]. The selection procedure and the measurements with their statistical and systematic errors are described in these references [10–12]. The L3 detector and its performance are described in [13]. In all cases except for the $\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}$ cross section measurement the low–statistics results at $\sqrt{s} =$ 170.3 GeV are combined with the results at 172.3 GeV to a centre–of–mass energy of 172.1 GeV.

For $\mathrm{e^+e^-}$ final states both leptons have to satisfy $44^\circ < \theta < 136^\circ$, where θ is the angle between the incoming electron and the outgoing fermion. For muon–pair production around the Z peak the angular acceptance is given by $|\cos\theta\,| < 0.8$. At higher energies, the angular range is extended to $|\cos\theta\,| < 0.9$.

At the Z resonance 72258, and at higher energies 1099 electron– and muon–pair events have been selected. These correspond to an integrated luminosity of 40.8 $\mathrm{pb^{-1}}$ and 26.2 $\mathrm{pb^{-1}}$, respectively.

For comparison of the measured values with the predictions from the Standard Model or from theories with broken R–parity the measurements are not extrapolated to the full solid angle. The model expectations are computed with the same angular cuts as applied to the data.

Exchange of Tau Sneutrinos

Lepton–pair production in e^+e^- collisions is affected by the R–parity violating exchange of sneutrinos in the s– and/or t–channel. The corresponding diagrams for e^+e^- final state events are shown in Figure 1. For muon– and tau–pair production only the s–channel diagram is present in the Standard Model. Diagrams with sneutrino, $\tilde{\nu}_j$, exchange are present if the couplings λ_{ijk} are not zero at both vertices.

Interactions which violate R–parity will introduce at energies well below the mass of the exchanged sneutrino the usual four–fermion contact interactions. In this letter, the impact of nearby resonances is investigated, which necessitate the inclusion of propagator and non–zero width effects [8].

Lepton number conservation places severe constraints on the couplings λ in the general case. Only if the effective four–fermion Lagrangian does not violate L conservation, the allowed values reach

$$\lambda \leq 0.1 \times (\frac{m_{\tilde{\nu}}}{200 \ \ \mathrm{GeV}}) \ , \tag{3}$$

where $m_{\tilde{\nu}}$ is the mass of the exchanged sneutrino.

This is possible if only some of the operators with a particular generation structure are present in Equation (1). Two main options lead to s–channel sneutrino exchange and potentially large effects [8]:

- case (A): one single Yukawa coupling λ is much larger than all the others, so that the latter are negligible; two options are present: the muon sneutrino coupling to electrons λ_{121} is heavily constrained by the R–violating interpretation of the HERA data [8], but the coupling of tau sneutrinos to electrons λ_{131} can be sizeable and is considered further.

- case (B): two Yukawa couplings violating the same lepton flavour are much larger than the others; for s–channel exchange mainly the case where the coupling of tau sneutrinos to electrons, λ_{131}, and to muons, λ_{232}, are not equal to zero is of interest.

The cross section for e^+e^- final states in case (A) contains both s– and t–channel contributions from the exchange of γ/Z bosons and of tau sneutrinos and anti–sneutrinos. Muon–pair production is not affected. In tau–pair production only very small effects due to t–channel electron sneutrino exchange occur.

In case (B), the reaction $e^+e^- \rightarrow \mu^+\mu^-$ receives large additional contribution from tau sneutrino exchange in the s–channel and effects similar to those in $e^+e^- \rightarrow e^+e^-$ are obtained.

Deviations from the Standard Model predictions are computed with a program provided by the authors of [8]. Initial–state radiation (ISR) changes the effective centre–of–mass energy in a large fraction of the observed events. These effects are taken into account by computing the first order exponentiated cross sections and asymmetries following [14]. Other QED corrections give smaller effects and are neglected.

Examples of calculations before and after the inclusion of initial–state radiation are shown in Figure 2a for $e^+e^- \rightarrow e^+e^-$ and in Figure 2b for $e^+e^- \rightarrow \mu^+\mu^-$. Large effects are observed, especially in case of a radiative return to a nearby resonance. The typical interference curve in e^+e^- final state events is smeared after the inclusion of ISR, due to the integration over areas with constructive and destructive interference.

