νPRISM TITUS

J-PARC **E61** EXPERIMENT

REDUCING CROSS-SECTION UNCERTAINTIES IN NEUTRINO OSCILLATION EXPERIMENTS

NUFACT 2017

UPPSALA

SEPTEMBER 29TH, 2017

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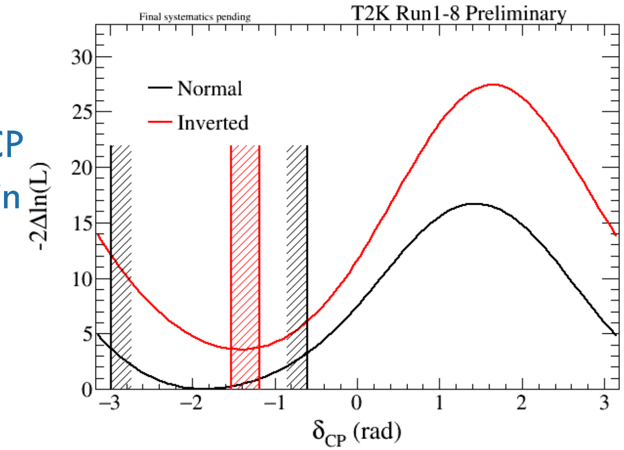
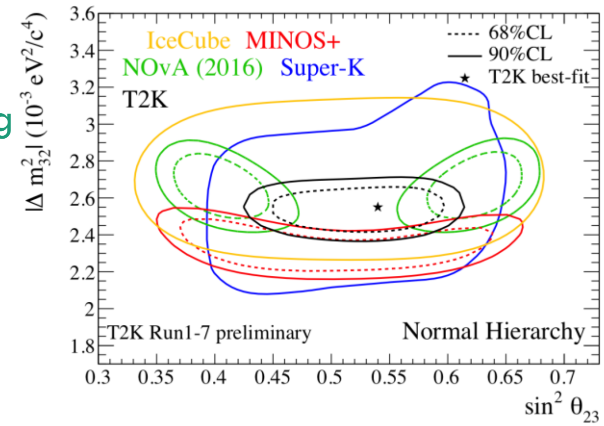
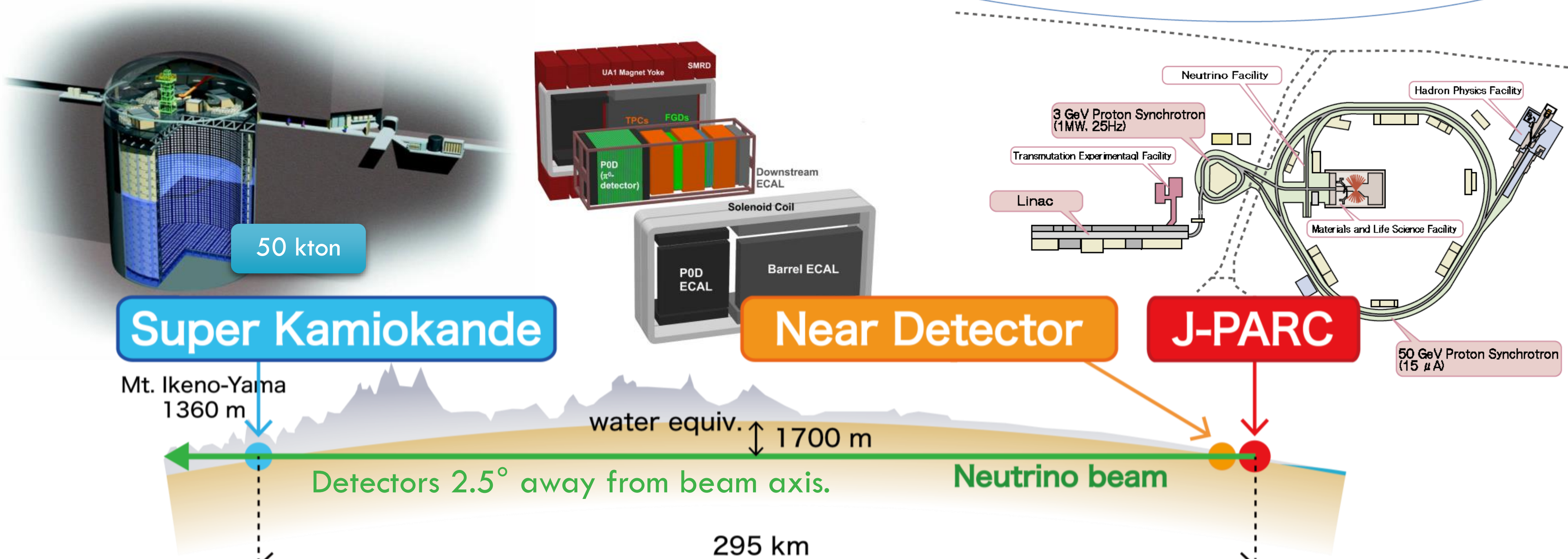
THE TOKAI-TO-KAMIOKA (T2K) EXPERIMENT

Exclusion of CP conservation in lepton sector at **2σ**.



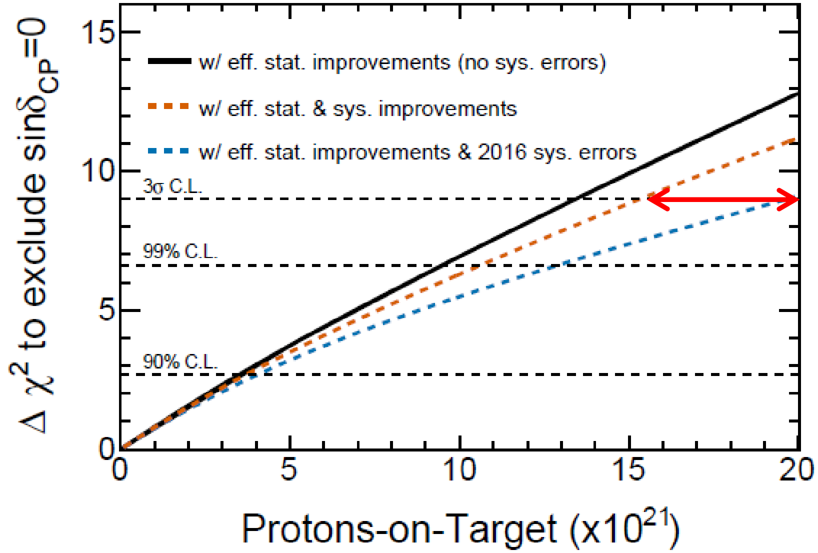
World-leading measurements of $\sin^2\theta_{23}$ and Δm^2_{23}.

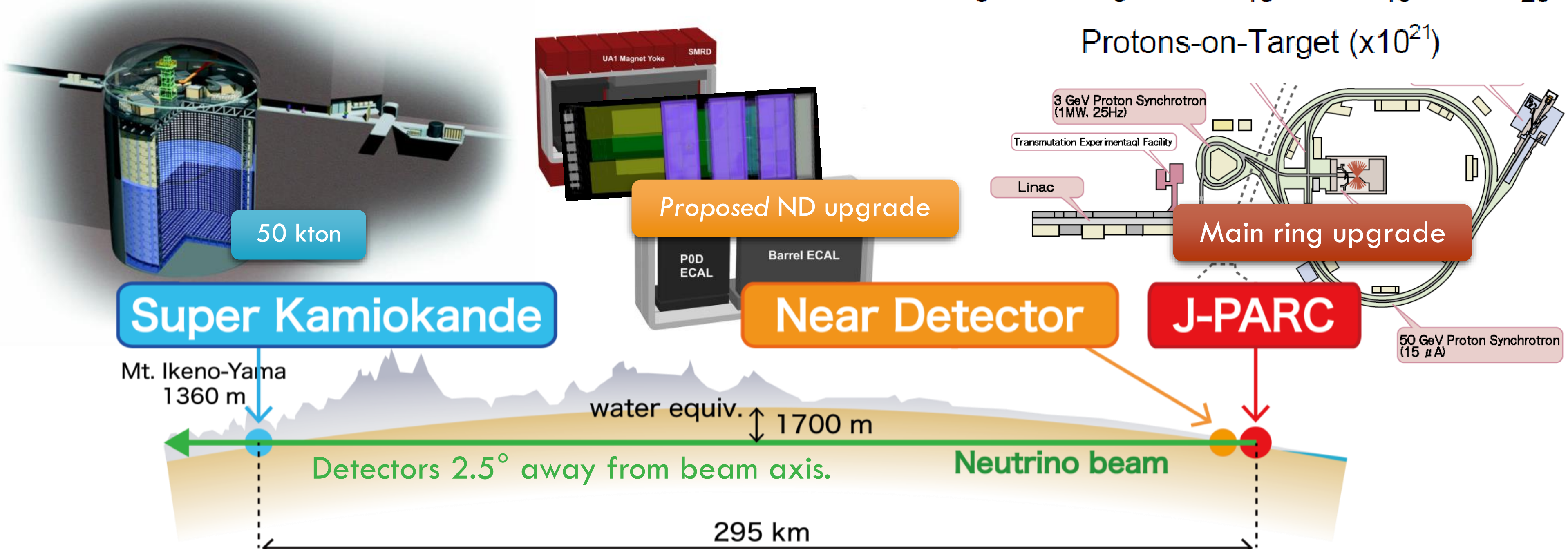




PROPOSED EXTENDED RUN OF T2K (T2K-II)

