Joint $\nu_\mu/\bar{\nu}_\mu$ Cross Section Measurement on Carbon in the T2K Near Detectors

09.Sep.2020

Zurich PhD Seminar 2020

Outline

- Introduction
- The T2K Experiment
- My Analysis
- Event Selection
- Outlook

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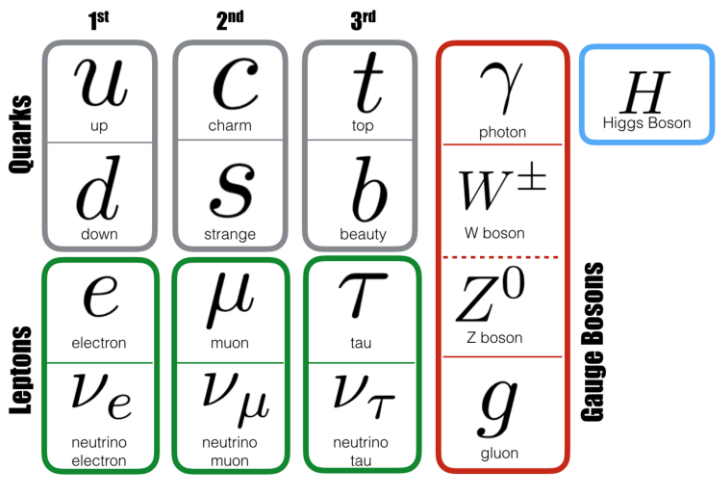
Neutrinos

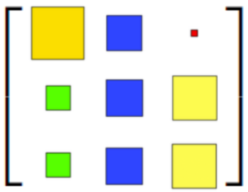


- Particles of extremes:
  - Extremely light: $m_\nu < 1\, eV$
  - Extremely abundant in the Universe: $\rho_\nu > 10^8\, m^{-3}$
  - Extremely weak interaction with matter: $\frac{\sigma}{E_\nu\, nucleon} \sim 10^{-38} \frac{cm^2}{GeV}$
- Why study neutrinos?
  - Neutrino oscillations only possible with nonzero mass
    - First evidence of physics beyond the Standard Model
  - Possible Charge-Parity Violation in the lepton sector
    - Might explain matter-antimatter asymmetry in the universe

Neutrino Oscillations

- Neutrinos have 2 sets of eigenstates:
  - Flavor → Interaction
  - Mass → Propagation
- These are related through the PMNS matrix:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} =$$



$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Oscillations can be described with 6 parameters:
  - 3 angles: $\theta_{12}, \theta_{13}, \theta_{23}$
  - 2 mass differences: $\Delta m^2_{21}, \Delta m^2_{32}$
  - 1 CP violating phase: δ_{CP}

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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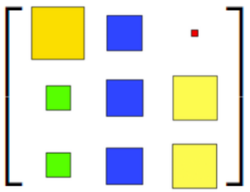


$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Oscillations can be described with 6 parameters:
  - 3 angles: $\theta_{12}, \theta_{13}, \theta_{23}$
  - 2 mass differences: $\Delta m^2_{21}, \Delta m^2_{32}$ Sign still unknown
  - 1 CP violating phase: δ_{CP} Value still unknown

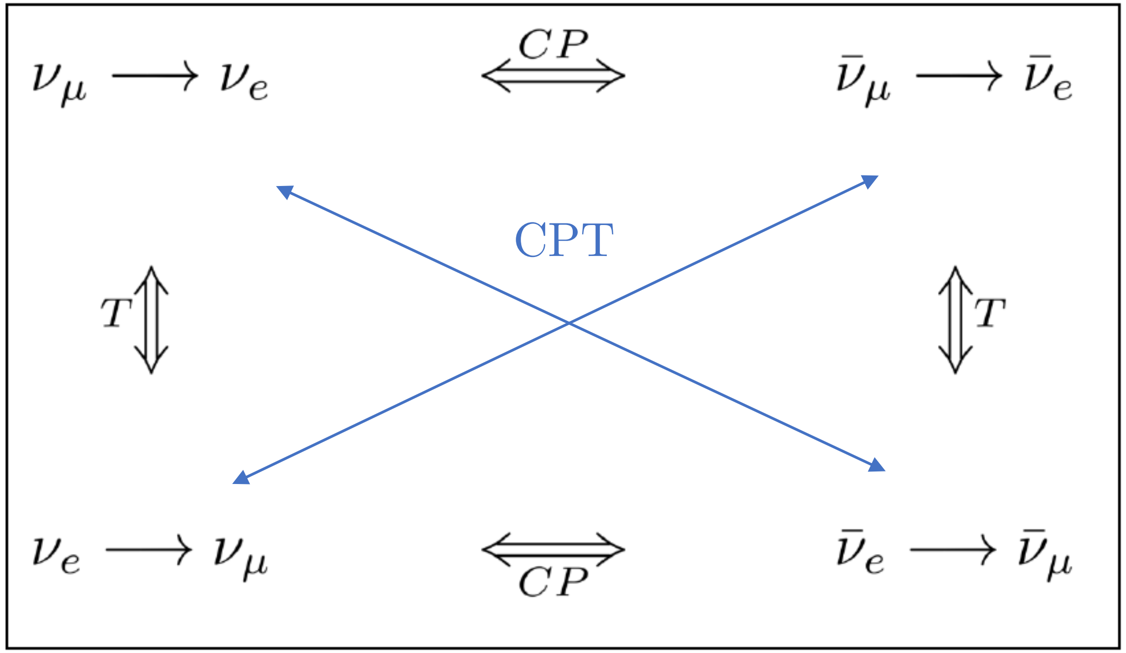
$c_{ij} = \cos\theta_{ij}$

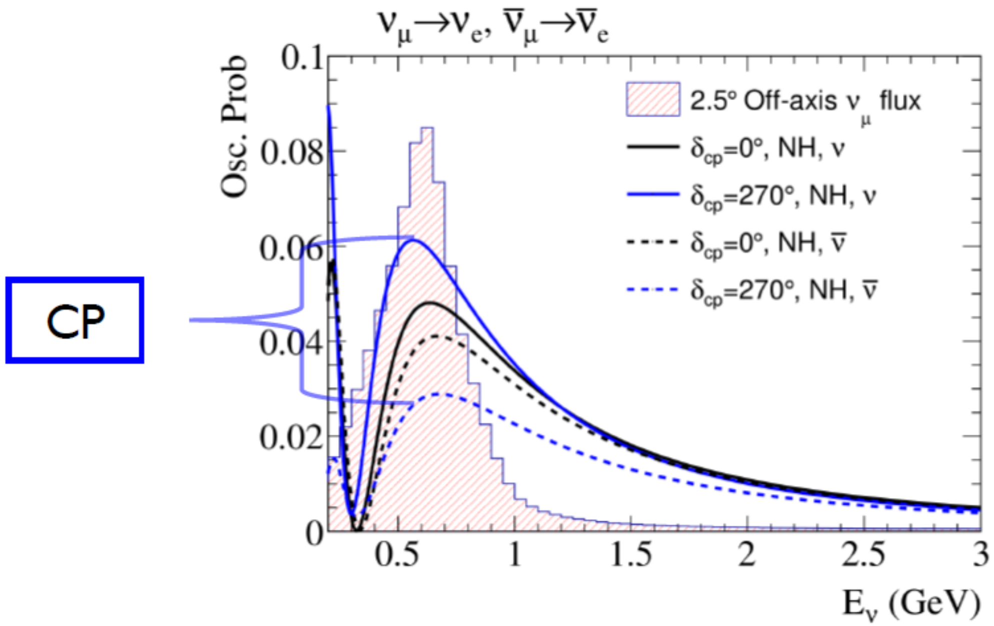
$s_{ij} = \sin\theta_{ij}$

$\Delta m^2_{ij} = m_i^2 - m_j^2$

CP Violation

- δ_{CP} unknown: Possibility of CP violation in the lepton sector
  - Preference for nonzero value
- $\delta_{CP} \neq 0, \pi \Rightarrow$ Difference in oscillation probabilities between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





