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Neutrino Beams Using the Main Injector

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1 Introduction

TM-1946[1] summarizes the status of the NuMI project. This note presents more details on the technical design of the various NuMI beams. Several beamline options are investigated for producing neutrinos--(1) a wide-band beam(WBB) using a Double Horn, (2) a beam using only a single Lithium Lens, and (3) a two stage narrow-band beam(NBB) using a Lithium Lens, quadrupoles and dipoles. The first two are designed to maximize the muon neutrino event rate; the third is designed to have a tunable range of parent momenta from 5-45 GeV/c. In the context of NuMI, the Double Horns and its target were concepts first described[2] in 1991. The Lithium Lens has been used at Fermilab for pbar production for several years. With recent upgrades[3], it forms the basis of what will be used by NuMI. Narrow band beams using conventional dipoles and quadrupoles have been studied, but have less acceptance than one using a lithium lens.

The following practical limits are imposed on each of the systems:

(1) Horns: the necks will not have a smaller radius than 1 cm; the maximum current will not exceed 170 kAmp. Keeping the inside diameter large allows the primary proton beam to vary in position, yet not strike the fragile neck. In addition, there is a trade-off between decreasing the radius and increasing the wall thickness to maintain the required strength of the conductor material.

(2) Magnets: reasonable conventional designs are used. The maximum gradient for quadrupoles is 12 kG/half-aperture; the maximum field for dipoles with a 2 inch full gap is about 16 kG; larger apertures scale the field down. Although not a primary consideration, it is desirable for the magnification in each plane to be comparable (within a factor of 2 or 3 is OK).

(3) Lithium Lens: the maximum radius is 1.0 cm with a maximum gradient of 100 kG/cm.

(4) Dumps: at the place where the primary protons are absorbed, the transverse beam center is $\approx$ 1 inch off the edge of the acceptance; the minimum length for a primary beam dump is 12 feet.

2 Horns

The nominal design has a system with Horn#1 being 4 meters long and Horn#2 being 3 meters long. For purposes of construction and handling, it is desirable to have horns shorter in length. This may also have an advantage with respect to the total amount of shielding needed around the elements in the Target Hall. It is almost a certainty that the 4 meter horn cannot be manufactured in one piece. Furthermore, from a structural point of view, it is desirable to have the neck at one end of the horn, not in the middle. I have therefore looked at the possibilities for making a WBB with shorter horns and they are listed in the Table below. For purposes of identification, the horn systems carry a name having the total length of both horns (i.e., H5 is a 2 meter Horn#1 followed by a 3 meter Horn#2).

Table 1

All horn designs use the long segmented carbon target(r=2mm, 100 cm graphite, 56 cm total gap) discussed in TM-1946 and all have the neck at the downstream end, except H7. Using a coordinate system which has Z=0. as the upstream end of Horn#1, the target begins at Z=-1.6 meters. Both horns use the same current as the nominal design, 170 kAmps each. At this time the length of the muon shield from the dump to the experimental hall has not been fixed, pending the outcome of GEANT runs. For purposes of running the program NUADA[4] for a comparison between the various length horns, I have used a length of 250 meters, which should be conservative. The other parameters of interest are, (a) decay length = 800 meters, (b) decay pipe radius = 1 meter, (c) distance to the long baseline detector = 732 km, (d) radius of the long baseline detector = 10 meters, (e) radius of the short baseline detector = 0.9 meters. One year of running is taken to be 3.7E20 incident protons.

Although the list is not exhaustive, it indicates the general trade off with flux and events as the length of the horn system is reduced. A comparison of the NuMu event rate for horn systems of different lengths is shown in Figure 1 for the short baseline and in Figure 2 for the long baseline. Absorption in the horn conductors has been taken into account. One can notice that the "shoulder" around 20 GeV is most pronounced for H7, compared to all the others. For the most part, this comes from the "vee" shape of H7; the others could be described as "half vee".

An interesting property of the various horn systems is their depth of field. This can be thought of as a correlation between the spectrum in the detector and the Z position of the target. Since the conical shapes of the horns are designed to focus a certain p_t, secondary particles coming from the "front" of the target will produce higher energy neutrinos than those from the "back" of the target. The depth of field not only determines the energy, but also the relative number; the weighting will be greatest from the upstream end of the target, because that's where the number of protons is greatest. The depth of field for each horn system is shown in Figure 3 and Figure 4 for the short and long baselines. The depth of field for a horn system(Horn#1 and Horn#2) is obtained by comparing the event rate at the detector while moving a one-quarter interaction length target in Z. All curves are normalized with respect to the nominal horn system (i.e., 1.0 is the highest point of H7 at $Z \approx -0.5$ meter).

For ease of construction, handling, and production, a one interaction length target placed at the peak of the depth of field would be adequate. However in the case of NuMI, all the non-interacting protons travel down the decay pipe to the dump where they create background from charm decay. For the short baseline experiment it is therefore desirable to have a long target to interact as many protons as possible. The long target also gives a slightly higher event rate. NUADA results for a single one interaction length target and the nominal(2λ plus gaps) show about a 30% decrease in NuMu events.

3 Single Lithium Lens

A lithium lens is a cylinder of solid lithium carrying current so that a particle passing through the lithium at an angle with respect to the lens axis will experience a radial Lorentz force. A lens with radius r_O, length L carrying a current I, will produce an azimuthal magnetic induction $B(r)= \mu_O Ir/2\pi r_O^2$. An ideal lens will make a beam parallel when the distance from a point source to the upstream face of the lens is $d=1/(k \tan(kL))$ where $k=(0.03G/p)^{1/2}$, L=length of lens(meter), G=lens gradient(kG/m), and p= particle momentum(GeV/c).

The lens used for pbar collection at Fermilab has a radius of 1 cm and a length of 15 cm. Outside the 2 cm diameter is a thin water cooled container which is encased inside a steel cylinder having cooling tubes. The point is that particles traveling through the lithium are absorbed slightly, while particles at radii larger than 1 cm get completely absorbed. The upgraded lens[3] is designed to produce a peak magnetic gradient of 100 kG/cm with high reliability. The single lithium lens was optimized for event rate by fixing the gradient at this highest value and adjusting the distance between the target and the lens. Since the lens is short, it is important to keep the length of the target short to minimize the divergence of various momenta. NUADA results analogous to the horn runs for the optimized single lithium lens is shown in Figure 5 and Figure 6 for the short and long baselines. The center-of-target to beginning of lens distance is optimum at about 75 cm. This corresponds to ideal point to parallel focusing for about 35 GeV/c. Absorption in the lithium has been taken into account and is about an 8% effect.

