INSTITUTO DE FISICA
DE PARTICULAS Y DEL COSMOS

UNIVERSIDAD COMPLUTENSE DE MADRID

Neutrino nucleus interactions for neutrino oscillations

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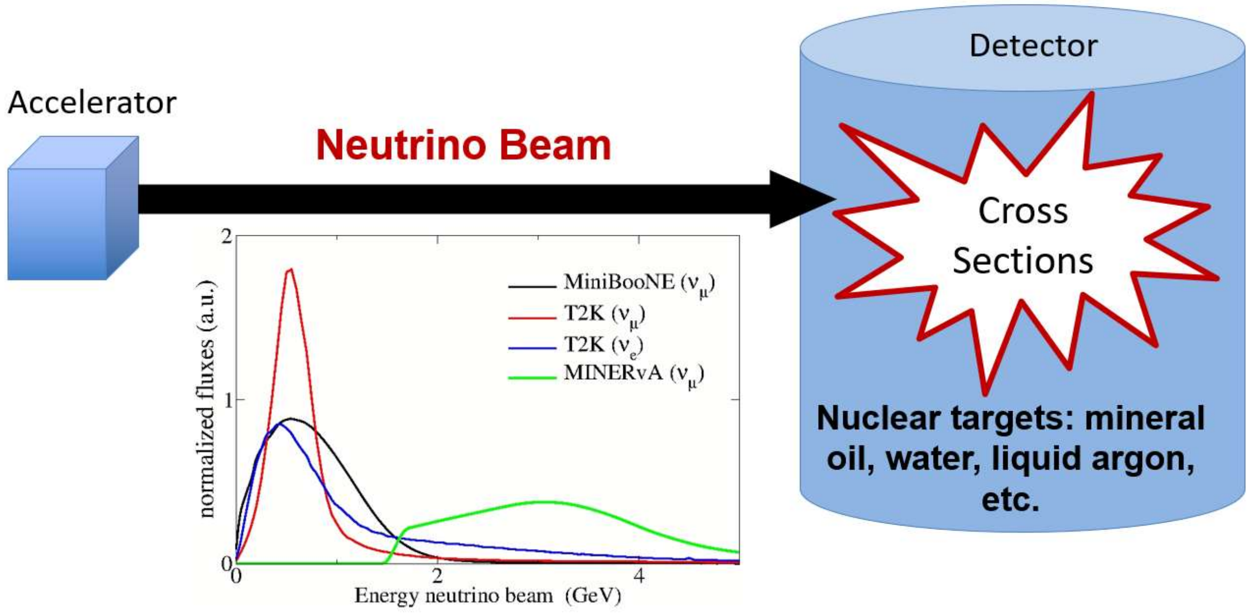
(…)

Neutrino oscillation experiments

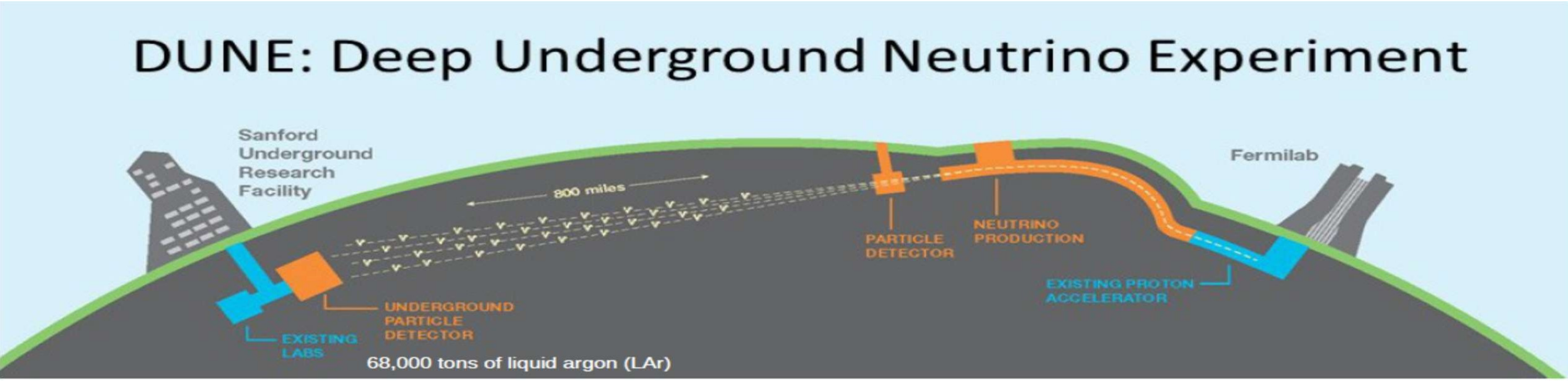
- Both present and future generations of **ν-oscillation experiments use nuclei as target material.**
- A good understanding of ν-nucleus scattering processes, including nuclear effects, is essential.

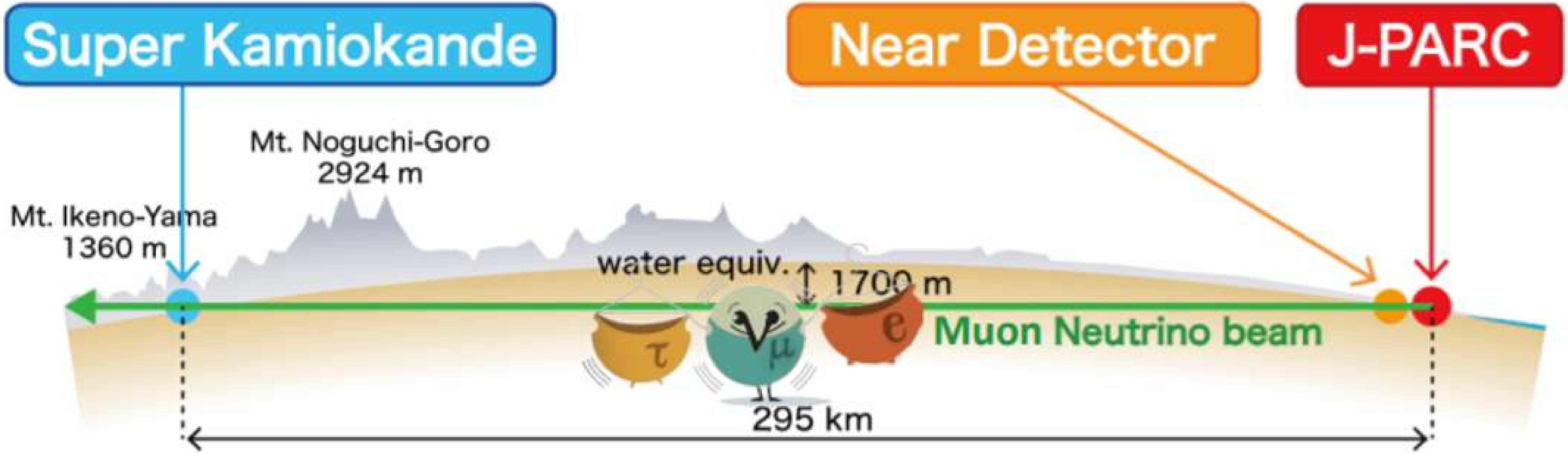


- **Mono-energetic neutrino beams are not available.**

Summary of experiments

Experiment	Nuclear Target	Beam	Process Detected	E_ν (GeV)
MiniBooNE	CH_2	$\nu_\mu, \bar{\nu}_\mu$	CCQE-like, Pion production	0.2-3.0
MINERνA	CH, C, Fe, Pb	$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$	CCQE-like, Pion production, DIS, Inclusive	1-20
T2K	H_2O, C_8H_8	$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$	CCQE-like, Inclusive	0.2-30
ArgoNeuT	Ar	$\nu_\mu, \bar{\nu}_\mu$	Pion production, Inclusive	0.5-10.0
SciBooNE	C_8H_8	ν_μ	CCQE-like, Inclusive, Kaon production, Pion production	0.2-3.0
NOMAD	64%C, 22%O, 6%N, 5%H, 1.7%Al	$\nu_\mu, \bar{\nu}_\mu$	CCQE	2.5-300
MINOS	Fe	ν_μ	CCQE-like, Pion production	0.2-6.0
NOνA	CH_2	ν_μ	CCQE-like	0.2-3.0
MicroBooNE	Ar	$\nu_\mu, \bar{\nu}_\mu$	CCQE-like	0.2-5.0
Hyper-Kamiokande	H_2O	$\nu_\mu, \bar{\nu}_\mu$	CCQE-like	0.3-5.0
DUNE	Ar	$\nu_\mu, \bar{\nu}_\mu$	CCQE-like, Inclusive	0.2-15.0

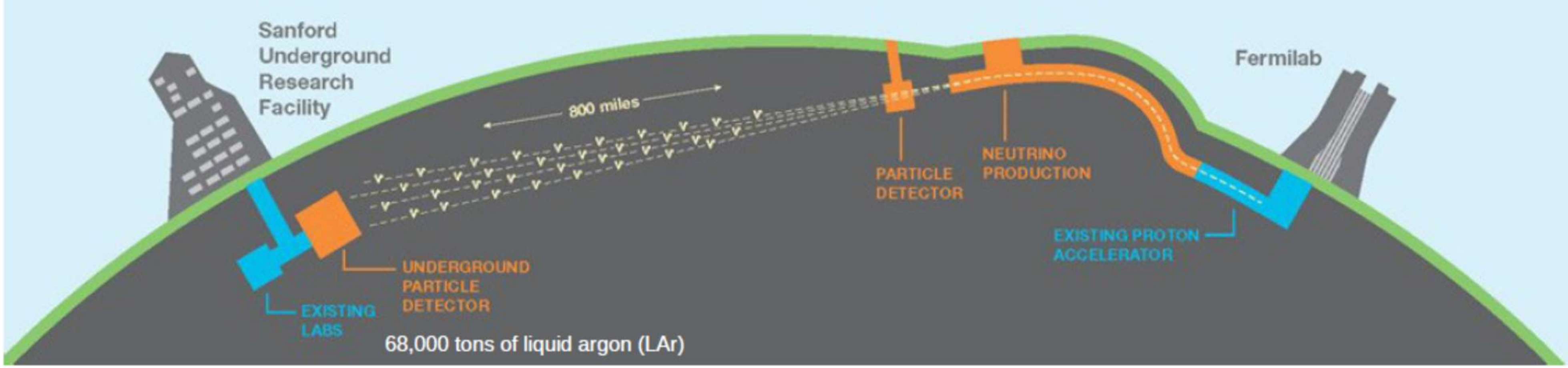

DUNE: Deep Underground Neutrino Experiment
Sanford Underground Research Facility
800 miles
Fermilab
PARTICLE DETECTOR
NEUTRINO PRODUCTION
EXISTING PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS
68,000 tons of liquid argon (LAr)


Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Muon Neutrino beam
295 km

Neutrino oscillation experiments

- We are entering in the **precision era of neutrino oscillation experiments**, neutrino interaction uncertainties must be reduced for DUNE/Hyper-K to succeed.

