νPRISM: An Experimental Method to Remove Neutrino Interaction Uncertainties from Oscillation Experiments

Mike Wilking
Stony Brook University
NNN Water Detector Satellite Meeting
October 27th, 2015

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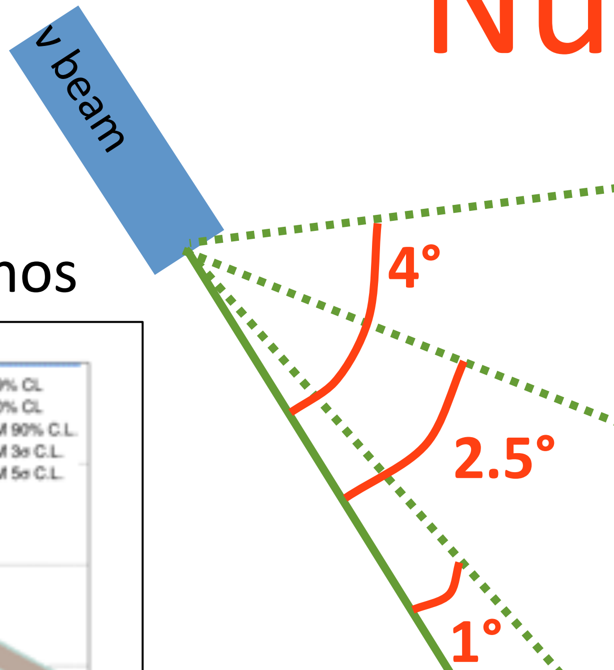
Brief Introduction

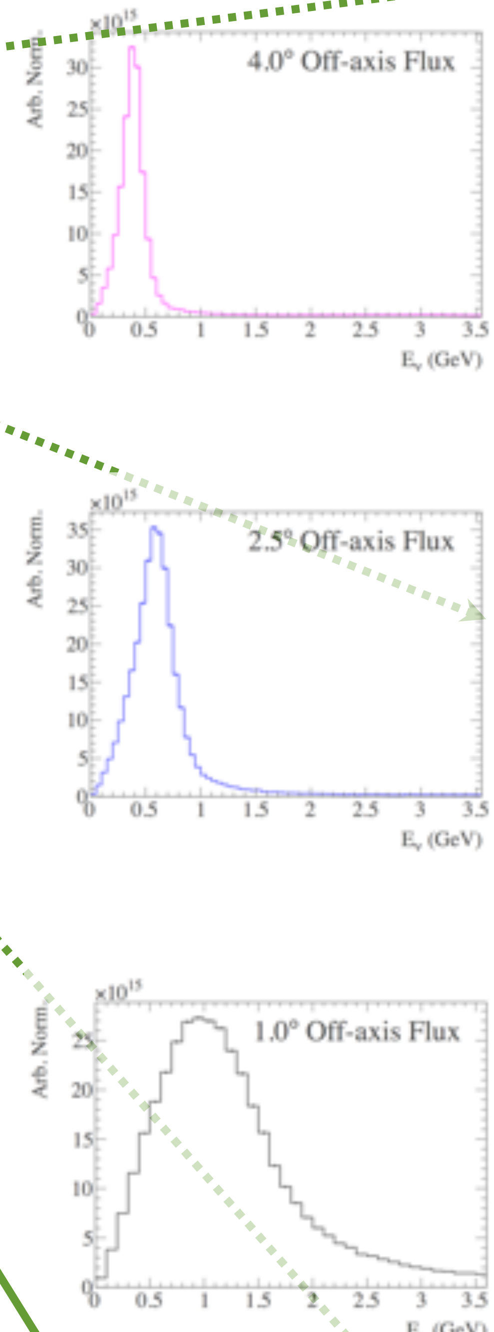
- NuPRISM is a water Cherenkov detector that spans a wide angular range (~1°-4°) off-axis from the neutrino beam direction
- This type of detector can perform a wide variety of interesting neutrino physics measurements

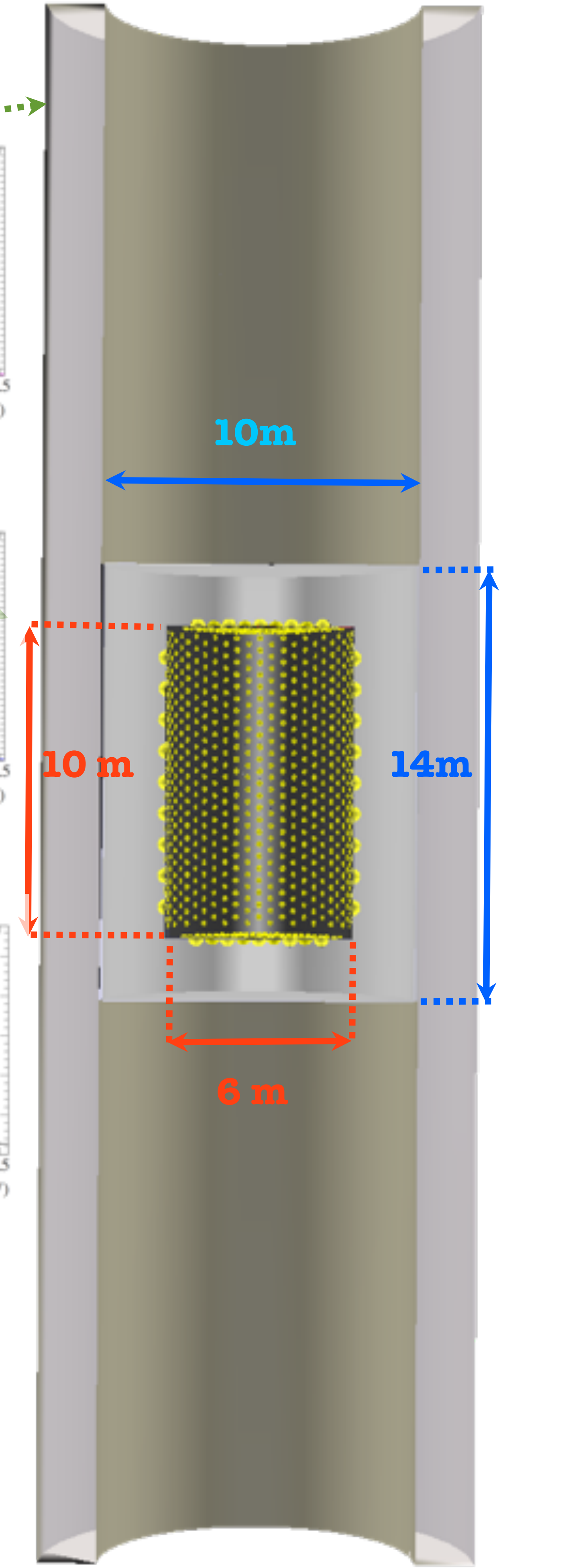
1. NuPRISM can greatly **reduce neutrino interaction uncertainties** in T2K and Hyper-K
   - These are likely to be the largest uncertainties for the full T2K dataset
2. NuPRISM can perform a high precision search for **sterile neutrino** oscillations
3. NuPRISM can determine neutrino interaction final states from **mono-energetic neutrino beams**
   - Electron-scattering-like measurements are now possible
   - Very interesting probe for nuclear physics, and to constrain the relationship between neutrino energy and observable lepton kinematics
4. NuPRISM is required to measure **CP violation** using Super-K sub-GeV atmospheric neutrinos
   - Largely removes the uncertainties in relating lepton kinematics to neutrino energy and direction, which are large below 1 GeV

