Lepton Photon 2019

The T2K ND280 Upgrade

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for the
T2K Collaboration
(ND280 Upgrade Working Group)
The T2K Collaboration

~ 500 members, 68 Institutes, 12 countries

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U. Toronto
U. Victoria
U. Winnipeg
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6 August 2019
McGrew -- Lepton Photon 2019
Search for CP Violation w/ T2K-II

➢ T2K-II extends T2K exposure from $7.8 \times 10^{21}$ POT to $20 \times 10^{21}$ POT.
➢ Requires systematic uncertainty be significantly reduced
  ➔ Goal: $3\sigma$ sensitivity for CP violation

Expected exposure to exclude $\sin \delta_{CP} = 0$

![Graph showing expected exposure to exclude $\sin \delta_{CP} = 0$.]

Reduction in flux & cross section systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current ND280 (%)</th>
<th>Upgrade ND280 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK flux normalisation</td>
<td>3.1</td>
<td>2.4</td>
</tr>
<tr>
<td>$(0.6 &lt; E_\nu &lt; 0.7$ GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$MAQE$ (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>

T2K-II CP conservation exclusion goal
w/ $20 \times 10^{21}$ POT (the 2025 goal)
The Existing ND280 Detectors

- Off-Axis: ND280 @ 2.5 deg
  - Water Target for stat. subtraction
  - Uses “UA1” magnet (@ 0.2 T)
    - Target+Particle Tracking
    - $\pi^0$ detection
    - EM calorimetry
    - Side muon range detection

- Proton momentum threshold:
  - 450 MeV/c (i.e. ~100 MeV KE)

- Acceptance in forward direction
  - SK has $4\pi$ acceptance

- Uncertainty in track direction and charge
  - Limit timing and TPC acceptance

Phase-space where muon is well measured at the ND280

Reconstructed SK Electrons

Reconstructed ND280 Muons

Different acceptances contribute to systematic uncertainty

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The ND280 Upgrade Detector

➢ Goal: Reduce ND systematics
  ➢ Fully active target
  ➢ “4π” acceptance for charged particles
  ➢ Improved $e^\pm/\gamma$ separation
  ➢ Neutron detection
    ➢ Measure kinetic energy

➢ SuperFGD
  ➢ Active Target Mass: $\sim$2 tonne
  ➢ Scintillator: 1 cm$^3$ cubes

➢ New TPCs
  ➢ High Angle TPCs
    ➢ Good acceptance for muons transverse to $\nu$ beam

➢ New TOF
  ➢ Clear tag for entering charged particles

➢ Existing Components
  ➢ Surrounding ECals
    ➢ Minimum of $\sim$5 Rad. Lengths
  ➢ Downstream TPCs
  ➢ Magnet: 0.2 T

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The SuperFGD Concept

➢ Neutrino interactions have particles going in all directions
➢ A plastic scintillator active target is usually constructed with bars
   - Defines a preferred axis → Acceptance varies relative to bar orientation
➢ Need a “4π” scintillator detector
   - Use cubes not bars (light contained in each cube)
   - Read-out in 3 projections using wavelength shifting fiber
     - A single energy deposit gives an “XYZ” coordinate (not just “XZ”, or “YZ”)
➢ Segmentation scales like volume → Readout scales like area
   - 2M cubes need ~60K channels (a ~ 200cm × 200cm × 60cm target)
➢ Uniform target material (Scintillator and WLS fibers)
➢ Excellent performance in Beam Tests

A T2K ND280 CR Muon
Need 2 layers for 3D

Yuri Kudenko – Scintillating perspective, 2017
SuperFGD Performance

- High Granularity
  - Reduces proton threshold
  - Detailed track reconstruction
- Precise timing
  - Identify track direction and reduce external backgrounds
- High light yield
  - Unambiguous proton identification
  - Low hit threshold
- Improved Sensitivities
  - Light and timing → neutrons
  - Reduced proton threshold

Beam test events from SuperFGD

D. Sgalaberna – CERN Det. Sem 2018

Efficiency for protons stopping in SuperFGD

Efficiency vs. True Proton Momentum (MeV/c)

Proton Momentum from NEUT

(1901-03750)
High Angle TPC
(Instrumented with Resistive Micromegas)

- Instrumented with Resistive Micromegas
  - Minimizes sparking
  - Improves resolution (per pad)
- Field Cage
  - Thin solid insulator wall to minimize dead space volume

