Constraining systematics at T2K with the near-detectors

Your friendly T2K ND280-fitters,

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Outline

- Need for near detector fits
- The T2K oscillation analysis chain
- Selections at ND280
- Systematics at ND280
- Making it all fit
- Looking forwards
Estimating SK event rates

- Number of predicted events at SK has dependence on flux and cross-section model
  \[ N_{SK} \sim \Phi_{SK}(E_{\nu}) \sigma(E_{\nu}) \epsilon_{SK} P(\nu_{\alpha} \rightarrow \nu_{\beta}) \]

- Large systematics from flux and cross-sections: can be improved on by fitting near-detector data

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Pre-fit</th>
<th>Pre-fit (no flat priors)</th>
<th>Post-ND fit</th>
<th>Post-SK fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>All errors</td>
<td>12.6%</td>
<td>12.7%</td>
<td>4.8%</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

- Changes central value and uncertainty in SK event spectra
Estimating SK event rates

- Fit may mimic oscillation parameters, needs thorough attention
- Use alternate model as “data” and fit our model: “fake-data” studies
- Aim: robust oscillation results independent of input models

Fit z-expansion fake-data at ND280

Propagate to SK prediction

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T2K oscillation chain

**External data**
- NA61/HARP hadron prod.
- INGRID ($\nu$) and MUMON ($\mu$)
- External $\nu$ and $\pi$ scattering

**Internal data**
- Cosmics, test beam
- Cosmics, atmospheric, linac

**Model building**
- Beam+flux model
- Interaction model
- ND280 model + sel.
- SK model + sel.

**Simulation**
- ND280
- SK

**Data**
- + oscillations

**Cross-sections, flux, detector parameters**

**Nuisance parameters**

**Oscillation parameters**
- $\delta_{CP}$
- $\theta_{13}$
- $\Delta m_{23}$

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**Flux systematics**

- Bin up changes to underlying beam simulation
  - Highly correlated normalisation parameters in $E_\nu$

- Binning in $E_\nu$ for FHC(PF)/RHC(NF) ND280 and SK reflect flux shape

\[
\begin{align*}
\nu_\mu \text{ PF}/\bar{\nu}_\mu \text{ NF}: & \quad 0.0, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 2.5, 3.5, 5.0, 7.0, 30.0 \\
\bar{\nu}_\mu \text{ PF}/\nu_\mu \text{ NF}: & \quad 0.0, 0.7, 1.0, 1.5, 2.5, 30.0 \\
\nu_e \text{ PF}/\bar{\nu}_e \text{ NF}: & \quad 0.0, 0.5, 0.7, 0.8, 1.5, 2.5, 4.0, 30.0 \\
\bar{\nu}_e \text{ PF}/\nu_e \text{ NF}: & \quad 0.0, 2.5, 30.0
\end{align*}
\]
ND280 selections

- Use FGD1 and FGD2 in ND280 as targets: CH and H$_2$O

- 14 topological event selections (data events per FGD up to 2015)$^\dagger$:
  - $\nu$: CC0$\pi$ (17000), CC1$\pi$ (4500), CCOther (4000)
  - Anti-$\nu$: CC1Trk (2700), CCNTrk (800), CC1Trk $\nu$ bkg (900), CCNTrk $\nu$ bkg (1000)

- Selections are developed by the cross-section groups

- Constrains oscillation signal interaction (CC0$\pi$) and backgrounds (1$\pi$, CCOther or NTracks, neutrino in anti-neutrino)

$^\dagger$Doubling in 2018 analyses
ND280 systematics

- Fit and systematics binned as normalisations in \((p_\mu, \cos\theta_\mu)\)
  - Less sensitivity to nuclear effects or FSI (vs e.g. \(T_\pi\) or \(q_0q_3\)) but very good reconstruction in ND280

- Vary underlying ND280 detector parameters, e.g. TPC PID, B-field distortions, momentum scales
  - 556 correlated detector parameters!

- Desire to move to direct event-by-event detector re-weighting
  - Significant computational overhead
Cross-section systematics

- Rapidly developing field: update model every analysis
- 2017 analysis: 31 systematics for various interaction modes in NEUT MC
- 12 CCQE(-like) systematics:
  - $M_A^{QE}$ is the only nucleon parameter
  - 2p2h shape and normalisation parameters, RPA shape and normalisation
- 3 CC1π on nucleon + 3 CC1π coherent parameters
- $\nu_\mu/\nu_e$ normalisation for neutrino and anti-neutrino
- 6 pion final state interaction parameters
- CC DIS normalisation, CCOther, NCOther, NC1γ
Setting up the fit

- Use external constraints for all flux and ND280 systematics
  - Developed by the beam group and selections group
- Cross-section parameters get external constraints from the Neutrino Interaction Working Group (NIWG)
  - Using external data from NUISANCE
  - Phenomenological arguments, e.g. $\nu_\mu/\nu_e$ and C to O scaling
2017 ND280 data fits