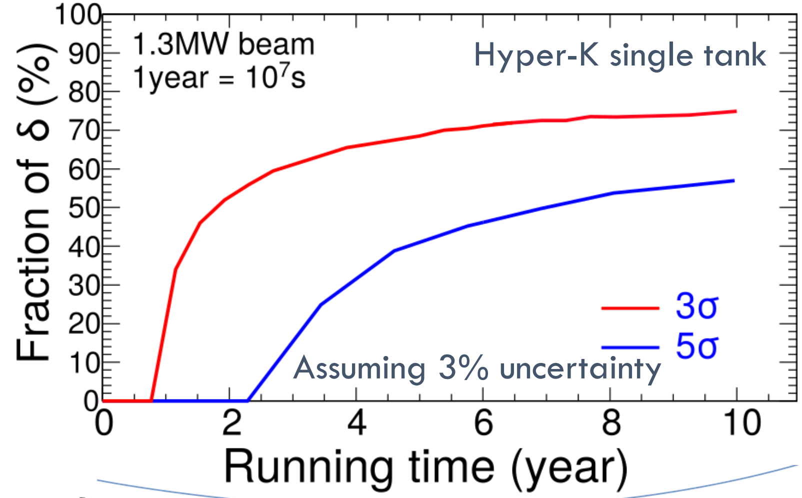
- *Proposal* to extend T2K run from 7.8×10^{21} to 20×10^{21} POT. K. Abe et al, arXiv:1609.04111
- Benefit from:
  - Accelerator upgrade to 800 kW (and then 1.3 MW).
  - *Proposed* near detector upgrade.
  - *Proposed* intermediate water Cherenkov detector: **E61**
- 3σ sensitivity to maximal CP violation.

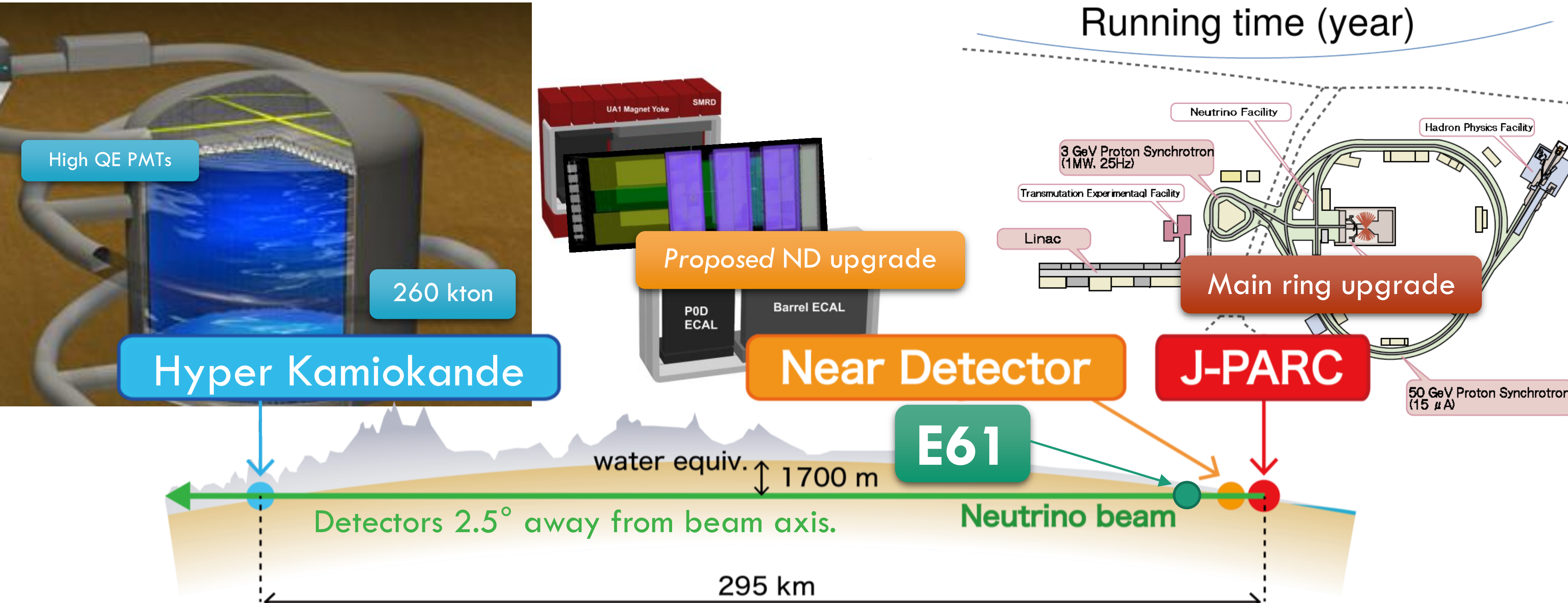




HYPER KAMIOKANDE PROJECT

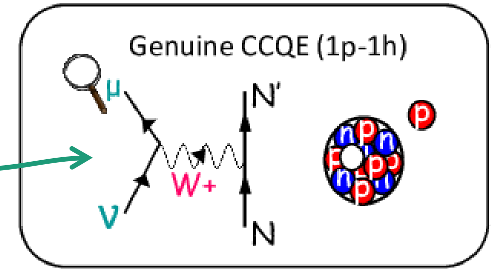
- Next-generation water Cherenkov detector with extensive Physics program.
- 5σ sensitivity for a wide range of δ_{CP} values.
  - Requires strong constraints on systematic uncertainties.
- A **kiloton-scale intermediate water Cherenkov** detector is foreseen as part of the strategy to mitigate the effect of neutrino interaction uncertainties: **E61**

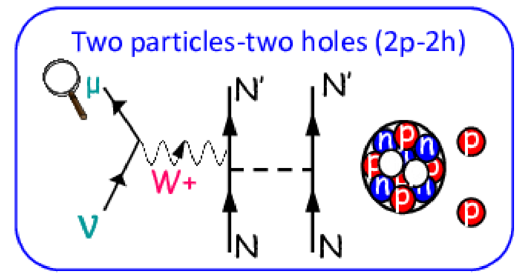




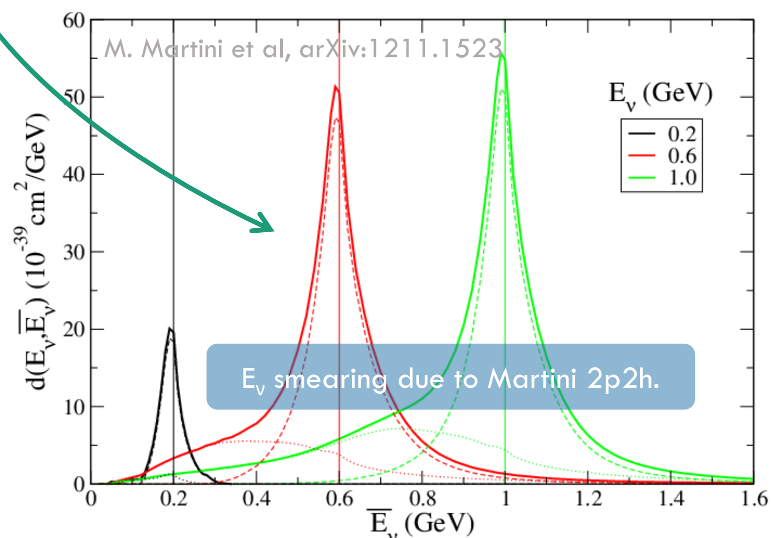
MEASURING NEUTRINO ENERGY

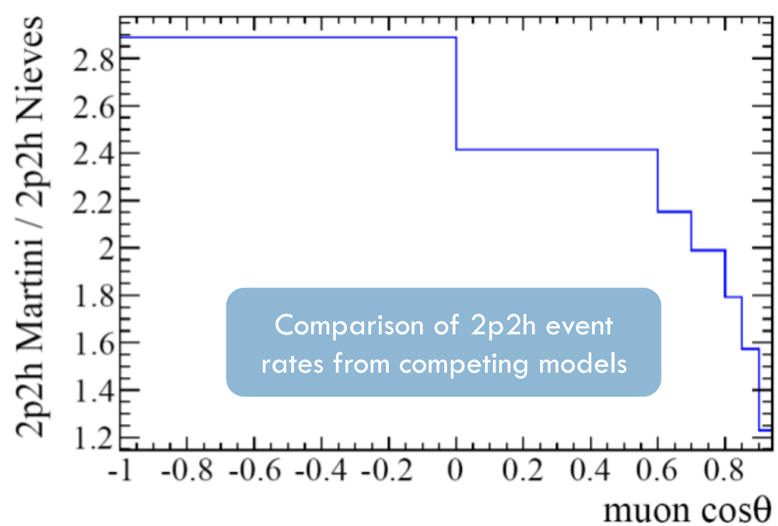
- Model assumptions play important role in inferring neutrino energy from detected neutrino-nucleus interaction products.
- In Super-K charged lepton kinematics are measured and CCQE dynamics are assumed.
  - Multi-nucleon contributions to CCQE cross-section can bias E_ν significantly.
  - Large uncertainties from final state and secondary interaction models.
- Calorimetric measurements suffer from similar model dependence.
  - For example, through uncertainties in the multiplicity of (undetected) neutrons.





