Investigation of neutral pion production in anti-neutrino beam in the T2K experiment

Sergey Martynenko
Stony Brook University
Agenda

• Phenomenology of neutrino oscillations
• Purposes and construction features of the T2K experiment
• Motivation for investigation of anti-neutrino reactions with $\pi^0$ production
• Algorithm of reconstruction of anti-neutrino charged-current events with $\pi^0$ production
Neutrino oscillations

- Neutrino is electrically neutral elementary particle with half-integer spin, which interacts with matter through weak and gravitational interactions;
- Neutrino oscillations violate Standard model (neutrino should have mass to oscillate);
- Mass eigenstates made up of linear combinations of weak interaction eigenstates (flavor eigenstates);
- The mixing can be parameterized by minimum six quantities: $\Delta m^2_{21}, \Delta m^2_{32}, \theta_{12}, \theta_{23}, \theta_{13}$ and CP-violation phase $\delta_{cp}$;
- Probability of oscillations depends on mixing matrix, neutrino energy $E$, and length of the path, that neutrinos traveled $L$.

\[
\begin{pmatrix}
v_e \\ v_\mu \\ v_\tau 
\end{pmatrix} = U \begin{pmatrix}
v_1 \\ v_2 \\ v_3 
\end{pmatrix}
\]

\[
P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \left( \frac{\Delta m^2_{ij} L}{4E} \right) 
\]
\[
+ 2 \sum_{i>j} \text{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \left( \frac{\Delta m^2_{ij} L}{2E} \right)
\]

Last results from T2K // Marcela Batkiewicz talk at 17th Lomonosov Conference on Elementary Particle Physics, Moscow 24.09.2015

https://en.wikipedia.org/wiki/Neutrino_oscillation
Neutrino interactions

- The dominant charged current process for sub-GeV neutrino interactions (A) is the quasi-elastic mode (CCQE) interaction;
- Resonant production (B). The W boson excites a $\Delta$ resonance of the nucleon, which subsequently decays to a nucleon and a pion;
- The coherent pion production process (C). It produces a single pion, leaving the whole nucleus in the ground state;
- Deep inelastic scattering (DIS) processes (D). It happens for neutrinos of higher energies ($\geq 2.5$GeV). There is multi pion production in final state.
T2K (Tokai-to-Kamioka)

- **Goals of experiment:**
  - Measure parameters of neutrino oscillations $\theta_{13}$, $\theta_{23}$, $\Delta m^2_{23}$;
  - Search of CP-violation;
  - Measure cross-sections for neutrino interactions with matter.

- **Facility:**
  - Complex of 2 near detectors INGRID+ND280 280 meters from neutrino source;
  - Far Cherenkov detector Super-Kamiokande 295km away from neutrino source.

Super-Kamiokande

- 295km away from neutrino source;
- 50 kton water Cherenkov detector;
- Particle identification based on the shape of Cherenkov ring;
- No magnetic field to separate particles from anti-particles.

Last results from T2K // Marcela Batkiewicz talk at 17th Lomonosov Conference on Elementary Particle Physics, Moscow 24.09.2015
ND280

- **Magnet:** magnetic field ~0.2T

- **Pi0 detector P0D:** Reconstruction of NC events, possibility for using water target

- **Three Time-projection chambers TPC:** identify particles by mean energy loss for ionization, measure their momentum

- **Two Fine Grained detectors FGD:** Target for analysis in TPC, FGD1 – scintillator plates, FGD2 – scintillator + water target

- **Electromagnetic Calorimeter ECal:** reconstruction of showers from events occurred in tracker

- **SMRD:** Scintillator plates in the air gaps of the magnet, a veto for neutrino events outside the tracker, trigger for cosmic muons

Motivation for investigation CCπ0 anti-neutrino events

- Need precise reconstruction of neutrino energy, since probability of oscillations depends on it;
- Neutrino energy is reconstructed from kinematics of outcome particles;
- Default assumption in T2K: All reactions are quasi-elastic scattering;
- Make improvements in the energy reconstruction by exploring other reactions;
- One of these reactions is charged-current antineutrino interaction with π⁰ production (CCπ0).

\[ P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left( \frac{\Delta m^2_{ij} L}{4E} \right) \]

\[ + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left( \frac{\Delta m^2_{ij} L}{2E} \right) \]

\[ E_{\nu} = \frac{E_\mu - m^2_\mu/(2M)}{1 - (E_\mu - P_\mu \cos \theta)/M} \]

M. Martini, M. Ericson, G. Chanfray Neutrino energy reconstruction problems and neutrino oscillations //DOI: 10.1103/PhysRevD.85.093012
Analysis Samples

Signal:

- **CC1π⁰**: \( \bar{\nu}_\mu + \text{nucleon} \rightarrow \mu^+ + \text{nucleons} + \pi^0 \)
- **CCπ⁰ + X**: \( \bar{\nu}_\mu + \text{nucleon} \rightarrow \mu^+ + \text{nucleons} + \pi^0 + \text{others} \)

**Pi0 properties:**

- Mass \( \sim 135 \text{ MeV}/c^2 \);
- Lifetime \( \sim 8 \times 10^{-17} \text{ s} \);
- Decay into two photons (probability 98.8%).
Reconstruction of antineutrino events with pi0 production (CCpi0)

Reconstruction of anti-neutrino CC events:
• Take positive track with highest momentum starts in fiducial volume of one of Fine Grained Detectors;
• Track looks like $\mu^+$ due to energy loss for ionization in TPC;
• Track should have a part in multiple sub-detectors.

