Measurement of Charged-Current ν_e On-Water Interaction Rate with the π^0 Detector at T2K

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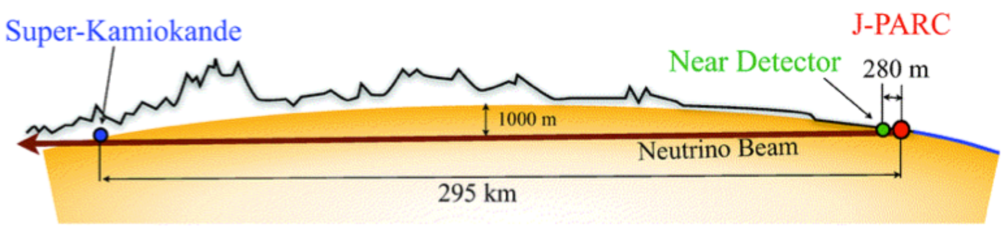
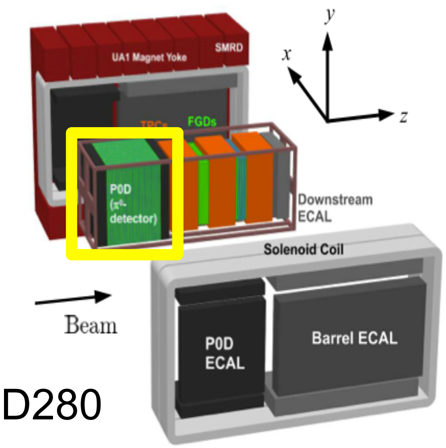
The T2K Experiment

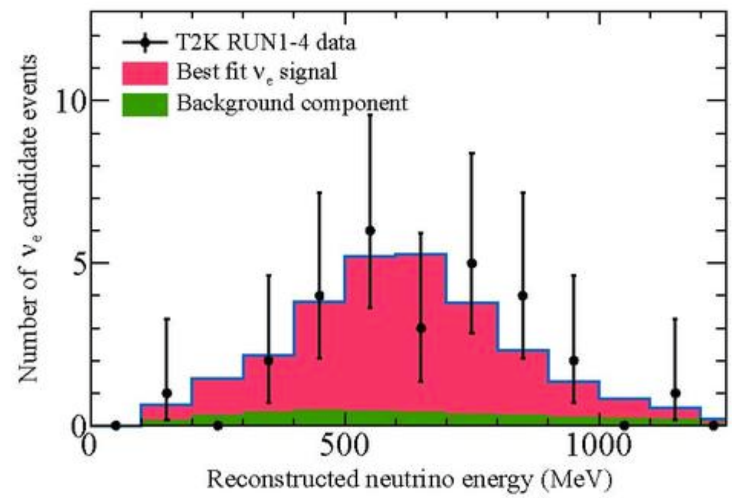
- T2K is a long-baseline neutrino oscillation experiment designed to observe ν_e appearance in a ν_μ beam





