Identifying CC1\(\pi^+\) at Super-Kamiokande

Sophie Berkman
University of British Columbia

CAP Congress
June 16, 2014
T2K $\nu_\mu$ Disappearance

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23}) [1 - \cos^2(\theta_{13}) \sin^2(\theta_{23})] \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right) \]

$L = 295\text{km}$

Data
MC with Oscillation
MC without Oscillation

Reconstructed Neutrino Energy (GeV)

Events/0.10GeV

E= Neutrino Energy

68% (dashed) and 90% (solid) CL Contours
- T2K [NH]
- T2K [IH]
- SK I-IV [NH]
- MINOS 3-flavor+atm [NH]
T2K CCQE Signal

- T2K Signal: charged current quasi-elastic
  \[ \nu_\mu + n \rightarrow \mu^- + p \]
  - Dominant interaction at T2K energies
  - Look for single muon events at SK
  - Proton is typically below Cherenkov threshold
- Reconstruct neutrino energy
  - Only depends on muon kinematics \((p_\mu, \theta_{\mu\nu})\)

\[ E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m^2_\mu + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_{\mu\nu})} \]

- Largest contribution to background are interactions that produce charged pions
Pion Backgrounds at SK

- **Signal:**
  \[ \nu_\mu + n \rightarrow \mu^- + p \]

- **Neutral Current 1\pi^+:**
  \[ \nu_\mu + p \rightarrow \nu_\mu + \pi^+ + n \]
  - Misidentify pion as muon

- **Charged Current 1\pi^+:**
  \[ \nu_\mu + p/n \rightarrow \mu^- + \pi^+ + p/n \]
  - Miss pion and reconstruct as signal
  - Misreconstruct neutrino energy

- **Current T2K analyses only separate electrons from muons**
- Pion and muon rings look similar at SK, except for hadronic interactions

**Diagram:**
- Single Ring Muon Sample
  - \( \nu_\mu \) CCQE
  - \( \nu_\mu \) CC \( \pi^+ \)
  - \( \nu_\mu \) CC others
  - \( \nu_\mu \) CC
  - \( \nu_e \) CC
  - NC

**Graph:**
- Neutrino Energy (GeV)
- Events/50MeV/1.43E20POT

**Images:**
- Electron MC
- Muon MC
- Pion MC
CC1π⁺ as SK signal

- Charged current single pion
  \[ \nu_\mu + p/n \rightarrow \mu^- + \pi^+ + p/n \]
  - Second most dominant interaction at T2K energies
  - Look for events with \( \mu^- \) and \( \pi^+ \)
  - Proton or neutron too low energy to reconstruct
  - Reconstruct neutrino energy
    - Analogous to CCQE reconstruction
    - Only depends on muon and pion kinematics
  - Constrain background in single muon sample
  - Additional oscillation signal

\[
E_\nu = \frac{m_\mu^2 + m_{\pi^+}^2 - 2m_N(E_\ell + E_{\pi^+}) + 2p_\ell \cdot p_{\pi^+}}{2(E_\ell + E_{\pi^+} - |p_\ell| \cos \theta_{\nu \ell} - |p_{\pi^+}| \cos \theta_{\nu \pi^+} - m_N)}
\]
Reconstructing $\pi^+$ and CC1$\pi^+$

- Reconstruct kinematics of particles in SK

$$\mathcal{L}(x) = \prod_{i=1}^{N_{\text{unhit}}} \mathcal{P}_i(\text{unhit}; x) \prod_{j=1}^{N_{\text{hit}}} \mathcal{P}_j(\text{hit}; x)f_q(q_j; x)f_t(t_j; x)$$

- Charged pions:
  - Kinked track signature: pion changes direction after hadronic interaction
  - Can scatter below Cherenkov threshold so abruptly stops producing light
- Upstream pion reconstruction:
  - Assume below threshold after hadronic interaction
- Multi-ring framework, allows construction of CC1$\pi^+$ hypothesis
  - $\mu^-$ and $\pi^+$ from same vertex

![Diagram showing kinked track and its reconstruction](image-url)
MC Selection of CCQE and CC1\(\pi^+\)

• Ability to reconstruct CC1\(\pi^+\) makes it possible to add an additional sample to oscillation signal

