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Proposed MINERvA Start-Up Run Plan

Abstract. Upcoming shutdowns will upgrade the accelerator complex for higher proton intensity and also reconfigure the NuMI facility to operate in the "Medium Energy" configuration for NOvA. The present note proposes a set of running conditions for MINERvA that optimizes its use of the current "Low Energy" configuration before the "Medium Energy" switchover and a period of dedicated beam studies directly following this switchover.

INTRODUCTION

The MINERvA Experiment [1] will measure cross sections over a span of neutrino energies. Low energy (~1-5 GeV) measurements are of interest to neutrino oscillation experiments [2-5], while measurements across a wide range of energies (~1-10 GeV) are of intrinsic interest and as a probe of nucleon structure and nuclear physics.

The NuMI beamline [6,7] at Fermilab may be reconfigured to operate at a variety of neutrino energies by suitable placement of the target and horns within the large target station cavern. Each reconfiguration requires re-stacking of the surrounding shielding, new placement and alignment of the target, horns and support systems (cooling, instrumentation, and current-carrying striplines). The MINOS Experiment [2] is currently running in the "Low Energy" configuration ($\langle E_\nu \rangle$~4 GeV) with horns separated by 10 m and target fully-inserted inside the upstream horn. NOvA [3] will run in the "Medium Energy" configuration ($\langle E_\nu \rangle$~8 GeV) with target 135 cm upstream of the 1st horn and the 2nd horn 20 m downstream of the first.

In addition to the "coarse" adjustments to the neutrino energy spectrum described above, the NuMI facility at present permits a 'fine-tuning' of the neutrino energy by remote manipulation of its target along a rail-drive mechanism [8]. Such fine-tuning has been quite useful in the MINOS experiment for the purposes of de-convolving systematic uncertainties from the experiment with those associated with the neutrino flux and beam focusing elements. However, the MINOS analysis utilized inclusive neutrino interactions (rather than a well-known process as a normalization mode) and the scattering on Iron introduces uncertainties due to heavy nuclei effects. While the MINOS data serves as a useful proof of principle that the beam Monte Carlo flux can be tuned to agree with the observed (flux)X(cross-section), the MINERvA plan proposed here will constitute a unique effort to derive a flux using a well-known standard-candle cross section, such as quasi-elastic (QEL) scattering.

The rail-drive system introduces a level of complexity to the target station deemed risky for higher beam power, and will be no longer be supported during NOvA running. The present memo discusses how MINERvA can best make use of "Low Energy" running, and also discusses the need for a period of dedicated studies using the flexible target rail-drive system before this system is decommissioned (~4.9×10^{20} POT during LE running and ~0.9×10^{20} POT after the shutdown that converts to the ME horn configuration). MINERvA will be ready mid 2010. Subsequently, according to present schedule, a 4-6 week shutdown is scheduled in late 2010 and a longer shutdown for will occur early 2012 to early 2013 to, among other things, convert from the low energy to medium energy horn configuration.

In brief, we request a series of systematics studies outlined in Table I (occurring both before and immediately after the switchover of NuMI horn 2 to the ME position). Similar studies conducted by MINOS were used to rapidly diagnose inaccuracies in

Table I: Proposed Running Requests for the MINERvA Experiment (all of which require use of the LE target design with motion capability)

Before LE-to-ME Shutdown		After LE-to-ME Shutdown	
Exposure (10^{20} POT)	**Beam Configuraton**	*Exposure (10^{20} POT)*	**Beam Configuraton**
4.0	LE010cm/185kA	0.005	ME Beam Based Alignment [9]
0.15	LE010cm/150kA	0. 15	ME010cm/200kA
0. 15	LE010cm/200kA	0. 15	ME100cm/100kA
0. 15	LE010cm/000kA	0. 15	ME100cm/150kA
0. 15	LE100cm/200kA	0. 15	ME100cm/200kA
0. 15	LE150cm/200kA	0. 15	ME150cm/200kA
0. 15	LE250cm/200kA	0. 15 [(a)]	ME250cm/200kA
0.005	LE Beam Based Alignment [9]		Switch to ME target design

[(a)]MINERvA would like a longer exposure at this ME250cm/200kA setting if NOvA is delayed.

the neutrino flux calculation, and in the placement of the beam line elements. Such inaccuracies have long delayed results from previous neutrino experiments, and their rapid diagnosis in MINOS facilitated quick publication of results.

