Systematic uncertainties in long baseline experiments
Tokai to Kamioka (T2K) experiment

- Near detectors used to predict unoscillated neutrino rate at far detector
- Fit far data to prediction to measure oscillation parameters
Measuring neutrino oscillations

- Detectors measure interaction rate:
  - Near detector (ND280)
    - $\Phi(E_{\nu},\nu_i) \ast \sigma(E_{\nu},\nu_i) \ast \varepsilon(E_{\nu})$
  - Far detector
    - $\Phi(E_{\nu},\nu_i) \ast \sigma(E_{\nu},\nu_i) \ast \varepsilon(E_{\nu}) \ast P[\nu_i \rightarrow \nu_j](E_{\nu},\nu_i)$
- Systematic on each term

- If near and far detectors are identical, and see same flux
  - Near detector directly measures product of flux and cross-section
  - Compare to SK data to get oscillation parameters
Measuring neutrino oscillations

- Detectors measure interaction rate:
  - Near detector (ND280)
    - $\Phi_{\text{ND}}(E_{\nu},\nu_i) \times \sigma_{i}^{\text{C/O}}(E_{\nu},\nu_i) \times \varepsilon_{\text{ND}}(E_{\nu})$
  - Far detector
    - $\Phi_{\text{FD}}(E_{\nu},\nu_i) \times \sigma_{j}^{\text{O}}(E_{\nu},\nu_i) \times \varepsilon_{\text{FD}}(E_{\nu}) \times P[\nu_i \rightarrow \nu_j](E_{\nu},\nu_i)$

- Systematic on each term

- If near and far detectors are identical, and see same flux
  - Near detector directly measures product of flux and cross-section
  - Compare to SK data to get oscillation parameters

- This is not the case:
  - Different fluxes – energy dependence and flavour both change
  - Different nuclear target
  - Different detection efficiencies
Near detector fit

- Use parametrised models for flux, cross-section and detector
- Tune models using data from beam monitors, other experiments, control samples
- Joint fit of models to ND280 data allows constraint on rate
- Propagate tuned models to far detector with reduced uncertainties
ND280 fit

- Postfit MC agrees much better with data
- Plot on left shows SK anti-neutrino flux parameters
  - Central value of model parameters shifted from prior
  - Uncertainty on model parameters is reduced

Prefit CC-0π sample

Postfit CC-0π sample

SK $\bar{\nu}_\mu$, $\bar{\nu}$ beam mode

Events/(100 MeV/c)

Muon momentum (MeV/c)

Data

- $\nu$ CCQE
- $\nu$ CC 2p-2h
- $\nu$ CC Res 1π
- $\nu$ CC Coh 1π
- $\nu$ CC Other
- $\nu$ NC modes
- $\bar{\nu}$ modes

Prefit CC-0π sample

Postfit CC-0π sample

Events/(100 MeV/c)

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000
T2K oscillation analysis

- Cross section model
- Flux model
- ND280 detector model

- External cross section data
- NA61 data
- INGRID + Beam monitor data
- ND280 data
- SK data

- ND280 fit
- Oscillation fit
- Oscillation parameters

Mark Scott, TRIUMF
T2K 2016 systematics

- CP measurement depends on uncertainty on $\nu_e$/anti-$\nu_e$ ratio
- Dominant uncertainties:
  - Final state interactions (FSI), secondary interactions (SI) – nuclear model extrapolation from pion-nucleus scattering experiments
  - Electron/Muon cross-section ratios – No good data in energy range of interest, low statistics and large background for electron samples
  - ND280 flux + cross-section constraint - affected by nuclear model uncertainties, hard to constrain with ND280
Flux systematics

- Flux simulation tuned to data from hadron production experiments, beam line monitors, beam direction monitor (INGRID) etc.
- Gives tuned prediction and uncertainty
- Currently ~8% at beam energy peak
- Improvements expected from T2K replica target measurements
  - Near detector fit → Reducing flux uncertainty allows better constraint on cross-section model uncertainties
Flux systematics at T2HKK