NuPRISM

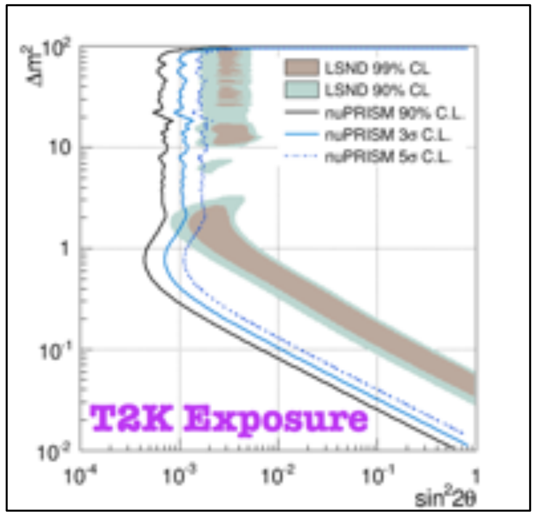
Spans many off-axis angles to measure many E_ν spectra





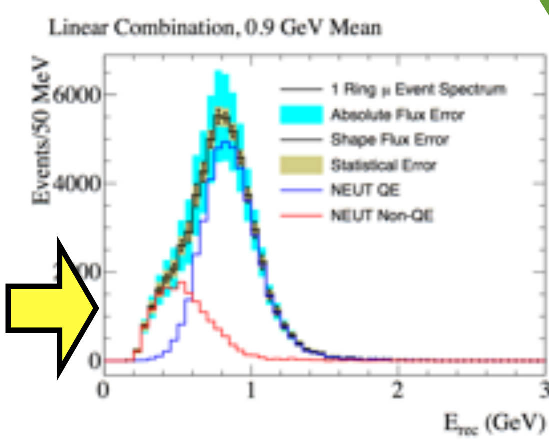


Sterile Neutrinos

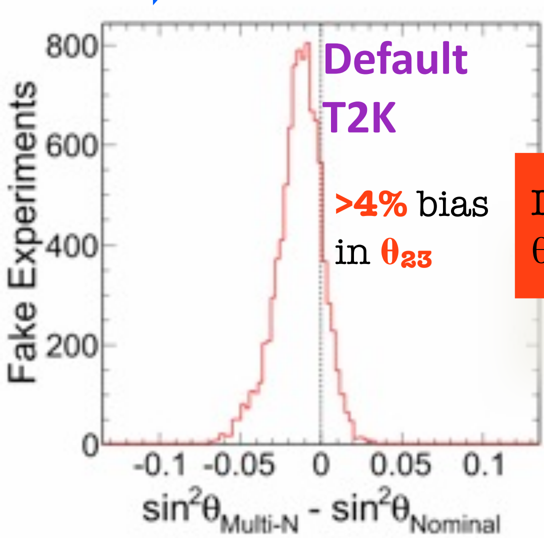


Unique σ_ν Measurements

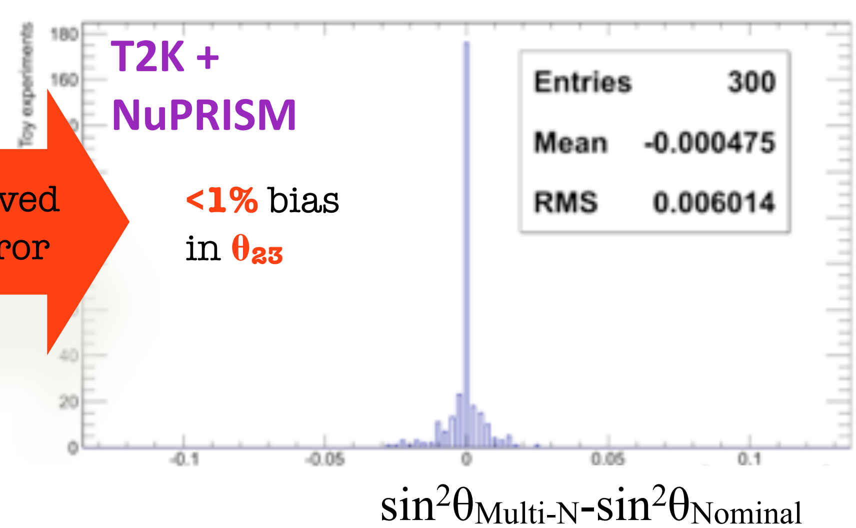
- First ever measurements of $\sigma_{\text{Neutral Current}}(E_\nu)$
- Clear separation of single and multi-nucleon events



Enhanced Sensitivity for T2K and T2HK



Improved θ_{23} Error



The NuPRISM Collaboration

- NuPRISM has 56 members (primarily physicists) from 10 countries
- In addition, the NuPRISM proposal to the J-PARC PAC includes letters of support from several nuclear physicists:

  J. Carlson (LANL)
  T.W. Donnelly (MIT)
  M. Ericson (IPN Lyon, CERN)
  S. Gandolfi (LANL)
  A. Lovato (ANL)
  M. Martini (Ghent)
  S.C. Pieper (ANL)
  R. Schiavilla (JLAB/ODU)
  R.B. Wiringa (ANL)

Proposal for the NuPRISM Experiment in the J-PARC Neutrino Beamline

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(Dated: June 16, 2015)

T2K Systematic Uncertainties

ν_μ Disappearance		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only)	10.0 %	
	multi-nucleon effect on oxygen	9.5%	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

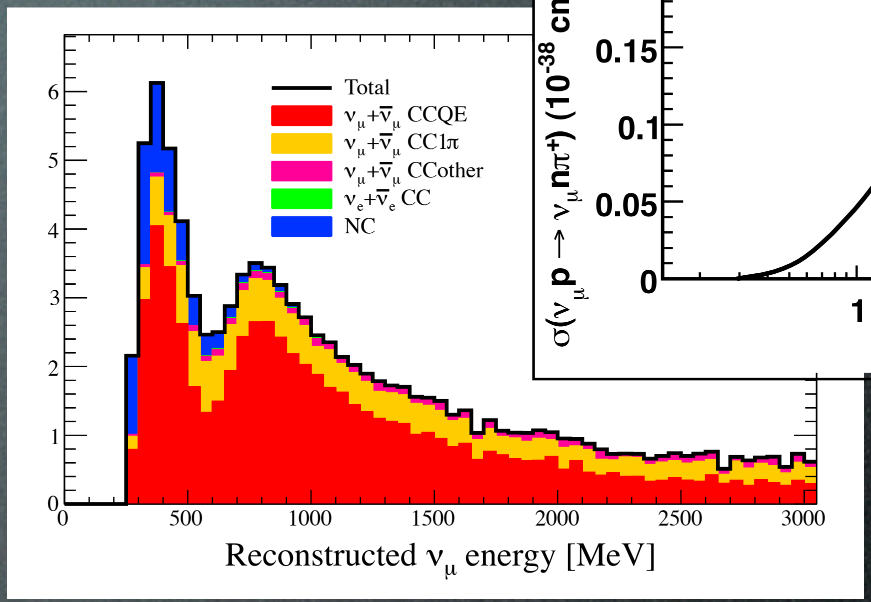
ν_e Appearance		w/o ND measurement	w/o ND measurement
ν flux and cross section	Flux	8.0%	3.5%
	Cross Section (ND280)	4.9%	1.8%
	Flux x Cross Section (ND280)	9.4%	3.0%
	Cross Section (SK only)	9.8%	
	Multi-nucleon Oxygen	9.3%	
Final or Secondary Hadronic Interaction		2.2%	
Super-K detector		3.0%	
Total		13.5%	11.0%

