Physics and Performance of the Upgraded T2K's ND280

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The T2K Experiment

Physics Motivations
- Neutrino Oscillation Experiment
- Precise measurement of $\Delta m^2_{23}$, $\theta_{23}$
- Searching for the CP violation in the lepton sector ($\delta_{CP}$)
- Neutrino mass hierarchy

Scientific Instruments
- J-PARC Neutrino Beam
- Super-Kamiokande
- ND280, INGRID, Wagasci, Baby MIND

295 km

~ 600 MeV $\nu_\mu$ / anti-$\nu_\mu$ beam
T2K - Super-Kamiokande (SK)

Super-Kamiokande
A water Cherenkov detector.

- Excellent particle identification
- Excellent momentum reconstruction (through range)
- Interaction vertex reconstruction
- Track Multiplicity
- Particle range

Main Challenges
- Accumulation of statistics
- Good understanding of systematics
  - $\nu_\mu/\bar{\nu}_\mu$ flux
  - Neutrino-Nucleus Int. Models
- Near and far detectors
• Last publication shown the results with $3.1 \times 10^{21}$ POT
• Approx. 50% neutrino - 50% anti-neutrino
• 515 kW stable operation in 2019
  • + 33% of v-mode for next analysis
T2K - The Near Detectors

INGRID: On-axis

ND280: Off-axis

Wagasci/Baby MIND: Off-axis
**T2K - Off-axis ND280**

- ND280 detector provides:
  - 2 neutrino interaction targets: one with Carbon, one with Water (like SK)
  - 3 TPCs for particle tracking
  - 1 surrounding magnet which provide particle charge identification
- ND280’s role in T2K is to provide stringent constrains on the systematic parameters:
  - Events are gathered in samples by their topologies
  - Neutrino/Anti-Neutrino data are fitted with prior uncertainties

**X-sect parameters**

**Flux parameters**

**ND280 Fit**

**SK Fit**
• **\(\delta_{CP}\) measurement has been published** by the T2K collaboration on the 15th of April
  • “No CP violation” scenario excluded at C.L. ~ 2\(\sigma\)
  • Including reaction constrains (\(\theta_{13}\))

• **The next generation of experiments is willing to push the constrains further on** \(\delta_{CP}\)
Improving ν-Nucleus Interaction Models

- Main source of systematic uncertainties
  - Binding Energy ($E_b$)
  - Final State Interaction (with $\pi$ absorption)
  - $\nu_\mu$ 2p2h normalisation

- CCQE formulae for energy reconstruction of the neutrino does not work well for other components
- 2p2h component is not very well known: $2p2h/CCQE = 10\%-20\%$?
- We need to study with better precision the kinematics of outgoing particles in order to better constrain 2p2h in the fit

T2K Run 1-10 Preliminary

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Low energy recoil protons allow us to measure transverse momentum imbalance to access nuclear effects: Fermi momentum and re-interactions.

\[(p_\mu, \cos\theta_\mu) \rightarrow (\delta p_T, \delta\alpha_T, p_n \ldots)\]

- \(\delta p_T\) is almost a direct measurement of the Fermi momentum
- Measuring \(\delta p_T\) in bins of \(\delta\alpha_T\) may allow excellent separation of 2p2h and FSI (Final State Interactions)
The Upgrades of ND280: Super-FGD

- x2 in statistics for equal POT
- **Super-FGD**
  - Quasi-3D imaging
  - Improved tracking
  - Lower proton detection threshold
  - Neutron measurement capabilities
  - Time of Flight for background reduction
The Upgrades of ND280: HA-TPCs

- High Angle TPCs
  - Improved high angle acceptance
  - Better tracking capabilities

These upgrades are being constructed and will be installed at J-PARC in 2022.
• Very promising results:
  • 2p2h will be constrained to less than 5% (prior uncertainty is currently at 100%)
  • Binding Energy ($E_b$) parameter could be constrained at better than 1 MeV

• Next step is to include more systematics
  • Adding them to the simple fitter
  • Or using a more robust framework to imitate the fit
Conclusion

- We are now closing the measurement of the PMNS matrix.
  - Atmospheric angle close to maximal.
  - Rejected CP conservation ($\sin(\delta_{CP}) = 0$) @ 2σ C.L.
  - Mild preference for normal hierarchy.

- Today’s state of the art
  - Main systematics are from the beam modelling (improved with the NA61/SHINE hadron production experiment) and x-section modelling.
  - T2K made a great job to reduce x-sec uncertainties to ~3%.
  - To reduce even further the x-sec uncertainties an upgrade is being constructed.
  - T2K measurements are important for HK, DUNE, NOvA and atmospheric neutrino oscillations.

- Heading toward 3σ sensitivity on $\delta_{CP}$
  - Several key-instruments are being upgraded: beam/far-detector/near-detectors
  - ND280 will provide a major role for understanding neutrino-nucleus models uncertainties
  - Especially thanks to 2 new integrated detectors: HA-TPC and Super-FGD
  - Will be able to measure hadrons kinematic along with the outgoing lepton
  - It will allow to take advantage of the transverse kinematic imbalance to provide new stringent constrains on each systematic parameters and models

- Upgraded ND280 will be an essential part of the Hyper-Kamiokande Near Detector complex
Questions