Long baseline neutrino experiments
(accelerator LBL & reactor)

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ICHEP2018, Seoul
July 9, 2018
Neutrino oscillations

$$|\nu_\alpha\rangle = \sum U_{\alpha i}^* |\nu_i\rangle$$

Weak eigenstates \quad Mass eigenstates

Production \quad Propagation \quad Detection

Flavor change during flight

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$ (for 2 flavor)

Quantum effect over very macroscopic length!

\(\Delta m^2\): mass-squared difference

\(\theta\): mixing angle
We learned a lot about neutrinos through neutrino oscillation, but many questions emerged and remains

- Origin of tiny mass
- Why mass is much smaller than other fermions?
- Large mixing parameters
- Why so different from quarks?
- Symmetry behind the pattern?
- Mass hierarchy (ordering)
  - Which is the heaviest?
- CP violation
  - Is it violated just as in quarks?
- Extra neutrino families?

Properties of neutrino are considered to be connected with fundamental questions

- Source of baryon asymmetry of Universe?
- Very high scale physics? (seesaw?)
- Origin of generations?
Oscillation parameter status

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[
\begin{array}{l}
\Delta m^2_{21} [10^{-5} \text{eV}^2] & 7.55_{-0.16}^{+0.20} & 7.05-8.14 \\
|\Delta m^2_{31}| [10^{-3} \text{eV}^2] (\text{NO}) & 2.50_{-0.04}^{+0.03} & 2.41-2.60 \\
|\Delta m^2_{31}| [10^{-3} \text{eV}^2] (\text{IO}) & 2.42_{-0.04}^{+0.03} & 2.31-2.51 \\
\sin^2 \theta_{12}/10^{-1} & 3.20_{-0.16}^{+0.20} & 2.73-3.79 \\
\sin^2 \theta_{23}/10^{-1} (\text{NO}) & 5.47_{-0.30}^{+0.20} & 4.45-5.99 \\
\sin^2 \theta_{23}/10^{-1} (\text{IO}) & 5.51_{-0.30}^{+0.18} & 4.53-5.98 \\
\sin^2 \theta_{13}/10^{-2} (\text{NO}) & 2.160_{-0.069}^{+0.083} & 1.96-2.41 \\
\sin^2 \theta_{13}/10^{-2} (\text{IO}) & 2.220_{-0.076}^{+0.074} & 1.99-2.44 \\
\delta/\pi (\text{NO}) & 1.32_{-0.15}^{+0.21} & 0.87-1.94 \\
\delta/\pi (\text{IO}) & 1.56_{-0.15}^{+0.13} & 1.12-1.94 \\
deSalas et al, 1708.01186 (May 2018) \\
\end{array}

M. Tórtola @ NEUTRINO2018

Current major targets

- More precision measurements
- CP violation
- Mass hierarchy
- \( \theta_{23} \) octant (\( \leq \)45°?)
Reactor $\theta_{13}$ measurement

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left[ \frac{\Delta m_{ee}^2 L}{4E} \right] - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left[ \frac{\Delta m_{21}^2 L}{4E} \right] \]

At ~km with reactor $\nu_e$ energy, almost pure $\sin^2 2\theta_{13}$ measurement

Inverse beta decay for detection (delayed coincidence)

$\nu_e + p \rightarrow e^+ + n$

captured on Gd after thermalization

prompt signal  
delayed signal

$6 \times 10^{20} \bar{\nu}_e / s / 3 \text{GW}_\text{th}$

Control systematics by two detector configuration

Near detector

Far detector

Masashi Yokoyama (UTokyo)
Reactor $\theta_{13}$ experiments

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay (China)</th>
<th>Double Chooz (France)</th>
<th>RENO (South Korea)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power (GW$_{th}$)</td>
<td>17.4</td>
<td>8.5</td>
<td>16.8</td>
</tr>
<tr>
<td>Baseline</td>
<td>470/576/1650</td>
<td>400/1050</td>
<td>409/1444</td>
</tr>
<tr>
<td>Overburden near/far (m.w.e.)</td>
<td>250/265/860</td>
<td>80/300</td>
<td>120/450</td>
</tr>
<tr>
<td>Gd target mass for far detectors (tons)</td>
<td>80</td>
<td>8.3</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Parallel talks by H.Seo, L.Zhan, A.Stahl, B.Z.Hu, M.C.Chu
Reactor $\theta_{13}$: latest results