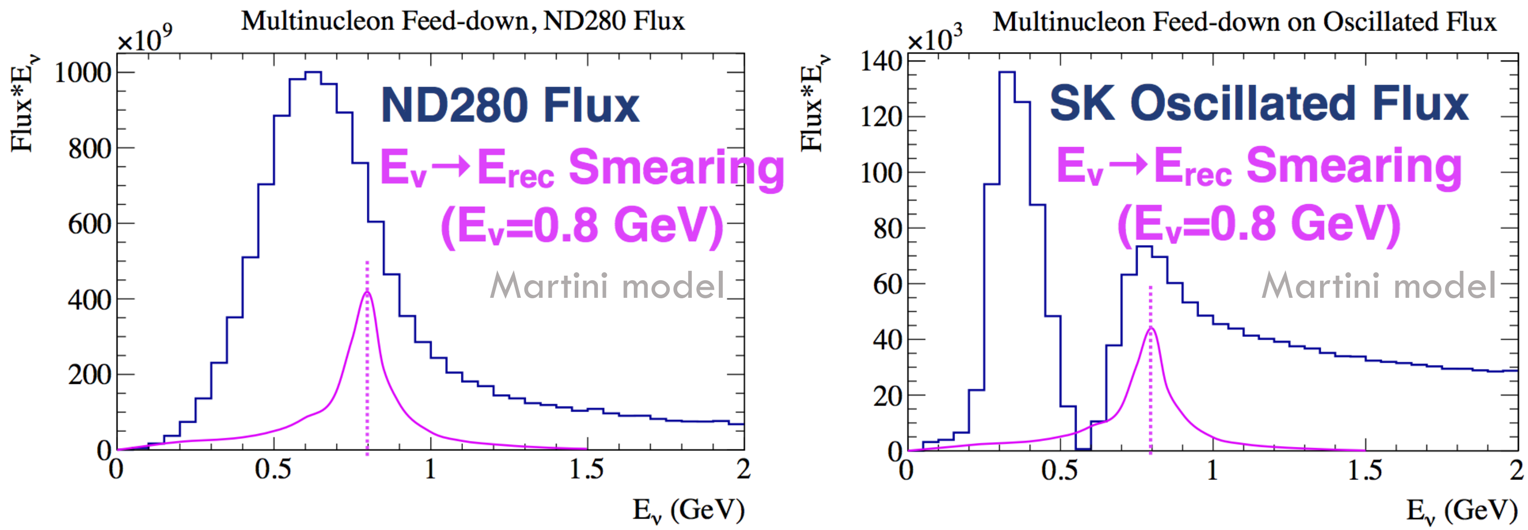
T. Katori, M. Martini, arXiv:1611.07770





NEAR DETECTOR CONSTRAINTS

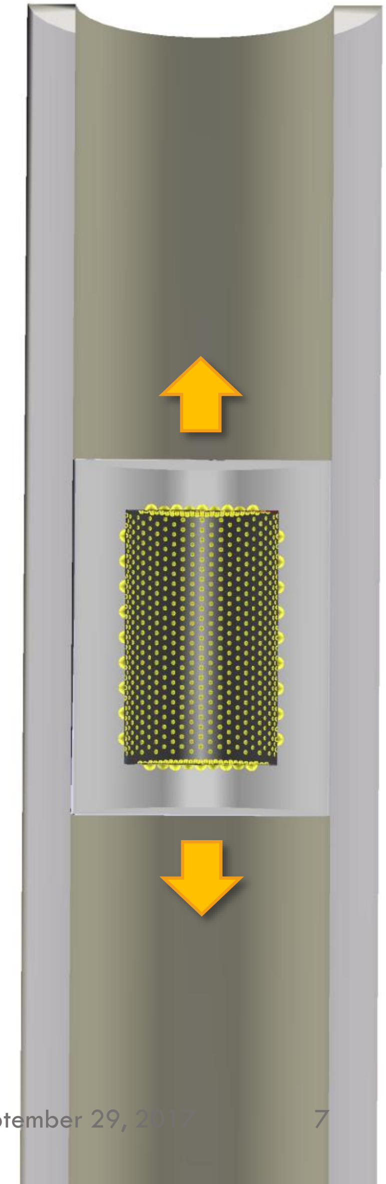
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!



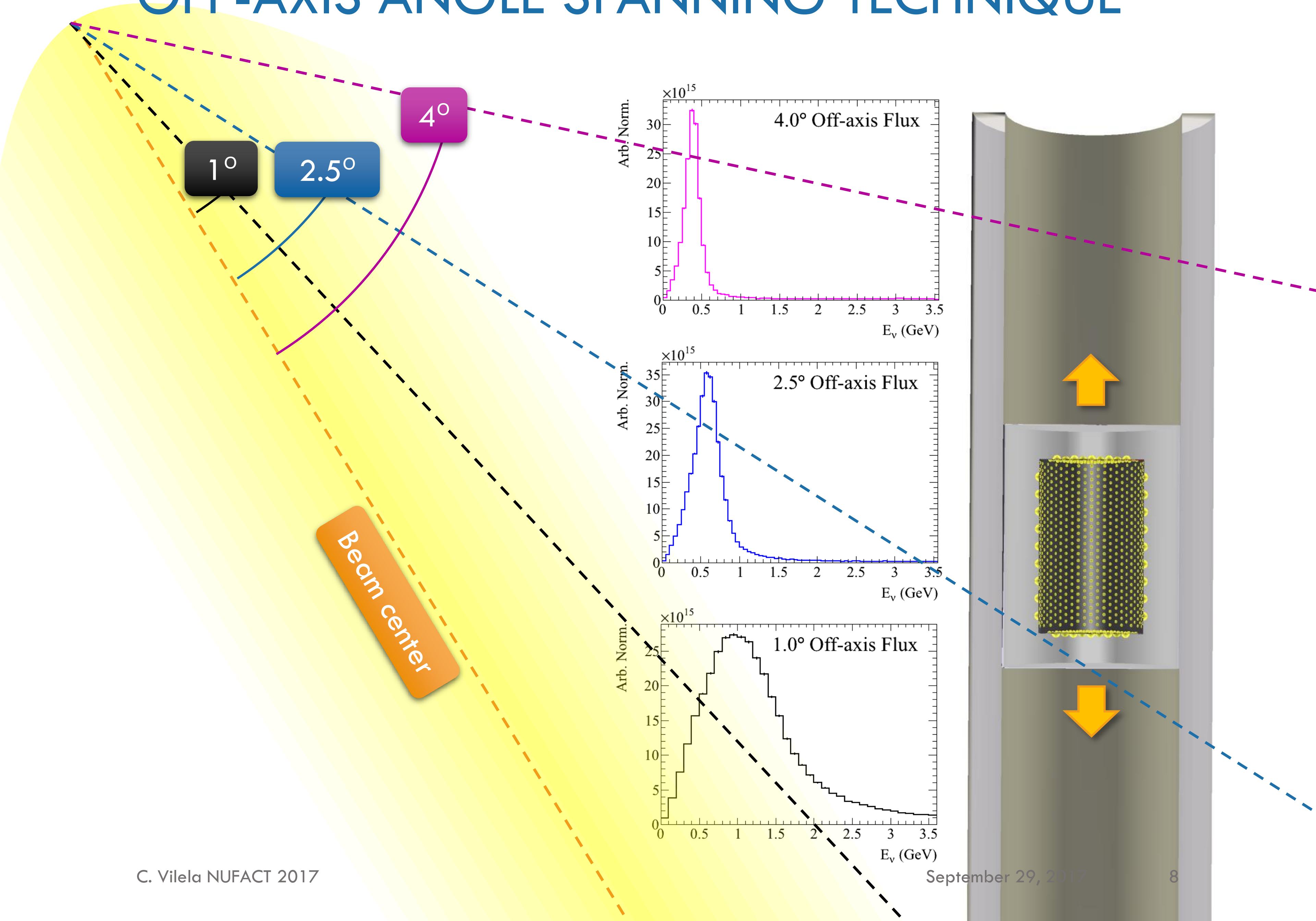
- This presents an additional difficulty in constraining neutrino interaction models.
- We only ever measure a combination of flux and cross-section.
- Multi-nucleon effects can smear reconstructed neutrino energy into oscillation **dip** at far detector, biasing the measurement.
  - But this is obscured by the flux **peak** at the near detector!

THE E61 DETECTOR

- An intermediate water Cherenkov detector on the J-PARC beam path.
- Instrumented portion of the detector is moveable within a deep pit.
  - Sample neutrino interactions from a wide range of off-axis angles.
- Optically separated inner and outer detector volumes.
  - Inner detector 6 – 10 m tall and 8 m diameter.
  - Outer detector 10 – 14 m tall and 10 m diameter.
- Populated with multi-PMT modules.
- Aim to load water with Gadolinium.
  - Precise measurements of neutron emission in neutrino interactions.



