Chapter 6

Long Baseline Neutrino Oscillation Search

Experimental results on neutrino oscillations are usually presented assuming oscillations between two neutrino flavors, as 90% confidence level excluded oscillation regions in a plot of $\Delta \mathrm{m}^2 = \mathrm{m}^2_{\nu i} - \mathrm{m}^2_{\nu j}$ versus $\sin^2 2\theta$. In the two flavour oscillation approximation the oscillation probability may be written as

$$P = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E}\right) \tag{6.1}$$

where L is the distance from the neutrino source to the detector in Km, E is the neutrino energy in GeV and Δm^2 is the mass difference in eV^2.

The apparatus can detect both atmospheric neutrinos and neutrino beam interactions. The direction allows an efficient event identification which can possibly be improved by the timing of the beam spill . Moreover, it will be possible to take data on atmospheric neutrino interactions during runs with the long baseline neutrino beam.

In the following we discuss the sensitivity of the $N^O E$ experiment in the search for long baseline neutrino oscillations. The sensitivity to atmospheric neutrino oscillations will be discussed in chapter 7.

6.1 Oscillation Searches

The $N^O E$ detector can perform several different oscillation searches based on different oscillation signatures (see sect. 3.1.1) In the following sections two different kind of searches will be examined:

- $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillation searches based on a statistical muon deficit in the apparatus.
- direct ν_τ appearance searches based on kinematical τ decay signatures.
- direct ν_e appearance search, as an excess of electron events.

To perform an appearance oscillation search, we must be able to tag the appearance of ν_e or ν_τ out of the bulk of ν_μ events.

The first and simpler search, based on the measure of the ratio $\frac{no\mu}{\mu}$ of the events without muons to the events with muons will be described in details in § 6.2.

In the CERN ν_μ beam the expected ν_e and ν_τ contamination are of the order or smaller than 10^{-2} and 10^{-7} respectively. These figures allow to search for oscillations by looking at ν_e and ν_τ appearance.

The second method is more strictly an appearance search, it requires a detailed event reconstruction that can be achieved by a high granularity detector and will be described in § 6.3.

As shown in sect. 3.1.1 the design choice of the NOE detector (high granularity on a moderate mass detector) leads to the possibility of performing independently the two searches discussed above.

With the set up described in Chap. 3 a fiducial mass of ~ 4 Kton acting as target and detector can be considered. With this mass and the beam characteristics described in sec. 2.1 a total number of ~ 15000 ν_μ CC interactions can be observed in a few years.

To fix numbers, in the following sections all the considerations will refer for reference to 15000 ν_μ CC interactions.

If no significant appearance signal is observed, we can set limits to the oscillation probability of ν_μ. This probability can then be converted into a $\Delta m^2 - \sin^2 2\theta$ 90% confidence level contour using eq. 6.1.

The experimental sensitivity is determined by the background rate, the ν_μ interaction rate and by the value of L/E.

6.2 Statistical Searches

In the ideal case of a pure ν_μ beam and in absence of oscillations, there would be two classes of events

- ν_μ Charged Current interactions, characterized by the presence of the muon track

- ν_μ Neutral Current interactions, where the muon track is absent

In the case of a pure beam, contributions to these classes by different neutrino flavors would signal neutrino oscillations.

In real cases there are contributions to beam contamination (mainly electron neutrinos) that constitute the background of the experiment.

Neither Neutral nor Charged Current ν_e interactions produce muons, so the presence of electron neutrinos in the beam, either due to beam contamination or to $\nu_\mu \rightarrow \nu_e$ oscillations will enrich the sample of events without muons among the produced secondaries.

In case of $\nu_\mu \rightarrow \nu_\tau$ oscillations, only a small fraction of the ν_τ charged current interactions produces muons: tau neutrino charged current events, where the τ decays into hadrons or an electron, will look like neutral current ν_μ events in the apparatus; but in addition to the usual hadron production at the vertex, a substantial amount of hadronic energy will be added to the event from the τ decay.