DUNE: Deep Underground Neutrino Experiment



$$P_{a\to b} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

To extract the parameters we need to know the energy of the neutrino

Accelerator-based oscillation experiments

$$\nu_\alpha \rightarrow \nu_\beta$$

Number of events

Adapted from M.Martini (NuFact17)

$$N_\beta(E_\nu?) \sim \Phi_{\nu_\alpha}(E_\nu)\ \sigma_{\nu_\beta}(E_\nu)\ \varepsilon_{det.}\ P_{\nu_\alpha \rightarrow \nu_\beta}(\{\Theta\}, E_\nu)$$

ν flux | ν cross section | Detector efficiency | ν Energy in the oscillation probability

Summary of an oscillation experiment:

1) Source of a neutrinos with a given energy distribution Φ_α (neutrino flux) at the source.

2) In the far detector, N_β neutrino interaction events are detected, each event with a different topology (e.g. electrons are detected for different scattering angles and energies).

3) One wishes to determine the oscillation probability $P_{\alpha\rightarrow\beta}$ as a function of the neutrino energy, so that the neutrino parameters can be extracted.

Problems:

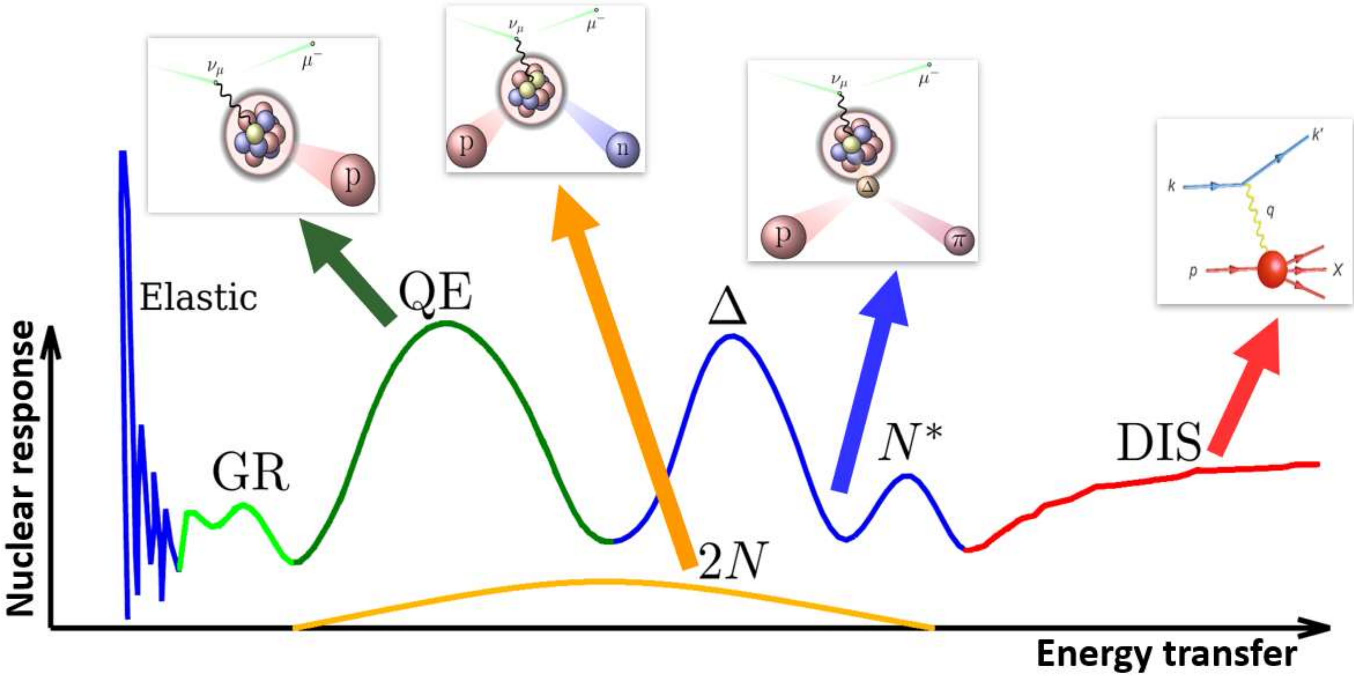
1) A cross section model is needed.

2) The energy of the incident neutrino is not known: it has to be reconstructed combining theoretical information (cross sections) and experimental data.

The reconstruction procedure introduce important uncertainties in the oscillation analyses.

Neutrino-nucleus interactions

- We need theoretical models able to describe **all possible reaction channels** in the wide energy region covered by the neutrino beams.

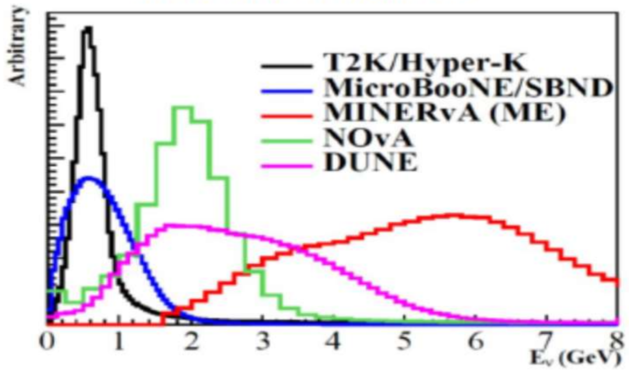


- Four main channels: **quasielastic scattering** (QE), **resonance production** (RES), **two-nucleon knockout** (2N) and **deep inelastic scattering** (DIS).

Two main problems slow down the progress:

1. Neutrino beams are not mono-energetic.

Neutrino fluxes

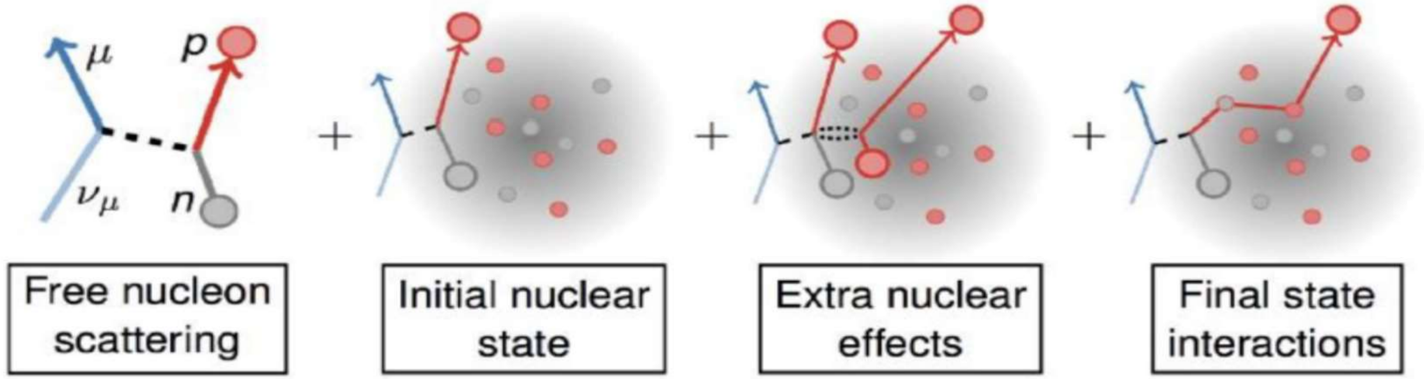


The neutrino energy has to be reconstructed:

+ from the energy deposited in the detector.

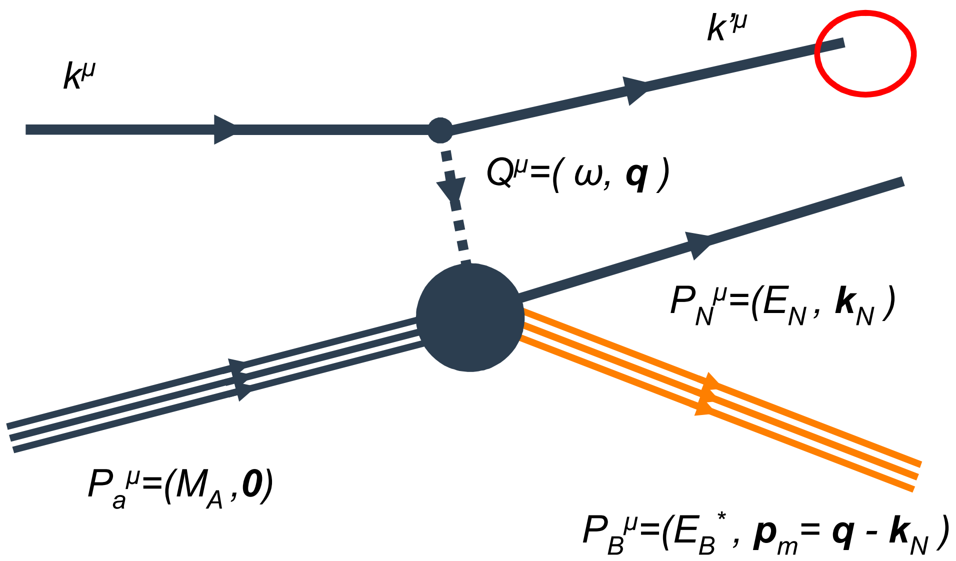
+ by using models for the neutrino-nucleus interaction.

2. Detectors are made of complex nuclei or molecules (H_2O, Ar liquid, CH_x, ...). Complex in comparison with the 'easy-to-model' hydrogen target.



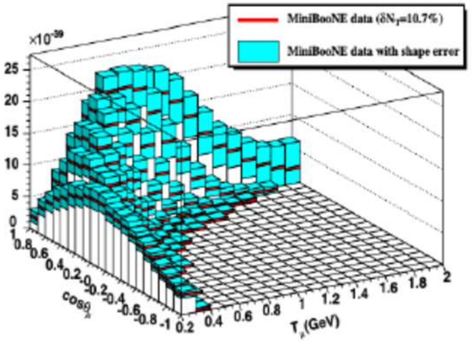
Kajetan Niewczas @ NuFact2018

Neutrino-nucleus experiments
Inclusive: only the lepton (muon, electron) is detected



Example: **the reconstruction procedure at the MiniBooNE experiment:**

1) In MiniBooNE a **QE-like event** happens when a muon and no pions are detected. The event is characterized by the scattering angle and the energy of the muon.