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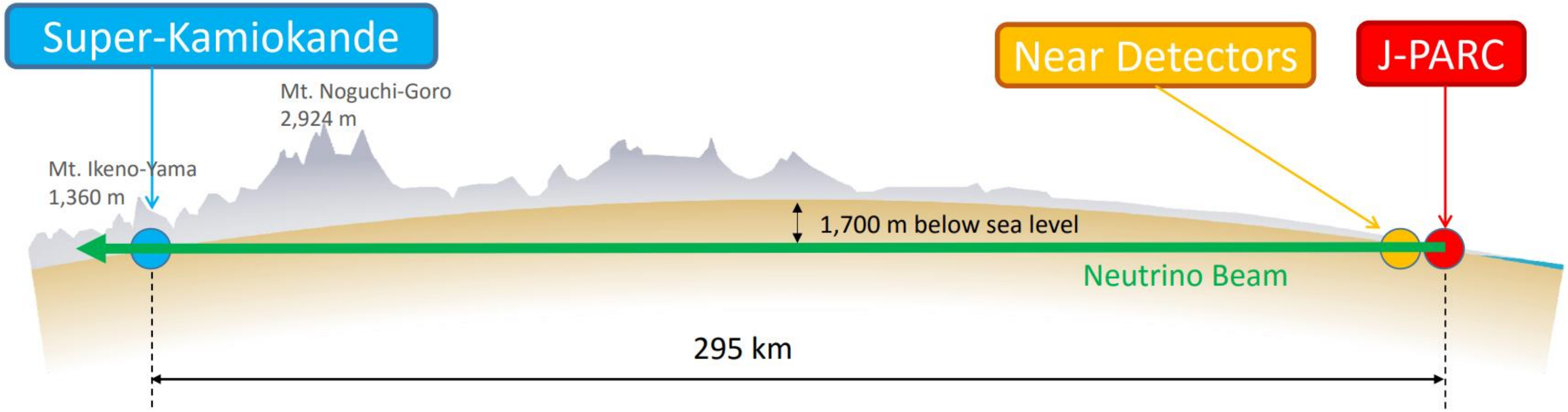
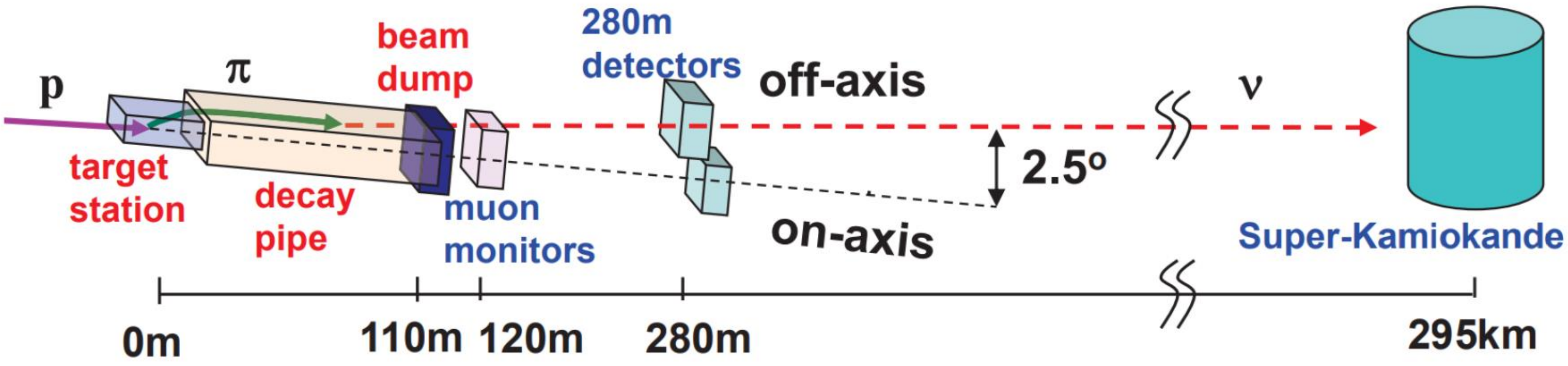
The T2K Experiment

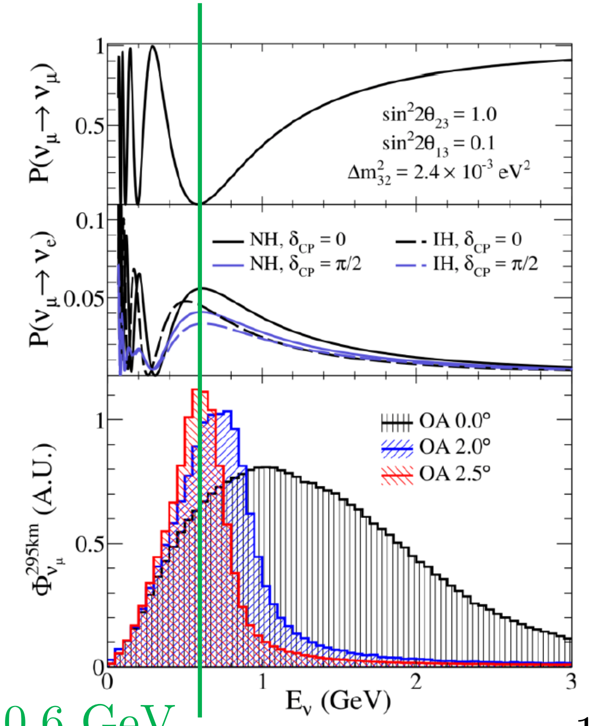
- Long baseline neutrino oscillation experiment
- J-PARC: Production of high intensity $\nu_\mu/\bar{\nu}_\mu$ beam
- Near Detectors: Measure unoscillated spectrum
- Far Detector: Measure oscillated spectrum
- Main Goals: Measure the oscillation parameters $\theta_{23}, \theta_{13}, \Delta m^2_{32}, \delta_{CP}$



