Usefulness of a **Carbon target in DUNE ND**: first thoughts

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S.Bolognesi – IRFU/CEA

Why neutrino-nucleus interactions are important

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

- different Eν 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 ν_μ, $\bar{\nu}_\mu$ at ND → need also ν_e and $\bar{\nu}_e$ at FD
need to measure xsec and flux of ν_μ 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 Eν

$$\frac{N^{FD}_{\nu_{\alpha'}}}{N^{ND}_{\nu_\alpha}} \approx \frac{\int_{oscillated\ flux} P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu)\,\phi^{FD}_{\nu_{\alpha'}}(E_\nu)\,\sigma_{\nu_{\alpha'}}(E_\nu)\,dE_\nu}{\int_{unoscillated\ flux} \phi^{ND}_{\nu_{\alpha'}}(E_\nu)\,\sigma_{\nu_\alpha}(E_\nu)\,dE_\nu}$$

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)	X	cross-section of fundamental EWK interaction $\sigma(\nu+p \to \mu+p+\pi^+)$	X	probability for the proton/pion to exit the nucleus

Different component of the cross-section: intial state nuclear effects (IS), fundamental EWK interaction (σ), 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 CCRes 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 CCRes xsec is different

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

Need to separate each component IS/σ/FSI in order to extrapolate them correctly from ND measurements to far detector

Reconstruction of Eν

$$\frac{N^{FD}_{\nu_{\alpha'}}(E_{vis})}{N^{ND}_{\nu_{\alpha}}(E_{vis})} \approx \frac{\int_{oscillated\ flux} P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu)\,\phi^{FD}_{\nu_{\alpha'}}(E_\nu)\,\sigma_{\nu_{\alpha'}}(E_\nu)\,F_{theo}(E_{vis}-E_\nu)\,dE_\nu}{\int_{unoscillated\ flux} \phi^{ND}_{\nu_{\alpha'}}(E_\nu)\,\sigma_{\nu_{\alpha'}}(E_\nu)\,F_{theo}(E_{vis}-E_\nu)\,dE_\nu}$$

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

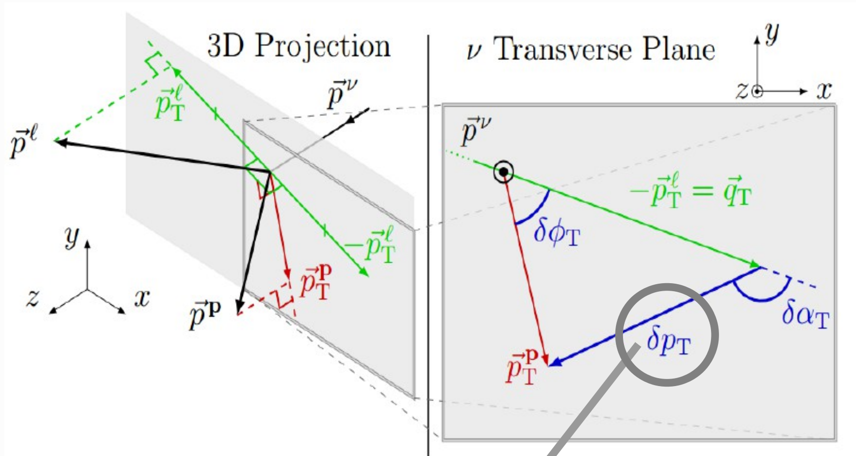
Again we need to control each component separately **IS/σ/FSI** to get it right:

- 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/σ/FSI)!

