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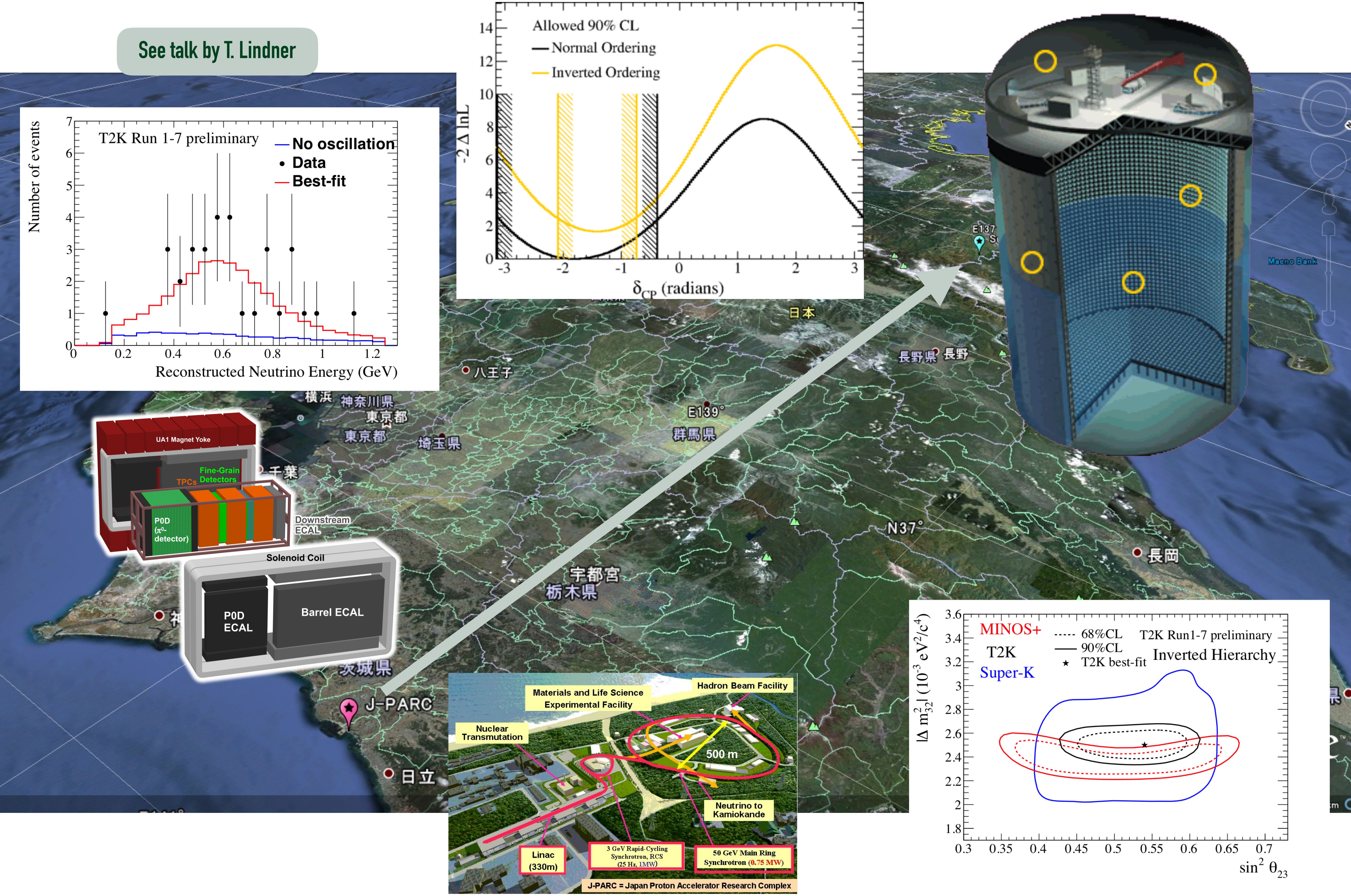
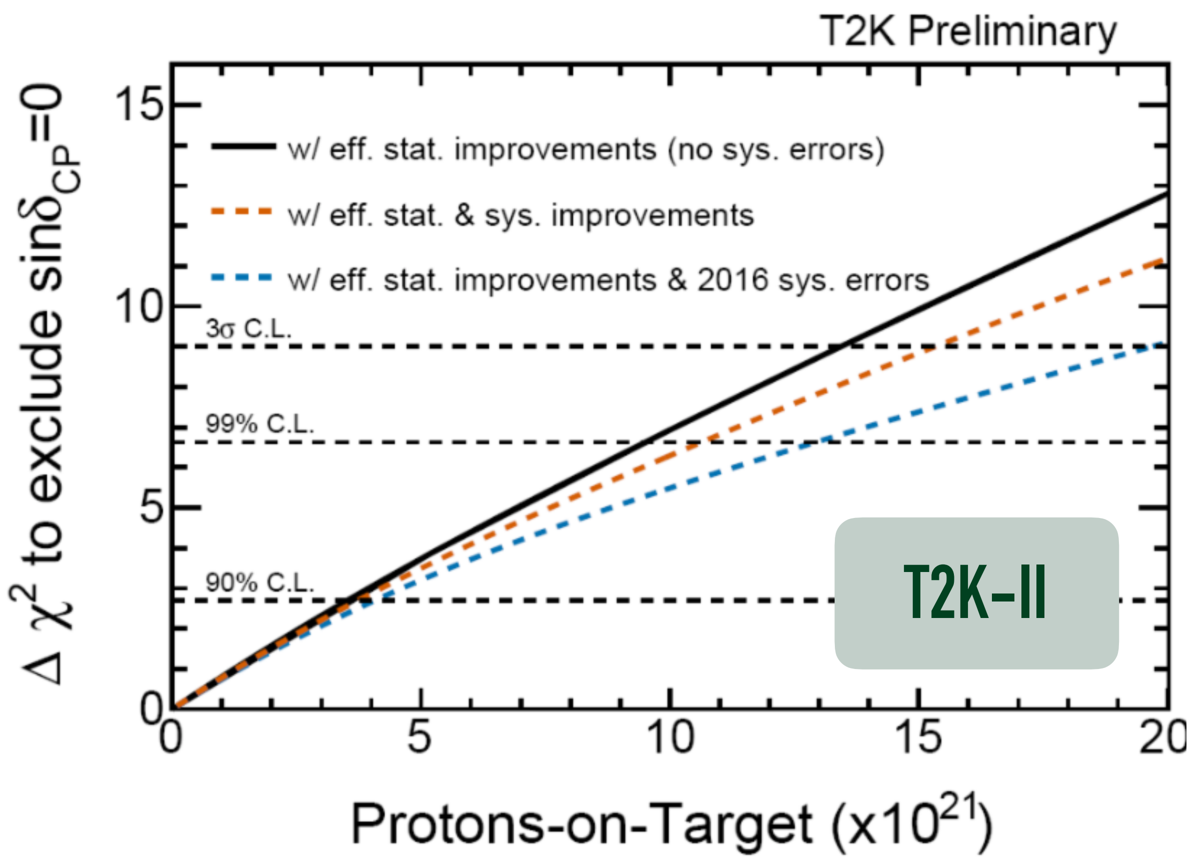
NUPRISM: REDUCING NEUTRINO INTERACTION MODEL DEPENDENCE FOR OSCILLATION EXPERIMENTS

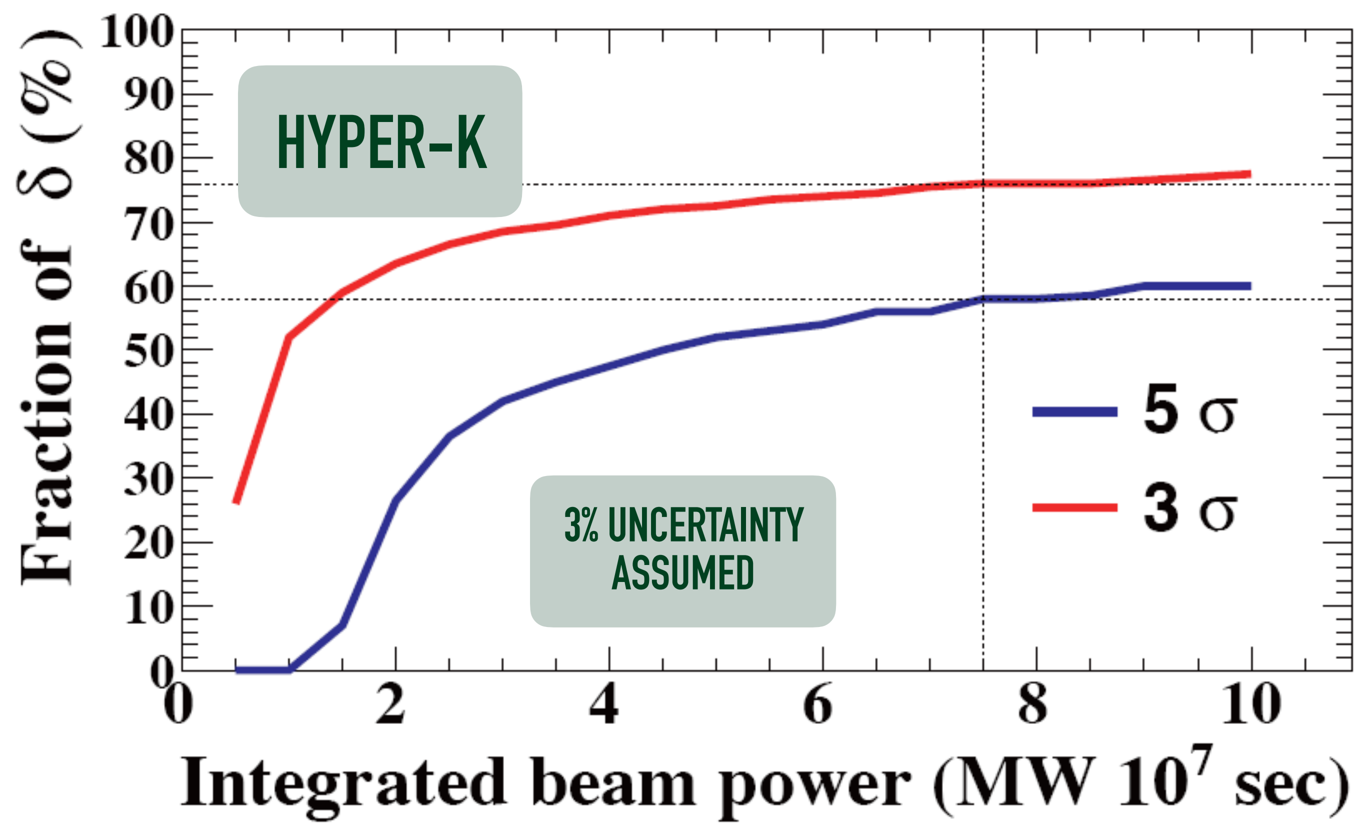
T2K (TOKAI TO KAMIOKA) EXPERIMENT

See talk by T. Lindner



DISCOVERING LEPTONIC CP VIOLATION

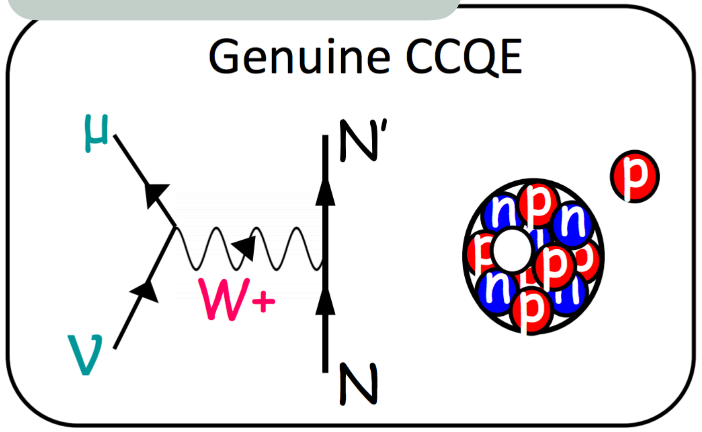


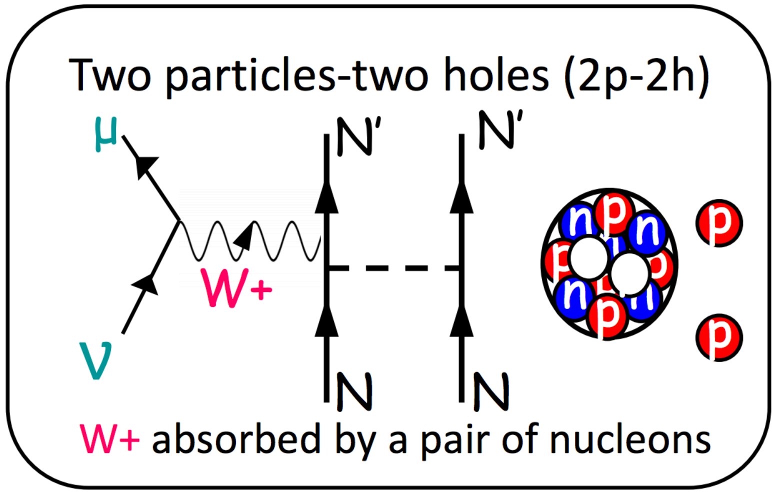


- T2K Phase-II will be sensitive to maximal CP violation at the 3σ level.
- Hyper-K will be sensitive at 5σ over a range of values of δ_{CP}.
- Future long baseline experiments will be limited by systematic rather than statistical uncertainties.

