T2K and future

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Weak and mass eigenstates are different: Mixing

Neutrino particle (mass eigenstate) has mixed flavours $e/\mu/\tau$ (weak eigenstates)!

$\langle \nu_l | \nu_i \rangle = U_{li} : PMNS$ matrix

$l = e, \mu, \tau : weak$ eigenstates

$i = 1, 2, 3 : mass$ eigenstates

Figure: Boris Kayser
Neutrino oscillation

• Quantum mechanical interference:

\[ e^{i\omega t} = e^{i\omega L/c} \]
\[ e^{i\omega t'} = e^{i\omega L'/c} \]

\[ \omega t = 2\pi vt = \frac{2\pi E}{\hbar} = \frac{E}{\hbar} \quad (\hbar = h/2\pi) \]

Difference in the masses creates phase difference as neutrino propagates

\[ \nu_e \rightarrow \nu_\mu \]

\[ \nu_e \rightarrow e^{-iE_1 t/\hbar} \cos \theta \]

\[ \nu_e \rightarrow e^{-iE_2 t/\hbar} \sin \theta \]

Weak

\[ \cos \theta \]

\[ \sin \theta \]
Neutrino oscillation

- Quantum mechanical interference:
  \[ \omega t = 2\pi \nu t = \frac{2\pi E}{\hbar} = \frac{E}{\hbar} \quad (\hbar = h/2\pi) \]

- Lepton flavour oscillates!
  \[ P_{l \rightarrow l'} = \left| < \nu_{l'}(t) | \nu_l(t) > \right|^2 = \left| \sum_i < \nu_{l'} | \nu_i > e^{-iE_i t} < \nu_i | \nu_l > \right|^2 = \left| \sum_i U_{l_i}^* U_{l'i} e^{-im_i^2 L/2E} \right|^2 \]

\[ \Delta m_{23}^2 \sim 2.5 \times 10^{-3} \]: oscillation max at 300km for 0.6GeV
PMNS matrix

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

Atm/long-baseline $\nu$

CP violation and $\theta_{13}$

solar/reactor $\nu$

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \cos \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\cos \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
T2K Long Baseline Neutrino Experiment

Super-Kamiokande (ICRR, Univ. Tokyo)

J-PARC Main Ring (KEK-JAEA, Tokai)

Super-Kamiokande

J-PARC

Near Detector 280 m

Neutrino Beam 295 km

Passage of the muon neutrino beam from J-PARC to Super K

Off-axis beam tuned at the oscillation max.
Super-Kamiokande water Cherenkov detector

11,146 of 20inch PMTs

Tank is open this summer for preparation of Gd loading
• Anti-neutrino tag
  - Relic supernova neutrinos
  - Sub-GeV atmospheric neutrino direction

Open for the first time since 2007

UBC undergraduate student and Canadian scientists participate in the work
Neutrino production

hadron production

off-axis beam
Stable operation at 485kW in 2017/18
Accumulated proton on target (POT)

- Total POT till May 2018:
  - $3.16 \times 10^{21}$ POT
    - $\nu$: $1.51 \times 10^{21}$
    - $\bar{\nu}$: $1.65 \times 10^{21}$
  - Data analyzed till Dec. 2017
    - $\nu$: $1.49 \times 10^{21}$
    - $\bar{\nu}$: $1.12 \times 10^{21}$
**Near detector samples**

**Selection:**
- Identify highest momentum muon-like track
- Separate by number of tagged pions
Near detector fit for far detector prediction

- Likelihood fit to tune the cross section models:
  - CC0\(\pi\), CC1\(\pi\), CCOther
- Far detector prediction
  - Covariance matrix (effectively taking ratio)
Improvements in far detector (SK) analysis

- Expand the fiducial volume by 20%
  - new reconstruction code (fiTQun)
  - with small “wall” but long enough “towall”
- Additional 1 decay electron events (+10%)
  - CC1π with π track below Cherenkov threshold
    - π track visible case to come [S.Berkman (UBC)]

