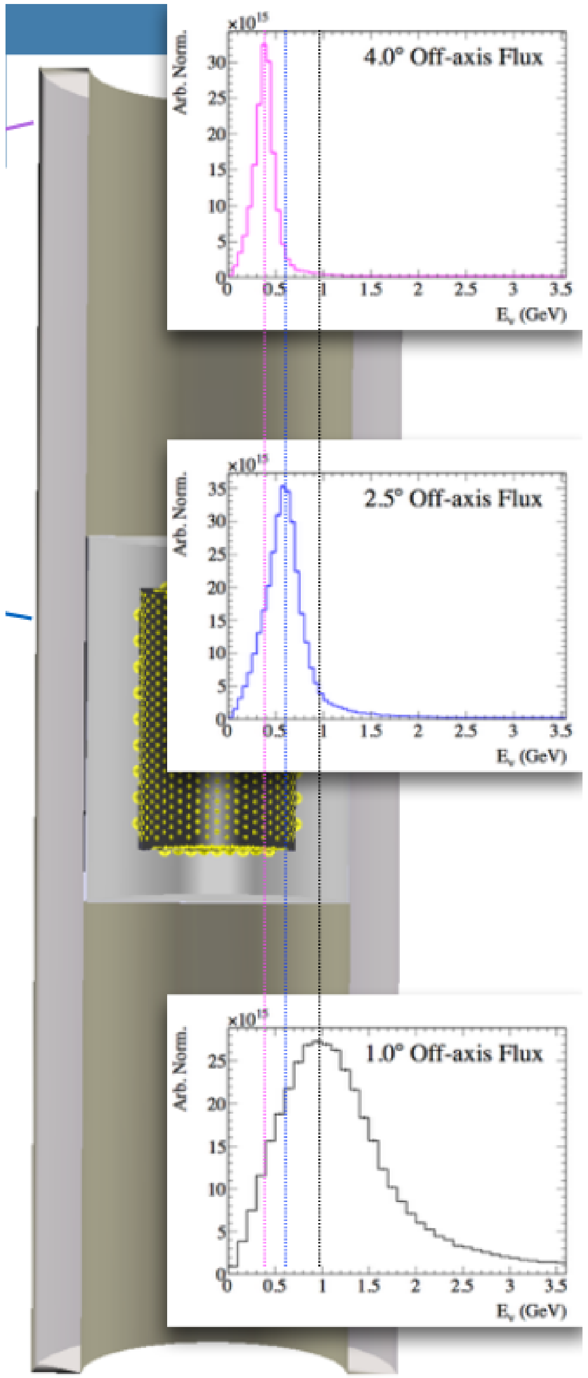
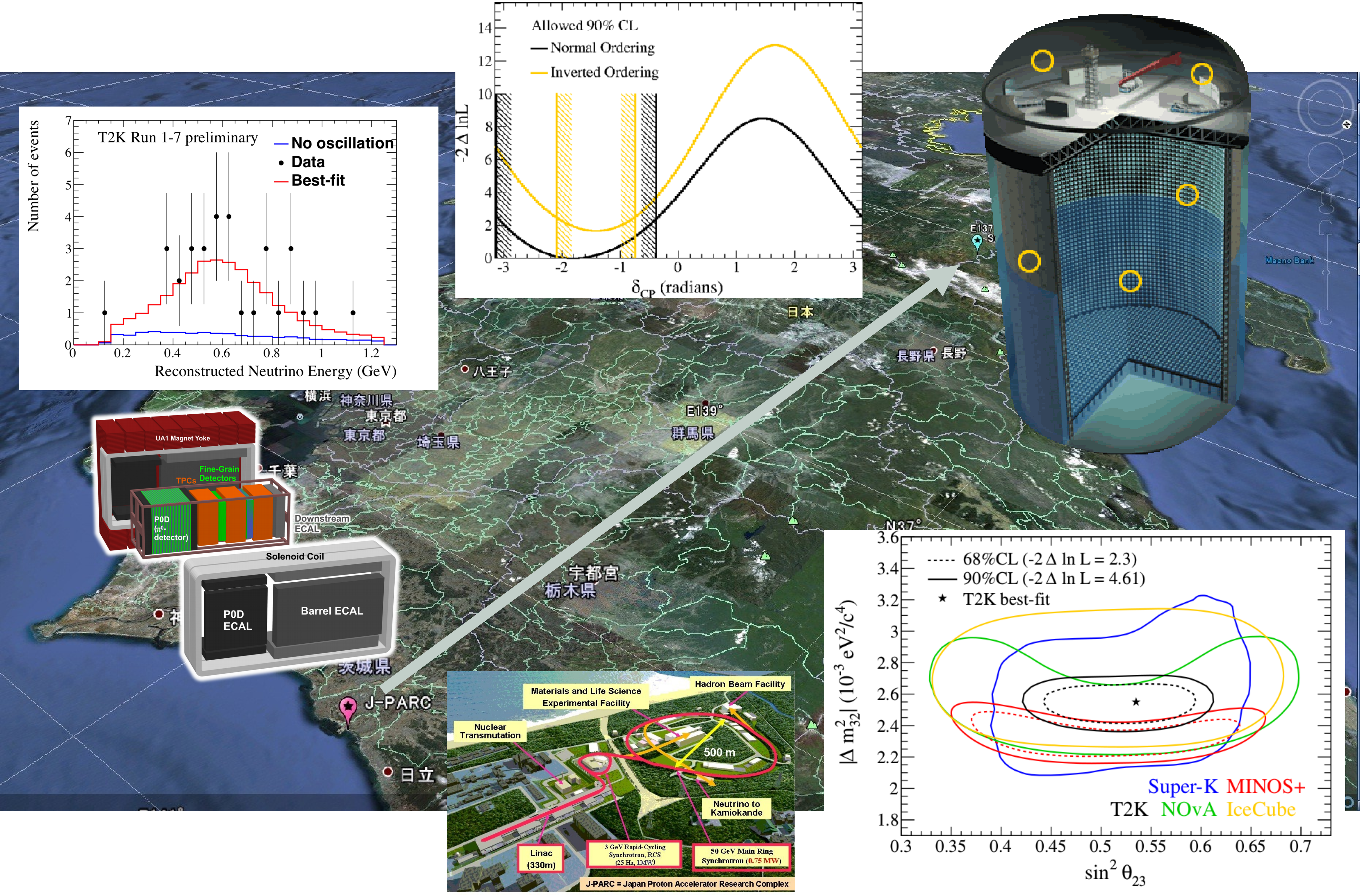


E61 JPARC INTERMEDIATE WATER CHERENKOV DETECTOR

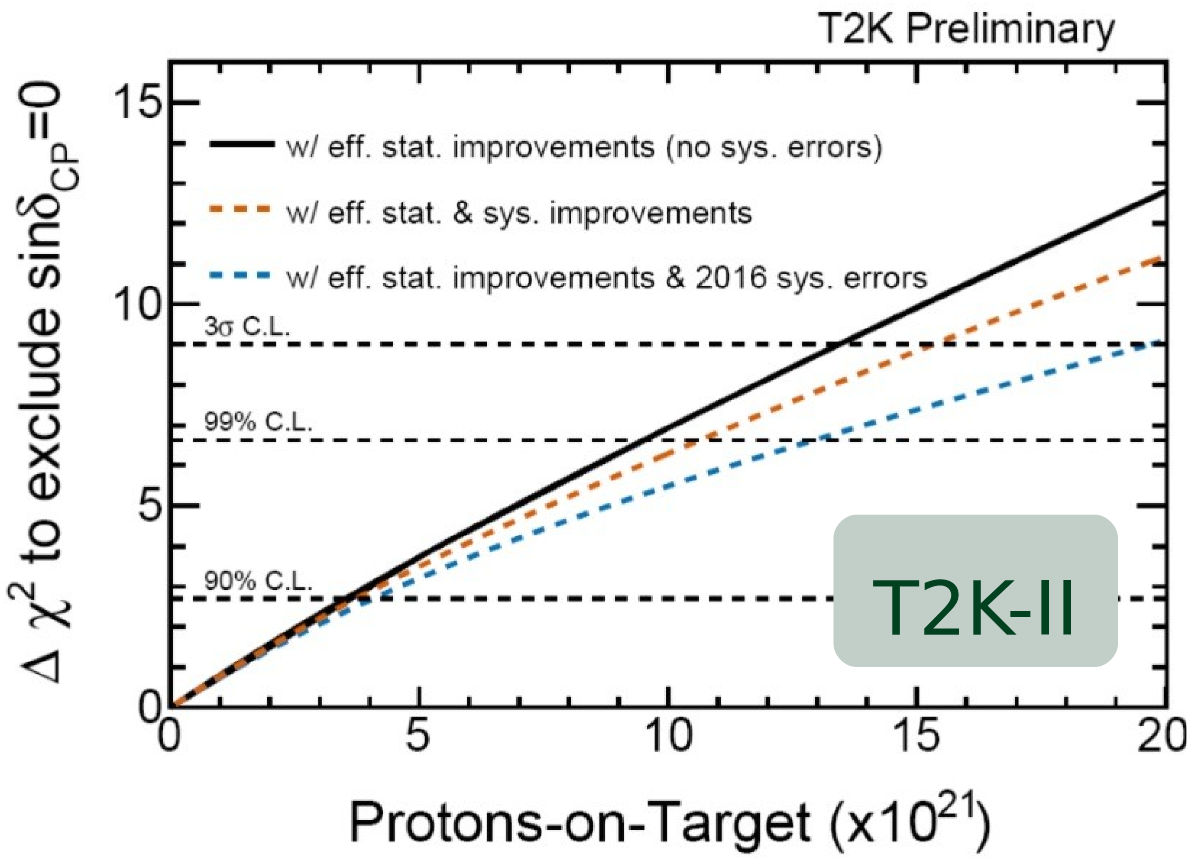
B. Jamieson (University of Winnipeg)
presented on behalf of the E61 Collaboration

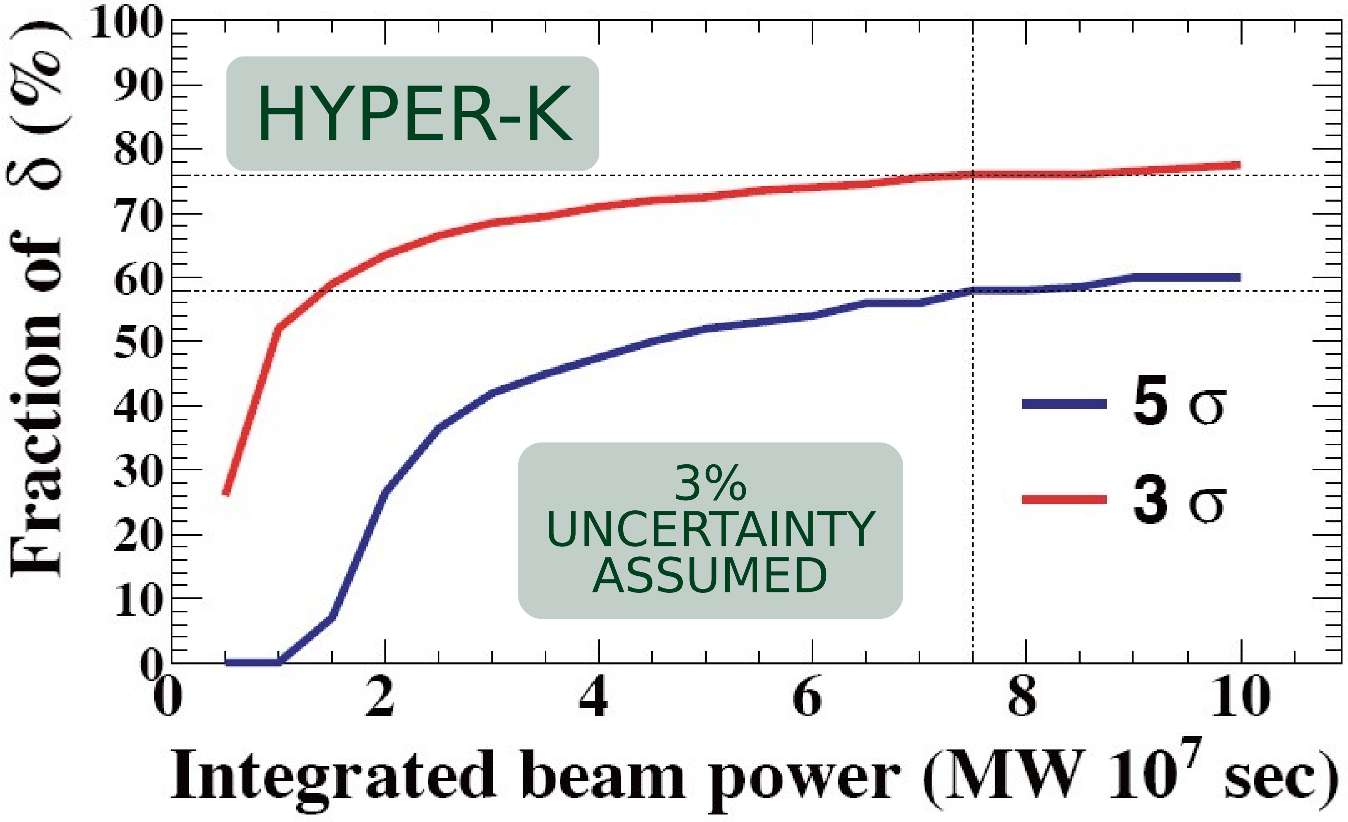
NUINT 2017
June 29, 2017, Fields Institute, Toronto, ON

T2K (TOKAI TO KAMIOKA) EXPERIMENT



Search for Leptonic CP Violation

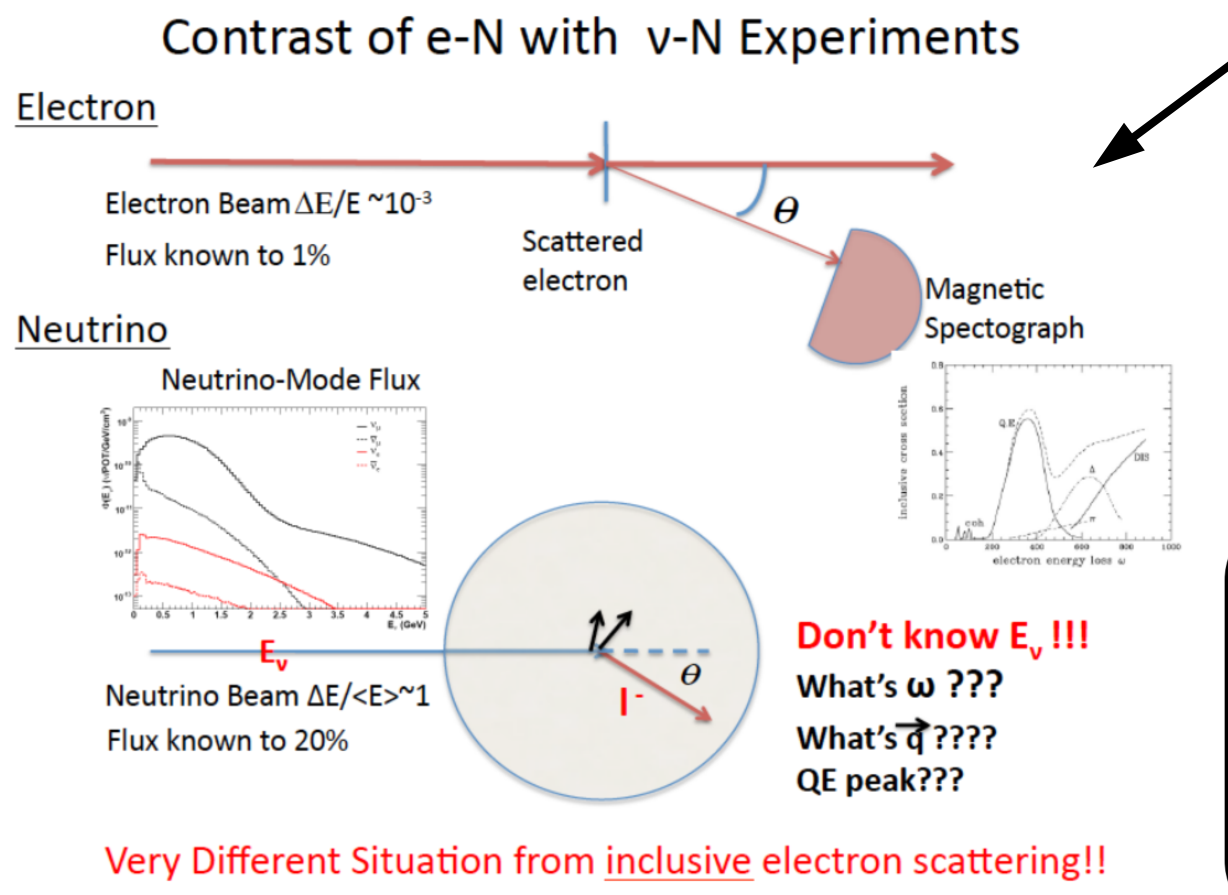




- T2K Phase-II will be sensitive to maximal CP violation at the 3σ level.
- Hyper-K will be sensitive at 5σ over a range of values of δ_{CP}.
- Future long baseline experiments will be limited by systematic rather than statistical uncertainties.

Measuring Neutrino Energy

3. Remark from Gerry Garvey (circa 2010)



Contrast of e-N with ν-N Experiments

Electron

Electron Beam ΔE/E ~10^{-3}

Flux known to 1%

Scattered electron

Magnetic Spectograph

Neutrino

Neutrino-Mode Flux

Neutrino Beam ΔE/<E>~1

Flux known to 20%

Don't know E_ν !!!

