Neutrino interactions & cross sections

Marco Martini

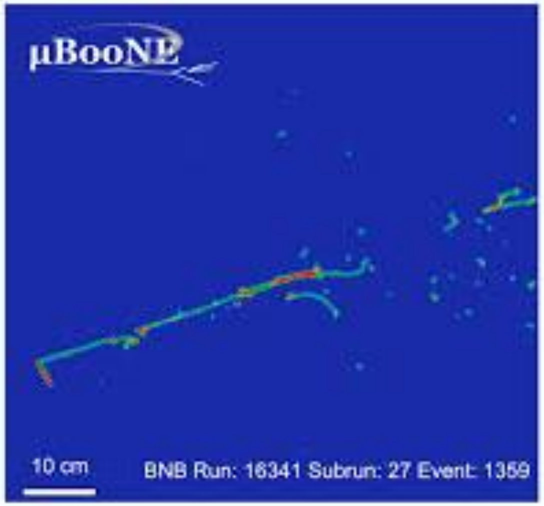
IPSA ÉCOLE D'INGÉNIEURS DE L'AIR, DE L'ESPACE ET DE LA MOBILITÉ DURABLE
SORBONNE UNIVERSITÉ
LPNHE PARIS
T2K

DUNE-France Analysis workshop #2
15 November 2023 IJCLAB

- Summary of my lectures at Ecole de GIF 2022

  [Ecole de Gif 2022: La Physique des Neutrinos (5-9 septembre 2022): Sections efficaces d'interaction de neutrinos]

- Emphasis on recent cross sections on Argon



Some Review papers

1305.7513.pdf (arxiv.org)

REVIEWS OF MODERN PHYSICS, VOLUME 84, JULY–SEPTEMBER 2012

From eV to EeV: Neutrino cross sections across energy scales

J. A. Formaggio*

Laboratory for Nuclear Science Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

G. P. Zeller†

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

1706.03621.pdf (arxiv.org)

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso [a], M. Sajjad Athar [b], M.B. Barbaro [c], D. Cherdack [d], M.E. Christy [e], P. Coloma [f], T.W. Donnelly [g], S. Dytman [h], A. de Gouvêa [i], R.J. Hill [j,f], P. Huber [k], N. Jachowicz [l], T. Katori [m], A.S. Kronfeld [f], K. Mahn [n], M. Martini [o], J.G. Morfín [f,*], J. Nieves [a], G.N. Perdue [f], R. Petti [p], D.G. Richards [q], F. Sánchez [r], T. Sato [s,t], J.T. Sobczyk [u], G.P. Zeller [f]

1611.07770.pdf (arxiv.org)

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **45** (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

2206.13792.pdf (arxiv.org)

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 129, March 2023, 104019

Review

Neutrinos and their interactions with matter

M. Sajjad Athar, A. Fatima, S.K. Singh

2108.12212.pdf (arxiv.org)

symmetry MDPI

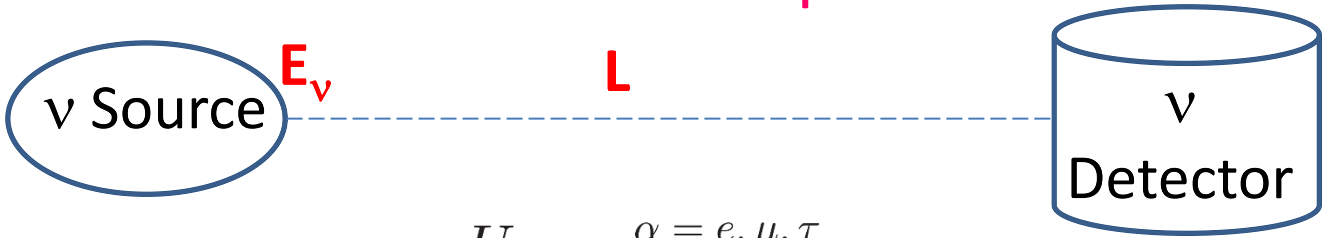
Review

A New Generation of Neutrino Cross Section Experiments: Challenges and Opportunities

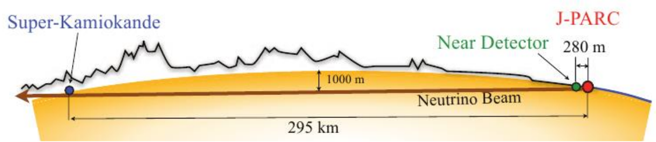
Antonio Branca [1,*], Giulia Brunetti [1], Andrea Longhin [2,3], Marco Martini [4,5], Fabio Pupilli [3] and Francesco Terranova [1]

Neutrino oscillation experiments

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



$$\nu_\alpha = U_{\alpha i}\nu_i \quad \alpha = e, \mu, \tau \quad i = 1, 2, 3$$



Reconstructed ν energy

True ν energy

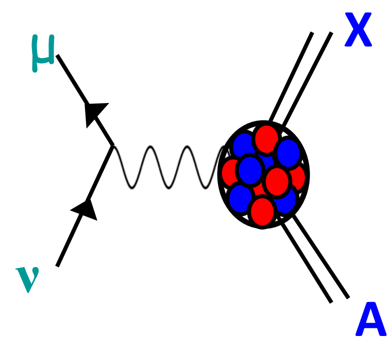
$$N_{\nu_\beta}(\overline{E_\nu}) \sim \int \Phi_{\nu_\alpha}(E_\nu) P_{\nu_\alpha \rightarrow \nu_\beta}(E_\nu, L, \{\Theta\}) \sigma_{\nu_\beta}(E_\nu) \epsilon_{\rm det.} d(E_\nu, \overline{E_\nu}) dE_\nu$$

Number of detected events

ν flux	ν oscillation probability	ν cross section	Detector efficiency	Migration matrix

Modern accelerator-based neutrino oscillation experiments:

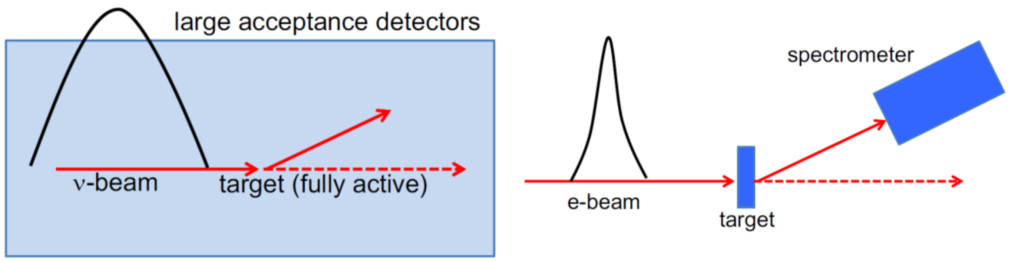
- The neutrino energy is reconstructed from the final states
- Nuclear targets (C, O, Ar, Fe…)

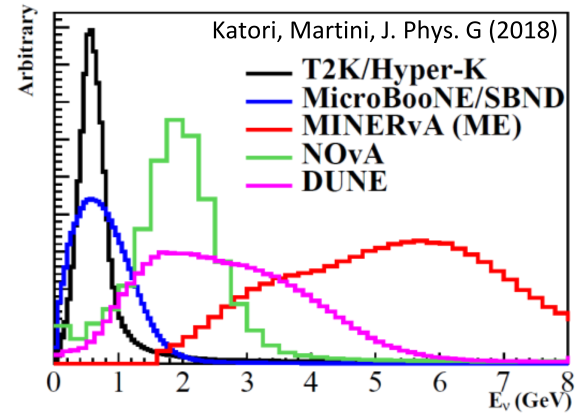


→ the knowledge of the neutrino-nucleus cross section is crucial

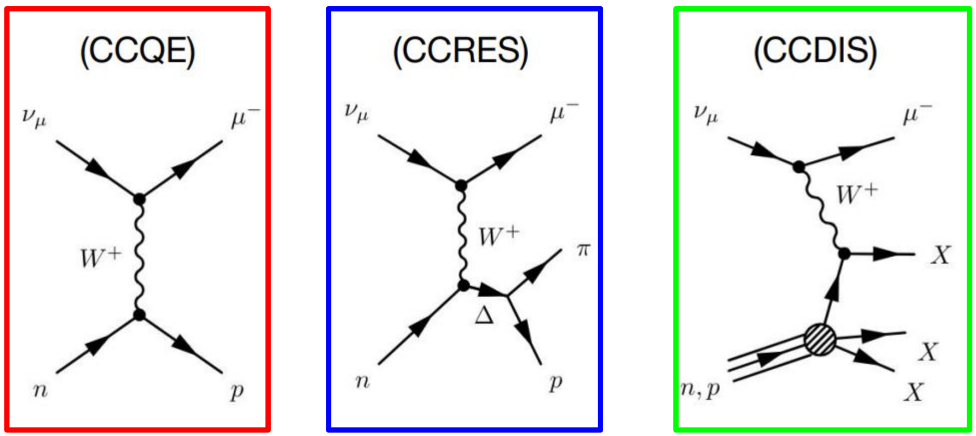
Some important points of the accelerator-based ν experiment

