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NuMI Wide Band Neutrino Beam Alignment Requirements, Calculated using a Modified Version of the PBEAM Monte Carlo Program

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ABSTRACT

Detailed design of NuMI wide band neutrino beam requires calculating the size of deviations of various beam element parameters from nominal that can be allowed without significantly affecting the result of the neutrino energy spectrum oscillation test. Early knowledge is vital if any of these tolerances can not be met with standard techniques. Modifications were made to the PBEAM monte carlo program to efficiently calculate the muon neutrino spectrum in the far detector (735 km) and obtain 0.5% flux precision for one GeV energy bins in an acceptable amount of computer time. Results show that horn magnetic field must be constant (throughout each proton beam spill and from spill to spill) to 0.4% or an accurate monitoring system is required. Oscillations should be looked for in the FAR/NEAR ratio, rather than in the far detector energy spectrum only.

1. Introduction

The goal of this study is to calculate the effect of translations and rotations of the three focussing horns of the NuMI wide band neutrino beam, the proton beam and target (moving together as a unit), and proton beam (moving relative to the target) as well as variations of the horn magnetic field and proton beam transverse width on the neutrino energy spectra at the near and far detectors. The accuracy of the MINOS neutrino energy spectrum oscillation test is assumed to be degraded unless the muon neutrino flux energy spectrum in far detector, assuming no oscillations, is known to 2% for one GeV bins. Other evaluation criteria are clearly possible, such as further restricting the range of far detector neutrino energies used in oscillation tests or weighting the tolerance evaluation by the expected event rate as a function of energy, but these will not be considered further here. The displacement of a beam element parameter which gives a 2% flux change in the worst one GeV neutrino energy bin, in the range 1 to 80 GeV, is given in this note.

The monte carlo program PBEAM [1], written by Dr. Noel Stanton to calculate the neutrino beam for the COSMOS experiment, was selected for this study. The original version of this program distributes primary beam protons in the production target and interacts them, yielding secondary pi and K mesons distributed according to published experimental data [2,3,4]. HBOOK [5] is used in the generator of these secondaries. Each meson is stepped through the magnetic fields of the three focussing horns and propagated through drift spaces between the horns and through the decay pipe until it is lost in the walls of the target enclosure or decay pipe, reaches the dump and is lost, or decays to yield a neutrino. Interactions of these mesons in the production target and interactions and multiple scattering in the horns are included. At the decay point, one specific neutrino is thrown and propagated downstream. If it hits the detector it is recorded in HBOOK histograms or an NTUPLE, otherwise it is discarded. Neutrinos from muon decay or from scraping (any hadron interaction other than the primary beam proton in the target) are not included, but these have a only a small effect on the muon neutrino spectrum above a few GeV.

Ten million primary protons can be calculated in a two hour run on a DEC Alpha (3000 Model 400), but there are a million times this number of protons in each expected pulse from the main injector. There is almost no chance a single neutrino will hit the MINOS far detector (3.5 m radius at 735 km) in a typical run, let alone enough to give better than 2% statistics in each one GeV energy bin between 1 and 80 GeV. The modifications needed for PBEAM to calculate alignment tolerances within a practical time are described in the next section. I call the modified version PBEAM_WMC.

The following two sections describe how alignment tolerances are obtained by analyzing the muon neutrino flux energy spectra calculated with PBEAM_WMC. Two detector positions are considered; the MINOS Far detector, at 735 km, and the presently planned position for the MINOS Near detector, 500 m beyond the end of the decay pipe (1300 m from the production target). These are followed by conclusions from these results.

Examples of the general and horn input files are given in the appendices. These serve both as a detailed record of the actual neutrino beam line used in the calculations and as a guide for anyone wishing to run the PBEAM_WMC program.

2. Modifications to PBEAM

One way to increase the number of monte carlo neutrinos at the far detector is to count all that are within a few hundred meters of the beam axis, not just the actual 3.5 m detector radius. However, this will induce errors in the calculated neutrino energy spectrum, see section 4. I have used the weighted monte carlo scheme developed by Rick Milburn for MINOS [6]. This uses the standard PBEAM up to the meson (pi or K) decay, then:

Standard	Weighted Monte Carlo
Throw one neutrino at the decay point and see if it will go through detector.	Calculate the probability a neutrino from this decay point will go through the detector
If yes, add it to the flux, if not discard it.	Add all neutrinos to the flux, weighted by this probability.

By making use of neutrinos from every meson decay, the weighted monte carlo is much more effective for the MINOS far detector.

With this weighting scheme, the neutrino flux is calculated at a point in the detector (in the note, at r=0 in the near detector). This is good for the far detector and studying variations with position in the near detector, but requires further calculation to find the average flux over a finite area in near detector.

PBEAM faithfully models the geometry and physics of a neutrino beam, so it produces many low momentum hadrons, which hit the beam enclosure walls before decaying or decay to wide angle low energy neutrinos with a low probability of reaching the detector, see figures 1a and b, and few high momentum hadrons which can decay to high energy neutrinos. Since it would require a two million hour computer run to calculate the same number of primary protons on target that are expected in just one beam pulse from the Main Injector, PBEAM can not duplicate the number of neutrinos in the actual beam and some departure from the "actual beam" model is unavoidable.

Since I am already weighting neutrinos for Milburn's scheme, I go further and modify the PBEAM hadron generator to produce fewer low momentum hadrons (but compensated by assigning a higher weight to each one) and more high momentum hadrons (each with a lower weight). For example, instead of tracking one hundred 1 GeV pi+'s through the beam line, I discard 99 of them and assign a weight of 100 to the remaining one, saving most of the computer time. Since the flux in a neutrino energy bin is the sum of the weights, it will be unchanged by this procedure (provided the weighting is done correctly). The number of events in the bin is adjusted to get the desired statical error for the flux calculation. I call this importance weighting.

In PBEAM, the number of hadrons generated per longitudinal momentum (Plong) bin has been proportional to the published cross sections [4]. For importance weighting, the number per bin is made constant (for bins below 90 GeV for the data in this note), and the Plong cross section is used as the weight for each bin. This is done separately for each of the 6 types of mesons. Perhaps another 20-30% of the computer time could be saved by more detailed tuning of the Plong weights, but this has not been done to date.

As an option, the overall number of any type of meson (for example K+) generated can be increased and the weight reduced to compensate. Another new option is to only generate decay channels which yield one type of neutrino (muon neutrinos in this note) and correct the flux by weighting.

For all these changes, the PBEAM event generator was modified to produce only mesons with the desired parameters, and weighting used to compensate for the ungenerated mesons. The result is less computer time used generating and then discarding tracks and more neutrinos in the detectors for the same length computer run.

PBEAM was accounting for secondary meson interactions in the target or horn material by calculating the interaction probability and then using it to randomly discard tracks. In order not to waste the computer time used to generate and track the meson, all are now retained and the probability of not interacting is used as a weight to multiply the other weights for the meson.

The result of these changes can be seen in figure 2a, which has over 5 times as many hadron decays as figure 1a, but was produced in the same length computer run. Figure 2b shows the ratio of decays (after importance weighting/before) for the two runs; note there are more events in the after run for all energies above 6 GeV. In the before case, many low energy hadrons were lost in the walls of the target enclosure before decaying and do not appear in figure 1a.

The percentage flux errors before and after important weighting for equal length computer runs are shown in figures 3a and b, note the factor of 10 change in the vertical scale. Figure 3c is the ratio of these two and gives the factor of improvement in the flux error. The error has been reduced for all energies above 6 GeV, usually by a factor of 10 or more, and is about 0.5% between 4 and 80 GeV. Importance weighting has effectively increased the throughput of PBEAM by almost two orders of magnitude.

Other changes to PBEAM were made for the segmented production target and to allow for horn and beam + target translations and rotations. Hadrons with Plong less than 0.5 GeV are cut. The weights are scaled to produce the neutrino flux (per m**2) from 10 million beam protons. To keep track of the many runs required, a few descriptive lines are automatically appended to a summary file at the end of each run.

Milburn recommended PBEAM track the hadrons to the decay point and then generate a NTUPLE. The weighting would then be applied with a fortran subroutine using PAW [7] and would not require another PBEAM run for a different detector position. I have found this not to be practical for this alignment study. Since the NTUPLE from a 130 minute DEC Alpha run is about 750,000 blocks, or 400 megabytes long, and many are needed for this alignment study, finding space to store them is difficult. The version of PAW on the Alphas here ran fortran subroutines very inefficiently; over an hour would be needed to process a full NTUPLE for a single detector position. I have chosen not to make the NTUPLEs (they can still be made as an option) and added production of the histograms needed for the alignment study to PBEAM_WMC.

The standard PBEAM_WMC run with 4 detector positions (250, 500, 1000 m past the end of the decay pipe, and 735 km) takes 130 minutes on a DEC Alpha (3000 Model 400) running VMS, and each additional detector position adds about 1 minute. A run is needed for each value of the shift of each beam line element parameter.

3. Analysis of the Muon Neutrino Energy Spectra

PBEAM_WMC is first run with all beam elements at their nominal values and positions ("onaxis"). This produces reference muon neutrino flux energy spectra at both the far and near detectors; these are stored by HBOOK as histograms which can later be read directly and analyzed by PAW [7]. We wish to find how big a change to one of the beam element parameters will produce a 2% flux change in the most affected one GeV bin in these spectra.