The entries in Table I denote beam configurations: "LE" or "ME" refers to the separation between the two focusing horns. LE010cm refers to the target location being 10 cm upstream of its position fully-inserted inside the first horn, 100 cm denotes a 100 cm separation, etc. The addition of "/200kA" refers to the current in the focusing horns. Thus "ME100cm/150kA" is a configuration with the horns separated by 20 m, the target 100 cm upstream of the first horn, and the horns pulsed at 150 kA.

To effect these studies, it will be necessary for MINERvA to have a spare LE target module. Use will be made of the MINOS LE target, but the spare will allow rapid switchover in the event that the MINOS target has frozen in position, its drive mechanism possibly being frozen after prolonged radiation exposure. The situation with spares should be evaluated sufficiently in advance of MINERvA's planned studies to order an additional LE target if necessary.

ANTICIPATED CHANGES IN THE NUMI BEAM AFTER THE LE-TO-ME SHUTDOWN

The MINOS experiment has run in the "Low Energy" configuration LE10cm/185kA. The LE target is a special design, with the graphite fins and their cooling lines encased in a small "snout," as shown in Figure 1. Also shown in Figure 1 is the new "Medium Energy" target design, which differs from the "LE Target" in that it is encased in a larger vacuum chamber whose cooling channels are further removed from the proton beam centerline, thus making it more robust at higher beam power and less susceptible to beam accident conditions. The larger (290 mm ∅) canister does not permit the ME target to be inserted into the focusing horn, and the end flange design precludes any configuration closer than the ME100cm configuration. Fortunately, the current ME target design calls for target fins 6.4 mm in width, identical to the LE target design. This similarity now reduces the concern that the production spectrum of hadrons off the LE and ME targets will differ due to geometric effects.

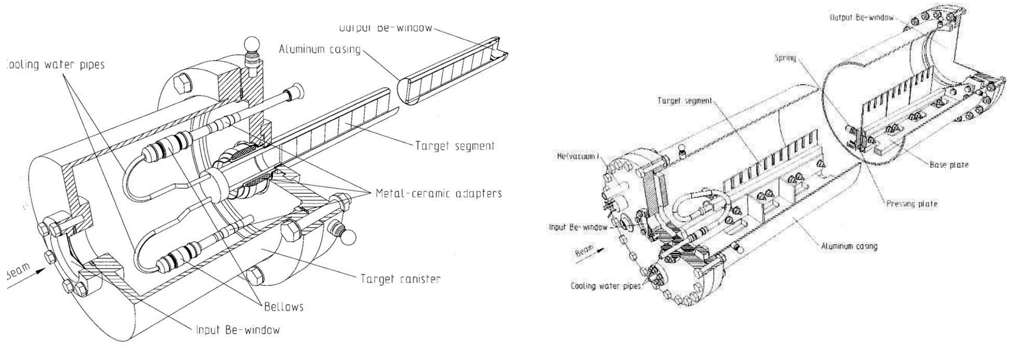

FIGURE 1. (left) Drawing of the LE target canister, whose long snout at right permits the graphite fins and stainless cooling lines to be cantilevered inside the focusing horn. (right) Drawing of the ME target canister. The graphite fins grow in vertical size in the downstream end, requiring a cooling channel further separated from the beam centerline. Figures taken from [10].

Another important design change after the LE-to-ME shutdown is that the ME target would not be moveable. The current target is supported under the shielding by a special module, shown in Figure 2, which has a rail drive system permitting up to 250 cm of travel along the beam direction. The frame of this module has been a challenge to design, with particular concern for its mechanical alignment under the thermal load of the beam. Further, the cooling and drive mechanism are a particular challenge and would be at risk of failure under the higher radiation levels anticipated in 700 kW or 1.2 MW operations. For these reasons, the flexible support module will be dispensed with during the NuMI upgrades for NOvA.

