# Limitations of Current Near Detectors and Requirements for the Future

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### Candidate Samples for Oscillations

 Near detector measurements are used to constrain the predicted contributions to the oscillation candidate samples at the far detector

#### v<sub>e</sub>(-bar) Candidates

Channel	Fraction in Neutrino Mode	Fraction in Antineutrino mode
$CC v_{\mu}+v_{\mu}$ -bar	0.003	0.003
CC v <sub>e</sub>	0.134	0.065
CC v <sub>e</sub> -bar	0.005	0.117
NC	0.046	0.078
Signal v <sub>e</sub>	0.804	0.117
Signal v <sub>e</sub> -bar	0.007	0.621

Channel	Fraction in Neutrino Mode	Fraction in Antineutrino mode
CC v <sub>e</sub> +v <sub>e</sub> -bar	0.003	0.001
NC	0.052	0.048
Signal $v_{\mu}$	0.889	0.373
Signal $v_{\mu}$ -bar	0.056	0.578

- Significant wrong sign background in antineutrino mode magnetized near detector needed to directly constrain it
- Large  $\theta_{13}$ , fiTQun: NC backgrounds for appearance analysis are now ~5-10% of the total event rate
- Dominant background for appearance is the intrinsic  $v_e$  in the beam

### T2K Systematic Errors

		$\nu_{\mu}$ sample	$\nu_{\rm e}$ sample	$\overline{ u}_{\mu}$ sample	$\overline{ u}_e$ sample
ν flux		16%	11%	7.1%	8%
$\nu$ flux and	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
cross section	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
v cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

 $2014 \rightarrow 2015$ 

- It is difficult to draw conclusions about future needs from this table
- How much we can shrink this uncertainty with water measurements in ND280 is now being studied within T2K
  - Difficulty is understanding how much we can trust our model of interactions to extrapolate constraints from the near detector

# Systematic Error Requirements - CP violation

- For extended T2K, reducing systematic errors from 7% to 2% is equivalent to ~0.3 sigma increase in significance
  - Equivalent to ~25% more data
- We must be careful to not rely too much on models to reduce the systematic errors
  - Should be reduced by our measurements in the near detectors



### Systematic Error Requirements - CP violation

- Studies for Hyper-K (R. Shah) have shown the how different error sources affect the CP violation sensitivity
- Dominant effect is the uncertainty on the difference in the electron neutrino and electron antineutrino cross sections





intrinsic v<sub>e</sub>,v<sub>e</sub>-bar



#### Systematic Error Requirements - θ<sub>23</sub> M. Wilking - NuPRISM Talk

- Create "fake data" samples with flux and cross section variations
  - With and without multi-nucleon events
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- For Nieves model, "average bias" (RMS) = 5.6%
- For Martini model, mean bias = -2.9%, RMS = 3.2%
  - Full systematic =  $\sqrt{(2.9\%^2 + 3.2\%^2)} = 4.3\%$
  - This is expected to be one of the largest systematic uncertainties for the full T2K run
- But this is just a comparison of 2 models
  - How much larger could the actual systematic uncertainty be?
- A data-driven constraint is needed



#### Normalization vs. "Shape" Uncertainties



- Detection of CP violations comes from observation of significant difference in the appearance signal in the two samples rate effect
- Constraint on  $sin(\delta)$  is largely from the rate measurements
- Constraint on  $cos(\delta)$  depends on measuring the spectrum shape (green points)
  - Requirements to measure  $\cos(\delta)$  need to be explored

ND Limitations and Future Needs

# Physics Requirements vs. Detectors (First Pass)

	v <sub>e</sub> Cross Section	Wrong Sign Bgnd	NC, v <sub>e</sub> Bgnds.	Neutron # (Gd)	Hadronic (Charged) FS	FS Muon vs. Neutrino	Beam Dir.	4π	H <sub>2</sub> O x-sec	CCπ <sup>0</sup>
INGRID										
ND280										
ND280 Upgrade (WAGASCI)										
ND280 Upgrade (WbLS)		Ο	nly m	y own	first pa	ass eva	lluatic	n!		
ND280 Upgrade (HP-TPC)										
NuPRISM style WC										
TITUS style WC										

Capability Key:

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= Good



#### ND280 Detector

- 0.2 T magnetic field
- Targets with segmented X and Y planes
- Active plastic scintillator targets interspersed with passive water layers
- $\pi^0$  detector with brass radiator layers
- Surrounding ECALs



#### How we use the near detectors

We can consider three primary ways that we use the near detectors

Will focus on this

- 1. Measurements that directly constrain signal or background predictions for oscillation measurements
- 2. Measurements that input to cross-section model building, may eventually feed back into the oscillation measurements
- 3. Measurements that constrain signal or background predictions for atmospheric neutrino or proton decay measurements in the far detectors