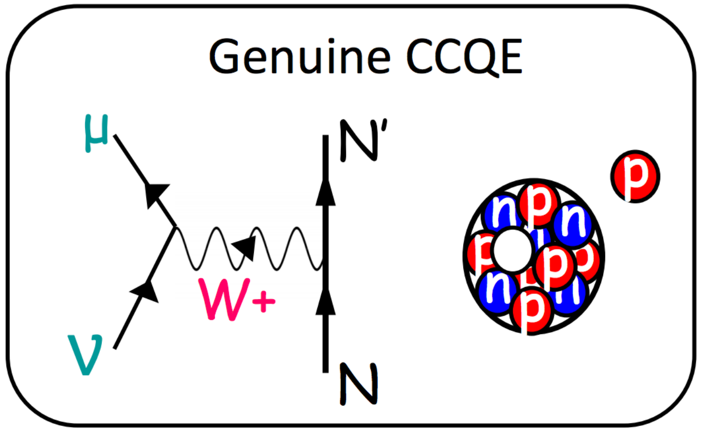
What's ω ???

What's $\vec{q}$????

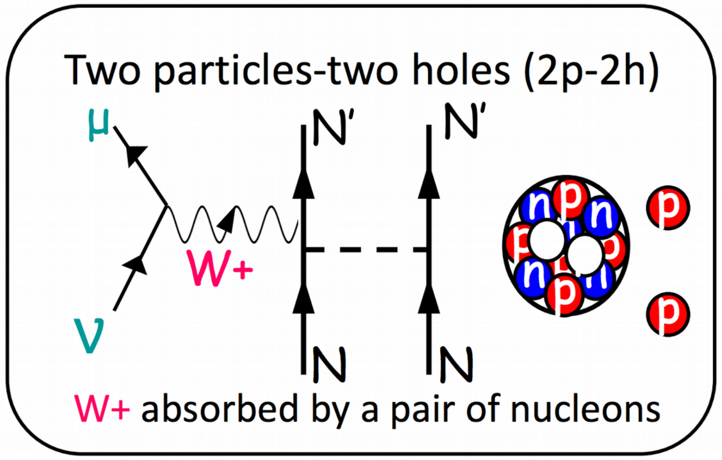
QE peak???

Very Different Situation from inclusive electron scattering!!

Reminder of Teppei's remark – no nearly mono-energetic neutrino beam to study multi-nucleon effects as done in electron scattering

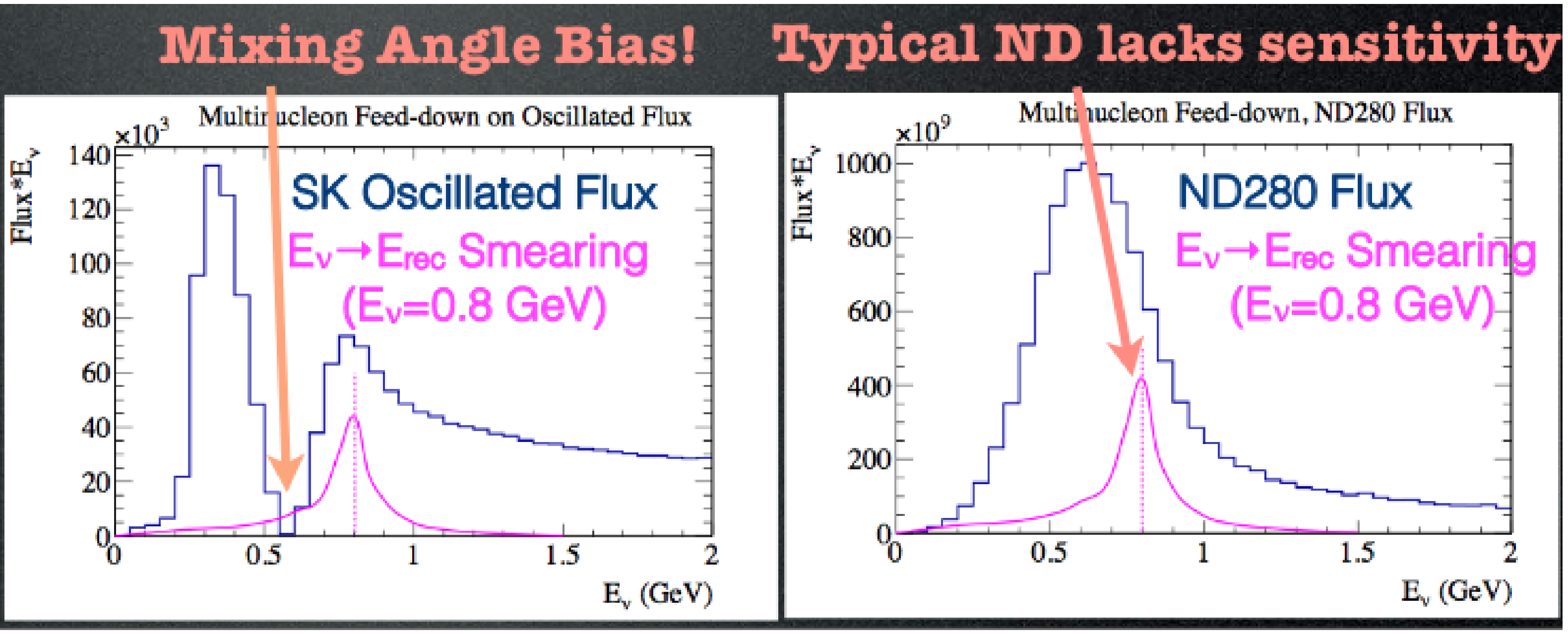


Genuine CCQE



Two particles-two holes (2p-2h)

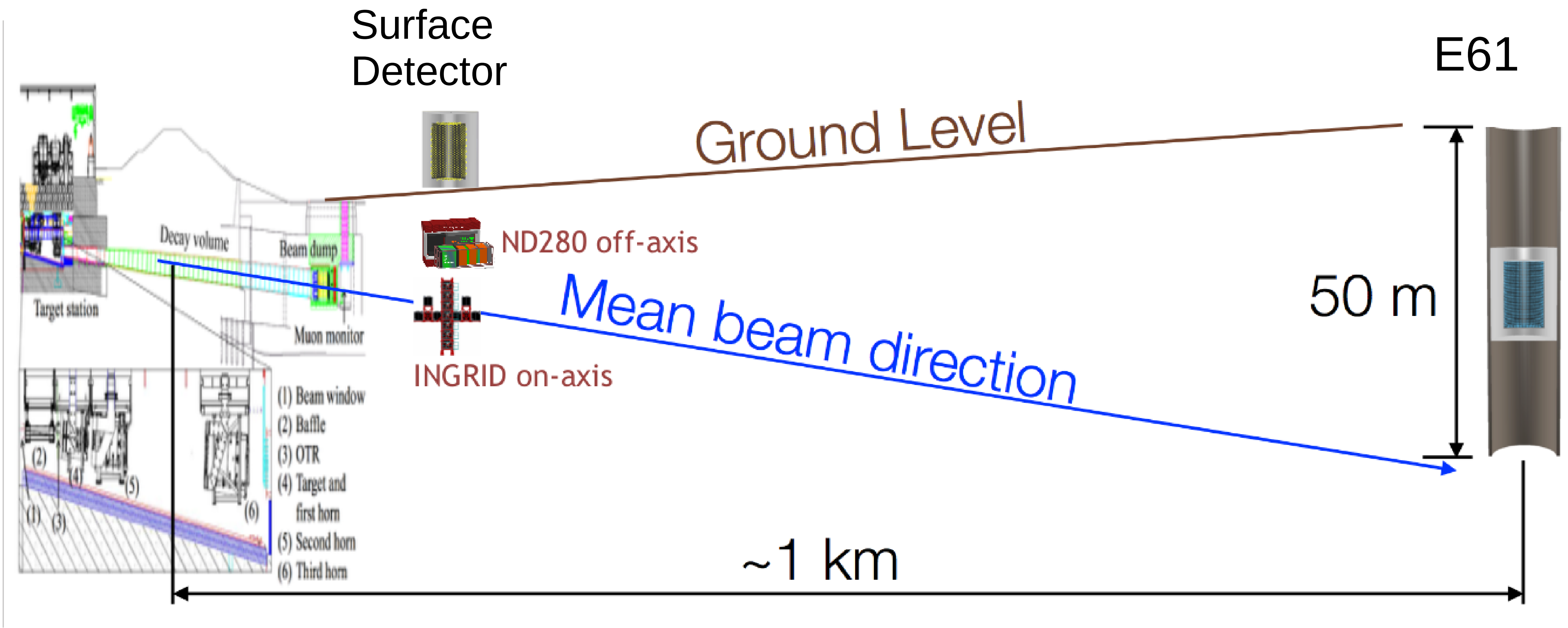
W+ absorbed by a pair of nucleons



- Multi-nucleon effects make it difficult to reconstruct neutrino energy
- Can lead to biases in osc. analyses

J. Nieves, I. Ruiz Simo, and M.J. Vicente Vacas, PRC 83:045501 (2011)
M. Martini, M. Ericson, G. Chanfray and J. Marteau, PRC 80:065501 (2009)

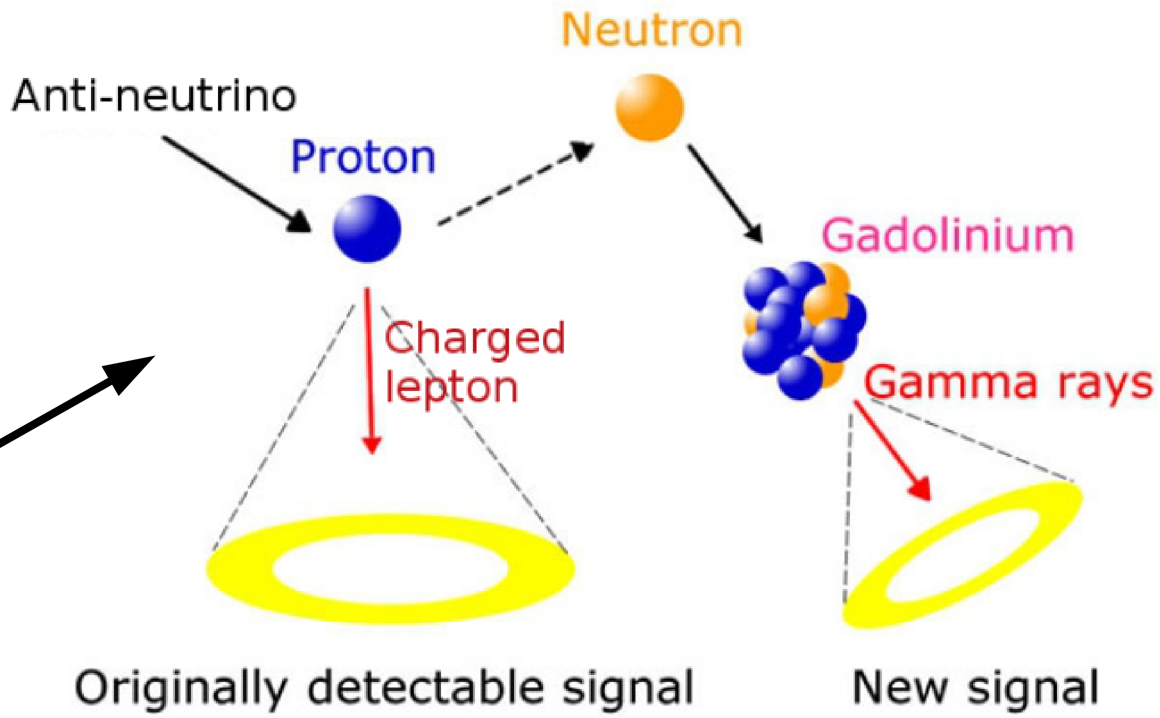
E61 Experiment Setup

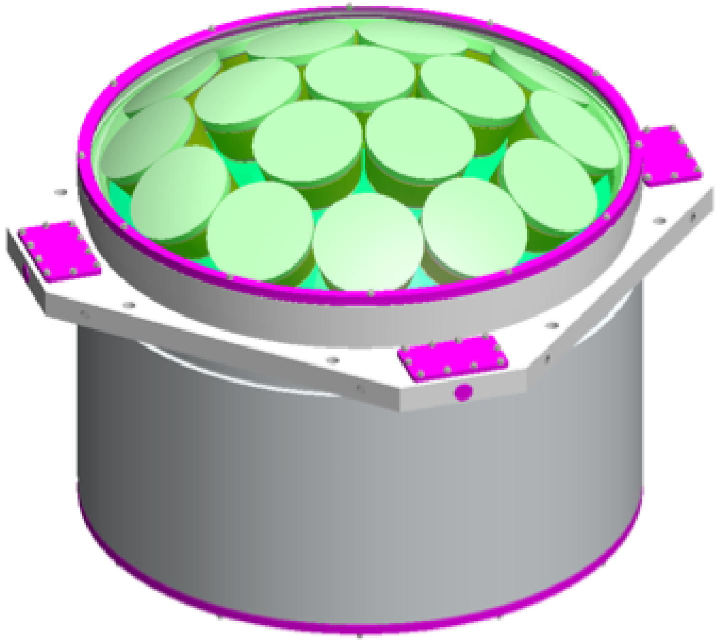


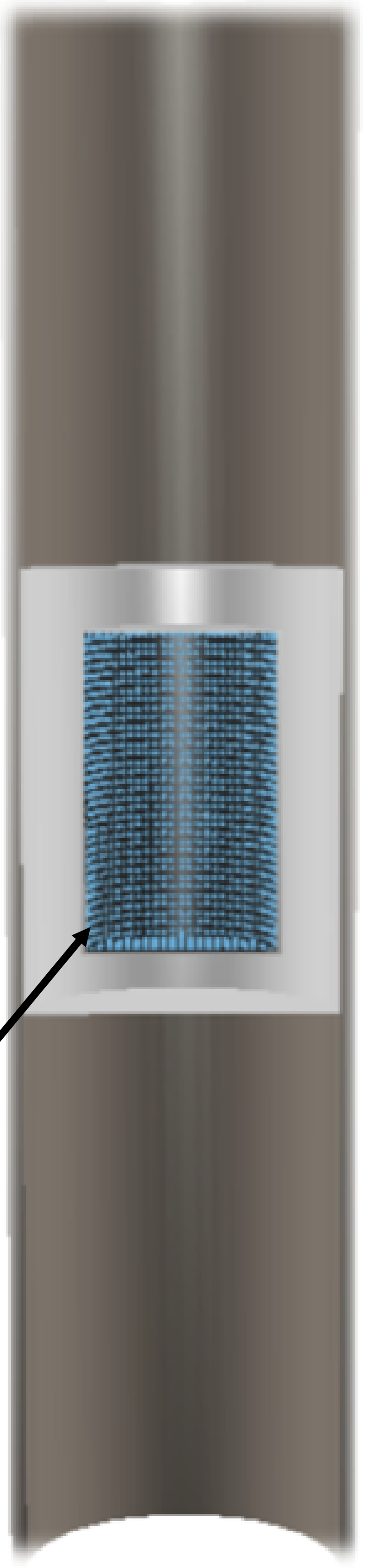
- nuPRISM + TITUS merged into new E61 Collaboration with new ICA
  - Initial spokespeople: Mark Hartz, Mike Wilking
  - Project Manager: Masaki Ishitsuka + Executive Committee: Francesca Di Lodovico
- An intermediate distance water Cherenkov detector with Gd loading
- 50 m tall, 8m diameter , movable instrumented portion
  - ID: 10m tall, 8m diam., OD: 14m tall, 10m diameter

The E61 Experiment Features

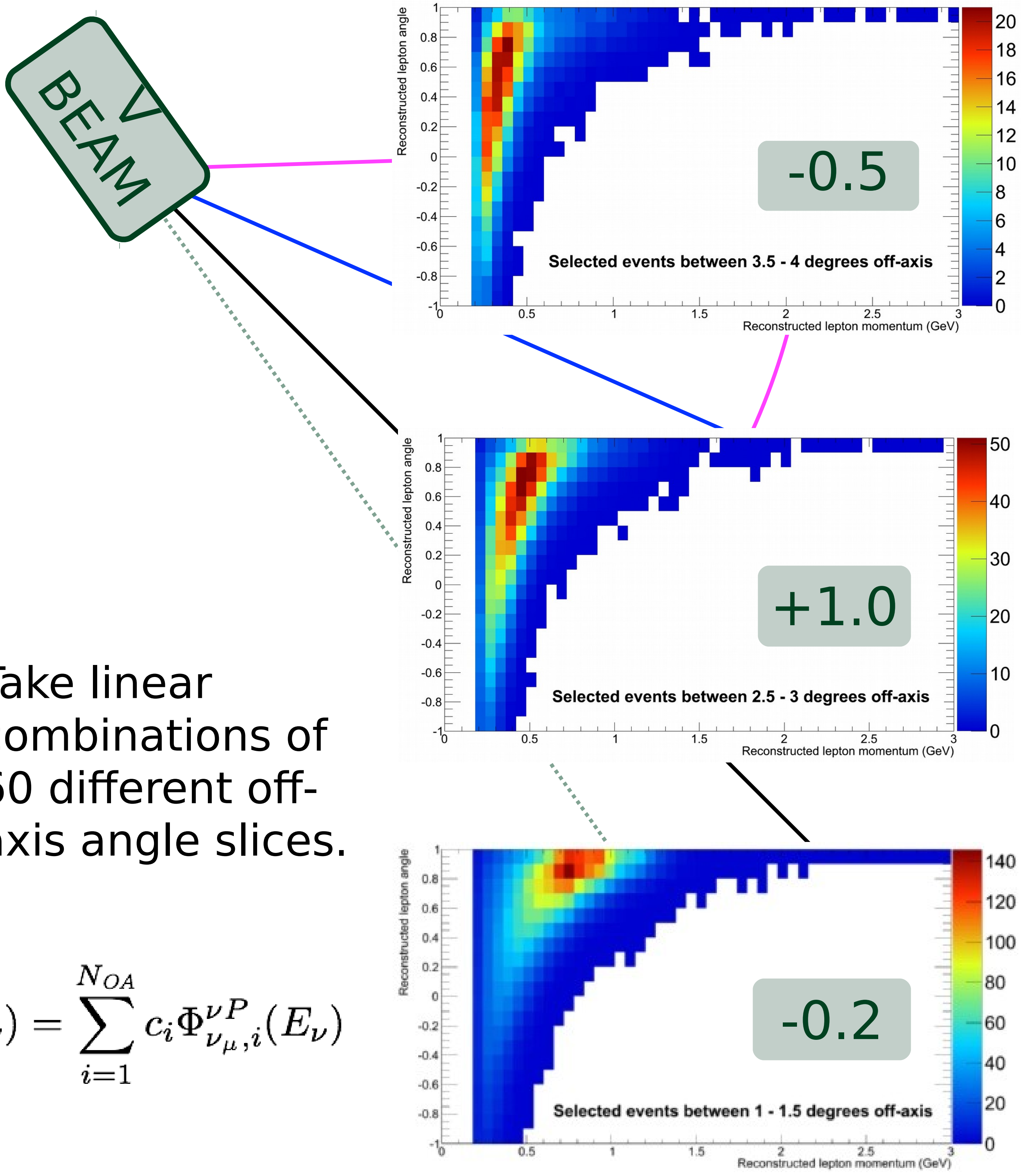
- An intermediate water Cherenkov detector
  - Same nuclear target and acceptance as the far detector.
  - Smaller near to far extrapolation systematic.
  - Spans 1-4 degrees from the neutrino beam axis.
  - Probes neutrino energy vs final state kinematics relationship.
  - Gd loading to measure neutron production.
  - multi-PMT concept for photonsensor allows finer granularity detection

