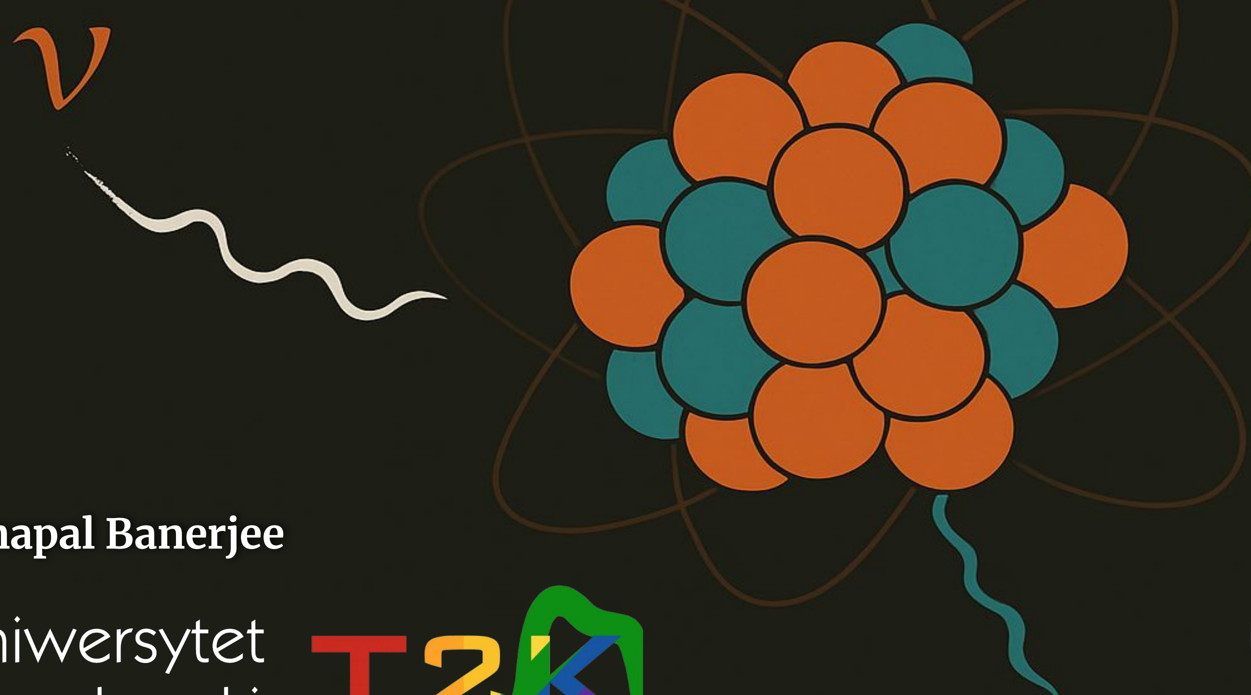
Spectral function approach in NuWro: modeling of multi nucleon final states in quasielastic scattering

Matter To The Deepest, Katowice, 15-19 September, 2025



Rwik Dharmapal Banerjee

Uniwersytet Wrocławski

T2K

NuWro Wrocław Neutrino Event Generator

@WhoamI

- PhD scholar at University of Wroclaw
  Supervisors : Jan T Sobczyk, Artur M Ankowski

- **Developer of NuWro Monte Carlo event generator**,
  a MC generator of lepton-nucleus events

- Part of T2K collaboration

- Working on Quasielastic scattering in Spectral function framework

- Contact : rwik.dharmapal@uwr.edu.pl

Motivation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2(1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)})$$


Motivation
$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2(1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)})$
Neutrino oscillation parameters
Long journey of precise theories and experiments
Detector systematics
Flux uncertainties
Nuclear effects

Motivation


$P(\nu_\alpha \to$
$(eV^2)\frac{L(km)}{E_\nu(GeV)})$
Neutrino oscillation parameters
Long journey of precise theories and experiments
Nuclear effects

The precision era of ν oscillations

- In the next 5-10 years new experiments will collect ~100 times more data
- Results will not be dominated by Statistical uncertainties
- Challenge of theory efforts is to pace up, reduce systematic uncertainty
- Major source of systematic error is modeling of nuclear effects
- I will discuss improved implementation of nuclear effects in **NuWro MC generator** using **spectral function framework**

