Upgrade Project of the T2K Near Detector

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On behalf of the ND280 Upgrade Working Group

ICHEP 2018, Seoul
T2K to T2K-II

Latest Result of T2K (NEUTRINO 2018)

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

- Normal
- Inverted

T2K rejects CP conservation at 2$\sigma$ CL in both mass hierarchies

- Beam power upgrade (485 kW $\rightarrow$ 1.3 MW)
- Plan to accumulate $20 \times 10^{21}$ POT by 2026
- Reaches $> 3\sigma$ sensitivity to CP violation in lepton sector (for $\sim 40\%$ of the $\delta_{CP}$ values with known mass hierarchy

T2K-II Protons-On-Target Request

- MR Power Supply upgrade
- T2K-II Protons-On-Target Request

Mass hierarchy unknown

$\nu_3$ $\rightarrow$ $\nu_1$

$\Delta \chi^2$ to exclude $\sin \delta_{CP} = 0$

- 3$\sigma$ C.L.
- 99% C.L.
- 90% C.L.

Protons-on-Target ($x10^{21}$)
Impact of Systematic Uncertainties

Improved understandings of the systematic uncertainties allow to achieve the $> 3\sigma$ sensitivity with less POT:

- Flux uncertainty
- Detector uncertainty
- Neutrino cross-section uncertainty

<table>
<thead>
<tr>
<th>Source (%)</th>
<th>$\nu_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-unconstrained</td>
<td>0.7</td>
<td>3.0</td>
<td>0.8</td>
<td>3.3</td>
</tr>
<tr>
<td>cross section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux and ND280-constrained</td>
<td>2.8</td>
<td>2.9</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td>cross section</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super-Kamiokande detector systematics</td>
<td>3.9</td>
<td>2.4</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Final or secondary hadron interactions</td>
<td>1.5</td>
<td>2.5</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Total</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Goal to reduce the systematic uncertainty from ~6% to ~4%

→ND280 Upgrade
T2K Off-Axis Near Detector Complex: ND280

- Measures particles produced by neutrino interactions prior to oscillations
  - 3 Time Projection Chambers (TPCs)
  - 2 Fine-Grained Detectors (FGD1, FGD2 w/ water target)
    - Planes of plastic scintillator bars along horizontal and vertical directions
  - $\pi^0$ Detector (P0D)
  - Electromagnetic Calorimeter (ECAL)
  - Side Muon Range Detector (SMRD)
  - Magnetized by 0.2 T UA1 Magnet
ND280 Upgrade

- Keep 2 FGDs, 3 TPCs, ECals
- Implement new upstream trackers:
  - 2 High-Angle TPCs (HA-TPCs)
  - 1 fine-grained scintillator target (SuperFGD)
  - Time-of-Flight (ToF) counters around the new trackers
    - Provides timing information for track reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Current (FGDs)</th>
<th>Upgrade (FGDs + SuperFGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target mass (tons)</td>
<td>2.2</td>
<td>4.3</td>
</tr>
</tbody>
</table>
High-Angle TPC

- **Resistive Micromegas:**
  - Pads covered by resistive foil
  - Developed by the ILC-TPC collaboration

- **Field Cage Design:**
  - Thin field cage wall (~3 cm)
  - Multi-layer structure to minimize the material budget (~3% $X_0$)
  - Designs with carbon fiber and aramide fiber based layers in progress

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<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values/TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>$1.8 \times 0.6 \times 2.0 , \text{m}^3$</td>
</tr>
<tr>
<td>Drift distance</td>
<td>90 cm</td>
</tr>
<tr>
<td>Gas ratio ($\text{Ar}, , \text{CF}_4, , \text{iC}<em>4\text{H}</em>{10}$)</td>
<td>95%, 3%, 2%</td>
</tr>
<tr>
<td>Pad dimensions</td>
<td>$11 \times 11 , \text{mm}^2$</td>
</tr>
<tr>
<td>Micromegas dimensions</td>
<td>$340 \times 410 , \text{mm}^3$</td>
</tr>
<tr>
<td># Micromegas</td>
<td>16</td>
</tr>
<tr>
<td># Channels</td>
<td>$3.2 \times 10^4$</td>
</tr>
</tbody>
</table>
Time-of-Flight Counter

