# Electron scattering and neutrino scattering
# Key questions

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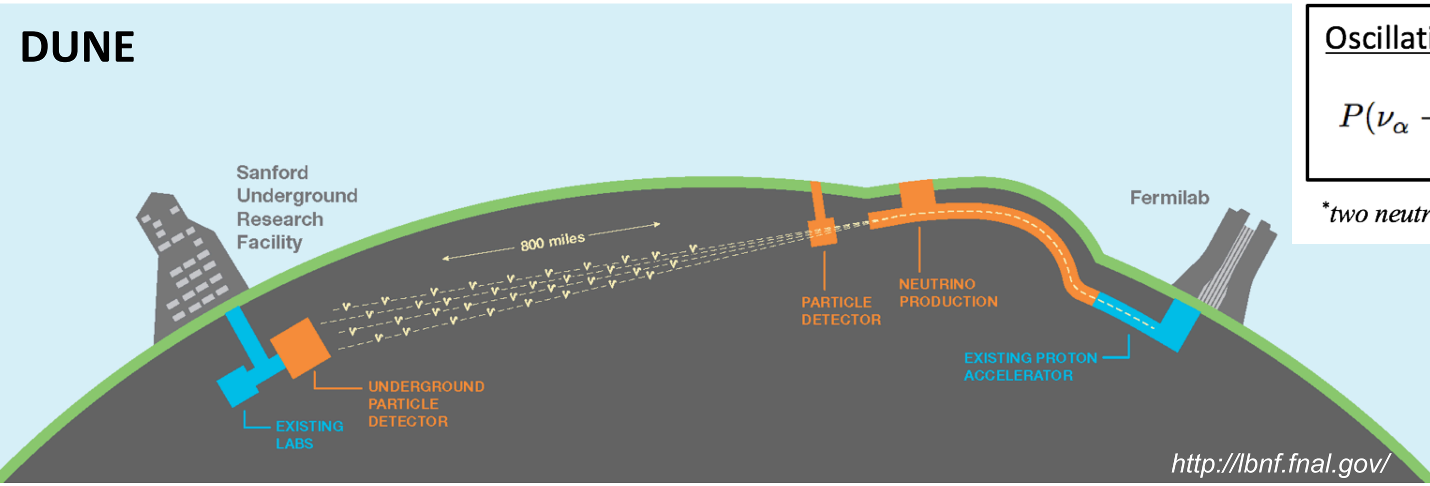
# Motivation and Contents

- Dune and oscillation analysis
- Lesson from the past: reactor experiments measured mixing angle at sub-% level
- DUNE challenges:
  - ND - can we extrapolate between C and Ar ?
  - Neutrons - do we understand their role in the energy determination problem ?
  - Last but not least: neutrino interaction generators - data comparison, tunes vs predictions, different model implementations, limitations, etc....
- Current status and future strategy

# Accelerator-based neutrino-oscillation experiments




Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

*two neutrino flavors, for simplicity*

Experiments measure event rates which, for a given observable topology, can be naively computed as:

Event Rate at near detector:

$$N^{\alpha}_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}})$$

Event Rate at far detector:

$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}})$$

# Reactor experiments

- Oscillation analysis based on near/far detector ratio
- Identical near and far detectors
- Near/far detector events ~4 M/0.5 M
- Flux prediction at 5% level (reactor anomaly is a 3% effect)
- Never extracted oscillation parameters and other quantities like neutron lifetime, cross-sections or absolute normalization all at the same time
- Cross section for IBD has an uncertainty of 3% or better (comparable to neutron lifetime)
- Oscillation fit - non-trivial - has order of 100 parameters

# DUNE challenges- super summary

Liquid Ar vs Water Cherenkov

Including non-QE interactions gives an advantage in sensitivity over similar water Cherenkov detectors.

DUNE will have almost 2/3 of the neutrino interaction to be non-QE, 1/3 only will be QE. There is a problem in neutrino energy reconstruction for non-QE events.

After 10 years of neutrino experiments we barely understand QE interactions:

- treat nucleus as uncorrelated system - 1p1h - barely works
- adding correlations - 2p2h - not easy and ongoing
- neutron emission - a possible second order problem and depends on details of the microscopic models - depends on A, Z and A-Z - isospin non symmetric vs isospin symmetric

# What have we learned from our generators

Neutrino interactions generators are divided in two fundamental categories, depending on their goals.

