NEUTRINO TOWN MEETING
CERN, OCTOBER 22-24 2018
FRANCESCA DI LODOVICO (QMUL)

LONG BASELINE NEUTRINO EXPERIMENTS:
T2K, T2K-II, HYPER-KAMIOKANDE (JAPAN, AND JAPAN+KOREA FAR DETECTORS)
The T2K, T2K-II and Hyper-Kamiokande (T2HK and T2HKK) experiments provide a continuous period of data-taking in Japan from ~2010 to the next decades.

- They address crucial open questions in particle physics.
- Increase in powerful detectors and high powered beams.
- There is a strong legacy of neutrino experiments in Japan.
- Proven technology but very challenging: largest cavern and WC detector in the world.
- Short baseline, high statistics, main interaction CC quasi-elastic, simple topology.
Neutrino flavours are a mix of mass eigenstates: $|\nu_\alpha\rangle = U_{\text{PMNS}} |\nu_i\rangle$

Main Open Questions to be answered: what is the value of $\delta_{\text{CP}}$? what is the mass ordering? what is the value of $\theta_{23}$?

**CP Violation**

Complex mixing of these 4 elements causes:

$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

Key parameter: $\delta_{\text{CP}}$

**Octant degeneracy**

Lower ($\theta_{23} < 45^\circ$) Upper ($\theta_{23} > 45^\circ$)

**Mass Ordering (Hierarchy)**

Normal (NO) Inverted (IO)
Long baseline neutrino experiments
- Baseline in Japan: ~295km
- Baseline in Korea: ~1000km
- Beam from J-PARC
  - 2.5deg off-axis beam with peak energy around 0.6GeV
- Near detectors:
  - ND280 (T2K)
  - ND280 upgraded (T2K-II)
  - ND280 upgraded and WC intermediate detector (Hyper-K)
- Far detector:
  - Super-K (T2K and T2K-II)
  - Hyper-K (T2HK)
  - Hyper-K and Korean detector (T2HKK)
Neutrino Beam to Kamioka

Material and Life Science Facility

J-PARC Facility (KEK/JAEA)

LINAC 400 MeV

Rapid Cycle Synchrotron
Energy: 3 GeV
Repetition: 25 Hz
Design Power: 1 MW

Currently 0.525 MW

Hadron Hall

Main Ring
Top Energy: 30 GeV
FX Design Power: 0.75 MW
SX Power Expectation: > 0.1 MW

Currently 0.485 MW (FX) and 0.051 MW (SX)
TOKAI-TO-KAMIOKA (T2K)
Beam delivery since 2010

$3.16 \times 10^{21}$ protons on target so far

Steadily increasing beam power:
- Have exceeded 500 kW
- Steady running now at 485 kW

March 2011: Great East Japan Earthquake

May 2013: Hadron Hall Radiation Accident

Analysed $1.12 \times 20^{21}$ POT

JUNE 2014: FIRST ANTINEUTRINO DATA
T2K MEASUREMENTS

- Enhanced for $\nu$ if $-\pi < \delta_{CP} < 0$
- NO/NH also enhances $\nu$

**Disappearance Channel**

- Magnitude of peak: $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$, $\delta_{CP}$
- Location of dip: $\Delta m^2_{32}$
- Depth of dip: $\sin^2 \theta_{23}$

**Appearance Channel**

- Magnitude of peak: $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$, $\delta_{CP}$
OSCILLATION ANALYSIS MODELS

- HADRON PRODUCTION DATA
- INGRID/BEAM MONITOR DATA
- EXTERNAL CROSS SECTION DATA
- SUPER-K DATA
- FLUX MODEL
- ND280 DETECTOR MODEL
- ND280 DATA
- CROSS SECTION MODEL
- NEAR DETECTOR FIT
- FAR DETECTOR FIT
- COMBINED OSCILLATION FIT
- OSCILLATION PARAMETERS
- ND+FD BAYESIAN ANALYSIS
- ND->FD FREQUENTIST ANALYSIS
Analysis uses pairs of samples from 2 active target volumes

**Pure scintillator**: Carbon (+H)
**Water+ scint.**: Oxygen (+C, H)

Allows separate constraints for C vs O nuclear effects

**Neutrino beam**
- Require 1 muon-like track
- Sub-samples with \{0, 1, ..., n\} pion-like tracks

**Antineutrino beam**
- Require 1 muon-like track
- Sub-samples based on muon charge and \{0, n\} extra tracks
  - (Larger ‘wrong-sign’ B/G in RHC mode)
**SUPER-KAMIOKANDE SAMPLES**