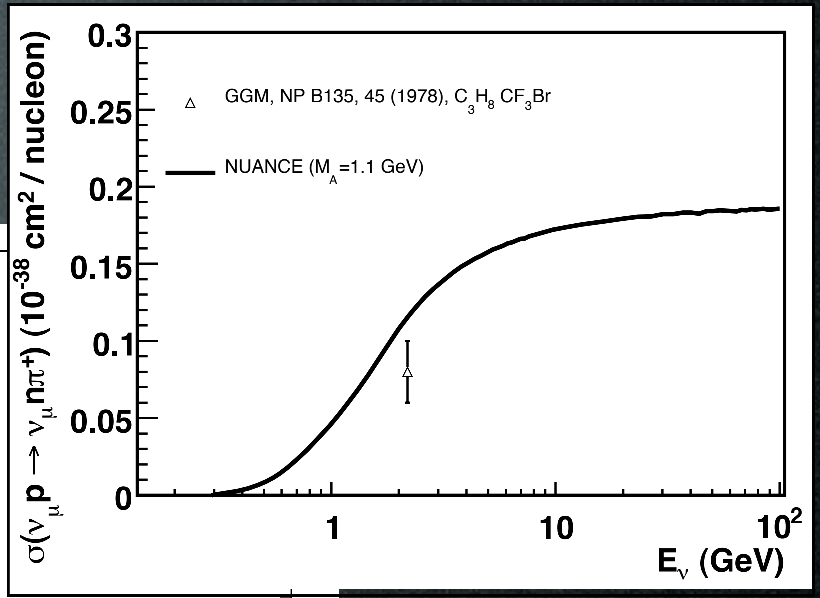
- Goals for the full T2K dataset include the θ_{23} octant (ν_μ disappearance) and δ_{CP} (ν_e appearance)
- At full statistics, the largest systematic errors are due to neutrino interactions
  - (Note: the errors shown above will be somewhat reduced when ND280 water targets are incorporated)
- To make a 3σ measurement of δ_{CP}, the systematics on ν_e appearance must be reduced to the 2-3% level (in addition to extended beam time)

ν Cross Section Measurements

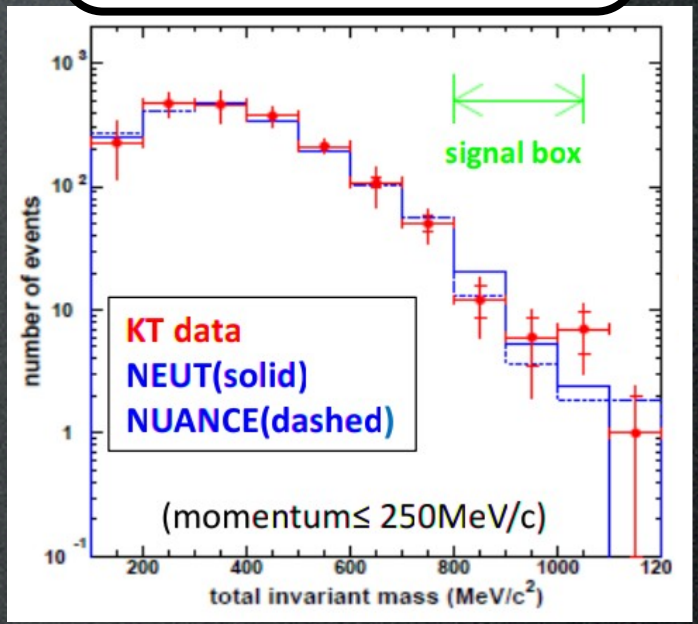
- T2K ν_μ disappearance is subject to large NCπ^+ uncertainties
- NuPRISM is an ideal setup to measure proton decay backgrounds
    - Repeat $p \to e^+\pi^0$ background measurement from K2K 1 kton detector
    - 50% of the $p \to K^+\nu$ background is from ν-induced K+ production
        - Production rate has large uncertainties
- Can also calibrate Gd response vs lepton momentum and angle
    - In some sense, could be considered ANNIE phase II