Next we select a parameter to investigate and guess an amount to vary it from its nominal value. For this example, we move both the upstream and downstream ends of the first focussing horn 4 mm in the same direction transverse to the beam axis ("Horn 1 X shift of 4 mm"), and use PBEAM_WMC to calculate the resulting spectra at both detectors.

PAW is used to read the file containing these two "displaced" spectra as histograms and the similar file with the onaxis data, and to further analyze these data. The displaced flux spectrum at the far detector is shown as the data points with errors in figure 4, along with the corresponding onaxis flux which is drawn as the line histogram. The largest fractional differences between the two spectra occur at about 30 Gev, a region where the flux is decreasing rapidly with neutrino energy.

Since it is difficult to make quantitative assessments directly from these flux plots, I next divide the flux (displaced) by the flux (onaxis) for each one GeV neutrino energy interval and display the quotient in figure 5a. A dashed line has been drawn for a flux ratio of 1.0, which would be the result if there were no change in the flux. It is now easy to pick out the largest fractional difference (in the interval 1 to 80 GeV), which occurs at 31 GeV. I find it convenient to fit the two bins between 30 and 32 GeV with one parameter and save the result and its error in PAW vectors for further analysis. Note that the horn 1 X shift by 4 mm has made a -13.0% change in neutrino flux at 31 GeV at the far detector. Figure 5b is a similar graph for the center (ie, at a radius of 0 in the transverse direction) of the near detector (500 m beyond the end of the decay pipe). Here, the change is -27.0% at 30 GeV.

There has been some hope that the spectra at both the far and near detectors would be equally affected by beam element perturbations, and the ratio of far/near flux would be less sensitive than either spectra. I therefore calculated RR, the ratio of these flux ratios:

$$RR = \frac{FAR(displaced)/FAR(onaxis)}{NEAR(displaced)/NEAR(onaxis)}$$

This is shown in figure 5c. The peak deviation of +19.6% is at 30 GeV. While some energy ranges (1-13, 42-69 GeV) do indeed show smaller deviations in RR than in FAR (top section figure 5a), RR is clearly worse in the sensitive 18-32 GeV range for an X shift of horn 1. These ranges do not change as the size of the X shift is reduced.

Since the deviations found above are all much larger than our desired limit of 2%, PBEAM_WMC was also run for horn 1 X shifts of 1, 2, and 3 mm and the resulting spectra analyzed as above. The value of the flux ratio at the far detector in the valley at 31 GeV is shown in figure 6a plotted against the horn 1 X shift in meters. The dashed line is our desired maximum deviation of 2% in the flux ratio. The fit to these data shows the flux ratio deviation is proportional to the square of the horn X shift, and a horn shift of 1.6 mm gives a 2% deviation in the flux ratio. Figure 6b is a similar fit at the near detector position. An addition term, in X shift to the fourth power, is needed for a good fit and finds that a horn shift of 0.9 mm gives a 2% deviation in the flux ratio.

Beam element changes which break the azimuthal symmetry of the WBB, such as this horn 1 X shift, should be measurable in the near detector. The lego plot in figure 7 gives the ratio of flux with a horn 1 X shift of 4 mm to flux with horn 1 on axis for each of 21 bins along the x axis (ie, transverse to the neutrino beam direction) of the detector. The large effect at 27 GeV changes sign as you move across the detector along the direction of the horn shift. Such an azimuthal asymmetry should clearly identify a large misalignment of a beam line element.

This analysis was also done for a reduction of 10% in the magnetic field in all three focussing horns and the results are shown in figure 8. The main features in the flux ratios at the far and near detectors are dips just above 30 and 90 GeV. Most neutrinos at the first dip come from the decay of high energy pi+; neutrinos at the second dip come from the decay of high energy K+. If the field in all three horns is increased 10%, increases appear at these two energies, indicating the nominal field in the horns is not strong enough to completely bend these highest energy mesons parallel to the beam axis. PBEAM_WMC was also run for all horn fields shifted to -5, +5, and +10% of nominal, and the effect of these shifts on the region just above 30 GeV fit with the results shown in figure 9. The dependence for field shifts is approximately linear.

In figure 8c, RR is shown for the -10% shift of the field in all horns. Except for a small range at 18 GeV, it is less sensitive to this shift than the flux ratios at the far and near detectors.

4. Alignment tolerances for the NuMI Wide Band Neutrino Beam

Table I shows the results for a variety of shifts in beam line element parameters. The first line gives the results for a horn 1 X shift of 4 mm; the analysis steps to obtain these were described in detail in the previous section. The entries under "Effect" give the largest percent change in flux in a one GeV neutrino energy bin (between 1-80 GeV) calculated by PBEAM_WMC for the actual shift (in this case 4 mm) used in the run.

"Allow" is the calculated shift that would result in a 2% flux change in this worst bin if it were input into a PBEAM_WMC run. In this example, it was obtained by a fit to the results of four PBEAM_WMC runs, using four different horn 1 X shifts, as described in the previous section. For entries without the word fit, "allow" is interpolated from the "Effect" found in the PBEAM_WMC run, assuming a linear dependence for the shifts in horn field or beam sigma which maintain the azimuthal symmetry of the beam, and a quadratic dependence for the asymmetric translations and rotations. These dependences were found to be rather good approximations in the fits described in the previous section.

All but 3 entries in table I (horn 1 X, Horn 1,2 Angle) have larger allowed shifts under RR, the FAR/NEAR ratio of ratios, than under FAR. In particular, we can tolerate over twice as large a shift in the magnetic field in all 3 horns if we look for neutrino oscillations in the FAR/NEAR ratio (ie, in RR) rather than the FAR detector alone.

Each entry in Table I uses the entire 2% flux change tolerance for the shift shown, ie, all other beam line element parameters are assumed to be at nominal values. Since it is likely that several parameters will be off-nominal at the same time, the shifts to give a 1% flux change are given in table II. The neutrino energy of the one GeV interval with the largest flux change is also given in table II; these are all close to 30 GeV (range 24-35 GeV). Referring back to the sign of the Effect in table I, we find that all the shifts, except for an increase in beam width and the unlikely increase in horn field, give flux dips in FAR and NEAR, and peaks in RR. This means that effects from (almost) all the various shifts will add linearly to produce a dip near 30 GeV and it is worthwhile to take measures to reduce each shift as much as possible.

The flux spectrum in the far detector as a function of the distance from the center of the neutrino beam is shown in figure 10. The tolerance for this shift is included in the tables. It is clear that accepting neutrinos several hundred meters away from the beam axis at the far detector to obtain enough rate with a conventional monte carlo program will induce errors in the energy spectrum. Use of the weighted monte carlo scheme developed by R. Milburn [6] has avoided this problem in the data presented here.

Similar data for the near detector 500 m beyond the end of the decay pipe is shown in figure 11. At 0.25 m from the center of the beam, there are almost 10% fewer events from 29 GeV muon neutrinos than at the center.

5. Conclusions

PBEAM, with the addition of the weighted monte carlo and importance weighting, provides a powerful tool to study the effects of shifts in the beam line elements of the NuMI wide band neutrino beam.

Beam+target and horn 1 X alignment will need to be done very carefully, but should be practical unless they vary with time or because of beam heating in the target and the 170 kA current through the horn.

Horn 1 angle and horn 2 & 3 alignment should be readily achievable

We will need to keep horn current constant to 0.4% during the pulse or monitor horn current and protons on target through out the pulse for every pulse and then use this information to calculate the muon neutrino energy spectra in the near and far detectors.

This study indicates we should look for oscillations in the FAR/NEAR ratio (RR), rather than in the far detector energy spectrum only.

If an oscillation dip is found in RR or the detector at about 30 GeV, we should consider a confirming run at a proton beam momentum different from 120 GeV/c.

References

1. PBEAM by Noel Stanton, see P-875: A Long-baseline Neutrino Oscillation Experiment at Fermilab, 33 (1995) for a description

2. Particle Data Group, Phys. Lett. B 204, 121 (1988)

3. Barton, D. S., et. al, Phys. Rev. D 27, 2580 (1983)

4. Brenner, et. al, Phys. Rev. D 26, 1497 (1982)

5. HBOOK, Version 4.15, CERN Program Library Long Writeup Y250 (1992)

6. Milburn, R. H., NuMI-B-109 Note (1995)

7. PAW - Physics Analysis Workstation, Version 2.03, CERN Program Library Long Writeup Q121 (1993)

Table I

Changes in the muon neutrino flux caused by shifts (from nominal) of beam line element parameters. "Effect" is the largest flux change in a one GeV neitrino energy interval (in the range 1 to 80 GeV) caused by the shift, and "allow" is the shift which would give a 2% Effect. These data are for one parameter shift at a time, ie it is assumed that all other beam line elements are at their nominal values.