• Monte Carlo selection
  – **CC1\(\pi^+\)-like**: 1 \(\pi^+\) and one \(\mu^-\) after final state interactions and before secondary interactions
  – **CCQE-like**: one \(\mu^-\) after final state interactions

• \(~40\%\) additional events

With Current T2K Statistics, \(6.57 \times 10^{20}\) POT

<table>
<thead>
<tr>
<th>Interaction Mode</th>
<th>Number of Events without oscillation</th>
<th>Number of Events with oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>375.1</td>
<td>86.62</td>
</tr>
<tr>
<td>CC1(\pi^+)</td>
<td>83.64</td>
<td>35.84</td>
</tr>
</tbody>
</table>
Pion Systematic Errors

- Existing secondary interaction systematic error
- CC1\(\pi^+\) will be a new SK sample
  - Evaluation of systematic errors required for use in analysis
- Studies are especially important for pions close to Cherenkov threshold (160MeV/c)
  - PICCOLO Detector
  - DUET Experiment – See Elder Pinzon’s talk tomorrow

<table>
<thead>
<tr>
<th>Source of uncertainty (number of parameters)</th>
<th>(\frac{\delta n_{SK}^{exp}}{n_{SK}^{exp}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-independent cross section (11)</td>
<td>4.9%</td>
</tr>
<tr>
<td>Flux and ND280-common cross section (23)</td>
<td>2.7%</td>
</tr>
<tr>
<td>SK detector and FSI+SI systematics (7)</td>
<td>5.6%</td>
</tr>
<tr>
<td>(\sin^2(\theta_{13}), \sin^2(\theta_{12}), \Delta m^2_{21}, \delta_{CP}) (4)</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total (45)</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

![True CC1\(\pi^+\) Events](image-url)
PICCOLO Detector

- Understand amount and properties of Cherenkov light produced by pions close to Cherenkov threshold.
  - May be different than for muons/electrons due to hadronic interactions
- Cylinder filled with water with 4 PMTs to collect total light

![PICCOLO Detector Diagram]

- 1 cm beam window
- PVC pipe painted with white reflective coating
- 12 in
- 1 m
- $\pi^+$
- 5 inch PMT
- 2 inch PMTs with chimney attachments
PICCOLO Data Collection & Analysis

- Data collection in TRIUMF M11 secondary beam-line contains: $e^+$, $\mu^+$, $\pi^+$.
  - ~2% momentum resolution
  - Scan pion Cherenkov threshold from 130-300 MeV/c
  - Separate particle types with time of flight
- To study primary pions, remove light from decay electrons produced

Below Threshold
$p_\pi=130$ MeV/c

Above Threshold
$p_\pi=180$ MeV/c
PICCOLO Analysis

- Mean amount of light produced over the momentum range (130-300 MeV/c)
- Evidence of the Cherenkov threshold
Conclusions

• A CC1π⁺ sample at SK can provide a new signal sample for T2K oscillation analyses.

• A framework exists for identifying CC1π⁺ events.

• Use of the CC1π⁺ sample will require better understanding of pion light production in water which can be done using the PICCOLO beam test data.
Backup Slides
Appearance Formula

• Full formula for electron neutrino appearance

\[ P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \text{ Leading term} \]

\[ +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \]

\[ -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \]

\[ +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \]

\[ -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{a L}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \text{ matter effects} \]

\[ +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31} \]

T. Nakaya, Neutrino2012
T2K $\nu_\mu$ Energy Spectrum

![Energy Spectrum Diagram](image-url)

**Figure 25:** $E_{\text{rec}}$ distribution for data (black point), the best data fit (red line), and the no oscillation (blue line). The error bars on data represent the statistical error. Below is the same as the top but with the number of bins reduced to better see the shape of the data spectrum.