ND280

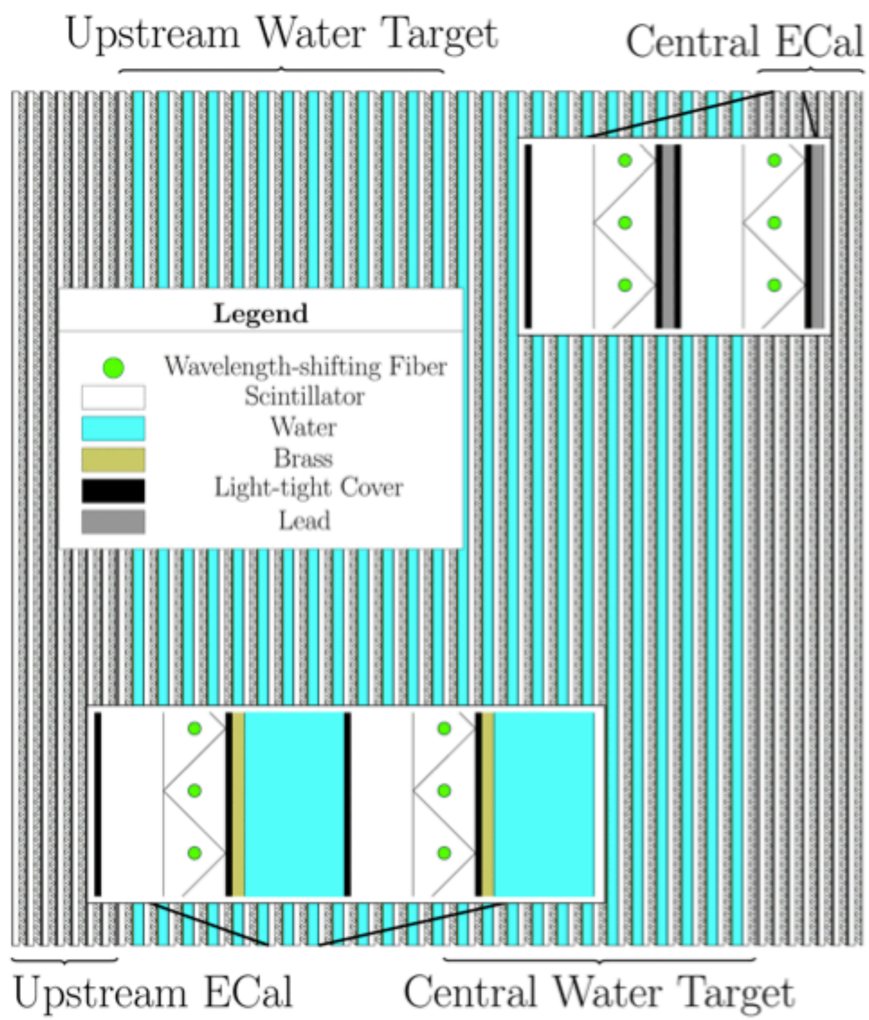
- High purity ν_μ beam is produced at J-PARC
- The near detector (ND280) measures unoscillated neutrino spectrum (280m)
- Neutrinos after oscillation are detected with the Super-Kamiokande detector (295km)



- **Presented observation (7.5σ) of ν_e appearance at the EPS-HEP conference 2013**

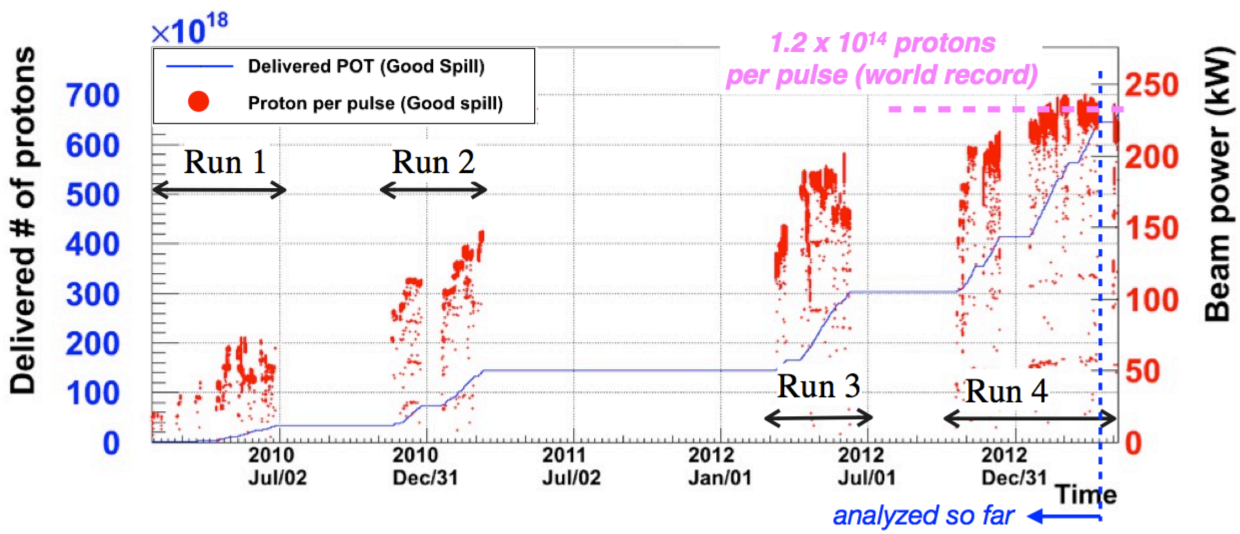
The π^0 Detector (P0D)