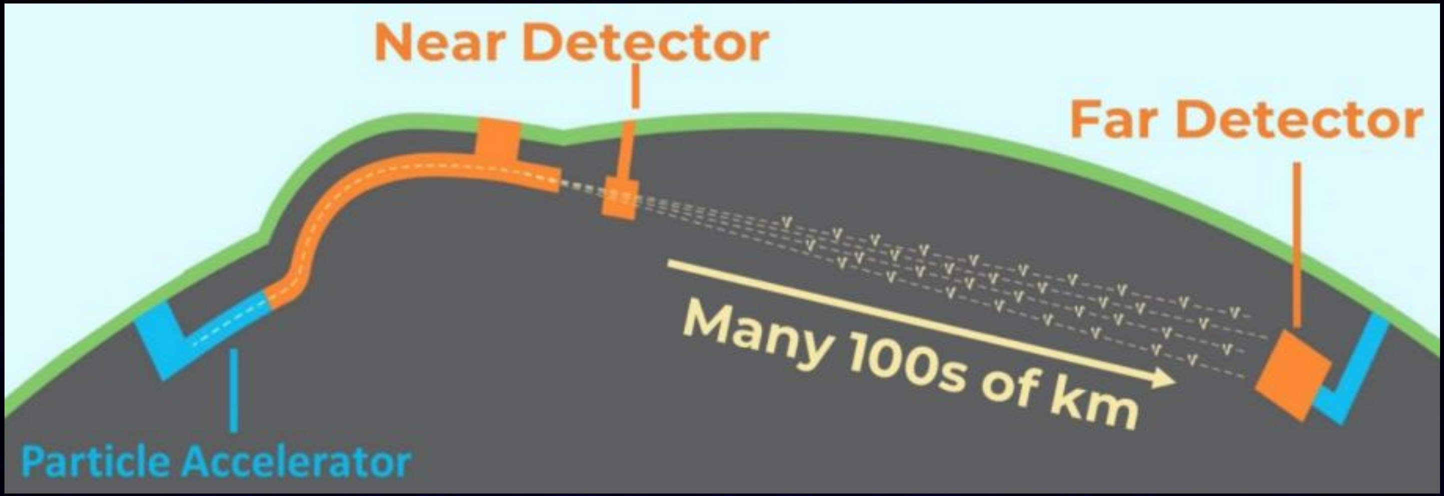
Current systematic uncertainties

Source	T2K	NOvA
cross-sec	~4%	~3.5%
total syst.	~5%	~3.5%

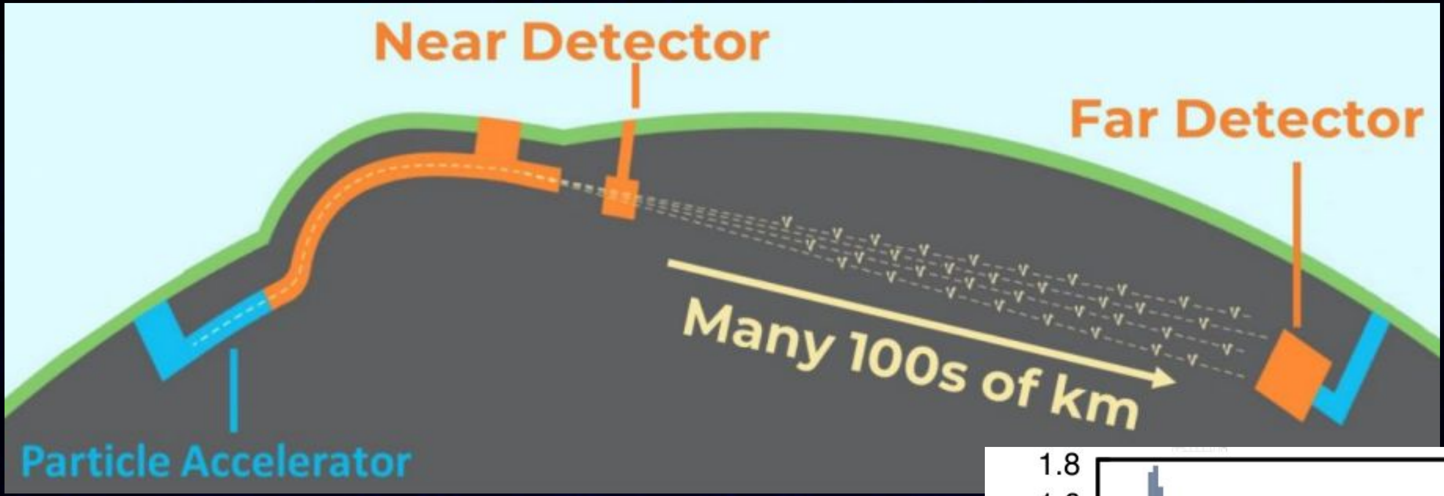
S Dolan, NuFact 2024

https://github.com/NuWro

Accelerator neutrino experiments



Accelerator neutrino experiments

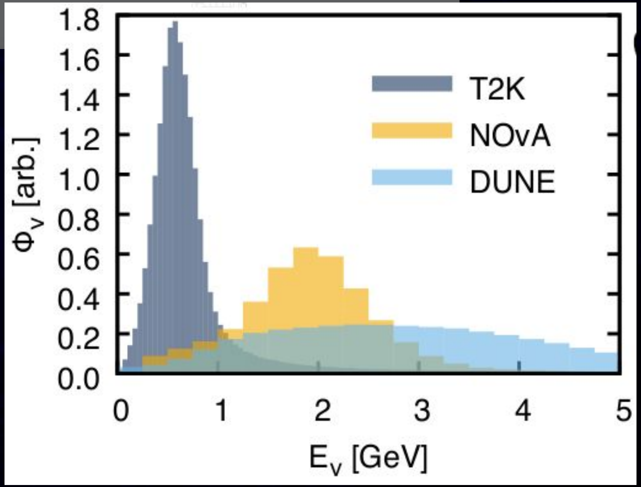


$$N \propto P_{\nu_\alpha \to \nu_\beta} \, \Phi \, \sigma \, \epsilon$$

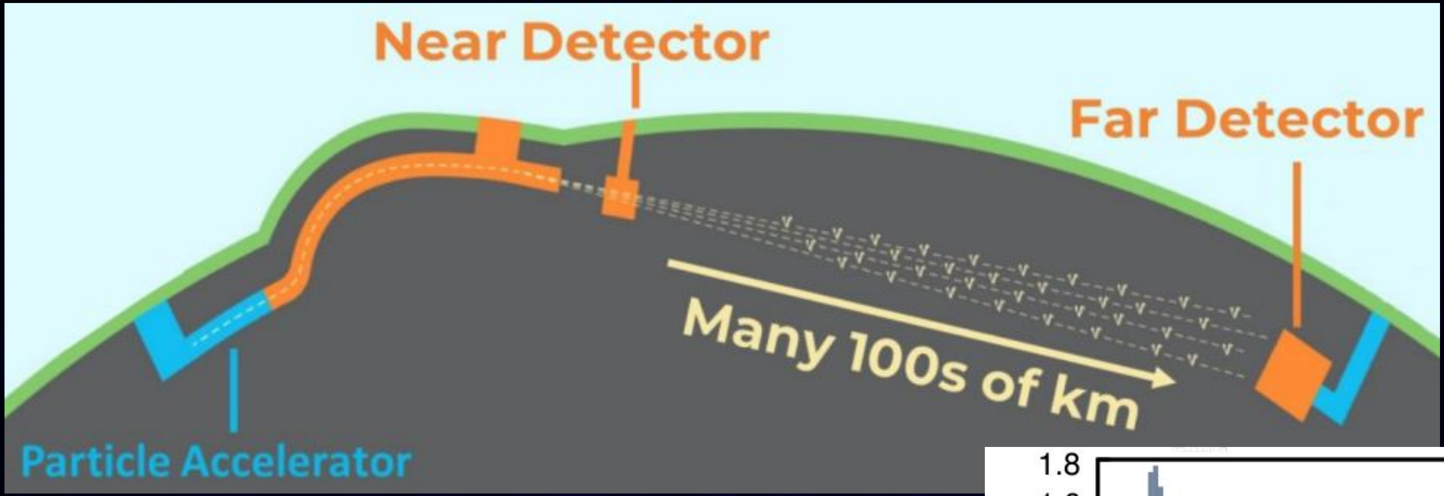
flux

cross-section

detector efficiency



Accelerator neutrino experiments

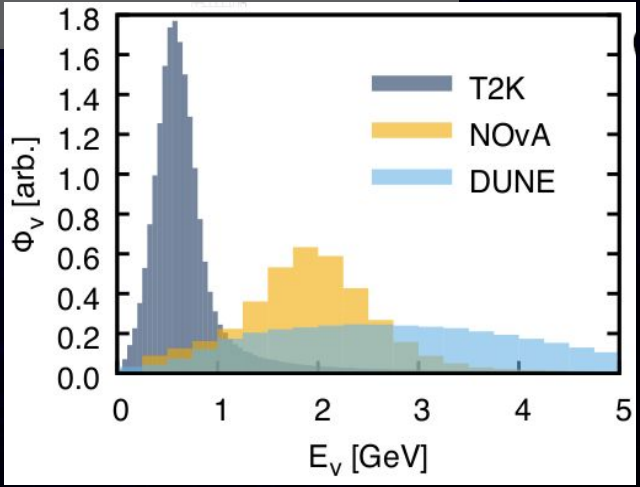


$$\boxed{N} \propto \boxed{P_{\nu_\alpha \to \nu_\beta}} \boxed{\Phi \, \sigma \, \epsilon}$$

