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NuMI–B–XXX
September 10, 2001

Optimization Studies of Beam Optics for the Low Energy Neutrino Production

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1 Introduction

The two horns focusing system PH2, which was developed for the NuMI Project, provides in the three steps wide band neutrino beams WBB (these are labeled the low energy (LE), medium energy (ME) and high energy (HE) beams) in the energy range from 1 GeV up to 24 GeV [1, 2]. All beam configurations use the same horns and power supply system, but different targets and different positions of the second horn (Figure 1.1). The current in horns is equal to 200 kA for all beams. Energy spectra of ν_μ CC events in the far MINOS detector are shown in Figure 1.2.

The shapes of horn inner conductors were originally optimized for producing a neutrino beam mainly in the ME range (2–12 GeV), and more recently somewhat modified in favor of the LE beam (1–6 GeV). Taking into account that the HE beam configuration (4–24 GeV) covers the remaining part of the total desired energy range, this focusing system is a compromise allowing for both high and low energy running. Tunes intermediate between the three given can be easily achieved, but more extreme tunes are problematic.

This Report is dedicated to optimization studies of beam optics for a neutrino production in the half GeV to couple GeV energy range in the MINOS far detector. The studies assumed 120 GeV primary proton beam energy, the current design size of target hall chase and decay pipe.

Section 2 shows neutrino spectra resulting from an attempt to decrease the beam energy through variation of position and current of existing horn(s), as well as position and length of the LE target (the target designed for the NuMI low energy beam configuration [3, 4]). The latest version of a target cross-section, realized in the final package of target drawings, is shown in Figure 1.3.

Preliminary results of investigations of the low energy neutrino production into more wider space of horn and target parameters are presented in **Section 3**. The task was to show if a new set of horns, designed specifically for the lower energy range, could significantly improve the NuMI beam efficiency. Shape of inner conductor, length, radius and current of horns were considered here as adjustable parameters, as well as the target material and geometry.

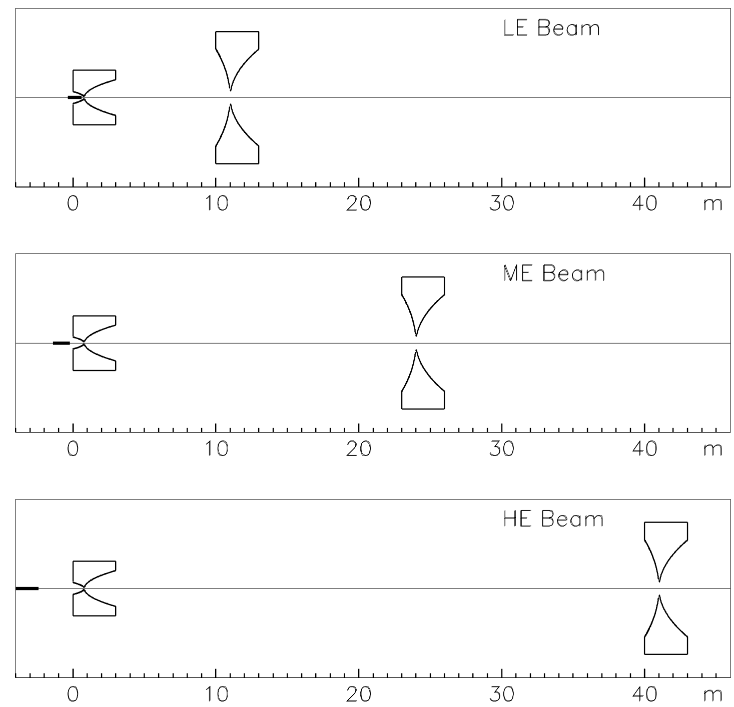


Figure 1.1: Layouts of three configurations of the PH2 wide band neutrino beam (Z = 0 corresponds to the upstream end of the first horn).

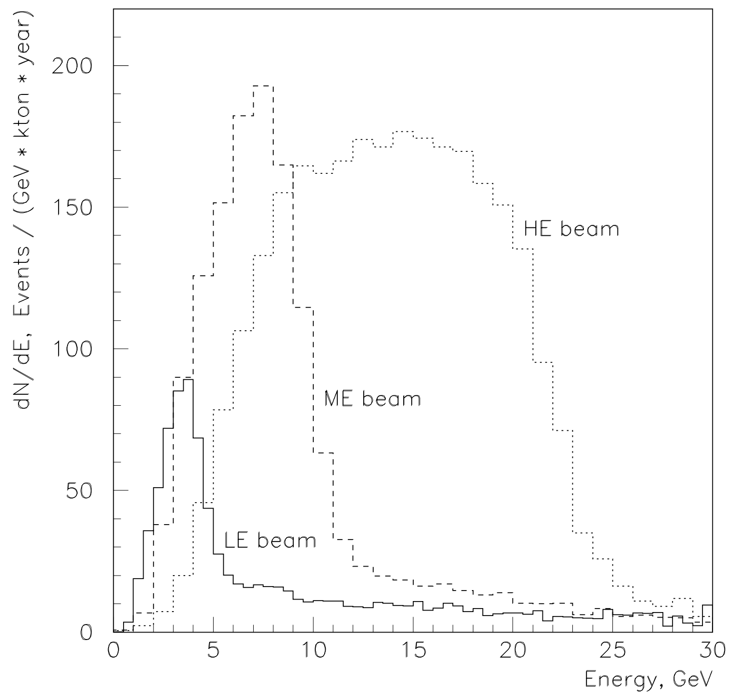


Figure 1.2: Energy spectra of ν_μ CC events in the far detector for three WBB configurations of the PH2 focusing system.