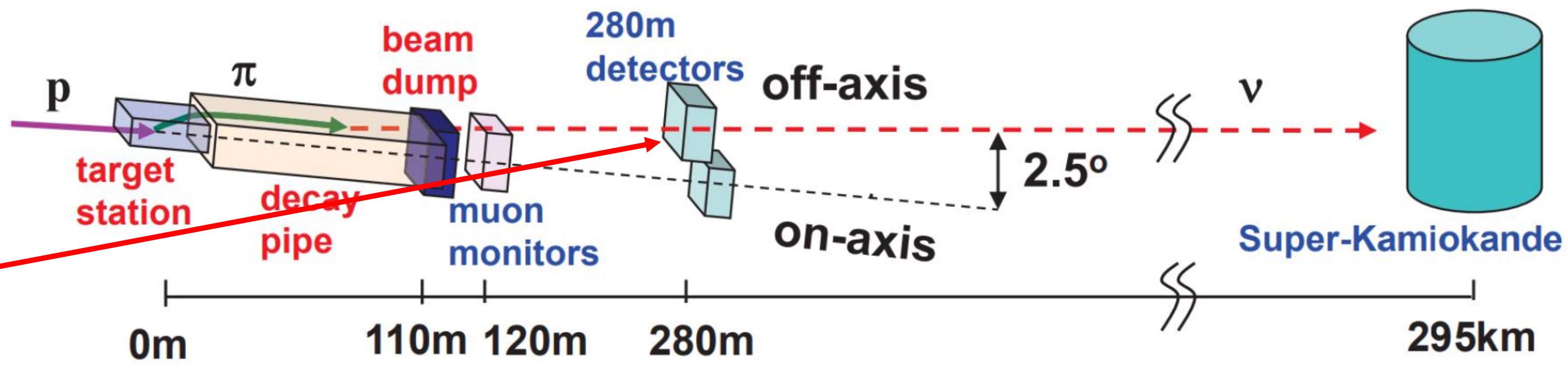
Creating a Neutrino Beam

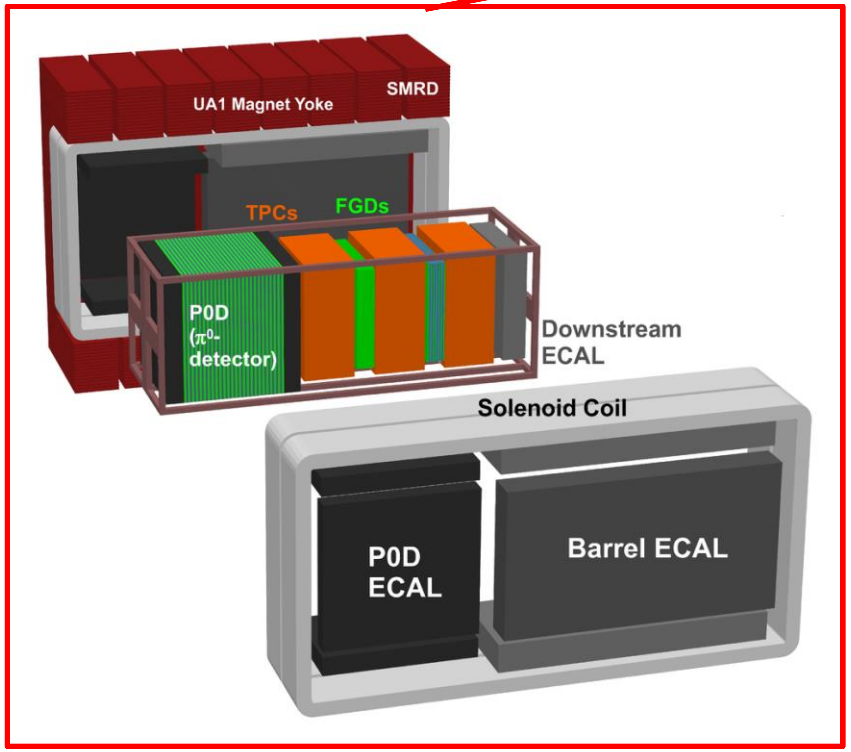


- 30 GeV protons collide with carbon target and produce pions
- Magnetic horns can focus either positive or negative pions
  - 2 different beam modes
- $\pi^+ \rightarrow \mu^+ + \nu_\mu, \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- All particles except neutrinos stopped in beam dump
- Use off-axis beam for narrower energy spectrum
  - Centered at oscillation maximum of 0.6 GeV