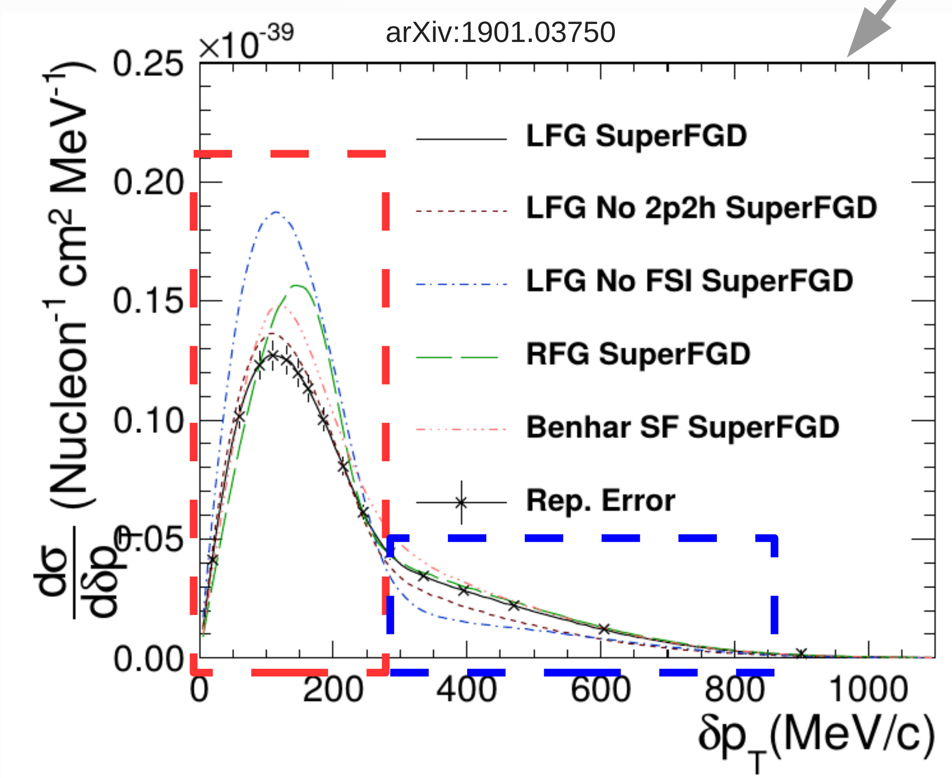
How to constrain IS/σ/FSI

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...)

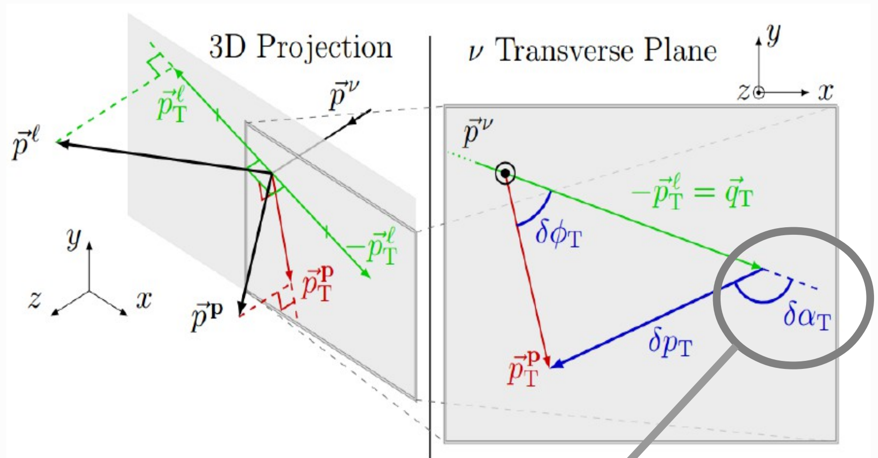
I will mostly discuss protons, neutrons, similar arguments holds for pions



- The bulk of δp_T is sensitive to **initial state effects:** Fermi momentum distribution
- **Fundamental interaction:** separate CCQE from 2p2h δp_T tail
- What about **FSI**?