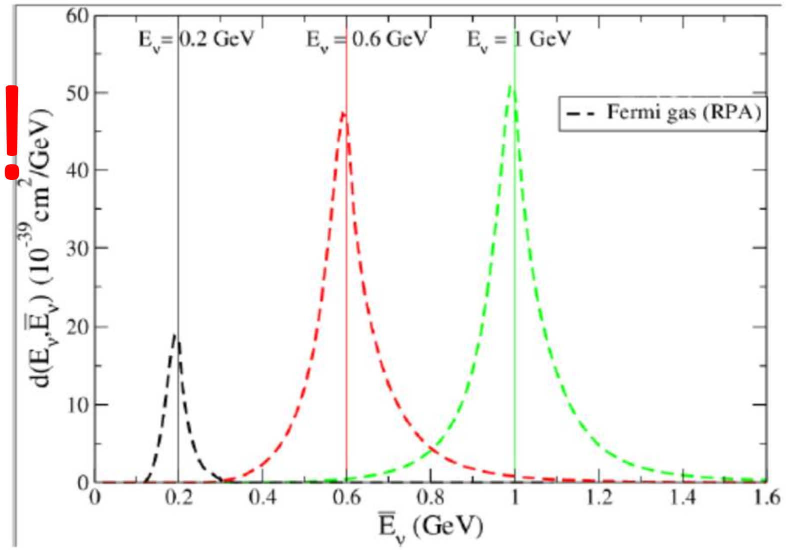


2) The neutrino energy is reconstructed using the formula:

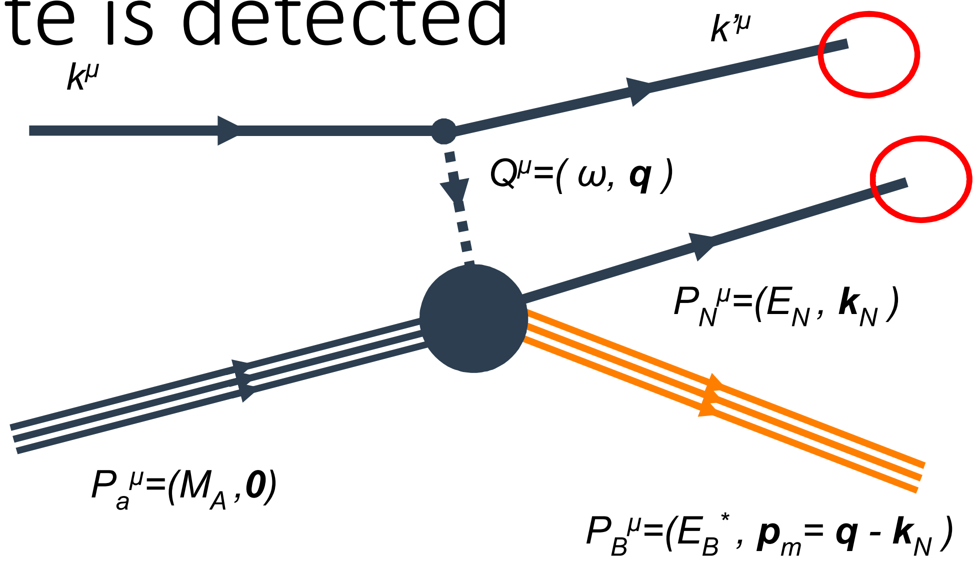
$$E_\nu^{QE} = \frac{m_p^2 - m'^2_n - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

3) Assuming pure QE interaction one can compute the **probability density of the reconstructed energy E^{QE} matching the true energy E: $P(E^{QE}|E)$**
(MiniBooNE used a Fermi gas model to simulate nuclear system)

INCLUSIVE?!



Semi-inclusive: both the lepton (muon, electron) and one particle from the hadronic vertex (proton, pion) in the final state is detected



μBooNE

- 1 proton (> 300 MeV/c)
- No $\pi^{\pm}$ (> 70 MeV/c)

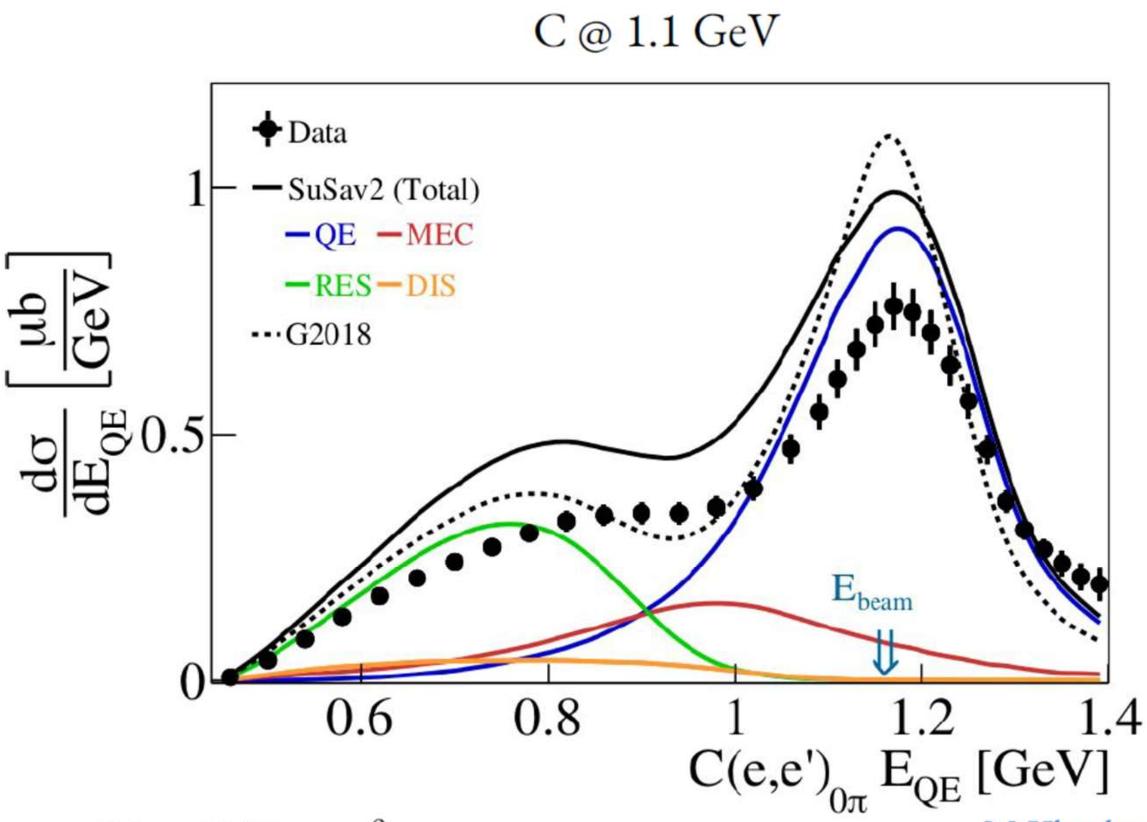
e4ν

- 1 proton (> 300 MeV/c)
- No $\pi^{\pm}$ (> 150 MeV/c)
- Scale by $\sigma_{\nu N} / \sigma_{eN} \propto Q^4$

- Study energy reconstruction
- Test against GENIE event generator

Better tan RFG: SuSav2+factorization, (Seville-MIT-Madrid RGJ et al, tuned to inclusive data). Results not that good

QE Energy Reconstruction



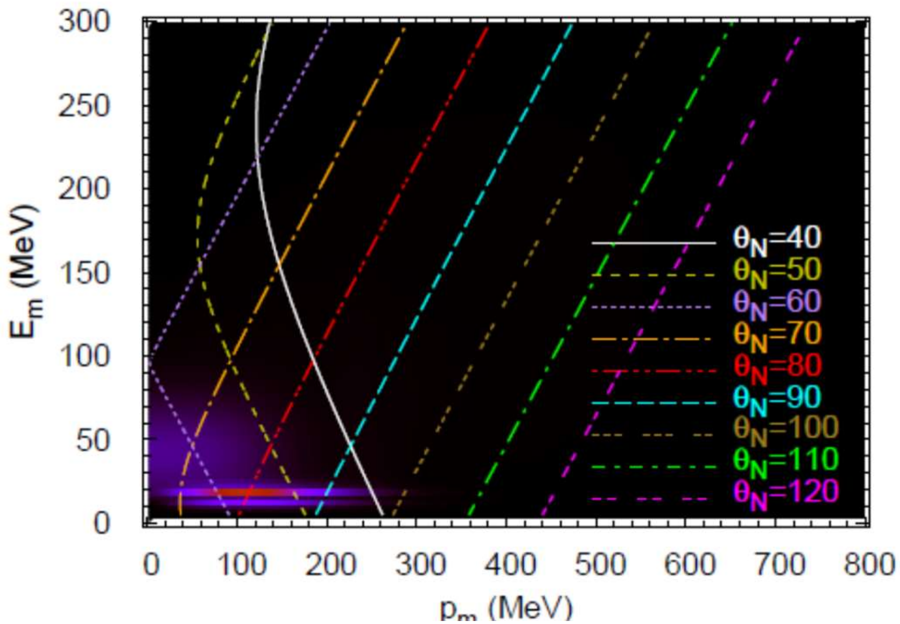
- Relevant for T2K
- Overestimation of QE peak & RES tail

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$

M.Khachatryan, A.Papadopoulou, et al.
Nature 599, 565–570 (2021)

- If particles in the hadronic vertex are also detected, we can use more accurate fo algorithms to derive the energy of the neutrino
- The nuclear model employed to model events, most often, is the RFG, too bad
- Better proposal: use the most realistic model available, obtain the most likely energy of the neutrino using the model cross-sections, averaged over events (RGJ et al, Phys. Rev. C 105, 025502, 2022)

$$\langle E \rangle = \frac{\int dE\, E\, \phi(E) \frac{d^6\sigma(E)}{d\Omega_l dk_l d\Omega_N dp_N}}{\int dE \phi(E) \frac{d^6\sigma(E)}{d\Omega_l dk_l d\Omega_N dp_N}}$$

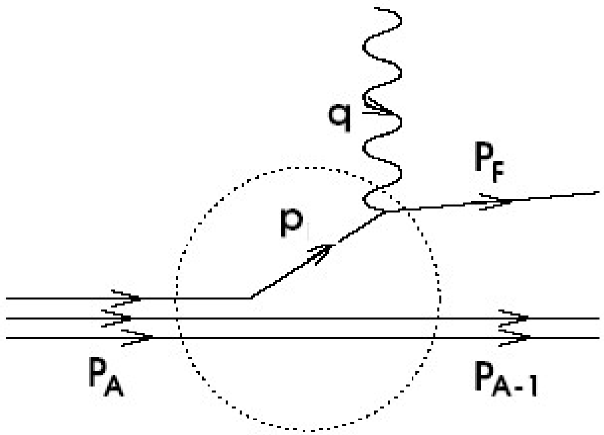


OVERVIEW OF INGREDIENTS FOR THE SEMI-INCLUSIVE CASE

Impulse Approximation

A weak probe will interact with similar probability with both surface nucleons or deep ones

The nuclear matrix element is obtained as a sum over individual contributions, assuming that the nucleon that interacts in the vertex is the one detected



$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\bar{\psi}_F(\vec{p}+\vec{q})\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

Ingredients

- Initial state, we will see in a moment
- Final state: Optical Potential vs Intranuclear cascade (INC)

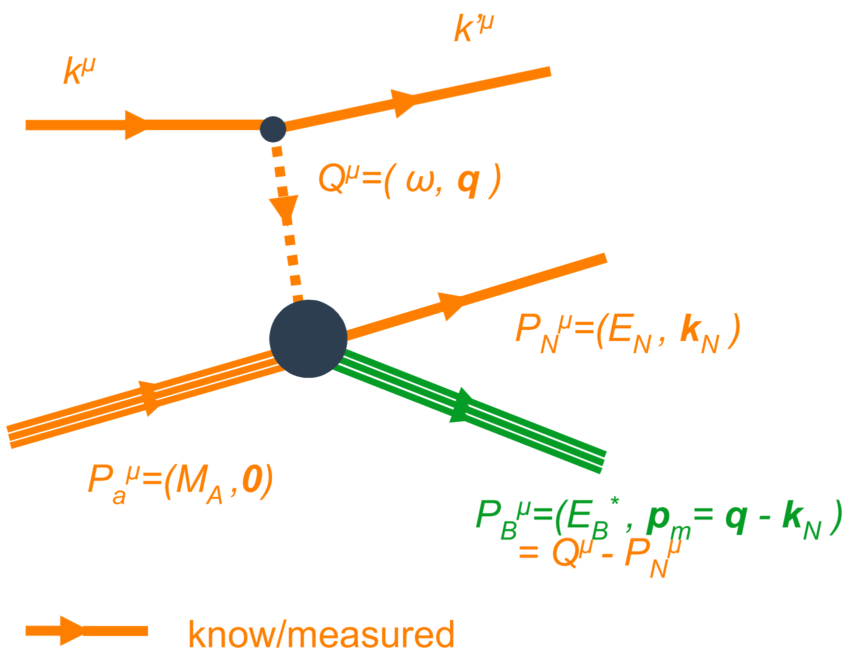
$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^\mu(\omega,\vec{q})\,\psi_B(\vec{p})$$