Element	Change	by	FAR Flux(x)/Flux(0) Effect(%)	FAR allow	NEAR Flux(x)/Flux(0) Effect(%)	NEAR allow	RR=FAR/NEAR Effect(%)	RR allow
Horn 1	X	4mm	-13.0		-27.0		+19.6	
		fit		1.6mm		0.9mm		1.1mm
Horn 2	X	4	-2.6	3.5	-2.6	3.5	+2.1	3.9
Horn 3	X	4	-0.9	5.8	-1.3	5.0	+0.9	6.0
Horn 1	Angle	4mm	-5.7	2.4mm	-12.9	1.6mm	+9.5	1.8mm
Horn 2	Angle	4	-2.1	3.9	-2.9	3.3	+3.3	3.1
Horn 3	Angle	4	-1.0	5.7	-0.7	6.8	+0.6	7.3
Beam+Tg	UpStr	2mm	-12.8	0.79mm	-17.6	0.67mm	+9.3	0.93mm
Beam+Tg	X	2	-6.1	1.15	-11.0	0.85	+5.6	1.20
Beam+Tg	Angle	2	-18.7	0.65	-21.4	0.61	+9.8	0.90
Far Det	X	75 m	-2.2	71 m				
+500m	X	.25m			-9.4			
		fit				.11m		
Horn123	Field	-10%	-45.5		-52.6		+31.5	
		fit		0.39%		0.31%		0.84%
Horn 1	Field	-10	-20.8	0.96	-24.5	0.82	+13.6	1.47
Horn 2	Field	-10	-13.5	1.48	-16.4	1.22	+6.5	3.1
Horn 3	Field	-10	-16.8	1.19	-19.9	1.01	+8.6	2.3
Beam #	Sigma	+25%	+2.1	24.%	+2.0	25.%	+1.3	38.%
Beam #	Sigma	-25	-3.5	14.	-2.9	17.	-1.6	31.

Notes:

X — Shift upstream(US) and downstream(DS) ends in the same direction transverse to the neutrino beam axis

Angle — Shift US and DS ends in opposite directions

Upstr — Shift US end only

Field — Horn magnetic field (proportional to horn current)

Sigma — Primary proton beam width. exp(-.5(r/sigma)**2) is the fraction of protons at radii > r.

With a 2mm radius target and 0.89mm nominal beam width, 91.99% of the protons will be inside the target radius and have a chance of interacting. If the beam width (Sigma) is increased to 1.11mm (+25%), only 80.27% of the protons will have r<2mm; this is 87.26% of the nominal case. If the beam width is decreased to 0.67mm (-25%), 98.83% of the protons will have r<2mm; this is 107.44% of the nominal case. Entries for the FAR and NEAR detector effects are relative to this overall flux change of 87.26% or 107.44%

Table II

Shift of beam line element parameters which would give a 1% flux change in the most affected one GeV neitrino energy interval in the range 1 to 80 GeV. The neutrino energy of this interval is also given. Two (or possibly more) beam line elements may have the shifts shown here without exceeding the 2% flux change requirement.

Element	Shift	FAR Flux(x)/Flux(0)		NEAR Flux(x)/Flux(0)		RR=FAR/NEAR Ratios	
		Shift	Energy(GeV)	Shift	Energy(GeV)	Shift	Energy(GeV)
Horn 1	X	1.1mm	31	0.6mm	30	0.8mm	30
Horn 2	X	2.5	28	2.5	25	2.8	24
Horn 3	X	4.1	33	3.5	29	4.2	29
Horn 1	Angle	1.7mm	28	1.1mm	31	1.3mm	31
Horn 2	Angle	2.8	28	2.3	34	2.2	34
Horn 3	Angle	4.0	34	4.8	34	5.2	30
Beam+Tg	UpStr	0.56mm	33	0.47mm	31	0.66mm	30
Beam+Tg	X	0.81	31	0.60	30	0.85	30
Beam+Tg	Angle	0.46	34	0.43	32	0.64	31
Far Det	X	51 m	30				
+500m	X			0.08m	29		
Horn 123	Field	0.19%	33	0.16%	31	0.42%	30
Horn 1	Field	0.48	35	0.41	32	0.74	31
Horn 2	Field	0.74	34	0.61	32	1.54	31
Horn 3	Field	0.60	33	0.50	31	1.16	26
Beam #	Sigma	9.4%	35	10.5%	35	17.%	32

Changing the beam width changes the fraction of protons passing through the target and hence the overall neutrino flux. Effects on this line are relative to this new overall flux. See Notes at the end of Table I.

APPENDIX I

General PBEAM_WMC Input File
(for the standard "onaxis" run described in this note)

```
******************  File starts with the next line  **************************
 Data file NEUBM_D8.DAT for program PBEAM_WMC ** AJM3H
 8 Segment pencil carbon target, from pink book (cold)
  TGZSTR* TGTLEN  TGTRAD  TGTDEN  TGTANO  TGTZNO  TGNSEG  TGLSEG  TGTMTL
   -1.60    1.56   0.002    1.81    12.0     6.0      8.   0.125      C
 Variables to specify decay region
  DCYLEN DCYRAD1 DCYRAD2 DCYRAD3 DCYZDN1 DCYZDN2 DCYZDN3   RLOSS
    800.    0.26    1.00   -1.00   43.63    800.    800.    0.425
 Variables to specify detector for detailed transverse grid histogram
  DETECZ  DETHWX  DETHWY  DETTHK  DETDEN
   1300.   0.500   0.500  14.826   3.815
 specify beam, secondary min. momentum, sec./interaction, gen only spec Nu(1-4)
    PBM    SIGBM  ENEUMN  MulGen  NuType
   120.   .00089     0.5       7       1
 Apply importance Weight up to hadron longitudinal momentum of ~(Iwt*PBM)/400
 Secondary Hadron            PI-     PI+      K+      K-      K0     K0B
 1=-2GeV(none), 400=PBM      300     300     300     300     300     300
 Multiply generation by      1.0     1.0     4.0      1.0  0.125     .02
 Variables to specify horn
  LHORN   ........ HRNFIL ..............  HRNDEN  HRNANO  HRNRLN
      T   HORN_AJM3H.DAT                    2.70    27.0   24.01
 Offsets (m) at Up & Downstream ends of (Beam), Beam & Target, and Horn Pairs
                  X Upstr X Dnstr Y Upstr Y Dnstr
 Beam *inactive*     0.0     0.0     0.0     0.0
 Beam & Target       0.0     0.0     0.0     0.0
 Horn Pair 1      0.0000  0.0000     0.0     0.0
 Horn Pair 2      0.0000  0.0000     0.0     0.0
 Horn Pair 3      0.0000  0.0000     0.0     0.0
 # of protons on target, control diagnostic printout, make Ntuple, Hist select
      NBM   NPDMP  LHPRNT LNTUPLE  LHopts  NHopts
  5500000       0       F       F TTFFFFF 2000000
******************  File ends with the previous line  **************************
```

Notes:

Dimensions are in meters
RLOSS, DETTHK, DETDEN are inactive

Since DCYRAD3 is negative, the optional third cylinderical decay pipe boundary is not used in this run.

Mulgen secondary hadrons will be generated for each of the NBM protons which interact in the target. The weights are adjusted to give the same flux as if the multiplicity from the published data and 10 million protons were used

If NuType is 1 (or 2,3,4), only numu (nubmu, nue, nube) will be generated.
For any other value all four neutrino types will be generated.

The horn file (Appendix II) uses two elements to specify each of the 3 horns,
Offsets are applied to each horn (pair of elements).

```
There are 7 logical (LHopts) and 7 one digit inputs to select the histograms
that will be generated. Energy spectra histograms at the 4 detector
positions are always produced. Currently, the only active choices are:
 LHopts(1)=T Importance weight tuneup hists at Z=1300m (+500m)
 LHopts(2)=T 21 hists at Z=DETECZ  from -DETHWX to +DETHWX
 LHopts(3)=T 441 hists at Z=DETECZ from -DETHWX to +DETHWX, -DETHWY to +DETHWY
For the last two options, NHopts(1) must be 0, unless you know the neutrino
distribution is symmetric in X and Y (use 2 to save time), or Y only (use 1).
```

APPENDIX II

Horn Input File

```
    A       B      C       D      E       F        G       H       I          J
******************  File starts with the next line  **************************
   6  HORN_AJM3H.DAT   New AJM horn (thin) , but 170kA  5 Dec 95
   0.000   1.600  0.0290  0.0100 0.00200 0.00200  0.2500  0.2927  0.0340 170000.
   1.600   0.030  0.0100  0.0100 0.00300 0.00300  0.2500  0.0696  0.0340 170000.
   7.900   2.500  0.1600  0.0200 0.00200 0.00200  0.2500  0.0170  0.0340 170000.
  10.400   0.030  0.0200  0.0200 0.00300 0.00300  0.2500  0.0696  0.0340 170000.
  41.100   2.500  0.2358  0.0400 0.00200 0.00200  0.2500  0.2927  0.0340 170000.
  43.600   0.030  0.0400  0.0400 0.00300 0.00300  0.2500  0.1846  0.0340 170000.
******************  File ends with the previous line  **************************
```

Notes:
  Dimensions are in meters
  The 6 at the beginning of the first line is NHORNS =
     Number of horns or lips in this configuration

Parameters for each horn (or lip):

```
A  ZUP   Z coordinate of start of horn
B  ZLEN  Length of horn

C  RUP   Radius at upstream end
D  RDN   Radius at downstream end

E  THKUP Wall thickness at upstream end
F  THKDN Wall thickness at downstream end

G  RMAX  Radius beyond which no tracking occurs
H  PPERP Pt Kick = 0.3 * B * ZLEN at MAX(RUP,RDN) ***INACTIVE, not correct above

I  BB    mu0 * CURR /( 2. * pi)
J  CURR  Current needed to produce PPERP          ***INACTIVE, but correct above
```

