Long-baseline neutrino oscillation physics in Japan

Mark Scott
University of Warwick
10th June 2021
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Neutrino Oscillations

Art McDonald
2015 Nobel

Takaaki Kajita
2015 Nobel
Neutrino Oscillation Formalism

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
c_{ij} = \cos \theta_{ij} \\
s_{ij} = \sin \theta_{ij} \\
\delta = \delta_{CP}
\]

\[
\mathbf{U} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

\[
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\]

\[
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Atmospheric /Beam  
Beam /Reactor  
Reactor /Solar
Neutrino Oscillation Formalism

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\begin{pmatrix}
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\nu_2 \\
\nu_3
\end{pmatrix}
\]

What do we know?
- \(\theta_{23} = 45.6^\circ \pm 2.3^\circ\)
- \(\theta_{13} = 8.3^\circ \pm 0.2^\circ\)
- \(\theta_{12} = 33.6^\circ \pm 0.8^\circ\)
- \(|\Delta m_{32}^2| = (2.45 \pm 0.05) \times 10^{-3} \text{ eV}^2c^{-4}\)
- \(\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2c^{-4}\)

What don’t we know?
- Is \(\theta_{23} = 45^\circ\) (octant)?
- Is \(\Delta m_{32}^2 > 0\) (mass ordering)?
- Do neutrinos violate CP-symmetry?
- New physics?
Neutrino Oscillation Formalism

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- Is \( \theta_{23} = 45^\circ \) (octant)?
- Is \( \Delta m^{2}_{32} > 0 \) (mass ordering)?
- Do neutrinos violate CP-symmetry?
- New physics?
Long-baseline neutrino experiments

- Leading order oscillation probabilities for $\nu_\mu$ survival and $\nu_e$ appearance

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right) \]

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]
Long-baseline neutrino experiments

- Leading order oscillation probabilities for $\nu_\mu$ survival and $\nu_e$ appearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

- Need to sample spectrum at different values of $L/E$
- Build two detectors
- One close to neutrino source
- Other at maximal oscillation
**CP violation in neutrino oscillation**

\[
P(\nu_\mu \rightarrow \nu_\ell) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E_\nu} \right) \left( 1 + \frac{2a}{\Delta m_{31}^2} (1 - 2\sin^2 \theta_{13}) \right)
\]

- Probability for $\nu_e$ appearance around the oscillation maximum, including CP-violating term
  - $\delta \rightarrow -\delta$ when switching from neutrinos to antineutrinos

- Can measure $\delta_{\text{CP}}$ by comparing rate of electron neutrino appearance to rate of electron antineutrino appearance
  - Can also use absolute rate for neutrinos/antineutrinos if other oscillation parameters known well enough
Tokai to Kamioka Experiment – T2K

Super-Kamiokande (SK)

Near detectors

Kamioka

Tokai

JPARC

Materials and Life Science Experimental Facility

Hadron Beam Facility

Nuclear Transmutation

Linac (330m)

3 GeV Rapid Cycling Synchrotron (RCS)

56 GeV Main Ring Synchrotron (56 GeV FL)

56 GeV Main Ring Synchrotron (56 GeV M14)

JPARC = Japan Proton Accelerator Research Complex

Super-Kamiokande

Tokai

Tokyo

Tokai to Kamioka Experiment – T2K

Long-baseline neutrino oscillations in Japan

10th June 2021
Neutrino beams

- Proton beam collides with fixed target to produce charged mesons.
- Focus positive or negative mesons to produce neutrino-dominated or antineutrino-dominated beam.
- Wait for pions to decay into neutrinos.
Off-axis beams

- Two-body pion decay
  - Angle and energy of neutrino directly linked
- Moving off axis:
  - Lower peak energy
  - Smaller high energy tail
  - Less energy spread
- T2K is at 2.5° off-axis
Integrated POT (Full T2K - up to Run 10)

23 Jan 2010 - 12 Feb 2020

23 Jan 2010 - 12 Feb 2020
POT Total: $3.64059 \times 10^{21}$
(maximum power 522.627 kW)

$\nu$ mode: $1.99006 \times 10^{21}$ (54.7%)
$\bar{\nu}$ mode: $1.65053 \times 10^{21}$ (45.3%)
Near detectors