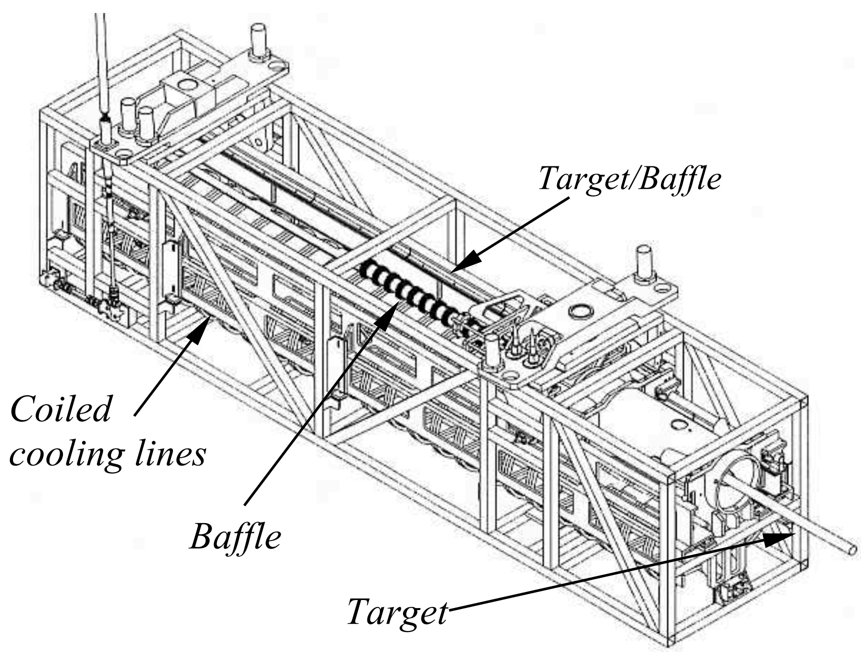

FIGURE 2. Drawing of the LE target support module. The proton beam enters from the upper left, the target (at lower-right) is cantilevered inside the first horn. The module consists of an aluminum frame, target and baffle supported on a rail mechanism driven by a worm gear, and vacuum, cooling and electrical lines servicing the target supported underneath. Figure courtesy A. Marchionni.

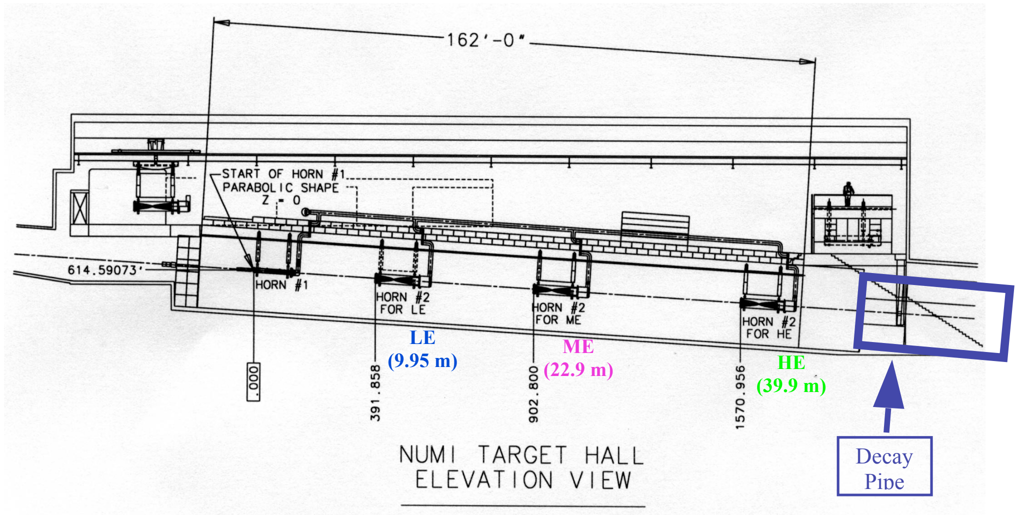

FIGURE 3. Drawing of the NuMI target station indicating the position of "Horn 1", which remains in its current position. Horn 2 will move from its current "LE" location 10 m from the first horn to a new location ~20 m from the first horn. The old "HE" position is now precluded due to the construction of the Work Cell above the shielding. Figure courtesy J. Hylen.

The final difference after the LE-to-ME shutdown will of course be the re-location of the second focusing horn. It will be moved an additional 10 m downstream, as indicated in Figure 3. Because of the need to bring the electrical strip line and cooling services this extra distance, the need to accurately survey the new horn location, and the need to work safely within the radiation field of the target station, the move is a lengthy process and is not easily reversible.

THE NEED FOR DEDICATED STUDY TIME

The run plan outlined in Table I serves two purposes: (1) to acquire a large sample of "Low Energy" beam data for the MINERvA Experiment before the NOvA experiment takes over, and (2) the study of systematic effects which will aid the experiment in understanding its beam flux. Such studies were essential for the MINOS experiment. The studies outlined benefit not only MINERvA but also the NOvA experiment as well. The larger protons-on-target request relative to the MINOS studies is necessitated by the smaller MINERvA fiducial mass (3-5 ton vs. 50 ton fiducial mass for the MINOS Near Detector).