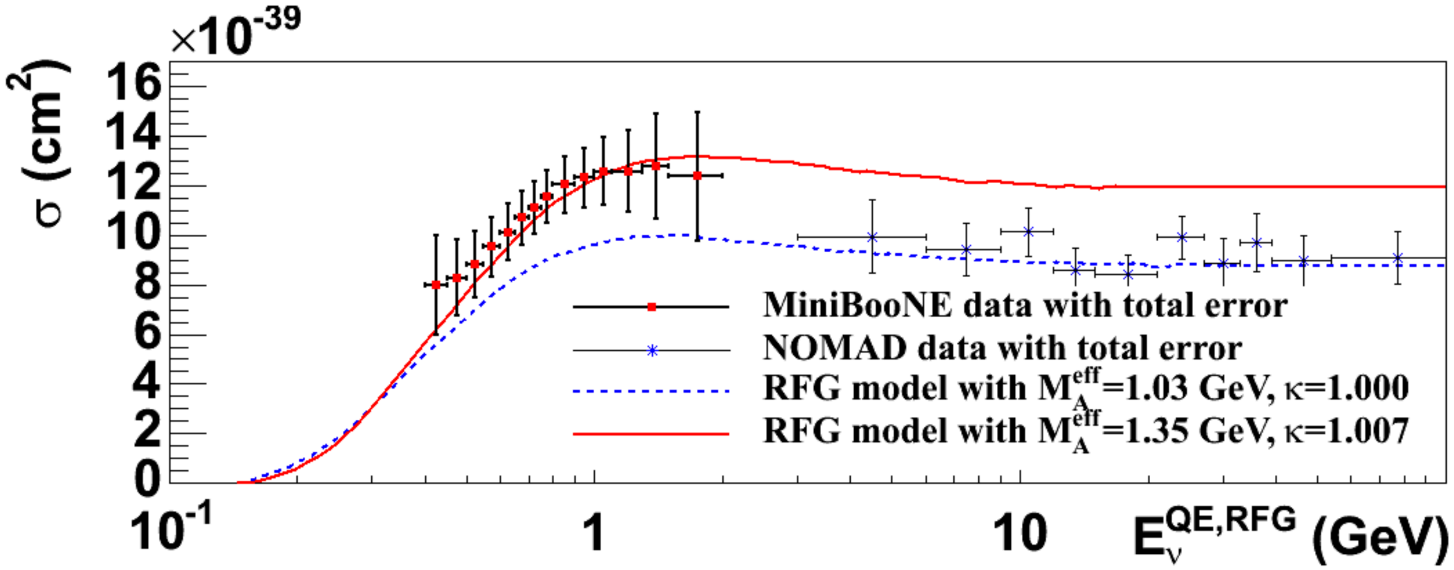
MEASURING NEUTRINO ENERGY

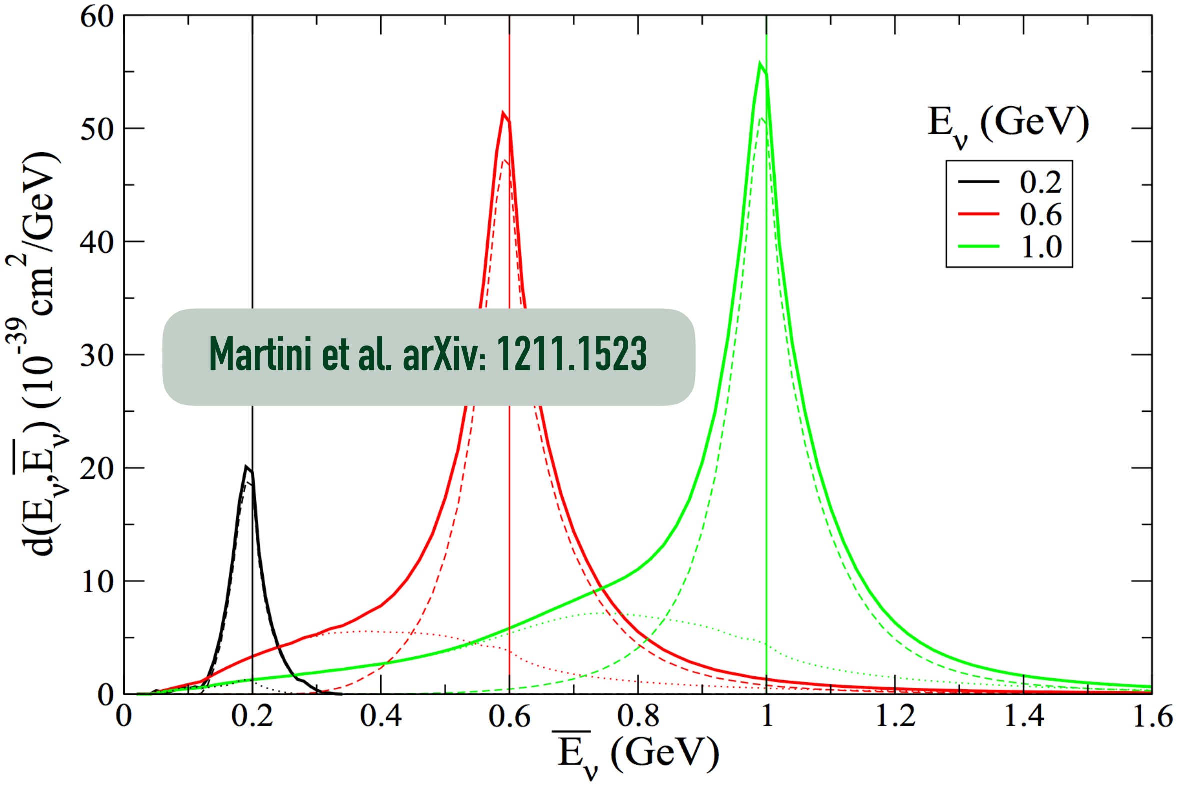
M. Martini NuFACT 2015





- Multi-nucleon effects.
  - Hadronic state not reconstructed.
  - Must assume mass of recoiling hadrons.
  - Problematic due to multi-nucleon interactions.
  - Explains larger axial mass preferred by MiniBooNE over NOMAD.
- Further missing hadronic energy from unseen pions.
- Both effects lead to energy underestimation.
- Many different multi-nucleon models - hard to separate experimentally.
- Energy loss different for neutrinos and anti-neutrinos.