$\sin^2 2\theta_{13} = 0.0856 \pm 0.00429$

$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} eV^2$

$\sin^2 2\theta_{13} = 0.105 \pm 0.014$

$|\Delta m^2_{ee}| = (2.68 \pm 0.12 \pm 0.07) \times 10^{-3} eV^2$

- Precision measurements of $\sin^2 2\theta_{13}$ (~5%) and also $\Delta m^2$ (~3%)
- Many other measurements are also reported (see later talk)
- Further improvement expected from all experiments in near future
**20kton** liquid scintillator detector at 53km from reactors
- Mass hierarchy determination
- Precision measurements (<1%) of $\sin^2\theta_{12}$, $\Delta m^2_{21}$, $|\Delta m^2_{ee}|$
- Other rich physics potentials

- **Central detector**
  - Mechanical structure: Acrylic sphere, Stainless-steel truss
  - PMT: 18,000 20" PMTs, 25,000 3" PMTs
  - Liquid scintillator: 20 kton LS

- **Calibration system**
  - ACU, ROV, etc.

- **VETO detector**
  - Top Tracker: 62 Plastic scintillator walls

- **Overburden ~ 700 m**

- **Civil construction ongoing**
- Detector R&D and fabrication are progressing
- Aim to start data-taking in 2021

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**JUNO Location**

- Daya Bay
  - NPP: Operational
  - Power: 17.4 GW
- Huizhou
  - NPP: Planned
  - Power: 17.4 GW
- Lufeng
  - NPP: Under construction
  - Power: 17.4 GW
- Yangjiang
  - NPP: Under construction
  - Power: 17.4 GW
- Taishan
  - NPP: Planned
  - Power: 17.4 GW

- **Overby 2020: 26.6 GW**

- **By 2020: 26.6 GW**

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**Parallel talks by Q.Zhang, L.Wen, Z.Qin,**
Accelerator-Based long baseline experiments

Accelerator

Beamline

Horns

Target

Horns

Target

Near Detectors

ν_μ

Far detector

ν_μ, ν_τ, ν_e?
Accelerator-Based long baseline experiments

Long baseline neutrino experiments

Accelerator

Target

Beamline

Horns

$\pi^+$

$\pi^-$

Near Detectors

$\nu_\mu$

Far detector

$\nu_\mu$, $\nu_\tau$, $\nu_e$?

In-situ beam measurements

External hadron production measurements

Prediction of neutrino flux, uncertainties and correlation

Neutrino Mode Flux at the far detector

$\nu_e$, $\nu_\mu$, $\nu_\tau$

Event rate

Day

[events/1e14 POT]

0.4

0.6

0.8

1

1.2

1.4

1.6

1.8

Beam Position at Target

x mean = -0.257, RMS = 0.281

y mean = -0.581, RMS = 0.454

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Accelerator-Based long baseline experiments

