Measuring The $\bar{\nu}_\mu$-induced Charged-Current Coherent Pion Production Cross Section Using The T2K Near Detector ND280

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Overview

- What is the T2K experiment?
- How do neutrinos interact?
- What is neutrino coherent pion production?
- How to measure neutrino coherent pion production?
  - What is the selection?
  - How to remove the background events?
  - How to extract cross-section measurement?
The T2K Experiment

- What are neutrinos?
  - The most abundant massive particles that rarely interact
  - Neutrinos can also change identities while they propagate through space (neutrino oscillation)
- The Tokai-to-Kamioka (T2K) experiment is a long baseline neutrino oscillation experiment (See M. Hartz’s talk R2-10 Thursday @ 13:15)
  - Muon (anti)neutrinos are produced by the J-PARC proton accelerator facility
  - The near detector complex measures (un-oscillated) muon neutrino properties
  - The far detector Super-Kamiokande (SK) measures the appearance of electron neutrinos (neutrino oscillation)
- T2K provides rich neutrino interaction programs at its near detector (this talk)
  - To understand neutrino interactions
T2K Off-axis Near Detector ND280

- Magnet
  - All the detector components are surrounded a magnet (0.2 T)
- P0D
  - Dedicated $\pi^0$ detector
  - Provide $\pi^0$ background constraints on Oxygen for Super-K (main background)
- TPC
  - 3 time projection chambers (Argon gas)
  - Momentum reconstruction (track curvature)
  - Particle identification (dE/dx)
- FGD
  - 2 fine-grained detectors
  - Carbon and Oxygen target mass
  - FGD1: plastic scintillator layers
  - FGD2: alternating plastic and water layers
  - Also provide particle identification for stopped particle tracks
- ECal
  - Various Electromagnetic Calorimeters (ECal) detectors surrounding
  - Reconstruction of neutral particles (i.e. photons)
Neutrino interactions

- Neutrinos (anti-neutrinos) can only interact via weak interactions
  - Neutral-current (NC) mediated by the $Z^0$ boson
  - Charged-current (CC) mediated by the $W^\pm$ boson
- CC and NC interactions can be subcategorized based on the outgoing particles of the interactions
  - e.g. a neutrino interaction with a nucleon producing an outgoing charged lepton is called Charged-Current Quasi-Elastic (CCQE) scattering

![Diagram of neutrino interactions](https://via.placeholder.com/150)

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Anti-neutrino coherent pion production

- Neutrino (anti-neutrino) coherent pion production
  - A neutrino scatters off an entire nucleus
  - Produces 1 lepton and 1 pion
    - Small angle w.r.t. neutrino direction
    - no fragmentation of the nucleus
    - small four-momentum transfer
- Neutrino coherent pion production
  - NC-coherent (NC-COH) has an outgoing $\pi^0$
  - CC-coherent (CC-COH) has an outgoing $\pi^-$
- Why do we care about such an interaction?
  - This is not well understood theoretically - interesting measurement
  - $\pi^0$ from NC-COH can also mimic electron neutrino appearance in the T2K oscillation analysis
    - 3% of the electron neutrino background
    - 30%-100% COH model uncertainty
- Measurements of NC-COH and CC-COH would help to constrain the physics model used in neutrino interaction generators
  - Underlying physics model for NC-COH and CC-COH are the same
Neutrino Coherent Pion Production Models

- Wildly varying predictions for different models
- Rein and Sehgal (1983, 2007)
  - Partially conservation of the axial current (PCAC)
- Berger and Sehgal (2009)
  - PCAC
  - External pion-carbon scattering data
- Alvarez-Ruso (2007)
  - Microscopic
  - Nucleon level process

- Pions are produced from (virtual) Δ resonances or N*
- Nucleon must remain in the same quantum state
Current Status of CC-COH Measurements

