Effect of Multinucleon Processes in the T2K Oscillation Analysis

Mark Hartz
Kavli IPMU (WPI), University of Tokyo/TRIUMF
For the T2K Collaboration

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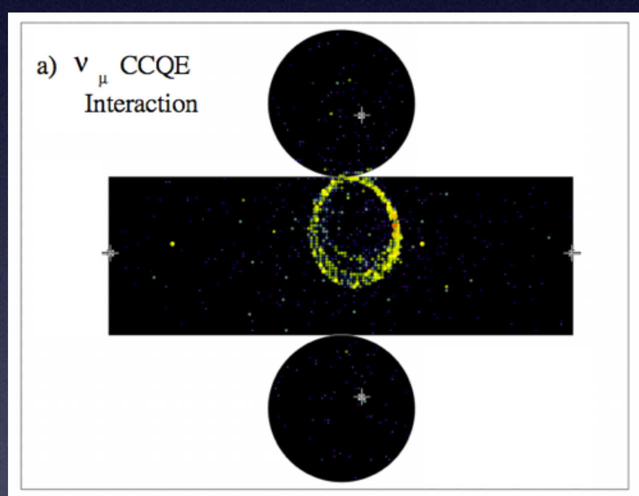
Reminder of T2K Oscillation Selection

ν_μ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu}$$

- Single muon-like ring



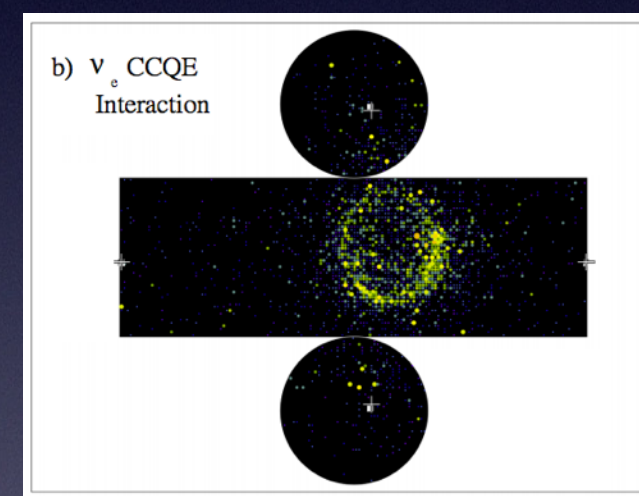
- 1 or 0 decay electrons

Phys. Rev. Lett. 111, 211803 (2013)

ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$$

- Single a single electron-like ring

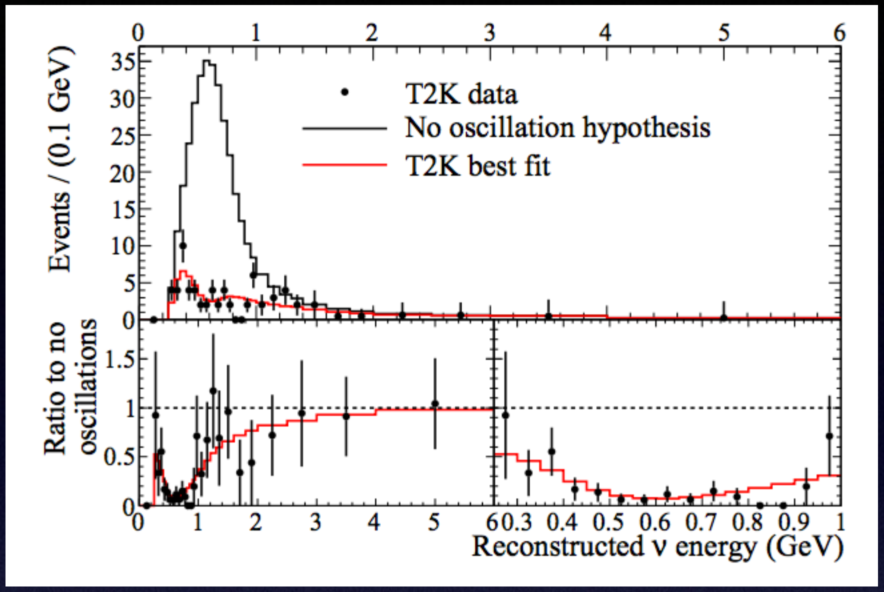


- No decay electrons
- Reject $NC\pi^0$ events

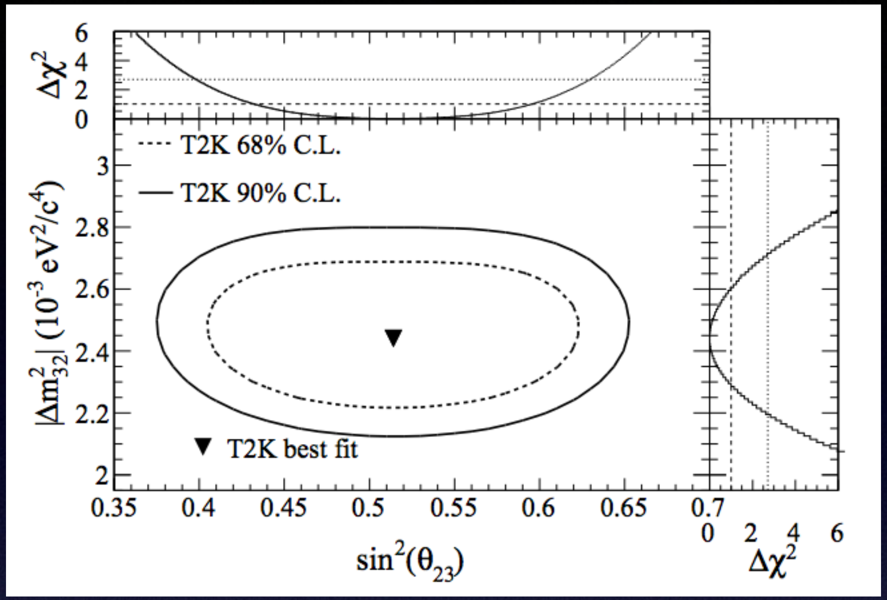
arXiv:1311.4750

In both cases, selecting CC0π candidates

Oscillation Parameter Fits



Fit data with model to extract allowed regions of oscillation parameters



How do we build the model?