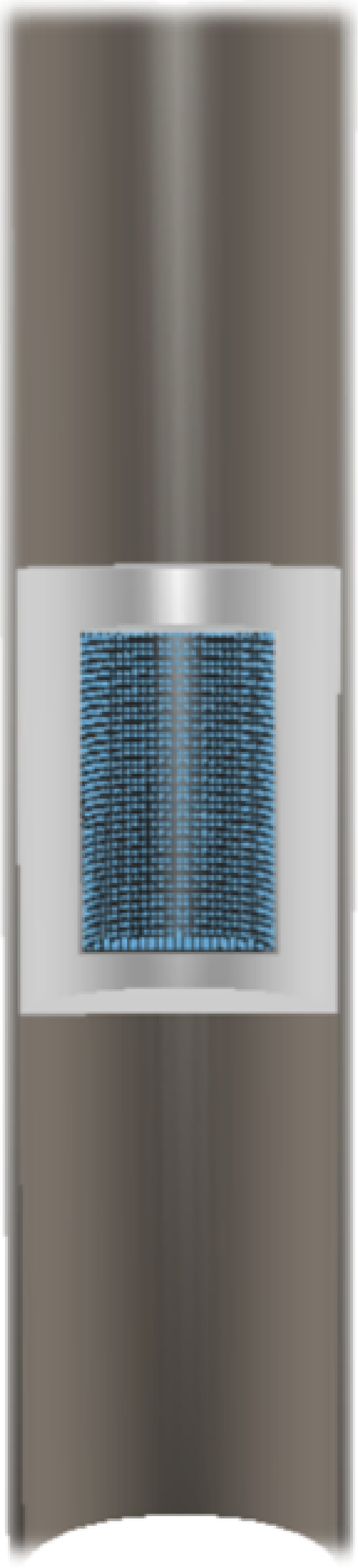


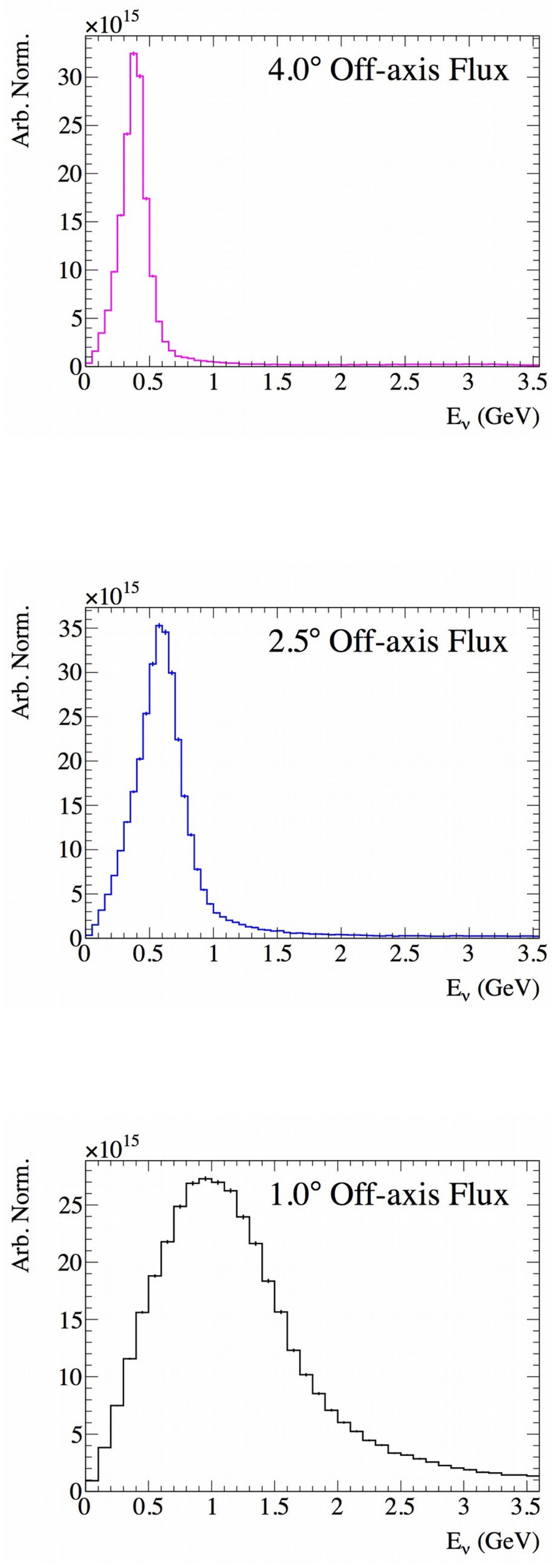




E61 Concept



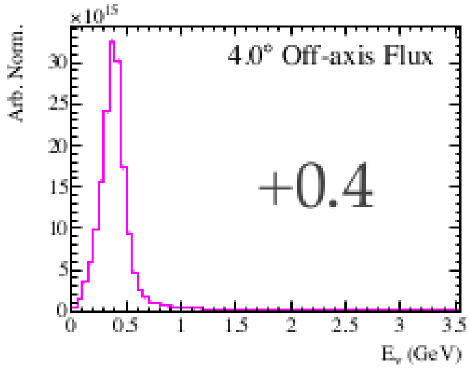


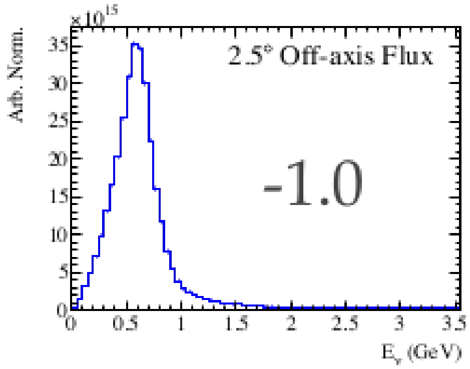


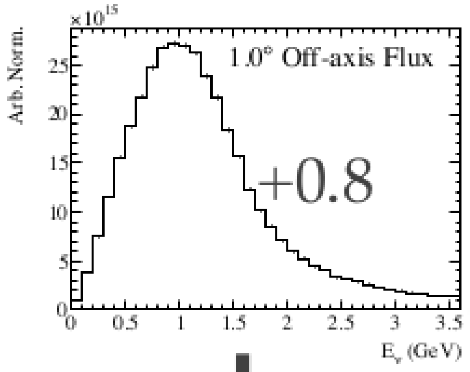
- Take linear combinations of 60 different off-axis angle slices.

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

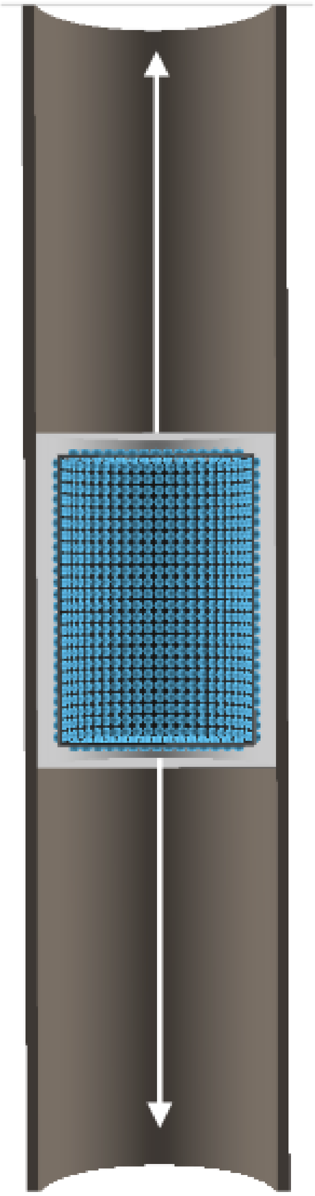
Off-Axis Linear Combinations



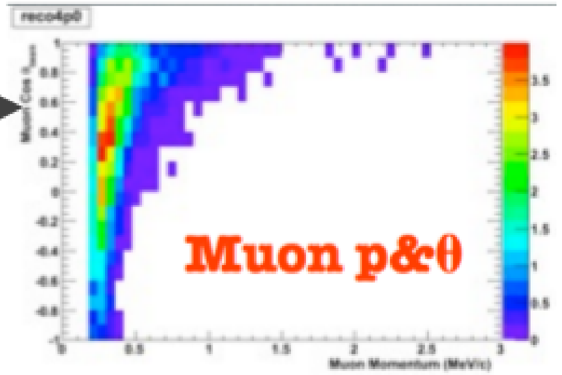


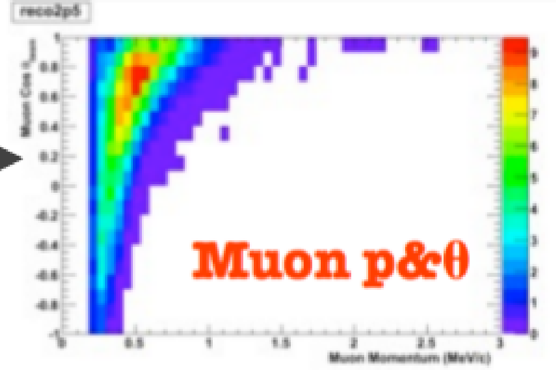


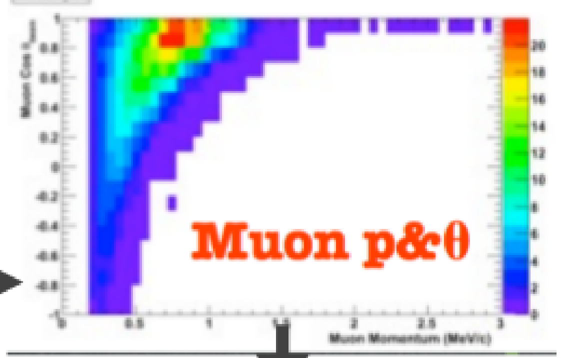
Spectra at each off-axis bin

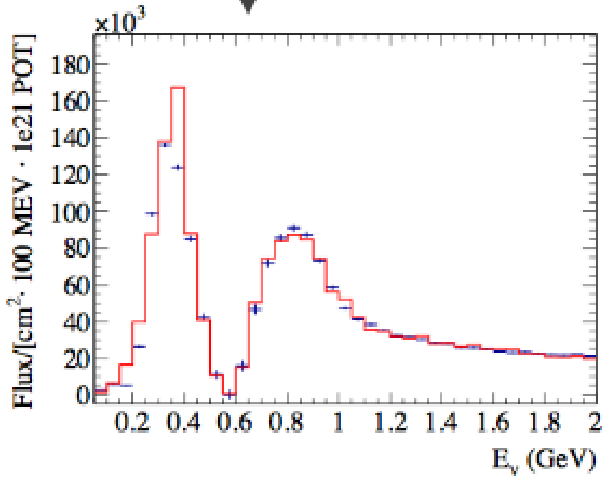


Observed muon kinematic distributions

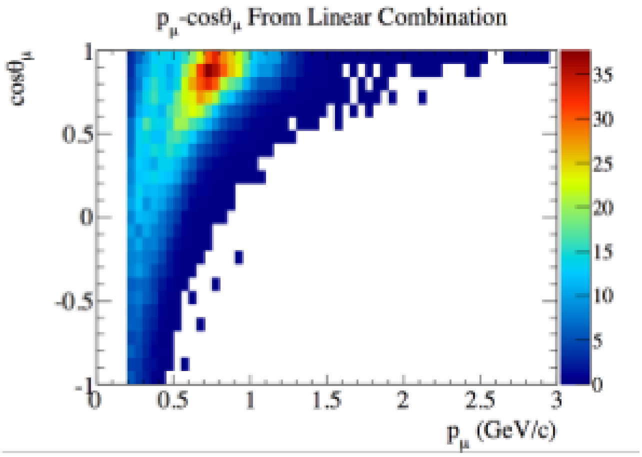




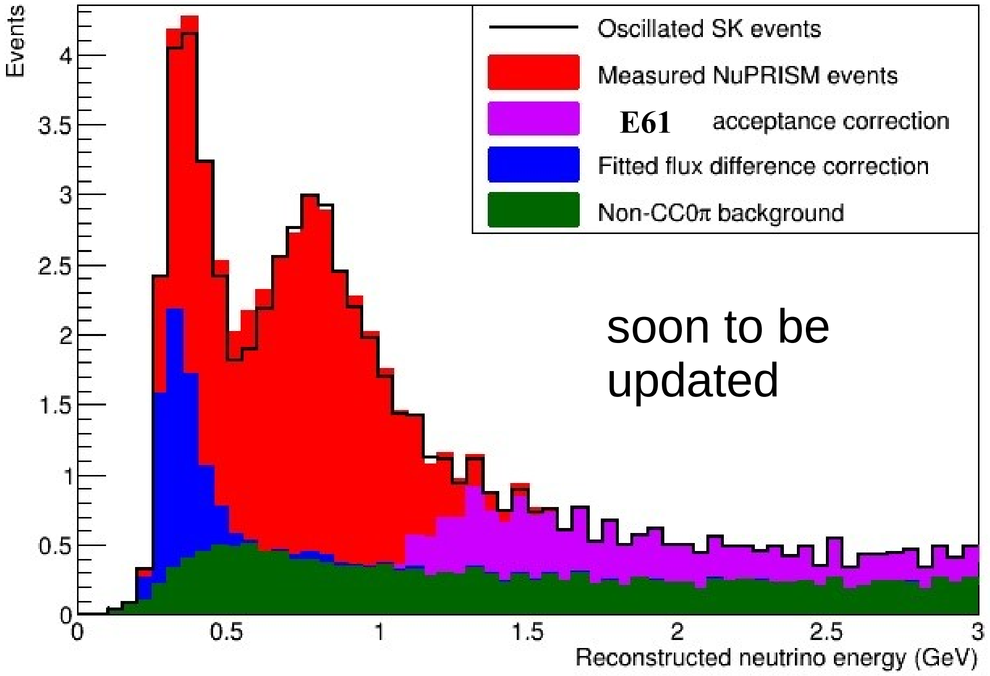




Linear combinations reproduce the oscillated flux, and predict muon kinematic distributions for the oscillated flux



Muon Neutrino Disappearance



soon to be updated

Measured E61 event rate:

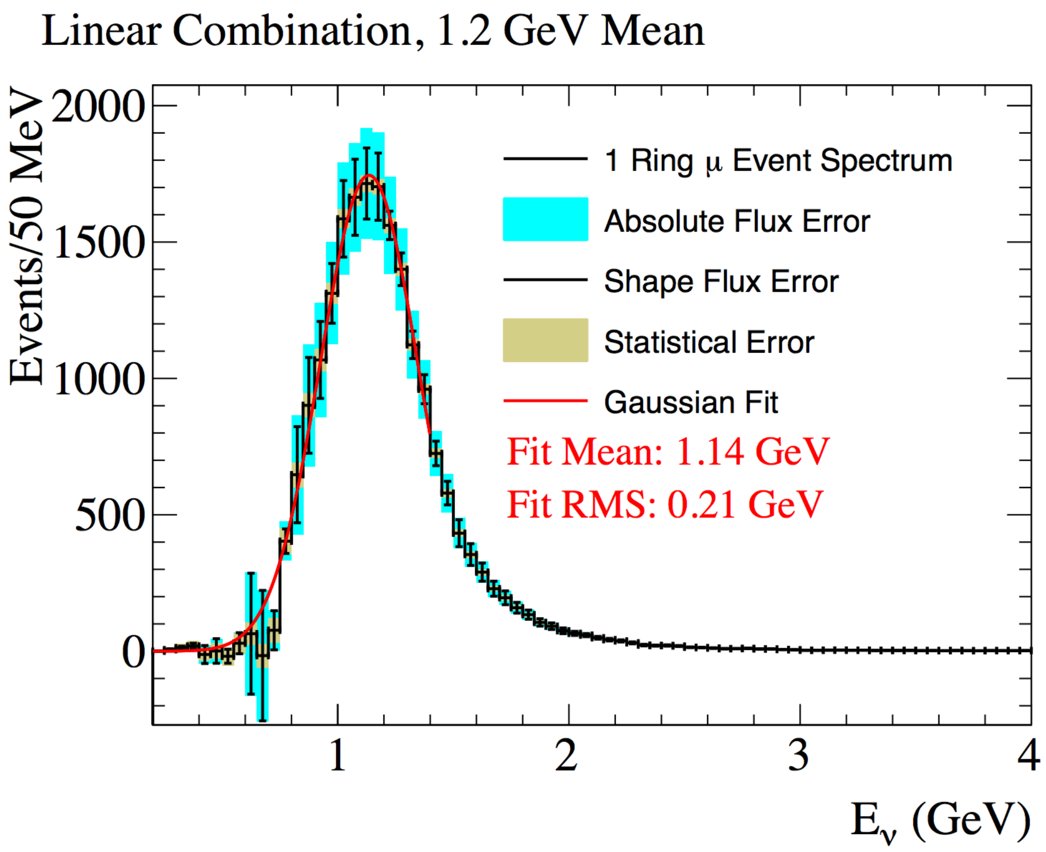
$$N_{SK}(E_{rec};\theta_{23},\Delta m^2_{32}) = \sum_{i}^{\text{Off-axis bins}} c_i(\theta_{23},\Delta m^2_{32}) N_i^{\nu P}(E_{rec})$$

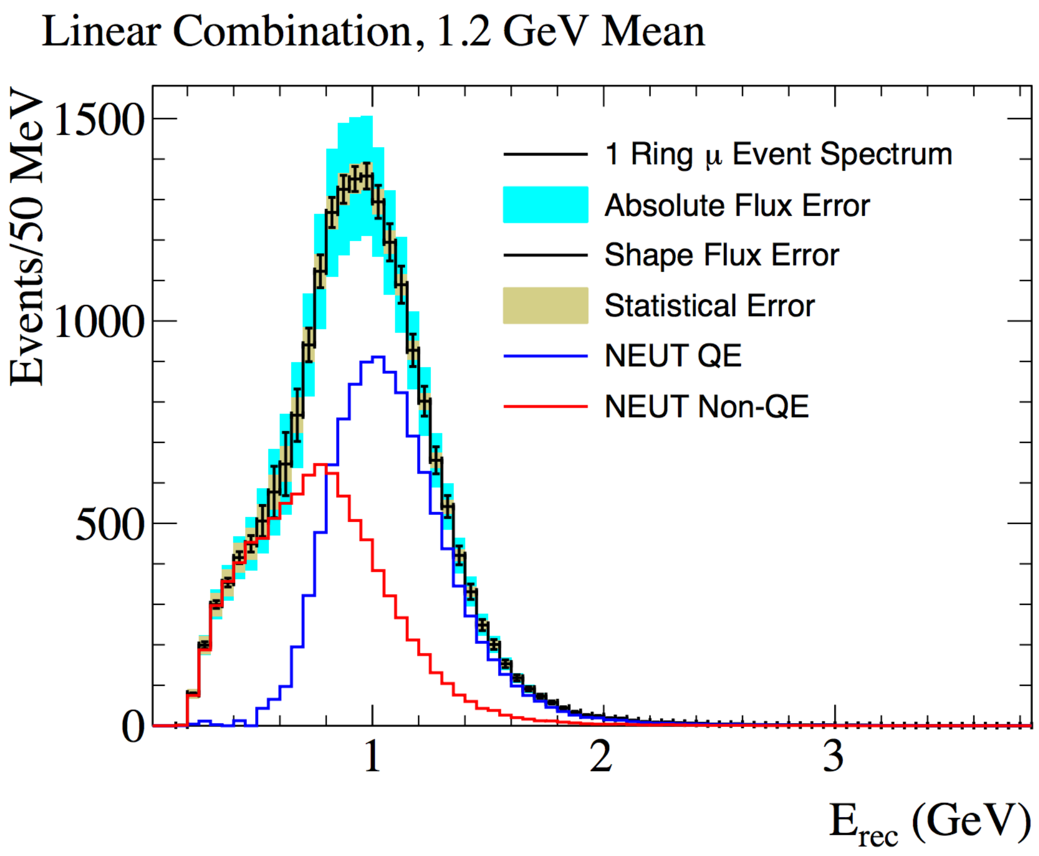
SK expected event rate:

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

- Red: Directly measured E61 events in far detector prediction.
- Green: Non-CC0π background subtracted at E61 and re-added at SK – expect significant reduction in systematic uncertainties
- With matched fluxes:
  - E61 linear combination event rate the same as oscillated SK event rate.
  - Directly compare E61 measurement to observed SK events to obtain oscillation parameters.
  - E61 and SK have the same interaction material - same interaction cross-section.
  - No cross-section model, no effect from wrong model choice.

Pseudo-monochromatic Beams

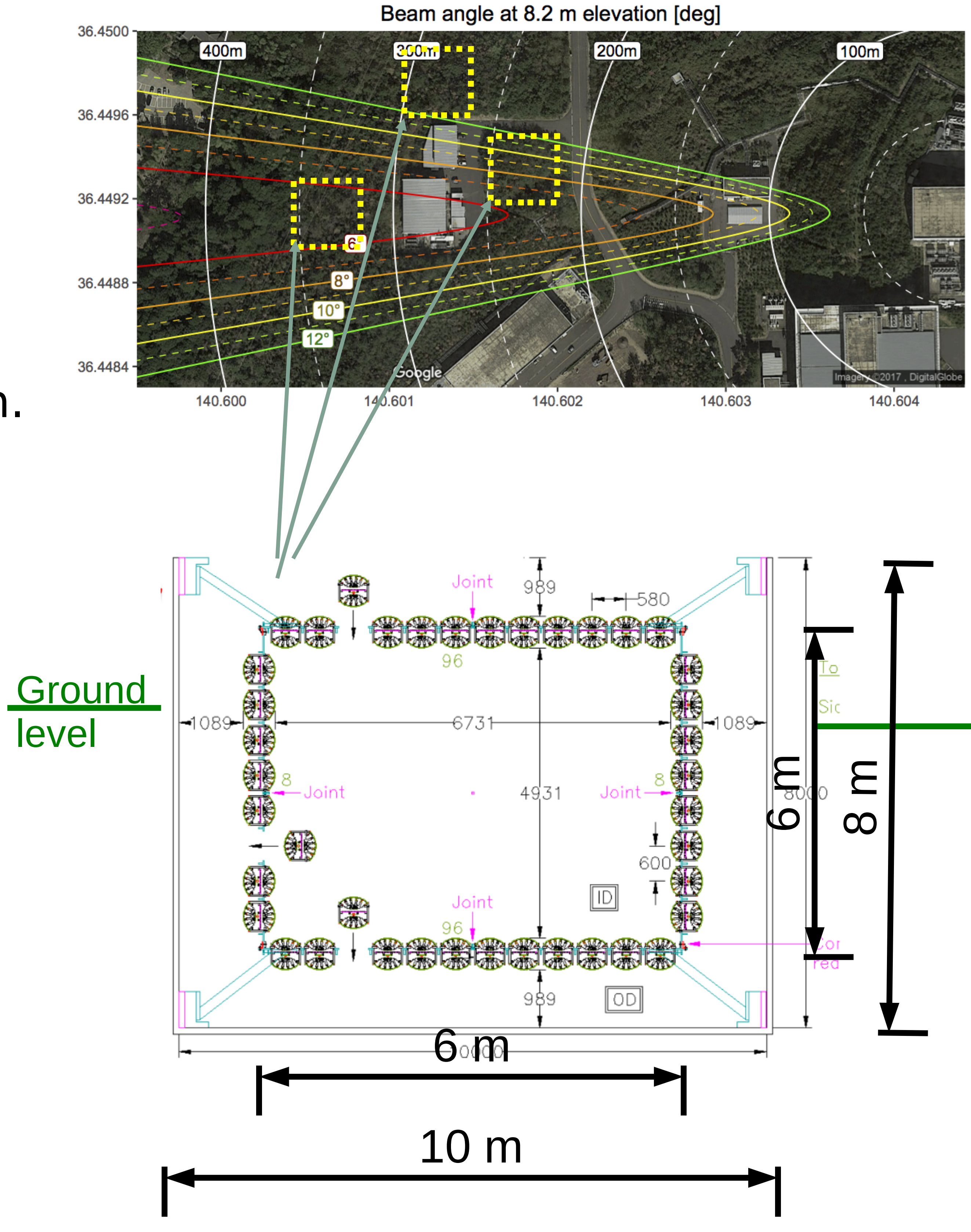




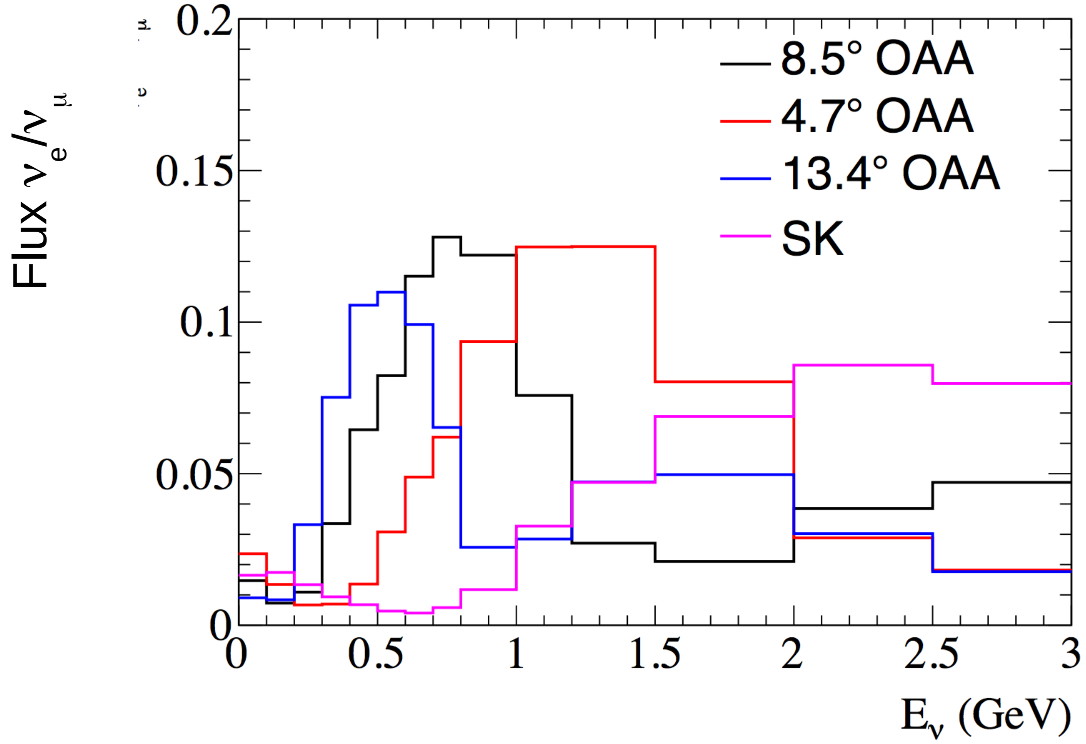
- Simulated energy distribution (true left, reconstructed right) for single muon candidates after applying the 1.2 GeV linear coefficients.
- Separation of QE and non-QE (including multi-nucleon) scatters.
  - Directly predict the effect of non-QE scatters in oscillation measurements and provide a unique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

Phase 0 – instrument portion near ND280

- Allows us to demonstrate detector/calibration precision.
- Provides a test detector for Hyper-K R&D.
- Physics goals:
  - Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ goal ~3% precision.
  - Expect ~3300 ν_e events below 1 GeV in 1×10^{21} POT with 76% purity.
  - Gd loading: n multiplicities in νN
- A range of locations being studied.



480 mPMT Modules



Phase 0 ν_e sample

- New selection
- 8.5 degrees off axis
- Shallow pit
- 2.4% statistical uncertainty, compared to 2.5% on the surface

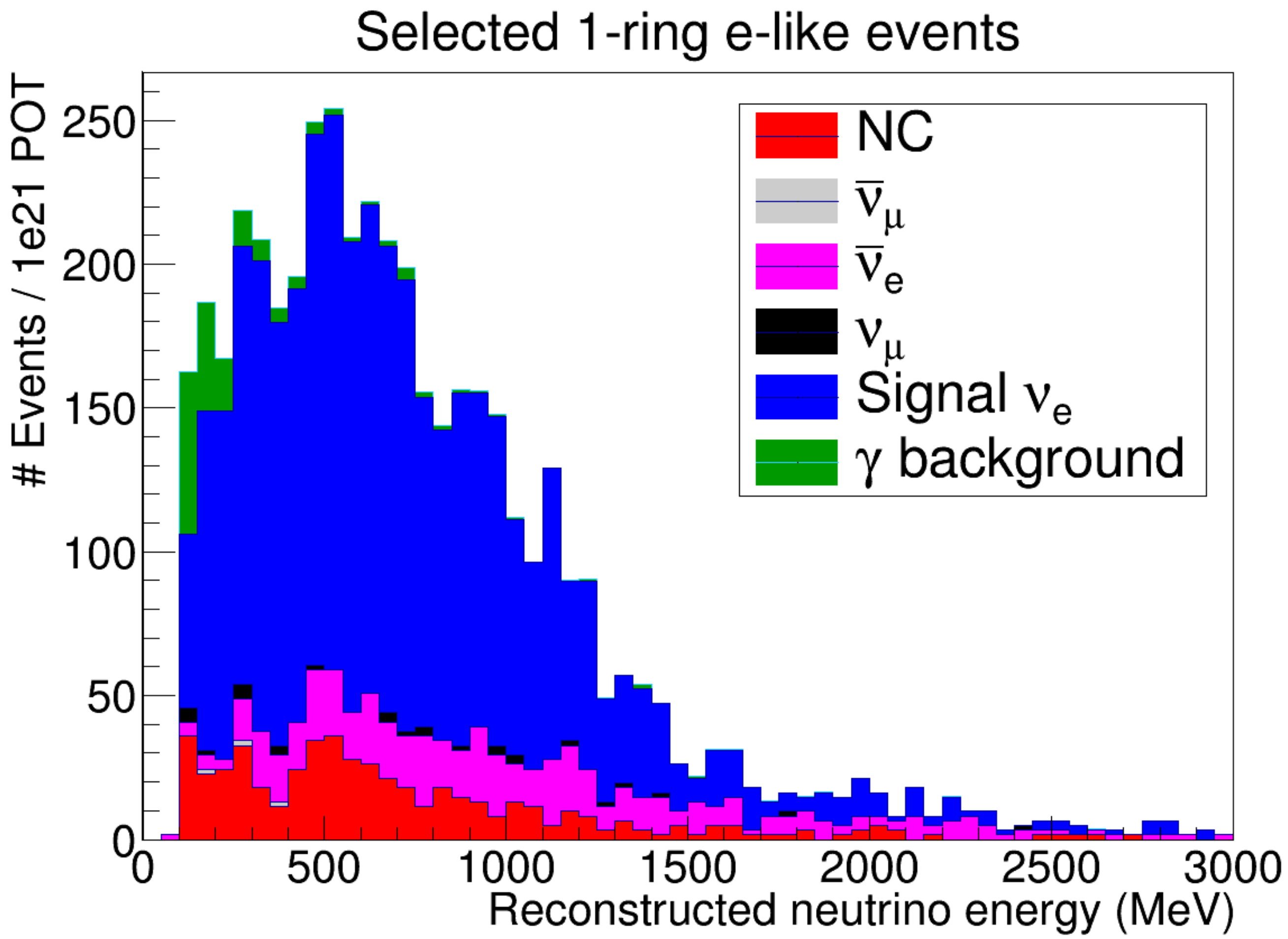
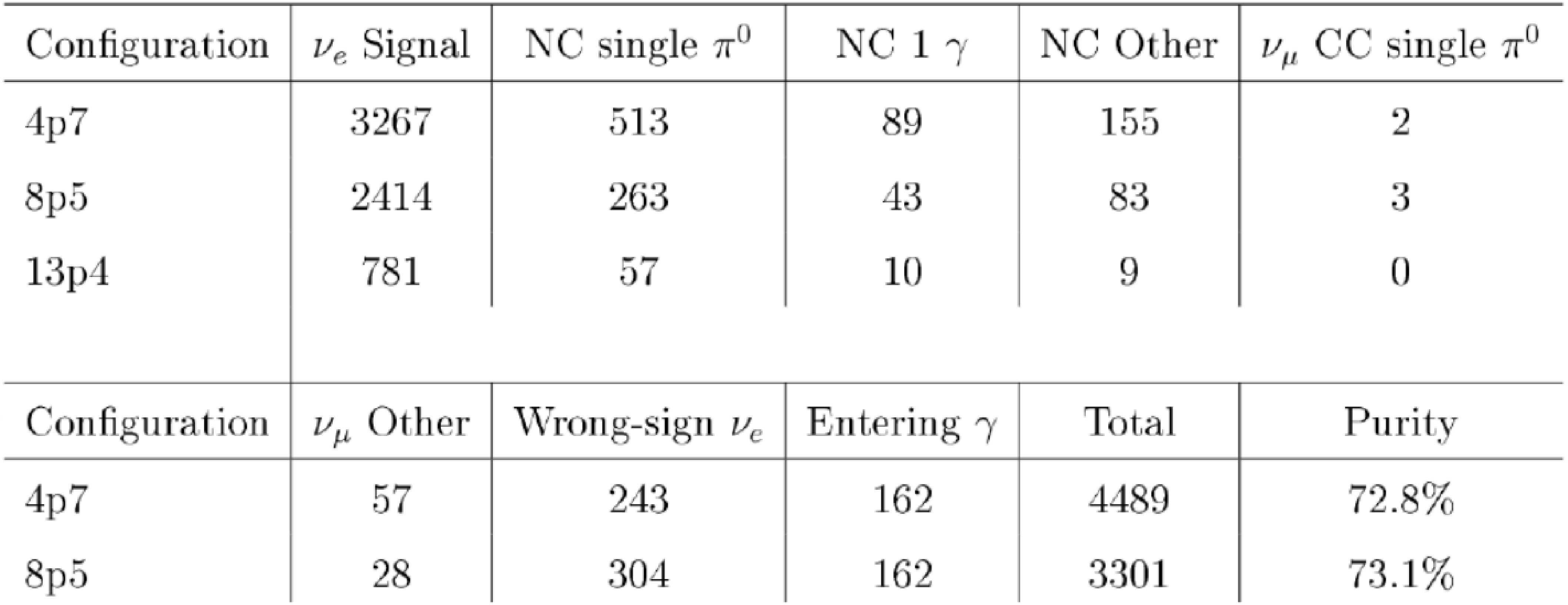


