How to observe $\nu_\tau N$ interactions at an extremely asymmetric e^+e^- collider

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We investigate the possibility to generate intense beams of τ neutrinos at an e^+e^- collider with very unequal beam energies. We study a practical detector concept and we estimate detection efficiencies in the presence of background. The observation of $\nu_\tau N$ interactions is feasible with the integrated luminosity of 300 fb^{-1} at the energy $E_{\text{c.m.}} \simeq m_{Z^0}$. We discuss the possibilities to reach these specifications at future linear accelerators and notice the stringent requirements set on the transverse emittance of the low-energy beam.

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Three neutrino species are known to exist [1]. The interactions of electron neutrinos (ν_e) [2] and muon neutrinos (ν_μ) [3] have been researched extensively using wideband and narrow-band neutrino beams. There are good reasons to label the third type of neutrino as the weakly interacting partner of the τ lepton (ν_τ) [4]. Fundamental questions have remained unsettled concerning the CP structure, finite masses, and mixings of neutrinos, as suggested by the solar neutrino deficit [5]. The ongoing appearance- or disappearance-type of experiments utilizing available ν_e and ν_μ beams can clarify these topics. It may appear interesting in the future to receive direct quantitative information about the τ neutrino and its interactions.

Unsuccessful searches for the reaction $\nu_\tau N \to \tau X$ have been executed in beam dump experiments [6] in which a wideband ν_τ flux results from D_s decays. Upper limits have been set to the ν_μ-ν_τ mixing in μ-neutrino experiments [7, 8], based on the nonappearance of τ final states. Among several experimental ideas, it has been recently proposed to utilize the ν_τ flux generated in decays of heavy-quark states at a future high luminosity proton-proton collider [CERN Large Hadron Collider (LHC)] [9]. The uncertainties in the production rate of τ neutrinos through hadronic intermediate states complicate these experimental approaches.

This paper introduces an alternative possibility to generate a beam of τ neutrinos and an experimental concept to observe $\nu_\tau N$ interactions. In our proposal a collimated flux of τ neutrinos results from boosted annihilations of positrons and electrons with very unequal beam energies (asymmetric collider). Asymmetric colliders are feasible [10]. Figure 1 shows the configuration of the extremely asymmetric e^+e^- collider and the τ neutrino detector. The high-energy positron beam is supplied by a storage ring, or by a linear accelerator (linac). In the latter case, the asymmetric interaction point can be attempted at a position after the main interaction point, with the precaution that the disruption of the high energy beam may prohibit refocusing. The low-energy linac provides us with an intense current of electrons in bunches which match the frequency and the beam spot of the high-energy beam.

We consider here a detector concept suitable for observing the reaction $\nu_\tau N \to \tau X$, and the charge conjugate. Events of interactions are triggered and recorded with the detector designed to observe energetic muons. These signal muons are produced in 17.8% of the τ decays $\tau \to \mu \bar{\nu}_\mu \nu_\tau$. With a long coarsely sampled iron absorber instrumented with several modules of magnetized muon spectrometers (see Fig. 1), it is possible to reconstruct muons efficiently with a sufficient resolution, $\sigma(p)/p \simeq 15\%$. The spatial resolution of detector planes in each muon spectrometer is of the same order as that in classic type of neutrino detectors ($\sigma_{x,y} = 1 - 10$ mm) [8, 11]. This type of instrument maximizes the detector density, i.e., the probability of neutrino interactions. We specify tentative detector dimensions described by the total length of 100 m (iron) with 20 muon spectrometers. The neutrino detector, which begins at the distance of 15 m from the e^+e^- interaction point, covers the polar angles in the range $5-100$ mrad and the average radius of the toroidal magnets at spectrometers is 7 m. The e^+e^- collision region is instrumented with a calorimeter and with position sensitive detectors for charged particles.

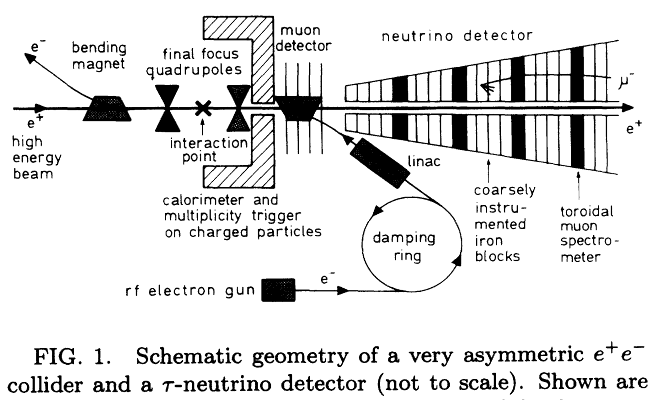

FIG. 1. Schematic geometry of a very asymmetric e^+e^- collider and a τ-neutrino detector (not to scale). Shown are the particle beams and the main components of the detectors and accelerators. A topology of a typical signal event is also drawn.