**ν_μ**

- **1R-μ**
  - FHC sample, expect: **94%+6% ν_μ + ν̄_μ**
  - RHC sample, expect: **60%+40% ν̄_μ + ν_μ**

**ν_ε**

- **1R-ε**
  - FHC sample, expect: **81% (ν_μ →) ν_ε, 18% beam ν_ε + ν_μ**
- RHC sample, expect: **45% (ν_μ →) ν̄_ε, 10% (ν_μ →) ν_ε**

- **1R-ε + d.e.**
  - FHC sample, expect: **79% (ν_μ →) ν_ε, 21% beam ν_ε + ν_μ**

New! Sample added with delayed-coincidence Michel electron (tags low momentum pion in FHC)

Pion collection & focussing depends on Horn Current

**Forward Horn Current (FH):** \( π^+ → \mu^+ + ν_μ \)

**Reverse Horn Current (RH):** \( π → \mu^- + \bar{ν} \)
### SUMMER 2018 RESULTS - EVENTS RATES

<table>
<thead>
<tr>
<th>Sample</th>
<th>Expectation, $\sin^2 \theta_{23} = 0.528$, $\delta =$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-\pi/2$</td>
<td>$0$</td>
</tr>
<tr>
<td>FHC 1R-$\mu$</td>
<td>268.5</td>
<td>268.2</td>
</tr>
<tr>
<td>RHC 1R-$\mu$</td>
<td>95.5</td>
<td>95.3</td>
</tr>
<tr>
<td>Sum of 1R-$\mu$</td>
<td>364.0</td>
<td>363.5</td>
</tr>
<tr>
<td>FHC 1R-$e$</td>
<td>73.8</td>
<td>61.6</td>
</tr>
<tr>
<td>FHC 1R-$e$ +d.e.</td>
<td>6.9</td>
<td>6.0</td>
</tr>
<tr>
<td>RHC 1R-$e$</td>
<td>11.8</td>
<td>13.4</td>
</tr>
</tbody>
</table>

- Excess in d.e. sample has $\rho \sim 1\%$, but does not have big impact on fit

See fewer $\nu_{\mu}$ like events than expected, 
\[\Rightarrow \text{fit will prefer maximal disappearance}\]

See more $\nu_e$ and fewer $\bar{\nu}_e$ than expected, even for \[\delta = -\frac{\pi}{2}\] 
\[\Rightarrow \text{fit will have a strong preference for CP-violation that enhances neutrino rates}\]
Parameter fit with reactor constraint

Consistent with maximal mixing ($\theta=45^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>NH ($\Delta m_{23}^2 &gt; 0$)</th>
<th>IH ($\Delta m_{23}^2 &lt; 0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.536 \pm 0.031$</td>
<td>$0.536 \pm 0.031$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{32}^2</td>
<td>\times 10^{-3}$ (eV$^2$/c$^4$)</td>
</tr>
</tbody>
</table>
SUMMER 2018 RESULTS: CONSTRAINT ON $\delta_{CP}$

• Binned-likelihood oscillation fits to all far-detector samples simultaneously.
• Two oscillation fits: 1) T2K-only 2) T2K+2016 PDG reactor data as constraint
• $2\sigma$ interval calculated w/ Feldman&Cousins
• CP conserving values ($0, \pm \pi$) outside of $2\sigma$ region for both hierarchies

<table>
<thead>
<tr>
<th>Mass ordering</th>
<th>Best fit $\delta_{CP}$</th>
<th>2σ interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>$-1.82 (-0.58\pi)$</td>
<td>$[-2.91, -0.64]$</td>
</tr>
<tr>
<td>Inverted</td>
<td>$-1.38 (-0.44\pi)$</td>
<td>$[-1.57, -1.16]$</td>
</tr>
</tbody>
</table>
T2K-II

HYPER-KAMIOKANDE (STAGED 2 DETECTORS)
SECOND PHASE OF T2K (T2K-II)

T2K-II aims to reach a $>3\sigma$ sensitivity for CP violation if near current best fit

Extension of T2K run (approved $7.8 \times 10^{21}$ POT) to $20 \times 10^{21}$ POT