- Monte Carlo simulation of experiment includes:
  - Flux simulation (see Kendall's talk)
  - Neutrino interaction model - NEUT (or GENIE)
  - Detector models (GEANT3 or GEANT4)
- Simulated Monte Carlo events are pushed through the same reconstruction and selection chains as data
- Stored truth information from MC events used to apply systematic variations and oscillation probabilities

Varying the Model

- We need to vary the model in two ways:
  - Systematic variations that represent the uncertainties in the flux, interaction cross section and detector modeling
  - Apply oscillation probabilities that depend on the oscillation parameters

MC events weighted by osc. probability

$$N(E_{rec}, \Delta E_{rec}) = \sum_{i}^{\#\text{ of MC Events}} P_{osc}(E_\nu^i, \theta, \Delta m^2) \times [1 + f_{flux}(E_\nu^i)] \times$$
$$[1 + f_{xsec}(E_\nu^i, p_\mu^i, \theta_\mu^i)] \times [1 + f_{det}(p_{rec}^i, \theta_{rec}^i)] \times$$
$$[H(E_{rec}^i - E_{rec}) - H(E_{rec}^i - E_{rec} - \Delta E_{rec})]$$

Also weighted by nuisance parameters that describe systematic variations

Each MC event has associated true and reconstructed variables that are used when applying the oscillation and systematic weights

Neutrino Models in Oscillation Analyses

Interaction Model:
NEUT interaction generator and cascade model
Uncertainty - combination of:
- model parameter (M_A, p_F, E_b) errors
- x-sec normalization errors
- cascade model cross section errors
- model comparisons

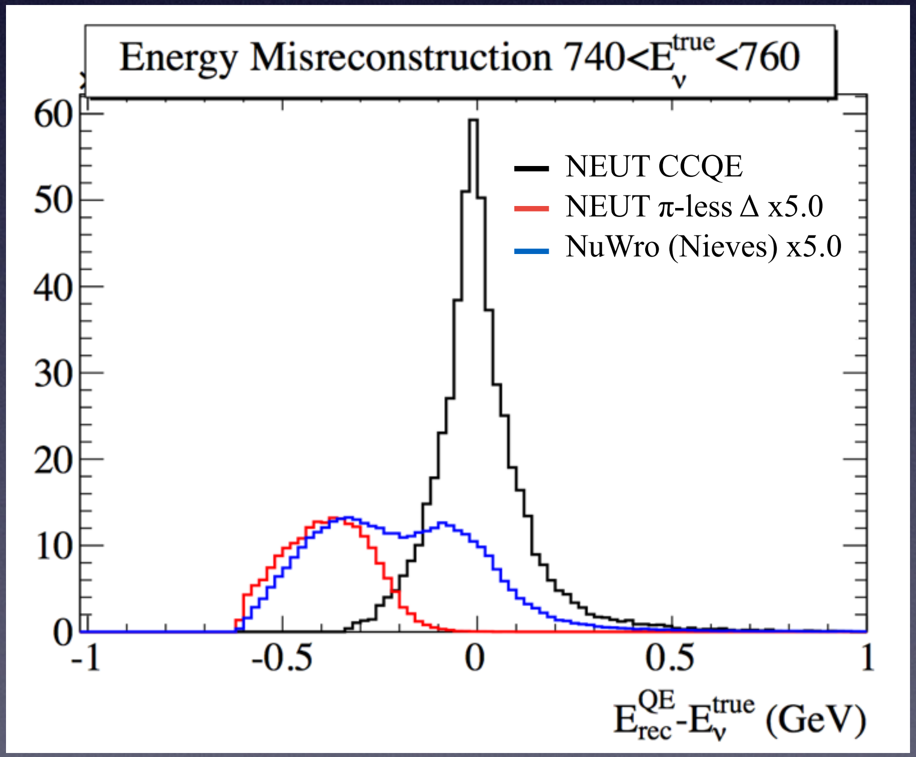
Flux Model:
Data driven FLUKA/GEANT3 simulation
Uncertainty - normalization as function of neutrino flavor and energy

Near Detector (ND280) Constraint:
Fit to CC0π, CC1π and CC Other data samples from ND280 detector
Fit varies parameters in the flux and cross section model to achieve data/MC agreement
Fitted values for M_A, p_F, etc., are **not** measurements of those physical parameters
Fitted values represent how the processes in the NEUT model must be adjusted to achieve agreement with the near detector data

Fit to SK Data:
Uses flux and interaction models after the ND280 constraint is applied
Uncertainty on neutrino rate prediction is reduced

CC0π in NEUT

- CCQE model uses RFG
- Version of NEUT used in current oscillation results does not implement any of the new np-nh models
- Does include a π-less Δ decay model:



Applied to 20% of Δ production, independent of energy

Motivated by S.K. Singh, M.J. Vicente-Vacas and E.Oset, Phys. Lett. B 416, 23 (1998).

- Does include pion absorption by FSI with the NEUT microscopic cascade

Oscillation Fit Bias Study

- What is the potential bias in the measured oscillation parameters due to the lack of a full np-nh description in NEUT?
- Papers investigating nuclear effects and multinucleon contributions on the T2K or T2K-like experiment:

O. Lalakulich and U. Mosel, Phys. Rev. C 86, 054606 (2012).
D. Meloni and M. Martini, Phys. Lett. B 716, 186 (2012).
P. Coloma, et al, arXiv:1311.4506 (2013).

- We perform a study using toy data and the T2K oscillation analysis framework to estimate potential biases
- Results presented here use the np-nh model of Nieves et. al. as implemented in NuWro
- Study is preformed for the muon neutrino disappearance analysis since statistics are larger

Toy Experiment Study

Toy Generation:
- Generate toy data for the near and far detector that includes the multinucleon predictions from the np-nh model of Nieves et. al. (QE is from the NEUT model)
- Only apply the Nieves model for E_ν<1.5 GeV
- Remove the NEUT π-less Δ decay in that region to avoid double counting
- For a control, also generate toy data with the nominal NEUT model

↓

ND280 Fit:
- Fit the toy data with the fit model that is used for the current oscillation analyses (does not include multinucleon except for NEUT π-less Δ decay)
- Pass the constrained fit model to the SK toy data fits

↓

SK Oscillation Fit:
- SK toy data are fit for the oscillation parameters, using the constrained flux/interaction model from the near detector fit
- The bias in the fitted oscillation parameter values is evaluated by comparing to control experiments where the fake data and fit models are the same

, 015504 (2012)

Multinucleon Modeling

Phys. Rev. C 83, 045501 (2011)

- The NuWro implementation of the J. Nieves et. al. model is used
- Nucleon ejection is from the model of J. Sobczyk