Ingredients

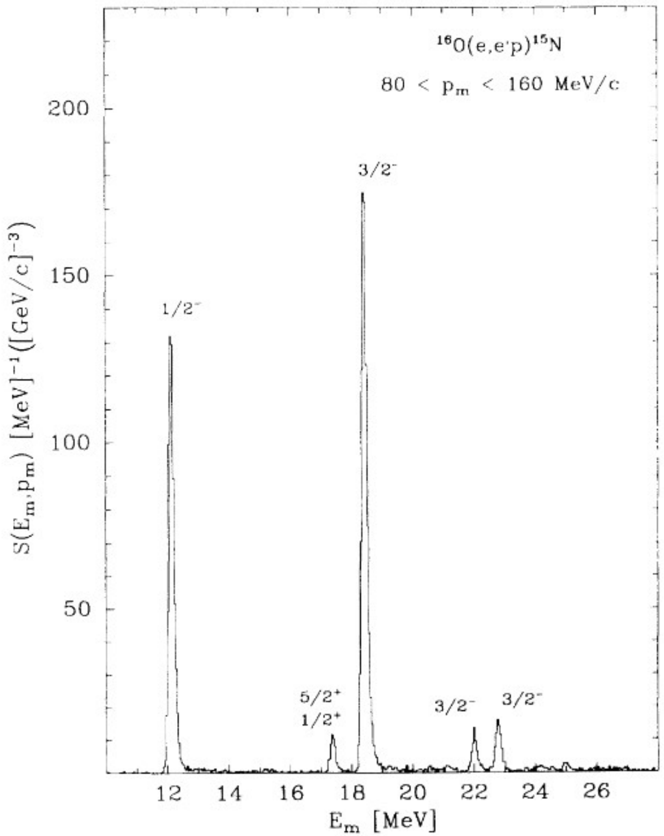
- Initial state: nucleons in a nucleus: IPSM (exclusive case)+correlations (semi-inclusive)

$$J_N^{\mu}(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\hat{J}_N^{\mu}(\omega,\vec{q})\psi_B(\vec{p})$$

Exclusive electron scattering

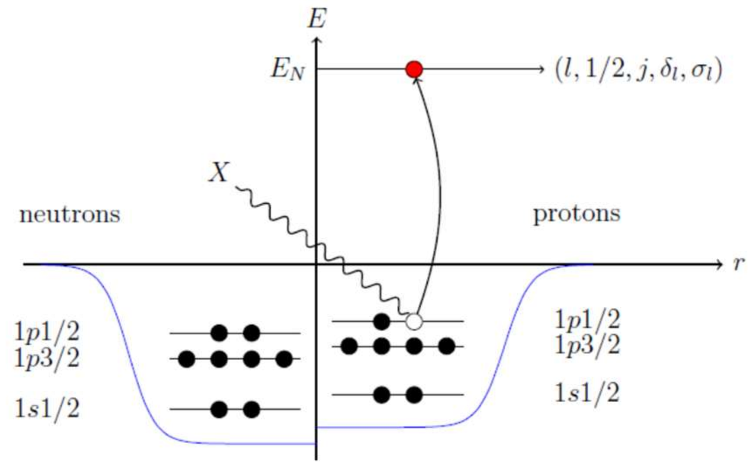


Exclusive conditions : everything is known



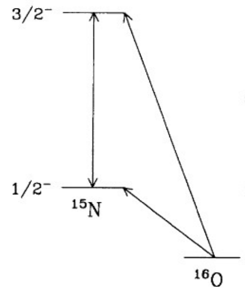
[M. Leuschner et al. PRC49, 955 (1994)]

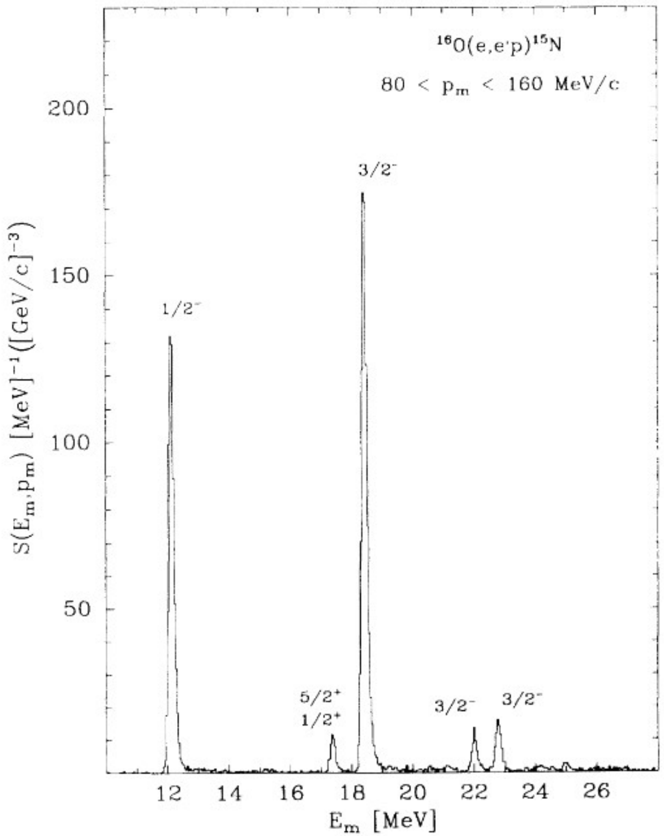
Independent particle model



Quantum numbers:
angular momentum
Energy

No momentum eigenstates

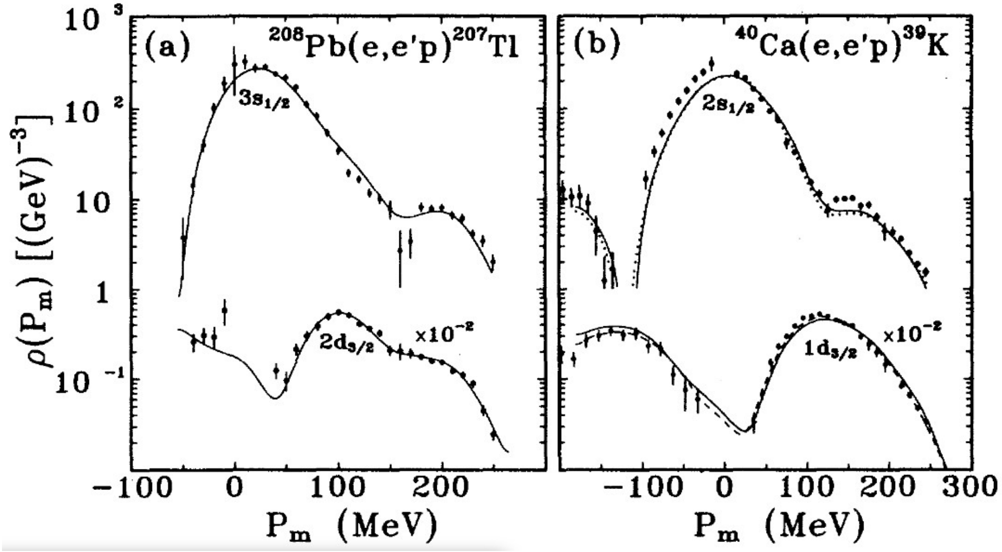




[M. Leuschner et al. PRC49, 955 (1994)]

RDWIA with ROP for exclusive (e,e’p)

[Udias et al. PRC48, 2731]



[Meucci et al. PRC64, 014604]

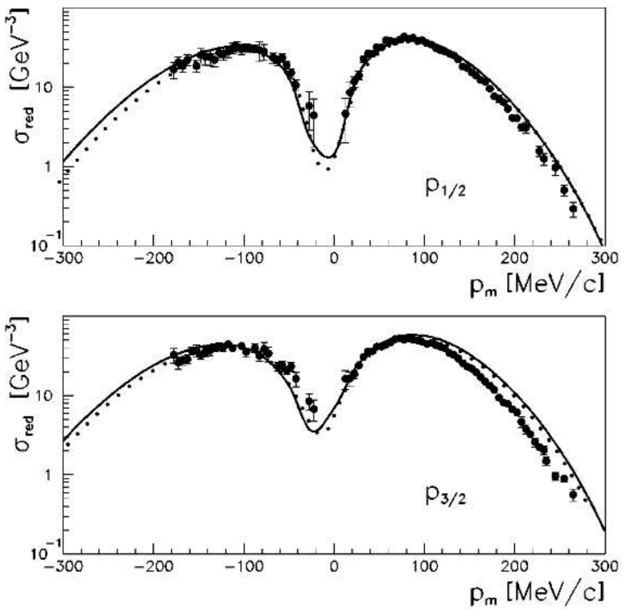
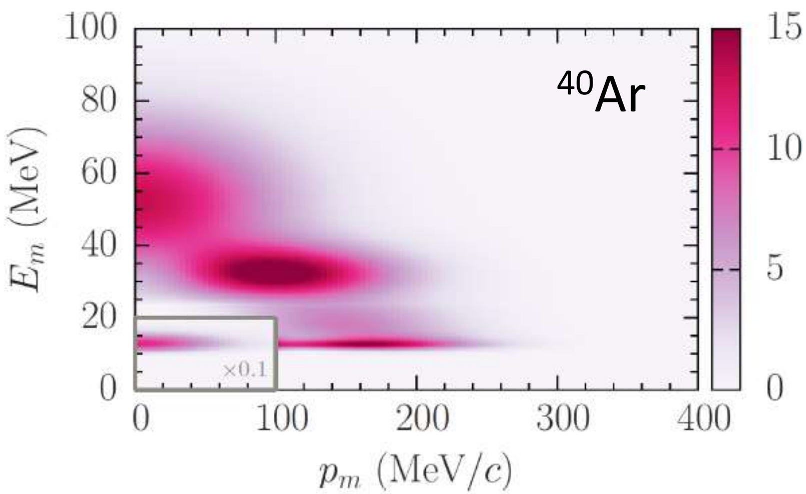
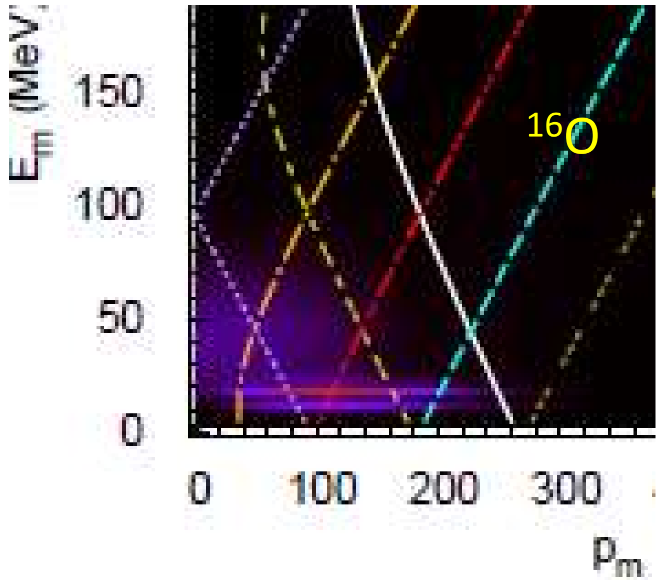


FIG. 11. The reduced cross section (σ_{red}) of the $^{16}O(e,e'p)$ reaction as a function of the recoil momentum p_m for the transitions to the $1/2^-$ ground state and to the $3/2^-$ excited state of ^{15}N, in

- Initial state: Spectral function. It displays the most realistic missing energy and momentum distributions of the initial nucleon. It is constrained to a good extent by experimental data.