T2K upgrade details:
• Beamline upgrade toward 1.3 MW beam power
• Near Detector upgrade (see Y. Kudenko’s and M. Zito’s talks) to achieve a systematic error improvement $6\% \rightarrow 4\%$
• Analysis improvement (enlarging fiducial volume and $\nu_e$ CC1$\pi$ sample)
**Beam Upgrade for T2K-II**

- **Beam power to reach 1.3 MW**
- **Strategy**

<table>
<thead>
<tr>
<th>Beam Power (kW)</th>
<th>Achieved</th>
<th>Goal for T2K-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>485</td>
<td>(940)</td>
<td>1,300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#p/p(10^{12})</th>
<th>250</th>
<th>250</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep T (s)</td>
<td>2.48</td>
<td>1.28</td>
<td>1.16</td>
</tr>
</tbody>
</table>

**Method:**

**Higher rep rate:**
- MR magnet power supply upgrade
- MR RF upgrade (High grad/PS)
- MR Fast Extraction Kicker upgrade

**Higher #p/p:**
- MR RF upgrade (PS)

**J-PARC plan to upgrade to 750kW and then 1.3MW**
- Funding for 750kW is started (FY2016-)
- Modest upgrade and budget from 750kW to 1.3MW

**Highest priority project in KEK-PIP**
- Higher beam power should also be pursued
SECOND PHASE OF T2K (T2K-II)

- **T2K-II goal:** reduce detector systematics to ~4% -> improve acceptance, timing, efficiency for short tracks.
- Re-design of the upstream part of ND280
- Down-stream tracker (FGD+TPCs) unchanged

[Graphs and diagrams showing statistical analysis and detector performance]
**SK-Gd phase:**

Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

<table>
<thead>
<tr>
<th>FY2018</th>
<th>FY2019</th>
<th>FY2020</th>
<th>FY202X</th>
<th>FY202X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

**T0:** Start SK detector refurbishment (**May 31, 2018**)
- Jan. 2019 ~: pure water run

**T1:** Load first 10 ton Gd2(SO4)3 [0.01% Gd, 50% eff.]
- **First possible T1 is ~2019/2020** (will be decided with T2K/J-PARC ν beam)

**T2:** Load additional 90 ton Gd2(SO4)3[0.1% Gd, 90% eff.]
Measurement of magnetic field in the inner detector.

The water level is about 3m. The ID PMTs will be appeared to the surface of water soon.

Works in the outer detector. The outer detector is about 2m wide.

Replacement work of inner detector PMTs.

The gondola lift in the inner detector.

All the water of the tank is drained.
HYPER-KAMIOKANDE
HYPER-KAMIOKANDE: A MULTIPURPOSE EXPERIMENT

- Excellent capability for a broad area of science.
- Proven technology but very challenging: largest cavern and WC detector in the world
- Full picture of neutrino oscillation with precise measurement of CP and mixing parameters
NEUTRINO SOURCES AND FLUXES

Hyper-K coverage: MeV ~ TeV

- Cosmological $\nu$
- Solar $\nu$
- Supernova burst (1987A)
- Reactor anti-$\nu$
- Background from old supernovae
- Terrestrial anti-$\nu$
- Atmospheric $\nu$
- $\nu$ from AGN
- Cosmogenic $\nu$

Neutrino energy vs. Flux (cm$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$)
HYPER-KAMIOKANDE

From T2K-II to Hyper-Kamiokande:
- 1 tank: 10 times larger than SK
- 1.3MW beam power
- near detector (possible) upgrade
- new intermediate (~1km) Water Cherenkov detector (see M. Scott’s talk)
- staged second far detector

1.3MW beam power upgrade

J-PARC MR Fast Extraction Power Projection

3kton x 17 = 50kton

0.52Mton = 520kton

Staged approach: first tank as soon as possible, second later

APPROVED EXCAVATION OF THE CAVERN TO START IN 2020

Interchangeable detector (E61)
**HYPER-KAMIOKANDE**

**NEXT GENERATION WATER CHERENKOV DETECTOR**

- Construct two detectors in stage
- Build the **first detector as soon as possible**
- An **option of second detector in Korea**

**FIRST DETECTOR (JAPAN)**

- **Φ74m x H60m**
- 260 kton total mass
- 190 kton fiducial volume
- ~10 x **Super-K fiducial mass**
- 40% Photo coverage (ID)
- 40,000 x new 20” PMTs
- x2 higher photon detection efficiency
EXPECTED EVENTS IN HYPER-KAMIOKANDE LBN PROJECT

