recent results on cross-section measurements

Ciro Riccio on behalf of the T2K collaboration
NUFACT2017, Uppsala University
September 25th 2017
Overview

• Experimental setup
• Neutrino interactions at T2K
• Motivation for measuring cross sections
• Recent cross-section results
• Future work and summary
The T2K experiment

Super-Kamiokande

Near Detectors

J-PARC

Mt. Noguchi-Goro 2,924 m

Mt. Ikeno-Yama 1,360 m

1,700 m below sea level

295 km

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**T2K Flux**

- Beam 2.5° off the direction to the far detector
- Narrow beam centered around 0.6 GeV
- Reduce $\nu_e$ component from $K$ decays
- Flux estimation by hadron production measurements from NA61/SHINE

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The Near Detector complex

**ND280** off-axis detector located 280 m from the target:
- $\pi^0$ detector **P0D** target: CH+H2O
- 3 Time Projection Chambers (**TPC**)
- 2 Fine-grained detectors **FGD** target: CH+H2O
- Electromagnetic calorimeters (**ECal**)
- UA1 refurbished **Magnet** instrumented with side muon range detector (**SMRD**)

**INGRID** on-axis detector:
- Monitor the beam direction
- 14 modules arranged as a cross and other 2 outside the main cross target: CH+Fe
- Extra module - Proton Module target: CH

Where T2K cross-section measurements have been performed!
Relevant $\nu$ interactions at T2K

- **CCQE** (Charged-Current Quasi-Elastic)
- **CCRES** (Charged-Current Resonant pion production)
- **CCDIS** (Charged-Current Deep Inelastic Scattering)

Diagrams:
- **CCQE**
- **CCRES**
- **CCDIS**

Mathematical expressions:
\[
\nu \rightarrow \mu \rightarrow W^+ \rightarrow n, p
\]
\[
\nu \rightarrow \mu \rightarrow W^+ \rightarrow n, p, \pi^+
\]
\[

\nu \rightarrow \mu \rightarrow W^+ \rightarrow n, p
\]

**NEUT MC, $\nu_\mu$, C target**

- Total
- 2p2h
- CCQE
- CCDIS
- CCRES
- Other

**ND280 Flux** ($\nu_\mu$, shape)

**SK Osc. Flux** ($\nu_\mu$, shape)

\[
\sigma(E_{\nu}) \left(10^{-38} \text{ cm}^2 \text{ nucleon}^{-1} \text{ GeV}^{-1}\right)
\]

**Legend:**
- Total
- 2p2h
- CCQE
- CCDIS
- CCRES
- Other

**Axes:**
- $E_{\nu}$ (GeV)
- $\sigma(E_{\nu}) \left(10^{-38} \text{ cm}^2 \text{ nucleon}^{-1} \text{ GeV}^{-1}\right)$

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What can we measure?

Nucleons bound in the nucleus $\Rightarrow$ Nuclear effect!

- **Nuclear and detector effects** obfuscate interaction mode
- Minimise the model dependence measure interaction topologies

<table>
<thead>
<tr>
<th>Magnet</th>
<th>SMRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0D</td>
<td>CC-Inclusive</td>
</tr>
<tr>
<td>ECal</td>
<td>FGD CC-0$\pi$ CCQE-like</td>
</tr>
<tr>
<td></td>
<td>FGD CC-1$\pi$ CCRRes-like</td>
</tr>
<tr>
<td></td>
<td>TPC $p$</td>
</tr>
<tr>
<td></td>
<td>ECal $\pi$</td>
</tr>
</tbody>
</table>
Event generators

- Neutrino MC Generators connect the true and observed event topologies and kinematics
- Every observable is a convolution of flux, interaction physics and detector effects
- Re-weighting tools allow to assess uncertainties and tune the physics models
- T2K official generators are NEUT and GENIE
- We compare our results against different models: GIBUU, NuWro
Why cross-sections measurement

Neutrino scattering understanding is crucial for the interpretation of neutrino oscillation since it affects background estimation and energy reconstruction.

One of the **largest systematic uncertainties** in neutrino oscillation comes from neutrino interaction uncertainty.