- The P0D is a layered tracking/ sampling calorimeter with scintillators, water targets, and absorber materials
- Triangular scintillator bars for improved position resolution
- Water targets are drain-able allowing on-water cross section measurements
- Primary goal is to constrain ν_e appearance background:
  - Neutral-current π^0 rate
  - ν_e contamination in the beam



P0D ν_e On-Water Measurement

- The ν_e interaction rate on-water hasn't been measured before
- A measurement of high-energy ν_e rate with P0D water-in configuration was presented at APS 2012 (based on Run 1+2 water-in data)
- In the meanwhile, T2K collected enough data with P0D water-in and water-out configuration to perform an on-water measurement (based on Run 1-4 data):
  - Water-in: 2.64×10^{20} p.o.t.
  - Water-out: 3.31×10^{20} p.o.t.



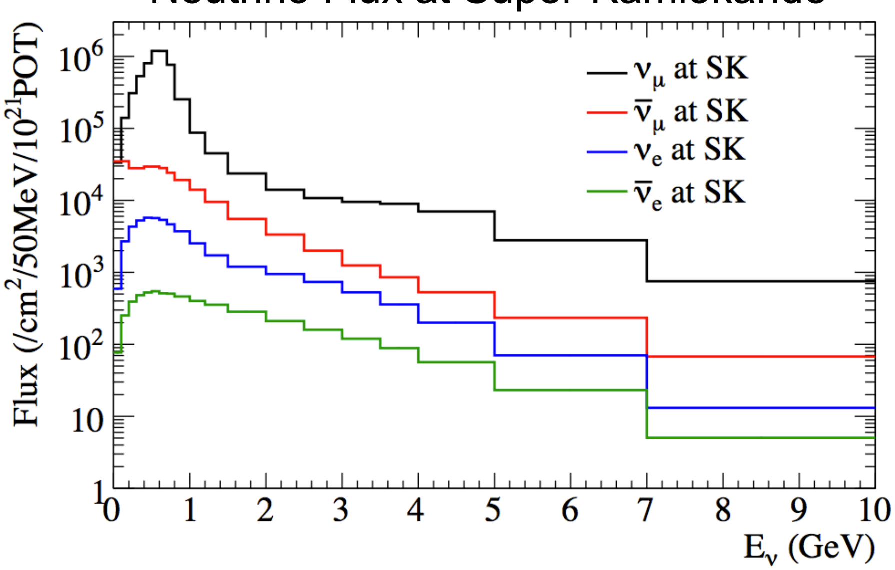
P0D High-Energy ν_e Measurement Motivation

- The 30GeV proton beam of J-PARC produces pions and kaons, where π^+ and K^+ are selected by three horns
- Two sources for ν_e contamination in ν_μ beam arriving at Super-Kamiokande (SK):

