Usefulness of a Carbon target in DUNE ND: first thoughts
Why neutrino-nucleus interactions are important

Modeling of neutrino-nucleus interactions is needed for ND → FD extrapolation because of:

- different $E_\nu$ energy spectrum at ND (before oscillation) and at FD (after oscillation)
  ND constrain only the convolution of xsec and flux → need to disentangle them to extrapolate correctly from ND energy to the oscillated energy spectrum at FD

- reconstruction of neutrino energy from particles observed in the final state

- extrapolation between different neutrino species:
  mostly $\nu_\mu$, $\bar{\nu}_\mu$ at ND → need also $\nu_e$ and $\bar{\nu}_e$ at FD
  need to measure xsec and flux of $\nu_\mu$ and $\bar{\nu}_\mu$ at ND to minimize model-dependence

- extrapolation between different acceptances at ND and FD (due to different size)

- extrapolation between different nuclear target:
  even for same active target in the fiducial volume at ND and FD, still different composition for background coming from out-of-fiducial volume

usage of different nuclei is a handle for better understanding of neutrino-nucleus interactions!
Dependence on $E_{\nu}$

$$\frac{N_{\bar{\nu}_\alpha}^{FD}}{N_{\bar{\nu}_\alpha}^{ND}} \approx \int_{\text{oscillated flux}} P_{\bar{\nu}_\alpha \rightarrow \nu_\alpha}(E_{\nu}) \phi_{\bar{\nu}_\alpha}^{FD}(E_{\nu}) \sigma_{\nu_\alpha}(E_{\nu}) dE_{\nu}$$

$$\int_{\text{unoscillated flux}} \phi_{\bar{\nu}_\alpha}^{ND}(E_{\nu}) \sigma_{\nu_\alpha}(E_{\nu}) dE_{\nu}$$

What we actually constrain is the probability of a given final state observed in the detector

E.g. Rate ($\mu+p+\pi^+$) is actually the convolution of:

- probability of finding the proton in the nucleus (and extract it)
- cross-section of fundamental EWK interaction
- probability for the proton/pion to exit the nucleus

Different component of the cross-section: initial state nuclear effects (IS), fundamental EWK interaction ($\sigma$), final state interaction (FSI) in the nucleus.

Each component has a different neutrino energy dependence

E.g.: a final state without pion can be due to a CCQE event or to CCRRes pion production followed by FSI absorption of the pion → if FSI is wrongly estimated, the extrapolation to the far detector is wrong because the energy dependence of CCQE and CCRRes xsec is different

This is a particularly complex problem in a wide-band beam where many different processes (CCQE, 2p2h, CCRRES, Multipion, DIS) have all large xsec

Need to separate each component IS/$\sigma$/FSI in order to extrapolate them correctly from ND measurements to far detector
Reconstruction of $E_\nu$

\[
\frac{N_{\nu_\alpha}^{FD}(E_{\text{vis}})}{N_{\nu_\alpha}^{ND}(E_{\text{vis}})} \approx \int_{\text{oscillated flux}} P_{\nu_\alpha \rightarrow \nu_\alpha'}(E_\nu) \phi_{\nu_\alpha'}^{FD}(E_\nu) \sigma_{\nu_\alpha'}(E_\nu) F_{\text{theo}}(E_{\text{vis}} - E_\nu) \, dE_\nu
\]

\[
\int_{\text{unoscillated flux}} \phi_{\nu_\alpha'}^{ND}(E_\nu) \sigma_{\nu_\alpha'}(E_\nu) F_{\text{theo}}(E_{\text{vis}} - E_\nu) \, dE_\nu
\]

We need to go from the observed particles in the final state to the incoming neutrino energy.

Again we need to control each component separately IS/$\sigma$/FSI to get it right:

- initial state effects: e.g. energy lost in the nucleus ("binding energy")
- fundamental interaction: e.g. CCQE (p final state) vs 2p2h with neutron component (pn final state)
- final state effects: e.g. proton deceleration, pion absorption...

We need to correct for each of these effects (IS/$\sigma$/FSI)!
How to constrain IS/σ/FSI

New kind of observables including the proton (neutron) information

I will use single transverse variables as a proxy: many more can be thought (p_n, Ehad, vertex activity...)

I will mostly discuss protons, neutrons, similar arguments holds for pions

- The bulk of \( \delta p_T \) is sensitive to initial state effects: Fermi momentum distribution
- Fundamental interaction: separate CCQE from 2p2h \( \delta p_T \) tail
- What about FSI?
How to constrain IS/$\sigma$/FSI

New kind of observables including the proton (neutron) information

I will use single transverse variables as a proxy: many more can be thought (pn, Ehad, vertex activity...)

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$\delta\alpha_T$ is sensitive to FSI:
how much acceleration/deceleration of the proton in the nucleus $\rightarrow \delta\alpha_T$ shape
(~flat without FSI)
Usefulness of Carbon

The capability of separating the different effects (IS/σ/FSI) in these variables is only 'partial', there is always some degeneracy in the shapes between the different effects.