How to constrain IS/σ/FSI

New kind of observables including the proton (neutron) information



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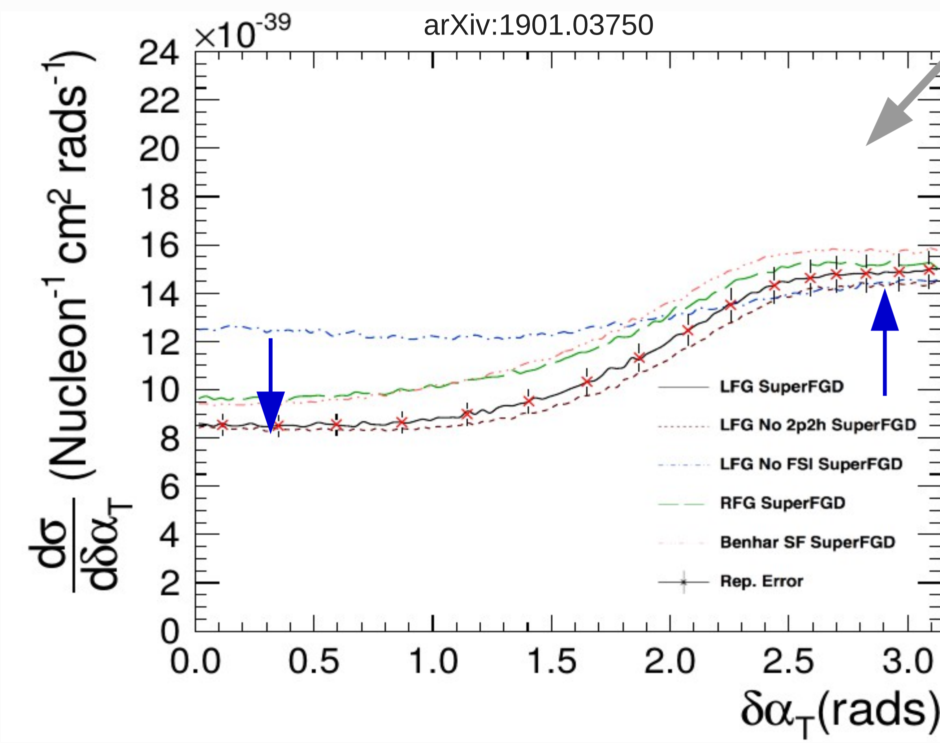
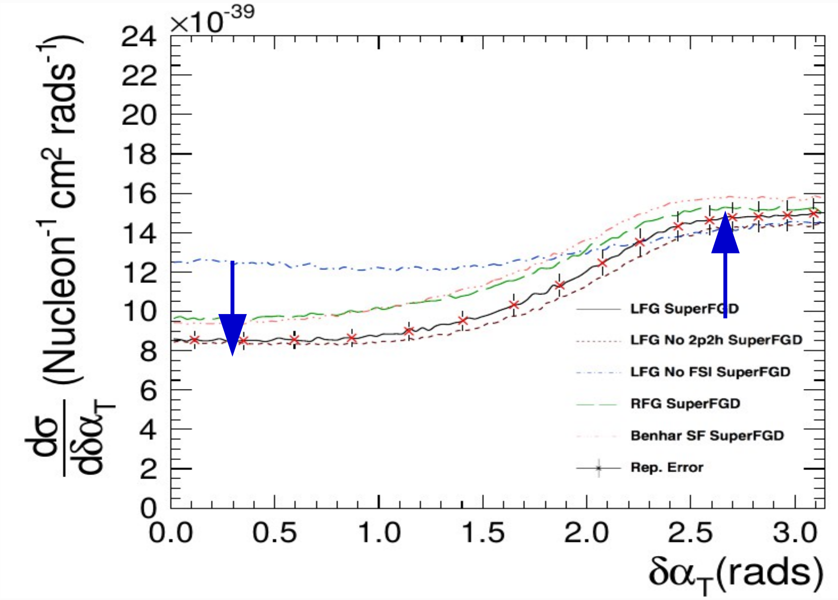


$\delta\alpha_T$ is sensitive to **FSI**:
how much acceleration/deceleration of the proton in the nucleus → $\delta\alpha_T$ shape
(~flat without FSI)

Usefulness of Carbon

The capability of separating the different effects (IS/σ/FSI) in these variable 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

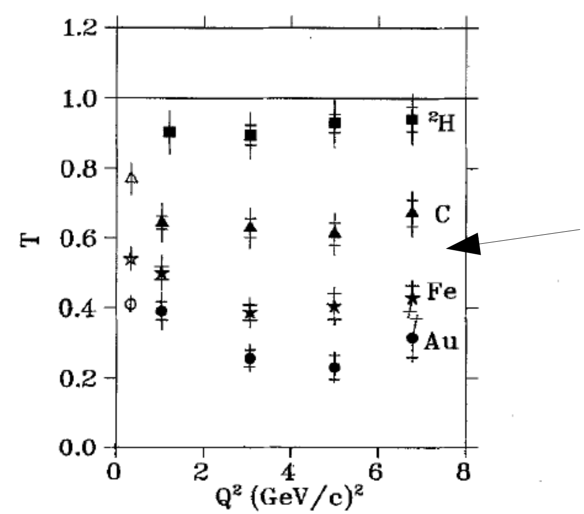


Fig. 1. Nuclear transparency for $A(e,e'p)$ as a function of Q^2. The inner error bars are the statistical uncertainty, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The open points at $Q^2 = 0.33$ (GeV/c)^2 are from Ref. [27] for C, Ni, and Ta targets.