- Studied by M. Hartz
- Off-axis angle uncertainty currently ~0.12 mrad for T2K
  - Shifts flux normalisation and shape
  - Distorts HK 1Re event spectrum in similar way to 15° change in value of $\delta_{CP}$
- Need to ensure we can constrain both shape and normalisation with near detector information
- Also important to measure at off-axis angle of Korean detector
Cross-section systematics

- Uncertainty on $\delta_{CP}$ measurement dominated by:
  - Neutrino interaction uncertainties
  - Final state (FSI) and secondary interaction (SI) uncertainties

- No clear picture from dedicated cross-section experiments
- Limiting systematic errors from theory
  - Multi-nucleon events...
Nuclear models

- Example of nuclear model uncertainty – 2p2h interactions

- CCQE process is main signal at far detector
  - 2-body interaction
  - Lepton kinematics give neutrino energy
Nuclear models

- Example of nuclear model uncertainty – 2p2h interactions

- CCQE process is main signal at far detector
- Also have '2p-2h' interactions:
  - Mimic CCQE signal
  - Lepton kinematics do not give neutrino energy
  - Depends on nuclear model

T. Katori, arXiv:1304.6014v3

Bias in reconstructed energy
- CCQE peaked at 0
- Two extreme examples of 2p-2h models
  - All PDD (blue)
  - No PDD (red)
2p2h shape at T2HKK

- PDD and Non-PDD are two extremes of the 2p2h shape variation
- Expect systematic uncertainty to be smaller than range shown

- 2p2h shape uncertainties have similar effect to variations of $\delta_{CP}$ around 90°
- Directly limits precision on measurement
- At Korean detector (KD, right), variations in $\delta_{CP}$ have different shape and larger effect than at HK
- Expect to be less affected by 2p2h shape uncertainty
Systematics Summary

- T2HK will be limited by systematics rather than statistics
- Cross-section uncertainties currently dominate T2K error budget
  - Driven by theoretical considerations – little good data constraint
  - Lots of quasi-degenerate effects are hard to disentangle (FSI, 2p2h, nuclear form factors, RPA)
  - Directly affect accuracy of $\delta$CP measurement

- Flux uncertainties can also directly affect $\delta$CP measurement
  - Will become more important as precision increases

- Need to consider effect of simultaneous variation of uncertainties
- Detector systematics also need to be reduced to achieve ultimate goal of ~3% systematic on far detector measurement
Systematic Improvements

- Improvements in flux prediction and new detectors will reduce uncertainties – previous talks by G. Catanesi and M. Wilking
  - Smaller flux uncertainties also allow better constraints on cross-section uncertainties
  - Dedicated cross-section experiments will improve understanding of cross-section models
  - Hard to predict how much reduction we can achieve

- T2HKK measurement less affected by systematic uncertainties
  - Larger CP effect
  - Smaller statistics
  - Higher energy neutrinos – measurements at Hyper-K and Korean detector break some of the degeneracy between cross-section uncertainties and oscillation effects
Backup slides

- Slides explaining fake data study procedure and example results with Martini 2p2h model
T2K oscillation analysis

External cross section data → Cross section model → Flux model → ND280 detector model → ND280 fit

NA61 data → Flux model

INGRID + Beam monitor data → Flux model

ND280 data → ND280 fit

ND280 fit → SK detector model

SK data → Oscillation fit

Oscillation fit → Oscillation parameters
T2K fake data analysis

External cross section data

Cross section model

Flux model

ND280 detector model

ND280 fake data

New model

SK fake data

ND280 fit

Oscillation fit

SK detector model

Oscillation parameters
Procedure at T2K

• Generate fake data at SK and off-axis near detector (ND280)
  • Apply event selections to nominal MC to create event samples
  • Weight events in sample by ratio of old cross-section model to the new model, as a function of some set of variables
    – Assumes selection efficiency does not change when cross-section model changes
• Fit fake data at ND280 (known as the BANFF fit) with nominal MC and nominal cross-section parametrisation
• Extrapolate to SK to make new far detector prediction with new parameter central values and constraints
• Perform oscillation fit to SK fake data using extrapolated prediction
• Compare results to nominal oscillation fit
T2K status