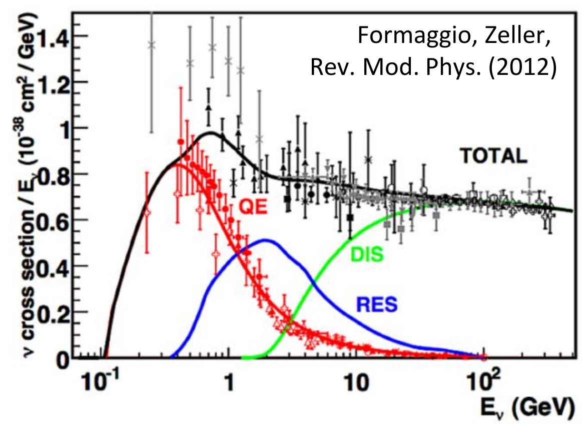
- Neutrino beams are not monochromatic
(at difference with respect to electron beams)



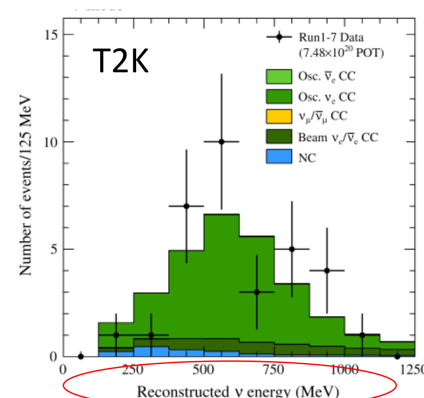


- Different reaction mechanisms contribute

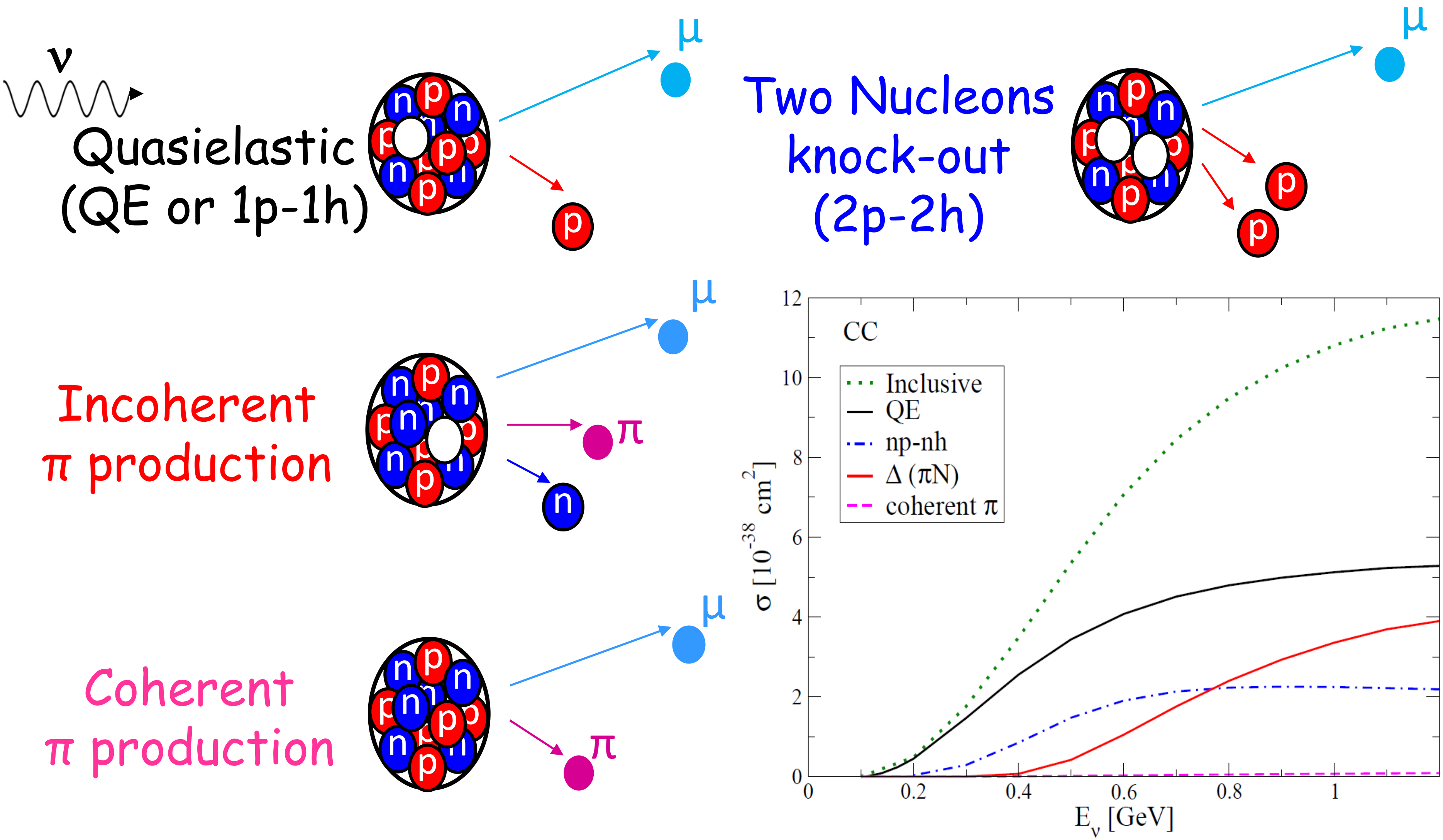




- The neutrino energy is reconstructed
from the final states of the reaction
(often from CCQE events)



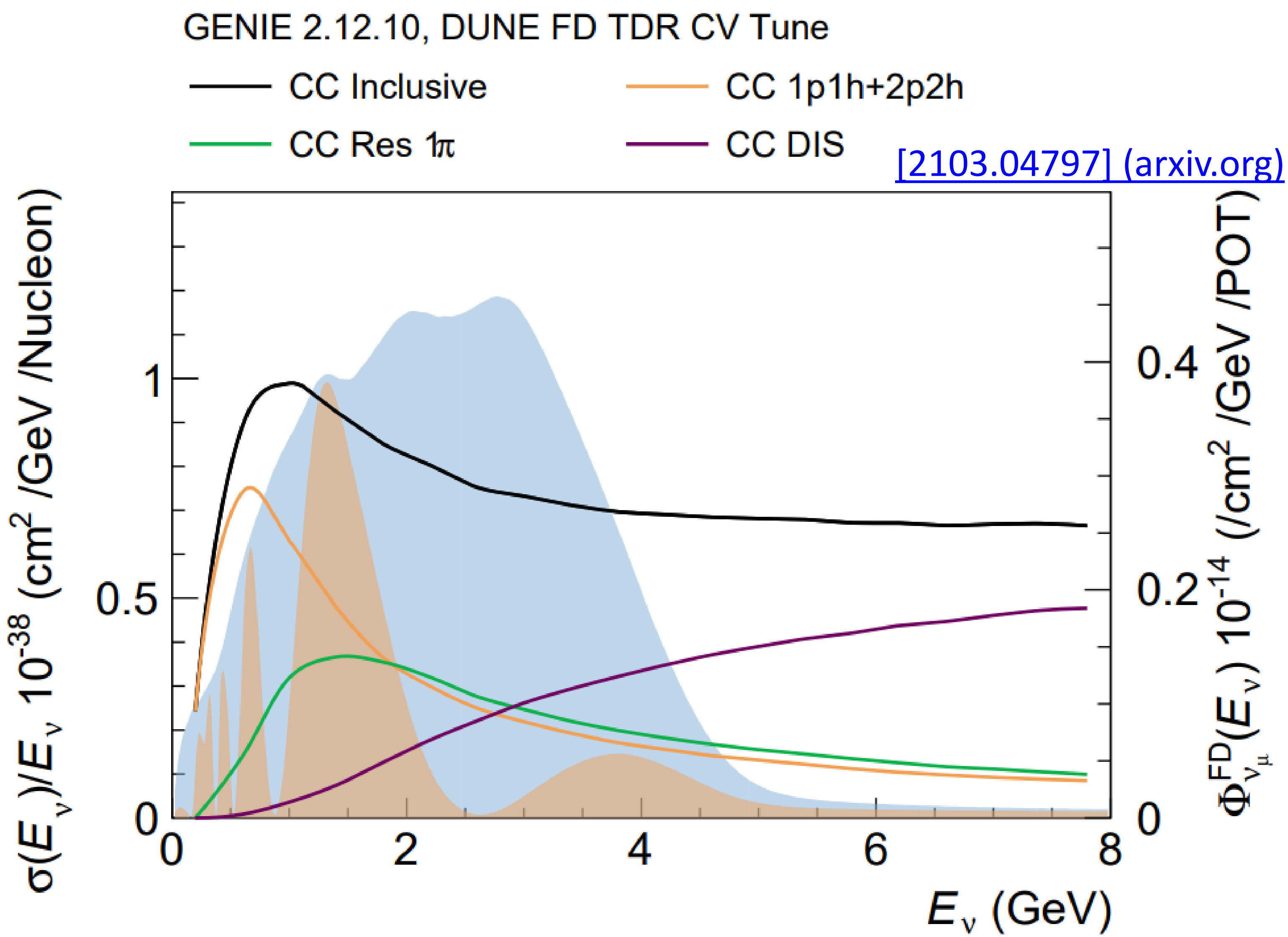
In this talk: Neutrino - nucleus interaction @ $E_\nu \sim O(1\ \text{GeV})$