- 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

Physics Letters B 351 (1995) 87–92

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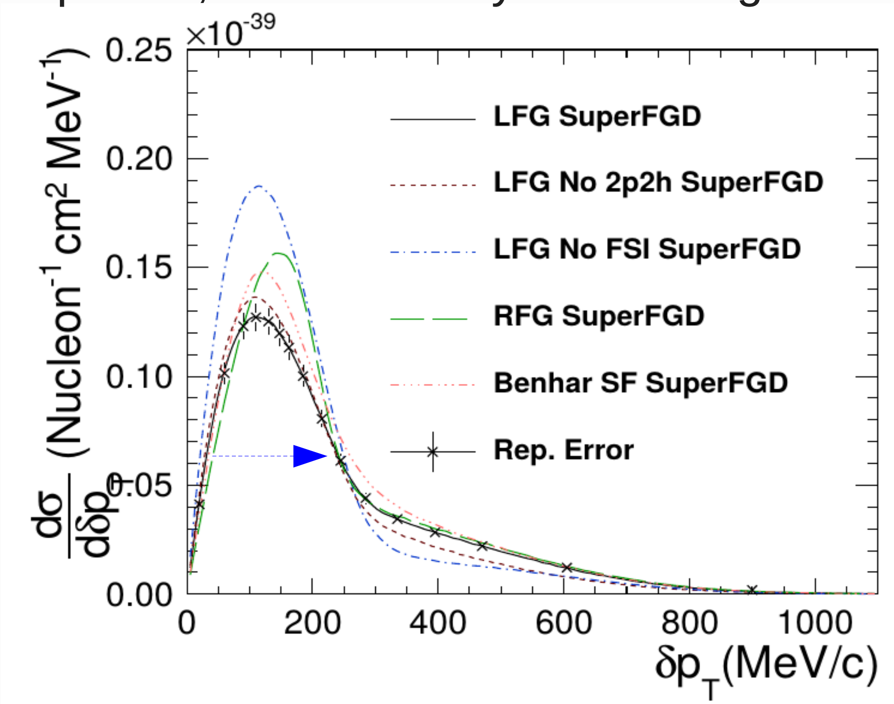

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Nucleus	k_F (MeV/c)
Lithium	165
Carbon	228
Magnesium	230
Aluminum	236
Calcium	241
Iron	241
Nickel	245
Tin	245
Gold	245
Lead	248

- Initial state effects (Fermi momentum) can be extracted from the width of the δp_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 2nd kind in the super-scaling functions for neutrino scattering