- Fake data studies in T2K technical note 285 completed and passed collaboration review
- Have since updated studies with full fits to expected T2K-II POT
  - Currently working on including SK CC1Pi samples and increased fiducial volume at SK
  - Will publish final studies in stand-alone paper this winter
  - Starting to work on fake data studies for HK and T2HKK
- Ran fits to five fake data sets
  - Spectral function (SF) vs relativistic Fermi gas (RFG) nuclear model
  - 2p2h shape study datasets:
    - PDD-like (like pion-less delta decay process)
    - Non-PDD-like (everything else)
- Differences between Nieves and NEUT CCQE (1p1h) models
- Martini vs Nieves 2p2h
Martini 2p2h study

- Neutrino interaction generators now include 2p2h interactions (right)
  - CCQE-like in most detectors
  - Hard to measure or constrain experimentally
  - Make up 10-20% of the T2K CCQE-like event sample

- Many models, have most information about Nieves and Martini models
- Nieves' model included in NEUT
- To study Martini model, weight 2p2h events by Martini-Nieves cross-section ratio as function of neutrino energy (left)
Martini fake data ND280 fit

- Fit results shown below:

- See large change in flux and cross-section parameters
  - Martini 2p2h cross-section \(~2\) times the nominal NEUT value – MEC_C and MEC_O pulled up
  - Martini fake data created by weighting as a function of neutrino energy – see effect in flux
  - Anti-neutrino 2p2h cross-section less affected – MEC_NUBAR pulled down
SK spectra

- Plot shows SK NuMu (top) and NuE (bottom) samples for Martini 2p2h fake data
  - Blue = nominal MC
  - Black = fake data
  - Red = extrapolated prediction from ND280 fit
- Prediction matches SK fake data within 1 sigma
- ND280 extrapolation under-predicts fake data
  - Around oscillation dip for NuMu
  - In low reconstructed energy region for NuE

T2K work in progress
Martini fake data SK fit

- Likelihood contour shown below for delta CP
  - Black dashed = nominal, red = fake data fit
  - Left = current statistics, right = T2K-II statistics
  - Maximal disappearance and CP violation

If Martini is correct model, using the Nieves 2p2h model artificially tightens constraints we get on delta CP
  - '1 sigma' error goes from 0.75 $\rightarrow$ 0.57
Why T2HKK?

- Different neutrino energy spectra help break degeneracies between oscillations and cross-section models
  - Higher neutrino energies at HKK
  - $2^{nd}$ oscillation maximum (probably) dominated by effect of dCP rather than model changes
- Shape information at HK will be more powerful for dCP measurements compared to T2K
  - Many new shape uncertainties entering T2K oscillation analysis, could increase bias when fitting near detector data
  - HKK (probably) less affected by these
- Role of near and intermediate detectors depends on which systematics/uncertainties are dominating oscillation analysis
  - Detector upgrades need to be informed by oscillation studies
Personal thoughts

- T2HKK will make a statement about CP violation without using reactor constraint, unlike T2K-II
  - Testing three-flavour oscillation paradigm rather than using it as a constraint
- What about non-standard interactions? Could study affect of these in more complete analysis framework
- Fake data choices:
  - Initially perform for same fake data models as studied at T2K
  - Should start including intermediate water Cherenkov information
  - Test differences between near and far detector sensitivity
    - Acceptance
    - Reconstruction
  - Test effects of detector systematic biases
    - Momentum
    - PID
Cross-section experiments

- MINERvA results for muon CCQE-like cross-sections
  - Neutrino energies from ~1.5 GeV up to 10 GeV
- Ratio to GENIE prediction versus cross-section models
- Muon kinematics weakly prefers TEM model, proton weakly prefers nominal GENIE – no model is consistent with the MiniBooNE and MINERvA data

CCQE cross-section using muon kinematics

CCQE cross-section using proton kinematics