M.C. ESCHER "Anneaux concentriques"

NEUTRINO PHYSICS AT LHC/SSC

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ABSTRACT

Neutrinos will be produced at LHC/SSC and in particular ν_τ beams will become available. We discuss the possibilities to study the interaction properties of the ν_τ, but also the exciting search for new heavy neutrinos which may be detected by their decays. This note will not give a comprehensive programme of neutrino physics at the future high-energy colliders since no formal proposal exists yet. It will rather describe some personal ideas which do not pretend to be complete.

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1. INTRODUCTION

When talking of a programme of physics for the future, one is bound to address the problems of physics within the Standard Model and physics beyond the Standard Model. This is also true with neutrinos, and the various topics which can be thought of are listed below:

– ν_e and ν_μ deep inelastic scattering. With high enough statistics, it is possible to study neutrino interactions in a new domain of energies up to several TeV. In particular there may be interest in ν_e interactions which have not been well measured so far at accelerators.

– ν_τ discovery. One must again stress that the ν_τ has never been seen experimentally and its detection remains a must to complete the Standard Model picture of our world.

– ν_τ study. The difference with the previous topic is statistics. Here we would like to accumulate 100 times more events, to be able to analyse in some detail the properties of ν_τ interactions.

– ν_τ oscillations.

– New interactions of the ν_τ, particularly possible anomalous electromagnetic interactions.

– ν_τ decays.

– Search for new particles, in particular very heavy neutrinos.

At this point a personal prejudice is in order: the new colliders will be built to discover new phenomena. For the first time they will produce ν_τ beams of detectable intensity. I will assume that the ν_τ, because it is the last and the most unknown of the classical neutrinos, may be an intermediary to the physics beyond the three generations of today. Thus this paper will concentrate on ν_τ properties, focusing especially on exotic phenomena which may arise beyond the Standard Model frame.

2. NEUTRINO BEAMS AT LHC/SSC

2.1 Neutrino production

Neutrinos always come at the end of decay chains. LHC will accelerate protons to 8 TeV, SSC to 20 TeV with a step at 2 TeV, using a High Energy Booster (HEB). Both machines offer a multiple choice of neutrino sources.

One can think of generating neutrinos from 2-TeV, 8-TeV or 20-TeV proton beams hitting a target. A neutrino beam requires a dedicated ejected beam and an evacuated tunnel, this is necessary to fulfil the programme of ν_e and ν_μ physics. We will not discuss further this possibility.

Another option consists in beam dumps in which the protons are absorbed in a block of heavy material. Finally one can take advantage of the collider mode. As first pointed out in [1], pp collisions produce neutrino beams. This option is very favourable since a neutrino experiment can be run for free, in parallel with a generic pp experiment. This is also the option with the highest c.m. energy which is an essential condition for producing heavy objects, in particular top. This is relevant for the search for new heavy neutrinos.

We will concentrate mainly on this last option of neutrino sources. In such a mode π and K are sterile: because of their high energy they are stopped before they decay, so that neutrinos come predominantly from decays of heavy quarks. The beams are very energetic and of 'beam-dump quality' with a ν_τ flux as high as 10% of ν_e and ν_μ fluxes.

2.2 ν_τ flux at the HEB

Before discussing the collider mode, let us consider the HEB option at SSC. A 2-TeV proton beam will be available one year before completion of the SSC. It could be used to discover a ν_τ signal (if the ν_τ is not found before in oscillation searches). A calculation adapted from a UNK estimate [2] shows that a 3-ton detector (mass of the present NOMAD target) positioned 500 m away from the dump would register about 1000 ν_τ interactions in an exposure of 10^{19} protons on target. As emphasized below, NOMAD is able to reconstruct a large part of these events in the different τ decay modes with a background typically of order 5% of the signal. This is enough to check beyond doubt the expected behaviour of the ν_τ. So the question arises: is the discovery of the ν_τ worth a dedicated HEB run taking advantage of an existing detector?