4 Lithium Lens with Quadrupoles and Dipoles

The NBB beam follows a different trajectory than the horn beam. To make the final beam position and direction the same after it passes through either the horn or a bending dichromatic, compensating bends are needed in the primary proton beam. A possible solution that puts the NBB on the same final trajectory as the WBB was given in TM-1946.

The proposed NBB design uses a lithium lens in the first stage and dipoles, quadrupoles and collimators in the second stage. By itself, the lithium lens produces a large angular divergence as well as a large momentum acceptance. The second stage is added to select dp/p, to dump the primary protons, and to decrease the angular divergence. The schematic of the design is given in Figure 7. The optics consist of:

(1) point to parallel--target through lithium lens,
(2) parallel to point--first doublet to momentum slit,
(3) point to parallel--momentum slit through 2nd doublet.

The first bending magnet separates the secondary beam from the primary protons and also gives a dp/dx correlation at the momentum slit. Even at 60 GeV/c, the primary protons are separated from the secondaries by more than an inch outside the acceptance. The second bending magnet, along with the quadrupole near the slit recombine the momenta. The dipoles bend in the same direction giving a total of 14 mr. To keep the wide-band background small, it is important to have an insert in the dipole following the target that collimates the beam. It also serves to limit the radiation on the downstream magnets.

The NBB can be tuned to various momenta, by changing the focal length of the lithium lens, keeping its gradient constant, and then scaling the currents in the dipoles and quadrupoles. This retains the highest acceptance while moving only the target position, keeping the lithium lens and downstream magnets at fixed positions. The optics of the primary protons are adjusted to move the waist in Z as the target location moves. Tunes for 30, 45 and 60 GeV/c parent particles have a center-of-target to upstream end of the lithium lens distance of 1.985 ft. 3.063 ft. and 4.141 ft respectively. Since the depth of field for a lithium lens is very short compared to the Double Horn System, the NBB target drill be different from the WBB design. It will be a shorter and higher density--about one interaction of nickel, like the Fermilab pbar target.

NUADA runs at 30, 45 and 60 GeV/c give the muon neutrino event rates and are plotted in Figure 8 for the long baseline. Absorption in the lithium has been taken into account. At this time only the long baseline has expressed an interest in NBB running, however for completeness, the NuMu total event rates for the short baseline are 4.07E5, 4.50E5 and 2.87E5 at 30, 45 and 60 GeV/c tunes.

6 Appendix A

NUADA has been modified to put in more accurate values for the total(includes quasi-elastics) muon neutrino cross section when it converts flux to events. The default value of 0.67*E is low by more than 10% for energies below 10 GeV, and is over 30% low at 1 GeV. Table 2 lists the cross sections[5] versus energy that has been used to calculate the event rates. Graphically the NuTau/NuMu ratio is shown in Figure 9. The NuTau/NuMu ratio of cross sections for maximal mixing [$\sin^2(2\theta) = 1.$] is 1/2 for the average oscillation probability. The values plotted are therefore

1/2 those listed in reference[6]. Adding the quasi-elastics will make a slight increase in the ratio.

It is important to run NUADA with more than one bin into which the target is divided(in Z). Otherwise there may be steep fall-offs in the flux as a function of energy. I have typically run with five divisions for the NBB, and 12 divisions for the WBB; i.e., the line in the file has "TARGET 5".

References

[1] D. A. Crane et al., "Status Report: Technical Design of Neutrino Beams for the Main Injector (NuMI)." (Batavia, IL.: Fermilab Internal Report TM-1946, 1995).

[2] R. Bernstein et al., "Conceptual Design Report: Main Injector Neutrino Program." (Batavia, IL.: Fermilab Internal Report version 1.1, June 14, 1991).

[3] S. O'Day and K. Anderson, "Electromagnetic, Thermal and Structural Analysis of the Fermilab Antiproton Source Lithium Lens." (Dallas, TX.: Proceedings of the 1995 IEEE PAC Conference).

[4] D. C. Carey and V. A. White, "NUADA, The Fermilab Neutrino Flux Program." (Batavia, IL.: Fermilab Internal Report, June 1,1975). See modifications in Appendix A.

[5] The NuMu total cross section values are from Soudan 2. H. Gallagher, (Batavia, IL.: Fermilab Internal Report NuMI-112, 1995). Basically this uses two data sets, one from low energy and the other from high energy; 1-10 GeV is from N. J. Baker et al., Physics Rev. D 25, 617(1982), and from 40-250 GeV from R. Blair et al., Phys. Rev. Letters 51, 343(1983).

[6] B. P. Roe, "Calculation of Tau Neutrino Cross Sections." (Ann Arbor, Michigan: University of Michigan Internal Report UM-HE94-10, June 1, 1994).