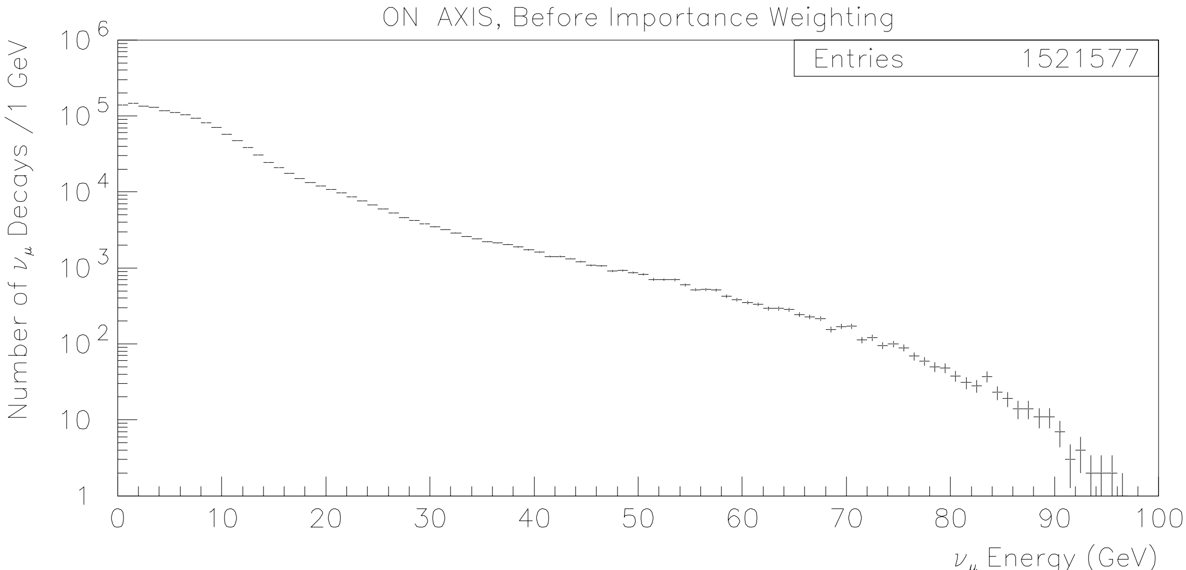


Fig. 1a, Number of Decays at +500m, R=0

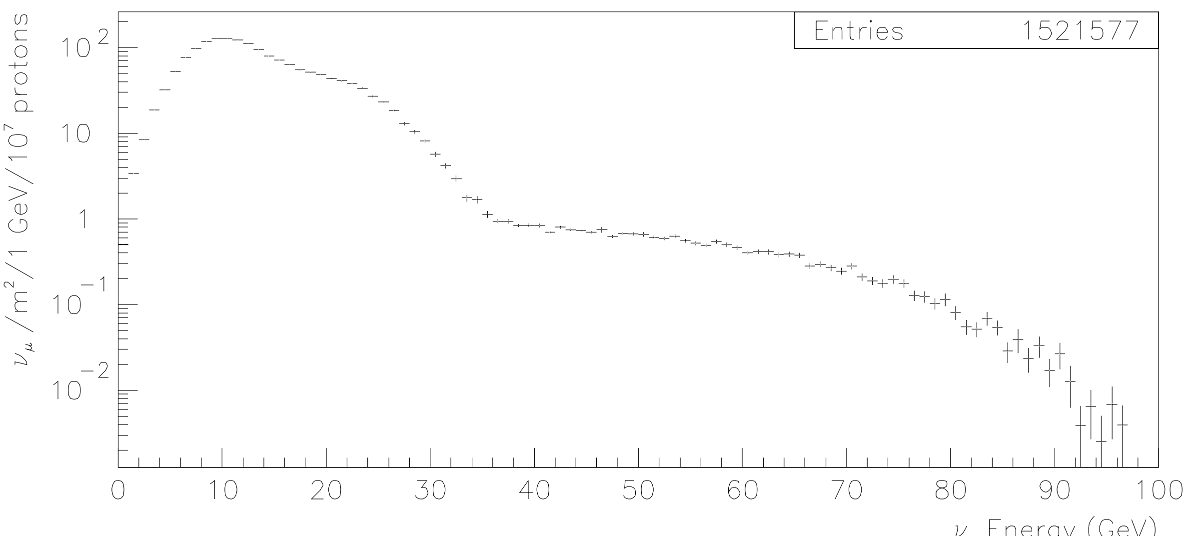


Fig. 1b, FLUX at +500m, R=0

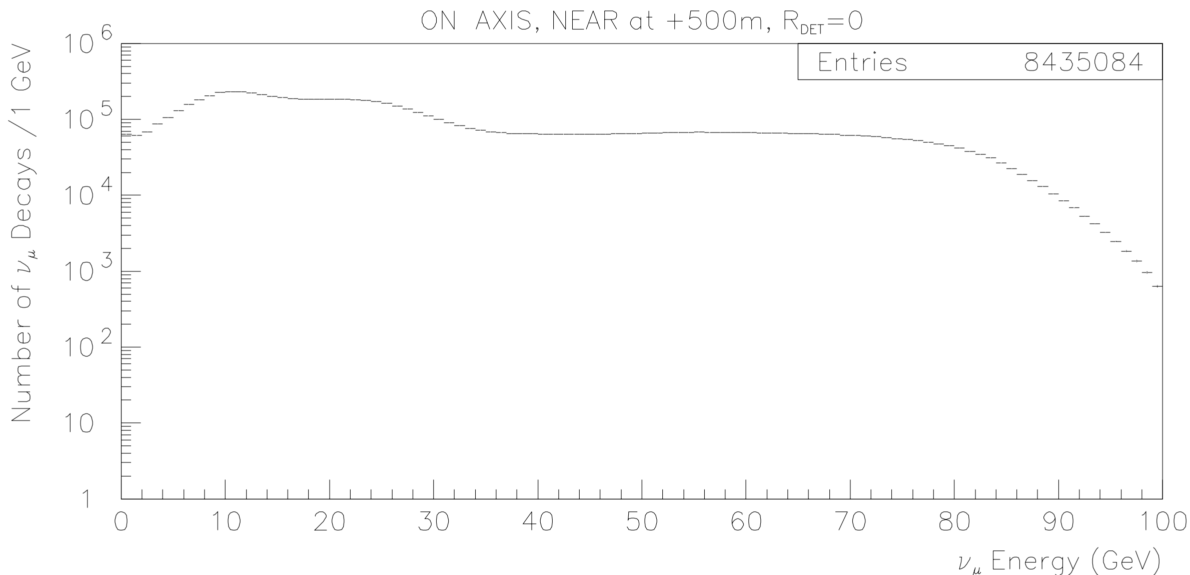


Fig. 2a, Number of Decays After Importance Weighting

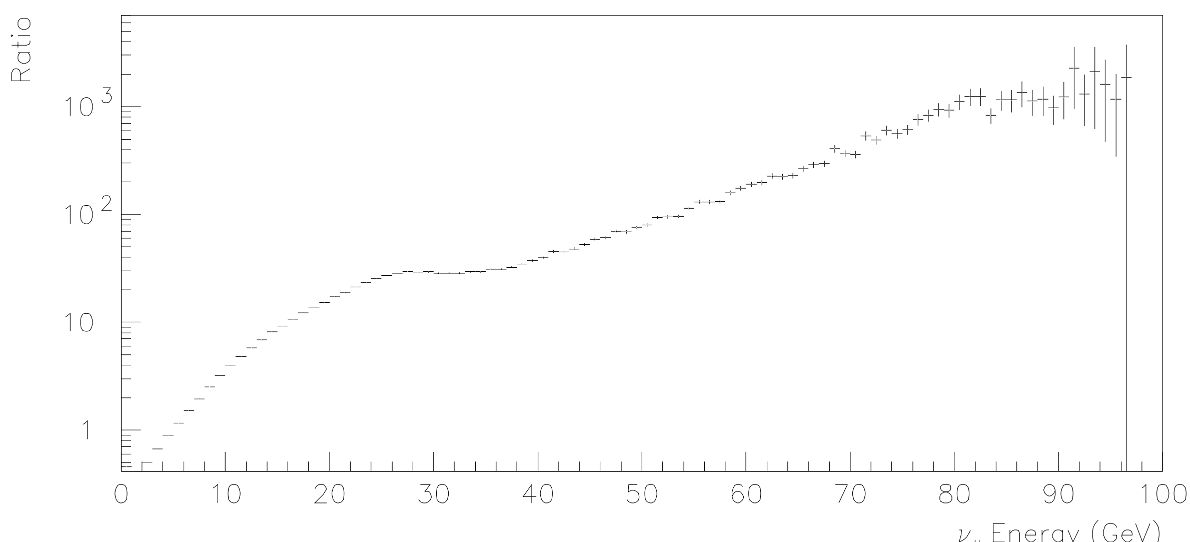


Fig. 2b, Number of Decays After Importance Wt./Before

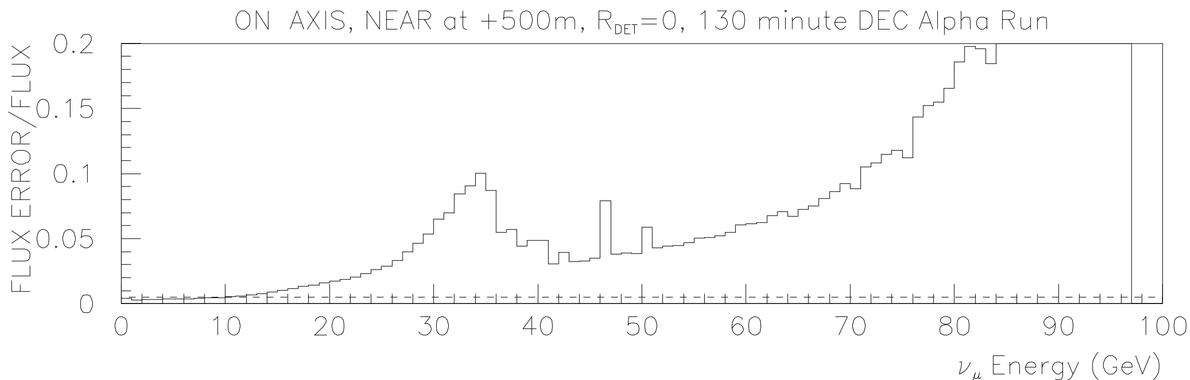