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>PREDICTED</th>
<th>OBSERVED</th>
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<tbody>
<tr>
<td></td>
<td>δ_{CP=-π/2}</td>
<td>δ_{CP=0}</td>
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<tr>
<td>ν mode 1R_μ</td>
<td>268.5</td>
<td>268.2</td>
</tr>
<tr>
<td>¯ν mode 1R_μ</td>
<td>95.5</td>
<td>95.3</td>
</tr>
<tr>
<td>ν mode Re 0 decay-e</td>
<td>73.8</td>
<td>61.6</td>
</tr>
<tr>
<td>ν mode Re 1 decay-e</td>
<td>6.9</td>
<td>6.0</td>
</tr>
<tr>
<td>¯ν mode 1Re 0 decay-e</td>
<td>11.8</td>
<td>13.4</td>
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νμ disappearance
• Maximal mixing favoured by T2K
  - Indication of symmetry in PMNS?
• NOvA’s new result is consistent but best fit at non-maximal
### ν_e appearance

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<tr>
<td></td>
<td>$\delta_{CP}=-\pi/2$</td>
<td>$\delta_{CP}=0$</td>
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<tr>
<td><strong>ν mode 1R$_{\mu}$</strong></td>
<td>268.5</td>
<td>268.2</td>
</tr>
<tr>
<td><strong>$\bar{\nu}$ mode 1R$_{\mu}$</strong></td>
<td>95.5</td>
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<tr>
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**Figure Legends:**

- **T2K Run1-9c Preliminary**
  - **ν_e CCQE**
  - **ν_e CC1π**
  - **$\bar{\nu}_e$ CCQE**

**Note:** The figures show distributions of events in the reconstructed energy (GeV) vs. θ (degrees) space for different channels (CCQE, CC1π). The colors represent the number of events, with a color bar indicating the range of events from 0.01 to 0.18.
• T2K’s $\theta_{13}$ consistent with Reactor neutrino result
• Disfavour CP conserving $\delta_{cp}=0, \pi$ at 2$\sigma$
• Normal hierarchy favoured
Comparison with NOvA

T2K Run1-9c Preliminary

Antineutrino mode 1Re candidates

- $\sin^2 \theta_{13} = 0.50, 0.45, 0.55$
- $\Delta m^2_{\odot} = 2.44 \times 10^{-3}$ eV$^2$/c$^4$
- $\Delta m^2_{\odot} = 2.41 \times 10^{-3}$ eV$^2$/c$^4$

- $\delta_{CP} = \pi$
- $\delta_{CP} = +\pi/2$
- $\delta_{CP} = 0$
- $\delta_{CP} = -\pi/2$
- syst err
- stat + syst err
- Data

Total events - antineutrino mode

NOvA FD

- $9.48 \times 10^{20}$ POT ($\nu$)
- $6.91 \times 10^{20}$ POT ($\bar{\nu}$)

- $\sin^2 \theta_{23} = 0.082$
- $\sin^2 \theta_{23} = 0.59$
- $\Delta m^2_{\odot} = -2.55 \times 10^{-3}$ eV$^2$
- $\Delta m^2_{\odot} = +2.50 \times 10^{-3}$ eV$^2$

- $\delta_{CP} = 0$
- $\delta_{CP} = \pi/2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = 3\pi/2$

Total events - neutrino mode

Data
Systematic uncertainties

- Taking the ratio with the near detector cancels systematics
  - higher order error remains

- Source of systematics
  - Detector (SK) efficiency
  - Flux
    - near-to-far extrapolation
    - cross section

