Impact of Systematic Uncertainties for the Hyper-Kamiokande Experiment

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The Hyper-K Experiment

1 Mton water-Cherenkov detector (0.56 Mton fiducial mass)

295 km and 2.5° off-axis from the J-PARC neutrino beam

Broad physics program includes:

- Long baseline accelerator neutrinos
- Atmospheric Neutrinos
- Nucleon Decay

![Diagram of the Hyper-K Experiment](image-url)
Sources of Systematic Uncertainty

Systematic errors arise in the modeling of:

- **Neutrino Flux**
- **Neutrino Interactions**
- **Near detector response**
- **Far detector response**

Focus of this talk
• Larger wrong sign flux is larger in antineutrino mode
• The electron neutrino background is \(~0.5\%\) near the peak
Event Rate Distributions

7.5 MW x 10^7 s
Near/Intermediate Detectors

• Near detector data are used to constrain the predicted event rate in the far detector through the flux and cross section models

• HK is considering an upgrade to ND280 and a new intermediate water-Cherenkov detector (at 1-2 km baseline)

TITUS

~2km from J-PARC
2.5° off-axis

2kton Gd-doped (0.1%) water Cherenkov detector

Magnetized muon-range detectors

Tuesday 11:00 AM WG1-WG2 Session
K. Mahn, T2K Near Detectors
A. Minamino, T2K Upgraded and HK Near Detectors

WAGASCI in ND280 magnet

NuPRISM
Neutrino Flux Model

Flux prediction from data driven simulation:
- Proton beam monitor measurements
- Horn field measurements
- Beam-line component alignment measurements
- Hadron production measurements (NA61/SHINE)

Dominant source of systematic error
• Projected flux uncertainty for HK is based on the T2K uncertainty
• Error reduction due to assumption of hadron production data for replica target
• Replica target data from NA61/SHINE is now being incorporated in the T2K flux prediction
Flux Near to Far Uncertainty

- Estimate the flux uncertainty in the near to far extrapolation: error on the far/near ratio
- In the flux peak region, error is <1% for near detector at 280 m (T2K ND280 detector)
- <0.5% uncertainty for intermediate detector sites at 1 km and 2 km
- We can achieve a sufficiently small flux uncertainty for the extrapolation
- Reducing the flux error is also important for testing the cross section model with near/intermediate detector data
The current approach for interaction model errors is based on the T2K parameterization of the NEUT model and the near detector constraints. The fit to ND280 data constrains the flux and interaction models to the 3% level (excluding separate systemic parameters for the nuclear model/FSI). Include uncertainties in the FSI and nuclear model assigned due to different target in the near and far detector (CH vs. H₂O). Should be reduced with measurements on H₂O in near and intermediate detectors.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_e$ CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux and common cross sections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(w/o ND280 constraint)</td>
<td>21.7%</td>
<td>26.0%</td>
</tr>
<tr>
<td>(w ND280 constraint)</td>
<td>2.7%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Independent cross sections</td>
<td>5.0%</td>
<td>4.7%</td>
</tr>
<tr>
<td>SK</td>
<td>4.0%</td>
<td>2.7%</td>
</tr>
<tr>
<td>FSI+SI(+PN)</td>
<td>3.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(w/o ND280 constraint)</td>
<td>23.5%</td>
<td>26.8%</td>
</tr>
<tr>
<td>(w ND280 constraint)</td>
<td>7.7%</td>
<td>6.8%</td>
</tr>
</tbody>
</table>

For Hyper-K Sensitivities

For the published Hyper-K sensitivities, we have assumed improvements in the near/intermediate detector constraints.

The uncertainty from the part of the models constrained by the near detector stays the same.

Increased uncertainty in antineutrino mode due to modeling of the wrong sign component.

Assume no correlation between neutrino and antineutrino mode - conservative approach for CPV measurement.

Uncertainties in the interaction model that cannot be constrained by the near detector are reduced.

Improved H$_2$O measurements in upgraded ND280, measurements in intermediate water-Cherenkov detector.

Table 9. Uncertainties (in %) for the expected number of events at Hyper-K from the systematic uncertainties assumed in this study. ND: near detector.