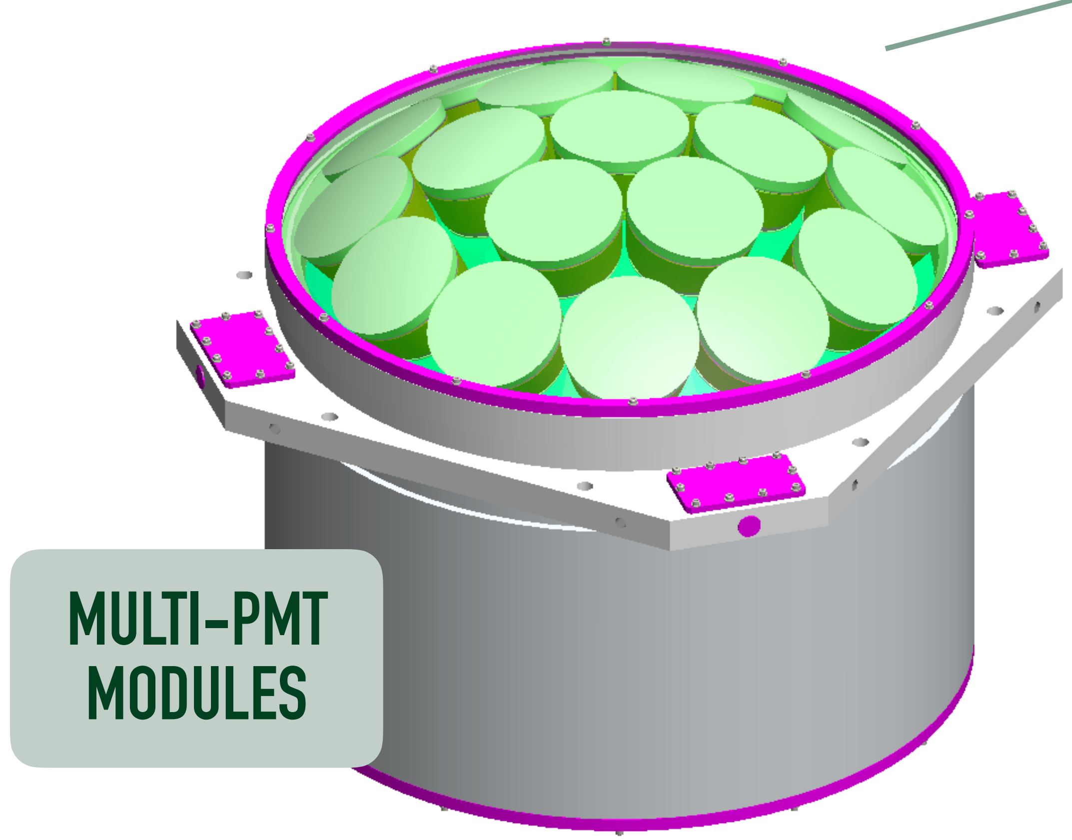


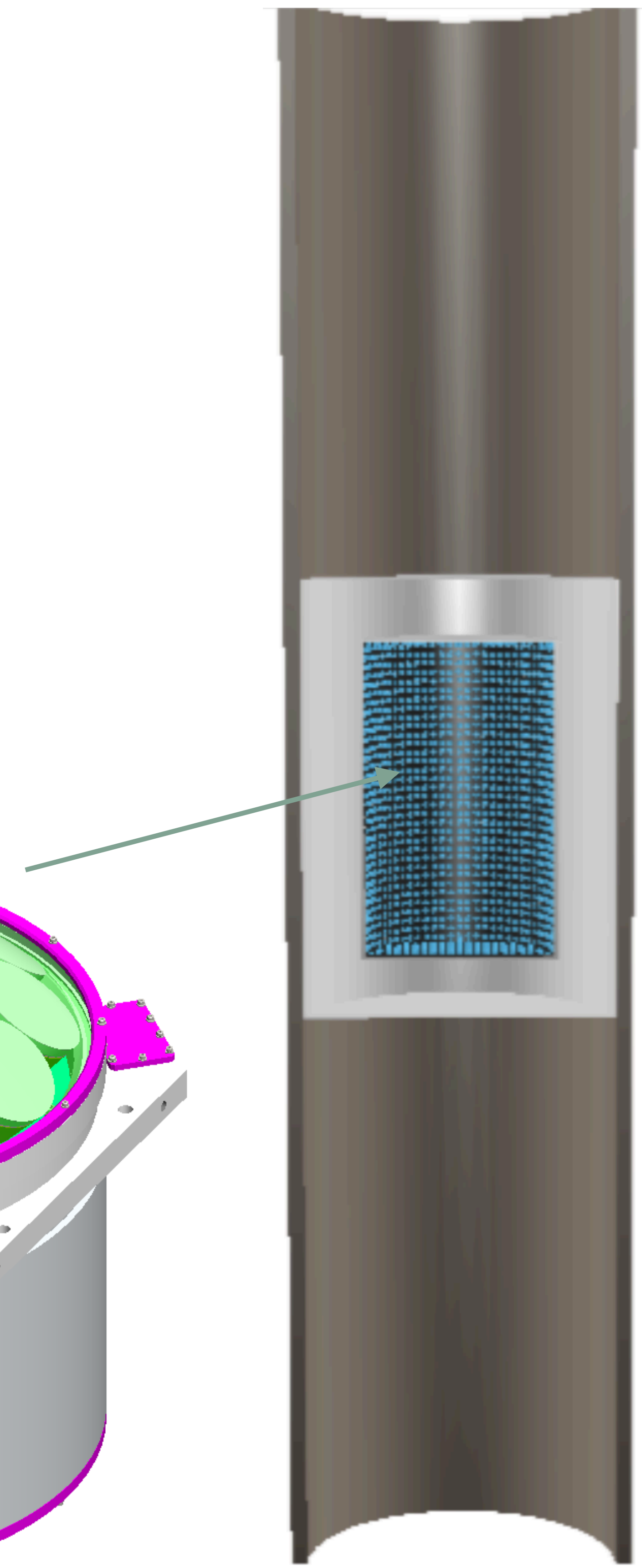


Martini et al. arXiv: 1211.1523

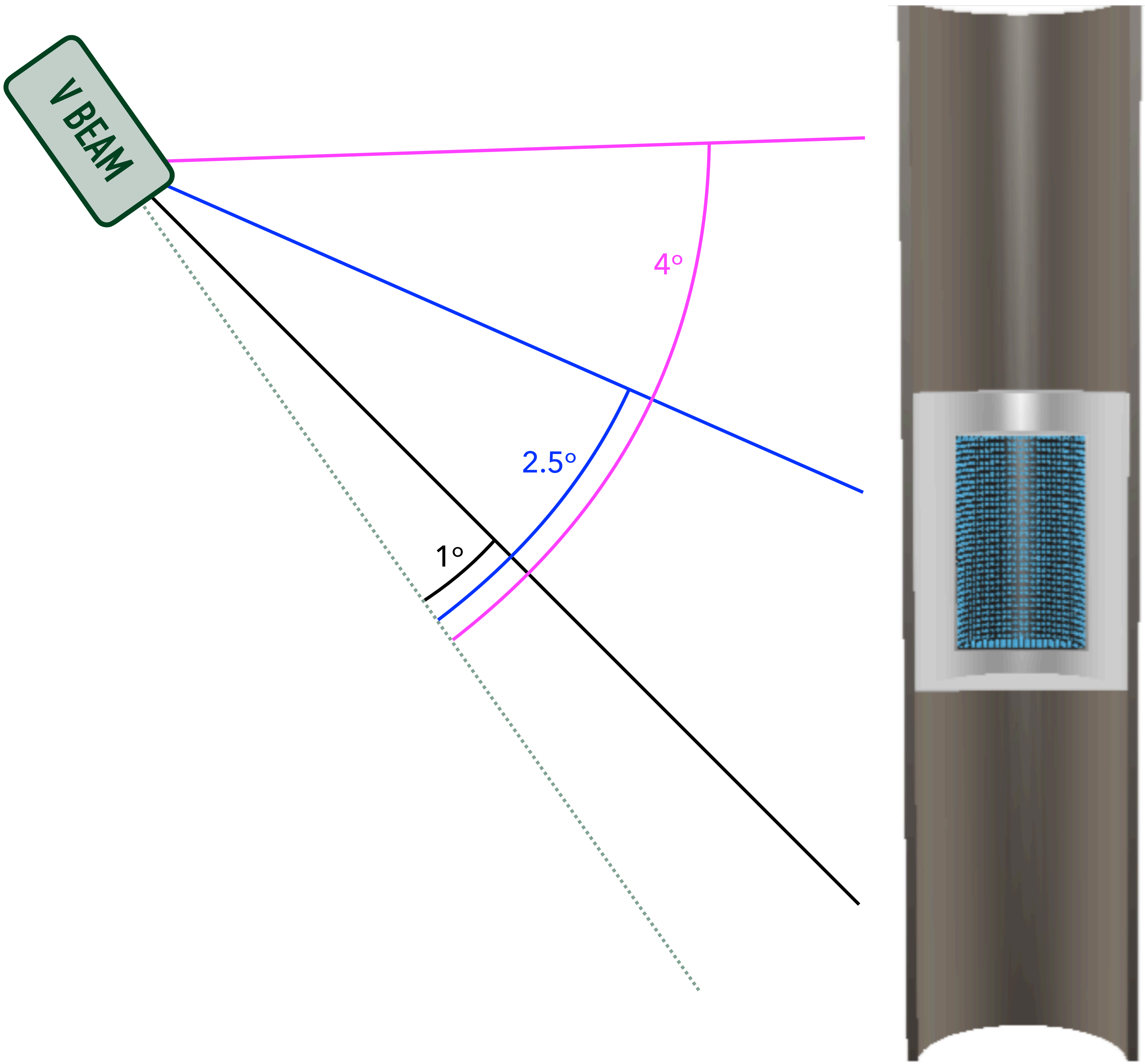
THE NUPRISM EXPERIMENT

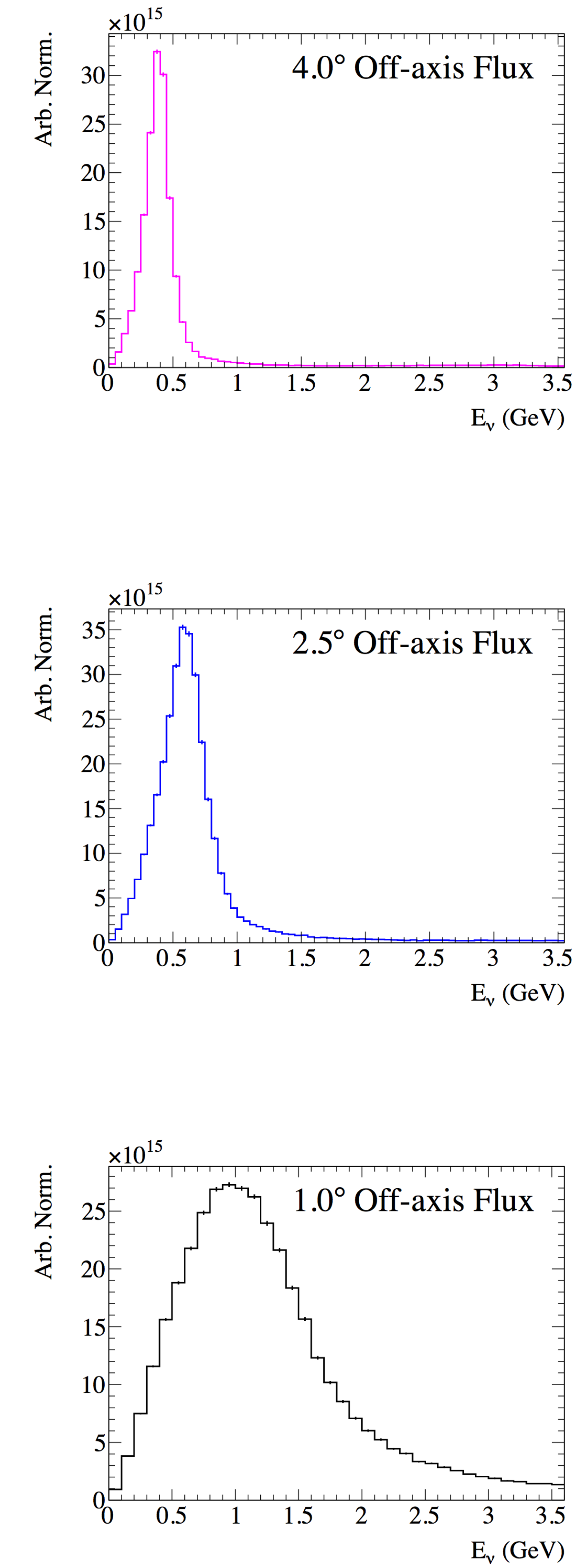
- An intermediate water Cherenkov detector.
  - Same nuclear target and acceptance as the far detector.
  - Smaller near to far extrapolation systematic.
- 50 m tall and 1 km downstream of neutrino beam.
  - Detector moves through cylindrical chamber.
  - Inner detector: 8 m diameter, 10 m tall.
  - Outer detector: 10 m diameter, 14 m tall.
  - Tank is lined with multi-PMT (mPMT) modules.
  - Spans 1-4 degrees from the neutrino beam axis.
  - Probes neutrino energy vs final state kinematics relationship.
  - Gd loading to measure neutron production.