Phys. Rev. C 86, 015504 (2012)

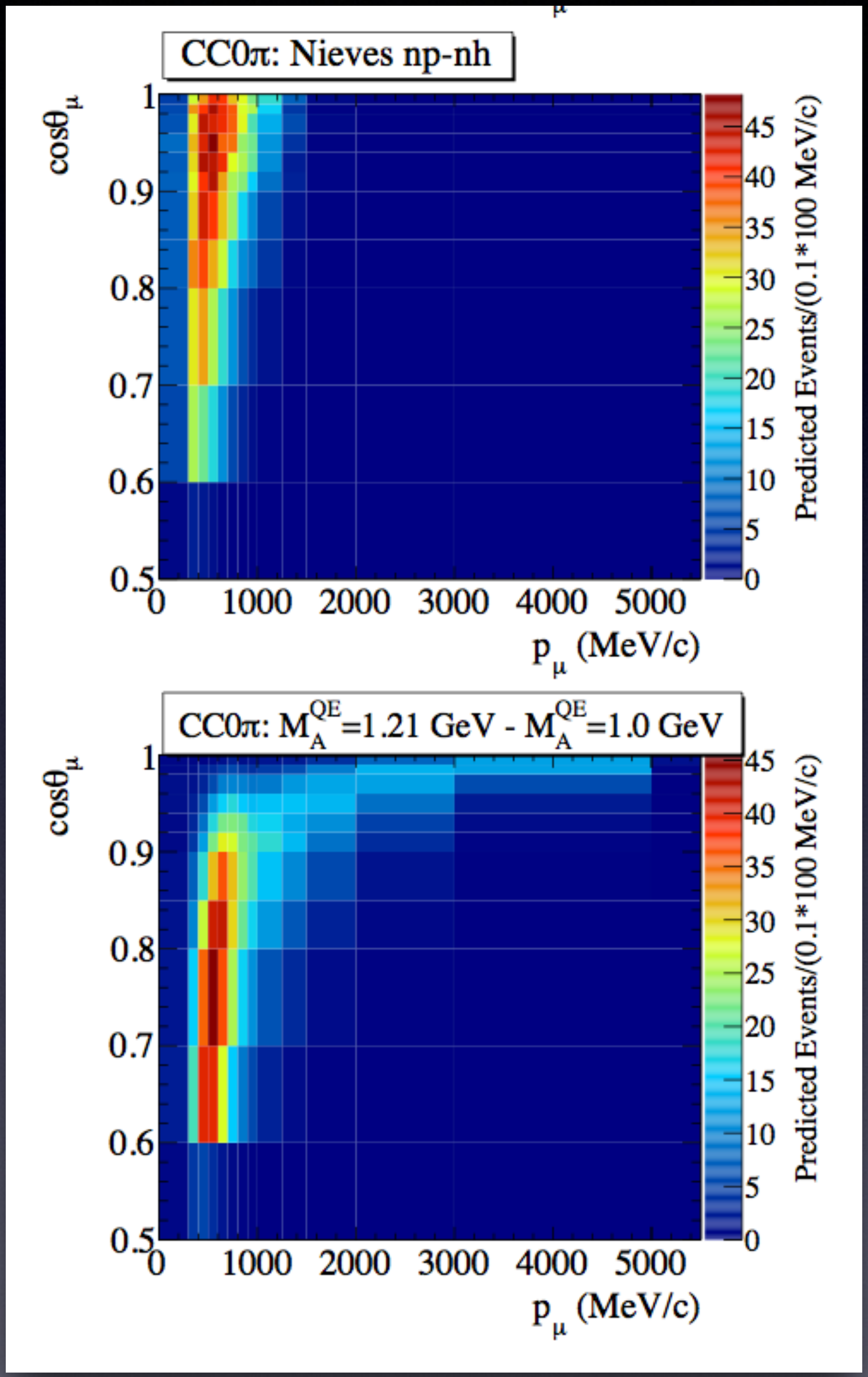
- **For the ND280 prediction:**
  - Simulate interactions in the fine-grained detector (FGD1) that is the target for the selected ND280 data
  - Includes effect of final state nucleons on selection
- **For the SK prediction:**
  - Use a muon particle gun to model the efficiency, resolution
  - Assumes final state protons are below Cherenkov threshold. Is this a reasonable assumption?

Multinucleon Prediction in ND280

	CC0π	CC1π	CC Other
Total NEUT Prediction (M_A=1.21 GeV)	19980	5037	4729
Multinucleon Prediction (NuWro - Nieves et. al.)	939	17	12
NEUT π-less Δ Decay Prediction	542	20	24
NEUT (M_A=1.21)-NEUT (M_A=1.0)	1362	57	38

- The contribution to the CC1π and CC Other samples is small
  - Selection requires a pion, electron or photon candidate for event to be in one of those samples - not very sensitive to nucleon ejection model
- The π-less Δ decay contribution from NEUT is subtracted

ND280 Results

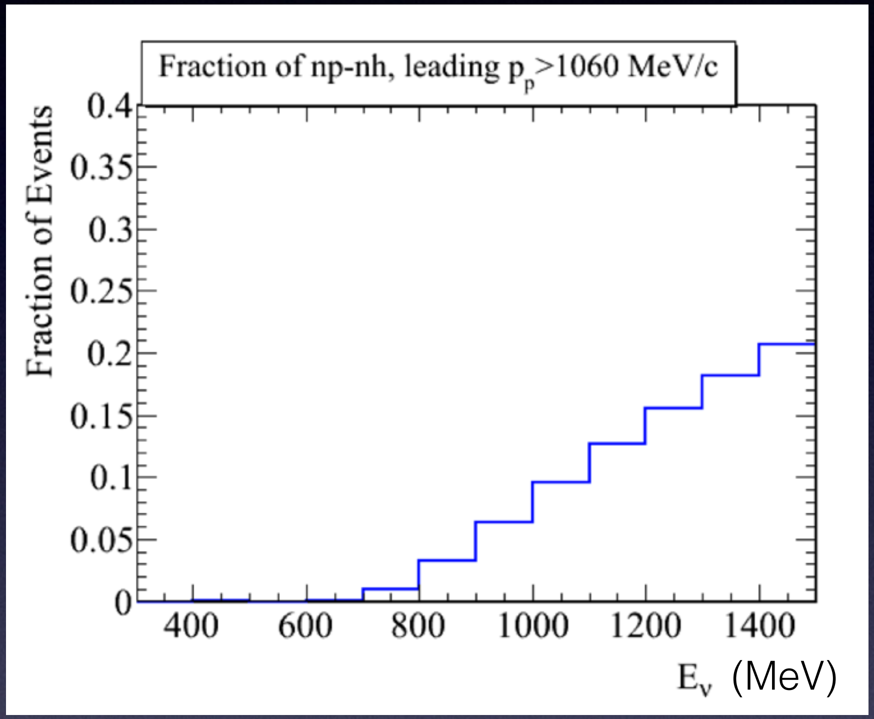


- The multinucleon prediction does fill the phase space differently than a change to M_A
- We fit a "nominal" toy generated with multinucleon events (NuWro-Nieves) included and M_A=1.08 GeV
- The fit model does not include the NuWro-Nieves multi nucleon events, does include NEUT π-less Δ decay
- Parameter biases are small:

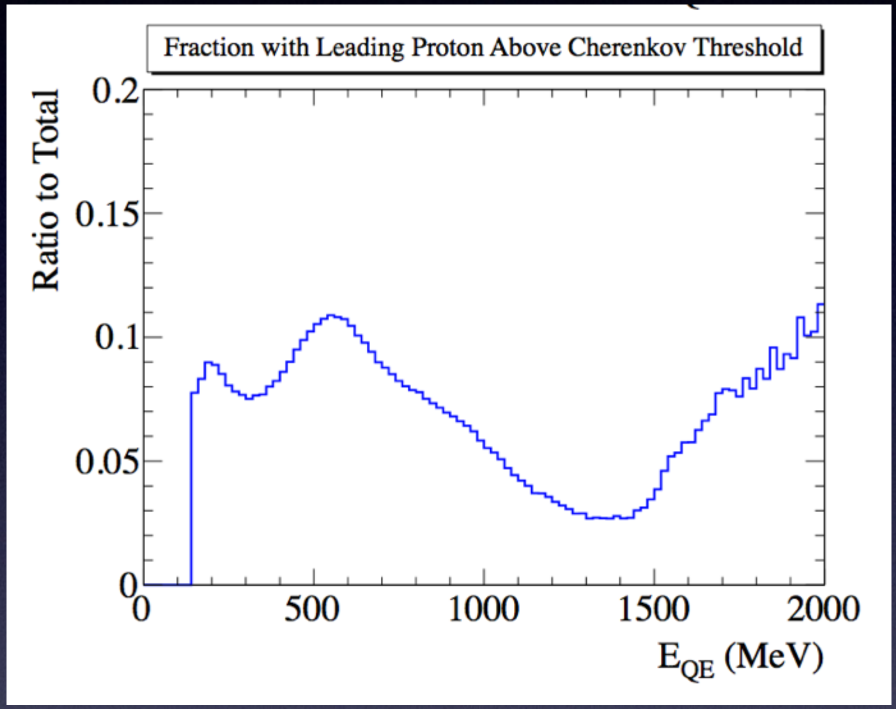
M_A: 1.08 -> 1.11 GeV
CCQE Norm.: 1.00 -> 1.02

SK Final State Protons

- Given our nucleon ejection model, is it reasonable to assume that we don't have significant number of protons above Cherenkov threshold?



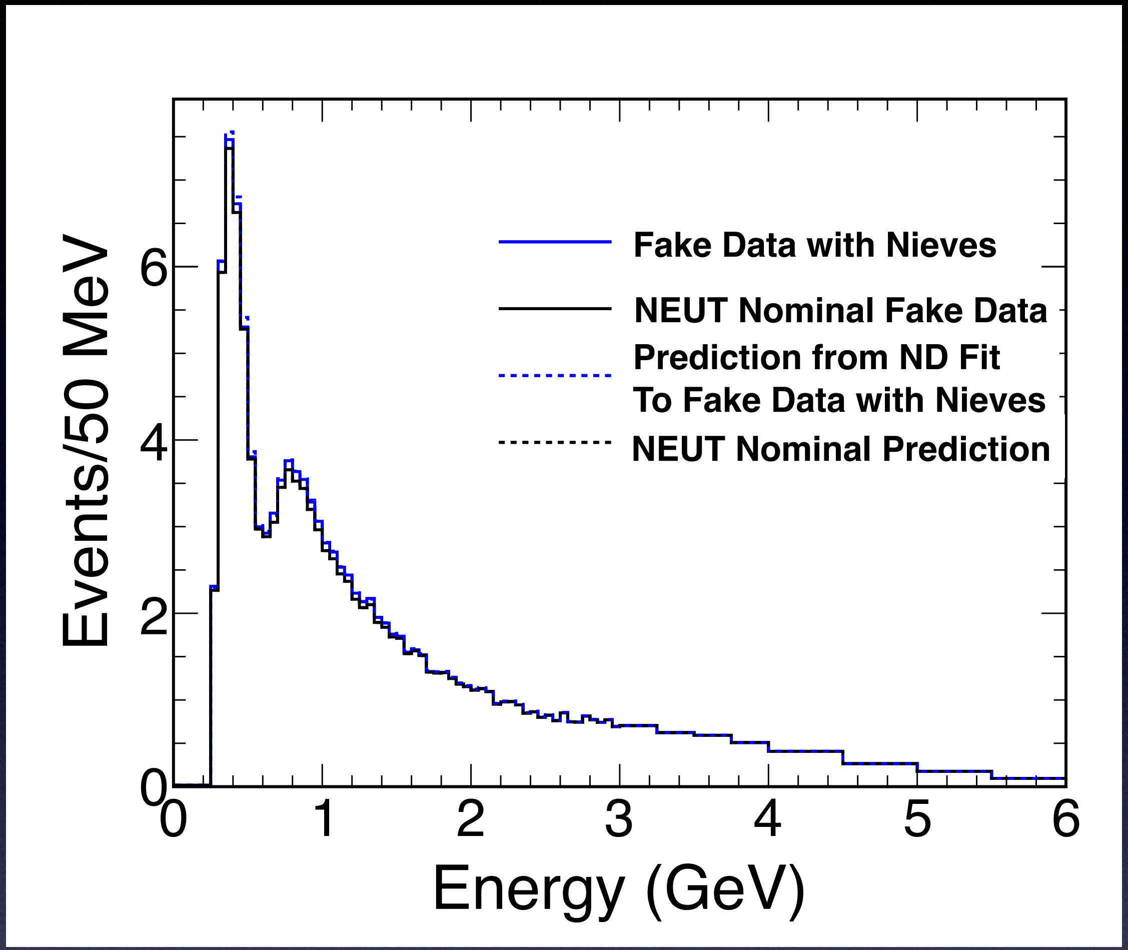
~20% of events have p above Cherenkov threshold at E_ν=1.4-1.5 GeV