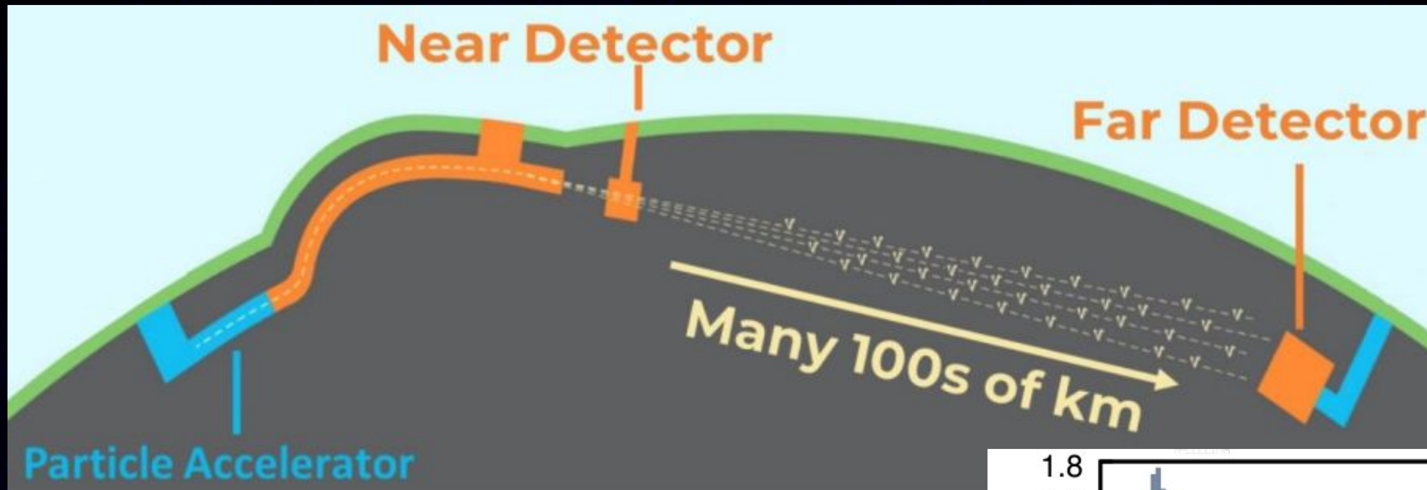
measured

Need with high precision

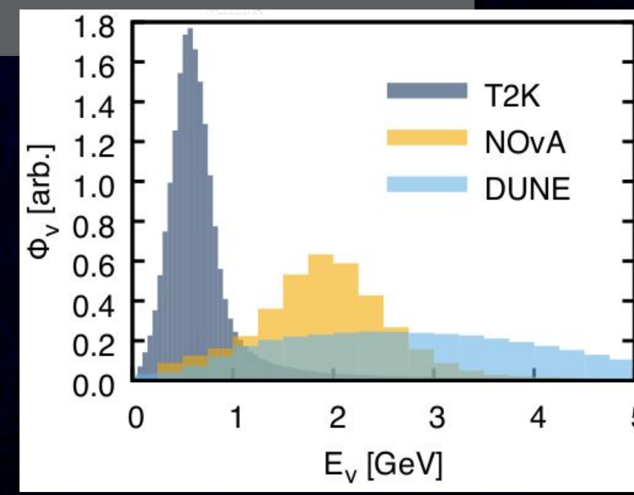
Precise modeling input



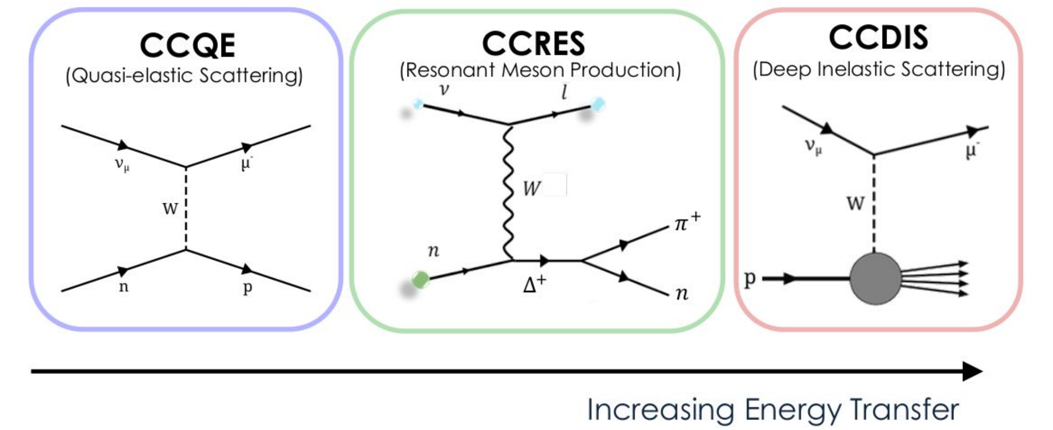
Accelerator neutrino experiments



- Neutrinos are usually NOT produced at fixed energies
- Various complex interaction mechanisms happen
- Precise determination of σ(E) is crucial to extract ν oscillation parameters

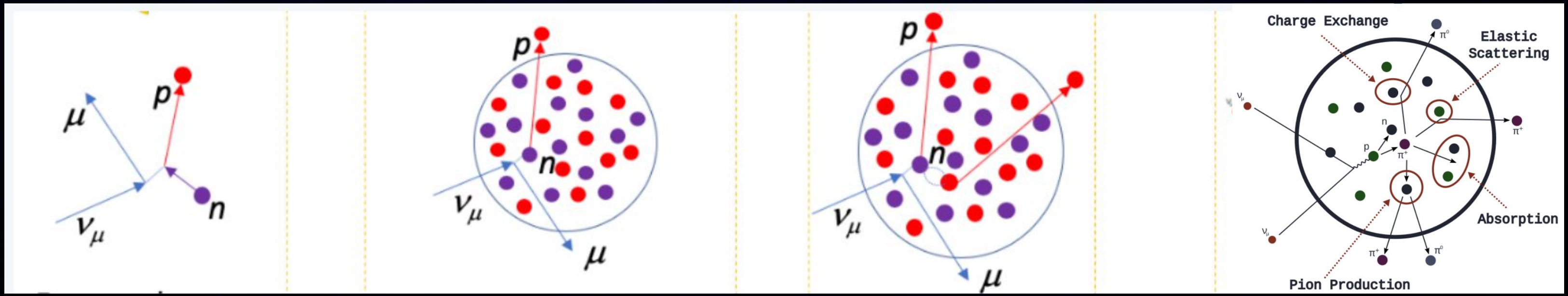


Nuclear mechanisms



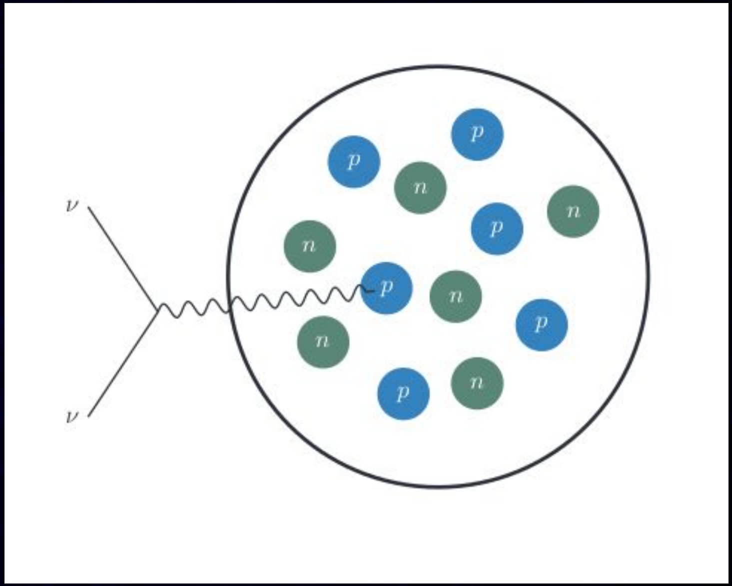
- Various nuclear effects need to be modelled accurately to correctly predict the final state

Free nucleon cross-section | Initial state modeling | Multinucleon interaction | Final state interaction



Impulse approximation

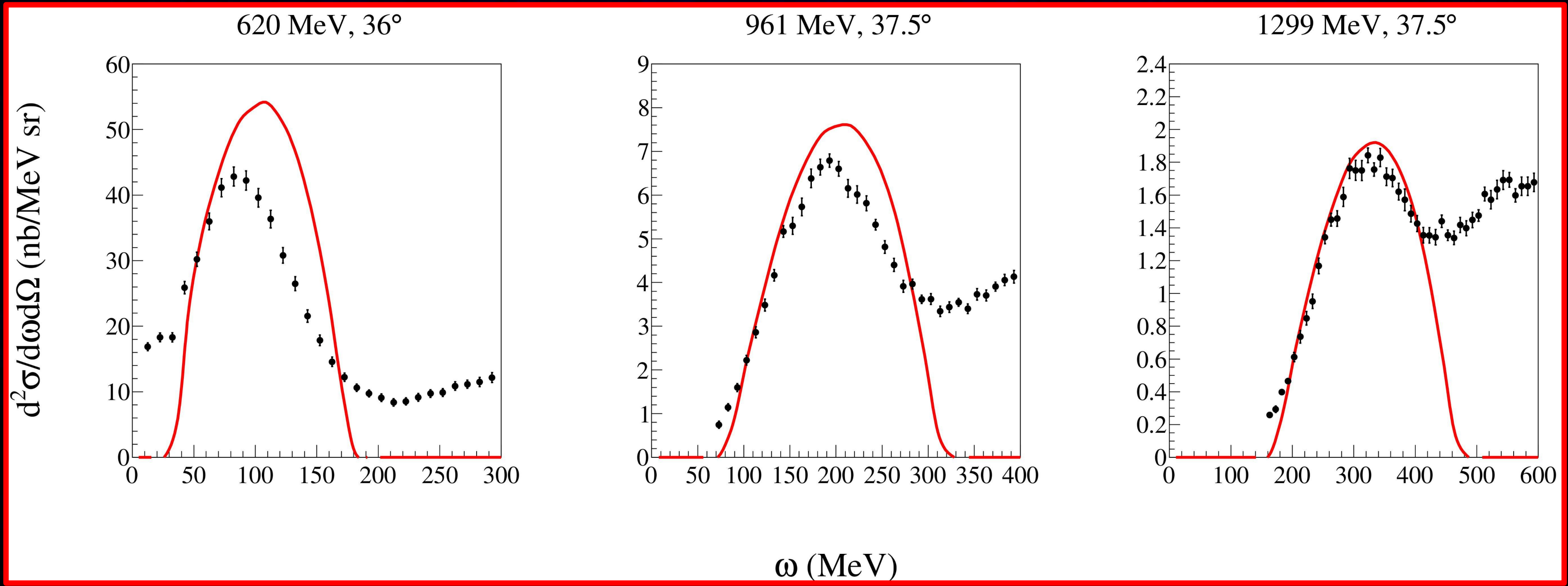
- In the 1 GeV region nuclear effects are typically treated in the impulse approximation (IA)
- Neutrinos interact with individual bound nucleons
- Valid when momentum transfer is high enough
- Within IA one needs a joint probability distribution of momenta and removal energies of target nucleons
- In IA any neutrino-nucleus interaction is viewed in factorization scheme as a two-step process: a primary interaction is followed by final state interactions (FSI) - before leaving nucleus hadrons undergo re-interactions