<table>
<thead>
<tr>
<th>Error source</th>
<th>1-Ring $\mu$ v mode</th>
<th>1-Ring $\mu$ $\bar{\nu}$ mode</th>
<th>1-Ring $e$ v mode</th>
<th>1-Ring $e$ $\bar{\nu}$ mode</th>
<th>$\bar{\nu}/\nu$ ratio</th>
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<tr>
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<tr>
<td>SK Detector</td>
<td>2.40%</td>
<td>2.01%</td>
<td>2.83%</td>
<td>3.79%</td>
<td>13.16%</td>
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<tr>
<td>SK FSI+SI+PN</td>
<td>2.20%</td>
<td>1.98%</td>
<td>3.02%</td>
<td>2.31%</td>
<td>11.44%</td>
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<tr>
<td>Flux + Xsec constrained</td>
<td>2.88%</td>
<td>2.68%</td>
<td>3.02%</td>
<td>2.86%</td>
<td>3.82%</td>
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<tr>
<td>$E_b$</td>
<td>2.43%</td>
<td>1.73%</td>
<td>7.26%</td>
<td>3.66%</td>
<td>3.01%</td>
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<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>0.00%</td>
<td>0.00%</td>
<td>2.63%</td>
<td>1.46%</td>
<td>2.62%</td>
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<tr>
<td>NC1$\gamma$</td>
<td>0.00%</td>
<td>0.00%</td>
<td>1.07%</td>
<td>2.58%</td>
<td>0.33%</td>
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<tr>
<td>NC Other</td>
<td>0.25%</td>
<td>0.25%</td>
<td>0.14%</td>
<td>0.33%</td>
<td>0.99%</td>
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<tr>
<td>Osc</td>
<td>0.03%</td>
<td>0.03%</td>
<td>3.86%</td>
<td>3.60%</td>
<td>3.77%</td>
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<tr>
<td>All Systematics</td>
<td>4.91%</td>
<td>4.28%</td>
<td>8.81%</td>
<td>7.03%</td>
<td>18.32%</td>
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<tr>
<td>All with osc</td>
<td>4.91%</td>
<td>4.28%</td>
<td>9.60%</td>
<td>7.87%</td>
<td>18.65%</td>
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- Systematics improved but limited
  - cross section systematics is challenging
    - theoretical uncertainties
    - binding energy $E_b$ is introduced this year

- Systematics is significant in the neutrino mode:
  - statistics: 11.5% (75 events)
  - systematics: 8.8% (hope to go back to ~6%)
Challenge in the neutrino cross section

- Primary interaction
  - Nucleon form factor
  - Multi-nucleon effects
- Initial nucleons
  - Initial nucleon momentum
    - Random Phase Approximation?
    - Binding energy?
- Final State Interaction
  - Nucleon traveling nucleus
    - Cascade model?
      - (traveling like real particle)
  - Energy-momentum conservation?
- Neutrino challenge
  - Initial neutrino energy not known

Similar challenge in electron and pion scatterings

Model tuning at a few% level has limitations
CP violation sensitivity at Hyper-Kamiokande

- HyperK water Cherenkov
  - 187kton fiducial (x8 of SK)
  - 20k-40k photosensors

- HyperK CP sensitivity will be limited by systematics
  - Improving systematics will be essential

HK Sensitivity for $\delta_{CP}=-\pi/2$ (maximal CP viol.)

\[
\sqrt{\chi^2} = 0
\]

- $5\sigma$ C.L. for $\delta_{CP}=-\pi/4$
- $5\sigma$ C.L. for $\delta_{CP}=-\pi/2$

Running Time [years]

- w/ eff. 2016 sys. errors
- w/ eff. sys. improvements
- w/o syst. errors
Solving cross section systematics by E61(NuPRISM)
Linear combination of events at different off-axis position:

→ Monochromatic \( \nu \) beam response
NUPRISM linear combination

monochromatic

atmospheric $\nu$

oscillated $\nu_{\mu}$

oscillated $\nu_{e}$
• Precise vertex reconstruction required
  - fiducial error \(\sim 1\% \rightarrow 1\text{-}2\text{cm} \) in vertex error
    • buoyancy and distortion of the support in water
    • SNO, KamLand, JUNO: \(\sim 3\text{cm} \) in vertex error
• Fine granularity
  - multi-PMT with 3-inch PMT’s
• Precise in-situ/ex-situ calibration
  - in-situ: photogrammetry (3D reconst. by camera)
    • SNO+ demonstrates 0.5-1cm precision in a pool
  - ex-situ
    • Photosensor test facility: angular response
    • Charged particle beam test of test water Cherenkov
      - vertex, hadronic effect, multi-ring reconstruction
Flux systematics