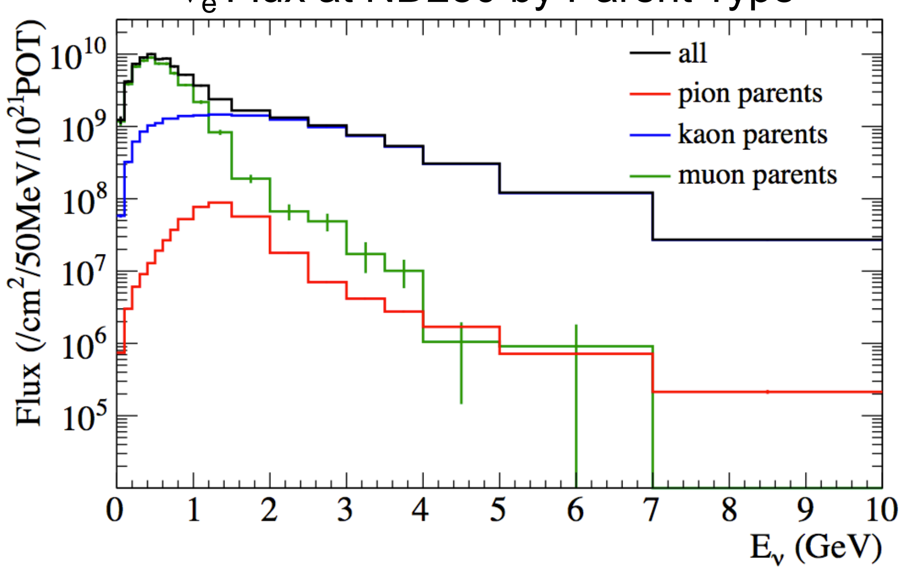
$$\pi^+ \to \nu_\mu + \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad K^+ \to \pi^0 + e^+ + \nu_e$$

- Above 1.5GeV, the ν_e contamination is predominantly from kaon decays

Neutrino Flux at Super-Kamiokande



ν_e Flux at ND280 by Parent Type



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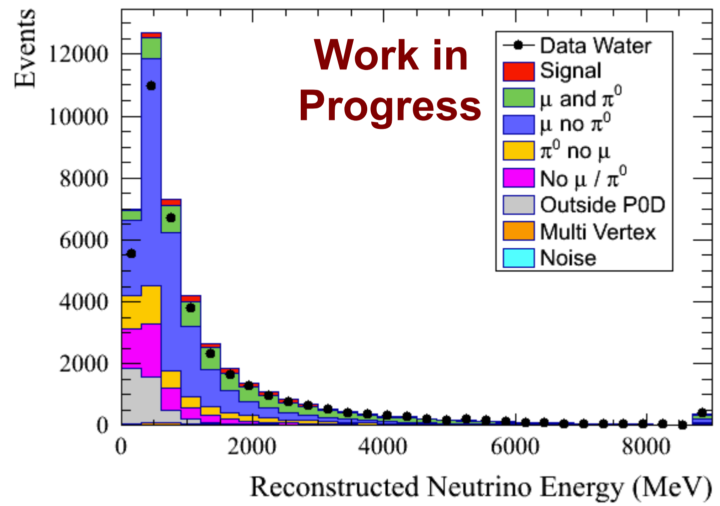
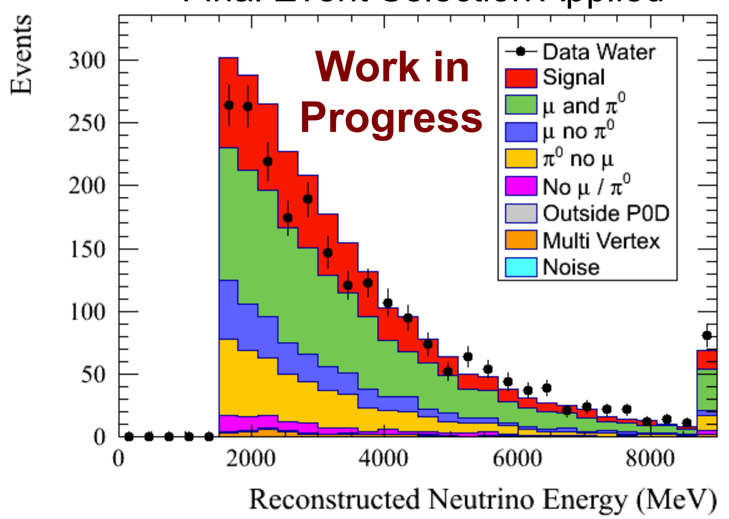
Event Selection