Expected # of events in \( \nu_e/\bar{\nu}_e \) appearance

Assumption
- 1.3MW x 10 years (\(10^8\) s)
- \( \nu : \bar{\nu} = 1:3 \)
- \( \sin^2 2\theta_{13} = 0.1 \)
- Normal hierarchy

A few % stat. uncertainties on \( \nu_\mu \to \nu_e \) & \( \bar{\nu}_\mu \to \bar{\nu}_e \) signals

The results are from the HK Design Report (arXiv:1805.04163 [physics.ins-det])
Exclusion of $\sin\delta_{CP} = 0$

- $8\sigma$ for $\delta = -90^\circ$ (T2K best fit)
- $80\%$ of coverage of $\delta$ parameter space for CPV discovery $> 3\sigma$
- After 10 years of running, HK will be able to measure $\sim 50\%$ of the $\delta_{CP}$ space to better than $5\sigma$

$\delta_{CP}$ precision measurement

- $22^\circ$ for $\delta = -90^\circ$
- $7^\circ$ for $\delta = 0^\circ$

Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K
- Realistic systematic uncertainties plus expected reduction of errors
- $3\sim4\%$ syst. Error ($6\sim7\%$ in T2K)
Earth matter effect in upward-going multi-GeV νe sensitive to mass hierarchy

- “Resonance” pattern appears in $\nu_e(\bar{\nu}_e)$ appearance for NH (IH)
- Combination of atmospheric and beam to determine mass hierarchy
- Determination possible within ~5 years ($\sin^2\theta_{23} = 0.5$) at HK even if MH not determined before HK era.
FAR DETECTOR SITE

- Tochibora mine in Kamioka
- ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5°) to Super-K for J-PARC beam
- Overburden ~650m (~1755m.w.e.) cf. SK ~2700m.w.e.
- The detector site surrounded by faults
  - Identified during the mining in the past
- Confirmed the geological condition (rock quality) good for a large cavern excavation
- Identified the best location for cavern excavation, where has good rock quality and no faults or fracture zone

Hyper-K cavern will be the world largest underground cavern

APPROVED EXCAVATION OF THE CAVERN TO START IN 2020
Continuous effort for improvements. Noise reduction, cover design, light concentrator, etc. under study

New 20-inch photo-sensors: higher performance

- Single-photon efficiency: x2
- 1 p.e. timing resolution: 2ns → 1ns
- 1 p.e. charge resolution: 53% → 35%
- Large impact on detector performance/physics sensitivity

140 new PMT's installed in Super-K during tank opening.

Single-sided mPMT module being investigates as option for inner detector (20”PMT + mPMTs)
Second tank option in Korea is being considered (PTEP 2018, 063C01)

Advantages:
• Large CP effect at second oscillation maximum
• Higher mass hierarchy sensitivity with longer baseline

Possible site:
• Mt. Bisul at L=1,088km, OA=1.3°
• Mt. Bohyun at L=1,043km, OA=2.3°
An additional far detector in Korea will allow to have:

- improved $\delta_{CP}$ measurement precision
  $22^\circ \rightarrow < 15^\circ$ at $\delta_{CP} = -90^\circ$

- a higher mass hierarchy sensitivity
  $4.5\sigma \rightarrow 9\sigma$ at $\sin^2\theta_{23} = 0.5I$
THE INTERNATIONAL ORGANISATION

- **International Hyper-K proto-collaboration**
  - 15 countries, 73 institutes, ~300 members, ~75% from abroad
  - International project leaders, steering members, WG conveners

- **2 host institutes**: UTokyo/ICRR and KEK/IPNS (MoU of cooperation for HK)

- UTokyo launched a institute for HK construction: **Next Generation Neutrino Science Organization (NNSO)**

- External review by **International Advisory Committee (HKAC)**
There is a strong EU contribution in the LBN J-PARC-based LBN experiments.

Work are CERN has been crucial for T2K, it is currently for T2K-II and will be vital for HK as well.

“Hyper-Kamiokande Technical Report” is being internally reviewed - timescale for completion 2019

Other recent references:

Physics potentials with the second Hyper-Kamiokande detector in Korea
PTEP 2018 (2018) no.6, 063C01
Work on the ND280 upgrade within the CERN platform ongoing

**Expansion of current work for the Hyper-Kamiokande detector planned**

Focussing on the following areas:

- J-PARC upgrade for higher beam power
- Far detector:
  - New photosensors
  - Electronics
  - LINAC for low energy calibration with low energy electron beam
- Intermediate detector
The long baseline experiment T2K, T2K-II and Hyper-Kamiokande (with one and two far detectors) provide a continuous excellent physics from 2010 with J-PARC up to the next decades.

