Nuclear Effects in Neutrino-Nucleus Cross Sections

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Seminar@Fermilab, September 12, 2024

Overview

1. Introduction and motivation
2. Quasielastic and Single-Pion Production: the impulse approximation
3. Nuclear effects
4. Beyond Impulse Approximation: two-body currents
5. Final remarks

Goals of the Neutrino Oscillation Program

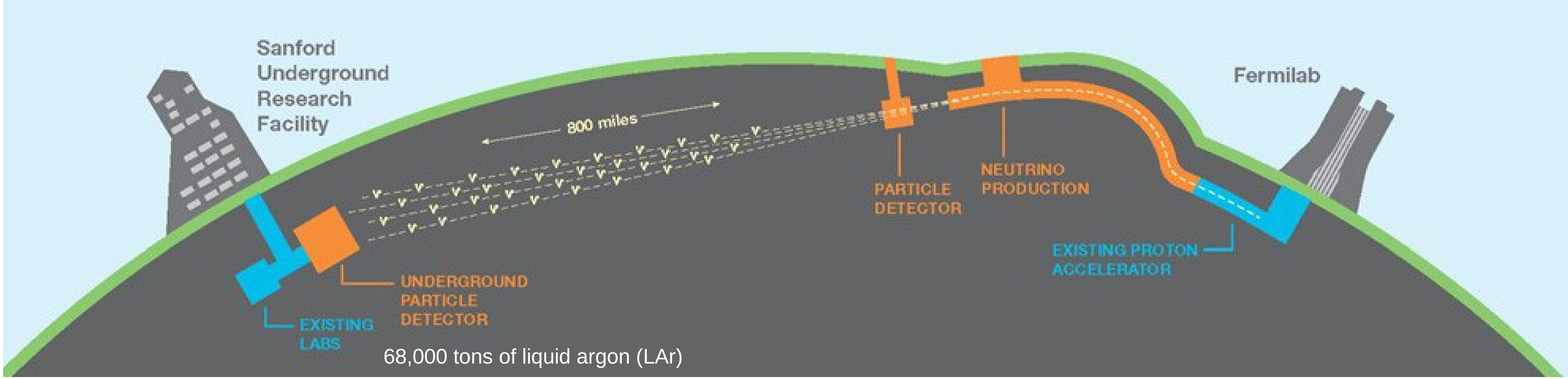
NuSTEC[a] White Paper: Status and Challenges of Neutrino-Nucleus Scattering

L. Alvarez-Ruso,[1] M. Sajjad Athar,[2] M. B. Barbaro,[3] D. Cherdack,[4] M. E. Christy,[5] P. Coloma,[6] T. W. Donnelly,[7] S. Dytman,[8] A. de Gouvêa,[9] R. J. Hill,[10,6] P. Huber,[11] N. Jachowicz,[12] T. Katori,[13] A. S. Kronfeld,[6] K. Mahn,[14] M. Martini,[15] J. G. Morfín,[6] J. Nieves,[1] G. Perdue,[6] R. Petti,[16] D. G. Richards,[17] F. Sánchez,[18] T. Sato,[19,20] J. T. Sobczyk,[21] and G. P. Zeller[6]

1. establish whether nature violates CP in the lepton sector and, if so, measure δ_{CP};
2. improve the accuracy on θ_{23} and, if not maximal, a determination of the octant it belongs to: $\theta_{23} < \pi/4$ vs. $\theta_{23} > \pi/4$;
3. determine the neutrino mass ordering at high confidence level: $m_1 < m_2 < m_3$ vs. $m_3 < m_1 < m_2$.

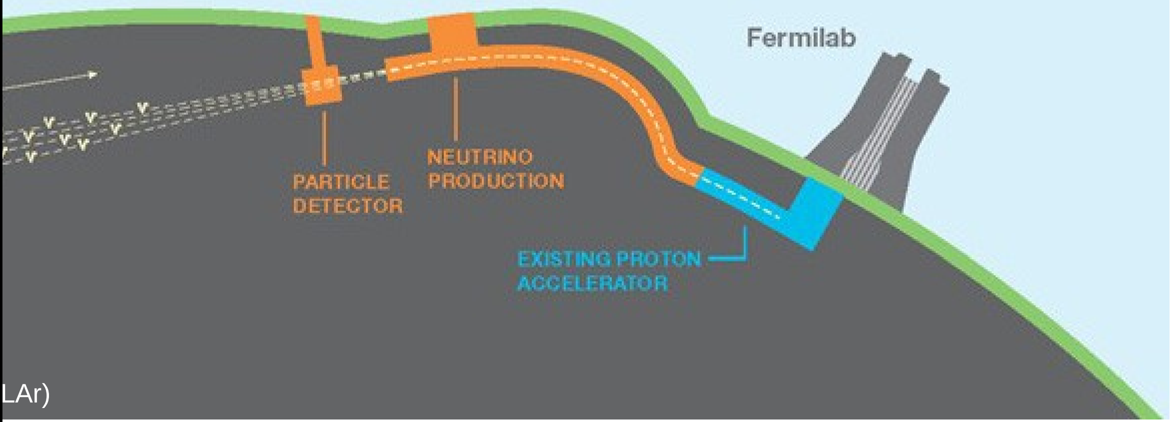
	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

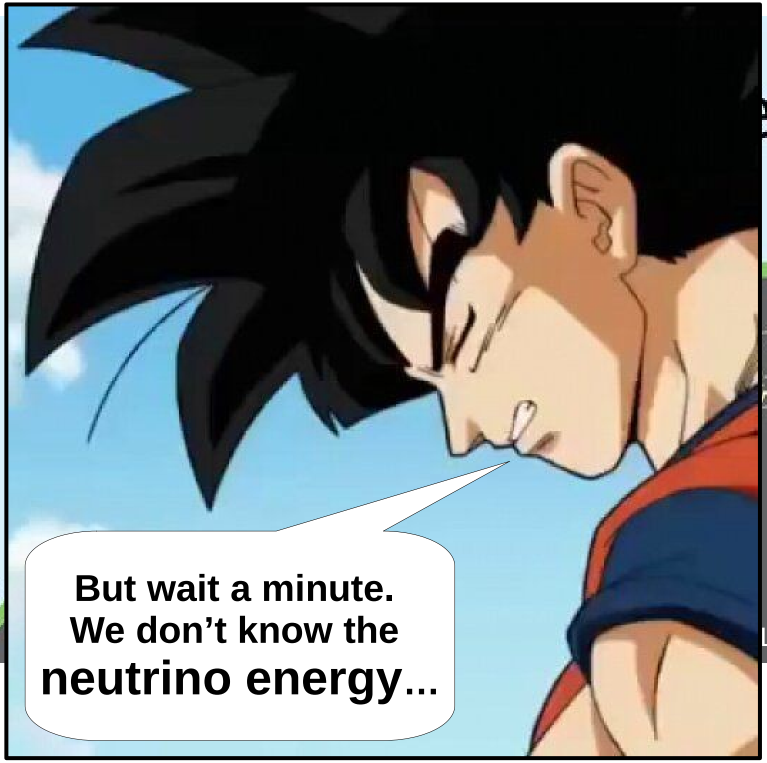
DUNE: Deep Underground Neutrino Experiment



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

erground Neutrino Experiment





LAr)

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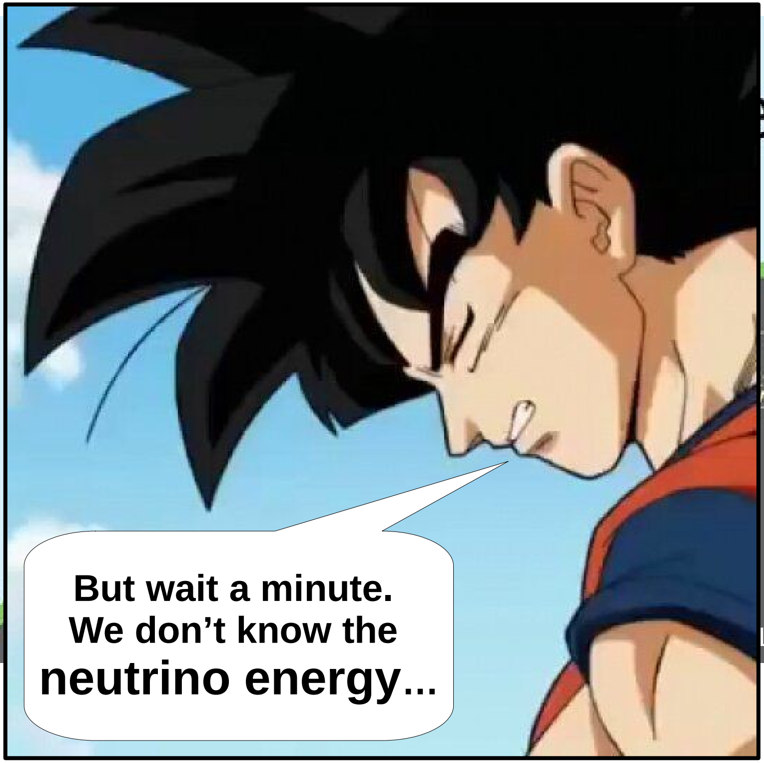

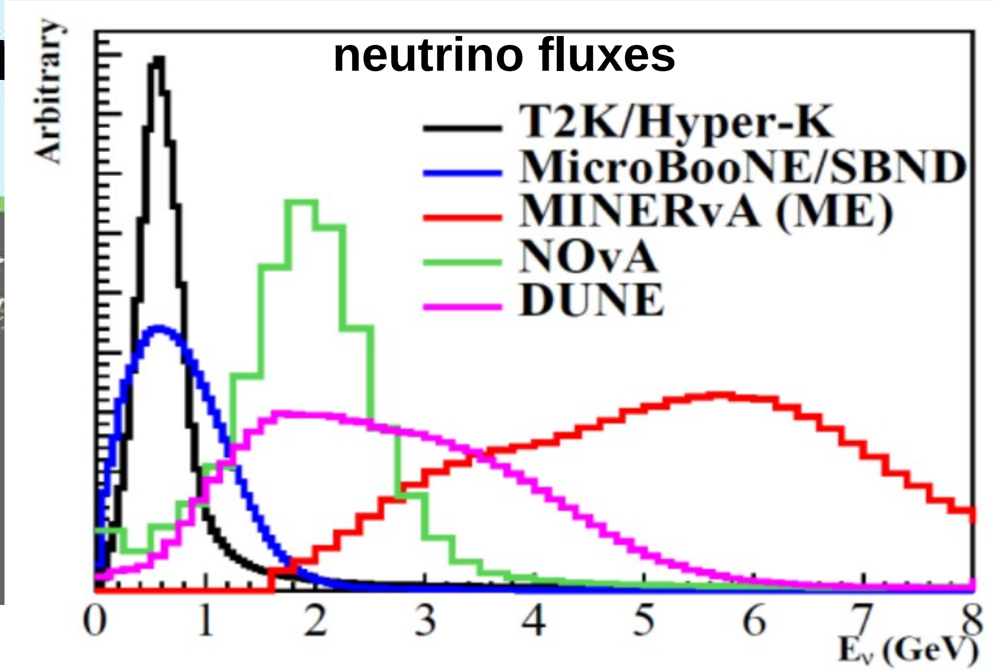

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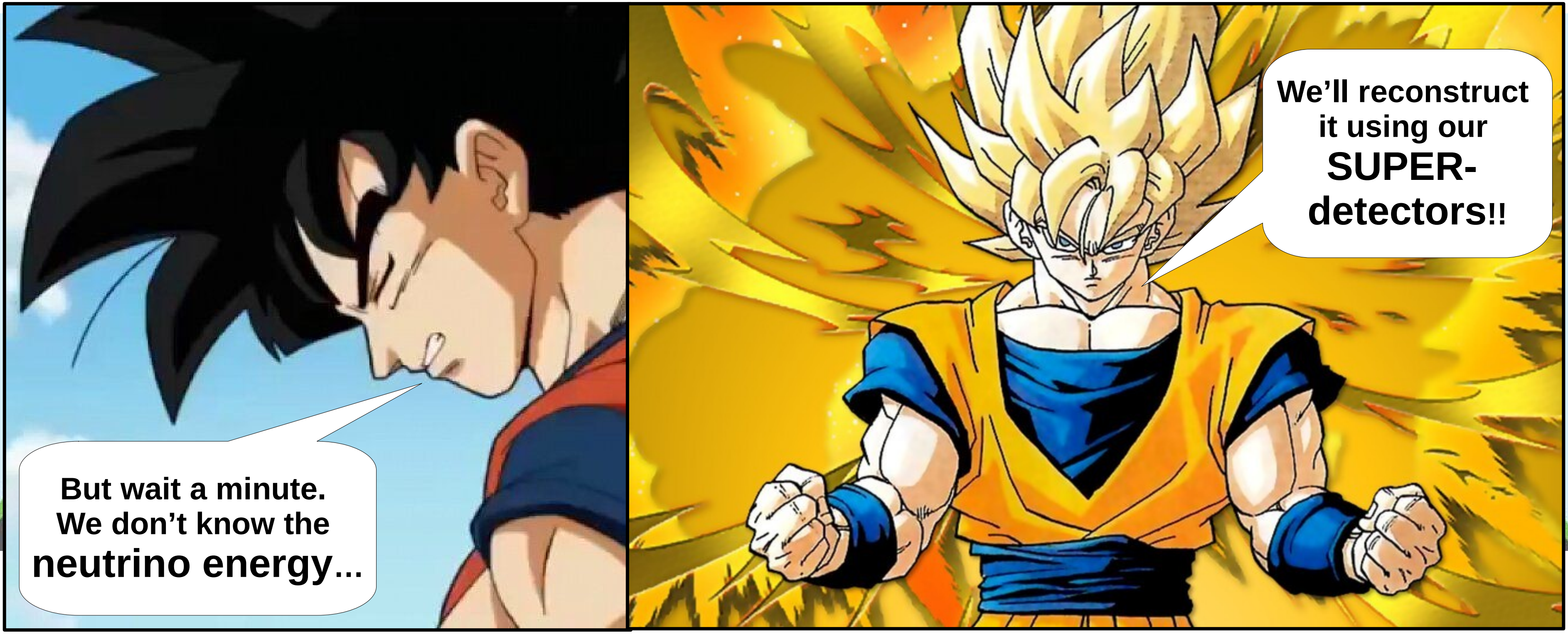

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SLOW
DOWN!


Nuclear Physics

ν-oscillations experiment 101

***STEP 1**: Making a beam*
***STEP 2**: Checking twice*
***STEP 3**: Gonna find out if you've more of one type*

$$N^{\mu\to e}_{FD}(Er) = \int \phi^{\mu}_{FD}(Et)\, \mathbf{P}_{\mu\to e}(Et)\, \sigma^{e}(Et)\, \varepsilon^{e}(Et)\, U_{FD}(Et, Er)\, dEt$$

Neutrino Flux — Oscillation Probability — ν_e Cross Section — Signal efficiency — Detector Response

ν_μ ν_τ ν_e ν_τ

Sanford Underground Research Facility

$$N^{\mu}_{ND}(Er) = \int \phi^{\mu}_{ND}(Et)\, \sigma^{\mu}(Et)\, \varepsilon^{\mu}(Et)\, U_{ND}(Et, Er)\, dE$$

ν_μ ν_μ ν_μ ν_μ ν_μ

Fermilab

Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy… but your **oscillation probability** is a function of the true neutrino energy & it is convoluted with quantities depending on your model: flux, **cross section** and detector response.

slide from Elena Gramellini's talk in NuFact 2023

Summarizing,

cross section <u>models</u> are needed, for two reasons:

1) To get $\mathbf{P}_{\alpha\rightarrow\beta}$ from the measured $\mathbf{N}_\beta$.

2) To reconstruct the neutrino energy (keep watching).