Reconstruction of events with $\pi^0$:
• Reconstruct all possible EM showers in ECal and $e^+/e^-$ candidates in TPC;
• Reconstruct gammas from EM showers and $e^+/e^-$ candidates;
• Reconstruct $\pi^0$ from these gammas;
• Take two gamma candidates with max energy;
• Every gamma must be used only once.
• At least one $\pi^0$ should exist.
Reconstruction of CC anti-neutrino events

Anti-neutrino CC events with reconstructed muon track:
• efficiency ~35%;
• purity ~90%.

Momentum of reconstructed mu+
Reconstruction of signal events (CCπi0)

Result of signal selection:
• Efficiency 18.7% and purity 47.5%

Number of events in FGD1:
• 141 expected*;
• 139±12 reconstructed from data;

FGD2:
• 140 expected*;
• 131±11 reconstructed from data;


Summary

• Neutrino oscillations violate Standard model;
• To measure probability of oscillations one needs precise reconstruction of energy of incoming antineutrinos;
• Investigation of reactions beyond quasi-elastic mode improves reconstruction of antineutrino energy.
• Developed Inclusive antineutrino CC-\pi0 selection for antineutrino mode of the T2K experiment with efficiency~20\%, purity~49\% (expect \~150\pm12 events from data in each FGD).
Backup
Selection of EM showers

- Choose all isolated objects in ECal
- Calculate EMEnergy of these objects;
- Put a cut on EMEnergy. If EMEnergy less than 130 MeV we assume this object to be EMShower. If EMEnergy more than 130 MeV we apply PID ECal to check if it is EM shower or not.

Energy of EM Showers

Efficiency (left) and purity(right) of selection with different cut on energy
PID $\mu^+$ in ECal

For tracks in Ecal apply particle identification (PID) module ECal. MIP_ECM(LLR) < -5, MIP_PION(LLR)< 5

for DsECal и MIP_ECM(LLR) < -10, MIP_PION(LLR)< 0

for Barrel ECal
**e+/e- Selection (1)**

- Choose all tracks using TPC;
- Define charge of chosen tracks;
- Apply particle identification module TPC. Positive tracks should be e+ like and negative e- like;
- Calculate the energy of particles;
- Put cut on minimum energy for e-(50 Mev);
- Put Cut on minimum energy(50MeV) and maximum energy(50MeV) for e+.

Efficiency(слева) and purity(справа) for electron selection with different values of min energy

Efficiency(слева) and purity(справа) for positron selection with different values of min energy

максимальную энергию позитронов
Reconstruction of e+/e-(2)

**e-:**
- Efficiency 72%
- Purity 71.2%

**e+:**
- Efficiency 80%
- Purity 73.5%
Combine e+ and e- in pairs

• Reconstruct $m_{\text{inv}}$ for all possible e+/e- pairs;
• Calculate the distance $\Delta_{e^\pm}$ between start positions of e+ and e-;
• For e+ and e- to be a pair the should have $m_{\text{inv}} < 50 \text{ MeV}$ and $\Delta_{e^\pm} < 100 \text{ nm.}$
Data Analysis

Reconstructed $\mu^+$ momentum for events with pi0 production in FGD1(right) and FGD2(left)
Data Analysis

- **top:** neutral pion momentum
- **bottom:** angle between pi0 direction and
Event topology

- Shower–Shower: 0
- Shower–Pair: 1
- Shower–Electron: 2
- Shower–Positron: 3
- Pair–Pair: 4
- Pair–Electron: 5
- Pair–Positron: 6
- Electron–Electron: 7
- Electron–Positron: 8
- Positron–Positron: 9
- $>1\pi^0$-candidate: 10
Antineutrino Flux

- Max beam power achieved so far 370kW
- Maximum for neutrino energy at 0.5GeV
Results of signal events selection

For selection in FGD1:
- **Efficiency 20.9% and purity 49%**

For FGD2:
- **Efficiency 18.7% and purity 47.5%**
Results of signal events selection

For selection in FGD1:
- Efficiency 20.9% and purity 49%

For FGD2:
- Efficiency 18.7% and purity 47.5%
Near Detectors

On-axis detector - INGRID

- Monitors the direction and the intensity of the neutrino beam on a daily basis
- Measures cross section

Off-axis detector - ND280

- Off-axis by 2.5° – same as far detector
- Measures the beam parameters before oscillations
- Measures neutrino cross sections → Reduces flux and cross section uncertainties for oscillation analysis
Reconstruction of CC anti-neutrino events

Anti-neutrino CC events with reconstructed muon track:

• efficiency 35%;
• purity 87%;
• 7% - signal from events with pi0 production.

Распределение событий по импульсу в FGD1(слева) и FGD2(справа)
Reconstruction of gammas and neutral pions

To reconstruct gammas we use:

• **EM showers in ECal.** Energy of gammas assumed to be the same as energy of shower, a direction of gammas is vector between start position of μ+ and start position of shower;

• **e+/e- pairs.** Energy and direction of gammas are derived from kinematics of e+/e- ;

• **Single electrons/positrons(not paired).** Energy and direction of gammas is the same as energy and direction of e+(e-) in it’s start position;

To reconstruct π⁰:

• Take two gamma candidates with max energy;

• Every gamma must be used only once.