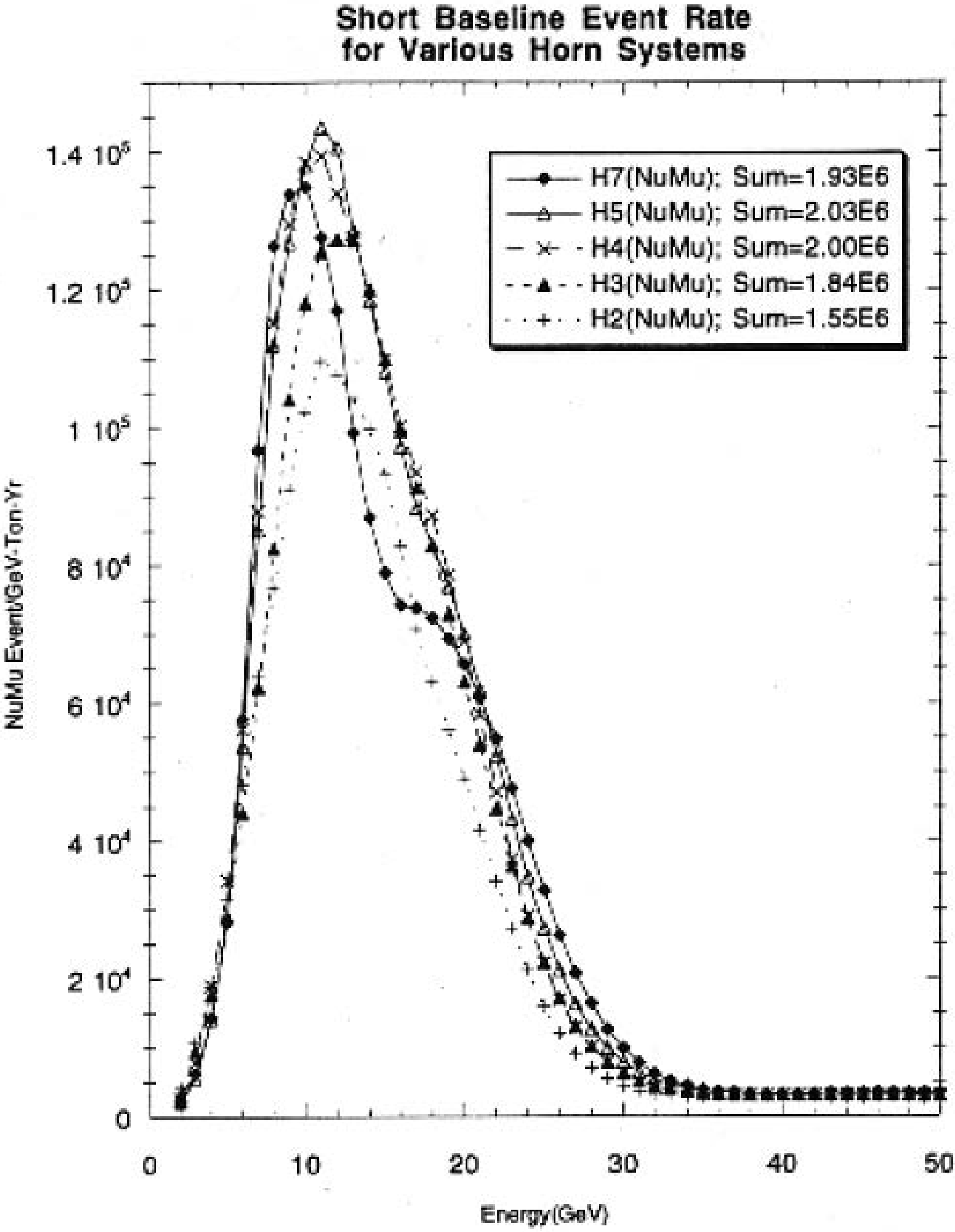

Short Baseline Event Rate
for Various Horn Systems
H7(NuMu); Sum=1.93E6
H5(NuMu); Sum=2.03E6
H4(NuMu); Sum=2.00E6
H3(NuMu); Sum=1.84E6
H2(NuMu); Sum=1.55E6
NuMu Event/GeV-Ton-Yr
Energy(GeV)
0
2 10⁴
4 10⁴
6 10⁴
8 10⁴
1 10⁵
1.2 10⁵
1.4 10⁵
0
10
20
30
40
50