2.3 ν_τ in collider mode

The collider mode allows a longer-term opportunity to study neutrinos. The ν_τ production rate has recently been computed [3]. At the present level of accuracy, the two accelerators give similar results provided that LHC is operated at 10^{34} cm^{-2} s^{-1}, and SSC at 10^{33} cm^{-2} s^{-1}. The main ν_τ contribution comes from the charm meson decay $D_s \to \tau\, \nu_\tau$. A 4% branching ratio is assumed. From this source alone, the fluxes corresponding to 1 year (10^7 s) of running are:

- some 10^{11} ν_τ of average energy 500–800 GeV are produced in a 2-mrad wide forward cone,
- some 10^{12} ν_τ of average energy 100–200 GeV are produced in a 20-mrad wide forward cone,
- up to 10^{13} ν_τ of lower energy are produced in a 200-mrad forward cone. More accurate estimates are being calculated.

One can also expect some contribution from beauty. It is small in a very forward narrow cone, but the p_T of B decays being high, it becomes important at larger angles. Beauty production is about 10% of charm production. But this is compensated by the branching ratio of $B \to \nu_\tau X$ which is around 10% for all B meson types, while the charm contribution comes from D_s only with a 4% branching ratio. Thus beauty will also contribute some 10^{13} ν_τ in a 200-mrad cone.

The contribution from top is more difficult to estimate. It could amount to 10^9 ν_τ if the top mass is around 130 GeV. Finally W bosons may themselves produce up to 10^{10} ν_τ.

3. TESTS OF THE STANDARD MODEL

As already mentioned in the introduction, this paper will be limited to the properties of ν_τ. The study of ν_e and ν_μ interactions requires further consideration and will not be developed here.

3.1 ν_τ detection

For the first time ν_τ beams of high intensity will be available. But the difficulty of ν_τ detection remains.

When interacting, the ν_τ creates a τ. Because of the Lorentz boost, the produced τ travels 1–2 cm. This is 10 times longer than at CERN or Fermilab energies, but the events being more collimated, the impact parameter which is characteristic of τ decays remains very small: 100–200 μm. Several techniques have been considered to extract a ν_τ signal, especially in the frame of the ν_μ to ν_τ oscillation search.

Detection of a kink

An interesting technique [4] consists in using scintillating fibres of very small diameter (20–30 μm). Figure 1 shows a clean example of τ production. But a modest-sized experiment would require some 10^9 fibres of at least one metre length and the technology seems still quite far off.

Detection of a secondary vertex

A liquid argon TPC [5] offers a realistic technique to build a several hundred ton target. The detection of the τ is limited to the decay channel $\tau \to 3\pi\ \nu_\tau$, which is identified by a jump in collected ionization by 2 units of mip. Figure 2 shows such a jump. The technique is relatively slow and the detector would have to be well shielded.

Detection by kinematics

This is the method used by NOMAD [6] for the oscillation search. Figure 3 shows the scatter plot of two angles defined in the plane transverse to the neutrino direction: one between the hadron jet and the τ remnant (for example e or μ), the other between the hadron jet and the missing p_T. A cut allows one to retain a large fraction of ν_τ events while rejecting most of the ν_μ and ν_e events. With this method one hopes to detect the appearance of a ν_τ signal in a ν_μ beam down to some 10^{-4} probability. At LHC/SSC we anticipate a ν_τ flux as high as 10% of the ν_μ or ν_e

fluxes. This is a much more comfortable situation. Besides, the angles cut works better at higher energies. The NOMAD technique would be completely satisfactory, but it is based on a very low density target and the event rate proves to be very small. This may be enough for ν_τ discovery but not for a systematic study of ν_τ interactions.

3.2 ν_τ physics

The ν_τ will probably be the last fundamental fermion to be discovered. Its detection remains important. We have already mentioned the real possibility offered by the HEB. For the collider mode, the fluxes are small: typically one can expect of the order of 1000 charge-current ν_τ interactions in a 50-ton detector at 500 m from the collision point, subtending a 2-mrad wide angle, during a one year run at the hoped-for luminosities.

To study the properties of the ν_τ interactions one would need much more statistics (100 times). In principle this could be achieved with a 5000-ton liquid argon TPC. But such a target requires a 1-km-long vessel, and without a magnet the method is limited to the channel $\tau \rightarrow 3\pi\, \nu_\tau$.