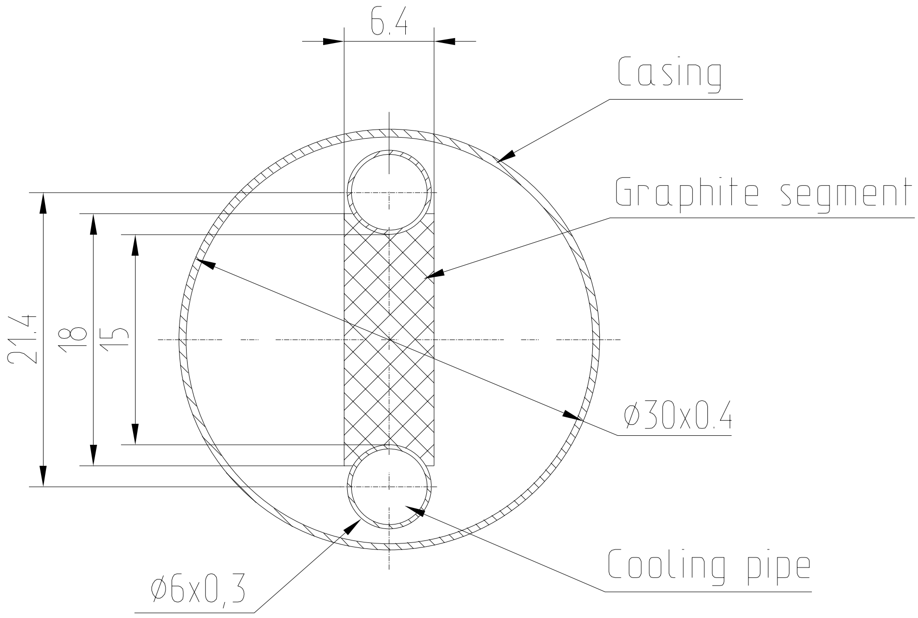


Figure 1.3: Cross-section of the LE target.

2 Possibilities for Lowering the Beam Energy using the Present NuMI Horns

2.1 Conventional On Axis Beam Configurations

The number and position of horns, their currents, as well as the length and position of the LE target were used as adjustable parameters in order to investigate the low energy performance of the PH2 focusing system.

Figure 2.1 shows the energy spectra of ν_μ CC events in the far detector for some typical of all considered Very Low Energy (VLE) beam configurations, while Table 2.1 summarizes the main parameters of given VLE beam configurations and corresponding neutrino event rates. The focusing systems consisting of one or two horns are marked H1 or H2 respectively. In case of two horn (H2) beam the space between horns is equal to 1 m.

Beam configuration	Target length, m	Target position, m	Horn current, kA	ν_μ CC events/ kton/year
H1–C120	0.94	–0.34	120	31
H1–C150	0.94	–0.34	150	45
H1–L50	0.50	0.10	200	25
H1–L70	0.70	–0.10	200	43
H2–C100	0.94	–0.34	100	35
H2–C120	0.94	–0.34	120	48
H2–L35	0.35	0.25	200	30
H2–L50	0.50	0.10	200	48

Table 2.1: Parameters of VLE beam configurations and far detector neutrino event rates with $E_\nu < 3.5$ GeV. Target positions, namely positions of the target upstream end, are given with respect to the upstream end of the first horn. The cross-section of target is shown in Figure 1.3.

One should note, that all obtained results assume the 50 m length target hall with 0.5 m radius space inside the target pile. An increase of this radius up to 1 m (the radius of the decay pipe) leads to 15–20% increase of the neutrino event rate for all considered beam configurations (Figure 2.2). By this it meant, that taking into account the possibility of lowering the NuMI beam energy it is necessary to provide the space inside the target pile with transverse sizes growing with length from 0.5 m near the second horn up to 1 m near the decay pipe. The alternative is an installation of target and horns at the end of the target pile.

2.2 Off Axis Beam

In accordance with [5], the Off Axis Beam (OAB) was considered as a possible variant of lowering of the NuMI beam energy. In this case the neutrino beam is produced by the original LE configuration of the PH2 focusing system and the far detector is displaced from the direction of the decay pipe axis.

Figure 2.3 shows the energy spectra of ν_μ CC events in the far detector in case of its different positions. At $\varphi = 1^\circ$ and $\varphi = 2^\circ$, which correspond to $\sim$12.5 and 25.0 km displacement of detector position in transverse direction, the numbers of neutrino events per kton/year are equal to 53 and 10 for neutrinos with $E_\nu < 2.5$ GeV and $E_\nu < 1.5$ GeV respectively.