In-situ beam measurements

External hadron production measurements

Prediction of neutrino flux, uncertainties and correlation

Extrapolation to far detector

Near detector measurements

External cross section measurements and models

Fractional Error

Flux (/cm$^2$ s)$^3$

Parameter Number

Nuclino Mode Flux at the far detector

$\phi_{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}$

Neutrino Mode Flux at the far detector

Near Detectors

Far detector

$\nu_\mu$, $\nu_T$, $\nu_e$

Beamlime Horns

Target

$p$

$\pm$
Accelerator-Based long baseline experiments

\[ p \to T^+T^- \]

\[ \mathcal{P}_\text{In-situ beam measurements} \]

\[ \mathcal{P}_\text{External hadron production measurements} \]

\[ \mathcal{P}_\text{Prediction of neutrino flux, uncertainties and correlation} \]

\[ \mathcal{P}_\text{Near detector measurements} \]

\[ \mathcal{P}_\text{Extrapolation to far detector} \]

\[ \phi_{\text{FD}}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{\text{FD}} \cdot P_{\text{osc}}(E_\nu) \]

\[ \phi_{\text{ND}}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{\text{ND}} \]

\[ \mathcal{P}_\text{External cross section measurements and models} \]

\[ \mathcal{P}_\text{Far detector data} \]

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Accelerator-Based long baseline experiments

External hadron production measurements

In-situ beam measurements

Far detector data

Far detector

Oscillation parameters

Prediction at far detector

\[ \phi_{FD}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{FD} \cdot P_{\text{osc}}(E_\nu) \]

Prediction of neutrino flux, uncertainties and correlation

Extrapolation to far detector

Near detector measurements

Near Detectors

\[ \nu_\mu ? \nu_T ? \nu_e ? \]

Accurate flux and energy distributions

\[ \sigma(\theta) \text{ (mb.(rad.GeV/c))} \]

\[ d\sigma/dp dT \]

Accurate flux and energy distributions

Horns

In-situ beam measurements

Accelerator

Target

Beamline

\[ p \]

\[ \pi^+ \]

\[ \pi^- \]

\[ \pm \]

\[ \nu_\mu \]

\[ \nu_\tau \]

\[ \nu_e \]

Accelerator-Based long baseline experiments

Data / Sim.

\[ \nu_\mu \text{-mode} \]

\[ \nu_\tau \text{-mode} \]

\[ \nu_e \text{-mode} \]

Far detector

Near detector measurements

\[ \phi_{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{ND} \]

External cross section measurements and models

\[ \phi_{ND}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{ND} \]

\[ \phi_{FD}(E_\nu) \cdot \sigma(E_\nu) \cdot \varepsilon_{FD} \cdot P_{\text{osc}}(E_\nu) \]

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Oscillations in accelerator LBL experiments

\(\nu_\mu \) “disappearance”

\[ P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} - \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \left[ \frac{\Delta m^2_{32} L}{4E} \right] \]

\(\sin^2 2\theta_{23}\) from the leading term

\(\nu_e\) “appearance”

\[ P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 [(A - 1)\Delta]}{(A - 1)^2} \]

\(\mp \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin \delta_{CP} \sin \Delta \frac{\sin A\Delta}{A} \frac{\sin [(1 - A)\Delta]}{1 - A} \]

\(+ \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \delta_{CP} \cos \Delta \frac{\sin A\Delta}{A} \frac{\sin [(1 - A)\Delta]}{1 - A} + O(\alpha^2)\)

The leading term dependent on \(\sin^2 2\theta_{13}, \delta_{CP}\) and mass hierarchy from sub-leading terms

\[\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} \ll 1 \quad \Delta = \frac{\Delta m^2_{32} L}{4E} \quad A = 2\sqrt{2} G_F N_e \frac{E_e}{\Delta m^2_{32}}\]

M. Freund, Phys.Rev. D64 (2001) 053003
Final results from MINOS/MINOS+

2005-2016

Baseline: 730km
Peak energy: ~3GeV (MINOS)
~7GeV (MINOS+)
+atmospheric ν

Precise measurements of $\theta_{23}$ and $|\Delta m^2_{32}|$
Consistency with three flavor prediction tightly constrains alternate oscillations hypotheses

$|\Delta m^2_{32}| = (2.28-2.55) \times 10^{-3} \text{ eV}^2 (NH)$
$\sin^2 \theta_{23} = 0.36-0.65$
$(90\% CL)$
Final $\nu_\tau$ results from OPERA