The need for detailed systematic study of the neutrino flux in an accelerator neutrino beam may be demonstrated in Figure 4, which compares data from the MINOS Near Detector [11] to the NuMI flux calculation [12]. Discrepancies at the level of 30-40% are evident, not unusual amongst present or past neutrino experiments. Such discrepancies are due to imperfect knowledge of the differential production of $\pi^{\pm}$, $K^{\pm}$, and K_L secondaries off the target in (x_F,p_T), as well as imperfections in modeling of the transport of the secondary hadrons through the focusing horns. As can be seen in Figure 4, discrepancies at a given E_ν differ in different beam configurations, indicating that the discrepancies are not simply cross section effects.

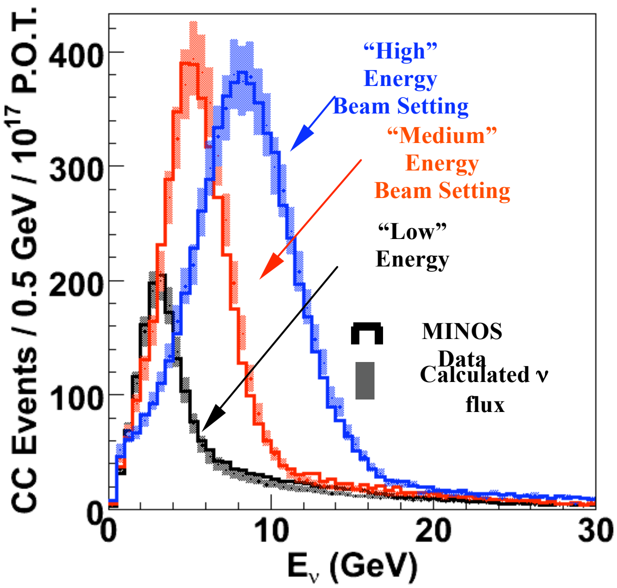

FIGURE 4. Energy spectra of charged-current (CC) ν_μ interactions in the MINOS Near Detector under three neutrino beam configurations. The MINOS data is compared to the NuMI flux calculation [12], which relies on the FLUKA2005 [13] cascade Monte Carlo to predict the flux of hadrons off the target.

The flexible configurations possible with the NuMI beam [8], including the ability to vary the current through the focusing horns and the location of the production target, allows one to effectively map out the (x_F, p_T) of hadrons which contribute to the neutrino flux [14]. Variation of the horn current changes of the p_T kick given to hadrons, hence the mean $\langle p_T \rangle$ of hadrons brought to focus parallel to the beam axis. Variation of the target position, by virtue of the fact that the focal length of a parabolic horn is proportional to the particle momentum, changes the $\langle x_F \rangle \approx \langle p_z \rangle / p_{\mathrm{proton}}$ focused by the horns. Acquiring data with both of these configurations thus allows a mapping in (x_F, p_T) space. Figures 5-6 shows the results of the MINOS Experiment's tuning of the production spectrum of secondaries off the target which conforms best to the charged current ν_μ and anti-ν_μ data in their Near Detector [14]. It is of note that the data accurately constrain the secondary production off the target, and the constrained fit actually conforms better to recent NA49 measurements [15] of particle production than does the FLUKA2005 [13] model.

Such studies will also permit MINERvA to diagnose discrepancies caused at a variety of calculable neutrino energies which arise from imperfect knowledge of the horns' current, alignment with respect to the beam axis, scraping of the proton beam on upstream collimators (which also act like production targets), *etc*. While such effects were not significant for a two-detector experiment like MINOS, they are of importance for a cross section experiment like MINERvA.

As a measure of the power of this constrained fit using several beam configurations, the MINOS experiment was able to discover that its target, replaced in October, 2006, was misaligned by ~1.5 cm. The resulting change in the neutrino spectrum was understood via the above fits to result from a target shift, whereupon the survey misalignment was discovered.