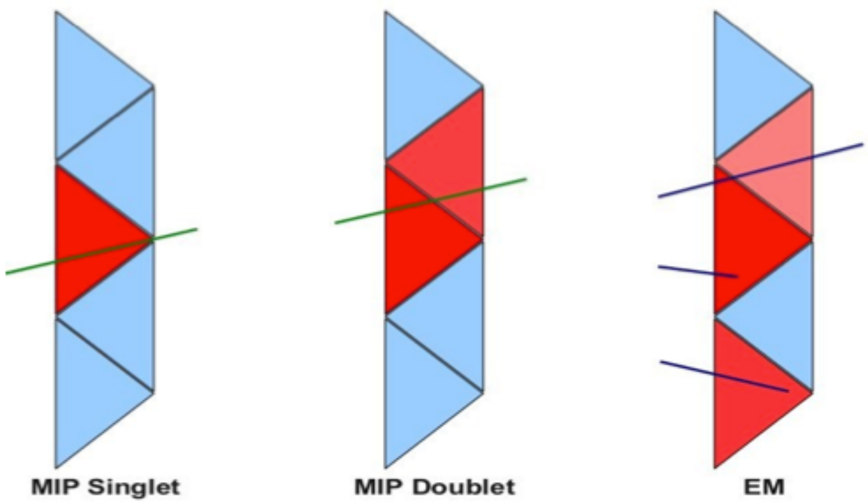
- Basic event selection:
  - Data quality and beam quality checks
  - Basic reconstruction quality checks
  - Fiducial vertex
- Selecting high energy charged-current ν_e interactions:
  - Particle angle with respect to beam axis < 45°
  - Reconstructed neutrino energy > 1.5 GeV
  - Width based particle ID to suppress muons
  - Reject events with more than 2 reconstructed electromagnetic showers



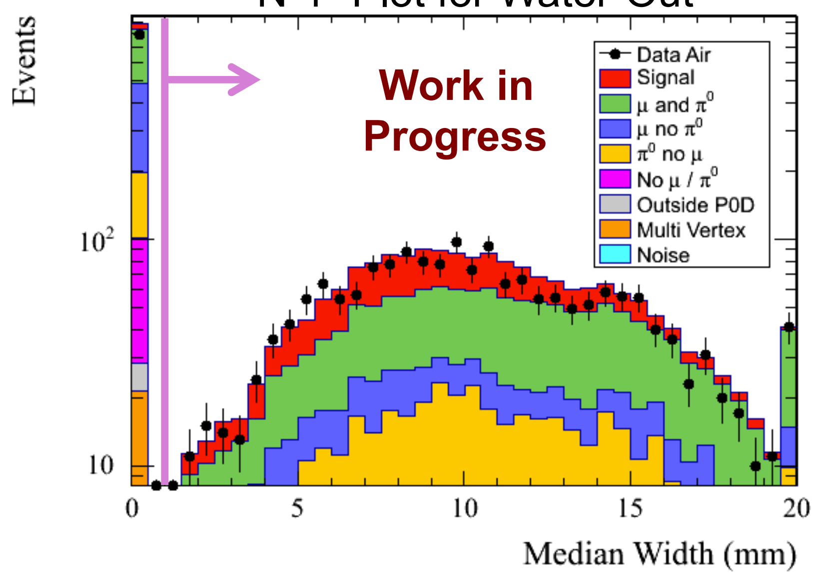


Width Based Particle ID

- The design of the P0D with high density materials (brass, lead) causes electrons to shower
- Electromagnetic particles in the P0D are therefore generally wider than MIP
- In addition, MIP hits in a scintillator layer are generally adjacent
- ➢ Reject narrow particle tracks to suppress muons in the selected event sample