INGRID
- Measure direction of neutrino beam
- Ensure stable beam operation
- Tune neutrino flux prediction

ND280
- Measure neutrino flux and cross section before oscillation
- UA1 magnet allows separation of neutrino and antineutrinos
- Oscillation analysis focuses on muon (anti-)neutrino samples
Super-Kamiokande

- 40,000 tons of ultra pure water
- 11,000 photo-multiplier tubes (PMTs)
- 1km overburden
- Separate electrons and muons by ring shape
  - Mis-ID <1%
  - No sign selection
Neutrino interactions

• Three principal types of neutrino interaction
• Occur as both charged current (CC) and neutral current processes

Quasi-elastic (CCQE)

Single pion production

Deep inelastic scattering / Multi-pion production
ND280 data

- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes
ND280 event samples

- Select highest momentum, muon-like, negative (positive) track as neutrino (antineutrino) candidate
- Count the number of tagged charged or neutral pions
• Fit parametrized models to near detector data
  – Two separate analysis, Markov Chain MC and Minimisation, Bayesian and Frequentist methods
Near detector analysis

- Produces tuned flux and cross-section models
- Use models to predict unoscillated event rate at Super-K
Near detector fit results

- Charged-current, zero-pion sample shown on right
  - Prefit on top, postfit on bottom

- Tuned muon neutrino flux at Super-K shown below
  - Prior in red, fit result in blue
Far detector analysis

- Apply oscillation parameters to prediction from tuned models
- Fit to data, marginalizing over nuisance parameters
  - Three separate analyses, using Markov Chain MC and Minimisation, and Bayesian and Frequentist methods
What T2K measures

- Muon-like neutrino candidates (left), electron-like candidates (right)
What T2K measures

- Muon-like neutrino candidates (left), electron-like candidates (right)
- Suppression in muon neutrino sample driven by $\sin^2\theta_{23}, \Delta m^2_{23}$
What T2K measures

- Muon-like neutrino candidates (left), electron-like candidates (right)
- Suppression in muon neutrino sample driven by \( \sin^2 \theta_{23}, \Delta m^2_{23} \)
- Increase in electron neutrino sample driven by \( \sin^2 \theta_{13}, \delta_{\text{CP}} \)
Effect of near detector fit on SK prediction

- Far detector single ring, muon-like sample on left, single ring electron-like sample on right
- ND280 fit result (red) increases predicted event rate, changes shape of spectrum and reduces systematic uncertainty
T2K systematic errors

<table>
<thead>
<tr>
<th>Error source (units: %)</th>
<th>1R_μ (FHC, RHC)</th>
<th>1R_e (FHC, RHC, CC1π⁺)</th>
<th>FHC/RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>2.9, 2.8</td>
<td>2.8, 2.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Xsec (ND constr)</td>
<td>3.1, 3.0</td>
<td>3.2, 3.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Flux + Xsec (ND constr)</td>
<td>2.1, 2.3</td>
<td>2.0, 2.3, 4.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Xsec (ND unconstrained)</td>
<td>0.6, 2.5</td>
<td>3.0, 3.6, 2.8</td>
<td>3.8</td>
</tr>
<tr>
<td>SK + SI + PN</td>
<td>2.1, 1.9</td>
<td>3.1, 3.9, 13.4</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.0, 4.0</td>
<td>4.7, 5.9, 14.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>

- Uncertainty on predicted SK event rate after ND280 fit
  - Flux and cross-section uncertainties are correlated so the combination gives a smaller uncertainty than the individual parts
  - Final column is error on rate of neutrino events compared to antineutrino events in the electron-like samples – critical for CP violation search
Latest Results – Neutrino mode beam samples

- Neutrino beam mode, muon-like CC-0π candidates (left), electron-like CC-0π candidates (right)
- Prediction (blue histogram) and RMS error (red band) after fit to data
Latest Results – Neutrino mode beam samples

- CC-1π sample only in neutrino beam mode
Latest Results – Neutrino mode beam samples

- CC-1π sample only in neutrino beam mode
- Use Michel electron tag to locate pion – below Cherenkov threshold
Latest Results – Antineutrino beam mode