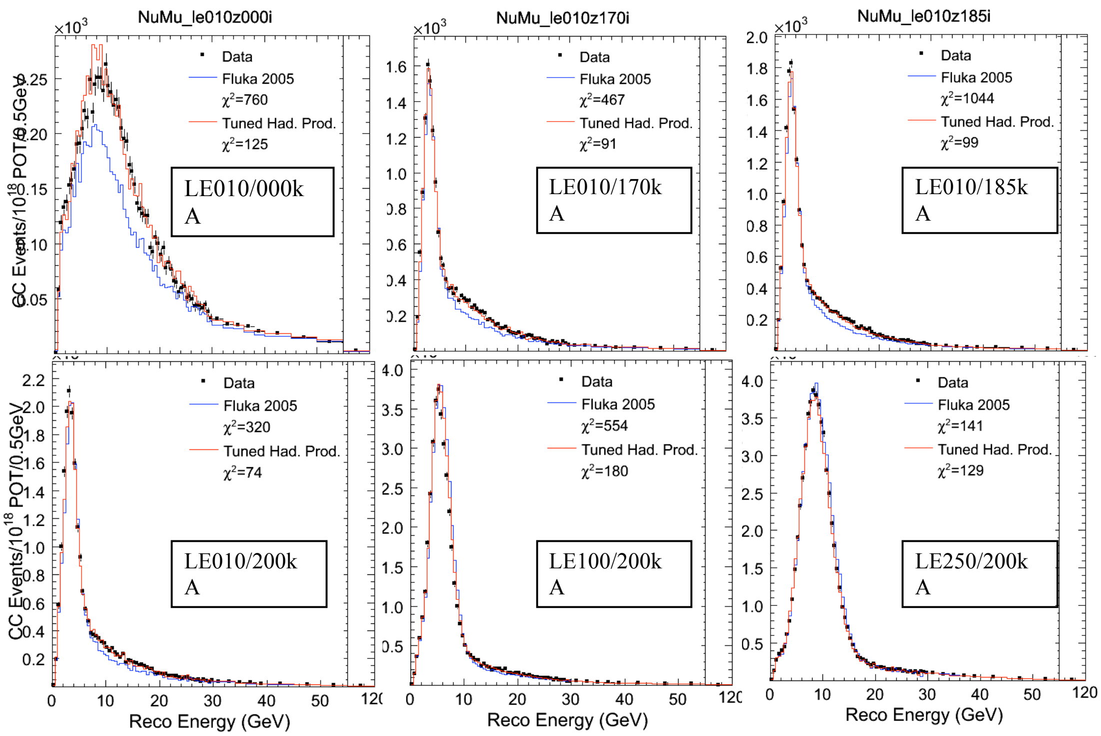

FIGURE 5. Energy spectra of charged-current (CC) ν_μ interactions in the MINOS Near Detector under six different neutrino beam configurations [14] of horn current and target position. Adjustment of the production spectra of secondaries off the target brings all the calculated flux spectra into agreement with the MINOS data. The MINOS data are the points, the blue curves are the flux predictions using the FLUKA2005 [13] prediction for yields of secondaries off the target, and the red curves are the result of a parameterized fit to the secondaries' yields which better accommodates the MINOS data.

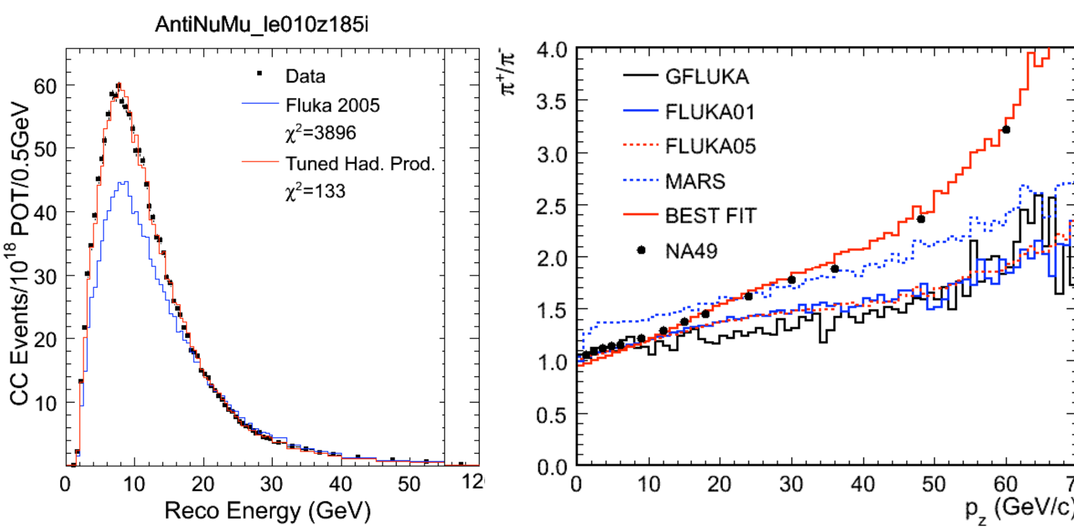

FIGURE 6. Energy spectra of charged-current (CC) Anti-ν_μ interactions in the MINOS Near Detector [14]. Adjustment of the production spectra of secondaries off the target brings all the calculated flux spectra into agreement with the MINOS data, and also suggests a ratio of π^+/π^-. The MINOS data are the points, the blue curves are the flux predictions using the FLUKA2005 [13] prediction for yields of secondaries off the target, and the red curves are the result of a parameterized fit to the secondaries' yields which better accommodates the MINOS data.