"N-1" Plot for Water-Out



Selected Events

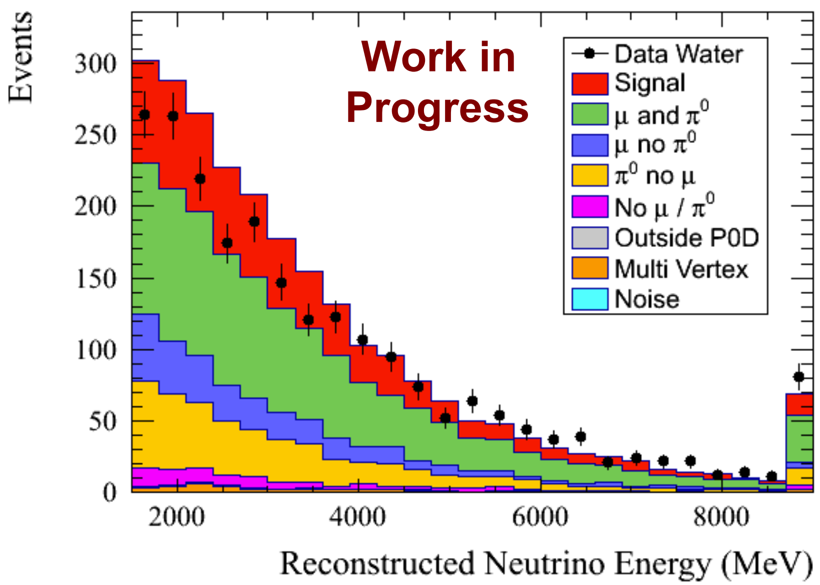
- Looking at events passing all the selection criteria

Work in Progress

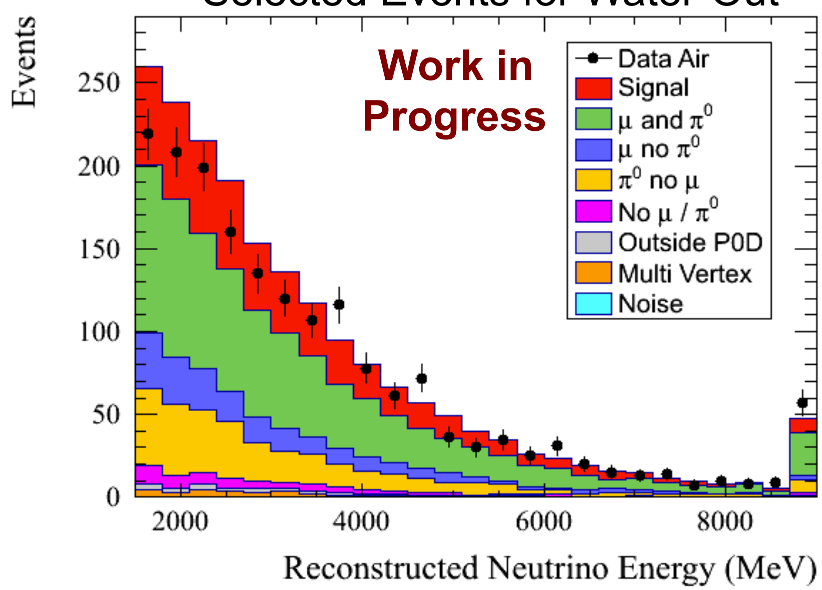
	N^{MC}_{Signal}	$N^{MC}_{\text{Background}}$	N^{MC}_{Total}	Data
Water-In	634.7 ± 9.1	1835.4 ± 16.0	2470.0 ± 18.4	2273
Water-Out	495.3 ± 7.8	1429.5 ± 13.8	1924.8 ± 15.9	1785