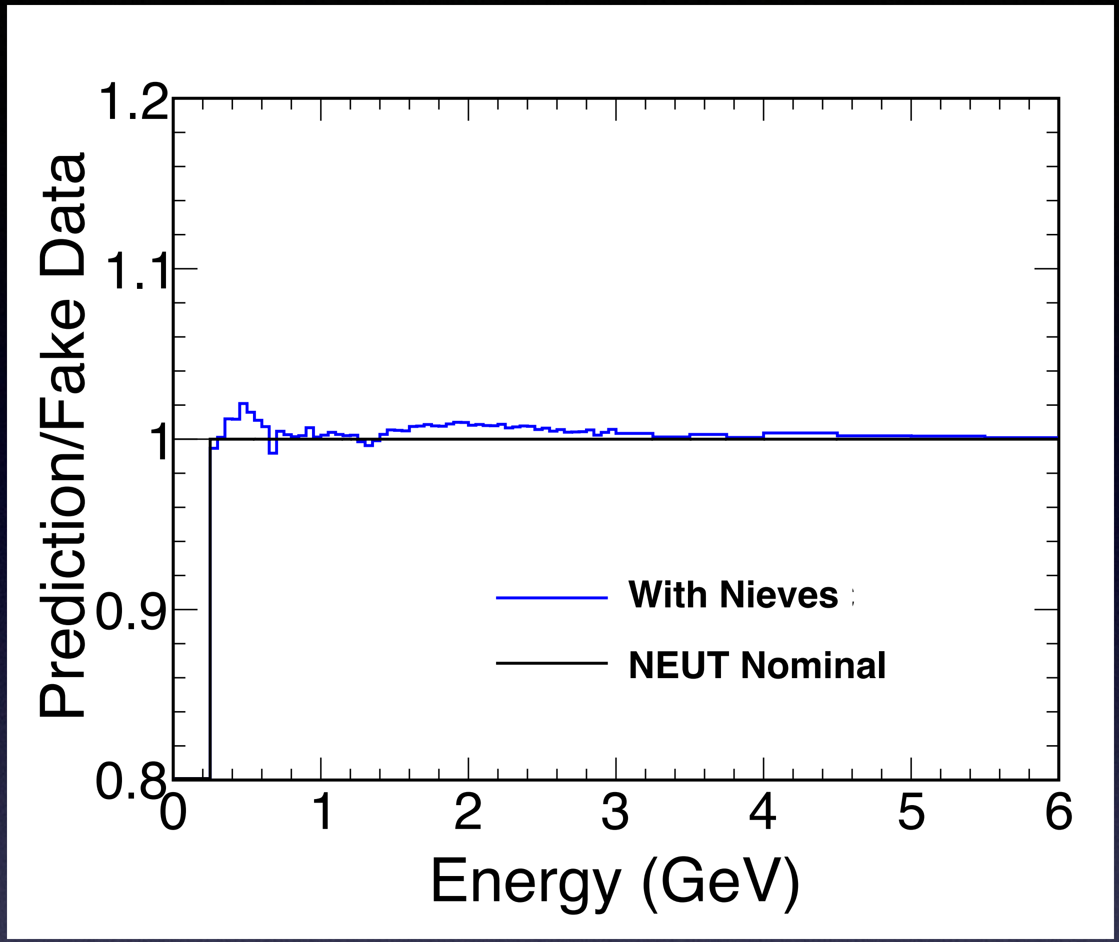


Corresponds to 10% of the multinucleon prediction near the oscillation peak

- Effect is smaller than 10% since protons near threshold are not reconstructed
- May be important as we extend the multi nucleon model to higher energy