- ToF planes placed around the new trackers
- Provides timing information for track reconstruction
- Improved particle identification ($p/e^+, \text{electrons/muons}$)
- Out-of-fiducial-volume event rejection
- R&D with a cast plastic scintillator design
  - 8 photo-sensors ($6 \times 6 \text{ mm}^2$)
  - Timing resolution is $< 100 \text{ ps}$
  - R&D at University of Geneva (for SHiP)
SuperFGD

- 1.8 x 0.6 x 2.0 m³ volume
- Consists of 1 x 1x 1 cm³ plastic scintillator cubes with the reflector obtained by chemical etching
- WLS fibers along each side of the cubes, allowing the light yield measurement from three views by the MPPCs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cube edge: 1 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td># of cubes</td>
<td>2,160,000</td>
</tr>
<tr>
<td># of channels</td>
<td>58,800</td>
</tr>
<tr>
<td>Total fiber length</td>
<td>65 km</td>
</tr>
</tbody>
</table>

arXiv:1707.01785
SuperFGD Cube Production

- Prototype cubes produced by extrusion method
  - Uncertainty of the cube dimension was ~75 μm
- ~50 μm thickness reflector obtained by chemical etching by Uniplast (Russia)

- Injection molding method established by INR RAS (Russia)
  - Uncertainty of the cube dimension reduced to ~35 μm with reflectors
SuperFGD Prototype Beam Tests

- Two beam tests completed, **one ongoing**
- **June 27 – July 11, 2018 @ CERN T9**
  - $8 \times 24 \times 48 \text{ cm}^3$ prototype, CITIROC readout (Baby MIND electronics), magnetized by the MNP17 magnet platforms (0.2-1T)
  - 1,728 MPPC channels
  - Upstream MDX dipole magnet (0.5T) to prepare photon beam
Simulation Studies

- **Wide angle acceptance**
- GEANT4 simulation of current and upgrade ND280 with T2K $\nu_\mu$ flux prediction ($1 \times 10^{21}$ POT)
- $\nu_\mu$ CC event selection using tracks reconstructed in TPCs
- Selection efficiency of backward going and wide-angle events increased by $\sim 40\%$
- Reduces systematic uncertainties by 20-40\% than the current ND280

- **High granularity**
- Reconstruction efficiency improvement in high-angle and low momentum tracks
  - $e/\gamma$ separation for $\nu_e$ selection with the track light yield difference (1 and 2 MIPs)

Work in progress
Conclusions

- **ND280 Upgrade for T2K-II**
  - Wide angle acceptance and low momentum measurement by HA-TPCs, SuperFGD, and ToF counters
  - R&D and simulation studies in progress
  - **Proposal submitted on Jan 2018 (SPSC@CERN & PAC@J-PARC)**

- **Plan for the ND280 Upgrade:**
  - June - August 2018: Prototype SuperFGD and HA-TPC beam test @ CERN
  - 2019-2020: Production at INR, integration at CERN, system test
  - **2021: Installation and commissioning in Japan**

- Open workshops every ~2 months
  - So far 8 open workshops were held since November 2016

- **The 9th open workshop at CERN on July 25 - 26:**
  - [https://indico.cern.ch/event/724624/](https://indico.cern.ch/event/724624/)
  - **New members are always welcome!!**
Thank you very much!!
Back-Up Slides
$\delta_{cp} = [−2.914, −0.642] (NH), [−1.569, −1.158] (IH) \text{ at } 2\sigma \text{ CL}$

T2K rejects CP conservation at $2\sigma$ CL in both mass hierarchies
### T2K Data Accumulation Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Run1</th>
<th>Run2</th>
<th>Run3</th>
<th>Run4</th>
<th>Run5</th>
<th>Run6</th>
<th>Run7</th>
<th>Run8</th>
<th>Run9</th>
</tr>
</thead>
<tbody>
<tr>
<td>POT (x 10^20)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Beam Power (kW)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Neutrino** statistics has doubled during 2016-2017 run
- **Anti-neutrino** statistics has doubled during the latest run

23 Jan. 2010 – 31 May 2018

POT total: $3.16 \times 10^{21}$

$\nu$-mode: $1.51 \times 10^{21}$ (47.83%)

$\bar{\nu}$-mode: $1.65 \times 10^{21}$ (52.17%)
Goals of ND280 Upgrade (1)