NCπ^+ at T2K

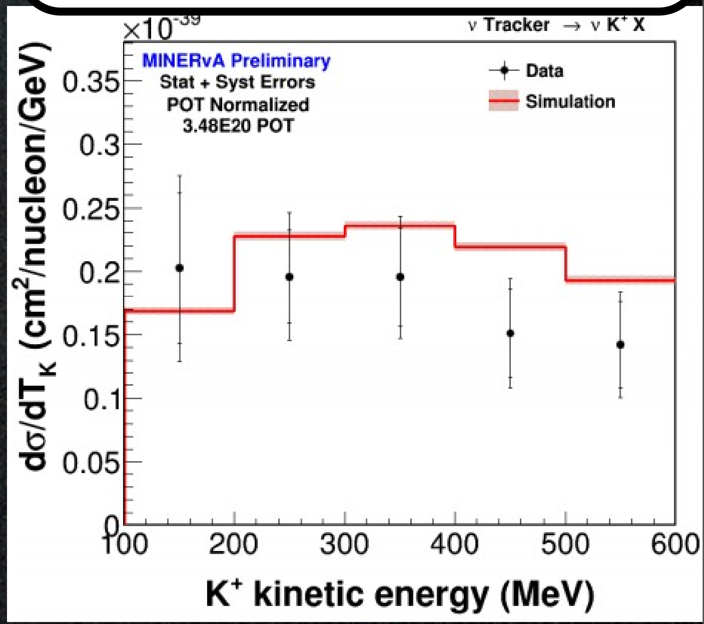




K2K $e^+\pi^0$ Bkgd Measurement



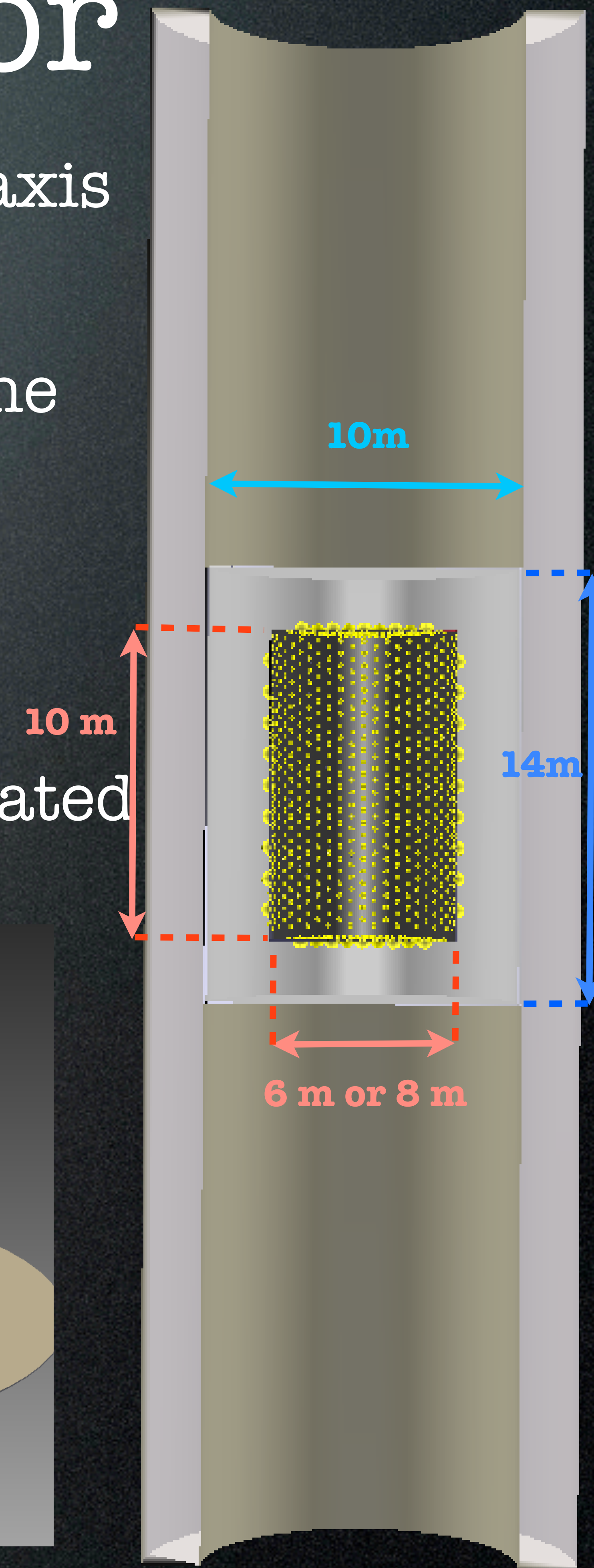
MINERvA K^+ Prod. Measurement

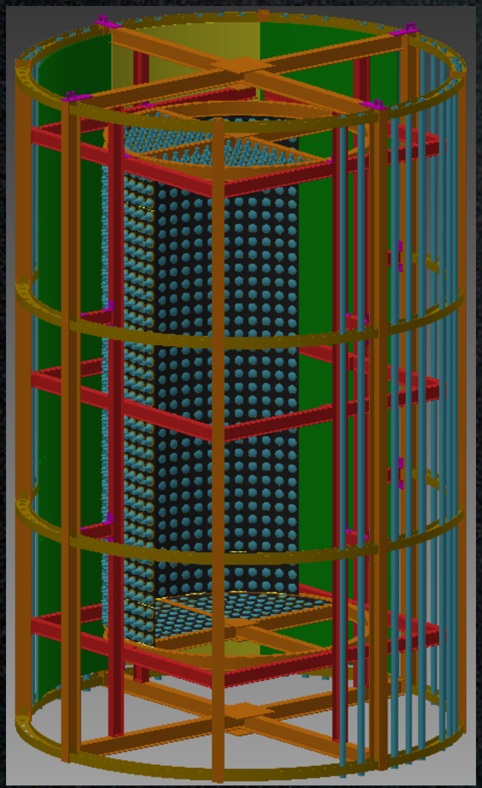


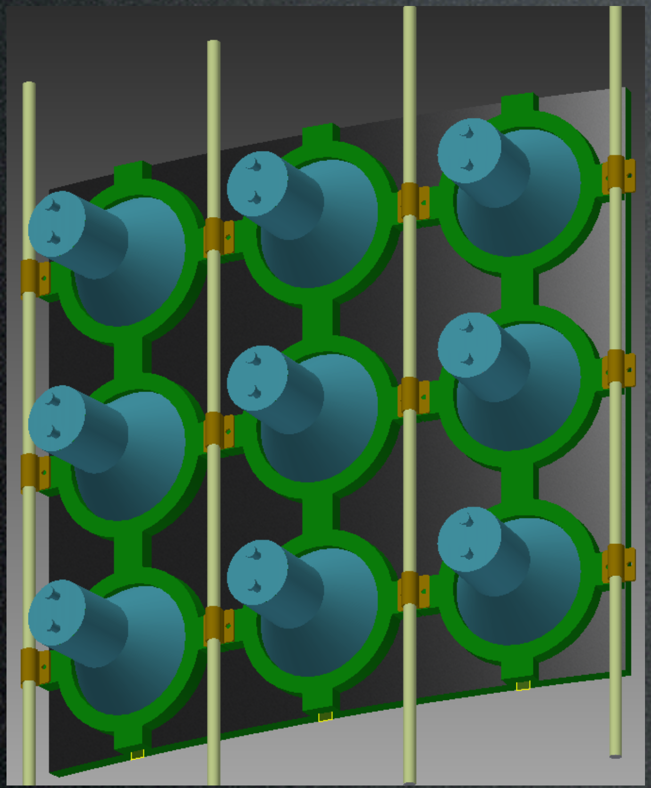
$$N(\mathrm{Mtyr}^{-1}) = 1.63^{+0.42}_{-0.33}(\mathrm{stat})^{+0.45}_{-0.51}(\mathrm{syst}).$$

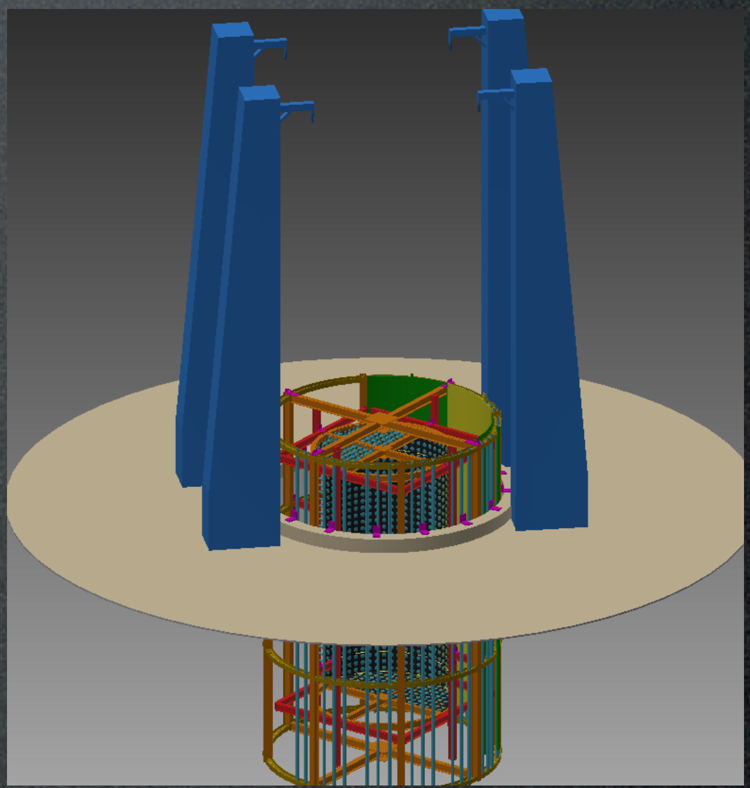
NuPRISM Detector

- At 1 km, need 50 m tall tank to span 1-4° off-axis angle
- Instrument one subsection of the tank at a time with a moveable detector
- Movable detector provides an ideal setup for detector R&D
  - Many photosensor types can be accommodated









Project Costs

- Current estimates of the project cost come from:
  - Direct consultations with manufacturers
  - The T2K 2km detector proposal (*)
- Company estimates have been obtained for cost drivers (civil construction and PMTs)
  - Civil construction cost could increase after geological survey of the chosen site
  - For PMTs, both high quantum efficiency (HQE) and hybrid photodetectors (HPD) are under consideration
- Reuse MiniBooNE or Daya Bay PMTs?