OFF-AXIS ANGLE SPANNING TECHNIQUE

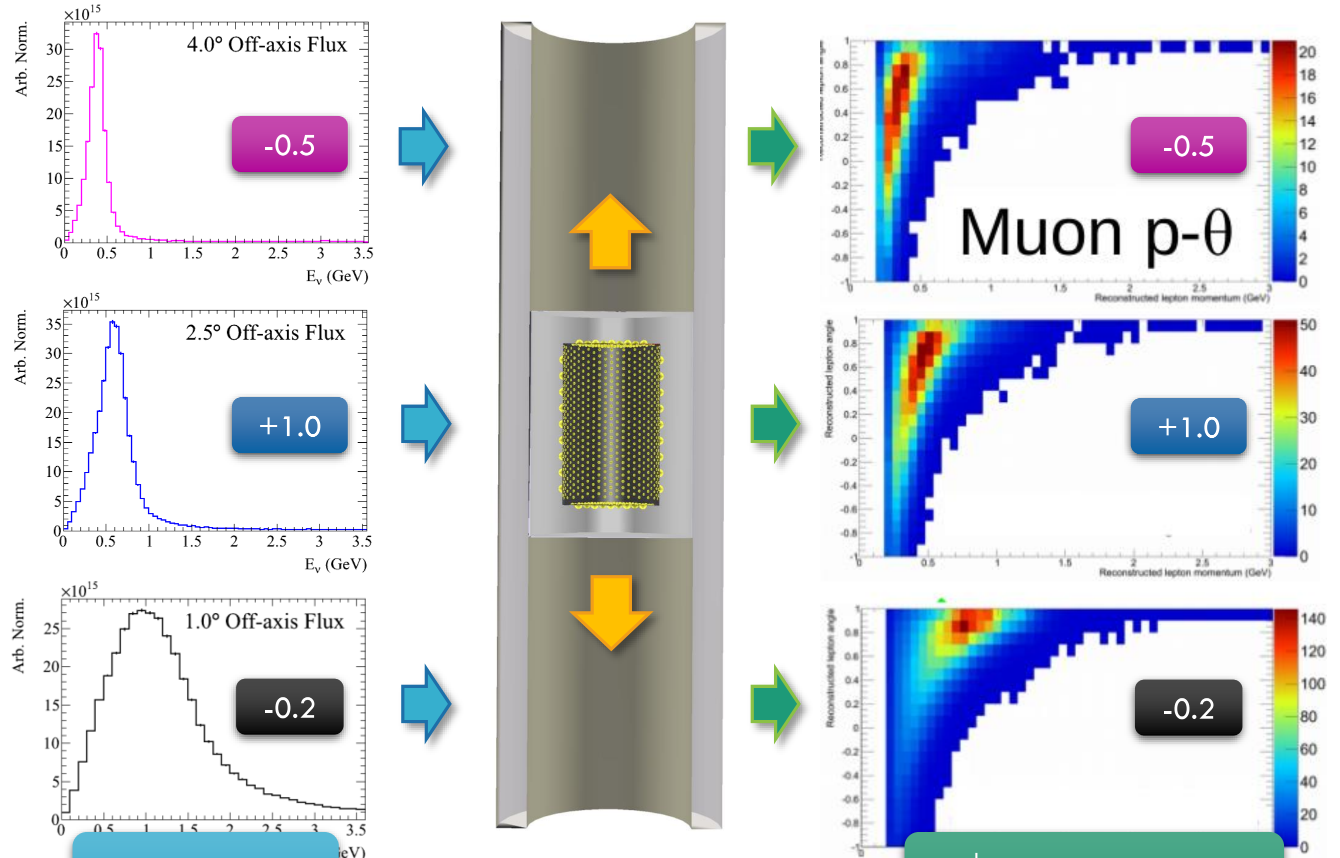


COMBINING OFF-AXIS SAMPLES

- Make use of the off-axis angle dependence of ν flux:

1. Bin data in off-axis angle.
2. Take combinations of different off-axis angle bins.
3. Get distribution of observables for a known E_ν spectrum.

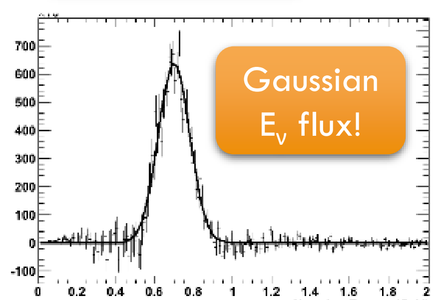
Coefficients determined by the desired E_ν spectrum.



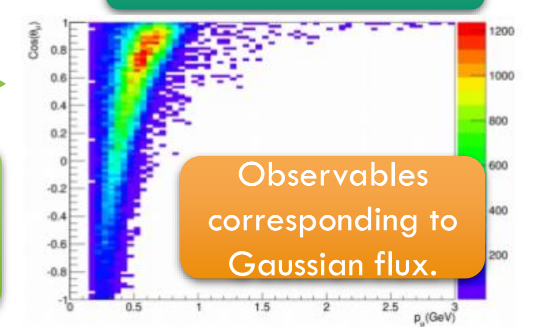
E_ν spectrum

$\ell^{\pm}$ observables

Take linear combinations of 60 off-axis angle bins.

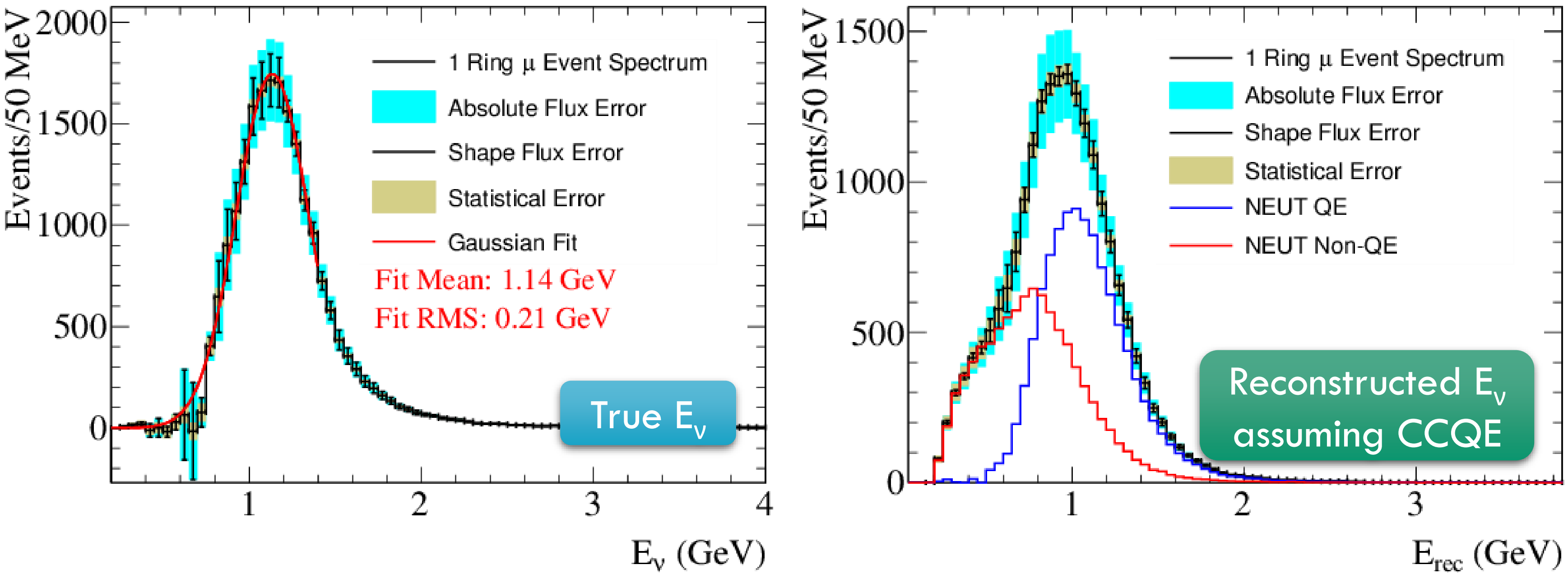


Apply same coefficients to distributions of observables.



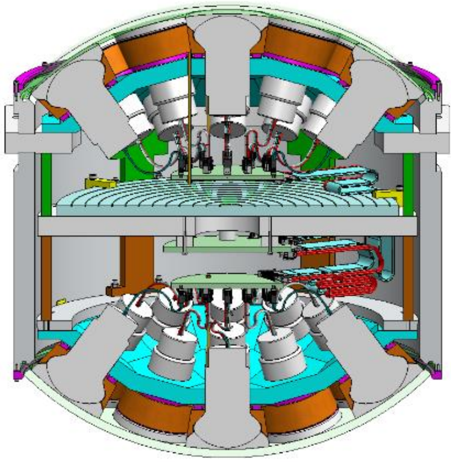
PSEUDO-MONOCHROMATIC BEAMS

- Single muon candidate events after off-axis coefficients are applied to give monochromatic flux centered at 1.2 GeV.

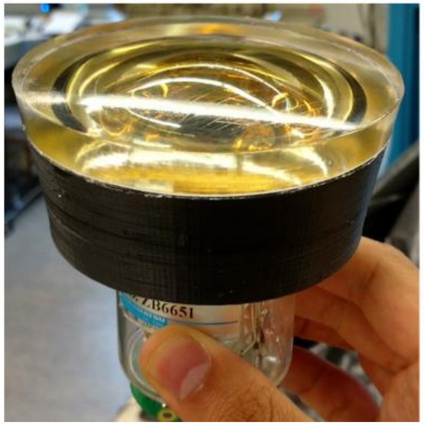


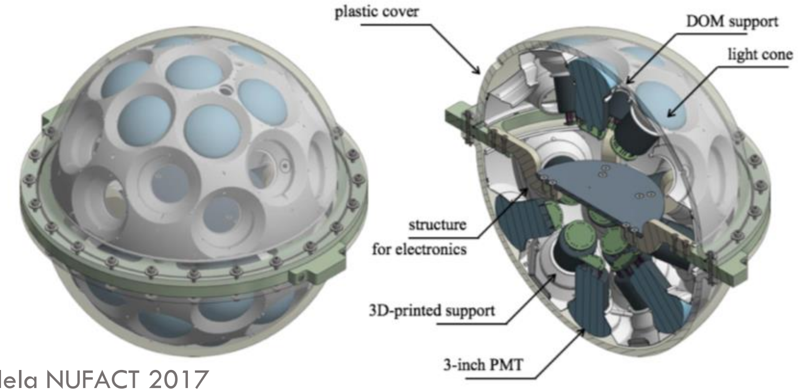
- Measure cross-sections as a function of true neutrino energy.
- Q^2 and ω available – detailed neutrino measurements *a la* electron scattering.
- Powerful probe of interaction models, such as departures from CCQE due to multinucleon effects.