Fig. 3a, Fractional FLUX ERROR, Before Importance Weighting

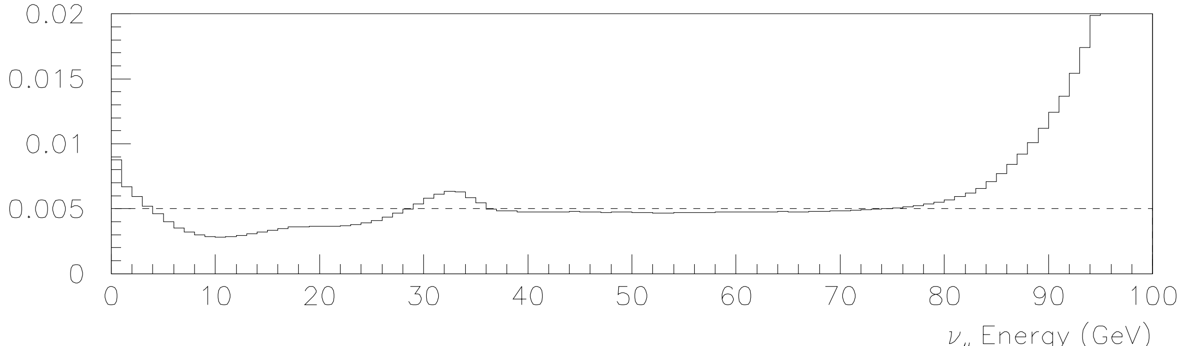


Fig. 3b, Fractional FLUX ERROR, After Importance Weighting

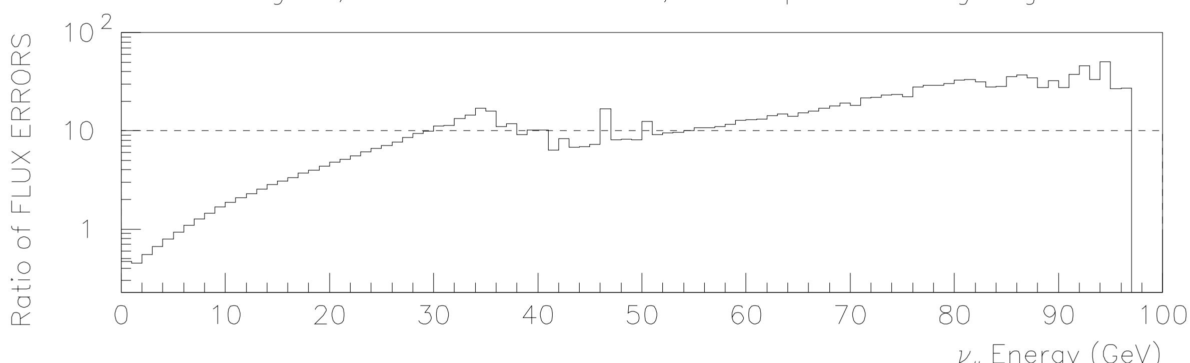


Fig. 3c, Fractional FLUX ERROR, Before Importance Weighting/After

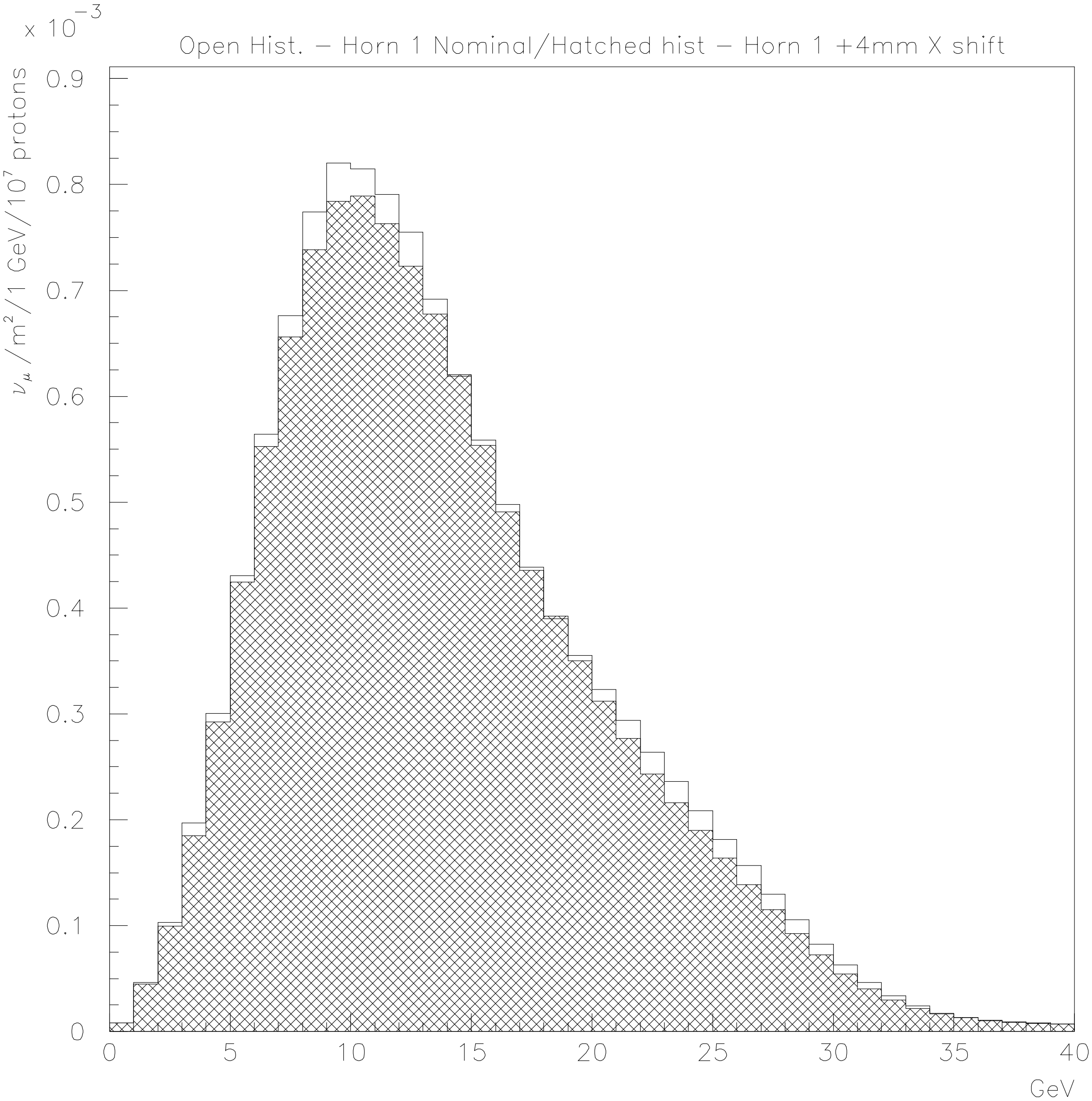
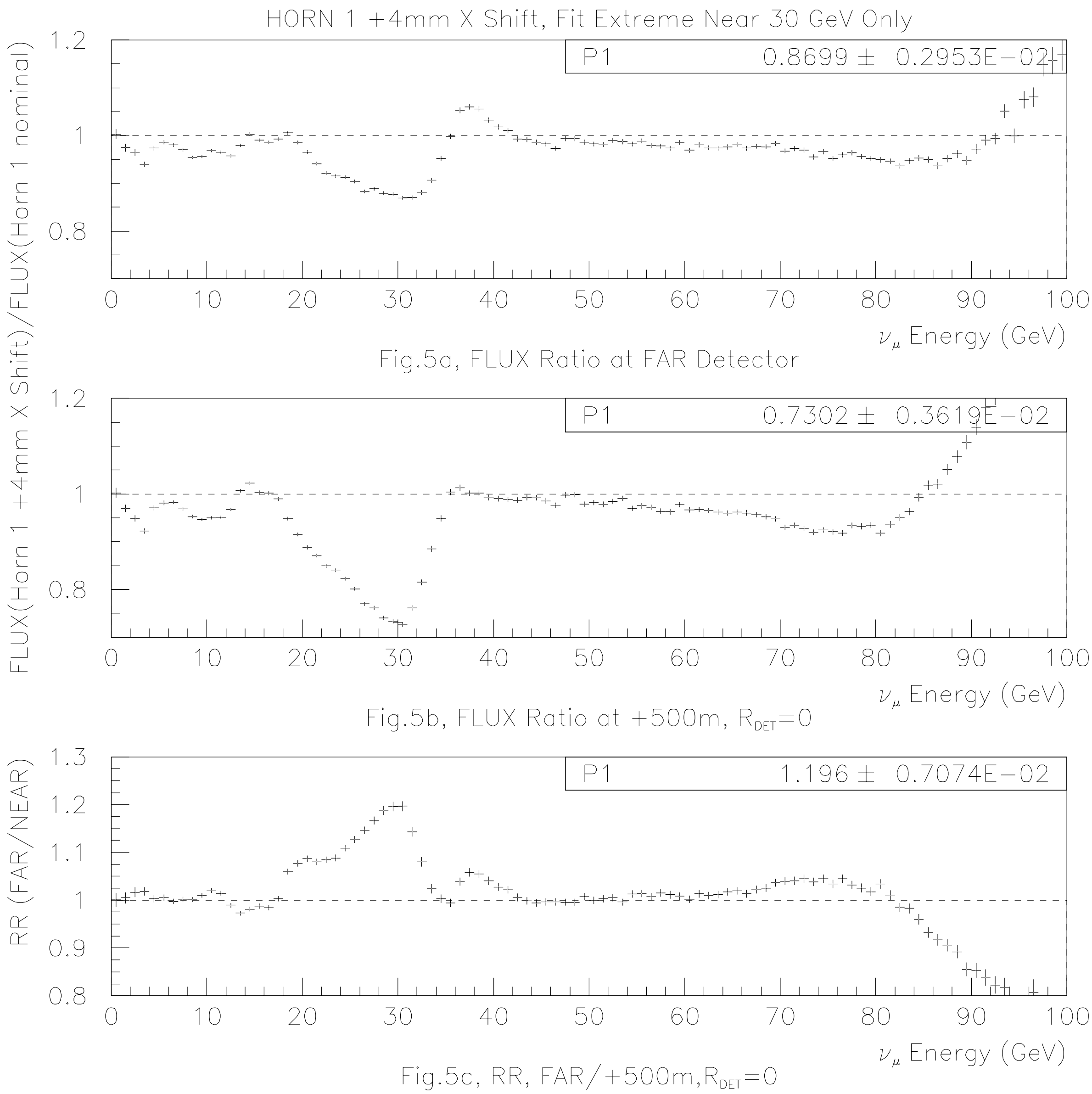