Another possibility consists in a NOMAD type detector but of much higher density. For example we studied a target consisting of a sandwich of uranium, scintillator and drift chambers. Uranium is chosen because it gives the maximum number of radiation lengths in one interaction length. With plates $2X^0$ thick the average density may reach 6 g/cm^3. Electromagnetic showers are absorbed in 20 cm, so that the charged particles can be well measured after they have exited the shower. The neutral energy is measured by calorimetry, and its direction is assumed to coincide with the direction of the charged energy. Preliminary Monte Carlo results show that a simple choice of cuts allows one to achieve a rejection against ν_μ events of 2×10^{-3} for a 30% acceptance of ν_τ events.

With a total statistics of 100 000 events, one would be left with about 7000 in the channel $\tau \rightarrow \mu\, \nu\, \nu$, 5000 in $\tau \rightarrow 3\pi\, \nu$... with a background as high as 20% of the signal. But such a statistics still requires a 200-m-long target inside a magnet!

This exercise shows how difficult it will be to study ν_τ interactions at LHC/SSC. A dedicated beam dump of TeV protons seems more efficient.

4. BEYOND THE STANDARD MODEL

The hope remains that the ν_τ will exhibit properties related to mass or mixing which go beyond the Standard Model. Effects can be looked for in oscillation searches but also in anomalous electromagnetic interactions or decay processes.

4.1 Oscillations

This is the golden method to search for massive neutrinos at accelerators, but the situation here is not very favourable.

Oscillation $\nu_\tau \to \nu_e$ *or* ν_μ

Barring large CP violation, these channels test the same parameters as the reversed channels: ν_e or $\nu_\mu \to \nu_\tau$. A large effort is being made to push the corresponding $\sin^2 2\Theta$ down to 10^{-4} for the region of $\delta m^2 > 1$ eV^2. It is impossible to do better at LHC/SSC where, to start with, the initial beam will be very contaminated (10 times more ν_μ or ν_e than ν_τ).

Oscillation $\nu_\tau \to \bar{\nu}_\tau$

In some models there is the possibility of neutrino antineutrino oscillations. Here again the search is almost impossible since the initial beam contains as many $\bar{\nu}_\tau$ as ν_τ.

Oscillation $\nu_\tau \to \nu_4$

ν_4 is a 4th neutrino which for some reason does not couple to the Z^0. Having no prejudice concerning the ν_4 signature, one has to search for the disappearance of the initial ν_τ flux. This is better done with two detectors. The nearest one can be positioned for instance at 500 m from the production point. To reach the level of $\delta m^2 = 1$ eV^2, the far detector has to be located at 10 km. At such a distance one expects about 30 events in a 1000-ton detector, intelligent enough to extract efficiently the ν_τ signal. Again this seems a very difficult challenge.

4.2 ν_τ magnetic moment

Magnetic moments give anomalous electromagnetic interactions. In particular they contribute to ν e scattering, giving a signal of isolated electrons on top of the electroweak cross-section. This contribution concentrates at low energies.

Such a search would necessitate a detector able to identify single electrons down to the smallest energy. A NOMAD type detector is able to reconstruct electrons down to 100 MeV. With a 3-ton fiducial target covering a 2-mrad forward cone, it would be possible to reach down to a few 10^{-9} Bohr magneton, a two orders of magnitude improvement on the present limit [7].

4.3 ν_τ decays

The search for neutrino decays is complementary to the search for oscillations: it also tests mixings between neutrinos, but it applies to much larger masses.

The present limit on $m(\nu_\tau)$ is 31 MeV. If the mass is larger than 1 MeV, the ν_τ may decay into $e^+ e^- \nu_e$, as shown by the graph of Fig. 4. The experimental signature is very clean: a V^0 springs from nothing visible.

The lifetime of such a process is:

$$\tau = 2.8 \times 10^4 \, 1/(m^5)/(U_{\tau e}{}^2) \text{ sec}$$

where m (in MeV) is the mass of the decaying neutrino and $U_{\tau e}$ its mixing with the electron. This is the same Kobayashi–Maskawa angle which appears in oscillations, but when masses are large, an incoherent admixture of states propagating independently is produced. With the expected ν_τ flux one can achieve the limit:

$$(U_{\tau e})^2 < 10^4/m^6$$

in a 10-m-long decay volume covering a 200-mrad forward cone. The result is shown in Fig. 5. It improves by two orders of magnitude the present limit [8].

