To CCQE and Beyond

Results and prospects of latest CCQE-like analyses from the T2K near detectors

Stephen Dolan

For the T2K Collaboration

s.dolan@physics.ox.ac.uk
Overview

• The T2K experiment
• Motivation for measuring CCQE-like cross sections
• Flux and near detectors’ details
• NuFact 15 recap
• CC0π on water cross section using the PØD
• FGD1 analyses using proton information
  - CC0π using proton kinematics
  - CC0π using inferred kinematic imbalance
  - CC0π using transverse kinematic imbalance
• Other analyses
  - CC0π measurements from ν + ν̄ joint fit
  - CC0π at INGRID
  - Extraction of free nucleon cross section using δp_{TT}
• Summary and future work
The T2K Experiment

**Far Detector**
Super-Kamiokande

**Near Detectors**
*Off-Axis: ND280*
*On-Axis: INGRID*

Super-Kamiokande

Muon Neutrino Beam

Mt.Ikenoyama 1,360m

sea level 1,000m

295km
Data Collection

- Continuous rise in beam power from ~225 kW (2014) to ~420 kW (2016)
- Using this to make world leading measurements of oscillation parameters (see talk by Benjamin Quilain – WG1, Tuesday, 14:00)

27 May 2016
POT total: $1.510 \times 10^{21}$

\( \nu\)-mode POT: $7.57 \times 10^{20}$ (50.14%)
\( \bar{\nu}\)-mode POT: $7.53 \times 10^{20}$ (49.86%)
Neutrino Scattering and OA

• Oscillation analysis (OA) requires $E_\nu$ spectrum (or similar)

• Can reconstruct using observed $\mu$ assuming stationary target and elastic scattering

$$E_{\nu,\text{rec}} = \frac{m_p^2 - m_n^2 - m_\mu^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos(\theta_\mu))}$$

Bias due to Fermi Moton and CCnonQE components
Neutrino Scattering and OA

- Essential to understand $\nu - N$ scattering to control the bias
  - CCQE particularly important for T2K
- Probe using CC0$\pi$ cross sections
  - Less FSI model dependence
  - Simplest channel to probe nuclear effects.

**Interaction Modes in CC0$\pi$ (NEUT):**

- CCQE 80.60%
- 2p2h 12.11%
- RES 6.91%
- Other 0.38%

\[ \text{Interaction Modes in CC0} \pi \text{ (NEUT):} \]

\[ \text{CCQE } 80.60\% \]
\[ \text{2p2h } 12.11\% \]
\[ \text{RES } 6.91\% \]
\[ \text{Other } 0.38\% \]
The Flux

- Off-axis $\nu_\mu$ beam
  - Tightly-peaked at 600 MeV 2.5° off-axis towards SK
  - Low contamination from non-$\nu_\mu$ components
  - Flux estimation aided by hadron production measurements from NA61/SHINE at CERN (see talk at WG1+2 session on Thursday 10:45)

Phys. Rev. D 87, 012001

Peak: 0.6 GeV
Peak: 1.1 GeV

Phys. Rev. D 87, 012001
INGRID (on axis)

On Axis ~ 1.1 GeV

Peak $E_\nu$

Off Axis ~ 0.6 GeV

INGRID Modules: Stacks of scintillator bars interleaved with Iron sheets.

Front View:

Top View:

Proton Module: Fully active polycarbonate scintillator tracker.
ND280 (off axis)

On Axis ~ 1.1 GeV

Peak $E_{\nu}$

Off Axis ~ 0.6 GeV

$\pi^0$ detector (PØD): Interwoven heavy targets, scintillator and drainable water bags affords water subtraction measurements.

UA1 Magnet:
Provides 0.2 T field.

Fine-Grained Detectors (FGD 1/2):
Polycarbonate scintillator bars provide tracking & target mass. FGD 2 also contains water target layers.