Analysis and Results

For each centre–of–mass energy the deviations from the Standard Model resulting from tau sneutrino exchange are computed, as a function of the tau sneutrino mass and coupling strength λ. This is done on a two–dimensional grid which contains 150 values for $m_{\tilde{\nu}_\tau}$ between 60 and 210 GeV, and 100 values for λ between 0.01 and 0.20.

Above the Z peak, the events at high effective centre–of–mass energy are used. They do not include the radiative return to the Z and have the largest sensitivity to a nearby resonance. For e^+e^- final states the programs ALIBABA [15] and TOPAZ0 [16] are used at the Z peak and at higher energies, respectively. For muon–pair production the program ZFITTER [17] is used throughout. The error on a deviation consists of three parts, which are combined in quadrature: the statistical, the systematic and the theoretical error. The systematic error for cross sections includes the luminosity error of our measurements ranging from 0.25% to 0.6%. Thus the cross section measurements depend on the normalisation. For A_{fb} measurements there is no such dependence, and the statistical errors above the Z peak are still dominant. The measurements of σ and A_{fb} are independent and are combined.

No statistically significant deviations from the Standard Model predictions are observed, see [10–12]. The maximum likelihood method is used to derive a one sided upper limit on the coupling strength λ at the 90% confidence level for a given value of $m_{\tilde{\nu}_\tau}$. The likelihood function, L, is constructed by combining the cross section and A_{fb} measurements at the different centre–of–mass energies:

$$-\ln L = \sum_{i=1}^{n} \left(\frac{(\sigma(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau}) - \sigma^{\mathrm{meas}})^2}{2\cdot\delta_\sigma^2} + \frac{(A_{\mathrm{fb}}(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau}) - A_{\mathrm{fb}}^{\mathrm{meas}})^2}{2\cdot\delta_{A_{\mathrm{fb}}}^2} \right)_i \tag{4}$$

$$\begin{aligned} \delta_\sigma &= \mathrm{error}(\sigma(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau}) - \sigma^{\mathrm{meas}}) \ , \\ \delta_{A_{\mathrm{fb}}} &= \mathrm{error}(A_{\mathrm{fb}}(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau}) - A_{\mathrm{fb}}^{\mathrm{meas}}) \ , \end{aligned} \tag{5}$$

where $\sigma(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau})$ and $A_{\mathrm{fb}}(\mathrm{SM};\lambda, m_{\tilde{\nu}_\tau})$ are the expectations for the cross section and the forward–backward asymmetry from the Standard Model combined with the additional effect of sneutrino exchange as a function of the mass and the coupling strength, and σ^{meas} and $A_{\mathrm{fb}}^{\mathrm{meas}}$ are the measured quantities. The index i runs over all centre–of–mass energy points. After proper normalisation the likelihood function gives the probability for $\lambda_{ijk} < \lambda_{\mathrm{lim}}$ for any value of λ_{lim} in the physically allowed region.

Finally, the results for the different sneutrino masses are combined in a single exclusion plot in the $(m_{\tilde{\nu}_\tau}, \lambda)$ plane. The results for e^+e^- final states are shown in Figure 3. The LEP high energy data has larger sensitivity to new physics of this type compared to the high precision measurements at the Z peak. This is due to the fact that the absolute, and not the relative, error is crucial in this search. The results are compared with limits on R–parity breaking interactions from processes at lower energies [7]. The strongest limit on the coupling λ_{131} comes from precise measurements of the ratio $R_\tau = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$. Using the latest data [18], a 90% confidence level upper limit is derived and also shown in Figure 3.