SK Multinucleon Prediction



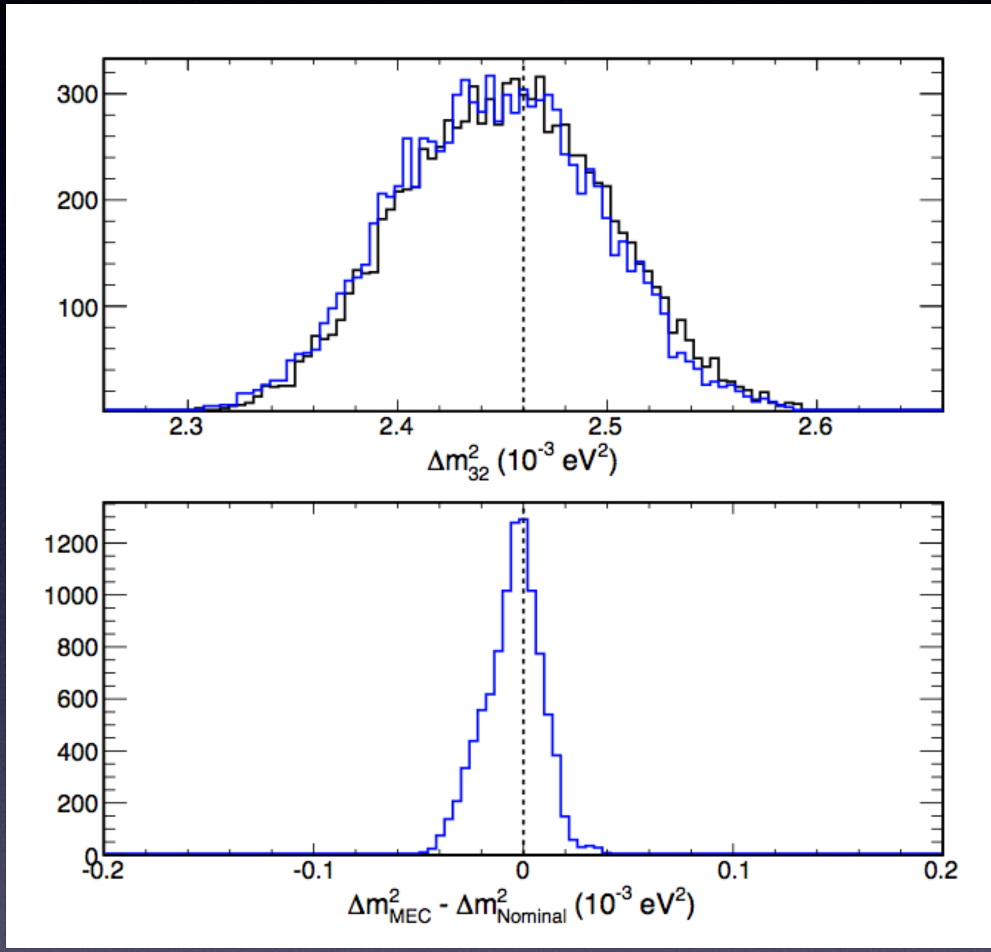


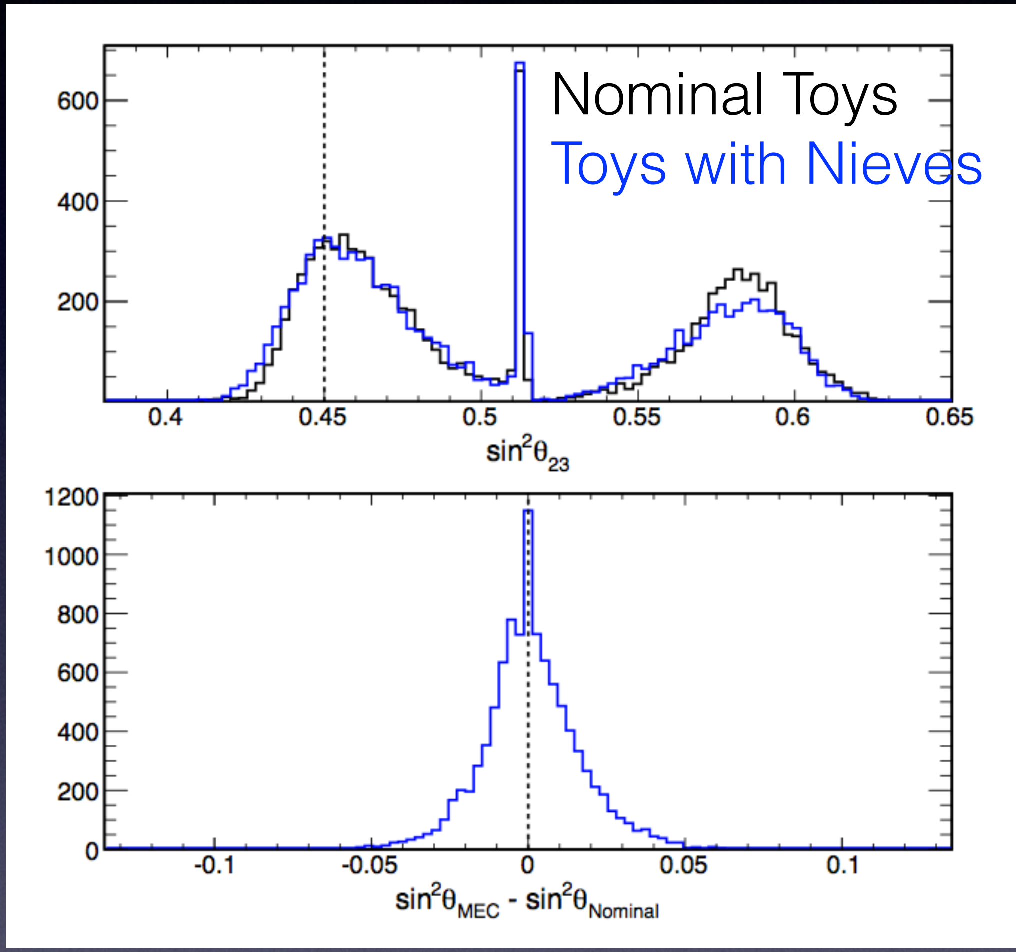
Left: solid lines are the SK toy data with (blue) and without (black) the multinucleon component. Dashed lines are the fit predictions that do not include the multinucleon model, but do include the ND280 constraint.

Right: The ratios of the fit predictions to the SK fake data. The bias in the spectrum is less than 2%

Oscillation Fit Results

Toy samples generated with Δm^2_{32}=2.46x10^{-3} eV^2, $\sin^2\theta_{23}$=0.514 (maximal mixing) or 0.45