What do we know about neutrino-nucleus cross sections

The nuclear response

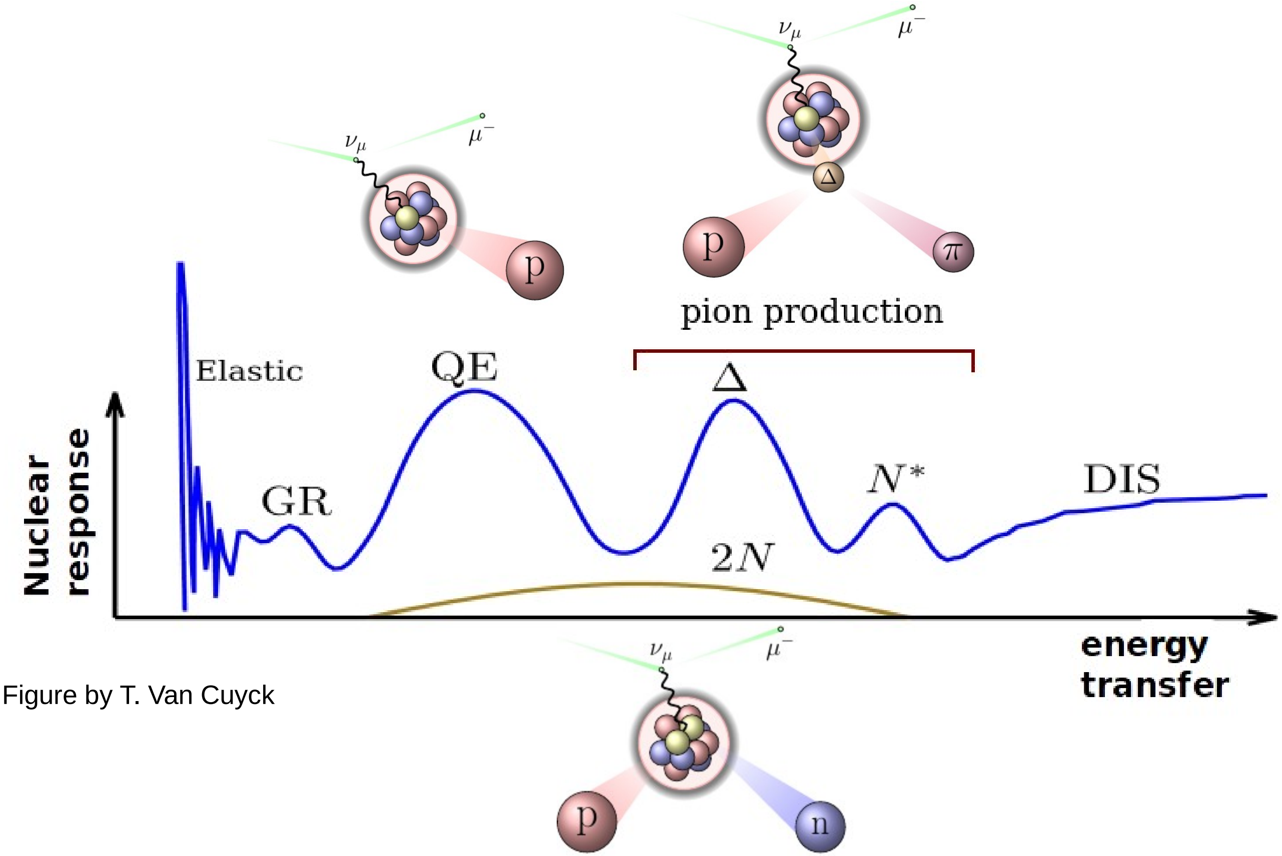


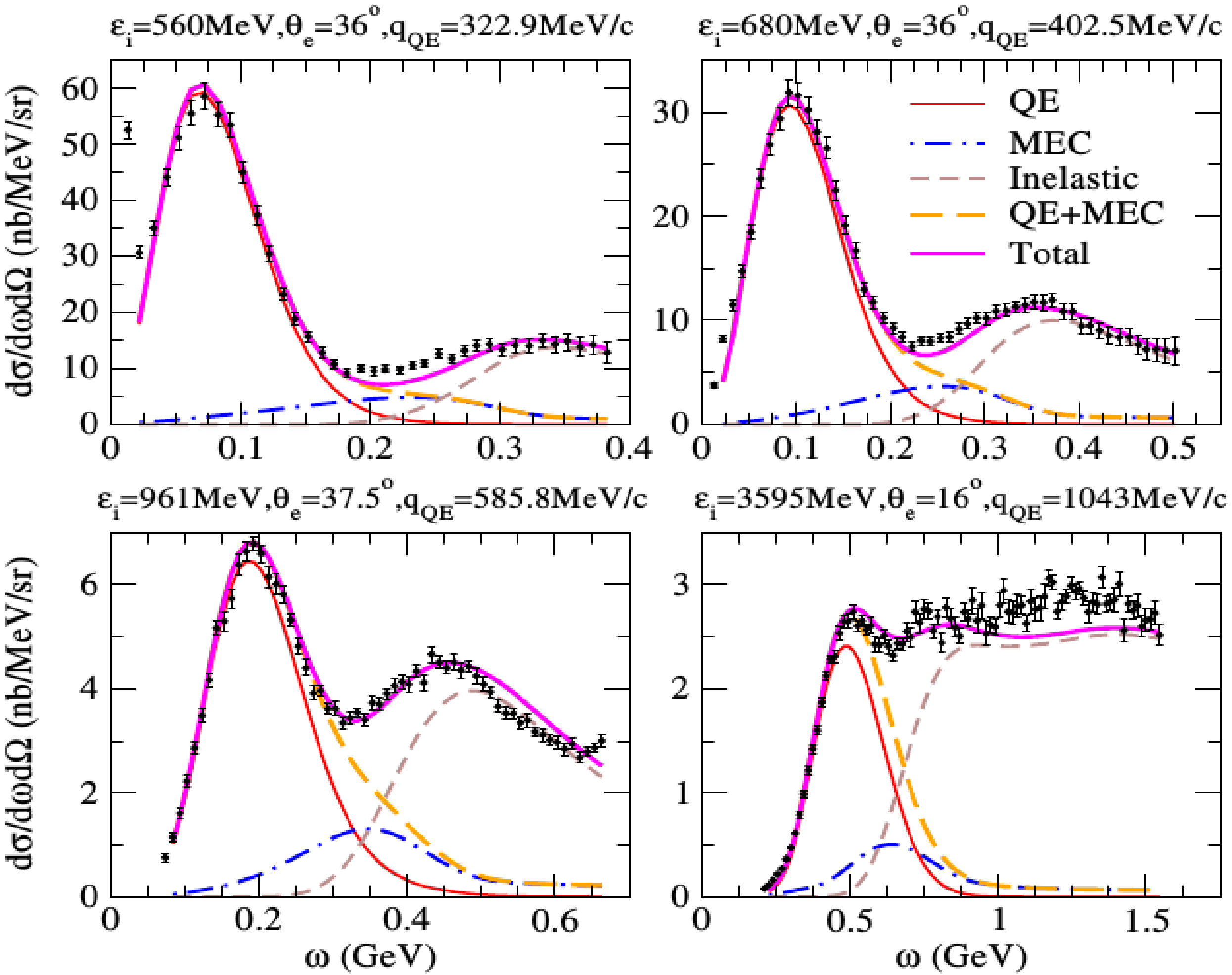
Figure by T. Van Cuyck

For a fixed incoming energy and scattering angle,

depending on the **energy transferred,**

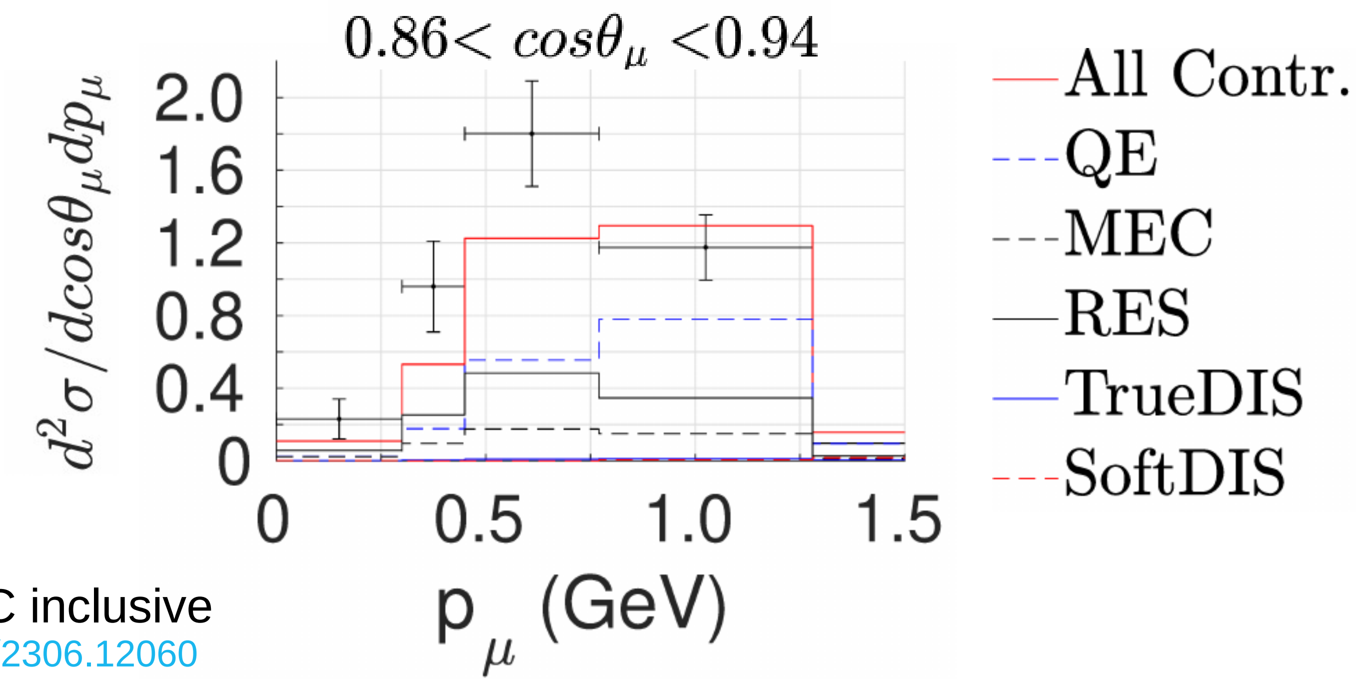
the lepton interacts differently with the nucleus **(different reaction channels)**

Superscaling approach Phys. Rev. D 91, 073004 (2015)



$^{12}C(e,e')$

Different reaction channels but **same event topology**

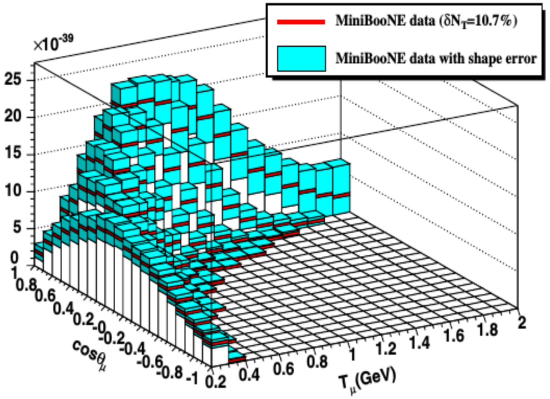


MicroBooNE CC inclusive
https://arxiv.org/abs/2306.12060

How does this affect the reconstruction of the neutrino energy?

Example:

1) **QE-like event** in MiniBooNE: muon and no pions are detected. Scattering angle and energy of the muon.



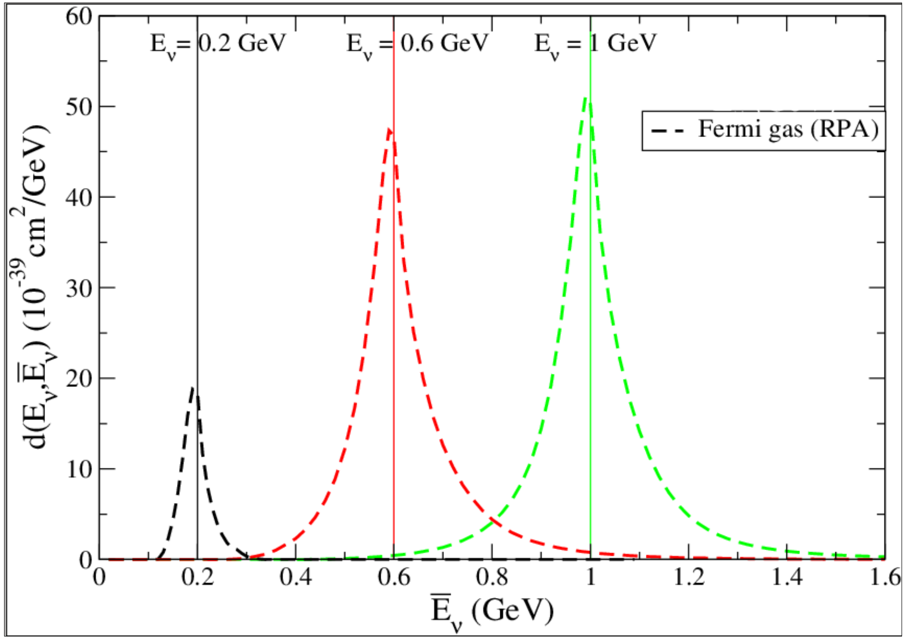
2) Reconstructed energy estimator:

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

This formula gives us an estimate of the energy of the neutrino.

3) One can compute the **probability of the reconstructed energy E^{QE} matching the true energy E: $P(E^{QE}|E)$**

Probability density of the reconstructed energy $\bar{E}$ matching the true energy E



https://doi.org/10.1103/PhysRevC.98.054603

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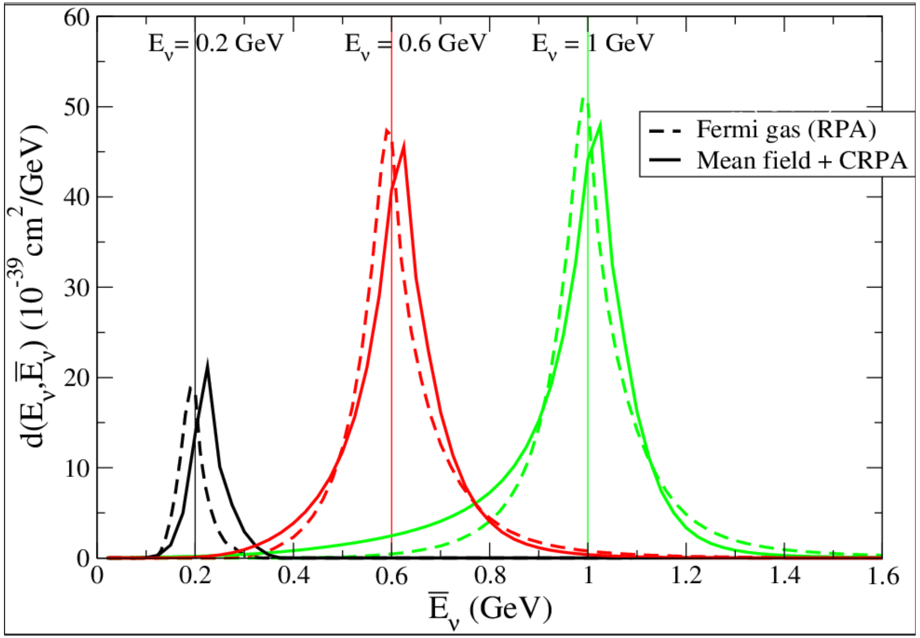

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+ The distributions are **model dependent**

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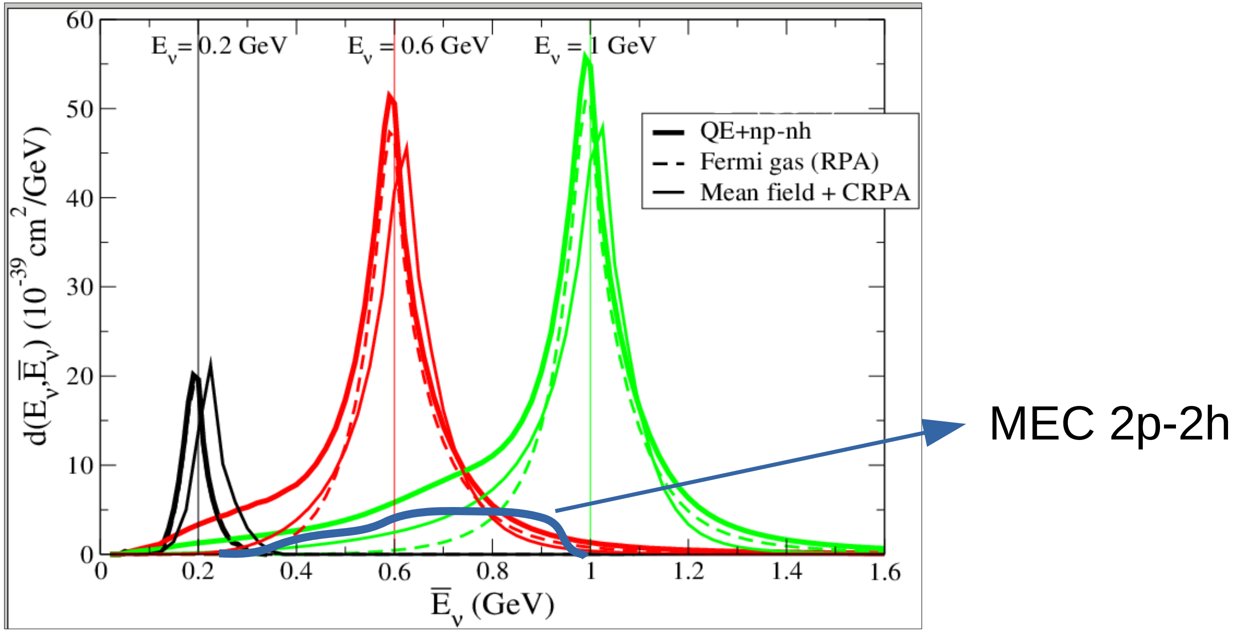


https://doi.org/10.1103/PhysRevC.98.054603

+ The distributions are **model dependent**
+ Different reaction channels produce VERY different distributions

Summarizing,

GOOD cross section <u>models</u> are needed, for two reasons:

1) To get $\mathbf{P}_{\alpha \to \beta}$ from the measured $\mathbf{N}_{\beta}$.

2) To reconstruct the neutrino energy.

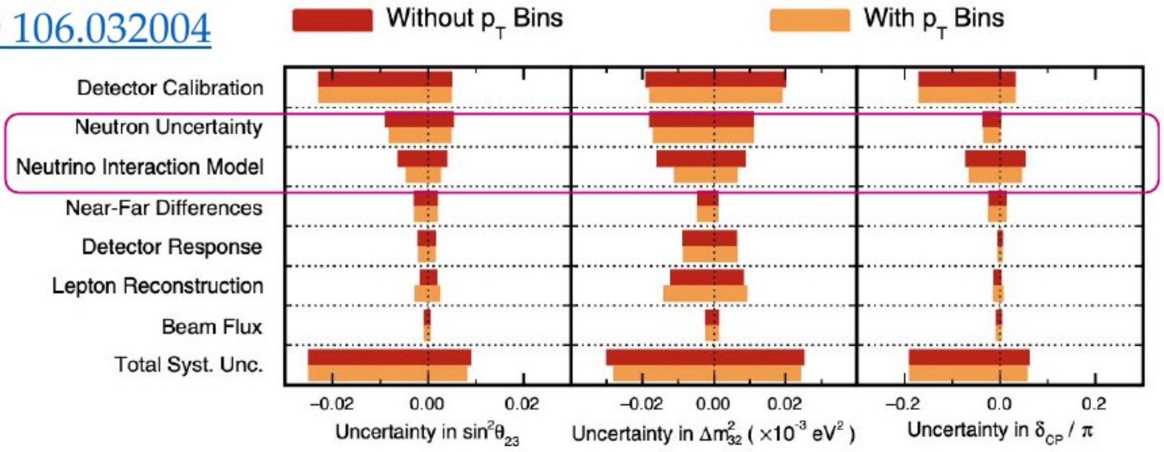
How does this feeds back into neutrino “new” physics? CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K, Nature 2020

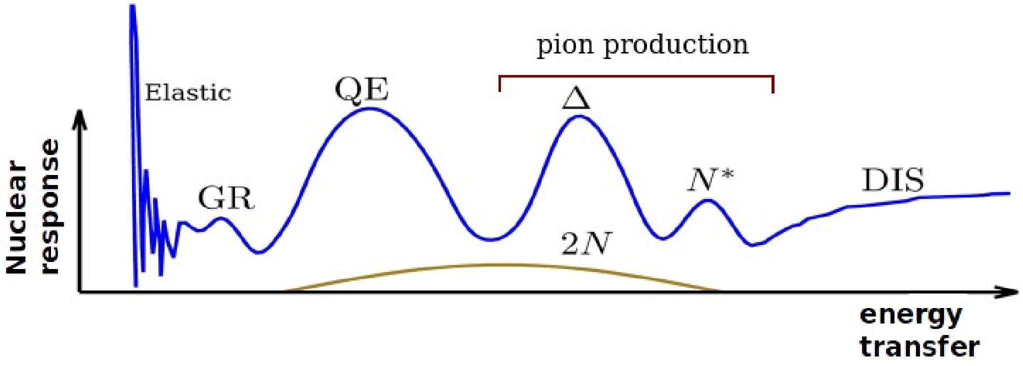
“uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections... [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement.”

NOvA PRD 106.032004



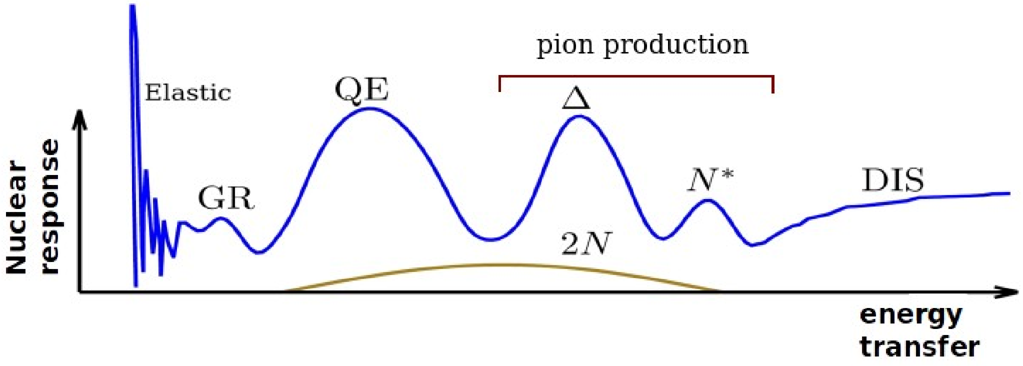
slide from Elena’s talk in NuFact 2023

Quasielastic scattering
and
Single-Pion production



How do we model

Quasielastic scattering
and
Single-Pion production?



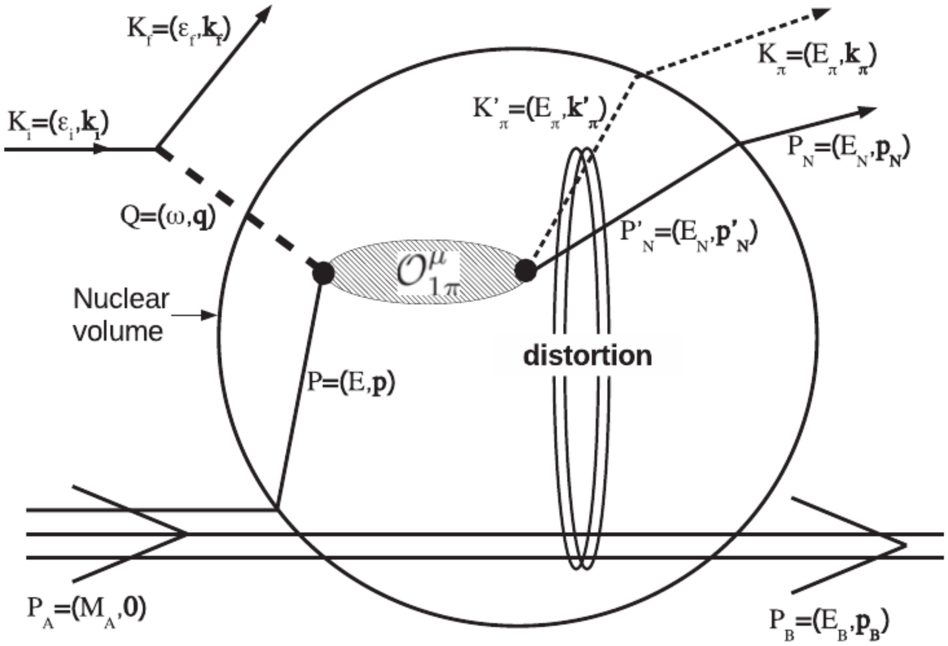
How do we model

Quasielastic scattering
and
Single-Pion production?

...