They cover a solid angle in the forward direction sufficient for triggering and identifying efficiently the multi-hadronic final states and muons.

The experimental principle is based on the favorable signal-to-background characteristics. With the exception of the channels $Z^0 \to \nu_\mu\bar{\nu}_\mu, \nu_e\bar{\nu}_e$, the background neutrinos due to annihilations are generated in hadronic and $\tau\bar{\tau}$ final states which are observable at the collision point. This part of the background can be eliminated by testing the coincidence between the event seen at the interaction point and the event seen in the neutrino detector. This is experimentally possible if the collisions of bunches are sufficiently separated in time and if the loss of signal efficiency due to multiple annihilations in a single bunch-bunch crossing over is small, which turns out to be the case in the most prominent designs discussed below. Concerning the background due to other sources, the total rate of secondary particles is low in our concept compared with the beam dump type of experiments since the noninteracted part of the high-energy beam is transported through the neutrino detector. It is also expected that the signal-like muons coming from cosmic particles or from hadronic showers of the charged- and neutral-current reactions can be reduced to sufficiently low level, analogously to ν_μ experiments [12].

Two points of center-of-mass energies are favorable for ν_τ production in terms of signal rate and background characteristics: (1) the center-of-mass energy above the $\tau\bar{\tau}$ threshold $(e^+e^- \to \tau\bar{\tau} \to \nu_\tau\bar{\nu}_\tau\, X)$,

$$E_{\text{c.m.}} = 4.25 \text{ GeV},$$

$$\sigma_{\max} = 3.5 \text{ nb};$$

(2) on the Z^0 pole $\left(e^+e^- \to Z^0 \to \nu_\tau\bar{\nu}_\tau \,, \tau\bar{\tau} \to \nu_\tau\bar{\nu}_\tau X\right)$,

$$E_{\text{c.m.}} = 91.16 \text{ GeV},$$

$$\sigma_{\max} = 4.5 \text{ nb}.$$

We notice that the first configuration can be realized by utilizing the existing or scheduled positron beams [the SLAC linac, $E_{\text{beam}} = 50$ GeV, the CERN e^+e^- collider (LEP) ring now at $E_{\text{beam}} = m_{Z^0}/2$, and $E_{\text{beam}} = 95$ GeV in phase II]. The short electron linac consists of an advanced relativistic electron source [13] and a preaccelerator which are able to produce directly intense electron bunches at suitable energies in the range $E_{\text{beam}} \lesssim 100$ MeV. However, the required luminosity $\mathcal{L} \gtrsim 10^{36}$ cm^{-2}s^{-1} is much beyond what seems to be possible at these accelerators with minor and conventional upgrades. A higher beam energy $E_{\text{beam}} \simeq 250$ GeV expected at future linear colliders produces more energetic neutrinos and a stronger collimation, and the requirement on luminosity is reduced accordingly. In Fig. 2(a) we show the energy-weighted energy spectrum of signal neutrinos and the spectrum of the background due to muon neutrinos when running this type of an extremely asymmetric $\tau\bar{\tau}$ factory.

The second configuration gains from the monochromatic neutrinos produced in the channel $Z^0 \to \nu_\tau\bar{\nu}_\tau$. A meaningful collimation is reached at beam energies $E_{\text{beam}} \gtrsim 0.5$ TeV, which are possible to reach at future linear e^+e^- colliders. This configuration is attractive from the accelerator point of view, because the energy of the short linac is in the range of few GeV, which is readily extractable from the damping rings. In Fig. 2(b) we visualize the energy-weighted energy spectrum of the signal neutrinos and of the background due to μ neutrinos. Selection criteria can be applied on the observed charged current events with muons, in order to distinguish the ν_τ signal from the background of μ neutrinos produced in Z^0 decays. We estimated the selection efficiency in a straightforward simulation study [14]