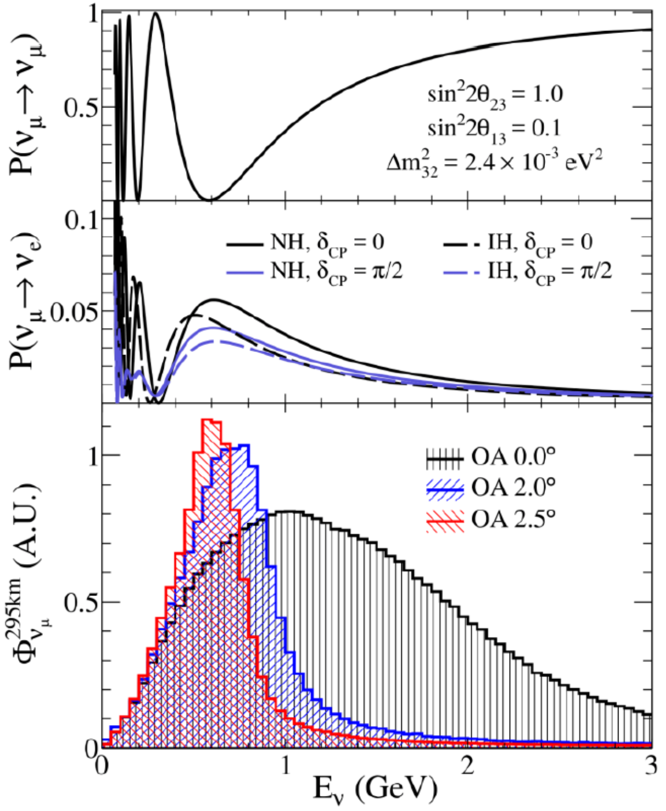


Near Detectors

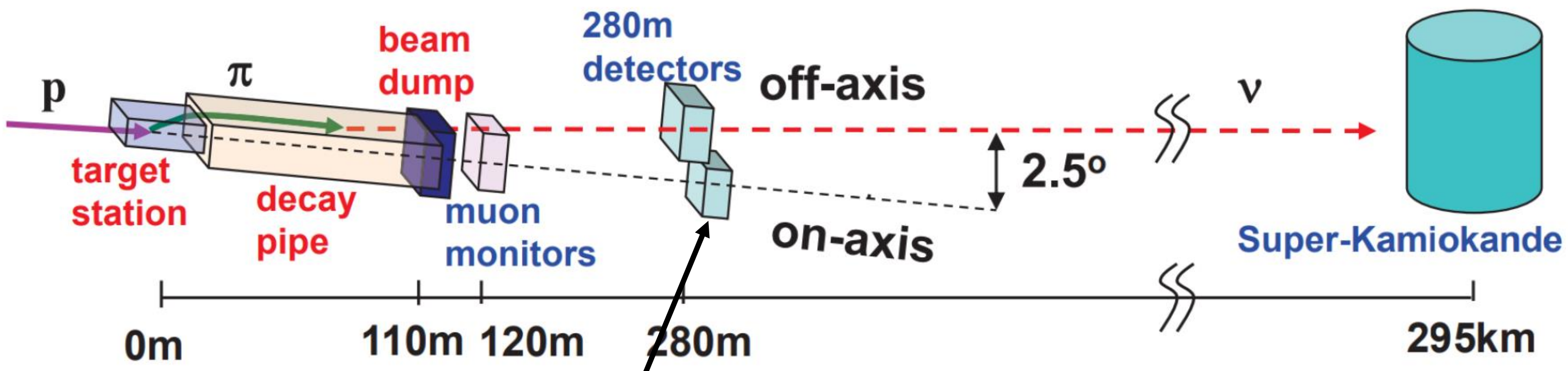




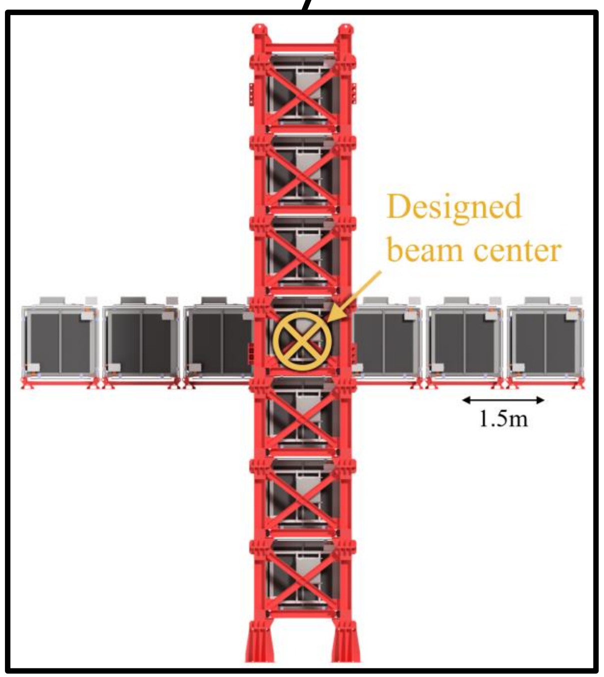
- ND280: the off-axis near detector
- Situated 280 m from the target station
- Fully magnetized detector
  - Can differentiate between $\nu/\bar{\nu}$
- 2 fine-grained detectors (FGDs) act as target for neutrinos
- 3 argon time projection chambers (TPCs) act as tracker and measure particle momentum and charge
- Detector is encased in electromagnetic calorimeters (ECALs)
- Goals: Measure unoscillated neutrino spectrum and neutrino-nucleus cross sections

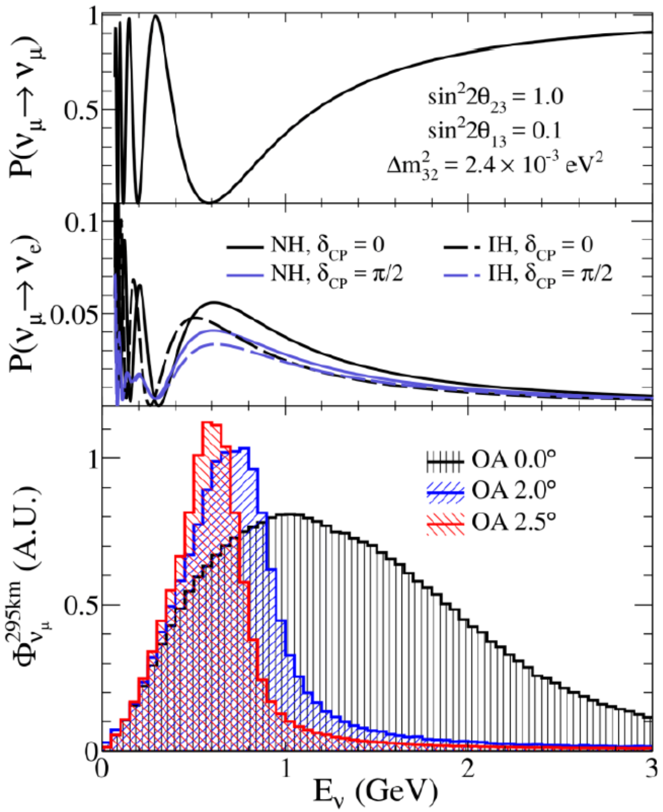


Near Detectors

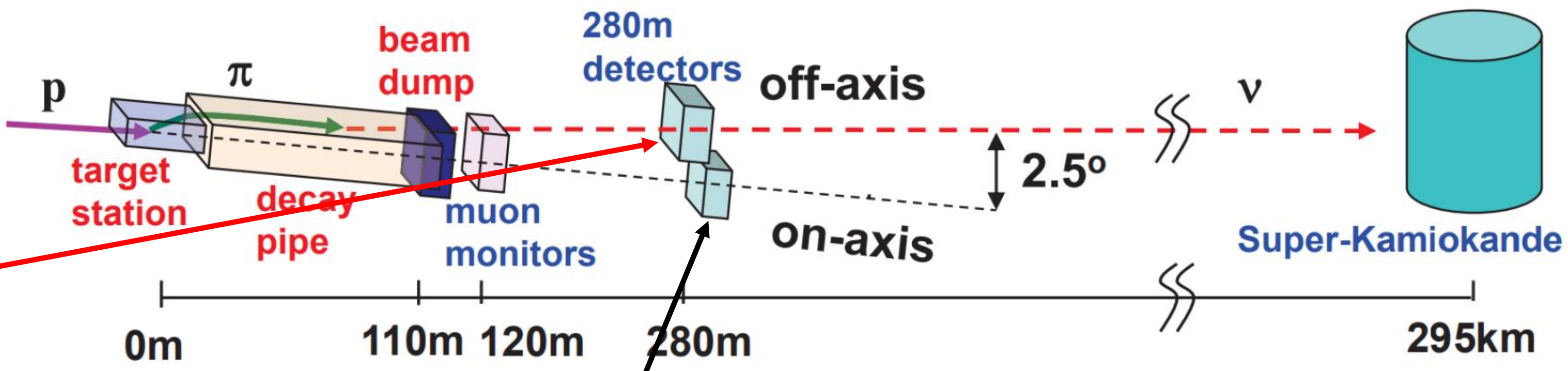


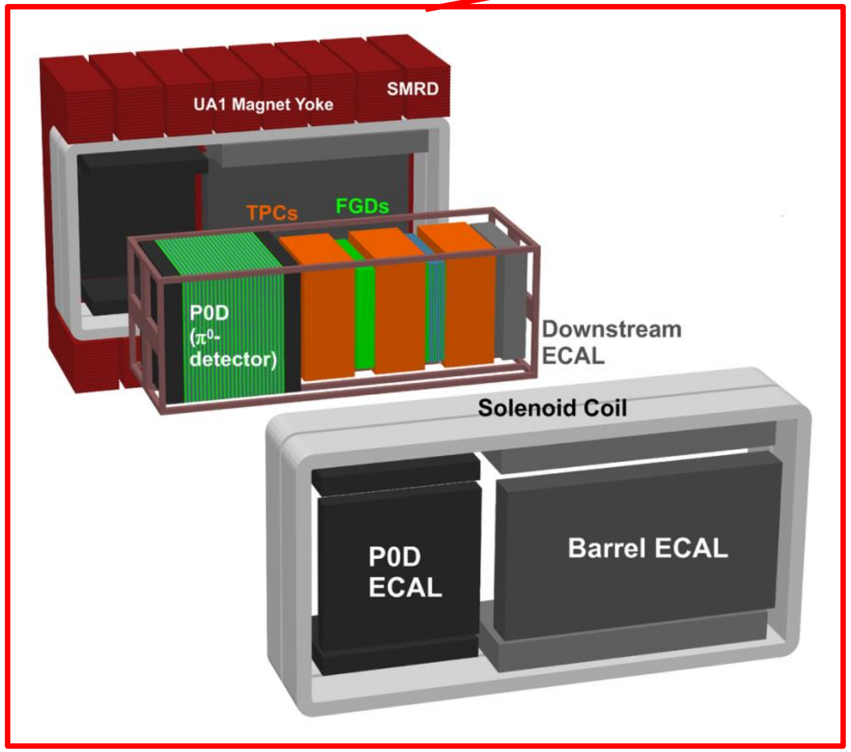
- INGRID: the on-axis detector
- Consists of 16 identical modules arranged in a cross
- Each module consists of sandwiched iron plates and tracking scintillator plates
- Goals: measure neutrino beam profile and neutrino-nucleus cross sections