For muon–pair production the results are shown in Figure 4, together with the 90% confidence level constraints derived from the lower energy measurements. In this case the strongest limit on λ_{232} comes from precise measurements of the ratio $\mathrm{R}_{\tau\mu} = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$. In order to simplify the presentation of the limit in two dimensions, it is assumed that $\lambda_{131} = \lambda_{232}$. In both cases, large and previously unexplored areas in the $(m_{\tilde{\nu}_\tau},\ \lambda_{131})$ and $(m_{\tilde{\nu}_\tau},\ \lambda_{131} = \lambda_{232})$ planes are excluded.

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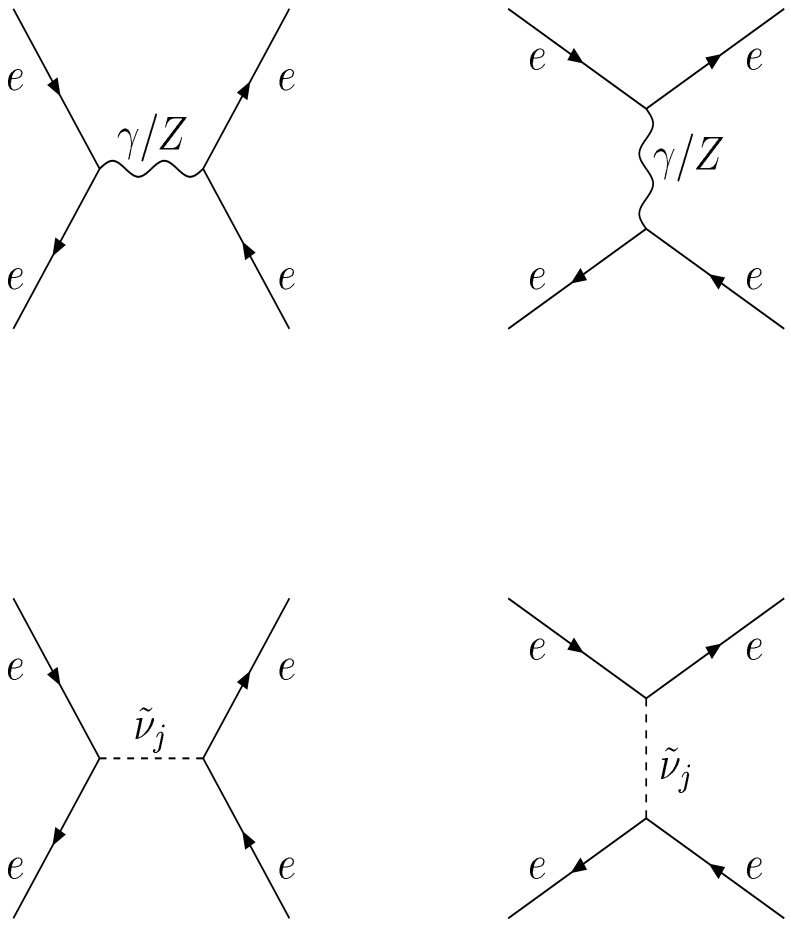

Figure 1: Feynman diagrams for the reaction $e^+e^- \rightarrow e^+e^-$, including the exchange of $\tilde{\nu}_j$ in the s– and t–channel with $\lambda_{1j1} \neq 0$.