2008-2012

- Observation of $\nu_\tau$ interaction using a huge emulsion-based detector
- **10** $\nu_\tau$ candidates observed
  - 2.0$\pm$0.4 BG expected
  - 6.1$\sigma$ significance of $\nu_\tau$ appearance

PRL 120 (2018) 211801

$\Delta m^2$ consistent with disappearance measurements
T2K and NOvA

- Different baselines — different effect from matter effect (and possibly others not dependent on L/E)
- T2K has a shorter baseline, purer effect of CPV
- NOvA has a longer baseline, more matter effect and sensitivity to mass hierarchy
- Can provide complementary information

Long baseline neutrino experiments

Parallel talks by P. Litchfield and J. Bian
Different baselines — different effect from matter effect (and possibly others not dependent on L/E)
- T2K has a shorter baseline, purer effect of CPV
- NOvA has a longer baseline, more matter effect and sensitivity to mass hierarchy
- Can provide complementary information

Antineutrino data
\( \times 1.5 \) compared to 2017
(neutrino data doubled in 2016 → 2017)

First analysis including antineutrino beam data
T2K: reconstruction and analysis

- Improved reconstruction algorithm applied since 2017
  - Maximize likelihood based on charge and time from all PMTs
  - Improved signal efficiency and purity
  - Optimized fiducial selection to increase statistics (+~20%)
  - Improvements in cross section modeling
T2K: far detector (SK) data

Energy reconstructed from lepton kinematics assuming 2 body interaction

ν beam, 1 ring e, no decay-e

ν beam, 1 ring e, 1 decay-e

ν̅ beam, 1 ring e, no decay-e
T2K: $\Delta m_{32}^2$ and $\theta_{23}$

Joint fit of all samples

Normal hierarchy:

$$\sin^2 \theta_{23} = 0.536^{+0.031}_{-0.046}$$

$$\Delta m_{32}^2 = (2.434 \pm 0.064) \times 10^{-3} \text{eV}^2$$

Inverted hierarchy:

$$\sin^2 \theta_{23} = 0.536^{+0.031}_{-0.041}$$

$$\Delta m_{13}^2 = (2.410^{+0.062}_{-0.063}) \times 10^{-3} \text{eV}^2$$

Posterior probabilities based on a Bayesian analysis

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{23} &lt; 0.5$</th>
<th>$\sin^2 \theta_{23} &gt; 0.5$</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>0.204</td>
<td>0.684</td>
<td>0.888</td>
</tr>
<tr>
<td>IH</td>
<td>0.023</td>
<td>0.089</td>
<td>0.112</td>
</tr>
<tr>
<td>Sum</td>
<td>0.227</td>
<td>0.773</td>
<td>1</td>
</tr>
</tbody>
</table>

Bayes factor NH/IH = 7.9
\[ \bar{\nu}_e \] appearance search in T2K

- Dedicated searches performed by hypothesis testing:
  - PMNS $\bar{\nu}_e$ appearance ($\beta=1$) and no $\bar{\nu}_e$ appearance ($\beta=0$)

  **Expected events:**
  - 11.8 for $\beta=1$
  - 6.5 for $\beta=0$

  **Observed:** 9 events

Construct $\Delta \chi^2$ with rate+shape ($p, \theta$)
- other oscillation parameters constrained from T2K data other than $\bar{\nu}_e$ sample

Obtained p-values:
- PMNS appearance ($\beta=1$): $p=0.0867$
- No appearance ($\beta=0$): $p=0.233$