• $4\pi$ Acceptance
  • Current ND280 has strong forward track acceptance yet low efficiency to the vertical and backward tracks
  • Detector with larger phase space to apply constraint on the cross section models

arXiv:1204.3666
Goals of ND280 Upgrade (2)

- Low momentum (< 200 MeV/c) particle measurement
  - **2p2h models**
    - Energy reconstruction bias
  - **Electron-photon separation**
    - ~23% of the ND events that are selected as $\nu_e$ are misidentified photons from $\nu_\mu$ NC1$\pi^0$
  - Detector with higher granularity to be sensitive to low momentum

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**Phys. Rev. Lett. 113, 241803**
SuperFGD Assembly

- Assembly method developed by INR RAS
- 1.3 mm $\phi$ fishing lines through the cubes to assemble, replaced with 1.0 mm $\phi$ WLS fiber line by line
- Feasibility proved with 9,216-cube prototype (8 x 24 x 48 cm$^3$)
- Other methods for an actual detector design under investigation
SuperFGD Prototype Beam Tests

- **October 18 - November 1, 2017 @ CERN T10**
  - $5 \times 5 \times 5$ cm$^3$ prototype, digitizer readout
  - Light yield, cross-talk, timing resolution

- **June 1-3, 2018 @ Tohoku University**
  - $4 \times 4 \times 6$ cm$^3$ prototype, EASIROC readout
  - ~500 MeV/c positron beam
  - Position dependence, inner cube uniformity of light yield, test of different cube design
SuperFGD Prototype Beam Test @ CERN T9

- Using Baby MIND electronics with signal amplifications in the FE board (CITIROC)
- Uses micro-coaxial cables to provide connections between ceramic type MPPCs and FE boards
- Mechanical structure made in UniGe
MPPCs for the Beam Test @ CERN T9

**MPPC sorting/mapping**

| S12571-025C | Top middle | 24 cm |
| Top middle | Bottom middle | 8 cm |
| S13081-050C | Top upstream | 16 cm |
| Bottom upstream | All sides | All faces |
| S13360-1325CS | Top downstream |

**Three MPPC types:**
- ×1160 type S13360-1325CS
- ×490 type S13081-050C
- ×200 type S12571-025C

Type S13360-1325CS and S13081-050C: The MPPCs are **delivered** by the **manufacturer** usually according to the **serial number**:
- One bag per MPPC, with a small label indicating:
  - Serial number
  - $V_{op}$ (operating voltage)
  - Dark (μA)
- Then 10 bags in a larger bag (without label)... and several larger bags/box.

**The sorting/cabling sequence:**
- Sorting MPPCs into groups according to operating voltage ($V_{op}$): range 100 mV.
- Further sorting into batches of 32 (to match cable bundles).
- Assembly onto cable bundles, registration in database.

**Traceability:**
- Each MPPC must be traceable back to its serial number and $V_{op}$.
- Until it is connected to the cable bundle and registered in the database, it must be kept in its bag.

**Sorting details:**
The MPPCs must be kept separated by type. The MPPCs are then sorted according to $V_{op}$ in 100 mV ranges:
- S13360-1325CS:
  - 56.4<56.5, 56.5<56.7, 56.7<56.8, 56.8<56.9, 56.9<57.0, 57.1<57.2, 57.2<57.3 V
- S13081-050C:
  - 53.8<53.9, 53.9<54.0, 54.1<54.2, 54.2<54.3, 54.3<54.4, 54.4<54.5, 54.5<54.6, 54.6<54.7 V

Since we do not expect exact multiples of 32 in each voltage range, some further choices will be made to put MPPCs from two adjacent ranges in the same 32-channel bundle.
SuperFGD PCB-Box Integration

• Goal to minimize the space and material budget
• Surface mount type MPPC
  • [https://www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf](https://www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf)
• Preliminary design and R&D in progress

T. Matsubara

D. Sgalaberna
Intrinsic $\nu_e$ Component in the Flux

*Phys. Rev. D. 89, 092003 (2014)*

- Expected scaling factor obtained with 6.0e20 POT:

\[
R(\nu_e) = 1.01 \pm 0.06\text{(stat)} \pm 0.06\text{(flux} \oplus x. \text{sec)} \\
\quad \pm 0.05\text{(det} \oplus \text{FSI)} \\
= 1.01 \pm 0.10,
\]