NEUT - extrapolate from near to far detector - never intended to be a full model of neutrino interactions and have prediction powers. Based on the assumption of having fairly identical near and far detector and external data to predict flux between far and near

GENIE/Nuwro - prediction and full description of neutrino interactions - new approach is the tuning - tune on one experiment and propagate to others

GiBUU - approach based on pdf just not an event by event description - try to implement nuclear models in a effective way and make predictions

# Minerva Experiment

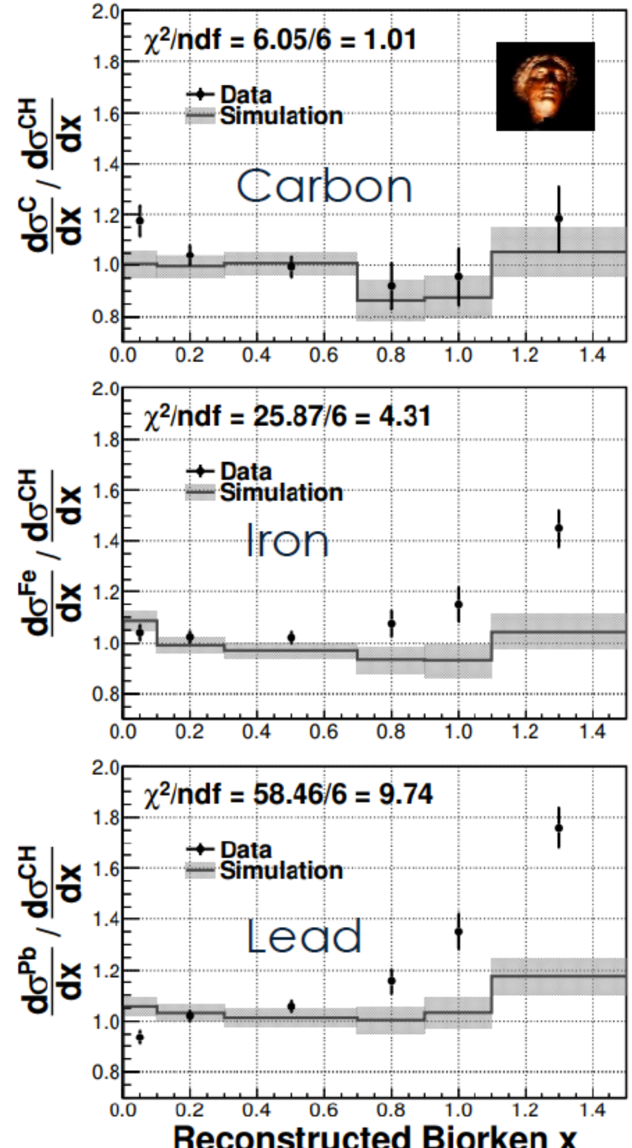
$$x = \frac{Q^2}{2M_N \nu}$$

Description of scattering on nuclear targets is not great

Inclusive: only measure the leptons

Exclusive: measure all particles in final state

Semi-Inclusive: measure leptons and hadrons when possible (detector effect and resolutions)




Phys. Rev. Lett. **112**, 231801 (2014)