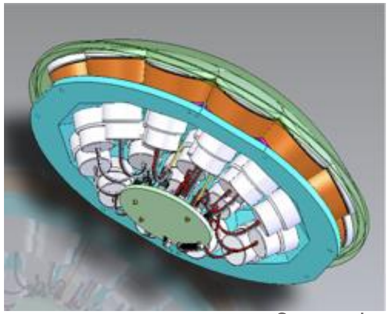
MULTI-PMT MODULES



- The E61 baseline design has the detector populated with multi-PMT modules.
    - Modules contain 3″ PMTs facing both the inner and outer detector volumes.
    - Aluminium reflectors give an effective increase in photosensor area of ~20%.
    - Modules contain integrated HV and read-out electronics.
- Expected Physics benefits:
    - Improved time resolution: particularly important for resolving inter-bunch pileup.
    - Finer granularity allows Cherenkov rings to be imaged with a better resolution: expected reconstruction improvements.
    - Reflectors and PMT orientation might provide additional directional information.
- Extensive R&D programme with significant international collaboration:
    - Photosensor testing and characterization.
    - Development of integrated electronics.
    - Optical testing of materials: acrylic, silicon gel, …
    - Mechanical modelling and prototyping.

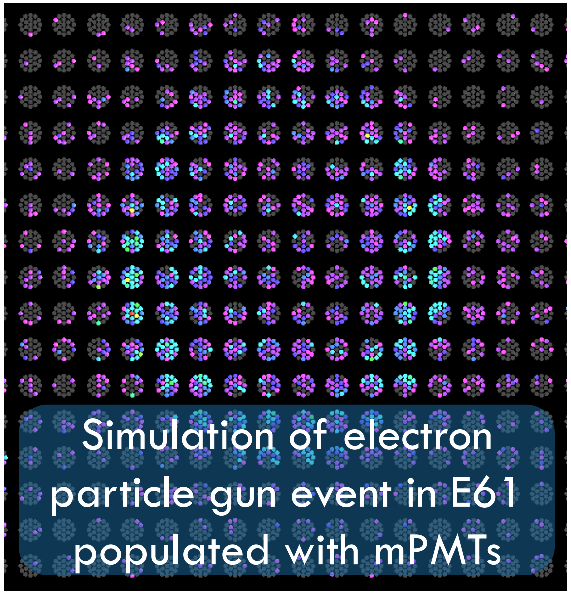




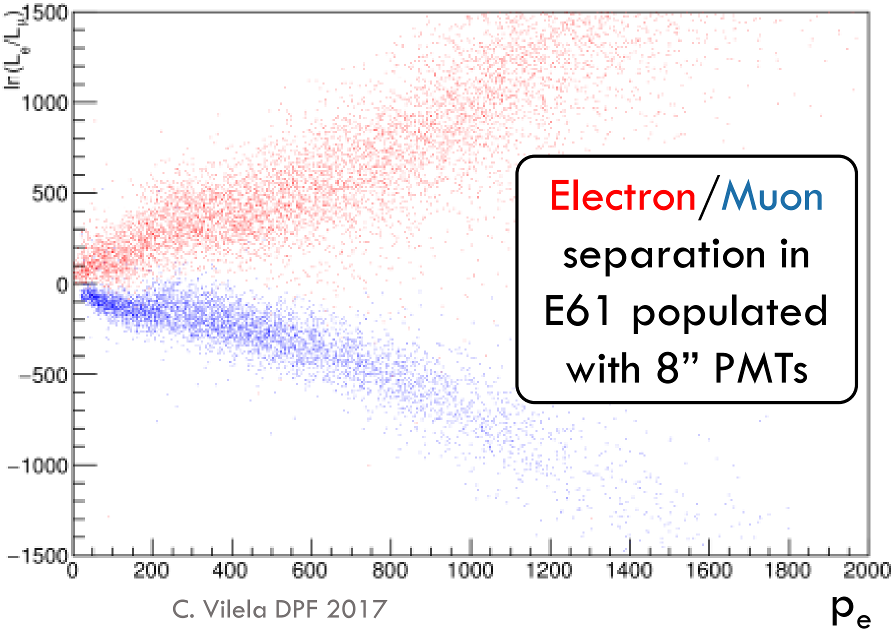


E61 SIMULATION AND RECONSTRUCTION

- Complete simulation and reconstruction chain has been developed for E61.
  - In use for physics and detector optimization studies
- The Geant4-based WCSim package is used for simulation.
  - Highly configurable water Cherenkov detector geometries, several PMT models available.
  - Recently implemented multi-PMT modules.



Simulation of electron particle gun event in E61 populated with mPMTs



Electron/Muon separation in E61 populated with 8" PMTs

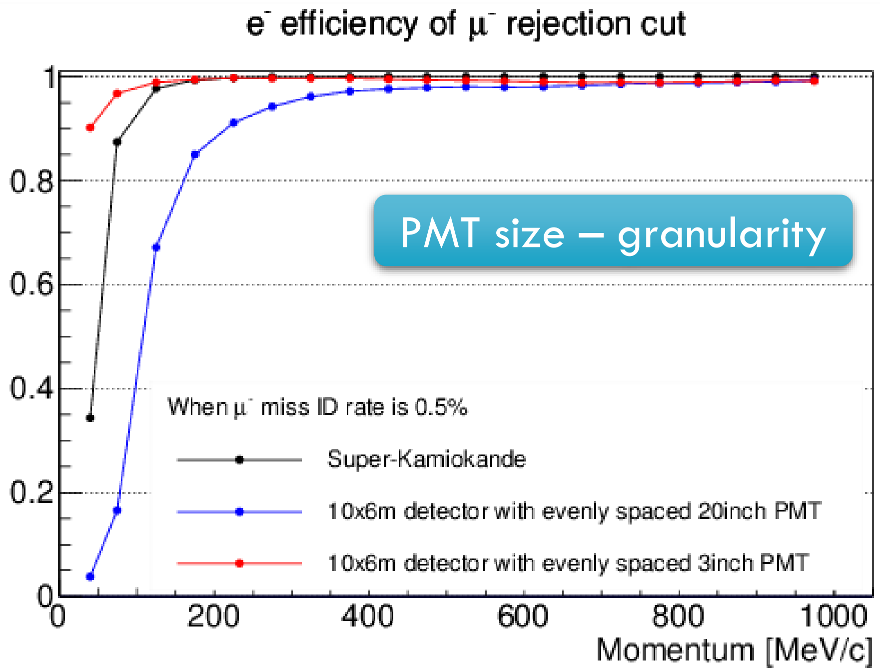
C. Vilela DPF 2017

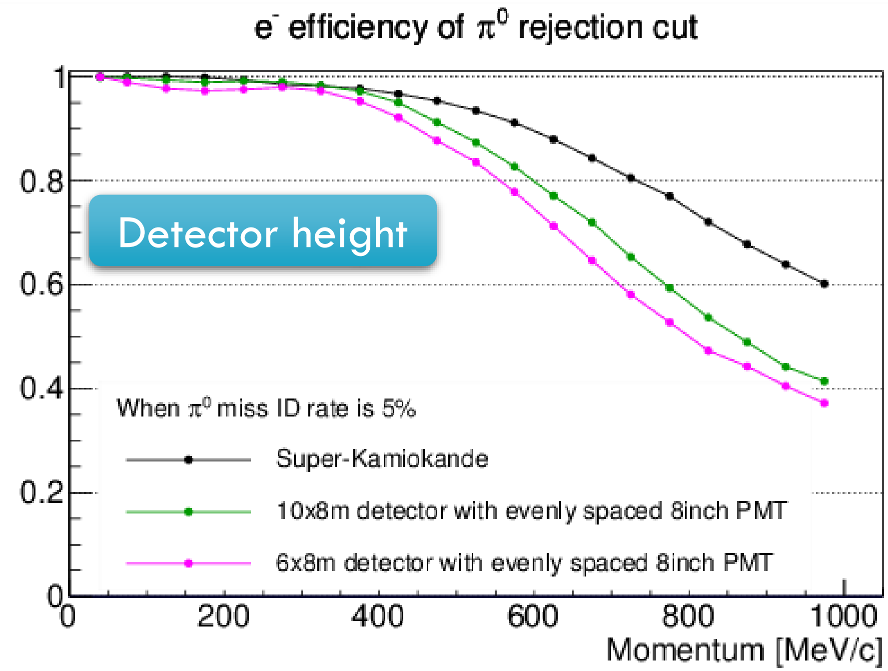
- Reconstruction with fiTQun.
  - Maximum likelihood estimation of track parameters using all the information in an event.
    - Hit/unhit, time and charge.
  - Developed and deployed at Super-K, now also running on WCSim output.

Same software chain as Hyper-K

E61 DETECTOR OPTIMIZATION STUDIES

- Complete simulation and reconstruction chain using WCSim and fiTQun is being actively used in detector optimization studies.