This leads to investigate appearance of ν_τ and ν_e as a changing of the ratio: $\frac{no\mu\ evts}{\mu\ evts}$ with respect to expectations. In this kind of search, based on the measure of the ratio $\frac{no\mu}{\mu}$, or apparent 'NC/CC', the signatures of the ν_e and ν_τ appearance are thus an increase of apparent neutral current 'NC' and a decrease of apparent charged currents 'CC'. Such comparison has to be performed independently for the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ channels.

Detailed event reconstruction, which could be of help to enrich the data sample recovering the low energy muons, is not however essential in this 'statistical' method which is rather insensitive to detector granularity, calorimetric and particle identification capabilities.

6.2.1 ν_μ Event Recognition.

The identification of ν_μ CC events is based on the search of the long muon track in the event. The definition of this signal is achieved by imposing a cut on the penetration of the muons in the detector. Taking into account that 10 BCE planes are containing the major part of the hadronic shower (Fig. 5.5) a cut at 1.5 $\sim$ 2 Gev of muon energy, corresponding to more than 15 BCE, seems to be adequate. Considering the muon energy distribution in ν_μ CC interaction and a conservative average energy of the ν_μ beam of 15 GeV, such a cut saves more than 90% of the signal. A very small background originated by pions on the high end tail of the energy distribution, produced in neutral current, which do not interact and pass the cut (punch thru, few %) can be reduced using either a π, K decay timing.

Taking this into account one expects a total efficiency for muon identification not smaller than 90%.

6.2.2 Statistical Search of $\nu_\mu \to \nu_e$ Oscillations

In the hypothesis of $\nu_\mu \to \nu_e$ oscillations, taking into account that in the energy range of interest the ν_e and ν_μ cross sections (both charged and neutral current interactions) are approximately equal:

$$\sigma_{C\mu} \sim \sigma_{Ce} \sim \sigma_C \tag{6.2}$$

$$\sigma_{N\mu} \sim \sigma_{Ne} \sim \sigma_N \tag{6.3}$$

the $\frac{no\mu}{\mu}$ event ratio measured in the N^OE experiment can be written as

$$\frac{no\mu}{\mu} = R_{obs} = \frac{(1-P)\sigma_N + P(\sigma_N + \sigma_C) + \varepsilon(\sigma_N + \sigma_C)}{(1-P)\sigma_C} \tag{6.4}$$

where P is the oscillation probability and ε is the ratio of ν_e to ν_μ in the beam.

The first term is due to neutral current interactions of the surviving muons at the detector, the second gives the contribution to the events without muons from neutrinos produced as ν_μ at the source and that oscillated to ν_e and the latter accounts for ν_e beam contamination.

By defining $R_{th} = \sigma_N/\sigma_C$ we get

$$P = \frac{R_{obs} - R_{th} - \varepsilon(R_{th}+1)}{1 + R_{obs}} \tag{6.5}$$

From this probability value and its error ΔP obtained assuming statistical errors on R_{obs} and neglecting the error on R_{th}, the 90% excluded region contour can be drawn.

The ability to recognize the muon in the N^OE detector has been discussed in the previous section. Assuming a 90% efficiency, the contour of the 90% confidence level excluded region is reported in Fig. 6.1.

6.2.3 Statistical Search of $\nu_\mu \to \nu_\tau$ Oscillations

In the case of $\nu_\mu \to \nu_\tau$ oscillations, using the same approximations and notation as above we have

$$\frac{no\mu}{\mu} = R_{obs} = \frac{(1-P)\sigma_N + P\sigma_N + P\eta\sigma_C(1-B) + \varepsilon(\sigma_N + \sigma_C)}{(1-P)\sigma_C + P\eta\sigma_C B} \tag{6.6}$$

where P is the oscillation probability, ε is the ratio of ν_e to ν_μ in the beam, B is the branching ratio of the τ decay in muon plus neutrinos and η is a kinematical suppression factor due to the τ mass:

$$\eta = \frac{\int \Phi_\nu(E)\sigma_{\nu_\tau}(E)dE}{\int \Phi_\nu(E)\sigma_{\nu_\mu}(E)dE} \tag{6.7}$$

In our case, with the beam of ref. [1] $\eta \sim 0.24$.