statistical errors due to limited MC statistics

Selected Events for Water-In



Selected Events for Water-Out



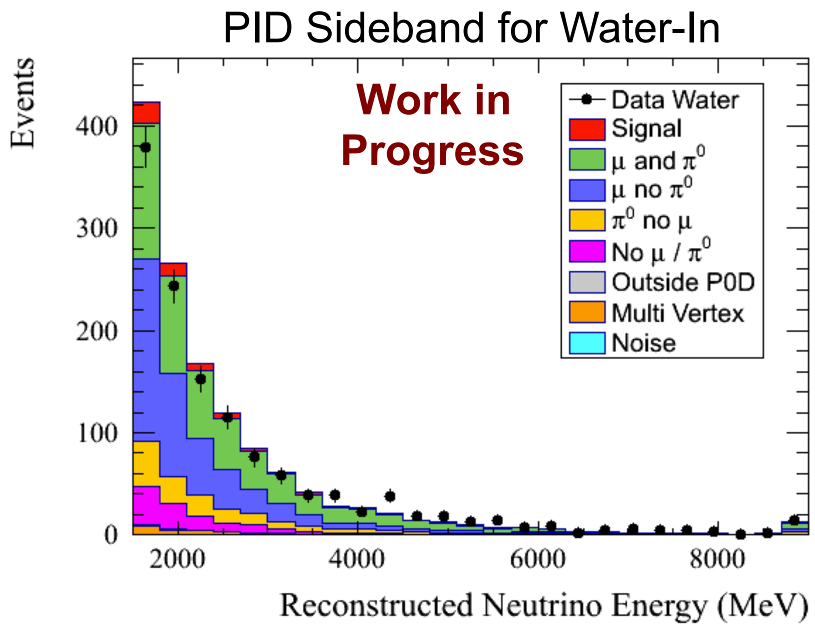
PID Sideband

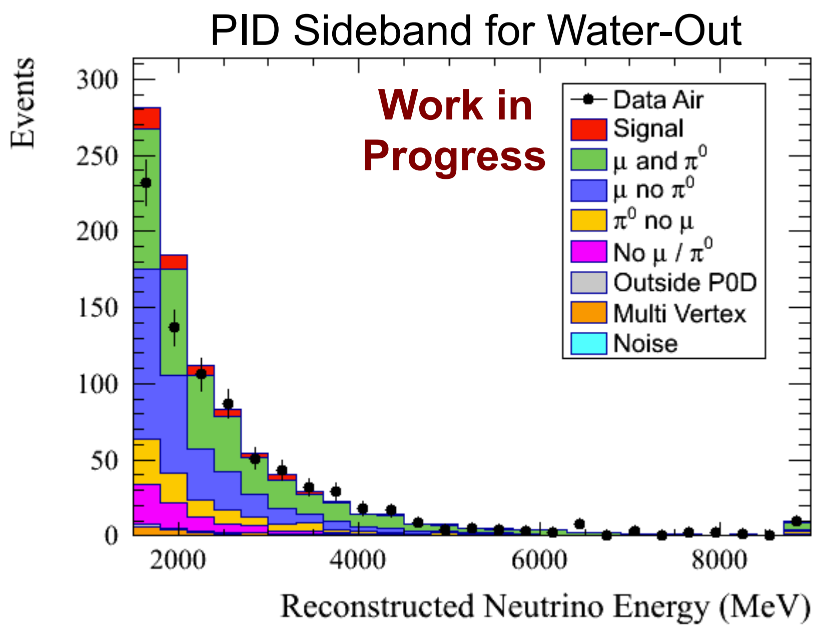
- Using events failing the width based ID selection to constrain the background

Work in Progress

	N^{MC}_{Signal}	$N^{MC}_{\text{Background}}$	N^{MC}_{Total}	Data
Water-In	60.2 ± 2.8	1266.6 ± 13.2	1326.8 ± 13.5	1284
Water-Out	49.3 ± 2.5	840.7 ± 10.5	890.0 ± 10.8	805

statistical errors due to limited MC statistics





Charged-Current ν_e Interactions in Data

- Subtracting scaled Monte Carlo background from data samples collected during water-in ("water") and water-out ("air") configuration:

$$N^{Data}_{CC\nu_e,\mathrm{water}} = D_{\mathrm{water}} - g_{\mathrm{water}} \cdot B_{\mathrm{water}}$$
$$N^{Data}_{CC\nu_e,\mathrm{air}} = D_{\mathrm{air}} - g_{\mathrm{air}} \cdot B_{\mathrm{air}}$$