- 1.0 equates to nominal un-tuned model: variation is relative uncertainty
- 2016 analysis’ +10% flux pulls are gone (inset)
  - Encouraging? Moving towards “realistic” cross-section?
2017 ND280 data fits

- $M_A^{QE}$ around value from bubble chamber data (~1.08 GeV)

- Large excursions from priors for RPA, 2p2h shape pushed to boundary

- Importantly, our 1σ prescription is exceeded even with RPA priors from Nieves and Federico Sanchez

- Our 2p2h shape parameter (inspired by placing all the 2p2h shape in PDD or non-PDD according to Nieves) is pushed to its PDD limit
2017 ND280 data fits

- Similar story for non CC0\(\pi\) parameters

- Data prefers a model other than nominal
- Many times at the 1\(\sigma\) boundary or further

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Why is BeRPA pulled?

- Projecting onto “reconstructed” $Q^2_{QE}$ (assuming CCQE kinematics)

- Clear deficiency at low $Q^2_{QE}$ for FGD1 and FGD2 CC0π selections which is why we see the excursion from the prior

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Post-fit evaluation

- Bayesian (MCMC) and Frequentist (Minuit) analyses for ND280-only
  - Propagate post-fit to SK as Gaussians from Frequentist analysis
  - Or fit ND280 simultaneously with SK data with MCMC
  - Approaches compared at SK: see Patrick’s talk

- P-value testing on the post-fit model
  - Decides if we abandon all hope and start from scratch

Frequentist p-value on total test statistic: 47.3%
Bayesian posterior predictive p-value, FGD2 CC0π: 10.9%

- Not happened… yet!
Post-fit evaluation

- Propagate cross-section constraints to external neutrino cross-section data to hint at possible over-tuning or effective tuning
  - MINERvA CC-inclusive low recoil data worse post-fit

NIWG model 2015/6

ND280 post-fit 2015/6

By Patrick Stowell

- Run large number of fake-data studies on plausible alternatives
  - How much do we bias oscillation parameters if model B is the perfect model but we’re fitting using model A
Group comparisons

- Minuit and MCMC post-fits agree well

- Post-fit correlations look reasonable:
  - Flux internally correlated and inversely correlated with cross-sections
To look forward to

- More than double neutrino and anti-neutrino data at ND280
  - Very interesting to see how fit develops
  - Need to continue emphasis on nailing down systematics
- More ND280 selections – better topology separations
  - Larger acceptance at ND280, including backward going
  - CC0\(\pi\), CC1\(\pi\), CCOther selections for anti-neutrino
- More interaction model developments end of summer
  - 2p2h model developments
  - New single pion model
- Large systematic reductions from the beam group
  - Using new NA61/SHINE replica target data
- GENIE fits?
- More in Claudio’s talk!
Summary

- T2K uses a near-detector fit to estimate systematics for oscillation analyses at SK
- Uses 14 topological samples at ND280 in \((p_\mu, \cos\theta_\mu)\)
- Rapidly moving cross-section model updates systematics (at least) once a year
- Some cross-section parameters move outside the conservative pre-fit 1\(\sigma\) prescription, flux and ND280 parameters don’t (for 2017)
- Two methods of propagating ND280 result: assume Gaussianity or do a simultaneous ND280 and Super-K fit
- Lots of statistics coming up for Neutrino 2018 analysis, additional cross-section systematics, and reduction of flux systematics
Thank you!
Likelihood

- Sample modelled as Poisson
- Nuisance parameters as Gaussians

\[-\ln L = -\ln L_{samples} - \ln L_{systematics}\]

\[-\ln L = \sum_{i=1}^{n_{bins}} (N_i^{MC}(x) - N_i^{Data} + N_i^{Data} \ln \left(N_i^{Data}/N_i^{MC}\right)) + \sum_{j=1}^{n_{sys}} \sum_{k=1}^{n_{sys}} \Delta x_j (V^{-1})_{jk} \Delta x_k\]

- About 750 parameters at ND280
- 12 selections at ND280, about 120 bins/selection
  - 1400 bins in $p_\mu \cos \theta_\mu$
2017 Asimov fits

- Asimov/closure fits show no surprises

- “Bias” in 2p2h norm and BeRPA A due to marginalisation
2017 ND280 data fits

- Looking closer at cross-section parameters
- See large changes for BeRPA and 2p2h shape
  - Are we pushing the parameterisation too far?