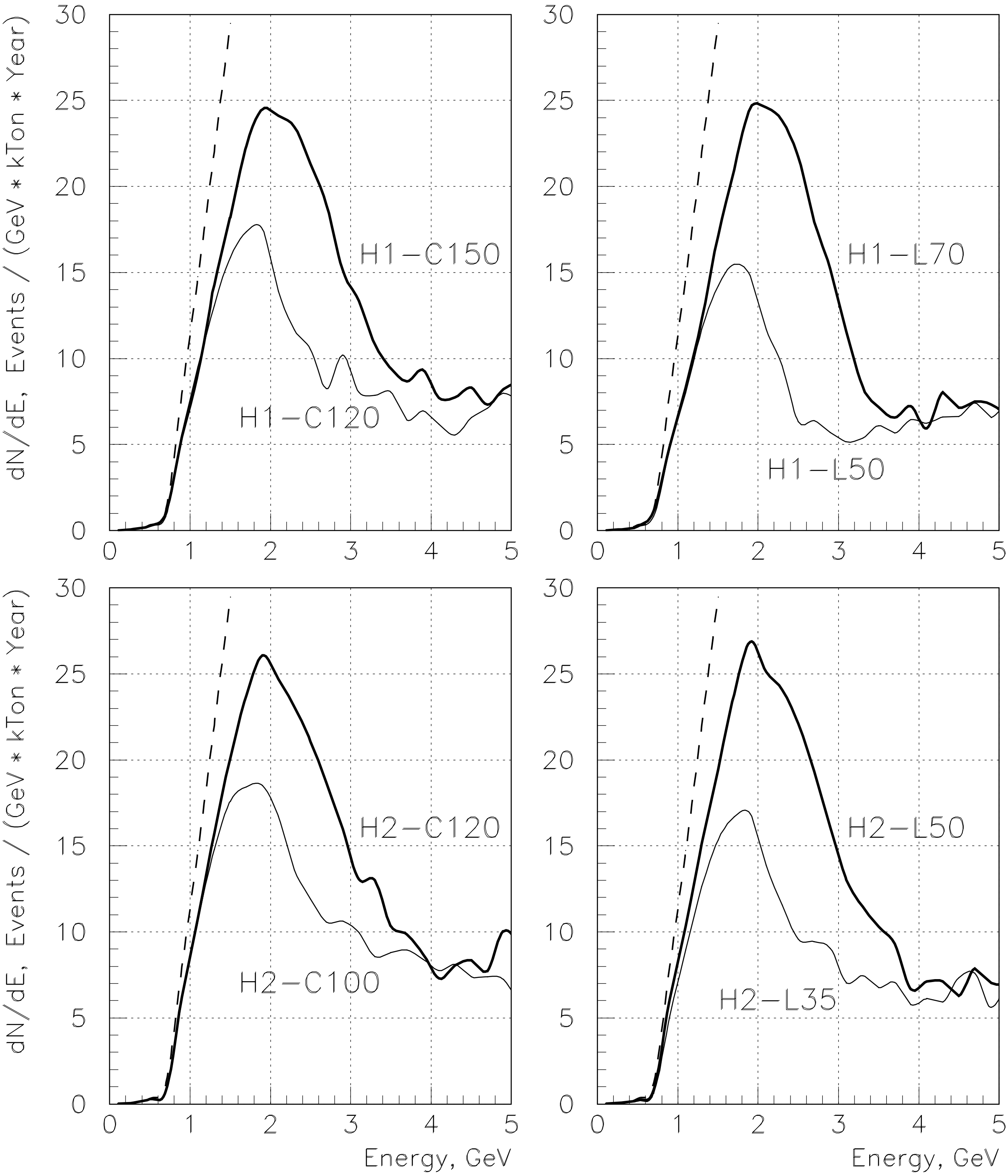


Figure 2.1: Energy spectra of ν_μ CC events in the far detector for the original LE (dash line) and for some VLE beam configurations with the present NuMI horns (solid lines).

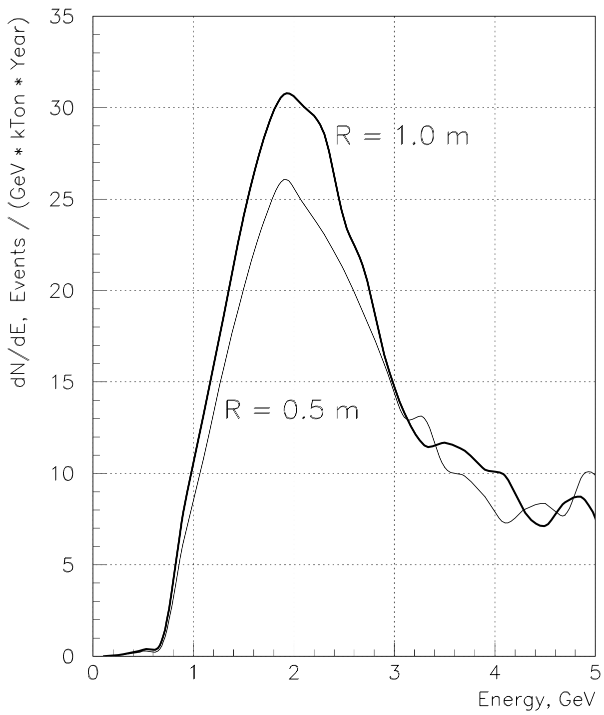


Figure 2.2: Energy spectra of ν_μ CC events in the far detector for the H2–C120 beam configuration in case of two inner radii of the target pile.

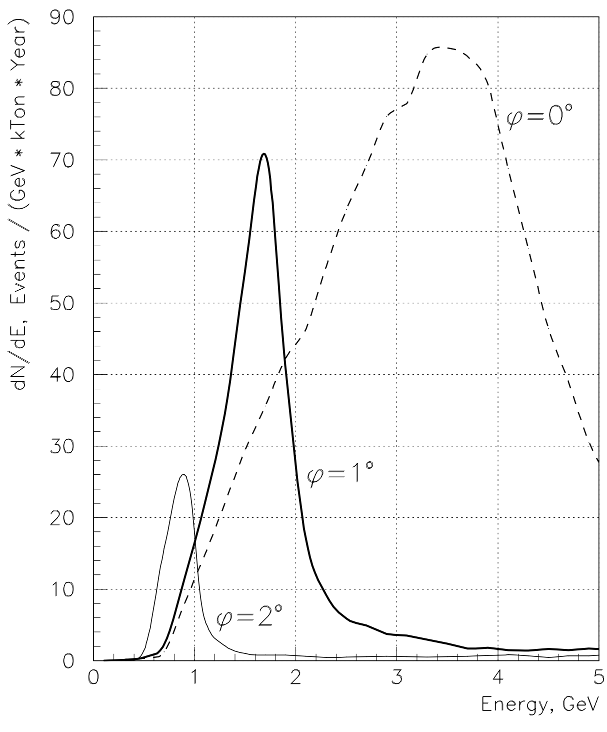


Figure 2.3: Energy spectra of ν_μ CC events in the far detector for the original LE beam configuration in case of different detector positions. $\varphi = 0$ corresponds to the baseline LE beam.

3 Lowering the NuMI Beam Energy using a New Set of Horns

3.1 General Approach

From the preceding it may be seen, that parameters of the present NuMI horns were optimized mainly for the 1–6 GeV neutrino energy range (LE beam configuration) with the mean energy of 3.5 GeV. The desired energy range from 0.5 up to 2.5–3.0 GeV assumes approximately two times decrease of the momentum of pions accepted by a focusing system. As was shown in [6], in order to estimate the possible range of new horn parameters we can use the solution of the particle motion equation in a toroidal field $B \propto 1/r$

$$\frac{d^2 r}{dz^2} + \frac{kI}{rp} = 0,$$

where $k = 6 \times 10^{-5}$, I is the current (kA) and p is the particle momentum (GeV/c). For the "point to parallel" focusing of parent particles with the transverse momentum $p_\perp$

$$r = r_0 \, \exp(p_\perp^2 / 2kpI),$$

where r_0 and r are input and output particle coordinates; or otherwise

$$p_\perp^2 = 2kpI \ln \frac{r}{r_0}.$$

Therefore, to keep the reasonable acceptance of a focusing system in the lower energy range (pion production peaks at $p_\perp \sim 0.3$ GeV for all pion momenta), a decrease of parent particle momentum should be compensated by an increase of the horn current or/and by an increase of the value of $\ln \frac{r}{r_0}$. At the same radii of the inner conductor in the first part of horn, the last leads to increase of the horn radius (the radius of horn outer conductor).