Fig. 4, FLUX vs ν_μ Energy at FAR Detector



HORN 1 +4mm X Shift, Fit Extreme Near 30 GeV Only
FLUX(Horn 1 +4mm X Shift)/FLUX(Horn 1 nominal)
P1 0.8699 ± 0.2953E−02
ν_μ Energy (GeV)
Fig.5a, FLUX Ratio at FAR Detector
P1 0.7302 ± 0.3619E−02
ν_μ Energy (GeV)
Fig.5b, FLUX Ratio at +500m, R_{DET}=0
RR (FAR/NEAR)
P1 1.196 ± 0.7074E−02
ν_μ Energy (GeV)
Fig.5c, RR, FAR/+500m,R_{DET}=0

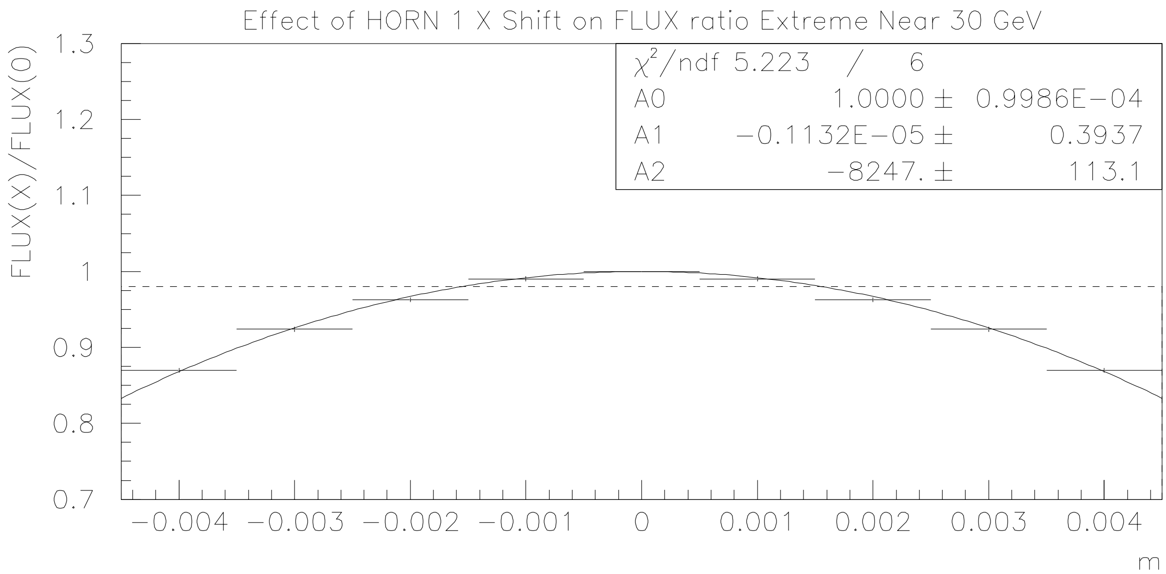


Fig. 6a, FLUX Ratio at 31 GeV at FAR Detector vs HORN 1 X Shift