4.4 Search for new heavy neutrinos

The see-saw model gives a plausible explanation for the smallness of the known neutrino masses. This model predicts the existence of three heavy right-handed Majorana neutrinos accompanying the three light neutrinos. In this scenario, the weak eigenstates ν_e ν_μ and ν_τ are superposition of six mass eigenstates, three of them being light and three heavy. The hope is that among the physical neutrinos, the ν_τ will be the one to display the largest contribution of high mass component.

If the ν_τ mixes with a heavy state ν_H, any ν_τ beam will exhibit a contribution of ν_H at the level $U_{\tau H}{}^2$. By virtue of the same coupling, ν_H will subsequently decay into τ and W. This is shown in Fig. 6. So the search for ν_H goes as follows: in a ν_τ beam one looks for decay patterns in vacuum exhibiting the characteristic decay branching fractions of the τ and the W.

As was discussed before, ν_τ can be produced from charm, beauty, top or W. Each source will open a different range of accessible ν_H masses: for example top will allow the production of neutrinos with masses as high as 100 GeV. Below 2 GeV the ν_H cannot decay into a τ and the mixing which is tested is the product $U_{\tau H} U_{H\mu}$, but above 2 GeV the relevant mixing is $U_{\tau H}{}^2$. With the flux estimates discussed previously one could reach the limits shown in Fig. 7. This is obtained in a simple detector appended on a generic pp experiment and consisting of a decay volume instrumented with a few drift chamber planes and ending with an electromagnetic calorimeter and a muon filter. The signature is very clean and the apparatus consists in a cheap add-on to the mammoth experiments being envisaged.

This decay detector can also be used to look for any new particle (supersymmetry?) produced in the pp collisions and subsequently decaying with long enough lifetimes. Figure 8 shows the region of production cross-section vs. lifetime which could be explored in such a search.

5. CONCLUSION

This paper summarizes what could be a programme of neutrino physics at the new high-energy colliders. The main interest stems from the large percentage of ν_τ in the available beams.

Unfortunately, the tests of the Standard Model involving the ν_τ look difficult because of the too-small fluxes. The technique for a very large target able to reconstruct with high efficiency ν_τ events characterized by a short-lived τ does not exist yet. One can easily think of an experiment to discover the ν_τ by detecting some 100 ν_τ interactions, but a much higher statistics poses a technological challenge which does not seem commensurate with the interest of the measurement, at least as guessed today.

On the other hand, a search programme exists which may result in surprises. One possibility which has been emphasized here consists in looking for heavy neutrinos (possibly right-handed Majorana neutrinos) which would mix with ν_τ. They would show up in a simple detector covering a forward region of a pp collision point, and able to reconstruct various decay configurations.

It is to be stressed that such a search opens a completely new domain: for the first time one can look for heavy neutrinos mixing with the τ at tiny levels, in an extended mass region. The odds are not completely unfavourable for a major discovery.

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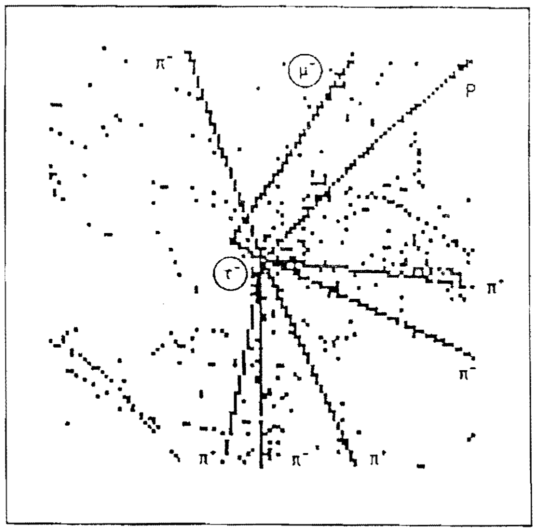
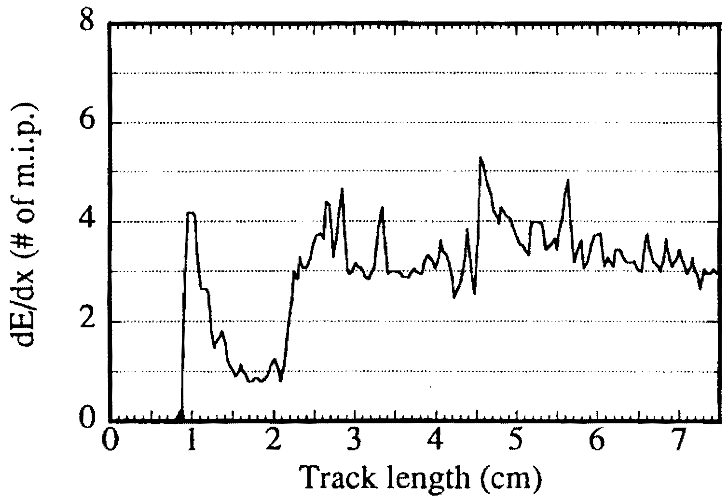