#### Near to Far Correlations

- We use near detector (ND) measurements to infer the predicted event rates in the far detector (FD)
- · Simplified calculation of the ND event rate based on the flux and cross section models:

$$N^{ND}(p,\theta) \sim \sum_{i}^{v \text{ Flavor } v \text{ Energy Int. Mode Target Nuclei}} \sum_{k} \sum_{m}^{V} \Phi_{i}^{ND}(E_{j}) \sigma_{i,k,m}(E_{j}, p, \theta) \epsilon_{i,k,m}^{ND}(p, \theta) N_{m}^{ND-target}$$

- The flux and cross section models are constrained by comparing this prediction to the observed event rates
- We can write a similar calculation for the event rate in the FD:

$$N^{FD}(p,\theta) \sim \sum_{l}^{v \text{ Flavor } v \text{ Flavor } v \text{ Energy Int. Mode Target Nuclei}} \sum_{k} \sum_{m}^{V \text{ Flavor } v \text{ Flavor } v \text{ Flavor } v \text{ Flavor } v \text{ Flavor } \sum_{k} \sum_{m}^{v \text{ Flavor } v \text{ Flavor }$$

 To minimize systematic errors in the extrapolation, factors in ND event rate calculation should match the factors in the FD event rate calculation as much as possible

#### **Detector Acceptance**

$$N^{ND}(p,\theta) \sim \sum_{i}^{v \text{ Flavor } v} \sum_{j}^{\text{Energy Int. Mode Target Nuclei}} \sum_{m}^{ND} \Phi_{i}^{ND}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \mathbf{\epsilon}_{i,k,m}^{ND}(p,\theta) N_{m}^{ND-target}$$
$$N^{FD}(p,\theta) \sim \sum_{l}^{v \text{ Flavor } v} \sum_{j}^{\text{Flavor } v} \sum_{j}^{\text{Energy Int. Mode Target Nuclei}} \sum_{m}^{ND} P_{l \to i}(E_{j}) \Phi_{l}^{FD}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \mathbf{\epsilon}_{i,k,m}^{FD}(p,\theta) N_{m}^{FD-target}$$

- Super-K detector has 4π coverage
- So far, ND280 measurements used in oscillation analysis are limited to leptons produced in the forward hemisphere



#### Current muon candidate angular efficiency



- The efficiency as a function of the muon candidate scattering angle
- No use of TOF between FGD1 and P0D/ECAL
- Global reconstruction assumes that tracks are forward going by default

#### ND Limitations and Future Needs

# Importance of large angle measurements



- Systematic error on on the RPA correction from Nieves et. al. calculation (Phys. Rev. C70 (2004) 055503) has been estimated by F. Sanchez
- Systematic is ~10% in the region of low efficiency for ND280

- ~27% of the total cross-section is in the  $Q^2$  region where ND280 efficiency is <50% ( $Q^2$ >0.4 GeV<sup>2</sup>)
- This region in Q<sup>2</sup> may be susceptible to certain types of modeling systematic uncertainties
  - Long range correlations (RPA modification of the boson propagator in the nuclear medium)
  - Deviations from dipole form factors



Systematic Variation of RPA Correction

# ND280 High angle and Backward Reconstruction

- T2K is working on expanding the angular acceptance with high angle and backward reconstruction (everything shown here is work in progress)
- High angle (forward and backward): <18 hits in TPC, and stops in ECAL or SMRD, deposited energy consistent with muon, TOF to ECAL is >0 ns
- Backward: >18 hits in TPC, passes dE/dx cut, positive TOF to P0D or ECAL

Work in progress!							
Purity	FV&Muon	FV&NotMuon	OOFV				
Fwd	90.7	5.2	4.1				
Bwd	79.0	1.9	19.1				
HA_Fwd	77.6	4.8	17.6				
HA_Bwd	71.5	3.2	25.3				

At least 10% of the efficiency in the backward hemisphere can be recovered, out-of fiducial backgrounds are ~20%



For FGD1 Only

Can it be improved?

ND Limitations and Future Needs

#### Discussion on $4\pi$ Reconstruction

- Improvements to the backward reconstruction?
- A looser cut on the FGD fiducial volume reduces the number of vertices migrating out of the fiducial volume - can recover ~4% efficiency for very backward tracks
- Efficiency is higher in FGD2 since the FGD2-FGD1 TOF resolution is better: ~75% efficiency
- Can FGD1-P0D and FGD1-ECAL TOF be improved?
- Large contribution to the inefficiency is from the requirement of >18 TPC hits. Can it be reduced without degrading PID too much?
- Improvements to high angle reconstruction?
  - Inefficiency from requirement of penetration to the ECAL
  - PID in ECAL is optimized for electron vs. through-going muon, not stopping muons

Conclusion: High efficiency backward reconstruction may be possible with better TOF calibration. Large angle reconstruction is limited by geometry of the FGD (too much material to traverse parallel to the planar structure of the FGD)

ND Limitations and Future Needs

# $NC\pi^0$ Reconstruction in the POD



The NC $\pi^0$  reconstruction in the P0D is also limited to  $\pi^0$  in the forward direction

Do we need to improve this, or can we rely on the far detector measurement?