Measurement of $\delta \alpha_T / \delta p_T$ for different targets help disentangling IS/σ/FSI effects! Since they all have a different dependence on nucleus size $A$

Difference between C vs Ar give enough leverage for extracting $A$-depending effects separately

- FSI can be extracted from $\delta \alpha_T$ shape:
preliminary parametrization of $A$-dependence can be extracted from electron scattering data and further tuned with ND data

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Initial state effects (Fermi momentum) can be extracted from the width of the $\delta p_T$ distribution

(other variables are sensitive to binding energy)

Fermi momentum dependence on $A$ from electron scattering

PHYSICAL REVIEW C 65 025502

SuSaV2 model: these values applied to Relativistic Mean Field model assure scaling of 2$^{nd}$ kind in the super-scaling functions for neutrino scattering

Phys. Rev. C 71, 065501
Usefulness of Carbon

The capability of separating the different effects (IS/σ/FSI) in these variables is only 'partial', there is always some degeneracy in the shapes between the different effects.

Measurement of $\delta \alpha_\tau / \delta p_\tau$ for different targets help disentangling IS/σ/FSI effects!

Since they all have a different dependence on nucleus size $A$

Difference between C vs Ar give enough leverage for extracting $A$-depending effects separately

- Fundamental interaction, eg. 2p2h/CCQE, affect the height of peak/tail in $\delta p_\tau$

2p2h and CCQE cross-section have different $A$ dependence (e.g. SuSa model: $2p2h \sim A k_F^2$, CCQE $\sim A/k_F$)

A-dependence of the cross-section is a powerful handle to evaluate CCQE and 2p2h separately (thus extrapolating properly the xsec from ND to FD)
Usefulness of Carbon: further steps

Need to be more quantitative:

- Quantify IS vs FSI precision with multidimensional fit in 3DST-like detector (spoiler: % level accuracy!!)

- Study how to combine C and Ar target: is our 'cascade' semi-classical model enough?
  - interesting existing electron scattering data to explore
Ev reconstruction: neutrons (1)

- Big advantage of DUNE is the capability of reconstructing the total final state energy as a proxy of the incoming neutrino energy
  While this minimize the model-dependence of the Ev reconstruction, same model-dependence still remain (binding energy, neutrons ...)

- The modeling of the 'hadronic' part of the final state (all what is not the lepton) is (almost) terra-incognita
  - First 'calorimetric' measurement from Minerva + first measurements of outgoing proton in T2K ND
    → both show clear discrepancy with available MC models

- Moreover with Argon only protons/pions are accessible → measurement of neutrons is crucial for high energy (DIS) events and for all events with antineutrino
  (neutrino-antineutrino differences are at the core of $\delta_{CP}$ systematics!)
**Ev reconstruction: neutrons (2)**

- **An example:**

  - smearing of $E_{\nu}^{CCQE}$ is dominated by Fermi momentum
  - smearing of $E_\mu + E_p$ is dominated by flux (and detector effects)

  → more robust estimator of $E_\nu$ against model biases

  ![Diagram](image)

  - low binding energy
  - high binding energy

  - $E_\nu^{CCQE}$ CCQE formula (i.e. constraining the model using the muon info only)

  - Generator level

  - MC Events

  - $E_{\nu}^{true}$

  - $E_{\nu}^{true}$

  - $(E_{\nu}^{true} - E_{\nu}^{true})/E_{\nu}^{true}$

  - $E_{\nu}$ reconstruction: neutrons (2)

  - But still important to correct for the right binding energy to get $E_\nu$ correct at the FD!

  - Fit to $E_\mu + E_p$ variable can extract the binding energy with very good precision at ND (depending on the precision of the flux → $\sim 1$ MeV)

  different binding energy for proton and neutron → important to perform $E_\mu + E_n$ measurement at the ND to avoid $\nu/\bar{\nu}$ bias at the FD!

- Need to be quantitative

  How well neutron measurements can be performed (at 3DST-like detector)?

  Spoiler: $\sim$ a factor two worse than proton (e.g. 2p2h with $< 5\%$ precision)
Conclusions

With the huge stat + phenomenal amount of information on the final state of DUNE, we can move from model constrains to “data parametrization” of the model!

the capability of measuring/disentangling IS/σ/FSI through their different A dependence is a crucial input to get the needed precision

• A-dependence of IS/σ/FSI can be driven by electron scattering data but need neutrino data at right energy (ND with Carbon + ND with Argon) to get the needed precision

• Carbon is an easier and well known nucleus → anchoring point to develop the constrains for Argon scattering

the capability of measuring all the final state, including neutrons, is a crucial input to get the needed precision

• The hadron part of the final state is not enough well known to rely on the model for the ν → ν̅ extrapolation

Joint sensitivity studies are needed on a Carbon-target + Argon-target near detectors to be more quantitative