The VALOR Oscillation analysis at T2K

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Introduction

- VALOR is a frequentist analysis package for long-baseline neutrino oscillation experiments.
- The package has been used for several official T2K results.
  - Most recently, the combined muon and electron fits for T2K.
- The analysis has been developed into an experiment-agnostic codebase that can be used for future experiments.
  - HyperKamiokande sensitivity studies are under active development.
- We're preparing the first batch of T2K antineutrino results.
Currently Active personnel

- Costas Andreopoulos (Rutherford/Liverpool)
- Steve Dennis (Warwick/Rutherford)
- Nick Grant (Lancaster)
- Davide Sgalaberna (ETHZ)
- Raj Shah (Oxford)
The T2K Experiment

- T2K is an ongoing long-baseline (295 km) neutrino oscillation experiment.

- We produce a beam of muon (anti)neutrinos with a sharp peak in energy at 0.6 GeV at J-PARC, and detect them at Super-Kamiokande, a 50 kt water Cerenkov detector 295km away.
  - On and off-axis near detectors are used to constrain flux and other systematic uncertainties.
The T2K Oscillation Analysis Model

- NEUT MC
- External CCQE Data Tune
- Near Detector Data
- SuperK Data Energy Spectrum
- Near Detector Prediction
- SuperK detector and FSI Errors
- SuperK Energy Spectrum Prediction
- Physics Fits!
- External Flux Tune
- Flux predictions

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The VALOR Fitting Package

- For T2K, currently able to fit any combination of:
  - Neutrino mode or antineutrino beam mode data.
  - Muon-like events at Super-K.
  - Electron-like events at Super-K.
  - A Super-K control sample (not used for official analyses).
- Hypotheses available:
  - Three-flavour neutrino fits.
  - Three-flavour neutrino fits with separate antineutrino parameters.
  - Three-flavour neutrino fit with nonstandard matter effects.
  - 3+1 and 3+2 sterile neutrino fits.
  - Two-flavour appearance or disappearance fits.
  - Neutrino decoherence or decay.
VALOR Fitting Method

- For T2K, we fit the reconstructed neutrino energy spectrum at Super-Kamiokande.
  - Neutrino energy is reconstructed using the observed lepton momentum and angle to the beamline assuming a charged-current quasi-elastic interaction.

\[ E_{\text{reco}} = \frac{(M_n - V)E_l - \frac{M_l^2}{2} + M_n V - \frac{V^2}{2} + \frac{M_p^2 - M_n^2}{2}}{M_n - V - E_l + p_l \cos(\theta_l)} \]

- We use 84 true energy bins, and 73 reconstructed energy bins, and minimise the negative log likelihood of our dataset prediction.
  - Varying oscillation parameters, and systematic uncertainties with a penalty term.
T2K in antineutrino mode

- T2K's previous neutrino beam running has been predominately in neutrino beam mode.
- By reversing the current of the magnetic horns that focus the pions in the beamline, we can produce a beam that is mostly muon antineutrinos.
  - Long term goal: look for differences between electron neutrino and electron antineutrino appearance signals.
- T2K has been running in antineutrino beam mode, and our first antineutrino oscillation results should be made public soon.
  - Initially, muon antineutrino disappearance only.
  - Soon, electron antineutrino and combined fits.
Muon anti-neutrino disappearance

• Fitting only antineutrino beam mode muon-like Super-K events.
• Use T2K neutrino-mode fit data (from previous VALOR analysis) to constrain standard oscillation parameters.
• Fit hypothesis: Separate neutrino and antineutrino oscillation parameters.
  • In order to evaluate if there is tension between our muon neutrino and muon antineutrino disappearance measurements.
  • Parameters of interest are \( \sin^2 \theta_{23} \) and \( \Delta m^2_{23} \).
• Systematic uncertainties are 25 flux normalisations, 5 cross-section normalisations, 7 cross-section model parameters, 6 SuperK detector/FSI/SI systematics and 1 uncorrelated reconstructed energy scale parameter.
Spectrum Predictions

Predicted reconstructed neutrino energy spectra for T2K at 2.5E20 POT in antineutrino beam mode.

Dashed line shows uncertainty without near detector, Red envelope shows predicted uncertainty with ND fit.

Unoscillated

Preliminary fake-data constraint

With typical oscillation parameters
Effect of Uncertainties on Event Rate

Flux

Preliminary, fake data constraint.

Cross-section

Preliminary, fake data constraint.

Blue bars show size of systematic uncertainty without near detector constraint.
Red show uncertainty with predicted near-detector information.
(using T2K 2014 oscillation results).
Conclusions

- The VALOR oscillation analysis package was originally developed for T2K, but it won't stop there.
  - It's an extensible framework for current and future oscillation analyses.
  - We support several physics hypotheses of varying plausibility.
- We will continue to put out T2K results as we move into the analysis of antineutrino data and joint running-mode fits.
- We will also produce high-quality sensitivity studies for future experiments.
Thank you for listening.
Backup
SuperK systematics

- 1: Energy scale
- 2: Nuμ CCQE 0-0.4 GeV
- 3: Nuμ CCQE 0.4-1.1 GeV
- 4: Nuμ CCQE 1.1-30 GeV
- 5: Nuμ CCnQE 0-30 GeV
- 6: Nuε CC 0-30 GeV
- 7: NC 0-30 GeV

SuperK+FSI

Preliminary
Flux Systematics

• 1-5: Numu
• 6-16: NumuBar
• 17-18: Nue
• 19-25: NueBar

Flux

Preliminary, fake data constraint.
Cross-section Systematics

• 1: MEC Normalization
• 2: CA5 Form Factor
• 3: Resonance background/
• 4: CCQE Axial Mass
• 5: Resonance Axial Mass
• 6: Fermi Momentum (Oxygen)
• 7: CC other pion multiplicity
• 8: Binding energy (Oxygen)
• 9: CC Coherent Normalization
• 10: NC Coherent Normalization
• 11: NC Other Normalization
• 12: Nue/Numu Normalization