Figure and table from M. Scott

Gamma bg from J. Walker

For 10^{21} POT, $E_{rec} < 1$ GeV



Configuration	ν_e Signal	NC single π^0	NC 1 γ	NC Other	ν_μ CC single π^0
4p7	3267	513	89	155	2
8p5	2414	263	43	83	3
13p4	781	57	10	9	0

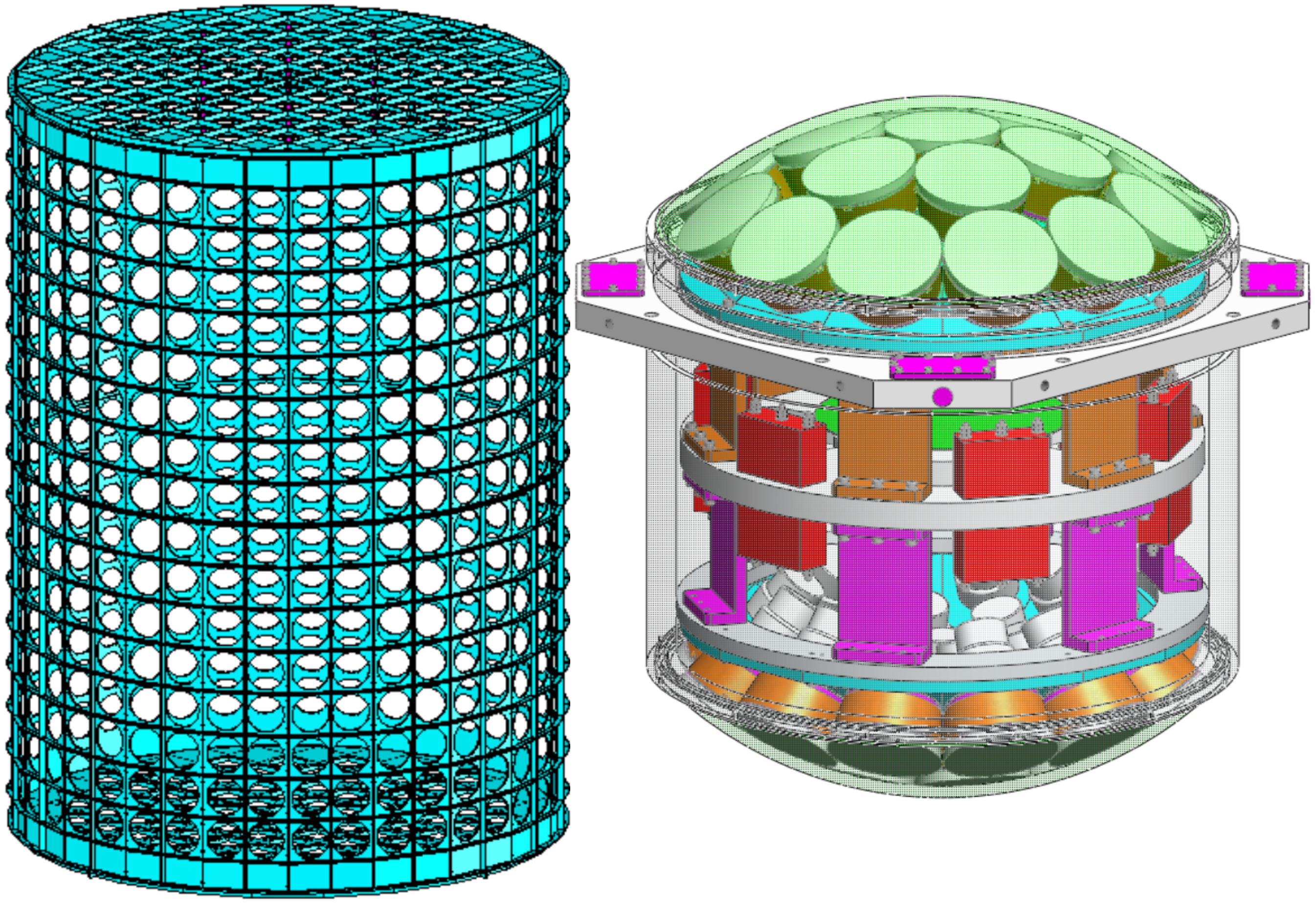
Configuration	ν_μ Other	Wrong-sign ν_e	Entering γ	Total	Purity
4p7	57	243	162	4489	72.8%
8p5	28	304	162	3301	73.1%

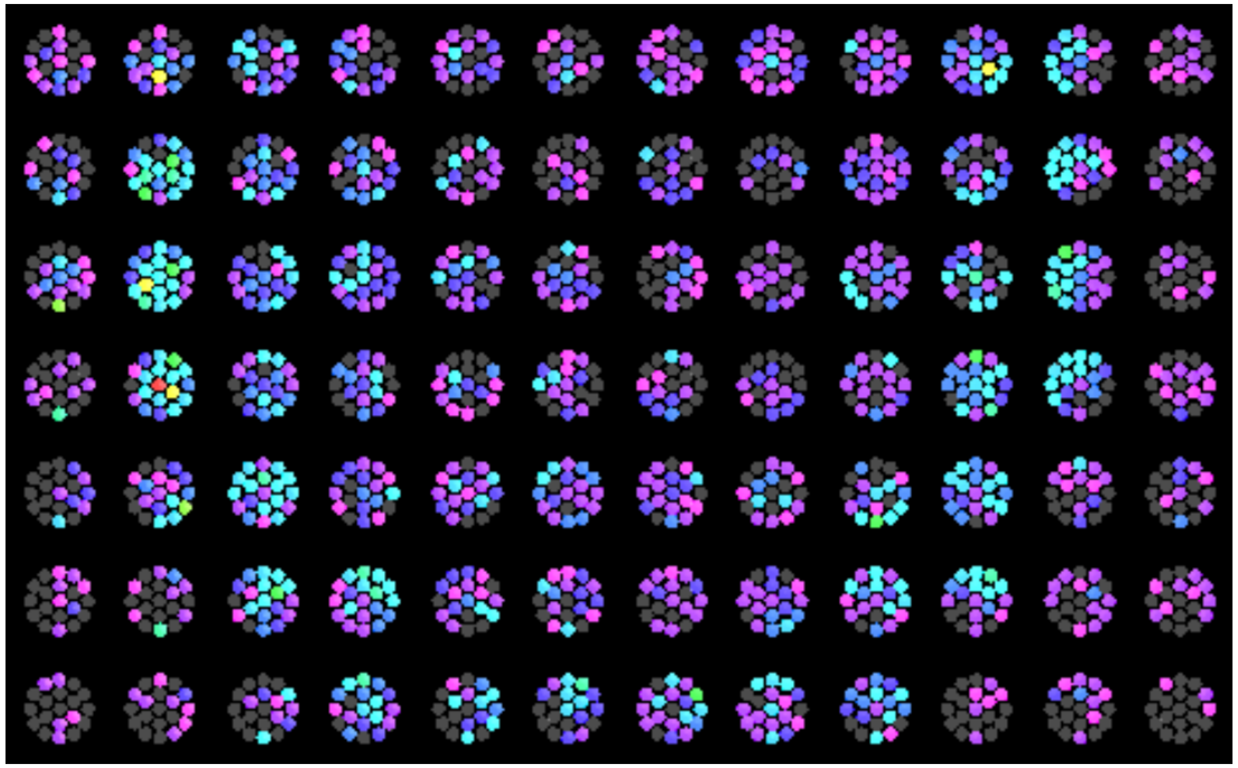
work in progress

only 4.7 and 8.5 degree good for cross-section measurement

Multi-PMT (MPMT) R&D

- Modular approach to PMT instrumentation.
  - Array of small (~3’’) PMTs instead of large one
    - Improved timing resolution → vertexing
  - Waterproofing, pressure protection, reduced cabling.
  - Readout electronics, monitoring, calibration devices located in vessel.
  - Directional information – improves reconstruction ability
- Leveraging 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.





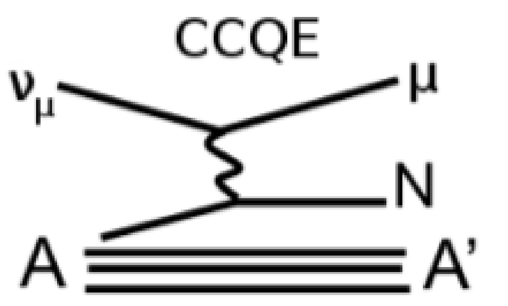
Gd loading

- Based on successes of ANNIE and EGADS
- Super-K will have Gd loading, so studies with near detector are important
- Statistical separation of ν and $\bar{\nu}$ events will be possible

Charged Current Quasielastic (CCQE):

ν_μ : $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons

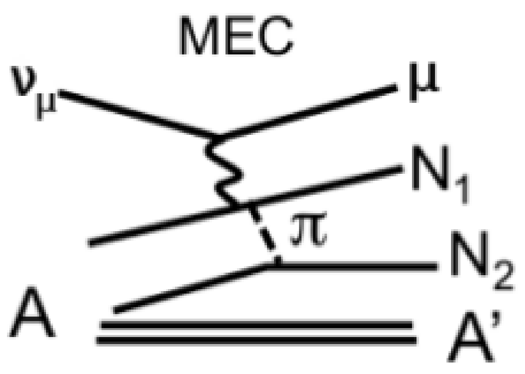
$\bar{\nu}_\mu$: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron



n-particle n-hole (CCnpnh), e.g. by meson exchange (MEC):

ν_μ : $\nu_\mu + (n + p/n) \rightarrow \mu^- + p + p/n$ 0 - 1 neutron

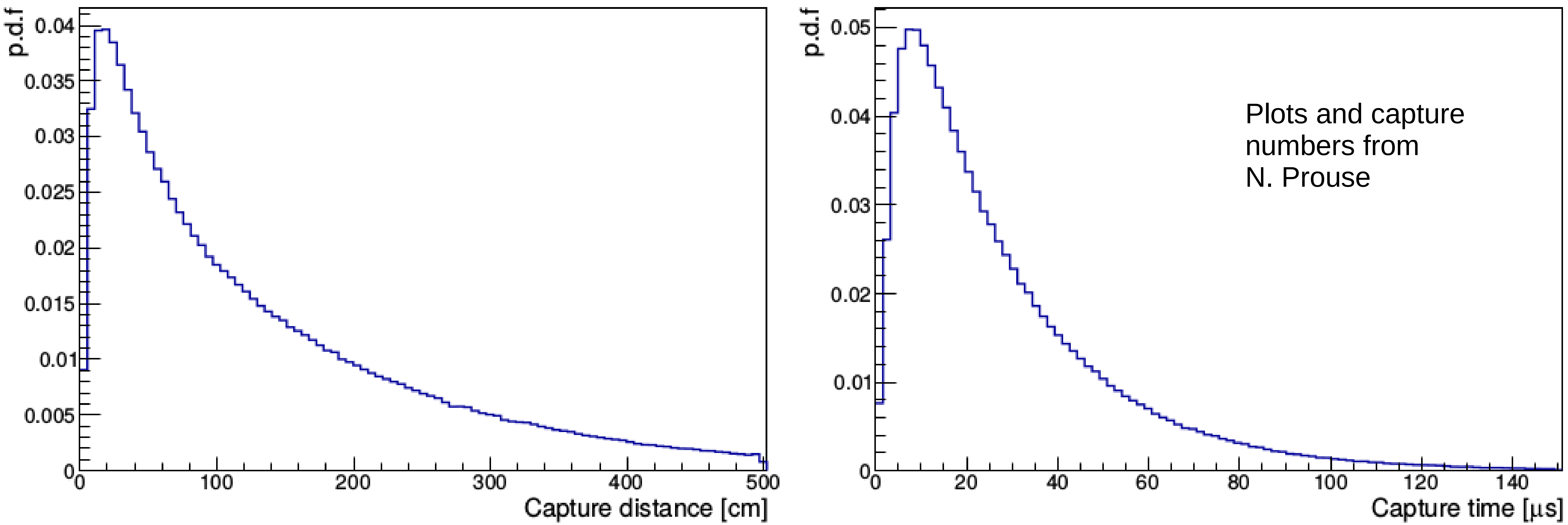
$\bar{\nu}_\mu$: $\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$ 1 - 2 neutrons



- FSI will complicate this simple picture
  - but can measure number of neutrons produced in ν interactions on water + Gd

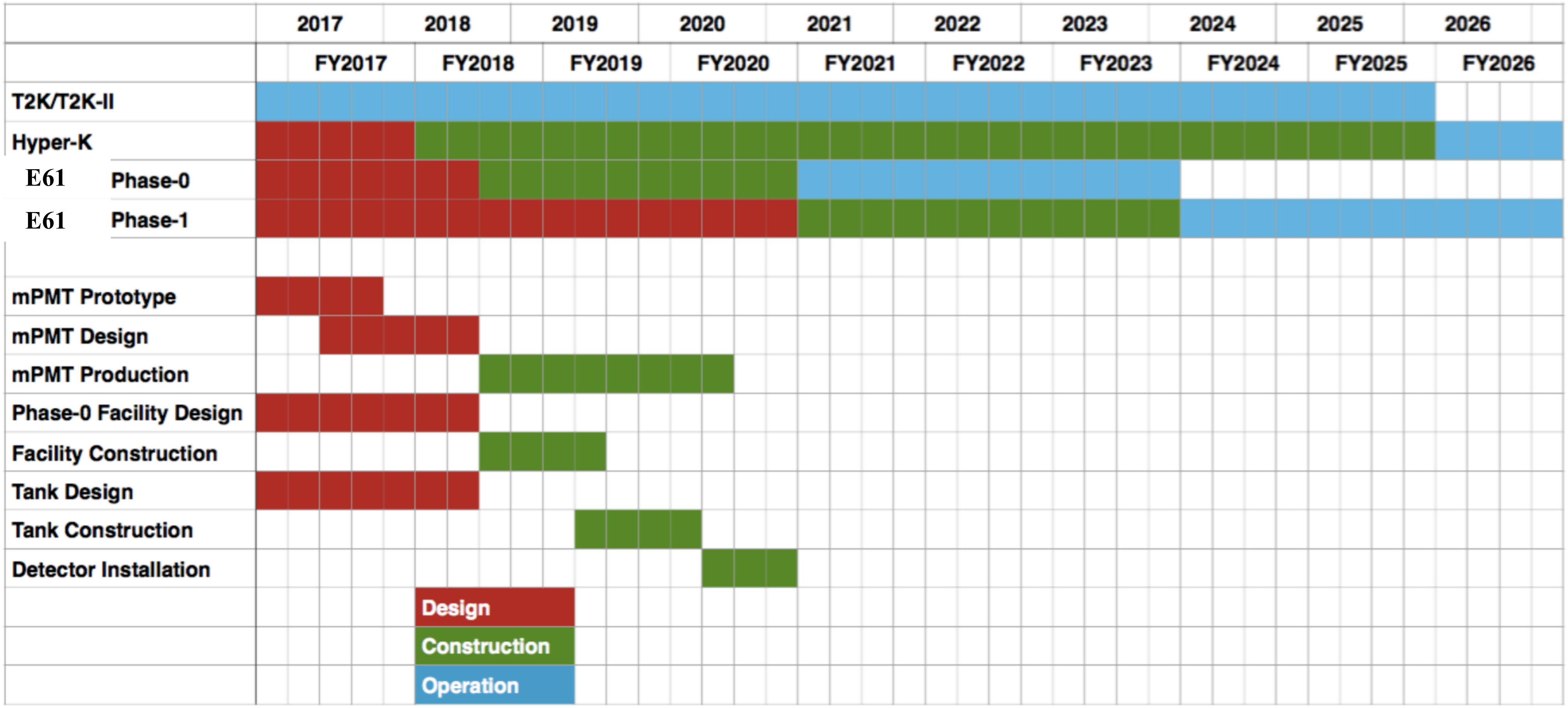
neutron signal in surface detector

- 93% of neutrons capture within detector:
  - 72% of captures on ^{157}Gd
  - 16% of captures on ^{155}Gd
    88% of captures on Gadolinium
  - 12% of captures on Hydrogen
  - <0.1% on Oxygen & other isotopes



Plots and capture numbers from N. Prouse

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.