Taking into account the possible difficulties in horn construction, as well as the present design sizes of the target pile, it is reasonable to restrict the space of main horn parameters by the following conditions:

- the horns radius does not exceed 50 cm;
- the horns length is in order of 3 m;
- the maximal horn current is equal to 300 kA.

3.2 Horn Parameters and Neutrino Event Rates in the 0.5–2.5 GeV Energy Range

Parameters of three possible VLE configurations of the NuMI beam with a new set of horns and corresponding neutrino CC event rates in the far detector are given in Table 3.1. Two first configurations use horns with parabolic shaped inner conductors and differ by the value of horn currents, while the third configuration use horns with conical inner conductors which are similar in shape and main sizes with 300 kA parabolic horns (Figure 3.1).

The radii of horns are equal to 32 cm and 47 cm for the first and second horns respectively. The thickness of inner conductor in the first 200 kA horn is equal to 3 mm in the neck region. Moving away from the neck, the thickness gradually decreases to 2 mm, whereafter the thickness remains constant. In a like manner, the thickness of the first 300 kA horn and all second horns varies from 4 mm to 3 mm. The space between horns is equal to 2 m for all beam configurations.

Beam configuration	Target length, m	Target position, m	Horn current, kA	ν_μ CC events/ kton/year
PH2A	0.94	–0.19	200	21.8
PH2B	0.94	–0.24	300	23.7
CH2	0.94	–0.24	300	26.3

Table 3.1: Parameters of VLE beam configurations and far detector neutrino event rates with $E_\nu < 2.5$ GeV. Target positions, namely positions of the target upstream end, are given with respect to the upstream end of the first horn. The cross-section of target is shown in Figure 1.3.

Figure 3.2a shows energy spectra of ν_μ CC events in the far detector for new PH2A and PH2B VLE beam configurations in comparison with those for the LE and H2–C120 beams with existing PH2 horns. These spectra were calculated assuming the 0.5 m radius space inside the target pile between the second horn and the upstream end of decay pipe. Similar to H1 and H2 beam configurations considered in Section 2, an increase of radius of target pile chase up to 1 m will cause the increase of neutrino events for new VLE beams also (Figure 3.2b). But in this case it reaches 35–40% instead of 15–20% for H1 and H2 beams.

The energy spectrum for the CH2 beam configuration is almost the same as the PH2B one, but with somewhat larger number of events in the fall part of spectrum ($1.5 < E_\nu < 2.5$ GeV).

3.3 Target Geometry and Material

All presented above results were obtained with the water cooled graphite fin target, developed for the LE configuration of NuMI beam. The other possible LE target design, which was considered at the stage of its initial conceptual designs [7], is a water cooled graphite rod target. To avoid the direct contact between cooling water and a target surface, the graphite rods are encapsulated in the 0.2 mm thick stainless steel pipe. Cooling water passes inside of a water channel formed by two co-axial pipes (the thickness of the external stainless steel pipe is equal to 0.3 mm).

Due to the high power of a primary beam, the cooling system should be located outside the range of possible missteered proton beam. This is provided with help of the baffle protection collimator located just before the target. Assuming the 10 mm diameter hole in the baffle, a minimal radius of graphite core is about 6 mm.

The use of this target with the PH2B horns gives a few percent increase of the ν_μ CC event rate with $E_\nu < 2.5$ GeV with respect to the present LE target (Figure 3.3). More detail calculations showed that the 6 mm radius of graphite core is close to an optimal one.

The other low Z material, which (as it was also shown in [7]) can be used for construction of the LE target, is a beryllium. However, as in the LE beam, its use in the considered here VLE beams gives no gain in the neutrino event rate with respect to graphite.

3.4 Higher Energy Beams with New Horns

Similar to the original PH2 focusing system, there is a possibility to adjust the focusing system with new VLE horns to a higher energy range. This may be done by changing the positions of target and second horn with respect to the first horn, i.e. moving the target upstream and the second horn downstream the beam.

Figure 3.4 shows energy spectra of ν_μ CC events in the far detector for the PH2B focusing system (with 300 kA horns) adjusted to different energy ranges. A switch from the 0.5–2.5 GeV neutrino energy range to the 0.5–3.5 GeV range is realized by changing the position of target, and subsequent switch to the 0.5–4.5 GeV range by changing the position of second horn (Table 3.2). One should note, that in the last case the position of second horn coincide with the position of second horn in the baseline LE beam.

Target position, m	Horn 2 position, m	Energy range, GeV	ν_μ CC events/ kton/year
–0.24	5.0	0.5–2.5	23.7
–0.74	5.0	0.5–3.5	62.0
–0.74	10.0	0.5–4.5	128

Table 3.2: Parameters of the PH2B focusing system adjusted for different energy ranges and corresponding far detector neutrino event rates. Target and Horn 2 upstream end positions are given with respect to the upstream end of the first horn. The length of target (Figure 1.3) is equal to 0.94 m.

3.5 Radius of the Decay Pipe

The length and radius of the decay pipe were optimized (chosen) for the high energy neutrino beam at the initial stage of the NuMI project [8] and, as was shown in [9], are not quite optimal even for the ME beam configuration of the PH2 focusing system.

To a greater extent the present radius of decay pipe is not adequate with parameters of beam after focusing system in the considered energy range. Figure 3.5 shows energy spectra for the PH2B VLE beam configuration calculated for various radii of the decay pipe. As it follows from these results, an increase of the decay pipe radius from 1.0 m up to 1.5 m and 2.0 m gives respectively 30% and 50% increase of neutrino events with $E_\nu < 2.5$ GeV in the far detector. One should note, that this gain in the number of neutrino events may be provided by increasing the radius only in the first part of decay pipe with a length of about 200 m (Figure 3.6).