The IMPULSE APPROXIMATION (IA)

Single-Pion Production
(in the Impulse Approximation)



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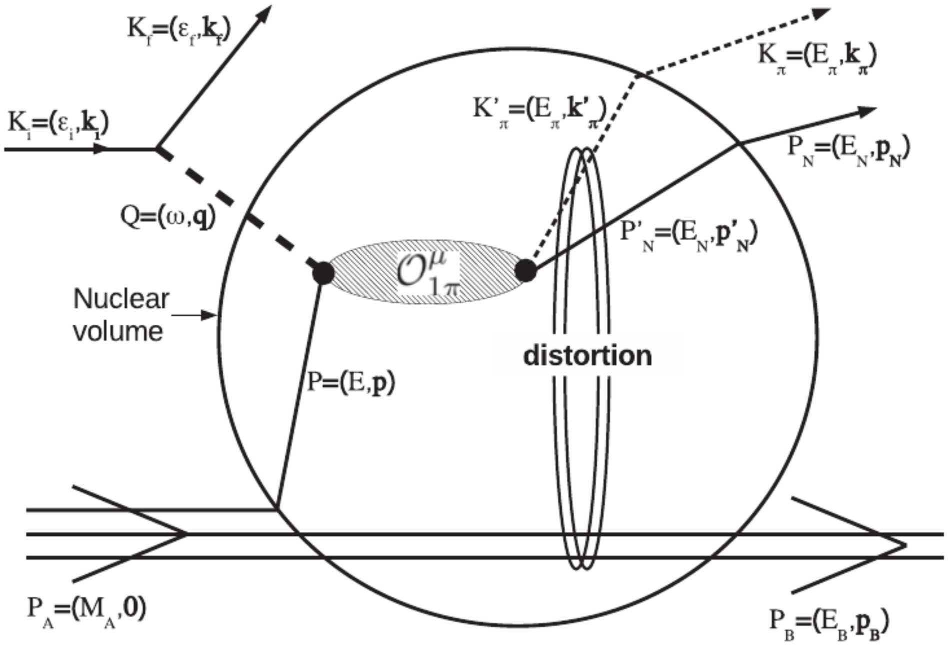

$$J^{\mu}_{\rm had} = \int d\mathbf{p} \int d\mathbf{p}'_N \overline{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N)\phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N, \mathbf{k}_\pi)\mathcal{O}_{1\pi}(Q, P'_N, P)\Psi_B(\mathbf{p})$$

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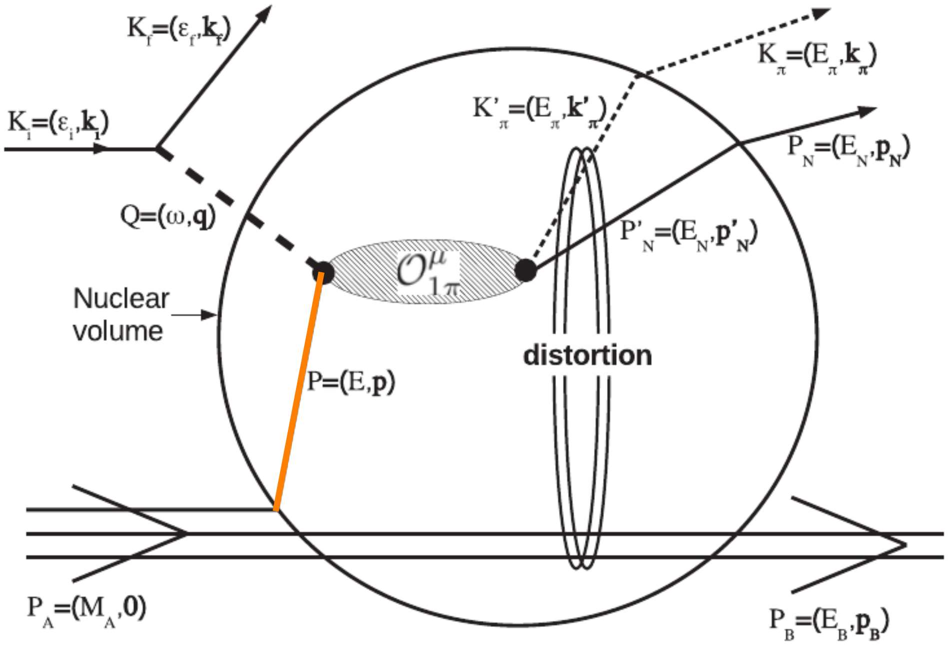

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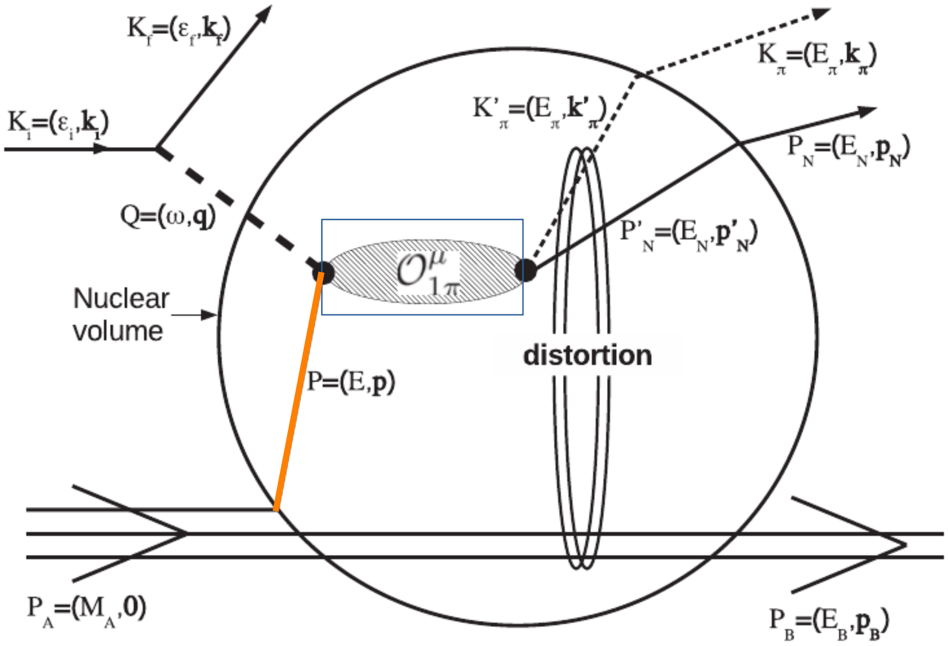

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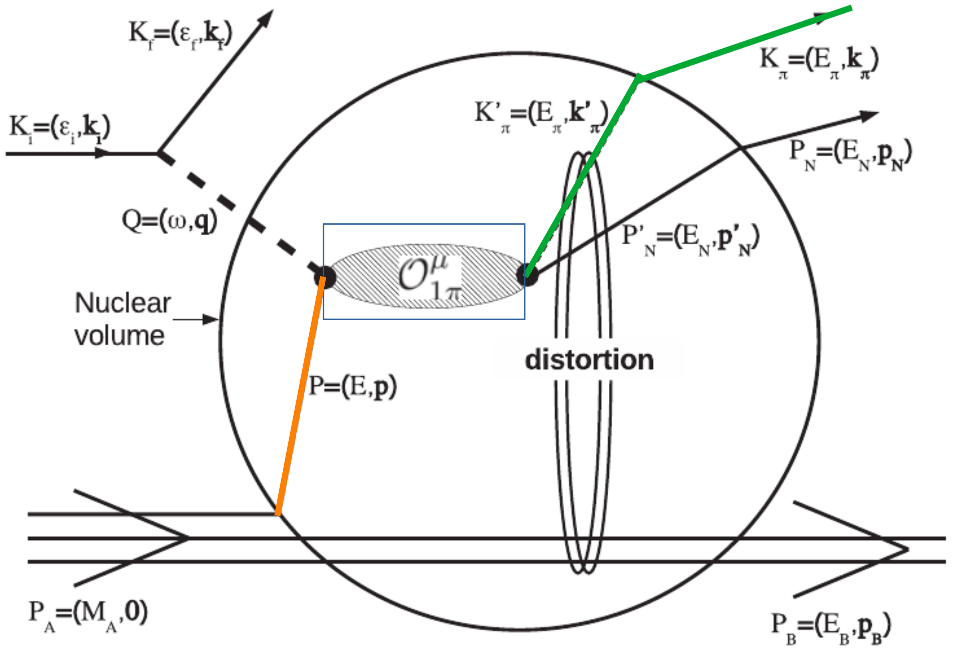

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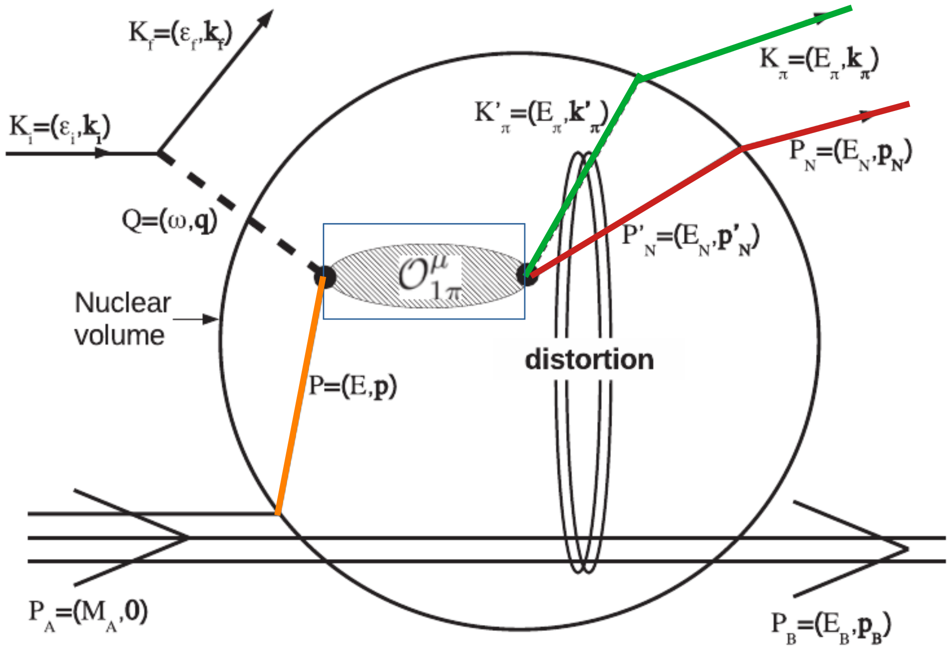

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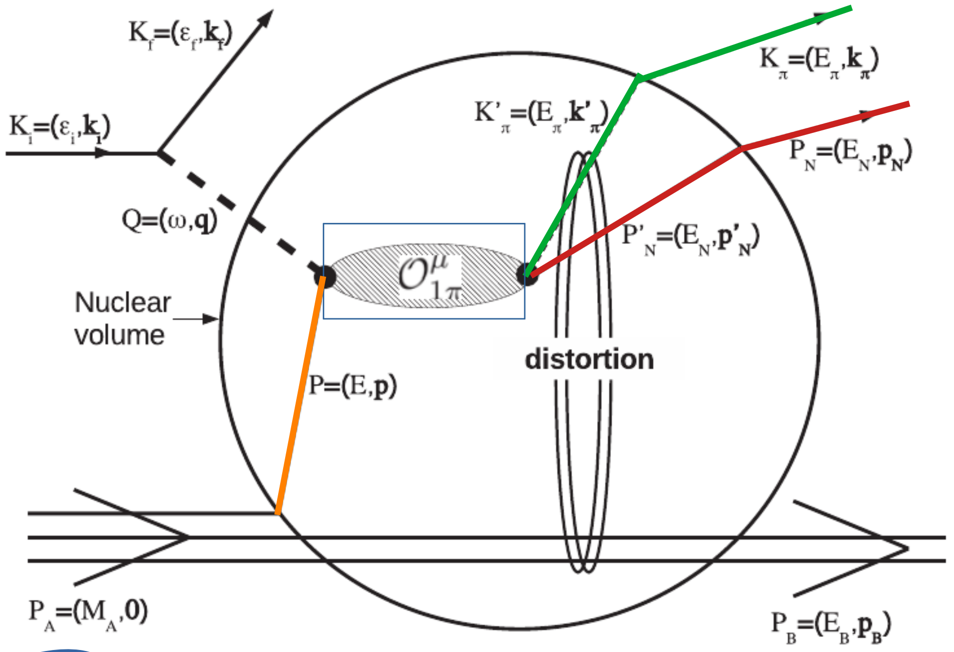

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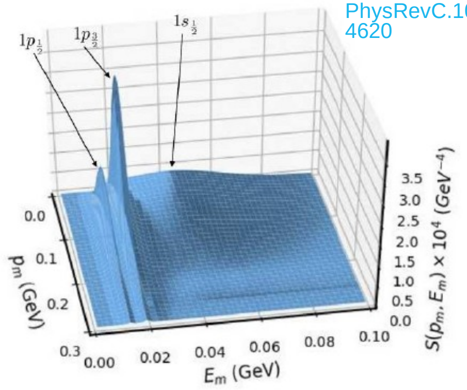
Nuclear effects in the cross sections

Small list of **nuclear and nucleonic effects** in the cross sections:

PhysRevC.100.044620



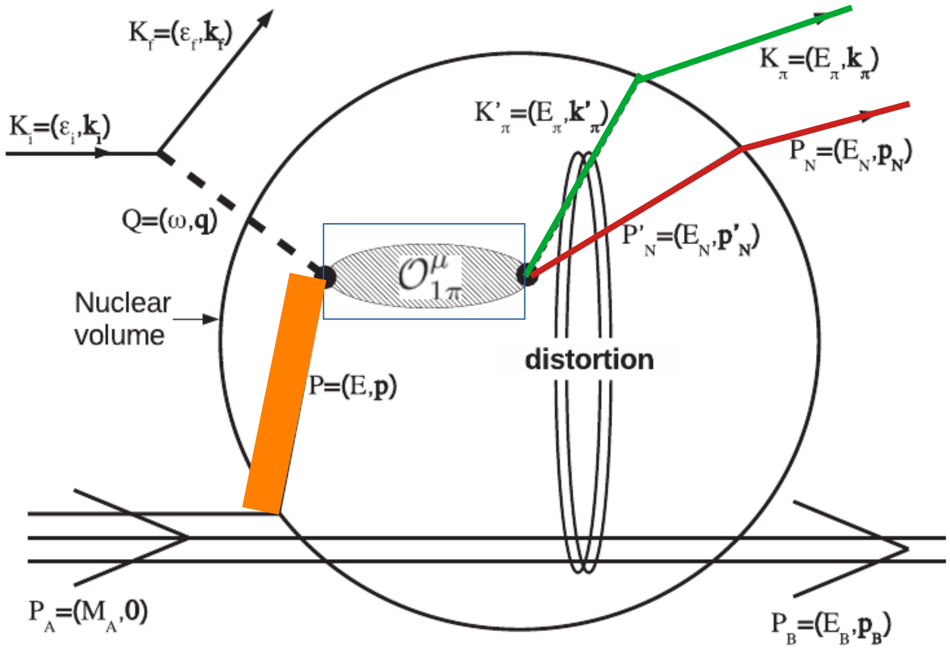
+ **Initial state**: binding energy, Fermi motion
(or momentum distributions), short- and long-range correlations

+ **Interaction:** nucleon form factors, Pauli blocking,
beyond one-body currents

+ **Final state interactions**:
    ++ Distortion effects or elastic FSI
    ++ Inelastic FSI (modeled with intranuclear cascade)

All this, and more, will be discussed in WG2 parallel sessions at NuFact 2024 workshop.

Single-Pion Production
(in the Impulse Approximation)



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Free nucleon

versus

RFG
(it accounts for **Fermi motion,** the initial state is an infinite gas of fermions)

versus

PWIA
(Fermi motion and the shell structure are accounted for, the **pion and final nucleon** are plane waves)

Praet et al. (2009), https://doi.org/10.1103/physrevc.79.044603

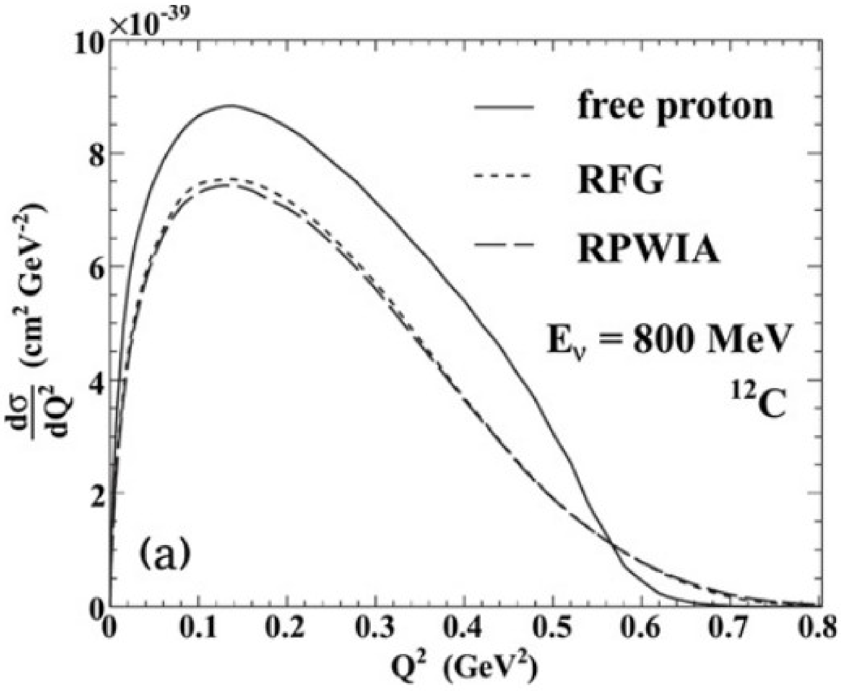

Figure: CC neutrino-^{12}C induced SPP.

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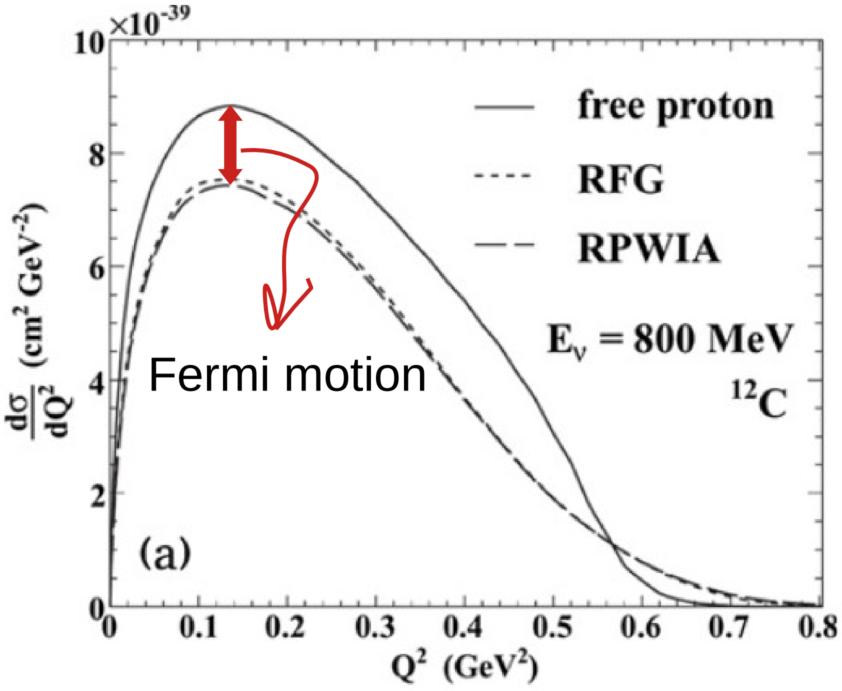

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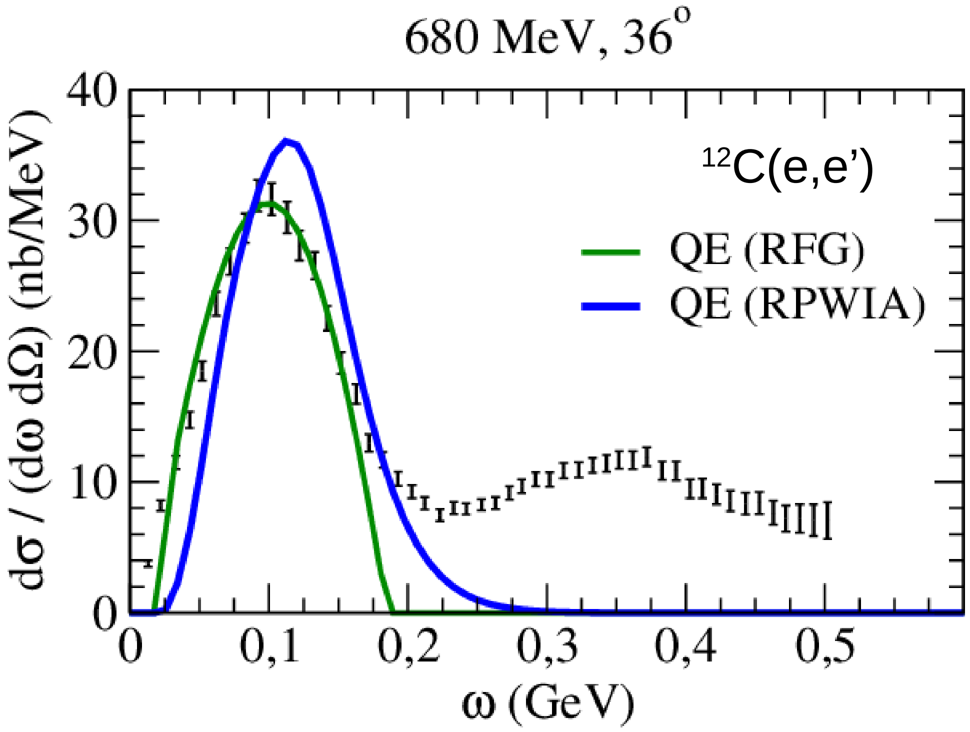