# Minerva (cont'd)

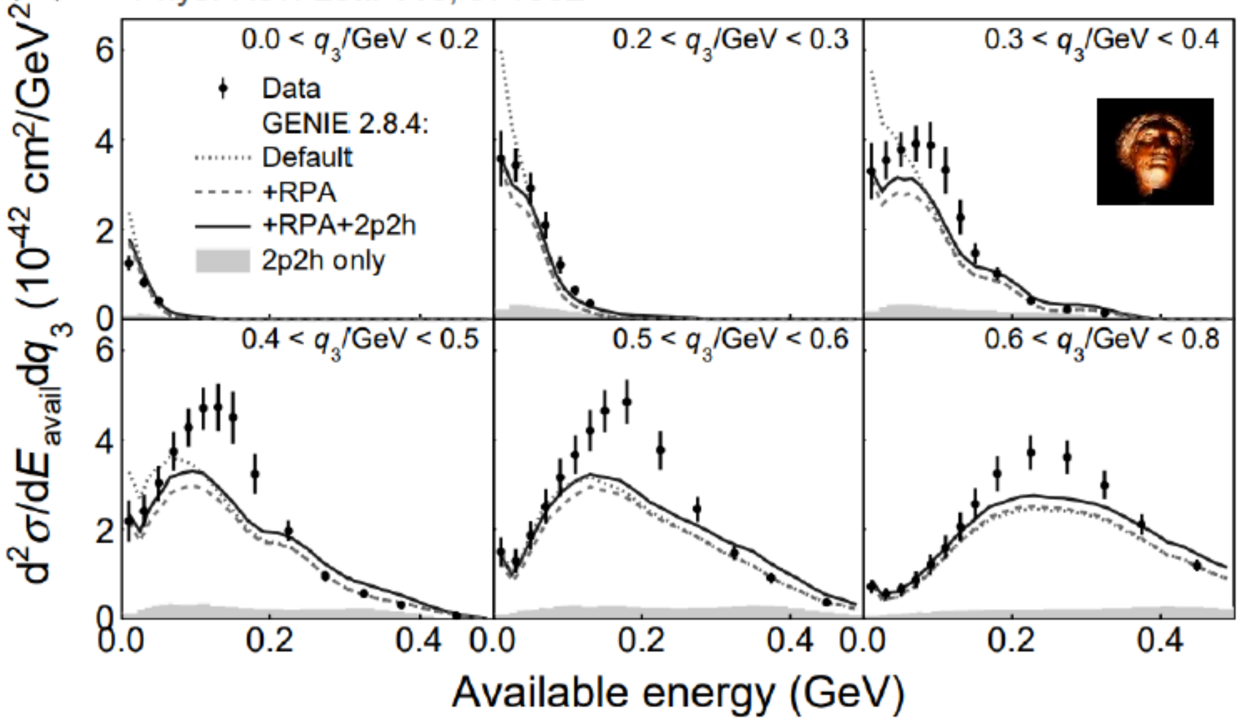
Try to stich together various models

Result: not great

Problem: Different models have different assumptions and cross sections leave in a continuum (next slide)

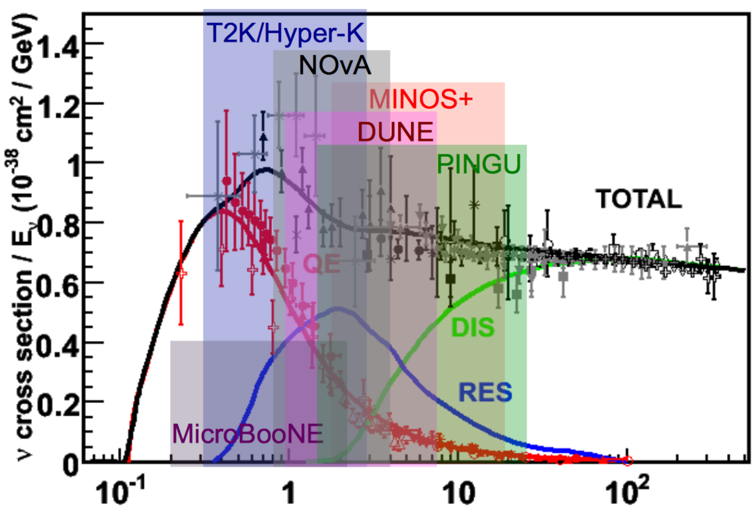
FIG. 2. The double-differential cross section $d^2\sigma/dE_{\text{avail}}dq_3$ in six regions of $q_3$ is compared to the GENIE 2.8.4 model with reduced pion production (small dot line), the same with RPA suppression (long-dashed), and then combined with a QE-like $2p2h$ component (solid). The $2p2h$ component is shown separately as a shaded region. GENIE predicts events with zero available energy (all neutrons in the final state); as is done here in order to compare to data, the cross section must be summed including the spike at zero to the edge of the the first bin in each $q_3$ range to produce an average cross section.