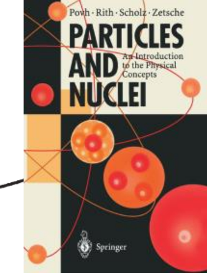
Different processes are entangled

DUNE unoscillated and oscillated ν_μ fluxes ϕ and cross sections σ in different channels

[2103.04797] (arxiv.org)

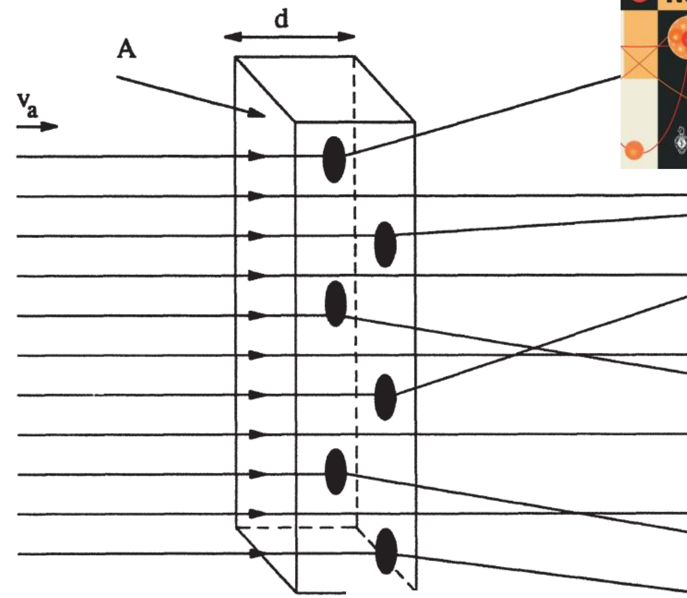


Cross Section generalities - textbook definitions



- **Definition**: The Cross Section is a measure for the probability of a process to happen
- **Dimensions**: Area

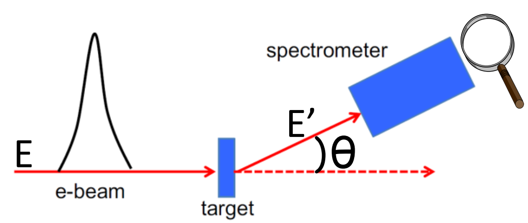
$$\mathrm{a} + \mathrm{b} \;\rightarrow\; \mathrm{a}' + \mathrm{b}^*$$



$$\Phi_a = \frac{\dot{N}_a}{A} = n_a \cdot v_a \qquad N_b = n_b\, A d$$

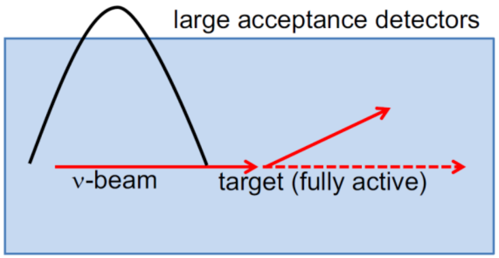
$$\sigma_b = \frac{\dot{N}}{\Phi_a \cdot N_b}$$

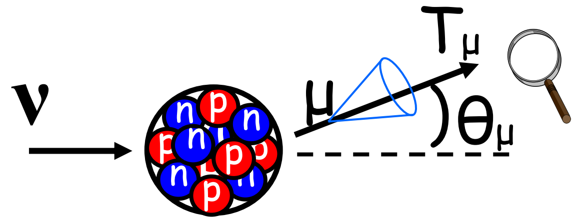
$$= \frac{\text{number of reactions per unit time}}{\text{beam particles per unit time per unit area} \times \text{scattering centres}}$$

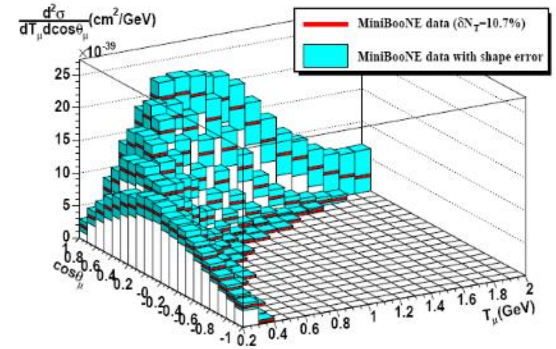


$$\sigma_{tot}(E) = \int_0^{E'_{max}} \int_{4\pi} \frac{d^2\sigma(E, E', \theta)}{d\Omega\, dE'}\, d\Omega\, dE'$$

Neutrino flux integrated double differential cross sections







Flux-integrated differential cross section is where theorists and experimentalists meet for ν interaction

Theory

$$\frac{d^2\sigma}{dT_l \ d\cos\theta} = \frac{1}{\int \Phi(E_\nu) \ dE_\nu} \int \ dE_\nu \left[\frac{d^2\sigma}{d\omega \ d\cos\theta} \right]_{\omega = E_\nu - E_l} \Phi(E_\nu)$$

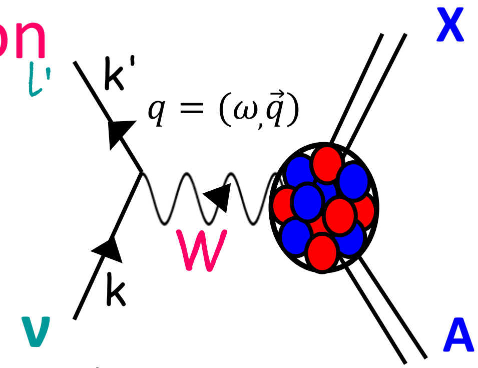
Experimental Definition

$$\left(\frac{d^2\sigma}{dT_l \cos\theta} \right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \epsilon_i \cdot (\Delta T_l, \Delta\cos\theta)_i}$$

- U_{ij}: Unfolding matrix to remove detector effects
- d_j: Number of observed events
- b_j: Background contribution
- Φ: Total integrated flux
- T: Number of target nucleons in the Fiducial Volume
- ϵ_i: Efficiency
- $(\Delta T_l, \Delta\cos\theta)_i$: Bin widths

Charged current neutrino-nucleus cross section

$$\nu_l\ (\bar{\nu}_l) + A \longrightarrow l^-\ (l^+) + X$$



$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \cos\theta_C l_\mu J^\mu$$

Frow weak Lagrangian to cross section in terms of **Leptonic** **and Hadronic tensors** *(see for example the GIF lectures)*

Lab frame

$$\frac{d^2\sigma}{d\Omega_{k'} d\omega} = \frac{G_F^2 \cos^2\theta_C}{4\pi^2} \frac{|\mathbf{k}'|}{|\mathbf{k}|} L_{\mu\nu} W^{\mu\nu}(\mathbf{q}, \omega)$$

$d\Omega_{k'}$ differential solid angle in the direction specified by the charged-lepton momentum **k'**

$k \equiv (E_\nu, \mathbf{k})$ $k' \equiv (E'_l, \mathbf{k}')$ — initial and final lepton 4-momenta

$q = k - k' \equiv (\omega, \mathbf{q})$ — four-momentum transfer

$\omega = E_\nu - E'_l$ — energy transfer

$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda$$

Leptonic tensor

$$W^{\mu\nu} = \sum_f \langle 0|J^{\mu\dagger}(q)|f\rangle\langle f|J^\nu(q)|0\rangle \delta^{(4)}(p_0 + q - p_f)$$

Hadronic tensor

The charged current cross section is a linear combination of five contributions

$$\frac{d^2\sigma}{d\Omega_{k'} d\omega} = \sigma_0 \left[L_{00} W^{00} + L_{33} W^{33} + (L_{03} + L_{30}) W^{03} + (L_{11} + L_{22}) W^{11} \pm (L_{12} - L_{21}) W^{12}\right]$$

A simplified expressions particularly useful for illustration

- Final lepton mass contributions ignored (m_l=0)
- Obtained by keeping only the leading terms for the hadronic tensor in the development of the hadronic current in p/M_N

$$\frac{d^2\sigma}{d\cos\theta d\omega} = \frac{G_F^2\cos^2\theta_c}{\pi}|\mathbf{k}'|E_l'\cos^2\frac{\theta}{2}\left[\frac{(\mathbf{q}^2-\omega^2)^2}{\mathbf{q}^4}G_E^2 R_\tau(\mathbf{q},\omega) + \frac{\omega^2}{\mathbf{q}^2}G_A^2 R_{\sigma\tau(L)}(\mathbf{q},\omega)\right.$$

$$\left. + 2\left(\tan^2\frac{\theta}{2}+\frac{\mathbf{q}^2-\omega^2}{2\mathbf{q}^2}\right)\left(G_M^2\frac{\mathbf{q}^2}{4M_N^2}+G_A^2\right)R_{\sigma\tau(T)}(\mathbf{q},\omega) \pm 2\frac{E_\nu+E_l'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}(\mathbf{q},\omega)\right]$$