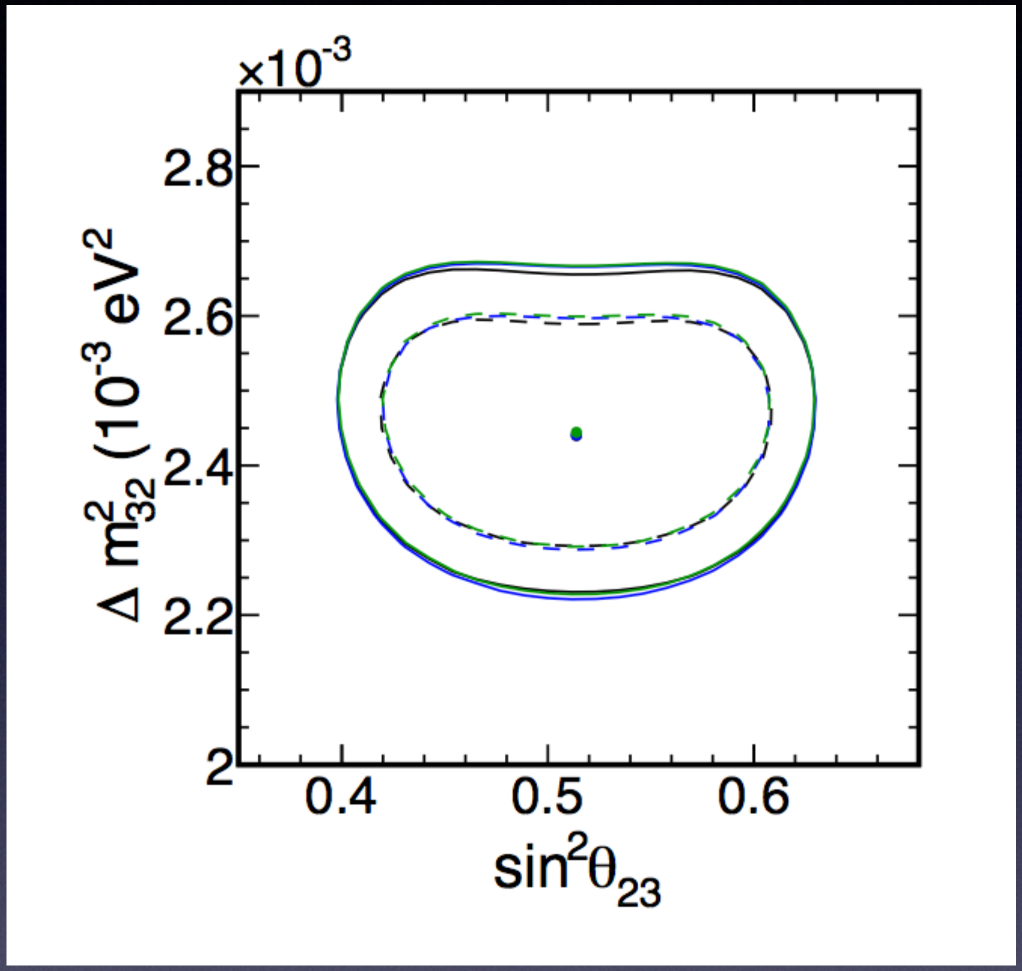


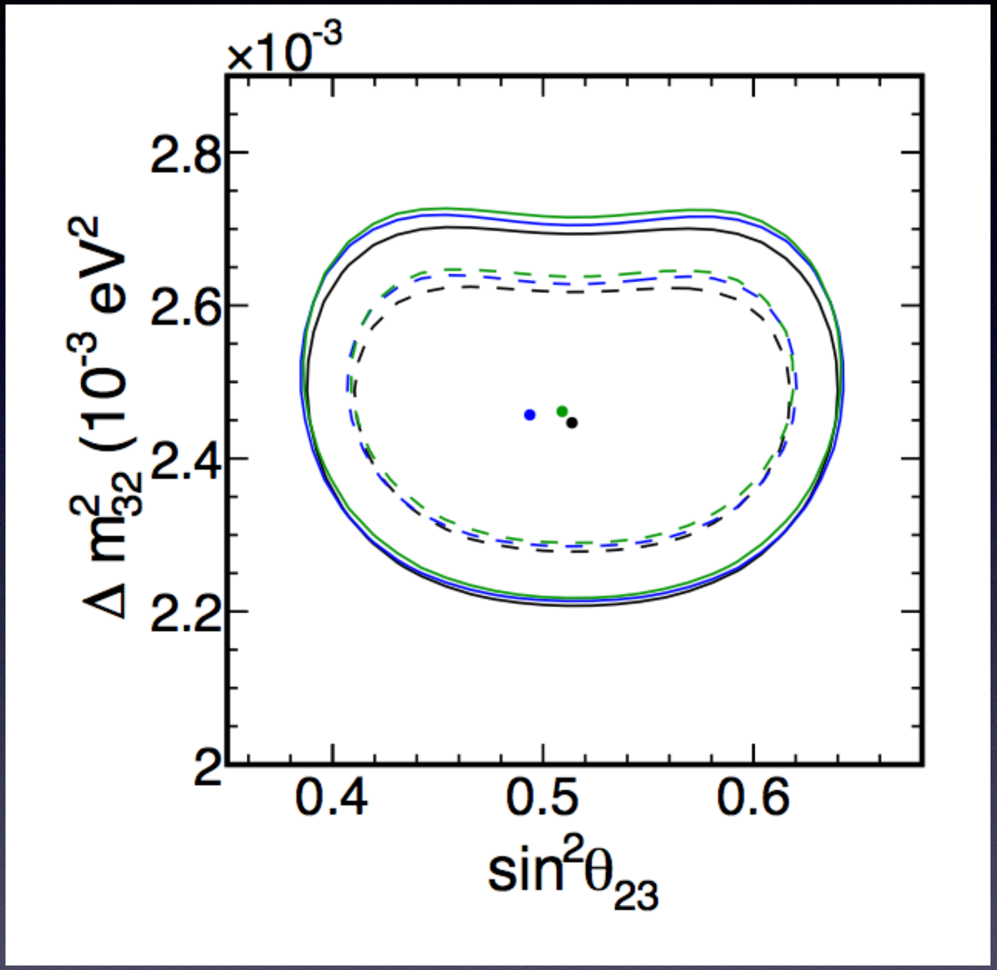


Parameter	Bias	RMS	Run 1-3 Data Fit Errors
$\sin^2\theta_{23}$	0.0012 (0.3%)	0.016 (3.6%)	±0.082
Δm^2_{32} (eV^2)	-0.005x10^{-3} (-0.2%)	0.014x10^{-3} (0.6%)	+0.17-0.15

Confidence Interval Shifts

NOT Official T2K Senstivities





Blue = fake data includes multinucleon, fit model doesn't
Green = fake data and fit model include multi nucleon
Black = fake data and fit model are both NEUT nominal