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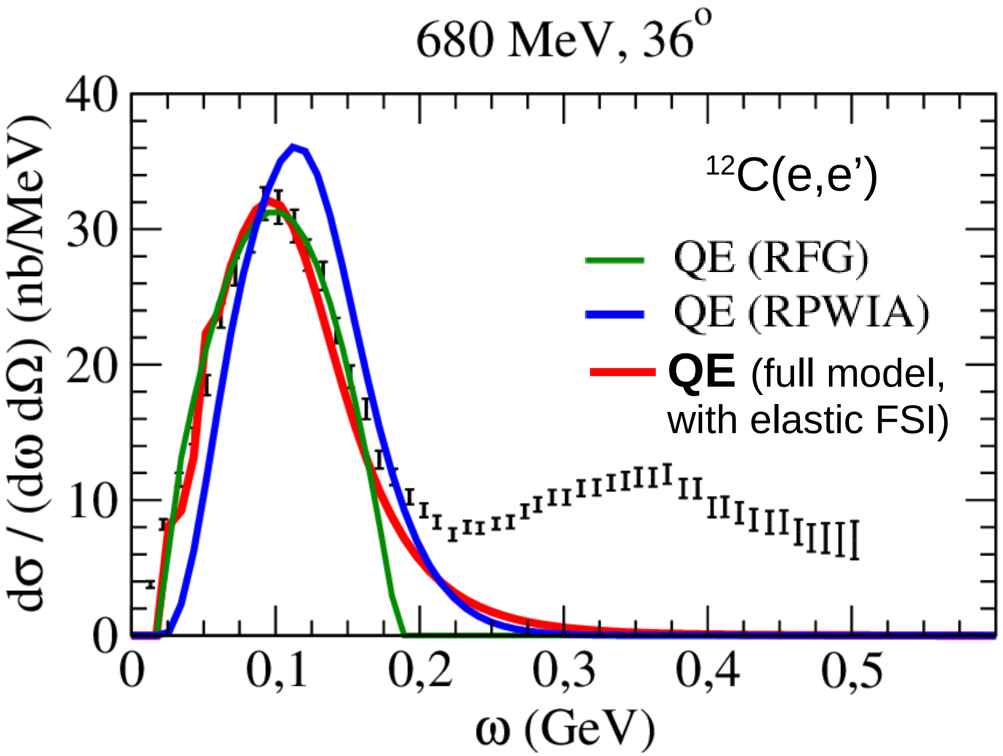
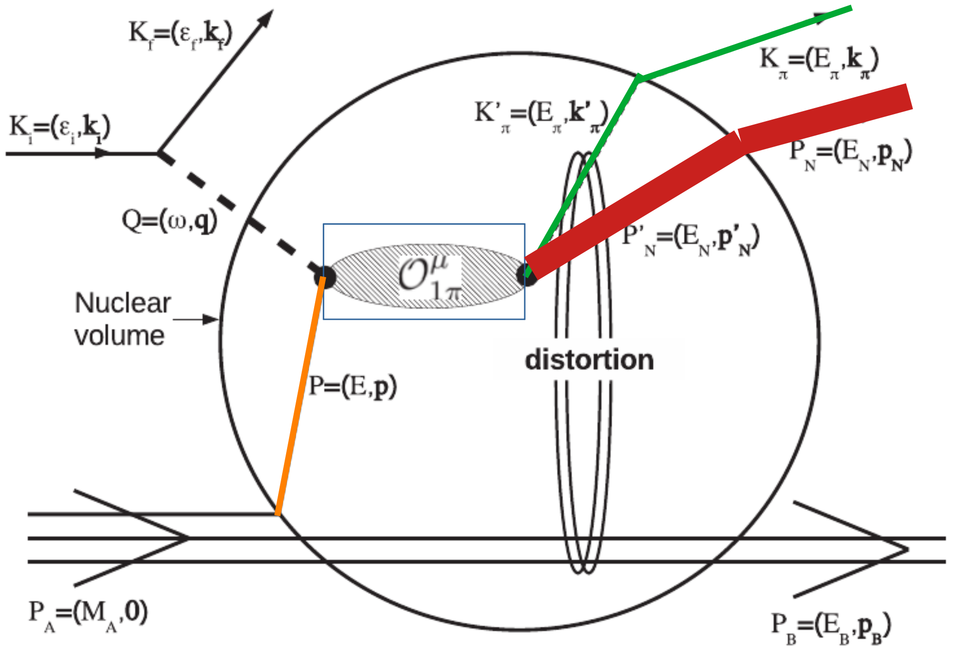


Single-Pion Production
(in the Impulse Approximation)



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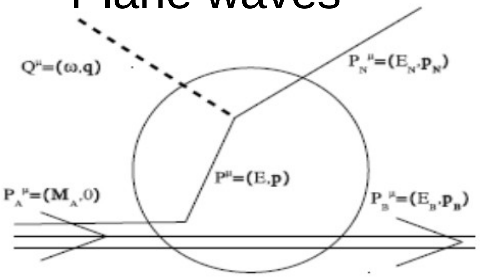
Pauli blocking and elastic FSI

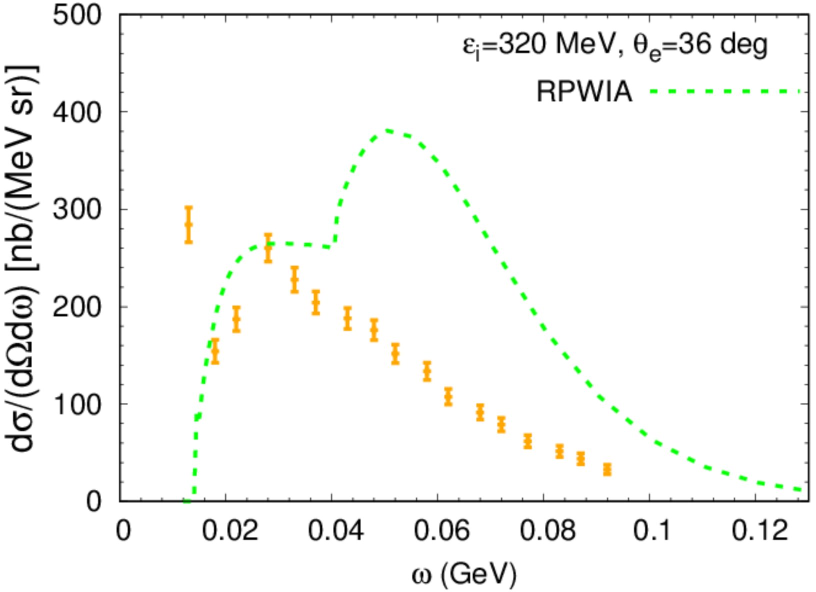
Pauli blocking and elastic FSI

Inclusive electron scattering **at low q:**

Plane waves



Phys. Rev. C 100 045501 (2019)



Pauli blocking and elastic FSI

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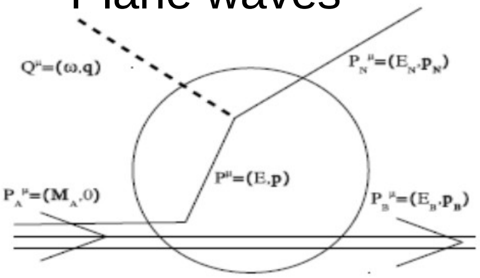

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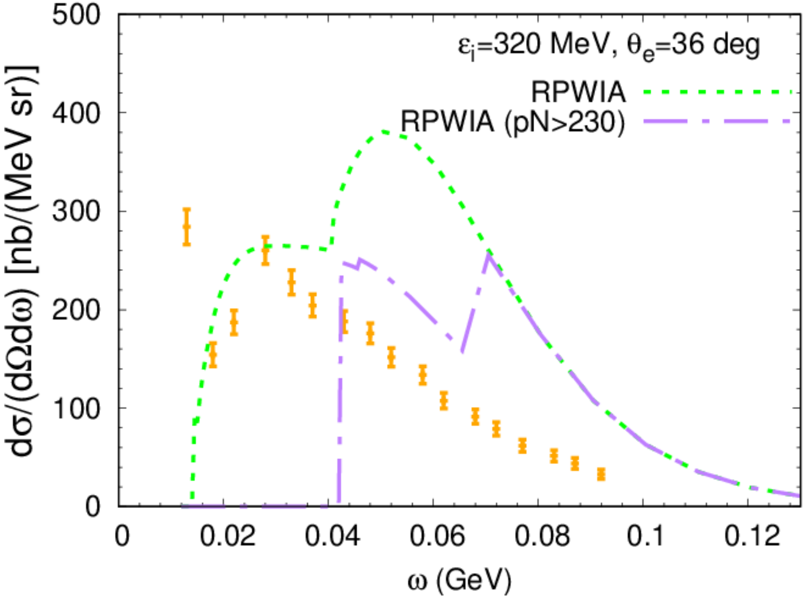

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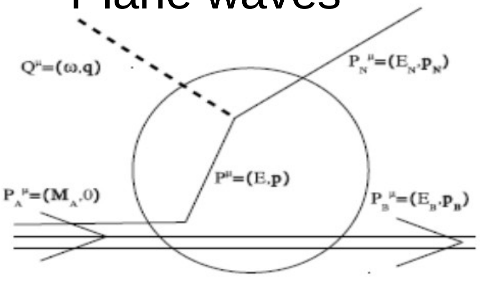

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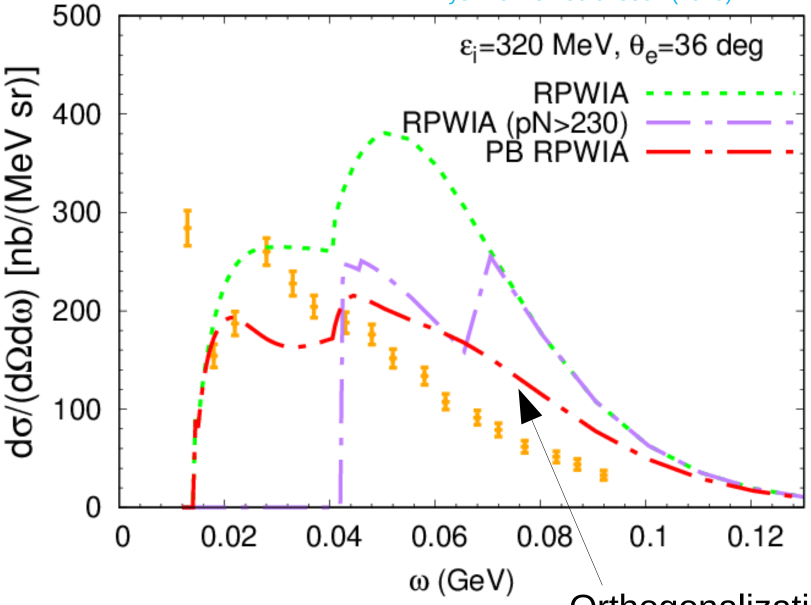


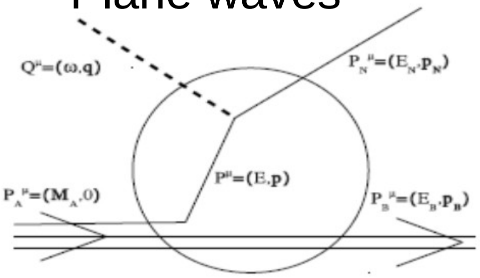
Orthogonalization

$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = \left|\psi^{s_N}_{pw}(\mathbf{p}_N)\right\rangle - \sum_{\kappa,m_j}\left[C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)\right]^\dagger \left|\psi^{m_j}_{\kappa}\right\rangle$$

Pauli blocking and elastic FSI

Inclusive electron scattering **at low q:**

Plane waves



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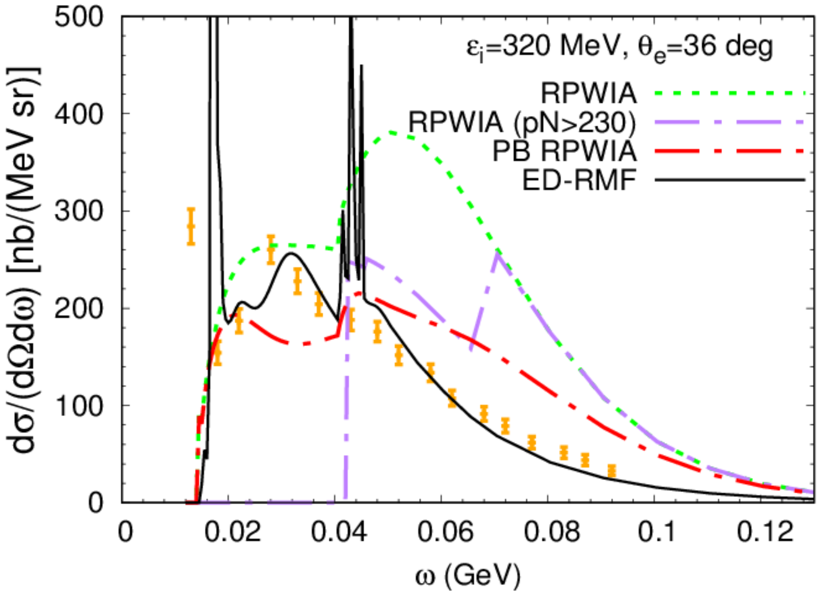
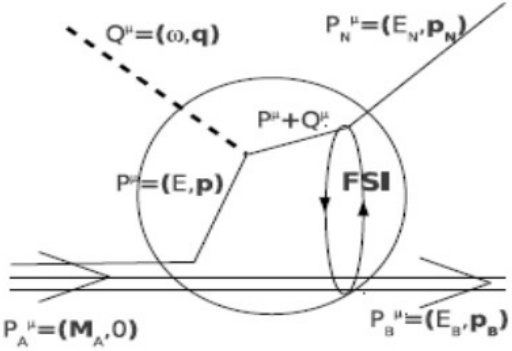


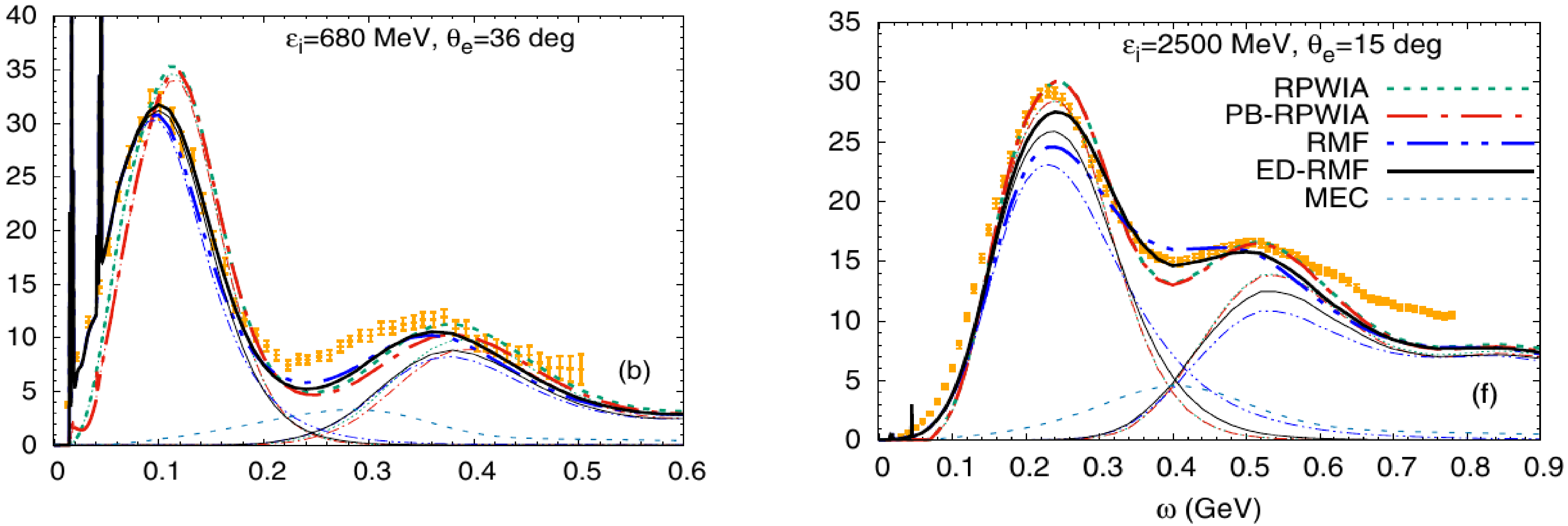
Distorted waves



Pauli blocking and elastic FSI

Inclusive electron scattering **at intermediate q:**

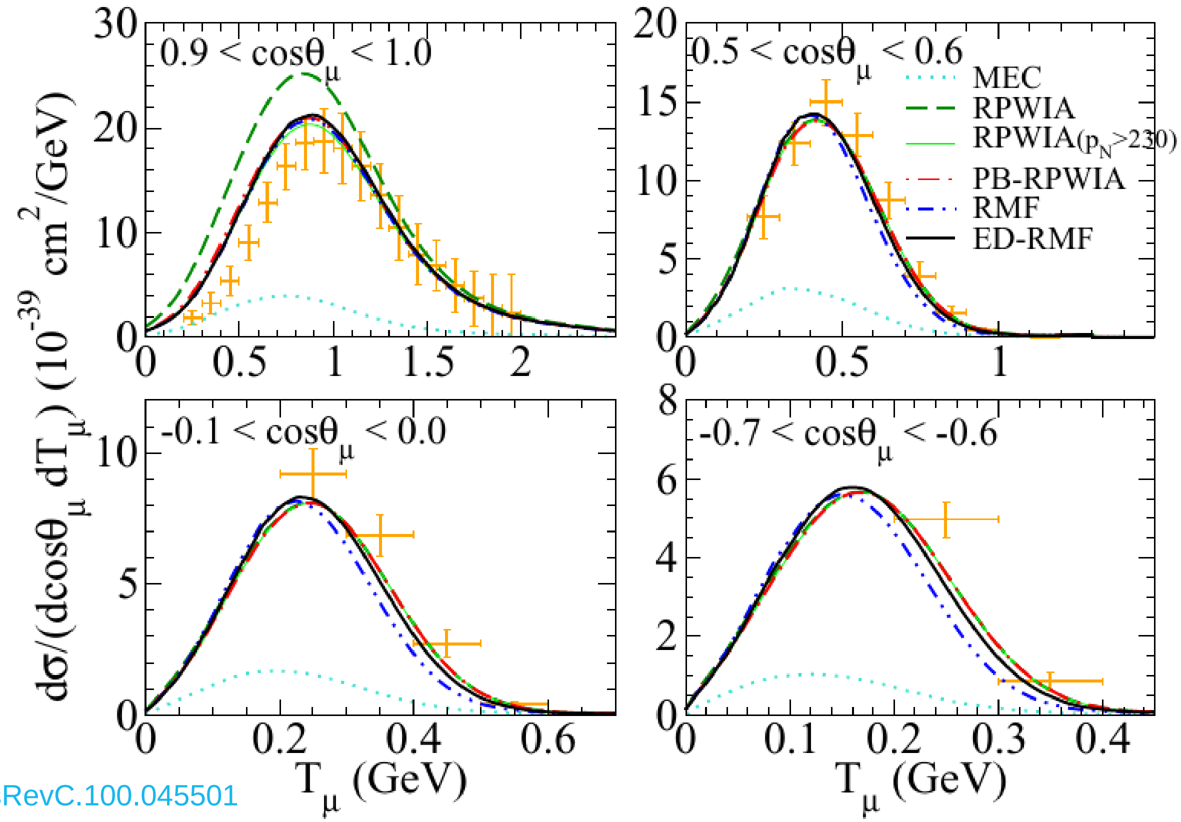
Phys. Rev. C 100 045501 (2019)



Distortion of the outgoing nucleon (elastic FSI in a Quantum Mechanical way)
is important at intermediate energies too !!!