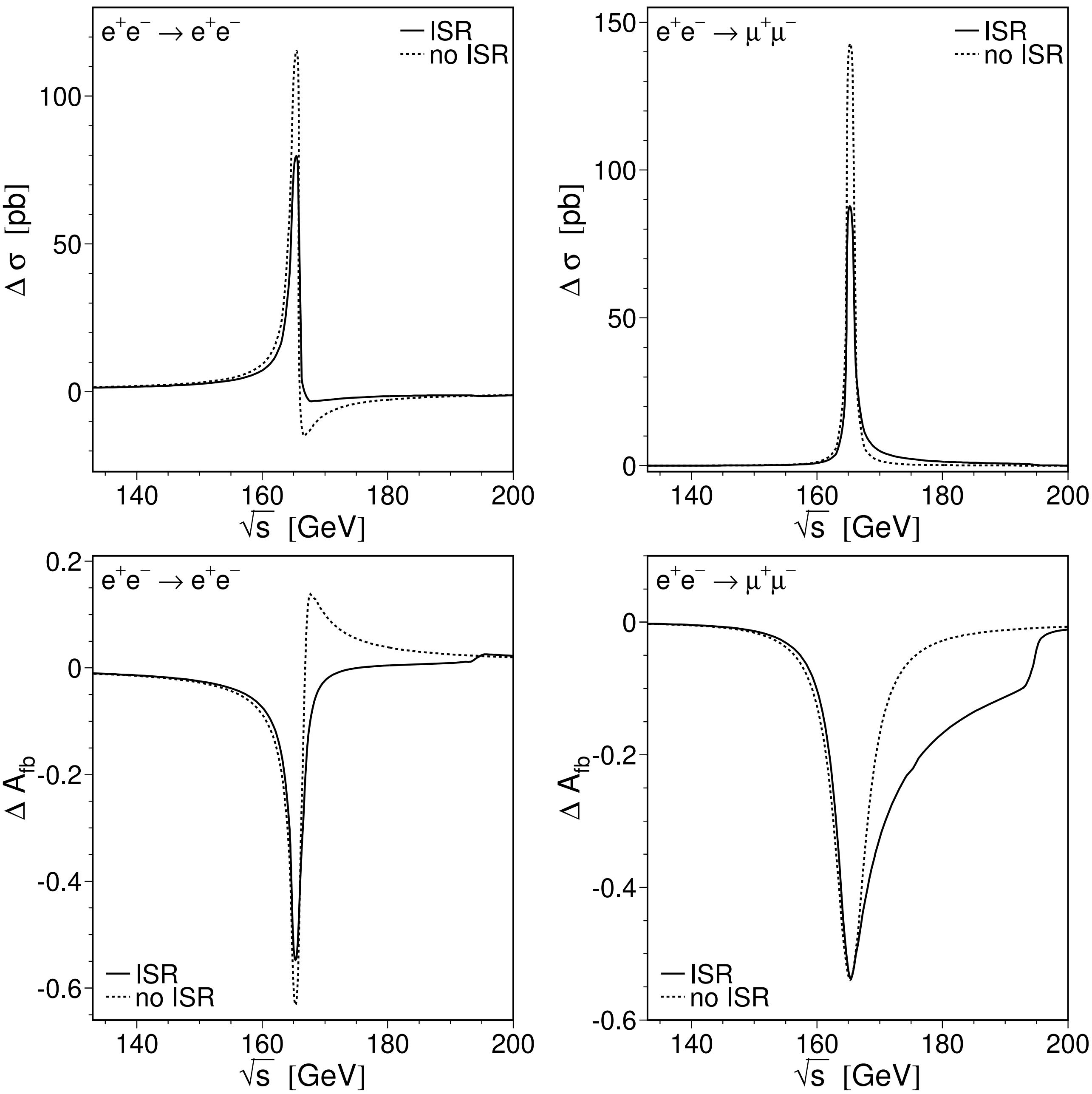

Figure 2: Deviations of the cross section, $\Delta\sigma$, and the forward–backward asymmetry, $\Delta A_{\rm fb}$ from the SM expectations due to sneutrino exchange as a function of the centre–of–mass energy: on the left for $e^+e^- \to e^+e^-$ and on the right for $e^+e^- \to \mu^+\mu^-$. The solid line shows the results with and the dashed line without inclusion of ISR. The parameter values for these calculations are $m_{\tilde{\nu}_\tau} = 165.3$ GeV, $\Gamma_{\tilde{\nu}_\tau} = 1$ GeV, $\lambda_{131} = 0.08$ and $\lambda_{232} = 0.08$.