Figure 1

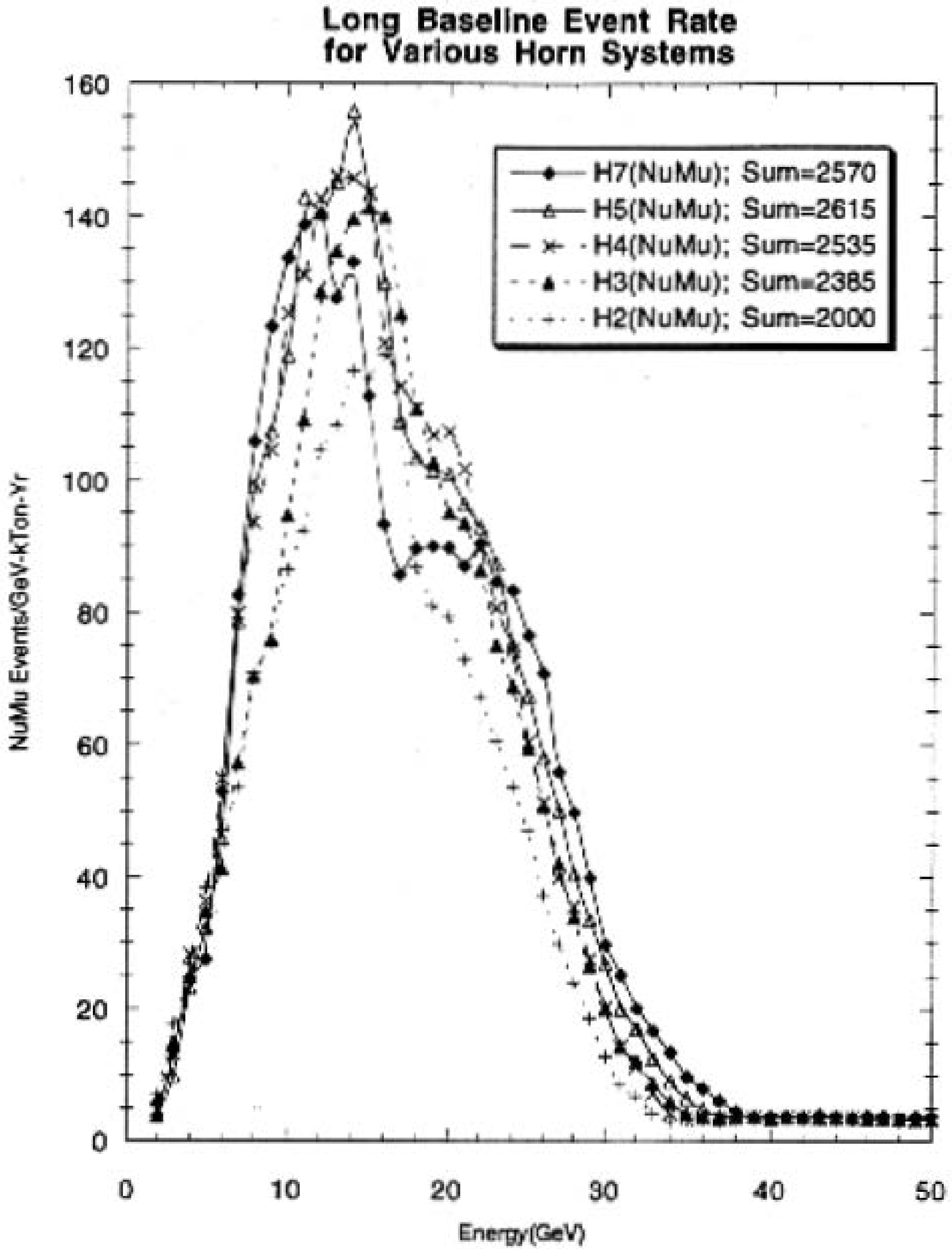
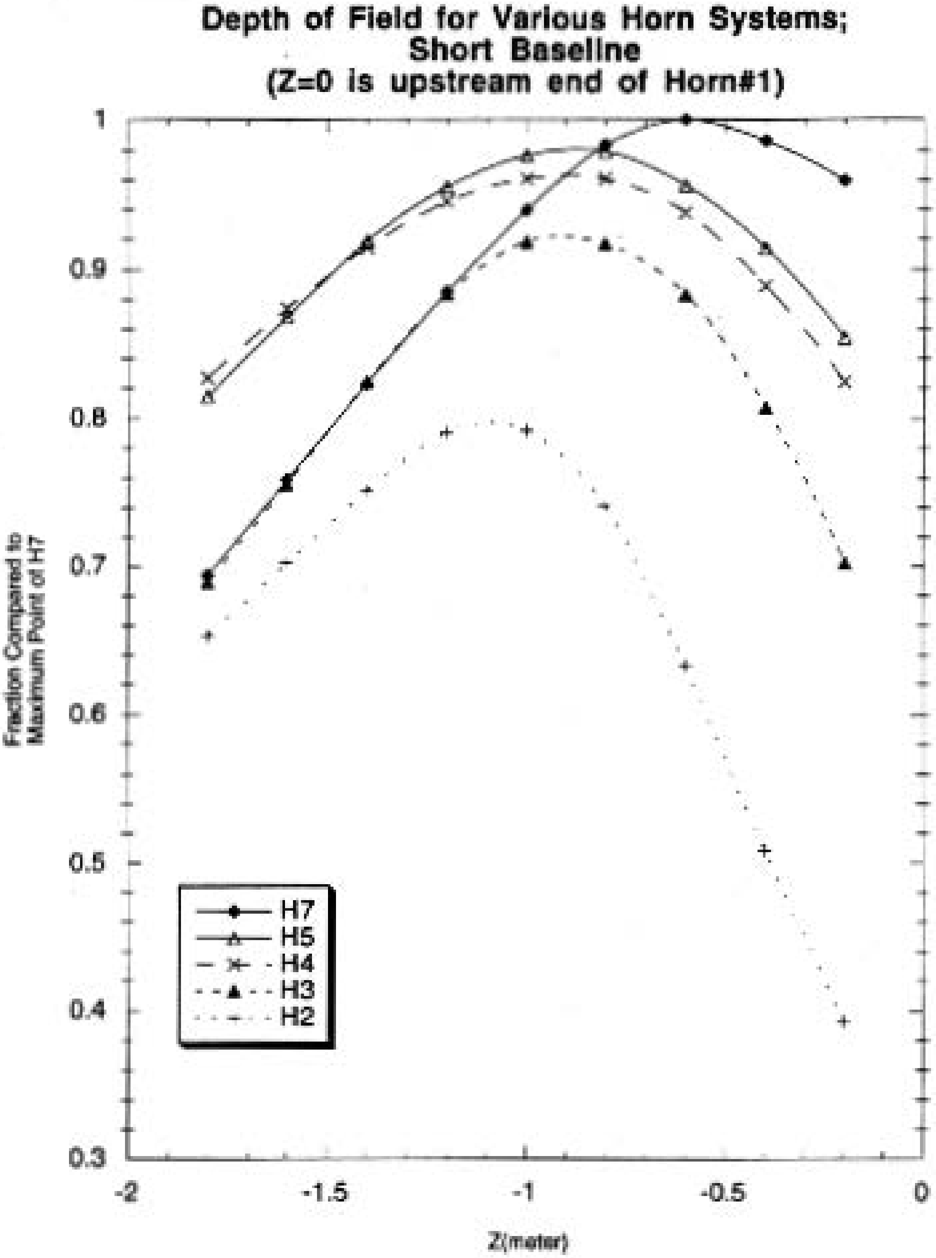

Long Baseline Event Rate
for Various Horn Systems
H7(NuMu); Sum=2570
H5(NuMu); Sum=2615
H4(NuMu); Sum=2535
H3(NuMu); Sum=2385
H2(NuMu); Sum=2000
NuMu Events/GeV-kTon-Yr
Energy(GeV)
0
20
40
60
80
100
120
140
160
10
30
50

Figure 2



Depth of Field for Various Horn Systems;
Short Baseline
(Z=0 is upstream end of Horn#1)
Fraction Compared to Maximum Point of H7
Z(meter)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
-2
-1.5
-1
-0.5
0
H7
H5
H4
H3
H2