Cost Summary

Item	Cost (US M$)
Cavity Construction, Including HDPE Liner	6.00
*Surface Buildings	0.77
*Air-Conditioning, Water, and Services	0.50
*Power Facilities	0.68
*Cranes and Elevator	0.31
*PMT Support Structure	1.27
3,215 8-inch PMTs	4.30
PMT Electronics	1.45
*PMT Cables and Connectors	0.13
Scintillator Panels	0.36
Water System	0.35
Gd Water Option	0.15
*GPS System	0.04
Total	16.31

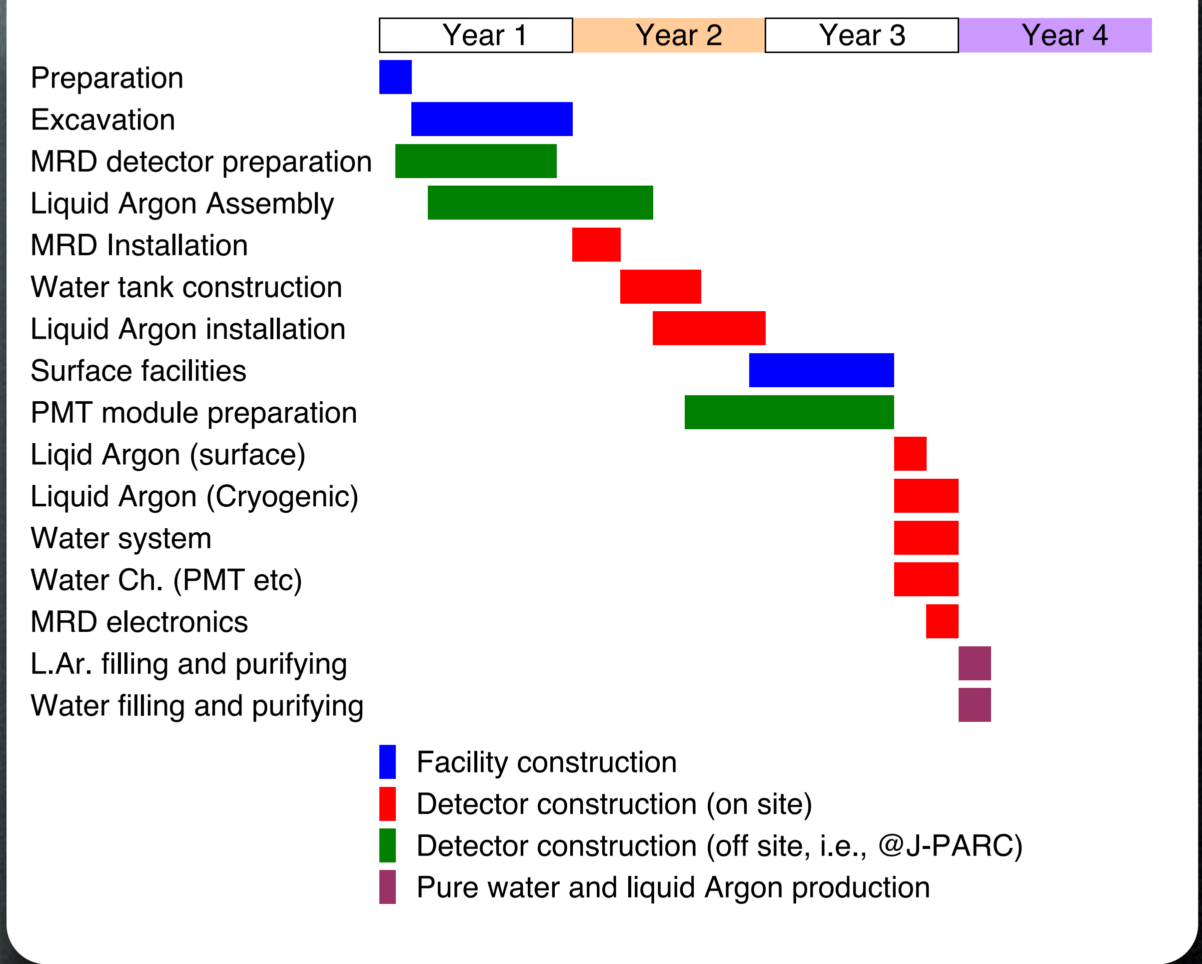
Hamamatsu PMT Quotes

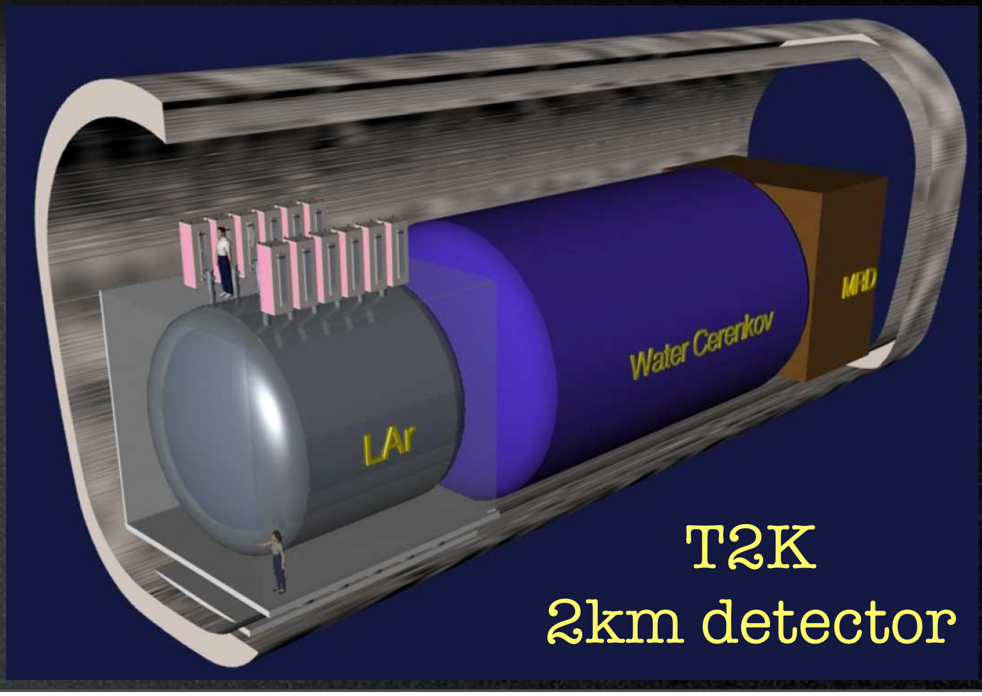
Name	QE%	Quantity	Price/PMT	Cost	Delivery
5” PMT	25	8,000	103,500	828M	any
5” PMT HQE	35	5,714	123,700	707M	any
8” PMT	25	3,215	143,000	460M	any
8” PMT HQE	35	2,296	170,500	391M	any
8” HPD HQE	35	2,296	264,000	606M	2014
	35	2,296	236,500	543M	2015
	35	2,296	209,000	480M	2016
20” PMT HQE	30	508	604,500	307M	2014
	30	508	572,000	291M	2015
	30	508	539,500	274M	2016
20” HPD HQE	30	508	715,000	363M	2014
	30	508	617,500	314M	2015
	30	508	520,000	264M	2016