Explicitly appear:

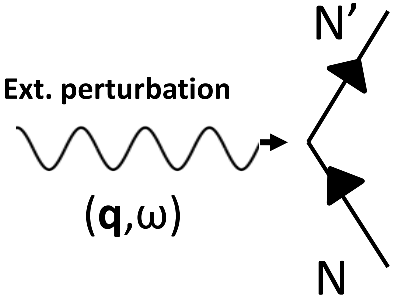
1. The different **kinematic variables** (related to the leptonic tensor)
2. The nucleon Electric, Magnetic, and Axial **form factors** (↔ nucleon properties)
3. The **nuclear response functions** (↔ nuclear dynamics)

Nuclear response functions R(q,ω):

$$R_\alpha^{PP'}(\mathbf{q},\omega) = \sum_n \langle n|\sum_{j=1}^{A} O_\alpha^P(j)\, e^{i\,\mathbf{q}\cdot\mathbf{x}_j}|0\rangle\langle n|\sum_{k=1}^{A} O_\alpha^{P'}(k)\, e^{i\,\mathbf{q}\cdot\mathbf{x}_k}|0\rangle^*\,\delta(\omega - E_n + E_0),$$

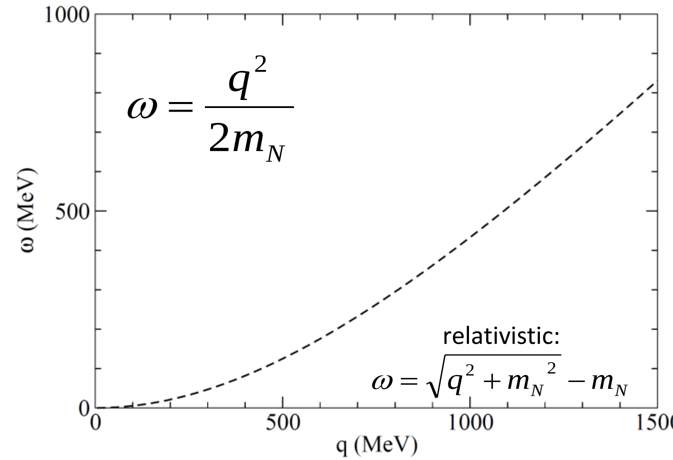
Isovector R_τ	Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$	Isospin Spin-Transverse $R_{\sigma\tau(T)}$
$O_\alpha^N(j) = \tau_j^\pm$	$(\boldsymbol{\sigma}_j\cdot\hat{q})\,\tau_j^\pm$	$(\boldsymbol{\sigma}_j\times\hat{q})^i\,\tau_j^\pm$

Free (or bare) nuclear response function



- **Free nucleon at rest:**

  Response functions $\propto \delta(\omega - q^2/2m_N)$



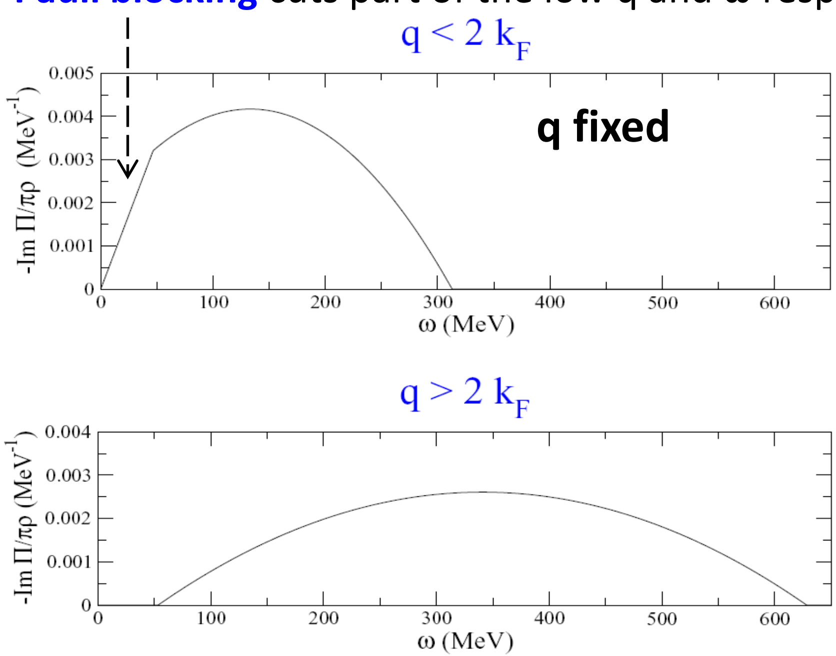
- **Nucleon inside the nucleus:**

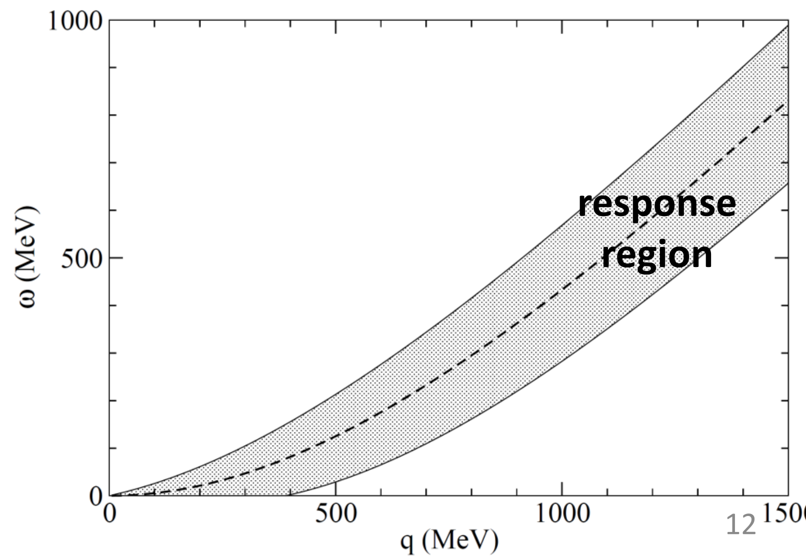
Nucleon-Nucleon interaction switched off ↔ Nucleons respond individually

Fermi Gas Quasielastic Response

- **Fermi motion** spreads δ distribution
- **Pauli blocking** cuts part of the low q and ω response

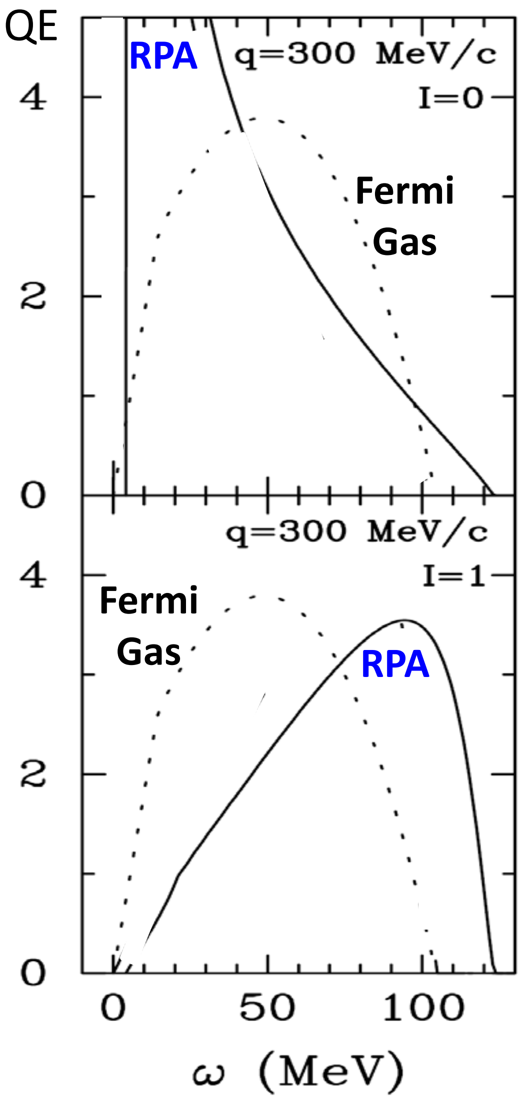
$$\frac{q^2}{2m_N} - \frac{qk_F}{m_N} \le \omega \le \frac{q^2}{2m_N} + \frac{qk_F}{m_N}$$



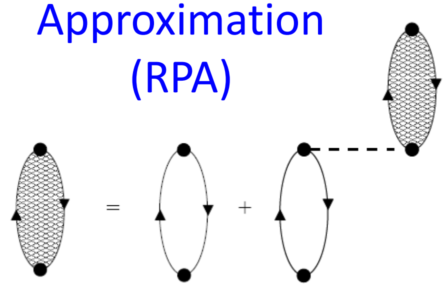


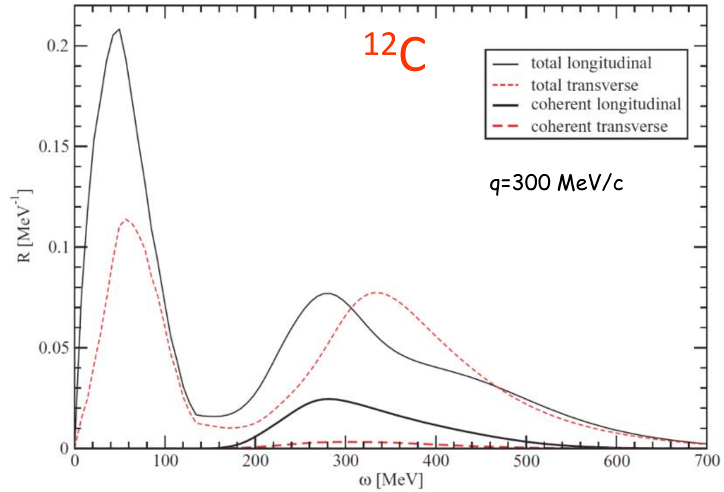
Switching on the nucleon-nucleon interaction