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall x x y x z (m)</td>
<td>$2.0 \times 0.8 \times 1.8$</td>
</tr>
<tr>
<td>Drift distance (cm)</td>
<td>90</td>
</tr>
<tr>
<td>Magnetic Field (T)</td>
<td>0.2</td>
</tr>
<tr>
<td>Electric field (V/cm)</td>
<td>275</td>
</tr>
<tr>
<td>Gas Ar-CF$_4$-iC$<em>4$H$</em>{10}$ (%)</td>
<td>95 - 3 - 2</td>
</tr>
<tr>
<td>Drift Velocity $cm/\mu s$</td>
<td>7.8</td>
</tr>
<tr>
<td>Transverse diffusion ($\mu m/\sqrt{cm}$)</td>
<td>265</td>
</tr>
<tr>
<td>Micromegas gain</td>
<td>1000</td>
</tr>
<tr>
<td>Micromegas dim. x y (mm)</td>
<td>$340 \times 410$</td>
</tr>
<tr>
<td>Pad x y (mm)</td>
<td>$10 \times 11$</td>
</tr>
<tr>
<td>N pads</td>
<td>36864</td>
</tr>
<tr>
<td>el. noise (ENC)</td>
<td>800</td>
</tr>
<tr>
<td>S/N</td>
<td>100</td>
</tr>
<tr>
<td>Sampling frequency (MHz)</td>
<td>25</td>
</tr>
<tr>
<td>N time samples</td>
<td>511</td>
</tr>
</tbody>
</table>

\[ \sigma \approx 12 \% \]

Muon dE/dX (2 GeV/c)

\[ \sigma \approx 11 \% \]

Electron dE/dX

\[ (1901-03750) \]
Resistive Micromegas
(Encapsulated resistive anode with grounded mesh)

➢ Beam Test at CERN 2018 using HARP field cage
  ➢ T2K MM Pad geometry with resistive foil
    ➢ T2K resolution: \( \sim 0.7 \) mm
    ➢ With resistive foil: < 0.5 mm
  ➢ Get similar resolution with fewer pads
➢ Recent test at DESY
  ➢ Used candidate resistive MM module

Position Resolution
Time Of Flight Detector

- New detectors are enclosed in a Time-of-Flight detector
  - Nearly hermetic coverage for the new TPCs and the SuperFGD.
- Improves rejection for incoming backgrounds
  - Achieved timing resolution is \( \sim 70 \) ps
  - Charged track direction unambiguously determined (in combination with the SuperFGD)

Sixteen 6x6 mm² MPPC attached in parallel used to achieve timing resolution.
Effects of the Upgrade:
Increased Acceptance for Muons

➢ Expanded coverage for TPCs
  ➢ Charge identification
  ➢ dE/dX
➢ High efficiency for stopping muons
  ➢ Measure kinematics
➢ Muon acceptance almost independent of angle
➢ Forward/Backward separation from timing
➢ Significant coverage for the full phase space

Efficiency to measure muon vs direction

Kinematics of muons in the TPCs

(For NEUT interactions)
Effects of the Upgrade: Neutrons in the sFGD

- Detector
  - High granularity gives significant efficiency for neutrons
  - Energy resolution for longer path lengths
- Neutron selection looks for hits separated from the vertex
  - Must also be outside of a 3cm x 3cm cube around the reconstructed vertex.
  - Time defined by the first neutron hit
  - Roughly 60% efficiency to detect neutrons from a neutrino interaction
- Neutron energy reconstructed from time-of-flight
  - Shown resolution assumes a 0.9 ns single fiber time resolution
Transverse Momentum for $\nu_{\mu}$ and $\bar{\nu}_{\mu}$

- Improved acceptance gives better "direct" probes of nuclear effects\(^1\)
  - Low sFGD proton threshold
  - sFGD sensitivity to neutrons
- Example: Lepton+Nucleon (CCQE-like) events
  - Magnitude of net transverse momentum $\rightarrow P_f$
  - Orientation of net transverse momentum $\rightarrow$ FSI

\(^1\) PRC 94 (2016) 015503
Summary and Conclusions

➢ To fully exploit T2K we need a better understanding of neutrino interactions
  ➔ Leads to a better understanding of oscillation systematic uncertainties

➢ The T2K ND280 detector is being upgraded to meet this challenge
  ➔ Measure neutrino events over an expanded phase space
  ➔ Nearly “4π” acceptance to measure muons in a TPC
  ➔ First significant acceptance for neutrons in the T2K ND280

➢ Active target using an innovative scintillator target (SuperFGD)
  ➔ Fully active, and 4π acceptance for charged particles

➢ TPCs instrumented with Resistive Micromegas
  ➔ Improved resolution (or reduced number of electronics channels)

➢ Beam tests have demonstrated the performance of the new systems
  ➔ Tests of SuperFGD, TPCs with resistive micromegas, and TOF

➢ Schedule:
  ➔ Production during 2019 and 2020
  ➔ Installation during 2021
  ➔ Propose a $20 \times 10^{21}$ POT exposure
Backup Slides
Basic Active Target Performance
CERN 2017 Beam Test – NIM A923 (2019) 134

- Measurements of
  - Light yield ~ 40 pe/fiber
    - MPPC readout
    - 1 mm Y11 fibers w/ 1.3 m length
  - Timing resolution
    - $\sigma_t \sim 0.9 \text{ ns/fiber} \rightarrow 0.7 \text{ ns for two fibers}$
  - Cube to cube light propagation (<4%)

![Diagram of active target setup]

1 Fiber/1 Cube

- MIP yield
  - Light yield for 1 fiber in cube transverse to beam

![Histogram of MIP yield]

1 Fiber/1 Cube

- Light yield
  - 1 Fiber/1 Cube

![Histogram of light yield]

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