Time Projection Chambers (TPC): Excellent tracking allows high-resolution charged-particle momenta and accurate particle ID.
From Reconstruction to Truth

- Measure *selected* number of CC0$\pi$ events in bins of a *reconstructed* quantity
- Need the *total* number of CC0$\pi$ events in bins of a *true* quantity

Two Methods

**Template Fit**

- Use MC to build unsmearing matrix
- Apply unsmearing matrix + efficiency correction to data

**Matrix Unfold**

- True bin $\rightarrow$ Reco Template
- Vary MC template norm to fit data
- Apply efficiency correction
Previously at NuFact

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- FGD1 analyses using proton information
  - CC0\(\pi\) using proton kinematics
  - CC0\(\pi\) using inferred kinematic imbalance
  - CC0\(\pi\) using transverse kinematic imbalance

- Other analyses
  - CC0\(\pi\) measurements from \(\nu + \bar{\nu}\) joint fit
  - CC0\(\pi\) at INGRID
  - Extraction of free nucleon cross section using \(\delta p_{TT}\)

- Summary and future work
INGRID On-Axis CCQE Result

- Carbon Target

- 2-bin measurement in neutrino energy

- Split into 1- and 2-track samples

- Used cuts on muon and proton kinematic variables to enhance purity

- Result depends on nuclear model used and the presence of 2p2h

ND280 Off-Axis CC0\(\pi\) Result

- Uses FGD1 as a CH target alongside TPC for tracking
- Flux integrated double-differential CC0\(\pi\) cross section in final state muon kinematic variables (\(p_\mu, \cos(\theta_\mu)\))
- Split into two analyses with different selection and cross-section extraction strategies - Good agreement
- Results compared to 2p2h models

**Detector:** ND280 – FGD1  **Target:** Carbon  **Signal:** CC0\(\pi\)  **Unfolding:** Matrix + Fit  **Status:** Phys. Rev. D 93, 112012

ND280 Off-Axis $\text{CC0}\pi$ Result

- Results compared to Martini et al. model with(red)/without(black) 2p2h
- Data prefer a 2p2h contribution

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC0\pi  
Unfolding: Matrix + Fit  
Status: Phys. Rev. D 93, 112012
What next?

• Would like to disentangle the role of separate nuclear effects

• Current results provide an important piece of the puzzle

• Now need complementary measurements ...
Ongoing measurements

• **CC0π** water cross section in muon kinematics
  - Measure of A-scaling, invaluable for OA

• **CC0π** measurement using muon + proton kinematics
  - Enhanced sensitivity to nuclear effects

• **CC0π** measurement using composite variables
  - Imbalance between the proton and muon can be a precision probe of nuclear effects

• **CC0π** using INGRID proton module
  - Model-independent measurement at higher $E_\nu$

• **CC0π** neutrino/anti-neutrino joint fit
  - $\sigma_{np-nh}/\sigma_{CCQE}(E_\nu)$ is substantially different for $\nu_\mu$ and $\bar{\nu}_\mu$

• Measurement of free-nucleon cross section using $\delta p_{TT}$

N.B: T2K employs a blind cross-section analysis strategy
- Ongoing or recently completed analyses not applied to real data (remain “blind”)

New PØD analysis

FGD1 ongoing analyses using proton information

Other FGD1 / INGRID analyses
PØD - CC0π on water

- The T2K experiment
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**CC0π water cross section**

- Isolate CC0π events starting in the PØD
- Separate data taking periods into when PØD water target is full/empty → subtract to get water cross section

**Event Selection**

- Uses PØD as a target, requires TPC for tracking
- Aim to find single μ only
- Two control samples
  - CC1π: look for 2 PØD tracks and Michel e⁻
  - CCOther: look for >2 PØD tracks

Detector: ND280 – PØD  
Target: Water  
Signal: CC0π  
Unfolding: Matrix  
Status: Unblind
CC$0\pi$ water cross section

- Construct flux integrated double-differential cross section
- Results compared to GENIE and NEUT predictions
- Can also compare to FGD1 CC$0\pi$ on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross section ratio

Detector: ND280 – PØD
Target: Water
Signal: CC$0\pi$
Unfolding: Matrix
Status: Unblind