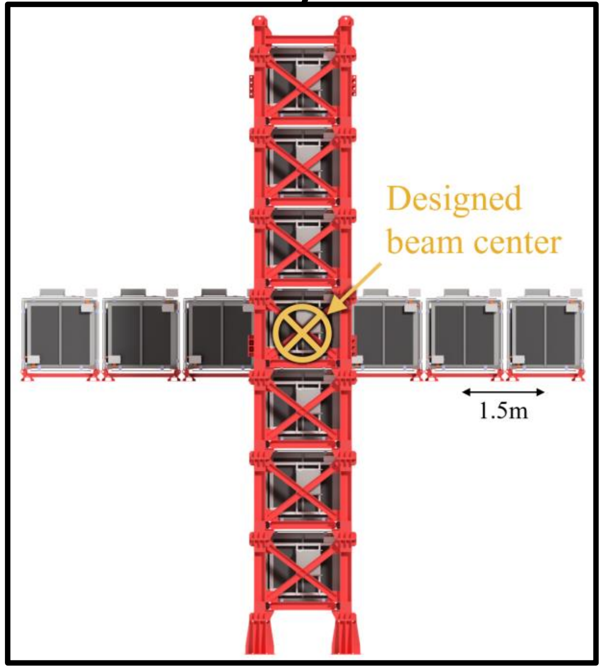


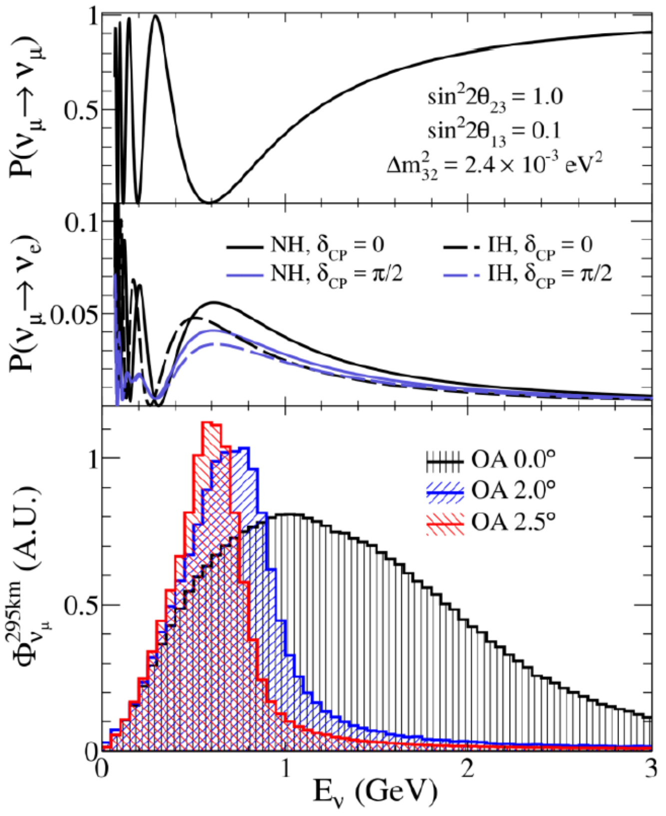


Near Detectors

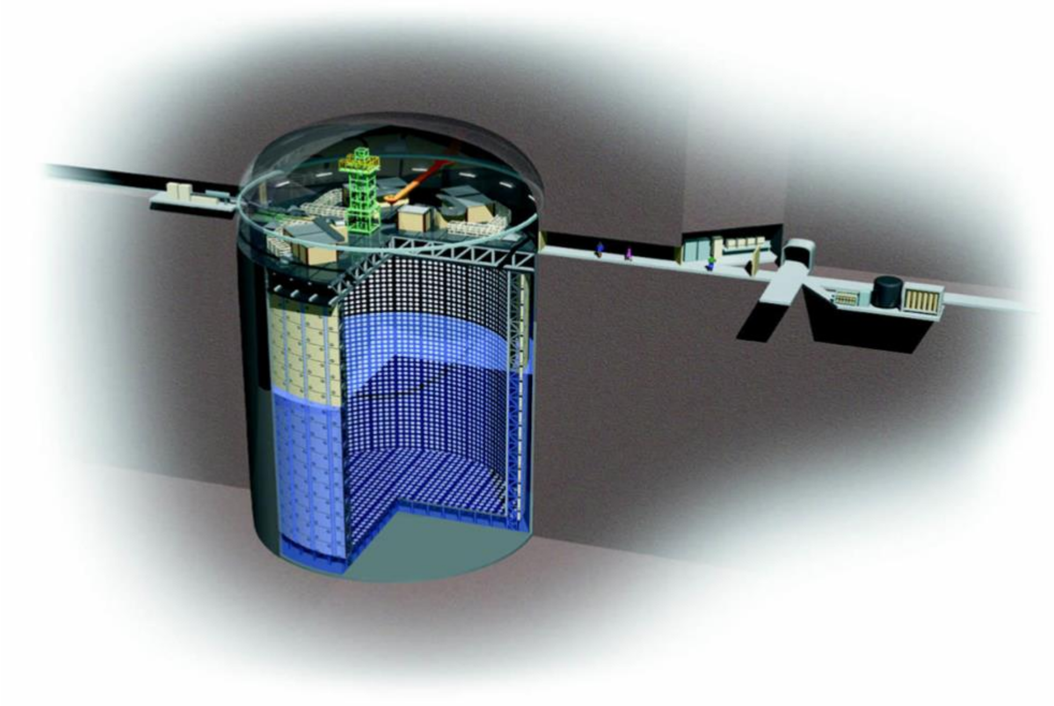




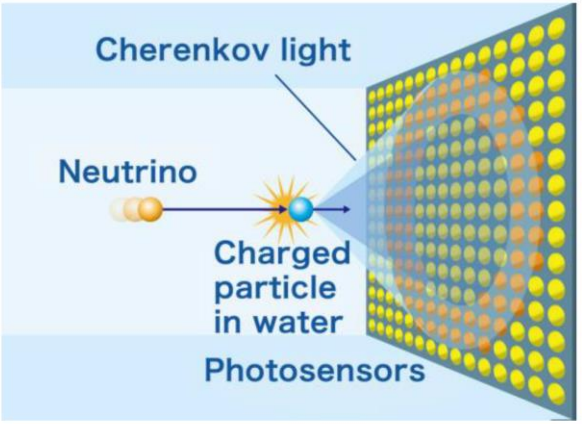


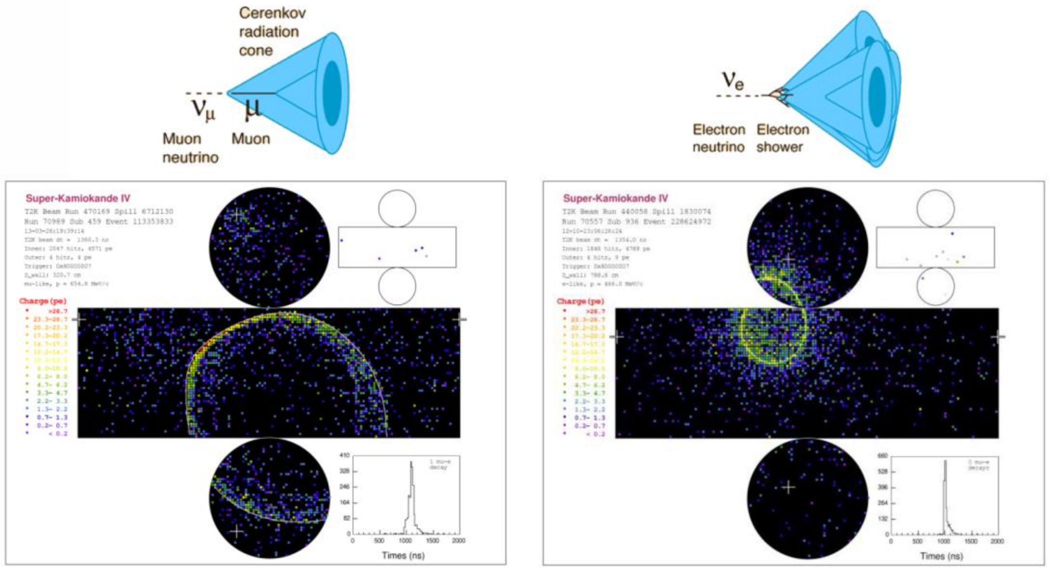


Far Detector: Super-Kamiokande

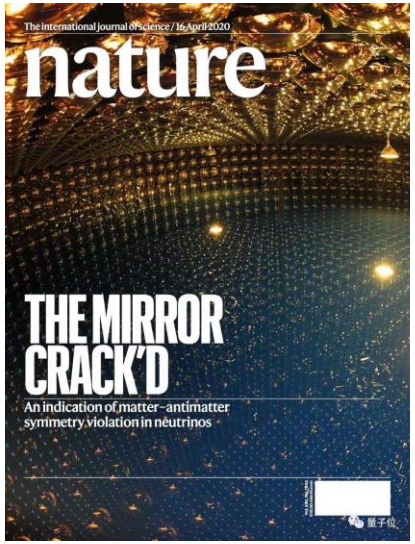


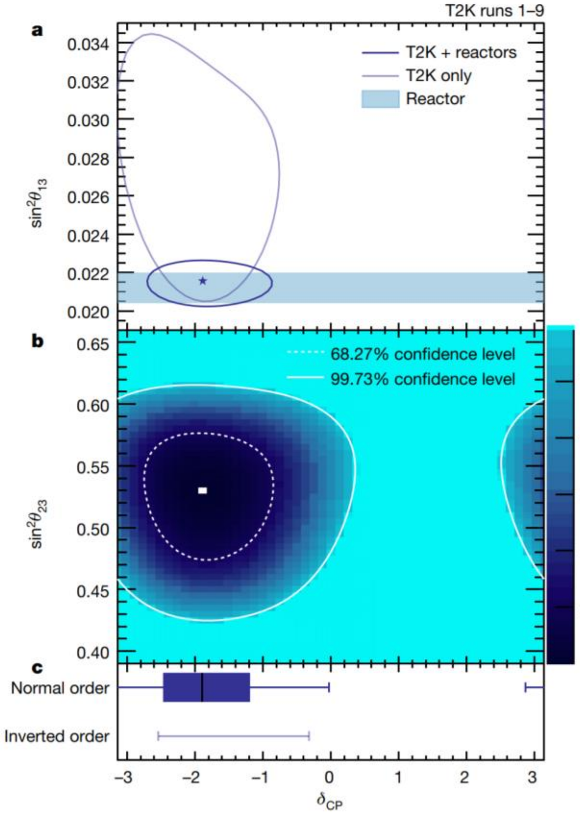
- 50 kiloton water Cherenkov detector
- under 1 km of screening rocks
- ν_μ, ν_e interact with water thus producing μ^-, e^-
- Cherenkov radiation is detected by the 11000 PMTs
- Muons produce sharp rings
- Electrons scatter more → "fuzzier" rings





Far Detector: Super-Kamiokande
Latest Results





- δ_{CP} conserving values excluded at 3σ
- Cross section uncertainties constitute major systematic errors in neutrino oscillation measurements
- These will only become more pronounced as we collect more data

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

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- Joint $\nu_\mu/\bar{\nu}_\mu$ charged current cross section measurement on carbon
- With zero pions in the final state
- Using the two T2K near detectors: on- and off-axis

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- Why?
  - Neutrino physics is entering high precision era
  - Oscillation parameter uncertainty is becoming dominated by systematic errors