- $\nu_\mu$ CC-coherent $\pi^+$ on C12
  - Has been observed by MINERvA with mean neutrino energy from 2 GeV
  - Not observed by SciBooNe (1.1 GeV and 2.2 GeV) and K2K (1.3 GeV)
    - upper limits for cross section set
  - T2K (0.6 GeV) measures CC-coherent $\pi^+$ on C12 for the first time
- $\bar{\nu}_\mu$ CC-coherent $\pi^-$ on C12
  - Not observed yet at sub-GeV region
  - T2K has collected roughly equal neutrino and anti-neutrino data
  - An observation of the process at sub-GeV region is possible (this talk)
Analysis Strategy

- Physics goal: CC-COH cross section
  - Dependent on resonant pion production (RES) background modelling
  - Dependent on the detector modelling of FGD reconstruction
- T2K is trying to promote more model independent cross-section measurements
  - The background can be measured together with the signal
  - Introducing a new topology for a double differential cross-section measurement
- Topology definition
  - CC1Pi-0rP
  - Signal: CC-COH, or CC-RES with no reconstructable protons
    - FGD has low proton reconstruction efficiency below 450 MeV/c
    - These signals can be calculated and compared to by theorists
- Extract (model dependent) CC-COH cross section from the CC1Pi-0rP result
  - Can switch to different RES and COH models for additional (model dependent) CC-COH cross sections
CC1Pi-0rP Topology Selection

• Selection Step
  1. Highest momentum particle in an event to be positively charged and μ-like (particle likelihood based on dE/dx in TPC)
  2. Additional negatively charged π-like (and not proton-like) particle
  3. Exactly 2 FGD1 particle tracks
     • CC1Pi-0rP should have only 2 outgoing particles reconstructed
CC1Pi-0rP Topology Selection

1. Positively charged $\mu$-like track - selects all the $\bar{\nu}_\mu$ CC interaction events

2. Additional negatively charged $\pi$-like track - removes most CCQE background events

3. Exactly 2 FGD1 particle tracks requirement - removes DIS or RES background events with reconstructed protons

Selected CC1Pi-0rP Events
CC-COH Event Selection

- Characteristics of coherent events
  - Low energy deposition (vertex activity) around the neutrino interaction vertex
  - Low four momentum transfer to the nucleus

![Graph 1: Vertex Activity VA [PEU]](image1)

![Graph 2: Momentum Transferred Square $|t|$ [GeV$^2$]](image2)
Cross-section Likelihood Fitter

- Cross section
  - Likelihood of two particles to interact under certain conditions
    \[ \sigma = \frac{N_{\text{event}}}{\varepsilon \cdot T \cdot \Phi} \]
    - \( N_{\text{event}} \): measured number of events, \( \varepsilon \): efficiency of the selection, \( T \): number of target nucleus, \( \Phi \): number of incident neutrino

- Likelihood fitter
  - Finds the best fit value of measured number of events with a binned likelihood fit
  - Adjust simulation prediction to data (best fit)
  - Maximize (log)likelihood: minimizes the chi-square
    \[ \chi^2 = \chi^2_{\text{stat.}} + \chi^2_{\text{syst.}} = -2\ln L_{\text{stat.}} - 2\ln L_{\text{syst.}} \]

**SELECTION**

- Selected Events (Data)
- Selected Events (Simulation)

**SYSTEMATIC UNCERTAINTIES**

- Detector Systematics Covariance
- Neutrino Flux Covariance
- Cross-section Model Covariance

**Best fit result of measured number of events (with stat. and syst. uncertainties)**
Cross-section Likelihood Fitter

- Likelihood fitter adjusts parameters (analysis bins, other variables such as detector systematics, cross-section models) in the true distribution, to achieve best fit (to the data) in the reconstructed distribution.