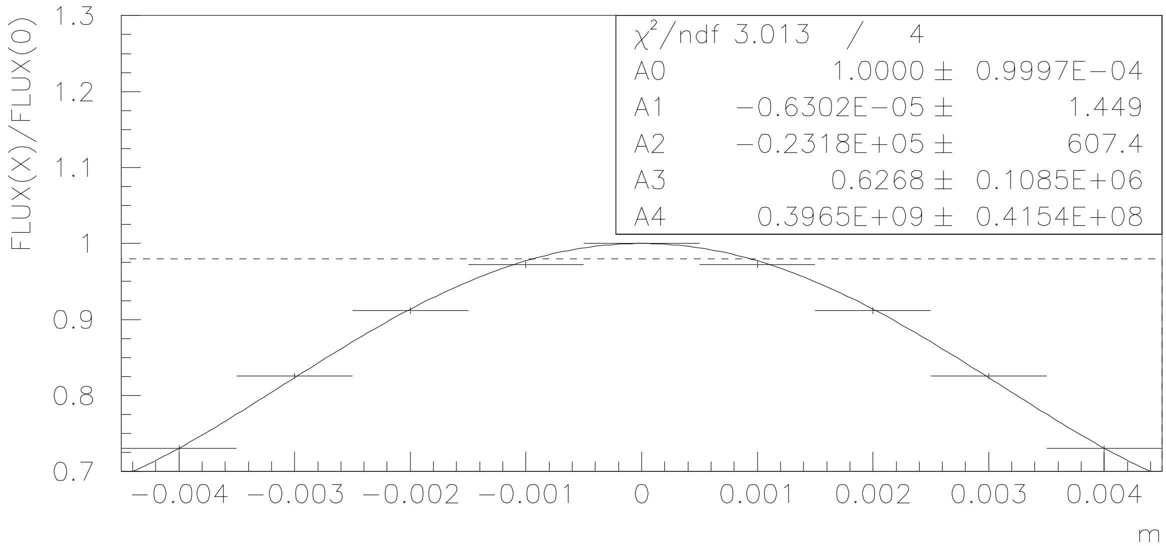


Fig. 6b, FLUX Ratio at 30 GeV at +500m, R=0 vs HORN 1 X Shift

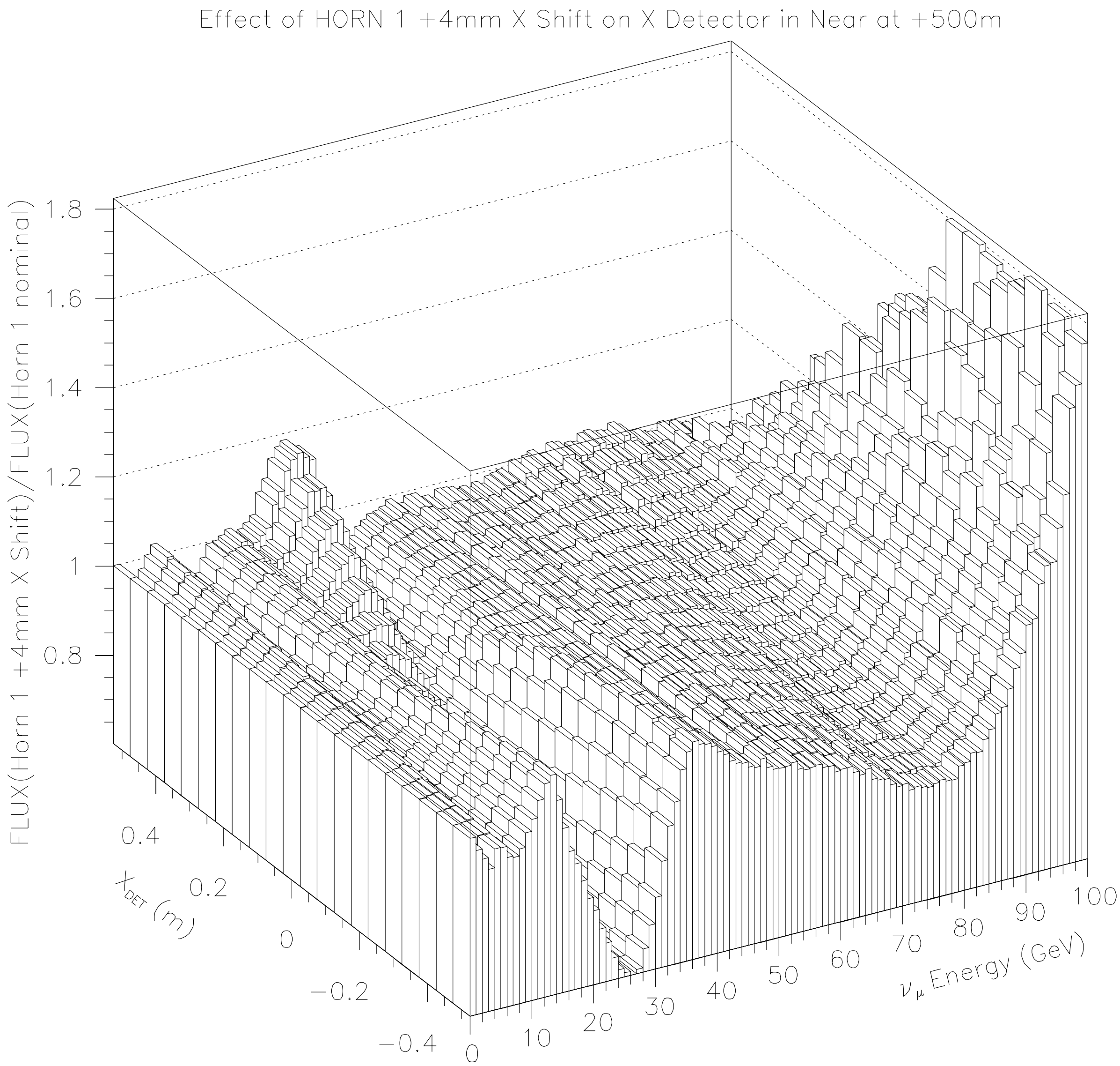


Fig. 7, FLUX Ratio vs X_{det} vs ν_μ Energy, at Y_{det}=0, +500m

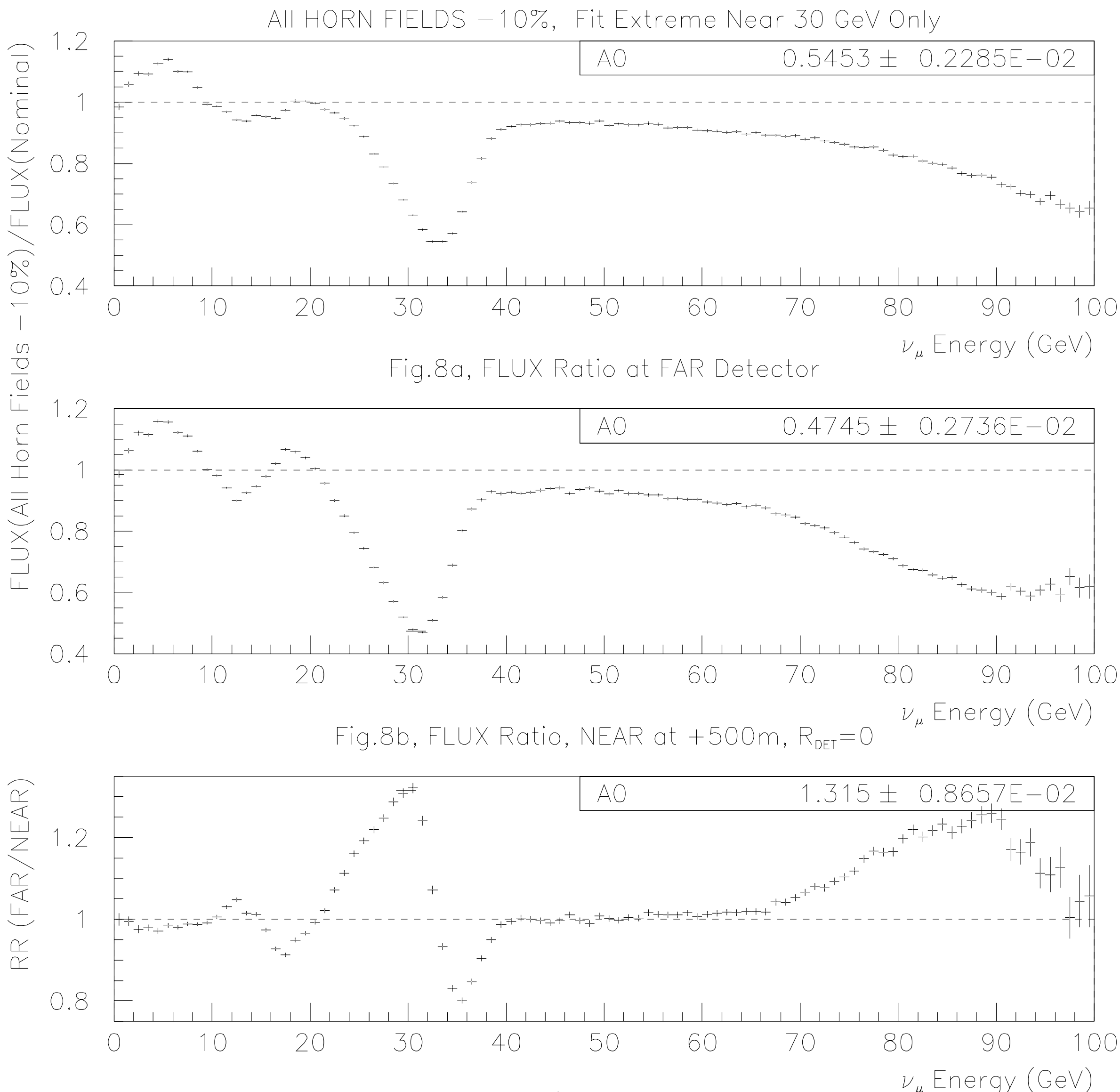


Fig.8a, FLUX Ratio at FAR Detector

Fig.8b, FLUX Ratio, NEAR at +500m, $R_{DET}=0$

Fig.8c, RR, FAR/NEAR at +500m, $R_{DET}=0$

Effect of ALL HORNS Magnetic Field Shift on FLUX Ratio Extreme Near 30 GeV