    - Cross section uncertainty being a major one
  - Just collecting more data will not help in the future
  - Good neutrino interaction model is essential to reduce systematics
    - near/far detectors have different target, acceptance, flux

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- Using the two T2K near detectors: on- and off-axis

- $\nu_\mu/\bar{\nu}_\mu$ cross sections differ by sign of axial-vector interference term
- Multinucleon excitations enter in this term
  - These can be tested by taking the difference between ν and $\bar{\nu}$ cross sections
- CP violation analyses measure the asymmetry between $\nu/\bar{\nu}$ oscillation rates
  - Important to consider neutrino-nucleus interaction asymmetry

$$\begin{aligned}\frac{d^2\sigma}{d\cos\theta d\omega} &= \frac{G_F^2\cos^2\theta_c}{\pi}|\mathbf{k}'|E_l'\cos^2\frac{\theta}{2}\left[\frac{(\mathbf{q}^2-\omega^2)^2}{\mathbf{q}^4}G_E^2 R_\tau(\mathbf{q},\omega)\right.\\ &+ \frac{\omega^2}{\mathbf{q}^2}G_A^2 R_{\sigma\tau(L)}(\mathbf{q},\omega)\\ &+ 2\left(\tan^2\frac{\theta}{2}+\frac{\mathbf{q}^2-\omega^2}{2\mathbf{q}^2}\right)\left(G_M^2\frac{\mathbf{q}^2}{4M_N^2}+G_A^2\right)R_{\sigma\tau(T)}(\mathbf{q},\omega)\\ &\left.\pm 2\frac{E_\nu+E_l'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}(\mathbf{q},\omega)\right]\end{aligned}$$

