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Progress of the Charged Pion Semi-Inclusive Neutrino Charged Current Cross Section in NOvA

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1 Introduction

The NOvA experiment is a long-baseline neutrino oscillation experiment. It uses two detectors, a near and a far detector, placed in a high intensity neutrino beam and separated by a distance of 810 km. The near and far detectors are functionally identical in detection technology, but differ in their sizes. The near detector has a total mass of 0.3 kton while the large far detector has a mass of 14 ktons [1]. Both detectors are placed 14 mrad off of the central axis of the Fermilab NuMI[1] beam. The experiment is designed to measure electron neutrino appearance and muon neutrino disappearance rates in a muon-neutrino beam with the goals of being able to determine the neutrino mass hierarchy, precise measurement of θ_{23} octant and establish if there is CP violation in the lepton sector.

In addition to oscillation physics, the NOvA experiment has a rich program of physics involving the measurement of neutrino interaction cross sections in the near detector. The NOvA detector design has been optimized as a low-Z tracking calorimeter, and as such is capable of measuring both ν_μ charged current interactions and ν_e charged current interactions with good energy resolution in the near detector. The NOvA near detector (right plot of Figure 1) consists of 21,192 PVC plastic cells that are 3.8 m long, 3.9 cm wide and 6.6 cm deep. They are filled with liquid scintillator which is mineral oil with 4% pseudocumene and comprises 62% of the detector mass. Each cell contains a wavelength shifting fiber (WLS) to collect the light coming from the scintillator. Cells are arrange into plane, that alternate between vertical (top view) and horizontal (side view) to allow for 3D reconstruction. Light from the WLS fiber is directed onto avalanche photo-diodes (APDs), producing an amplified electric signal. The signal is then shaped and digitized by the Data Acquisition System.

Both NOvA detectors are exposed to neutrinos with an energy spectrum that is centered around 2 GeV and is 14.8 milliradians off the NuMI beam axis (left plot of Figure 1). This off-axis position gives the highest probability for oscillations,

[1]NuMI: Neutrinos at the Main Injector

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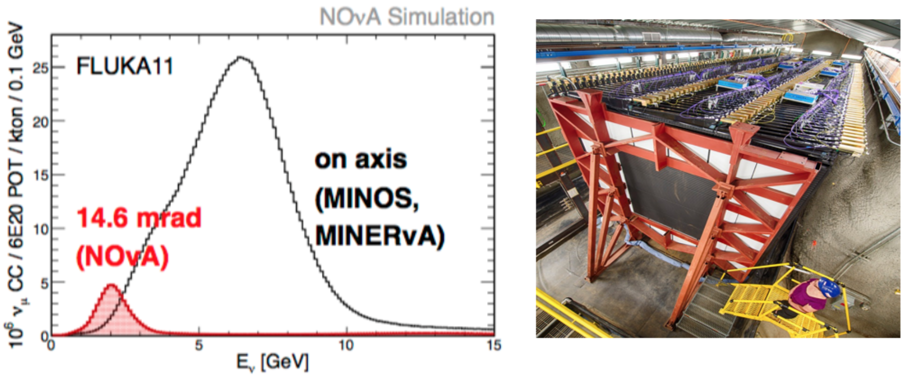

Figure 1: The left plot shows the neutrino energy spectrum in the NOvA ND (red curve) in comparison with on axis experiments (black curve). The right plot is a picture of the NOvA near detector.

while reducing the Neutral Current background. The energy range that NOvA's near detector is exposed to is important, as different interaction processes including quasi elastic scattering, resonant production and deep inelastic scattering contribute over different portions of the spectrum. Performing cross section measurements in this region yield results that can be used to tune the underlying nuclear interaction models and can be fed back into the oscillation measurements that NOvA is making to improve their sensitivities. Furthermore, in this neutrino energy range the charged current quasi elastic-scattering (CCQE) overlaps with the resonance production and modeling the rate of energetic pion production is important for measuring the total reconstructed energy. Therefore, ν_μ charged current cross section measurements with a final state topology featuring at least one charged pion are important for more precise oscillation measurements.

2 Semi-Inclusive $\nu_\mu CC(\pi^\pm)$

In this analysis we require one muon and at least one charged pion in the final state:

$$\nu_\mu + N \rightarrow \mu + \pi^{+/-} + X \tag{1}$$

Where N is the nucleus in the detector and X is the recoil nucleus plus any other particle.