Timescales

- Water Cherenkov construction was studied for the T2K 2 km detector proposed in 2005
- NuPRISM construction time is faster
  - Same pit depth as the 2km detector, but no excavation of a large cavern at the bottom of the pit
  - Smaller instrumented volume
  - No MRD or LAr detector
- < 3 year timescale from ground breaking to data taking
- Goal is to start data taking soon after the J-PARC 700kW beam upgrade expected in 2019
  - More than half of the T2K POT will be taken after the beam upgrade
  - Most optimistic ground breaking in 2016

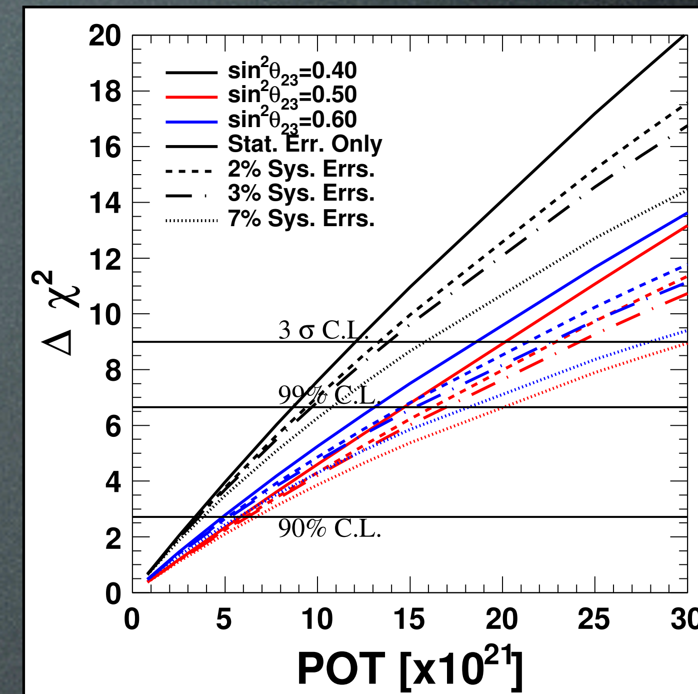
Old T2K 2 km Schedule



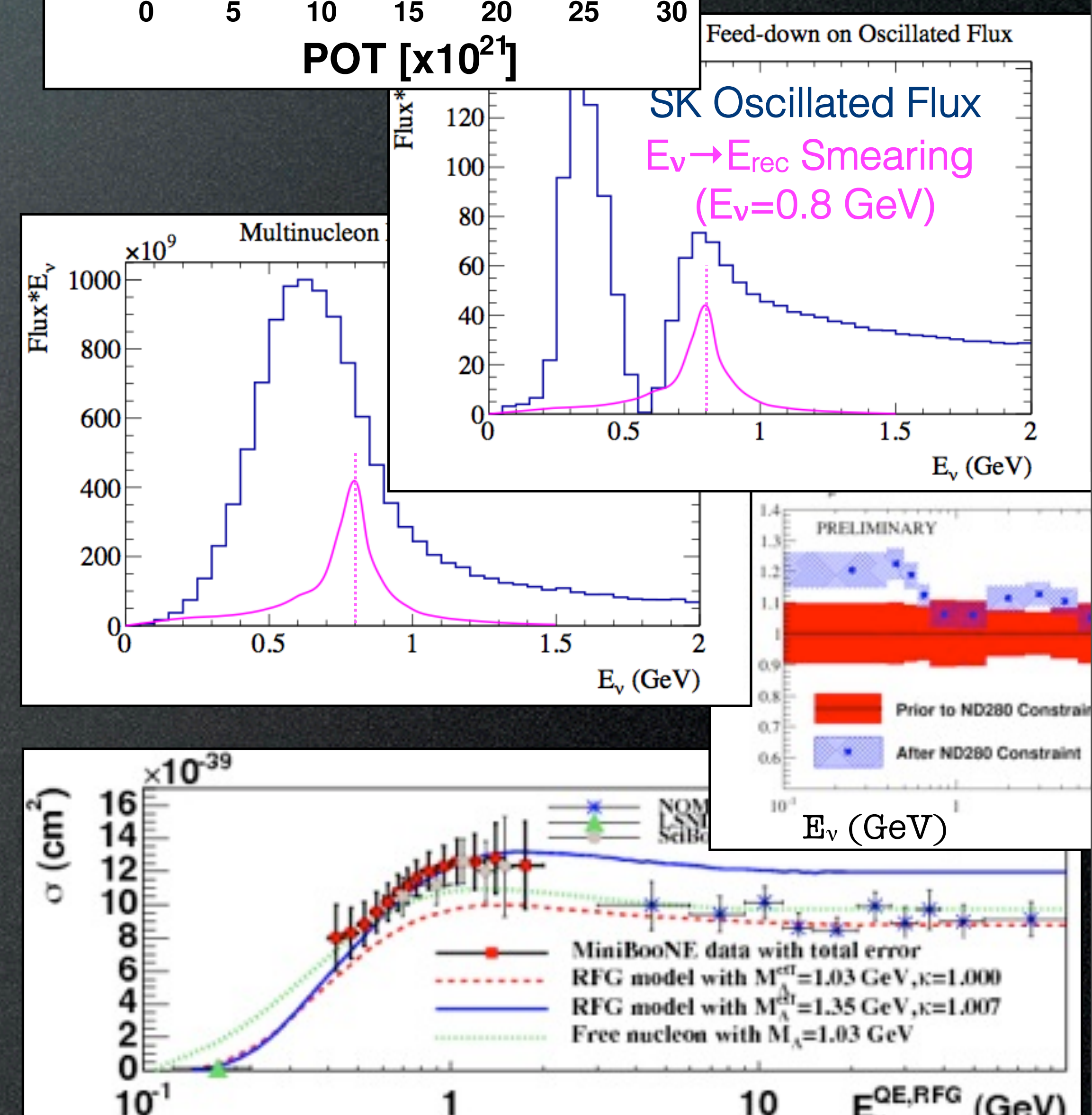


Feasibility

- First presentation to the J-PARC PAC last meeting (July)
  - Positive response, but case for standard T2K POT was marginal
    - Clear advantage for θ_{23} measurement, but δ_{CP} improvement was not clearly demonstrated
- Motivation is much stronger for T2K2
  - Needs 2-3% systematics
- Main logistical challenge is a new facility off the current J-PARC site
  - Strong support from J-PARC and other T2K2 and HK supporters
  - Japanese funds still needed
    - Waiting for PAC endorsement