Example: increasing one bin in $|t|$ by 50% Notice multiple bins in the reco. dist. are affected
Analysis Status and Outlook

- **Selected Events (Data)**
- **Selected Events (Simulation)**
- **Detector Systematics Covariance**
- **Neutrino Flux Covariance**
- **Cross-section Model Covariance**

**Next Steps**
- Expect analysis to be finalized by end of July
- Reveal real data and extract cross sections afterwards
- Aiming to have results (paper) by the end of the year

**Best fit result of measured number of events (with stat. and syst. uncertainties)**
Back up
Motivations for measuring coherent pion production

- **Measurements** of NC-COH and CC-COH would help to **constrain the physics model** used in neutrino interaction generators
  - Underlying physics model for NC-COH and CC-COH are the same
- **NC-coherent π⁰**
  - π⁰ production is the **main background** to the water Cherenkov detector (such as SK) detecting appearance of νₑ (neutrino oscillation)
  - π⁰ can be confused with an electron in water Cherenkov detectors
    - The π⁰ decay is **asymmetric** resulting one low energy photon, thus not reconstructed
    - The two photons would be **boosted in the π⁰ direction**, causing the rings to overlap with each other

Images: G. D. Lopez

T2K simulated νₑ selection energy distribution at SK

- mainly π⁰ background
- νₑ signal

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Images: G. D. Lopez

Thesis (2012)
Motivations for measuring coherent pion production

• NC-COH is a 3% background to the electron neutrino appearance measurement

• 30% uncertainty assigned to NC-COH
• Muon ring: sharp
• Electron ring: fuzzy
• Neutral pion ring: stacked 2 electron rings, can mimic electron signal if one is not reconstructed

Images: Z. Vallari
Thesis (2018)
SK Event Displays

**Super-Kamiokande IV**
Run 9999999 Sub 1 Event 68
16-03-10:18:48:25
Inner: 1325 hits, 2218 pe
Outer: 6 hits, 4 pe
Trigger: 0x07
D_wall: 351.3 cm
Evis: 179.6 MeV
e-like, p = 179.6 MeV/c

**Charge(pe)**
- >26.7
- 23.3–26.7
- 20.2–23.3
- 17.3–20.2
- 14.7–17.3
- 12.2–14.7
- 10.0–12.2
- 8.0–10.0
- 6.2–8.0
- 4.7–6.2
- 3.3–4.7
- 2.2–3.3
- 1.3–2.2
- 0.7–1.3
- 0.2–0.7
- < 0.2

- **MC**
- Asymmetric $\pi^0$ decay
- 1 photon reconstructed as electron
Neutrino coherent pion production

- Neutrino (anti-neutrino) coherent scattering
  - A neutrino scatters off an entire nucleus
  - nucleus unchanged, cannot be excited
    - no quantum number exchange
  - no fragmentation of the nucleus
    - small four-momentum transfer
  - outgoing lepton and pion has small angle w.r.t. neutrino direction
- Neutrino coherent pion production
  - NC-coherent (NC-COH) has an outgoing $\pi^0$
  - CC-coherent (CC-COH) has an outgoing $\pi^-$
- Modeling
  - Rein and Sehgal (1983, 2007)
    - Partially conservation of the axial current (PCAC)
  - Berger and Sehgal (2009)
    - PCAC
  - Alvarez-Ruso (2007)
    - Microscopic
CVC and PCAC Hypothesis

• Weak interactions are experimentally determined to have the form of Vector – Axial-Vector (V-A)

\[ j^\mu = \bar{u}_e (\gamma^\mu - \gamma^\mu \gamma^5) u_e \]

Vector  Axial-Vector

• In pure vector, or axial-vector interactions parity is conserved
• Weak interactions do not conserve parity due to the linear combination of vector and axial-vector
  • \( \gamma^\mu - \gamma^\mu \gamma^5 \rightarrow c_V \gamma^\mu - c_A \gamma^\mu \gamma^5 \)
  • \( c_V \) – correction to the vector ”weak charge”
  • \( c_A \) – correction to the axial vector “weak charge”

• Conserved Vector Current (CVC) hypothesis
  • Experimentally, \( c_V = 1.000 \)