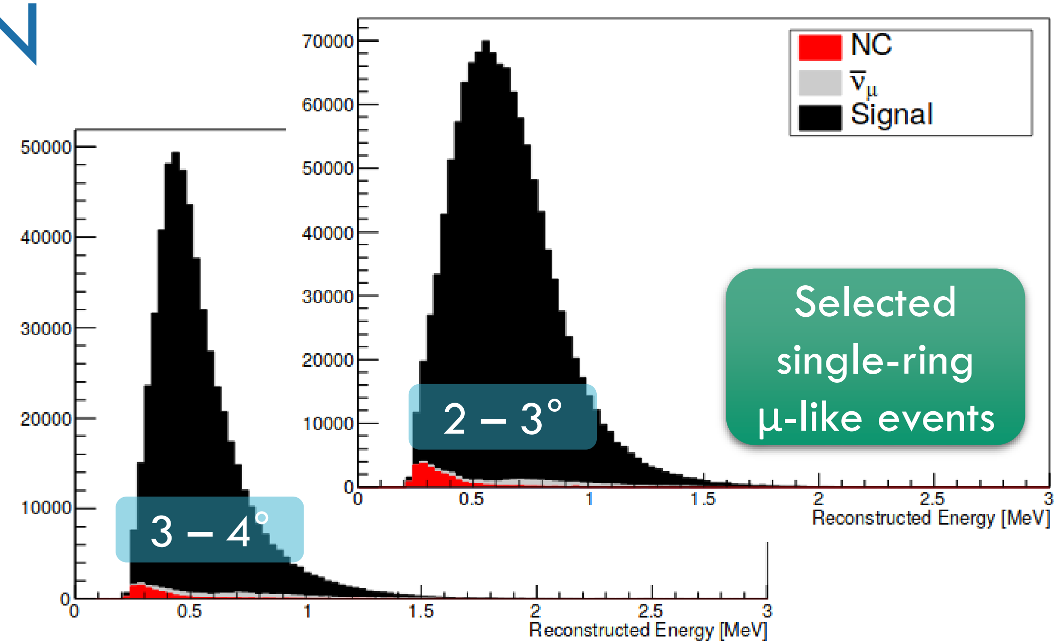


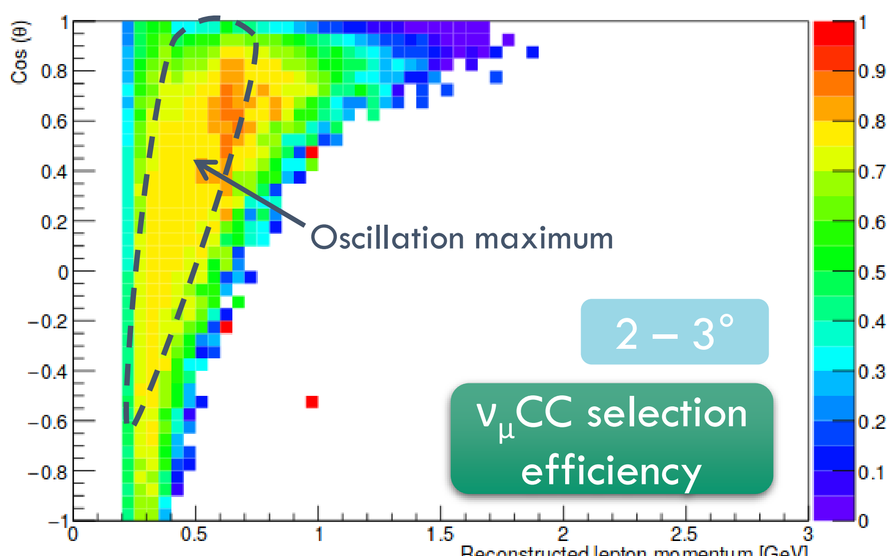


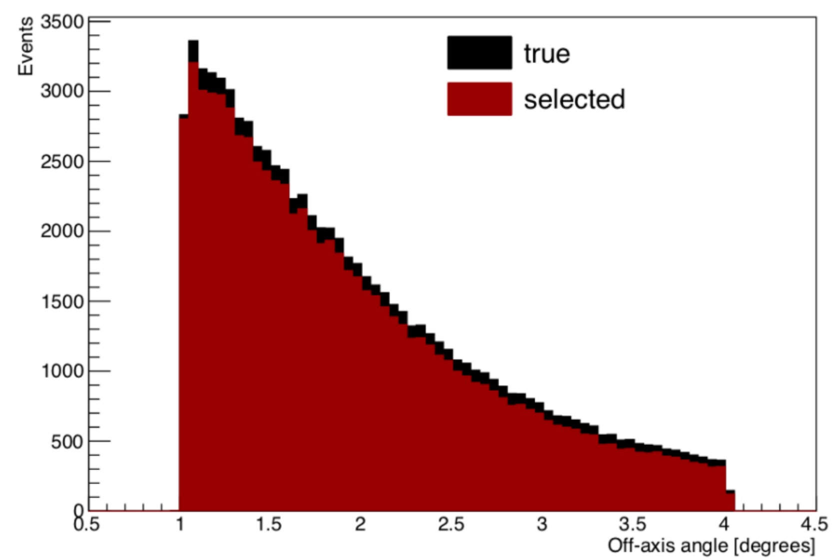
- Study major detector parameters such as overall dimensions, photosensor size and density, mPMT module configuration.
- Parameters are optimized as a function of detector performance:
  - Electron / muon separation; electron / π^0 separation, detection efficiencies, …

EVENT SELECTION

- Event selection developed using complete chain of simulation and reconstruction.
  - Single-ring, μ-like and fully contained events.
  - Shown here for detector populated with 8″ PMTs.
- Disappearance analysis using E61 simulated/reconstructed events in progress.

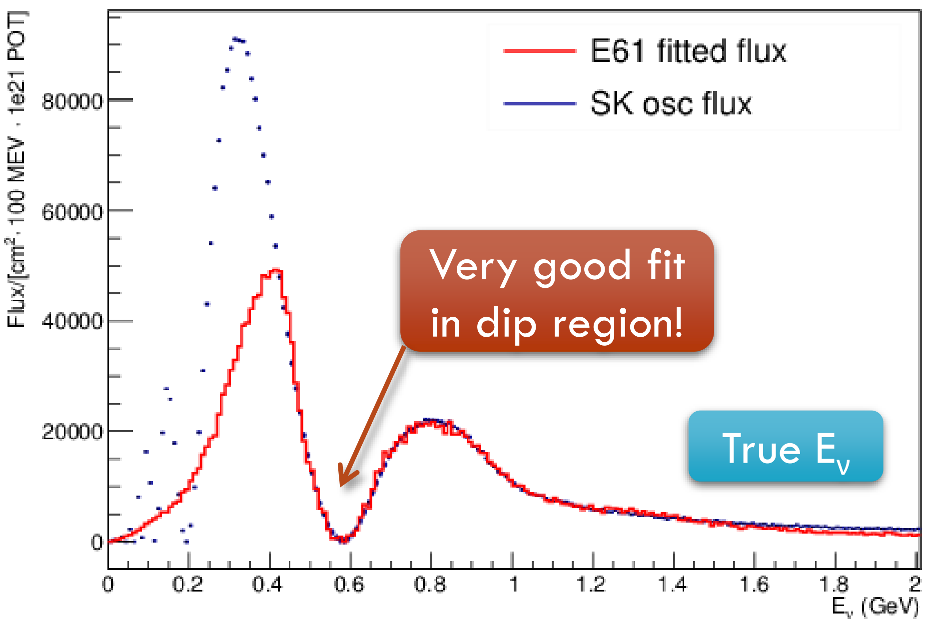


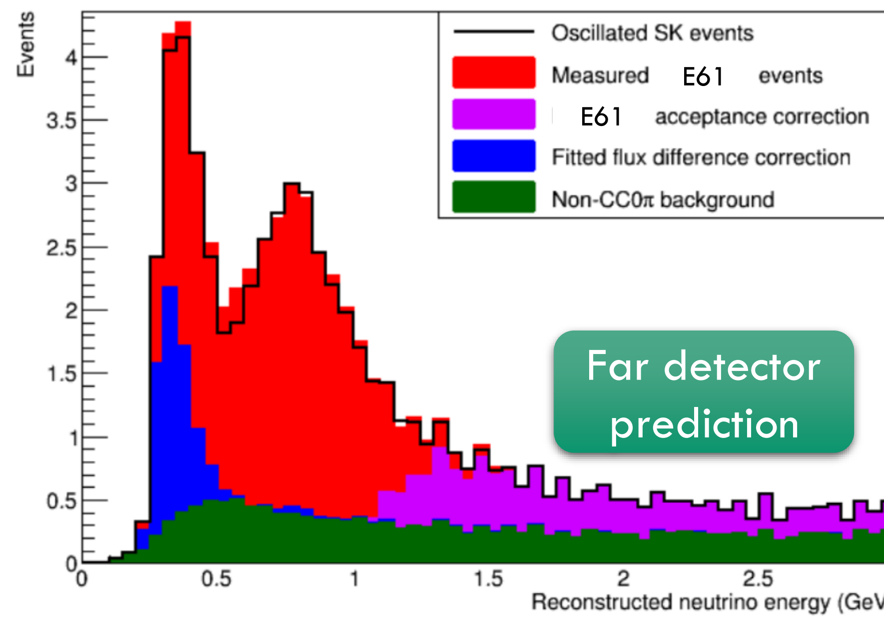




ν_μ DISAPPEARANCE WITH E61

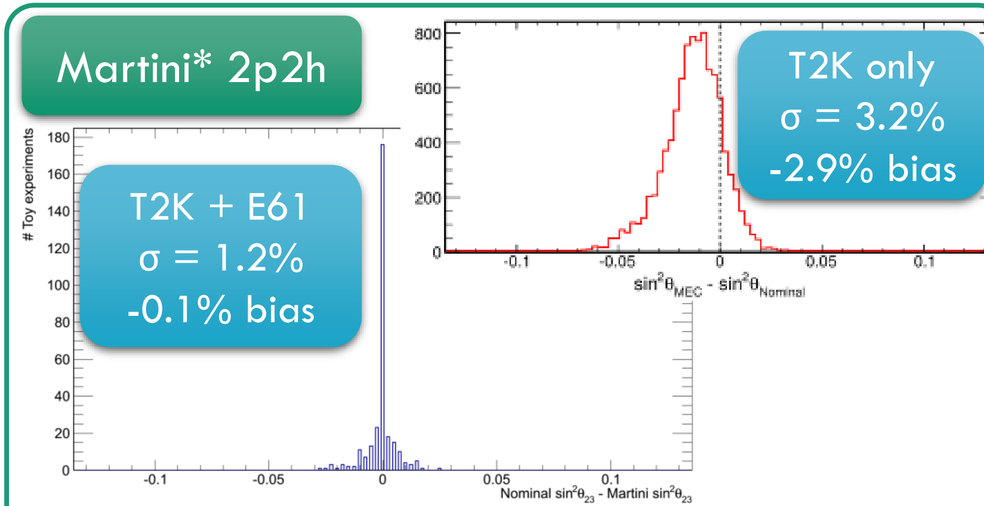
- Take linear combinations of off-axis binned data to reproduce the far detector **oscillated** neutrino flux.
- Use the corresponding observables to make a **prediction** for the far detector data with little model dependence.
- Background, flux and acceptance corrections necessary for SK prediction.
  - Significant uncertainty cancellation in neutral-current background subtraction.
  - In oscillation dip region prediction is dominated by **E61 data**.