Can select a pure sample of NC $\pi^0$  candidates with 22 predicted events in T2K Run 1-4 (can be improved with fiTQun)

Compare to 0.52 events of NC background in the appearance analysis



#### Measurements on Water

$$N^{ND}(p,\theta) \sim \sum_{i}^{v \text{ Flavor } v} \sum_{j}^{\text{Energy Int. Mode Target Nuclei}} \sum_{m}^{ND} \Phi_{i}^{ND}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \epsilon_{i,k,m}^{ND}(p,\theta) N_{m}^{ND-target}$$
$$N^{FD}(p,\theta) \sim \sum_{l}^{v \text{ Flavor } v} \sum_{j}^{\text{Flavor } v} \sum_{j}^{\text{Energy Int. Mode Target Nuclei}} \sum_{m}^{V} P_{l \to i}(E_{j}) \Phi_{l}^{FD}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \epsilon_{i,k,m}^{FD}(p,\theta) N_{m}^{FD-target}$$



Water mass: 383 kg Non-water mass: 438 kg Subtraction method: FGD1 vs. FGD2

ND Limitations and Future Needs



Water mass: 2900 kg Non-water mass: 12900 kg Subtraction method: Water in vs. water out

### The FGD2 Water Measurement

- The FGD2 is now being implemented in the ND280 fitting method for the oscillation analysis
- Water constraint if effectively derived as:

$$N_{FGD2} = N_{PS2} + N_{H2O}$$
$$N_{PS2} = N_{FGD1} \frac{M_{PS2}}{M_{PS1}}$$
$$N_{H2O} = N_{FGD2} - N_{FGD1} \frac{M_{PS2}}{M_{PS1}}$$

- Ignoring purity and efficiency differences between FGD1 and FGD2, the statistical error is 63% larger compared to a measurement on a pure water target of the same mass
- FGD1 and FGD2 systematic parameters and their correlations are now being studied for the combined FGD1+FGD2 data fit
  - Preliminary results suggest a <1% systematic error on the water rate very preliminary!
- Statistic for CC- $v_{\mu}$  are sufficient to make a measurement with <1% statistical error on the total rate

#### Neutrino Flux

$$N^{ND}(p,\theta) \sim \sum_{i}^{v \text{ Flavor } v} \sum_{j}^{\text{Flavor } v} \sum_{k}^{\text{Flavor } v} \sum_{m}^{\text{Flavor } v} \sum_{m}^{\text{Fl$$

- The near detector flux differs from the far detector flux in 3 ways:
  - Line source at ND, point source at FD
  - Oscillations change the energy dependence of the neutrino flux
  - Oscillations can change the flavor of the neutrino flux:  $v_{\mu} \rightarrow v_{e}$
- First point is relevant for extrapolating backgrounds where oscillation effect is small: NCπ<sup>0</sup>, intrinsic ve
- Difference in energy dependence is largest for the

#### Intrinsic Electron Neutrino Background

- The oscillations of the intrinsic  $v_e$  are small, so the flux at the near and far detectors are similar
- A direct extrapolation with little model dependence is possible
- The intrinsic  $v_e$  are measured in ND280 using the tracker
  - Interactions in the FGDs
  - Electron particle ID using dE/dx and ECAL PID

At low momentum, large background from converting photons where conversion pair is not identified.

Photon background is constrained a high purity photon enhanced sample





### Constraint on SK Rate

 Ignoring H<sub>2</sub>O-CH difference the rate of the electron neutrinos relative to the muon neutrinos is measured:

 $R(\nu_e) = 1.008 \pm 0.060(\text{stat}) \pm 0.061(\text{Flux-XSec}) \pm 0.053(\text{Det-FSI})$ 

• More relevant may be error on ratio for  $E_v < 1.2$  GeV

 $R(\nu_{e1}) = 0.828 \pm 0.257(\text{stat}) \pm$  (Flux-XSec)  $\pm 0.124(\text{Det-FSI})$ 

- Just considering the statistical error, this extrapolates to a statistical error of 10% for the full T2K neutrino mode exposure (3.9e21 POT)
  - Corresponds to ~2% error on the total  $v_{\rm e}$  candidate rate on the far detector
- Currently we rely on the correlations of the  $v_e$  and  $v_\mu$  fluxes and cross sections to constrain the intrinsic  $v_e$  background
- A more precise intrinsic  $v_e$  measurement could provide and independent check
- Work on the  $v_e$ -bar selection is underway