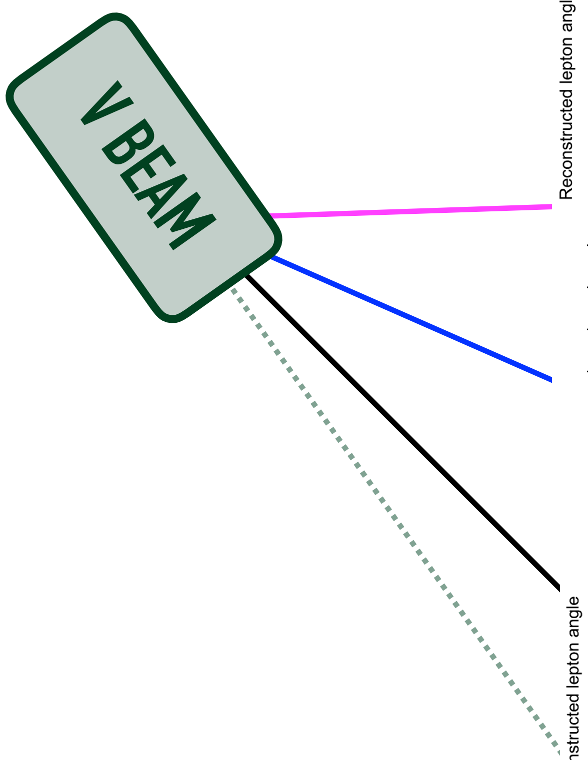


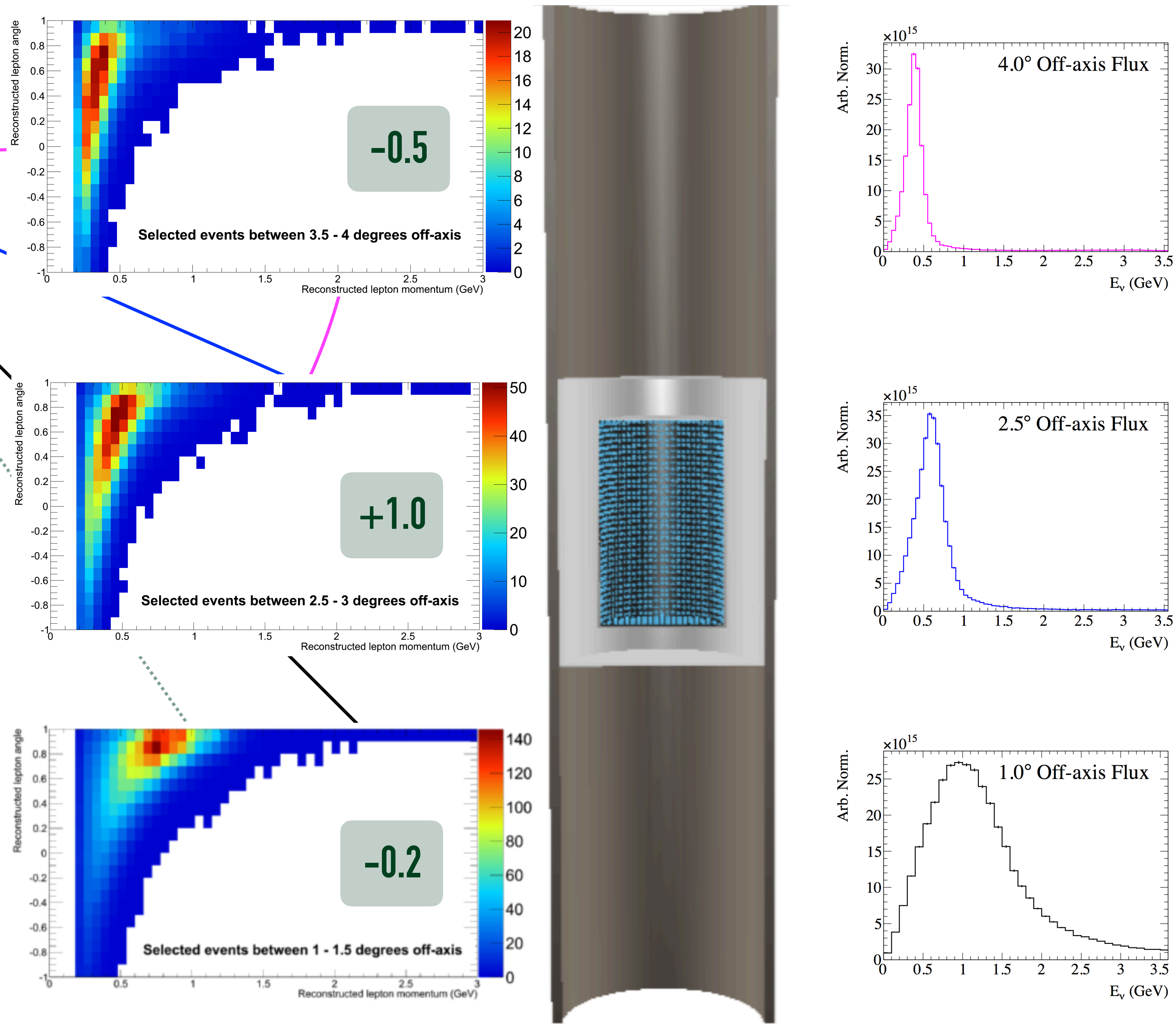
NUPRISM CONCEPT





NUPRISM CONCEPT

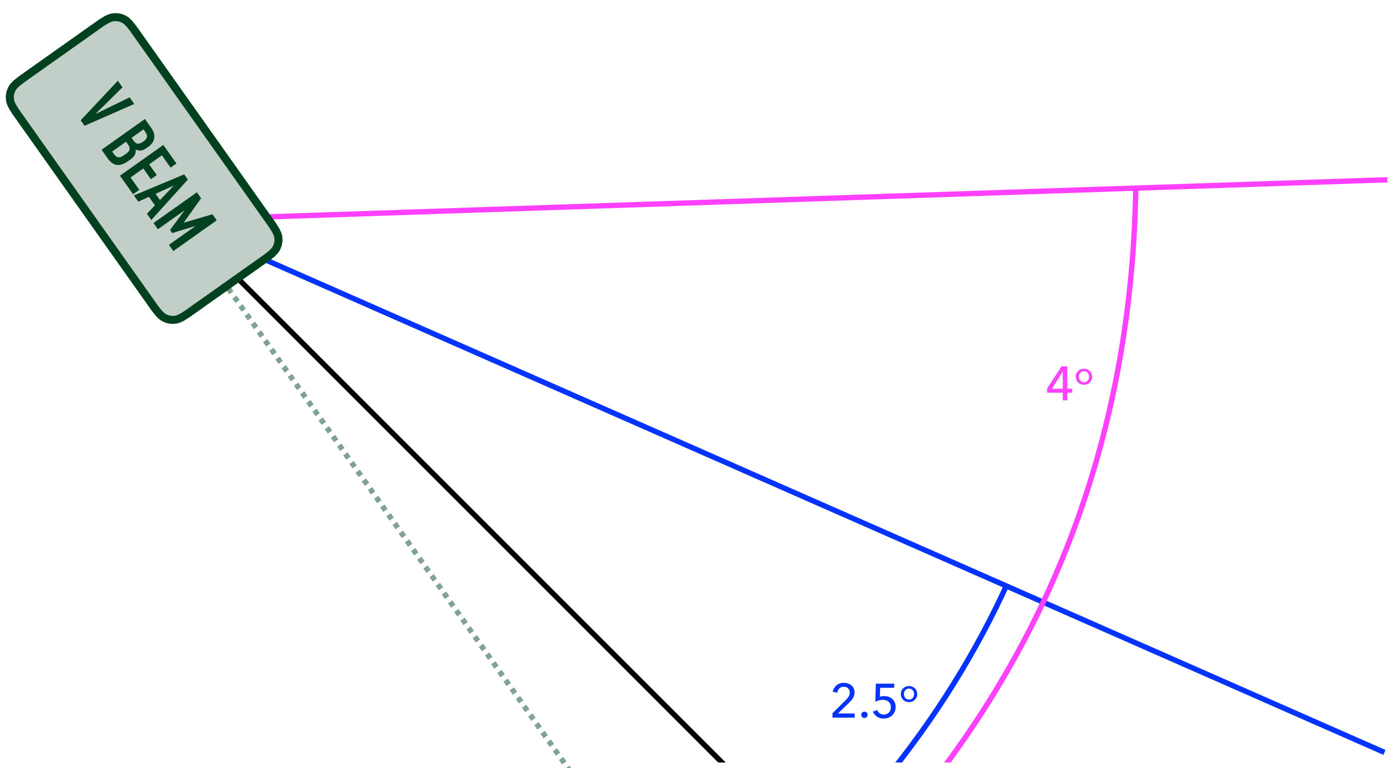


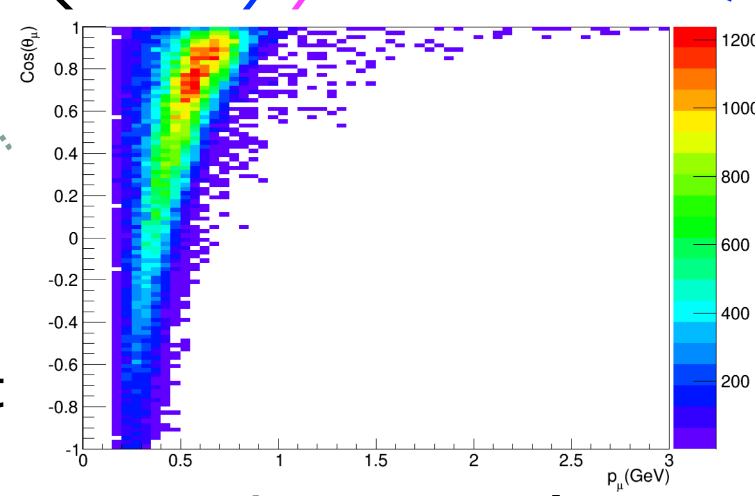


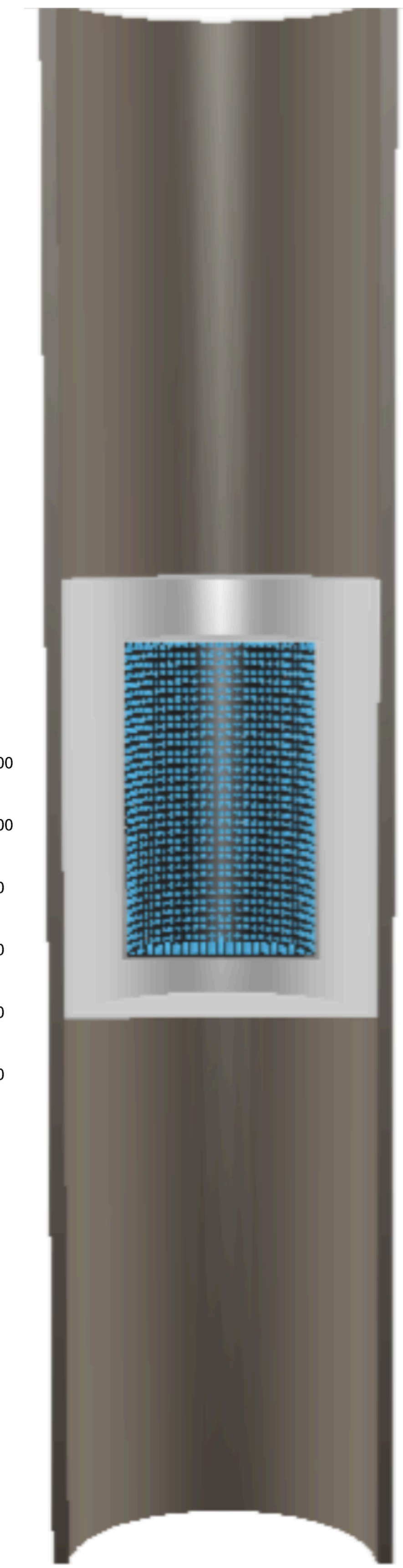
- Take linear combinations of different 60 different off-axis angle slices.

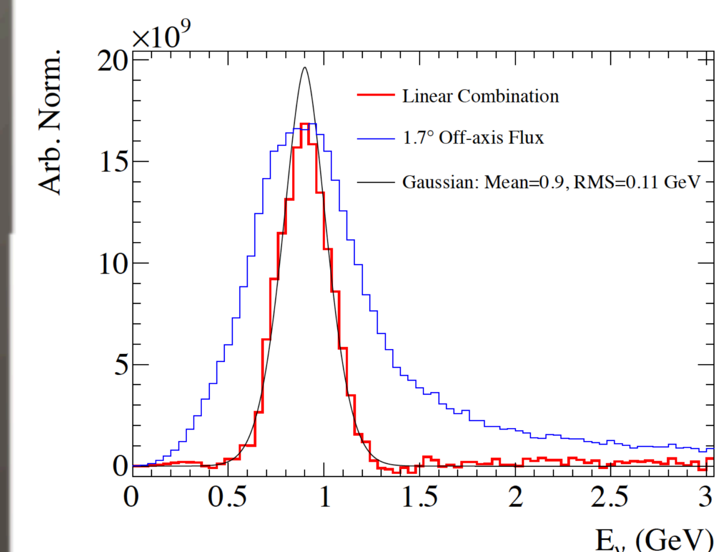
$$F(E_\nu) = \sum_{i=1}^{N_{OA}} c_i \Phi^{\nu P}_{\nu_\mu, i}(E_\nu)$$

NUPRISM CONCEPT







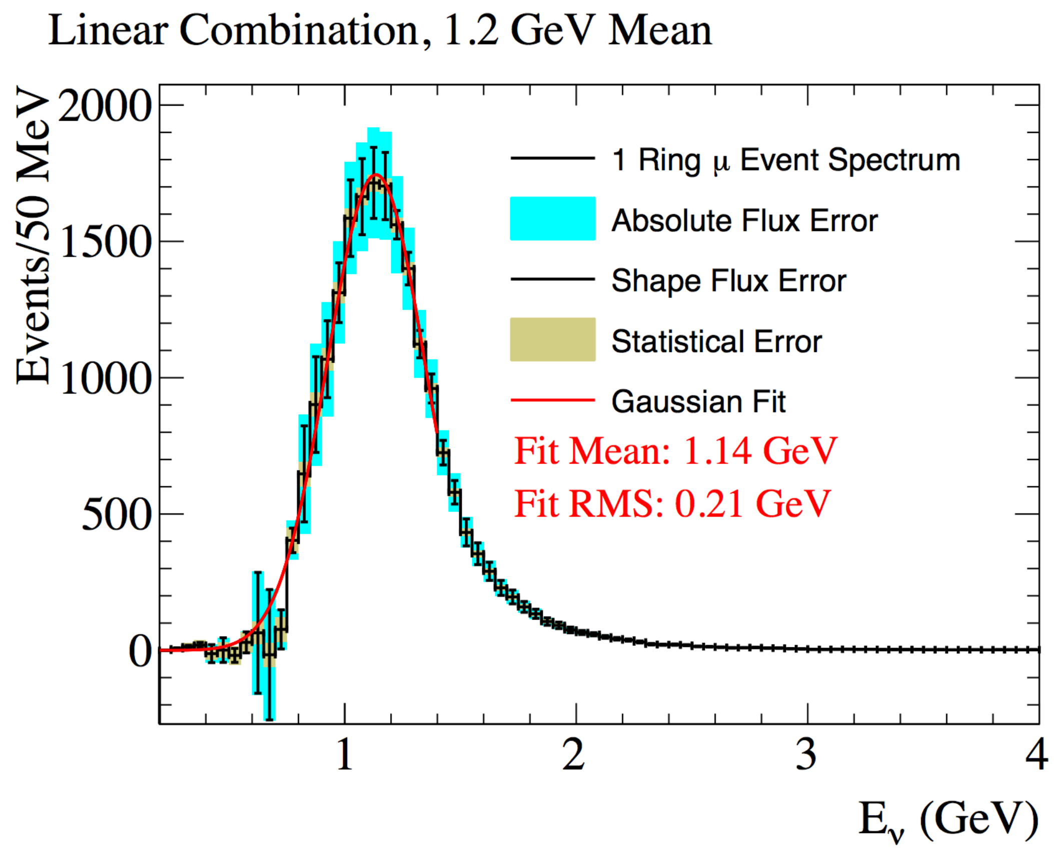


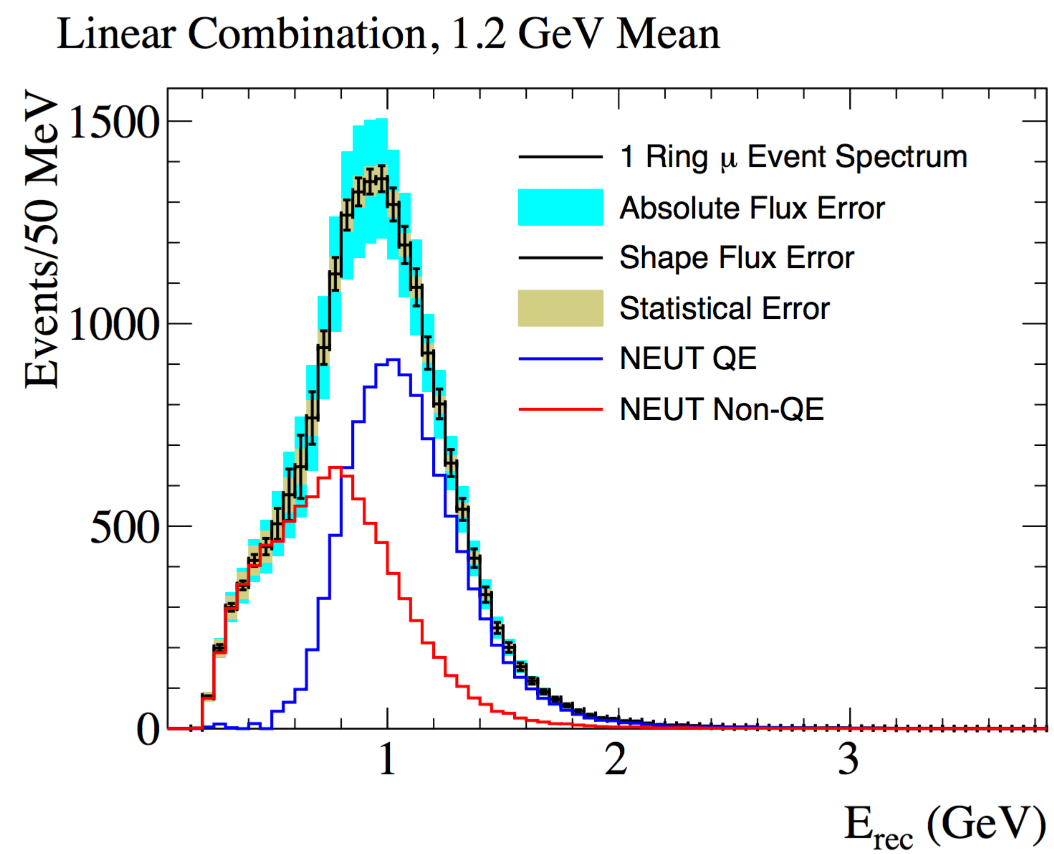
- Create a neutrino flux of interest e.g. Gaussian.
- Sum the observed events to give the expected event rate.