No strong statistical conclusion from T2K data yet

**Graphical Representation:**

- Data $\Delta \chi^2 = -1.67$

  - $\beta=0$
  - $\beta=1$

- Number of toy experiments

- Expected events:
  - 11.8 for $\beta=1$
  - 6.5 for $\beta=0$

- Observed: 9 events

- Obtained p-values:
  - PMNS appearance ($\beta=1$): $p=0.0867$
  - No appearance ($\beta=0$): $p=0.233$
T2K: $\theta_{13}$ and $\delta_{CP}$

- Constraint on $\delta_{CP}$ with T2K data alone
- Tighter constraint with $\theta_{13}$ value from reactor
Long baseline neutrino experiments

T2K: constraint on $\delta_{\text{CP}}$

$\sin\delta_{\text{CP}} = 0$ ($\delta = 0, \pi$) outside of $2\sigma$ CL region

First hint of CP violation in the lepton sector!
NOvA event classification

- Pioneering the use of Convolutional Neural Networks in neutrino experiment
- Treating cells as pixels and charge as color, extract features from data
- Improved classifier used for 2018 analysis
  - with separate training for the neutrino and antineutrino beams

Neutrino energy reconstruction from $E_1$ (range[µ]/calorimetric[e]) + $E_{had}$ (calorimetric)

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NOvA FD data

Neutrino beam

All Quartiles

\[ \nu_\mu \]

113

Reconstructed Neutrino Energy (GeV)

Antineutrino beam

All Quartiles

\[ \bar{\nu}_\mu \]

65

Reconstructed Neutrino Energy (GeV)

Neutrino mode

NOvA Preliminary

Events / 0.1 GeV

\[ \nu_e \]

58

Reconstructed Neutrino Energy (GeV)

Antineutrino mode

NOvA Preliminary

Events / 0.1 GeV

\[ \bar{\nu}_e \]

18

Reconstructed Neutrino Energy (GeV)

We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and Near ratio is used to obtain a FD prediction from ND data. Each quartile for the neutrino and antineutrino beams gets unfolded independently and the true Far/Near ratio is used to obtain a FD prediction from ND data.

Antineutrino beam

58 events and expect 15

Background interactions:

> 4 

On the neutrino beam we observe 113 events in neutrino mode (expect 730 +38/-49(syst.) w/o oscillations), 65 events in antineutrino mode (expect 266 +12/-14(syst.) w/o oscillations).
PREDICTING THE FD OBSERVATION

We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and Near ratio is used to obtain a FD prediction from ND data.

Each quartile for the neutrino and antineutrino beams gets unfolded independently and the true Far/Near ratio is used to obtain a FD prediction from ND data.

>4σ evidence of $\bar{\nu}_e$ appearance!
NOvA: $\Delta m^2_{32}$ and $\theta_{23}$

- Results from joint fit of $\nu_\mu$ and $\nu_e$
  \[
  \sin^2 \theta_{23} = 0.58 \pm 0.03
  \]
  \[
  \Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3} \text{eV}^2
  \]

  Prefer non-maximal at 1.8$\sigma$
  Exclude lower octant at similar level
Comparison: $\Delta m^2_{32} - \theta_{23}$

- Normal Hierarchy 90% CL
- $\sin^2 \theta_{23}$: <10%
- $|\Delta m^2|$: 3-4%
- NH preferred by T2K, NOvA, SK
NOvA: $\delta_{CP}$ and mass hierarchy

- Best fit: Normal Hierarchy, $\delta_{CP} = 0.17\pi$
- Prefer NH by 1.8$\sigma$
- Exclude $\delta_{CP} = \pi/2$ in the IH at >3$\sigma$
Beginning of lepton CPV era!
The excitement continues…

- Both experiments envision to further enhance their capabilities
- T2K: beam power increase (1.3MW) and ND280 upgrade
- NOvA: accelerator improvement (0.9MW) and test beam
- Analysis improvements
- Good prospects for mass hierarchy, CP violation, …

![T2K sensitivity graph](image)

![NOvA Simulation graph](image)

Parallel talk by K.Iwamoto
Masashi Yokoyama (UTokyo)

Long baseline neutrino experiments

...to the next generation!