Conclusions

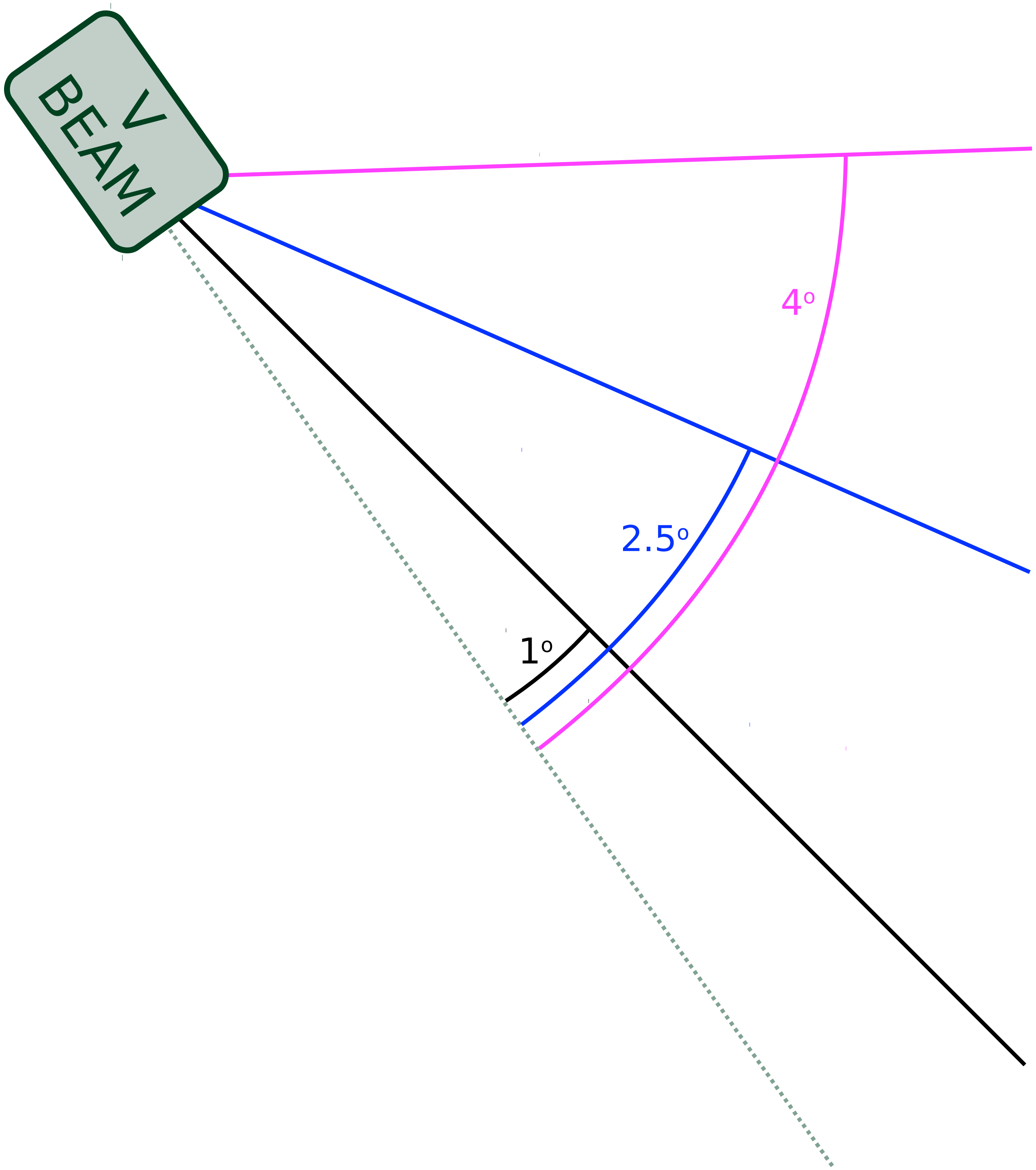
- E61 collaboration newly formed from nuPRISM and TITUS
  - An off-axis angle spanning water Cherenkov detector with Gd for neutron tagging
- E61 detector will help reduce model dependence on future oscillation experiments
- Measure effect of different neutrino interaction models using pseudo mono-energetic beams to feed back to neutrino interaction community

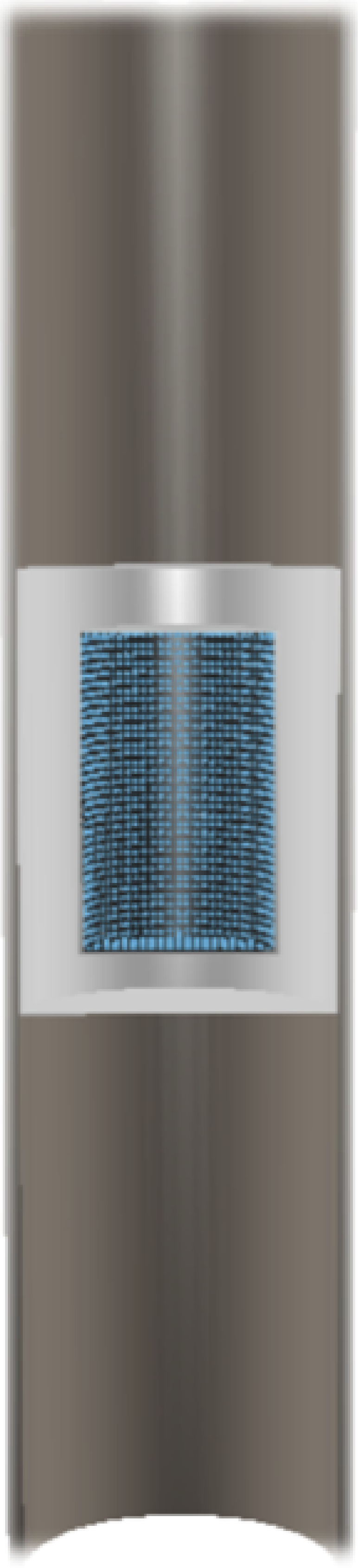
Thanks!

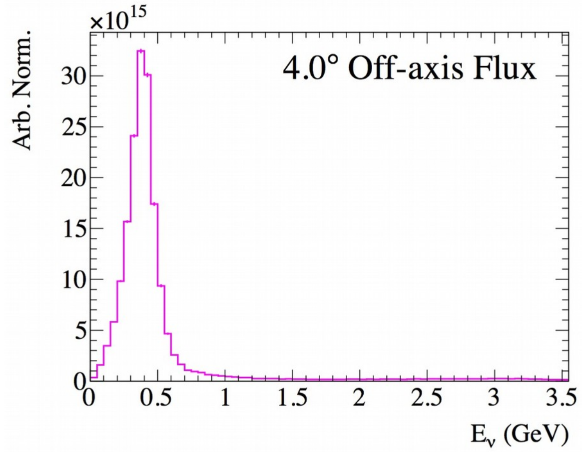
And enjoy the rest of your stay in...

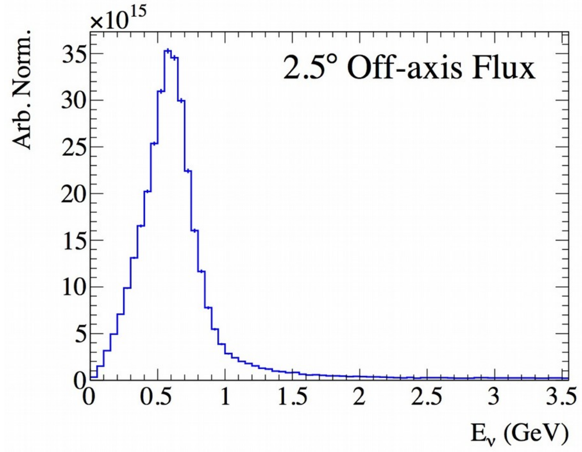
The End

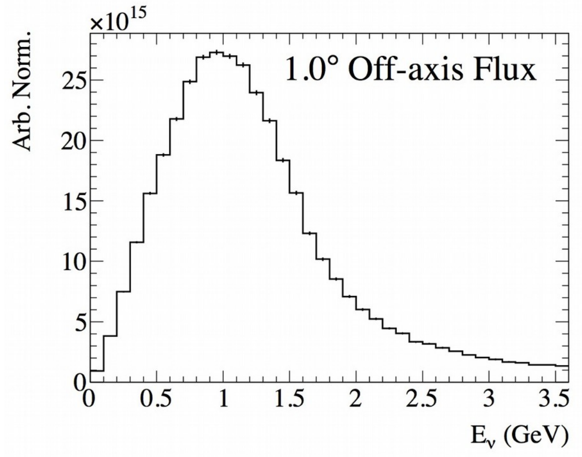
E61 Off Axis Concept



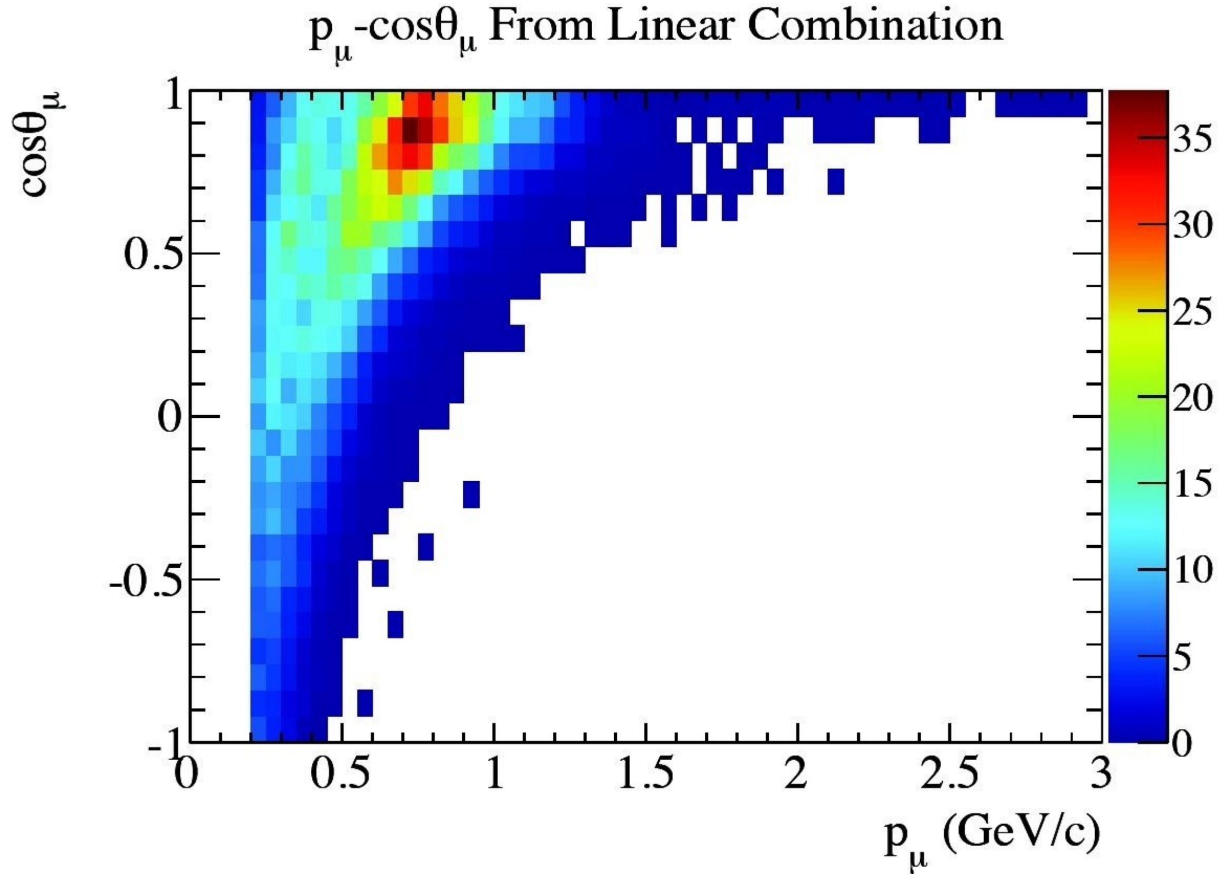




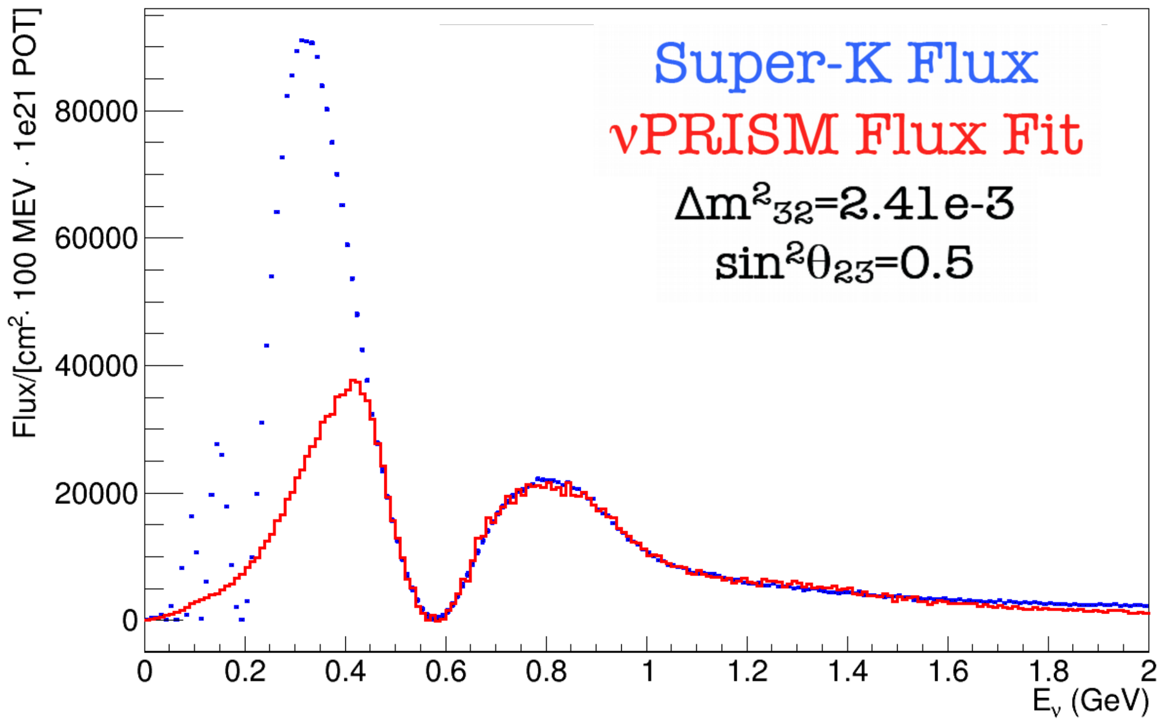




Muon Neutrino Disappearance



p_μ-$\cos\theta_\mu$ From Linear Combination

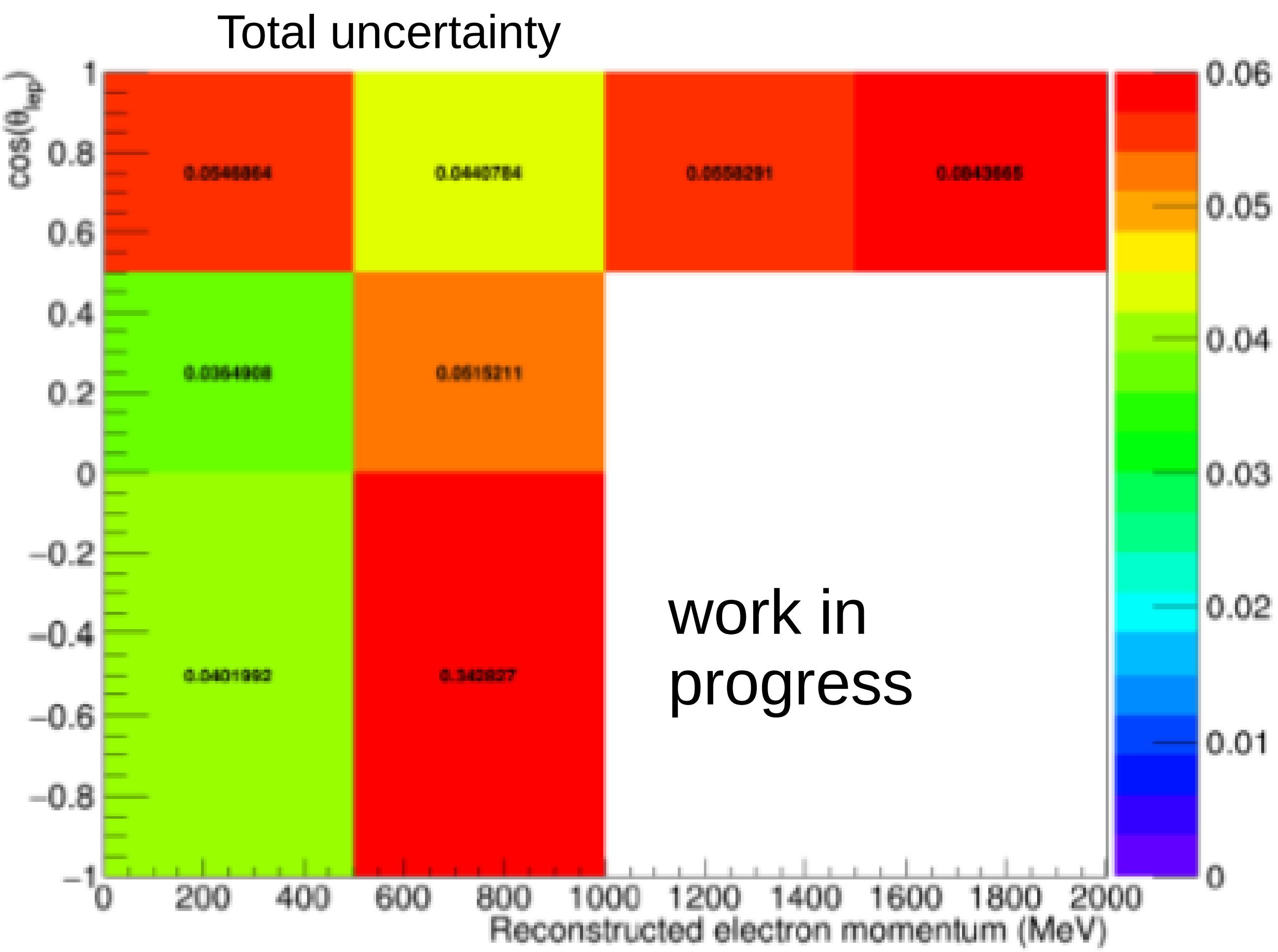


- Instead of monochromatic beams, use a linear combination to produce an oscillated flux.