Contact:
Tianlu Yuan
tianlu.yuan@colorado.edu
CC0$\pi$ water cross section

- Compare results to RPA/RPA+2p2h on Carbon
- Data prefer 2p2h contribution
- Difficult to untangle role of A-Scaling

Detector: ND280 – PØD  
Target: Water  
Signal: CC0$\pi$  
Unfolding: Matrix  
Status: Unblind

Stephen Dolan  
NuFact 2016, Quy Nhon, Vietnam
FGD1 - CC0π + Np

• The T2K experiment
• Motivation for measuring CCQE-like cross-sections
• Flux and near detectors details
• NuFact 15 recap
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• FGD1 analyses using proton information
  - CC0π using proton kinematics
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FGD1 CC0π Analyses

**Signal**

- Require one \(\mu\)-like track or one \(\mu\)-like and \(p\)-like track(s) starting in FGD1
- Use a Michel electron tag and ECal EM shower veto to reject \(1\pi\) backgrounds
- Use of many samples gives wide kinematic acceptance

**Sidebands**

- Require extra \(\pi\)-like track(s)

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Stephen Dolan  
NuFact 2016, Quy Nhon, Vietnam  
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CC0π using $\mu + p$ kinematics

- $\mu$ kinematics only tell us everything about $\nu + N$ scattering assuming a stationary target and an elastic scatter.

We may see a low-momentum, high-angle muon in a CC0π selection.

- Measuring $p$ kinematics allows us to move beyond these assumptions.

But this could come from ...

- A low $E_\nu$ and transverse $p_F$
- A high $E_\nu$ and large backward $p_F$
- A high $E_\nu$ and large $Q^2 \rightarrow$ RES with $\pi$ absorption
CC$0\pi$ using $\mu + p$ kinematics

- Aim to measure CC$0\pi$ cross section in bins of $\cos(\theta_\mu), \cos(\theta_p), p_p$ in samples with proton
- Use $\cos(\theta_\mu), p_\mu$ when no proton reconstructed
- Also measure proton multiplicity
- Construct flux-integrated double/triple-differential cross-section
- Fake data: GENIE*
- Nominal MC: NEUT

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC$0\pi$ (+Np)  
Unfolding: Fit  
Status: Blind

* GENIE fake data contains $5.73 \times 10^{20}$ POT ~T2K runs 2-4
CC0_{\pi} and inferred kinematic imbalance

- Can use proton and muon kinematics to form variables specifically engineered to probe nuclear effects

- Under **stationary target** and **elastic scattering** assumptions 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

- Measure:
CC0\(\pi\) and inferred kinematic imbalance

- CC1\(\pi\) sideband using Michel \(e^-\) tag
- Measure inferred kinematics in bins of \(p_\mu, \cos(\theta_\mu)\)
- Fake data: GENIE*
- Nominal MC: NEUT

* GENIE fake data contains \(5.73 \times 10^{20} \ P0T \sim T2K \ runs \ 2-4\)

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC0\(\pi\)+Np  
Unfolding: Matrix  
Status: Blind

Contact: Jiae Kim  
jiae@phas.ubc.ca
Single Transverse Variables

\[ \nu_\mu + n \rightarrow \mu + p \]

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC0\pi + Np  
Unfolding: Fit  
Status: Blind

No nuclear Effects
No nuclear Effects

\[ p_T^l = -p_T^p \]

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC0\pi+Np  
Unfolding: Fit  
Status: Blind
Single Transverse Variables

With Nuclear Effects

Detector: ND280 – FGD1
Target: Carbon
Signal: CC0π+Np
Unfolding: Fit
Status: Blind

$p_T^l \neq -p_T^p$
Single Transverse Variables

Detector: ND280 – FGD1  Target: Carbon  Signal: CC0\pi+Np  Unfolding: Fit  Status: Blind

With Nuclear Effects
CC0\(\pi\) and transverse imbalance

- 3 single transverse variables (STV) characterise imbalance in plane transverse to incoming \(\nu\) *
- For CCQE case any deviation from \(\delta p_T = 0, \delta \phi_T = 0\) is indicative of nuclear effects
- Minimal dependence on \(E_\nu\) for \(\delta p_T\) and \(\delta \alpha_T\)