L. Jiang *et al.*, arXiv:2203.01748



From RMF to MF part of the SF

spectroscopic factor

energy distribution

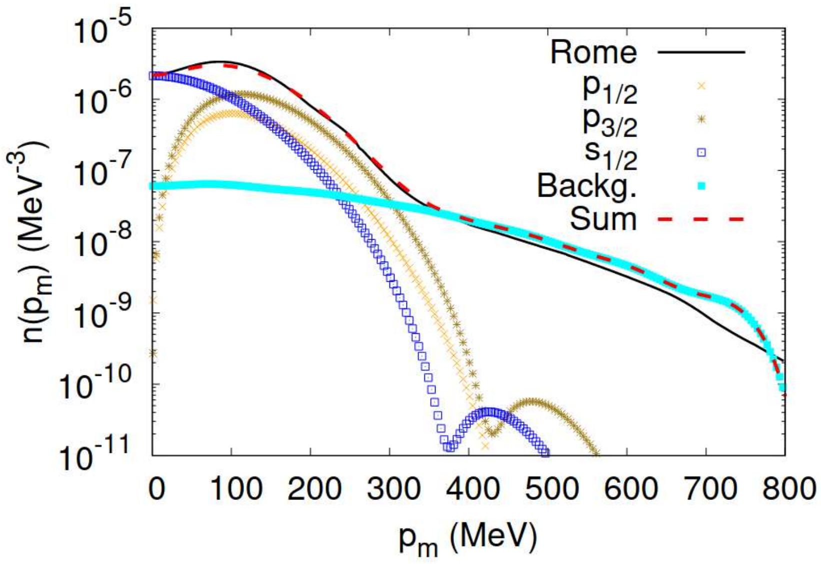
$$P_{\rm MF}(p_m, E_m) = \sum_\alpha S_\alpha |\phi_\alpha(p_m)|^2 f_\alpha(E_m)$$

wave function in momentum space

E_m (MeV)	Shells	^{16}O
$0-16.5$	$p_{1/2}$	1.51
$16.5-25$	$p_{3/2}$	3.47
$25-100$	$s_{1/2}$ + backg.	2.22
	$s_{1/2}$	1.62
	backg.	0.60
$100-300$	backg.	0.80

Single-particle states for GS, lorentzian or gaussians for the energy distribution

See [RGJ et al. PRC105, 025502] →
For inclusion of effective SF



- We get a representation of the SF which is amenable to complete RDWIA calculations, that is, unfactorized and with FSI

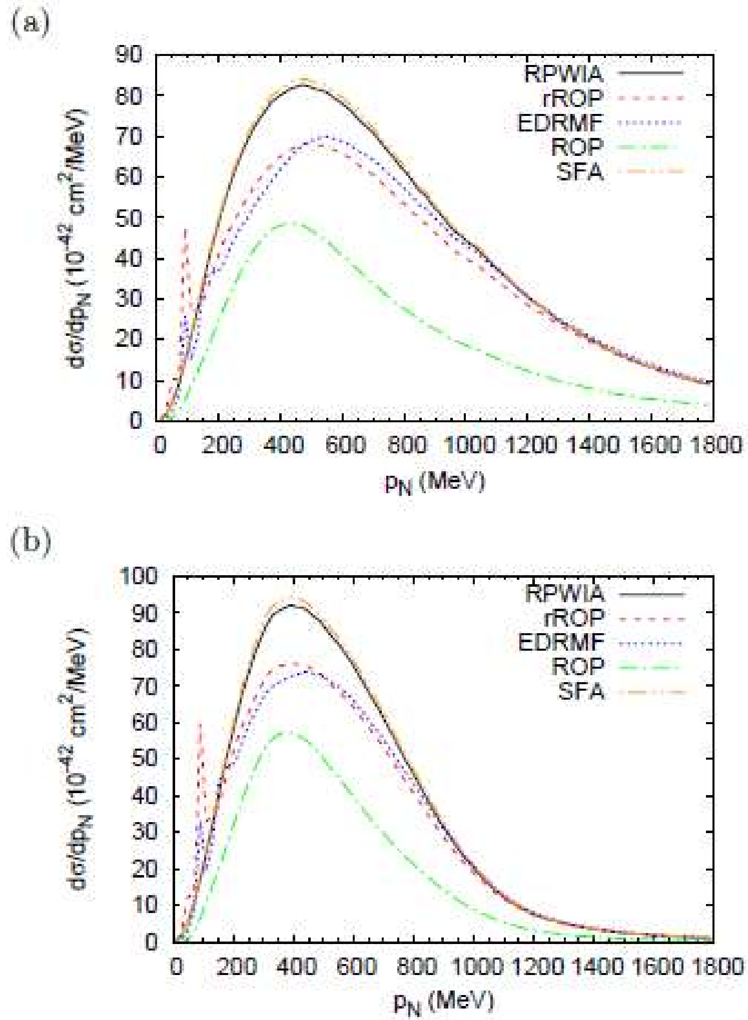


FIG. 2: Single-differential cross sections for the DUNE (a) and T2K (b) fluxes with the models discussed in the text.

No PB, no FSI, all 1-p events before cascade, SF model in NuWro, 1 GeV neutrino energy, CCQE cascade vs RWPIA

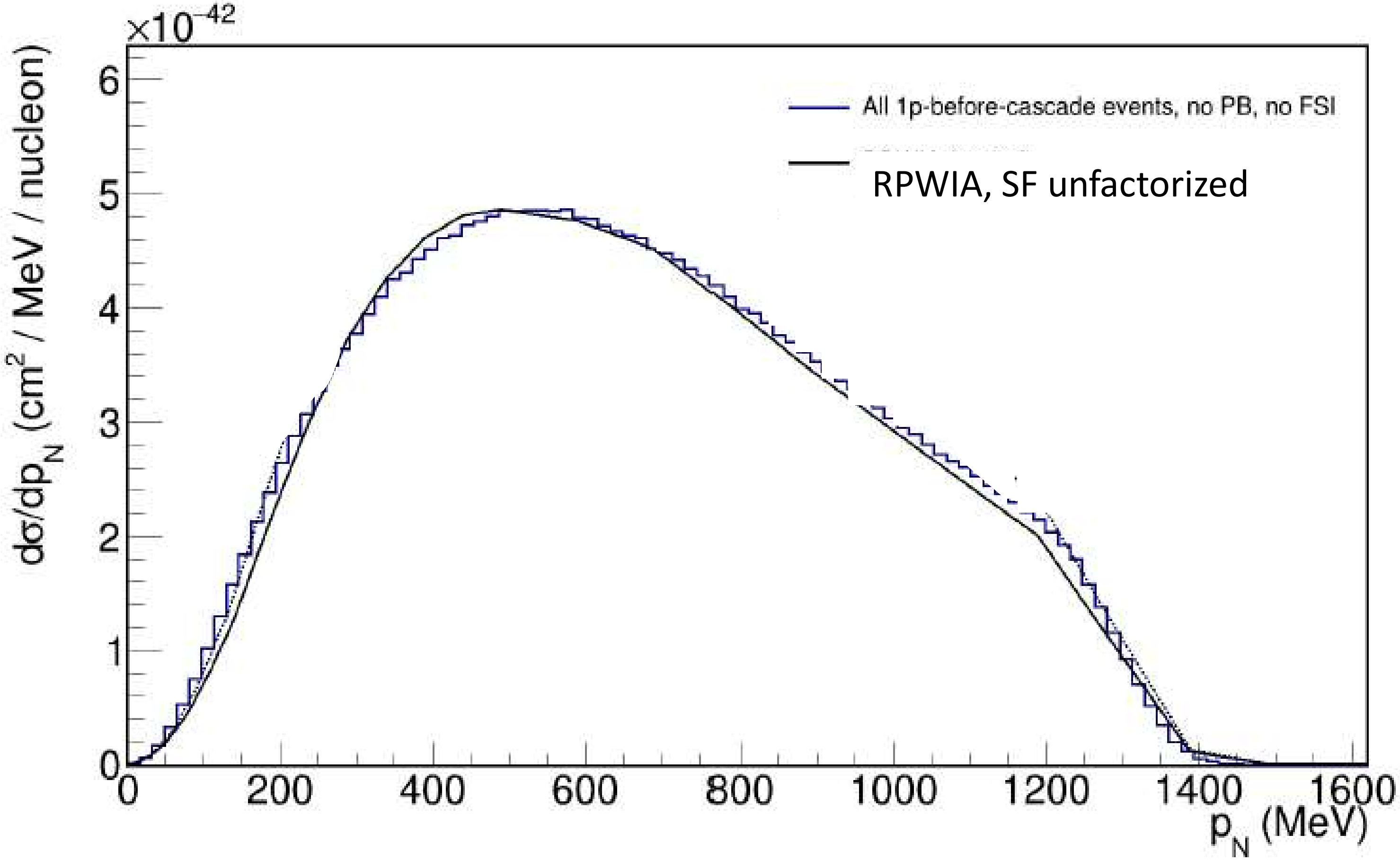


Figure 4: Scaling the RPWIA to fit no FSI no PB case for all 1-proton-before-cascade events.

Ingredients

- Final state: Optical Potential versus Intranuclear Cascade

Relativistic potentials to describe FSI

Scalar *and* Vector potentials

$$(\tilde{E}\gamma_0 - \vec{p}\cdot\vec{\gamma} - \tilde{M})\psi = 0 \qquad \begin{array}{l} \tilde{E} = E - V(r) \\ \tilde{M} = M - S(r) \end{array}$$

$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\overline{\psi}_F(\vec{p}+\vec{q})\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

Fit to ***elastic*** p-A scattering,
(from Cooper, Clark et al.)