Figure 1: Example of a ν_τ event as seen in a target made of thin longitudinal fibres



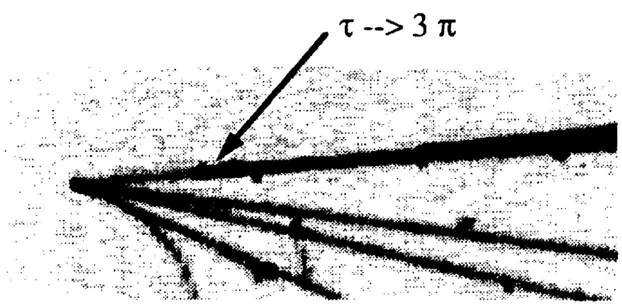


Figure 2: Pulse-height recorded on a sense wire of a liquid argon TPC for the decay $\tau^- \to \nu_\tau \pi^- \pi^- \pi^+$

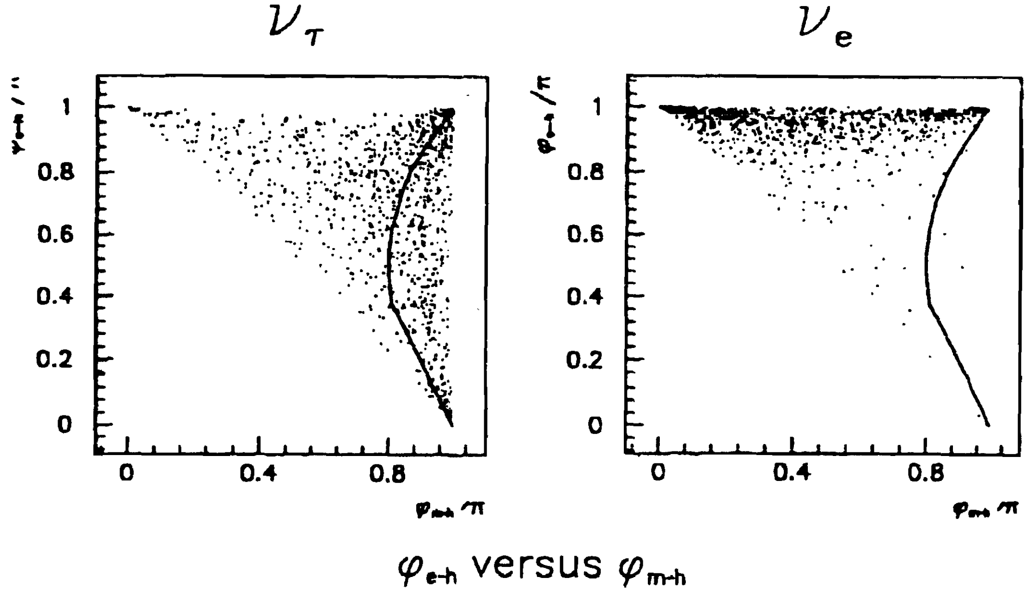


Figure 3: Scatter plot of two angles defined in the text for ν_τ and ν_e interactions respectively