Fermi gas model : results of electron-Carbon scattering

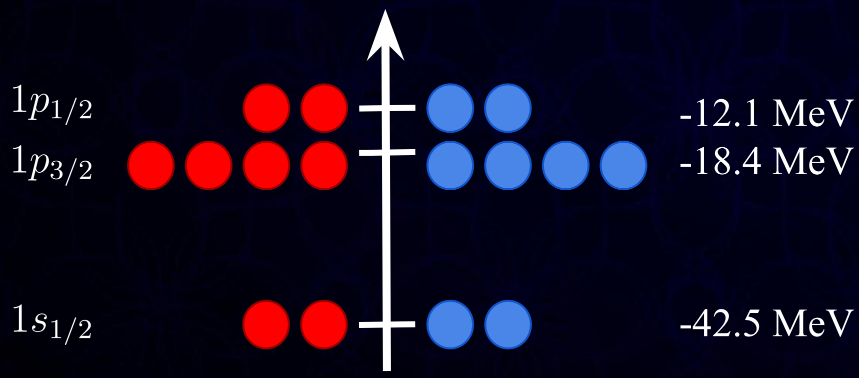
- All nucleons move freely inside the nucleus up to a common momentum cutoff (the Fermi momentum), with a uniform distribution in momentum space and a fixed average binding energy.

$$E_p = \sqrt{M^2 + \mathbf{p}^2} - \epsilon$$



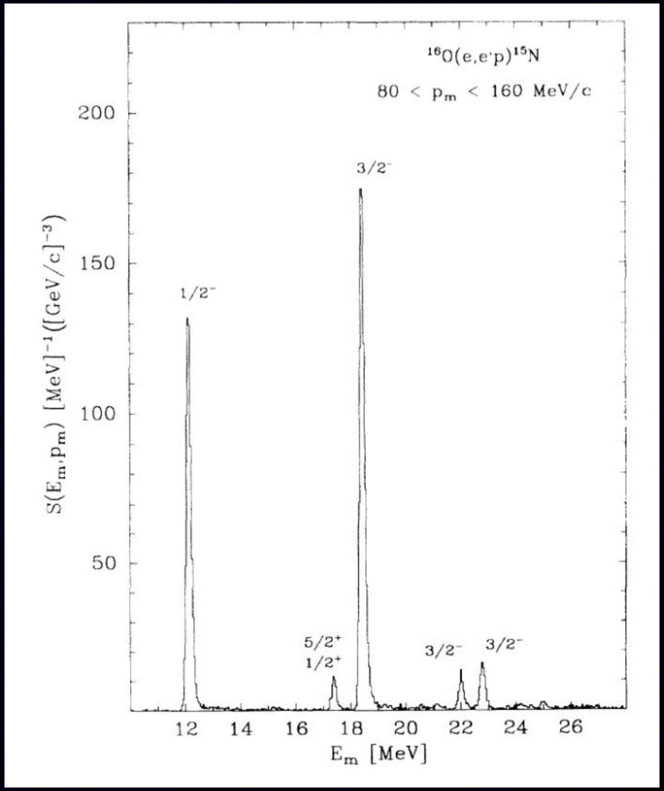
Nuclear shell model

- In a spherically symmetric potential, the eigenstates can be labeled using the total angular momentum



Example : Oxygen nucleus

Leuschner et al., PRC 49, 955 (1994)

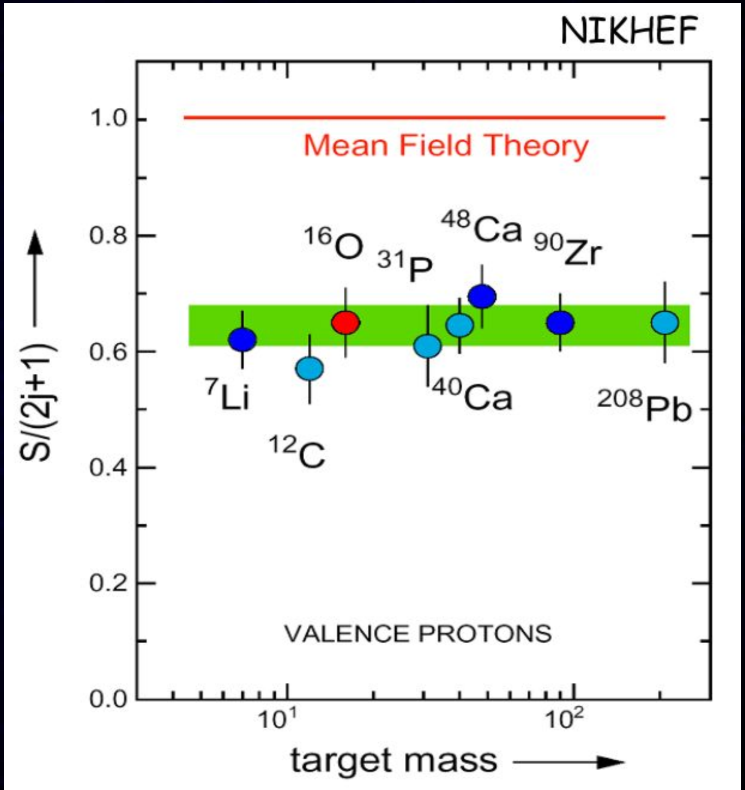


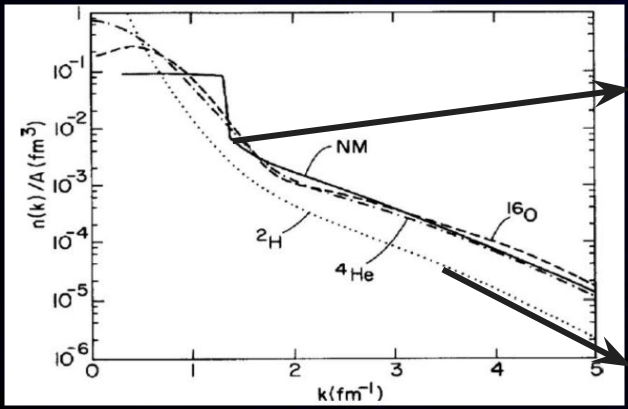
Nuclear shell model is not enough!

- In a spherically symmetric potential, the eigenstates can be labeled using the total angular momentum

- ~ 20-30% depletion of the shell-model states observed. Main source of depletion of the deeply bound shell-model states are short-range NN correlations (SRC)

Nucl. Phys. A553 (1993) 297c





Different structures for different nuclei

Deuterium-like distribution for all nuclei

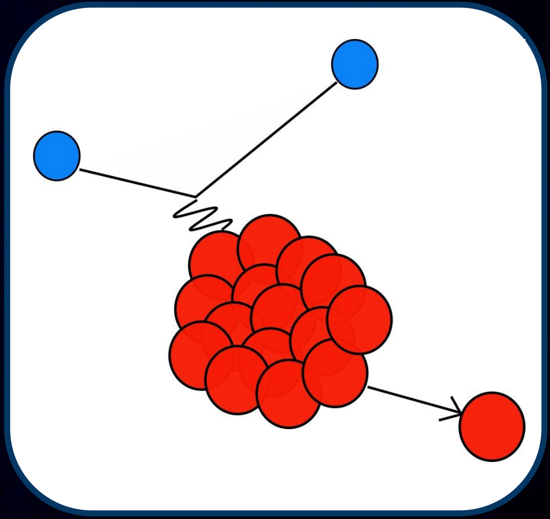
Benhar&Pandharipande, RMP 65, 817 (1993)