- See later talk by Prof. Jae Yu
Conclusions

- Rapid and steady progress in neutrino oscillation physics
- MINOS/MINOS+ and OPERA final results strongly support the three flavor scenario
- Daya Bay/Double Chooz/RENO continue to improve precision of $\theta_{13}$, JUNO is coming
- T2K and NOvA explore CP and mass hierarchy with neutrino and antineutrino beams
- Excitement will continue and grow. Stay tuned for more results!
3.1 Mass Hierarchy

- Oscillation probability is independent of CP phase and $\theta_{23}$ (Reactor neutrinos)

$$P_{\nu_e}(E/L) = 1 - P_{31} - P_{32} - P_{23}$$

$P_{31} = \cos^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{23})$

$P_{32} = \sin^2(\theta_{23}) \sin^2(\theta_{13}) \sin^2(\Delta_{31})$

$P_{23} = \sin^2(\theta_{13}) \sin^2(\Delta_{23})$

$$P_{23} = 1 - \cos^4(\theta_{23}) \sin^2(\theta_{13})$$

$\sin^2(\theta_{13}) \sin^2(\Delta_{23})$ can be evaluated.

- The big suppression is the “solar” oscillation ($\Delta m^2_{12}$, $\sin^2\theta_{12}$)
- “Large” value of $\theta_{13}$ is crucial

3.2 Measurement of Oscillation Parameters

Due to good energy resolution and proper baseline, JUNO can help to:

- Improve precisions of three parameters ($\Delta m^2_{12}$, $\Delta m^2_{32}$, and $\sin^2\theta_{12}$) to sub-percent level, several times improvement compared with current precision.
- Probe the unitarity of $U_{PMNS}$ to $\sim 1\%$ level

<table>
<thead>
<tr>
<th>$\sin^2\theta_{12}$</th>
<th>$\Delta m^2_{12}$</th>
<th>$\Delta m^2_{32}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal $\pm B2$ (1%)</td>
<td>$+ BG$</td>
<td>$+ EL$ (1%)</td>
</tr>
<tr>
<td>$0.54%$</td>
<td>$0.60%$</td>
<td>$0.62%$</td>
</tr>
<tr>
<td>$0.24%$</td>
<td>$0.27%$</td>
<td>$0.29%$</td>
</tr>
<tr>
<td>$0.27%$</td>
<td>$0.31%$</td>
<td>$0.31%$</td>
</tr>
</tbody>
</table>

3.3 Neutrino Astrophysics and Others

- Neutrinos from the Earth escape freely and bring the information about U, Th and K abundances and their distributions
- Due to its largest LS size, the expected geo-neutrino rate in JUNO is $\sim 1.1$/day.
- Within the 1st year, JUNO will record more geo-neutrino events than all other detectors

JUNO will be the most precise experiment for geo-neutrino study. In the meanwhile, JUNO is also attractive for other neutrino astrophysics, such as supernova neutrinos, diffuse supernova neutrinos, solar neutrinos and atmospheric neutrinos.

Beside these, additional physics is also rich in JUNO

- Sterile neutrinos
- Proton decay
- Dark matter searches
- Other exotic searches
# Neutrino beams and long baseline experiments

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Experiment</th>
<th>Baseline</th>
<th>Beam power</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK-PS (KEK)</td>
<td>K2K</td>
<td>250km</td>
<td>5kW</td>
<td>1999-2004</td>
</tr>
<tr>
<td>Main Injector (Fermilab)</td>
<td>MINOS(+)</td>
<td>730km</td>
<td>400kW+</td>
<td>2005-2016</td>
</tr>
<tr>
<td>SPS (CERN)</td>
<td>OPERA / ICARUS</td>
<td>730km</td>
<td>510kW</td>
<td>2008-2012</td>
</tr>
<tr>
<td>J-PARC MR (J-PARC/KEK)</td>
<td>T2K</td>
<td>295km</td>
<td>500kW (design: 750kW)</td>
<td>2009-</td>
</tr>
<tr>
<td>Main Injector (Fermilab)</td>
<td>NOvA</td>
<td>810km</td>
<td>700kW</td>
<td>2014-</td>
</tr>
</tbody>
</table>
### T2K: data and predictions