### The v<sub>e</sub>(-bar) Cross Section Measurement

- For the  $v_e(-bar)$  signal, we extrapolate from  $v_{\mu}(-bar)$  rates measured in the near detector
- Rely on models to predict the cross section ratios in the extrapolation, but there may be uncertainties
  - Second-class current terms that depend on the lepton mass Phys.Rev. D86 (2012) 053003
  - Uncertainty on the cross-section in the different kinematically allowed phase space
  - Need better evaluation of this uncertainty, but could be ~3%
- For CP violation measurement, the important quantity is:  $(\sigma_v / \sigma_v) / (\sigma_{\bar{v}} / \sigma_{\bar{v}})$
- Given the statistics in ND280, measuring this to ~2-3% is not possible especially if we want a measurement on  $H_2O$

#### Different Spectra at Near and Far Detectors

$$N^{ND}(p,\theta) \sim \sum_{i}^{v \text{ Flavor } v \text{ Energy Int. Mode Target Nuclei}} \sum_{m} \Phi_{i}^{ND}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \epsilon_{i,k,m}^{ND}(p,\theta) N_{m}^{ND-target}$$

$$N^{FD}(p,\theta) \sim \sum_{l}^{v \text{ Flavor } v \text{ Flavor } v \text{ Energy Int. Mode Target Nuclei}} \sum_{m} P_{l \to i}(E_{j}) \Phi_{l}^{FD}(E_{j}) \sigma_{i,k,m}(E_{j},p,\theta) \epsilon_{i,k,m}^{FD}(p,\theta) N_{m}^{FD-target}$$

- Neutrino oscillations mean that the near and far detector spectra can be quite different
  - Extrapolations from the near detector become model dependent
- Consider a toy experiment where we observe a deficit in the near detector:



# Toy Study - Correcting Model with ND Data



ND Limitations and Future Needs

### Toy Study - Far Detector Prediction

- We can now predict the far detector spectrum after oscillations.
  - How does it compare to the true spectrum?
- The predicted spectrum is not a particularly good match to the true spectrum in the far detector.
- In fact, we needed to enhance the multinucleon part of the cross section, not the single nucleon
- But we could not know this only from the near detector muon data because the problem is under-constrained!



# Adding Constraints

- To avoid an under-constrained problem we need to add constraints
  - Limit allowed models based on calculations of neutrino cross sections on nuclei.
  - Measure final state protons
  - Combine constraints from multiple
     experiments with different neutrino spectra
  - Make measurements with many different spectra in a single experiment
  - Produce mono-chromatic neutrino beams
  - Produce a near detector spectrum that matches the far detector spectrum

Calculations in a nuclear environment :(

No neutrons, connection to models is unclear

T2K is pursuing. Reconciling different experiments through models has not worked well so far

Three different ways of saying that we need NuPRISM

# Summary on ND280 and Future Needs

- The geometry of the ND280 detectors makes 4π coverage quite challenging
  - Can a better configuration that works with the magnetic field be found?
- The large amount of material surrounding the inner tracker is a source background for electron neutrino measurements
- Statistics are too low for ~few percent measurement of the electron neutrino to muon neutrino cross section ratio
- Full water subtraction analyses are underway and we will soon have a better idea of the systematic error propagation in the subtraction techniques
  - Statistics may be sufficient for muon neutrino interactions, but not for electron neutrinos
- The NC $\pi^0$  background may be sufficiently constrained with the measurement in the far detector
- The problem of a differing fluxes at ND280 and SK should be addressed, especially for precision  $\theta_{23}$  measurement
- How can we use final state proton measurements to constrain the interaction models and what are the requirements on proton tracking?

# Other Outstanding Questions for Future Needs

- Do we need new neutrino-nucleon cross section measurements?
- What are the requirements from atmospheric and proton decay measurements?
  - Neutron multiplicity measurements in Gd in near detectors
  - Kaon production for background to p->Kv
  - CC $\pi^0$  background for p->e $\pi^0$
  - Can we make a more precise estimate of the model uncertainty on the muon neutrino to electron neutrino cross section extrapolation?

#### Extra Slides

#### **Detecting Final State Protons**

There has been significant progress to reconstruct vertices for gas interactions in the TPC

Gas mixture is 95% Ar - how relevant are these measurements for constraining the modeling C, O interactions?



- Measurements of vertex activity and proton tracks can be made in the FGDs
  - How low in energy should the proton tracking threshold be?
  - Are measurements on CH sufficient, or is H<sub>2</sub>O absolutely necessary?

### Reconstructing the Vertex Position

Can also attempt to isolate water interactions based on the reconstructed vertex position



- How reconstructed vertices migrate into the upstream and downstream active layers must be understood
  - This is work in progress
- Comment for future detector designs having more than two active layers between passive water targets can help to better measure the vertex migration?