• Partially Conserved Axial Current (PCAC) hypothesis
  • Experimentally, \( c_A = 1.270 \pm 0.003 \rightarrow ”Almost” \text{ conserved} \)
From Adler’s theorem,
\[
\frac{d^2\sigma(\nu + N \rightarrow \ell^- + N')}{dQ^2 dW} = \frac{G_F^2 W}{2\pi^2 M_N} \frac{E_\ell}{E_\nu (E_\nu - E_\ell)} f^2_\pi \sigma(N + \pi \rightarrow N')
\]
\[
x_B = \frac{Q^2}{2M_N (E_\nu - E_\ell)} , \quad y_B = \frac{E_\nu - E_\ell}{E_\nu} \quad |t| = |(q - p_\pi)^2| = |(k - k' - p_\pi)^2|
\]
\[
\left( \frac{d\sigma}{dx_B dy_B d|t|} \right)_{Q^2=0} = \frac{G_F^2 M_N E_\nu}{\pi^2} \frac{1}{2} f^2_\pi (1 - y_B) \frac{d\sigma(\pi N \rightarrow \pi N)}{d|t|} \bigg|_{E_\nu y = E_\pi}
\]

Adding nucleus dependencies
\[
\frac{d\sigma(\pi N \rightarrow \pi N)}{d|t|} = A^2 |F_N(t)|^2 \frac{d\sigma(\pi N \rightarrow \pi N)}{d|t|} \quad \frac{d\sigma(\pi N \rightarrow \pi N)}{d|t|} = \frac{1}{16\pi} \left[ \sigma_{tot}^{\pi N} \right]^2 (1 + r^2)
\]
\[
|F_N(t)|^2 = e^{-b|t|} F_{abs} , \quad \text{with} \quad b = \frac{R_0^2}{3} A^{2/3} \quad r = \Re[f_{\pi N}(0)]/\Im[f_{\pi N}(0)]
\]

Rein-Sehgal triple differential coherent cross section
\[
\frac{d\sigma^{NC}}{dx dy d|t|} = \frac{G_F^2 M_N E_\nu}{4\pi^2} f^2_{\pi^0} (1 - y_B) \left( \frac{m_A^2}{m_A^2 + Q^2} \right)^2 A^2 F_{abs} e^{-b|t|} \frac{1}{16\pi} \left[ \sigma_{tot}^{\pi N}(E y) \right]^2 (1 + r^2)
\]

For charged-current cross section:
- Substitute pion decay constant: \( f^2_{\pi^+} = 2 f^2_{\pi^0} \)
Rein and Sehgal (2007)

- Following the original RS formulization

\[
\frac{d\sigma^{NC}}{dx \ dy \ dt} = \frac{G_F^2}{4 \pi^2} M_N E_\nu f_{\pi^0}^2 (1 - y_B) \left( \frac{m_A^2}{m_A^2 + Q^2} \right)^2 A^2 F_{abs} e^{-b|t|} \frac{1}{16\pi} \left[ \sigma_{tot}^{\pi^0 N}(E_\nu) \right]^2 (1 + r^2)
\]

- For CC-COH, deficit was found in forward going muon direction
  - Correction factor was added to reduce the CC phase space

\[
C = \left( 1 - \frac{1}{2} \frac{Q_{min}^2}{Q^2 + m_{\pi^+}^2} \right)^2 + \frac{1}{4} y_B Q_{min}^2 (Q^2 - Q_{min}^2) (Q^2 + m_{\pi^+}^2)^2 \quad Q_{min}^2 = m_{\text{lep}}^2 y_B / (1 - y_B)
\]

- The modified RS cross section:

\[
\frac{d\sigma^{CC}}{dx_B \ dy_B \ dt} = \frac{d\sigma^{NC}}{dx_B \ dy_B \ dt} \times 2C \theta(Q^2 - Q_{min}^2) \theta(y_B - y_{B, \min}) \theta(y_{B, \max} - y_B)
\]

- The reduced phase space is:

\[
y_{B, \min} = m_{\pi} / E \quad y_{B, \max} = 1 - m_{\text{lep}} / E
\]
The original and modified RS does not describe experimental measurements in the sub-GeV to few-GeV region.

2 further modification was added by Berger and Sehgal.

Approximation of the kinematic term $1 - y_B$ is replaced by the complete derived term:

$$1 - y_B + \frac{y_B^2}{4} \left(1 - \left| \frac{Q^2}{(E_\nu - E_\ell)^2} + 1 \right| \right)$$

BS used external pion-carbon scattering data to constrain the pion-nucleus cross section.

