Recent neutrino cross-section measurements at T2K

S. Bolognesi
(IRFU, CEA Saclay)
A hot topic...

- Oscillation measurements in Far Detector constrained from Near Detector (xsec x flux)
  - ND→FD extrapolation:
    - different acceptance and target
    - different $E_\nu$ spectrum
    - $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu$
    - rely on models to extrapolate

- Measurement of $\nu$ xsec at ND is experimentally complicated:
  - $E_\nu$ not known: xsec measurement always convoluted with flux → importance of minimization of uncertainties in flux modeling (and/or ratio measurements)
  - $E_\nu$ inferred from final state leptons/hadrons which have limited angular acceptance, threshold on low energy particles, very small info on recoiling nucleus...
What do we need to measure?

Uncertainties in ND→FD extrapolation:

- different $E_\nu$ distribution (because of oscillation) → need to reconstruct the neutrino energy from the final state particles

- different target → A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

- different acceptance → measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND

- different neutrino flavor (because of oscillation) $\nu$ ($\bar{\nu}$) flux has typically a wrong sign component → measure cross-section asymmetries between different neutrino species (e.g., $\nu$ vs $\bar{\nu}$ important for $\delta_{CP}$)
Outline

- Neutrino xsec as a **nuclear physics** problem

<table>
<thead>
<tr>
<th>T2K flux</th>
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<td>Formaggio, Zeller</td>
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<td>arXiv:1305.7513</td>
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- **CC0π** dominant at T2K
  → from the detector measurement (muon+proton) to the incoming neutrino energy

- **CC1π** (+ DIS)
  → how to disentangle Final State Interaction effects

- Impact on present and future oscillation measurements \( \delta_{CP} \): \( \mathbf{V}_{\mu} \)
T2K near detectors

- Iron plates alternated with CH scintillator (+ proton module: fully active scintillator)
- Coarser granularity, not magnetized but larger mass
- Fully magnetized (0.2 T)
- FGD: CH scintillators alternated with H2O
- TPC → good tracking efficiency, resolution (6% $p_t < 1$ GeV) and particle ID
- P0D scintillator with water target

INGRID: on-axis

ND280: off-axis (2.5°)
CC0π: recent results

- Neutrino interactions model tuned from bubble chambers νH data
- modern experiments scattering on heavy target (C,O) → nuclear effects

Charged Current Quasi-Elastic

higher order corrections in nuclear target

Model developed by Martini et al.

- CCQE
- CCQE + 2p2h (multi-nucleon interactions)

νμ n p → μ⁻ p p
νμ n p → μ⁺ n n

ν interactions on **carbon**

0.70 < true cosθμ < 0.80

ν interactions on **water**

0.700 ≤ True-μ cosθμ < 0.800

T2K preliminary
CC0π: models and MC

Measurements still dominated by statistical uncertainty

No universally preferred model or MC

The only way out: increase/improve the experimental data
improve neutrino interaction modelling
Why we need good models?

Neutrino oscillation goes like \(~L/E_\nu\) but we do not measure \(E_\nu\)! We measure the outgoing muon at SuperKamiokande and we infer the neutrino energy on the base of available models.

2p2h events fill the “dip” region sensitive to neutrino oscillation \(\rightarrow\) wrong modelling would cause bias on oscillation parameters.
Various 2p2h models available → completely generic mechanism to include any model in MC simulation: Hadron Tensors

Lookup tables encoding the nuclear physics as a function of transferred quadrimomentum to the nucleus

Nuclear effects important also on single nucleon scattering (screening, binding energy, ...)

Nucleus modeled as a Fermi gas of nucleons: nucleon momentum as a function of its radial position in the nucleus
Large effects from Final State Interaction: re-scattering of the π inside the nucleus (nuclear physics again!)

Cross-section and FSI have different A-dependence → important effect when extrapolation from ND and FD with different material
CC1\(\pi\) recent results

- **T2K FGD1 CC1\(\pi\):** carbon

- **T2K FGD2 CC1\(\pi\):** water and carbon
  
  passive water interleaved with CH scintillator modules
  
  upstream modules CH+H\(_2\)O
  
  downstream modules CH only
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SuperKamiokande events have muons over all angles (4\pi acceptance): backward muons happen for high transferred momentum to the nucleus

Need to constrain such kinematics region with Near Detector → new improved selection

Reconstruction efficiency

OLD
NEW
The measurement of $\delta_{CP}$ crucially depends on the comparison of $\nu$ vs $\bar{\nu}$ oscillation → bias on $\nu$ vs $\bar{\nu}$ cross section direct reflect in bias on $\delta_{CP}$ measurement.
Future experiments: $\nu_e$

- We are interested to $\nu_e$ appearance and $\delta_{CP}$ from $\nu - \bar{\nu}$ comparison but in ND we mostly measure $\nu_\mu$ cross-sections.

- In future (HK, DUNE) large samples of 4 $\nu$ species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on $\delta_{CP}$:
    - $\nu_e - \bar{\nu}_e$ uncorrelated 1%
  - For **DUNE** assumed: **uncorrelated** $\nu_\mu - \nu_\mu$ 5% and $\nu_e - \nu_e$ 2%

(shape of $\nu_\mu$ itself may be more important for DUNE: shape analysis and spanning over different xsec)
The way out?

- A given cross-section measurement is affected by many different effects

- To disentangle them we need to compare different measurements (C, O, ν species, different variables …) → long term plan

The role of theoreticians is fundamental here!
The role of Jennifer

- All (!!) the measurements presented here have been performed by Jennifer groups

- Jennifer is allowing to:
  - promote and enhance the European know-how on Near Detector analysis and Neutrino cross-section measurements
  - establish a strict collaboration with Monte Carlo builders in Japan (NEUT)
    - inject measurements into improved Neutrino Interaction modelling
    - implements improved models in MC simulations

Crucial for T2K but also for future generation of long baseline experiments
Recent neutrino cross-section measurements at T2K

S.Bolognesi
(IRFU, CEA Saclay)
CC inclusive: T2K

- Simple analysis: require at least one muon (small background from NC and flux pollution $\nu_\mu$)

- Dominated by CCQE at T2K $E_\nu$ energy:

  → indications in favour of new models with 2p2h

  → agreement also with old tuned models


T2K Collaboration, Phys.Rev. D87 (2013) 9, 092003
Nuclear physics is the name of the game

- CCQE model tuned from bubble chambers $\nu H$ data: $M_{\nu}^{QE} \sim 1$GeV
  → modern experiments (K2K) include nuclear effects on heavy target (C,O): Fermi Gas

- MiniBoone measurement shows large discrepancy wrt to this model (large $M_{\nu}^{QE}$)
  → explanation from theoretical models including:
  - long range correlation between nucleons (aka RPA)
  - possibility of interactions with NN pairs (aka 2p2h and MEC effects)

  $$\nu_\mu n p \rightarrow \mu^- p p$$
  $$\nu_\mu n p \rightarrow \mu^+ n n$$

  (well known in ep scattering but not definitive model)

- Final State Interaction only included in MC models: CC1\pi with pion re-absorption included in signal (CC0\pi)
New ways of looking at the data

Look into proton multiplicity and kinematics

for 2p2h events you expect 2 nucleons in the final state

presence of 2p2h induce large asymmetry between the transverse momentum of the outgoing muon and of the outgoing leading proton

- Fake data: GENIE*
- Nominal MC: NEUT