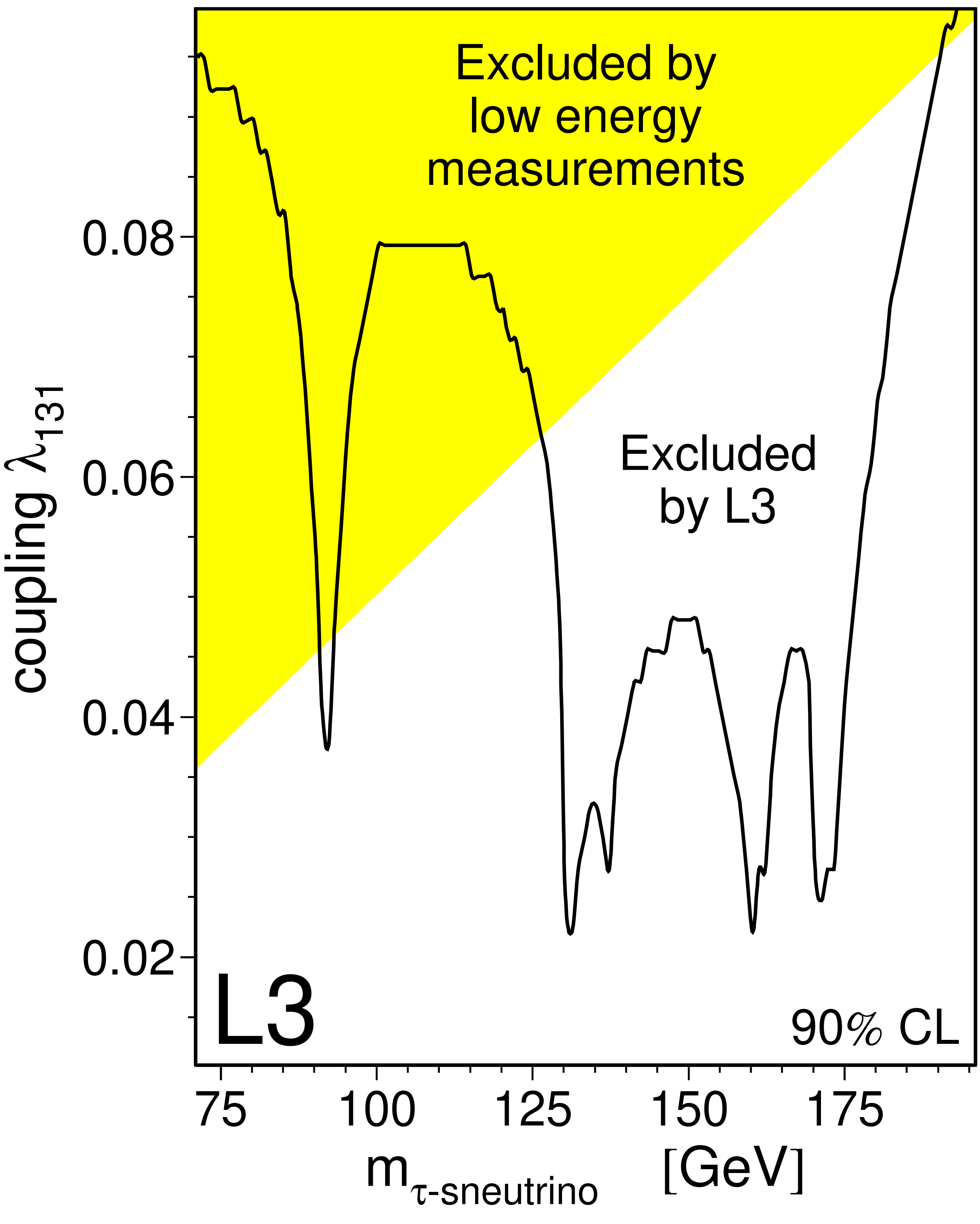

Figure 3: Upper limits on the coupling strength λ_{131} as a function of $m_{\tilde{\nu}_\tau}$ derived from the measurements of the reaction $e^+e^- \to e^+e^-$. The shaded area is excluded by lower energy measurements at 90% confidence level. The jagged curve is the 90% confidence level upper limit from this analysis.