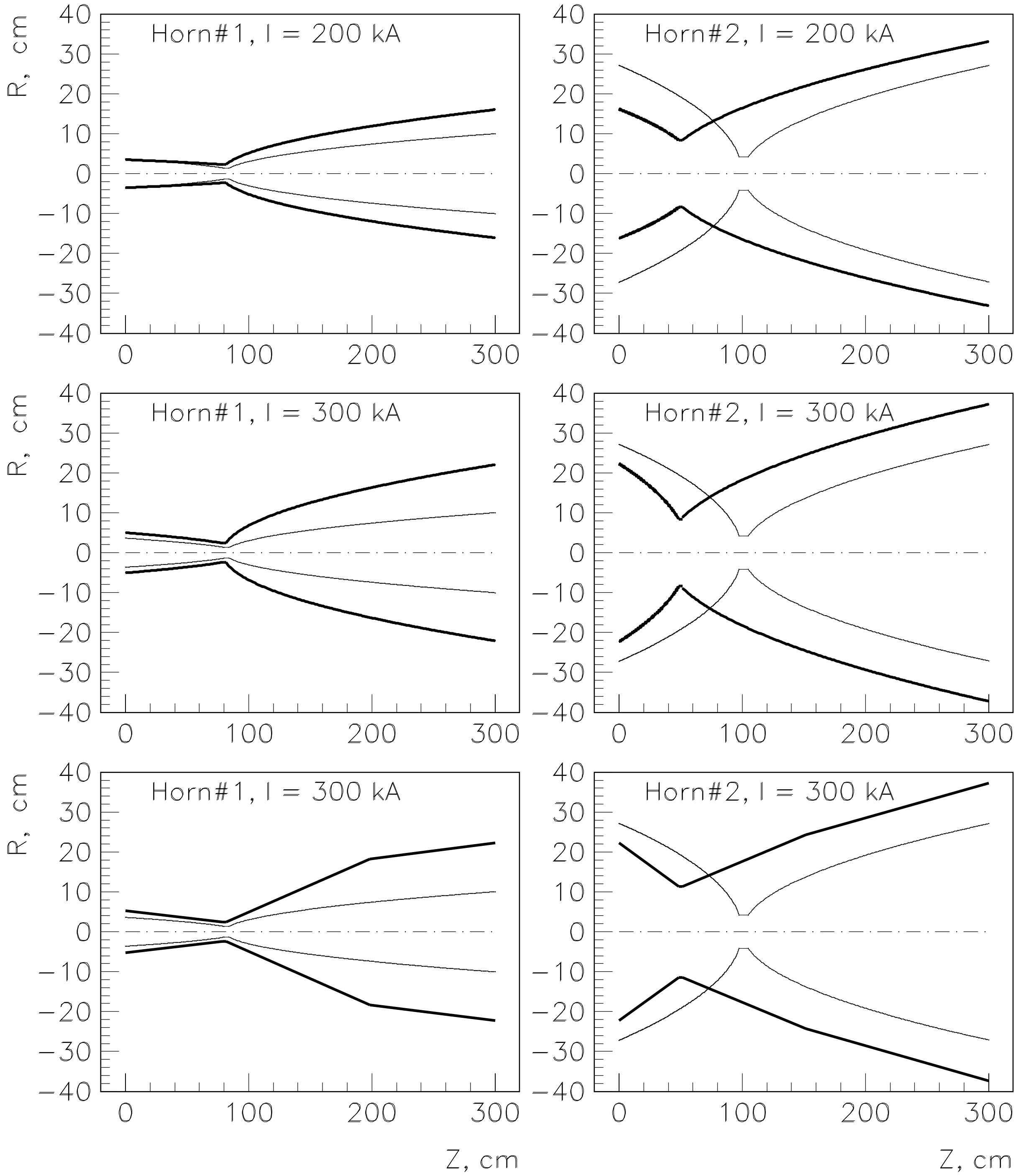
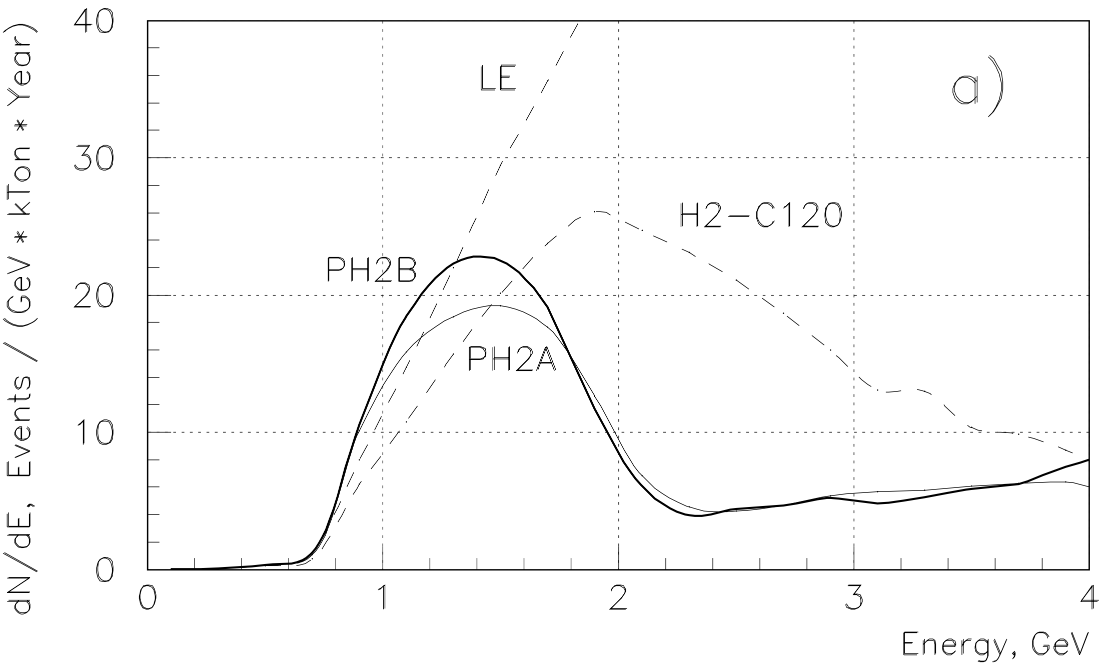


Figure 3.1: Shapes of inner conductors for new sets of VLE horns (thick lines) in comparison with those for the original PH2 design (thin lines). Top — PH2A, middle – PH2B and bottom — CH2.



