THE UNIVERSITY OF WINNIPEG

TRIUMF

JOHN WALKER

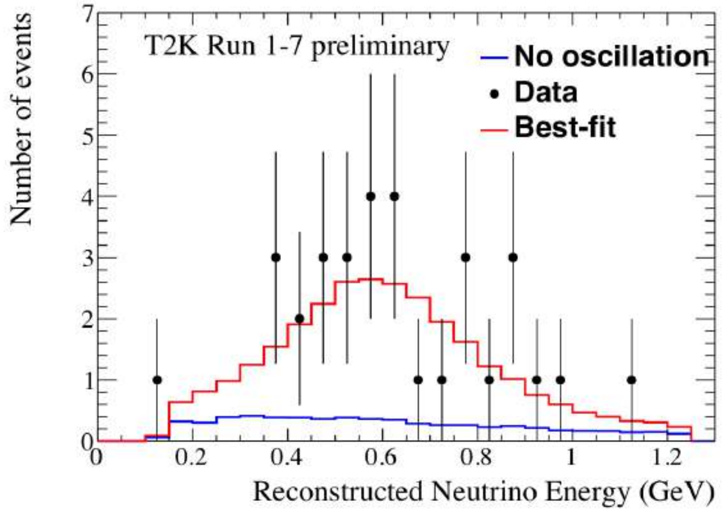
2019 CAP CONGRESS

06/06/2019

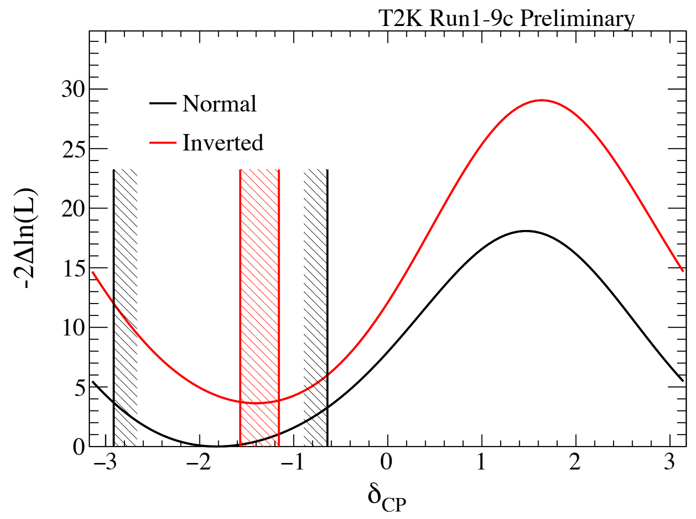
E61 STATUS AND SENSITIVITY STUDIES

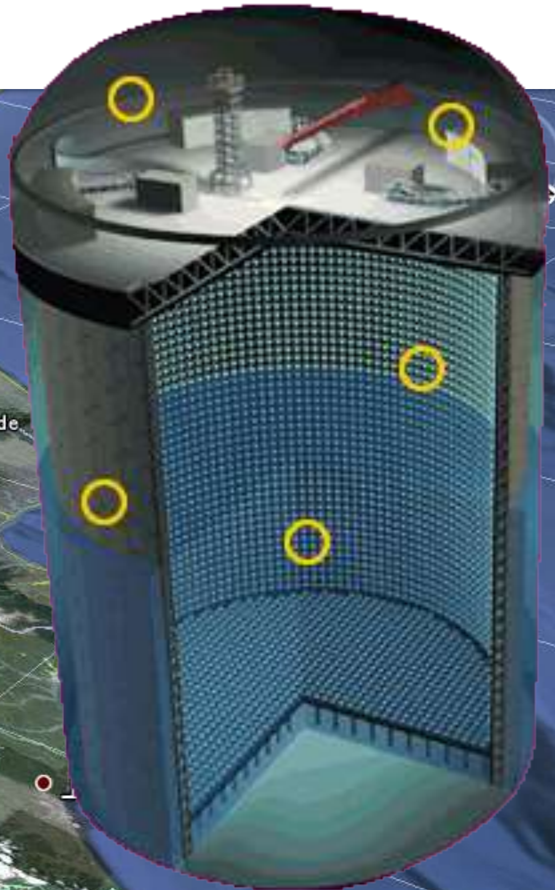
TOKAI TO KAMIOKA (T2K) EXPERIMENT

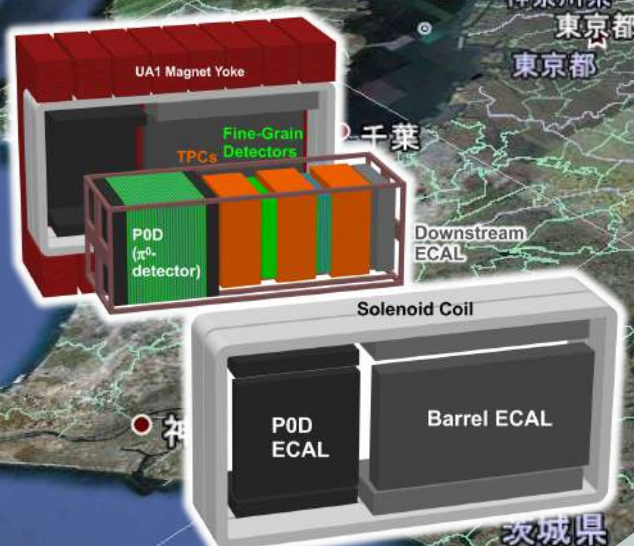
First observation of ν_e appearance



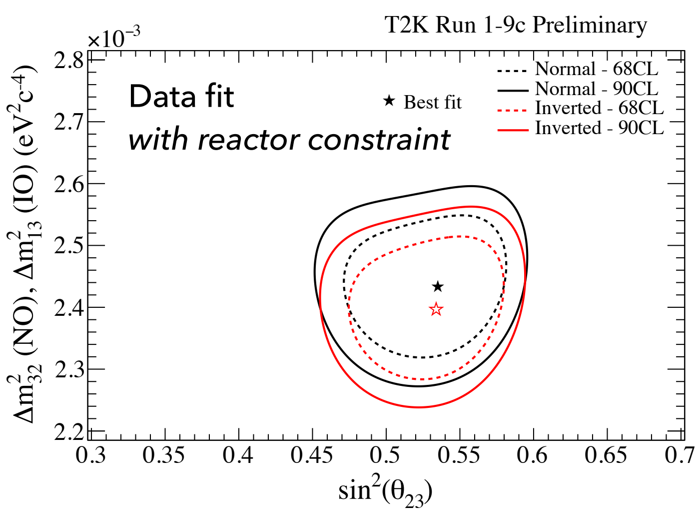
Exclusion of CP conservation in lepton sector at 2σ

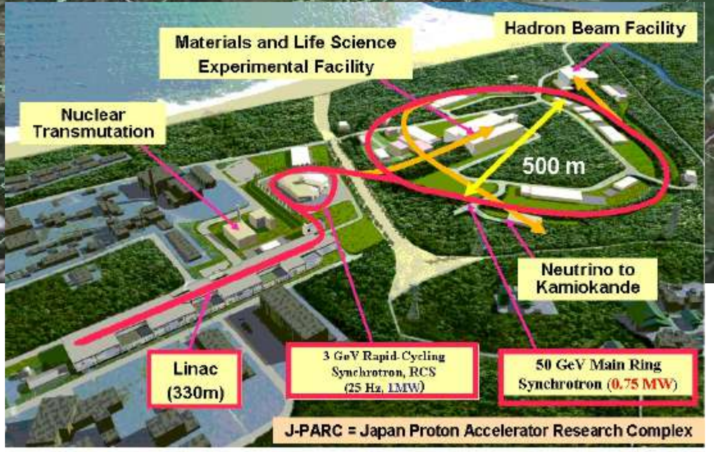






World-leading measurements of $\sin^2\theta_{23}$ and Δm^2_{23}.

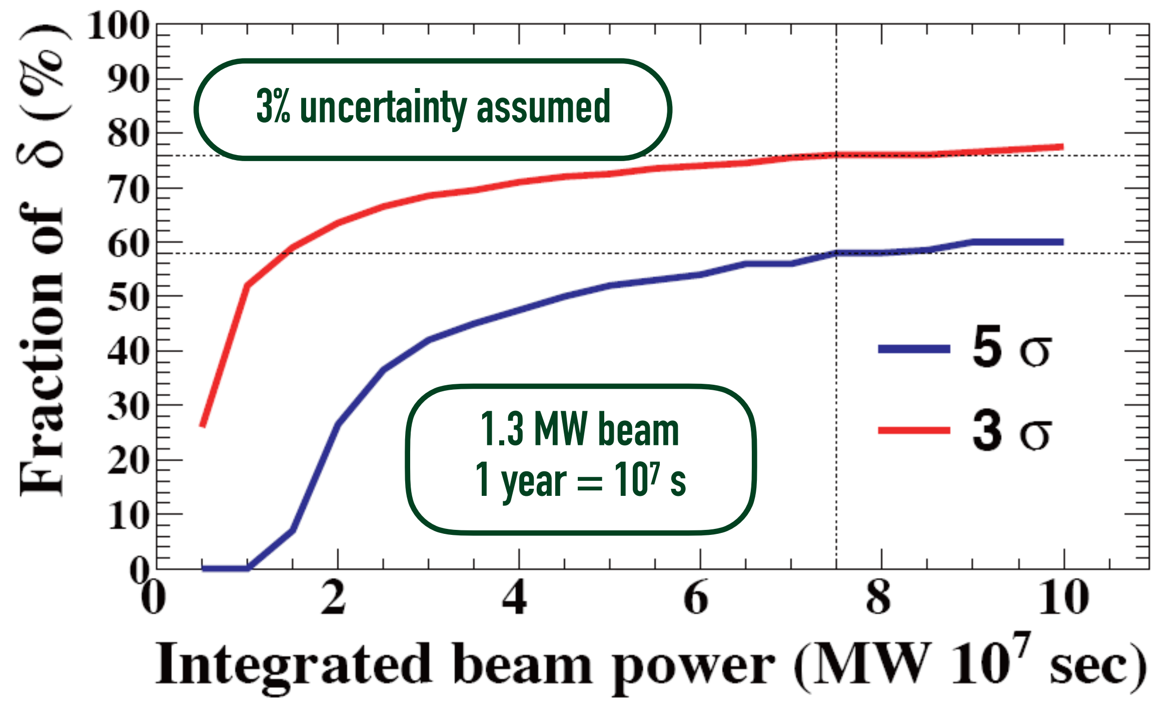


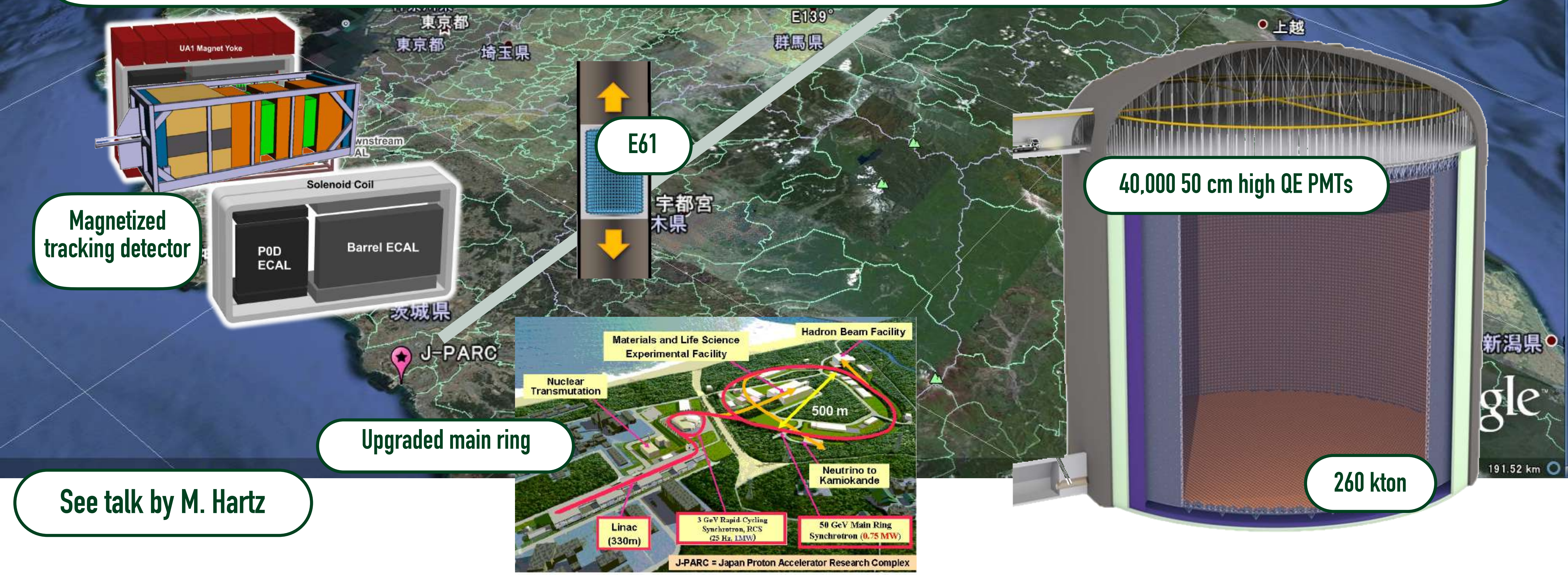


See talk by M. Hartz

HYPER-KAMIOKANDE PROJECT

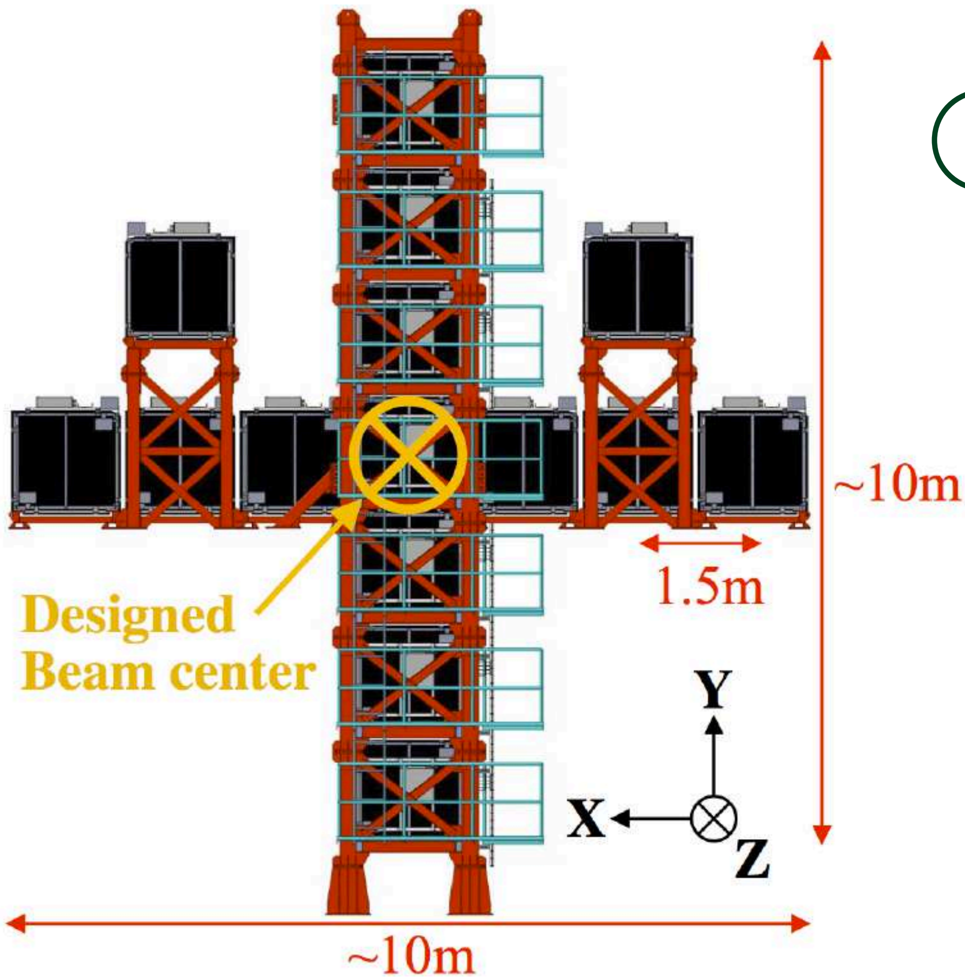
- Next generation water-Cherenkov detector with extensive physics program.
- Hyper-K 1st detector construction funding secured - starts in April 2020!
  - Potential for a second tank in Japan or Korea.
- Sensitive at 5σ over a wide range of values of δ_{CP}.
  - Limited by systematic rather than statistical uncertainty.
  - Requires reduction in systematic uncertainties.
- Improvements to near detectors integral to mitigating the effect of neutrino interaction uncertainties (ND upgrade and E61).



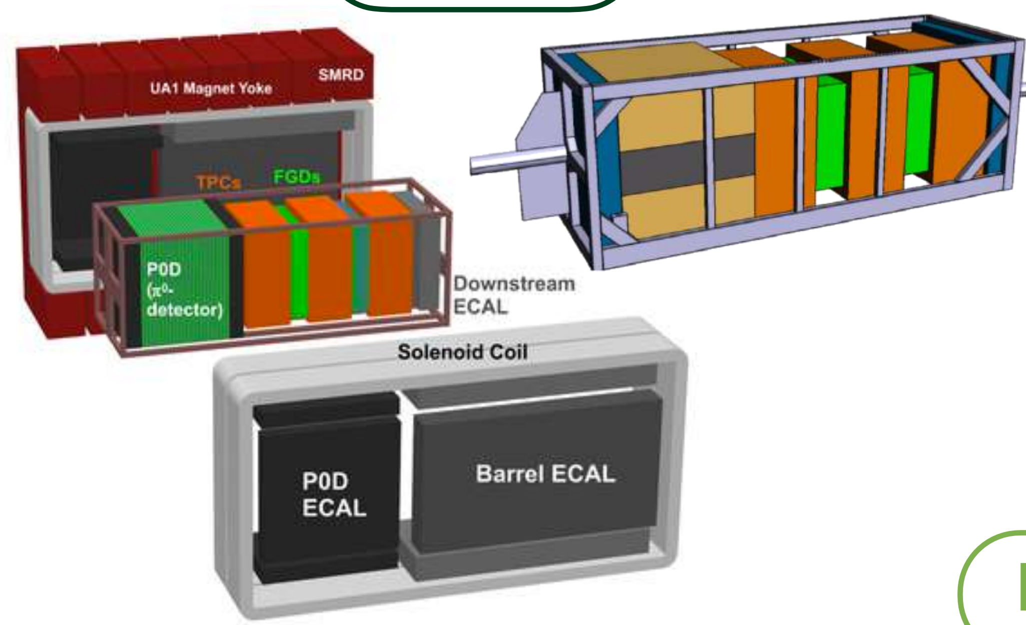


NEAR/INTERMEDIATE DETECTOR SUITE

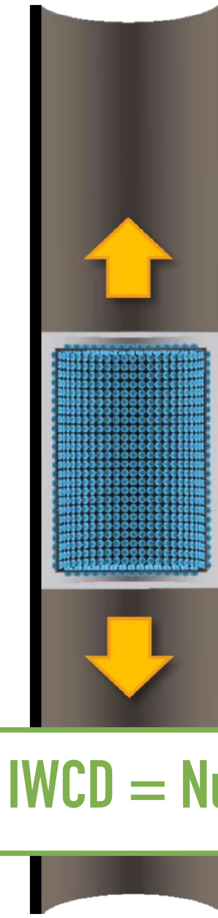
ND280 → ND280 upgrade for T2K → ?? for HK



On-axis detector (INGRID)



Off-axis magnetized tracker



E61 = IWCD = NuPRISM !