<table>
<thead>
<tr>
<th>2016 oscillation analysis</th>
<th>$\nu_\mu$ 1 muon-like ring</th>
<th>$\nu_e$ 1 electron-like ring</th>
<th>$\nu_\mu$ 1 muon-like ring</th>
<th>$\nu_e$ 1 electron-like ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux w/o ND280</td>
<td>7,6%</td>
<td>8,9%</td>
<td>7,1%</td>
<td>8,0%</td>
</tr>
<tr>
<td>$\nu$ flux w/ND280</td>
<td>3,6%</td>
<td>3,6%</td>
<td>3,8%</td>
<td>3,8%</td>
</tr>
<tr>
<td>$\nu$ cross section w/o ND280</td>
<td>7,7%</td>
<td>7,2%</td>
<td>9,3%</td>
<td>10,1%</td>
</tr>
<tr>
<td>$\nu$ cross section w ND280</td>
<td>4,1%</td>
<td>5,1%</td>
<td>4,2%</td>
<td>5,5%</td>
</tr>
<tr>
<td>$\nu$ flux+cross section</td>
<td>2,9%</td>
<td>4,2%</td>
<td>3,4%</td>
<td>4,6%</td>
</tr>
<tr>
<td><strong>Final or secondary hadron int.</strong></td>
<td>1,5%</td>
<td>2,5%</td>
<td>2,1%</td>
<td>2,5%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3,9%</td>
<td>2,4%</td>
<td>3,3%</td>
<td>3,1%</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>12,0%</td>
<td>11,9%</td>
<td>12,5%</td>
<td>13,7%</td>
</tr>
<tr>
<td>Total w/ ND280</td>
<td>5,0%</td>
<td>5,4%</td>
<td>5,2%</td>
<td>6,2%</td>
</tr>
</tbody>
</table>

For more detail see talk by D. Hadley on Wednesday.
\[ \nu_\mu \text{ CC Inclusive on CH} \]

Already published a \( \nu_\mu \) CC inclusive cross section on CH using FGD1 as target:

Phys. Rev. D 87, 092003

- Data tested against different models
- Limited statistics
- Phase space restricted to forward region of the outgoing muon

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**Martini et al. (2014)**

- T2K
- QE
- QE+np-nh
- QE+np-nh+1\( \pi \)
- \( \pi \) coherent

**Megias et al. (2016)**

- QE+MEC+1\( \pi \)
- 1\( \pi \)
- SuSAv2
- QE
- MEC
- T2K
\( \nu_{\mu} \) CC Inclusive on CH

New features of the revisited analysis:

- Statistics has been increased by a factor of five
- Increased angular acceptance for high-angle and backward-going muons using the timing information between the sub-detectors
- Increased purities and efficiency
- Used a maximum likelihood fit instead of the bayesian unfolding
- Flux integrated cross section to avoid neutrino energy dependence
- Background constrained with two sidebands

Next generation analysis!
CC Inclusive on CH

T2K preliminary

Publication in preparation!
\(\nu_\mu\) CC Inclusive on CH

-0.25 < \(\cos \theta_\mu\) < 0.25

T2K preliminary

0.6 < \(\cos \theta_\mu\) < 0.71

0.985 < \(\cos \theta_\mu\) < 1

NEUT using Relativistic Fermi Gas (RFG) as nuclear model and NuWro using Local Fermi Gas (LFG) overestimate the cross section in low momentum bins
• Next step: CC0π cross section in muon and proton kinematics
• Can give more and new information on nuclear effects
• Nuclear effects are very difficult to model
• Need to be less dependent on simulation
$\nu_\mu$ CC0$\pi$ using $\mu+p$ kinematics

Selection and analysis strategy:

- Check if there are zero, one or more than one protons in the final state;
- Increase the angular acceptance for high-angle and backward-going muons using the timing information between the sub-detectors;
- Used a maximum likelihood fit;
- Background (CC resonant and CC DIS) constrained with two sidebands.
\( \nu_\mu \) CC0\( \pi \) using \( \mu + p \) kinematics

- Cross section extracted as function of the muon momentum and angle for CC0\( \pi \)-0\( p \)
- Cross section extracted as function of the muon and proton angle and muon momentum for CC0\( \pi \)-1\( p \) with momentum greater than 500 MeV/c
- Observed interesting excess over GENIE (w/o 2p2h)

Publication in preparation!

true cos(\( \theta_\mu \)): 0.98

true cos(\( \theta_p \)): 0.8 1, true cos(\( \theta_p \)): 0.3 0.8

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$\nu_\mu$ CC0\pi using $\mu+p$ kinematics

- Cross section extracted also as a function of the number of protons with momentum greater than 500 MeV/c
- Observed interesting excess over GENIE (w/o 2p2h)
- More comparison under preparation

Publication in preparation!
$\nu_{\mu} CC0\pi$ using single transverse variables

What are single transverse variable?