Pauli blocking and elastic FSI

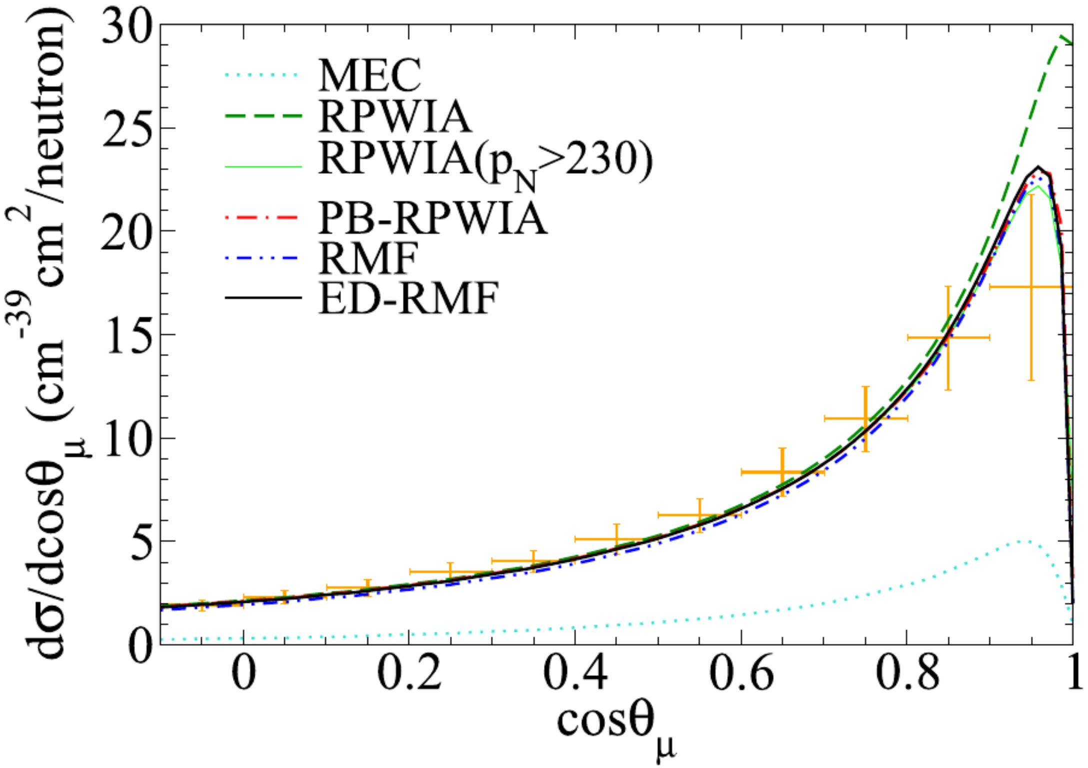
MicroBooNE data, neutrino-nucleus CCQE-like scattering:



https://doi.org/10.1103/PhysRevC.100.045501

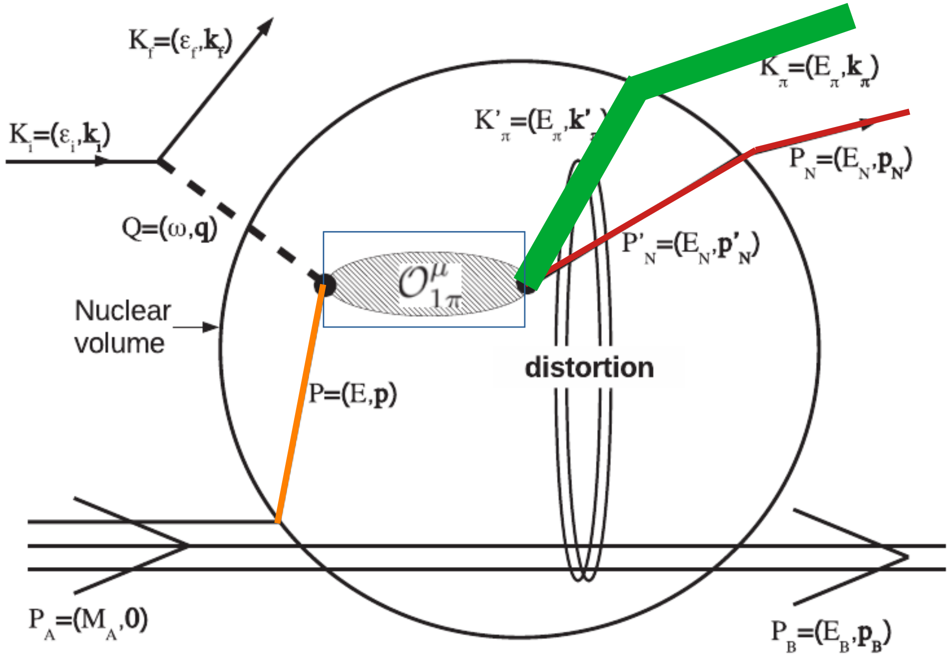
Pauli blocking and elastic FSI

MicroBooNE data, neutrino-nucleus CCQE-like scattering:



https://doi.org/10.1103/PhysRevC.100.045501

Single-Pion Production
(in the Impulse Approximation)

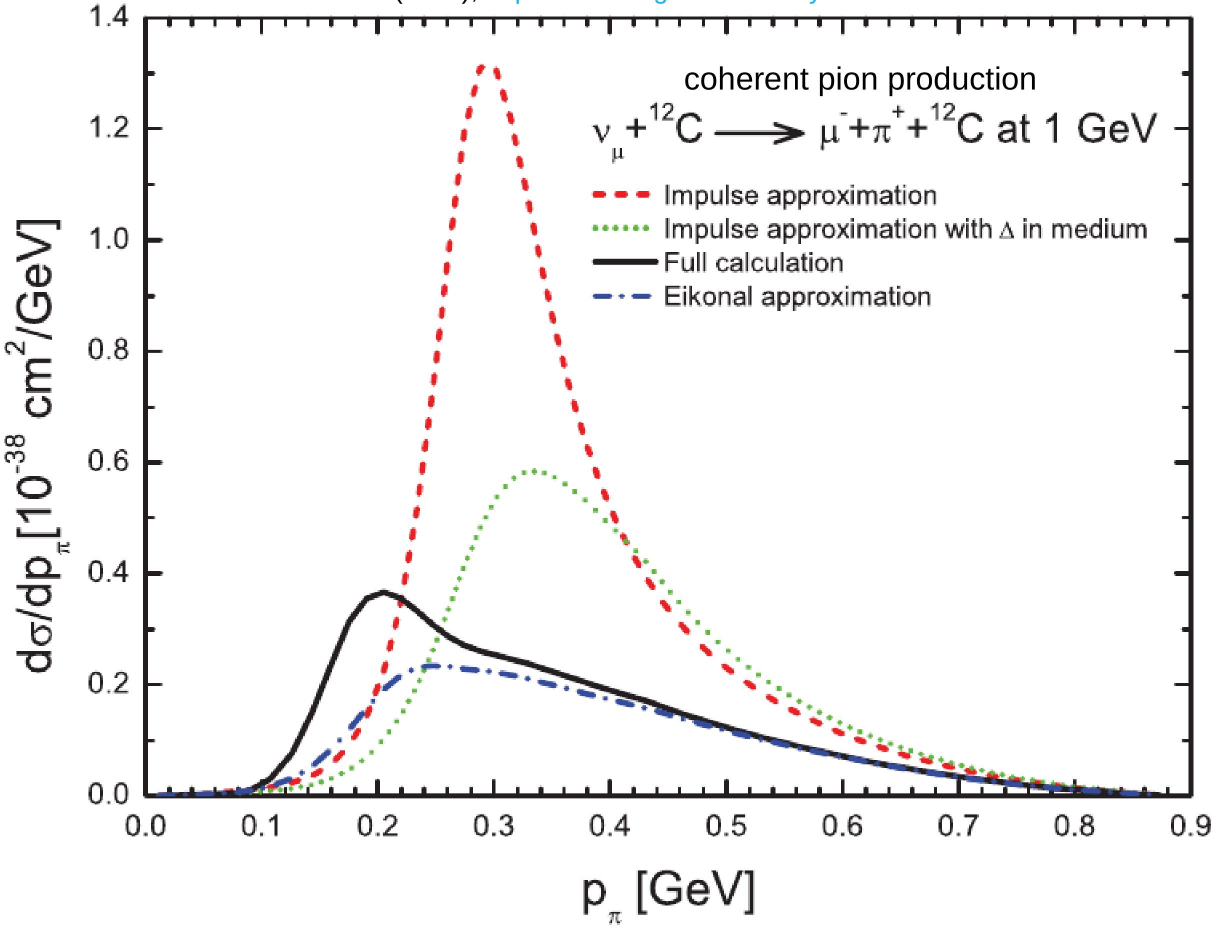


$$J^{\mu}_{\rm had} = \int d\mathbf{p} \int d\mathbf{p}'_N \overline{\Psi}_F(\mathbf{p}'_N,\mathbf{p}_N)\phi^*_\pi(\mathbf{p}+\mathbf{q}-\mathbf{p}'_N,\mathbf{k}_\pi)\mathcal{O}_{1\pi}(Q,P'_N,P)\Psi_B(\mathbf{p})$$

Distortion of the pion wave function

(or Elastic FSI of the pion)

Alvarez-Ruso et al. (2007), http://dx.doi.org/10.1103/PhysRevC.75.055501



Distortion of the pion wave function
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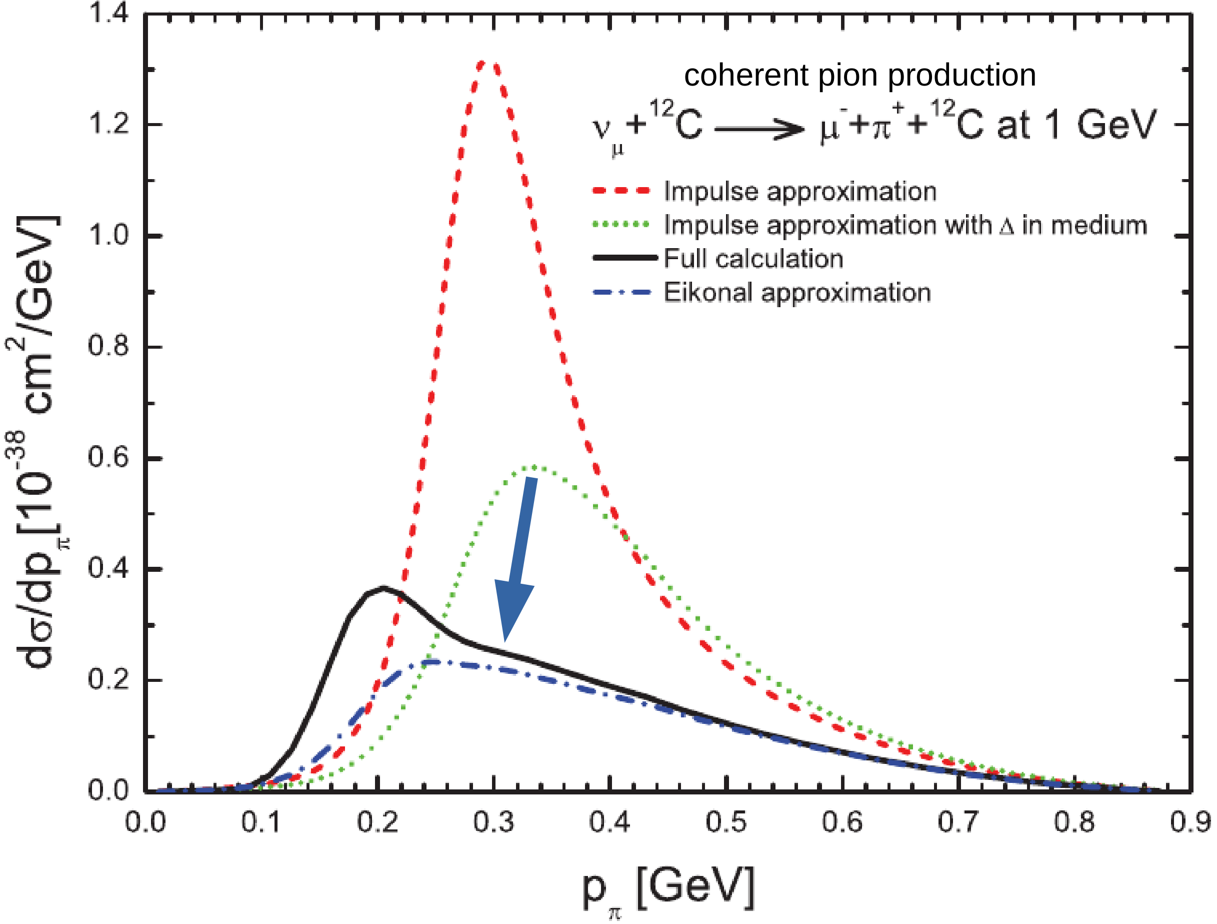
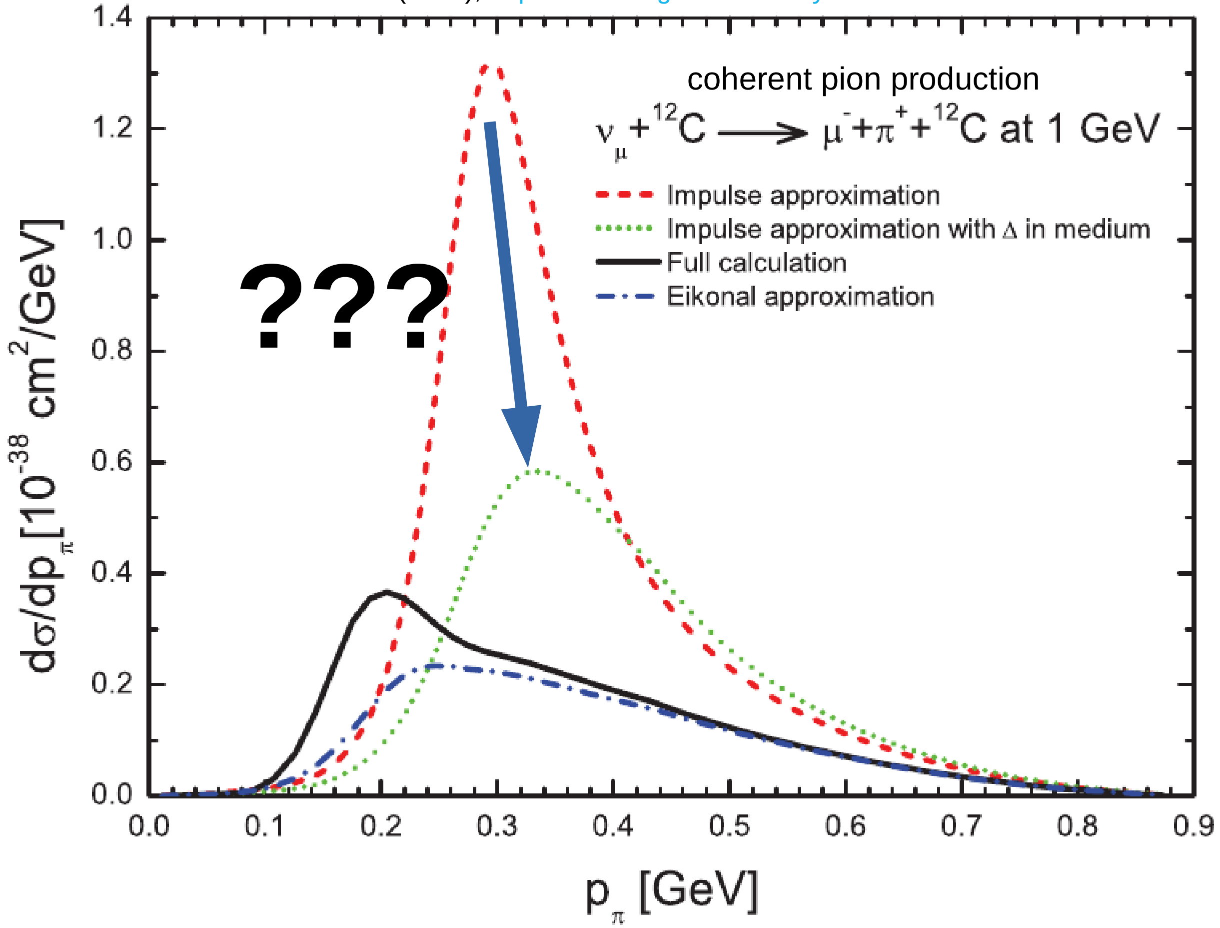
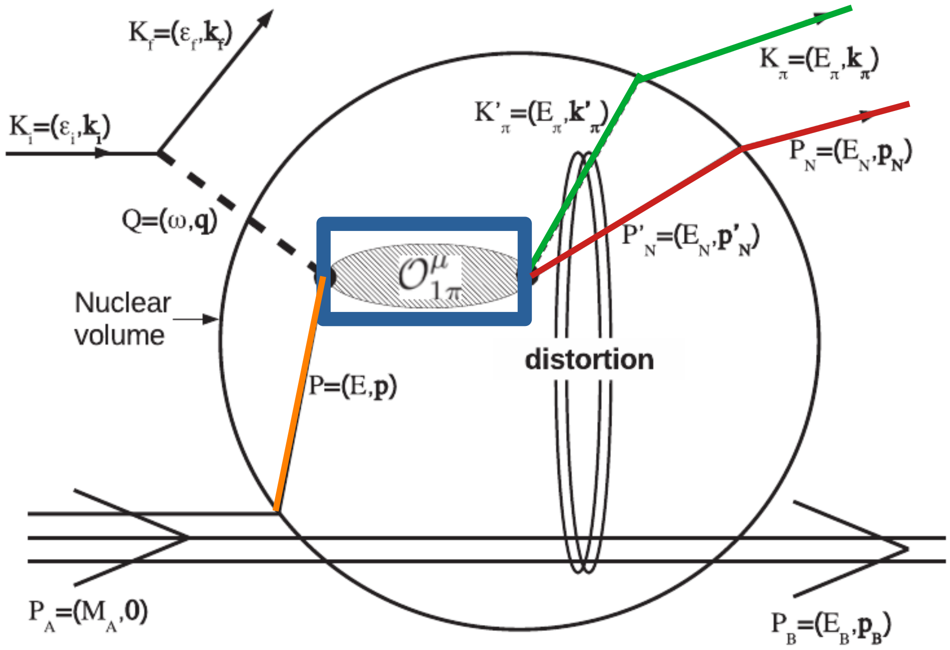


Alvarez-Ruso et al. (2007), http://dx.doi.org/10.1103/PhysRevC.75.055501



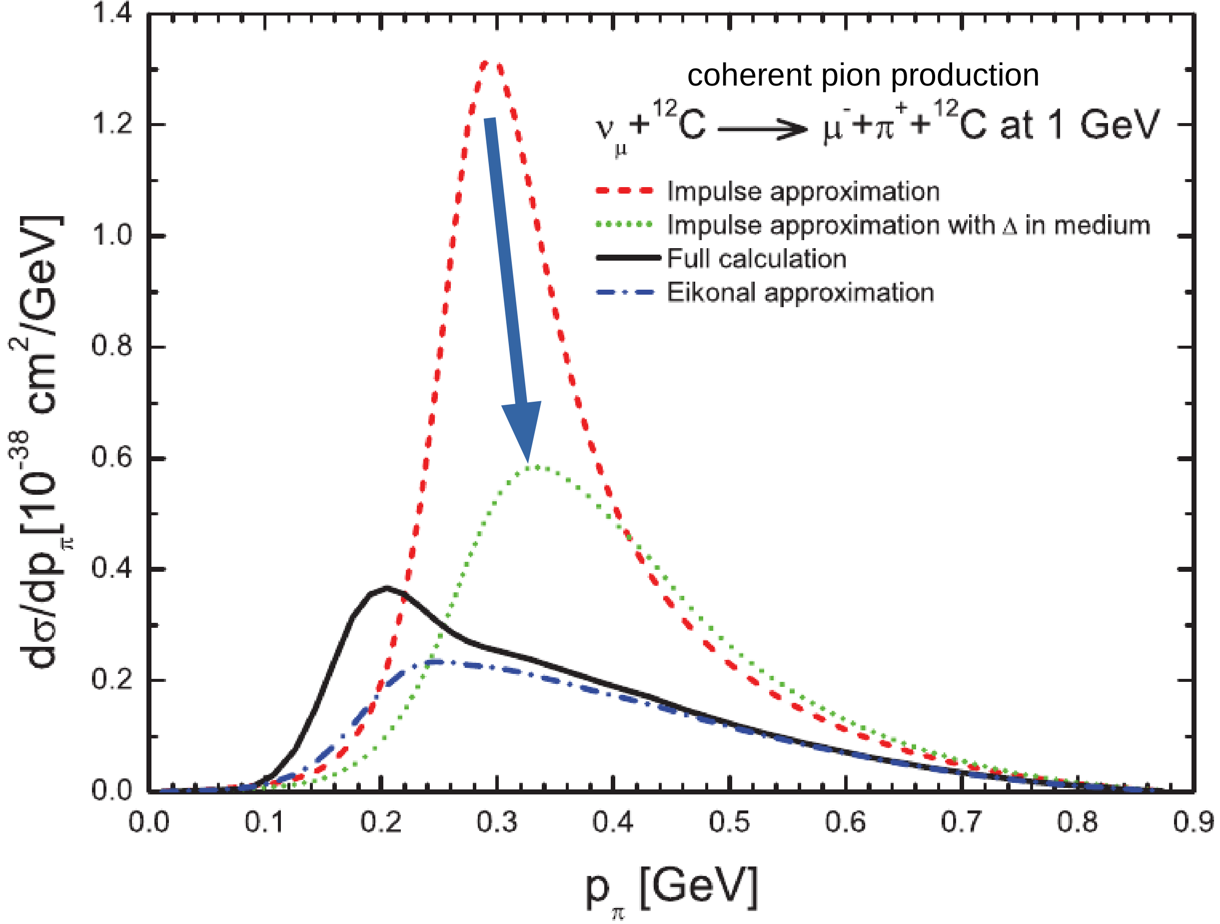
Single-Pion Production
(in the Impulse Approximation)



$$J^{\mu}_{\mathrm{had}} = \int d\mathbf{p} \int d\mathbf{p}'_N \overline{\Psi}_F(\mathbf{p}'_N, \mathbf{p}_N) \phi^*_\pi(\mathbf{p} + \mathbf{q} - \mathbf{p}'_N, \mathbf{k}_\pi) \mathcal{O}_{1\pi}(Q, P'_N, P) \Psi_B(\mathbf{p})$$

