Understanding neutrino cross sections for future oscillation experiments

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based on A.M.A. & C. Mariani, arXiv:1609.00258

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Outline

1. Can we afford using different target materials in the near and far detectors?

2. Are nuclear models relevant for the oscillation analysis?

3. Is the calorimetric energy reconstruction insensitive to nuclear effects?

4. Summary
Impulse approximation

Assumption: lepton-nucleus interaction involves only one nucleon, with the remaining nucleons acting as spectators. It is valid when the momentum transfer $|\mathbf{q}|$ is high enough, as the probe's spatial resolution is $\sim 1/|\mathbf{q}|$. 
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Extrapolation to a different nucleus

- Available cross sections or their ratios
  (# articles in the last 10 years):
  C or CH (25), Fe (7), Ar (3), H$_2$O (2)

- If the near and far detectors use different targets, the extrapolation is necessary
Extrapolation to a different nucleus

Consider a T2K-like $\nu_\mu \rightarrow \nu_\mu$ disappearance experiment

- water Cherenkov near (1 kt fiducial mass at 1 km) and far (22.5 kt at 295 km) detectors
- beam peaked at 600 MeV, primary beam power 750 kW
- running time 5 years

Assumed 20% systematic uncertainties for the shape and for the overall normalization.

True event rates for $^{16}\text{O}$. Fitted rates for $^{16}\text{O}$ or $^{12}\text{C}$.

All migration matrices from the RFG model in GENIE.
$^{12}\text{C} - ^{16}\text{O}$ extrapolation

Coloma et al., PRD 89, 073015 (2014)
$^{12}\text{C}-^{16}\text{O}$ extrapolation

Coloma et al., PRD 89, 073015 (2014)
Extrapolation to a different nucleus

Lower limit of the effect:

● crude description of nuclei (neglected shell-structure, differences in density distributions, $^{12}$C is non-spherical)

● extrapolation only between $A = 12$ and $A = 16$

The same target material in the near and far detectors is the best way to reduce the systematic uncertainties.
Impulse approximation

The cross section separates to

\[
\frac{d\sigma_{\ell N}^{IA}}{d\omega d\Omega} = \int d^3p \, dE \, P^N_{\text{hole}}(p, E) \frac{M}{E_p} \frac{d\sigma_{\ell N}^{\text{elem}}}{d\omega d\Omega} \, P^N_{\text{part}}(p', T')
\]
Impulse approximation

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\]

Hole spectral function

Particle spectral function
General remarks

● In neutrino scattering, uncertainties come from (i) interaction dynamics and (ii) nuclear effects.

● It is highly improbable that theoretical approaches unable to reproduce $(e,e')$ data would describe nuclear effects in neutrino interactions at similar kinematics.

● To be reliable, a description of nuclear effects has to be validated by systematic comparisons to $(e,e')$ data, allowing its uncertainties to be estimated.
SF approach vs RFG model

AMA et al.,
PRD 91, 033005 (2015)

data: Baran et al.,
PRD 61, 400 (1988)
SF approach vs RFG model

Consider a T2K-like $\nu_\mu \rightarrow \nu_\mu$ disappearance experiment

- Cherenkov detectors: near (1 kt fiducial mass at 1 km) and far (22.5 kt at 295 km) with the carbon target
- beam peaked at 600 MeV, primary beam power 750 kW
- running time 5 years

Assumed 20% systematic uncertainties for the shape and for the overall normalization.

True event rates from the SF approach.
Fitted rates from the RFG model or SF approach.
SF approach vs RFG model

Jen et al., PRD 90, 093004 (2014)
SF approach vs RFG model

Jen et al., PRD 90, 093004 (2014)
SF approach vs RFG model

Lower limit of the effect:

- the difference considered only in the QE channel
- for resonance excitation, similar model differences [Benhar & Meloni, NPA 789, 379 (2007)]
- in deep-inelastic channel a number of nuclear models compared to the MINERvA measurements “none of which is confirmed by the data” [Tice et al. (MINERvA), PRL 112, 231801 (2014)]
2p2h processes

Compare two purely phenomenological approaches

- **Effective** SF calculations with the axial mass 1.2 GeV [suggested by K2K, MiniBooNE, MINOS, T2K]

- **GENIE + νT** calculations–QE within the SF approach and multinucleon contribution from the Dytman model [Katori, AIP Conf. Proc. 1663, 030001 (2015) ]
QE with any number of nucleons

AMA et al., PRD 93, 113004 (2016)
Importance of $2p2h$ description

Consider a T2K-like $\nu_\mu \rightarrow \nu_\mu$ disappearance experiment

- Cherenkov detectors: near (1 kt fiducial mass at 1 km) and far (22.5 kt at 295 km) with the carbon target
- beam peaked at 600 MeV, primary beam power 750 kW
- number of unoscillated events $\sim$6000

Assumed 20% systematic uncertainties for the shape and for the overall normalization.

True event rates from the GENIE + $\nuT$ approach.
Fitted rates from the effective or GENIE + $\nuT$ approaches.
Importance of $2p2h$ for neutrinos

AMA et al., PRD 93, 113004 (2016)
Importance of $2p2h$ for neutrinos

AMA et al., PRD 93, 113004 (2016)
Importance of $2p2h$ for antineutrinos

AMA et al., PRD 93, 113004 (2016)
Missing energy

In an ideal detector, the calorimetric energy reconstruction would be perfect for any event type.

\[ E_{\nu}^{\text{calc}} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j, \]
Missing energy

In an ideal detector, the calorimetric energy reconstruction would be **perfect for any event type**.

\[ E_{\nu}^{\text{cal}} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j, \]

In a real detector, thresholds and efficiencies affect the reconstruction, introducing **sensitivity to event composition**. For example, 100 MeV proton may give a reconstructed energy different than two 50-MeV neutrons.
Missing energy

Detector effects

- thresholds: 20 MeV for mesons and 40 MeV for protons
- energy-independent efficiencies: 60% for π⁰'s, 80% for other mesons, 50% for protons, neutrons undetected
- finite energy resolutions
Missing energy

Consider a DUNE-like $\nu_\mu \rightarrow \nu_e$ appearance experiment

- far detector (40 kt at 1300 km) with the carbon target
- beam peaked at 2.5 GeV, primary beam power 1.08 MW
- running time 6 years (3 + 3)

Assumed 2% systematic uncertainties for the shape and for normalization; 5% bkgd normalization uncertainty

True event rates with all detector effects.

Fitted rates partly neglect the missing energy.
Missing energy

AMA et al., PRD 92, 091301 (2015)
Missing energy

AMA et al., PRD 92, 091301 (2015)
Missing energy

An accurate calorimetric energy reconstruction requires

- an accurate and detailed determination of detector response in test-beam exposures
- a realistic simulation of nuclear effects, including intranuclear cascade

Exclusive cross sections are necessary.
Summary

1. Nuclear uncertainties are minimal when the near and far detectors employ the same target.

2. Cross section differences are relevant for the oscillation analysis not only for quasielastic scattering through 1-body current.

3. Electron scattering data can and should be used to discriminate between different models and to estimate their uncertainties.

4. Nuclear effects are important also for the calorimetric energy reconstruction.
Backup slides