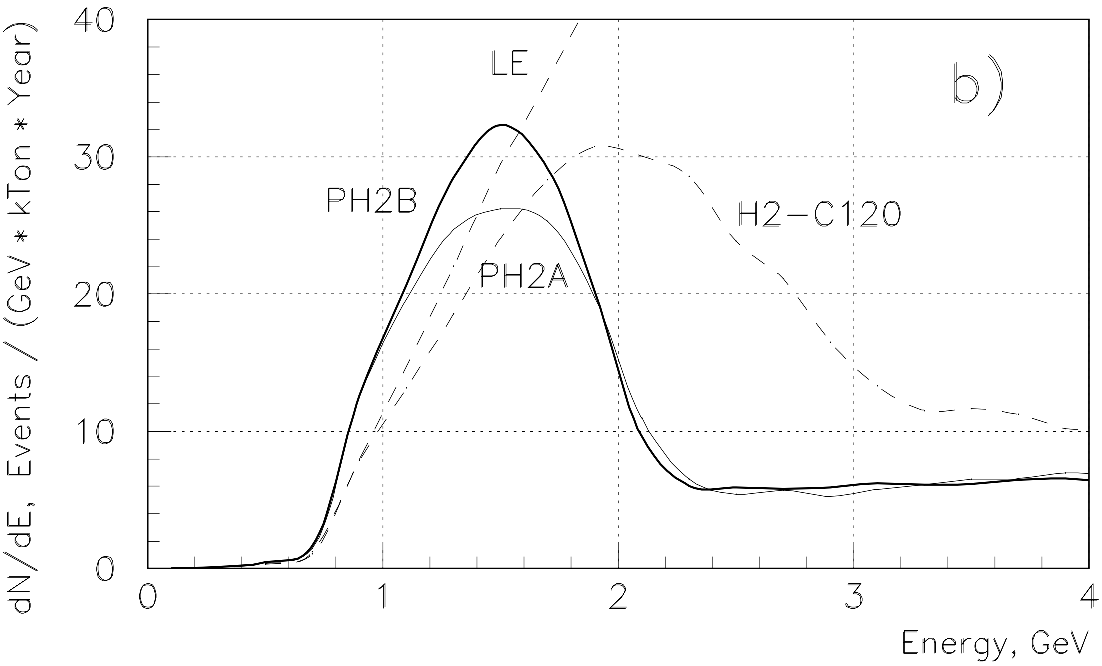


Figure 3.2: Energy spectra of ν_μ CC events in the far detector for PH2A and PH2B VLE beam configurations (solid lines) in comparison with spectra for the LE and H2-C120 beams with existing PH2 horns (dash lines). The radius of space inside the target pile are equal to 0.5 m (a) and 1.0 m (b).

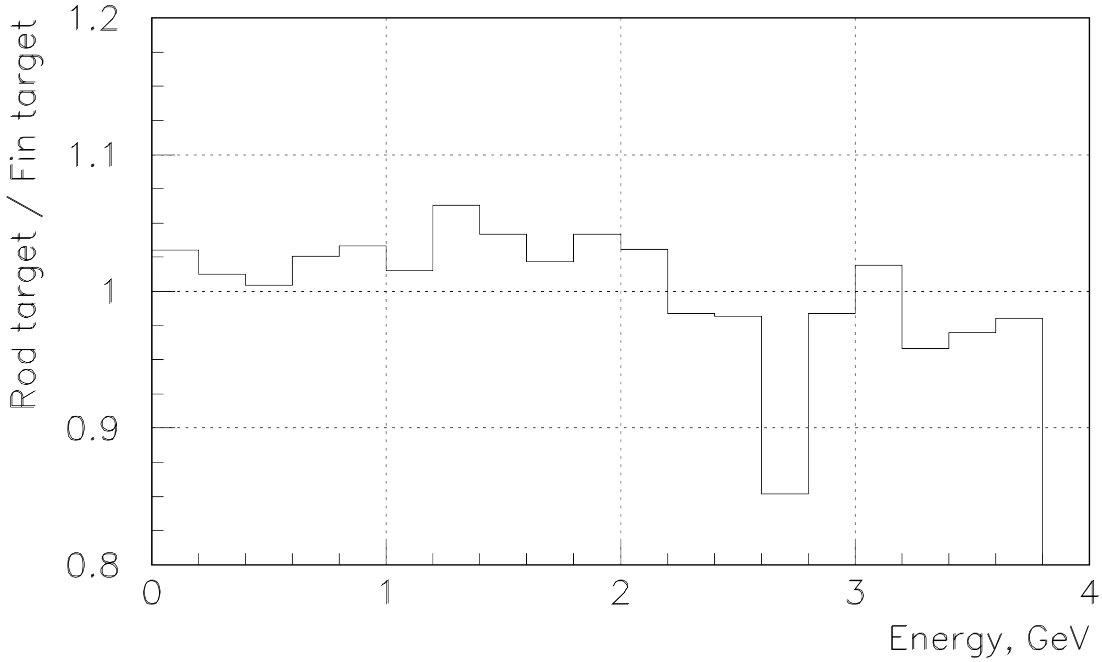


Figure 3.3: Ratio of neutrino spectra in the far detector for the PH2B VLE beam configurations with the 6 mm radius rod target and with the present LE fin target.