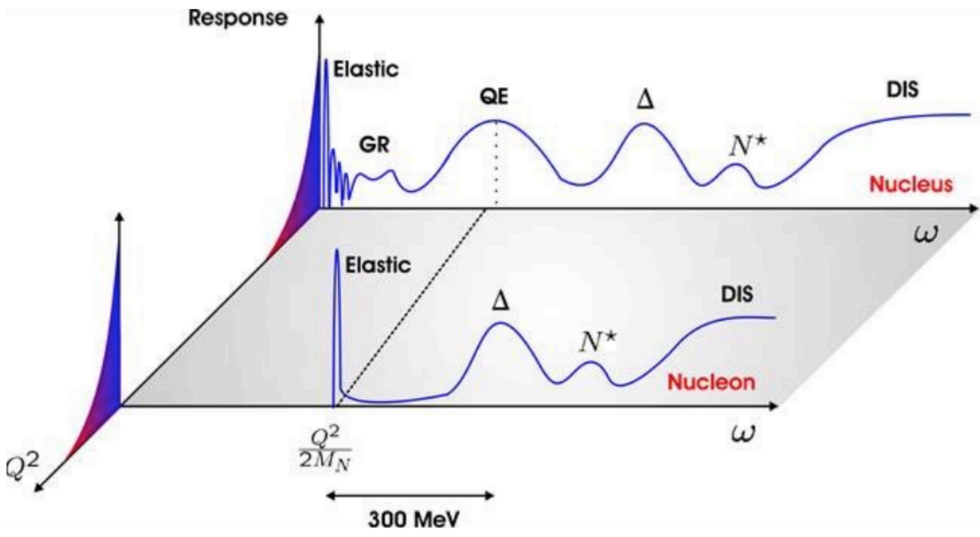
Phys. Rev. Lett. **116**, 071802



- Frankenstein models do not work: Need realistic nuclear model (in Monte-Carlo simulations) that can describe neutrino-nucleus cross sections over a wide range of energies.

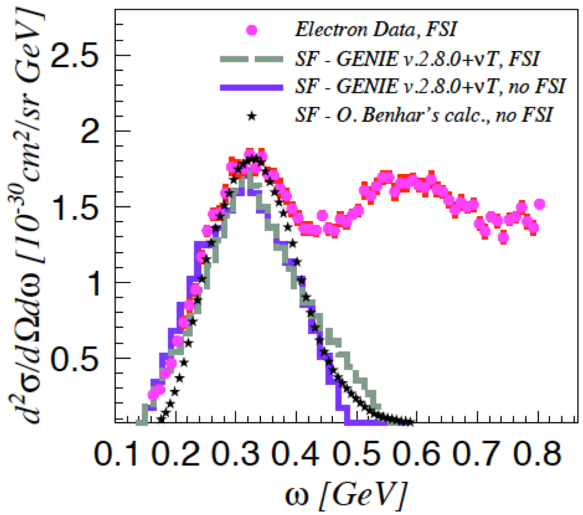
## Neutrino-nucleus cross section



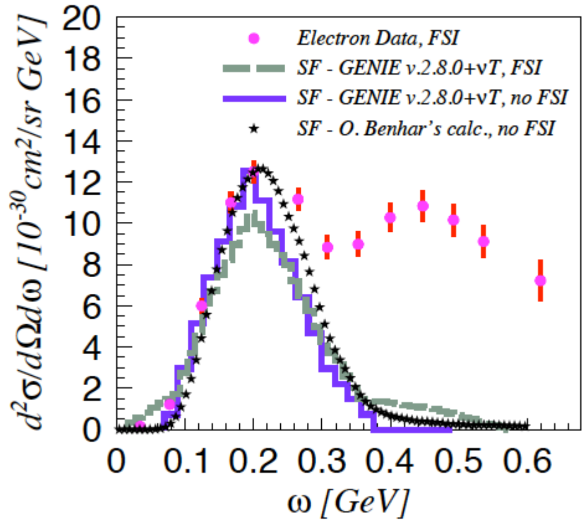



# Electron scattering - inclusive and FSI

VT group - 2013
(Phys. Rev. D90, 093004)



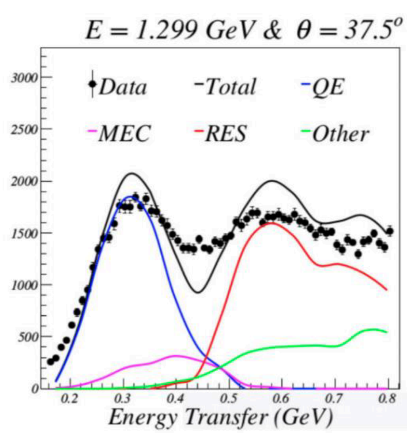

(b) $e + \mathrm{C} \rightarrow e' + X$, $E_e = 1.299$ GeV, $\theta_e = 37.5$ deg