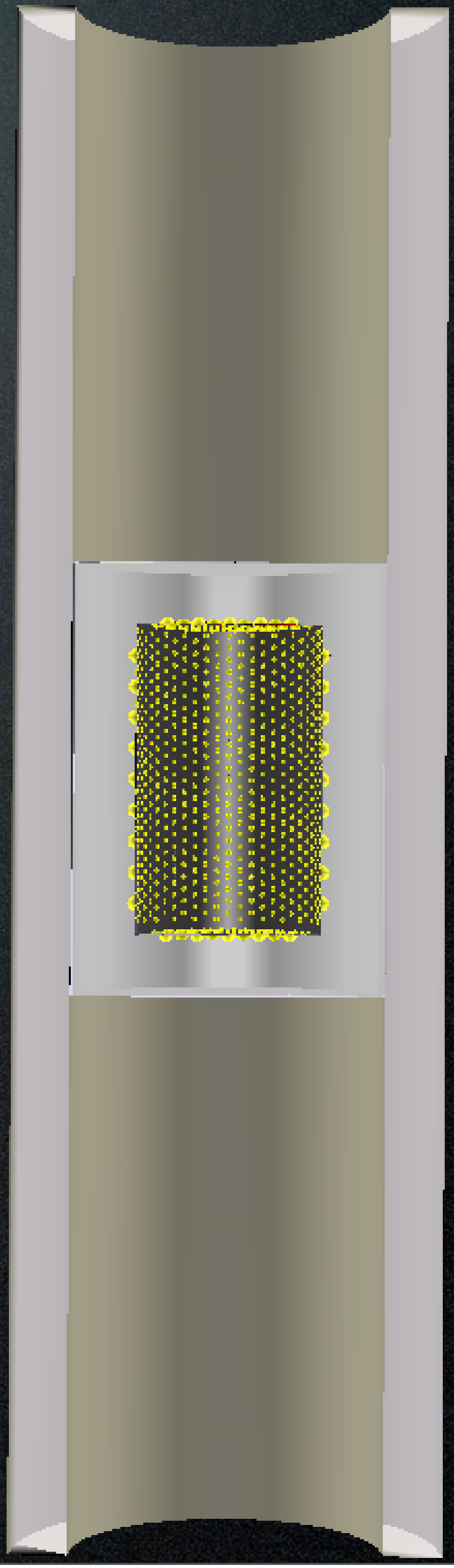


See Nakaya-san's Talk from this morning



Summary

- We are entering an era where the largest uncertainties in neutrino oscillation experiments will be determined by poorly understood models
  - NuPRISM provides an experimental solution to the neutrino energy measurement problem
- NuPRISM will produce a wide variety of other interesting measurements
  - A unique sterile neutrino search
  - Nuclear physics from mono-energetic beams
  - Enhanced measurements from existing Super-K data (e.g. ATM sub-GeV CPV)
  - A wide variety of unique cross section measurements and model constraints
- NuPRISM can supply an exciting physics program that bridges the gap between T2K and Hyper-K
- Looking for additional collaborators, particularly from the US and Europe

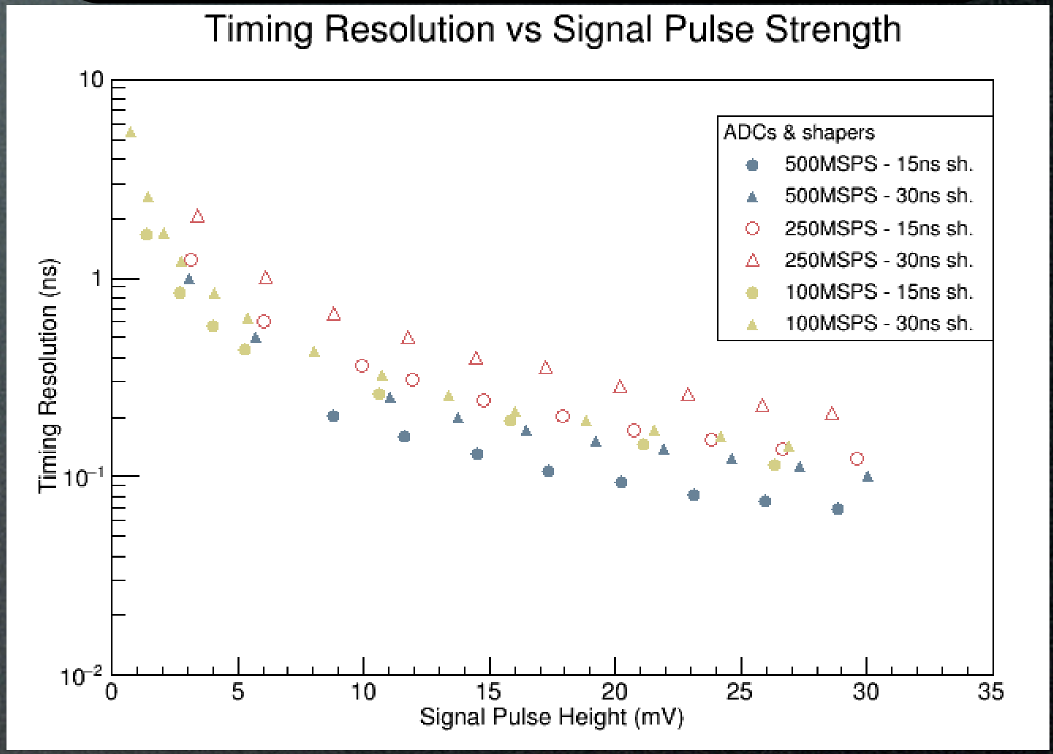


Supplement

Synergies with Hyper-K

- The systematic error constraints provided by NuPRISM will be required in the Hyper-K era
  - NuPRISM will become a Hyper-K near detector
  - Need to understand whether NuPRISM can control cross section systematics before Hyper-K starts taking data
- Hyper-K is considering in-water electronics
  - NuPRISM allows in-water electronics to be tested, and provides unique accessibility due to its ability to move out of the water
- A large scale PMT water tank test for Hyper-K PMTs is being planned, and NuPRISM can fill this role
  - Even if NuPRISM is not ready for the start of this test, it can be coordinated to make use of the detector hardware when it is ready to operate
    - This may fund a useful portion of the experiment
- NuPRISM provides new physics and a cohesive program between T2K and Hyper-K
  - Analogous to the Fermilab SBN program