Off-axis spanning intermediate water-Cherenkov detector (IWCD)

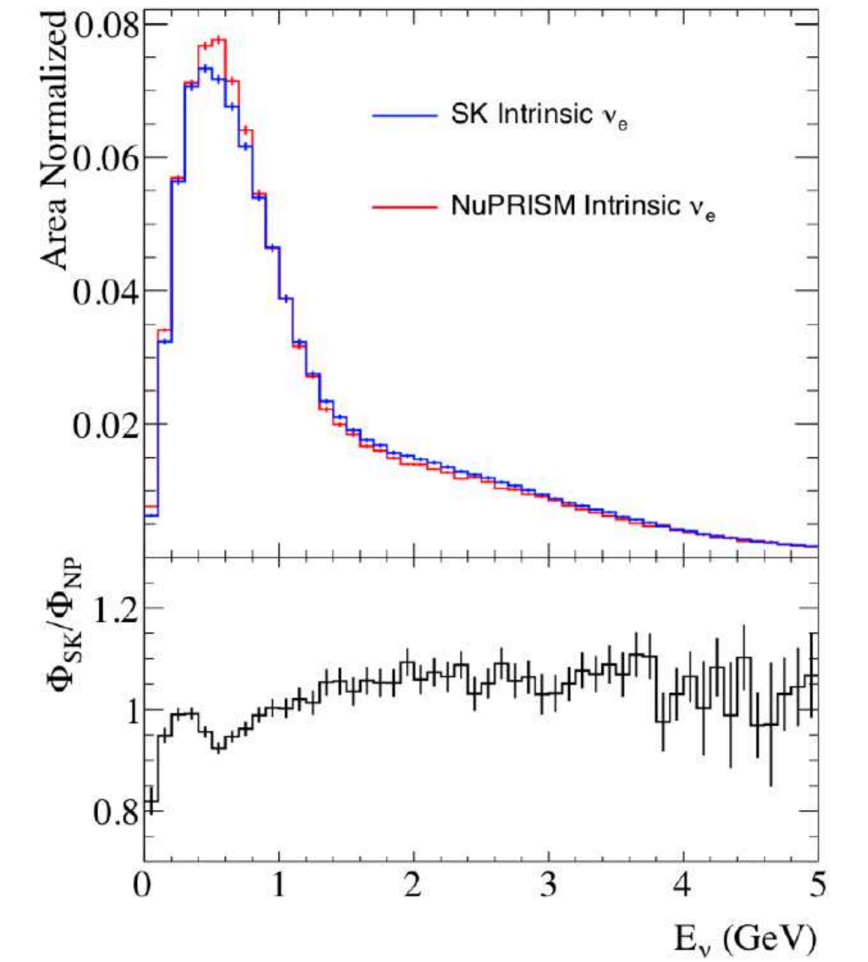
- On-axis detector: monitors beam direction and event rate.
- Off-axis magnetized tracker: charge separation to measure wrong-sign background, flux constraint, and study of recoil system.
- Off-axis angle spanning water-Cherenkov detector: intrinsic backgrounds, electron neutrino cross sections, neutrino energy versus observables, $H_2 0$ target, neutron multiplicity measurement.

CONTROLLING BACKGROUNDS FOR CPV MEASUREMENT

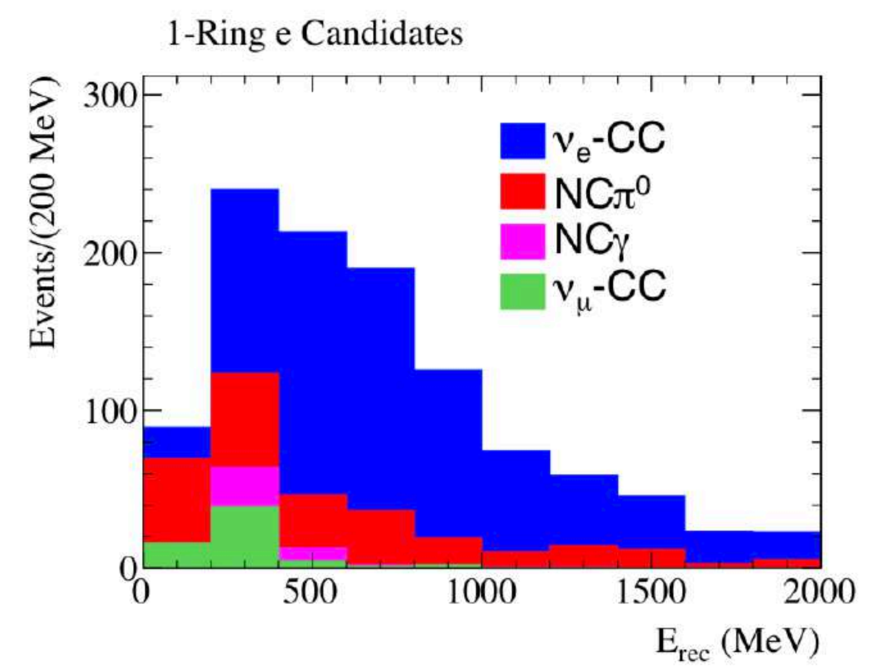
- Electron (anti)neutrino sample composition:

	Neutrino Candidates	Antineutrino Candidates
Signal	80%	62%
Wrong-sign Background	1%	11%
Intrinsic electron (anti)neutrino & NC	19%	27%

- Aiming for a 1% systematic error contribution from the wrong-sign and intrinsic electron (anti)neutrino and NC background.
- Wrong-sign background must be measured with 9% accuracy.
    - Can be achieved with a magnetized tracking detector.
- Intrinsic electron (anti)neutrino and NC background must be measured with 3% accuracy.
    - Achieved by intermediate water-Cherenkov detector.

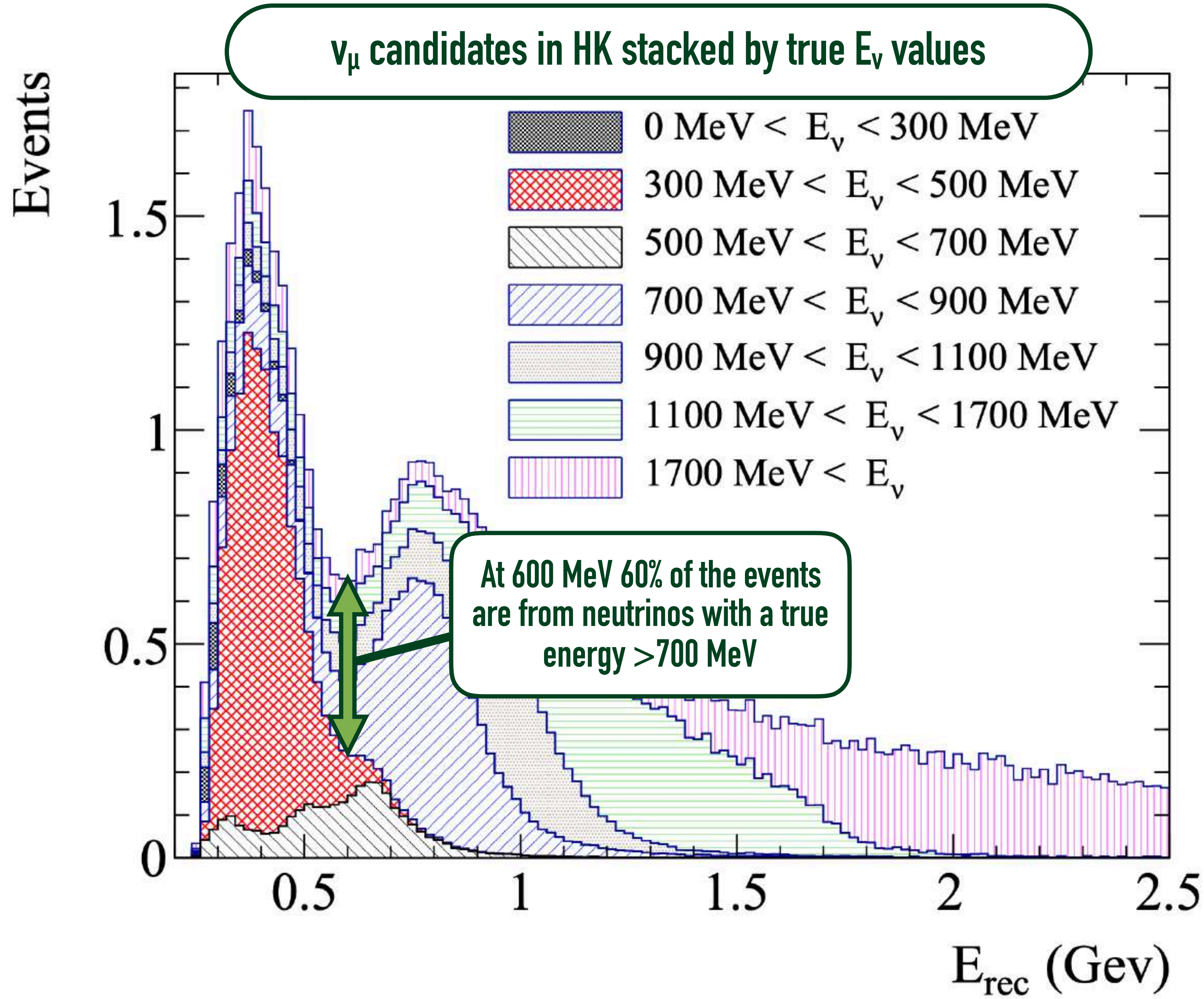


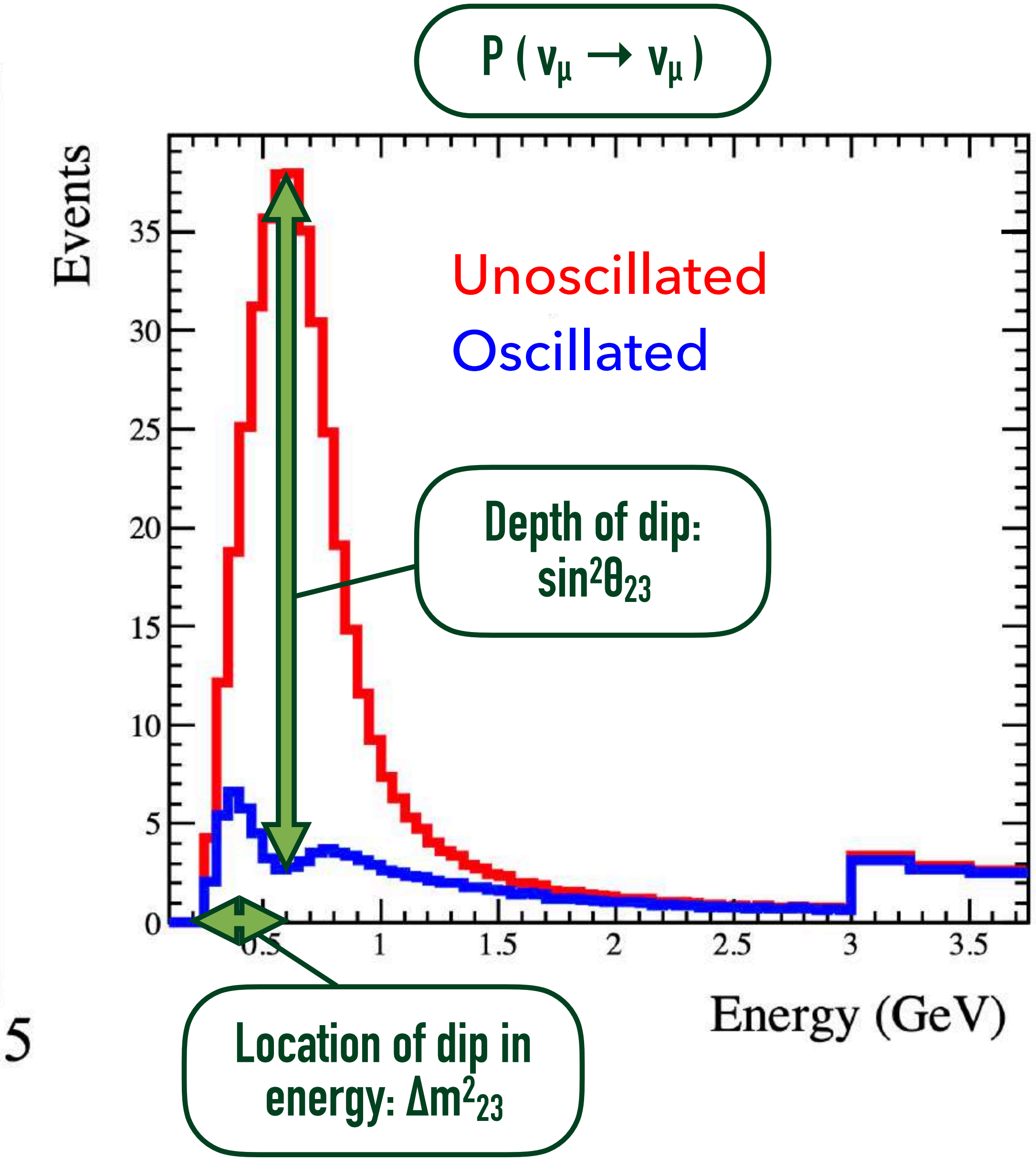
Spectra for intrinsic background at E61 and Hyper-K



