Measurement of $\pi^+$ Absorption and Charge Exchange Cross Sections for the T2K Experiment:

DUET Experiment

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for the DUET Collaboration

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Pions in $\nu$ Interactions

- Neutrino flavour and energy determined from flavour and momentum of outgoing lepton

**CCQE Interaction. Signal event**

Use two-body decay kinematics to reconstruct neutrino energy
Neutrino flavour and energy determined from flavour and momentum of outgoing lepton

**Signal event**

Use two-body decay kinematics to reconstruct neutrino energy

**Background**

CCQE Interaction.

CC$\pi^+$ Interaction.
Pions in $\nu$ Interactions

- Neutrino flavour and energy determined from flavour and momentum of outgoing lepton

**CCQE Interaction. Signal event**

Use two-body decay kinematics to reconstruct neutrino energy

**CC$1\pi^+$ Interaction. Background**

Unidentified pion leads to wrong reconstructed energy ($\text{FSI+SI}$)

- Inside nucleus: **Final State Interactions**
- Outside nucleus: **Secondary Interactions**
Pions in $\nu$ Interactions

- Neutrino flavour and energy determined from flavour and momentum of outgoing lepton

**CCQE Interaction.**

- Signal event
  - Use two-body decay kinematics to reconstruct neutrino energy

**Measure $\pi^+$ interaction cross sections!**

**Source of uncertainty (number of parameters) $\frac{\delta n_{SK}^{\text{exp}}}{n_{SK}^{\text{exp}}}$**

- ND280-independent cross section (11) 4.9%
- Flux and ND280-common cross section (23) 2.7%
- SK detector and FSI+SI systematics (7) 5.6%
- $\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, $\Delta m^2_{21}$, $\delta_{CP}$ (4) 0.2%
- Total (45) 8.1%

**Background**

- Inside nucleus: **Final State Interactions**
- Outside nucleus: **Secondary Interactions**

**Unidentified pion leads to wrong reconstructed energy (FSI+SI)**
Pion Interaction modes

1. Quasi-elastic Scattering

\[ \pi^+ + \pi^- \rightarrow \pi^+ + \pi^- \]

2. Absorption (ABS)

\[ \pi^+ + N \rightarrow N + \pi^0 + \gamma \]

3. Charge Exchange (CX)

\[ \pi^+ + N \rightarrow N + \pi^0 + \gamma \]
Pion Interaction modes

1. Quasi-elastic Scattering

2. Absorption (ABS)

3. Charge Exchange (CX)

Can measure combined ABS+CX

No $\pi^+$ in final state
Pion Interaction modes

1. Quasi-elastic Scattering

![Quasi-elastic Scattering Diagram]

2. Absorption (ABS)

![Absorption (ABS) Diagram]

3. Charge Exchange (CX)

![Charge Exchange (CX) Diagram]
DUET Experiment

GOAL

Measure pion absorption cross section with $\sim 10\%$ accuracy and charge exchange with $\sim 20\%$ accuracy

Use TRIUMF M11 beam line
TRIUMF M11 Beam line

- TRIUMF Cyclotron produces 500 MeV/c primary proton beam
- Secondary beam line with momentum tunable in the range from 150 MeV/c to 375 MeV/c delivers e, \( \mu \), p and \( \pi \).

- Beam PID from Time Of Flight (TOF) counters.
- Above 225 MeV/c use Cherenkov detector to select pions.

![Diagram of beam selection using Cherenkov detectors](image)
Detector setup: DUET

- **Main Components:**
  - **Piano:** 1.5 mm$^2$ scintillating fiber tracker (Full active target) + NaI crystals
  - **Harpsichord:** Miniature Fine Grained Detector (FGD from T2K) (Scintillating bars + Lead layers)

[Diagram showing detector components]
Main Components:

- **Piano**: 1.5 mm$^2$ scintillating fiber tracker (Full active target) + NaI crystals

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![Diagram of Detector setup: DUET](image)
Detector setup: **DUET**

**Main Components:**
- **Piano:** Scintillating fibers and NaI detectors
- **Harpsichord:** Miniature Fine Grained Detector for T2K (Scintillating bars + Lead layers)

Detector setup:

- **Piano**
- **Harpsichord**
  - 30 cm
  - 5 cm
  - 8x NaI
  - 8x NaI
  - 1.5mm
  - Cherenkov Counter
  - M11
- **Beam Line** (TRIUMF)

Cherenkov Detector

S0

S1

Nal

Nal

S2
Main Components:
- **Piano**: Scintillating fibers and NaI detectors
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Detector setup:

- **Cherenkov Detector**
- **Piano**
- **NaI**
- **Harpsichord**
- **NaI**

[Diagram showing the setup with labels and dimensions provided in the image]
Analysis Outline

- Using Piano fibers

Measure Abs+CX cross section
[No $\pi^+$ in final state]

Using NaI detectors and Harpsichord

Measure CX cross section
[Tag photon(s) from $\pi^0$]