Without nuclear effect

\[ p_{T}^{l} = -p_{T}^{p} \]

With nuclear effect

\[ p_{T}^{l} \neq -p_{T}^{p} \]

Deviation of $\delta p_{T}$ and $\delta \varphi_{T}$ from zero and of $\delta \alpha_{T}$ from a flat distribution indicative of nuclear effects

\( \nu_\mu \) CC0\( \pi \) with single transverse variables

Analysis strategy:

- Same selection used for CC0\( \pi \) with proton kinematics

- Measure flux-integrated cross section in bins of single transverse variable

- Restrict the phase space essential to mitigate model-dependence:
  - \( p_\mu > 250 \text{ MeV}/c \quad \cos\theta_\mu > -0.6 \)
  - \( 450 \text{ MeV}/c < p_p < 1 \text{ GeV}/c \quad \cos\theta_p > 0.4 \)

- Cross section extracted using a maximum likelihood fit with a regularization method

Publication in preparation!
ν_μ CC0π with single transverse variables

**Publication in preparation!**

Data strongly disfavor RFG in favor of LFG and Spectral Function

GIBUU with very different FSI seems close to data

GENIE shape in first bin of each STV related to FSI model ("hA")

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\( \nu_\mu \) CC0\( \pi \) with single transverse variables

The tails in \( \delta p_T \) and \( \delta \phi_T \) and the extent of the rise at large \( \delta \alpha_T \) partially isolate the effects of Fermi Motion from 2p2h.

Publication in preparation!
\[\nu_\mu \text{ CC0}\pi \text{ with inferred proton kinematics}\]

Analysis strategy:

- Under hypothesis of stationary target and elastic scattering can infer proton kinematics from measured \(\mu\).
- Non-zero imbalance between inference and measured proton indicates presence of nuclear effects or CC-non-QE interaction.
- Same selection used for CC0\(\pi\) with proton kinematic.

\[
\begin{align*}
\Delta p_p &= |p_p^{\text{inferred}}| - |p_p^{\text{measured}}| \\
\Delta \theta_p &= \theta_p^{\text{inferred}} - \theta_p^{\text{measured}} \\
|\Delta p_p| &= |p_p^{\text{inferred}} - p_p^{\text{measured}}|
\end{align*}
\]
Ongoing measurements

- $\nu_\mu$ CC Inclusive water over carbon ratio:
  - Use both FGDs
  - Cross section extracted in $\nu$ Energy

- $\nu_\mu$ CC Inclusive on water using INGRID
  - Use INGRID new water module
  - Cross section extracted in $\mu$-kinematics

- $\nu_\mu$ CC0$\pi$ water over carbon ratio:
  - Use FGD2 water layers
  - Cross section extracted using matrix inversion method and extended binned likelihood in $\mu$-kinematics
  - Next step: FGD1-FGD2 joint-fit: mitigate the water-carbon migration
Ongoing measurements

- $\nu_\mu - \bar{\nu}_\mu$ CC0$\pi$ on CH:
  - Joint fit of $\nu_\mu - \bar{\nu}_\mu$ CC0$\pi$ cross section using extended binned likelihood
  - Cross section extracted in $\mu$-kinematics
  - Evaluation of sum, difference and asymmetry

- $\bar{\nu}_\mu$ CC0$\pi$ on water:
  - Use P0D water layers
  - $\nu_\mu$ CC0$\pi$ cross section using extended binned likelihood
  - Cross section extracted in $\mu$-kinematics

- $\bar{\nu}_\mu$ CC0$\pi$ on CH:
  - Use INGRID proton module
  - Cross section extracted in $\mu$-kinematics
List of published measurements