Intrinsic one-ring electron background

NEUTRINO INTERACTION MODEL UNCERTAINTY

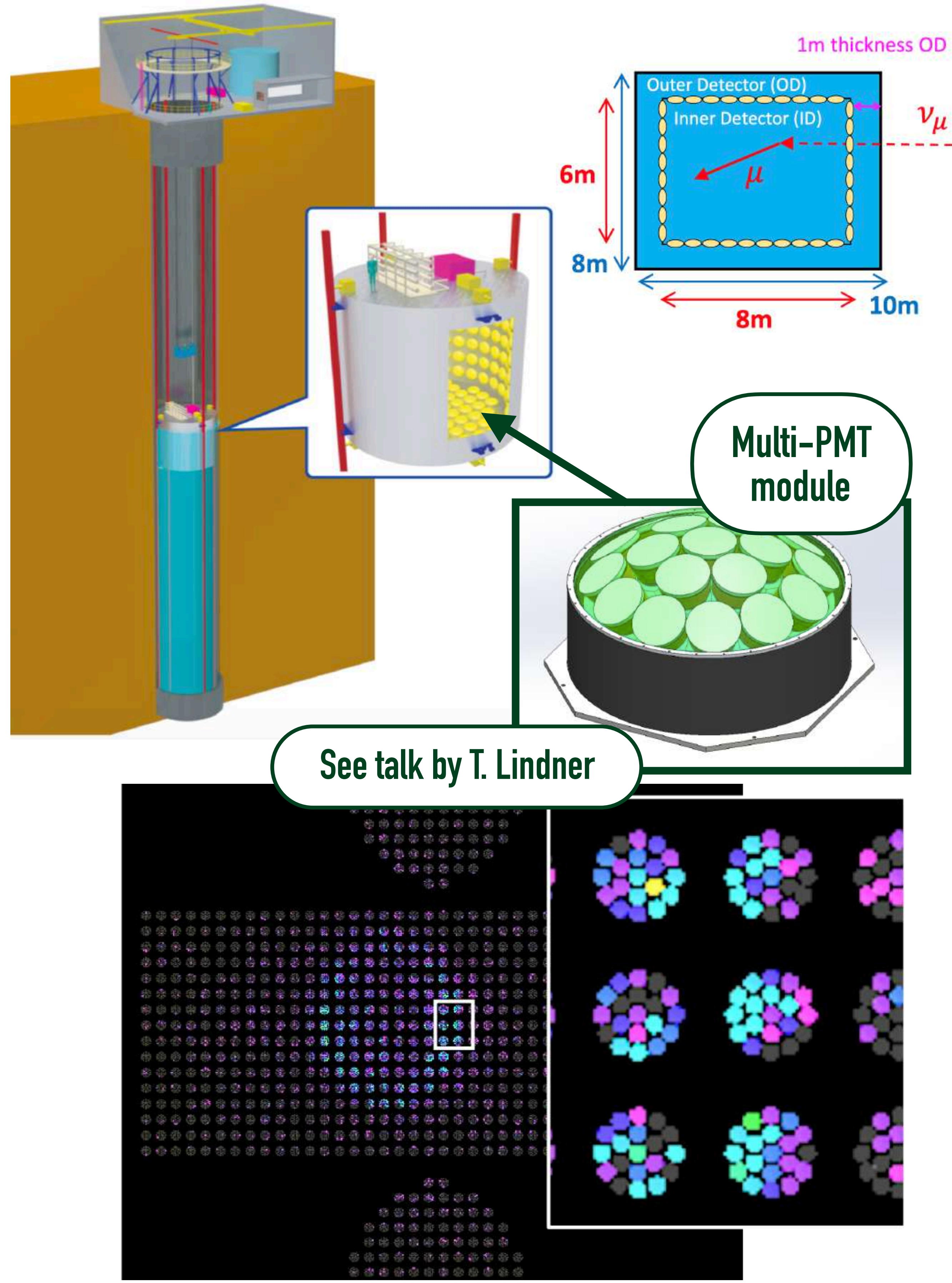




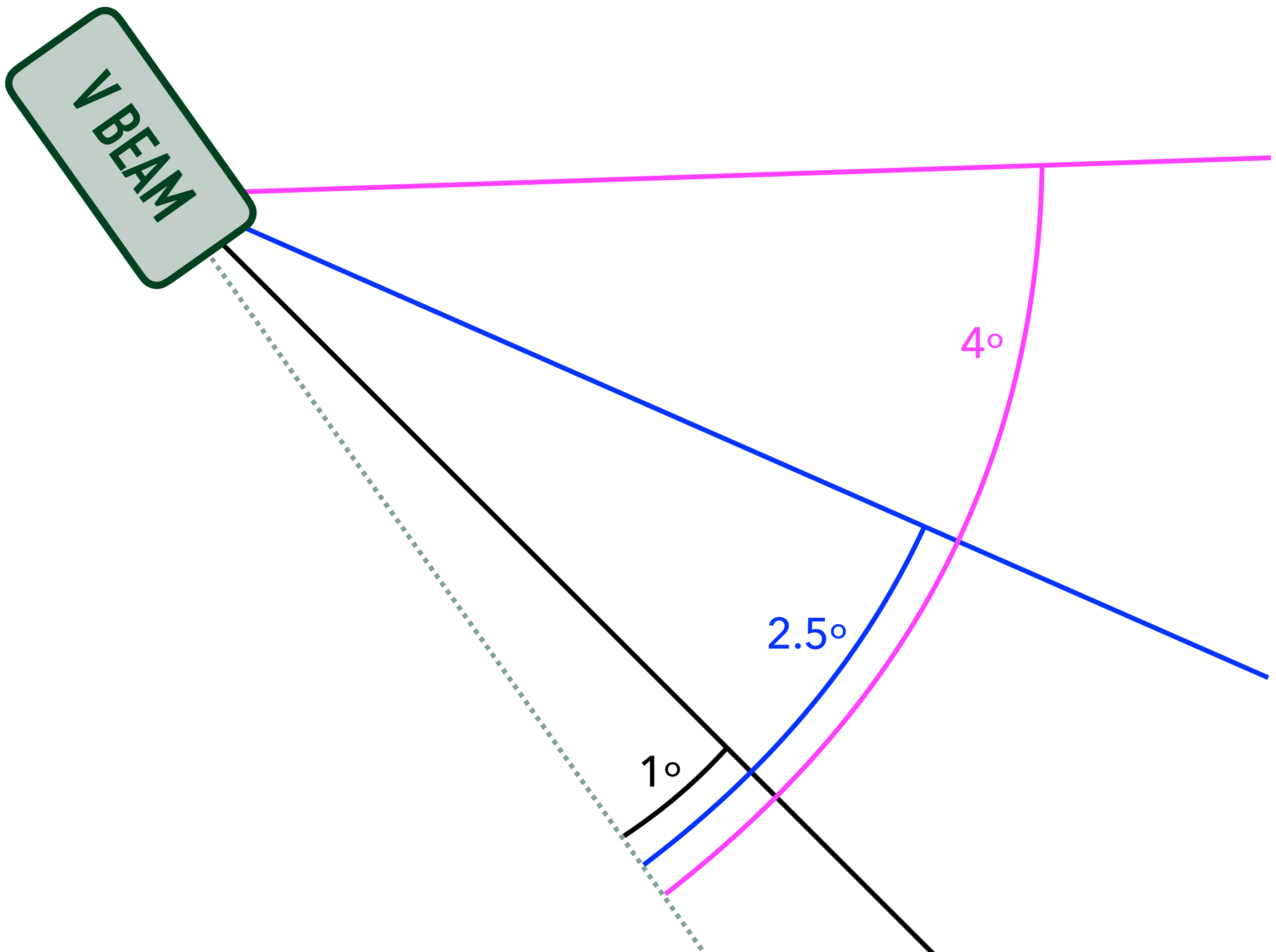
- We rely on a neutrino interaction model to reconstruct the neutrino energy from the final state lepton kinematics.
- Non-CCQE processes tend to feed-down to lower neutrino energies.
  - In the muon neutrino and antineutrino analyses this feed-down fills the region of the oscillation maximum and can bias the measurement if not properly modelled.
- Need 5% precision on measurement of feed-down to achieve 3.5% error on $\sin^2\theta_{23}$.

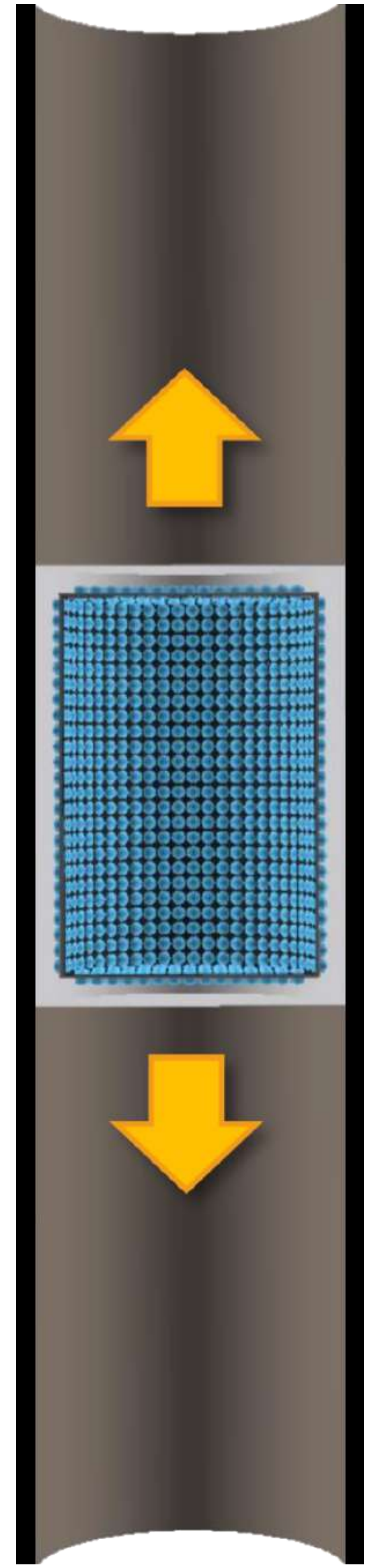
THE E61 DETECTOR

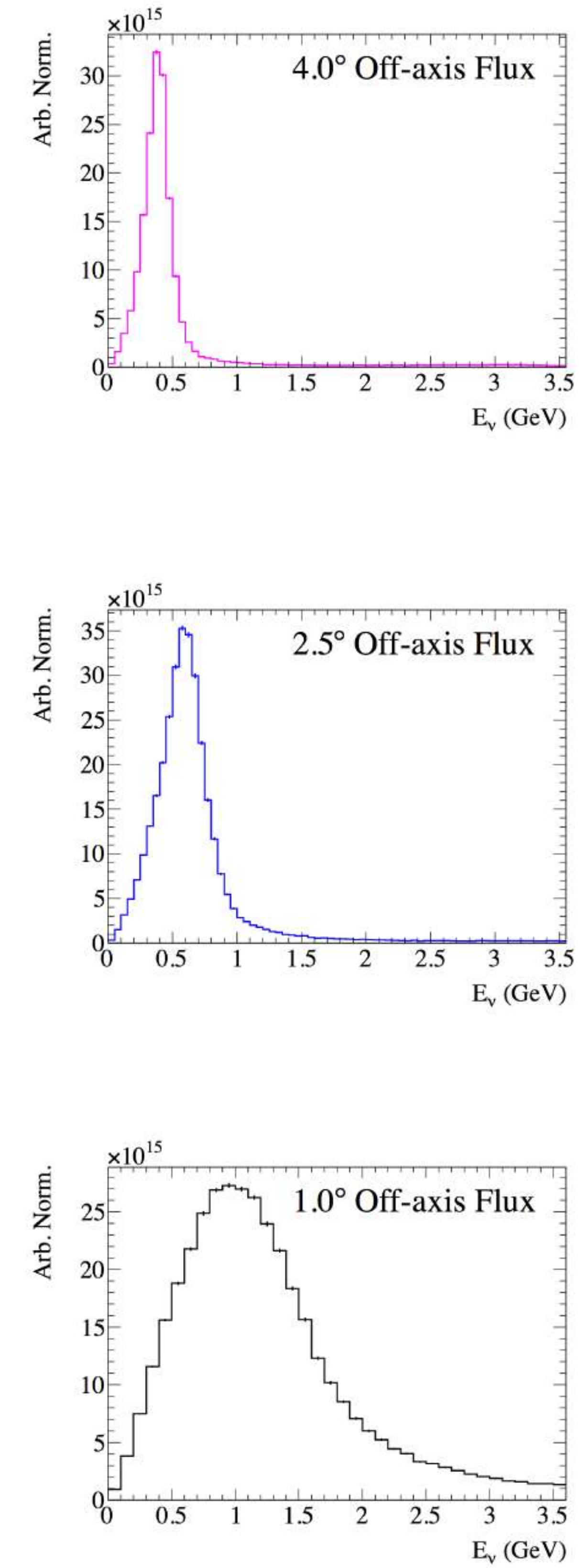
- An intermediate water-Cherenkov detector.
  - Same nuclear target as the far detector.
  - Smaller near to far extrapolation systematic.
- Instrumented portion of the detector moveable through deep cylindrical chamber.
  - Samples neutrino interactions from the J-PARC neutrino beam in the 1-4 degrees off-axis angle range.
- Has optically separated inner and outer volumes.
  - Inner detector: 8 m diameter, 6 m tall.
  - Outer detector: 10 m diameter, 8 m tall.
  - Contains up to 1 GeV muons.
- Tank is populated with multi-PMT (mPMT) modules.
  - Improves resolution of Cherenkov ring.
- Gadolinium doping (0.1% by weight) to measure neutron production in neutrino interactions.



E61 CONCEPT







- Neutrinos produced by pion decays.
  - Higher energy spectrum for more forward going neutrinos.
- Reduction in flux uncertainty from EMPHATIC experiment.

See talk by M. Pavin

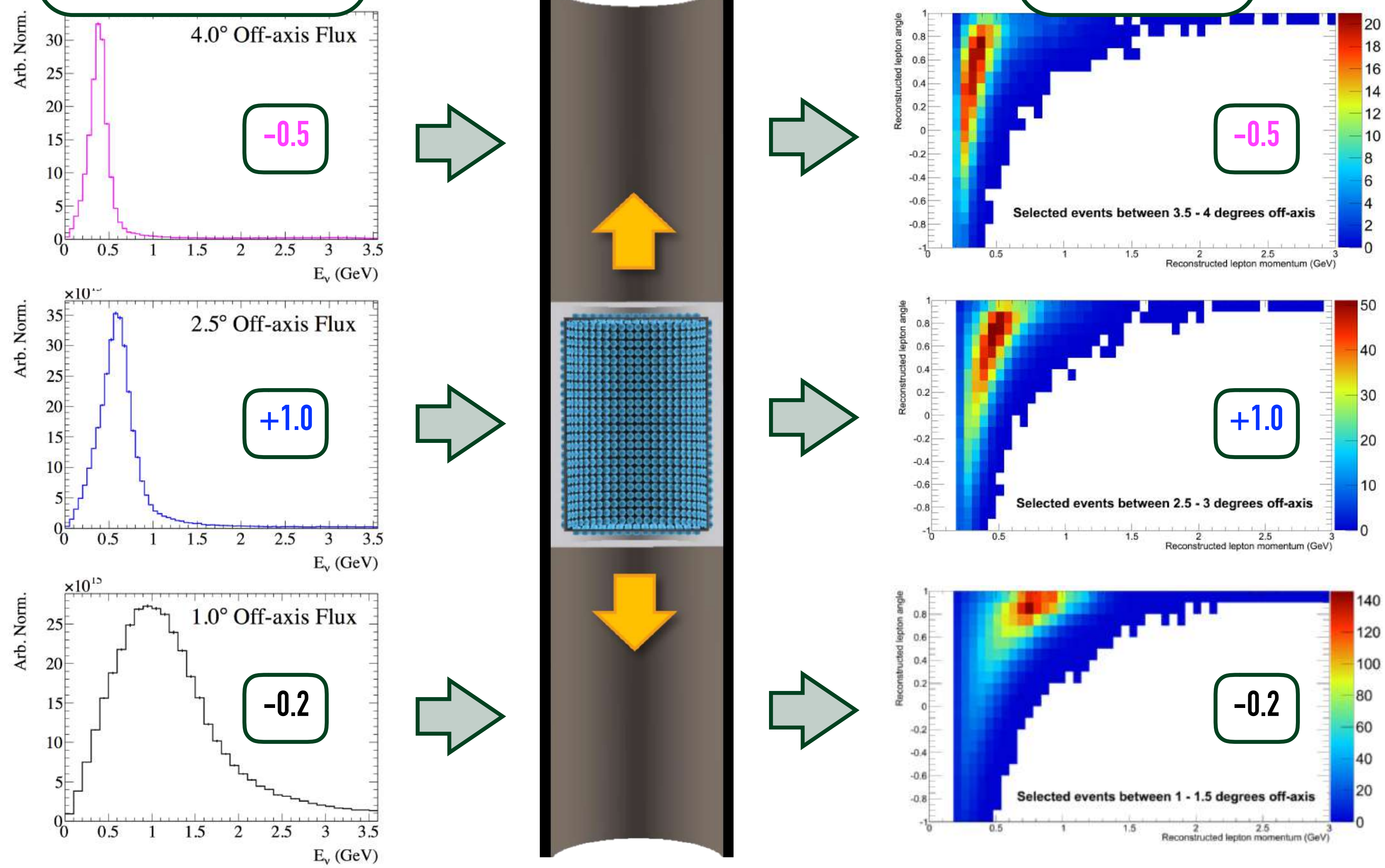
LINEAR COMBINATION ANALYSIS

Use off-axis angle dependence of ν flux:

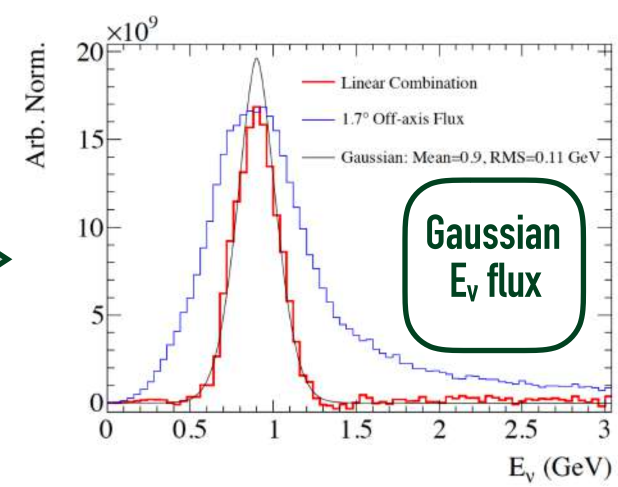
1. Bin E_ν flux spectrum into 60 different off-axis angle slices.
2. Take linear combinations of off-axis angle slices to create a neutrino flux of interest e.g. Gaussian.
3. Collect distribution of observables for same off-axis angle slices.

E_ν flux spectrum

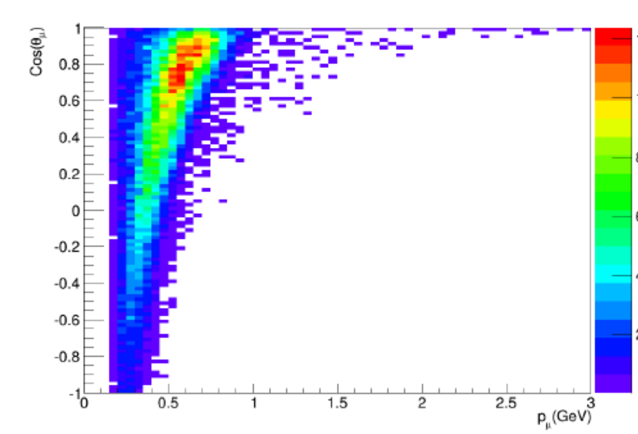
Observables



Find linear combinations for desired neutrino flux distribution.