Feed into FSI & Secondary Interaction models

Improve Systematics
Event Selection: No $\pi^+$ in final state

Sample $\pi^+$ absorption interaction in **Piano**

Example of dQ/dx distribution

Vertex inside Piano's Fiducial Volume

Piano event display

$\pi^+$

$\pi^+$

N

$\pi^+$

Pion-like track

Proton-like track

Reject: $\pi^+$

PID with angle dependent dQ/dx cut
Abs+CX Cross Section Result

\[ \sigma_{\text{Abs+CX}} \text{ [mbarn]} \]

- DUET Measurement

Good agreement and much smaller errors (~20% \( \rightarrow \) ~6%)

Presented at NuFact 2013. PRD in preparation
Extracting theCharge Exchange cross section
Harpsichord Simulation Validation

- Harpsichord GEANT4 simulation is based on the FGD (from T2K):
  - Only geometrical and calibration-related modifications
  - Need to validate simulation

- Use muons traversing the detector as control sample

- Tune MC and electronics simulation parameters to match Data vs. MC deposited charge distributions

Some tuned parameters:
- MeV to p.e. factor
- MPPC ADC to p.e. factor
- MPPC waveform parameters
- Mirror end of fibers

Use difference to apply systematic variation

Through going muon charge
- Data: 161324 entries
- MC: 457055 entries

Tuned single PE height of pulses in MPPCs

-10³
800
700
600
500
400
300
200
100
0
0.6
0.7
0.8
0.9
1
1.1
1.2
Single PE Pulse Height (PE)

0 10 20 30 40 50 60 70 80

Charge (p.e.)
**CX Event Selection: Using Harpsichord**

- Charged pions and **protons** immediately leave a signal in the scintillating detector.
- **Photons** are neutral, so they must interact before they can be detected.
- The **first two layers** are used as a **veto cut** in order to remove pions and protons.

Log( Number of events)

First two layers

- Data
- Proton
- CX
- Pions
- Neutron
- Other

Position of most upstream hit in Harpsichord [mm]

- 820
- 830
- 840
- 850
- 860
- 870
- 880
- 890
- 900
- 910
- 920
CX Event Selection: Neutron Rejection

- **Neutrons** will also mostly make hits after the first two layers
- Use number of hits and total charge deposited to remove most of background

**Efficiency** = \( \frac{\text{Selected CX events}}{\text{True CX events}} \approx 15\% \)

**Purity** = \( \frac{\text{Selected CX events}}{\text{Total selected events}} \approx 95\% \)

- Working on sources of systematic error:
  - Charge response
  - \( \pi^0 \) kinematics (opening angle & momentum)
Summary and Outlook

- **DUET measures** $\pi^{-12}C$ interaction cross-sections using the M11 pion beam line at TRIUMF
  - Also took data with water target ($\pi^{-16}O$)

- **Results for a combined Absorption + Charge Exchange cross section** are consistent with previous results and have much smaller errors ($\sim20\% \rightarrow \sim6\%$)
  - Paper will be submitted to PRD in the next few weeks

- **Work for a separate charge exchange measurement** is ongoing
  - Event selection finalized
  - Working on systematic errors
  - Results are coming

- **This will feed into a better model of pion Final State Interactions and Secondary Interactions**
  - Reduce systematics for current and future neutrino experiments
Thank you

Piano & Harpsichord!
DUET Experiment

**Goal:**
Measure pion absorption with ~10% accuracy and charge exchange with ~20% accuracy

**Source of uncertainty (no. of parameters) | \( \frac{\delta n_{\text{SK}}}{n_{\text{SK}}} \)**
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**Very relevant processes for pions in \( \nu \) experiments**

\( \nu_\mu \) disappearance systematics

**Pion momentum spectrum for T2K \( \nu \) CC\( \pi \) interactions**

**Use TRIUMF M11 beam line**
(a) Pia\nuo and Harpsichord in configuration 1. The angular distribution of photons can be measured using the NaI detectors.

(b) Pia\nuo and Harpsichord in configuration 2. Lead layers are added to Harpsichord to increase photon conversion.
Beam particle fraction

- electron
- muon
- pion

Incident Pion Momentum [MeV/c]
- TOF is not enough to separate pions and muons above 200MeV/c

- Different $\beta$ for $e$, $\mu$, $\pi$ \implies Detected light will be different due to different light yield and angle
- Scintillating light are read out by MAPMT \times 16
- Fiber \times 1024 \text{ ch}, \text{ NaI} \times 16\text{ch}
- Fiber main volume: 48mm \times 48mm \times 48mm
Harpsichord

- Harpsichord
  - 1/6 X 1/6 scale FGD
  - Same numbers of layers, electronics as FGD

- Cembalos
  - Added lead layers between XY scintillator modules
  - Increased photon conversion
Light from scintillation bar + WLS fibers read out by MPPCs
Previous experiments

Bellotti et al., Nuovo Cimento 14A, 567 (1973)
Previous experiments

1. Ashery1
2. Saunders
3. Bellotti1
4. Levenson
5. Ashery3
6. Jones
7. Bellotti2
8. Ashery2
9. Navon1
10. Navon2

\(\nabla\): DUET
dE/dx Distributions

- Used for PID in Piano’s fibers
Event Selection: Data/MC comparisons

- Distributions before applying the “no π⁺ in final state” cut:
- Good agreement between Data and MC.