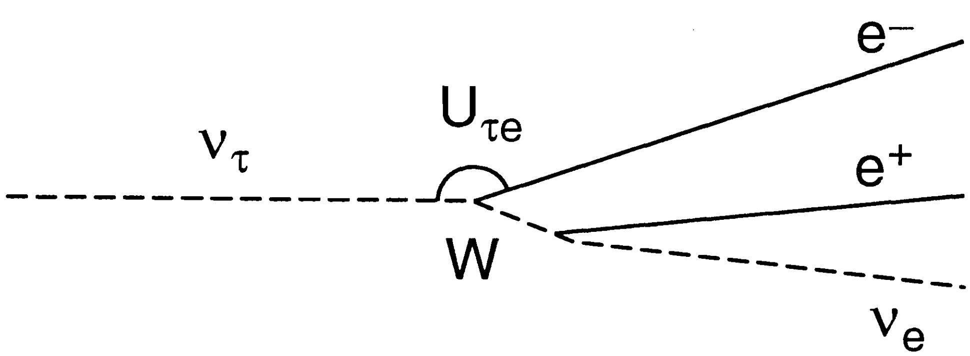


Figure 4: Graph representing the decay $\nu_\tau \rightarrow e^+ e^- \nu_e$

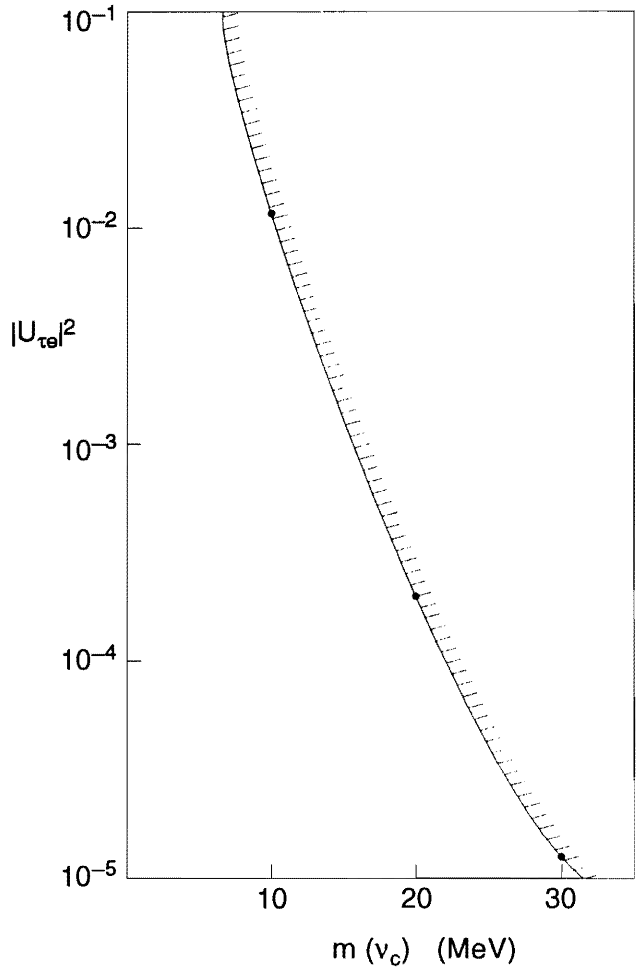


Figure 5: Achievable limits in the mixing between τ and e

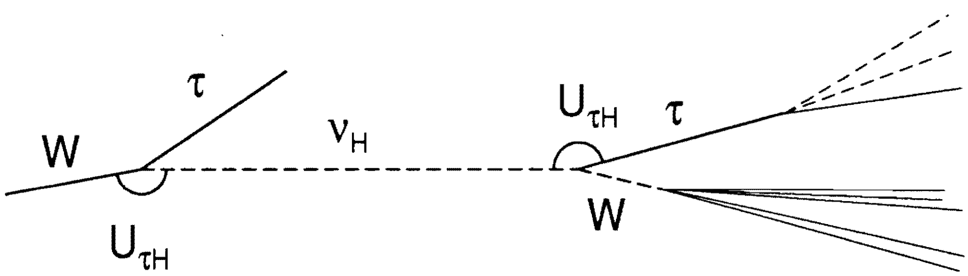


Figure 6: Graph explaining the search for ν_H