NEED FOR 4.9×10^{20} POT IN THE LE CONFIGURATION

The total request for protons on target for these studies was initially based entirely upon scaling the MINOS data set by the relative fiducial volumes of the MINERvA and MINOS detectors. But we may ask whether this scaling is appropriate, if, for example, MINOS acquired more data than was minimally necessary.

In Figure 7, we explore what would have happened in MINOS if less data had been accumulated in each beam configuration – for example if data sets of only 70% of the current MINOS data set were acquired, or 50% or 30%. The uncertainty shown in the figure is that which results from the fits to hadron yields off the target. This uncertainty is compared to the uncertainties in focusing and particle tracking through the horn or the uncertainty in the location of the target. At 70% of the above request based on fiducial-scaling of statistics could achieve the majority of MINERvA's goals. Applying this 70% scale factor to the relative fiducial volume scaling indicates the need for 0.9×10^{20} POT for flux studies before and after the LE-to-ME conversion.

Also in Figure 7 is shown what would happen if a fit to the MINOS data is performed, using all but one of the beam configurations in Table I. That is, would the uncertainty in the flux significantly increase if we did not use a particular data set in the fit. This question is motivated by the fact that many beam configurations requires time and effort to set up by the NuMI beam line physicists. As expected, the uncertainty goes up if we drop configurations like the LE10/170 beam configuration. Surprisingly, however, if the LE100/200kA or LE150/200kA configurations were set aside, the fit would *reduce* in uncertainty: the fit to all beams into one model of particle production produces a fit in which several data points are in tension against one another, and the particle production model is inadequate to relieve that tension in the fit. While it was not possible to study this further in MINOS, the superior energy resolution of MINERvA will allow us to fit a better model for particle production. These settings are therefore crucial to the measurements in this proposal.

It must be emphasized that the uncertainties in flux below include just those from the fit, to which must be added the uncertainty due to the knowledge of the cross section for the normalization neutrino scattering process. In the case of MINERvA, these are QELs which carry a ~10% uncertainty In the case of MINOS, QELs were not very separable due to the poor granularity, so inclusive events were utilized, making it impossible to even define such an uncertainty.

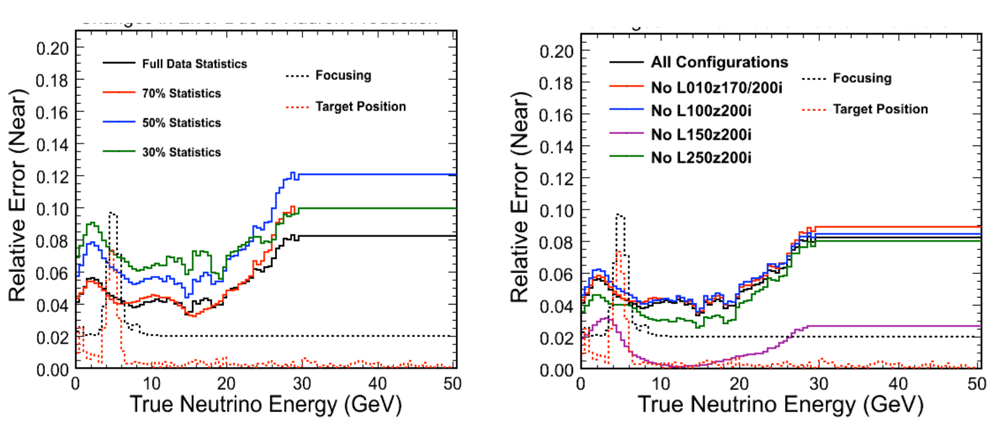

FIGURE 7. Uncertainty in the fit to then spectra of charged-current (CC) ν_μ's the Anti-ν_μ interactions in the MINOS Near Detector if less data is acquired in the special runs (left) or if one data set is omitted from the special runs (right).