*Phys. Rev. C 94, 015503
CC0π in STV - Fermi Motion and FSI

- Moving from CCQE→CC0Pi+Np, STV still a probe of nuclear effects

**NuWro, 0.6 GeV νμ on C, CC0π, FSI Off**

**Quasi-real CC0Pi selection**, keep events within rough ND280 acceptance:
- No Pions, 1 Muon, >0 Protons. \( p_\mu > 250 \text{ MeV}, p_p > 450 \text{ MeV}, \cos(\theta_\mu) > -0.6, \cos(\theta_p) > 0.4 \)

**Detector**: ND280 – FGD1  **Target**: Carbon  **Signal**: CC0π+Np  **Unfolding**: Fit  **Status**: Blind

CC0\(\pi\) in STV - 2p2h and \(M_A\)


- STV shape invariant with \(M_A\)
  - No ambiguity over \(M_A\) or nuclear effect contributions (MiniBooNE \(M_A\) puzzle)

<table>
<thead>
<tr>
<th>Detector: ND280 − FGD1</th>
<th>Target: Carbon</th>
<th>Signal: CC0(\pi)+Np</th>
<th>Unfolding: Fit</th>
<th>Status: Blind</th>
</tr>
</thead>
</table>

NuWro, 0.6 GeV \(\nu_\mu\) on C, CC0\(\pi\), FSI On, LFG
**CC0π in STV**

- Restrict cross section to ND280 acceptance
- Use a regularised template fit to unfold
  - Useful to deal with large STV smearing
  - Regularisation insists cross-sections should be smooth

- Fake data: GENIE*
- Nominal MC: NEUT

\[
\begin{align*}
  p_\mu &> 250 \text{ MeV/c} \\
  \cos(\theta_\mu) &> -0.6 \\
  450 \text{ MeV/c} &< p_\mu < 1 \text{ GeV/c} \\
  \cos(\theta_p) &> 0.4
\end{align*}
\]

* GENIE fake data contains \(5.73 \times 10^{20} \text{ POT} \sim \text{T2K runs 2-4} \)

**Detector:** ND280 – FGD1  \hspace{1cm} **Target:** Carbon  \hspace{1cm} **Signal:** CC0π+Np  \hspace{1cm} **Unfolding:** Fit  \hspace{1cm} **Status:** Blind

Contact: Stephen Dolan  
s.dolan@physics.ox.ac.uk
FGD - CC0π + Np

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- Summary and future work
Other Analyses

- **CC0π ν + ν̄ joint fit**  
  - Contact: Ciro Riccio, riccioc@na.infn.it
  - 2p2h contribution is different for ν and ν̄ *
  - Aim to extract ν̄ double-differential cross section in pμ, cos(θμ) with ν + ν̄ sum, difference, asymmetry

Detector: ND280 – FGD1  
Target: Carbon  
Signal: CC0π  
Unfolding: Fit  
Status: Blind

- **INGRID CC0π Analysis**  
  - Contact: Benjamin Quilain, quilain@llr.in2p3.fr
  - Extract CC0π on Carbon in pμ, cos(θμ) in proton module (Eνpeak ~ 1.2 GeV)
  - Complements similar FGD1 analysis (Eνpeak ~ 0.6 GeV)

Detector: INGRID  
Target: Carbon  
Signal: CC0π  
Unfolding: Matrix  
Status: Blind

- **CC1π1p on hydrogen**  
  - Use δpTT to isolate H in composite target **
  - Measure Δππ production
  - Free of nuclear effects

Detector: ND280 – FGD1  
Target: Hydrogen  
Signal: CC1π1p  
Unfolding: Fit  
Status: Blind

** XG Lu: PHYSICAL REVIEW. D 92, 051302(R)  
Contact: David Coplowe, david.coplowe@lmh.ox.ac.uk

* M Martini: PHYSICAL REVIEW C 80, 065501, PHYSICAL REVIEW C 81, 045502

Contact:
Ciro Riccio, riccioc@na.infn.it
Benjamin Quilain, quilain@llr.in2p3.fr
David Coplowe, david.coplowe@lmh.ox.ac.uk

