REDUCING CROSS-SECTION UNCERTAINTIES IN NEUTRINO OSCILLATION EXPERIMENTS

APS DIVISION OF PARTICLES AND FIELDS MEETING

FERMILAB, AUGUST 3\textsuperscript{RD}, 2017
Exclusion of CP conservation in lepton sector at 90% CL.

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

Super Kamiokande

50 kton

Mt. Ikeno-Yama
1360 m

Detectors 2.5° away from beam axis.

J-PARC

3 GeV Proton Synchrotron (1MW, 28Hz)

Neutrino Facility

Materials and Life Science Facility

50 GeV Proton Synchrotron (115 μA)

C. Vilela DPF 2017

August 3, 2017
Exclusion of CP conservation in lepton sector at 90% CL.

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

More detail in X. Li’s talk given last Monday.
New results in plenary session tomorrow at 8:30!
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

\[
\Delta \chi^2 \text{ to exclude } \sin^2 \theta_{CP} = 0
\]
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
- Intermediate water Cherenkov detector: E61

**Proposed ND upgrade**

- High QE PMTs
- 260 kton

**Near Detector**

- E61

**Main ring upgrade**

- J-PARC

Assuming 3% uncertainty
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.

**Graphs and Figures**

- Comparison of $2p2h$ event rates from competing models.
- $E_\nu$ smearing due to Martini $2p2h$. 

*References*

T. Katori, M. Martini, arXiv:1611.07770

M. Martini et al, arXiv:1211.1523
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 EXPERIMENT

- An intermediate water Cherenkov detector on the J-PARC beam path.
  - Measures unoscillated flux with the same nuclear target and experimental technique as the far detector.

- 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.
  - Modules contain 3” PMTs facing both inner and outer detector volumes.
  - Use of reflectors to increase effective photocathode coverage.
  - Integrated electronics.

- Option to load water with Gadolinium.
  - Precise measurements of neutron emission in neutrino interactions and capture rates.
OFF-AXIS SPANNING TECHNIQUE

Beam center

1°  2.5°  4°
COMBINATIONS OF 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.

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

- Apply same coefficients to distributions of observables.

- Observables corresponding to Gaussian flux.

- Gaussian $E_\nu$ flux!
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.
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.

Simulation of electron particle gun event in E61 populated with mPMTs

Electron/Muon separation in E61 populated with 8” PMTs

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 / \( \pi^0 \) separation, detection efficiencies, …
\( \nu_\mu \) DISAPPEARANCE WITH E61

- Take linear combinations of off-axis binned 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.

![Graph showing oscillated and predicted neutrino flux](image)

- Very good fit in dip region!
- True \( E_\nu \)

![Histogram of reconstructed neutrino energy](image)

- Far detector prediction

- Nieves 2p2h \( \sigma = 1.1\% \)
- T2K + E61 \( \sigma = 3.6\% \)
- Similar results for competing models

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August 3, 2017
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.
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
THANK YOU!
SUPPLEMENTARY
GADOLINIUM LOADING

• Program to load Super-K water with Gadolinium is now well established.
  • Required tank liner refurbishment work planned for 2018.
• Neutron tagging with Gd might be useful in separating \( \nu/\text{anti-}\nu \) interactions, reducing wrong-sign backgrounds.
  • Expect more neutrons in anti-\( \nu \) interactions.
  • However, large uncertainties on neutron multiplicity – unclear picture from both theory and experiment.
• Option to load E61 water with Gd provides an opportunity to measure neutron emission and capture on Gd as a function of \( E_\nu \).
E61 $\nu_\mu$ DISAPPEARANCE MODEL INDEPENDENCE

**Martini* 2p2h**

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

- T2K only
  - $\sigma = 3.2\%$
  - -2.9\% bias

* “Hacked” model, with Nieves final states.

**Nieves 2p2h**

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

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