- Phys.Rev. D87 (2013) no.9, 092003, “Measurement of the inclusive $\nu_\mu$ charged current cross section on carbon in the near detector of the T2K experiment”
- Phys.Rev. D90 (2014) no.7, 072012, “Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear de-excitation $\gamma$ rays”
- Phys.Rev. D91 (2015) no.11, 112002, “Measurement of the $\nu_\mu$ charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam”
- Phys.Rev. D93 (2016) no.7, 072002, “Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector”
- Phys.Rev. D95 (2017) no.1, 012010, “First measurement of the muon neutrino charged current single pion production cross section on water with the T2K Near Detector”
- Phys.Rev.D96 052001 (2017), “Measurement of $\bar{\nu}_\mu$ and $\nu_\mu$ charged current inclusive cross sections and their ratio with the T2K off-axis near detector”
Summary

• T2K near detectors provide a perfect opportunity to make precise cross-section measurements

• New inclusive cross-section measurement has been developed using new selection

• Measurement of the proton kinematics and single transverse variables very important to tune the model

• Many results with water as target are coming!

• Many anti-neutrino results in the near future!
Thank you for your attention
Backup
# Event generators: details

<table>
<thead>
<tr>
<th></th>
<th><strong>NEUT 5.3.2</strong></th>
<th><strong>GENIE 2.8.0</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCQE</strong></td>
<td>SF (Benhar et al., 2000)</td>
<td>RFG (Bodek et al., 1981)</td>
</tr>
<tr>
<td></td>
<td>BBA05 (Bradford et al., 2005)</td>
<td>BBA05 (Bradford et al., 2005)</td>
</tr>
<tr>
<td></td>
<td>$M_{A^{QE}} = 1.21 \text{ GeV/c}^2$</td>
<td>$M_{A^{QE}} = 0.99 \text{ GeV/c}^2$</td>
</tr>
<tr>
<td></td>
<td>$p_F^{[^{12}\text{C}]} = 217 \text{ MeV/c}$</td>
<td>$p_F^{[^{12}\text{C}]} = 221 \text{ MeV/c}$</td>
</tr>
<tr>
<td></td>
<td>$E_B^{[^{12}\text{C}]} = 25 \text{ MeV}$</td>
<td>$E_B^{[^{12}\text{C}]} = 25 \text{ MeV}$</td>
</tr>
<tr>
<td><strong>2p2h</strong></td>
<td>Nieves et al., 2011</td>
<td>-</td>
</tr>
<tr>
<td><strong>CCRES</strong></td>
<td>$W &lt; 2 \text{ GeV}$</td>
<td>$W &lt; 1.7 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>FF (Graczyk et al., 2008)</td>
<td>FF (Kuzmin et al., 2016)</td>
</tr>
<tr>
<td><strong>CCDIS</strong></td>
<td>$W &gt; 1.3 \text{ GeV} \text{ (w/o single } \pi)$</td>
<td>$W &gt; 1.7 \text{ GeV}$ (for $W &lt; 1.7 \text{ GeV}$ is tuned)</td>
</tr>
<tr>
<td></td>
<td>GRV98 PDF (Glück et al. 1998)</td>
<td>GRV98 PDF (Glück et al. 1998)</td>
</tr>
<tr>
<td></td>
<td>BY corr. at low $Q^2$ (Bodek et al. 2003)</td>
<td>BY corr. at low $Q^2$ (Bodek et al. 2005)</td>
</tr>
<tr>
<td><strong>Hadronization</strong></td>
<td>$W &lt; 2 \text{ GeV}$</td>
<td>$W &lt; 2.3 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>KNO scaling (Koba et al. 1972)</td>
<td>AGKY (Koba et al. 1972)</td>
</tr>
<tr>
<td></td>
<td>$W &gt; 2 \text{ GeV}$</td>
<td>$2.3 \text{ GeV} &lt; W &lt; 3 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td>PYTHIA/JETSET</td>
<td>AGKY (Koba et al. 1972) + PYTHIA/JETSET</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$W &gt; 3 \text{ GeV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PYTHIA/JETSET</td>
</tr>
<tr>
<td><strong>FSI</strong></td>
<td>Intra-nuclear cascade</td>
<td>Intra-nuclear cascade (INTRANUKE hA)</td>
</tr>
</tbody>
</table>
\( \nu_\mu \) CC Inclusive on CH