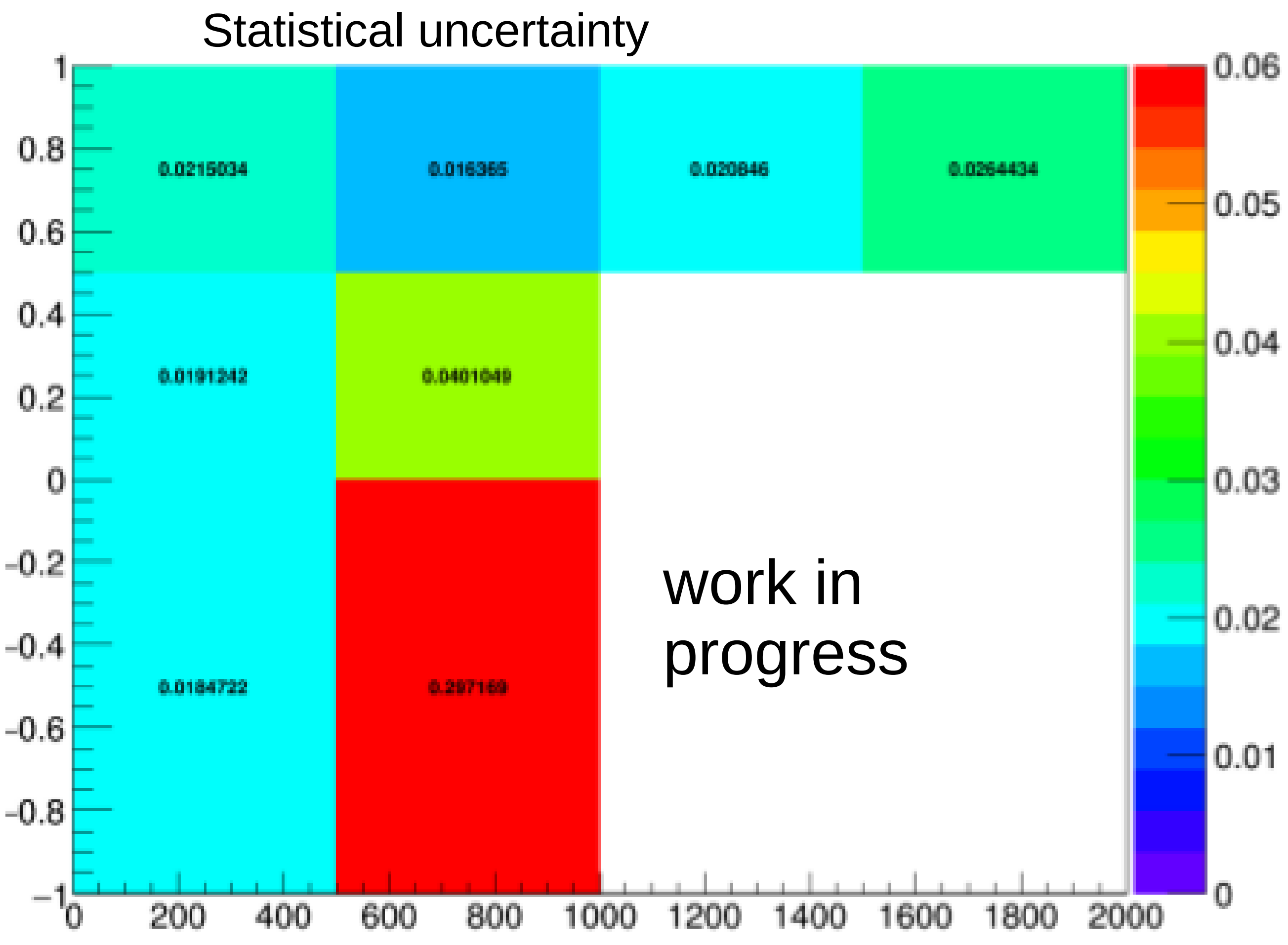
$$\Phi_{SK}P_{\nu_\mu\to\nu_\mu}(E_\nu;\theta_{23},\Delta m^2_{32}) = \sum_{i}^{\text{Off-axis bins}} c_i(\theta_{23},\Delta m^2_{32})\Phi_i^{\nu P}(E_\nu)$$

- 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 E61 off-axis fluxes to give the oscillated spectrum.

Phase 0 ν_e/ν_μ cross-section err for $4\text{x}10^{21}$

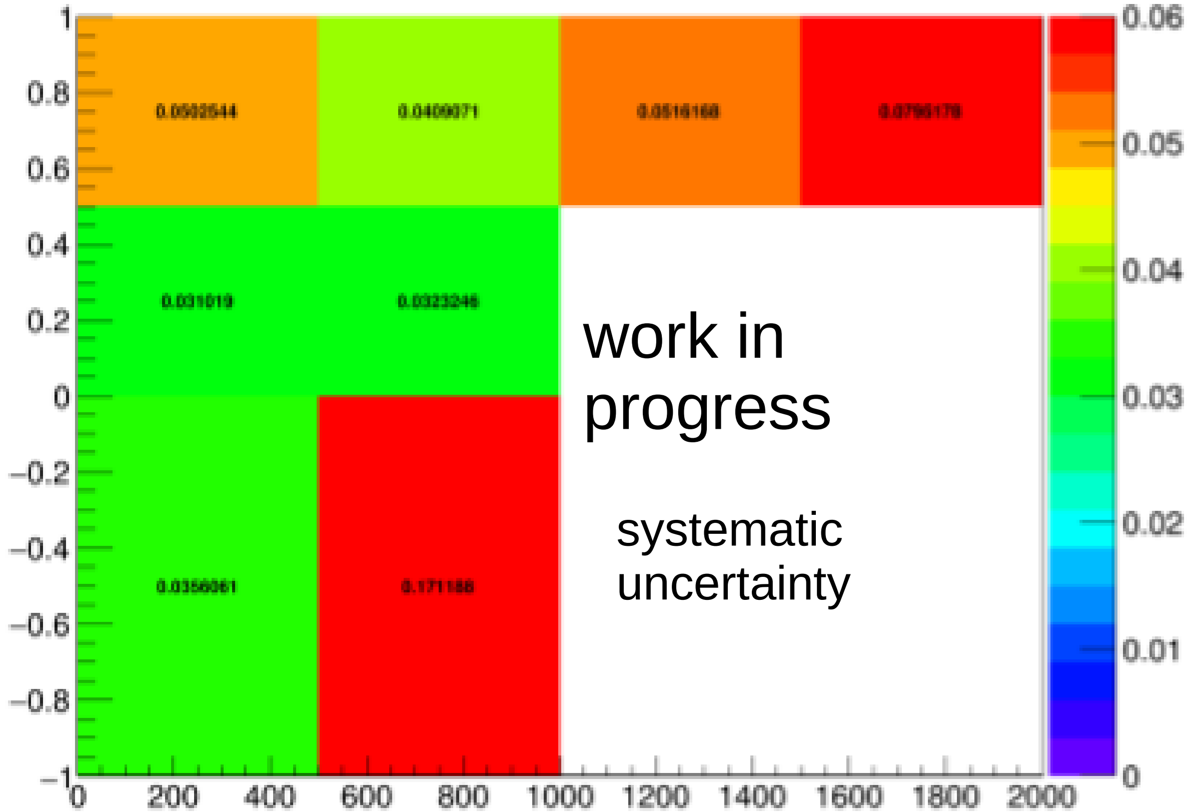

Total uncertainty

work in progress


Statistical uncertainty

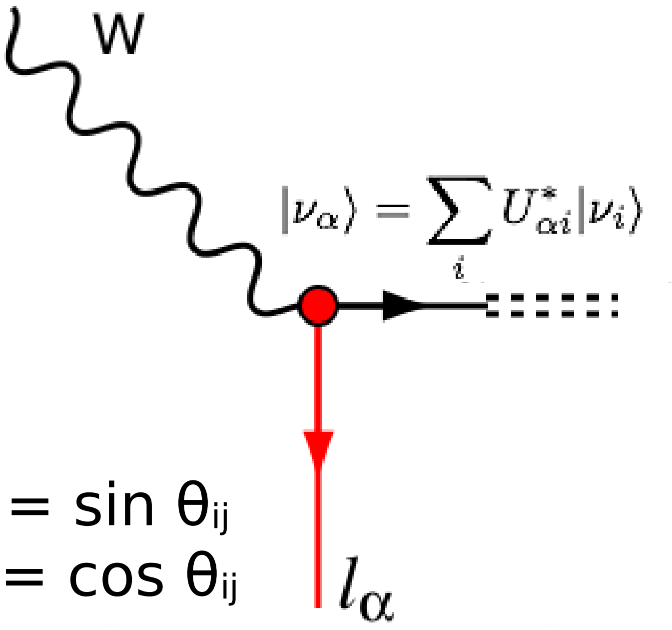
work in progress

- Total error on parameter on left
- Statistical uncertainty on right
- Systematics on bottom
- likelihood fit to ν_e and ν_μ
- used correlated flux uncertainty
- one independent parameter for each bin in ν_e p, cos θ


work in progress

systematic uncertainty

Mixing of Three Neutrinos



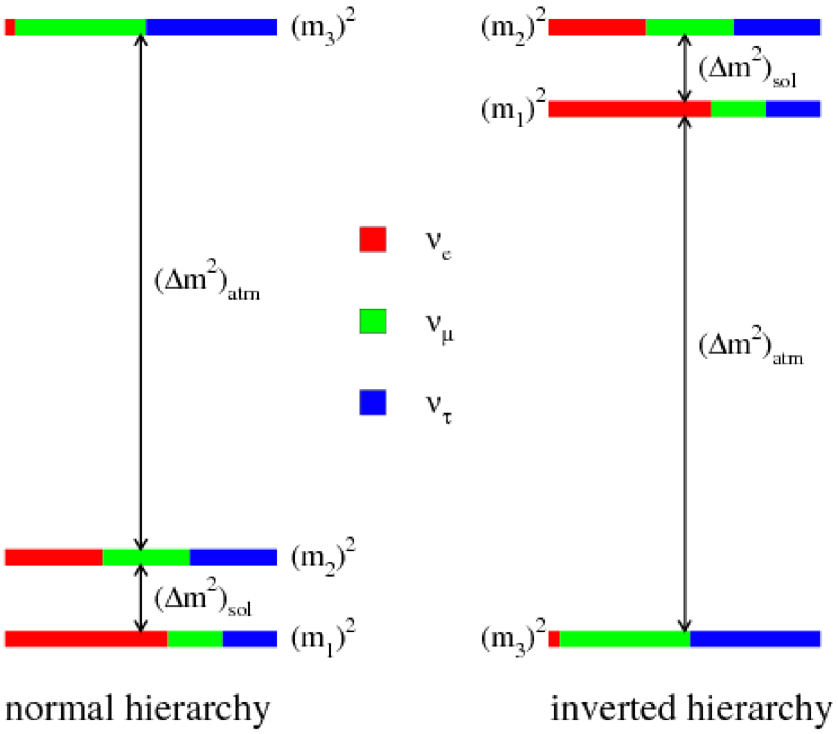
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

s_{ij} = sin θ_{ij}
c_{ij} = cos θ_{ij}

“standard” parametrization

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- Two mass splittings known
  - “ordering” still unknown
- One complex Dirac phase δ

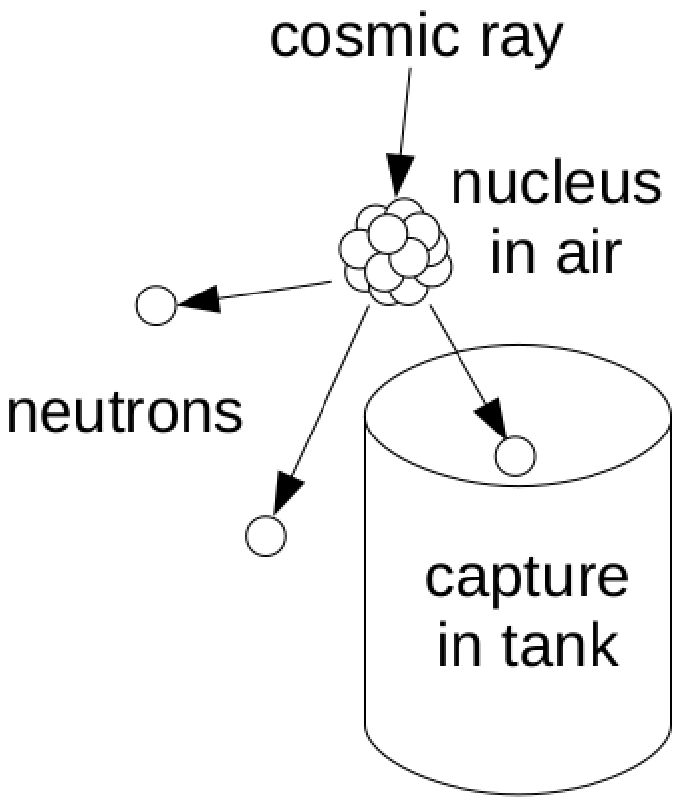


normal hierarchy inverted hierarchy

neutron background studies underway

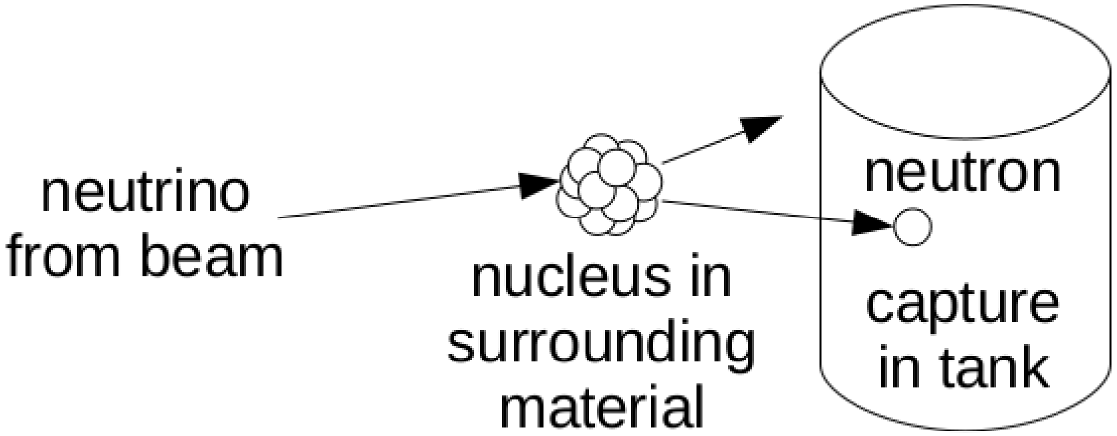
Studies of backgrounds, using GEANT4 are underway
Measurements of neutrons with 3He detector at J-PARC planned

- Cosmic spallation neutrons



  - Mostly at top of detector
  - Rate should be manageable
  - Small overburden could be useful