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted (sin²θ_{23}=0.528)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>δ=0</td>
<td>δ=+π/2</td>
</tr>
<tr>
<td>v beam, 1Rµ</td>
<td>268.2</td>
<td>268.5</td>
</tr>
<tr>
<td>v̅ beam, 1Rµ</td>
<td>95.3</td>
<td>95.5</td>
</tr>
<tr>
<td>v beam, 1Re 0 decay-e</td>
<td>61.6</td>
<td>50.1</td>
</tr>
<tr>
<td>v beam, 1Re 1 decay-e</td>
<td>6.0</td>
<td>4.9</td>
</tr>
<tr>
<td>v̅ beam, 1Re 0 decay-e</td>
<td>13.4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Consistent with maximal v_µ disappearance
Prefer large CP violation (δ_{CP} ~π/2)

\[
\sin^2\theta_{23} = 0.528 \\
\sin^2\theta_{13} = 0.0219 \\
\Delta m^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2
\]
## T2K systematic error

<table>
<thead>
<tr>
<th>Error source</th>
<th>1-Ring $\mu$</th>
<th>1-Ring $e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FHC</td>
<td>RHC</td>
</tr>
<tr>
<td>SK Detector</td>
<td>2.40</td>
<td>2.01</td>
</tr>
<tr>
<td>SK FSI+SI+PN</td>
<td>2.20</td>
<td>1.98</td>
</tr>
<tr>
<td>Flux + Xsec constrained</td>
<td>2.88</td>
<td>2.68</td>
</tr>
<tr>
<td>$E_b$</td>
<td>2.43</td>
<td>1.73</td>
</tr>
<tr>
<td>$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NC1$\gamma$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NC Other</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Osc</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>All Systematics</td>
<td>4.91</td>
<td>4.28</td>
</tr>
<tr>
<td>All with osc</td>
<td>4.91</td>
<td>4.28</td>
</tr>
</tbody>
</table>
$\delta_{CP}$ with T2K alone

T2K Run 1-9c Preliminary

- Normal
- Inverted

$-2\Delta\ln(L)$ vs $\delta_{CP}$ (Radians)

$2\sigma$ and $1\sigma$ confidence levels are indicated.
T2K sensitivity and data result

![Graph showing T2K sensitivity and data result](image-url)

- $2\Delta \ln(L)$ vs $\delta_{CP}$
- 68.27% of toys MC
- 95.45% of toys MC
- Data
Mass hierarchy from Super-K

Determination of hierarchy determination

Estimate p-values using pseudo-data for the smallest and largest $\sin^2 \theta_{23}$.

Hypothesis test $\sim$ CL$_s$ method: $\text{CL}_s (\text{IH rejection}) \equiv \frac{p_0(\text{IH})}{1 - p_0(\text{NH})}$

Normal hierarchy is favored

- SK only: 80.6 $\sim$ 96.7%
- SK + T2K model: 91.5 $\sim$ 94.5%
NOvA: $\nu_\mu$ and $\bar{\nu}_\mu$ data

PREDICTING THE FD OBSERVATION
- Each quartile for the neutrino and antineutrino beams gets unfolded independently and the true Far/Near ratio is used to obtain a FD prediction from ND data.
- We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and cosmic trigger data.