Traditionally, reconstruction of all the particles is required prior to signal identification. In the present work we do not require a reconstructed charged pion but rather identify signal based on the full topology of the event. The goal of this analysis is to measure the flux integrated double-differential cross section of $\nu_\mu CC(\pi^\pm)$ with respect to muon kinetic energy, T, and angle, θ:

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \frac{\sum_j U_{ij}(N^{Sel}(\cos\theta_\mu, T_\mu)_j - N^{Bkg}(\cos\theta_\mu, T_\mu)_j)}{\epsilon(\cos\theta_\mu, T_\mu)_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i N_{target}\Phi} \tag{2}$$

Where N^{Sel} and N^{Bkg} are the number of selected and background events respectively, U is the unfolding matrix that corrects the reconstructed distribution to the true distribution by removing all smearing effects, ϵ is the signal selection efficiency, Φ is the integrated neutrino flux and N_{target} is the number of targets in the fiducial volume.

3 Event Selection

To find muon tracks, a cluster of hits close in space and time is reconstructed as a muon trajectory using a Kalman Filter algorithm. Then a k-Nearest Neighbor method based on track reconstructed observables assigns a muon score into each track. To reject events that came from neutrino interactions in the rock that surrounds the near detector, the start of the best muon track candidate is required to be within a well defined fiducial volume. Additionally, events where the muon track is not fully contained in the detector or the hits in the cluster are not 4 cells away from the detector edges, are removed.

In NOvA "prong" is defined as a cluster of hits, close in space, following one direction. Figure 2 and Figure 3 show simulated events that have one charged pion in their final state categorized by the number of prongs. The former is a two-prong event with a pion produced by a coherent interaction, where the neutrino interacts with the cloud of virtual mesons surrounding the nucleus. Figure 3 shows a typical 3 prong signal event where the pion is coming from a Δ^{++} decay.

4 Event Classification

After the candidate neutrino interactions are selected, each event is further examined to determine its likelihood of being part of the $\nu_\mu CC(\pi^\pm)$ signal sample.

To do this, we can consider final state event identification as an image classification problem, and leverage state of the art techniques in computing vision which have been developed over the past decade. In particular, NOvA has successfully developed and used deep learning techniques, denoted as CVN [2]. This was used as the primary particle identification and event classification algorithm for electron neutrino events in the ν_e appearance measurements of the 2016 datasets. CVN showed a marked improvement in the physics sensitivity of the measurement. The increase in sensitivity was the equivalent of approximately a 30% increase in beam exposure.

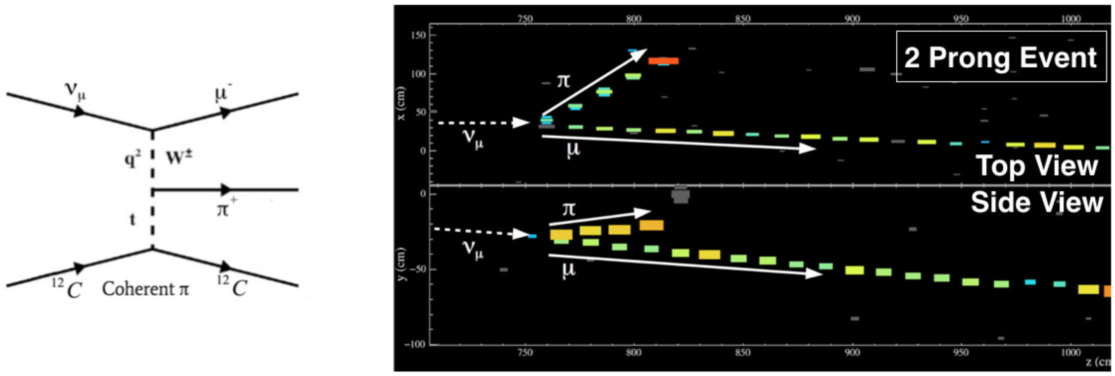

Figure 2: The plot on the right shows a simulated neutrino interaction event in the NOvA Near Detector, forming two prongs. Color represents energy deposit and top and side view belongs to horizontal and vertical planes respectively. In the left it is a schematic diagram of the coherent neutrino interaction that occurred.