- Antineutrino beam mode, muon-like CC-0π candidates (left), electron-like CC-0π candidates (right)
- Prediction (blue histogram) and RMS error (red band) after fit to data
Disappearance parameters

- T2K data shows preference for upper octant
- Best-fit point at non-maximal mixing, though maximal mixing still within 1σ
- Fits include reactor constraint on $\sin^2(\theta_{13})$
Disappearance parameters – global comparison

- 90% confidence level contours
- Normal mass ordering assumed
- All experiments in agreement
Appearance parameters – without reactor

- Fit without reactor constraint on $\sin^2(\theta_{13})$
- T2K best-fit point near maximal CP-violation
- Fully consistent with reactor measurements
Appearance parameters – with reactor

- Fit with reactor constraint on $\sin^2(\theta_{13})$
- T2K best-fit point nearer maximal CP-violation
- Regions of $\delta_{CP}$ space outside 2$\sigma$ contour
• **Fit with** reactor constraint on $\sin^2(\theta_{13})$

• Likelihood with respect to global minimum

• Using Feldman-Cousins method to ensure coverage

• $\delta_{CP} = \pi/2$ excluded at $>3\sigma$
Mass Ordering and $\theta_{23}$ Octant

- Table shows posterior probability for various hypotheses
  - Bayesian approach
  - Marginalising over other oscillation parameters
  - A flat prior is used for $\delta_{CP}$, $\sin^2 \theta_{23}$, $|\Delta m^2_{23}|$ and mass ordering
  - Solar parameters and $\sin^2 2\theta_{13}$ use Gaussian prior from PDG

- T2K data prefer the upper octant and normal mass ordering

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{23} &lt; 0.5$</th>
<th>$\sin^2 \theta_{23} &gt; 0.5$</th>
<th>Line total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal ordering</td>
<td>0.19</td>
<td>0.65</td>
<td>0.83</td>
</tr>
<tr>
<td>Inverted ordering</td>
<td>0.03</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>Column total</td>
<td>0.21</td>
<td>0.79</td>
<td>1.00</td>
</tr>
</tbody>
</table>
T2K bi-event rate

- T2K data consistent with Pontecorvo-Maki-Nakagawa-Sakata prediction
- Shaded area shows systematic uncertainty on prediction
$\delta_{CP}$ global comparison

- Fit with reactor constraint on $\sin^2(\theta_{13})$
- Assuming Normal mass ordering
- Experiments ~agree at 90% C.L.
  - Need more data!
Robustness checks
Neutrino cross section error

- Neutrino cross-section is ~largest source of uncertainty
- World data is imprecise around 1 GeV neutrino energy
- Multiple, plausible models exist, however:
  - Monte Carlo simulation based on a single model

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<td>Xsec (ND unconstr)</td>
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Simulated data studies

• Use information about simulated interactions to produce mock data based on a different neutrino interaction model
  – Detailed description can be found here: https://arxiv.org/abs/2101.03779

• Pass mock data through near and far detector fitters
  – Tune nominal interaction model to try and match mock data model
  – Extract oscillation parameter contours and compare to our expectation
  – Use results to add additional uncertainties to oscillation contours from real data fit
T2K cross-section model

- Many unknowns!

Image from K. McFarland
Example: 2p-2h events

- Lepton kinematics give energy
- Extra protons below detector threshold – missed energy
- If we get the model wrong
  - Biased energy reconstruction
  - Incorrect relationship between reconstructed and true neutrino energy
2p-2h event reconstruction

- Biased energy affects oscillation measurements
- Multiple possible models – Martini and Nieves are two examples
  - Different predicted rates for neutrinos and anti-neutrinos
  - ‘CP-violating’ uncertainty
The Martini 2p2h simulated data study

- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown
The Martini 2p2h simulated data study

- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown
- Increase in normalization with larger increase at larger neutrino energies
Martini 2p2h ND280 fit

- Changes in flux and 2p2h normalization
  - Normalisation change expected, larger cross-section
  - Energy dependence – only flux parameters allow this in current model
Martini 2p2h at SK

- See that Martini model (compare nominal MC to simulated data) increases neutrino event rate (left), but not antineutrino (right)
- ND280 fit (red shading) under-predicts neutrino data but over-predicts antineutrino data
Martini 2p2h at SK – 2D contours