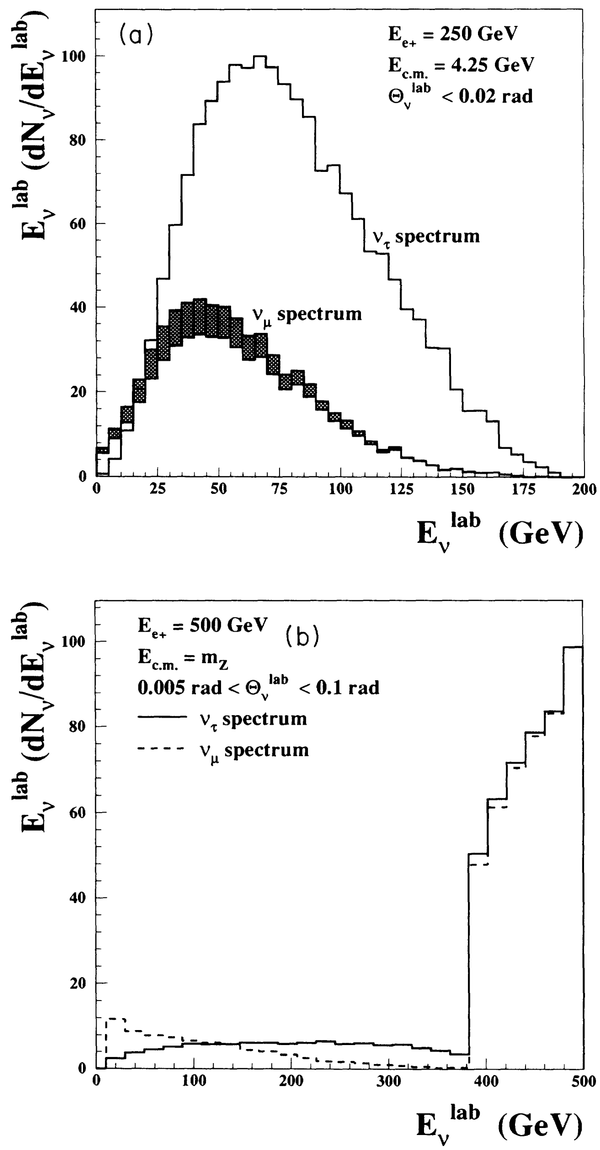

FIG. 2. The energy-weighted energy spectra of signal ν_τ and background neutrinos ν_μ for (a) the extremely asymmetric $\tau\bar{\tau}$ factory, (b) the very asymmetric Z^0 factory. θ_ν^{lab} is the polar angle of the neutrino with respect to the positron beam. The shadowed band in (a) describes the theoretical uncertainty on the ν_μ spectrum. The high energy peak in (b) comes from $Z^0 \to \nu\bar{\nu}$ decays. Neutrinos with energies less than 10 GeV are not included in (b). The absolute normalizations are arbitrary.

which describes the boosted e^+e^- annihilations, decays in flight of short-lived particles, and neutrino nucleon interactions in the detector including the smearing due to the finite momentum resolution. We assume that the multihadronic Z^0 decays can be eliminated with a high efficiency. Selection criteria analogously to Ref. [8], based on the longitudinal momentum of the muon and its scattering angle with respect to the known direction of the neutrino, allow us to select an event sample which contains more than 30% of the signal muons due to τ neutrino charged current interactions followed by the decay $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ (see Fig. 3). The muon contamination due to $\nu_\mu N \to \mu X$ interactions is less than 10 % of the selected sample. We conclude that three signal events in average are observed in the experiment in an effective year (10^7 s) if the τ-neutrino charged current interaction cross section is standard, $\sigma \simeq 0.67\times10^{-38}\ \mathrm{cm}^{-2}E_{\nu_\tau}$ /GeV, and if e^+e^- collisions take place at the average luminosity of

$$\mathcal{L} = 3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .$$

There are several designs of a linear collider with the luminosity of the order of $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ thought feasible with present technology [15]. These plans include scenarios to upgrade the machine to the center-of-mass energy of 1 TeV with a need to increase the luminosity in the nominal symmetric mode to a level closer to our asymmetric specification.

The high luminosity at the extremely asymmetric collider places great demands on the low-energy beam. At the level of elementary beam dynamics it can be seen that the transverse emittance of the intense low-energy beam must be significantly smaller than one of the high-energy beam, in order to allow for the focusing to the submicron size final focus, as designed at future linear colliders. With idealized beam optics, invariant emittances

$$\epsilon_{x,y}^{e^-} = \frac{E_{\mathrm{beam}}^{e^-}}{E_{\mathrm{beam}}^{e^+}}\epsilon_{x,y}^{e^+}$$

are needed. This condition is severe for the extremely asymmetric $\tau\bar{\tau}$ factory where the ratio of beam energies is of the order of $10^3 - 10^4$. The case of the asymmetric Z^0 factory looks more feasible in this respect, as the ratio of beam energies is of the order of a hundred and the electron-beam energy is in the practical range of optimal damping. For example, the parameters of the high-energy linac (see Tigner in Ref. [15]) with a moderate size final focus and the damping-ring design aiming at ultra low emittances [16] approach our specifications. We notice that the planned vertical emittance is three orders of magnitude smaller than the one reached at the SLAC Linear Collider (SLC) damping ring. The purpose of having electrons in the low-energy beam, injected possibly from a low-emittance electron gun, is to make the damping task easier. Investigations of the beam dynamics, technical feasibility, and further optimization of experimental aspects of the extremely asymmetric collider will be presented elsewhere [17].