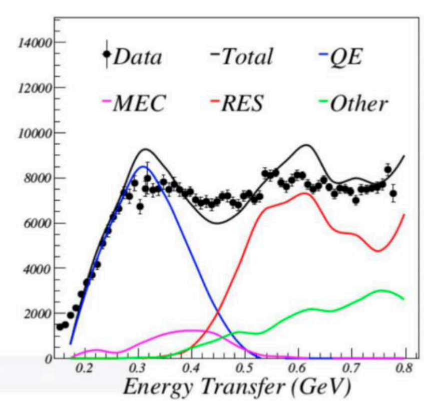

(c) $e + \mathrm{Ca} \rightarrow e' + X$, $E_e = 0.841$ GeV, $\theta_e = 45.5$ deg

e4ν - 2019

$^{12}$C




$^{56}$Fe




*Genie R-2_12_10

# Scaling

Experimentally has been found that the scaling function is mostly independent on the nuclear target for inclusive QE.

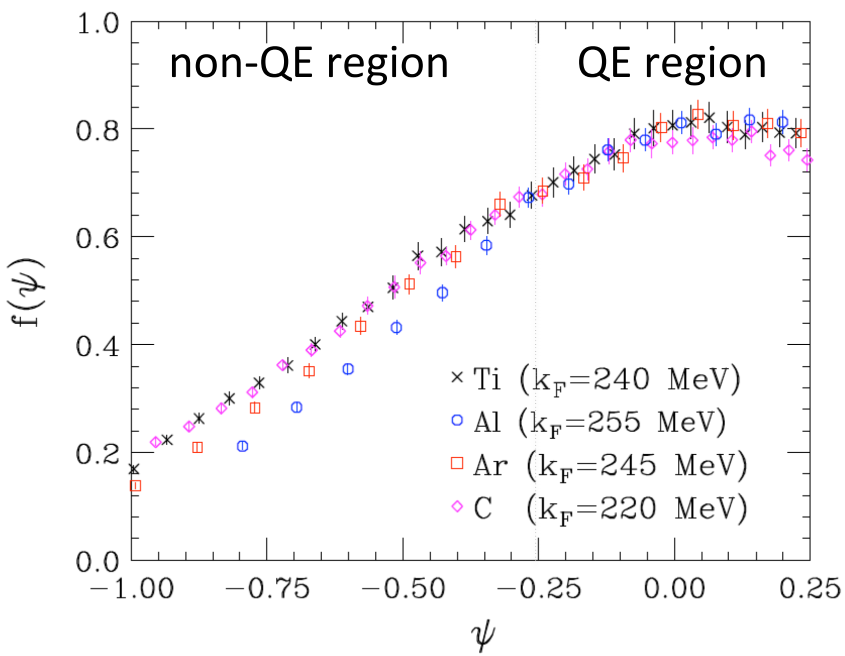



FIG. 10. (color online) Scaling functions of second kind, obtained from the inclusive cross sections measured by the E12-14-012 experiment using carbon, aluminum, argon and titanium targets.

If a model/data scales then we can extrapolate from one nuclei to the others - this is true only for the QE region, - there are a scaling violations (well known in the nuclear community) for non-QE interactions.

Jlab E12-14-012 (PRC 99.054608, PRC 98.014617)
D. B. Day et al., PRC 48, 1849 (1993).

# Current status

- DUNE ND - 3DST - not sure it will succeed to improve an Argon model based on C data, scaling only works for QE interactions not for non-QE interactions

- With current state of the art MCs/models
  - can DUNE expect to do a reliable extrapolation near to far with %-level constraints on neutrino interactions ? This is hard to answer with a complete yes or no.

- We need to do better …

# Future Strategy

- Renew Theory effort on neutrino-nucleus cross section modeling - progress in the last few years but still behind
- New MC generators - based on ab-initio nuclear theory with no tunable parameters
- Stop pretending that there is a physics meaning behind tuning parameters in a neutrino MC generator - those are effective parameters but they are far from physical (aka MiniBooNE $M_a$ and $K_f$) - not able to reproduce data from one experiment to another
- Stop try to create a Frankenstein model of nuclear theory putting together different models that starts with very different assumptions
- Use electron scattering data to understand the modeling of Ar nucleus