- Disappearance contour shifts to lower values of $\Delta m^2_{32}$
  - Bias in energy reconstruction
- Contour shrinks for $\delta_{\text{CP}} - \sin^2 \theta_{13}$
  - Relative rate of neutrino and antineutrino events changes
- $\Delta \chi^2$ for $\delta_{CP}$ changes by ~2 units at maximum
  - Apply change in $\Delta \chi^2$ to data to assess effect
- $\Delta m^2_{32}$ likelihood is ~Gaussian
  - Apply fractional shift in best fit point as an additional systematic
Martini 2p2h at SK – Assessing $\delta_{CP}$

- Change in $\Delta X^2$ on left
- Nominal data $\Delta X^2$ (green) and corrected data $\Delta X^2$ (red) on right
  - Feldman-Cousins $3\delta$ (blue) and $2\delta$ (magenta) critical values
  - Negligible effect – **true for all interaction models studied**
Likelihood of $\delta_{CP}$ result

- Use marginalisation ‘toy’ experiments to check how unlikely our data result is
  - Randomly vary nuisance parameters according to their prior

- Coloured regions contain stated fraction of toys
  - Data result within ~$1\sigma$ of median
Contribution to $\delta_{CP}$ result

- Can also replace individual data samples with nominal MC expectation
  - ‘Asimov’

- See that better-than-expected exclusion comes from neutrino mode electron-like samples
  - Both equally
Where next?
Water Cherenkov detectors in Kamioka

Super-Kamiokande
22.5kt fiducial mass

Kamiokande
3kt mass

Hyper-Kamiokande
188kt fiducial mass
Hyper-Kamiokande electron-like event samples

- Expect approx:
  - 2300 $\nu_e$ events
  - 1900 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$

- Difference between neutrino and antineutrino rates gives $\delta_{CP}$
CP violation sensitivity

- Ability to exclude CP conservation versus true value of $\delta_{CP}$

![Graph showing CP violation sensitivity](image)
CP violation sensitivity

- Ability to exclude CP conservation versus true value of $\delta_{CP}$
- Large electron-like samples provide high statistics
CP violation sensitivity

- Ability to exclude CP conservation versus true value of $\delta_{CP}$
- Large electron-like samples provide high statistics
- Limited by systematics
CP violation sensitivity

- Ability to exclude CP conservation versus true value of $\delta_{CP}$
- Large electron-like samples provide high statistics
- Limited by systematics
- Can exclude 60% of true $\delta_{CP}$ values at 5$\sigma$

Hyper-K preliminary
True normal hierarchy (known)
$\sin^2(\theta_{13}) = 0.0218$  $\sin^2(\theta_{23}) = 0.528$  $|\Delta m^2_{32}| = 2.509 E-3$
CP violation sensitivity over time

- Percentage of true $\delta_{CP}$ values where CP conservation can be excluded as a function of running year

\[
\sin^2(\theta_{13}) = 0.0218 \quad \sin^2(\theta_{23}) = 0.528 \quad |\Delta m^2_{32}| = 2.509 \text{E-3}
\]
CP violation sensitivity over time

- Percentage of true $\delta_{CP}$ values where CP conservation can be excluded as a function of running year

- Can achieve $3\sigma$ CP violation result over significant regions of $\delta_{CP}$ after 2 years operation
Summary

- T2K has measured neutrino oscillation parameters with $3.64 \times 10^{21}$ POT
  - Approaching $2\sigma$ exclusion of CP conservation
  - Preference for upper octant and normal mass ordering
- Detailed studies of neutrino interaction model robustness
  - Essential for future experiments
- Next generation experiment, HK, will give $5\sigma$ sensitivity to CP violation over large range of true $\delta_{CP}$ values
  - Systematics limited!
Backup Slides
SK detector systematics

- Understanding detector systematics and pion scattering crucial for future (+current) experiments

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- Particularly necessary for higher energy events
  - Multi-pion samples at far detector
  - Atmospheric neutrinos

- Table shows effect on rate of events, but must understand energy spectrum shape for precision measurements
Water Cherenkov Test Experiment