** T2K Work In Progress

** XG Lu: PHYSICAL REVIEW. D 92, 051302(R)
Contact: David Coplowe, david.coplowe@lmh.ox.ac.uk
Summary

• T2K is measuring cross-sections of exclusive final-state topologies
  - This talk: CC0\(\pi\)
  - Talk by Erez Reinherz-Aronis: CCInc, CC1\(\pi^+\), NCE (WG2, Friday, 10:45)

• Lots going on in T2K cross-section analyses – many results coming soon!

• First CC0\(\pi\) water cross section has been measured

• Many new techniques in use to complement each other and existing results
  - Analyses specifically engineered to probe nuclear effects
The Future
Thank you for listening

cảm ơn
Ongoing measurements

- **CC0π** water cross-section in muon kinematics
  - Measure of A scaling, invaluable for OA
  - Detector: ND280 – PØD
  - Target: Water
  - Signal: CC0π
  - Unfolding: Matrix
  - Status: Unblind

- **CC0π** measurement using muon + proton kinematics
  - Enhanced sensitivity to nuclear effects
  - Detector: ND280 – FGD1
  - Target: Carbon
  - Signal: CC0π(+Np)
  - Unfolding: Fit
  - Status: Blind

- **CC0π** measurement using inferred kinematics
  - Imbalance as a precision probe of nuclear effects
  - Detector: ND280 – FGD1
  - Target: Carbon
  - Signal: CC0π+Np
  - Unfolding: Matrix
  - Status: Blind

- **CC0π** measurement using STV
  - Imbalance as a precision probe of nuclear effects
  - Detector: ND280 – FGD1
  - Target: Carbon
  - Signal: CC0π+Np
  - Unfolding: Fit
  - Status: Blind

- **CC0π** using INGRID proton module
  - Model independent measurement at higher $E_\nu$
  - Detector: ND280 – FGD1
  - Target: Carbon
  - Signal: CC0π
  - Unfolding: Fit
  - Status: Blind

- **CC0π** neutrino/anti-neutrino joint fit
  - $\sigma_{np-nh}/\sigma_{CCQE}(E_\nu)$ is substantially different for $\nu_\mu$ and $\bar{\nu}_\mu$
  - Detector: INGRID
  - Target: Carbon
  - Signal: CC0π
  - Unfolding: Matrix
  - Status: Blind

- Measurement of free-nucleon cross-section using $\delta p_{TT}$
  - Detector: ND280 – FGD1
  - Target: Hydrogen
  - Signal: CC1π1p
  - Unfolding: Fit
  - Status: Blind

New PØD analysis
Ongoing FGD1 analyses using proton information
Other FGD1 / INGRID analyses
BACKUPS
Likelihood Fitting

- Each true bin has some template in reconstructed bins.
- Varying the number of events in a true bin applies a normalisation factor to the corresponding reconstructed template.
- Vary templates until reconstructed distribution best fits the data.

I.e. minimise:

$$\chi^2_{stat} = \sum_{j}^{\text{reco bins}} 2(N_j^{MC} - N_j^{obs}) + N_j^{obs} \ln \left( \frac{N_j^{obs}}{N_j^{MC}} \right)$$
Fitting summary

- The best fit parameters are those that minimise the following likelihood:

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

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

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

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

• Add term to the fit

$$\chi^2_{syst} = (\tilde{a}_{syst} - \tilde{a}_{prior})(V_{cov})^{-1}(\tilde{a}_{syst} - \tilde{a}_{prior})$$

• The fit is able to constrain systematic parameters (mostly through control regions) but picks up a penalty if it moves far from the prior.

• **Detector Systematics** (e.g. TPC momentum resolution):
  • Make many toy experiments, each varying detector properties we are unsure of.
  • Produce covariance matrix which tells the fit the overall uncertainty in the number of events in each bin and how this correlates between bins.