- Trying to answer this with neutrino interaction experts
2p2h shape

• Have Nieves 2p2h with leptonic tensor in NEUT
• No method of varying parameter other than normalisation
• Assume PDD-like (+1), non-PDD-like (-1), nominal shape: transition between them without interference terms in $q_0 \ q_3$ space

Realistically only covers Nieves 2p2h without any interferences
  • Not covering Martini 2p2h, SUSA, SF, etc
• Martini covered by fake-data analyses at SK and inflating parameter errors
RPA corrections

- Random Phase Approximation
- Correction to $W$ self-energy in presence of nuclear effects
- Absent for nucleon interactions (e.g. $H_2$, largely $D_2$)
Cross-section systematics

- 2017 analysis used 31 cross-section parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Error</th>
<th>Prior</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE model</td>
<td>2</td>
<td>N/A</td>
<td>N/A</td>
<td>D</td>
<td>MDLQE = 2 corresponds to the RFG model.</td>
</tr>
<tr>
<td>$SE\rightarrow$RFG</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>$M_\nu^\text{QE}$ (GeV)</td>
<td>1.21</td>
<td>0-10</td>
<td>flat</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>$M_\nu^\text{RE}$ (GeV)</td>
<td>1.03</td>
<td>0</td>
<td>N/A</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>$p_F^{12}\text{C}$ (MeV)</td>
<td>217</td>
<td>31</td>
<td>flat</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>$p_F^{16}\text{O}$ (MeV)</td>
<td>225</td>
<td>31</td>
<td>flat</td>
<td>B</td>
<td></td>
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<tr>
<td>2p2h norm. $\nu^{-12}\text{C}$</td>
<td>1</td>
<td>1</td>
<td>flat</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>2p2h norm. $\bar{\nu}^{-12}\text{C}$</td>
<td>1</td>
<td>1</td>
<td>flat</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>2p2h norm. $^{12}\text{C}$ to $^{16}\text{O}$</td>
<td>1</td>
<td>0.2</td>
<td>flat</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>2p2h shape $\nu^{-12}\text{C}$</td>
<td>0</td>
<td>1</td>
<td>flat</td>
<td>B (or N)</td>
<td>30% correlated with 2p2h shape $\nu^{-12}\text{C}$</td>
</tr>
<tr>
<td>2p2h shape $\bar{\nu}^{-16}\text{O}$</td>
<td>0</td>
<td>1</td>
<td>flat</td>
<td>B (or N)</td>
<td></td>
</tr>
<tr>
<td>BeRPA A</td>
<td>0.59</td>
<td>0.118</td>
<td>gauss.</td>
<td>B</td>
<td></td>
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<tr>
<td>BeRPA B</td>
<td>1.05</td>
<td>0.21</td>
<td>gauss.</td>
<td>B</td>
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<tr>
<td>BeRPA C</td>
<td>1.13</td>
<td>0.17</td>
<td>gauss.</td>
<td>B</td>
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<tr>
<td>BeRPA D</td>
<td>0.88</td>
<td>0.352</td>
<td>gauss.</td>
<td>B</td>
<td></td>
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<tr>
<td>BeRPA U</td>
<td>1.2</td>
<td>N/A</td>
<td>N/A</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>RES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>correlations in Fig.48</td>
</tr>
<tr>
<td>$M_\nu^\text{res}$</td>
<td>1.07</td>
<td>0.15</td>
<td>gauss.</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>$C_3^\text{res}$</td>
<td>0.96</td>
<td>0.15</td>
<td>gauss.</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>$I = 1/2$ Bkg.</td>
<td>0.96</td>
<td>0.40</td>
<td>gauss.</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

Other

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Error</th>
<th>Prior</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC coh. $\nu^{-12}\text{C}$</td>
<td>reweight</td>
<td>0.3</td>
<td>gauss.</td>
<td>B</td>
<td>$E_\nu$ weights are applied according to Table 12. Fully correlated with $^{12}\text{C}$</td>
</tr>
<tr>
<td>CC coh. $\nu^{-16}\text{O}$</td>
<td>reweight</td>
<td>0.3</td>
<td>gauss.</td>
<td>B</td>
<td>$E_\nu$ weights are applied according to Table 12. Fully correlated with $^{12}\text{C}$</td>
</tr>
<tr>
<td>CC other shape</td>
<td>0.0</td>
<td>0.4</td>
<td>gauss</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>NC coh. $\nu^{-16}\text{O}$</td>
<td>1.0</td>
<td>0.3</td>
<td>gauss</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>NC 1γ</td>
<td>2.0</td>
<td>2.0</td>
<td>gauss</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>NC Other</td>
<td>1.0</td>
<td>0.3</td>
<td>gauss</td>
<td>N,F</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu/\nu_\mu$</td>
<td>1.00</td>
<td>$\sqrt{2} \times 0.02$</td>
<td>gauss</td>
<td>F</td>
<td>2% anticorrelation between these two dials Sec.7</td>
</tr>
<tr>
<td>$\nu_\tau/\nu_\mu$</td>
<td>1.00</td>
<td>$\sqrt{2} \times 0.02$</td>
<td>gauss</td>
<td>F</td>
<td>2% anticorrelation between these two dials Sec.7</td>
</tr>
<tr>
<td>Pion FSI</td>
<td>N,F</td>
<td></td>
<td></td>
<td></td>
<td>see Sec. 5</td>
</tr>
</tbody>
</table>