- Goal: study detector systems and detector response to pions, muons, electrons and protons from 200 MeV/c up to 1000 MeV/c
  - Understand detector calibration needed for IWCD/HK
  - Physics: Cherenkov profile, secondary interactions, neutrons
- Use tertiary production target and spectrometer upstream of detector
Experimental area

- We are proposing to use the T9 beam line in the East Area
  - Enough space for 4m by 4m tank and tertiary beamline

- Tertiary beam for pions/protons
Experimental area

- We are proposing to use the T9 beam line in the East Area
  - Enough space for 4m by 4m tank and tertiary beamline

- Tertiary beam for pions/protons
- Secondary beam for low momentum electrons and muons
- Planned for early 2023
WCTE at CERN T9 beamline
WCTE Detector concept

- Instrumented with multi-PMT modules being developed for Hyper-K
- Integrated calibration system on detector lid
- Total mass ~50 tons
Best fit parameter values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Hierarchy</th>
<th>T2K only</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T2K only</td>
<td>T2K + reactor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normal</td>
<td>Inverted</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{13})$</td>
<td></td>
<td>0.109</td>
<td>0.120</td>
</tr>
<tr>
<td>$\sin^2(\theta_{13})$</td>
<td></td>
<td>$28.0 \times 10^{-3}$</td>
<td>$31.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td></td>
<td>$-2.22$</td>
<td>$-1.29$</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ (NH)/</td>
<td>$\Delta m^2_{31}$ (IH) [eV$^2/c^4$]</td>
<td>$2.495 \times 10^{-3}$</td>
<td>$2.463 \times 10^{-3}$</td>
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<tr>
<td>$\sin^2(\theta_{23})$</td>
<td></td>
<td>0.467</td>
<td>0.466</td>
</tr>
<tr>
<td>$-2\ln L$</td>
<td></td>
<td>597.72</td>
<td>598.56</td>
</tr>
</tbody>
</table>

- Global best fit (above) and Feldman-Cousins intervals for $\delta_{CP}$ (bottom left) and $\sin^2\theta_{23}$ (bottom right)

<table>
<thead>
<tr>
<th>$\delta_{CP}$</th>
<th>Confidence level</th>
<th>Interval (NH)</th>
<th>Interval (IH)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1$\sigma$</td>
<td>$[-2.66, -0.97]$</td>
<td>$[-1.79, -1.09]$</td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td>$[-3.00, -0.49]$</td>
<td>$[-3.52, -1.09]$</td>
</tr>
<tr>
<td></td>
<td>2$\sigma$</td>
<td>$[-\pi, -0.26] \cup [3.11, \pi]$</td>
<td>$[-2.20, -0.75]$</td>
</tr>
<tr>
<td></td>
<td>3$\sigma$</td>
<td>$[-\pi, 0.32] \cup [2.63, \pi]$</td>
<td>$[-2.82, -0.14]$</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>$\sin^2\theta_{23}$</th>
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<th>Interval (NH)</th>
<th>Interval (IH)</th>
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<tr>
<td></td>
<td>1$\sigma$</td>
<td>[0.528, 0.582]</td>
<td>[0.537, 0.584]</td>
</tr>
<tr>
<td></td>
<td>90%</td>
<td>[0.443, 0.592]</td>
<td>[0.505, 0.593]</td>
</tr>
<tr>
<td></td>
<td>2$\sigma$</td>
<td>[0.436, 0.597]</td>
<td>[0.505, 0.593]</td>
</tr>
</tbody>
</table>
Beam stability

- INGRID and muon monitors measure beam centre position
- Very stable neutrino beam over full run
T2K flux model

- Parametrised in neutrino energy and flavour
- Parameter uncertainties calculated by varying underlying systematics
- Performed simultaneously for near and far detector
- Correlates near and far flux parameters
Super-Kamiokande detector

- Signal in far detector:
- Measure rate of muon-like and electron-like events
- CCQE interactions are 'golden' channel

\[ E_{\nu}^{\text{QE}} = \frac{m_p^2 - m_n' - m_\mu^2 + 2m_n'E_\mu}{2(m_n' - E_\mu + p_\mu \cos \theta_\mu)} \]

- Assume nucleon at rest – 2-body process
- Can calculate neutrino energy from observed muon kinematics