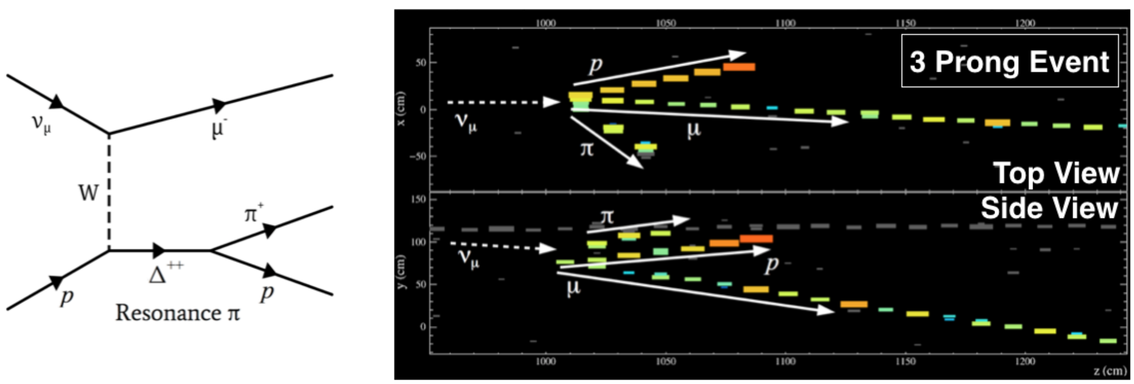

Figure 3: The plot on the right shows a simulated neutrino interaction event in the NOvA Near Detector, forming tree prongs. Color represents energy deposit and top and side view belongs to horizontal and vertical planes respectively. In the left it is a schematic diagram of the resonance neutrino interaction that occurred.

The CVN analysis architecture that was used was inspired by the GoogLeNet [3] architecture, where the two separate detector views (XZ and YZ) of the interaction topology where mapped into separate "color" channels, analogous to the separation RGB color channels that is perform in photographic image recognition. The networks were trained using Monte Carlo simulated neutrino events, comprised of both the signal and background, under a supervised learning paradigm.

In this analysis, the CVN training was performed using near detector simulated

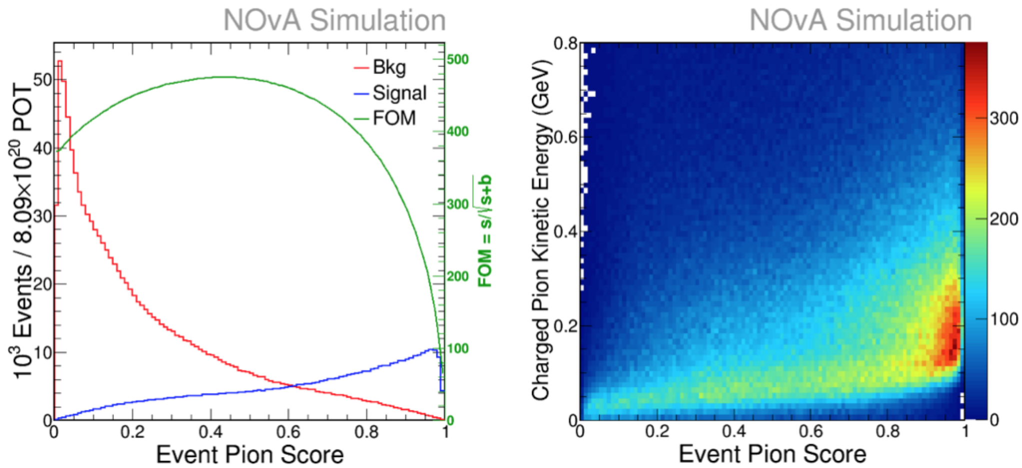

Figure 4: The left plot shows the score distribution of ν_μ events with at least one charged pion in the final state. The blue curve is the signal, the red curve is the background and the green curve is the statistical figure of merit. The right plot shows the event pion score as a function of pion kinetic energy.

events with two targets, signal and background. $\nu_\mu CC$ events with at least one charged pion where used as a signal and everything else was considered as background. We plan to use this event classification with the muon identification algorithm defined previously, to select events for the semi-inclusive charged-pion double differential cross section with respect to lepton kinematics.

The left plot of Figure 4 shows the score distribution of ν_μ events with at least one charged pion in the final state. We can see a good separation of the signal versus background above 0.7. The background curve (red curve) seems to be a superposition of two curves, one exponential falling for low score values and one linear falling for higher values. The right plot of Figure 4 shows the event score distribution as a function of charged pion kinetic energy. As expected events with higher energetic charged pions form a clear band for high score values, where as for lower energy pions we see less correlation with the event selector. This is an indication that the event classifier is more confident identifying events with more energetic pions (though higher multiplicity events are expected in that region, coming from DIS interactions).