<table>
<thead>
<tr>
<th></th>
<th>Flux &amp; ND-constrained cross section</th>
<th>ND-independent cross section</th>
<th>Far detector</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ mode</td>
<td>Appearance 3.0</td>
<td>1.2</td>
<td>0.7</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Disappearance 2.8</td>
<td>1.5</td>
<td>1.0</td>
<td>3.3</td>
</tr>
<tr>
<td>$\bar{\nu}$ mode</td>
<td>Appearance 5.6</td>
<td>2.0</td>
<td>1.7</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Disappearance 4.2</td>
<td>1.4</td>
<td>1.1</td>
<td>4.5</td>
</tr>
</tbody>
</table>

PTEP 2015, 053C02
Hyper-K Sensitivities

CP violation discovery potential
(known hierarchy)

\[ \theta_{23}, \Delta m_{32} \text{ measurement} \]

3σ at 75% of \( \delta_{\text{cp}} \) values

7.5 MW x \( 10^7 \) s
Individual Systematic Uncertainties

• We also carry out studies to evaluate the impact of individual systematic error sources

• Important input to the near/intermediate detector design

  • Identify the important systematic uncertainties

  • Choose near/intermediate detector designs that can make measurements to reduce the systematic uncertainties

• Will show some of the important systematic uncertainties in this talk
νₑ and ¯νₑ Cross Sections

• We measure νₑ and ¯νₑ rates in our near detectors
• To predict the νₑ and ¯νₑ rates at the far detector we need to correct for the cross-section difference
• No precision measurements of the νₑ, ¯νₑ cross sections at the energies of interest
• For CP violation measurement, the important quantity is \((\sigma_{νₑ}/\sigma_{νₘ})/(\sigma_{¯νₑ}/\sigma_{¯νₘ})\)
• What are the theoretical uncertainties?
\( \nu_e \) and \( \bar{\nu}_e \) Cross Section Uncertainties

- Sources of theoretical uncertainty are considered by Day & McFarland (Phys. Rev. D86 (2012) 053003)
  - Inclusion of second class currents can change the cross section ratio by 2% at the flux peak
  - The kinematically allowed region is different

\[
Q_{\text{max}}^2 = -m^2 + \frac{s - M^2}{\sqrt{s}} (E_\ell^* \pm |p_\ell^*|)
\]

- Effect is significant at the maximum \( Q^2 \) for neutrinos
- Radiative corrections - should be calculated
• Perform sensitivity study where the $\nu_e$ and $\bar{\nu}_e$ cross sections are assigned two uncorrelated normalization systematic parameters

• The uncertainties on the normalization parameters are varied and the impact on the CPV sensitivity is studied.

• The systematic uncertainty should be controlled to <1-2% to minimize the impact on the CPV discovery sensitivity
Direct measure of $\nu_e,\bar{\nu}_e$ Cross Sections

- Ideal place for measurement would be nuSTORM, but can we measure the cross sections in our conventional beam?
- The beam includes an intrinsic electron neutrino component (0.5% at the peak)

Can increase $\nu_e$ purity by going further off-axis

<table>
<thead>
<tr>
<th>Off-axis angle ($^\circ$)</th>
<th>$\nu_e$ Flux 0.3-0.9 GeV</th>
<th>$\nu_\mu$ Flux 0.3-5.0 GeV</th>
<th>Ratio $\nu_e/\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1.24E+15</td>
<td>2.46E+17</td>
<td>0.507%</td>
</tr>
<tr>
<td>3.0</td>
<td>1.14E+15</td>
<td>1.90E+17</td>
<td>0.600%</td>
</tr>
<tr>
<td>3.5</td>
<td>1.00E+15</td>
<td>1.47E+17</td>
<td>0.679%</td>
</tr>
<tr>
<td>4.0</td>
<td>8.65E+14</td>
<td>1.14E+17</td>
<td>0.760%</td>
</tr>
</tbody>
</table>

At 2.5°, SK has 77% purity in the absence of oscillations
$\nu_e, \overline{\nu}_e$ Cross Sections Precision

