Using the T2K near detector in neutrino oscillation measurements

Jordan Myslik

University of Victoria

June 16, 2014

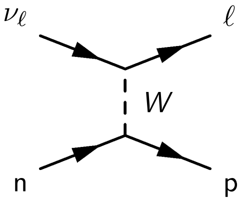
The T2K Experiment

The PMNS matrix and some Quantum Mechanics tells us:

- $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$
- $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1-\cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$

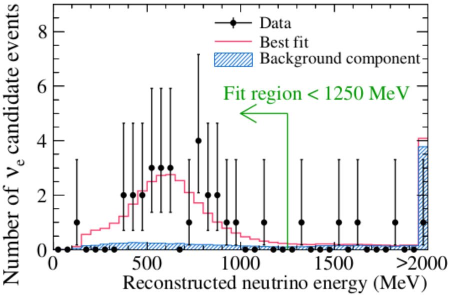
Neutrino oscillation: signal

- Oscillation probabilities are dependent on the neutrino energy (both include the term $\sin^2 \frac{\Delta m^2_{32} L}{4E_\nu}$).
- CCQE is the dominant interaction process for T2K's neutrino energy spectrum.

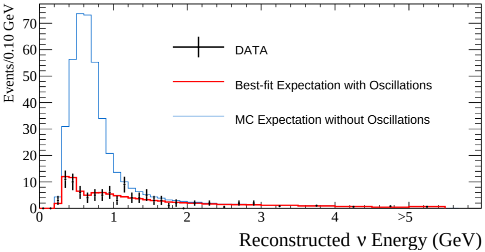


- The neutrino energy is reconstructed from the outgoing lepton's momentum and angle.

Electron neutrino appearance

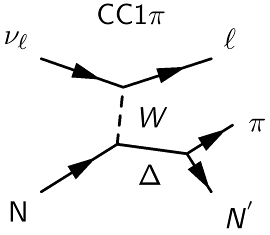


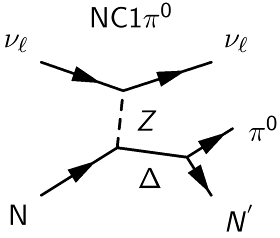
Muon neutrino disappearance



Neutrino oscillation: backgrounds

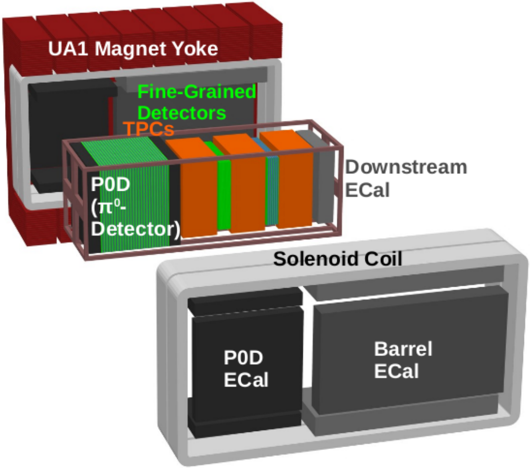
- CC1π would appear to be CCQE if the pion is absorbed before leaving the nucleus, or is otherwise not detected.
- For NC1π^0 the π^0 decay photons would produce charged leptons which could be mistakenly identified as originating from a CCQE interaction.
- In both cases, the energy spectrum would be distorted.



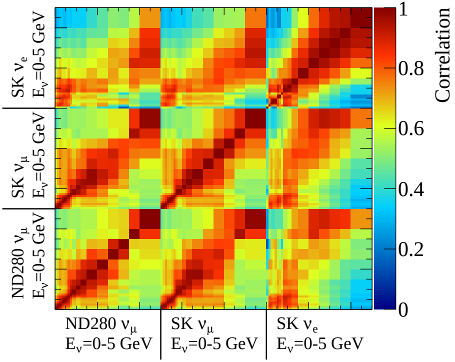


How can ND280 contribute?

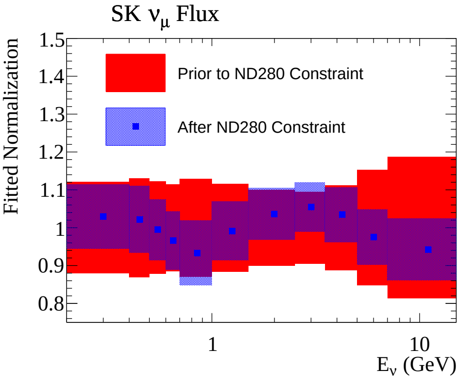
- The observed neutrino energy spectrum at SK is a function of the oscillation parameters, the interaction cross sections, and the neutrino flux provided by the beam.
- The measurements at ND280 constrain the beam flux at SK.
- Our cross section model has parameters that are common to ND280 and SK.
- ND280 has detector systematics of its own to consider.



Beam parameters



- Primary proton interactions with the target are modelled with FLUKA2008, with constraints from external data (such as NA61/SHINE).
- GEANT3 with GCALOR simulates propagation of secondary/tertiary pions/kaons and their decays.



- This provides the flux at ND280 and SK, and the correlations between ND280 and SK flux bins of energy.
- Fit to ND280 data includes normalization parameters for the ND280 flux bins. The correlations are then used to constrain SK flux bins.