STUDIES OCCURING AFTER THE LE/ME SHUTDOWN

In Table I we showed the size of the data sets requested in the special runs, which included 0.9×10^{20} POT after the LE-to-ME shutdown. The reason to repeat the analysis is that each of the two sets of special studies in Table I (before and after the shutdown) determines the flux only for that beam configuration. There are many effects which could impact the flux, such as the alignment of the horns or placement of the target, and it is important to separate these from issues of hadron production. In this section we show that the multi-configuration fits are likely to again succeed as they did in the LE configuration for MINOS, and we give a couple of examples of how a separate fit is well-motivated in the post LE-to-ME shutdown run period.

Figure 8 shows the distributions of pion (x_F,p_T) which produce neutrinos in the MINERvA detector when the horns are located in the ME position (separated by 20 m), and the target and horn currents are set to the values suggested in the second column of Table I. As can be seen, the sampling of pions changes as the target and horn settings change, and in fact the spread in (x_F,p_T) is even larger than in the LE configuration, suggesting that the fit will have an even greater lever arm to model the underlying distributions over a more significant portion of the phase space.

Figure 9 shows the neutrino spectra (calculated for MINOS) in the three of the beam configurations as shown in Figure 8. Each of the energy spectra are decomposed into 6 components which describe the trajectory of the parent meson through the focusing horns. Examples include pions that penetrate the two zero-field necks of the horns and are thus not given any focusing kick, pions going through only

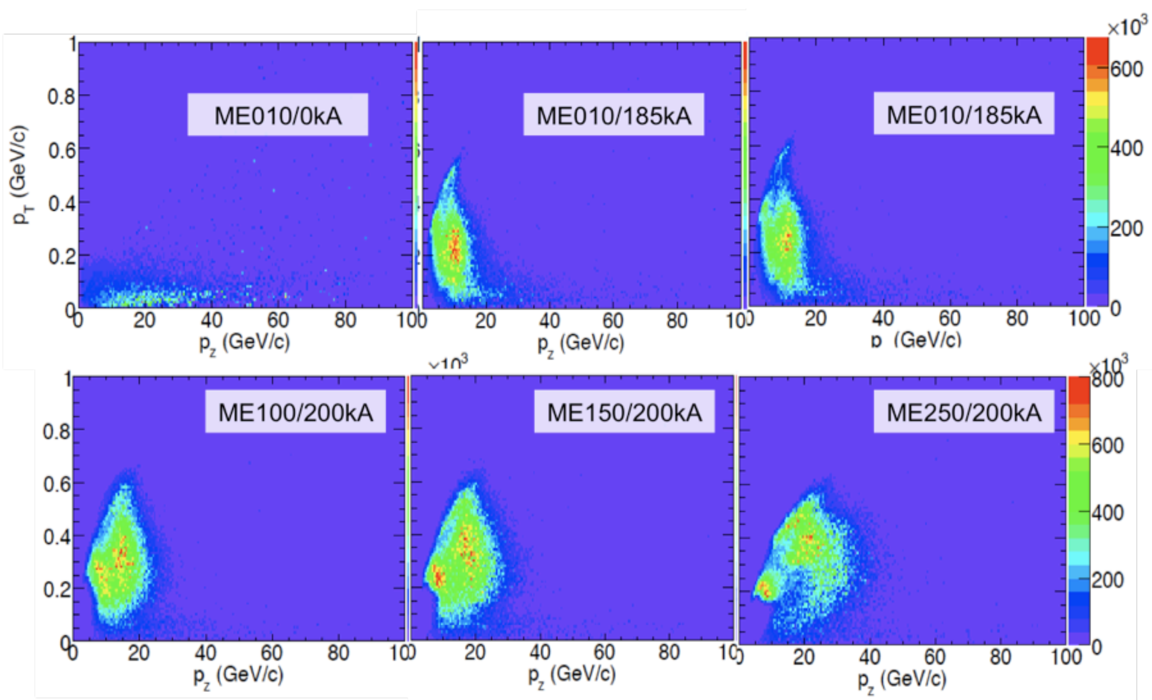

FIGURE 8. Flux of ν_μ in the MINOS Near Detector hall from the NuMI beam under six different neutrino beam configurations of horn current and target position (see Table I). The flux predictions use the FLUKA2005 [13] prediction for yields of secondaries off the target. The flux (in the color scale) is shown as a function of the (x_F,p_T) of pions off the NuMI target, where $x_F \sim p_z/p_{proton}$.