$$N^F(p_\mu, \theta_\mu | E_\nu) = \sum_{i=1}^{N_{OA}} c_i N^{\nu P}_{\nu_\mu, i}(p_\mu, \theta_\mu | E_\nu)$$

- Helps to constrain neutrino cross-section models.

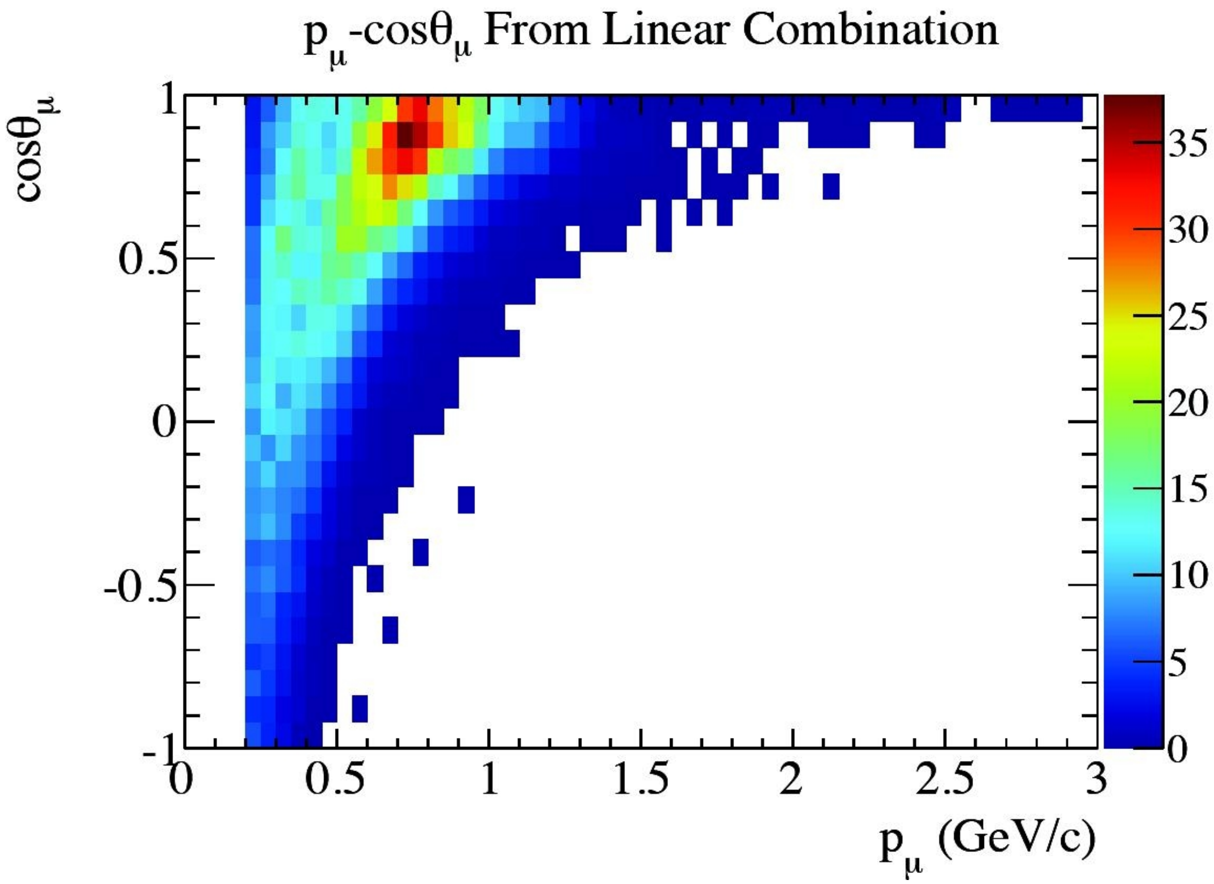
PSEUDO-MONOCHROMATIC BEAMS

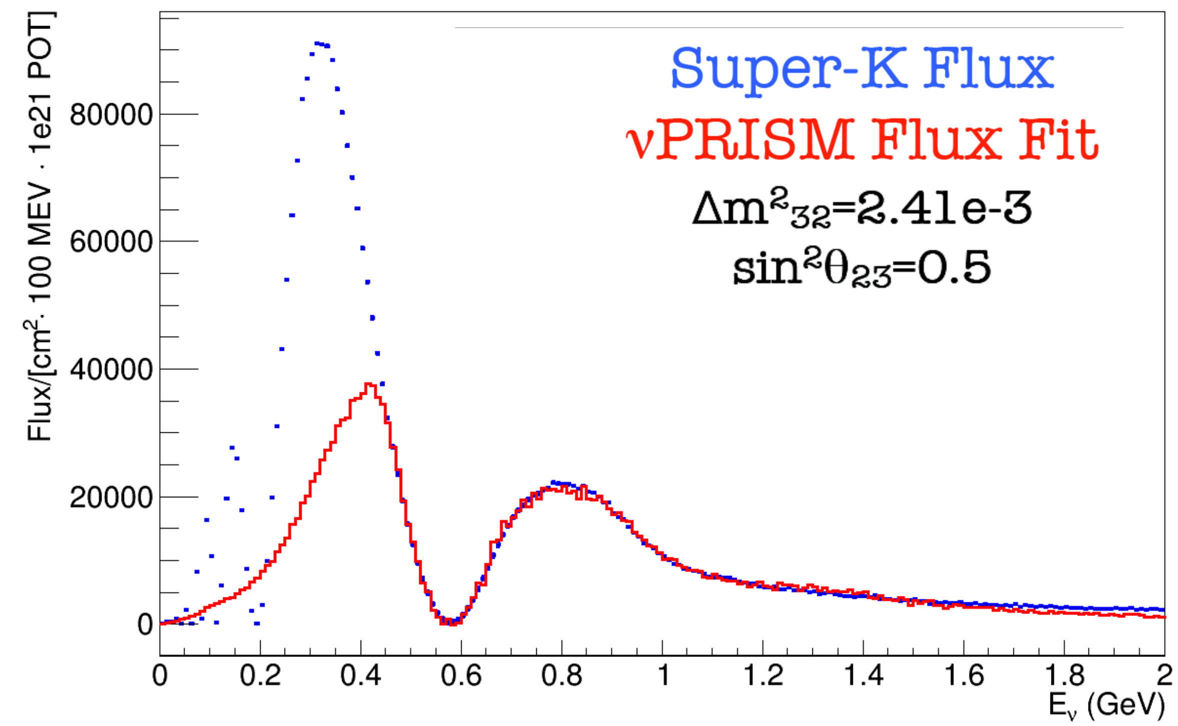




- Simulated reconstructed energy distribution for single muon candidates after applying the 1.2 GeV linear coefficients.
- Separation of QE and non-QE (including multi-nucleon) scatters.
  - Directly predict the effect of non-QE scatters in oscillation measurements and provide a unique constraint on nuclear models.
- Cross-sections as function of true neutrino energy.
- Measure vs true observables Q^2 and ω - variables controlling interaction mode.

MUON NEUTRINO DISAPPEARANCE



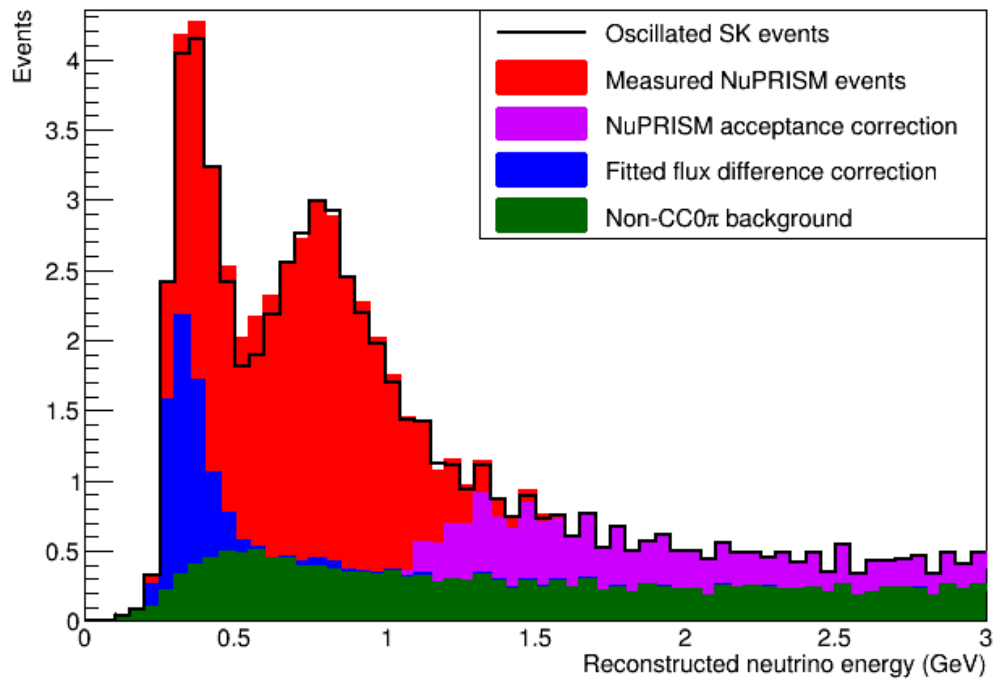


- Instead of monochromatic beams, use a linear combination to produce an oscillated flux.

$$\Phi_{SK} P_{\nu_\mu \to \nu_\mu}(E_\nu; \theta_{23}, \Delta m^2_{32}) = \sum_{i}^{\text{Off-axis bins}} c_i(\theta_{23}, \Delta m^2_{32}) \Phi_i^{\nu P}(E_\nu)$$

- Can reproduce oscillated flux between ~400 MeV and 1.2 GeV.
- Directly measure muon p-theta for given oscillation parameters.
- For each oscillation hypothesis we want to test, we find a linear combination of the NuPRISM off-axis fluxes to give the oscillated spectrum.