- We estimated flux model and statistical errors for a $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ measurement in NuPRISM

![Graph showing ratio of $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ vs $E_\nu$ (MeV)]

<table>
<thead>
<tr>
<th></th>
<th>Flux Error</th>
<th>Hadron x1/2</th>
<th>Stat. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-600 MeV</td>
<td>3.2%</td>
<td>1.7%</td>
<td>2.9%</td>
</tr>
<tr>
<td>600-900 MeV</td>
<td>5.2%</td>
<td>3.4%</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

- Preliminary study suggests that a 3% measurement or better is plausible.
Wrong Sign Background

- In antineutrino mode, neutrinos contribute ~20% to the event rate:

  ![Table 7](image)

  - Study a normalization uncertainty on the wrong sign background:

  ![Graph](image)

  - <10% uncertainty is necessary to have negligible impact on CPV sensitivity

  - Few % uncertainty can be achieved with a magnetized detector such as ND280
Intrinsic Electron Neutrino Background

- The intrinsic beam $\nu_e$ contribute ~15-20% to the event rate:

  - <5% uncertainty is necessary to have negligible impact on CPV sensitivity
  - <5% should be achievable with an intermediate WC detector (under study)
The problem of energy reconstruction was covered in the neutrino-nucleus theory overview by M. Martini on Monday (12:30).

- Non-QE interactions have a reconstructed energy that can deviate significantly from the true energy.
- Constraining this effect with near detector data is challenging since the near detector flux is broad and different from the far detector flux.
The uncertainty on the energy smearing due to nuclear effects has a large impact on the $\nu_\mu$ disappearance measurement since smeared events fill in the “dip” region.

HK aims for 1-3% precision on $\sin^2\theta_{23}$ (depends on the true value).

T2K studied the impact of np-nh modeling uncertainty:
- Generate toy data with an ad-hoc np-nh model.
- Fit the toy data with the NEUT model (includes pion-less delta decay).
- Evaluate the bias on the fitted oscillation parameters.

The average bias in the fitted $\sin^2\theta_{23}$ was 3%.
Energy Reconstruction with NuPRISM

- NuPRISM: take advantage of the neutrino spectrum dependence with off-axis angle to make a near detector flux (through linear combinations) that matches the far detector flux.
- In a study identical to the T2K study, the 3% bias on $\sin^2\theta_{23}$ is reduced to <0.1%.
Proton Decay $p \rightarrow e \pi^0$

- The atmospheric neutrino background to the $p \rightarrow e \pi^0$ mode is:

  \[ 1.63^{+0.42}_{-0.33} \text{(stat)}^{+0.45}_{-0.51} \text{(syst)} \text{ events/Megaton-year} \]

- This background can be reduced with neutron tagging using captures on H or Gd

- This introduces a systematic uncertainty on the neutron multiplicity in atmospheric neutrino interactions
  
  - Should be controlled by measurements in neutrino beams:
    
    - ANNIE (see talk by M. Sanchez in Tuesday morning WG1+WG2 session)
    
    - TITUS: added benefit of a magnetized muon range detector to tag neutrino and antineutrino interactions
Atmospheric Neutrinos (Mass Hierarchy)

- The individual contributions of the systematic errors on the mass hierarchy sensitivity have been evaluated:
  - Largest uncertainties are in the CC $\nu_T$ and CC DIS cross section models
  - CC DIS may be constrained in our near detectors
  - The flux uncertainties for the >1 GeV flux (7-12%) are also significant - May be reduced with new hadron production measurements
Conclusion

• Hyper-K is a precision neutrino oscillation experiment that requires control of systematic uncertainties at the few % level

• Studies to identify the dominant systematic effects on the Hyper-K sensitivities are being carried out
  • Feed into the near detector design and consideration of future hadron production measurements
  • The electron neutrino cross section is an important ongoing area of study

• Systematic uncertainties from neutrino interactions and atmospheric flux also enter the atmospheric neutrino and proton decay measurements
  • We are studying how to control these systematic errors to improve the sensitivity of Hyper-K
Thank you.