(a) CC QES interaction
Cross-section model – CC $0\pi$

- Axial mass parameter
- $2p2h$ normalisation
  - Different for neutrinos and antineutrino
- $2p2h$ shape – difference between true and reconstructed neutrino energy
  - Different for carbon and oxygen
- $Q^2$ normalization parameters
Cross-section model – Binding energy

- Affects CC $0\pi$ events
- Shifts momentum of outgoing lepton
- New modelling allows this to be constrained by near detectors
  - Previously was a large uncertainty on oscillation measurement
Cross-section model – CC $1\pi$

- CA5 – normalisation for the resonant form factor
- Axial mass parameter
- $I=1/2$ background norm.
  - Low momentum and high momentum pions
Cross-section model – Pion Final State Interactions

- Microscopic final state interaction cross-section parameters
- Alter charge, kinematics and presence of pions in final state of neutrino interaction
Cross-section model – CC Other

- CC coherent pion production normalization
  - Separate for carbon and oxygen
- NC coherent normalization
  - Not fit at near detector
- NC other normalization
  - Not extrapolated to far detector
Cross-section model – CC DIS

- Bodek-Yang correction uncertainty
  - Separate for DIS and multi-pion production events
- AKGY multi-pion production model uncertainty
- Miscellaneous events
- DIS/multi-pion normalization uncertainties
SK event selection – $0\pi$ samples

Look for fully contained, single ring events inside SK fiducial volume, then:

**If electron-like ring:**
- Visible energy $> 100$ MeV
- Reconstructed energy $< 1250$ MeV
- Not identified as $\pi^0$
- No decay electrons

**If muon-like ring:**
- Reconstructed momentum $> 200$ MeV/c
- At most 1 decay electron
SK event selection – e-like single pion sample

Look for fully contained, single ring events inside SK fiducial volume, then:

**If electron-like ring:**

- Visible energy > 100 MeV
- Reconstructed energy < 1250 MeV
- Not identified as $\pi^0$
- **One** decay electrons
PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position

$v_{\text{beam}}$
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
PRISM benefits - 2

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- Produce Gaussian energy distribution
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution

- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range
PRISM benefits - 3

- Can have different linear combination
PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data

\[
\sin^2 \theta_{23} = 0.5 \\
\Delta m^2_{32} = 2.41 \times 10^{-3}
\]
PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data

\[ \sin^2 \theta_{23} = 0.5 \]
\[ \Delta m_{32}^2 = 2.41 \times 10^{-3} \]

- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Oscillation analysis minimally dependent on neutrino interaction model
PRISM benefits - 4

- Fit ND $v_e$ flux
  - Directly measure electron/muon cross-section ratio

- Sterile neutrino searches
  - >5σ exclusion of LSND
  - Oscillation vs off-axis angle
1. Is the mass hierarchy “normal” or “inverted?”
2. Do neutrino oscillations violate \( CP \) symmetry?
3. What is the “octant” of \( \theta_{23} \)?
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2. Do neutrino oscillations violate \( CP \) symmetry?
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1. Is the mass hierarchy “normal” or “inverted?"
2. Do neutrino oscillations violate $CP$ symmetry?
3. What is the “octant” of $\theta_{23}$?

**Diagram:**

- $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$
- $P(\nu_\mu \rightarrow \nu_e)$

- $\delta=0$, $\delta=\pi/2$
- $\delta=\pi$, $\delta=3\pi/2$

**Legend:**

- **Antineutrino**
- **Neutrino**

**Text:**

$CP$-violation through $\delta$ creates opposite effects in neutrinos and antineutrinos.

*Slides by A. Himmel*
1. Is the mass hierarchy “normal” or “inverted”?
2. Do neutrino oscillations violate $CP$ symmetry?
3. What is the “octant” of $\theta_{23}$?

Matter effects also introduce opposite neutrino-antineutrino effects.

Slides by A. Himmel
1. Is the mass hierarchy “normal” or “inverted”?

2. Do neutrino oscillations violate $CP$ symmetry?

3. What is the “octant” of $\theta_{23}$?

The octant creates the same effect in neutrinos and antineutrinos.

Slides by A. Himmel