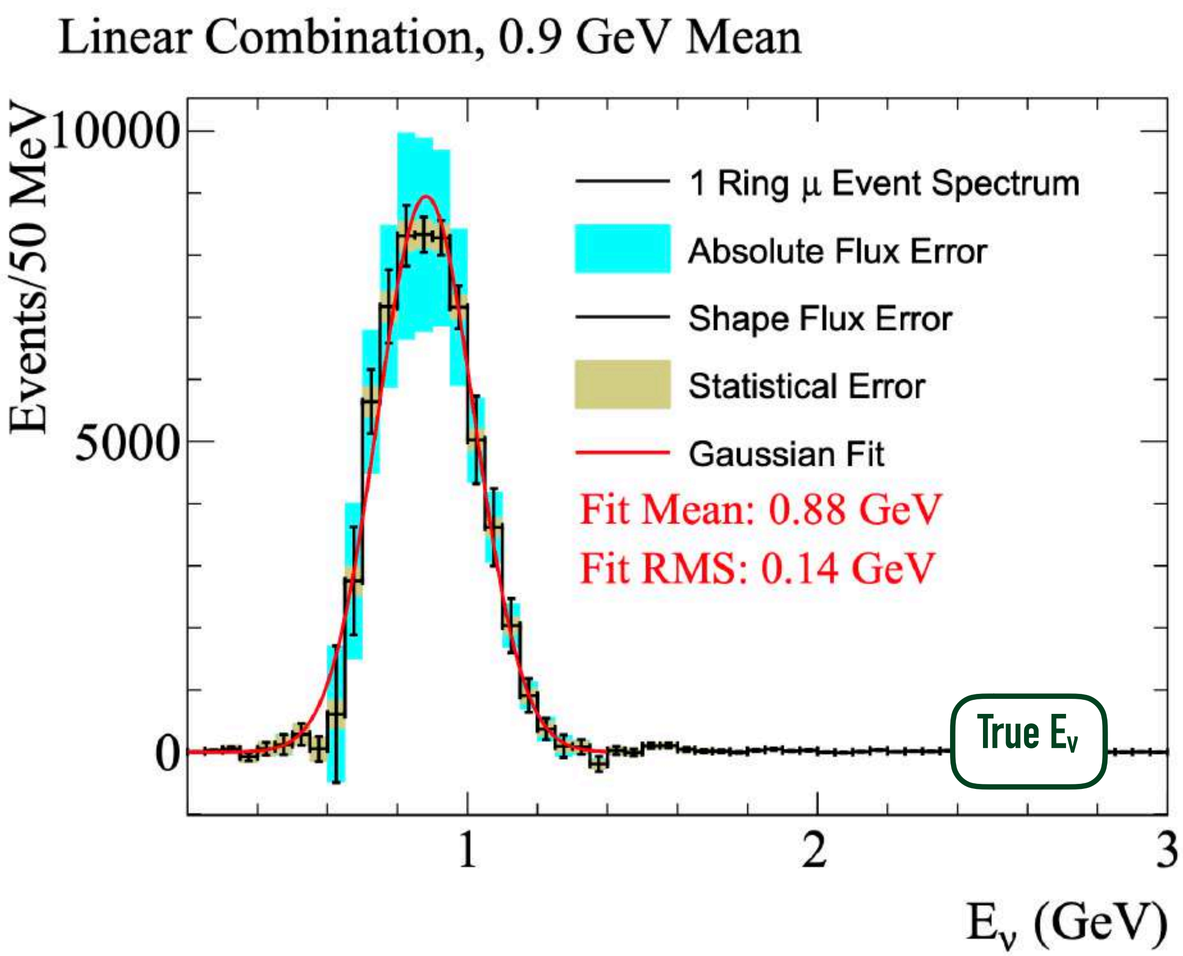


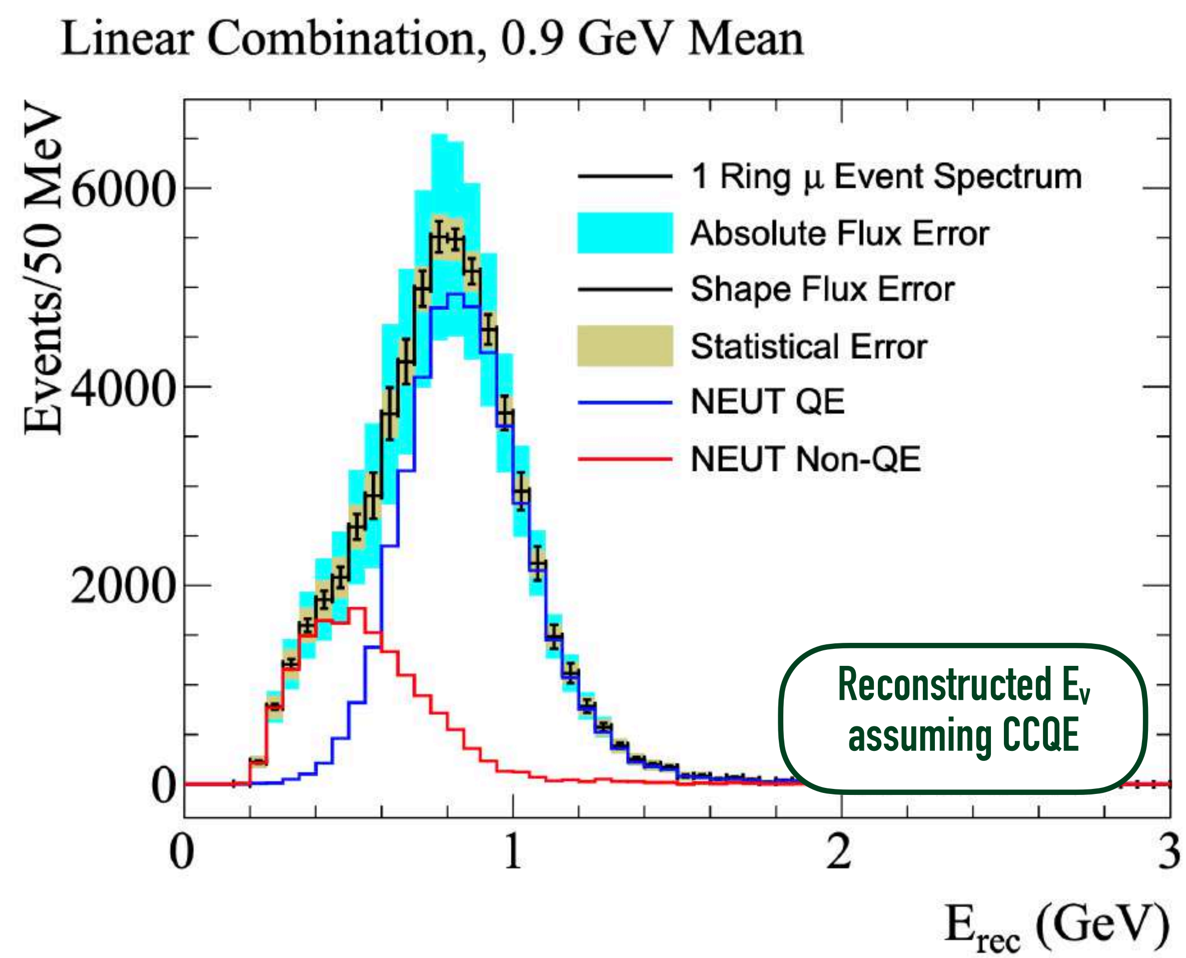
Apply coefficients to distribution of observables.



PSEUDO-MONOCHROMATIC BEAMS

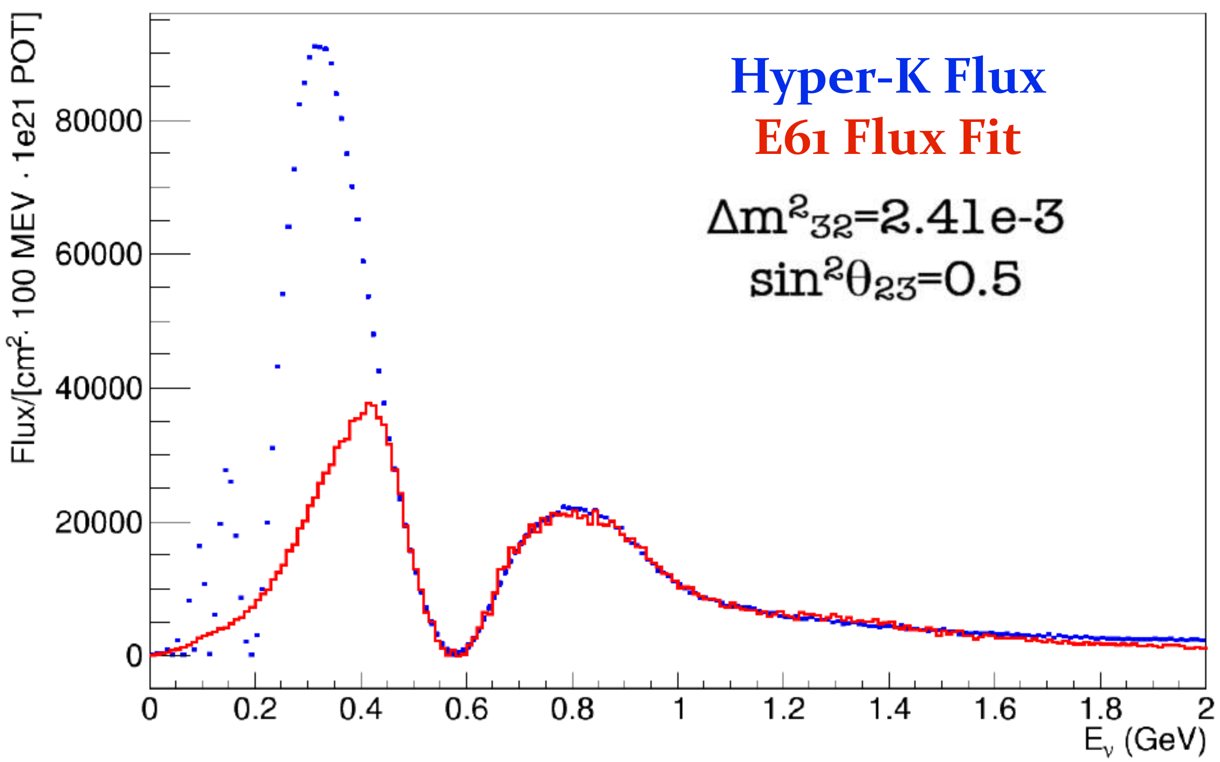
- Energy distribution for single muon candidate events after applying linear coefficients for a monochromatic beam centred at 0.9 GeV.

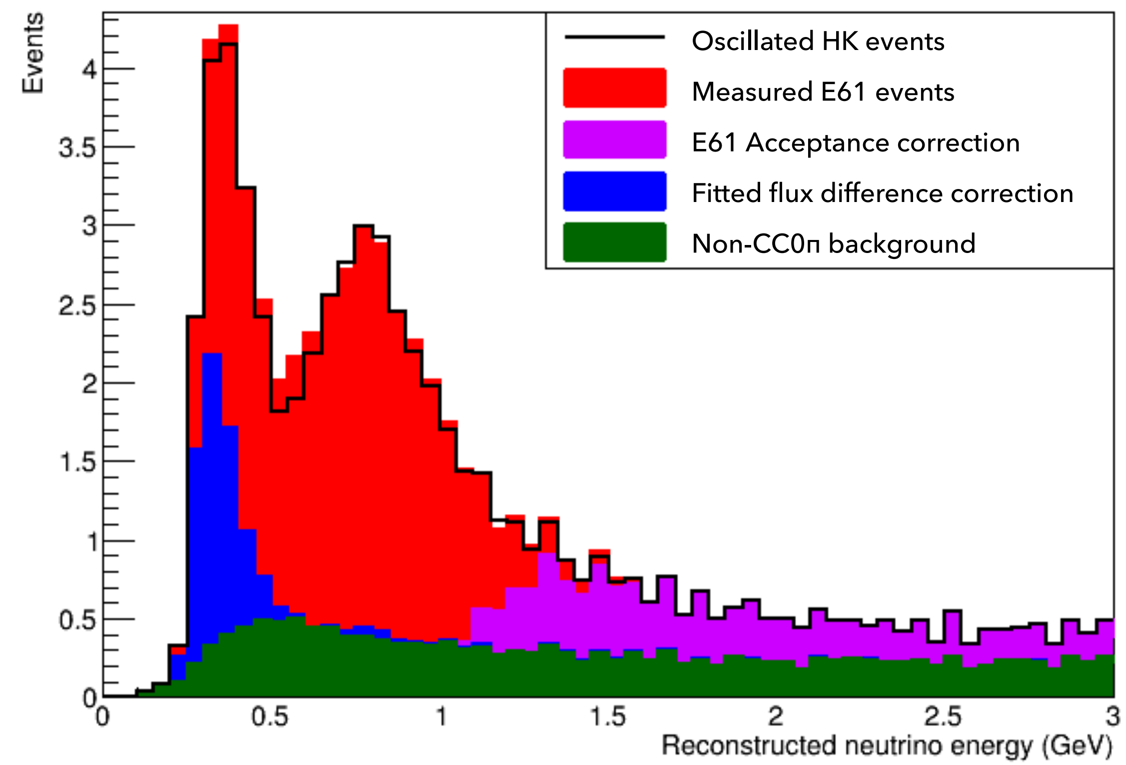




- Can observe the separation of CCQE and non-CCQE (including multi-nucleon) scatters.
  - Directly predict the effect of non-CCQE scatters in oscillation measurements and provide a unique constraint on nuclear models.
- Measure cross sections as function of true neutrino energy.
- Measure cross sections vs true observables Q^2 and ω - variables controlling interaction mode.

MUON NEUTRINO DISAPPEARANCE

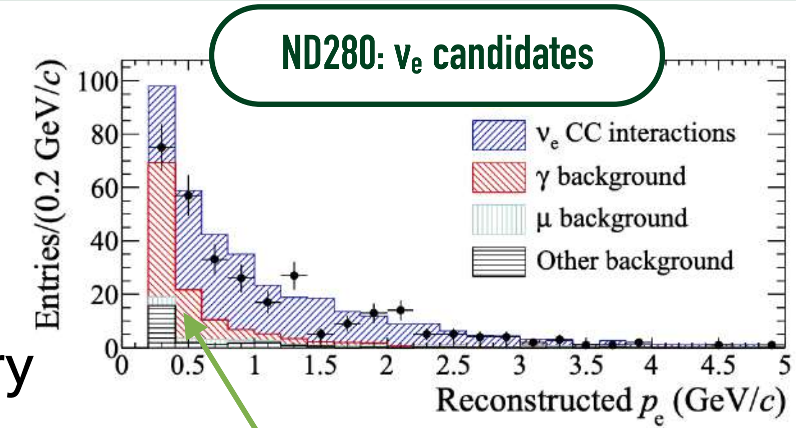


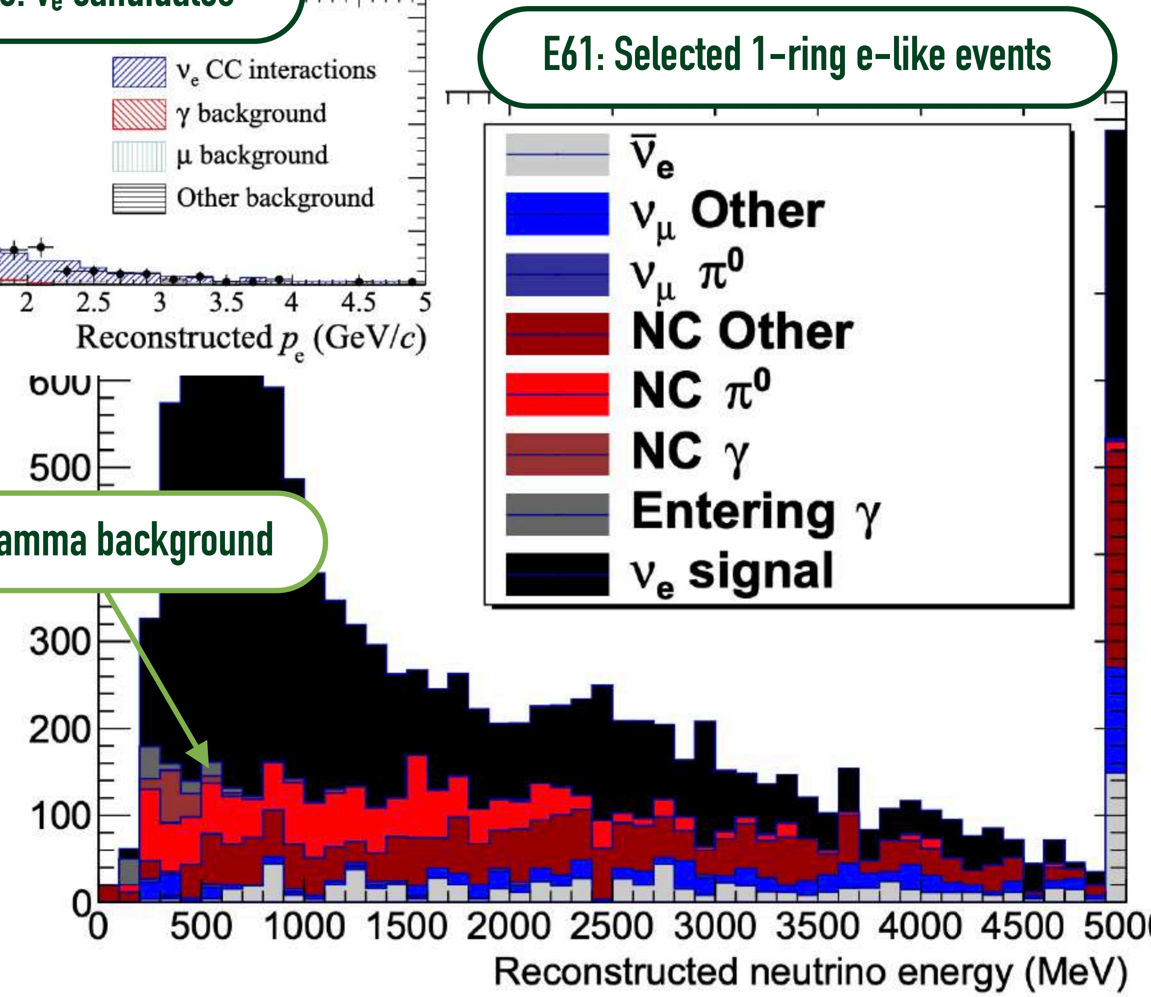


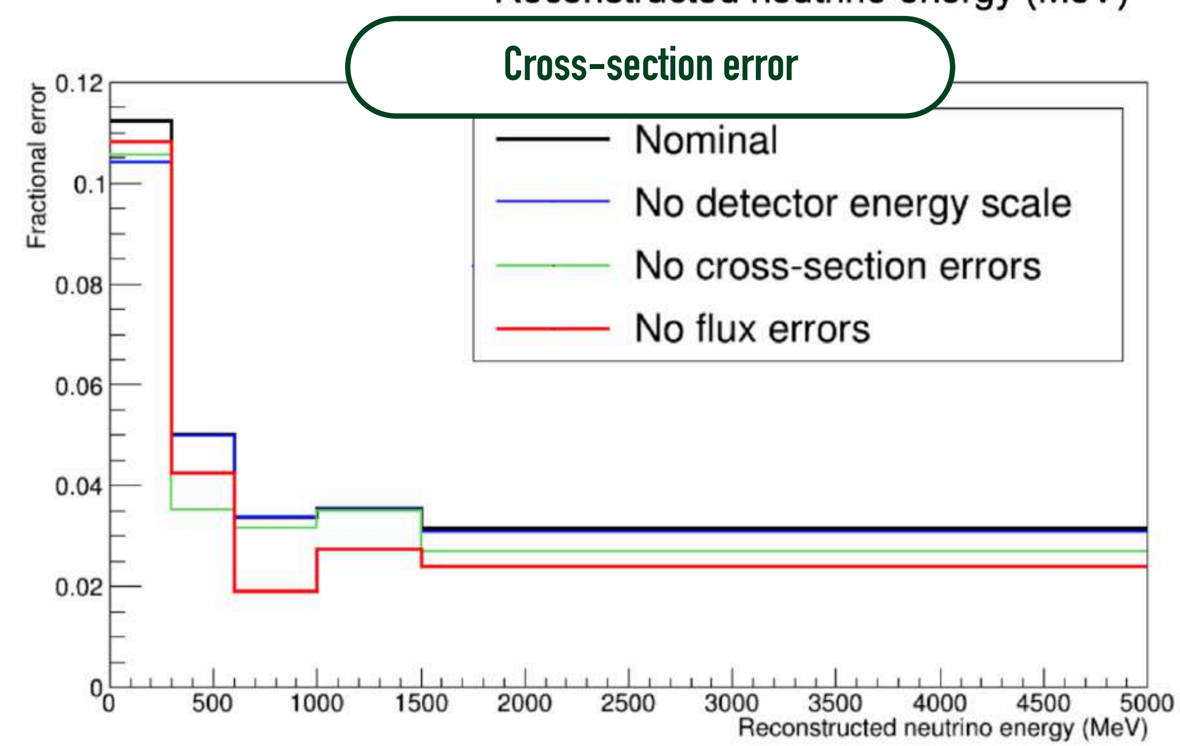
- Use linear combinations to produce the oscillated far detector neutrino flux between 400 MeV and 1 GeV.
- For each oscillation hypothesis to test, we can find a linear combination of the E61 off-axis fluxes to give the oscillated spectrum.
- Directly compare E61 muon p-theta prediction to observed HK events to obtain oscillation parameters.
- E61 and HK have the same interaction material - same interaction cross-section.
  - Reduced dependence on the cross-section model and sensitivity to wrong model choice.
- Background, flux, and acceptance corrections are necessary for HK prediction.
  - Significant uncertainty cancellation in background subtraction.

ν_e CROSS-SECTION MEASUREMENT

- Uncertainty on ν_μ to ν_e cross-section ratio contributes significantly to total error on CP violation measurement.
    - Current uncertainty of 3% is theory motivated. PRD86 (2012) 053003
- Relative ν_e flux increases with off-axis angle.
    - Can make a direct measurement of the ν_e cross section on water with E61.
- Active shielding significantly reduces gamma background.
- In momenta of interest for HK expect a 2% statistical uncertainty, with total uncertainty of <4%.
- Systematic uncertainties dominated by flux and cross section.
    - Expect reduction in uncertainty from improved external flux measurements (EMPHATIC) and cross-section modelling from E61 mono-energetic beam technique.