• **Model Systematics** (e.g. $M_{A,RES}$, pion FSI):
  • Use covariance matrix produced from external data fits which tells us the uncertainty on model parameters.
  • Make splines that tell the fitter how to reweight the MC if we alter model parameters that describe the background In the fit.

• **Flux Systematics**:
  • Use covariance matrix produced by beam group which tells us the uncertainty on the flux in bins of neutrino energy.
  • Store the neutrino energy of each event in the fit.
Regularising the fitter

- Reaching a fit result is an ‘ill posed problem’ -> there are often degeneracies in the fit solutions.
- E.g. can often lower a particular template scaling parameter so long as we raise the adjacent parameters
  - Strong anti correlations between bins!
- Can resolve with regularisation:
  - Add another term
  - Regularisation loosely ties bins together
- But how to choose the best $p_{reg}$?
- Want to have the maximum smoothing impact with the minimal effect on the $\chi^2$ of the fit.
  - This problem is well studied, can choose $p_{reg}$ using the “L-Curve”.
- Toy example fitting a Gaussian from a flat prior in backups.

$\chi^2_{reg} = p_{reg} \sum_i (c_i - c_{i-1})^2$
Regularising the fitter

Regularisation

- Penalty term in my fit from regularisation:

\[ \chi_{reg}^2 = p_{reg} \sum_i (c_i - c_{i-1})^2 \]

This looks like a rather non \( \chi^2 \)-like term slapped onto the fit...

But could also write it as:

\[ \chi_{reg}^2 = p_{reg} (p - p_{prior})(V_{cov})^{-1}(p - p_{prior}) \]

\[
(V_{cov})^{-1} = \begin{bmatrix}
1 & -1 & 0 & \cdots & 0 \\
-1 & 2 & -1 & \cdots & 0 \\
0 & -1 & 2 & \ddots & 0 \\
\vdots & \vdots & \ddots & \ddots & -1 \\
0 & 0 & 0 & -1 & 1 \\
\end{bmatrix}
\]

Or to make the matrix non-singular:

\[
(V_{cov})^{-1} = \begin{bmatrix}
1 & -1 & 0 & \cdots & 0 \\
-1 & 2 & -1 & \cdots & 0 \\
0 & -1 & 2 & \ddots & 0 \\
\vdots & \vdots & \ddots & \ddots & -1 \\
0 & 0 & 0 & -1 & 2 \\
\end{bmatrix}
\]

- Applying a penalty term in this way makes regularisation enter the fit identically to model parameters.

- In fact in some sense the application of regularisation is a model that says cross sections should be smooth relative to their prior.

- The uncertainty in the smoothness model is then \( 1/\sqrt{p_{reg}} \).
PØD - CC0\(\pi\) on water

**Analysis Strategy**
- MC used to generate purity, efficiency, and unfold data
- Water in Result → Subtract → Water out Result
- Identical procedure for water-out
- Sidebands for data-driven background constraint

**Systematic Errors**
- Corrections include: flux tuning, interaction model correction, EMC effect tuning, and pile-up correction
- Systematics include: flux uncertainties, interaction model uncertainties, and detector uncertainties
- Numerical propagation via throws of perturbed MC distributions
- Largest source is the flux uncertainty

**PØD**
- PØD-ECals consist of alternating layers of scintillator and lead
- Water target consists of alternating layers of scintillator, brass, and water
- Scintillation measured with wavelength-shifting fiber, readout via MPPCs
- Water can be drained

**Equation**
- The number of events on oxygen is given by
  \[ N_i^D = \frac{U_i^W}{U_i^W} \frac{N_i^W}{N_i^W} \]
- \( U_i^W \) and \( U_i^W \) indicate true and recon bins,
- \( N_i^W \) is the number of events in the bin,
- \( R \) the flux normalization ratio,
- \( \varepsilon \) the selection efficiency, and \( U \) the unfolding matrix.