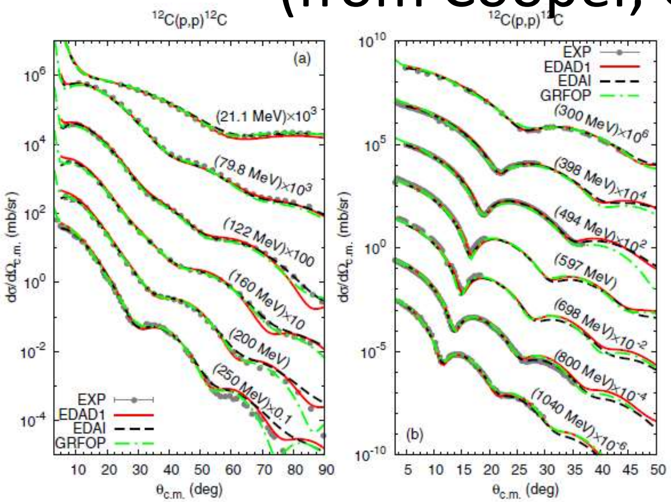
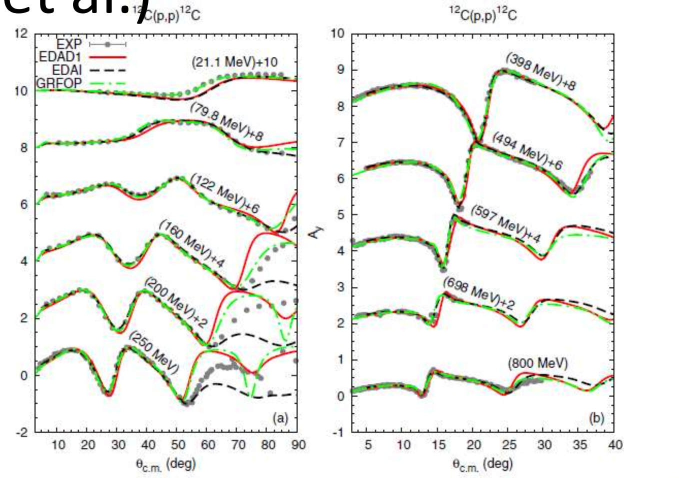


FIG. 2. Differential cross section for the elastic scattering of protons with T_p = 20–1040 MeV from ^{12}C. The dash-dotted curves display our predictions obtained using the GRFOP. The results obtained with EDAI (dashed line) and EDAD1 (solid line) are also shown for a comparison.



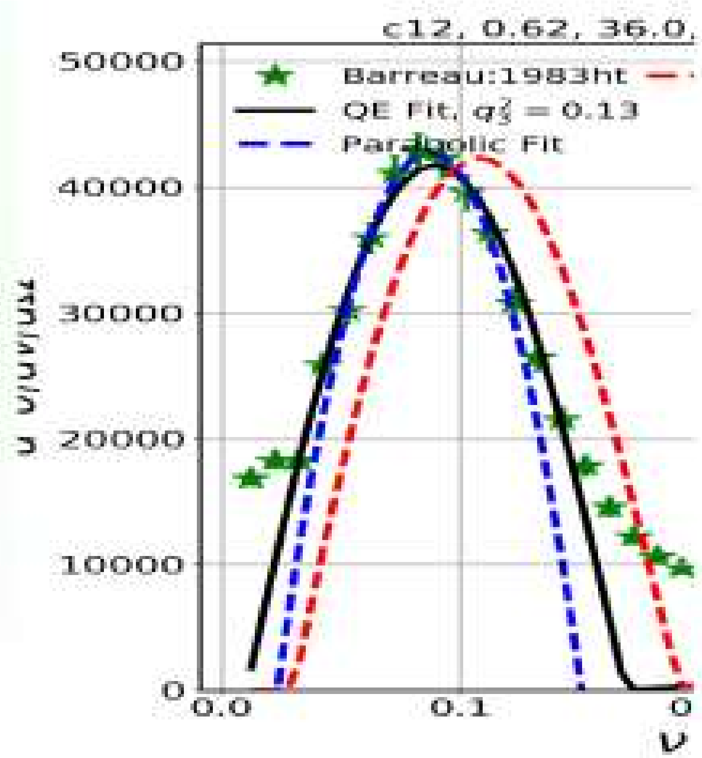
yzing power for the elastic scattering of protons with T_p = 20–800 MeV from ^{12}C. Line convention is as in Fig. 2.

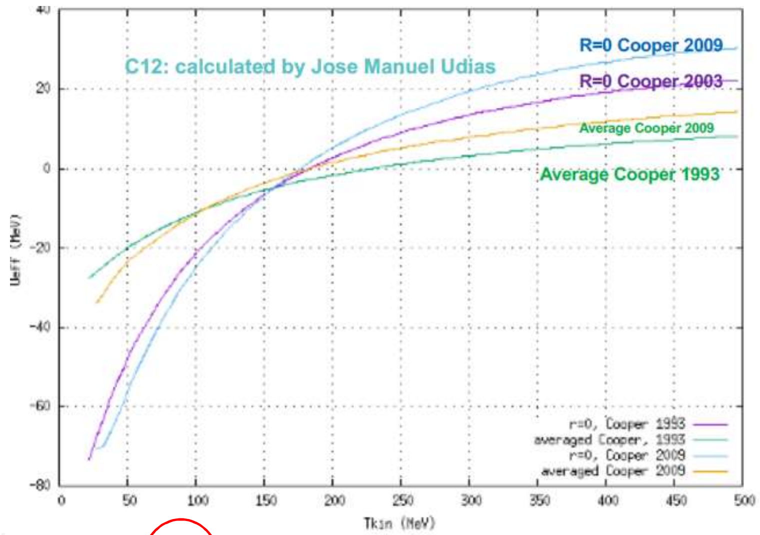
JM Udias,

M Ivanov et al, PCR94 (2016)

ROP: ‘effective energy’ approach

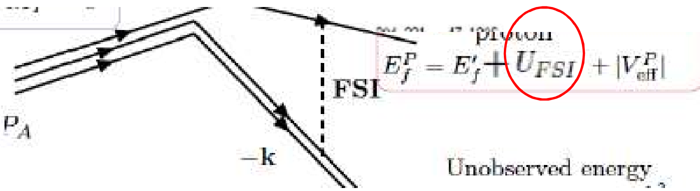
Fermi gas+ ‘Effective shift’ in energy momentum due to FSI, that is nuclear+***Coulomb*** interactions. This is contained in the real part of the OP, or some ‘effective’ combination of it





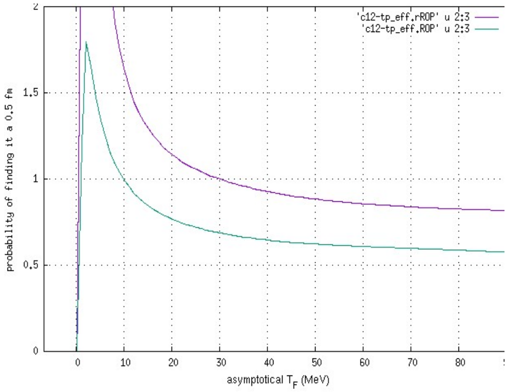
$$\nu + (M_P - \epsilon^P) = \sqrt{(k+q_3)^2 + M_P^2} + |U_{FSI}| + |V_{eff}^P|$$

$$\nu + (M_{N,P} - x^{\nu,\bar{\nu}}) = \sqrt{(k+q_3)^2 + M_{P,N}^2}$$



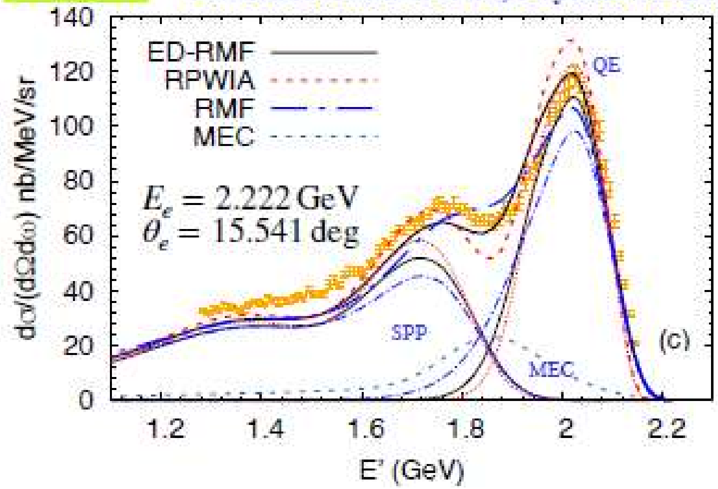
A. Bodek 2019, ECT*

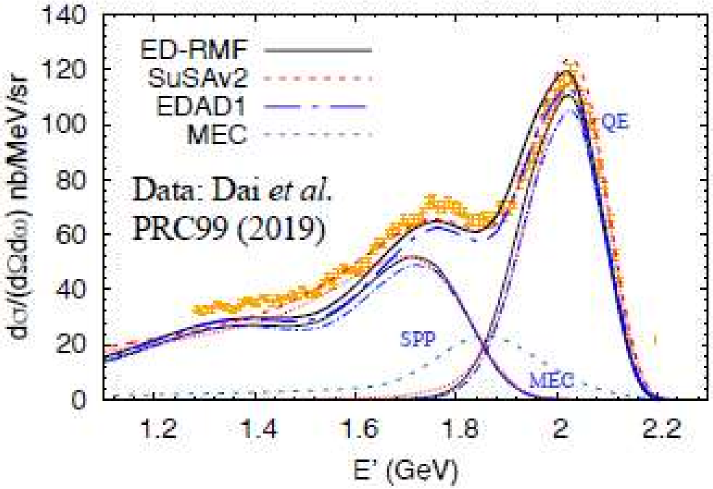
Due to FSI, the matrix element to be computed can have larger or smaller values for given asymptotic energies of the final nucleon, that is, for the same phase space of the final nucleon, the cross-section can be larger, smaller or whatever, due to the effect of FSI. Even if we integrate out the knocked out nucleon to get the inclusive result, there remains a dependence of the inclusive cross-section on FSI



$$J^{\mu}_{N}(\omega, \vec{q}) = \int d\vec{p}\, \bar{\psi}_F(\vec{p}+\vec{q})\, \hat{J}^{\mu}_{N}(\omega, \vec{q})\, \psi_B(\vec{p})$$

Ar(e, e') Gonzalez-Jimenez *et al.*, Phys.Rev.C 101 (2020)





Intra-Nuclear Cascade

1.) Nucleon propagates in the nucleus. In some original versions (Córdoba and *Oset , 1992*), following the classical trajectories consistent with the real part of the potential. *Or take a short cut and propagate in straight lines*

2.) Check for inelastic interaction, based upon MFP, derived from the imaginary part of the optical potential or otherwise. *Often: apply density corrections, Pauli blocking, in-medium nucleon-nucleon CS*

3.) When it has been determined that the nucleon interacts, according to previous step , determine the process , final particles, energies, ideally from experimental NN scattering experiments, *with some medium corrections.*

4.) Track created particles on the way out

5.) Cascade takes one nucleon out of the vertex and propagate it into different channels. Integrating on the cascade final states leaves the result invariant. *The cascade does not modify the inclusive result*