- Where g_{water} and g_{air} are the scaling factors obtained from the PID sideband

- The data/MC ratios for the water-in and water-out configuration is then given by:

$$R_{\mathrm{water}} = \frac{N^{Data}_{CC\nu_e,\mathrm{water}}}{S_{\mathrm{water}}}$$

$$R_{\mathrm{air}} = \frac{N^{Data}_{CC\nu_e,\mathrm{air}}}{S_{\mathrm{air}}}$$

Extraction of On-Water CC ν_e Interactions

- Determine the on-water data event rate by subtracting the event rates measured with P0D water-in and water-out configuration:

$$N^{Data}_{\text{on-water}} = D_{\text{water}} - \frac{\epsilon_{\text{water}} \cdot \text{POT}_{\text{water}}}{\epsilon_{\text{air}} \cdot \text{POT}_{\text{air}}} \cdot D_{\text{air}}$$

- Different efficiencies and different collected POT for water-in and water-out configuration are taken into account
- Determine the number of on-water charged-current ν_e events in the data sample by subtracting the Monte Carlo predicted background:

$$N^{Data}_{\text{CC}\nu_e,\text{on-water}} = N^{Data}_{\text{on-water}} - g_{\text{water}} \cdot B_{\text{on-water}}$$

with g_{water} the scaling factor obtained from the PID sideband

- The data/MC ratio is then given by: $R_{\text{on-water}} = \dfrac{N^{Data}_{\text{CC}\nu_e,\text{on-water}}}{S_{\text{on-water}}}$

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Systematic Uncertainties

- A wide range of potential systematic uncertainties have been investigated or are currently under investigation:

Work in Progress

Systematic Uncertainty for Data/MC Ratio	Water-In	Water-Out	On-Water
MC Statistics	0.04	0.04	0.11
PØD Mass	0.01	0.01	0.01
PØD Fiducial Volume	0.03	0.06	0.02
PØD Alignment	< 0.01	< 0.01	< 0.01
Energy Scale	0.15	0.12	Work In Progress
Particle Direction Reconstruction	0.01	0.02	
Neutrino Energy Threshold	0.15	0.06	
Shower Reconstruction	0.09	0.08	
Other Reconstruction	0.02	0.02	
Flux and Cross Sections	0.19	0.21	0.27

Systematic Uncertainties

- The largest systematic uncertainties coming from:
  - Flux and Cross Section Uncertainties:
    - Determined by re-weighting Monte Carlo using results of other neutrino experiments
    - Standard procedure also used for T2K oscillation results
  - Energy Scale and Energy Reconstruction:
    - Studied the effect of varied material densities in the Monte Carlo, time dependent variations in data, impact of hot channels in data
    - This systematic uncertainty will be reduced in future
  - Shower Reconstruction:
    - Systematic uncertainty in shower reconstruction due to noise in data that is not simulated in Monte Carlo
    - This systematic uncertainty will be reduced in future

Results and Outlook

- The previously described analysis results in the following data/MC ratio for charged-current ν_e interactions for the water-in and water-out configuration:

Work in Progress

$$\mathrm{Data/MC(water)} = 0.78 \pm 0.11(\mathrm{stat}) \pm 0.04(\mathrm{MC\ stat}) \pm 0.23(\mathrm{det}) \pm 0.19(\mathrm{flux/xsec})$$

$$\mathrm{Data/MC(air)} = 0.99 \pm 0.13(\mathrm{stat}) \pm 0.04(\mathrm{MC\ stat}) \pm 0.17(\mathrm{det}) \pm 0.21(\mathrm{flux/xsec})$$

- The obtained data/MC ratios are consistent with 1 within statistical and systematic uncertainties

- Currently, the stability of the on-water interaction extraction method is under investigation and the detector systematics for the on-water data/MC ratio are being determined