Figure 3

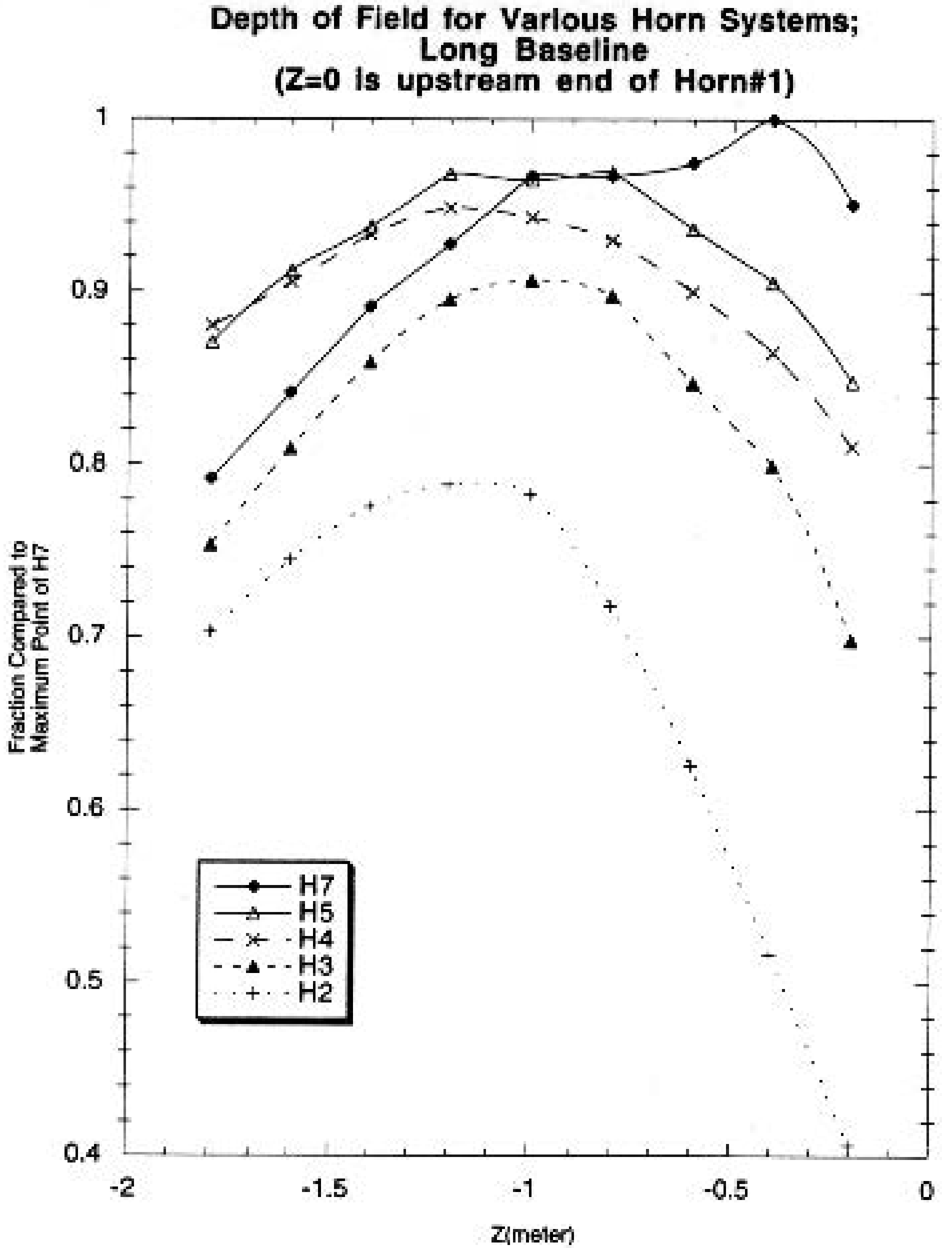
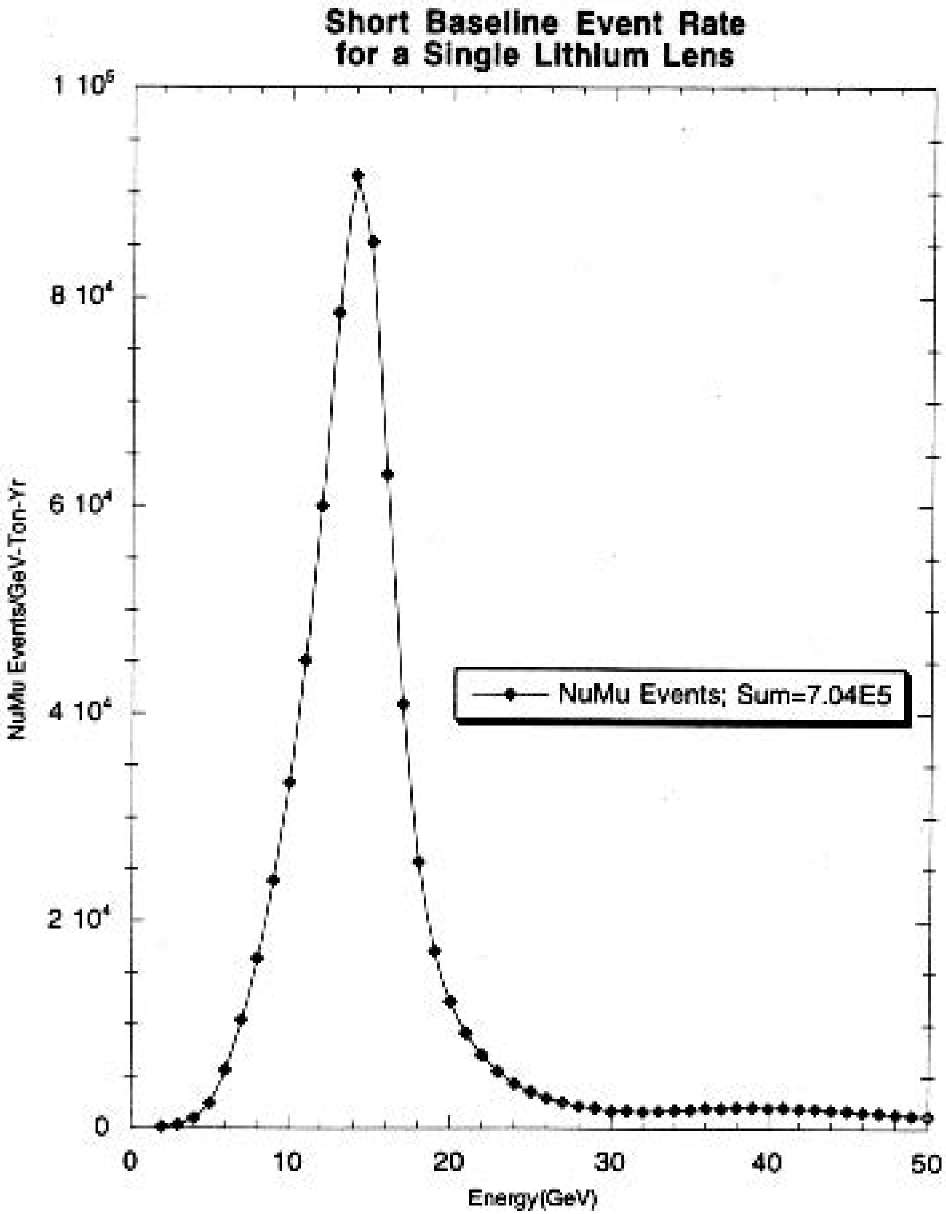