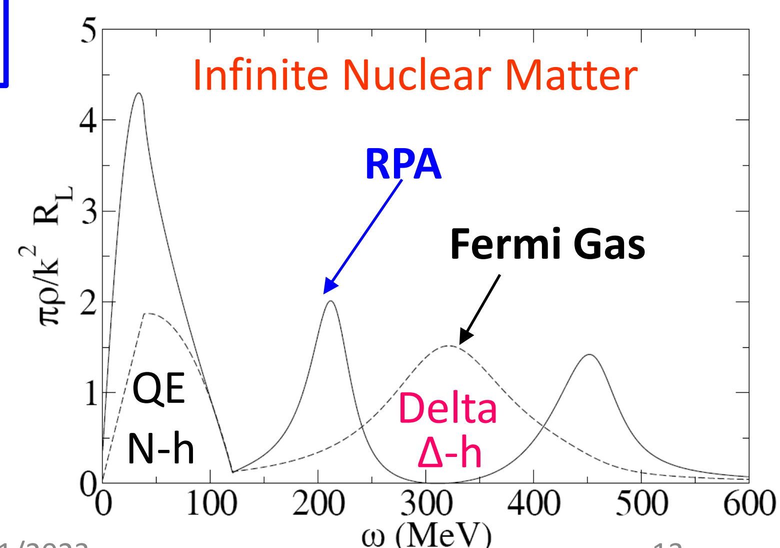
- External force acting on one nucleon is transmitted to the neighbors by the interaction – **Long Range Correlations**
- The nuclear response becomes collective
- Shift of the peak with respect to Fermi Gas, decrease, increase depending on the channels of excitation



Random Phase Approximation (RPA)



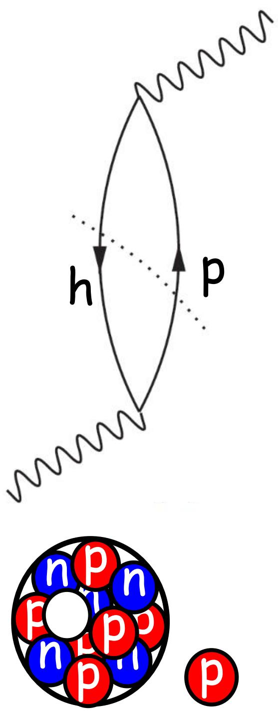




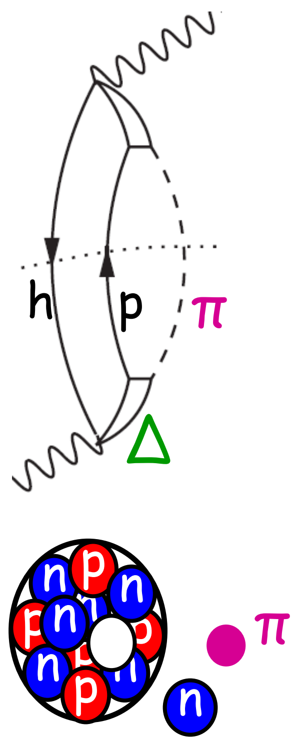
Nuclear Responses for different excitations

$$R_\alpha = \sum_{n \neq 0} |\langle n | \hat{O}_{(\alpha)} | 0 \rangle|^2 \; \delta[\omega - (E_n - E_0)]$$