- Dominated by Hadron production error
Hadron production experiment in Jan. 2018 at Fermilab

Aerogel (AC)\n\nn = 1.13, 1.045, 1.026, 1.013, 1.0044\n
emulsion+C\nC, Al, Fe, empty
Preliminary result of EMPHATIC

• Confusion in the definition of cross sections
  - e.g. interference terms
  - measure direct information of $t=-Q^2$ distribution for hadron production

• Khalid Gameil’s talk in this session
EMPHATIC for the water Cherenkov beam test

 inject beam with various angles

opening angle, light yield

range

EMPHATIC as front end of the tertiary beam line

TOF

WC1 WC2 WC3 WC4

Magnet

TOF

RICH

γ
e/μ/π/K/p
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<td>T2K/T2K-II/SK</td>
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<td>E61 beam test</td>
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<td>E61 facility</td>
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<td>E61 detector</td>
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<td>HK mPMT</td>
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<td>Hadron prod.</td>
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**Design** | **Construction** | **Operation**
• T2K experiment had successful data taking till May 2018
  - Stable operation with the proton intensity of 485kW
• Latest result up to December 2017 data
  - Normal mass hierarchy is preferred (posterior prob.=89%)
  - CP conserving $\delta_{cp}=0,\pi$ are disfavoured at 2$\sigma$ level
    • However, the results are started to be limited by systematics
• New studies to address systematic uncertainties
  - Cross section: E61(NuPRISM)
  - Flux: EMPHATIC hadron production experiment at Fermilab
  - Detector systematics: Water Cherenkov (E61) test at Fermilab
• Excellent prospect for HyperK funding in 2018
multi-PMT development for E61(NuPRISM) and HyperK

- **multi-PMT (mPMT)**
  - 19 of 3” PMT’s in a vessel
    - economical 3” PMT’s
- **mPMT for E61(NuPRISM)**
  - finer granularity for small WC
    - better than 8”
- **mPMT for HyperK**
  - multi-ring reconstruction
    - CC1π, mass hierarchy
  - angular sensitivity
    - accidental reduction for low E
  - provide calibration standard
• Fiducial calibration limited by the position calibration of PMT’s
  - buoyancy on PMT’s
  - distortion of the structure

• SNO+ uses six camera’s on the wall
  - 1 cm accuracy in a swimming pool
  - Nicon D5000 (12M pixel)
    • much better resolution possible now
    • water resistant camera available
      - SubC (Newfoundland company)

• 3D reconstruction tools available
  - camera positions and angles are fit
    • no need for precise camera position
NuPRISM (E61) prototype beam test for detection efficiency

• Water tank for e, μ, π, K, p beam test
  - Fermilab test beam
    • 200MeV/c to 120GeV
  - 3m diameter tank
    • Simulate particles starting at the centre of NuPRISM
    • μ up to 700MeV/c stop inside
    • 8.3 radiation length: fully contain EM shower

• Experimental goal
  - Establish the detector calibration
    • fiducial volume at ~1% → 1-2cm in vertex systematics
    • energy scale at ~1%
  - Response of water Cherenkov to hadrons: π, K, p
  - Immediate impact on T2K and SK analyses
    • multi-ring event reconstruction
PTF setup

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer

- Magnetic shielding
  - compensation coil, Giron shield

Tank (and PMT) will be put inside coil
PTF setup

- Robotic arms with laser and PMT
  - laser light with polarization
  - monitor PMT
  - magnetometer

- Magnetic shielding
  - compensation coil, Giron shield

Two optical boxes

Tank (and PMT) will be put inside coil