Cross section parameters

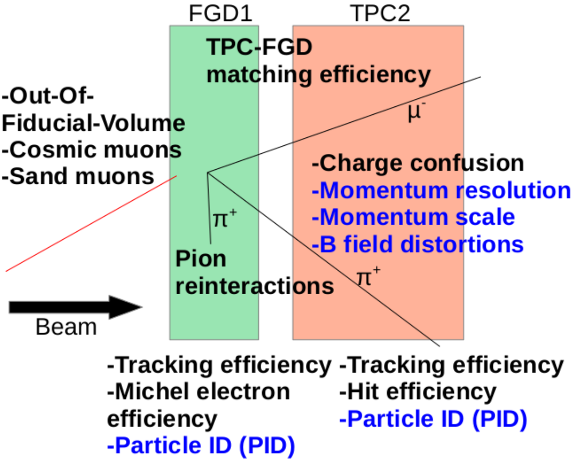
- NEUT is used to simulate neutrino interactions.
- The model also includes nuclear model parameters (detector specific and not shown.) These are not propagated to the SK oscillation analysis.
- Sufficient information from the simulation is saved to allow an event weight to be calculated if a parameter is varied.

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

- M_A^{QE} is the mass parameter in the axial dipole form factor for quasielastic interactions. (Affects shape of CCQE cross section.)
- M_A^{RES} is the mass parameter in the axial dipole for factor for resonant pion production interactions (Affects the shape of CC1π and NCπ^0 cross sections.)

ND280 Systematics

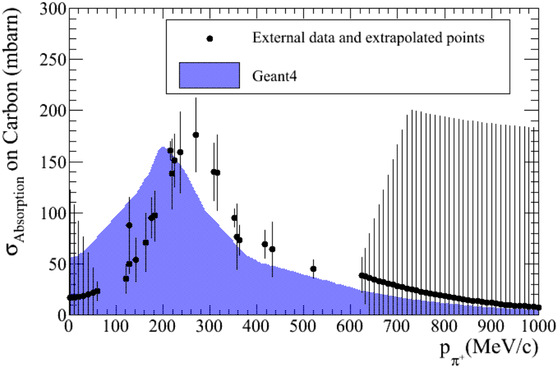
- Nearly all are calculated using control samples (i.e. not the neutrino spill data itself.) These include:
  - Sand muons.
  - Cosmic muons.
  - Stopping TPC1-FGD1 protons and muons.



- Methods of propagation in the fit:
  - Event weight (Black): Weight based on MC comparison to control samples or external information.
  - Event migration (Blue): Reconstructed quantities are changed and the selection re-performed using the new quantities.

ND280 Systematic: Pion reinteractions

- Occur outside nucleus pion produced in.
- Geant4 model differs from external data.
- Data uncertainties large, limited momentum range (extrapolate outside it).
- Two sets of weights:
  1. Correct MC to Data.
  2. Variation according to Data uncertainty.
- Given pion interaction process cross sections, calculate probability of the relevant pion trajectories in the event. Changing cross section changes probability. Event weight is ratio of probabilities.

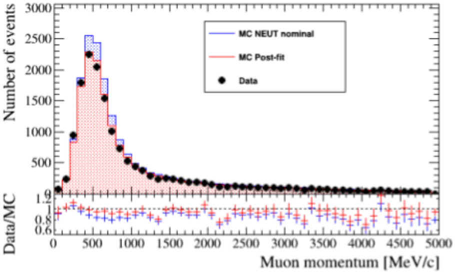


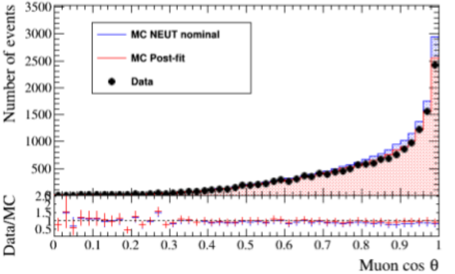
- Absorption of π^+ on Carbon-12.
- Geant4 cross section is in blue.
- Data is in black. The extrapolated points begin after the points get much denser, below and above the data region.

Fitting ND280 samples

- For the 2013 analysis ND280 provided 3 ν_μ samples defined by the particles leaving the nucleus.
  - CC-0π: A muon and no pions. Dominated by CCQE.
  - CC-1π^+: A muon and a positive pion. Dominated by CC1π.
  - CC-Other: A muon and any other combination of pions.
- These plots show the nominal Monte Carlo distribution and that re-weighted with the fit results, in comparison to the data for the CC-0π sample.

CC-0π sample



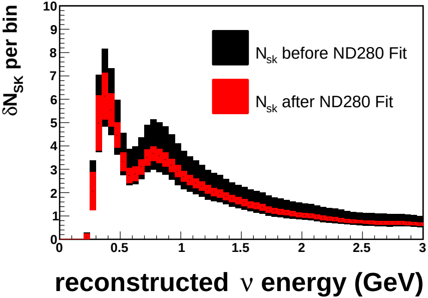


Impact on the oscillation analysis

Electron neutrino appearance

Error source [%]	$\sin^2 2\theta_{13} = 0.1$	$\sin^2 2\theta_{13} = 0$
Beam flux and near detector	2.9	4.8
(w/o ND280 constraint)	(25.9)	(21.7)
ν interaction (external data)	7.5	6.8
Far detector and FSI+SI+PN	3.5	7.3
Total	8.8	11.1

Muon neutrino disappearance



- For muon neutrino disappearance, this corresponds to a 21.6% uncertainty due to beam flux and near detector constrainable cross section parameters without the ND280 constraint, and 2.7% with the constraint.
- Overall, a large reduction in uncertainty for both electron neutrino appearance and muon neutrino disappearance analyses!

Summary

- Measuring neutrino oscillation parameters at T2K requires a good understanding of the neutrino flux at the far detector and the relevant interaction cross sections.
- The T2K near detector (ND280) makes measurements that constrain flux and cross section model parameters at the far detector.
- The ND280 constraint reduces uncertainties in the oscillation parameter measurements to a great extent, allowing more precise measurements than would otherwise be possible.