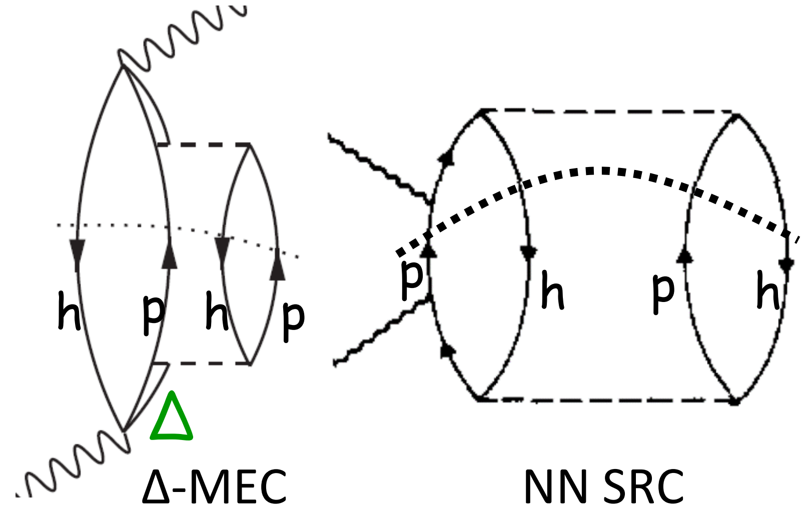
1p-1h
Quasielastic

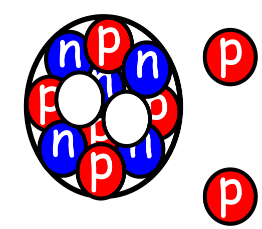


1p-1h
(Δ→πN) 1π production

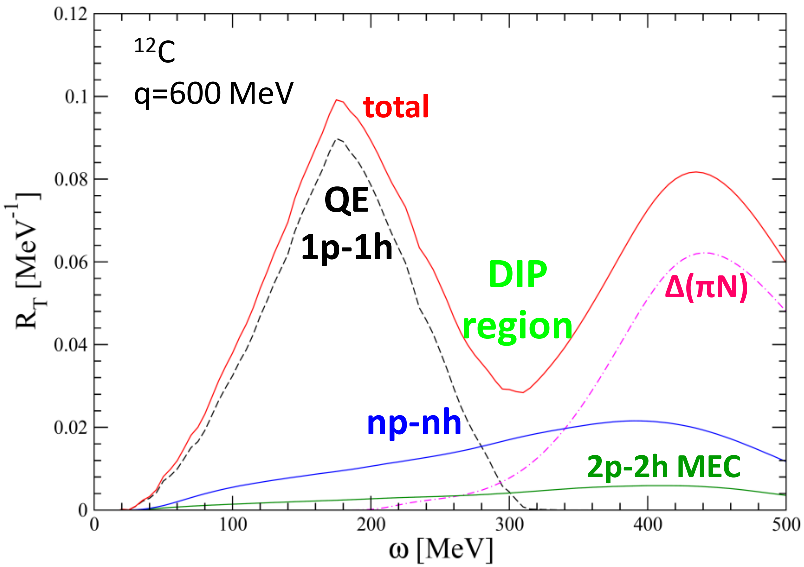


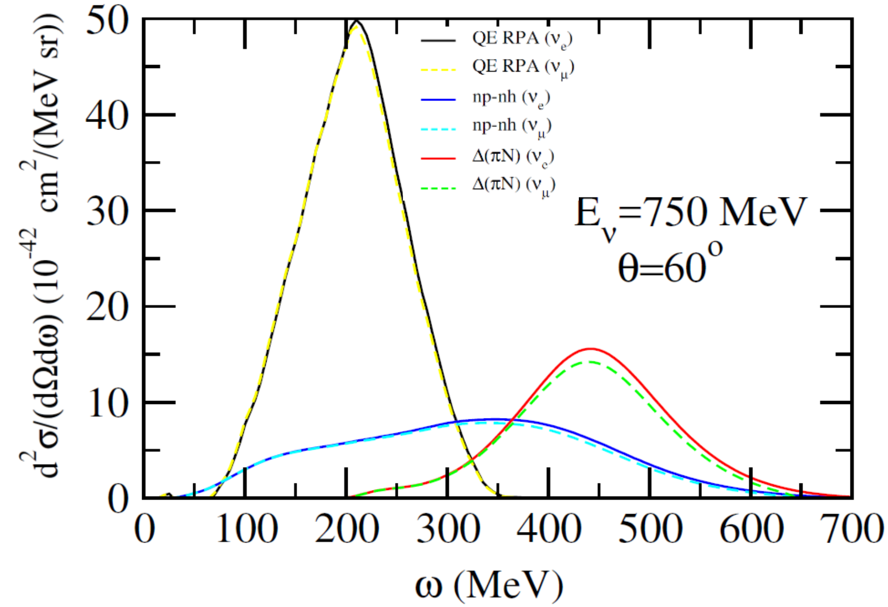
2p-2h:
two examples

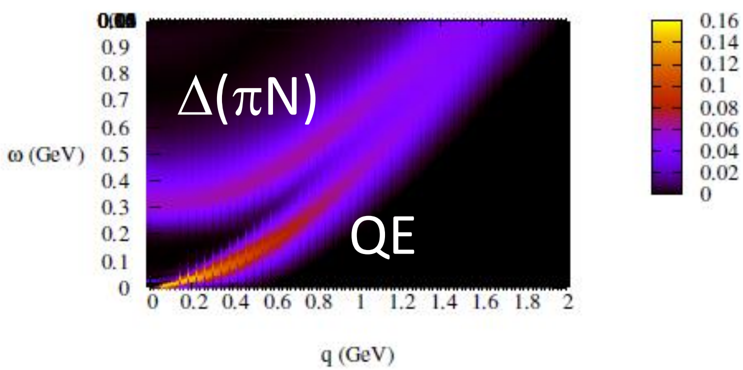


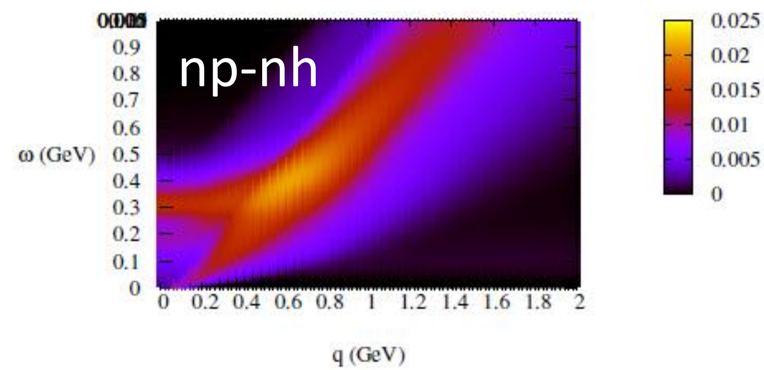


Nuclear responses and neutrino cross sections at fixed kinematics









QE peak:

$$\omega = \sqrt{\mathbf{q}^2 + M_N^2} - M_N = \frac{Q^2}{2M_N} = \frac{\mathbf{q}^2 - \omega^2}{2M_N}$$

Δ peak:

$$\omega = \sqrt{\mathbf{q}^2 + M_\Delta^2} - M_N = \frac{Q^2}{2M_N} + \frac{M_\Delta^2 - M_N^2}{2M_N}$$

np-nh excitations fill the DIP region

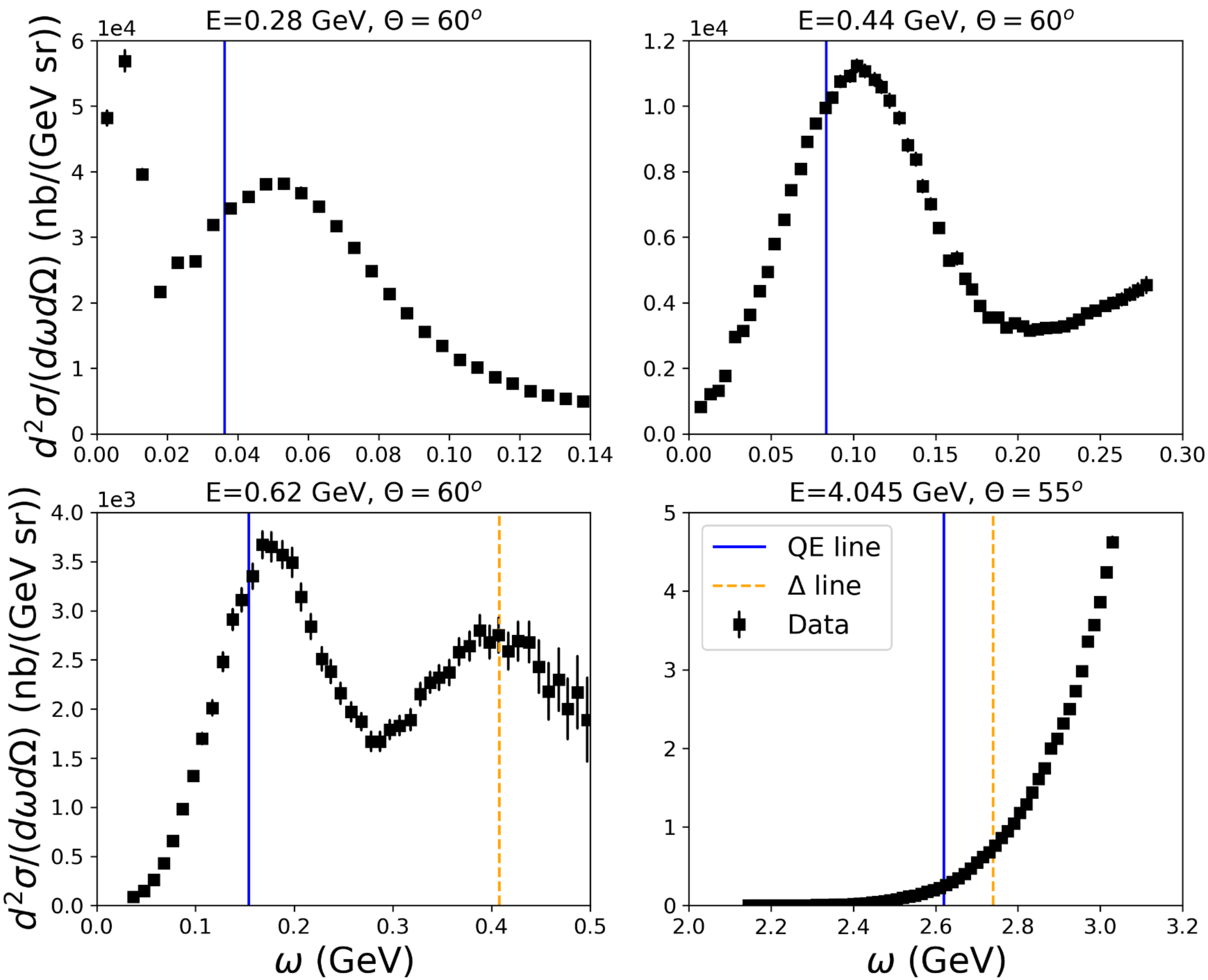
np-nh enlarges the region of response to the whole (ω,q) plane

N.B. The responses can be tested in other processes (scattering of e, π…)

Examples of electron scattering cross section on ^{12}C

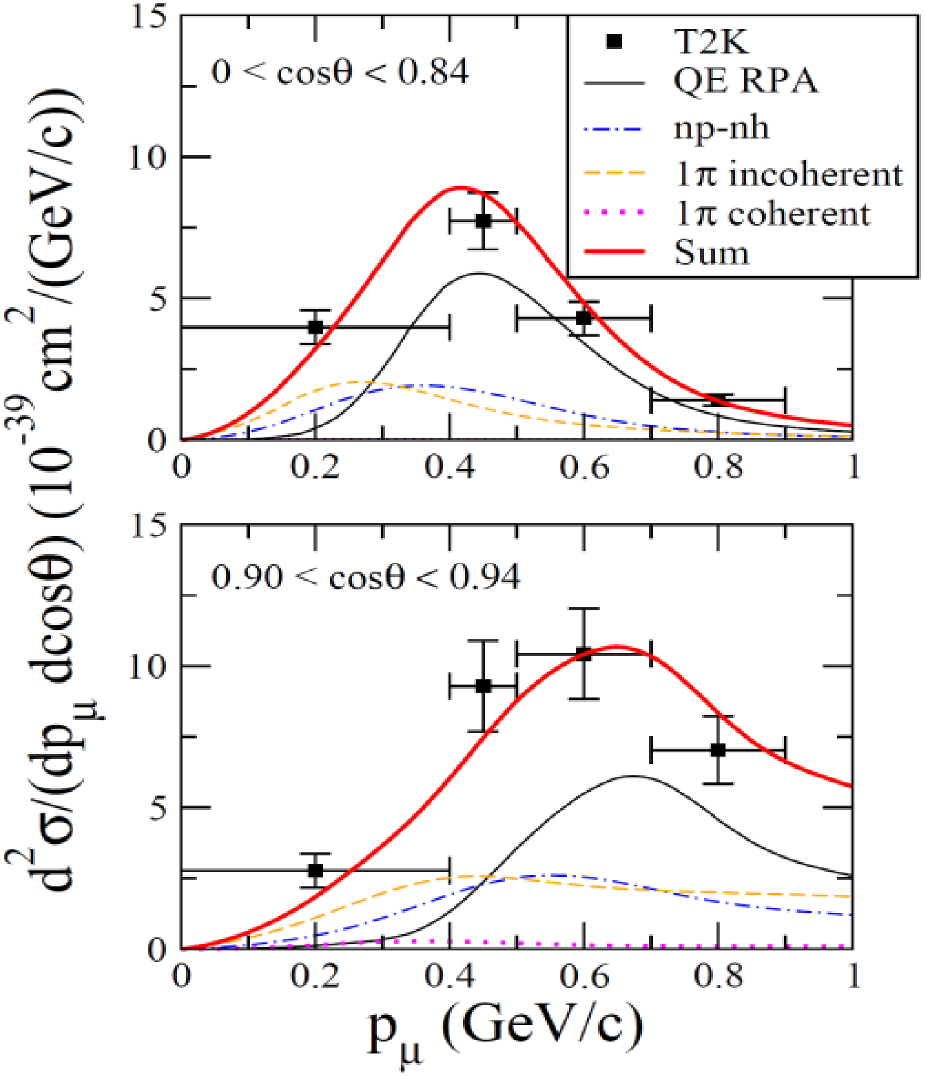
Remind: monochromatic beam

$$\omega_{QE} = \frac{E^2(1-\cos\theta)}{M_N + E(1-\cos\theta)} \qquad \omega_\Delta = \frac{M_N \Delta M + E^2(1-\cos\theta)}{M_N + E(1-\cos\theta)},$$