- Proven track record of experiments in Japan
- Major open questions are being addressed
  - CP violation search
  - Mixing parameters
  - Mass hierarchy
- T2K is searching for CP violation and measuring the other parameters
- Beam Power is being increased up to 1.3MW (during T2K-II and before Hyper-K)
- Near (and intermediate) T2K/T2K-II/Hyper-K detectors are being constructed (or planned)
- Super-Kamiokande was just refurbished and Gd will be added
- Hyper-Kamiokande will start cavern construction in 2020. It has a large physics potential and will determine CP violation. Open to new collaborators!
LONG BASELINE EXPERIMENTS IN A NUTSHELL

Predicted events in the Near Detector.

$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$

- Neutrino flux prediction
- Neutrino cross section model
- Near detector selection, efficiency

Predicted events in the Far Detector.

$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD}P(\nu_\alpha \rightarrow \nu_\beta)$

- Neutrino flux prediction
- Neutrino cross section model
- Far detector selection, efficiency

$\nu$ beam $\rightarrow$ NEAR DETECTOR $\rightarrow$ $\nu$ beam

~100 m

$\nu$ beam $\rightarrow$ FAR DETECTOR $\rightarrow$ $\nu$ beam

~100-1000 km
Comparison between the probabilities: \( P(\nu_\mu \rightarrow \nu_e) \) vs \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

Up to \( \sim \pm 30\% \) variation at \( \delta_{CP} = -90^\circ \) in NH (or \( 90^\circ \) in IH) wrt \( \sin\delta_{CP}=0 \)
TOKAI-2-KAMIOKA (T2K)

**T2K**

Far Detector
Super-Kamiokande

J-PARC &
Near Detector complex

2.5deg off-axis
Uncertainties come from underlying model parameters and normalisations.

- $M_{A^{QE}}$
- $M_{A^{RES}}$
- Fermi Momentum
- Binding Energy
- FSI
- 2p2h
- ….
ND280 EVENT DISPLAYS PER FINAL STATE INTERACTION

Separate samples according to topologies:

- **CC0π**: CC interactions w/ 0 pions in the final state
- **CC1π**: CC interactions w/ 1 pion in the final state
- **CC Other**: anything else
Examples of antineutrino signal and background events
• 14 total samples
• **Neutrino mode**: sort by pion multiplicity; Carbon and Oxygen fine-grained detectors
• **Antineutrino mode**: sort by muon charge and number of tracks; C and O fine-grained detectors
• Wrong-sign backgrounds constrained with ND280 magnetic field
ND280 DATA USED FOR OSCILLATION FIT
Selection categories in Super-Kamiokande: e-like, \( \mu \)-like events

New this year:

- an e-like 1-Michel electron sample in \( \nu \)-dominated beam—this sample is dominated by resonant pion events
- A new reconstruction algorithm that improves both efficiency and purity for all samples

- 66% of the data is \( \nu \)-dominated beam; 34% \( \bar{\nu} \)-dominated beam
SUPER-KAMIOKANDE SAMPLES

SELECTED SAMPLES AT SUPER-KAMIOKANDE

\[ \nu_\mu \text{ Disappearance} \]

- **\nu_\mu** Disappearance
- **\nu_\mu** -like
- 240 \( \nu_\mu \)

\[ \nu_e \text{ Appearance} \]

- **\nu_e** Appearance
- **\nu-e** -like
- 1 decay-e
- 74 \( \nu_e \)
- 15 \( \nu_e \)

**p-value = 0.42**

<table>
<thead>
<tr>
<th><strong>Observed events</strong></th>
<th>( \mu )-like</th>
<th>( e )-like</th>
<th>( e )-like 1 decay-e</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )-mode</td>
<td>240</td>
<td>74</td>
<td>15</td>
</tr>
<tr>
<td>( \bar{\nu} )-mode</td>
<td>68</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
T2K analysis oscillation fit

To fit use:

- Flux predictions from MC and external data
- Near-detector fits to constrain flux and interaction model
- Data fit result reduces error on SK event rate predictions to about 5-9% depending on channel
- Event predictions at SK
- Event reconstruction and selection at SK
- Obtain combined fit of all oscillation parameters using all data channels

Neutrino Interaction Model

- Relativistic Fermi Gas (RFG) with dipole form factor
- 1p1h (scattering off single nucleon) uses Random Phase Approximation parameters from Valencia group, applied to our RFG model
- 2p2h (scattering off correlated nucleon pairs) model also from Valencia group (Nieves et al.).
- Single- and multi-pion uses models by Rein and Sehgal normalized to match D$_2$ bubble chamber (resonant, non-resonant) and MINERvA (coherent) data
- Deep Inelastic Scattering through PYTHIA 5.9
- FSI via Salcedo Oset and Bertini cascade models, tuned to external pion nucleon scattering data
- We fit parameters for all these models (and flux model) to the ND280 data
Largest uncertainties are the Super-K detector modelling and $\pi$ interaction modelling, both for the $e$-like events with one decay electron.
### T2K SYSTEMATIC ERRORS

<table>
<thead>
<tr>
<th>Error Source</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode 1 dcy-e</th>
<th>$\nu/\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK Detector</td>
<td>1.86</td>
<td>1.51</td>
<td>3.03</td>
<td>4.22</td>
<td>16.69</td>
<td>1.60</td>
</tr>
<tr>
<td>SK final state and secondary interactions</td>
<td>2.20</td>
<td>1.98</td>
<td>3.01</td>
<td>2.31</td>
<td>11.43</td>
<td>1.57</td>
</tr>
<tr>
<td>ND280-constrained flux and cross section</td>
<td>3.22</td>
<td>2.72</td>
<td>3.22</td>
<td>2.88</td>
<td>4.05</td>
<td>2.50</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_\mu), \sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>\mu)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.63</td>
<td>1.46</td>
<td>2.62</td>
<td>3.03</td>
</tr>
<tr>
<td>NC1 $\gamma$</td>
<td>0.00</td>
<td>0.00</td>
<td>1.08</td>
<td>2.59</td>
<td>0.33</td>
<td>1.49</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.14</td>
<td>0.33</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>4.40</td>
<td>3.76</td>
<td>6.10</td>
<td>6.51</td>
<td>20.94</td>
<td>4.77</td>
</tr>
</tbody>
</table>

- No precise measurement of $\nu_e (\bar{\nu}_e)$ interactions in the near detector.
### T2K SYSTEMATIC ERRORS

#### SYSTEMATICS

<table>
<thead>
<tr>
<th>Error Source</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
<th>$\nu$-mode</th>
<th>$\bar{\nu}$-mode</th>
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</tr>
<tr>
<td>SK final state and secondary interactions</td>
<td>2.20</td>
<td>1.98</td>
<td>3.01</td>
<td>2.31</td>
<td>11.43</td>
<td>1.57</td>
</tr>
<tr>
<td>ND280-constrained flux and cross section</td>
<td>3.22</td>
<td>2.72</td>
<td>3.22</td>
<td>2.88</td>
<td>4.05</td>
<td>2.50</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}<em>e)/\sigma(\bar{\nu}</em>\mu)$</td>
<td>0.00</td>
<td>0.00</td>
<td>2.63</td>
<td>1.46</td>
<td>2.62</td>
<td>3.03</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
<td>1.08</td>
<td>2.59</td>
<td>0.33</td>
<td>1.49</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
<td>0.14</td>
<td>0.33</td>
<td>0.98</td>
<td>0.18</td>
</tr>
<tr>
<td>Total Systematic Error</td>
<td>4.40</td>
<td>3.76</td>
<td>6.10</td>
<td>6.51</td>
<td>20.94</td>
<td>4.77</td>
</tr>
</tbody>
</table>

- No near detector constraint on neutral current modes.
- Uncertainty based on modelling and external data.
**CP VIOLATION SENSITIVITY**

- Exclusion of $\sin\delta_{CP} = 0$
  - $8\sigma$ for $\delta = -90^\circ$ (T2K best fit)
  - 80% of coverage of $\delta$ parameter space for CPV discovery $> 3\sigma$
- After 10 years of running, HK will be able to measure $\sim 50\%$ of the $\delta_{CP}$ space to better than $5\sigma$

- $\delta_{CP}$ precision measurement
  - $22^\circ$ for $\delta = -90^\circ$
  - $7^\circ$ for $\delta = 0^\circ$

Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K
- Realistic systematic uncertainties plus expected reduction of errors
- 3~4% syst. Error (6~7% in T2K)
MASS HIERARCHY SENSITIVITY

Normal hierarchy case (opposite in inverted case)

Octant Determination
Seismic tomography and reflection imaging were conducted for a (400 m)^3 wide area.