Spectral function framework

- Nucleon spectral function *P(p, E)* describes the probability distribution of removing a nucleon of momentum p from the target nucleus, leaving the residual system with excitation energy $E - E_{thr}$

- Fundamental property of nucleus, independent of interaction

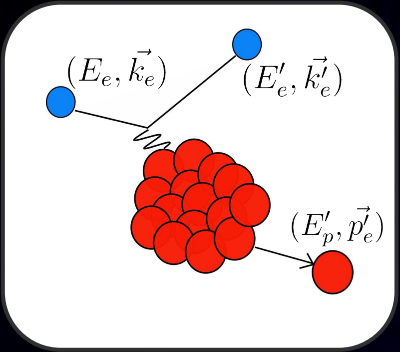
$$P(p,E) = P_{\text{MF}}(p,E) + P_{\text{correlation}}(p,E)$$



- Mean field part describes shell structure. Can be determined from experimental data. 70-80% contribution

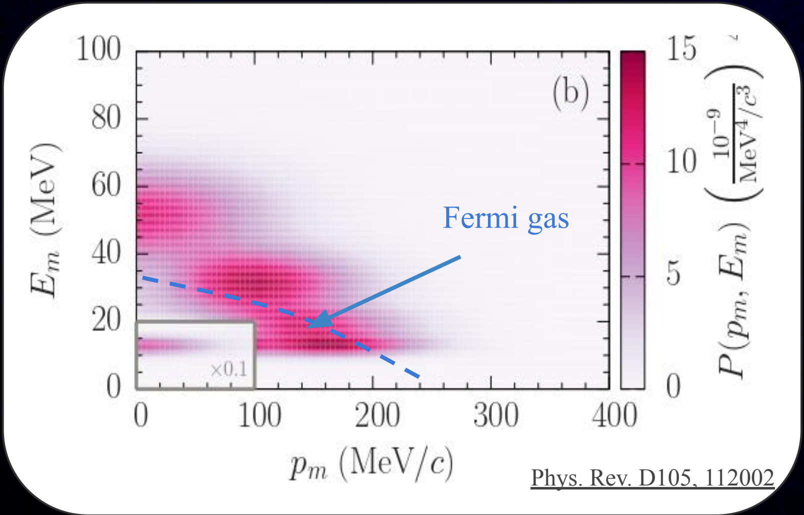
- Correlated part describes correlated high energetic nucleons. Easier to determine from theoretical calculation

JLab Spectral function of Argon and Titanium



Extracted for

- Beam energy 2.222 GeV
- $0 \leq p \leq 300$ MeV for Ar
- $12 \leq E \leq 80$ MeV

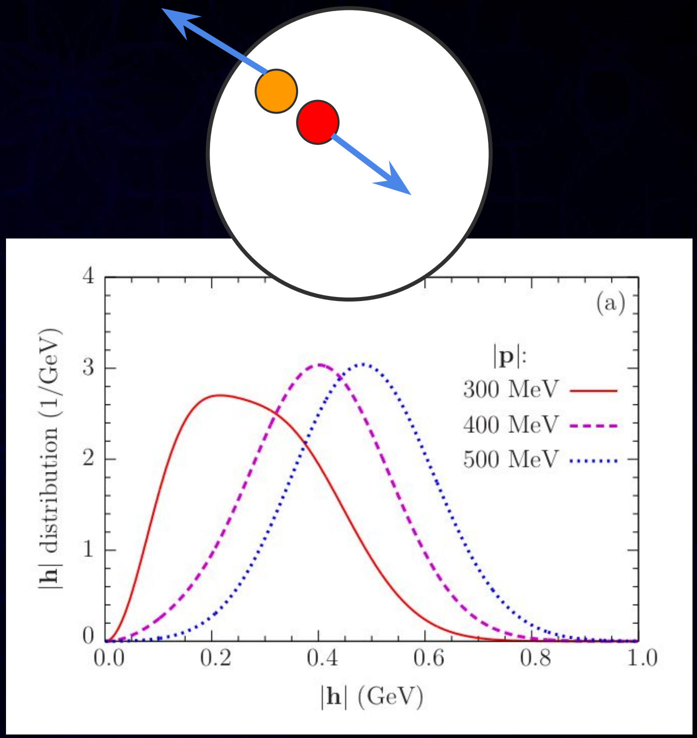


- Understanding neutrino-Argon interactions is of particular interest
- DUNE, MicroBooNE, SBND, ICARUS use liquid Argon as neutrino detector
- Argon : easy ionisation, high electron lifetime, dense and **very cheap** - \$2/L (\$3000/L for Xe, \$500/L for Ne)

Short range NN correlations

- Correlated spectral function is expressed as a convolution integral

$$P_{\rm corr}(p,E) = \int d^3h\,\delta(E - E_{\rm thr} - T_{A-1}) \times n^{pn}_{cm}(|p+h|)\,n^{pn}_{rel}(|\frac{p-h}{2}|)$$



- Correlated nucleon added to the primary vertex, if struck nucleon belongs to corr. contribution

- We assume correlated pair's dynamics to be largely decoupled from residual system

- Relative and centre-of-mass motion of the pair generates complex dynamics

Coulomb distortion

Alter momenta of charged particles
Introduce focusing of wave functions

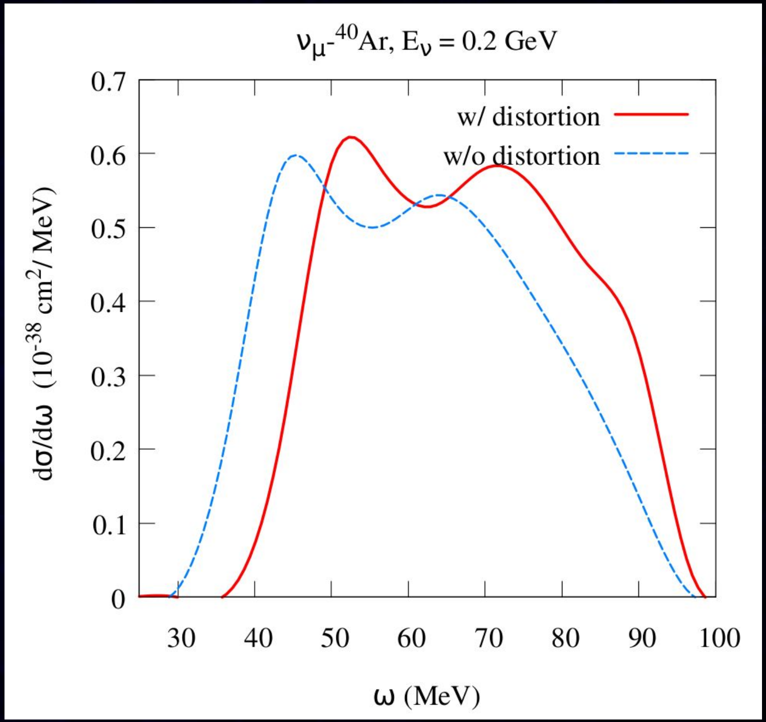
$$E_l \rightarrow E_l^{eff} = E_l + V_C$$

Average Coulomb potential

$$k_l \rightarrow k_l^{eff} = \sqrt{(E_l + V_C)^2 - m_l^2}$$

$$\sigma \rightarrow \sigma^{eff} = \left(\frac{k_l^{max}}{k_l^{eff}}\right)^2 \sigma$$

$$k_l^{max} = \sqrt{(E_l + V_C^{max})^2 - m_l^2}$$



Final state interactions

- FSI is implemented using convolution scheme

$$\frac{d^2\sigma^{\mathrm{FSI}}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega') \frac{d^2\sigma^{\mathrm{PWIA}}}{d\omega' d\Omega}$$