NEUT Cascade model

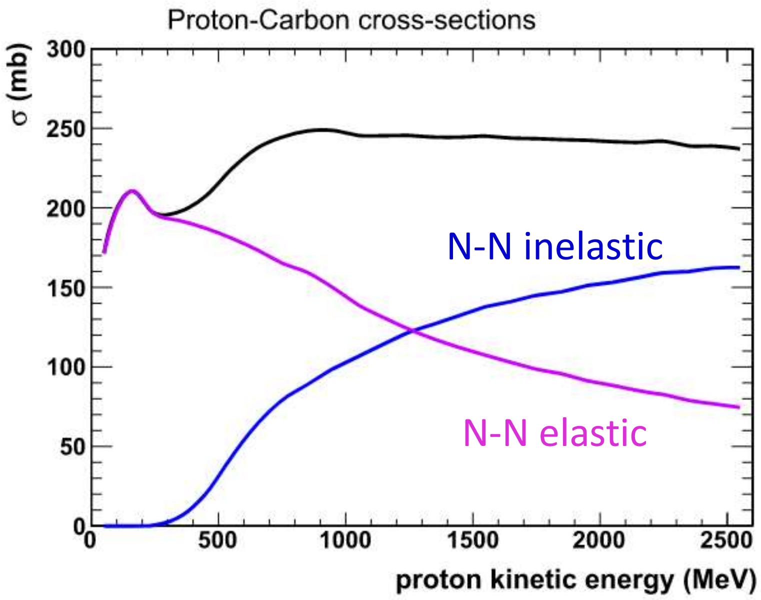
1.) Nucleon propagates in straight lines with step of 0.2 fm

2.) Check for interaction based on density and in-medium nucleon-nucleon CS

3.) Pauli-blocking: Reaction products must be above p_{Fermi}

4.) Track created particles on the way

Eur. Phys. J. Spec. Top. (2021) 230:4469–4481



Differences with ROP:

Explicit description of reaction products

No elastic FSI

Interactions only with constituent nucleons

Cascade does not affect inclusive CS

No PB, no FSI, all 1-p events before cascade, SF model in NuWro, 1 GeV neutrino energy, CCQE cascade vs RWPIA

Fraction of Events

final state	%fraction	final state	%fraction
$0p$	1.57	$2p$_atleast	13.32
$0p0\pi1n$	1.05	$2p$	11.14
$1p$_atleast	98.42	$2p0\pi0n$	5.95
$1p0\pi0n$	70.45	$1n$_atleast	22.63
$1p0\pi1n$	11.55	$1n$	17.78
$1p1\pi1n$	0.80	$2n$	3.96
$1p1\pi$	1.08	1π	2.09

Table 1: Fraction of all 1 *proton before cascade* events of different final states at neutrino energy, $E_\nu = 1000$ MeV

C. Cassuga MSc dissertation, UCM, 2021

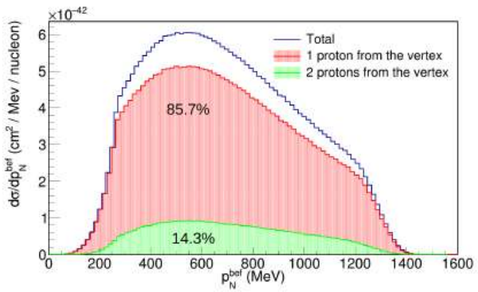
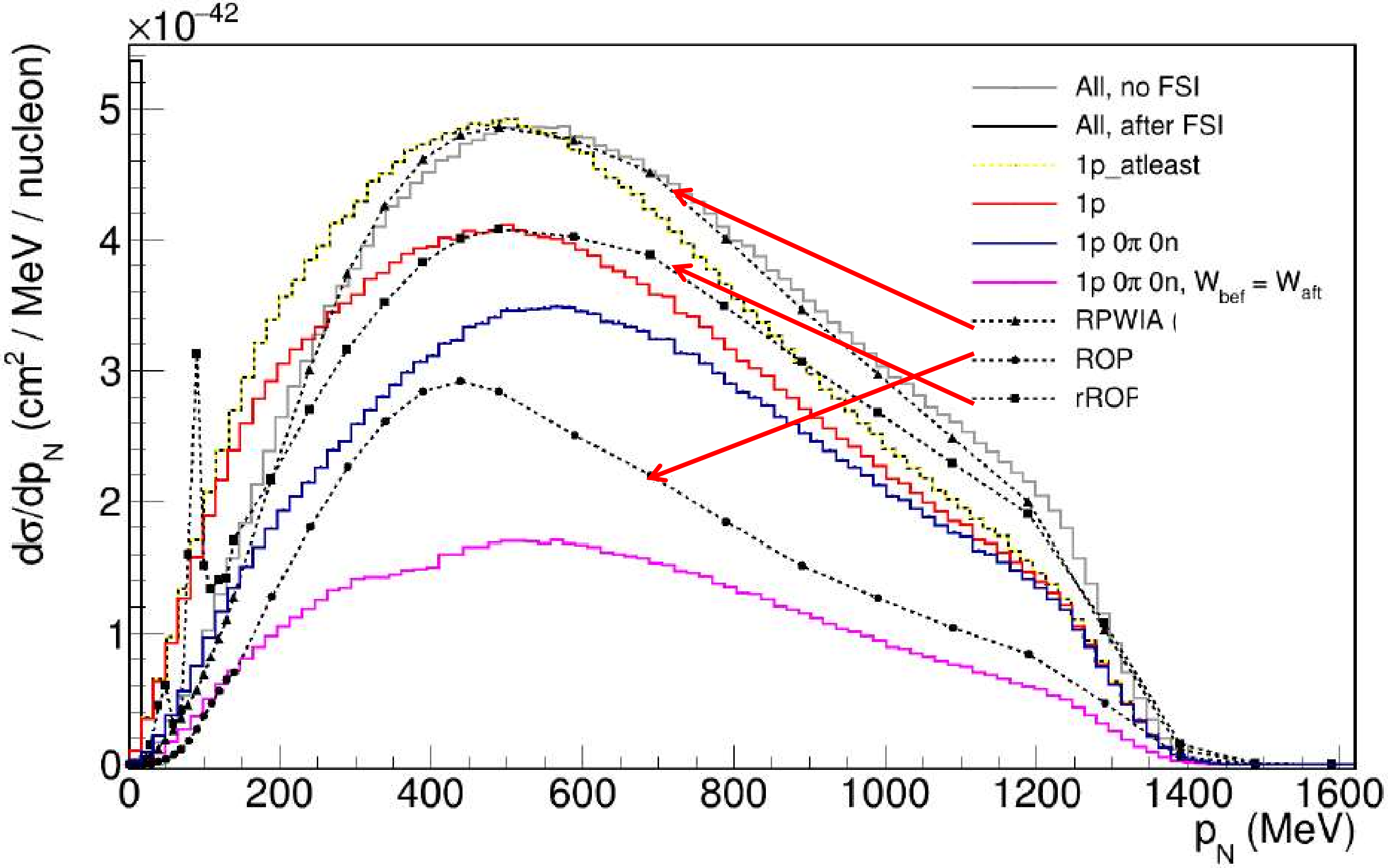


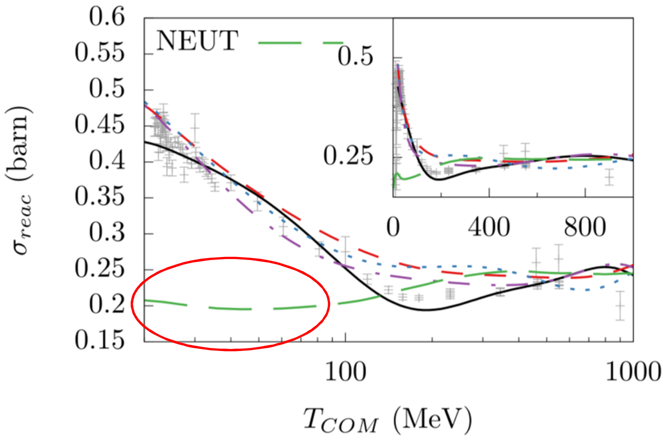
Figure 4: Momentum of the leading proton for when there is 1 or 2 protons produced in the CCQQE vertex.

Leading proton momentum histogram, no Pauli blocking, only one proton before cascade, SF



Nucleon – nucleus scattering

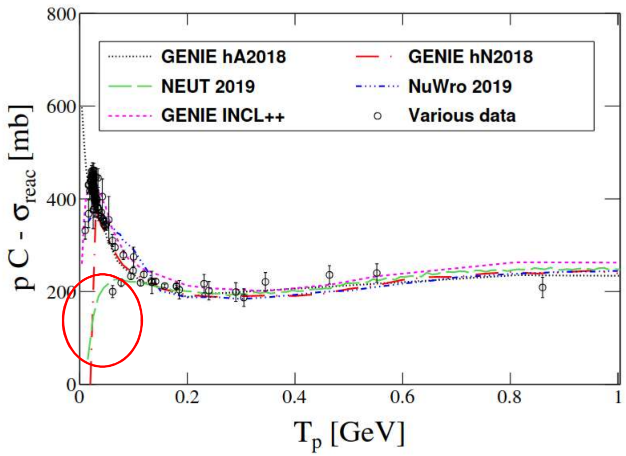
Used as benchmark (and/or input) to INC

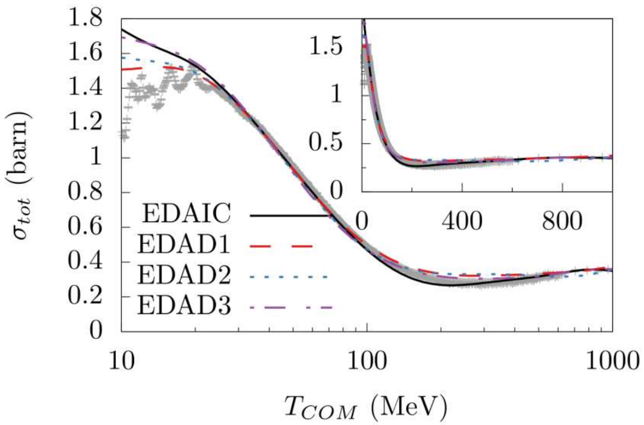


$$\sigma_{tot} = \sigma_{reac} + \sigma_{el}$$

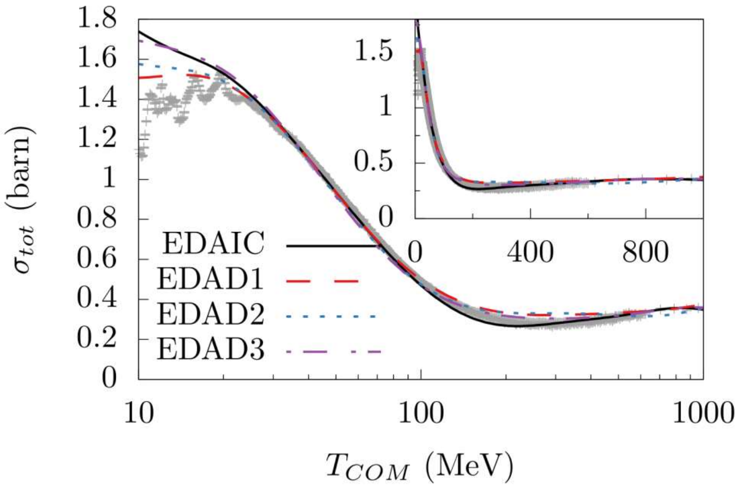
In NEUT σ_{el} is not modeled

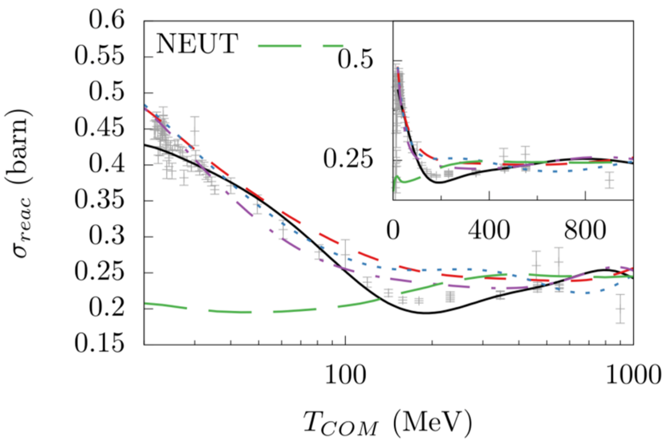
[Dytman et al. PRD104, 053006]





rROP+NEUT and ROP for carbon





Important:
E.g. large differences in produced neutrons at low T_n

At small energy optical model 'breaks down'

Should be more suitable than INC at intermediate energies: 20 to 150 MeV kinetic energy of the nucleon

Benchmarking intra-nuclear cascade models for neutrino scattering with relativistic optical potentials.

