Experimental status of T2K and NOvA

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XVth Rencontres du Vietnam
5th August 2019
• 30 GeV proton beam on 90 cm long graphite target
• $\nu_\mu$ and $\bar{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
• Invert magnet polarity to produce a $\bar{\nu}_\mu$ beam
• First off-axis neutrino beam experiment 2.5° (44 mrad)
  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum
The dominant neutrino interaction mode is Charged-Current Quasi-Elastic (CCQE).
(Anti)Neutrino interactions at T2K

Charged-Current $\pi$

Nieves et al. PRC 83 045501 (2011)
T2K near detector complex

*NIM A 659 (2011) 106–135*

- **Muon monitor:**
  - Spill-by-spill monitoring of the beam
- **On-axis detector (INGRID):**
  - Measure beam intensity / direction
- **Off-axis detector (ND280):**
  - 2.5° off-axis magnetized detector
  - Fine Grained Detector (plastic scintillator and water), TPCs, ECAL, P0D, SMRD
  - Precise measurement of neutrino flux and cross section
  - Measure wrong-sign background (20-30% $\nu_\mu$ in $\bar{\nu}_\mu$ beam after interaction)
Constraining the systematic uncertainties at ND280

- A joint fit of the following samples is performed: CC-0 pions, CC-1 pion, CC-Other for $\nu$ beam, CC-1 track, CC N-tracks for $\bar{\nu}$ beam

- Most of the parameters fall within 1σ of their assigned prior uncertainty
- The goodness-of-fit test shows a p-value for the model of 0.47
T2K far detector: Super-Kamiokande

- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events
Far Detector $\nu_\mu / \bar{\nu}_\mu$ event samples

- Data collected: $3.16 \times 10^{21}$ POT ($\nu$ - $1.51 \times 10^{21}$ POT, $\bar{\nu}$ - $1.65 \times 10^{21}$ POT)

### Systematic errors

<table>
<thead>
<tr>
<th>Sample</th>
<th>w/o</th>
<th>ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ CCQE</td>
<td>14.5%</td>
<td>4.1%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ CCQE</td>
<td>12.2%</td>
<td>4.5%</td>
</tr>
<tr>
<td>$\nu_e$ CCQE</td>
<td>17.2%</td>
<td>8.8%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ CCQE</td>
<td>14.1%</td>
<td>7.0%</td>
</tr>
<tr>
<td>$\nu_e$ CC1π</td>
<td>21.6%</td>
<td>18.3%</td>
</tr>
</tbody>
</table>

NO $\bar{\nu}_e$ appearance excluded at 2$\sigma$
Oscillation Analysis results

- **Consistent with maximal disappearance**
- **Agreement with reactor measurements**
- **Preference for $\delta_{CP} \sim -\pi/2$**

<table>
<thead>
<tr>
<th>Best-fit</th>
<th>Normal Ordering</th>
<th>Inverted Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>0.532</td>
<td>0.532</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$ ($\times 10^{-3}$ eV$^2$)</td>
</tr>
</tbody>
</table>

*Mass Ordering is fixed to either Normal or Inverted*
Confidence intervals of $\delta_{CP}$

- Confidence intervals were computed with Feldman-Cousins method
- Integrate over $\theta_{13}$ using the PDF from reactors’ measurement (PDG-2018)

```
                Allowed 2\(\sigma\) C.I.

\begin{itemize}
  \item The best-fit is $\delta_{CP} = -1.89$ radians and Normal Ordering
  \item Both $\delta_{CP} = 0$ and $\pi$ are excluded at 2\(\sigma\) CL
  \item Allowed 2\(\sigma\) CL region:  
    - Normal Ordering: $[-2.97, -0.63]$
    - Inverted Ordering: $[-1.80, -0.98]$
  \item Preference for maximal CP violation and Normal Ordering
\end{itemize}
```
Comparison between sensitivity and data results

• Toy MC study to compare the experiment sensitivity to the observed data set

• Less than ~5% of toy MC experiments show stronger exclusion than T2K data

• If Nature is $\delta_{CP} = -\pi/2$ and Normal Ordering:
  
  - The # of MC experiments that exclude $\delta_{CP}=0,\pi$ (both) at $2\sigma$ is 24%
The NOvA experiment

Long-baseline neutrino oscillation experiment based in US

- Measurement of Mass Hierarchy with significance better than 3\(\sigma\)
- Hint of CP violation in the leptonic sector

- Intense muon (anti)neutrino beam from NuMI in Fermilab
- Measure muon (anti)neutrino disappearance and electron (anti)neutrino appearance
The NOvA experiment

Long-baseline neutrino oscillation experiment based in US

- Measurement of Mass Hierarchy with significance better than $3\sigma$
- Hint of CP violation in the leptonic sector

- Off-Axis angle = 14 mrad
- 120 GeV proton beam
- Tuned with NA49 and MIPP experimental data
The NOvA experiment

Long-baseline neutrino oscillation experiment based in US

- Measurement of Mass Hierarchy with significance better than $3\sigma$
- Hint of CP violation in the leptonic sector

- Near Detector in Fermilab
  - 330 ton mass
  - 1 km from source
  - 300 ft underground
The NOvA experiment

Long-baseline neutrino oscillation experiment based in US
- Measurement of Mass Hierarchy with significance better than $3\sigma$
- Hint of CP violation in the leptonic sector

• Far Detector in Ash River
  - 14 kton mass
  - 810 km baseline
  - On surface
The NOvA Near and Far Detectors

- Same detector technology at Near and Far detectors
The NOvA Near and Far Detectors