Then the cross section is

\[ d\sigma = \frac{N_i^D}{F^*N_nD_i} \]

where \( F \) is the integrated flux, \( N_n \) the number of nucleons, and \( D_i \) the bin width.
PØD - CC0π on water

Less forward-going

More forward-going

detector
mass
flux
cross-section
fsi
statistical (mc)
statistical (data)
NEUT (tuned)
data (unfolded)
GENIE
PØD - CC0π on water

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

CC0π on water

Martini CCQE w. RPA on C

Martini CCQE w. RPA+2p2h on C
PØD - CC0π on water

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

T2K Preliminary

CC0π on water

CC0π on carbon (FGD1)
FGD2 Oxygen Cross Section

- Measure the cross section on **oxygen** and **carbon** simultaneously fitting events starting in FG2 water and carbon layers

\[
N = \left( c_i N_{i,\alpha,MC}^{\text{sig},C} + o_i N_{i,\alpha,MC}^{\text{sig},O} + N_{i,\alpha,MC}^{\text{bkg}} \right) \times f(r_{\alpha}^{\text{det}}, a_{\alpha}^{\text{model}}, \Phi)
\]

- **Carbon**
- **Oxygen**

\( i = p_\mu, \cos \theta_\mu \) bins
\( \alpha = X \) and \( Y \) FG2 layers

- **Contact:** Margherita Buizza Avanzini
  buizza@llr.in2p3.fr

- Extract **flux integrated Oxygen cross section and ratio oxygen/carbon flux integrated cross sections**

\[
\frac{d\sigma}{dp_\mu} = \frac{o_i N_{MC}^{\text{sig},O}}{\Phi \cdot N_{\text{neutrons}}^{FV,O}} \cdot \Delta p_\mu
\]

\[
\frac{o_i N_{MC}^{\text{sig},O}}{c_i N_{MC}^{\text{sig},C}} \quad \frac{N_{\text{neutrons}}^{FV,O}}{N_{\text{neutrons}}^{FV,C}}
\]
INGRID CC0Pi Analysis

- Select 1 $\mu$-like track beginning in the proton module
- Measure $\theta_\mu^{\text{rec}}$ and $d_\mu^{\text{rec}}$ - distance penetrated through the iron (no B field)
- Unfold into $\theta_\mu^{\text{true}}$ and $p_\mu^{\text{true}}$
- Build double differential cross-section
- With 4 momentum bins and 5 angular bins uncertainty is 10%-20%
- Blind analysis

**NEUT MC, 5.8 \times 10^{20} POT**

- Flux
- XS
- Stat.
- Work-in-progress
CC0Pi $\nu + \bar{\nu}$ joint fit

- 2p2h contribution is different for $\nu$ and $\bar{\nu}$ *
- Comparison of $\nu + \bar{\nu}$ can help identify 2p2h
- Aim to extract $\bar{\nu}$ double differential cross-section in $p_\mu, \cos(\theta_\mu)$ alongside $\nu + \bar{\nu}$ sum, difference and asymmetry
- Uses extra high angle and backward $\mu^+/-$ samples
- Cross-section extraction via a likelihood template fit
- Blind analysis

3.24x10^20 POT

* M Martini: PHYSICAL REVIEW C 80, 065501 (2009), PHYSICAL REVIEW C 81, 045502 (2010)
CC0Pi $\nu + \bar{\nu}$ joint fit measurements

$$c_i^\nu N_i^\nu_{MC CC0\pi}, c_i^\nu N_i^\nu_{MC CC0\pi} = \text{(what we measure) number of CC0\pi events in 'true' muon p, cos}\theta \text{ bins}$$

Extract 3 measurements:

- **CC0\pi $\bar{\nu}$ flux integrated cross-section**

$$\frac{d\sigma^\nu}{dp_\mu \, d\cos\theta_\mu} = \frac{c_i^\nu N_i^\nu_{MC CC0\pi}}{\Phi^\nu \cdot N_{protons}^{FV} \Delta p_\mu \Delta \cos\theta_\mu}$$