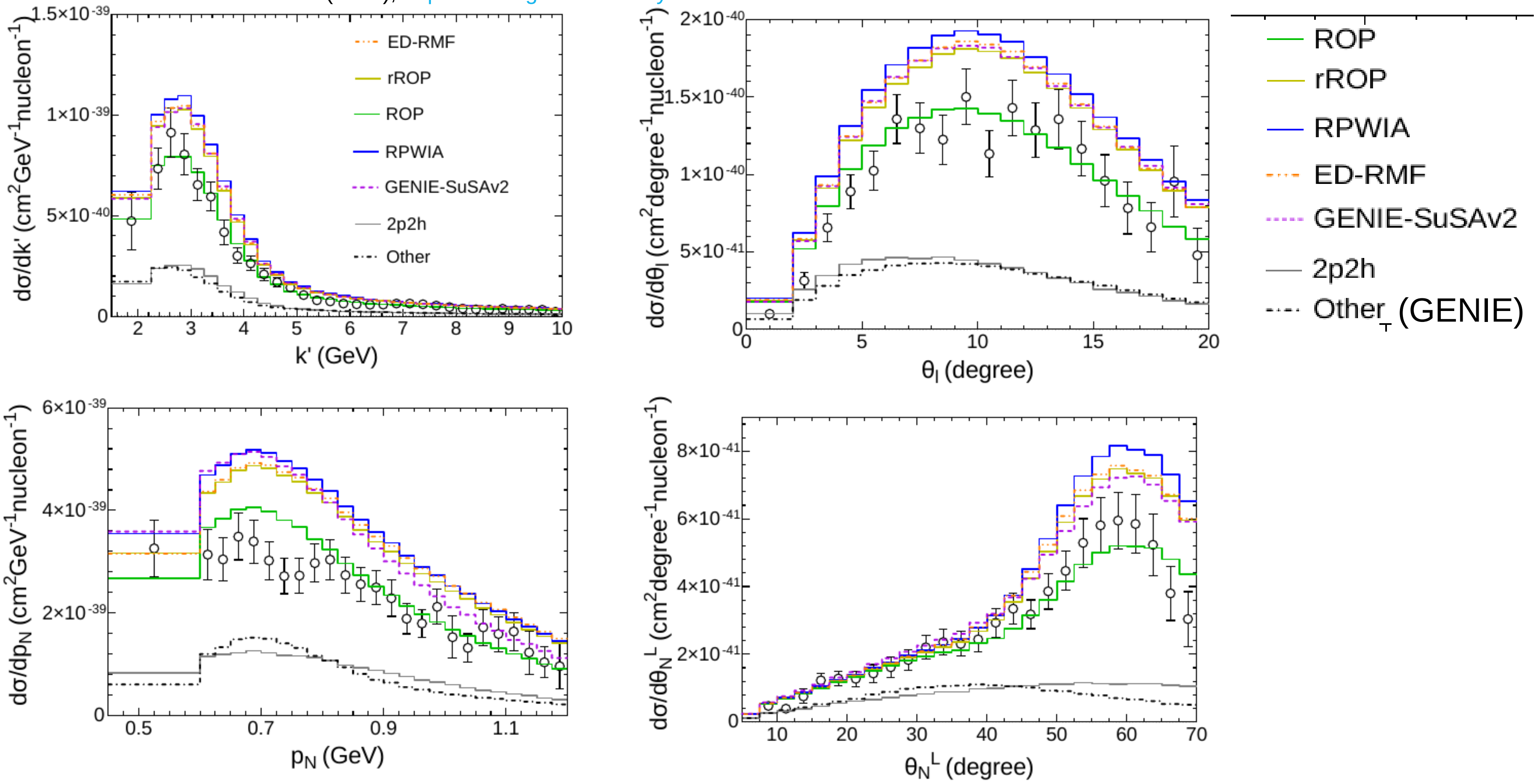
In-medium modification of the resonance properties

Alvarez-Ruso et al. (2007), http://dx.doi.org/10.1103/PhysRevC.75.055501



MINERνA no-pion ν_μ-^{12}C cross section

Franco-Patino et al. (2022), https://doi.org/10.1103/PhysRevD.106.113005



MINERνA no-pion ν_μ-^{12}C cross section

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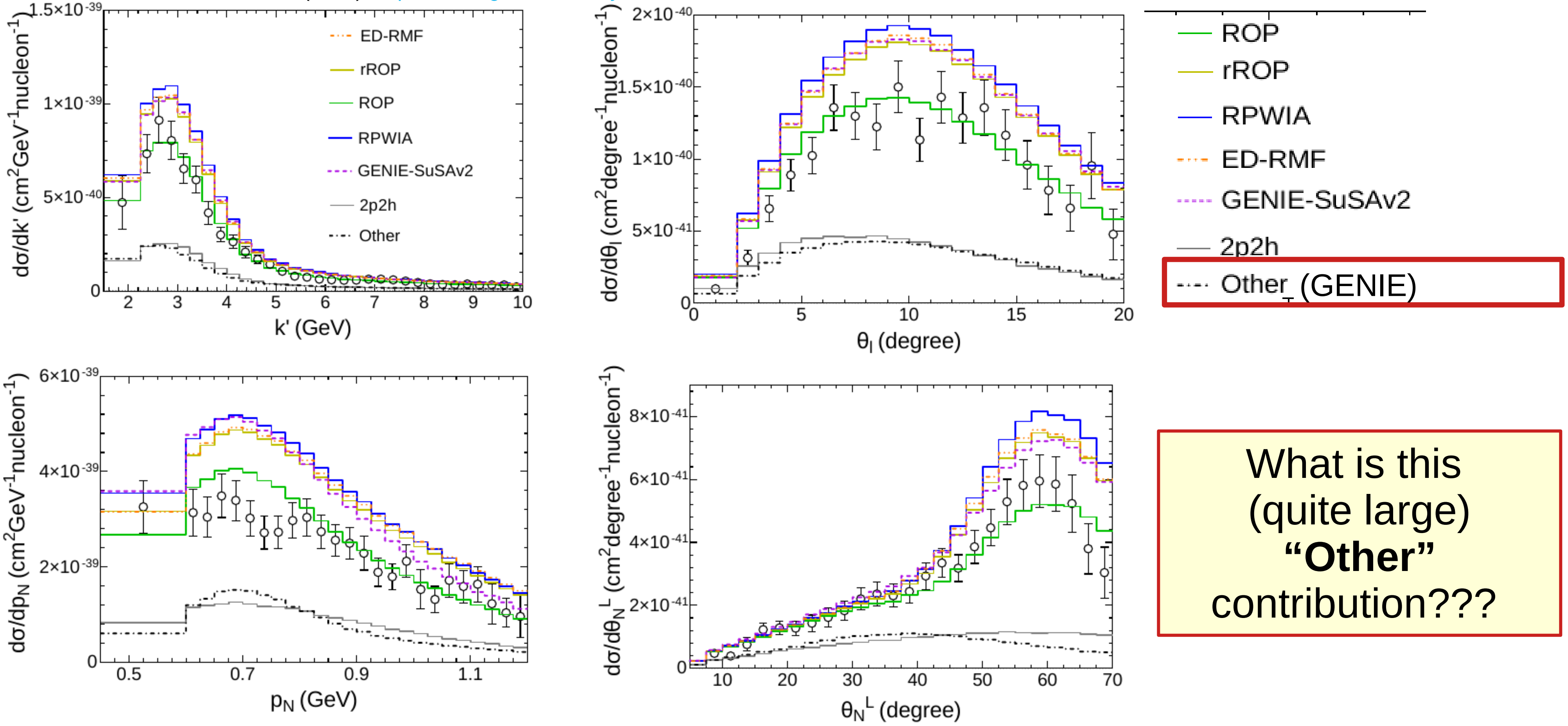
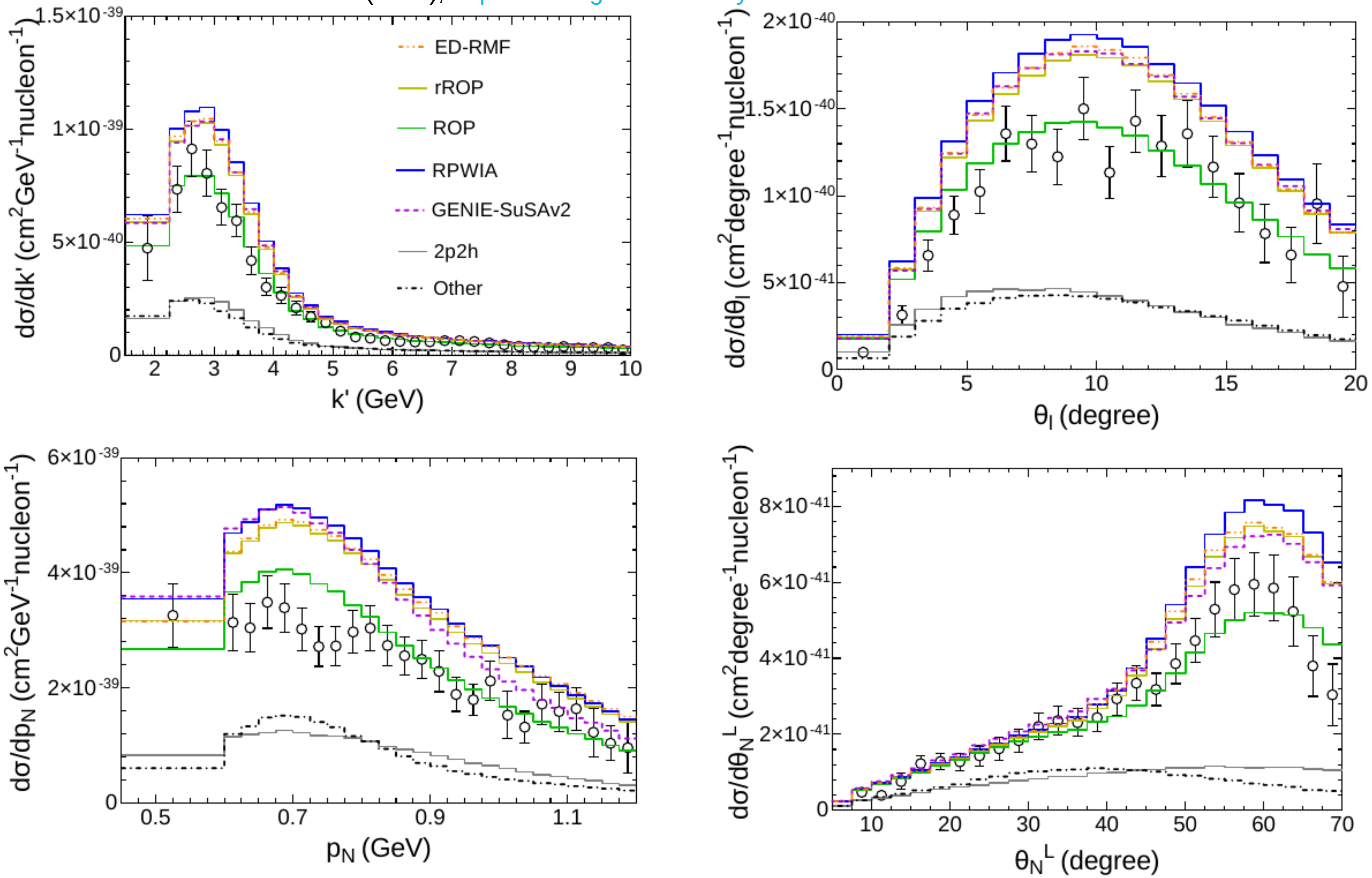
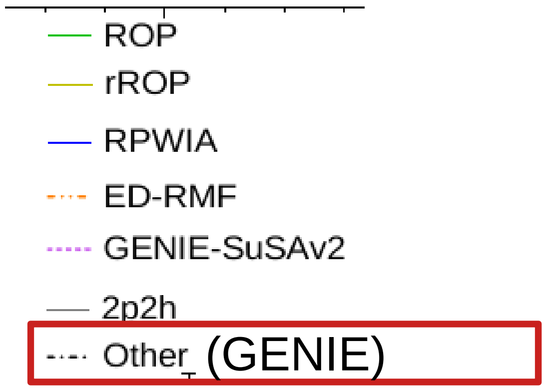


What is this (quite large) **"Other"** contribution???

MINERνA no-pion ν_μ-^{12}C cross section

Franco-Patino et al. (2022), https://doi.org/10.1103/PhysRevD.106.113005





“Other”:

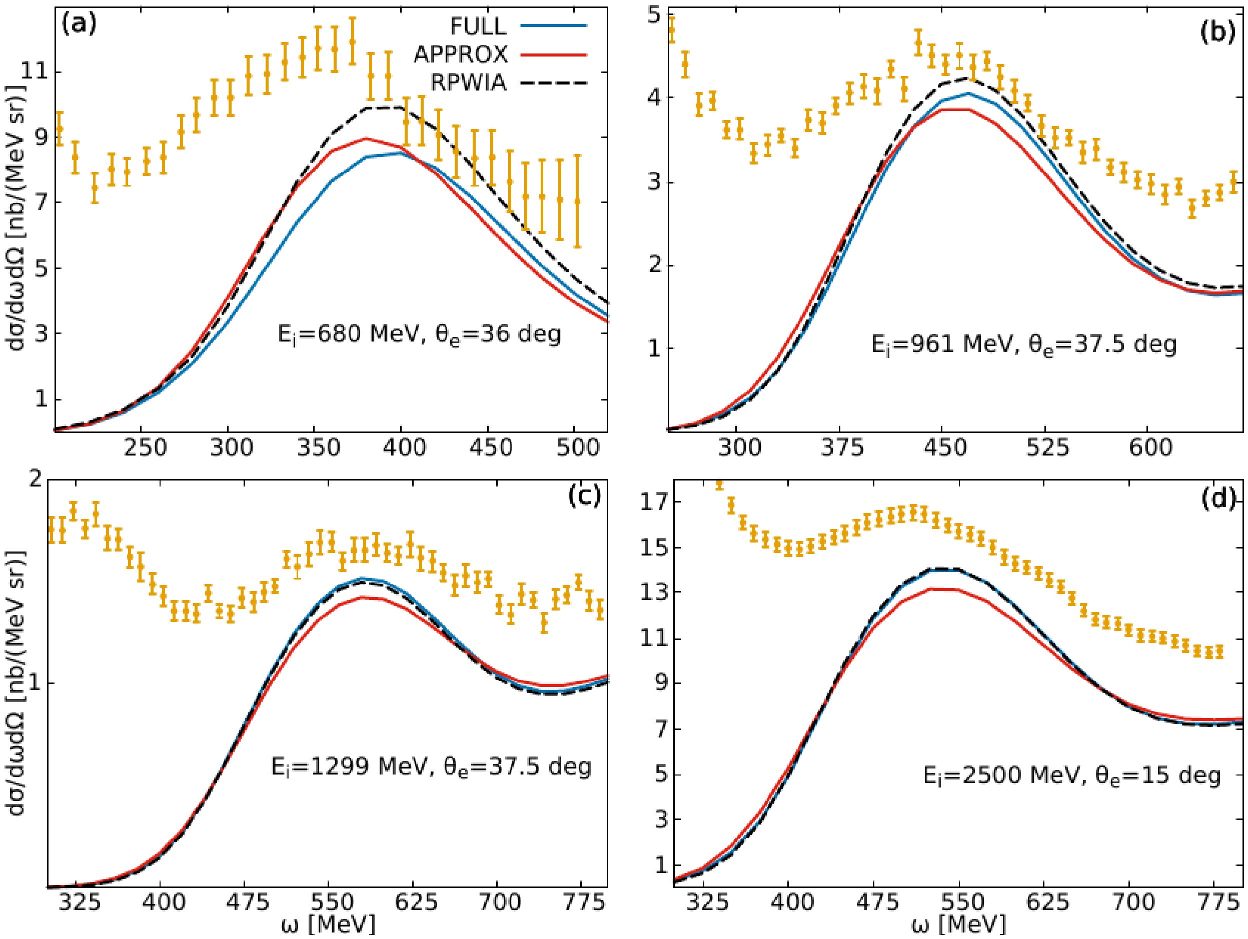
pion absorption contribution
evaluated using GENIE

J. García-Marcos et al., Towards a more complete description of nucleon distortion in lepton-induced single-pion production at low-Q2
https://doi.org/10.48550/arXiv.2310.18056

Distortion of the nucleon wave function
(or Elastic FSI of the nucleon)

and

Asymptotic approximation for the SPP operator
(or local versus non-local operator)



Beyond Impulse Approximation: two-body currents in the 1p-1h sector

https://arxiv.org/abs/2203.09996v3
https://arxiv.org/abs/2306.10823

Beyond Impulse Approximation: two-body currents in the 1p-1h sector

$$J^{\mu}_{had} = \int d\mathbf{p}\, \overline{\Psi}_F(\mathbf{p}+\mathbf{q}, \mathbf{p}_N) \left(\mathcal{O}^{\mu}_{\text{one body}} + \mathcal{O}^{\mu}_{\text{two body}} \right) \Psi_B(\mathbf{p})$$

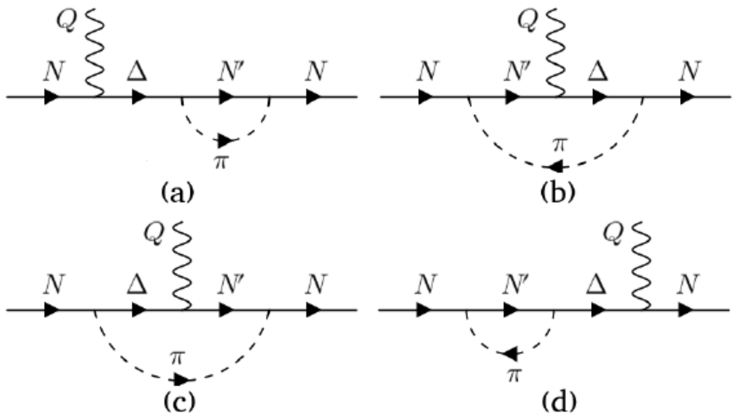


FIG. 1. Delta contributions.

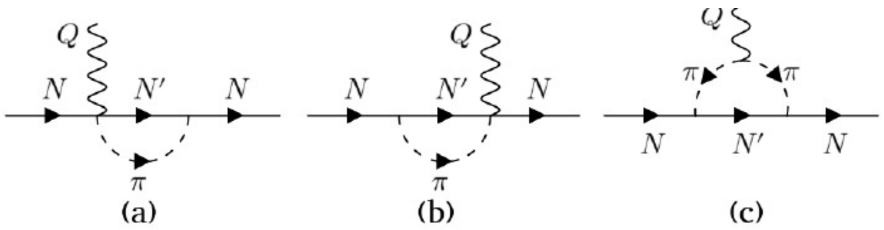
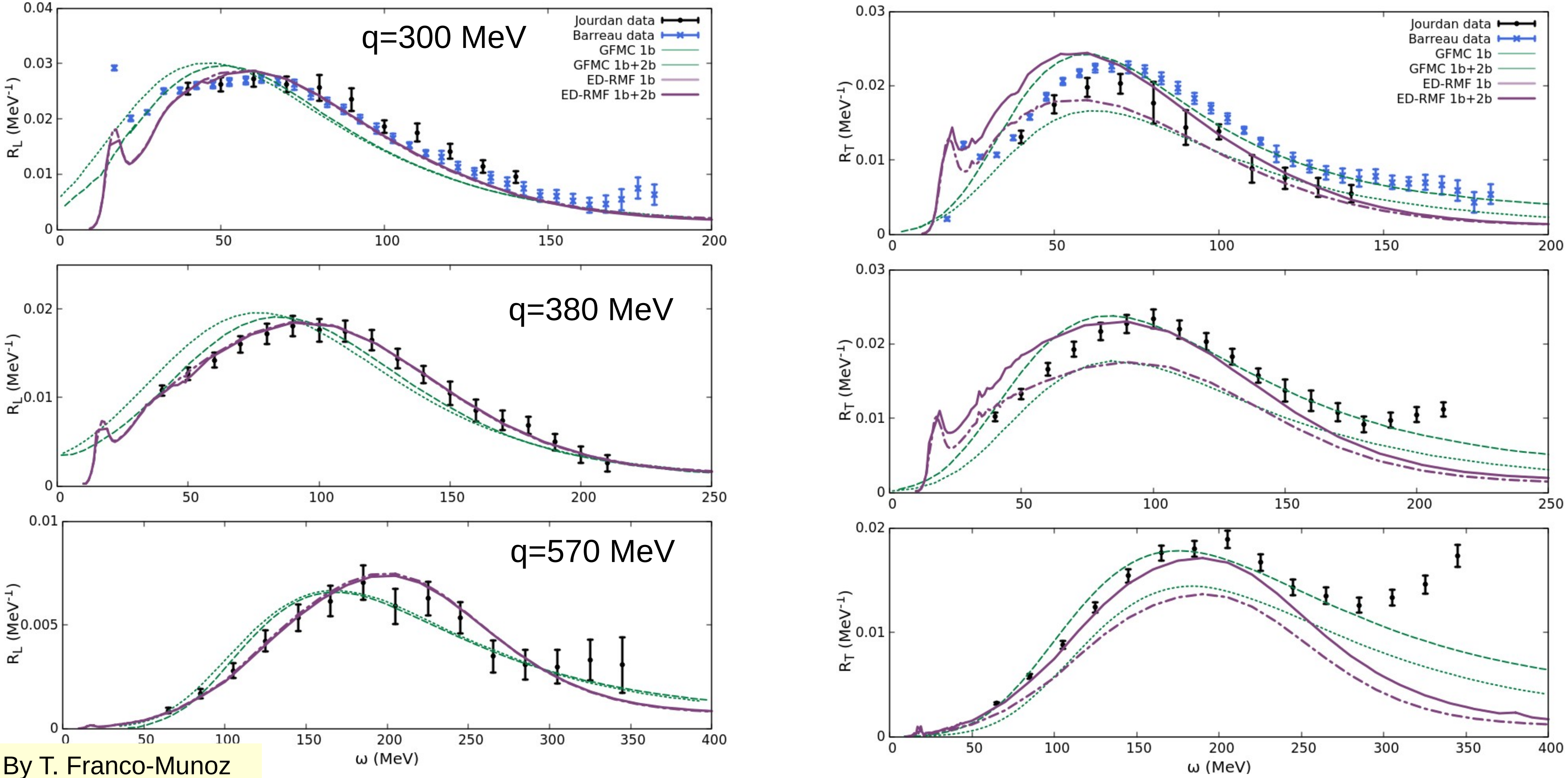