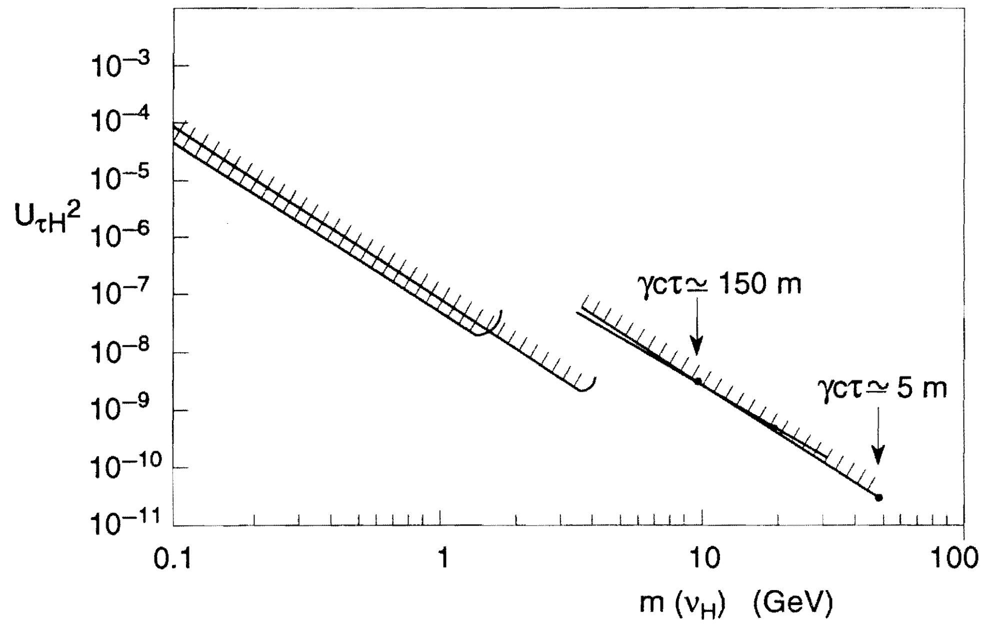


Figure 7: Limits on the mixing of a heavy neutrino with τ as a function of the neutrino mass.

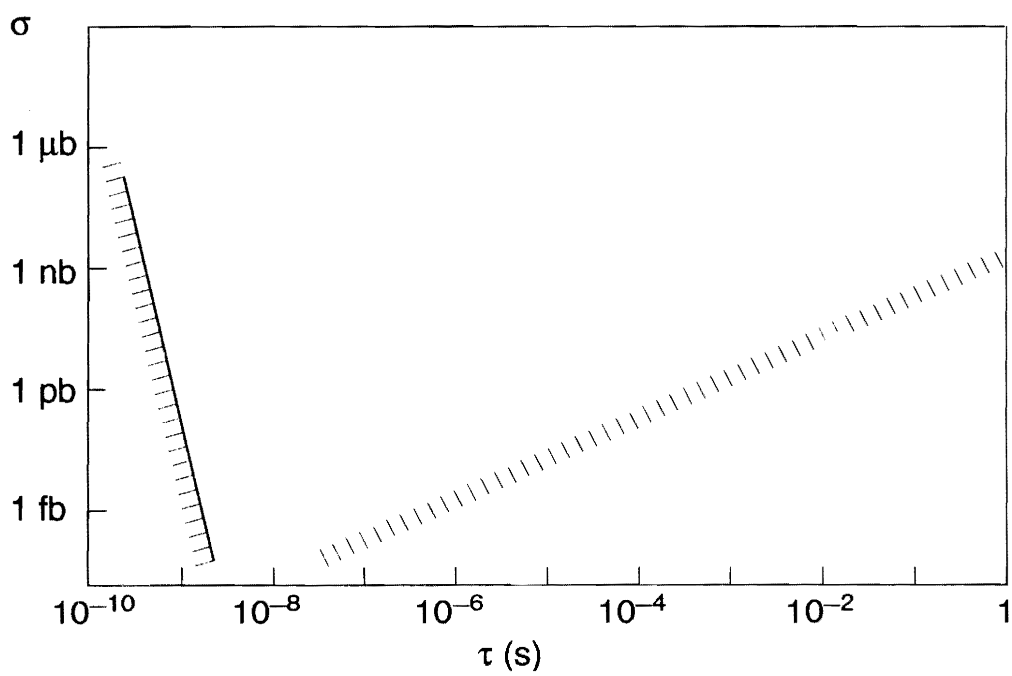


Figure 8: Exclusion plot in cross-section vs. lifetime which could be covered by a decay search at LHC/SSC for a 100-GeV object