As above the first term is due to neutral current interactions of surviving muons at the detector, the second to neutral current induced by neutrino tau, the third gives the hadronic contribution coming from $\nu_\tau \to \tau$ decays, and the latter takes into account the ν_e beam contamination.

With the same definitions as above we have

$$P = \frac{R_{obs} - R_{th} - \varepsilon(R_{th}+1)}{R_{obs}(1-\eta B) + \eta(1-B)} \tag{6.8}$$

As in the previous case this formula can be used to draw the 90% confidence level excluded region reported in Fig. 6.1.

It is worth noting that, due to the statistical nature of this search, the sensitivity in $\sin^2 2\theta$ parameter increases as the square root of the number of events, and hence the square root of the detector mass. Doubling the detector mass, the limit in $\sin^2 2\theta$ improves only by a factor 1.4.

6.3 Direct ν_τ Appearance Searches

An independent confirmation of oscillation is provided by direct appearance measurements. Such measurements are the ultimate goal of the NOE experiment and require excellent detector performances: good calorimetric features together with tracking and event topology reconstruction capabilities are needed to tag neutrino interactions on a event reconstruction basis.

Our choice to have a high granularity - moderate mass detector, compensates the loss of statistics with the ability to perform measurements in specific τ decay channels, either hadronic or leptonic.

The possibility of identifying τ decay channels based both on topology and on the energy distributions of produced secondaries, is presently under study.

In the following we analyze the purely leptonic decay channels.

At typical beam energies the τ track length before decay is of the order of 1 mm, too short to be observed in the NOE detector even pushing granularity

and readout resolution at extreme values.

The τ detection signature must rely on kinematical analysis. In the leptonic τ decay channels the event would be produced by the reaction

$$\nu_\tau + N \rightarrow \tau + X \tag{6.9}$$

and by the subsequent decay

$$\tau \rightarrow \ell + \nu + \bar{\nu} \qquad \ell = \mu, e \tag{6.10}$$

Events in these channels are characterized by

- A certain degree of **acoplanarity** since the lepton from τ decay would not necessarily lay on the plane defined by the beam line and the axis of the hadronic shower.
- In the decay process the two final neutrinos are undetected: a rather large fraction of the energy of the incoming neutrino would be taken away by the two undetected particles; this would lead to a sizeable **missing energy** in the detector.
- The two neutrinos take away also a fraction of the transverse momentum $p_\perp$, producing an **unbalanced $p_\perp$ distribution** of the interaction products.

A cut on $p_\perp$ will remove the ν_ℓ ($\ell = \mu, e$) neutrino interactions preserving most of the taus. The threshold of the $p_\perp$ cut and its efficiency will be strictly related to the ability of the $N^O E$ detector to reconstruct muon tracks, axis and energy of both electromagnetic and hadronic showers.

The detector set up described in Chap. 3 should allow a rather accurate reconstruction of the shower axis (see Sect. 3.2) in the plane perpendicular to the axis of the scintillating fibers, where both calorimetric and tracking informations are available. Simulated event projections on this plane are shown in Fig. 5.12, 5.13, 5.14, 5.15.

In the other projection, event reconstruction must rely on tracking only and the quality of the reconstruction is poorer. This effect could reduce the resolutions and the rejection power, so it may be necessary to look for alternative detector configurations. One possibility might be to have a detector set-up where the fibers are organized in planes, and planes are placed in the detector with the fibers of each layer perpendicular to the fibers of adjacent layers.

In this way the detector would have a cylindrical symmetry along the beam axis providing the same quality of reconstruction in all projected views. Such a configuration would also increase the NOE efficiency in the study of atmospheric neutrinos.

However in this case the mechanical structure supporting the detector would be significatively more complex than in the reference detector configuration discussed so far.

Simulations are in progress to achieve the best detector design. The final configuration will be determined by a compromise between the achieved resolutions and performances, complexity of the mechanical structure, granularity and cost.

6.3.1 $\tau \to e\nu\nu$ channel

As observed in the previous section, the signature of the τ production in our detector will be based on a kinematical analysis aiming to reject electron and muon neutrino interactions.

