J-PARC E61 EXPERIMENT

REDUCING CROSS-SECTION UNCERTAINTIES IN NEUTRINO OSCILLATION EXPERIMENTS

NUFACT 2017
UPPSALA
SEPTEMBER 29TH, 2017
EXCLUSION OF CP CONSERVATION IN LEPTON SECTOR AT 2σ.

WORLD-LEADING MEASUREMENTS OF $\sin^2 \theta_{23}$ AND $\Delta m^2_{23}$.

Super Kamiokande

Mt. Ikeno-Yama 1360 m

Near Detector

J-PARC

50 kton

Neutrino beam

Detectors 2.5° away from beam axis.

295 km

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September 29, 2017
PROPOSED EXTENDED RUN OF T2K (T2K-II)

• Proposal to extend T2K run from $7.8 \times 10^{21}$ to $20 \times 10^{21}$ 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

• $3\sigma$ sensitivity to maximal CP violation.
HYPER KAMIOKANDE PROJECT

- Next-generation water Cherenkov detector with extensive Physics program.
- $5\sigma$ sensitivity for a wide range of $\delta_{CP}$ 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

![Hyper Kamiokande](image)

- High QE PMTs
- 260 kton
- Proposed ND upgrade
- Near Detector
- J-PARC
- Main ring upgrade
- Hyper-K single tank

Assuming 3% uncertainty

1.3MW beam
1 year = $10^7$s

Fraction of $\delta$ (%) vs. Running time (year)

- $3\sigma$
- $5\sigma$

Detectors 2.5° away from beam axis.

295 km

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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 $E_{\nu}$ 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.

![Genuine CCQE (1p-1h)](image1)

![Two particles-two holes (2p-2h)](image2)

T. Katori, M. Martini, arXiv:1611.07770
M. Martini et al, arXiv:1211.1523

Comparison of 2p2h event rates from competing models
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 $\nu$ flux:
  1. Bin data in off-axis angle.
  2. Take combinations of different off-axis angle bins.

Coefficients determined by the desired $E_\nu$ spectrum.

1. Take linear combinations of 60 off-axis angle bins.

$E_\nu$ spectrum

Gaussian $E_\nu$ flux!

Apply same coefficients to distributions of observables.

Observables corresponding to Gaussian flux.

-0.5
-1.0
-0.2

Muon $p-\theta$

$\ell^\pm$ 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 $\omega$ 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.

• 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.

Electron/Muon separation in E61 populated with 8” PMTs
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 / $\pi^0$ separation, detection efficiencies, …
EVENT SELECTION

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

Very good fit in dip region!

Far detector prediction
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.

- T2K only
  - $\sigma = 3.2\%$
  - $0.3\%$ bias

- T2K + E61
  - $\sigma = 1.1\%$
  - $0.06\%$ bias

- T2K + E61
  - $\sigma = 1.2\%$
  - $-0.1\%$ bias

- T2K only
  - $\sigma = 3.6\%$
  - $0.3\%$ bias

* “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 $\nu$/anti-$\nu$ 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 $E_\nu$. 

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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 $\nu_e$ cross-section on water.
    • $\sigma(\nu_e)/\sigma(\nu_\mu)$ is a large, theory-driven contribution to the uncertainty on T2K $\delta_{CP}$ 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 $\nu_e$ 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.


• 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 $E_{\text{rec}}$ to $E_{\text{true}}$, 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!