MUON NEUTRINO DISAPPEARANCE



Measured NuPRISM event rate:

$$N_{SK}(E_{rec};\theta_{23},\Delta m^2_{32}) = \sum_i^{\text{Off-axis bins}} c_i(\theta_{23},\Delta m^2_{32}) N_i^{\nu P}(E_{rec})$$

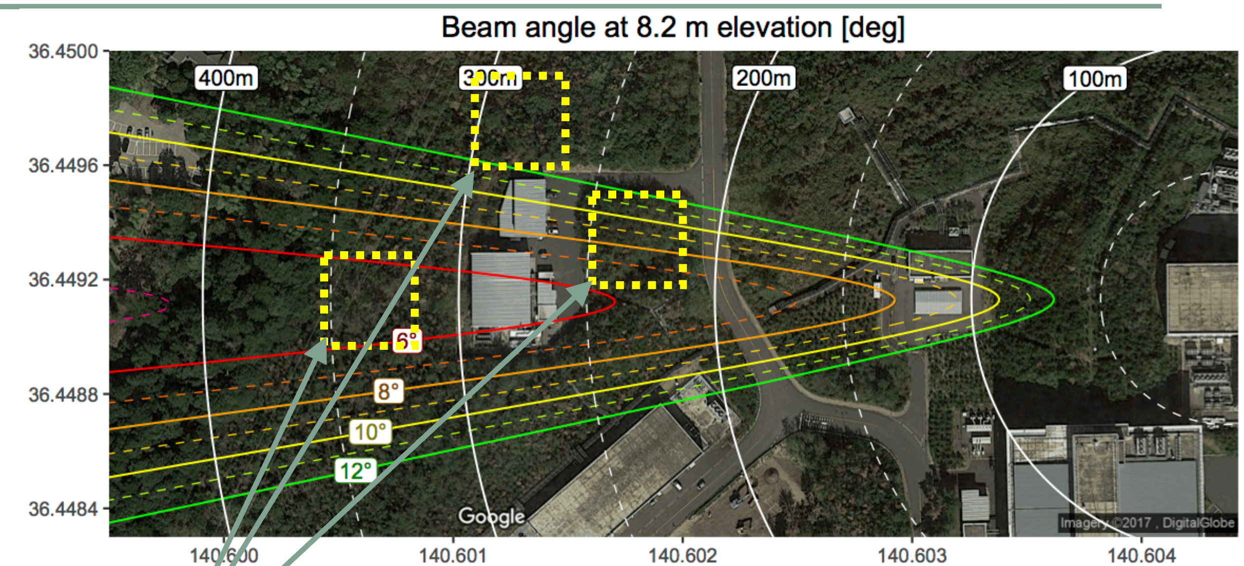
SK expected event rate:

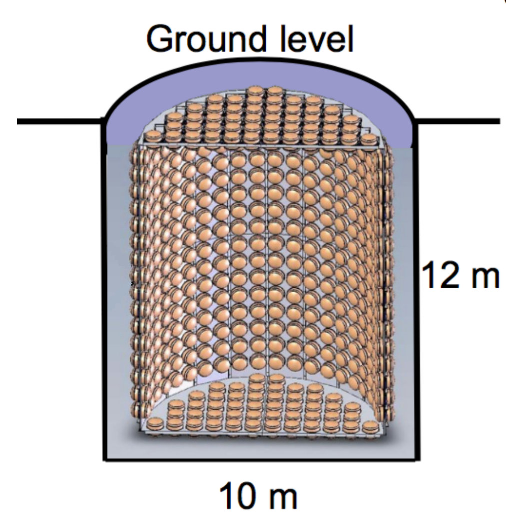
$$N_{SK} = \int \Phi^{SK}_{\nu_\mu} \times \sigma \times \epsilon_{SK} \times P(\nu_\mu \to \nu_\mu)\, dE_\nu$$

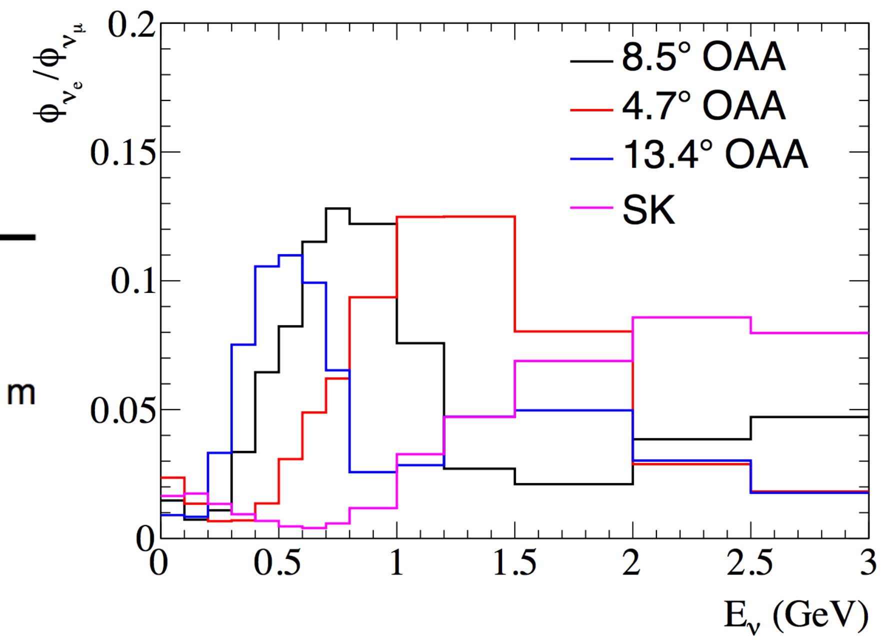
- Red: Directly measured NuPRISM events in far detector prediction.
- Green: Non-CC0π background subtracted at NuPRISM and re-added at SK with significant cancellation.
- With matched fluxes:
  - NuPRISM linear combination event rate the same as oscillated SK event rate.
  - Directly compare NuPRISM measurement to observed SK events to obtain oscillation parameters.
- NuPRISM and SK have the same interaction material - same interaction cross-section.
  - No cross-section model, no effect from wrong model choice.

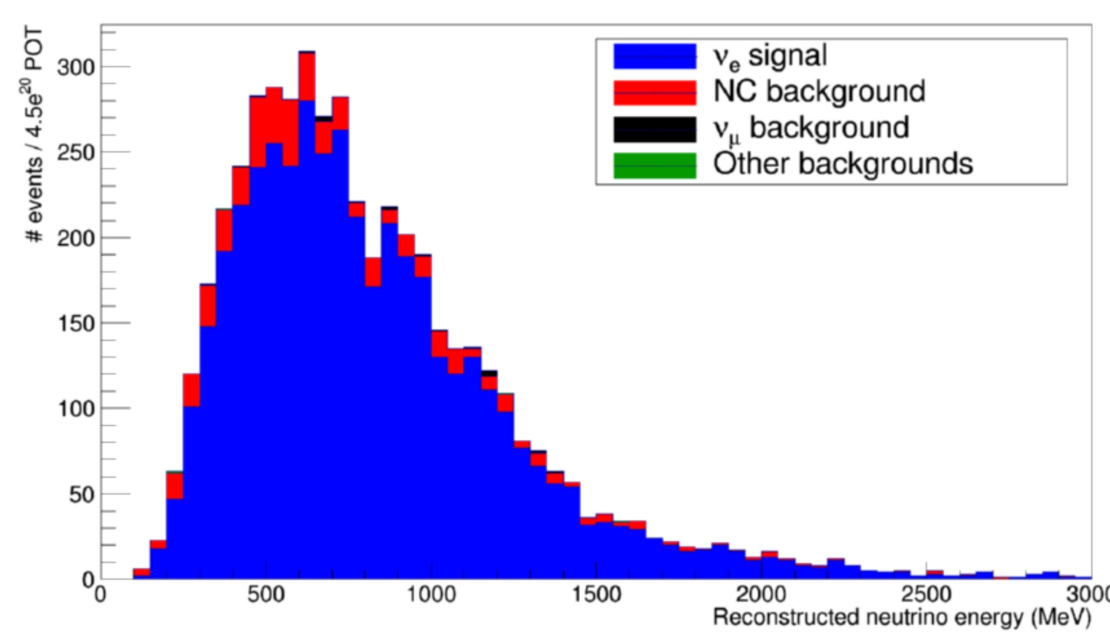
PHASE 0

- Instrumented portion of phase 1 is placed in a water tank near ND280.
- Allows us to demonstrate detector/calibration precision.
- Provides a test detector for Hyper-K R&D.
- Physics goals:
  - Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ to ~3% precision.
  - Expect ~5500 ν_e events below 1 GeV in $1\text{x}10^{21}$ POT with 76% purity.
  - Gd loading to measure neutron multiplicities in neutrino-nucleus interactions.
- A range of locations being studied.
  - Optimise flux uncertainties and flux ratios.
  - Investigating feasibility of construction.