<table>
<thead>
<tr>
<th>Neutrino beam</th>
<th>Antineutrino beam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>113</td>
</tr>
<tr>
<td>Best fit prediction</td>
<td>121</td>
</tr>
<tr>
<td>Beam BG</td>
<td>1.2</td>
</tr>
<tr>
<td>Cosmic BG</td>
<td>2.1</td>
</tr>
<tr>
<td>Unoscillated</td>
<td>730 +38/-49(syst)</td>
</tr>
<tr>
<td><strong>Observed</strong></td>
<td>65</td>
</tr>
<tr>
<td>Best fit prediction</td>
<td>50</td>
</tr>
<tr>
<td>Beam BG</td>
<td>0.6</td>
</tr>
<tr>
<td>Cosmic BG</td>
<td>0.5</td>
</tr>
<tr>
<td>Unoscillated</td>
<td>266 +12/-14(syst)</td>
</tr>
</tbody>
</table>
NOvA: $\nu_e$ and $\bar{\nu}_e$ data

On the neutrino beam we observe 58 events and expect 15 background interactions:

- 11 beam, 3 cosmic background and < 1 wrong sign background.

For the antineutrino beam we observe 18 and expect 5.3 background interactions:

- 3.5 beam background, < 1 cosmic background and 1 wrong sign background.

$$> 4\sigma$$ evidence of $\bar{\nu}_e$ appearance!

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Prediction</th>
<th>Wrong-sign</th>
<th>Beam BG</th>
<th>Cosmic BG</th>
<th>Total BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino mode</td>
<td>58</td>
<td>30-75</td>
<td>0.3-1.0</td>
<td>11.1</td>
<td>3.3</td>
<td>14.7-15.4</td>
</tr>
<tr>
<td>Antineutrino mode</td>
<td>18</td>
<td>10-22</td>
<td>0.5-1.5</td>
<td>3.5</td>
<td>0.7</td>
<td>4.7-5.7</td>
</tr>
</tbody>
</table>
• Improved systematic uncertainties. We are still statistics limited but calibration and cross sections are the largest uncertainties.

• Our upcoming test beam program will address the calibration and detector response uncertainties.
• The tuning is done independently for the neutrino vs antineutrino beam samples.

• Various corrections and tunings are applied:
  • Correct quasielastic component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
  • Apply same long-range effect as for QE to resonant baryon production as well. Nonresonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c²) weighted up 10% based on NOvA data.
  • Introduce custom tuning of GENIE “Empirical MEC” [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] based on NOvA ND data to account for multinucleon knockout (2p2h).
MUON NEUTRINO DISAPPEARANCE

- The combined data of neutrino and antineutrino beams are fitted assuming CPT invariance.
- We observe 113 events and expect 126 at this combined best fit for the neutrino beam mode and observe 65 events and expect 52 at the best fit in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution than the neutrino beam mode. However the $\chi^2$s are consistent with the combined fit oscillation parameters with $p > 4%$. 

![Graph showing oscillation parameters](image_url)

Mayly Sanchez - ISU
WHAT IS DIFFERENT IN ANTINEUTRINOS?
WRONG-SIGN CONTAMINATION

- 11% wrong-sign in the $\nu_\mu$ ND sample background
  - Consistent with data-based cross-check using neutron captures.
- 22% (32%) in the $\nu_e$ ND background in the high (low) PID bin
  - Consistent with data-based cross-checks using identified protons and event kinematics.
- $\sim 10\%$ systematic uncertainty from flux and cross section
- Does not include uncertainties from detector effects.
PREDICTING THE FAR DETECTOR OBSERVATIONS

- The neutrino spectrum is measured at the ND (before oscillations), this is a combination of neutrino flux, cross section and efficiency.
  - Estimate the underlying true energy distribution of selected ND events.
  - The measured spectrum is used to make a prediction of the expectation at the FD
    - Multiplying the true energy distribution by the Far/Near Ratio, applying oscillation probabilities and then converting to a predicted reconstructed energy distribution
  - Since NOvA has functionally similar Near and Far Detectors the flux combined with the cross sections uncertainties largely cancel.