Depth of Field for Various Horn Systems;
Long Baseline
(Z=0 is upstream end of Horn#1)
Fraction Compared to Maximum Point of H7
Z(meter)
H7
H5
H4
H3
H2
1
0.9
0.8
0.7
0.6
0.5
0.4
-2
-1.5
-1
-0.5
0

Figure 4



Short Baseline Event Rate
for a Single Lithium Lens
NuMu Events/GeV-Ton-Yr
Energy(GeV)
NuMu Events; Sum=7.04E5
1 10^5
8 10^4
6 10^4
4 10^4
2 10^4
0
0
10
20
30
40
50

Figure 5

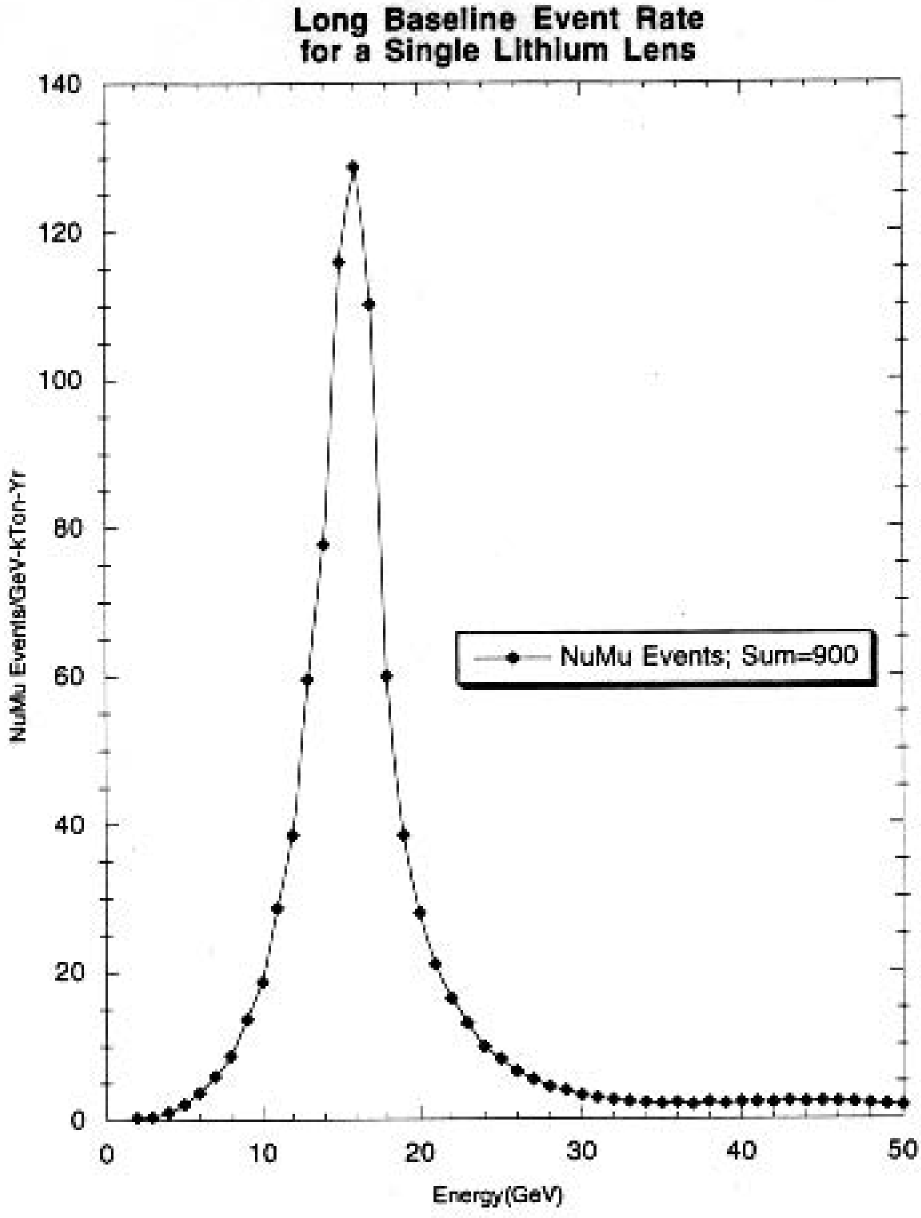

Long Baseline Event Rate
for a Single Lithium Lens
NuMu Events; Sum=900
NuMu Events/GeV-KTon-Yr
Energy(GeV)
0
20
40
60
80
100
120
140
0
10
20
30
40
50

Figure 6

NBB OPTICS

r=1cm Lens

(Not to Scale)

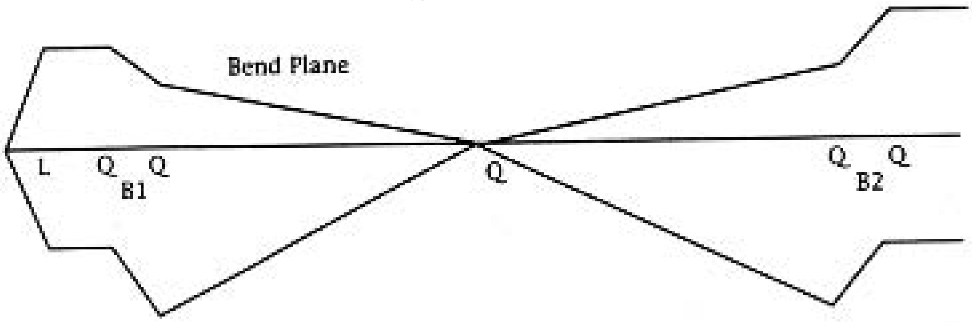


Figure 7

NBB at 45 GeV

Center of Target		
Drift	3.063 ft	
Lithium Lens	0.500 ft	100 kG/cm
Drift	12.0 ft	
Quad	4.00 ft	+1.54322 kG/cm
Drift	3.00 ft	
Bend	3.25 ft	+11.2407 kG
Drift	3.00 ft	
Quad	4.00 ft	-2.00832 kG/cm
Drift	39.0 ft	
Variable Slit(Dump)	Aperture=3.5 cm	
Quad	4.00 ft	+1.54344 kG/cm
Drift	52. 0 ft	
Quad	4.00 ft	-1.79131 kG/cm
Drift	3.00 ft	
Bend	3.25 ft	+10.1100 kG
Drift	3.00 ft	
Quad	4.00 ft	+1.43495 kG/cm

Quadrupole apertures have r=5 cm; bends are 10 cm x 10 cm.