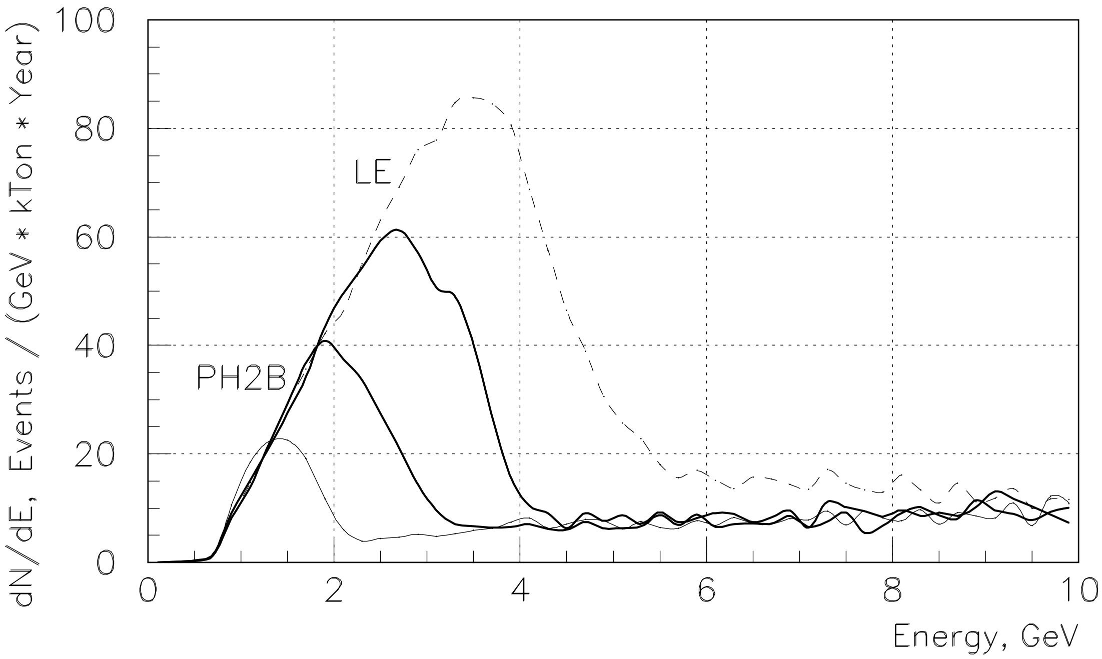


Figure 3.4: Energy spectra of ν_μ CC events in the far detector for the PH2B VLE beam configurations adjusted to different energy ranges in comparison with spectrum for the baseline LE beam.

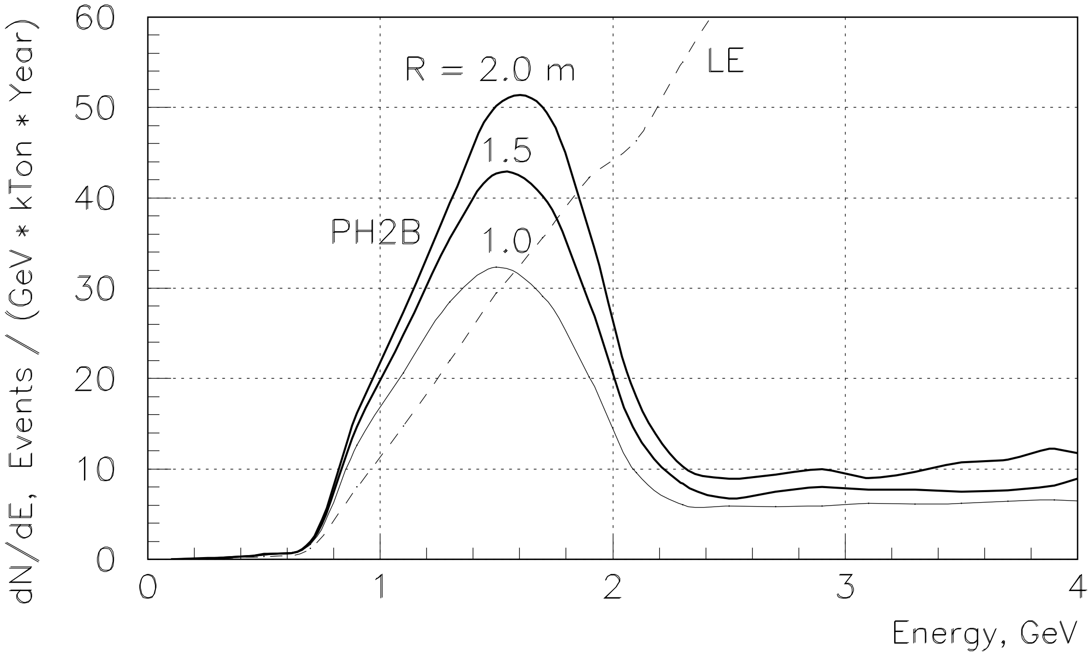


Figure 3.5: Energy spectra of ν_μ CC events in the far detector for the PH2B VLE beam configurations for various radii of the decay pipe. The radius of the target pile chase is equal to 1 m.