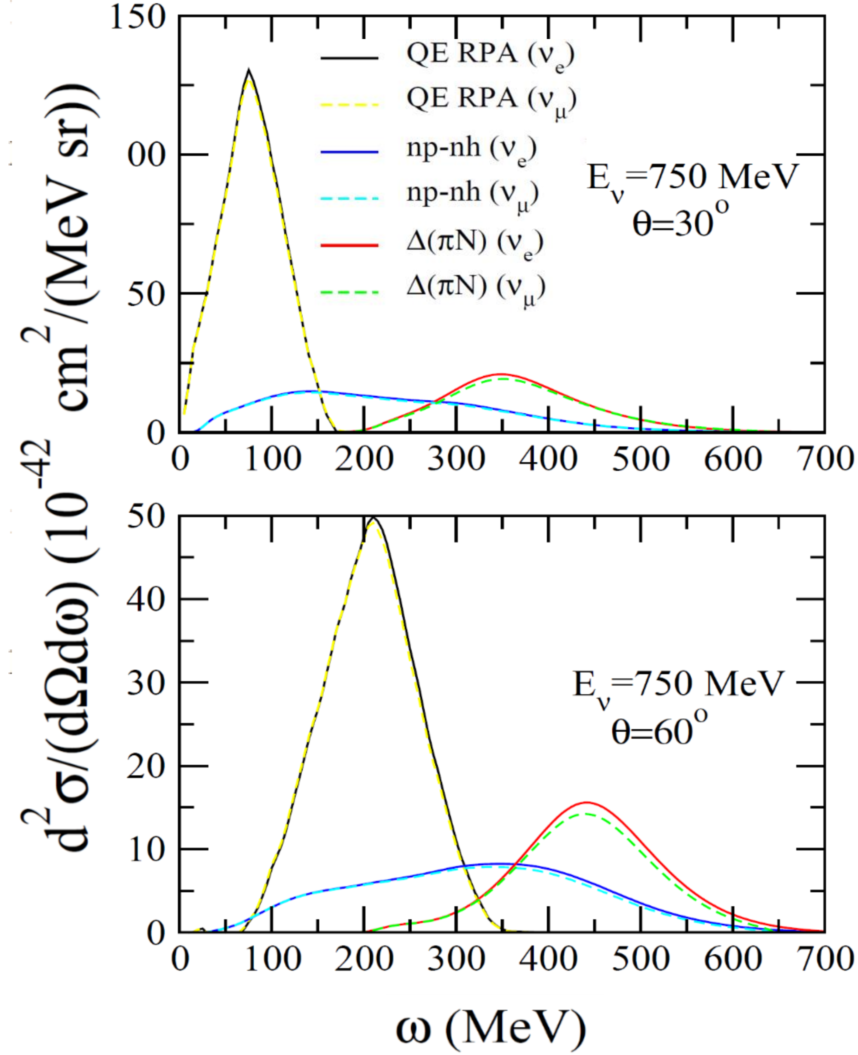


Remark: flux-integrated .vs. monochromatic beam cross sections

Neutrino flux-integrated d2σ



Monochromatic d2σ

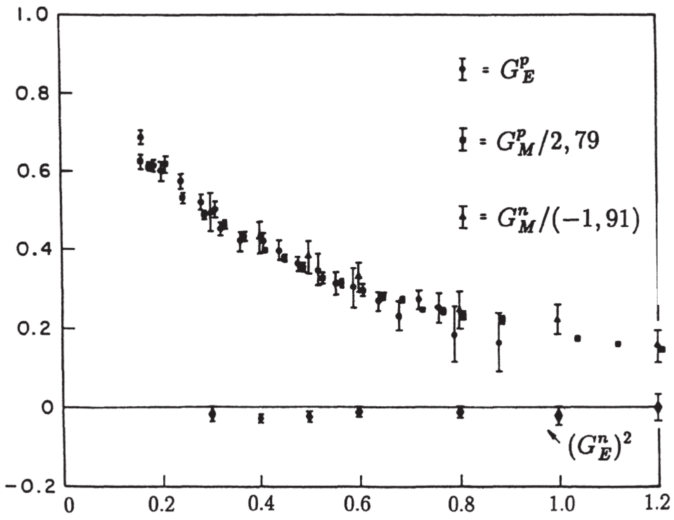


In the flux-integrated cross sections the different channels are entangled

The Form Factors

$$\frac{d^2\sigma}{d\cos\theta d\omega} = \frac{G_F^2\cos^2\theta_c}{\pi}|\mathbf{k}'|E_l'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2 R_\tau + \frac{\omega^2}{q^2}G_A^2 R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\frac{\epsilon+\epsilon'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}\right]$$

Vector form factors



$$G_E^p(Q^2) = \frac{G_M^p(Q^2)}{2.79} = \frac{G_M^n(Q^2)}{-1.91} = G^{\text{dipole}}(Q^2)$$

$$G^{\text{dipole}}(Q^2) = \left(1+\frac{Q^2}{0.71\,(\mathrm{GeV}/c)^2}\right)^{-2}$$

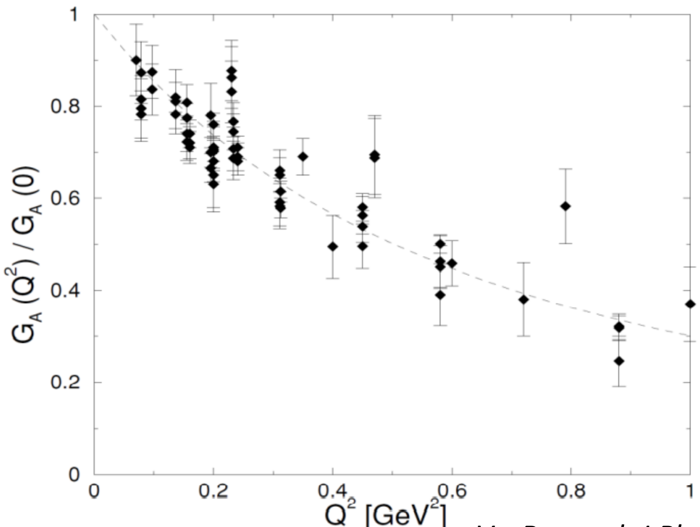
$$Q^2 = q^2 - \omega^2$$

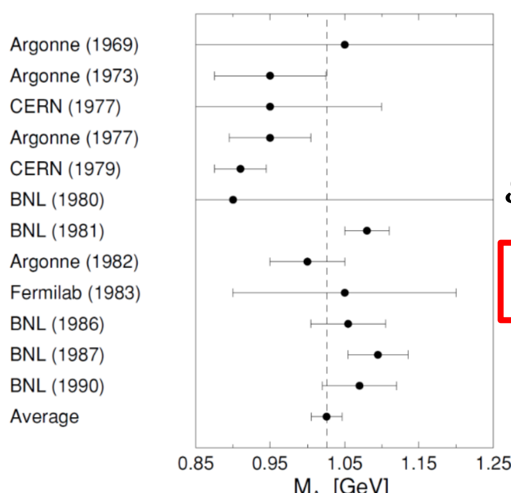
Global **dipole**-like behavior

Weak **vector form factors** are well constrained by electron scattering experiments (CVC)

Q^2 evolution of the **axial form factor** is less well-known, mainly based on old bubble chamber data

Axial form factor





V. . Bernard, J.Phys. G28 (2002) R1-R35

$$G_A(Q^2) = g_A(1+Q^2/M_A^2)^{-2}$$

$g_A = 1.26$ from neutron β decay

$$M_A = (1.026 \pm 0.021)\quad GeV/c^2$$

from ν-^{2}H (bubble-chamber) CCQE
and
from π electroproduction

CCQE, CCQE-like and CC0π

MiniBooNE CC Quasielastic cross section on Carbon and the M_A puzzle

First Measurement of Muon Neutrino Charged Current Quasielastic (CCQE) Double Differential Cross Section