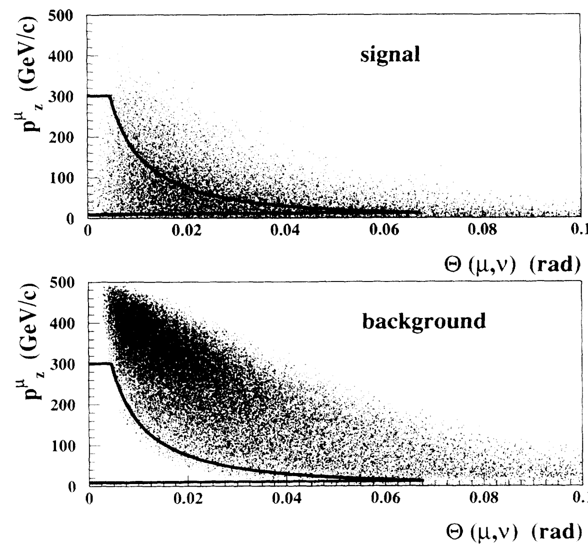

FIG. 3. Probability distributions of the muon longitudinal momenta p_z^μ vs. the muon scattering angle $\theta(\mu,\nu)$ from (a) the reaction $\nu_\tau N \to \tau X \to \mu X'$ and (b) the reaction $\nu_\mu N \to \mu X$. Contributions due to the antineutrino reactions are included with their appropriate weights. The areas inside the contours show the selected sample. The absolute normalization of density is arbitrary.

In conclusion, ν_τ beams generated in luminous asymmetric e^+e^- collisions may be of experimental interest. The required luminosity is not far beyond the design luminosities of future 1-TeV linear colliders. We point out that extraordinarily low-emittance electron beams are needed. The event rate increases with higher positron beam energies and furthermore the accelerator concept poses no fiducial constraints in extending the detector volume. The detector efficiency is expected to improve by instrumenting the iron absorber for an adequate energy measurement of the electromagnetic and hadronic showers in νN interactions. This option opens us a novel possibility to study the final states of neutral-current interactions of all known neutrino species with kinematic constraints given by the monochromatic neutrino beam from prompt Z^0 decays.

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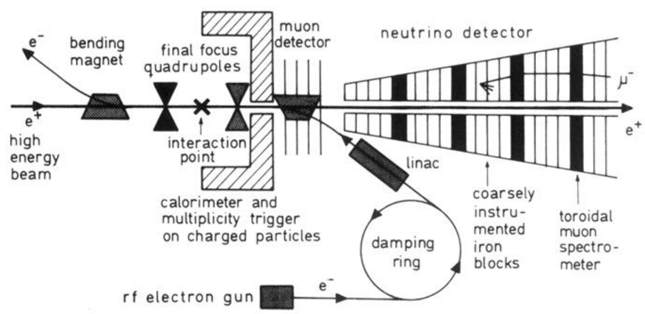

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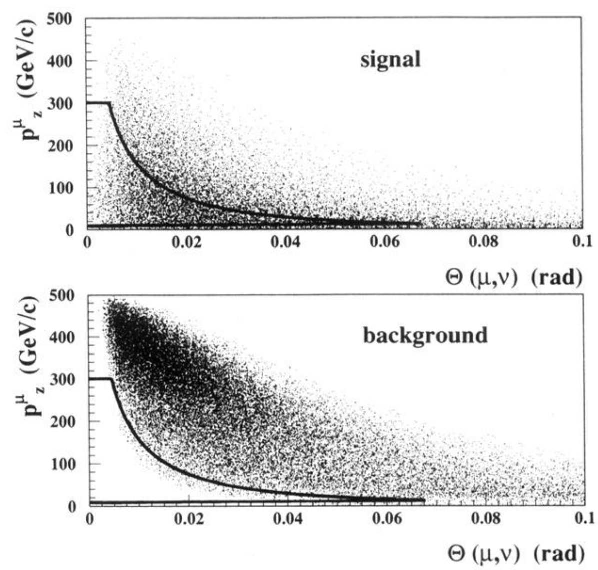

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