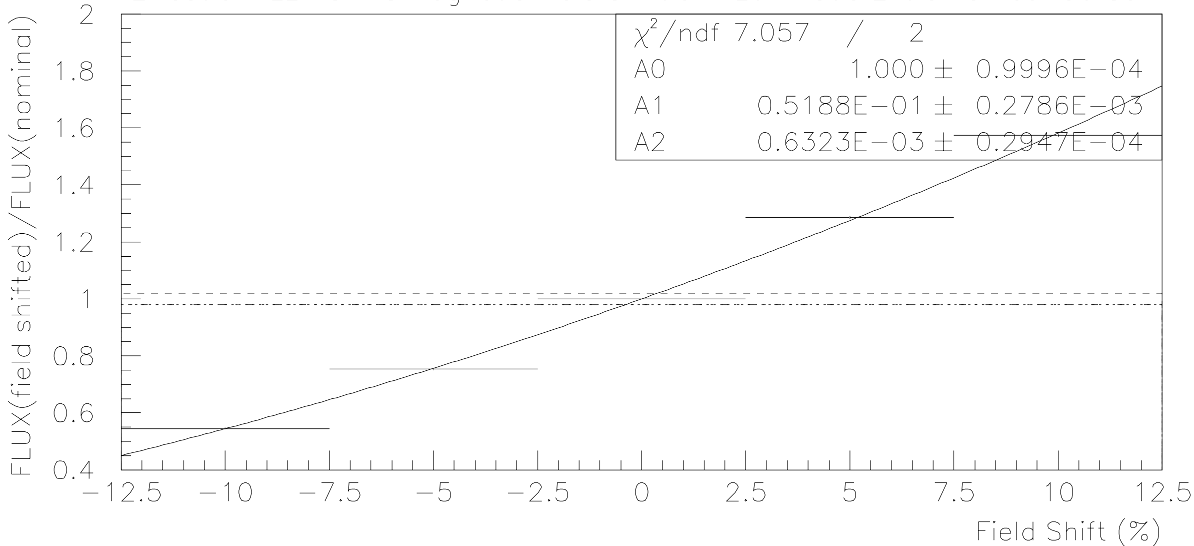


Fig. 9a, FLUX Ratio at 34 GeV in FAR Detector

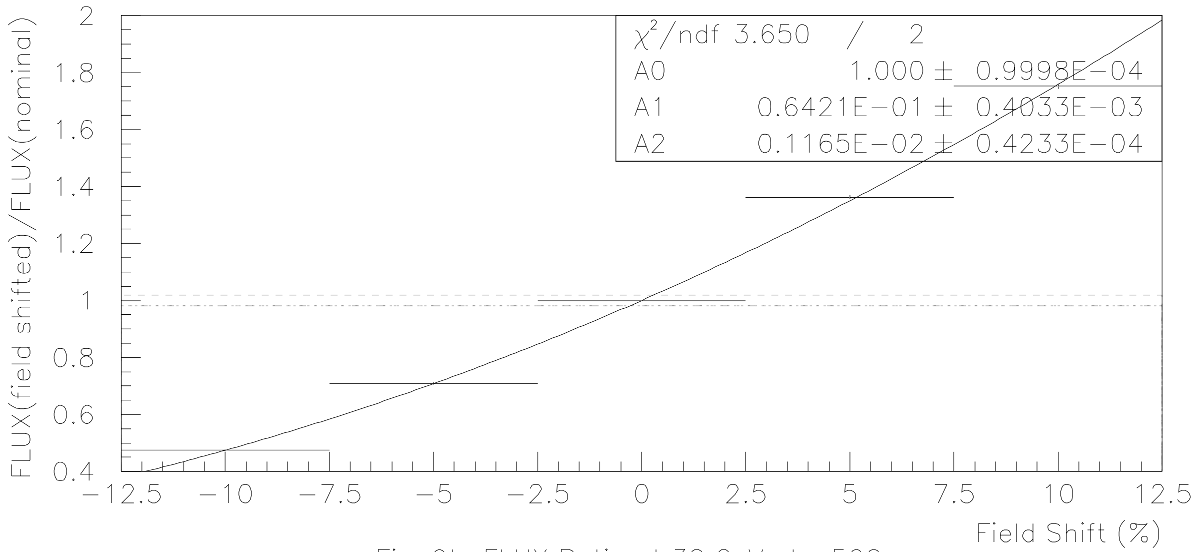


Fig. 9b, FLUX Ratio at 32 GeV at +500m

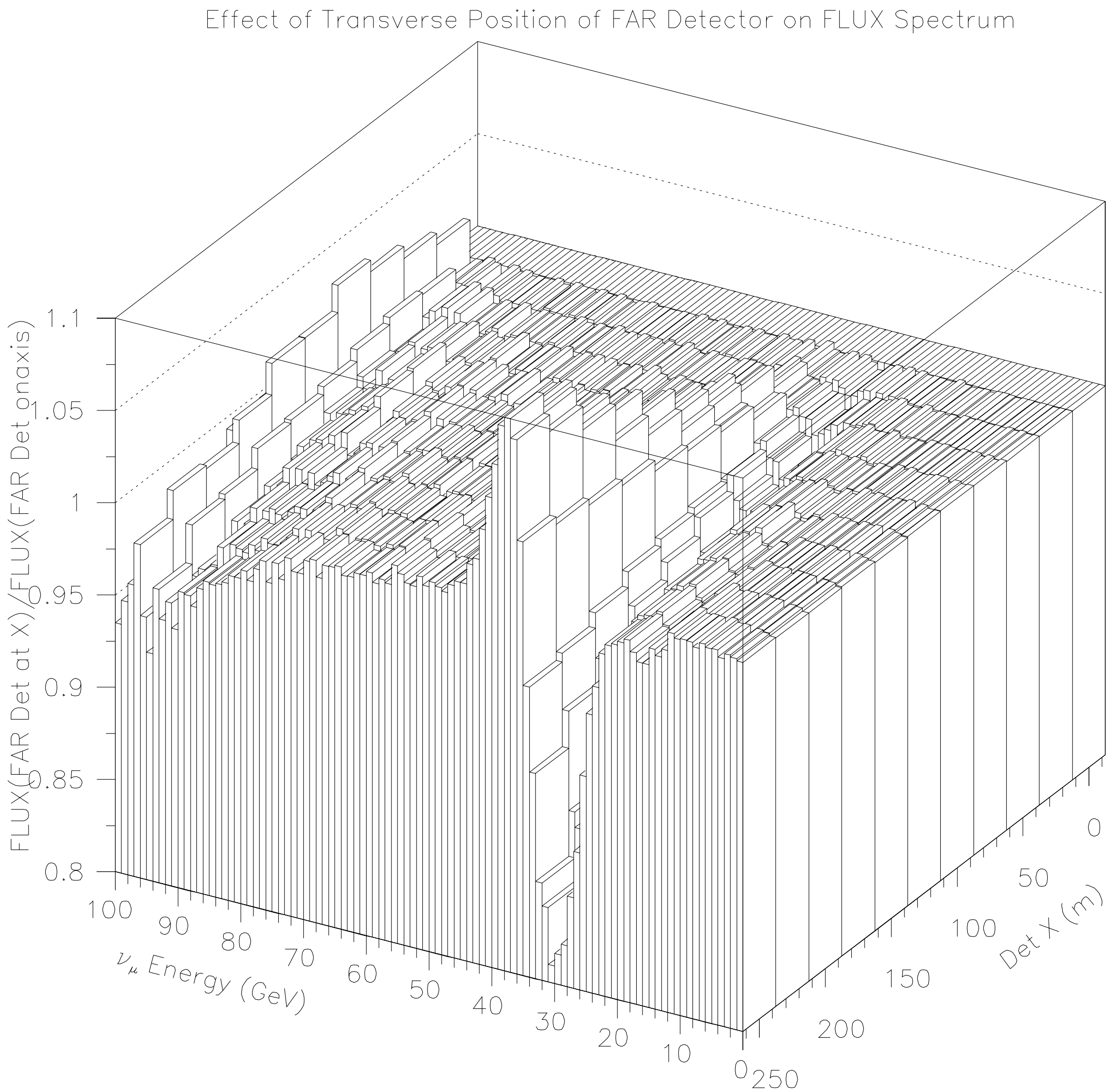


Fig. 10, FLUX Ratio if Far Detector is Off Beam Axis

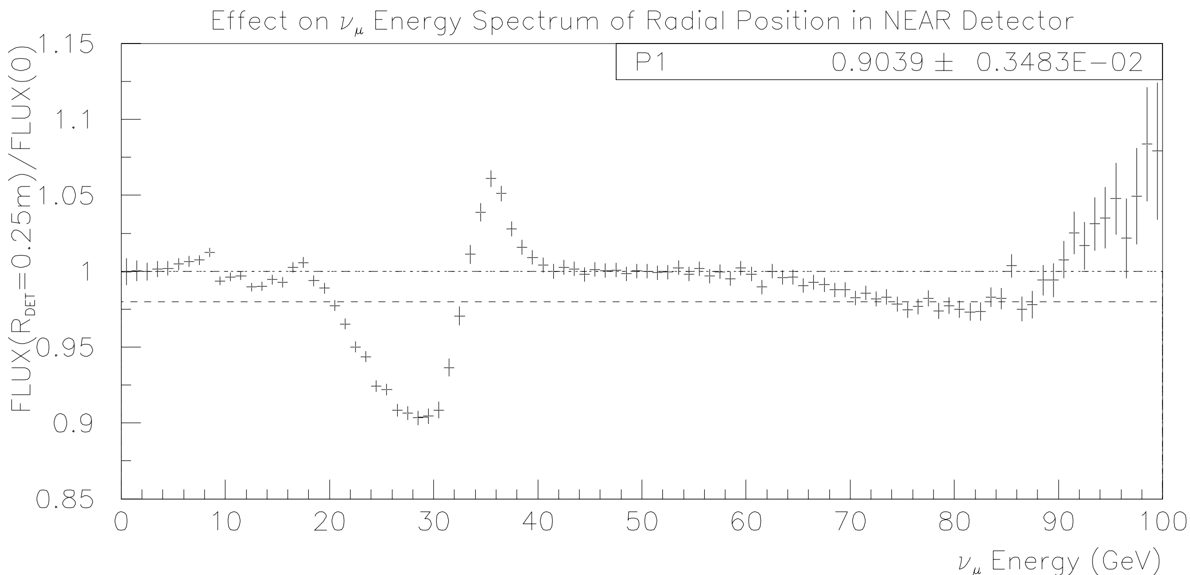


Fig. 11a, FLUX Ratio at R_{DET}=0.25m at +500m

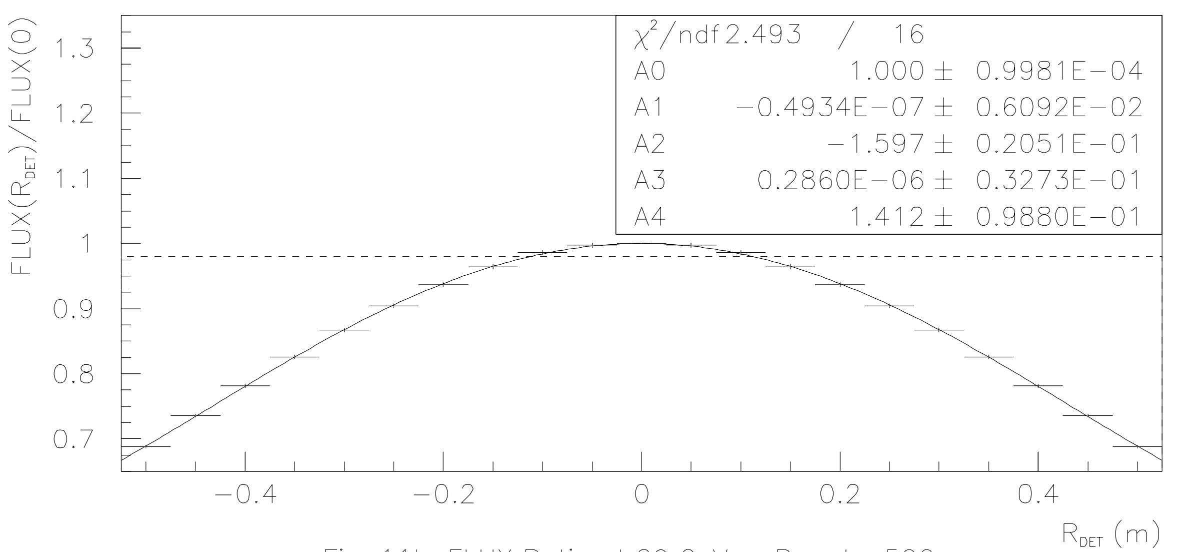


Fig. 11b, FLUX Ratio at 29 GeV vs R_{DET} at +500m