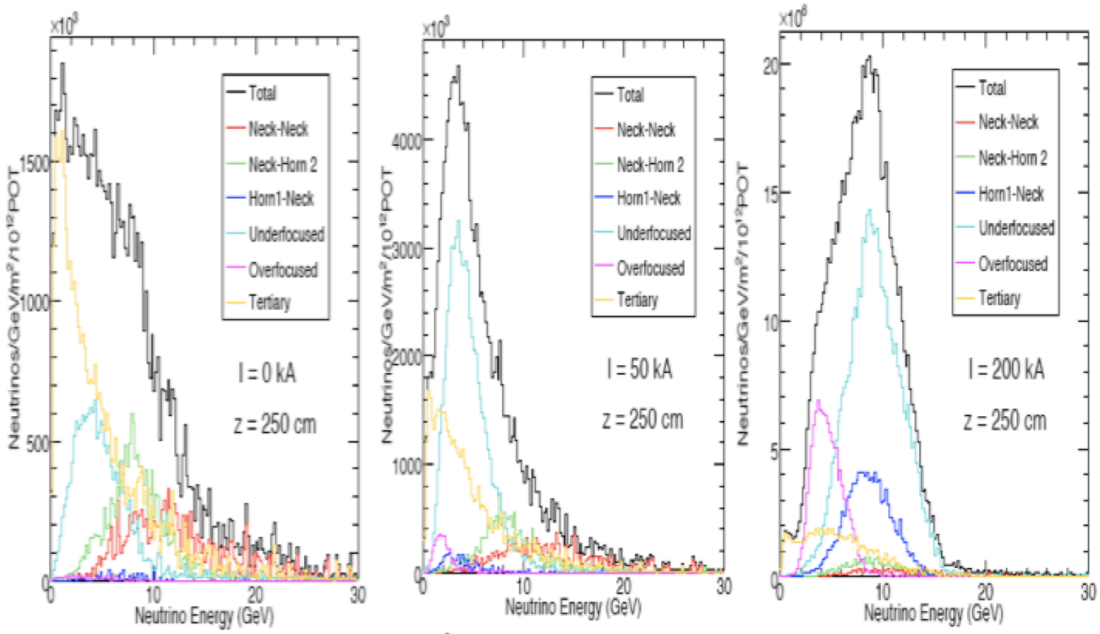

FIGURE 9. Energy spectrum of ν_μ in the MINOS Detector hall from the NuMI beam under three of the six different neutrino beam configurations of horn current and target position listed in Table I. The flux predictions use the FLUKA2005 [13] prediction for yields of secondaries off the target. The different components pertain to trajectories of pions through the focusing system and are explained in the text.

horn 1 and then the neck of horn 2, and vice versa, and then pions which go through both horns. The latter category is split into two components: those in which the pion is over-kicked by the first horn and then 'rescued' back to a more parallel trajectory with respect to the beam axis by horn 2, and pions which are underfocused by horn 1 and then brought into better parallelism by horn 2. Finally, one component is those neutrinos which result from a decay of a meson which itself is produced downstream of the target hall, such as those created when a pion from the target crashes into the decay pipe walls.

The distributions of Figure 9 actually suggest that the fit for the flux will be superior in the ME configuration. The individual components described above are very sensitive to focusing effects such as target and horn alignments, and the fact that they are so cleanly separated in the ME configuration means that they may well be individually measured by suitable fitting to templates of different alignment conditions. While alignment scans have been performed extensively for the NuMI beam components, it is compelling to see such information confirmed in the neutrino data itself, as it lends further evidence that the fit is accurately giving us the underlying (x_F,p_T) distributions. Further, the problem of tertiary production has been a significant uncertainty in the MINOS antineutrino oscillation analysis, and in the case of MINERvA it will be important to have a direct measurement of this component of the flux, since it does not originate from the target *per se*.

SUMMARY

In summary, it is desired to acquire 4×10^{20} POT in the LE beam configuration, and to conduct a series of runs totaling ~0.9×10^{20} POT prior to the LE-to-ME shutdown in order to vary target positions and horn currents. A similar set of measurements, again using the LE target and again requiring ~0.9×10^{20} POT, are desired after the horns are moved to the ME position. Upon completion of these tests, it is possible to switch over to the stationary ME target. These studies should provide good data for NOvA, which in any case will be commissioning during this time.

For MINERvA, it will be desirable to conduct the target scan studies using only a well-defined process like quasi-elastic events. While the MINOS study (using inclusive events) serves as a demonstration that the beam Monte Carlo can be tuned to the observed (flux)X(cross-section), the MINERvA plan proposed here will constitute a unique effort to derive a flux using a well-known standard-candle cross section, such as quasi-elastic (QEL) scattering.The requested exposures, when scaling for fiducial masses of the MINOS and MINERvA detectors, should accomplish these goals.

ACKNOWLEDGMENTS

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