FIG. 2. Background contributions: seagull or contact [CT, (a) and (b)] and pion-in-flight [PF, (c)].

https://arxiv.org/abs/2306.10823

Carbon 12 responses

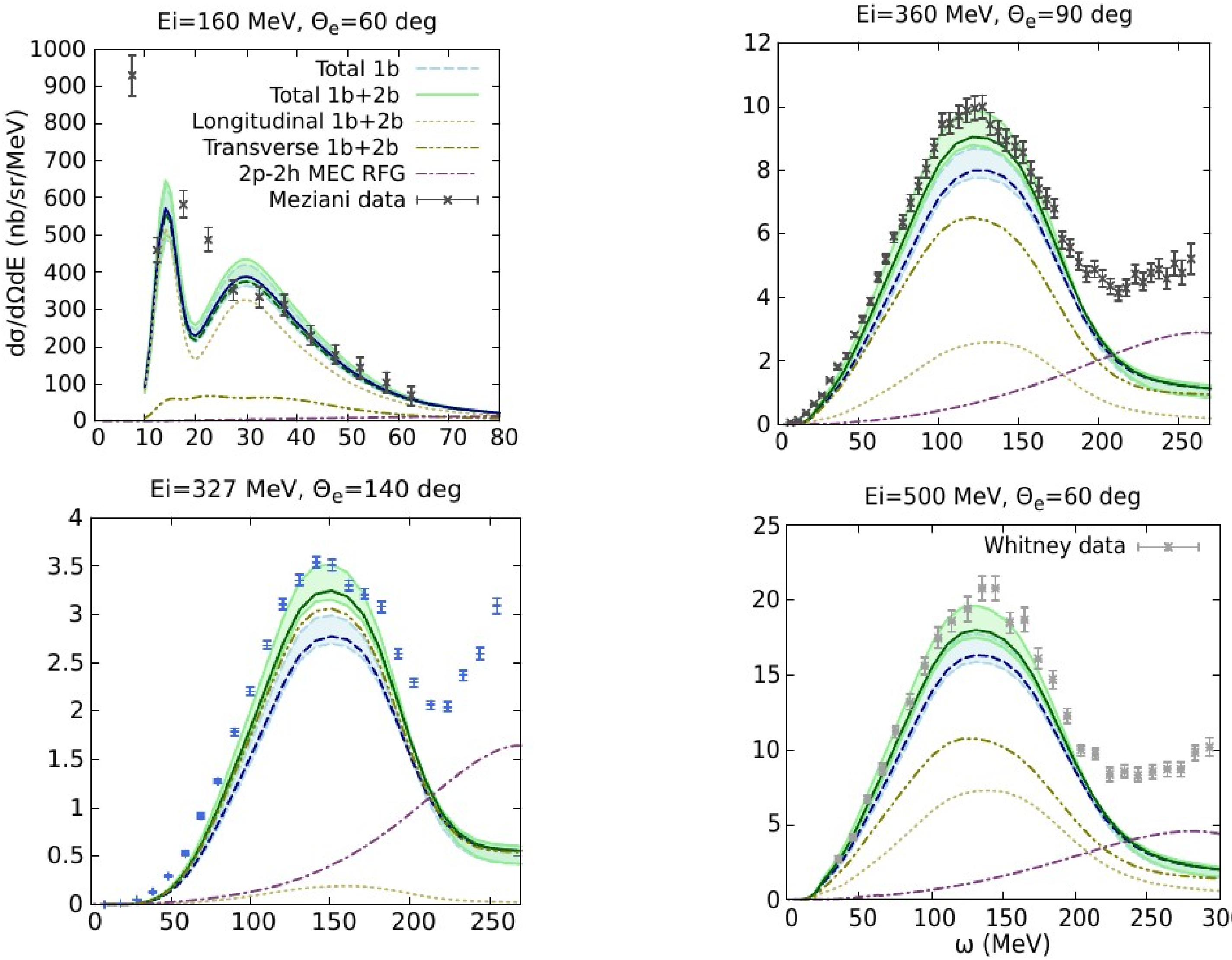
green lines from Lovato et al.
PRL 117, 082501 (2016)



By T. Franco-Munoz
as part of her PhD.

https://arxiv.org/abs/2203.09996v3

^{40}Ca electromagnetic inclusive cross sections



By T. Franco-Munoz
as part of her PhD.

Inelastic final-state interactions

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+ The primary nucleon knocks out other nucleon(s).

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+ The secondary hadrons also suffer FSI

+ ...

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Modeling all these reactions is necessary if the goal is to make predictions about the full hadron multiplicity in the final state.

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+ ...

Modeling all these reactions is necessary if the goal is to make predictions about the full hadron multiplicity in the final state.

… But, do we really need that ???

Inelastic final-state interactions: “*In Cascade we trust*”

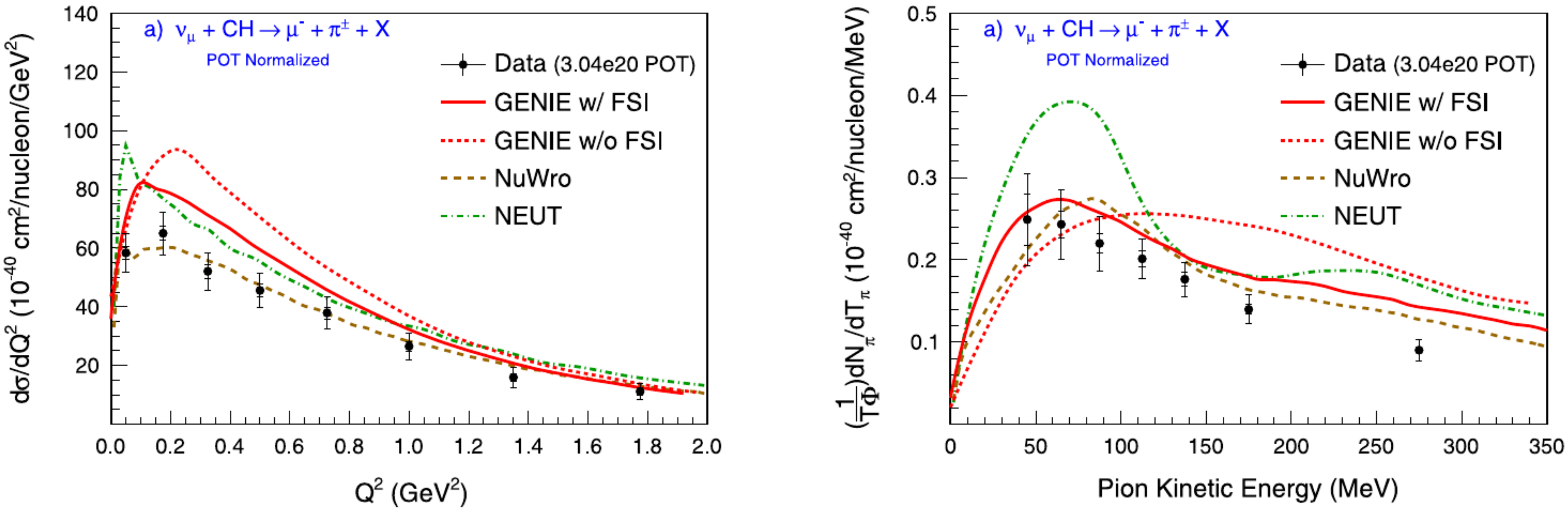


Fig. 13. Comparisons of event generator calculations with MINERνA $\nu_\mu CH$ CC π^+ data [290] (left) Q^2 and (right) kinetic energy. Both results include resonances at $W < 1.8$ GeV.

Inelastic final-state interactions: "*In GiBUU we trust*"

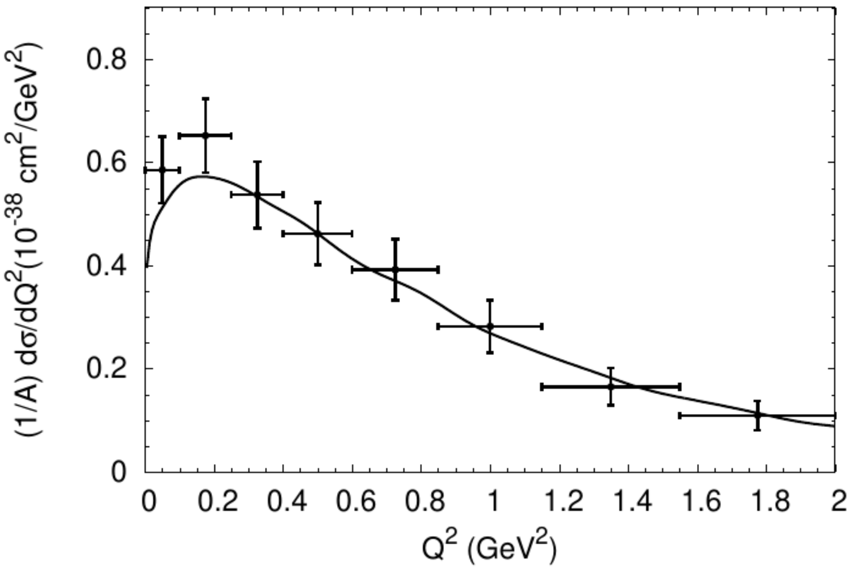


FIG. 12. Q^2 distribution of multiple charged pions in the MINERvA flux for a CH target with $W_{\rm rec} < 1.8$ GeV. Data are from [10]

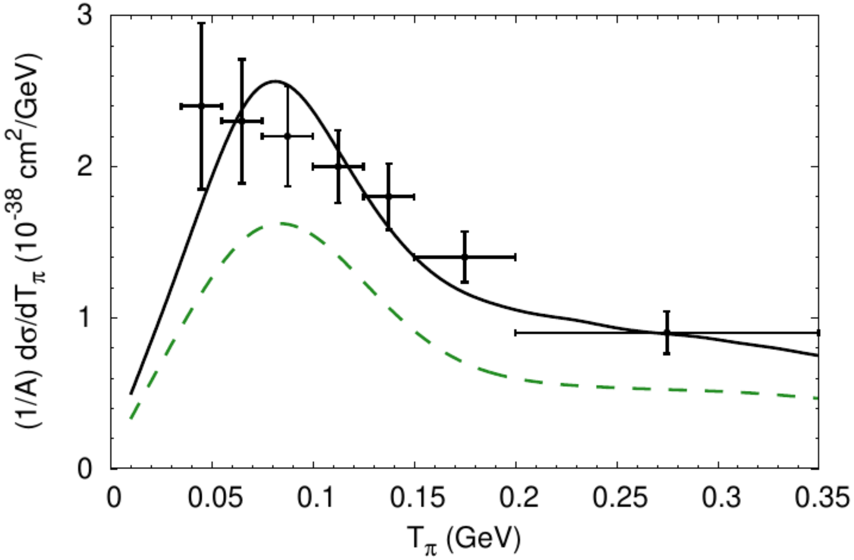


FIG. 8. Kinetic energy spectrum per nucleon of multiple charged pions in the MINERvA flux for a CH target with $W_{\rm rec} < 1.8$ GeV (solid line). The dashed line gives the 1-pion contribution. Data are from [10]

Final remarks

IMPORTANT:

Classical CASCADE models do NOT affect the inclusive* cross section, therefore, one should use models of the primary vertex that provide realistic predictions of the inclusive cross section.

For consistency, **the model of the primary vertex should also provide full information on the hadron(s),** which will later propagate through the nucleus via cascade.

*inclusive = only the scattered lepton is detected.

Complete discussion in https://doi.org/10.1103/PhysRevD.107.053007

Final remarks

+ For the **reconstruction of the neutrino energy** one needs models for the different reaction channels contributing to the neutrino-nucleus cross section.

+ The (miss)modeling of neutrino-nucleus cross section is in the top-three of uncertainties in oscillation analyses.

    The situation is worse for higher energy fluxes (DUNE), due to pion-production ‘and beyond’ mechanisms.

+ Small list of **nuclear effects**:

    ++ **Initial state**: binding energy, Fermi motion (or momentum distributions).

    ++ **Primary vertex:** Pauli blocking, distortion effects (or elastic FSI). Quantum mechanics needed.

    ++ **Secondary interactions** (or inelastic FSI): Cascade models (what else can we do?)

+ Combined and coordinated experimental and theoretical efforts are needed to move forward.

Thank you

ADDITIONAL SLIDES

The current operator in lepton-induced single pion production.

An example: Feynman diagram for Δ-mediated one-pion production.

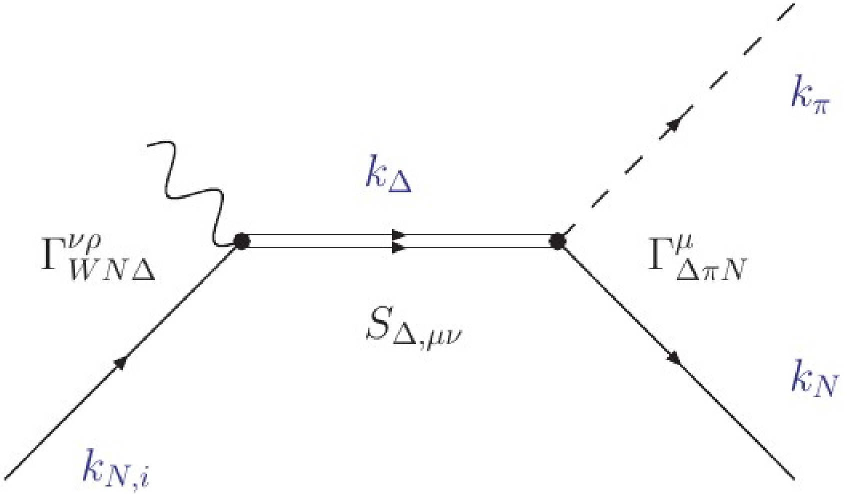
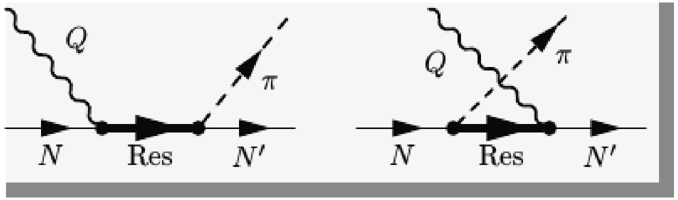


Figure from C. Praet's PhD Thesis

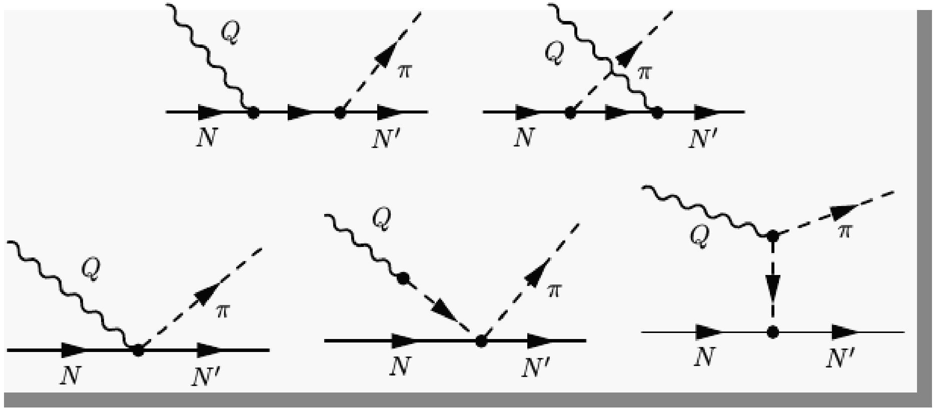
$$J^{\mu}_{had} \sim \overline{u}(k_N, s_N)\Gamma^{\rho}_{\Delta\pi N} S_{\Delta,\rho\sigma}\Gamma^{\sigma\mu}_{WN\Delta} u(k_{N,i}, s_{N,i})$$

Resonances:

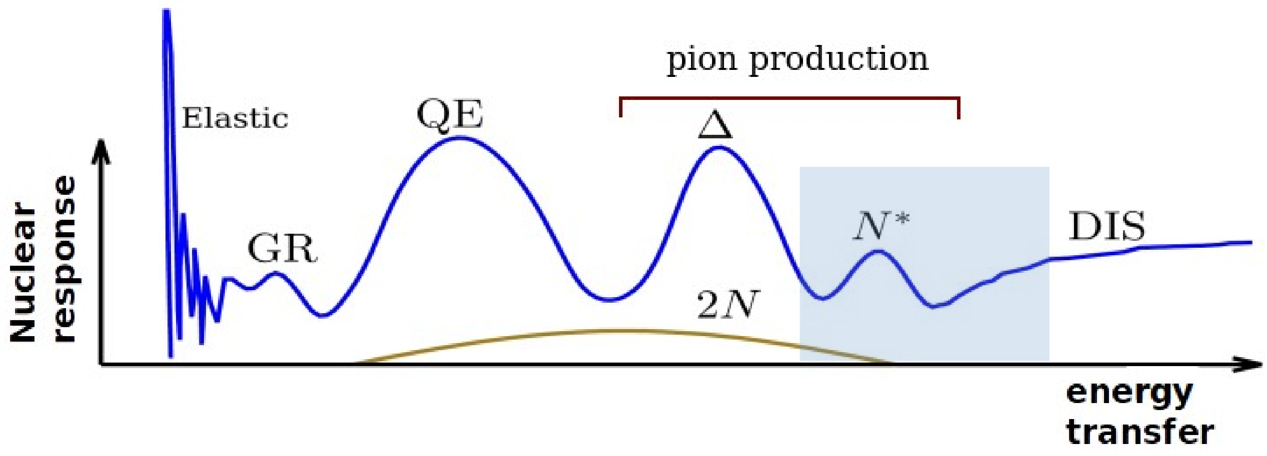
P33(1232), D13(1520), S11(1535), P11(1440)



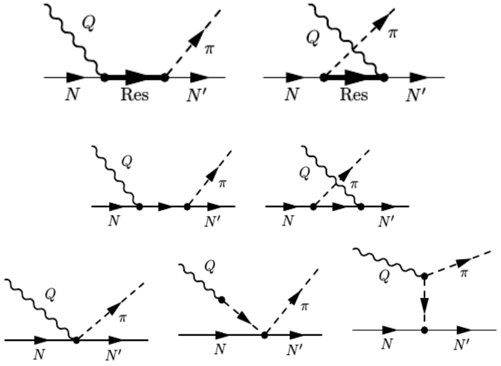
ChPT background:



Above single-pion production and below DIS



Low-energy model
(resonances + ChPT bg)



Unphysical predictions at large invariant masses.