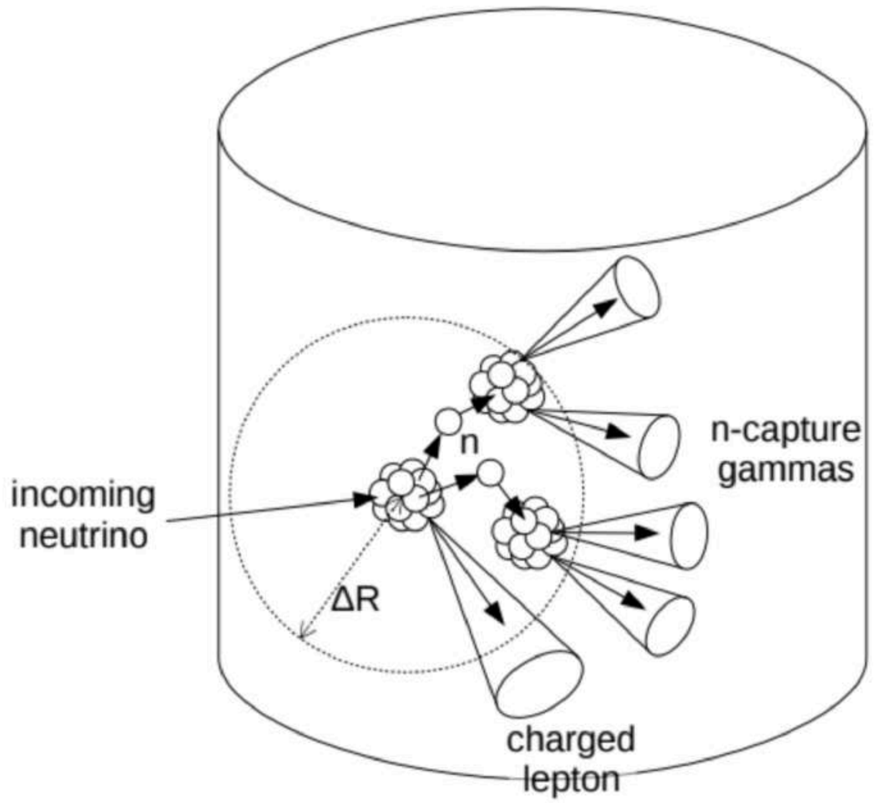


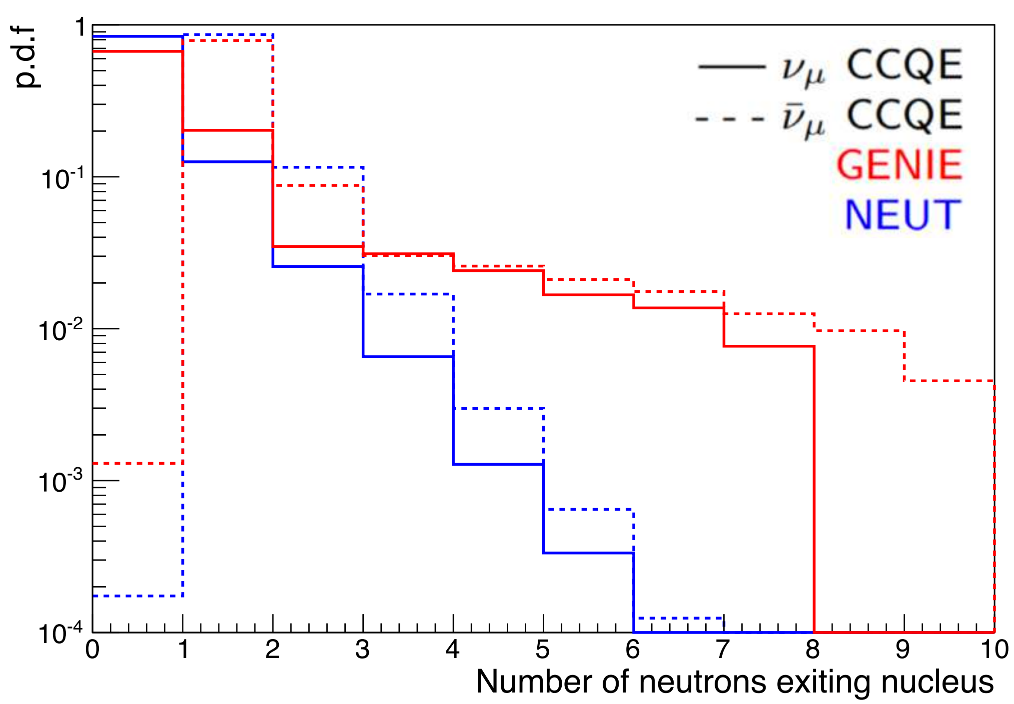




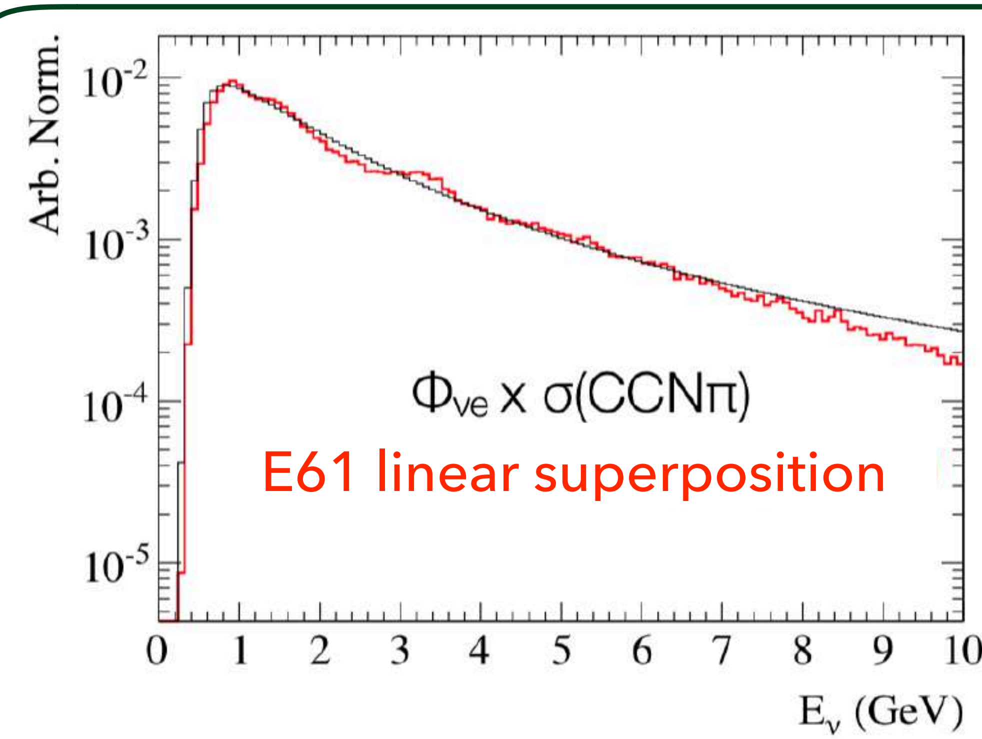
GADOLINIUM LOADING

- Gadolinium has a high neutron capture cross section.
    - Captures produce ~8 MeV photon cascade.
- Measurement of neutron multiplicity in order to statistical separate ν/anti-ν interactions.
    - Separate atmospheric neutrino samples.
    - Reduce wrong-sign background for beam samples.
- Can measure the $\mu^+\pi^0$ background from neutrino interactions to improve the $p \rightarrow e^+\pi^0$ proton decay search.
    - Simulation including neutron backgrounds shows 75% tagging efficiency with 92% purity can be achieved.





Significant differences between GENIE and NEUT neutron models



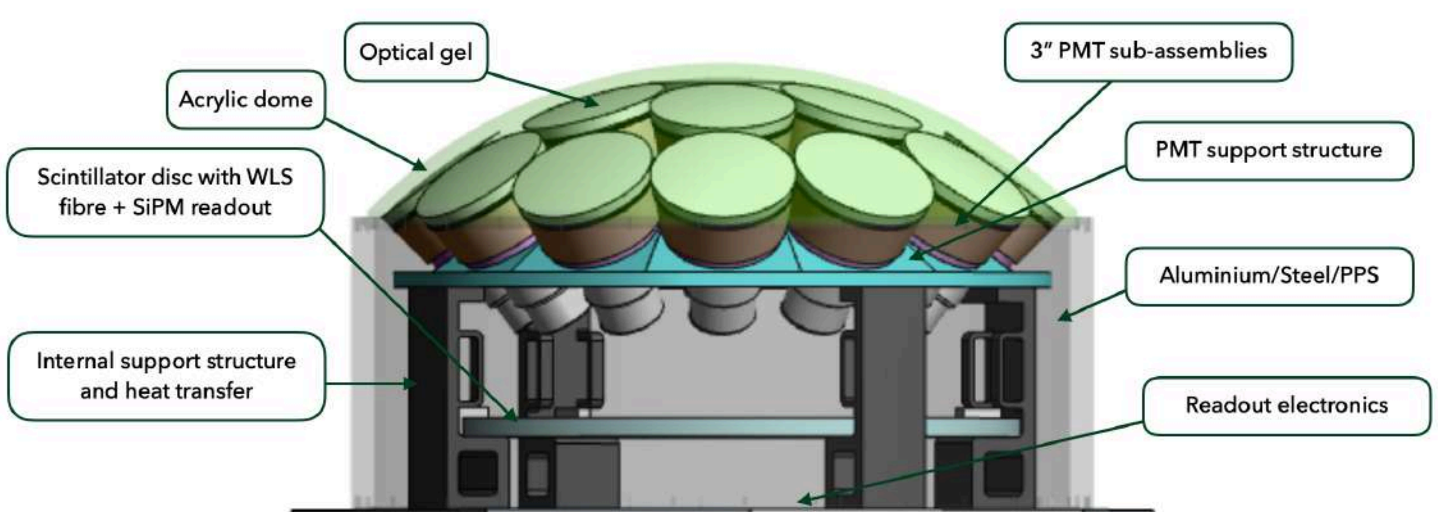
Directly measure $\mu^+\pi^0$ background with E61

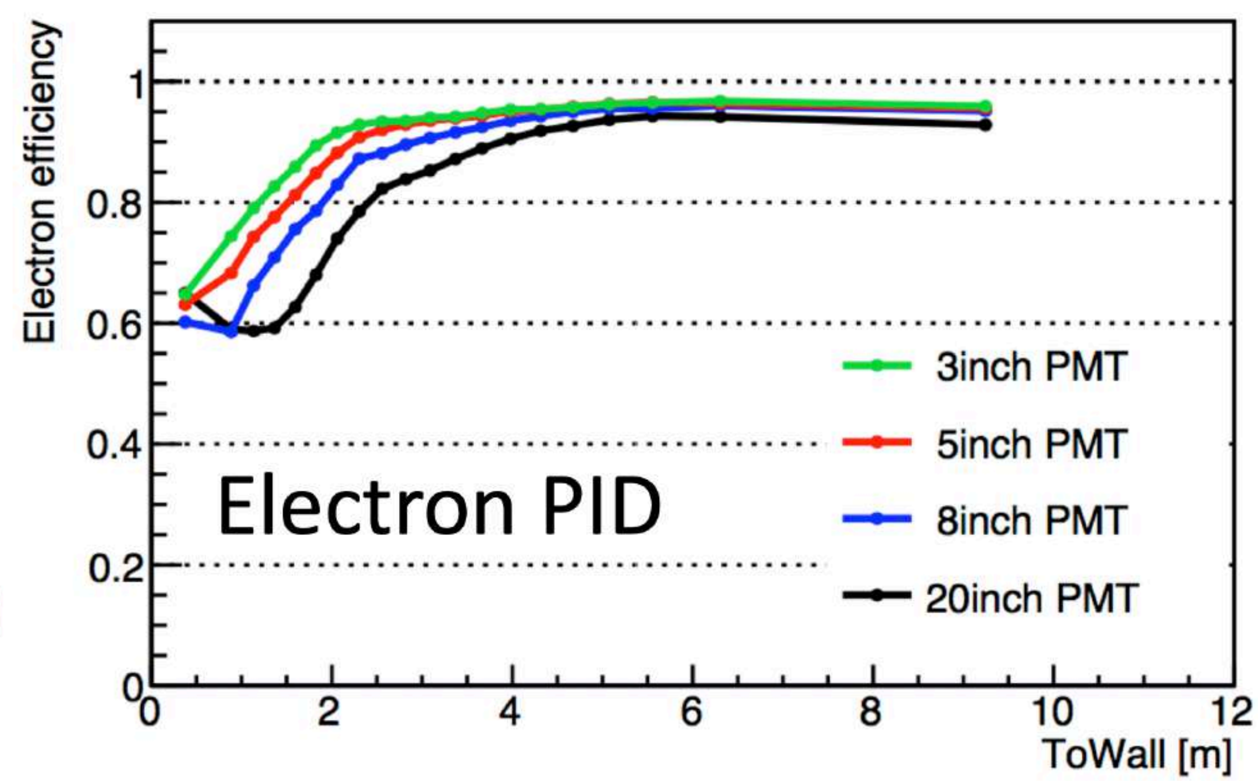
MULTI-PMT (MPMT) R&D

- Modular approach to PMT instrumentation.
  - Array of small (~3″) PMTs rather than one large one.
    - Finer granularity of Cherenkov image.
  - Directional information as each PMT images a different part of the tank - improved vertex resolution.
  - Waterproofing, pressure protection, reduced cabling.
  - Readout electronics, monitoring, calibration devices located in vessel.
- Leveraging lessons learned from KM3NeT.

See talk by T. Lindner

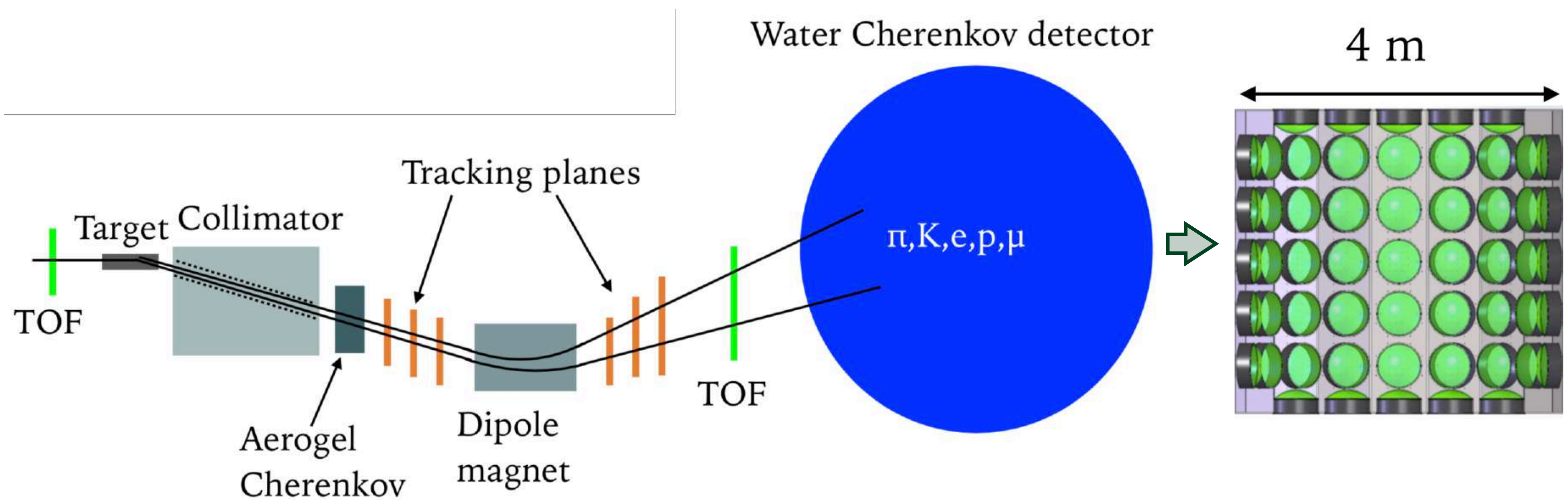
KM3NET LOI: https://arxiv.org/abs/1601.07459





E61 TEST BEAM EXPERIMENT

- Planning for an initial stage prototype experiment in a charged particle test beam.
  - Known particle type, momentum, track start point.
  - Beam momenta down to ~140 MeV/c are the goal.
  - In discussions with CERN.
- Goals:
  - Test critical components for full E61.
  - Prove bottom-up calibration of WC detector to 1% level.
  - Measure physics processes, such as Cherenkov light profile and pion scattering.
- Aim for data taking in 2021.



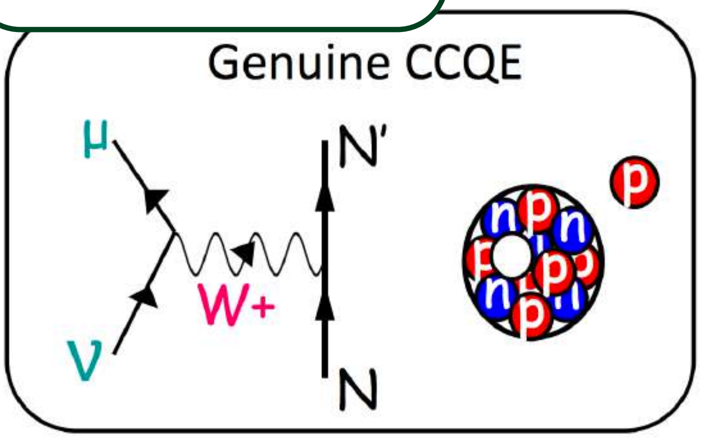
SUMMARY

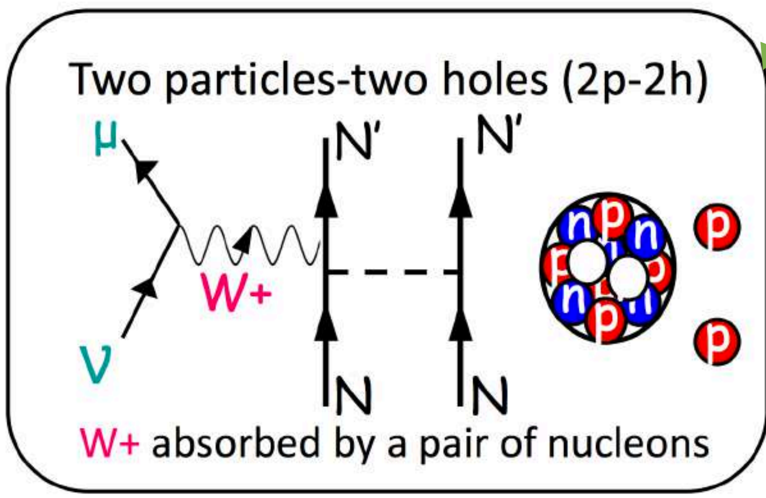
- Future long-baseline oscillation experiments, such as Hyper-K, will be dominated by systematic rather than statistical uncertainty.
  - Feed down effects from unobserved interaction products can bias measurements if not accurately modelled.
  - Difficult to constrain with traditional near detectors as they are exposed to a different flux than the far detector.
  - Improvements to the systematic uncertainty from the current levels are required for a 5σ observation of CP violation by the next generation of experiments.
- E61 provides a novel data-driven method of converting E_{rec} to E_{true} using the off-axis angle linear combination technique.
  - This decouples the flux shape from the interaction model.
- Currently building a multi-PMT prototype before large scale production for a test beam experiment which will characterise the detector response to a known beam of charged particles.