Limitations of This Study

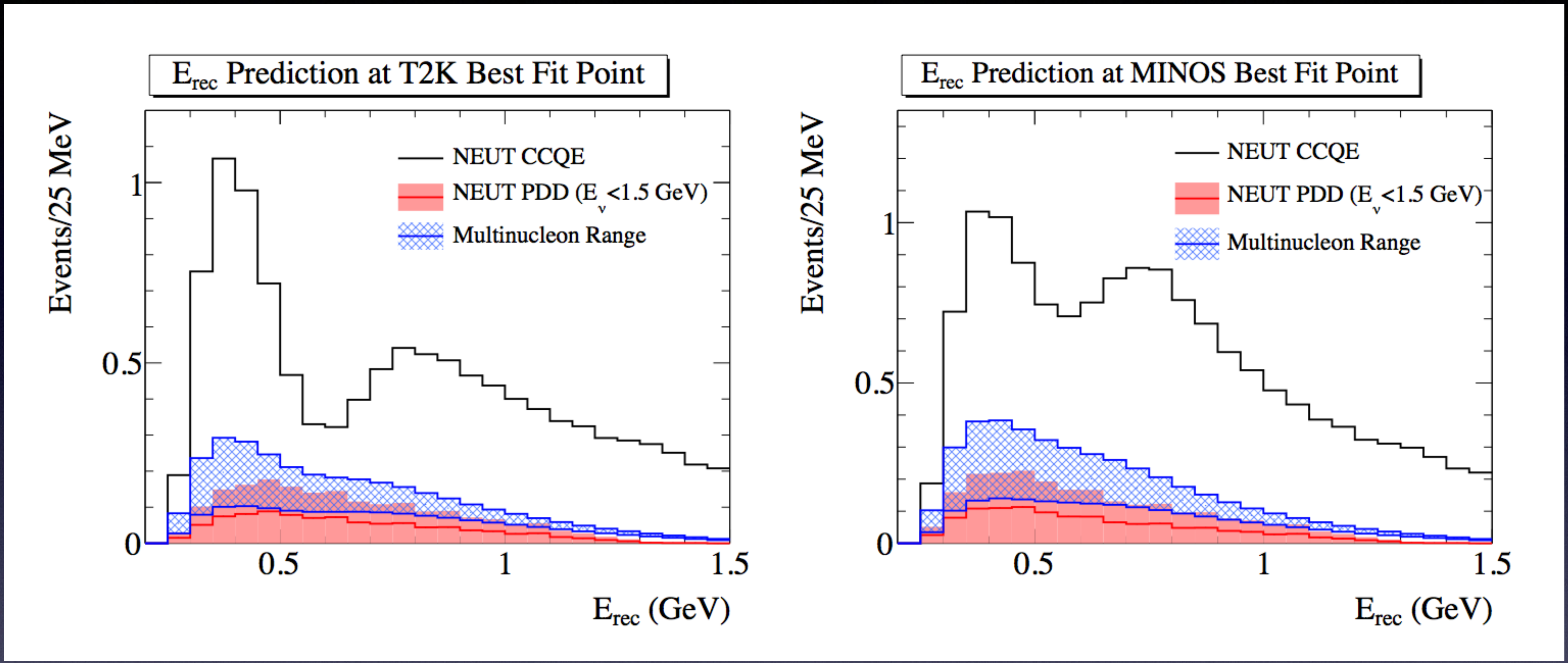
- This study only investigates one multinucleon model
  - Smaller multinucleon prediction than the Martini model
- The Nieves model is only applied for $E_\nu<1.5$ GeV
- Final state protons not simulated for SK prediction, and no uncertainty applied
- No uncertainty applied due to different nuclear target in the near detector
- No additional uncertainty applied to account for phase space difference in the near and far detector selection

Conclusion

- We have investigated how much the lack of a full multinucleon model in NEUT can affect the T2K disappearance analysis
- The effect on the oscillation fit parameters is smaller than the currently published parameter errors from T2K
  - In part due to the fact that the NEUT model already includes π-less Δ decays
  - See limitations of the study from previous slide
- Future oscillation analyses will include a full treatment of multinucleon model with the Nieves et. al. implementation in NEUT
  - This work is described in the following talks

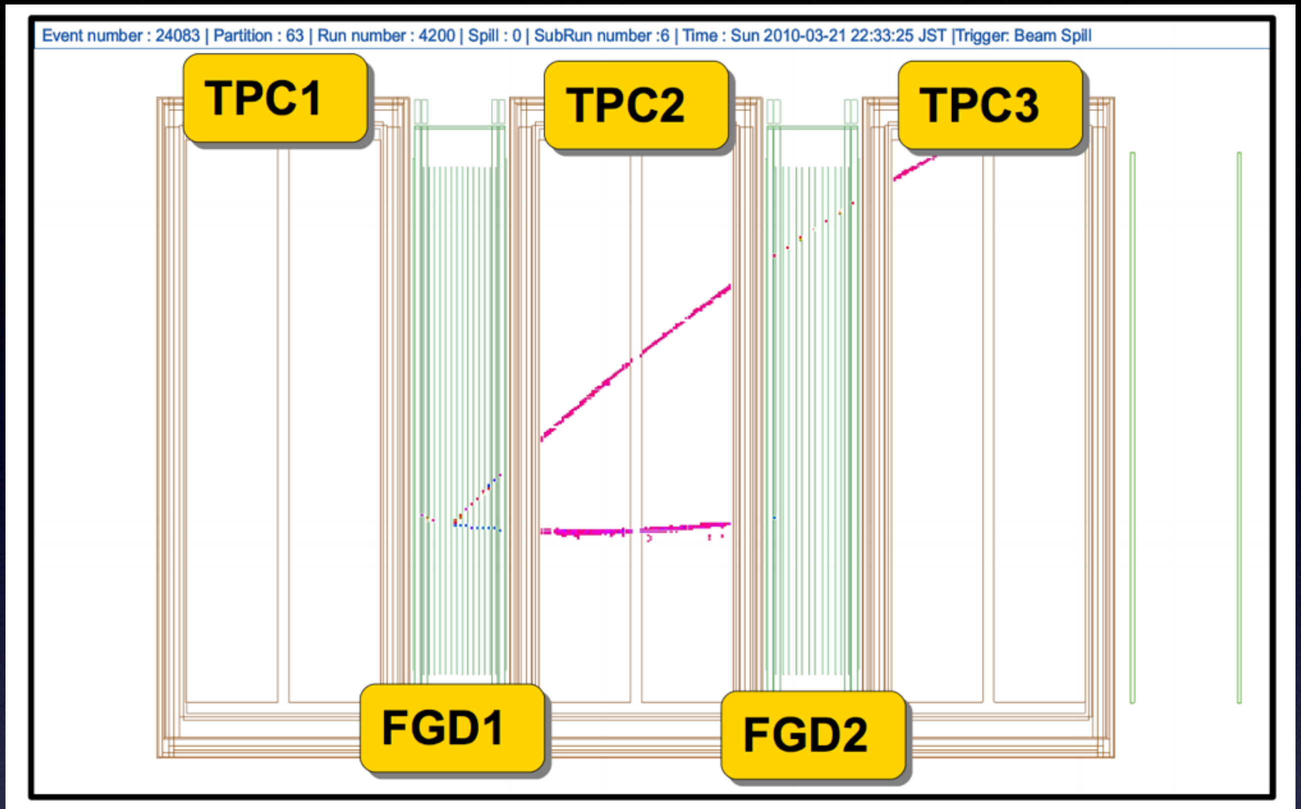
Extra Slides

SK Contributions



Comparison of the systematic variation of the NEUT π-less Δ decay (red) and the range of multi nucleon predictions (blue). Lower edge is the Nieves model and upper edge is estimate of the contribution in the Martini model.

ND280 Selection Improvements



Old and new selection begins with presence of negative muon originating in FGD1 and tracked by TPC2

Old selection split into CCQE-like and CCnonQE-like based on additional track penetrating to TPC2 - could be proton or pion

New selection split into:

CC0π - no pion or electromagnetic candidates
CC1π - a single π+ candidate from FGD1/TPC2 track, FGD1 only track or FGD1 decay electron candidate
CCOther - Presence of multiple pion candidates, π- candidate or electromagnetic object

Cross Sections