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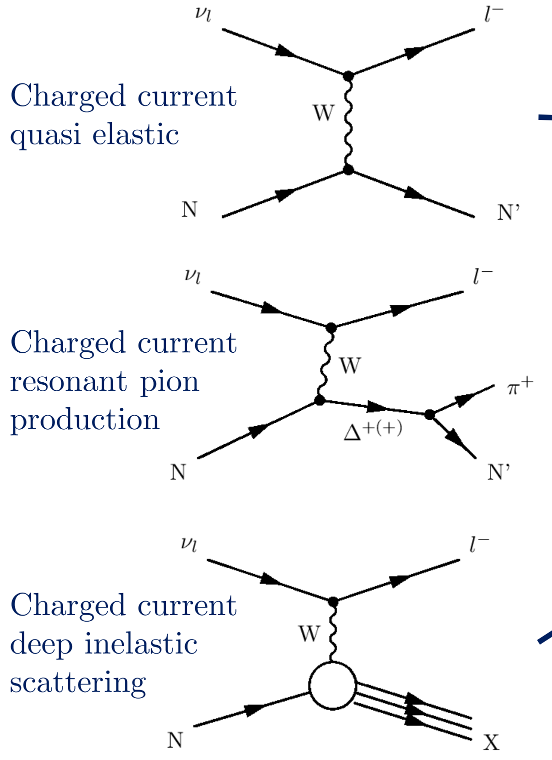
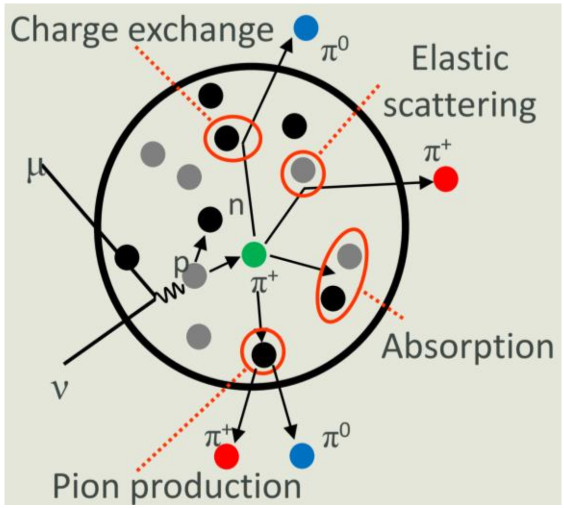
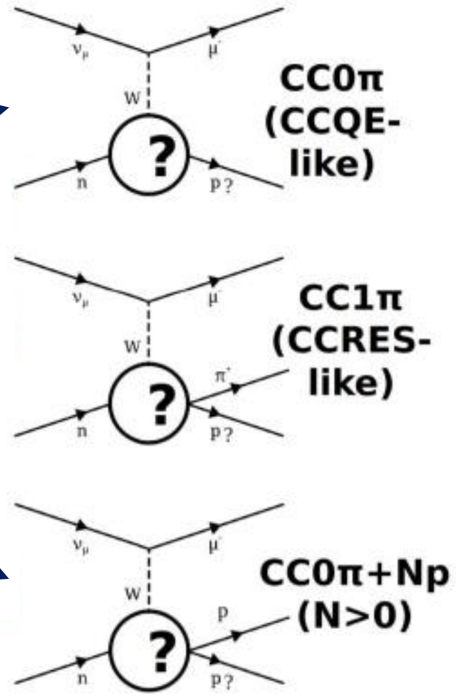
Interaction Modes





Interaction Topologies



- Several neutrino-nucleus interactions are possible
- Observed final state event topologies will be complicated mixture thereof after nuclear effects and final state interactions occurred
- Need model independent samples using final state signals:
  - CC0pi: 1 muon, 0 pions. Most CCQE-like signal
    - Most important channel for T2K

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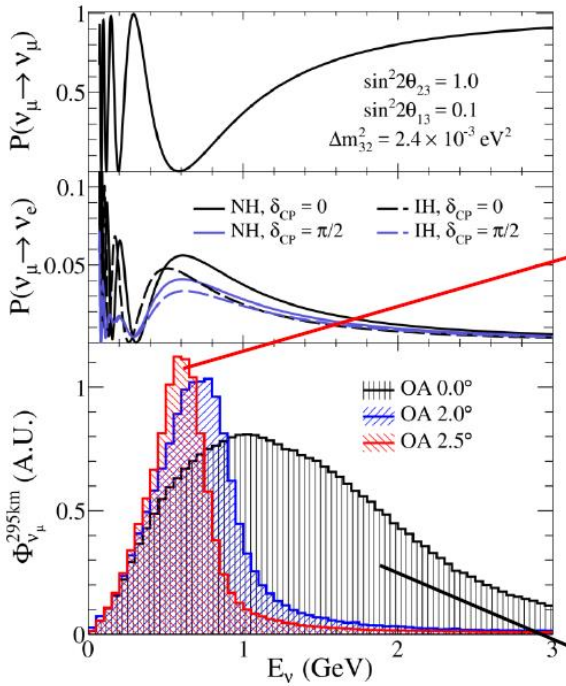

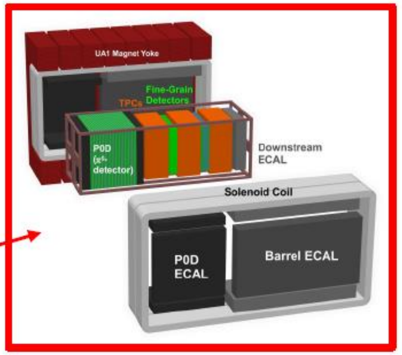

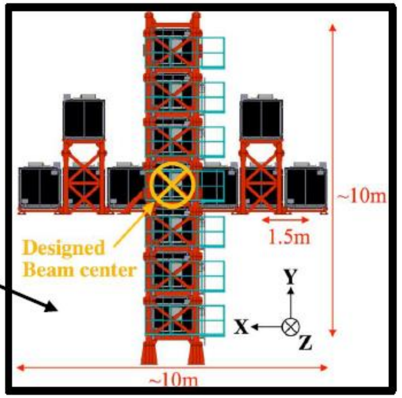

- Study neutrino cross sections as a function of energy
- Measured ν interaction rate is product of flux and cross sections → Degeneracy
- Difference in flux at the 2 near detectors can break this degeneracy
- Fluxes between detectors are correlated, leading to a reduction of the flux uncertainty in the analysis
- Important step towards planned future multi-axis measurements with DUNE, Hyper-K

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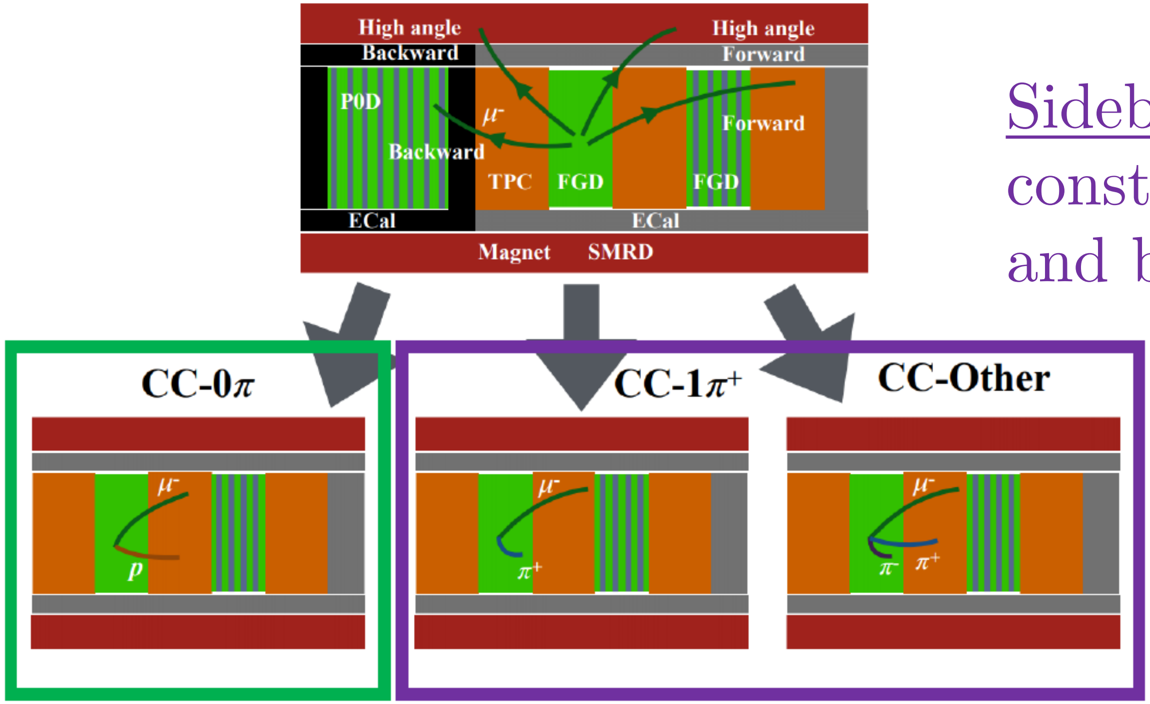
Event Selection