https://doi.org/10.1103/PhysRevD.95.113007

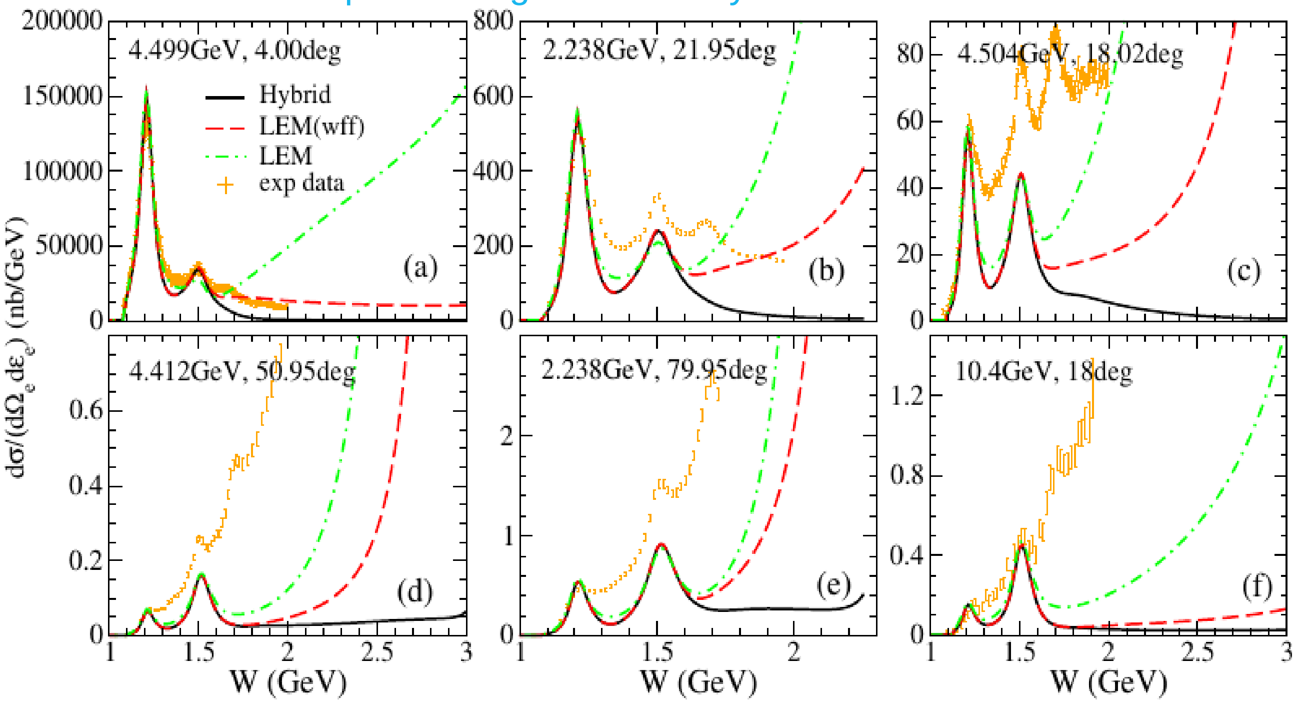
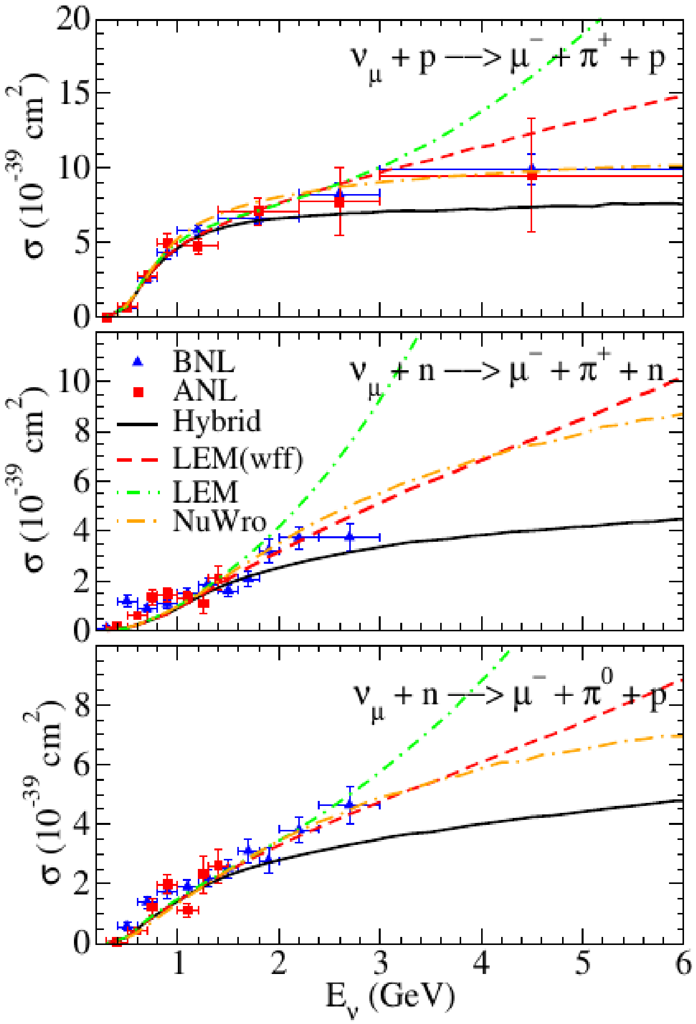


Figure: The model overshoots **inclusive electron-proton** scattering data.

Sample without cuts in W



https://doi.org/10.1103/PhysRevD.95.113007

Determining the oscillation probability

Oscillation experiment in a nutshell:

One wishes to determine the oscillation probability **P**$_{\alpha\rightarrow\beta}$ as function of the neutrino energy, so that the neutrino parameters can be extracted.

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

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

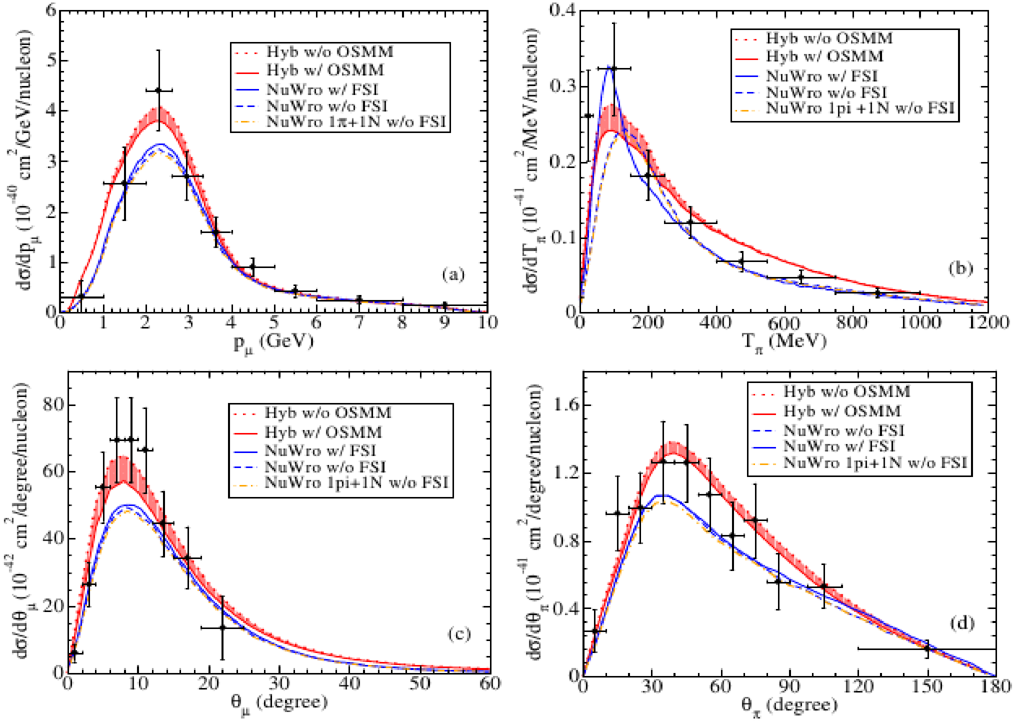
Problem: A **cross section <u>model</u>** is needed, for two reasons:

1) To get **P**$_{\alpha\rightarrow\beta}$ from the measured **N**$_\beta$.

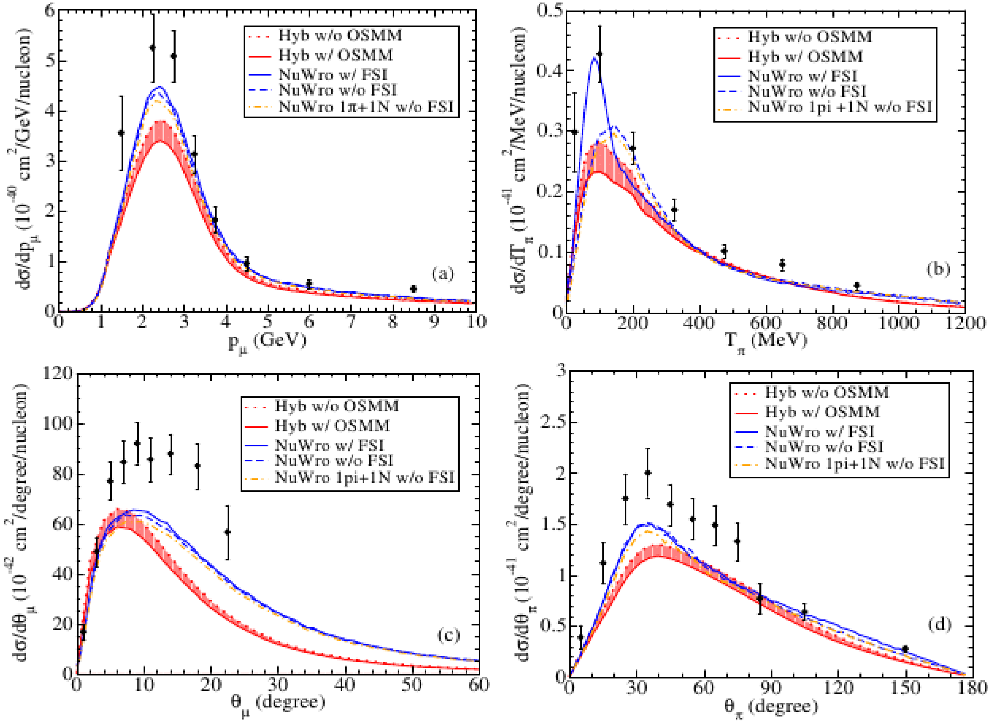
2) To reconstruct the neutrino energy.

Some model-data comparison

MINERvA antineutrino CC $1\pi^0$.



MINERvA neutrino CC $1\pi^0$.



Nikolakopoulos et al. (2018) https://doi.org/10.1103/PhysRevD.97.093008

Two-nucleon knockout processes

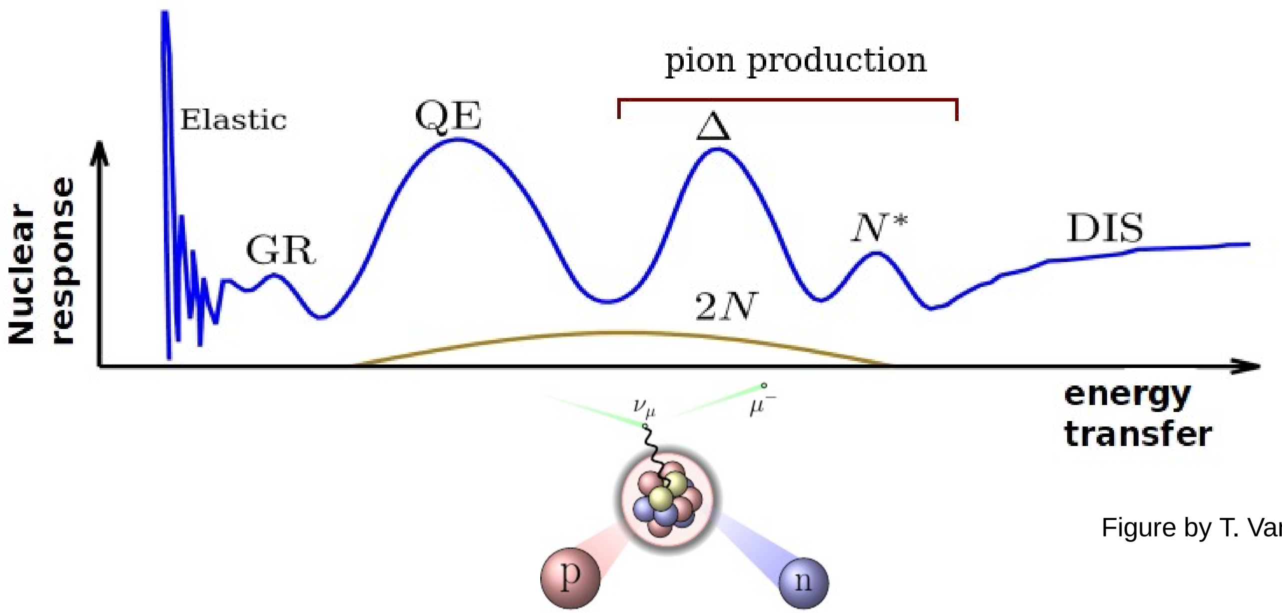
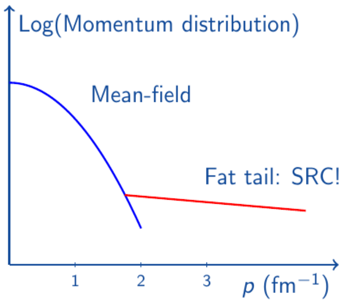


Figure by T. Van Cuyck

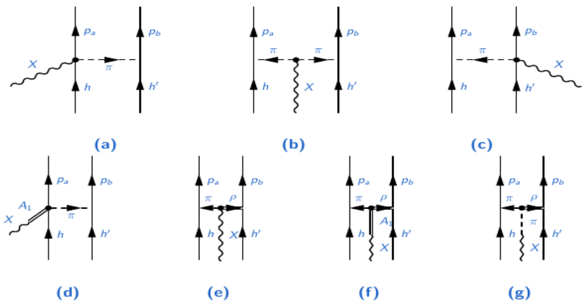
Two-nucleon knockout processes

Two mechanisms give rise to the emission of two nucleons (apart from FSI):

Short-range correlations

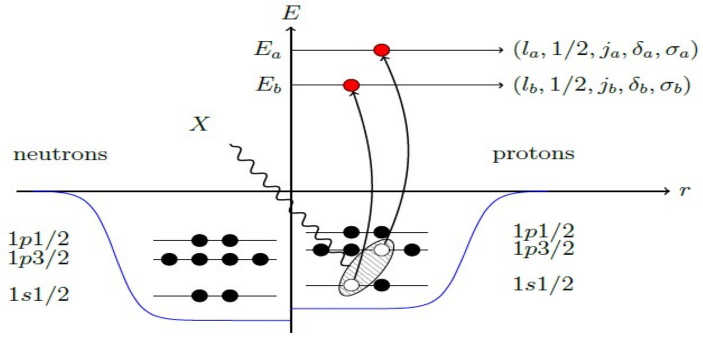


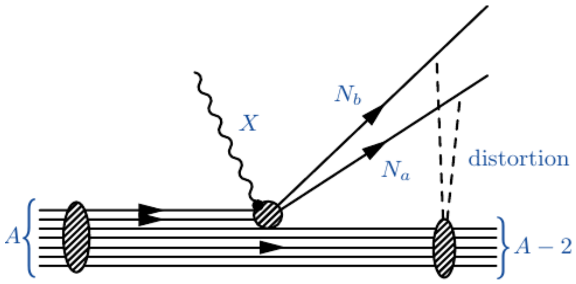
Meson-exchange currents



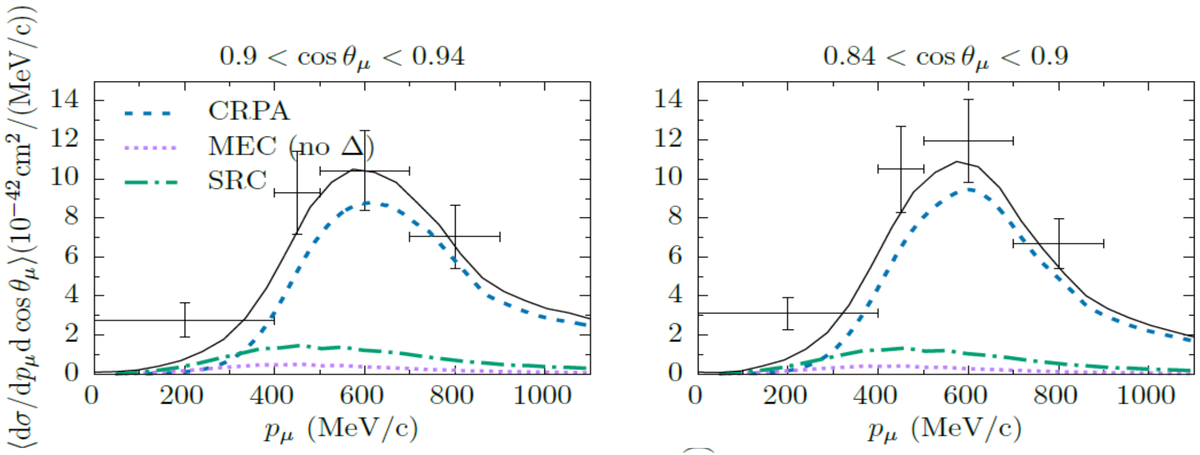
Images from T. Van Cuyck's PhD Thesis

The same **mean-field** model is used to describe the **bound and scattered nucleons**:





Short-range correlations



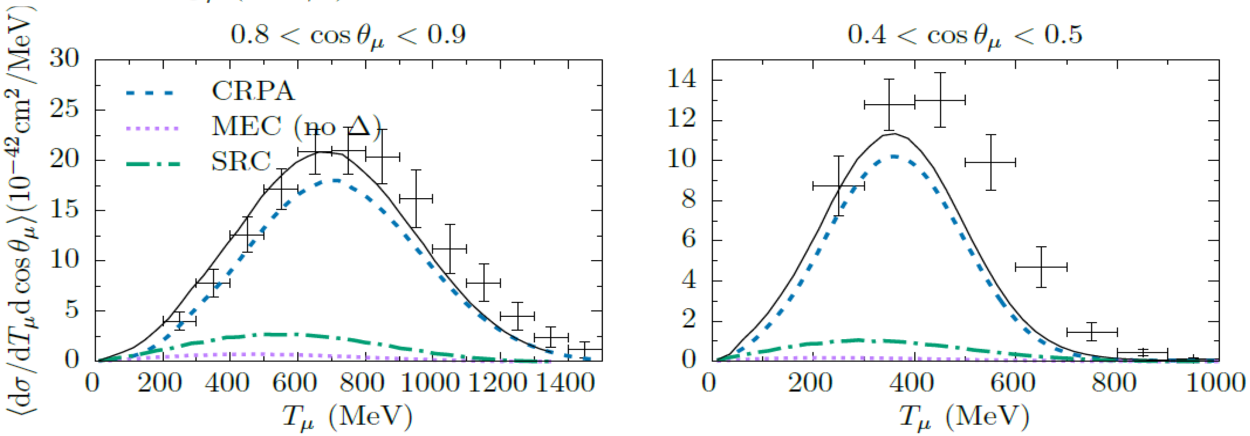
MiniBooNE

(QE-like: QE+2p2h)

T2K

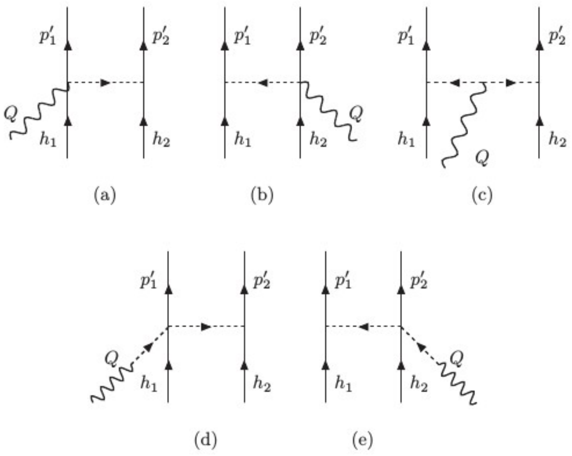
(inclusive data:
QE, 2p2h, pions, DIS)

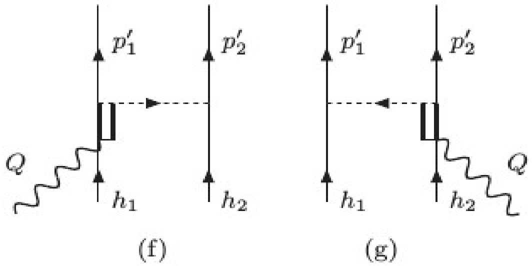
Van Cuyck et al., arXiv:1708.03723



Meson-exchanged currents

Other approaches (Superscaling coll.) consider MEC as the only contribution to the 2N-nucleon knockout responses. Fully relativistic calculation that includes both vector and axial current contributions.





Ruiz-Simo et al., arXiv:1604.08423

Meson-exchanged currents

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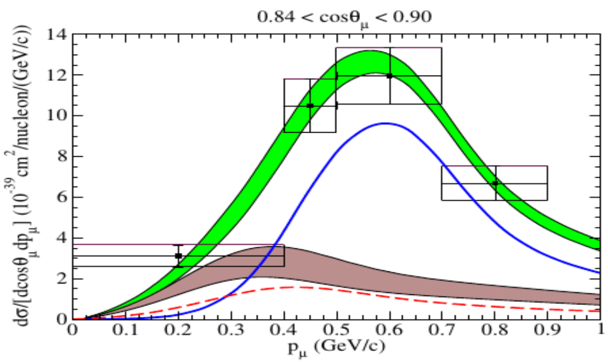
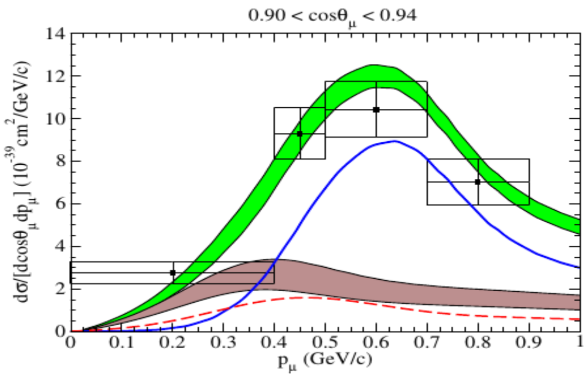
Megias et al., arXiv:1607.08565v2





T2K

(inclusive data: QE, 2p2h, pions, DIS)

MiniBooNE

(QE-like: QE+2p2h)