- FSI modifies struck nucleon's energy spectrum using real part of the optical potential

$$f_q(\omega - \omega') \rightarrow f_q(\omega - \omega' - U_V)$$

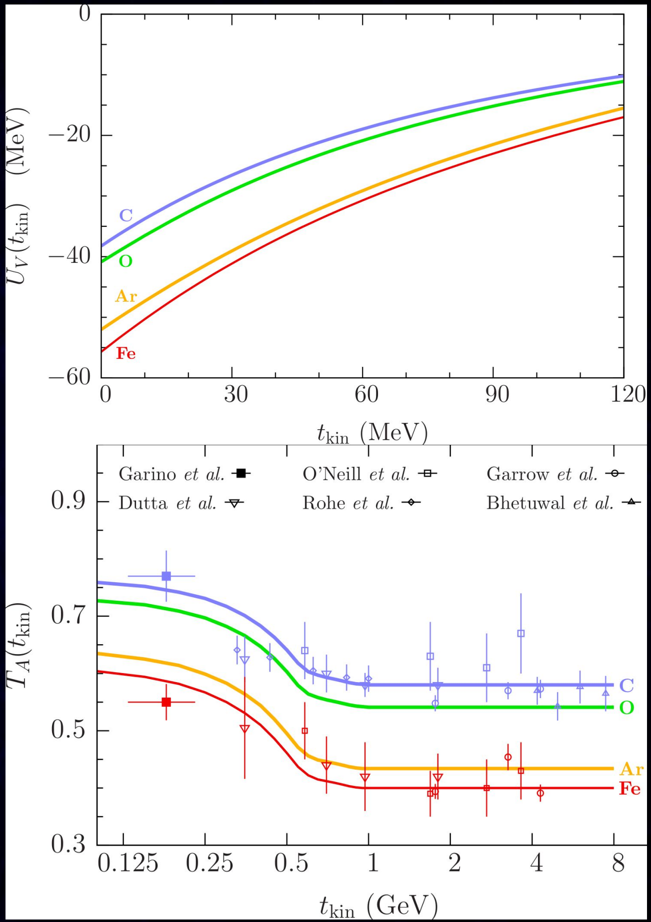
Real part of optical potential

- Folding function describes broadening of cross-section

$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + F_{\mathbf{q}}(\omega)(1 - \sqrt{T_A})$$

Nuclear transparency

- Smears inclusive cross sections, affects energy conservation and kinematics of lepton



Final state interactions

- Events are categorised into two parts

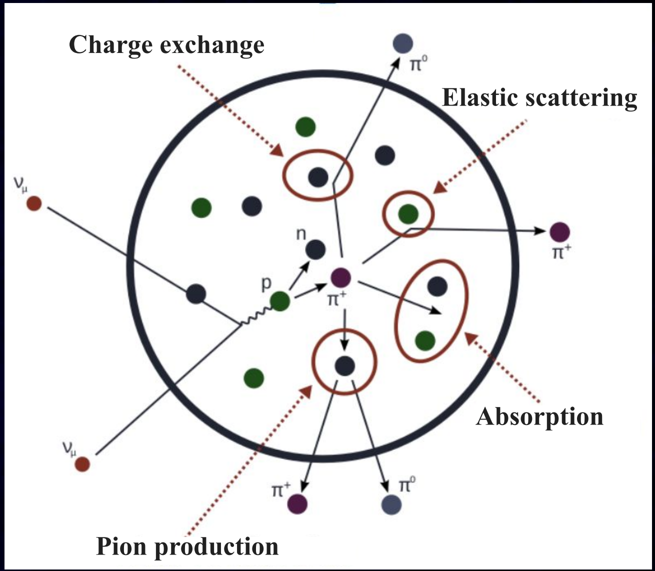
$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + F_{\mathbf{q}}(\omega)(1 - \sqrt{T_A})$$

Transparent

Passes through nuclear medium undisturbed

Non-transparent

Initiates at least one intranuclear collision



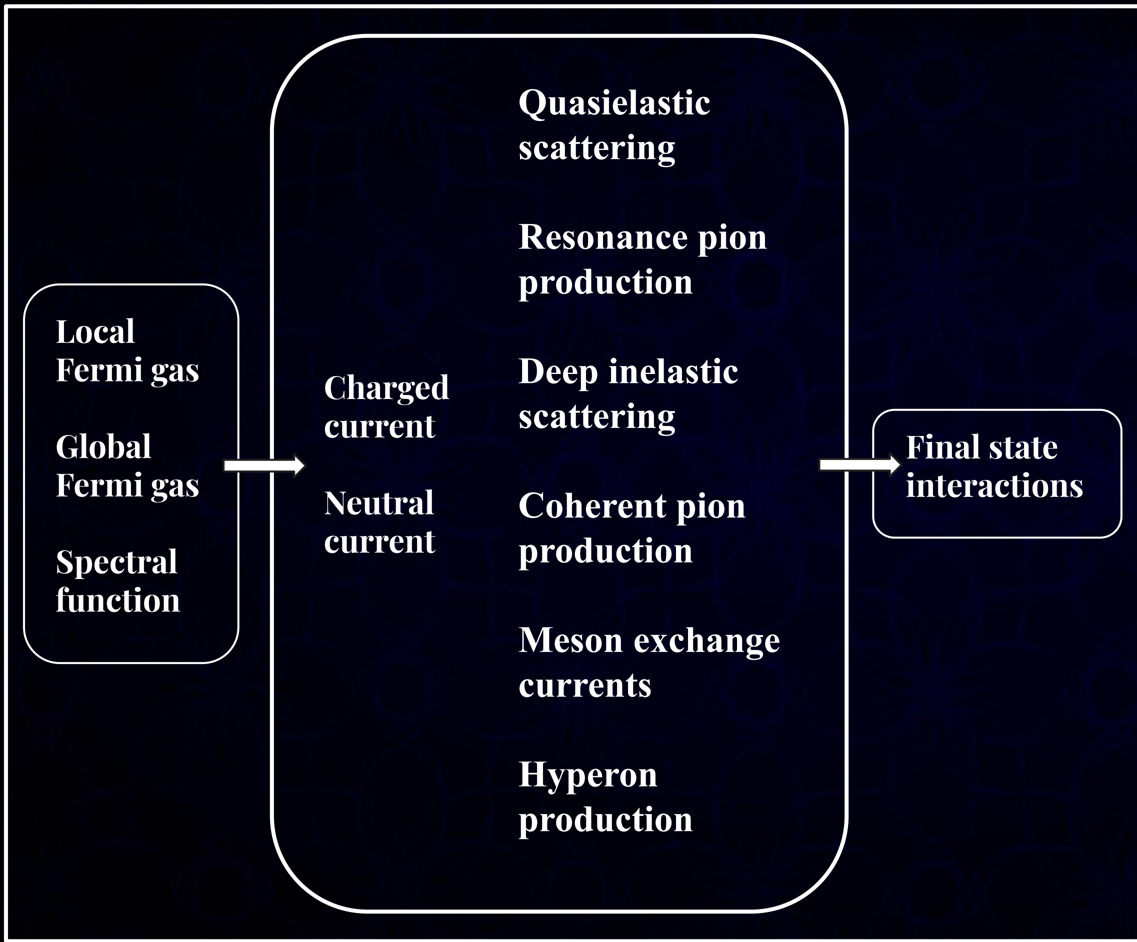
Credit : T Golan

- Intranuclear cascade modifies strength and opens new interaction channels

Monte Carlo event generators

- Monte Carlo generators connect experiment (what we see) and theory (what we think we should see)
- Any neutrino analysis relies on MC generators
- Integrations of cross sections, and event generation using acceptance and rejection techniques
- Accurate MC simulations required to better understand neutrino interactions