This cross section measurement will be limited by systematic uncertainties and so the figure of merit to select events is chosen to be the fractional uncertainty of the cross section:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta N_{bkg}^{syst}}{N_{sel} - N_{bkg}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2} \tag{3}$$

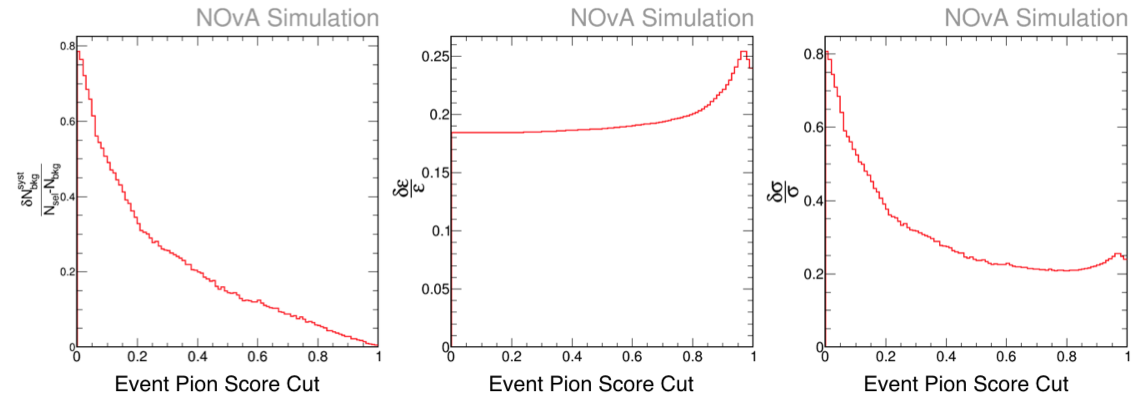

Figure 5: The plot on the left shows the fractional systematic uncertainty on background events, the middle plot shows the fractional uncertainty in the signal efficiency and the right plot shows the fractional systematic uncertainty in the cross section. The dominant systematic uncertainties that have been used for the presented plots are: flux and cross section uncertainties.

Where $\delta\epsilon$ is the fractional uncertainty in the signal efficiency and δN_{bkg}^{syst} is the systematic uncertainty in the background. The systematic uncertainties that have been used for the presented analysis are: flux uncertainties, cross section uncertainties and energy calibration uncertainties. The latter is a shift in the calorimetric energy of all hits by $\pm 5\%$. The event generator that was used, GENIE [5], uses a set of systematic shifts within the current experimental uncertainties. The flux uncertainties [4] are mainly coming from the poor knowledge of hadron production for the proton-nucleon scattering in the NuMI target.

In order to minimize the total cross section uncertainties we want to select events where the $\delta\sigma/\sigma$ distribution is minimized. The right and middle plot of Figure 5 shows the two components of equation 3, where we see that the fractional uncertainty in the background is falling for higher event pion score cut values. The fractional uncertainty in the signal efficiency appears to be flat for the most part, except in the region of higher pion score values where it starts raising. The combination of those two distributions can be seen in the total cross section uncertainty, right plot of Figure 5, where it starts to fall for lower event classifier score values and it reaches a plateau at around 0.7. Since those are not the final systematic uncertainties that are going to be used in this analysis without much further optimization we can temporarily use the 0.7 as a selection value.

Table 1 shows the signal purity and efficiency for events passing the classifier selection. From the selected 305,438 events, 2.9% of those are neutral current events and 13.3% are $\nu_\mu CC0\pi$ interaction type events. The main background is coming from

	Cut Value	Selected	Signal	Relative Eff(%)	Purity(%)
Presel		2,684,460	740,724	12.4	27.6
CVN-pi	0.7	305,438	237,519	32.1	77.8

Table 1: The table shows the number of events passed the selection criteria described in this analysis and the percentages of signal purity and efficiency for events with pion score larger than 0.7. The simulated events shown here are normalized to POT exposure of 8.09×10^{20}.

$\nu_\mu CC0\pi$ interactions and it is in line with previous studies showing a more difficult separation between charge pion and proton, relative to charge pion and muon. To reduce the remaining background we are exploring the use of kinematic variables to separate the different particle types, requiring a michel electron in the event, and data-driven constraints for events failing our selections. A different approach under consideration is to develop an event classifier trained on specific signal sub-categories. In that way, signal topologies that are poorly identified by the more general event classification may see a boost in selection efficiency.

5 Conclusion

The NOvA experiment is developing an analysis for the measurement of charged-current ν_μ interactions in the near detector with at least one charged pion in the final state. This analysis, presented here, uses a deep-learning based event classification technique. The analysis framework optimizes the selection and identification criteria based on a minimization of total cross section systematic uncertainties.

The event selection achieves a signal purity of 77.8%, 230k signal-events are expected to be selected, enabling a differential cross section measurement with respect to the leading muon kinematics. The analysis further looks to analyze events with higher energy charged pions that can be well reconstructed by classical reconstruction techniques used in NOvA, to perform additional measurement including the pion kinematics.

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