A. Nikolakopoulos,[1,2,*] R. González-Jiménez,[3] N. Jachowicz,[1] K. Niewczas,[1,4] F. Sánchez,[5] and J. M. Udías[3]

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[3] *Grupo de Física Nuclear, Departamento de Estructura de la Materia, Física Térmica y Electrónica, Facultad de Ciencias Físicas, Universidad Complutense de Madrid and IPARCOS, CEI Moncloa, Madrid 28040, Spain*
[4] *University of Wrocław, Institute of Theoretical Physics, Plac Maxa Borna 9, 50-204 Wrocław, Poland*
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arXiv:2202.01689v1 [nucl-th] 3 Feb 2022

A direct comparison of RDWIA with relativistic optical potential (ROP) with (NEUT) intra-nuclear cascade (INC) model

1.) Differences and similarities between RDWIA and INC

2.) Consistent input from the RDWIA for the INC

3.) Event selection to compare ROP and INC

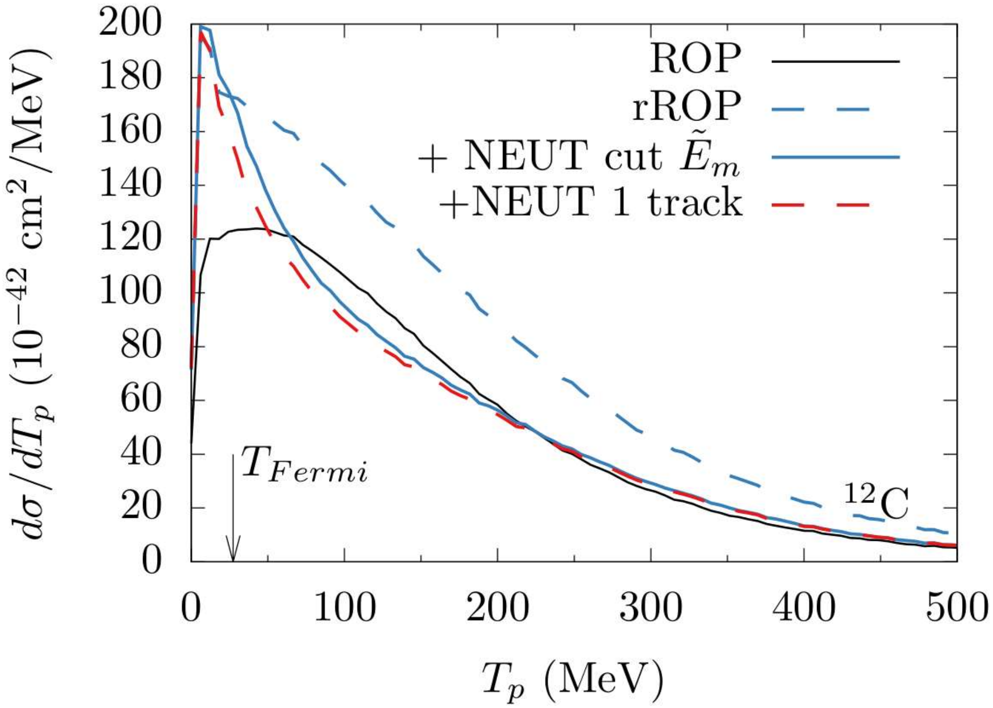
4.) The actual comparison

Avoiding inclusive-exclusive mismatch: rROP input

If we do not want to modify much the cascade, we can change the input to the cascade, so that the inclusive cross-section is reproduced better than in PWIA.
A rROP calculation can be introduced instead of the PWIA (no FSI) cross-section

We can benchmark the cascade by comparing the full ROP prediction, that is, the prediction of the optical potential for the elastic channel, with the rROP+cascade prediction to the elastic channel. Meaning: we take ***the 'real part of the potential***' before the cascade, right after the vertex, and use the cascade to ***'emulate' the non elastic interactions***

Selecting ‘elastic’ events



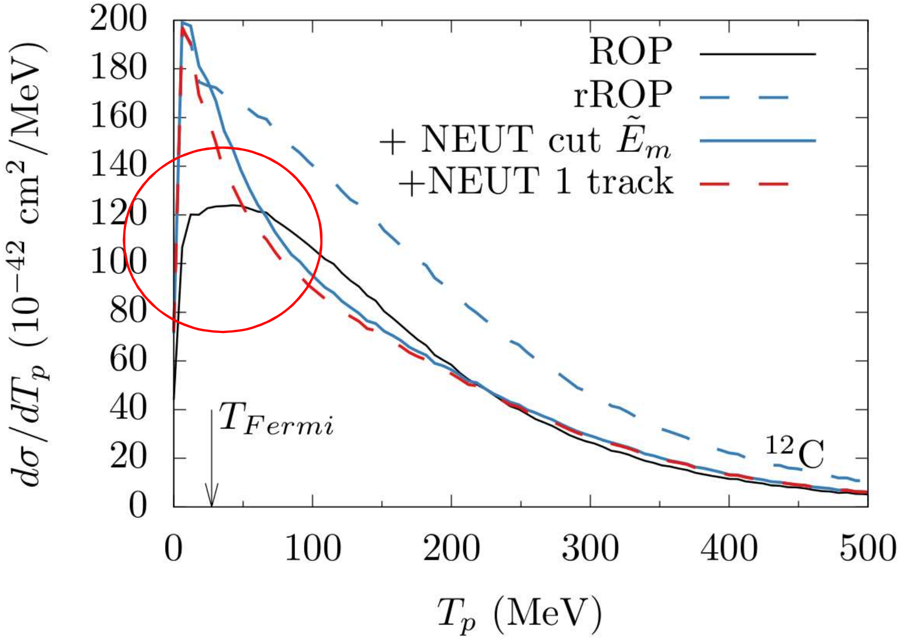
In NEUT any interaction will produce additional particle tracks

→ 1 track events ‘nothing happens’

→ Is equivalent to selecting missing energy from the shell-model region

A cut on E_m makes NEUT and ROP comparable

rROP+NEUT and ROP for carbon



Agreement for T_p large (T_p > 150 MeV)

Disagreement at small T_p

Below (local) T_F : Pauli-blocking
The cascade lets <u>all nucleons</u> escape without interaction

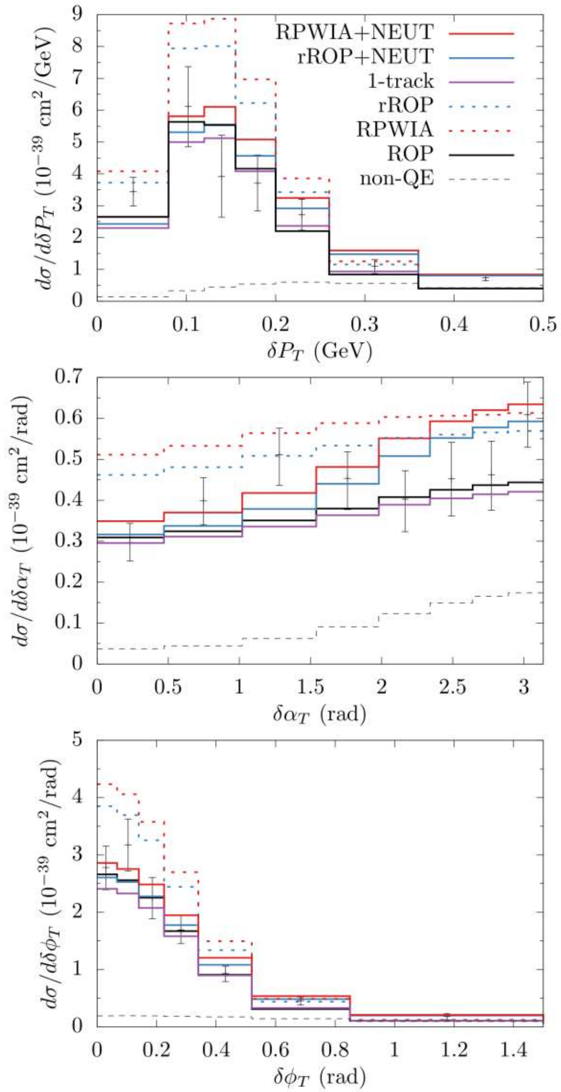
Avoiding incl-excl mismatch: rROP input

Generated unfactorized RDWIA events as input to cascade

Events are 1p 1μ with T2K flux
Distributed according to →

$$\langle \frac{d^6\sigma}{\mathrm{d}k_l \mathrm{d}\Omega_l \mathrm{d}p_N \mathrm{d}\Omega_N} \rangle = \int \mathrm{d}E_m \, \phi(E) \times \mathcal{F} \frac{k_l^2 p_N^2 M_B^*}{(2\pi)^5 E_B f_{rec}} \ell_{\mu\nu} H^{\mu\nu} \, ,$$

Transverse Kinematic Imbalance



Because p_p > 450 MeV low energy differences are not seen

Effect of non-elastic FSI visible in P_T and α_T

Large non-QE ‘background’ not separable from FSI effects

Non-QE from [Bourguille et al. JHEP04(2021)004]

Summary and Conclusions

- Nucleus and nuclear interaction are an essential ingredient in Accelerator based neutirno expeirments. Inistial nuclear description, FSI, we know that Fermi Gas or Shell model results with no FSI are not in good agreement with available data (neutrino or electron, inclusive or else)
- Effective spectral functions can be incorporated into microscopic calculations to ease the comparison of these with current event generator
- The elastic part of the FSI can be incorporated into event generators by substituting the inclusive PWIA cross-section by the rROP. The inclusive results can be further benchmarked against the full ROP.
- Have a Good inclusive result, with FSI and nuclear modelling and then apply CASCADE to get the channel distribution in the final state

- More generally: include sophisticated theoretical calculations into event generators employed to analyze data and describe experiments

NuSTEC: Neutrino Scattering Theory Experiment Collaboration

https://nustec.fnal.gov/

NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering (Jun 2017)

https://arxiv.org/abs/1706.0362

Theoretical tools for neutrino scattering: interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators (April, 2022)

https://arxiv.org/abs/2203.09030

Electron Scattering and Neutrino Physics (March 2022)

arXiv:2203.06853

Project: Unravelling the properties of the most elusive particles of the Universe: neutrinos and their interactions PR65/19-22430