(4)

- $E_\nu < 1.2$ GeV dominated by muon decay:

\[
R(\nu_e(\mu)) = 0.68 \pm 0.24\text{(stat)} \pm 0.11\text{(flux} \oplus x. \text{sec)} \\
\quad \pm 0.14\text{(det} \oplus \text{FSI)} \\
= 0.68 \pm 0.30
\]

(5)
CC $\nu_e$ Inclusive Cross Section on Carbon

$\langle \sigma \rangle_\phi = 1.11 \pm 0.10 \text{(stat)} \pm 0.18 \text{(syst)} \times 10^{-38} \text{cm}^2 / \text{nucleon}$

- Total flux averaged cross section obtained with $6.0 \times 10^{20}$ POT:

- Dominant components of systematic uncertainties:
  - Flux (13%)
  - Detector (8%)
  - Others (6%)
e/$\gamma$ Separation in ND280 Upgrade Target

- Goal to distinguish e/$\gamma$ events that are single-track, electron-like, low momentum ($200 < p < 600$ MeV/c)
- Distinction between 1 ($e^-$) and 2 ($\gamma \rightarrow e^- e^+$) MIP events using the MPPC light yield from the tracks
  - Considering the light yield before and after the $e^- e^+$ tracks split into different scintillator segments
$e/\gamma$ Separation using Light Yield

- Preliminary algorithm to separate $e/\gamma$ events using the total light yield for each view (YZ, XZ, XY)
  1. Locates the single electron track and the starting point using truth information
      - “Perfect pattern recognition”
  2. Split the track into two segments where the ratio between the mean values of the total p.e. is the largest
      - Ignores the first and last MPPC hits to avoid short path length

**e Sample**

![e Sample Graph]

**\gamma Sample**

![\gamma Sample Graph]
SuperFGD: $\nu_e$ MC and $\gamma$ 4\pi p-gun Comparison

77% efficiency to accept $\nu_e$ CC
39% to mis-ID $\gamma$ p-gun sample
(19% if 2-trk-like count as rejected)

Work in progress
Comparison of predicted event rate of selected events ($1 \times 10^{21}$ POT) between ND280 current and upgrade:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Current-like</th>
<th>Upgrade-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ (\textit{\nu} beam)</td>
<td>93,401</td>
<td>194,654</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ (\textit{\nu} beam)</td>
<td>33,437</td>
<td>63,687</td>
</tr>
<tr>
<td>$\nu_\mu$ (\textit{\nu} beam)</td>
<td>17,998</td>
<td>33,773</td>
</tr>
</tbody>
</table>

$\nu_\mu$ CC

<table>
<thead>
<tr>
<th>Selection</th>
<th># of events ($/10^{21}$ POT)</th>
<th>Purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of events ($/10^{21}$ POT)</td>
<td>CC0\pi</td>
</tr>
<tr>
<td>current</td>
<td>FGD 1</td>
<td>50012</td>
</tr>
<tr>
<td></td>
<td>FGD 2</td>
<td>48119</td>
</tr>
<tr>
<td>upgrade</td>
<td>FGD1</td>
<td>48332</td>
</tr>
<tr>
<td></td>
<td>FGD2</td>
<td>45636</td>
</tr>
<tr>
<td></td>
<td>SuperFGD</td>
<td>100686</td>
</tr>
</tbody>
</table>
ND data fit tool adapted to ND280 Upgrade to evaluate how much the systematic uncertainties are reduced (8×10^{21} POT):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current ND280 (%)</th>
<th>Upgrade ND280 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK flux normalisation (0.6 &lt; E_\nu &lt; 0.7 GeV)</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>M_{AQE} (GeV/c^2)</td>
<td>2.6</td>
<td>1.8</td>
</tr>
<tr>
<td>\nu_\mu 2p2h normalisation</td>
<td>9.5</td>
<td>5.9</td>
</tr>
<tr>
<td>2p2h shape on Carbon</td>
<td>15.6</td>
<td>9.4</td>
</tr>
<tr>
<td>M_{ARES} (GeV/c^2)</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Final State Interaction (\pi absorption)</td>
<td>6.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

On average the systematic uncertainties are reduced by about 30%