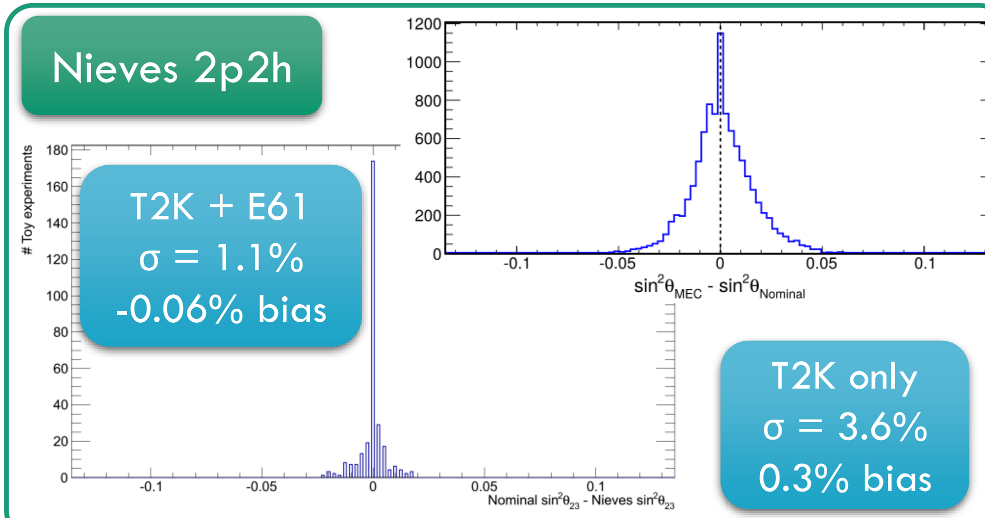


E61 DATA-DRIVEN CONSTRAINTS

- Disappearance analysis using off-axis angles combinations is shown to be robust against interaction mismodelling.
  1. Produce fake data with throws of flux and cross-section uncertainties both with and without multi-nucleon effects.
  2. Fit the fake data using interaction model without multi-nucleon contributions.
  - E61 significantly reduces uncertainty and removes bias.
- This is a **data-driven** constraint, independent of model choice.

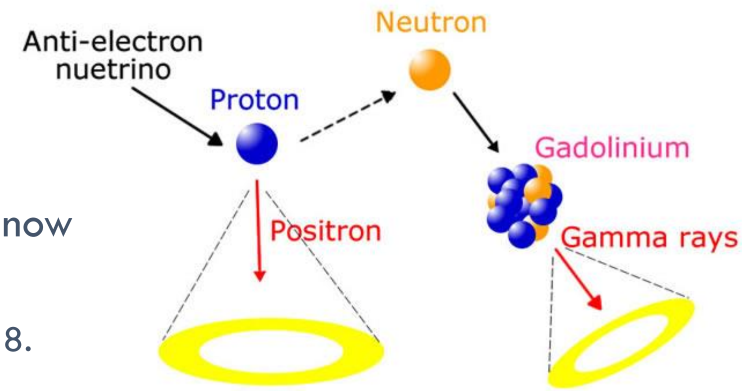


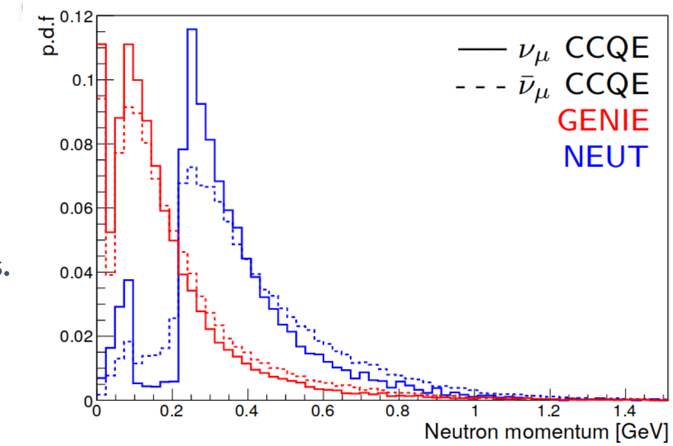
* “Hacked” model, with Nieves final states.

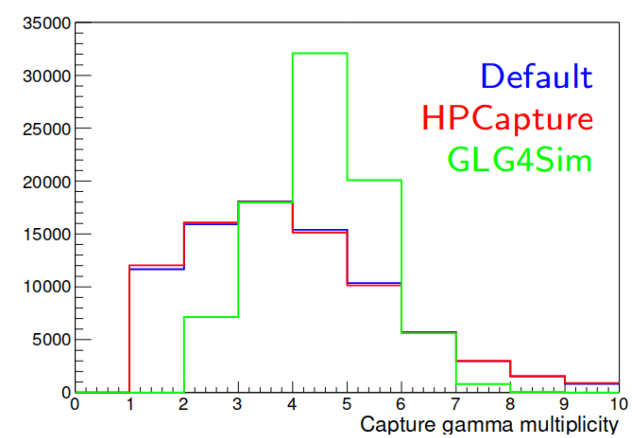


GADOLINIUM LOADING

- Program to load Super-K water with Gadolinium is now well established.
  - Required tank liner refurbishment work planned for 2018.
- Aside from IBD, Gd will be useful for higher energy Physics at Super-K:
  - Statistical separation of ν/anti-ν interactions in the atmospheric samples, as well as wrong-sign background reduction in beam samples.
  - Significant background reduction for proton decay searches.
- However, large uncertainties on neutron multiplicity lead to background uncertainties on the above.
- Near detector measurements with Gd critical for the precise use of neutron capture information.
- Option to load E61 water with Gd provides an opportunity to measure neutron emission rates and capture on Gd as a function of E_ν.