Angular distribution of reconstructed tracks

Distribution of number of reconstructed tracks in the final state
Event Selection: Data/MC comparisons

- For 238MeV/c $\pi^+$ data set, the efficiency is 79.8% and the purity is 76.8%.
- ~7000 events selected on each momentum data set after all cuts are applied.
- Agreement becomes worse.

Angular distribution of the proton-like track

Distribution of number of reconstructed tracks in the final state
Abs+CX Cross section

- We calculate the Abs+CX cross section using this formula:

\[
\sigma_{\text{DATA}} = \sigma_{\text{MC}} \times \frac{N_D - N_{\text{BG,MC}}}{N_{\text{MC}}}
\]

- All systematic errors have been evaluated.
- Corrections for interactions in other nuclei (O, Ti) are also applied.
CX using NaI crystals

- Events
- No reaction
- Elastic
- Inelastic
- Absorption
- CX
- Other

- Events
- Cut
- Nal Hit energy [MeV]

- Events
- Check angle between Nal and tracks

Preliminary

Red: DUET cx.

G4 Abs. (QGSP-BERT)

G4 CX. (QGSP-BERT)

Ashery Abs. ※

Ashery CX. ※

Errors: stat. + sys.
Systematic error \( p_\pi = 250 \text{MeV/c} \)

<table>
<thead>
<tr>
<th>Error source</th>
<th>Error</th>
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<tbody>
<tr>
<td>Profile</td>
<td>1.55%</td>
</tr>
<tr>
<td>Momentum</td>
<td>1.34%</td>
</tr>
<tr>
<td>FV</td>
<td>1.87%</td>
</tr>
<tr>
<td>Charge</td>
<td>0.46%</td>
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<tr>
<td>Crosstalk</td>
<td>0.53%</td>
</tr>
<tr>
<td>Alignment</td>
<td>0.82%</td>
</tr>
<tr>
<td>Hit efficiency</td>
<td>0.76%</td>
</tr>
<tr>
<td>( \mu ) contami</td>
<td>0.89%</td>
</tr>
<tr>
<td>Target</td>
<td>0.86%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>2.42%</td>
</tr>
<tr>
<td>Background</td>
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<tr>
<td>Total syst</td>
<td>4.76%</td>
</tr>
<tr>
<td></td>
<td>-5.44%</td>
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</table>

The dominant systematic error comes from BG estimation, and the error is estimated from the Data/MC difference in the BG enhanced sample.

Background sample angular distribution

![Background sample angular distribution graph](image-url)
p-theta for $\pi^0$’s

- GEANT4 (QGSP-BERT) and NEUT
- Initial 250 MeV/c $\pi^+$
p-theta for CX Photons

- GEANT4
Solid angle subtended

- Rough calculation
  - Take Piano as a point
  - Ignore rectangular shape of Harpsichord

- A cone with opening angle:
  \[ \theta = \arctan\left(\frac{w}{d}\right) = \arctan\left(\frac{175}{190}\right) = 42.6^\circ \]

- The solid angle is:
  \[ \Omega = 2\pi \left(1 - \cos \theta\right) = 0.53\pi \]

- Or, around 13% of the whole sphere
Neutron momentum

![Graph showing neutron momentum distribution with entries, mean, and RMS values.]
NEUT FSI

- NEUT FSI model simulates pion interaction by stepping through the nuclear medium (cascade).
- The interaction probability in each step is defined by the microscopic Scattering/Abs/CX cross sections.

![Diagram showing pion interactions in the nucleus (NEUT) resulting in \( \pi-N \) cross section (what we observe)]

- The microscopic cross sections are tuned so that the resulting Scat/Abs/CX cross section agree with external data.
- Add DUET data for tuning
Proton selection (Control sample)

- **Selection:**
  - Good incident pi+
    - TOF + Cherenkov
    - Straight incoming Piano track
  - Vertex in FV
  - Not low scattering pi+
  - Reconstructed proton track in Piano
  - Hits in Harpsichord

- **From MC:**
  - 88.4% proton hitting Harpsichord
  - 5.2% pion hitting Harpsichord
  - 4.2% neither proton nor pion hitting Harpsichord
  - 2.1% both proton and pion hitting Harpsichord

<table>
<thead>
<tr>
<th>htemp</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6308</td>
<td>427.5</td>
<td>289.8</td>
</tr>
</tbody>
</table>

Not stacked, just plotted on top of each other
Proton selection (Control sample)

**Contained in first layer**

Charge in first layer events not contained:

- **Data:** $\mu: 124.7 \pm 1.95, \sigma: 23.73 \pm 3.77$
- **MC:** $\mu: 124.63 \pm 1.62, \sigma: 22.64 \pm 2.88$

**Not Contained in first layer**

Charge in first layer events contained:

- **Data:** $\mu: 295.05 \pm 5.34, \sigma: 82.43 \pm 8.85$
- **MC:** $\mu: 287.01 \pm 3.13, \sigma: 61.42 \pm 3.53$
Tune FSI Model

- Current:

![Graph showing cross-section vs. initial momentum](image)