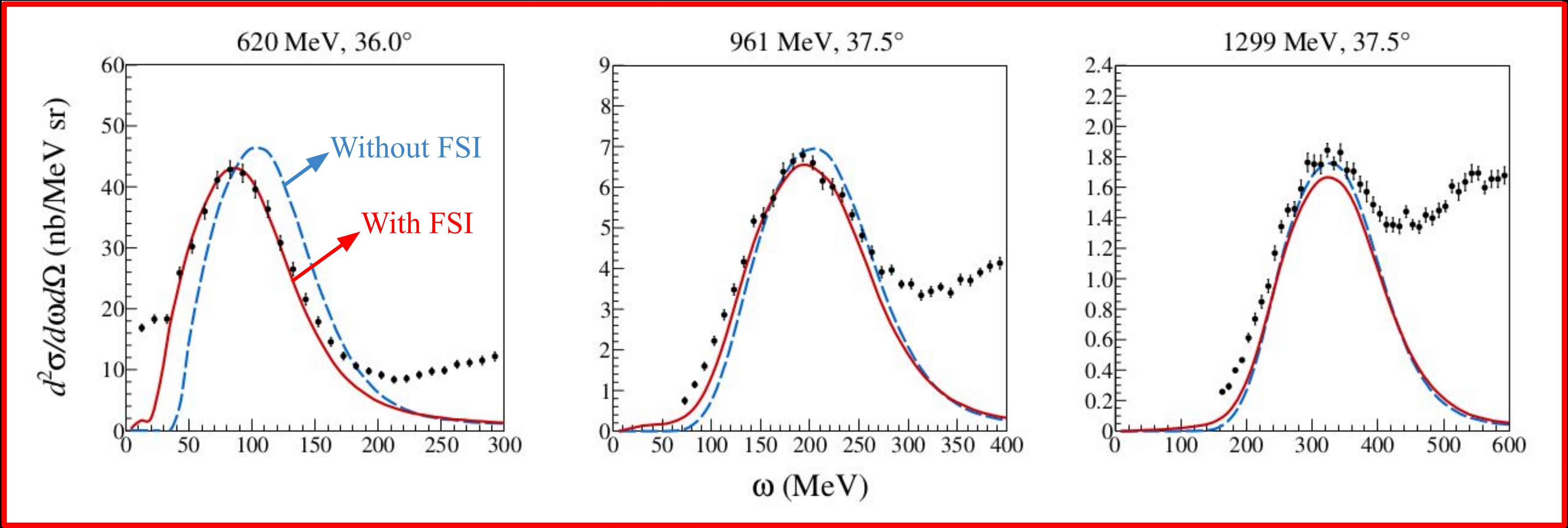
NuWro blackbox



- Developed by ~ 15 people since 2004
- Written in C++, output is a ROOT file with easy to analyse event
- Covers energy from ~100 MeV to ~100 GeV
- Used in various experiments worldwide
- https://github.com/NuWro/nuwro
  Latest released version :
  NuWro 25.03.2

Results from electron scattering : What NuWro predicts

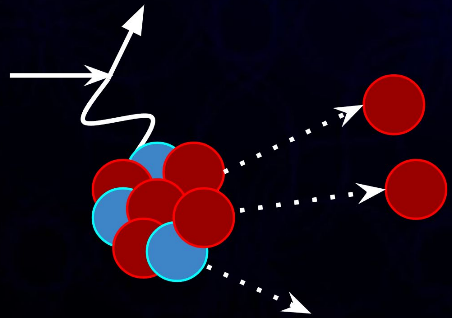
- It is good practice to test models with electron scattering data first. Electron beam is mono-energetic with less systematic uncertainties and larger cross-sections
- NuWro provides prediction only for Quasielastic channel (eWro)



MicroBooNE exclusive cross-sections

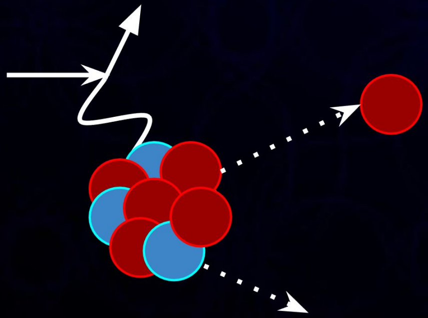
CC2p0π

- Exactly 2 protons with momentum (0.3, 1.0) GeV/*c*
- 1 muon with momentum (0.1, 1.2) GeV/*c*
- No neutral pions. Any number of neutrons
- No charged pion over 70 MeV/c momentum