BACKUP SLIDES

MEASURING NEUTRINO ENERGY

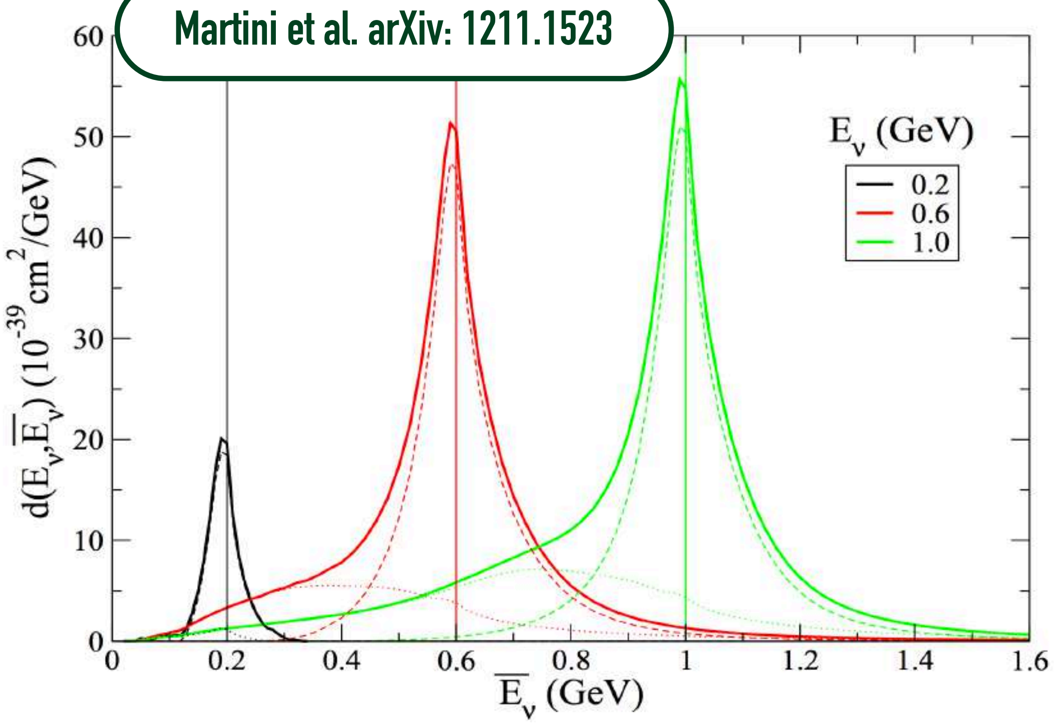
M. Martini NuFACT 2015

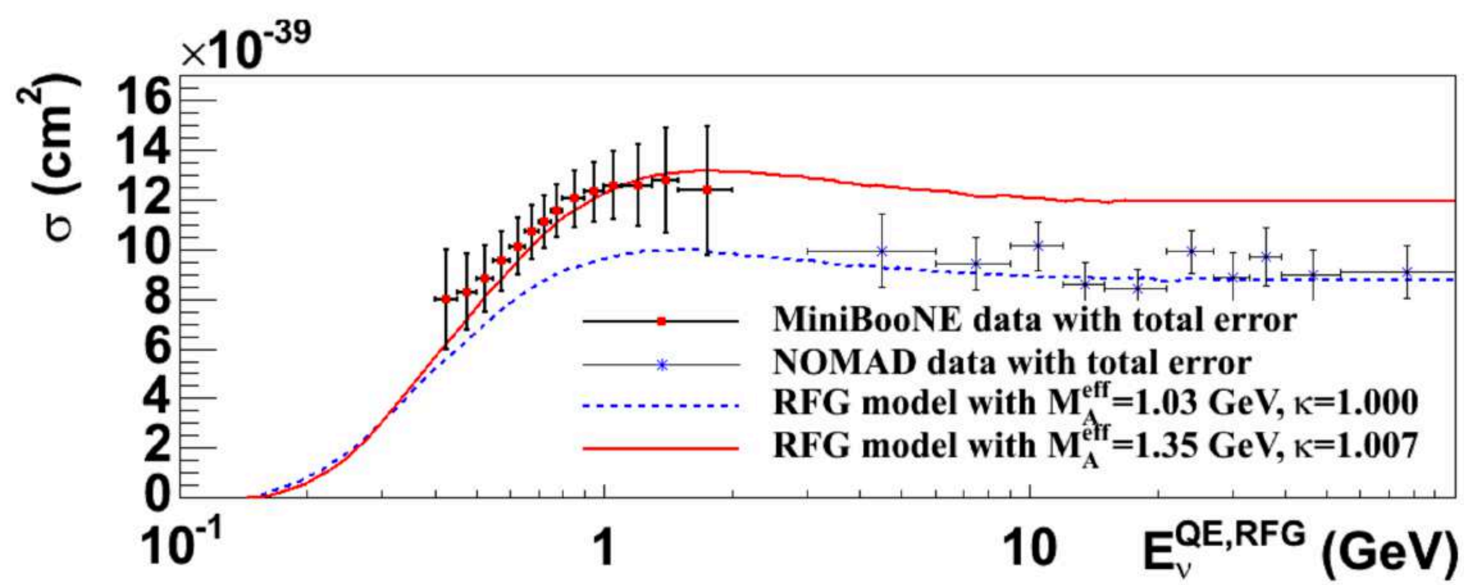




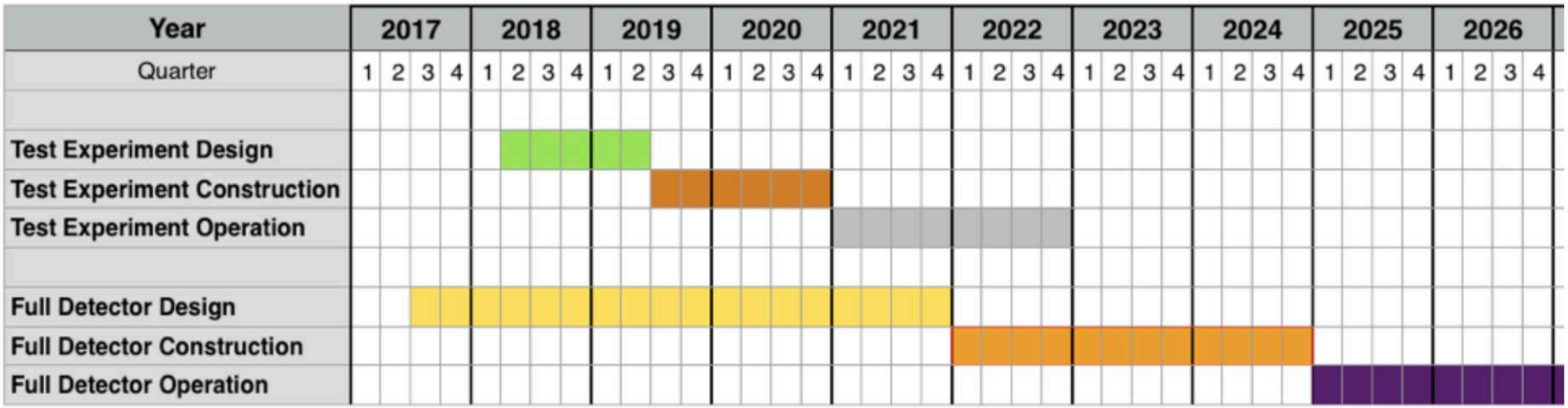
- Model assumptions play an important role in inferring neutrino energy from detected neutrino-nucleus interaction products.
- In Hyper-K charged lepton kinematics will be measured and CCQE dynamics assumed.
- Large uncertainties from final state and secondary interaction models.
  - Multi-nucleon interactions have two protons exiting a pair of nucleons.
  - Explains larger axial mass preferred by MiniBooNE over NOMAD.
  - Further missing energy from unseen pions.
- Calorimetric measurements suffer from similar model dependence.
  - For example, through uncertainties in the multiplicity of undetected neutrons.

Martini et al. arXiv: 1211.1523





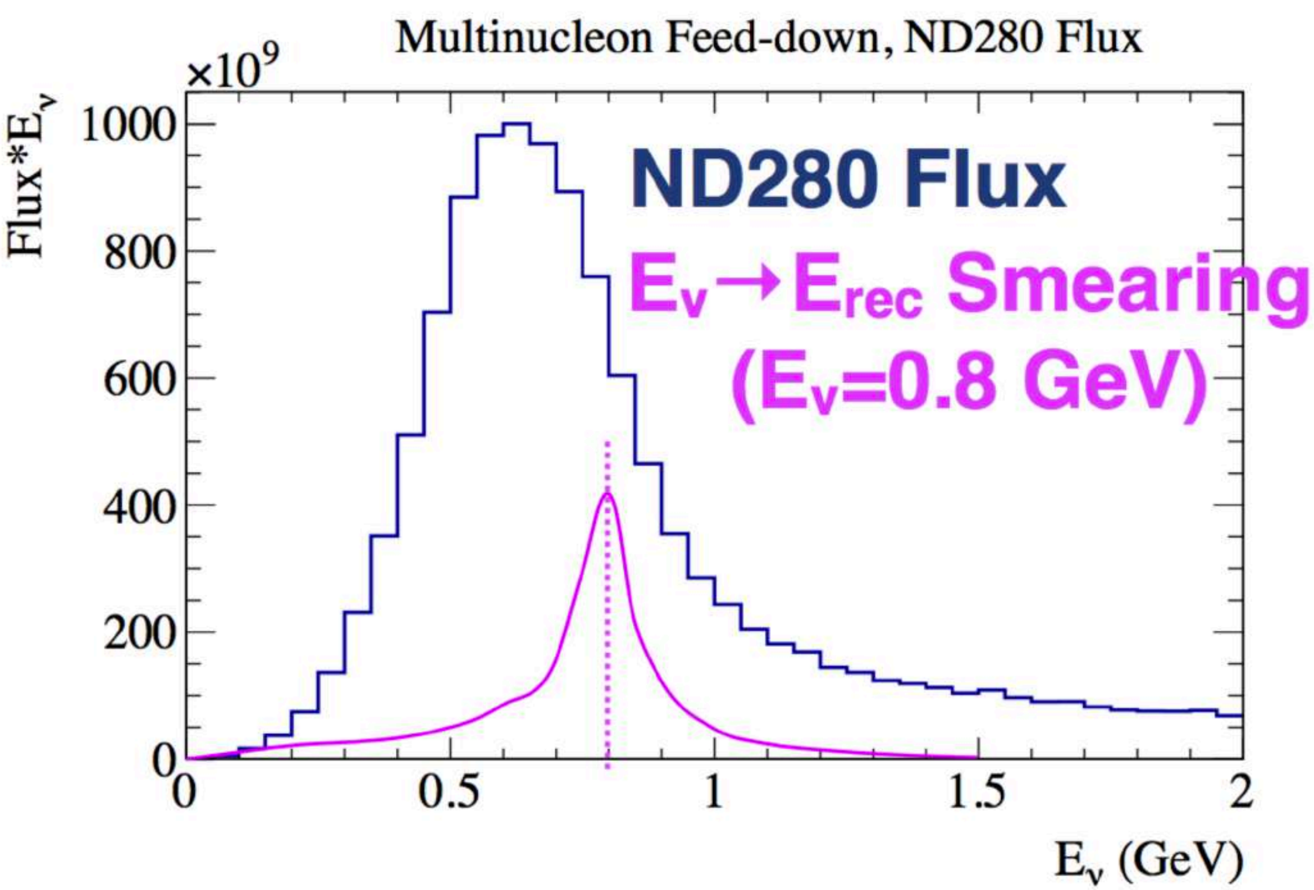
PROJECT STATUS

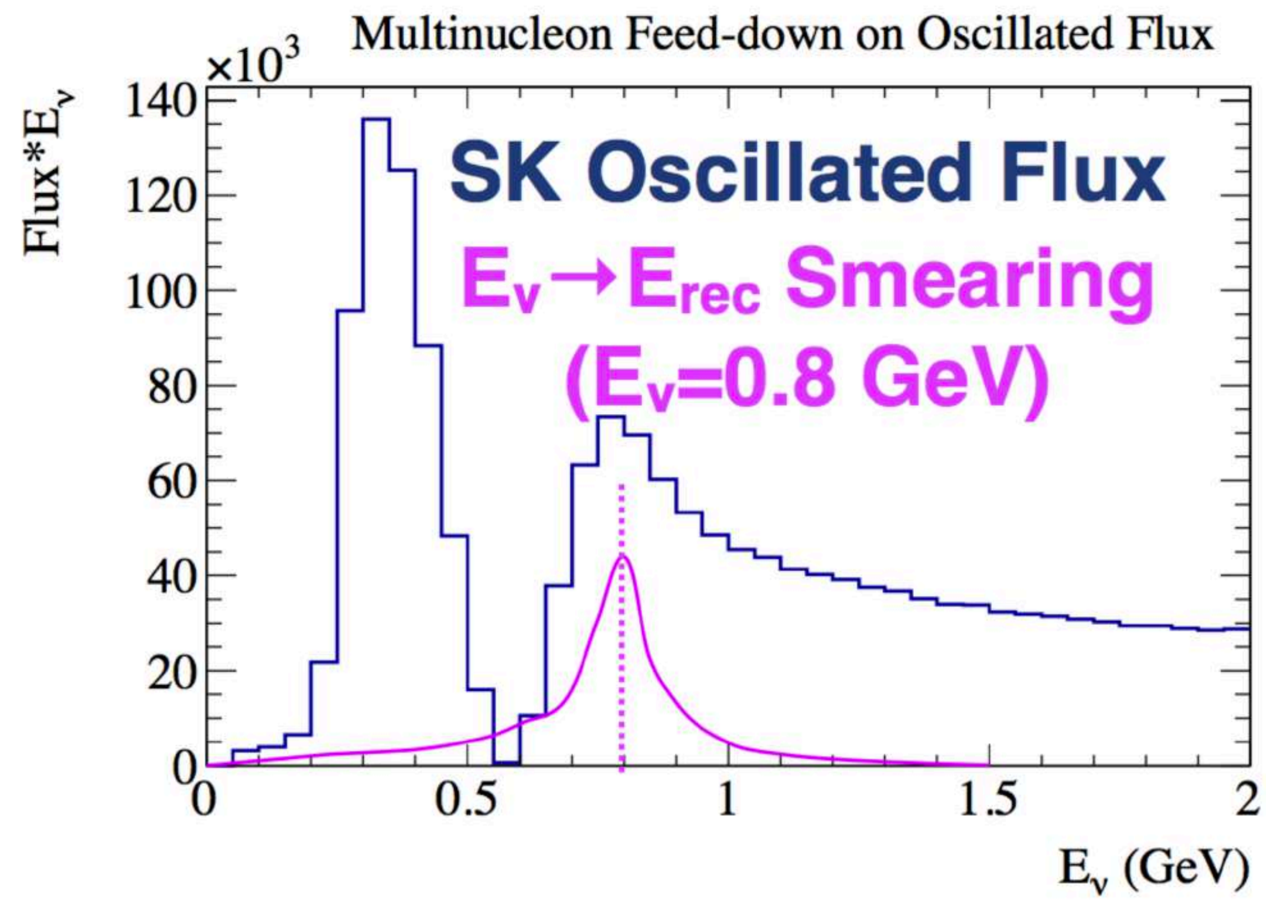


- Construction schedule is driven by multi-PMT module production.
- Aim to run the test beam experiment for two years starting 2021.
- Full-scale detector construction concurrent with test experiment operation.
- Aim for full-scale experiment to be taking neutrino data in 2025, one year before the start of Hyper-K.

NEAR DETECTOR CONSTRAINT

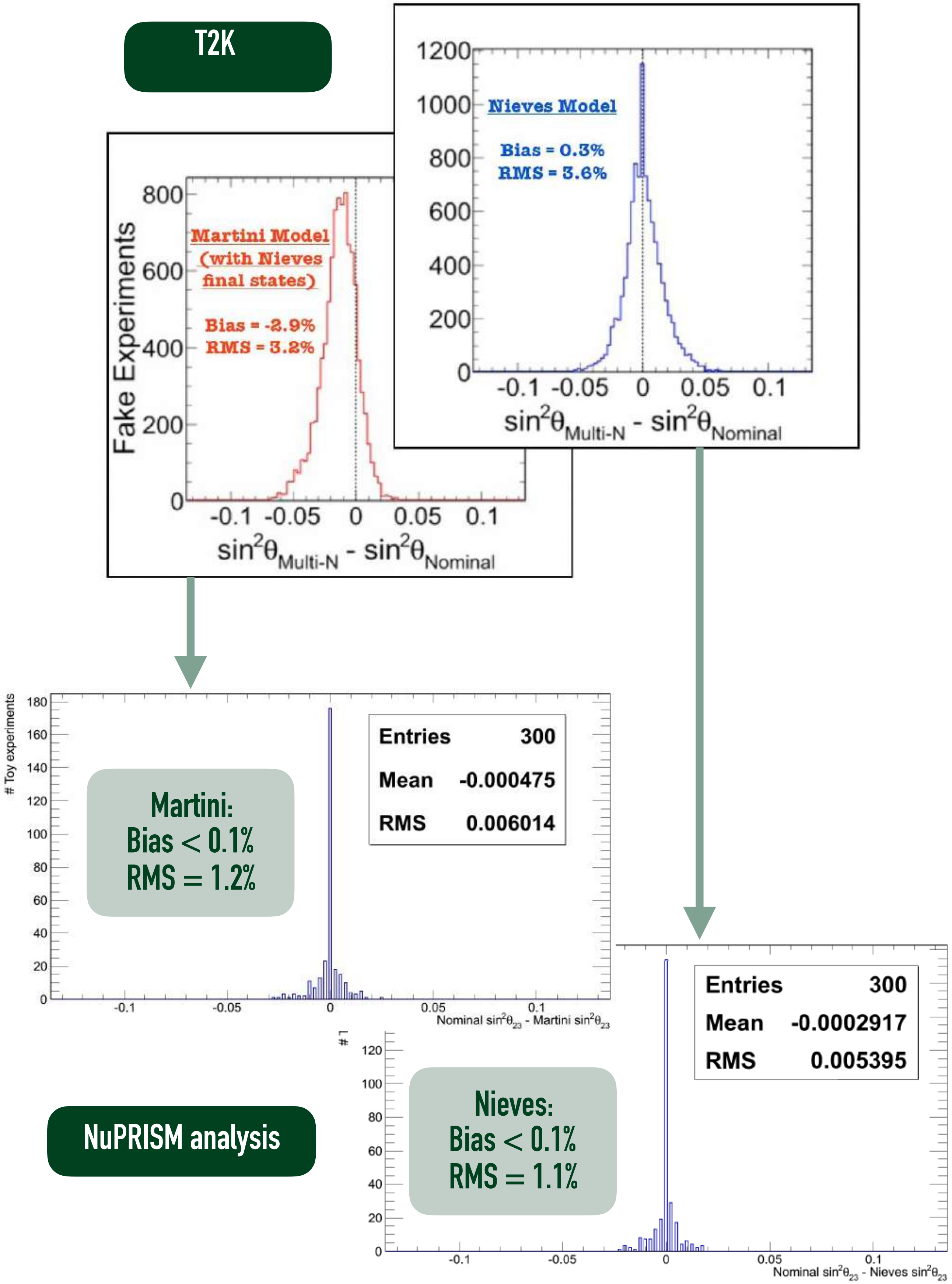
- Oscillations result in different fluxes at the near and far detectors.
  - Presents an additional complication in constraining interaction model that predicts far detector event rates.