- Beam induced background neutrons

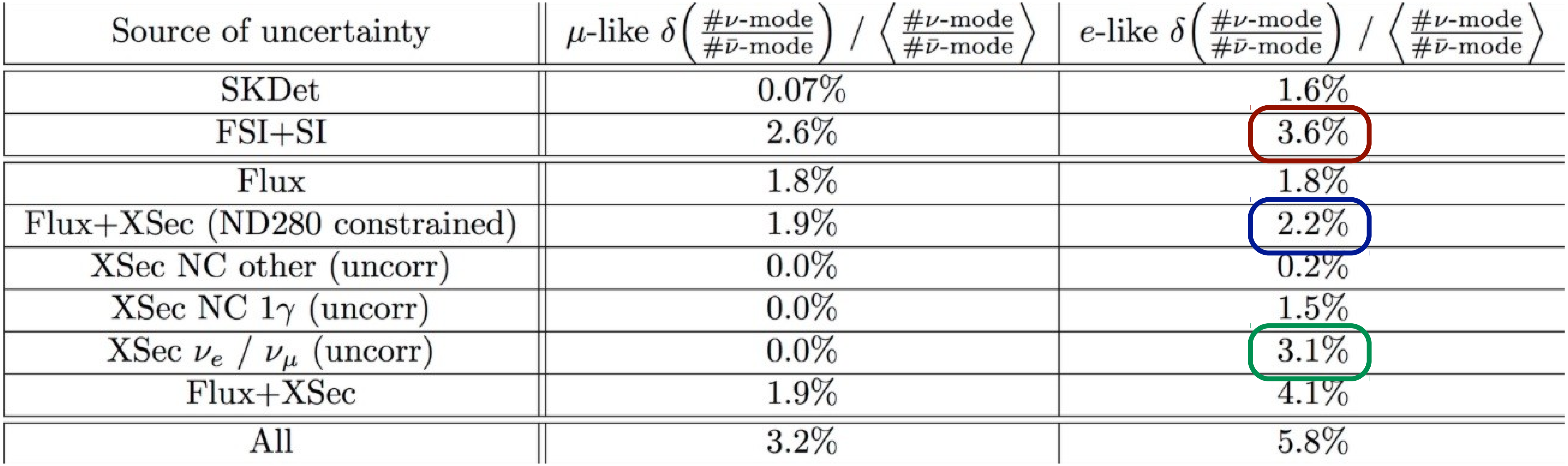


  - Rate could be significant
  - Possible incoming lepton
  - Attempt cuts on position and time
  - Outer detector region could help

slide from
N. Prouse

Current T2K Systematic Errors

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

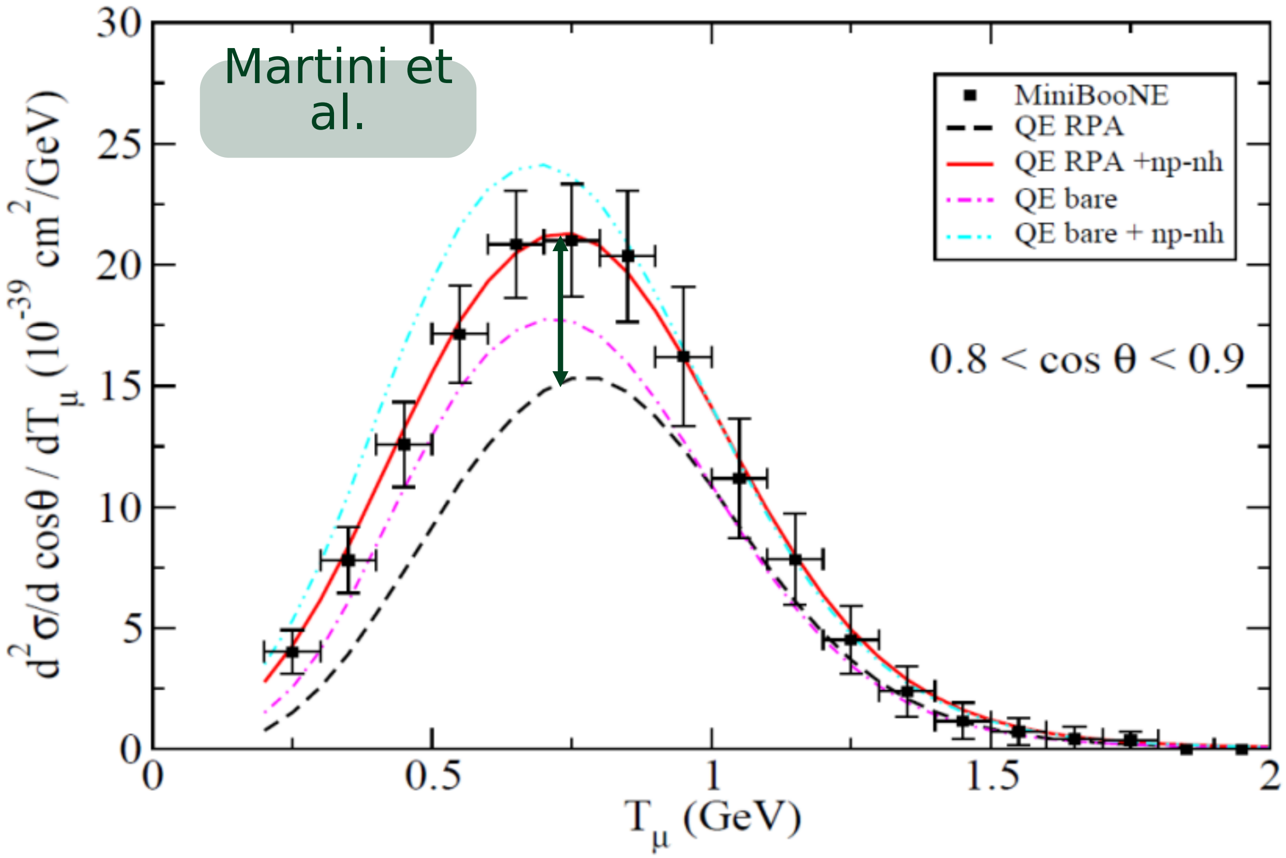


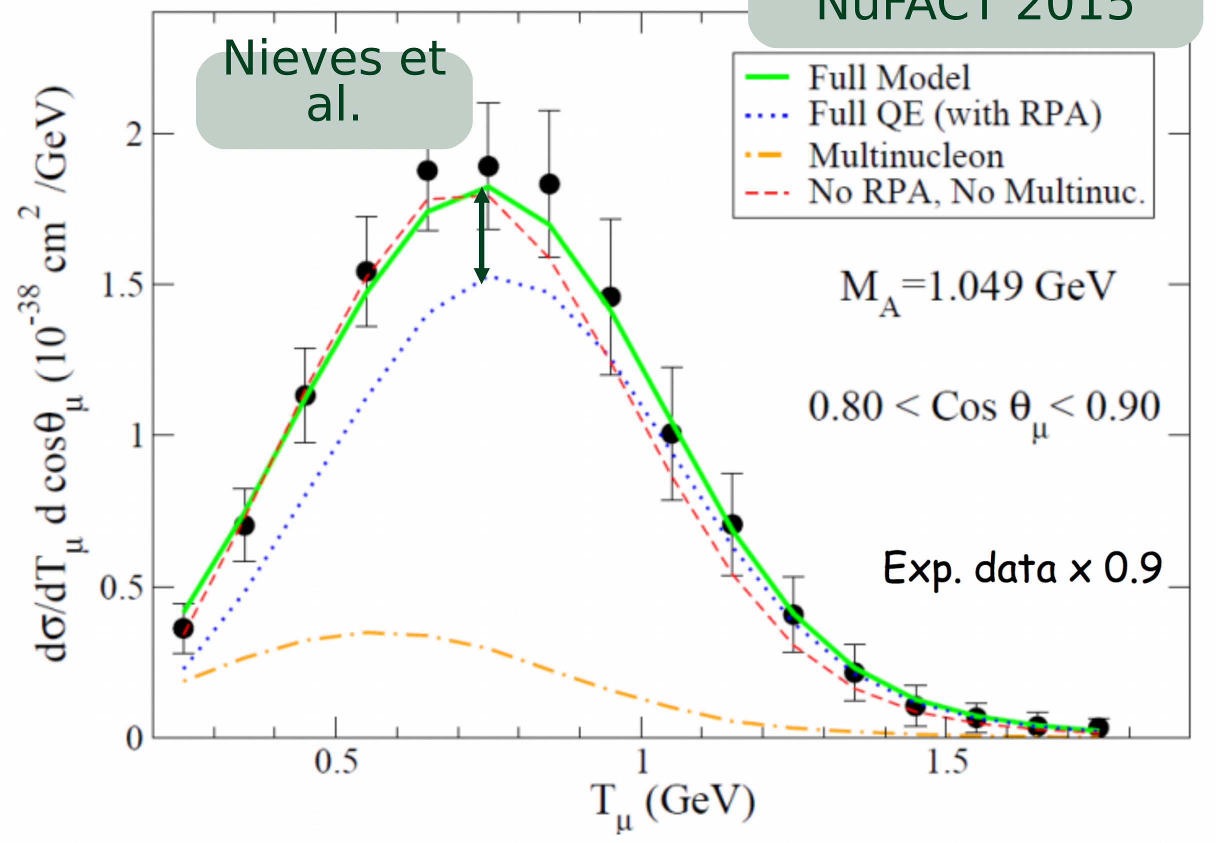
Source of uncertainty	μ-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$	e-like $\delta\left(\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right) / \left\langle\frac{\#\nu\text{-mode}}{\#\bar{\nu}\text{-mode}}\right\rangle$
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 $\nu_e/\bar{\nu}_e$ 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

M. Martini
NuFACT 2015

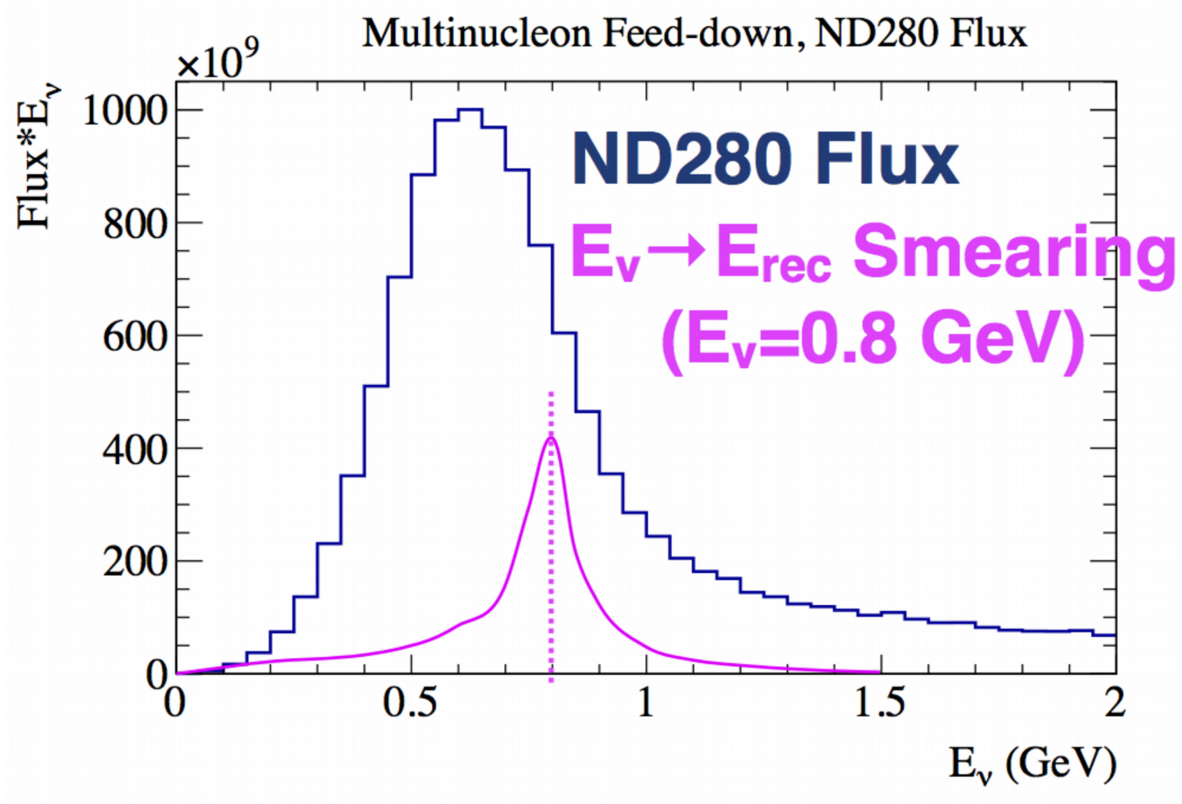


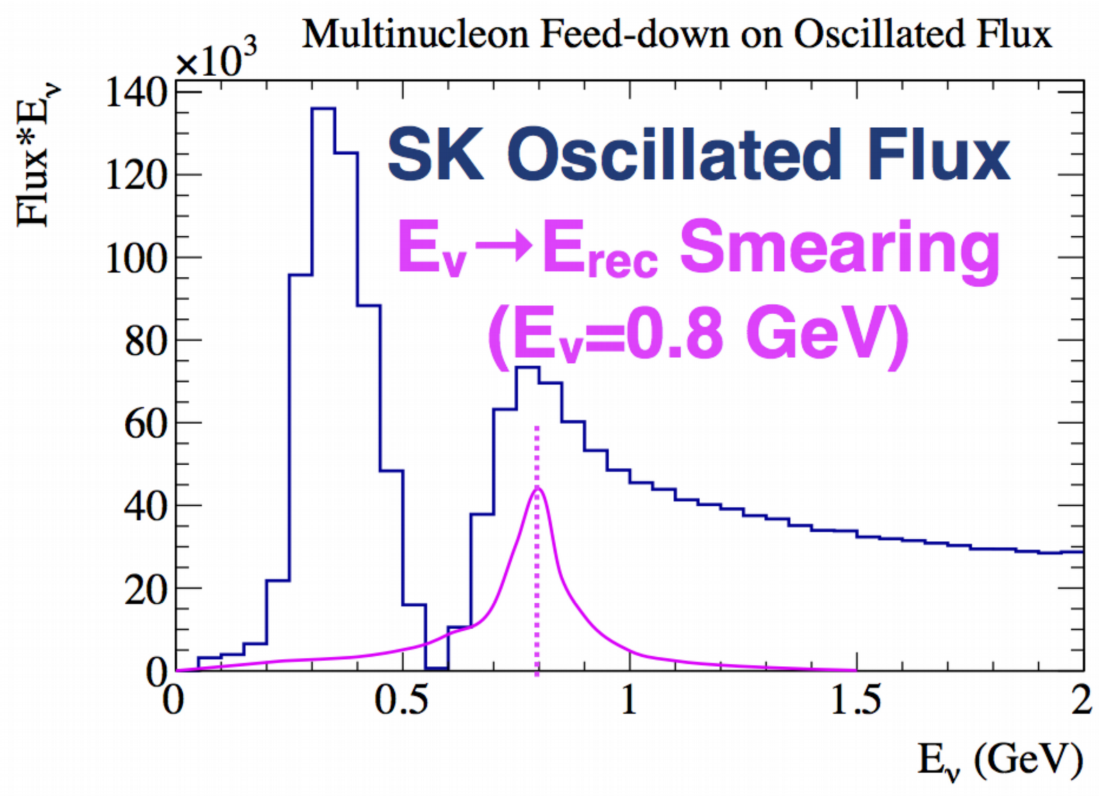


- Many different theoretical models.
- Martini et al. and Nieves et al. calculations are both consistent with MiniBooNE data within the MiniBooNE flux uncertainties.
- The np-nh contributions can differ by a factor of 2 in the region of interest.
- Predict different rates for neutrinos vs anti-neutrinos.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

Near Detector Constraint

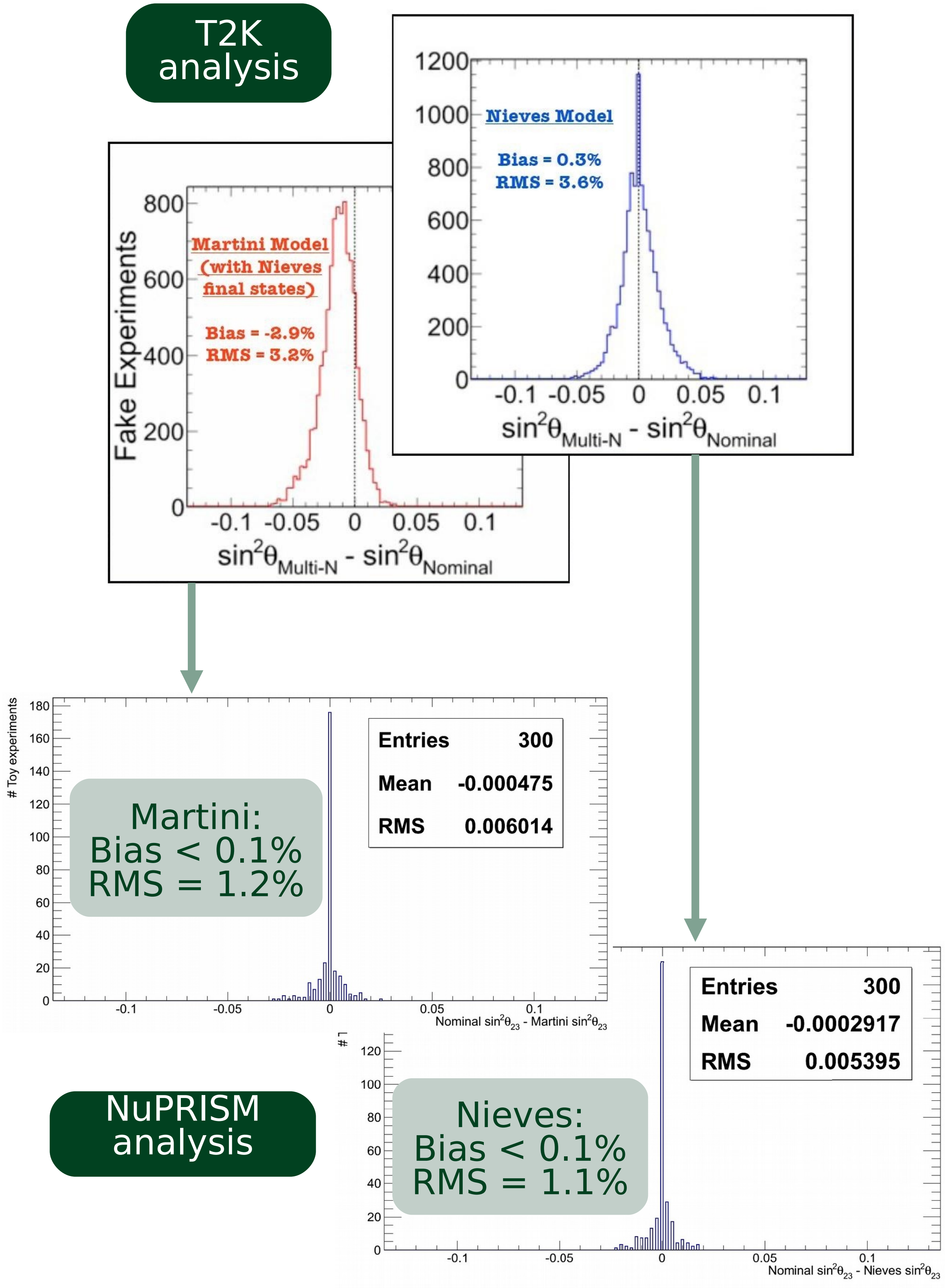
- Oscillations result in different fluxes at the near and far detectors.
  - Causes issues constraining interaction model that predicts far detector event rates.





- 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.

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.