An excellent site was identified.
<table>
<thead>
<tr>
<th>Physics Target</th>
<th>Sensitivity</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino study w/ J-PARC $\nu$</td>
<td></td>
<td>$1.3 \text{MW} \times 10^8 \text{ sec}$</td>
</tr>
<tr>
<td>- $CP$ phase precision</td>
<td>$&lt; 23^\circ$</td>
<td>@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known</td>
</tr>
<tr>
<td>- $CPV$ discovery coverage</td>
<td>$76%$ (3 $\sigma$), $57%$ (5 $\sigma$)</td>
<td>@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known</td>
</tr>
<tr>
<td>- $\sin^2 \theta_{23}$</td>
<td>$\pm 0.017$</td>
<td>$1\sigma$ @ $\sin^2 \theta_{23} = 0.5$</td>
</tr>
<tr>
<td>Atmospheric neutrino study</td>
<td></td>
<td>$10$ years observation</td>
</tr>
<tr>
<td>- MH determination</td>
<td>$&gt; 2.2\sigma$ CL</td>
<td>@ $\sin^2 \theta_{23} &gt; 0.4$</td>
</tr>
<tr>
<td>- $\theta_{23}$ octant determination</td>
<td>$&gt; 3\sigma$ CL</td>
<td>@ $</td>
</tr>
<tr>
<td>Atmospheric and Beam Combination</td>
<td></td>
<td>$10$ years observation</td>
</tr>
<tr>
<td>- MH determination</td>
<td>$&gt; 3.8\sigma$ CL</td>
<td>@ $\sin^2 \theta_{23} &gt; 0.4$</td>
</tr>
<tr>
<td>- $\theta_{23}$ octant determination</td>
<td>$&gt; 3\sigma$ CL</td>
<td>@ $</td>
</tr>
<tr>
<td>Nucleon Decay Searches</td>
<td></td>
<td>$1.9$ Mton-year exposure</td>
</tr>
<tr>
<td>- $p \rightarrow e^+ + \pi^0$</td>
<td>$7.8 \times 10^{34}$ yrs (90% CL UL)</td>
<td></td>
</tr>
<tr>
<td>- $p \rightarrow \bar{\nu} + K^+$</td>
<td>$6.3 \times 10^{34}$ yrs (3\sigma discovery)</td>
<td></td>
</tr>
<tr>
<td>- $p \rightarrow e^+ + \pi^0$</td>
<td>$3.2 \times 10^{34}$ yrs (90% CL UL)</td>
<td></td>
</tr>
<tr>
<td>- $p \rightarrow \bar{\nu} + K^+$</td>
<td>$2.0 \times 10^{34}$ yrs (3\sigma discovery)</td>
<td></td>
</tr>
<tr>
<td>Astrophysical neutrino sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- $^8$B $\nu$ from Sun</td>
<td>130 $\nu$’s / day</td>
<td>$4.5$ MeV threshold (visible energy) w/ osc.</td>
</tr>
<tr>
<td>- Supernova burst $\nu$</td>
<td>$52,000$–$79,000$ $\nu$’s</td>
<td>@ Galactic center (10 kpc)</td>
</tr>
<tr>
<td>- Supernova relic $\nu$</td>
<td>$\sim 10$ $\nu$’s</td>
<td>@ M31 (Andromeda galaxy)</td>
</tr>
<tr>
<td>- WIMP annihilation in the Earth</td>
<td>$70$ $\nu$’s / 10 years</td>
<td>$10$–$30$ MeV, $4.2\sigma$ non-zero significance</td>
</tr>
<tr>
<td>($\sigma_{SD}$: WIMP-proton spin dependent cross section)</td>
<td>$\sigma_{SD} = 10^{-40}$cm$^2$</td>
<td>@ $M_{WIMP} = 10$ GeV, $\chi\chi \rightarrow b\bar{b}$ dominant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>@ $M_{WIMP} = 50$ GeV, $\chi\chi \rightarrow \tau^+\tau^-$ dominant</td>
</tr>
</tbody>
</table>