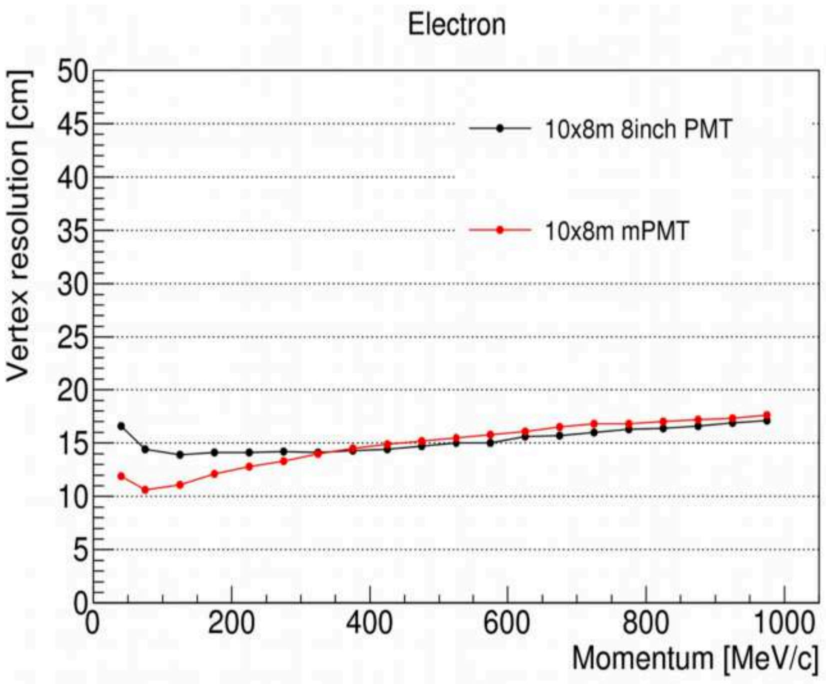
- We can only measure a convolution of the neutrino flux and cross section.
  - Hard to constrain uncertainties with a traditional near detector.
- Multi-nucleon effects and other missing interaction products can smear the reconstructed neutrino energy into the oscillation dip at the far detector.
  - Results in a bias in the measurement.
  - The bias is obscured by the flux peak at the near detector.

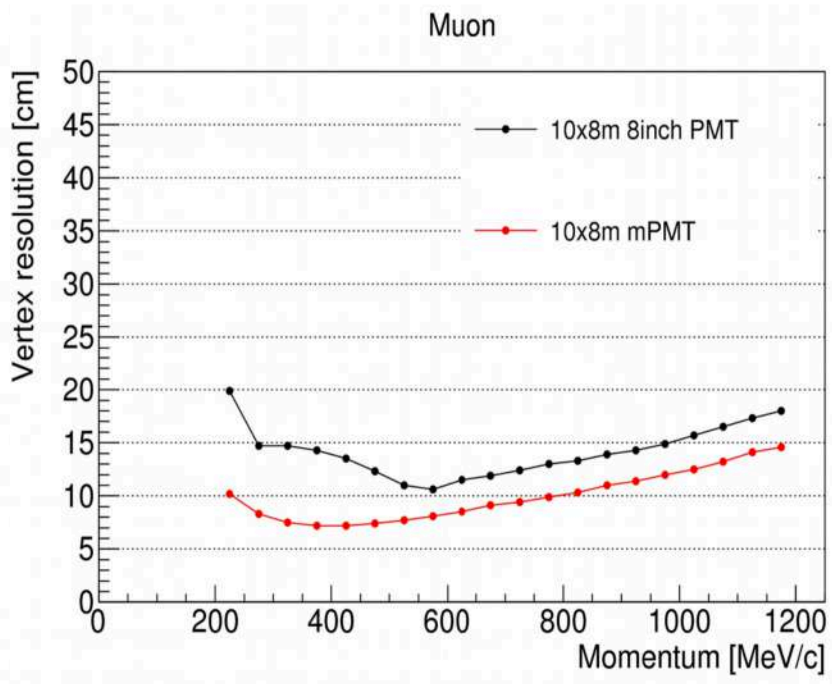
EFFECT OF MULTI-NUCLEON CROSS-SECTION MODELLING

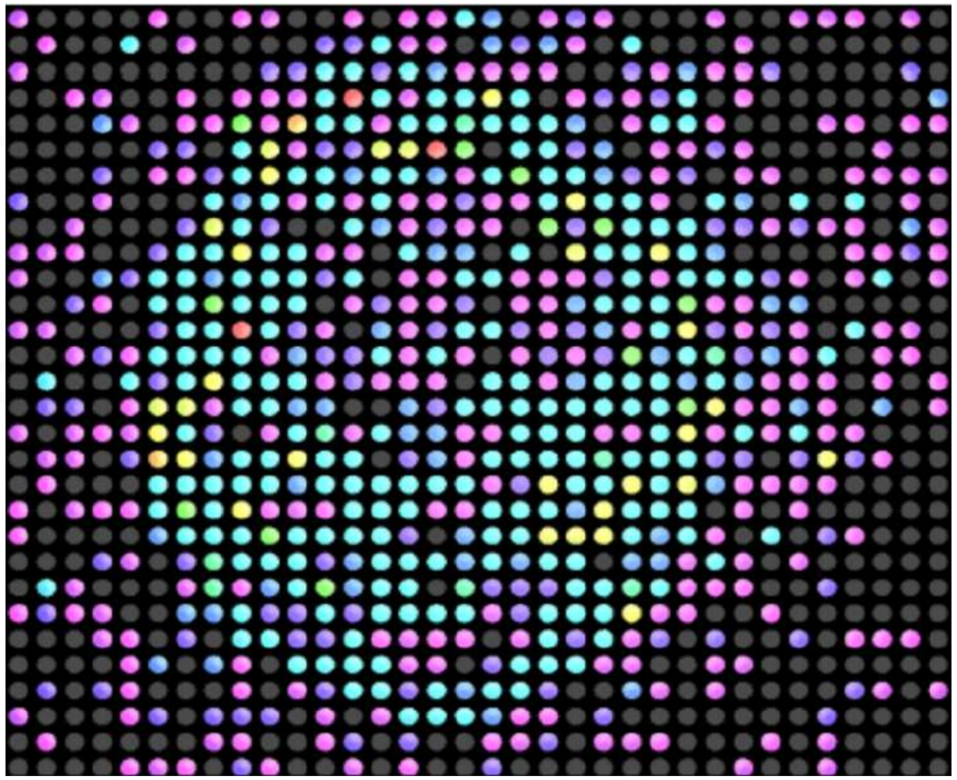


- T2K study of $\sin^2\theta_{23}$ uncertainty from mis-modelling the 2p-2h part of the cross-section found a significant bias and uncertainty.
- Same study is carried out using NuPRISM near detector fit.
- SK event rate is accurately predicted even with additional 2p-2h interactions added to the toy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

E61 RECONSTRUCTION PERFORMANCE

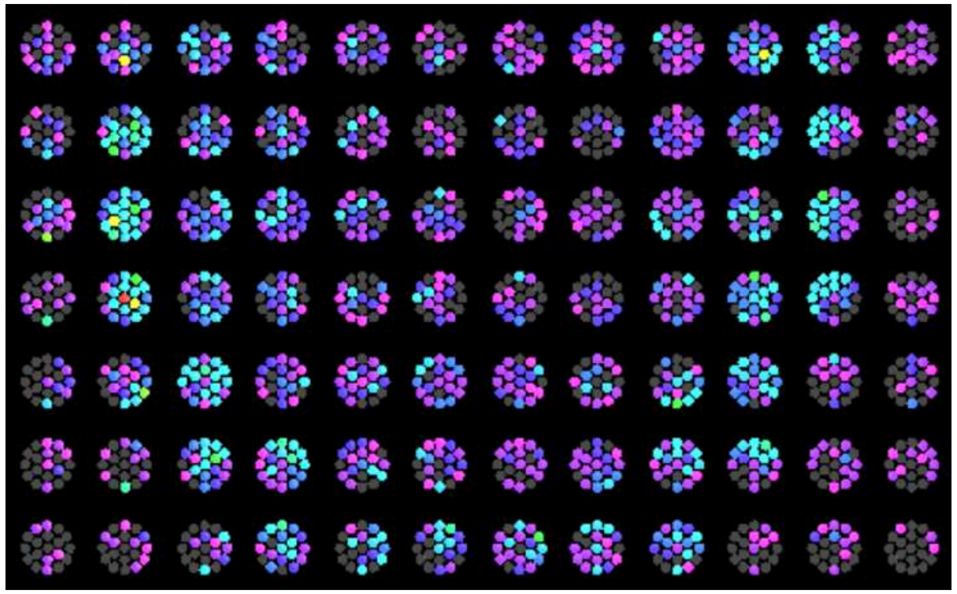






- Full detector simulation (Geant4-based WCSim) and reconstruction (fiTQun) developed for E61.
- Studies show good particle identification despite small size of inner detector.
- Quantifying reconstruction/PID improvements for mPMTs vs 8" PMTs.
- Ongoing reconstruction improvements:
  - Improve PMT angular response function.
  - Include PMT direction information to scattered and reflected light prediction.

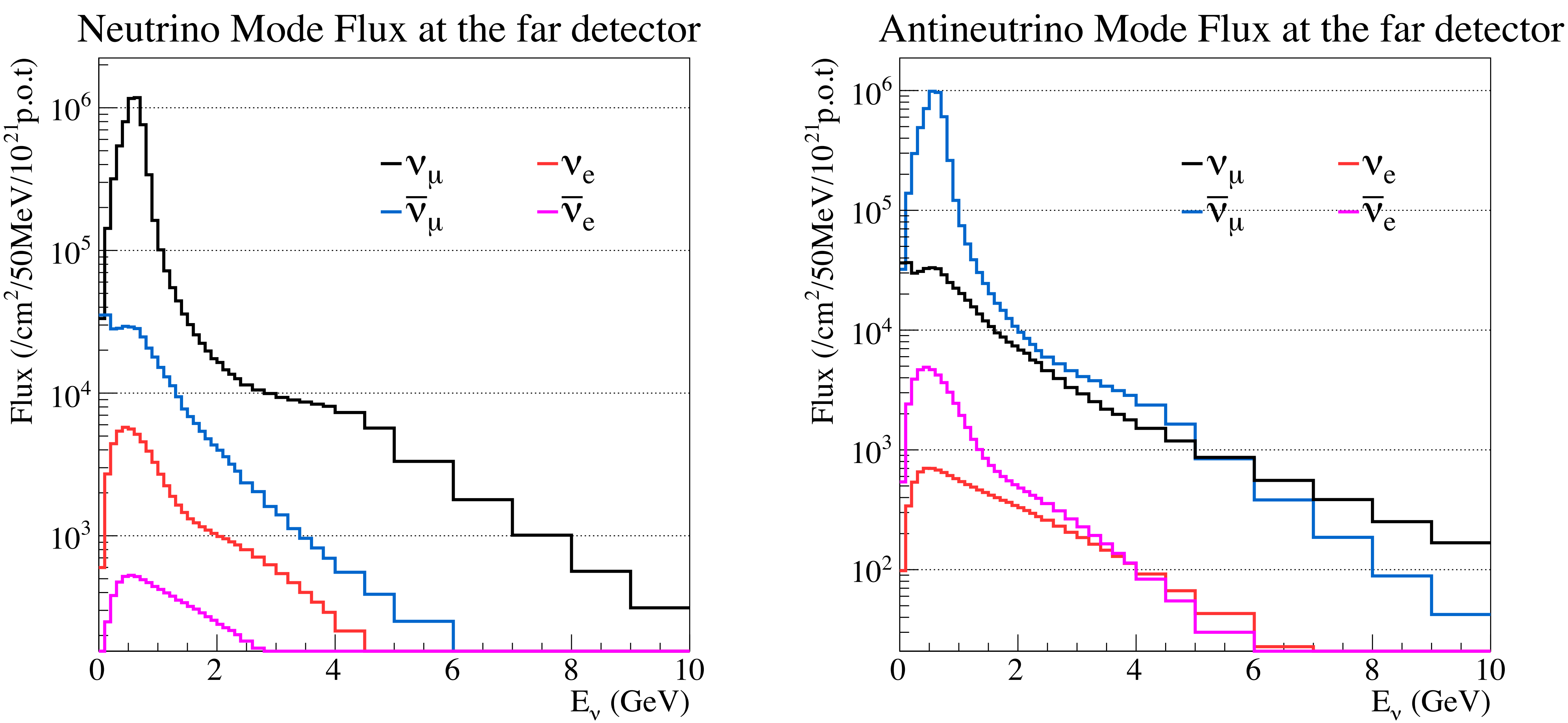
Better granularity
Same event, simulated with 8" PMTs (above) and mPMTs (below)



E61 DETECTOR OPTIMISATION STUDIES

ν_μ EVENT SELECTION

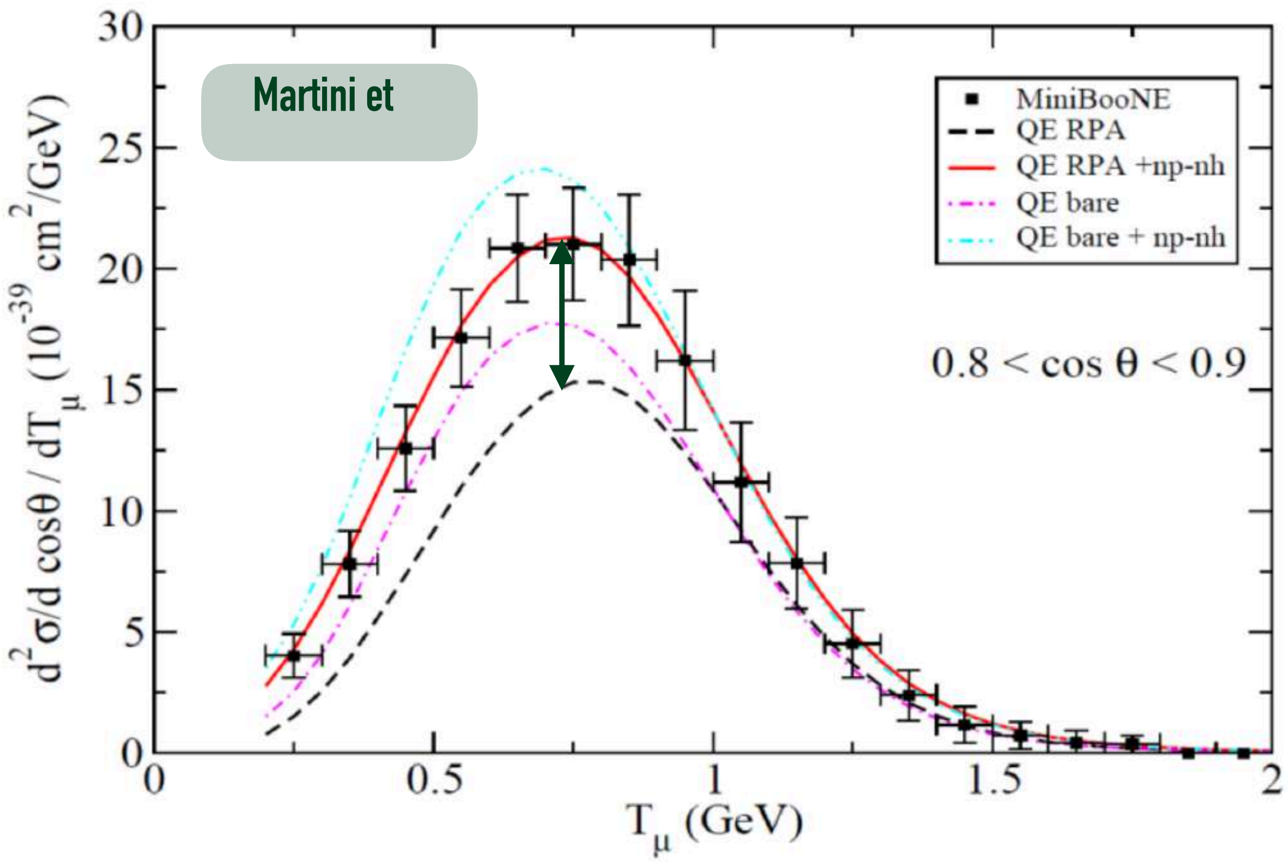
T2K NEUTRINO FLUX

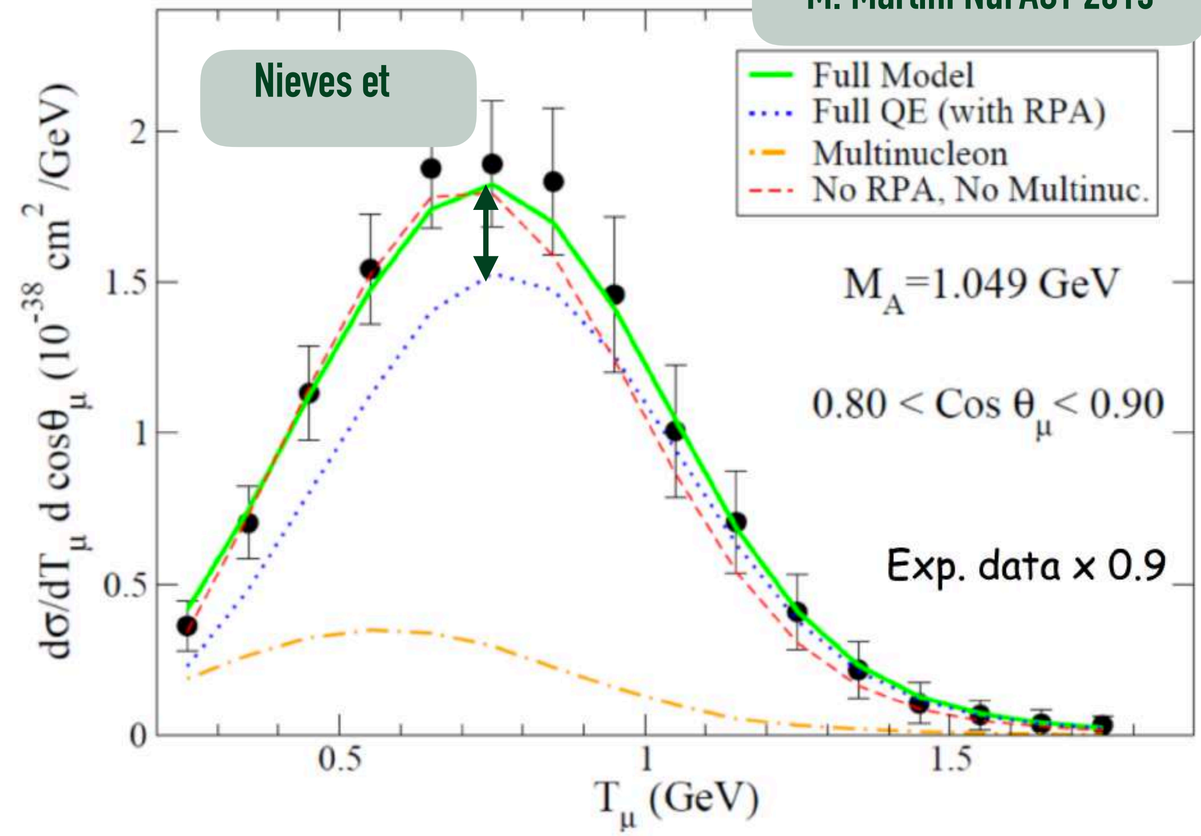


- Very low ν_e $(\overline{\nu}_e)$ contamination.
  - Less than 1% at oscillation maximum.
  - An irreducible background to ν_e $(\overline{\nu}_e)$ appearance.
- Wrong sign contamination more significant in antineutrino mode.
- Near and far flux shapes are not identical, but highly correlated.