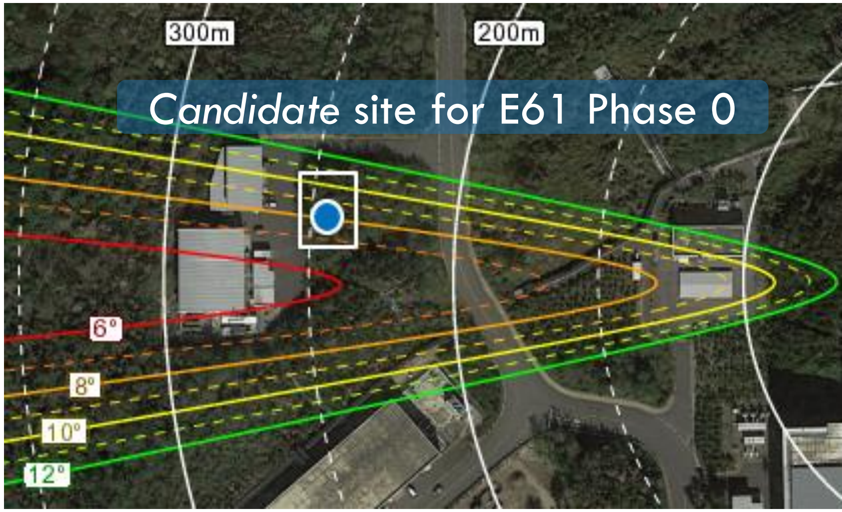


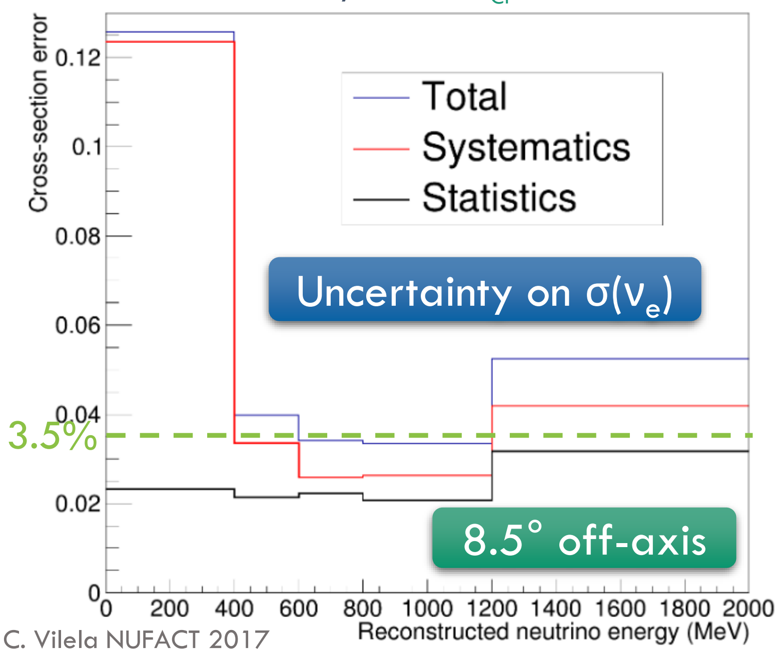


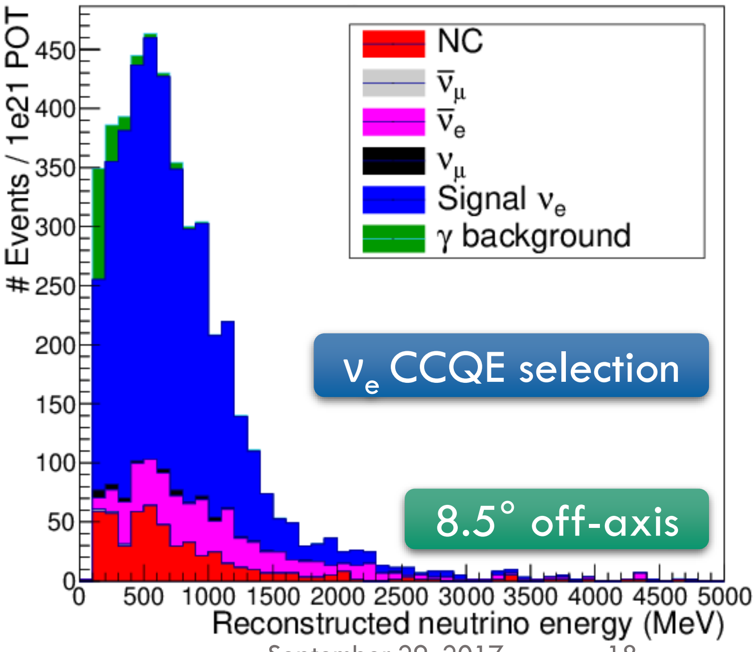


A STAGED APPROACH – E61 PHASE 0

- In an initial phase, the E61 detector will be built and installed on the surface at the J-PARC site.
- Running in this mode will allow for:
  - Detector performance and calibration requirements to be demonstrated;
  - A precise measurement of the ν_e cross-section on water.
    - $\sigma(\nu_e)/\sigma(\nu_\mu)$ is a large, theory-driven contribution to the uncertainty on T2K δ_{CP} measurement.

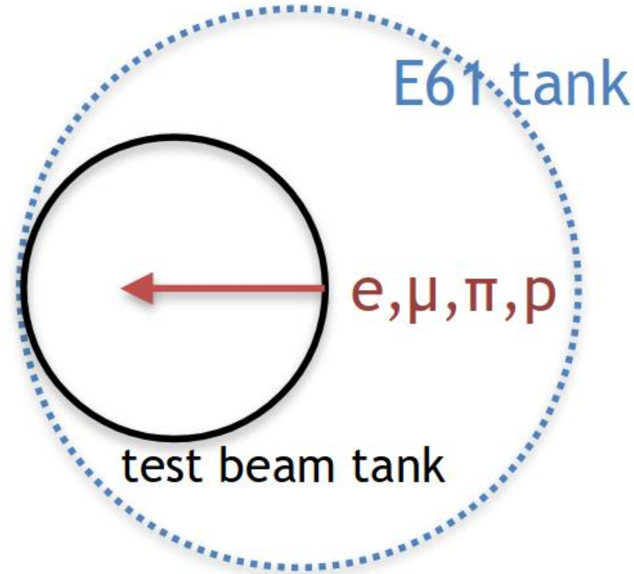


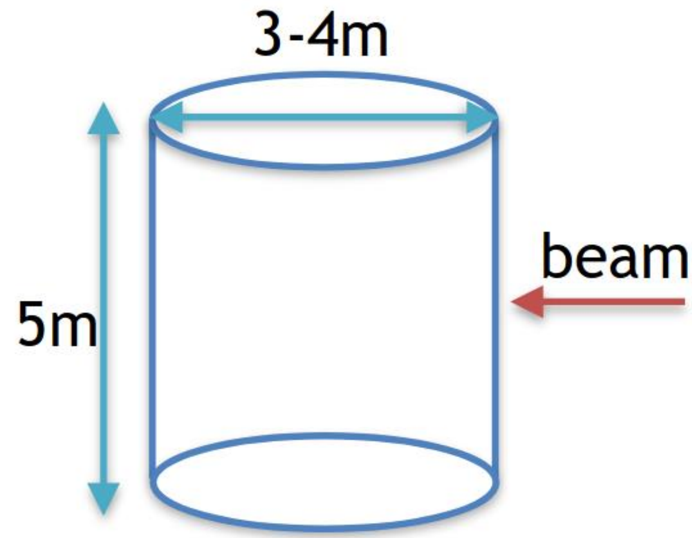




A STAGED APPROACH – BEAM TEST

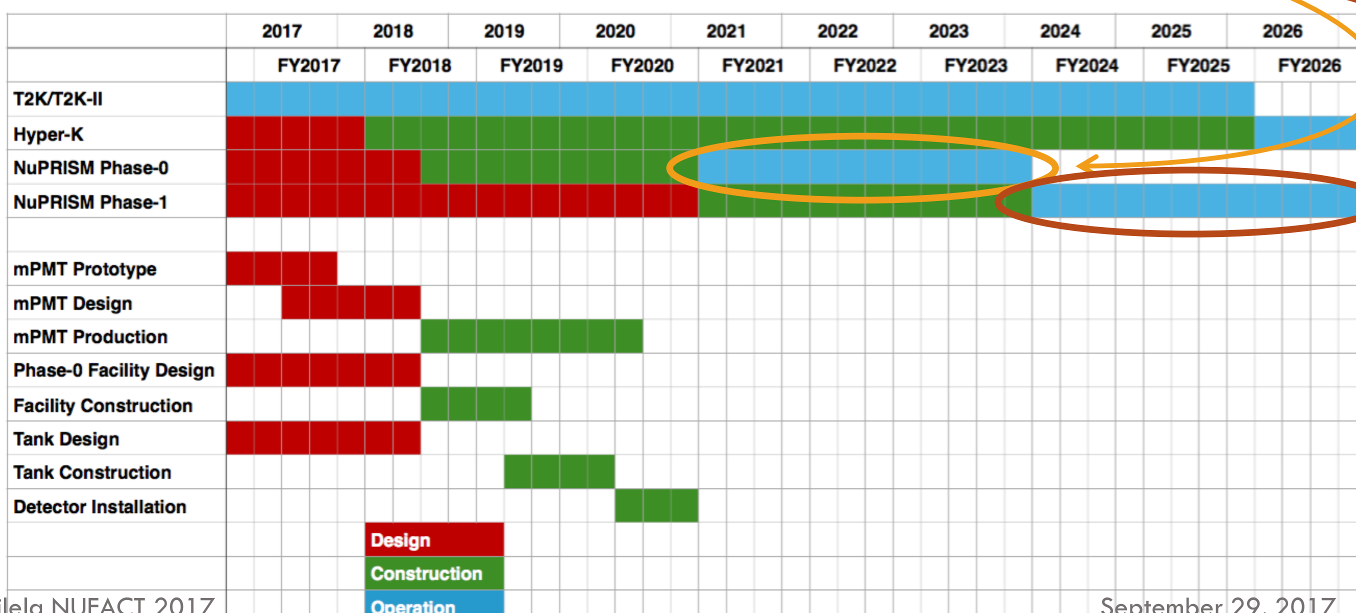
- The aggressive time-scale being pursued (more on next slide) might not allow for funding for a full-sized Phase 0 detector to be secured in time.
- Alternative initial phase set-ups are being considered using a smaller sized tank.
  - A precise ν_e cross-section measurement would not be possible with a small tank.
- However, such a small tank could be easily placed in a charged particle beam.
  - This would provide an excellent opportunity to achieve the initial phase goals of demonstrating performance and calibration requirements for a small water Cherenkov detector.
  - Such an experiment would also serve as a test-bed for multi-PMT and other water Cherenkov R&D.
- Beam test options are currently being investigated.





STATUS AND PROSPECTS

- Project received J-PARC Stage 1 approval in July 2016.
- NuPRISM and TITUS efforts merged into single collaboration: E61.
- Technical Design Report in preparation.
- Aim to take beam data:
  - For 2 years in Phase 0.
  - For 2 to 3 years in Phase 1 concurrently with T2K-II.



SUMMARY

- Long-baseline oscillation experiments are entering an era where interaction uncertainties will become **significant**.
  - Poorly understood feed-down effects can bias measurements and are difficult to constrain with traditional near detectors as they are exposed to a different flux.
- The E61 off-axis angle spanning technique gives a data-driven method to convert E_{rec} to E_{true}, decoupling the flux shape from interaction models.
- Significant effort has led to a mature project, with sophisticated analyses being developed using realistic simulation and reconstruction tools.
- An extensive R&D programme for multi-PMTs is in place, with initial prototypes currently in production.
- The construction of an initial phase of the detector has been proposed.
  - Either a full-sized detector at J-PARC or a reduced detector on a test beam.
- An aggressive time scale is being pursued, aiming at collecting a significant amount of Phase 1 data concurrently with T2K-II.

THANK YOU!