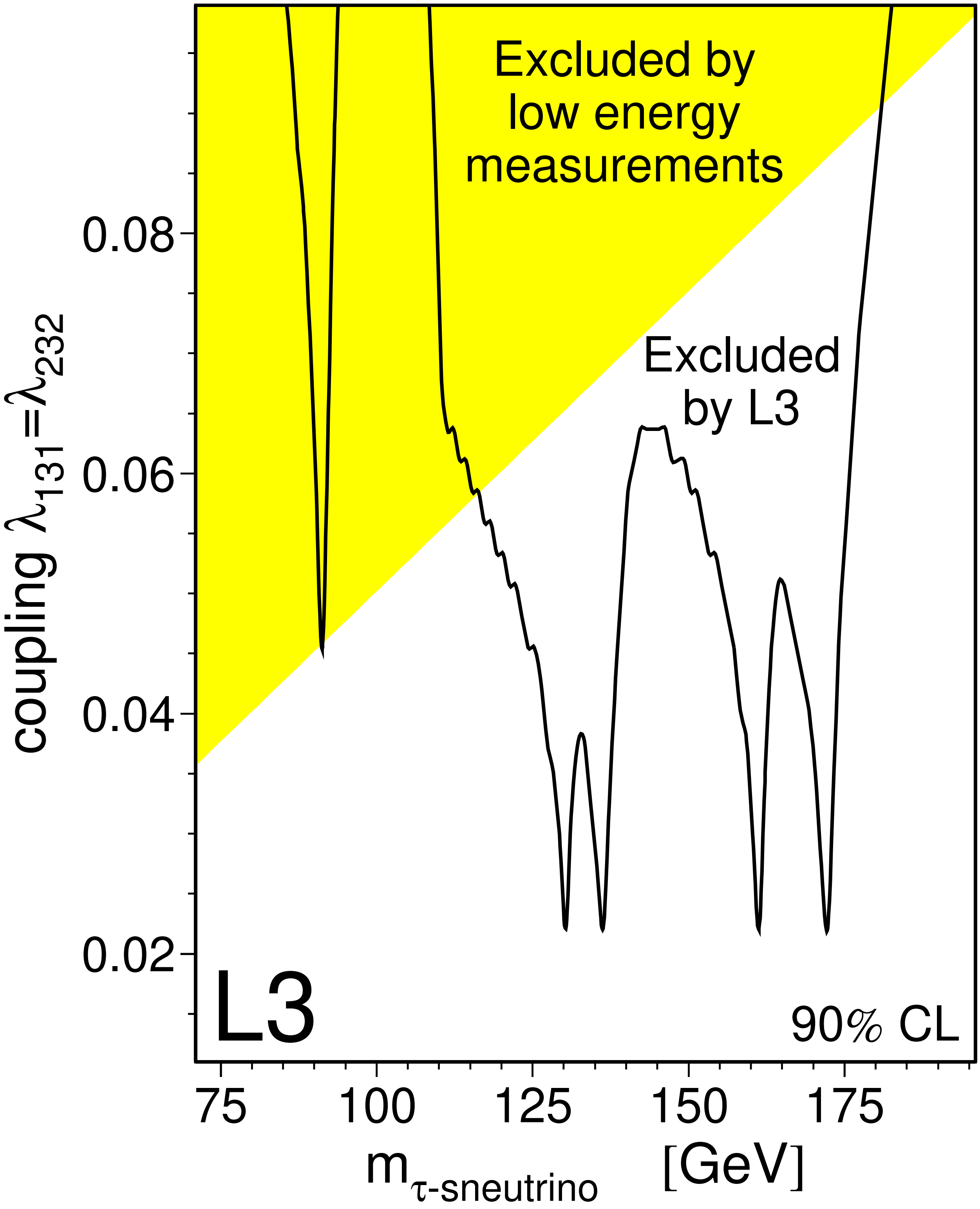

Figure 4: Upper limits on the coupling strength λ_{232} (assumed to be equal to λ_{131}) as a function of $m_{\tilde{\nu}_\tau}$ derived from the measurements of muon–pair production. The shaded area is excluded by lower energy measurements at 90% confidence level. The jagged curve is the 90% confidence level upper limit from this analysis.