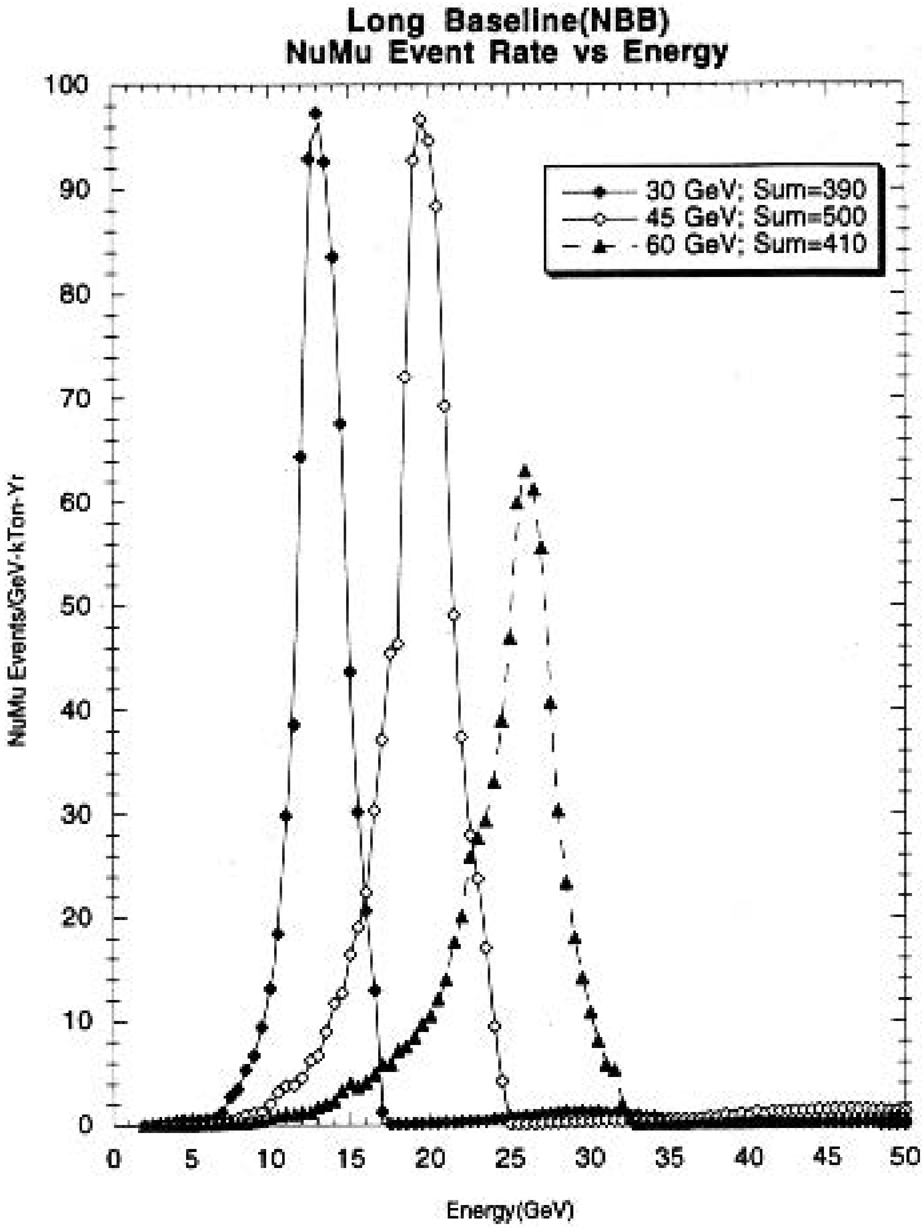

Long Baseline(NBB)
NuMu Event Rate vs Energy
30 GeV; Sum=390
45 GeV; Sum=500
60 GeV; Sum=410
NuMu Events/GeV-kTon-Yr
Energy(GeV)
0
10
20
30
40
50
60
70
80
90
100
5
15
25
35
45