The channel of τ decaying into an electron plus two neutrinos provides the best sample for ν_τ appearance identification due to the low background level.

The kinematical signature of the $\tau \to e\nu\nu$ decay must be searched for in the sample of events exhibiting an electromagnetic plus an hadronic shower.

The main background in this data sample is due to events with an electromagnetic shower, these are produced by the following classes of events:

1. CC interactions of the residual ν_e in the beam
2. ν_μ NC interactions producing π^0 faking an electron
3. ν_μ NC interactions producing D mesons decaying into an electron

A detailed study of the rejection power achievable with the NOE detector is in progress; however general estimates show that a rejection power on the total background $\sim 0.5 \cdot 10^{-2}$ is achievable. It is important to stress that, with the expected number of ν_μ CC events, this rejection power is more than adequate to reject background and therefore to achieve a limit in $\sin^2 2\theta$ of the order of 10^{-2}. Such a limit is clearly lower than those achieved on typical short baseline experiments, but it covers a wider Δm^2 region.

In order to estimate the background rejection power, simulated neutrino interactions have been generated. Neutrino energies have been sampled from the H20R40 spectrum reported in ref. [1] shown in Fig. 2.2. The Monte

Carlo generator is based on the LEPTO program [2] of the LUND package [3].

Preliminary estimates of the main background sources and tentative values of the required rejection power for $\tau \to e\nu\nu$ channel are discussed in the following.

π^0 Background in Neutral Currents Fake electrons could be produced by isolated π^0 directed outside of the hadronic core, which are mostly at large angle and low energy. Therefore a cut on the electromagnetic shower energy can reduce this background to a tolerable level.

CHARM background D mesons are produced in the hadronic component of ν_μ CC events. About 0.1% of the D mesons decay producing an electron. Roughly 50% of these events are rejected by a $E > 1.5$ GeV cut on the electromagnetic shower energy. By requiring a muon with energy greater than 1.5 Gev, only 0.003 % of the ν_μ CC events survives the cuts. Moreover D produced as decay of $C\bar{C}$ mesons generated in NC events are negligible.

Residual Beam ν_e CC Background Residual ν_e CC interactions are efficiently discriminated against $\nu_\tau \to \tau \to e\nu\nu$ events by the analysis on $p_\perp$ distribution. In fact ν_τ CC interactions differ from ν_e CC events by missing $p_\perp$ due to to neutrinos generated in tau decays. The missing $p_\perp$ tends to be opposite to the hadronic transverse momentum in ν_τ reaction and nearly symmetric in ν_e reaction [4].

The required rejection power is $\sim 10^{-2}$. Calculations are still in progress but to date preliminary considerations show that by requiring that the lepton produced in tau decay is not to back to back to with the hadron jets, and adding cuts on coplanarity and missing energy, this rejection power could be achieved with an estimated τ efficiency of the order of 20%.

The total background is so reduced to less than one event per 15000 ν_μ CC interactions for each of the examined background channels with a overconservative efficiency estimate for τ detection of the order of 20 %. In the following, a conservative estimate of 2 background events will be used. With these numbers one can estimate the minimum $\nu_\mu \to \nu_\tau$ oscillation probability to produce a detectable ν_τ signal over background.

In absence of oscillations, given this background level, one can set an upper limit to the oscillation probability (at a 90% confidence level) by com-

puting the maximum number of background events N_{bck} compatible at 90% CL with this background estimate.

Taking into account that only a fraction $B \sim 18\%$ of the taus decays through this channel, that the detection efficiency ε is of the order of 20% and that at our beam energies the kinematical suppression due to the tau mass (see sect. 6.2.3) is $\eta \sim 0.25$, the minimum number of ν_τ charged current interactions needed to observe a number of events greater than N_{bck}

$$N_\tau = \frac{N_{bck}}{\eta B \varepsilon} \tag{6.11}$$

which corresponds to a 90% confidence level probability given by

$$P = \frac{N'_\tau}{N_\mu} \tag{6.12}$$

where N'_τ is the maximum number of background events at 90% confidence level compatible with the N_{bck} actually observed and N_μ is the total number of ν_μ CC interactions.