-1 < \( \cos \theta_\mu \) < -0.25

0.45 < \( \cos \theta_\mu \) < 0.6

0.8 < \( \cos \theta_\mu \) < 0.87

0.96 < \( \cos \theta_\mu \) < 0.985

-0.25 < \( \cos \theta_\mu \) < 0.25

0.6 < \( \cos \theta_\mu \) < 0.71

0.87 < \( \cos \theta_\mu \) < 0.92

0.985 < \( \cos \theta_\mu \) < 1

0.25 < \( \cos \theta_\mu \) < 0.45

0.71 < \( \cos \theta_\mu \) < 0.8

0.92 < \( \cos \theta_\mu \) < 0.96

T2K preliminary

DATA FIT W/ NEUT
DATA FIT W/ GENIE
\( \nu_\mu \) CC [ NEUT -> RFG ]
\( \nu_\mu \) CC [ NUWRO -> LFG ]
QE
2p2h
RES
DIS
COH
$\nu_\mu$ CC Inclusive on CH

![Graphs showing data and model distributions for different ranges of $\cos \theta_\mu$ with corresponding $p_\mu$ values.](image)

- $-1 < \cos \theta_\mu < -0.25$
- $-0.25 < \cos \theta_\mu < 0.25$
- $0.25 < \cos \theta_\mu < 0.45$
- $0.45 < \cos \theta_\mu < 0.6$
- $0.6 < \cos \theta_\mu < 0.71$
- $0.71 < \cos \theta_\mu < 0.8$
- $0.8 < \cos \theta_\mu < 0.87$
- $0.87 < \cos \theta_\mu < 0.92$
- $0.92 < \cos \theta_\mu < 0.96$
- $0.96 < \cos \theta_\mu < 0.985$
- $0.985 < \cos \theta_\mu < 1$

DATA
- GENIE 2.8.0
- NEUT 5.3.2
- CCQE
- CCRESC
- CCRES
- CCDIS
- 2p2h
- BCKG

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$\nu_\mu$ CC Inclusive on CH

\[ -1 < \cos \theta_\mu < -0.25 \]
\[ 0.45 < \cos \theta_\mu < 0.6 \]
\[ 0.8 < \cos \theta_\mu < 0.87 \]
\[ 0.96 < \cos \theta_\mu < 0.985 \]

\[ -0.25 < \cos \theta_\mu < 0.25 \]
\[ 0.6 < \cos \theta_\mu < 0.71 \]
\[ 0.87 < \cos \theta_\mu < 0.92 \]

\[ 0.25 < \cos \theta_\mu < 0.45 \]
\[ 0.71 < \cos \theta_\mu < 0.8 \]
\[ 0.92 < \cos \theta_\mu < 0.96 \]

\[ \mu p^{-1} \times 10 \]

Relative errors:

-0.25 < $\mu_\theta$ < 0.25
STV and FSI

NuWro 11, 0.6 GeV $\nu_\mu$ on C, CC0$\pi$, FSI Off

Comparison of initial state nuclear models

T2K preliminary

Effect of nucleon final-state interactions

STV and MAQE

**Comparison of 2p2h and QE shape (separately normalised)**

**T2K preliminary**

**NuWro 11, 0.6 GeV $\nu_\mu$ on C, CC0\(\pi\), FSI On, LFG**

**Effect of varying the nucleon axial mass**

**NuWro 11, 0.6 GeV $\nu_\mu$ on C, CC0\(\pi\), FSI On, LFG**
Extended binned likelihood fit

\[ \chi^2 = \chi^2_{\text{stat(fit goodness)}} + \chi^2_{\text{syst(penalty)}} + \chi^2_{\text{reg}}. \]

\[ \chi^2_{\text{stat}} = \sum_{j}^{\text{recobins}} 2(N_{j}^{MC} - N_{j}^{obs} + N_{j}^{obs} \ln \frac{N_{j}^{obs}}{N_{j}^{MC}}) \]

\[ \chi^2_{\text{syst}} = (\bar{a}_{\text{syst}} - \bar{a}_{\text{prior}})(V_{\text{cov}})^{-1}(\bar{a}_{\text{syst}} - \bar{a}_{\text{prior}}) \]

\[ \chi^2_{\text{reg}} = p_{\text{reg}} \sum_{i} (c_{i} - c_{i-1})^2 \]