Figure 8

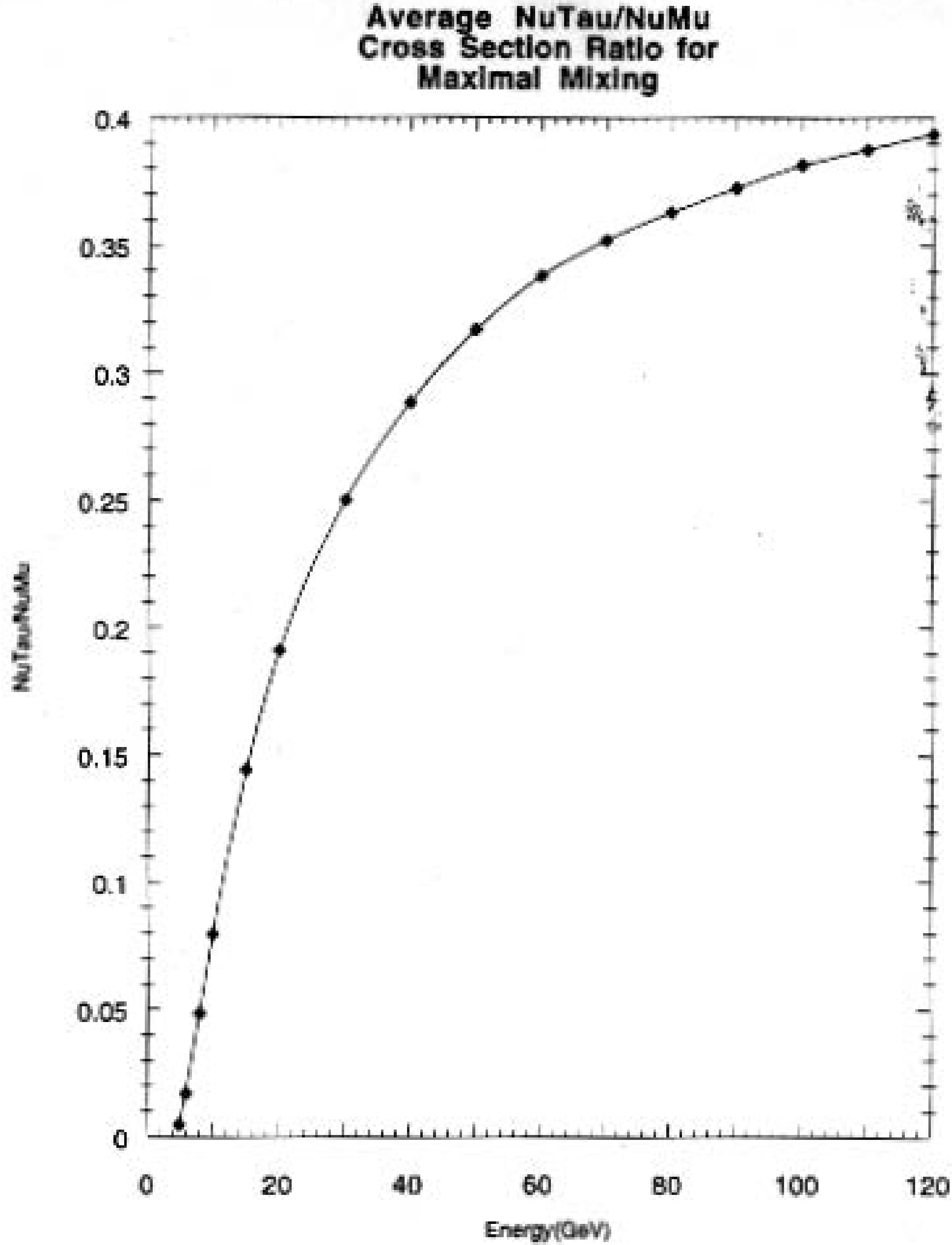

Average NuTau/NuMu
Cross Section Ratio for
Maximal Mixing
NuTau/NuMu
Energy(GeV)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
20
40
60
80
100
120

Figure 9

Table 1

Name	H7	H5	H4	H3	H2
Horn #1	4 meter	2 meter	2 meter	1.5 meter	1 meter
Z1(meter)	0.00	0.00	0.00	0.00	0.00
r1(cm)	6.2	3.4	3.6	2.3	1.6
Z2(meter)	2.00	2.00	2.00	1.50	1.00
r2(cm)	1.0	1.0	1.0	1.0	1.0
Z3(meter)	4.00	2.03	2.03	1.53	1.03
r3(cm)	6.2	1.0	1.0	1.0	1.0
Horn #2	3 meter	3 meter	2 meter	1.5 meter	1 meter
Z4(meter)	19.00	20.00	22.00	22.00	22.00
r4(cm)	15.6	17.8	14.5	11.0	8.2
Z5(meter)	22.00	23.00	24.00	23.50	23.00
r5(cm)	2.6	2.5	2.5	2.5	2.5
Z6(meter)	-	23.03	24.03	23.53	23.03
r6(cm)	-	2.5	2.5	2.5	2.5

Table 2

Muon Neutrino Cross Section vs. Energy(x 1E-38 square cm)

Energy	Cross Sec	Energy	Cross Sec	Energy	Cross Sec
1.0	1.0120	41.0	28.323	81.0	54.603
2.0	1.8426	42.0	28.987	82.0	55.259
3.0	2.5901	43.0	29.651	83.0	55.914
4.0	3.2784	44.0	30.316	84.0	56.570
5.0	3.9696	45.0	30.975	85.0	57.226
6.0	4.6656	46.0	31.633	86.0	57.881
7.0	5.3518	47.0	32.291	87.0	58.537
8.0	6.0330	48.0	32.949	88.0	59.192
9.0	6.7230	49.0	33.607	89.0	59.848
10.0	7.4512	50.0	34.265	90.0	60.504
11.0	8.1793	51.0	34.923	91.0	61.159
12.0	8.8769	52.0	35.581	92.0	61.815
13.0	9.5712	53.0	36.239	93.0	62.471
14.0	10.265	54.0	36.897	94.0	63.126
15.0	10.944	55.0	37.555	95.0	63.782
16.0	11.623	56.0	38.212	96.0	64.437
17.0	12.303	57.0	38.868	97.0	65.093
18.0	12.977	58.0	39.524	98.0	65.749
19.0	13.646	59.0	40.179	99.0	66.404
20.0	14.314	60.0	40.835	100.0	67.060
21.0	14.982	61.0	41.490	101.0	67.716
22.0	15.650	62.0	42.146	102.0	68.371
23.0	16.319	63.0	42.802	103.0	69.027
24.0	16.988	64.0	43.457	104.0	69.682
25.0	17.656	65.0	44.113	105.0	70.338
26.0	18.325	66.0	44.769	106.0	70.994
27.0	18.993	67.0	45.424	107.0	71.649
28.0	19.662	68.0	46.080	108.0	72.305
29.0	20.330	69.0	46.736	109.0	72.961
30.0	20.997	70.0	47.391	110.0	73.616
31.0	21.665	71.0	48.047	111.0	74.272
32.0	22.333	72.0	48.702	112.0	74.928
33.0	23.001	73.0	49.358	113.0	75.583
34.0	23.669	74.0	50.014	114.0	76.239
35.0	24.337	75.0	50.669	115.0	76.894
36.0	25.001	76.0	51.325	116.0	77.550
37.0	25.665	77.0	51.981	117.0	78.206
38.0	26.330	78.0	52.636	118.0	78.861
39.0	26.994	79.0	53.292	119.0	79.517
40.0	27.658	80.0	53.947	120.0	80.173