Joint NuPRISM/Hyper-K
Electronics Development Tests

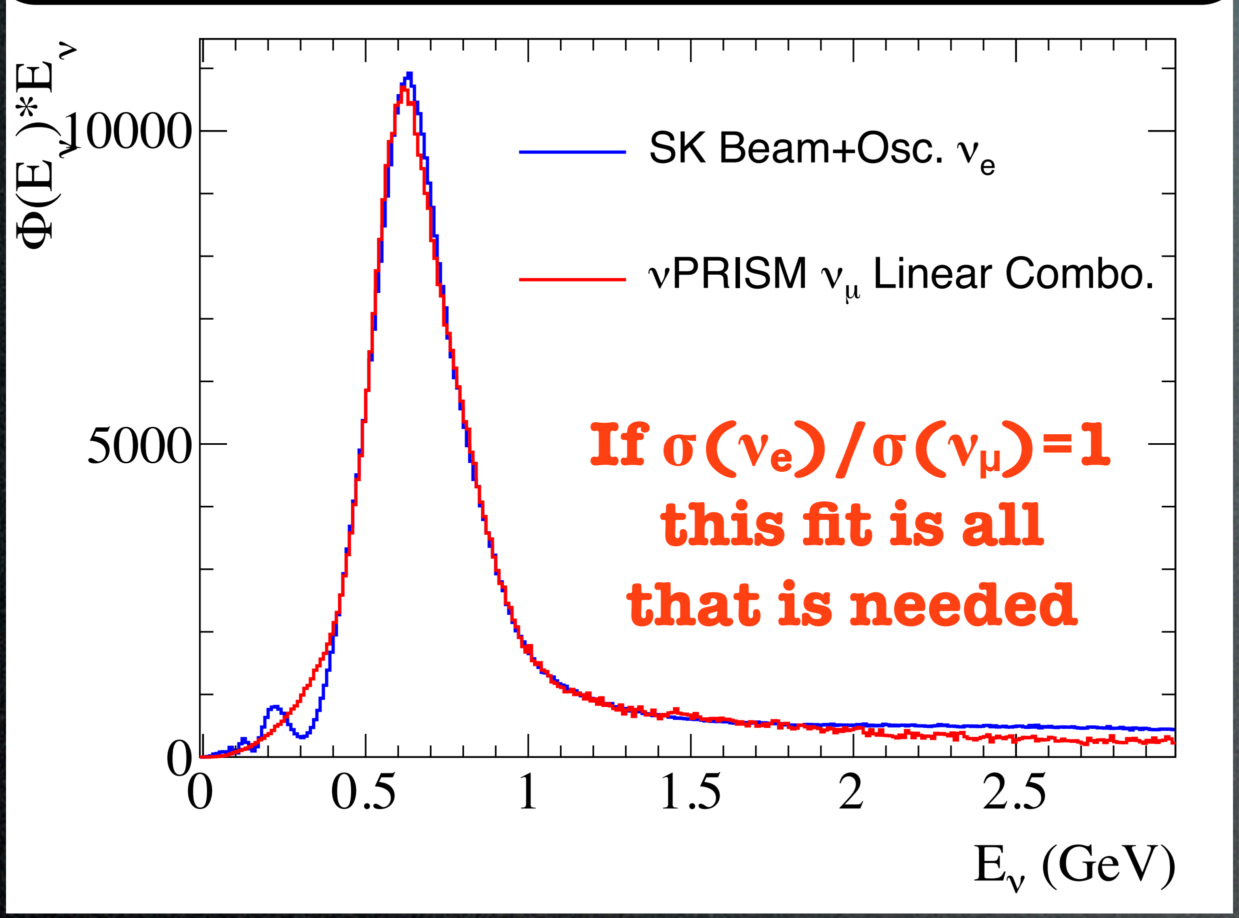


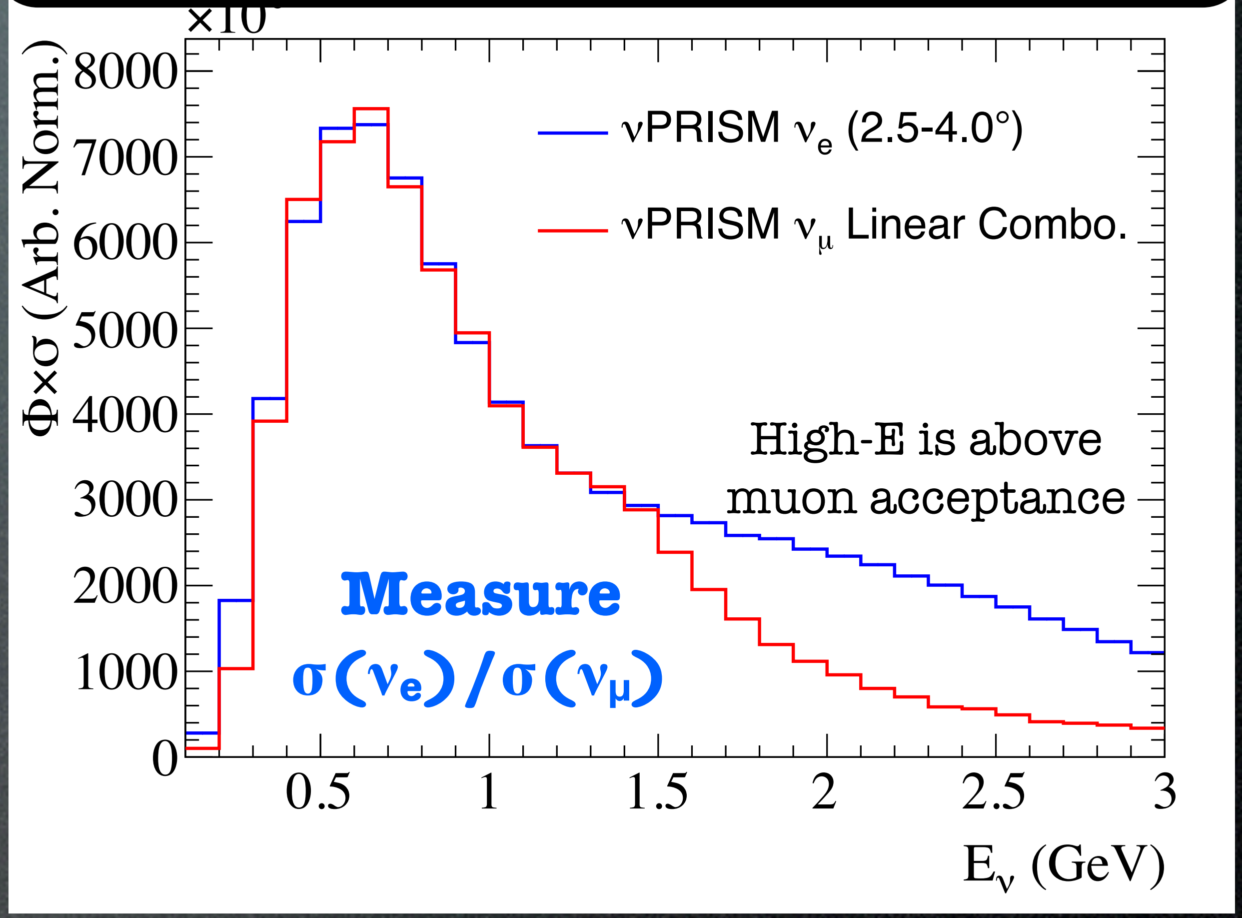
NuPRISM ν_e Appearance (CPV)

2 step approach:

Step 1: Measure **Super-K** ν_e response with nuPRISM ν_μ

Step 2: Measure **nuPRISM** ν_e response with nuPRISM ν_μ





- Step 1 is the ν_e version of the ν_μ disappearance analysis
- Step 2 uses only nuPRISM to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
    - High energy disagreement is above muon acceptance
- Need large mass near detector to make a few percent measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$ (ND280 target is a few ton, NuPRISM target is a few kton)

Constraining the ν_e Cross Section

- Water Cherenkov detectors can achieve high ν_e purities
  - In T2K, 3.50 intrinsic ν_e events vs 0.96 NC events ➜ **77% ν_e purity**
- Studies to optimize PMT size/granularity to maximize ν_e purity in NuPRISM are ongoing
- NuPRISM can also make use of higher off-axis angles:

50% increase in ν_e fraction from 2.5° to 4.0° off-axis

Off-axis angle (°)	ve Flux 0.3-0.9 GeV	vμ Flux 0.3-5.0 GeV	Ratio ve/vμ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%

CP Violation in Atmospheric Neutrinos

- Sub-GeV atmospheric neutrinos show up to 20% rate changes due to δ_{CP}
- Requires precise percent-level knowledge of the relationship between lepton and neutrino kinematics
- Up to **4σ** measurement is possible with existing Super-K data if systematics can be controlled well enough
  - This is exactly the E_ν range where NuPRISM is most sensitive (>400 MeV)