Phys. Rev. C 71, 065501

Usefulness of Carbon

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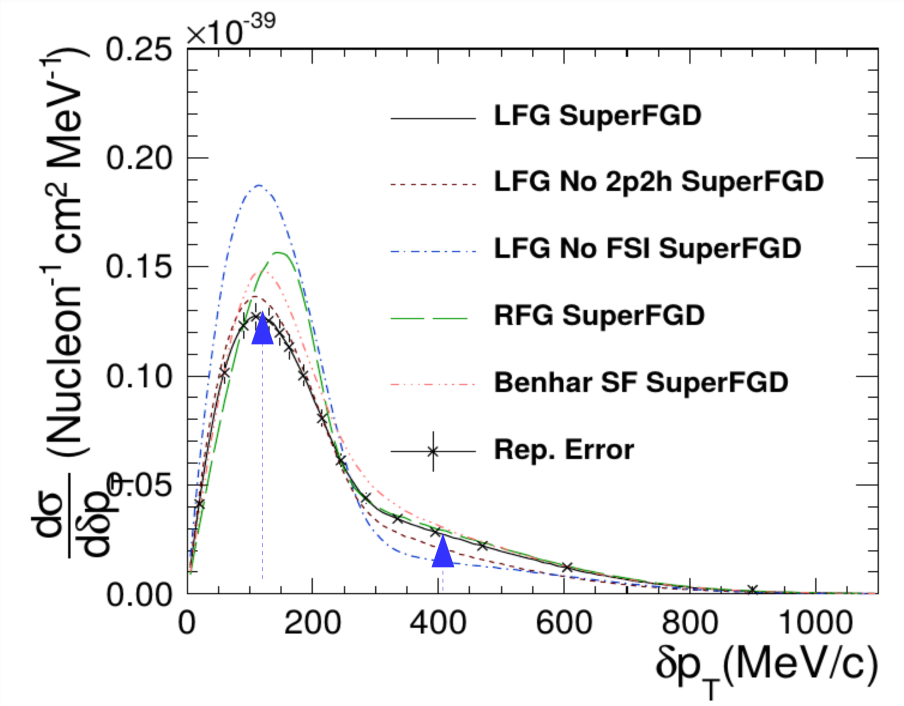

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Difference between C vs Ar give enough leverage for extracting A-depending effects separately

- Fundamental interaction, eg. 2p2h/CCQE, affect the height of peak/tail in δp_T

2p2h and CCQE cross-section have different A dependence
(e.g. SuSa model: 2p2h ~ $A^*k_F^2$, CCQE ~ 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

Eν 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 Eν 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

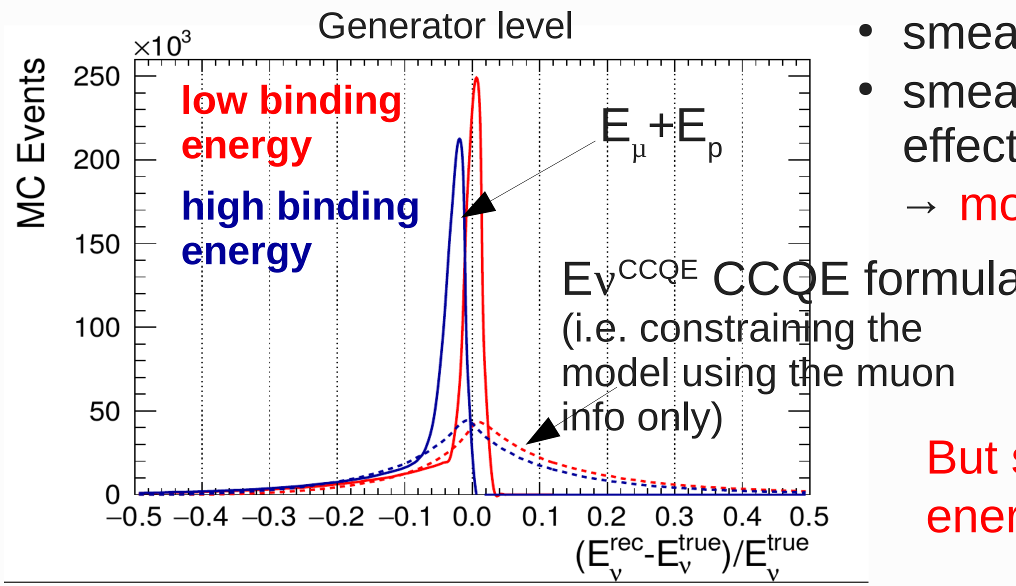
- Moreover with Argon only protons/pions are accessible →

measurement of neutrons is crucial for high energy (DIS) events and for all events with antineutrino

(neutrino-antineutrino differences are at the core of δ_{CP} systematics!)

Eν reconstruction: neutrons (2)

- An example:



- smearing of $E\nu^{CCQE}$ is dominated by Fermi momentum
- smearing of Eμ+Ep is dominated by flux (and detector effects)

→ more robust estimator of Eν against model biases

But still important to correct for the right binding energy to get Eν correct at the FD!

- Fit to Eμ+Ep variable can extract the binding energy with very good precision at ND (depending on the precision of the flux → ~1 MeV)

different binding energy for proton and neutron → important to perform Eμ+En 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: ~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 $\nu \rightarrow \bar{\nu}$ extrapolation

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