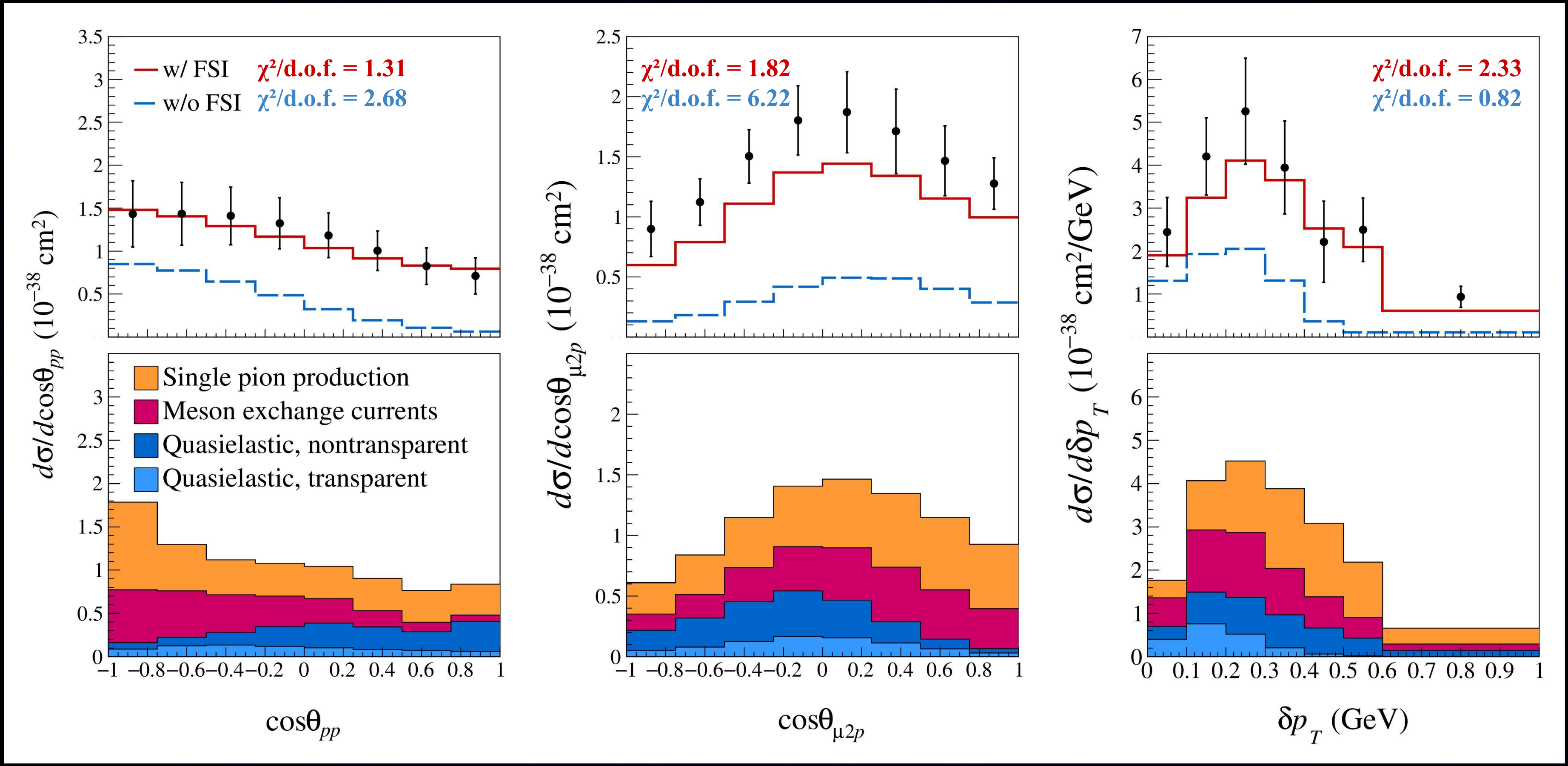


CC1p0π

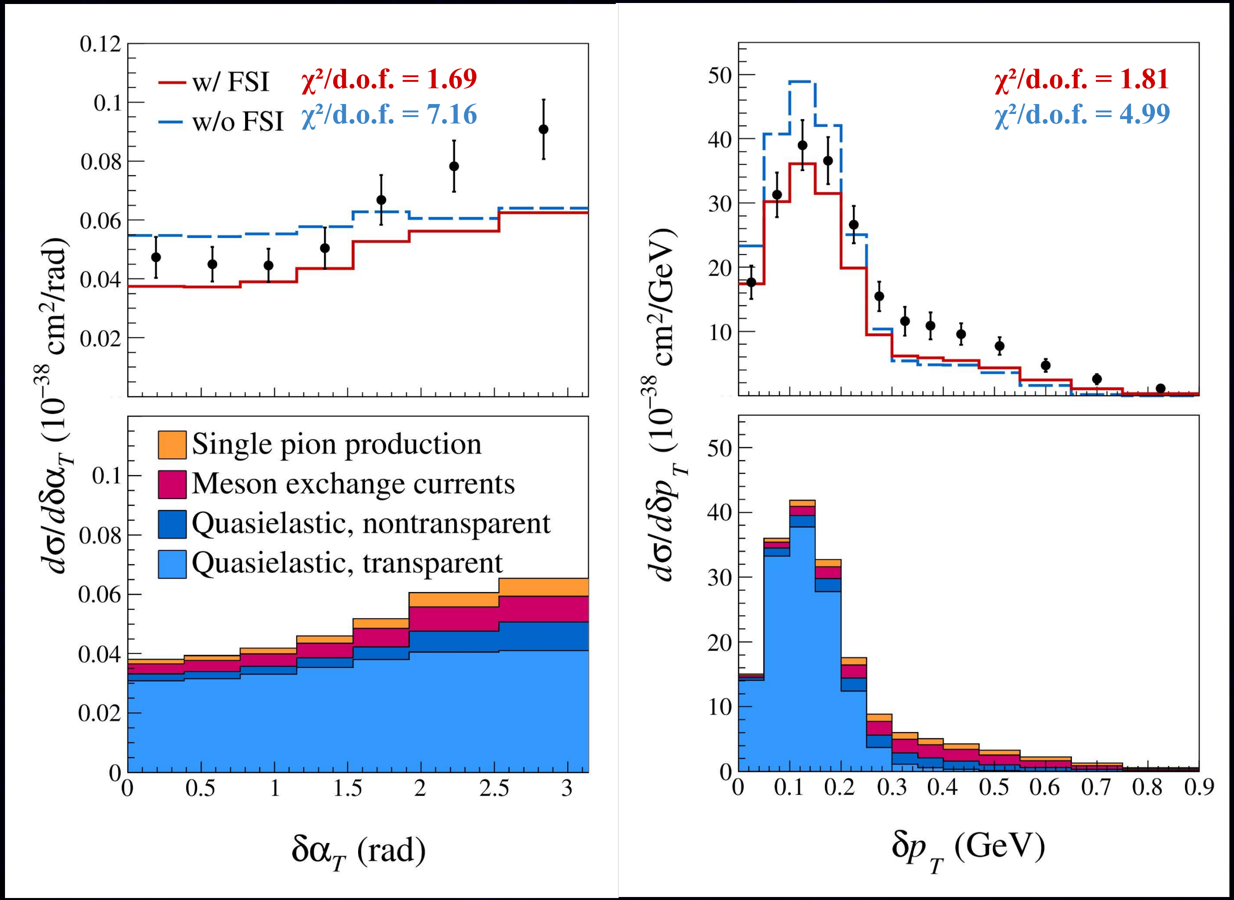
- Exactly 1 proton with momentum (0.3, 1.0) GeV/*c*
- 1 muon with momentum (0.1, 1.2) GeV/*c*
- No neutral pions. Any number of neutrons
- No charged pion over 70 MeV/c momentum



MicroBooNE CC2p0π cross-sections : What NuWro predicts



MicroBooNE CC1p0π cross-sections : What NuWro predicts



I am at the end of my talk!

- Recently in the SF approach in NuWro, we implement (*work in progress*) a consistent treatment of multinucleon final states in QE scattering and other low energy corrections
- For Argon, we implement improved description of short range NN correlations
- Accurate description of nuclear effects is crucial for extracting neutrino oscillation parameters
- Plenty of new experimental data coming soon from existing program
- Exciting time to ‘strongly’ interact with neutrinos!


Thank you for your attention

BACKUP SLIDES

Short range NN correlations

- Correlated spectral function is expressed as a convolution integral

$$P_{\text{corr}}(p, E) = \int d^3h\delta(E - E_{\text{thr}} - T_{A-1}) \times n_{cm}^{pn}(|p+h|)n_{rel}^{pn}(|\frac{p-h}{2}|)$$

2-nucleon threshold energy

Excitation energy of (A-1) system

CoM momentum distribution of pair

p and h are initial momenta of the struck and correlated nucleon

Relative momentum distribution of pair

Short range NN correlations

- Correlated spectral function is expressed as a convolution integral

$$P_{\text{corr}}(p,E) = \int d^3h\delta(E - E_{\text{thr}} - T_{A-1}) \times n_{cm}^{pn}(|p+h|)n_{rel}^{pn}(|\frac{p-h}{2}|)$$

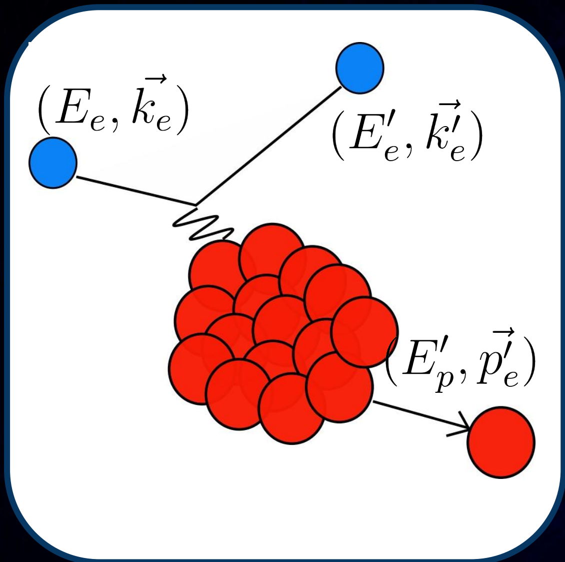
- center-of-mass momentum distribution of the pair is

$$n_{cm}^{pn}(p) \;=\; Z\left(\frac{\alpha_{cm}}{\pi}\right)^{3/2}\exp\left(-\alpha_{cm}p^2\right)$$

- relative momentum distribution of the pair is

$$n_{rel}^{pn}(p) \;=\; \frac{C^A}{4\pi}\left[A_1\exp\left(-\alpha_1 p^2\right) + A_2\exp\left(-\alpha_2 p^2\right)\right]$$

Missing energy and missing momentum



$$E_e + M_A = E'_e + E'_p + E^*_{A-1}$$

known

determined

$$\vec{k}_e + \vec{0} = \vec{k}'_e + \vec{p}' + \vec{p}_{A-1}$$

In general,

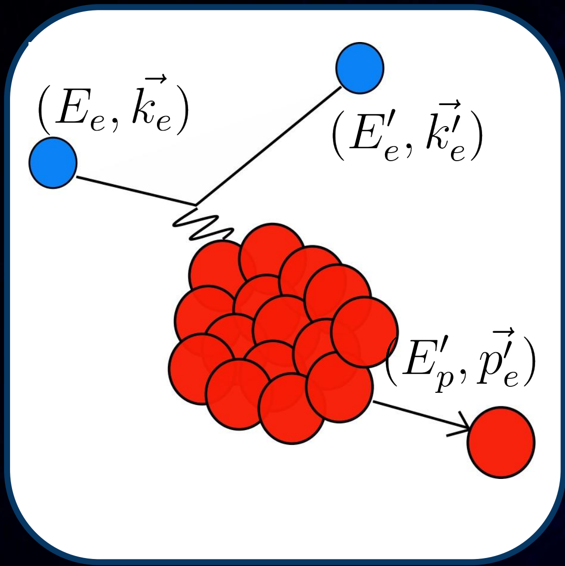
$$E^*_{A-1} = \sqrt{(M_A - M + E)^2 + \mathbf{p}^2_{A-1}}$$

Without final state interactions,

$$-\vec{p}_{A-1} = \vec{p}$$

is the initial proton momentum

Missing energy and missing momentum



$$E_e + M - E = E'_e + E'_p$$

known

determined

$$\vec{k}_e + \vec{p} = \vec{k}'_e + \vec{p}'$$

For negligible recoil energy,

$$E^*_{A-1} = M_A - M + E$$

Without final state interactions,

$$-\vec{p}_{A-1} = \vec{p}$$

is the initial proton momentum