- PVC extrusion + Liquid Scintillator (mineral oil + 5% pseudocumene)
- Read out via wavelength-shifting fiber to Avalanche PhotoDiode (APD)
- ~344k channels at Far Detector
Effect of CP violation and Mass Hierarchy

- About 30% effect both in $\delta_{CP}$ and Mass Hierarchy

Matter effects enhanced thanks to the longer baseline
(Anti)Neutrino interactions at NOvA

- Higher energy compared to T2K
- NC background: EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Nuclear effects and 2p-2h are important components
NOvA event topologies

Convolutional Visual Network technique to identify the event topology
(Aurisano, et al., JINST 11 (2016) no.09, P09001)
Joint Neutrino and Anti-Neutrino analysis

- Data collected: $2.12 \times 10^{21}$ POT ($\nu - 0.89 \times 10^{21}$ POT, $\bar{\nu} - 1.23 \times 10^{21}$ POT)

* $\nu_{\mu}$ candidates

- Observe 113 $\nu_{\mu}$ (expect 730) and 102 $\bar{\nu}_{\mu}$ (expect 476)

* $\nu_{e}$ candidates

- Observed 58 $\nu_{e}$ (expect 15) and 27 $\bar{\nu}_{e}$ (expect 10.3)

- Wrong-sign background is $\sim$ 3% in beam and 11% $\bar{\nu}$

arXiv:1906.04907
Confidence region $\sin^2\theta_{23}$ and $\Delta m^2_{32}$

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<tbody>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>0.56</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
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$\sin^2\theta_{23} < 0.5$ (lower octant) is disfavored at 1.5 $\sigma$
- Preference for Normal Hierarchy, Inverted Hierarchy excluded 1.9σ.
- All values for Normal Hierarchy are allowed at 1.1σ (NH, upper octant).
- Region around $\delta_{CP} \sim +\pi/2$ and Inverted Hierarchy is excluded at $>4\sigma$.
- Results are in agreement with T2K.
Comparison of different experimental results

NOvA FD $8.85 \times 10^{20}$ POT equiv $\nu + 12.33 \times 10^{20}$ POT $\bar{\nu}$

- NH Lower octant
- NH Upper octant
- IH Lower octant
- IH Upper octant

NOvA Preliminary

-2Δln(L)

-3 -2 -1 0 1 2 3

δ_CP (radians)

Allowed 2σ C.I.

Normal
Inverted

T2K Run 1-9 Preliminary

-Δχ²

0 2 4 6 8 10

Δχ²

99%
95%
90%
68%

δ_CP (radians)

SK-IV 3118.5 days
(FITQun analysis)

Super-K
(Jan 2019)

arXiv:1901.03230

- NO
- IO

-Δχ²

0 90 180 270 360

δ_CP (degrees)

NuFIT 4.1 (2019)
Prospects for the future

T2K data taking will be extended to phase II up to 2025. Increased beam intensity up to ~1 MW in 2021.

NOvA expected improvements: beam intensity, test beam for detector response.

NOvA+T2K joint data fit foreseen for 2021.
Conclusions

- T2K and NOvA are currently the most sensitive experiments for the measurement of the neutrino CP violating phase and mass ordering.

- Similar in the concept but the different configurations (water Cherenkov vs plastic scintillator, different vs identical ND-FD technologies, different energies) make any comparison of the oscillation comparison more robust.

- Latest results are in good agreement.

- Future improvements are foreseen, i.e. T2K Near Detector upgrade and NOvA test beam data analysis to characterize the detector response.

- Plan for combined NOvA+T2K data analysis.
BACKUP
Effect of CP violation and Mass Hierarchy at T2K

- Asymmetric effect on $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$:
  
  - $\delta_{CP} = -\pi/2 \rightarrow$ maximizes $P(\nu_\mu \rightarrow \nu_e)$ and minimizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  
  - $\delta_{CP} = +\pi/2 \rightarrow$ minimizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ and maximizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- Effect of $\delta_{CP}$ on $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ is about $\pm 20$-$30\%$

- Effect of Mass Hierarchy is about $\pm 10\% \rightarrow$ 295 km baseline not long enough
Prospects for the future: T2K-II

- Expect to reach the approved T2K statistics (7.8x10^{21} POT) around 2021
- **T2K-II phase**: proposed to extend T2K run to 20x10^{21} POT by 2025 (Stage-I status at summer JPARC PAC)
- Plan to gradually increase the beam intensity up to ~1 MW in 2021
- Aiming for >1 MW intensity for 2021 and 1.3 MW in ~2026: accelerator and beam-line upgrade is needed
- Demonstrated 3.41x10^{13} protons per beam operation → 1 MW equivalent

**arXiv:1609.04111**

**TODAY**

Will reach 500 kW soon
We use convolutional neural network called CVN (Convolutional Visual Network).

- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify $\nu_e$, $\nu_\mu$, $\nu_\tau$, NC and cosmic.

A. Aurisano et. al, JINST 11, P09001 (2016)
120 GeV protons on a carbon target, produce mesons which yield neutrinos. Beam purity with $\nu(\bar{\nu})$: 95% $\nu_\mu$, 4% $\bar{\nu}_\mu$, 1% $\nu_e$ (93% $\bar{\nu}_\mu$, 6% $\nu_\mu$, 1% $\nu_e$).

NOvA is designed for the 700 kW NuMI beam, with $6 \times 10^{20}$ POT/year (POT = Protons On Target).

Running at 700 kW since January 2017.

78% increase in $\bar{\nu}$ exposure:

$6.91 \times 10^{20} \rightarrow 12.33 \times 10^{20}$

(2018 → 2019)