- **sum, difference and $\nu-\bar{\nu}$ xsec** → allow to disentangle different terms of xsec (compare with 2p2h models)

$$\frac{d(\sigma^\nu \mp \sigma^\bar{\nu})}{dp_\mu \, d\cos\theta_\mu} = \frac{1}{\Delta p_\mu \Delta \cos\theta_\mu} \left[ \frac{c_i^\nu N_i^\nu_{MC CC0\pi}}{\Phi^\nu \cdot N_{protons}^{FV}} \mp \frac{c_i^\nu N_i^\nu_{MC CC0\pi}}{\Phi^\nu \cdot N_{neutrons}^{FV}} \right]$$

- **asymmetry of $\nu-\bar{\nu}$ xsec** → direct effect on $\delta_{CP}$ measurement

$$\frac{d(\sigma^\nu - \sigma^\bar{\nu})}{d(\sigma^\nu + \sigma^\bar{\nu})} = \frac{c_i^\nu N_i^\nu_{MC CC0\pi}}{(\Phi^\nu \cdot N_{protons}^{FV})} - \frac{c_i^\nu N_i^\nu_{MC CC0\pi}}{(\Phi^\nu \cdot N_{neutrons}^{FV})}$$
\[ \delta p_{TT} \]

\[
\{X, Y\} = \{p, \pi^+\} \text{ for } \nu + p \rightarrow l^- + \Delta^{++}
\]
or \[
\{p, \pi^-\} \text{ for } \bar{\nu} + p \rightarrow l^+ + \Delta^0
\]

FIG. 1. Schematic illustration of the double-transverse kinematics. The incoming and outgoing particle momenta are represented by \( \vec{p}_\nu \) and \( \vec{p}_l \), \( \vec{p}_p \) and \( \vec{p}_x \), respectively. The double-transverse momentum imbalance, \( \delta p_{TT} \), is given by \( p^x_{TT} + p^y_{TT} \) with respect to the axis \( \vec{z}_{TT} \) defined by \( \vec{p}_N \times \vec{p}_l \).

\[ \nu_l + p \rightarrow \mu^+ + \Delta^+, E_{\nu_l} = 1 \text{ GeV} \]

NuWro

\[ \text{H, downscaled by 10} \]

\[ \text{d} \]

\[ \text{He} \]

\[ \text{C} \]

\[ \text{Ar} \]

\[ \text{Pb} \]

Phys. Rev. D 92, 051302(R)
CC1p1π on hydrogen

- Cross-section measurement on H allows measure of \( \sigma(\nu + p) \) without nuclear effects

- Can use \( \delta p_{TT} \) to isolate H content of composite target *

- Aim to measure \( \Delta^{++} \) production on H

* Phys. Rev. D 92, 051302(R)
Reconstructing the Neutrino Direction

Mean Neutrino Parent Decay Point (PDP)

Reconstructed Neutrino Direction

Reconstructed Interaction Vertex

Decay Tunnel

280 m

FGD 1

T2K Work In Progress

T2K Work In Progress

T2K Work In Progress

T2K Work In Progress
Pauli Blocking

\[ \frac{d\sigma}{dQ^2} (10^{-38} \text{ cm}^2 \text{ nucleon}^{-1} \text{ GeV}^{-2}) \]

\[ \times 10^{-3} \]

\[ Q_{QE}^2 \text{ (GeV}^2) \]

\[ \times 10^{-3} \]

\[ \frac{d\sigma}{dp_p} (10^{-38} \text{ cm}^2 \text{ nucleon}^{-1} \text{ GeV}^{-1}) \]

\[ \text{NuWro, ND280 } \nu_\mu C(\text{RFG}) \]

- Nominal
- No PB
- No FSI
- No PB, No FSI

\[ p_p \text{ (GeV)} \]
Neutrino Scattering and OA

Interaction Modes in all CC0π events at ND280 (NEUT):

- CCQE: 80.60%
- 2p2h: 12.11%
- RES: 6.91%
- Other: 0.38%

Interaction Modes in selected 1 ring μ-like events at SuperK (NEUT):

- CCQE: 52.48%
- RES: 13.48%
- 2p2h: 15.12%
- Other: 18.92%
ND280 Off-Axis CC0π Result