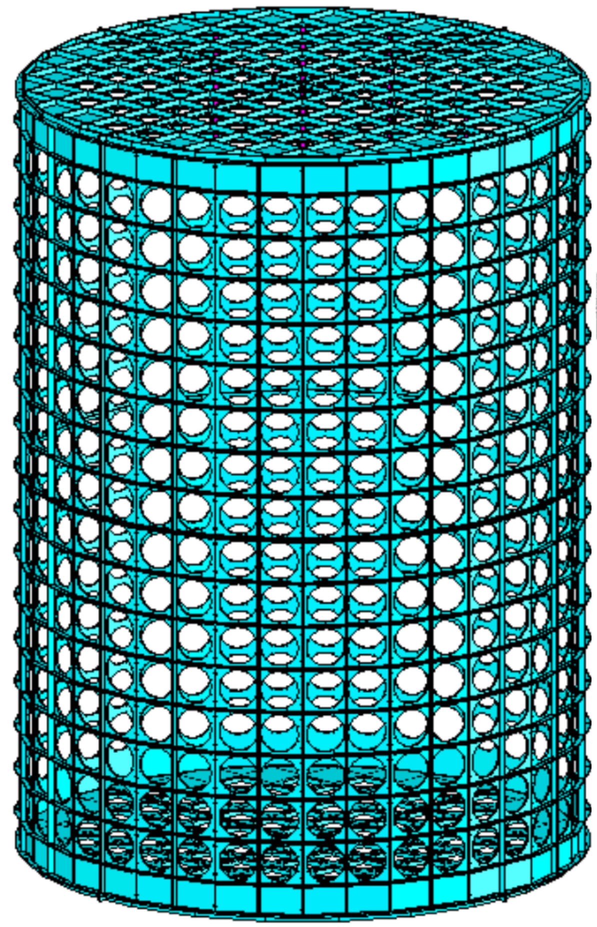


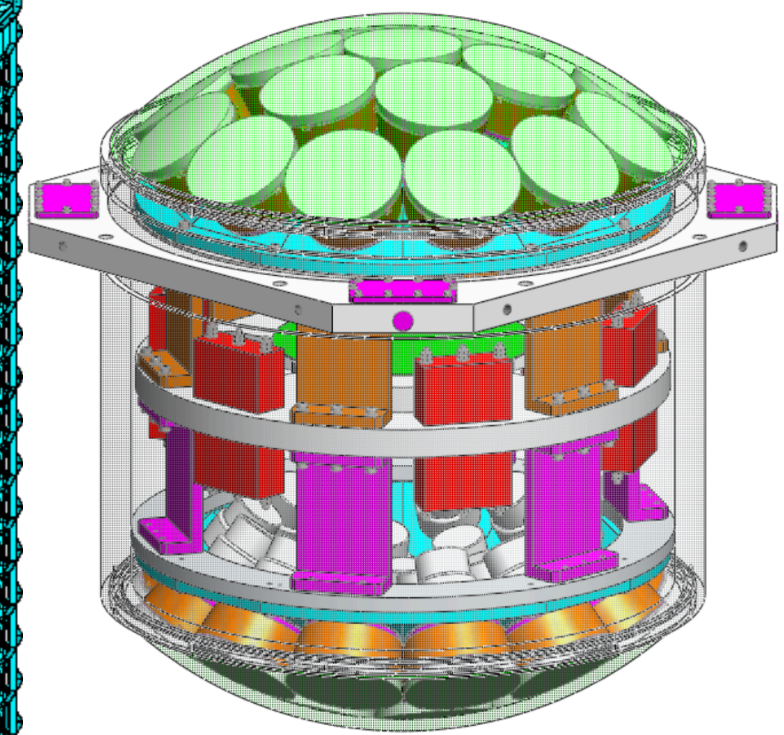


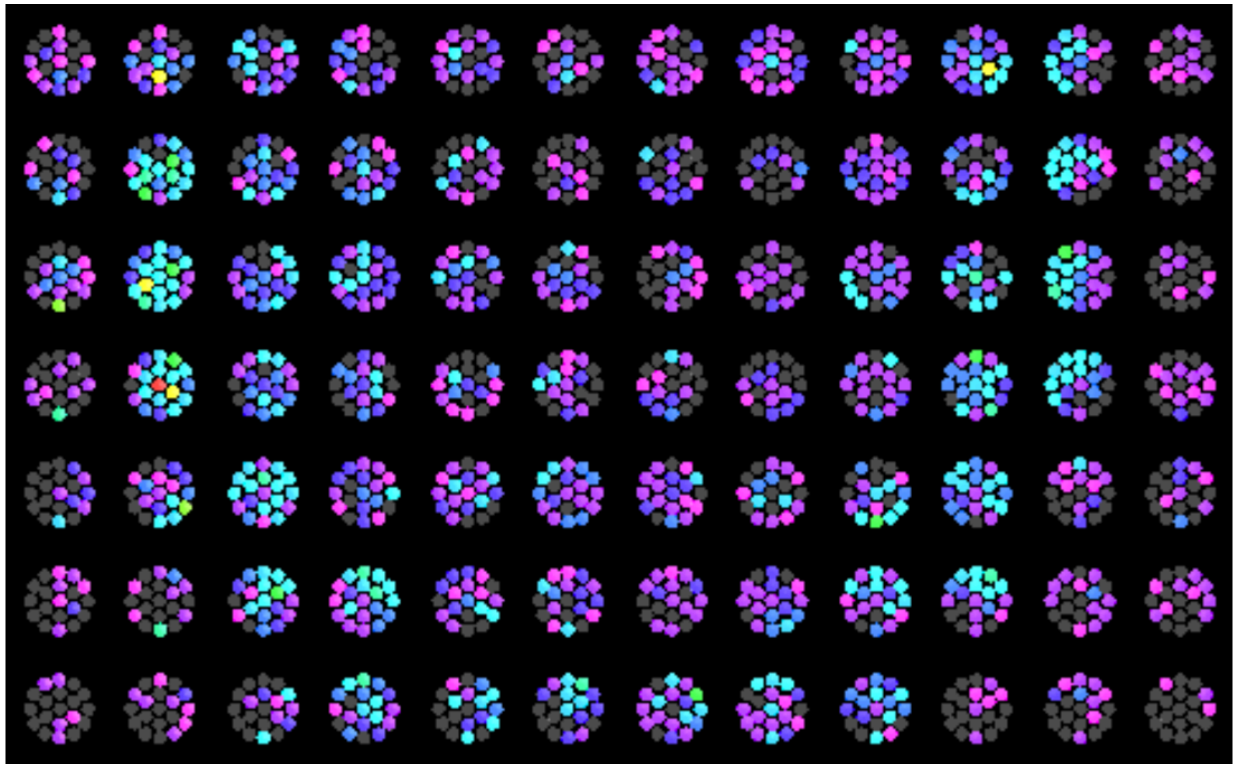


MULTI-PMT (MPMT) R&D

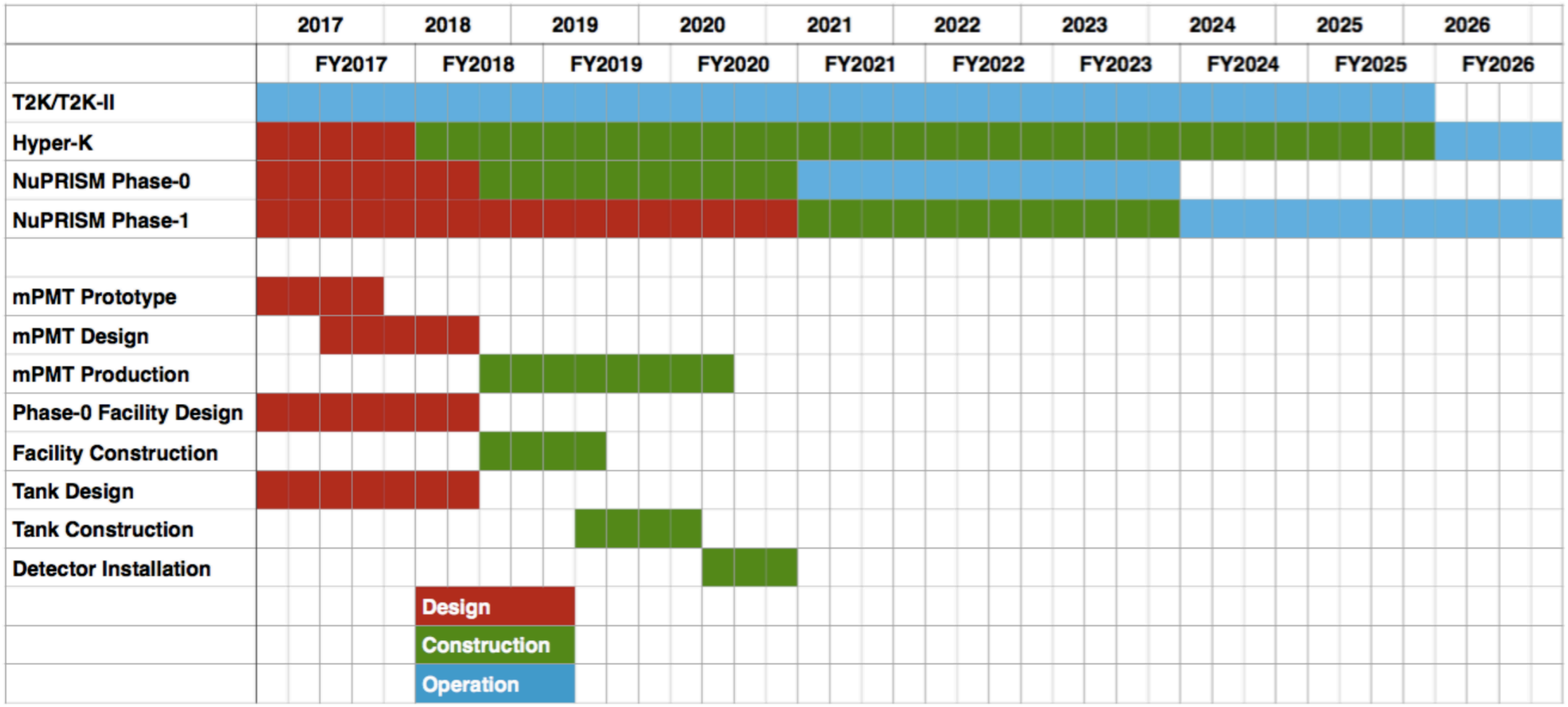
- Modular approach to PMT instrumentation.
  - Array of small (~3″) PMTs rather than one large one.
  - Waterproofing, pressure protection, reduced cabling.
  - Readout electronics, monitoring, calibration devices located in vessel.
  - Directional information - improved vertex resolution.
- Leveraging lessons learned from KM3NeT/IceCube mPMT design.
- Mechanical design (TRIUMF, Toronto).
- Optical characterisation of PMTs, acrylic, etc. (Toronto, York, Alberta, TRIUMF).
- Electronics development (TRIUMF, Warsaw UT, Michigan State) .
- Ongoing studies of support structure, acrylic vessel engineering, reflector assembly, optical gel, etc.







PROJECT STATUS



- J-PARC PAC Stage 1 status granted in July, 2016.
- Stage 2 requires Technical Design Report - aim to complete by November 2017.
- First chance for full approval at the January 2018 PAC meeting.
- Plan to take 2 years of Phase 0 data starting 2021.
    - Phase 0 start driven by mPMT development and construction.
- Aim to take Phase 1 data ~3 years after Phase 0 start.
    - Data taking for last 2-3 years of T2K-II run.

BACKUP SLIDES…

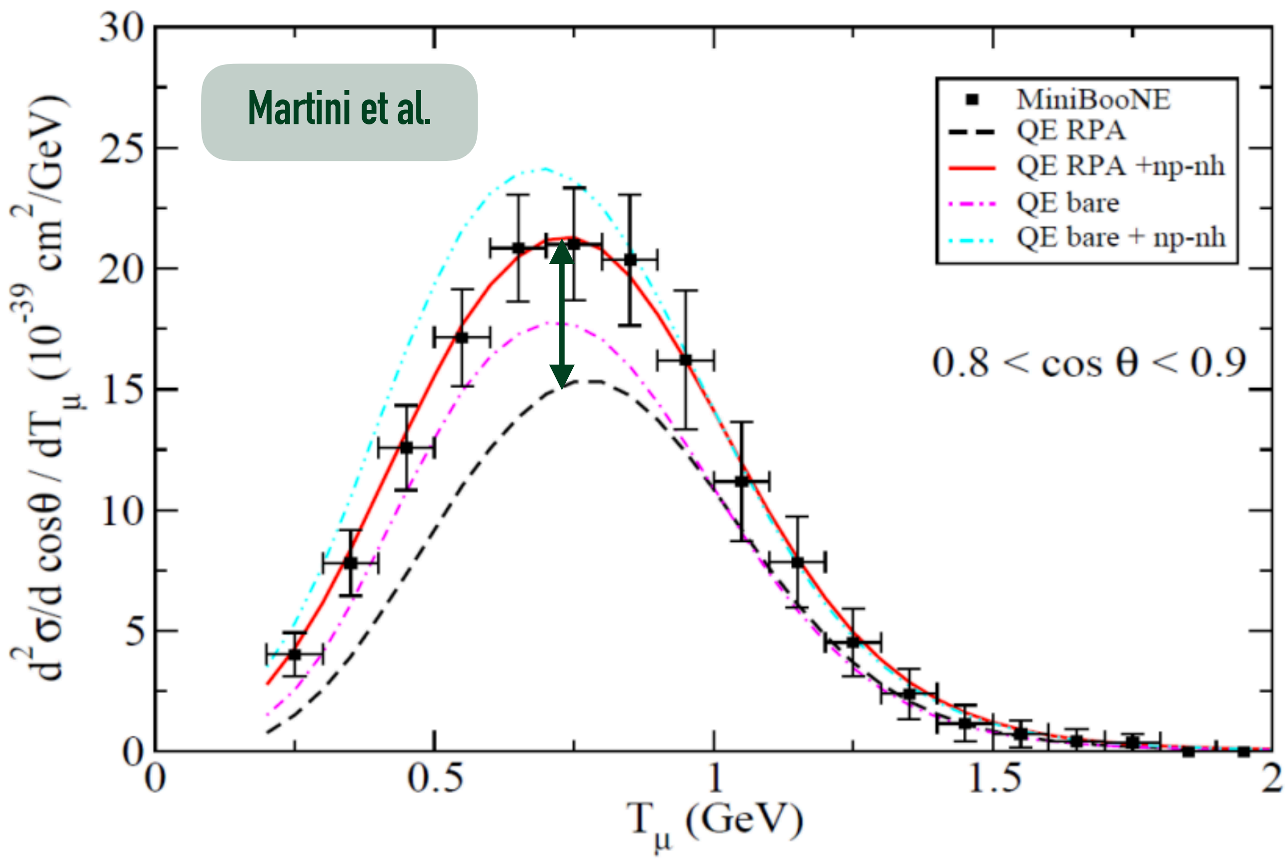
CURRENT T2K SYSTEMATIC ERRORS

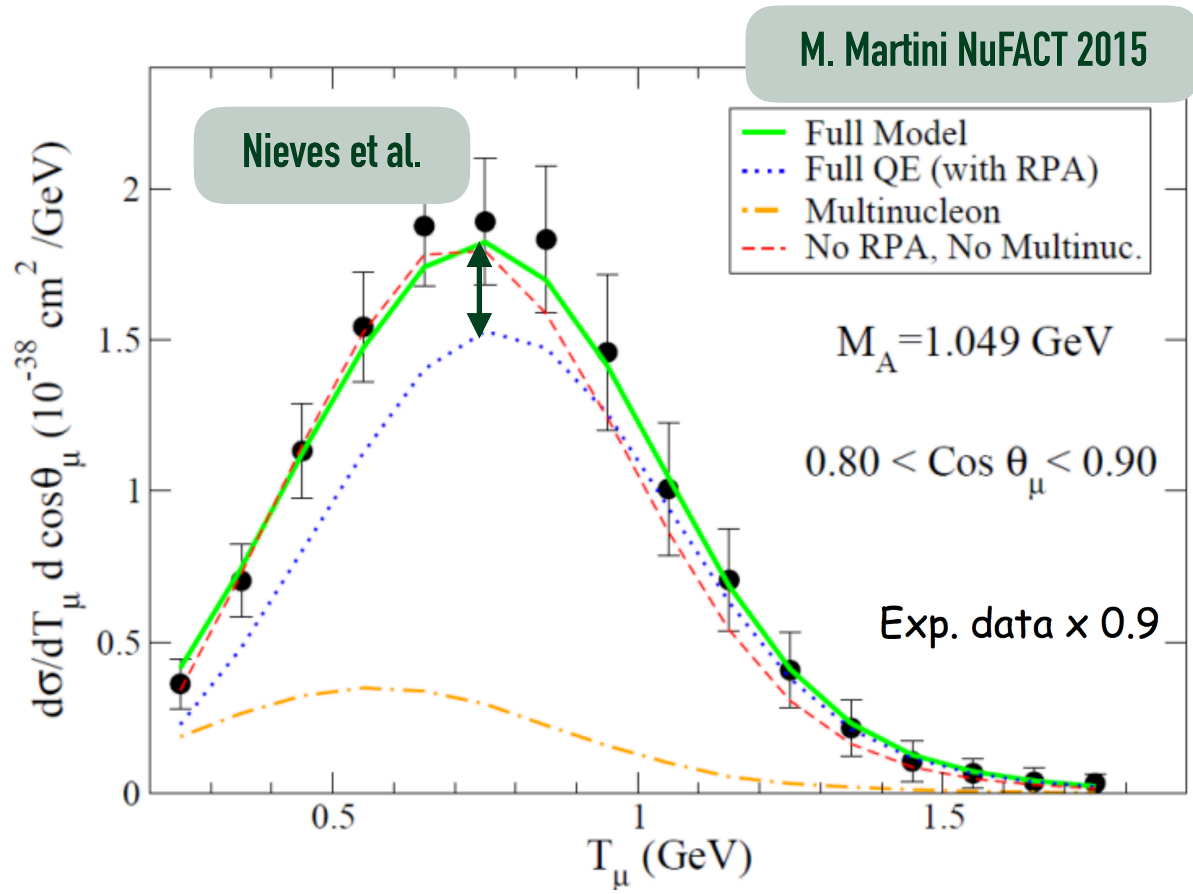
- Systematic uncertainty at the 6% level. Need reduction to ~3% level for Hyper-K.