- Strategy: define multiple samples and bin the events in outgoing muon momentum and angle

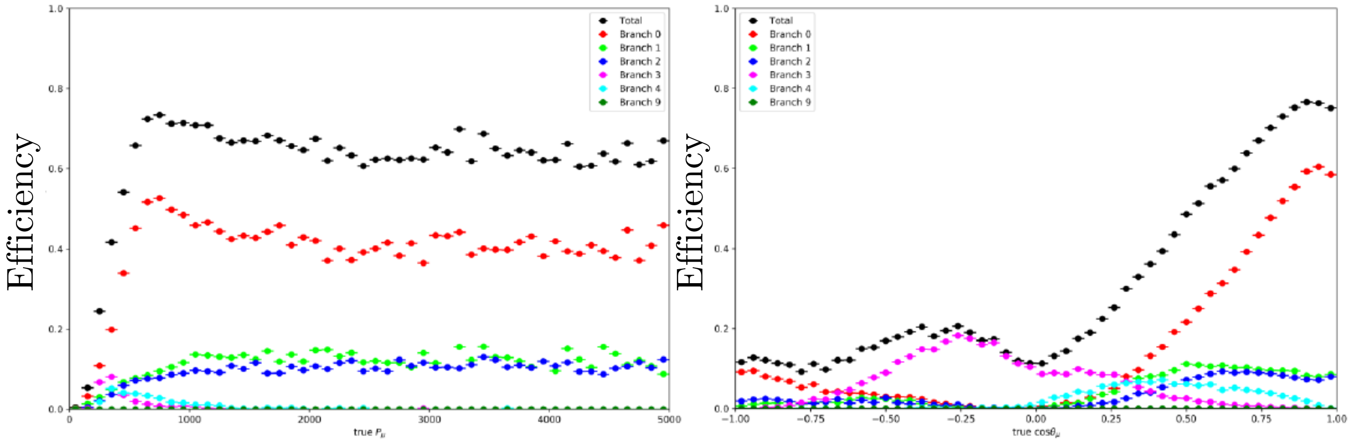
Signal

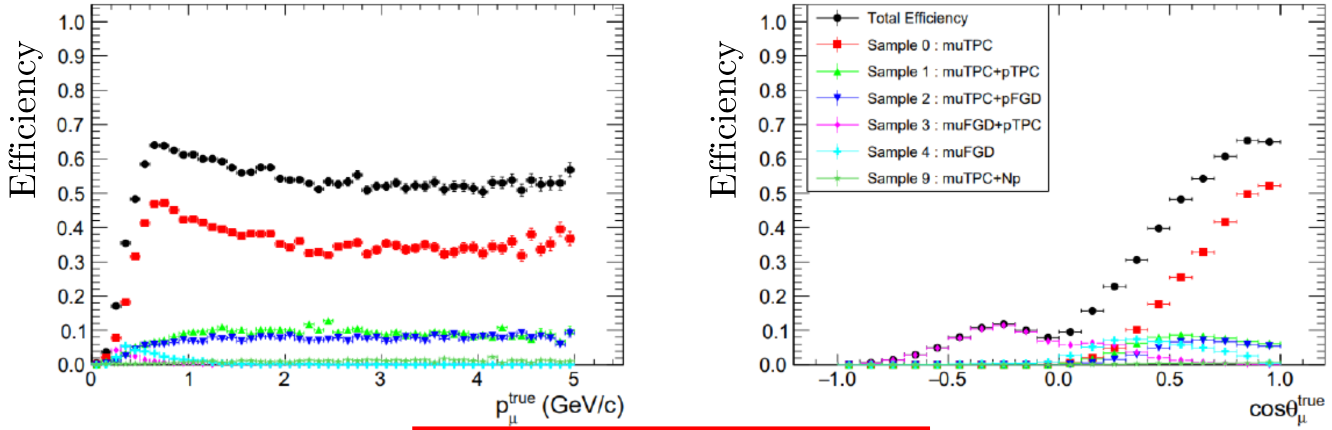


Sidebands: used to constrain fit parameters and break degeneracies

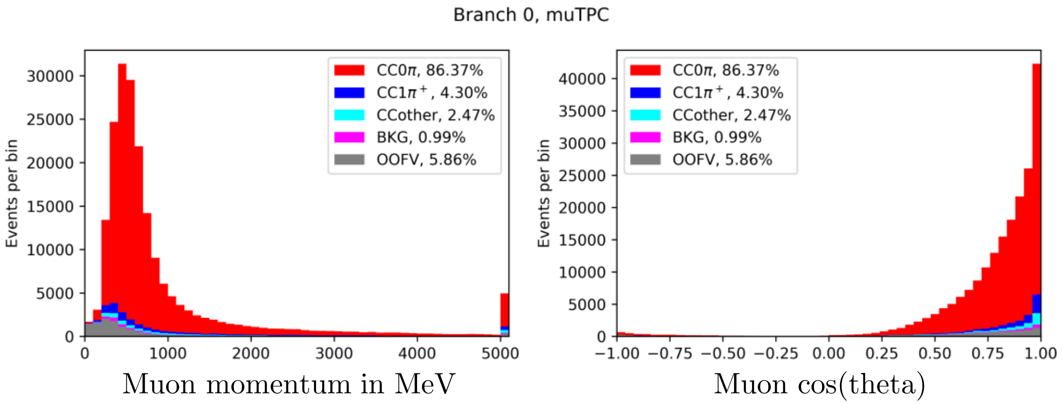
Event Selection - Improvements

New selection





Previous selection



- Very similar purity for previous and improved selection
- But efficiency is greatly improved for high angle and backwards going tracks

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Outlook

- After events are selected, the cross section can be extracted
- Method: perform maximum-likelihood fit to unfold into truth space
  - Additional fit parameters: flux, detector model, cross section model
- Challenge: avoid overfitting
  - Highly correlated parameters work in our favor
  - Novel flux correlation framework has been developed
- New model independent fitting techniques have been produced

Summary

- Cross section measurements play important role in reducing systematic errors in neutrino oscillation measurements
  - $\nu/\bar{\nu}$ interaction asymmetry important for CP violation measurements
- Joint measurements can break degeneracies
- Significant selection improvements have been achieved
- My analysis will measure the energy dependence of CC0Pi cross sections
- Allows to discriminate between different theoretical models
- Stay tuned for a novel cross section measurement from T2K