**Table 16:** Fit results for several likelihoods

<table>
<thead>
<tr>
<th>Likelihood Fitted</th>
<th>$N_{\text{exp}}$</th>
<th>$\sin^2\theta_{23}$</th>
<th>$m_{21}^2$</th>
<th>$m_{32}^2$ (eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{norm}} \cdot L_{\text{shape}}$</td>
<td>121.41</td>
<td>0.514</td>
<td>2.51</td>
<td>$\times 10^3$</td>
</tr>
<tr>
<td>$L_{\text{norm}} \cdot L_{\text{syst}}$</td>
<td>122.39</td>
<td>0.514</td>
<td>2.50</td>
<td>$\times 10^3$</td>
</tr>
<tr>
<td>$L_{\text{syst}}$</td>
<td>120.88</td>
<td>0.514</td>
<td>2.60</td>
<td>$\times 10^3$</td>
</tr>
</tbody>
</table>

T2K $\nu_\mu$ Energy Spectrum

**June 16, 2014**

S. Berkman -- CAP Congress 2014
Super-Kamiokande & Cherenkov Radiation

- **Super Kamiokande**
  - 50 kTon cylindrical water Cherenkov detector
- Cherenkov light is produced when charged particles have speed of
  \[ v > \frac{c}{\lambda} \]
- Minimum momentum to produce Cherenkov light:
  \[ p_{\text{min}} = \frac{mc}{\sqrt{n^2 - 1}} \]
  - Called “Cherenkov threshold”
- Light is produced in a cone around trajectory of particle
- See rings of light projected on the walls

11,129 20 inch PMTs
Event Reconstruction

• Need to reconstruct kinematics of outgoing particles from neutrino interactions to calculate the neutrino energy

• Event: times and charges registered by PMTs
  – Charges are clustered into groups of similar times
  – Clusters arranged into “subevents” with one time, one charge per PMT

• Event Reconstruction for SK (fiTQun):
  – Maximum likelihood algorithm:

\[
\mathcal{L}(\mathbf{x}) = \prod_{i=1}^{N_{\text{unhit}}} P_i(\text{unhit}; \mathbf{x}) \prod_{j=1}^{N_{\text{hit}}} P_j(\text{hit}; \mathbf{x}) f_q(q_j; \mathbf{x}) f_t(t_j; \mathbf{x})
\]

  – Track parameters \( \mathbf{x} \): position, time, direction, momentum
Event Reconstruction

• Charge PDF:
  - Determining what happened in an event:
    - Number of rings
    - Kinematics of each ring
    - PID of ring
  - Unify these questions by comparing likelihood ratios

Simulated charge distribution
Reconstructed charge prediction

June 15, 2014
S. Berkman
Toy Study Contours

- CCQE is comparable to T2K result for current data set
  - Note different scales
- No systematic errors included

Best Fit Values

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Delta m^2_{32}$ (eV$^2$)</th>
<th>$\sin^2(2\theta_{23})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>0.00242</td>
<td>1</td>
</tr>
<tr>
<td>CC1$\pi^+$</td>
<td>0.00240</td>
<td>1</td>
</tr>
<tr>
<td>CCQE+CC1$\pi^+$</td>
<td>0.00240</td>
<td>1</td>
</tr>
</tbody>
</table>

$90\%$ CL

$68\%$ CL

June 16, 2014
S. Berkman -- CAP Congress 2014
PICCOLO Data Collection

- TRIUMF M11 beam
  - Secondary beamline
  - Contains: $e^+$, $\mu^+$, $\pi^+$
- Select momenta in a range from 130 – 300 MeV/c
- Collected PMT waveform on an oscilloscope
Particle Identification

- Beam contains $e^+$, $\mu^+$, $\pi^+$ so need to separate particles for analysis
- Particles travel at different speeds because of different masses
- Distinguish particles using different flight times from production to detector

<table>
<thead>
<tr>
<th>Time of Flight (ns)</th>
<th>130 MeV/c</th>
<th>160 MeV/c</th>
<th>190 MeV/c</th>
<th>220 MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>$\mu$</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$e$</td>
<td>$e$</td>
<td>$e$</td>
<td>$e$</td>
</tr>
<tr>
<td>$e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

June 16, 2014
S. Berkman -- CAP Congress 2014
Muon Lifetime

- Muons decay as: \( \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \)
- Particle Data Group \( \mu^+ \) lifetime: \( \sim 2.197 \mu s \)
  - Ran beam with positive particles so expect lifetime measurement without any muon capture effect
- Extract lifetime as a check of the data
- Identify muons and look for a decay electron peak

![Graph showing decay time vs. number of counts with fitted line and statistical data]

Lifetime = 2.24±0.06 \( \mu s \)