- RS tries to model the nuclear processes for the pion-nucleus elastic differential cross section used inside the model.
Alvarez-Ruso (2007)

- Microscopic model approach
  - Nucleon level process
  - Pions are produces of $\Delta$ resonances or $N^*$
  - Outgoing pion’s wave function is distorted by the nuclear potential
  - Nucleon must remain in the same quantum state
- Alvarez-Ruso’s triple differential coherent pion production cross section

$$\frac{d\sigma}{dE_\ell d\Omega_\ell d\Omega_\pi} = \frac{1}{8(2\pi)^5} \frac{|\vec{k}'| |\vec{p}_\pi| |A|^2}{|k|}$$
CC1Pi-0rP Selection

- CC1Pi0rP (0 reconstructable proton)
  - CCCOH or CCRES with proton momentum less than 450MeV/c
- Selection is the same as the CCCOH selection shown before
  1. Highest momentum track in an event to be positively charged and μ-like
  2. Additional negatively charged π-like (and not proton-like) track
  3. Exactly 2 FGD1 particle tracks
    - CC-COH should have only 2 outgoing particles
    - CCRES with proton momentum less than 450MeV/s (not reconstructable) should have only 2 tracks
- Analysis variables
  - Vertex activity (VA) and momentum transferred |t|
  - These two variables are chosen to since they are also the selection variables for the CCCOH measurement
Event Selection: Vertex Activity

- FGD1: plastic scintillator layers
- Vertex Activity (VA)
  - energy deposition around the neutrino interaction vertex
  - measured in photon-equivalent unit (PEU)
  - VA low for CC-coherent $\pi$ events
    - Only generates $1\mu + 1\pi$
    - No protons to deposit additional energy near the vertex

FGD1

Reconstructed neutrino interaction vertex

e.g. 5X5 scintillator layers volume
- Energy deposition inside this volume is VA

T2K run5 MC only
Rein-Sehgal COH Model

Vertex Activity VA [PEU]
Event Selection: Momentum Transferred Square

- Momentum transferred square
  - Note this is not the standard $|t|$ since the existence of the extra pion

\[
|t| = \left| (q - P_\pi)^2 \right| = \left| (P_\nu - P_\mu) - P_\pi \right|^2
\]

\[
Q^2 = -q^2
\]

\[
P_\nu = (E_\nu, 0, 0, E_\nu) = (E_\mu + E_\pi, 0, 0, E_\mu + E_\pi)
\]

\[
|t| = \left( \sum_{i=\mu,\pi} (E_i - p_i^z)^2 \right) + \left( \sum_{i=\mu,\pi} p_i^x \right)^2 + \left( \sum_{i=\mu,\pi} p_i^y \right)^2
\]
Cross-section Likelihood Fitter

- Likelihood fitter
  - Finds the best fit value of measured number of events with a binned likelihood fit
  - Adjust simulation prediction to data (best fit)
  - Maximize (log)likelihood minimizes the chi-square

\[
\chi^2 = \chi^2_{\text{stat.}} + \chi^2_{\text{syst.}} + \chi^2_{\text{reg.}} = -2\ln\mathcal{L}_{\text{stat.}} - 2\ln\mathcal{L}_{\text{syst.}} - 2\ln\mathcal{L}_{\text{reg.}}
\]

\[
\chi^2_{\text{stat.}} = \sum_i^N 2(N_i^{\text{MC}} - N_i^{\text{Data}} + N_i^{\text{Data}} \ln \left( \frac{N_i^{\text{Data}}}{N_i^{\text{MC}}} \right))
\]

\[
\chi^2_{\text{syst.}} = \Delta^T \mathbf{V}_{\text{syst.}} \Delta, \quad \mathbf{V}_{\text{syst.}}: \text{Systematics covariance matrix, } \Delta: \text{difference between data and predicted value}
\]

- Extra regularization term to ensure the smoothness of the best fit distribution (cross section should be continuous)

\[
\chi^2_{\text{reg.}} = \lambda \sum_i^N |c_i - c_{i-1}|^2
\]