A similar calculation can be performed in the ideal case of zero background events, yielding the largest possible exclusion region with our statistics In Fig. 6.1 the excluded region after 15000 ν_μ CC events is reported. The shaded region, bounded by the two limit cases considered above indicates the uncertainty produced by the present knowledge of the background rejection.

For the appearance measurements, it is essential to know precisely the ν_e contamination of the beam. For its characteristics, the calorimeter described in this letter of intent could be easily scaled to perform this task.

6.3.2 $\tau \to \mu\nu\nu$ channel

The events in this channel are topologically simpler than those produced by the $\tau \to e\nu\nu$ decays, since the muon is more easily identified. Here the relevant background is constituted by all the ν_μ charged current interactions.

The background in this data sample is due to:

1. π and K punch thru in ν_μ NC interactions , or π and K decays muons
2. Muons generated in D meson decay
3. Muons from beam ν_μ CC interactions

Concerning the first channel, since the number of NC interactions in the considered data sample are ~ 5000, the rejection power needed is somewhat better than 10^{-3}. It can be achieved using both cut in energy, angular distribution and timing of the muon. It should be noted that muons from π and K are produced essentially at low energy and large angle. To reject the punch thru, it will be possible to define a depth on the detector such that the probability for π and K to overcome the cut is lower than 10^{-3}. Beyond this cut a track will be identified as a muon. A depth corresponding to ~ 25 BCE ($6 \div 7$ interaction lengths) gives a punch thru probability lower than $\sim 6 \cdot 10^{-4}$ setting an energy cut on muons of ~ 2 GeV (see Fig. 5.5). Such a cut saves $\sim 80\%$ of the $\tau \to \mu$ signal. In case of π and K decay, timing and cuts on the angular distributions can be used.

Muons from D mesons originated in $C\bar{C}$ production in NC are absolutely negligible.

As in the case of the previous section, the level of the charm background is negligible and it is due to those events in which muons from D overcome the energy cut, while the muon from ν_μ CC is not visible. This case is completely analogous to the corresponding channel in the $\tau \to e\nu\nu$ analysis.

The most challenging background is the one due to the ν_μ CC interactions, for which the rejection is heavily based on the study of the coplanarity of the event and on the balancing of the $p_\perp$ distribution of secondaries produced in the interaction.

In fact, as in the previous case τ events are characterized by acoplanarity, missing energy carried away by the outgoing neutrinos and by the unbalanced $p_\perp$ distribution of secondaries.

For a total sample of 15000 ν_μ CC interactions, an overall rejection power of $\sim 10^{-4}$ is required. This is bigger than required in the $\tau \to e\nu\nu$ analysis, but the events here are much more easily reconstructed, due to the lack of the electromagnetic shower and to the presence of a long muon track.

The expected final background amounts to a few events as in the previous case, giving a similar exclusion plot (see Fig. 6.1).

The work relative to reconstruction of event is not completed so far and further simulations are in progress.

The feasibility of an appearance neutrino oscillation search depends heavily on the possibility of reaching this rejection level. Work is in progress on this crucial item and will be the subject of an addendum to this letter of intent.