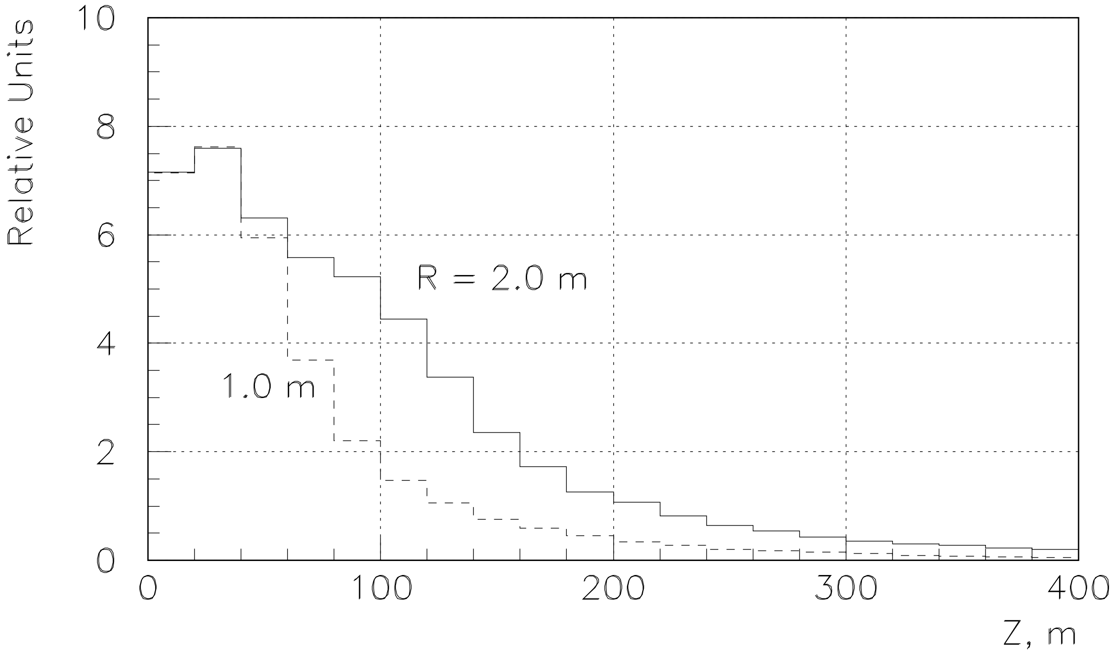


Figure 3.6: Longitudinal distributions of decay points of parents of ν_μ CC events with $E_\nu < 2.5$ GeV in the far detector for two values of the decay pipe radius. $Z = 0$ corresponds to the upstream end of the first horn. The radius of the target pile chase is equal to 1 m.

4 Conclusions

Preliminary results of optimization studies of beams optics for the NuMI beam in the half GeV to couple GeV energy range (which extends further than those presented in this Report) showed that:

- the 0.5 m radius of target pile chase is not enough for the VLE focusing systems with almost the same size of second horn. An increase of the this radius up to 1 m gives 35–40% gain in the number of neutrino events with $E_\nu < 2.5$ GeV provided by considered focusing systems [1];
- the use of horns with a current of 300 kA gives the 10-15% increase of neutrino event rate in the far detector with respect to focusing system with the 200 kA horns;
- the water cooled cylindrical target with the 6 mm radius graphite core is quite competitive with the baseline LE target design in the energy range under investigation. The use of beryllium instead of graphite gives no visible advantages in the neutrino production;
- contrary to LE and ME configurations of the NuMI beam, horns with more simple (conical) shapes of inner conductors are equally applied for the VLE neutrino beams along with parabolic horns.

One should note also, that only exploited all mentioned above possibilities for increasing of the low energy neutrino production (including an increase of the decay pipe radius from 1 up to 2 m), the described in this Report focusing systems provide at this stage of its study approximately the same number of ν_μ CC events with $E_\nu < 2.5$ GeV as the $\sim 1^\circ$ Off Axis Beam (OAB) from the baseline LE configuration (Figure 4.1). On the other hand, the high energy tail of OAB neutrino spectrum is significantly smaller than that in the considered VLE beam configurations, as well as in others low energy neutrino beams obtained from high energy primary proton beams. The possibility to suppress the high energy part of neutrino spectrum in the VLE beams with help of the beam plug was not studied for the present.

[1] Note, that for the baseline LE beam the similar increase of the target pile chase gives about 3% increase of neutrino events with $E_\nu < 6$ GeV.

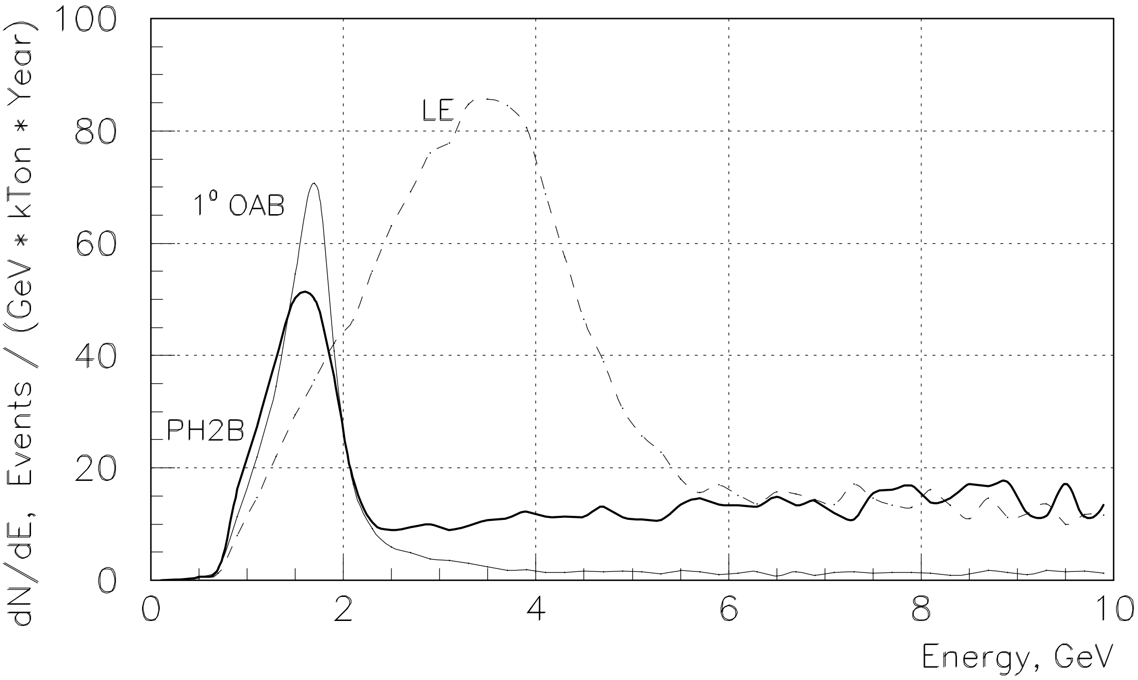


Figure 4.1: Energy spectra of ν_μ CC events in the far detector for the PH2B VLE beam configuration in comparison with the 1° Off Axis Beam from the baseline LE configuration. For the PH2B beam the radii of target pile chase and decay pipe are equal to 1 m and 2 m respectively.

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