Source of uncertainty	μ-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$	e-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$
SKDet	0.07%	1.6%
FSI+SI	2.6%	3.6%
Flux	1.8%	1.8%
Flux+XSec (ND280 constrained)	1.9%	2.2%
XSec NC other (uncorr)	0.0%	0.2%
XSec NC 1γ (uncorr)	0.0%	1.5%
XSec ν_e / ν_μ (uncorr)	0.0%	3.1%
Flux+XSec	1.9%	4.1%
All	3.2%	5.8%

- CP violation measurement depends on uncertainty of $\nu_e/\overline{\nu}_e$ ratio.
- Dominant uncertainties:
    - Final state interactions (FSI) and secondary interactions (SI) - nuclear model extrapolated from pion-nucleus scattering experiments.
    - Electron/muon neutrino cross-section ratio - need data in energy range of interest, low statistics and large background for electron samples.
    - ND280 flux + cross-section constraint - affected by nuclear model uncertainties.

MULTI-NUCLEON MODELS

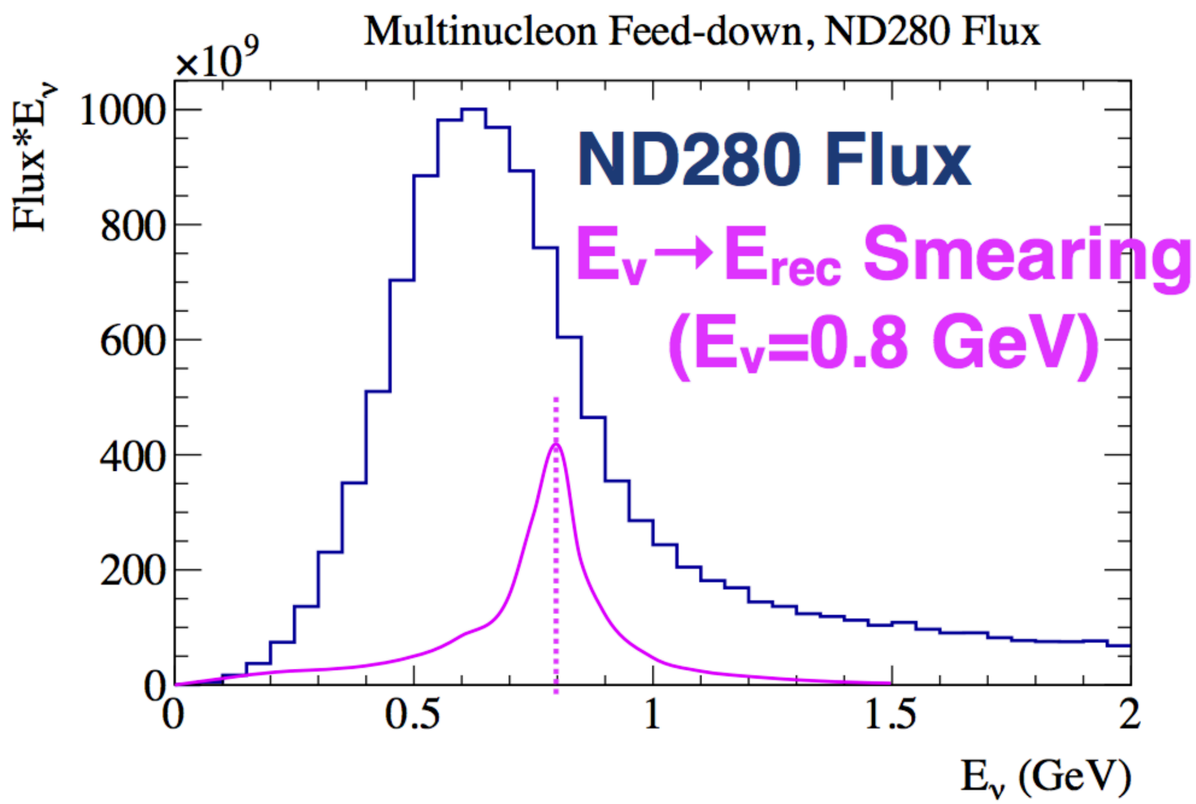


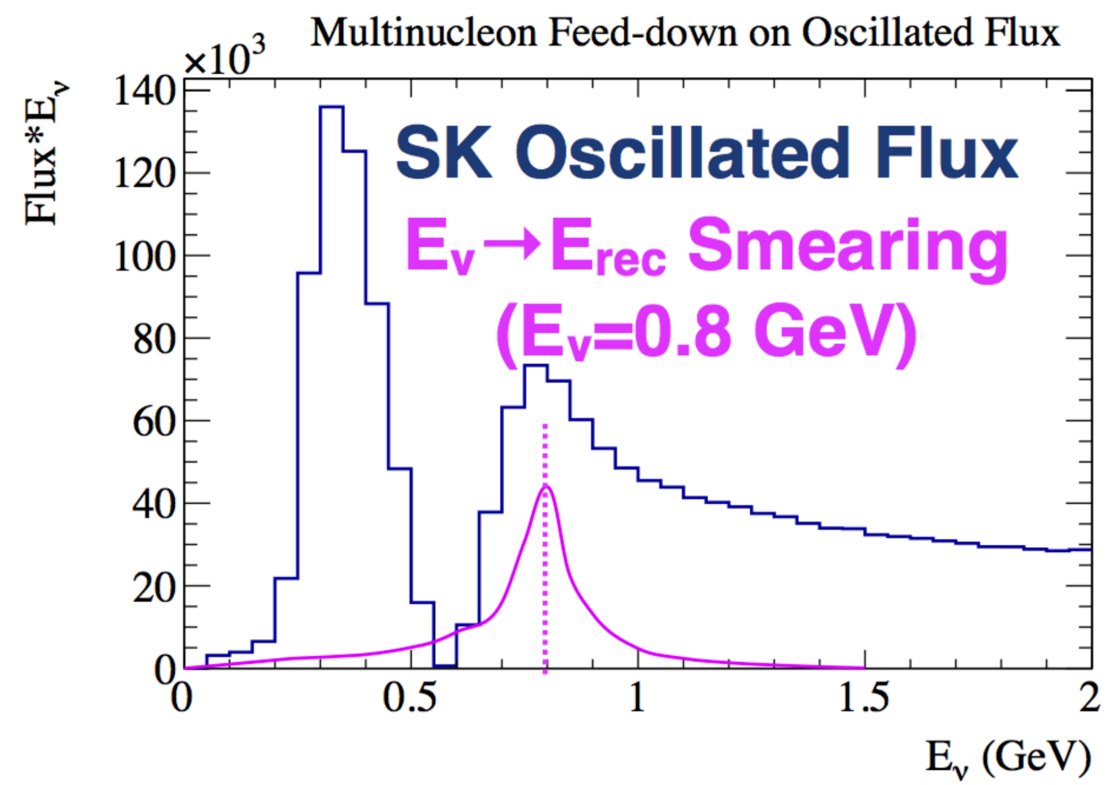


- Many different theoretical models.
- Martini et al. and Nieves et al. calculations are both consistent with MiniBooNE data within the MiniBooNE flux uncertainties.
- The np-nh contributions can differ by a factor of 2 in the region of interest.
- Predict different rates for neutrinos vs anti-neutrinos.
- Hard to separate models experimentally.

NEAR DETECTOR CONSTRAINT

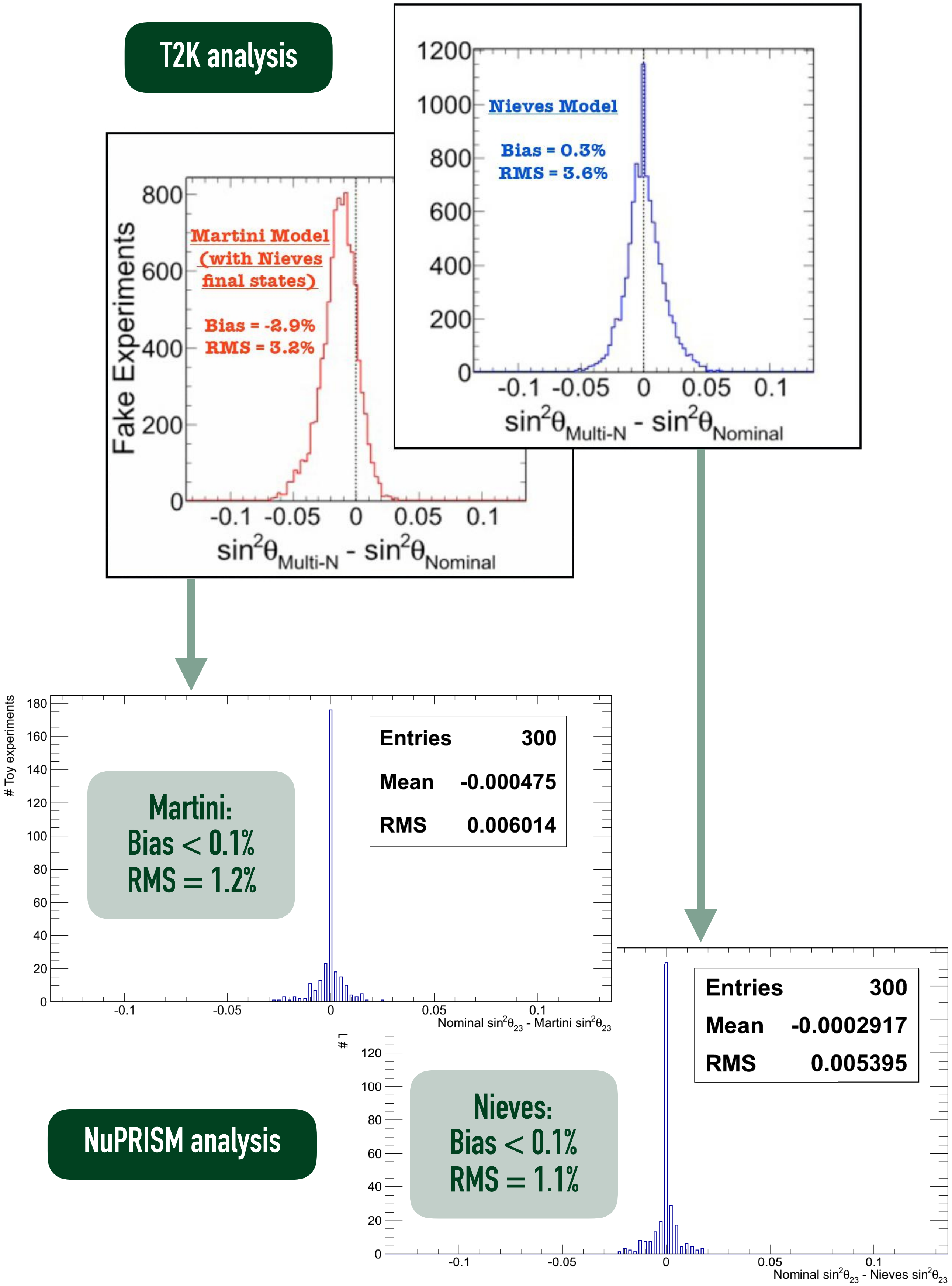
- Oscillations result in different fluxes at the near and far detectors.
    - Causes issues constraining interaction model that predicts far detector event rates.





- Detectors measure convolution of neutrino flux with interaction model.
    - Measurement of near detector does not directly constrain far detector event rate.
- Smearing of neutrino energy a relatively small effect at the near detector but significantly impacts measurement of oscillation parameters.
- Different acceptances causes further issues.

EFFECT OF MULTI-NUCLEON CROSS-SECTION MODELLING



- T2K study of $\sin^2\theta_{23}$ uncertainty from mis-modelling the 2p-2h part of the cross-section found a significant bias and uncertainty.
- Same study is carried out using NuPRISM near detector fit.
- SK event rate is accurately predicted even with additional 2p-2h interactions added to the toy data.
- The $\sin^2\theta_{23}$ bias and uncertainty are reduced to ~1% with the NuPRISM measurement.
- NuPRISM analysis largely independent of cross-section model.