MULTI-NUCLEON MODELS

M. Martini NuFACT 2015

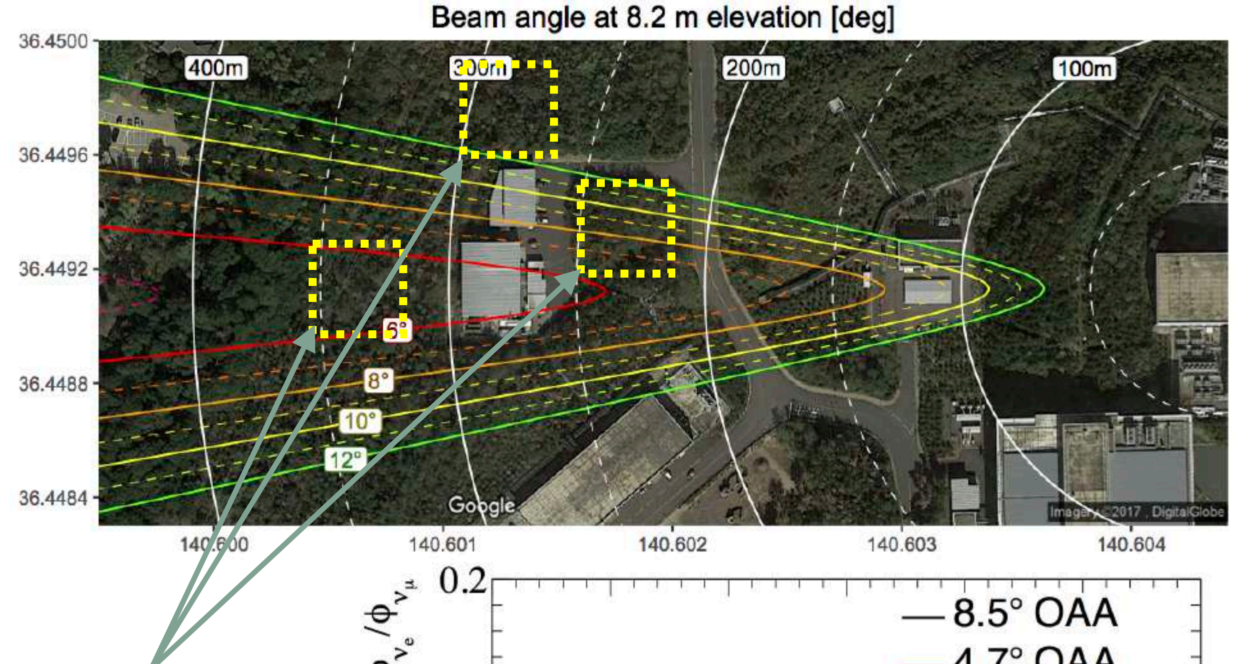


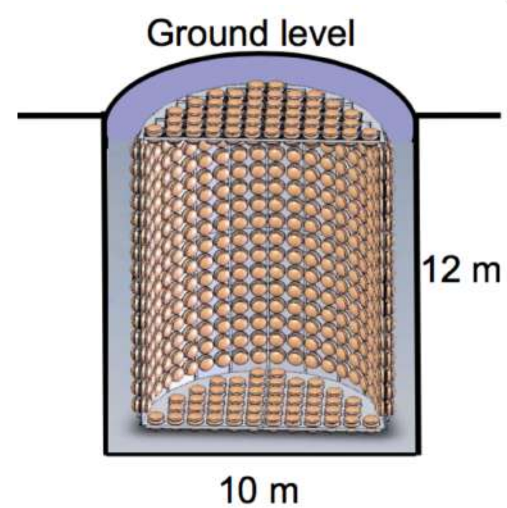


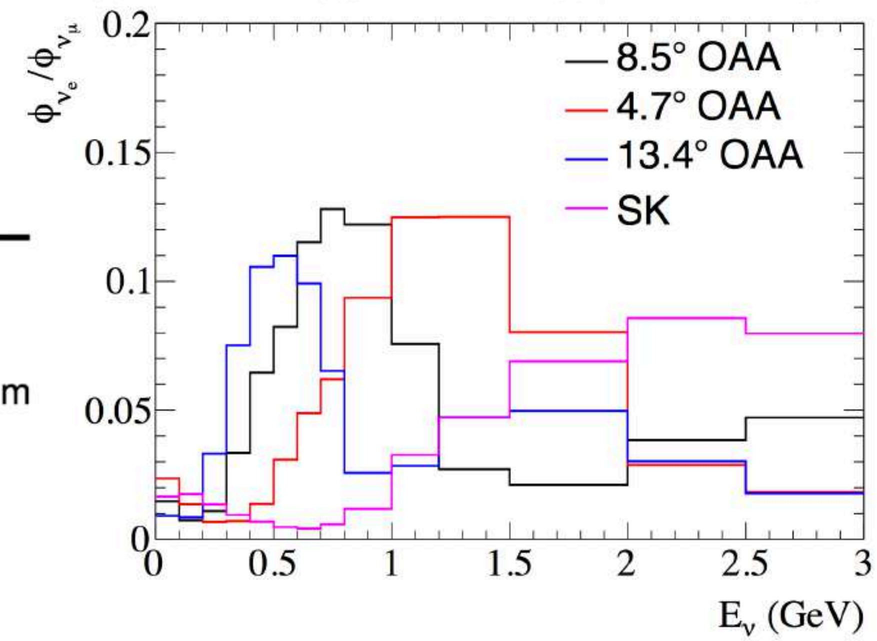
- Many different theoretical models.
- Martini et al. and Nieves et al. calculations are both consistent with MiniBooNE data within the MiniBooNE flux uncertainties.
- The np-nh contributions can differ by a factor of 2 in the region of interest.
- Predict different rates for neutrinos vs anti-neutrinos.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

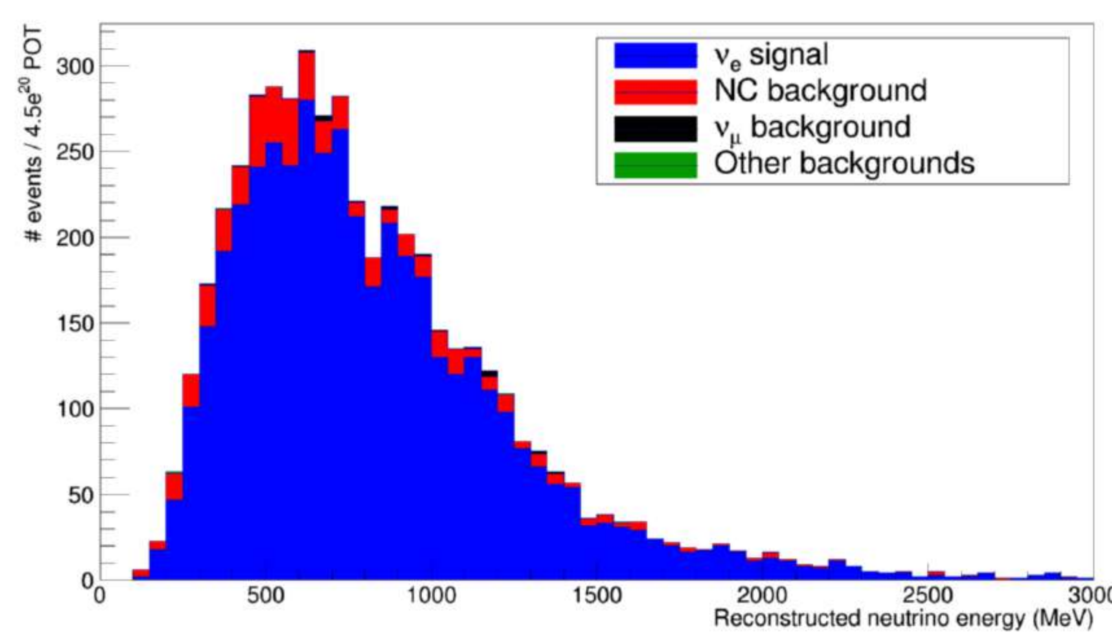
PHASE 0

- 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 1x10^{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.



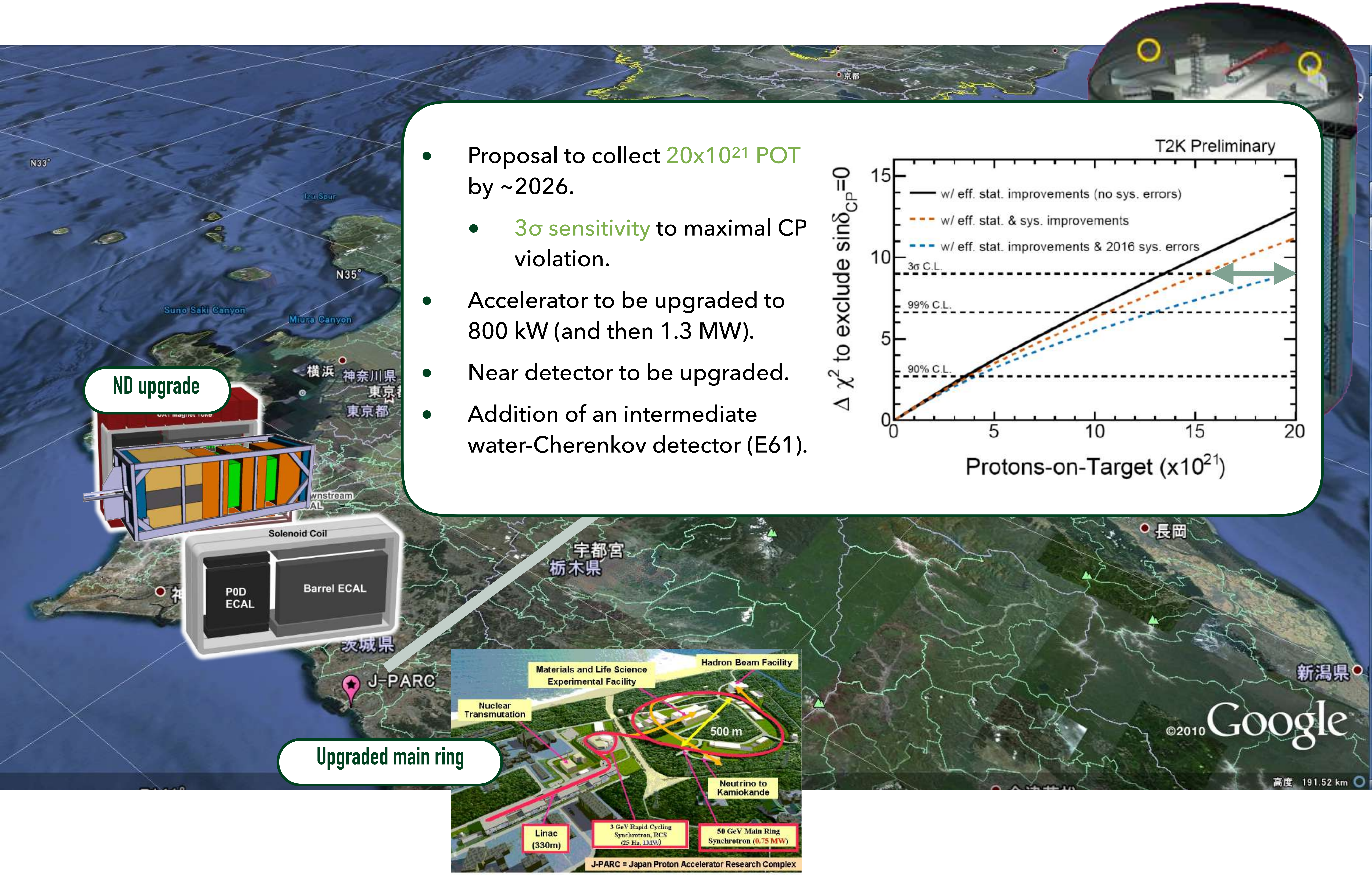






PROPOSED EXTENDED RUN OF T2K (T2K-II)

- Proposal to collect 20x10[21] POT by ~2026.
  - 3σ sensitivity to maximal CP violation.
- Accelerator to be upgraded to 800 kW (and then 1.3 MW).
- Near detector to be upgraded.
- Addition of an intermediate water-Cherenkov detector (E61).



CURRENT T2K SYSTEMATIC ERRORS

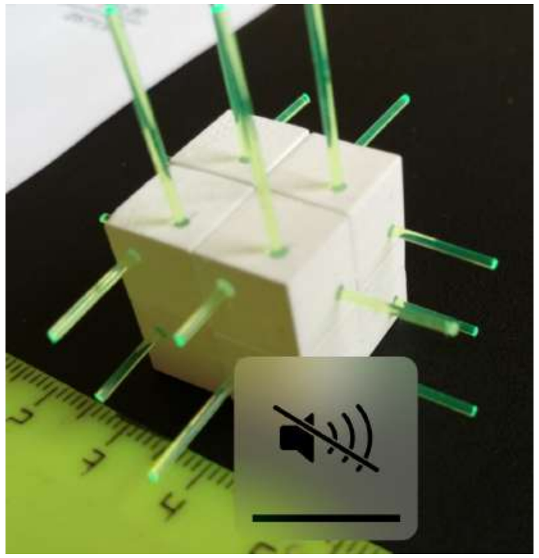
- Systematic uncertainty at the 6% level. Need reduction to ~3% level for Hyper-K.

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%

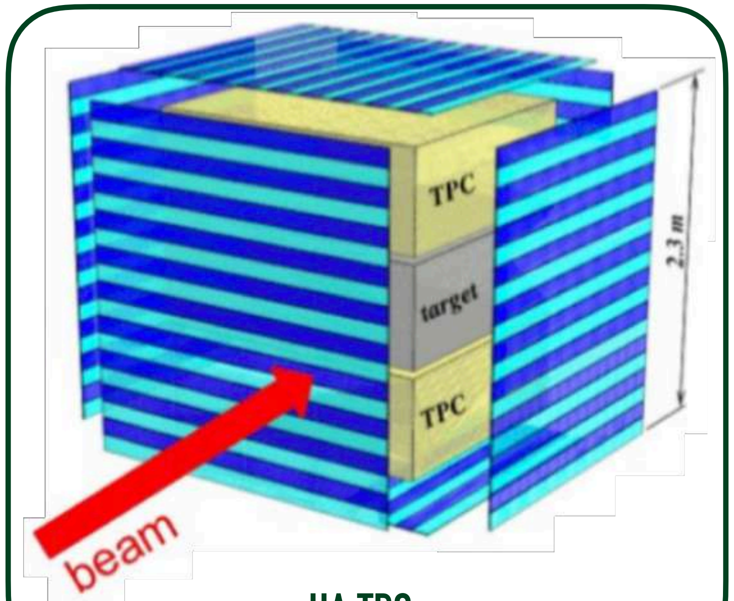
- CP violation measurement depends on uncertainty of $\nu_e/\overline{\nu}_e$ ratio.
- Dominant uncertainties:
  - Final state interactions (FSI) and secondary interactions (SI) - nuclear model extrapolated from pion-nucleus scattering experiments.
  - Electron/muon neutrino cross-section ratio - need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

TRACKING DETECTOR UPGRADES

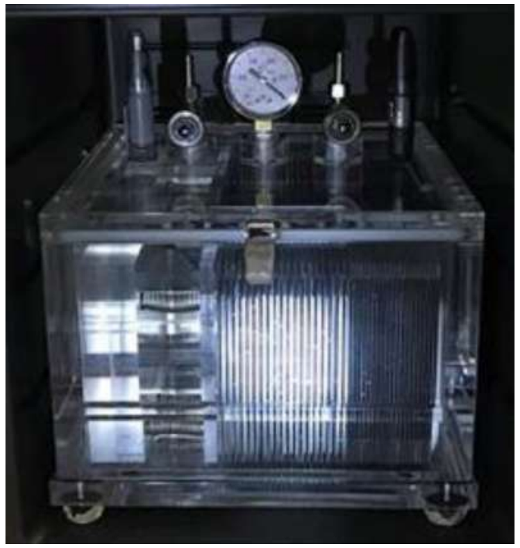
- ND280 upgrade:
  - Horizontal High Angle TPCs (HA TPCs) to improve high angle tracking.
  - SuperFGD: fine-granularity scintillator detector as an active neutrino target.
  - Time of flight detector
    - Precise timing of tracks detected in the TPC determines particle direction.
- NINJA
  - Nuclear emulsion detector measuring neutrino-nucleus interactions.
  - Water target may be installed as a hybrid detector with ND280.
  - Measure ν_e interactions and anti-ν_e interactions separately.
- High Pressure TPC (HP TPC)
  - Improved reconstruction of low energy hadrons in the final state recoil system and better reconstruction of photon conversions.



SuperFGD



HA TPCs



NINJA