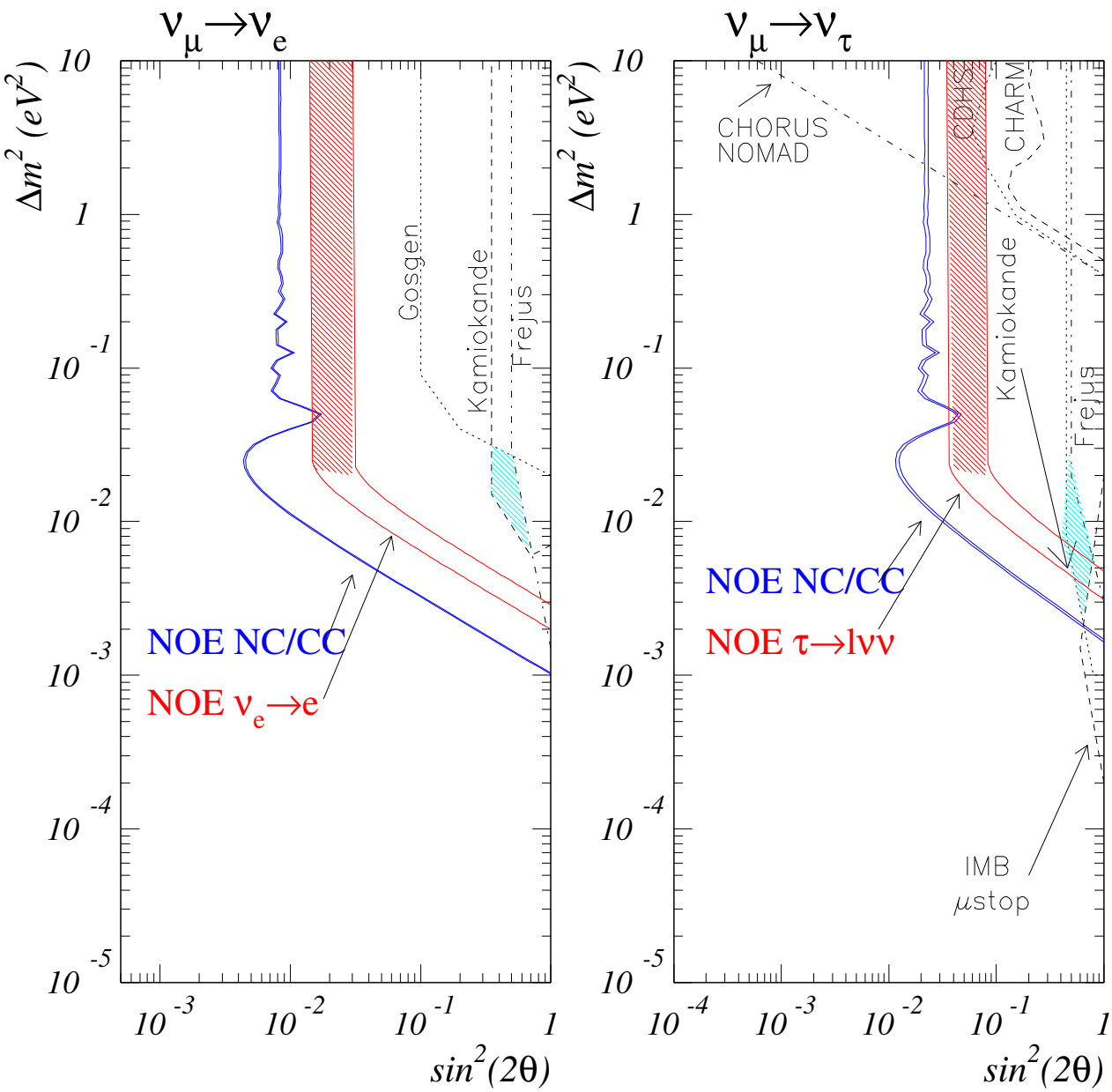

Figure 6.1: The N^OE sensitivity for long baseline neutrino oscillation measurements. The shaded region show the present uncertainty due to the spread of ν_e beam contamination values and to the still preliminary background estimates

6.4 Direct $\nu_\mu \to \nu_e$ searches

In this channel an energetic electron in final state is required. The main background is due to residual ν_e in the beam. This is an unavoidable background producing events that it is not possible to distinguish from an oscillation signal and sets a limit in the sensitivity of the measure. For this reason, as already seen in §6.3.1 in the case of the $\tau \to e\nu\nu$ channel a monitor of the residual ν_e in the beam is mandatory.

Further background is produced by π^0 generated in neutral current interactions and directed outside the hadronic core that simulate the signal. This background can be rejected as discussed in sect. 6.3.1 with a cut on the electromagnetic shower energy and coplanarity.

By measuring an excess of electron over the background a limit of $\sim 2.5 \cdot 10^{-2}$ can be obtained. The excluded parameter space region after 15000 ν_μ CC interactions is reported in Fig. 6.1. The shaded area shows the present uncertainty due to the spread of ν_e beam contamination values for the beam calculations reported in table 2.3.

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