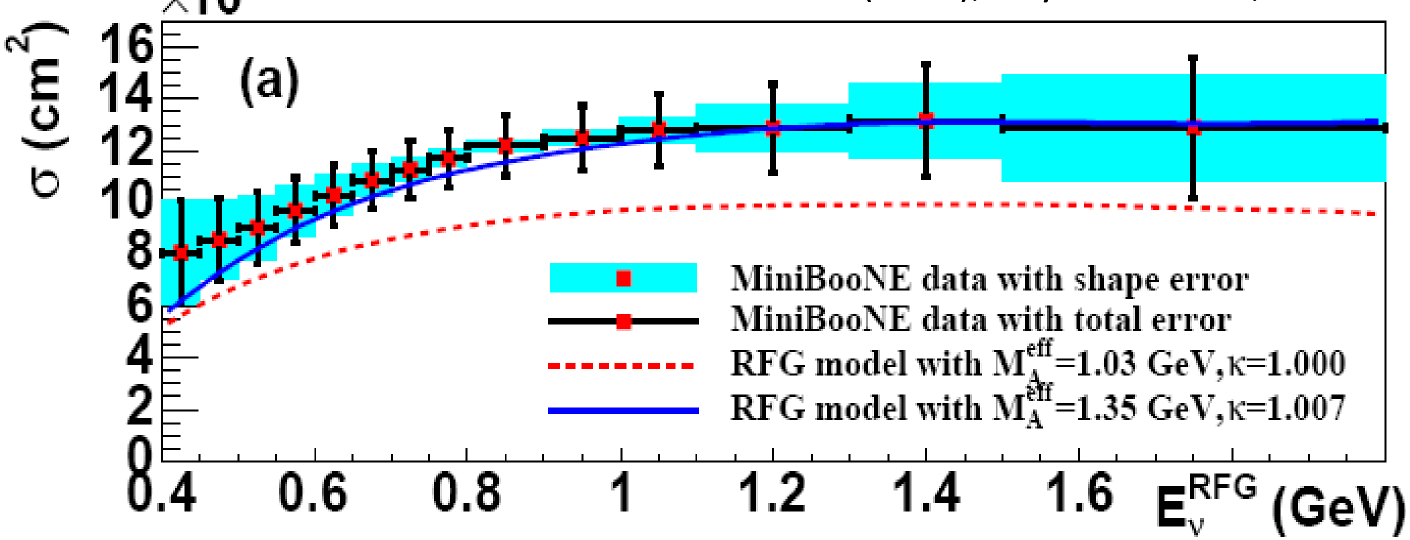
Cite as: AIP Conference Proceedings **1189**, 139 (2009); https://doi.org/10.1063/1.3274144
Published Online: 02 December 2009

Teppei Katori and MiniBooNE collaboration

PHYSICAL REVIEW D **81**, 092005 (2010)

First measurement of the muon neutrino charged current quasielastic double differential cross section

AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)



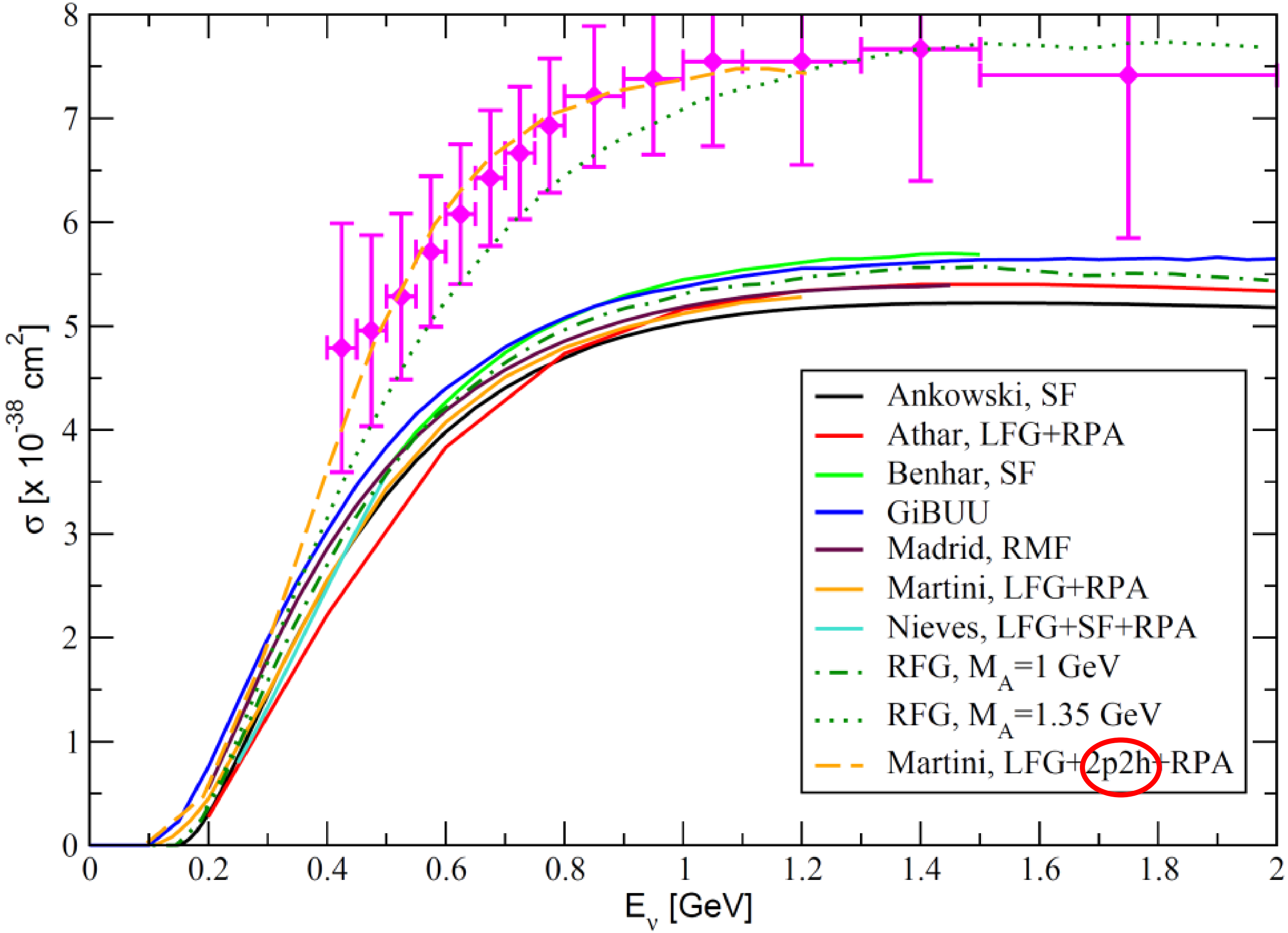
Comparison with a prediction based on Relativistic Fermi Gas (**RFG**) using **M_A=1.03 GeV** (standard value) reveals a discrepancy

In the Relativistic Fermi Gas (RFG) model an axial mass of **1.35 GeV** is needed to account for data

puzzle??

Comparison of different theoretical models for Quasielastic

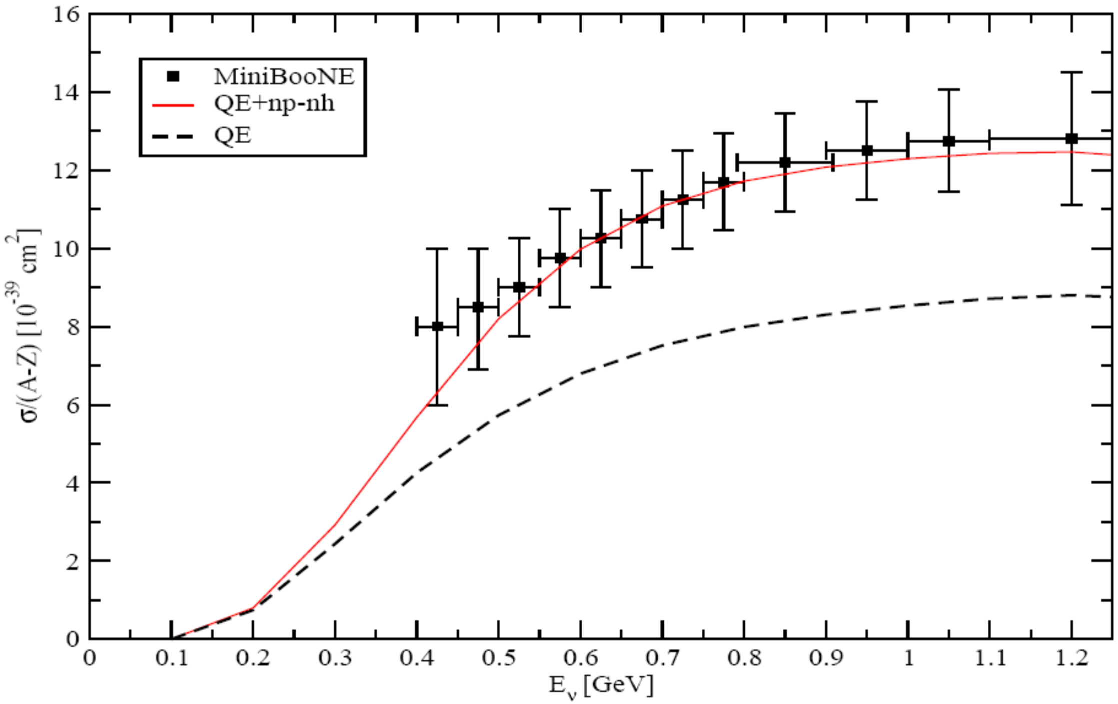
L. Alvarez-Ruso , arXiv:1012.3871 (Neutrino 2010)

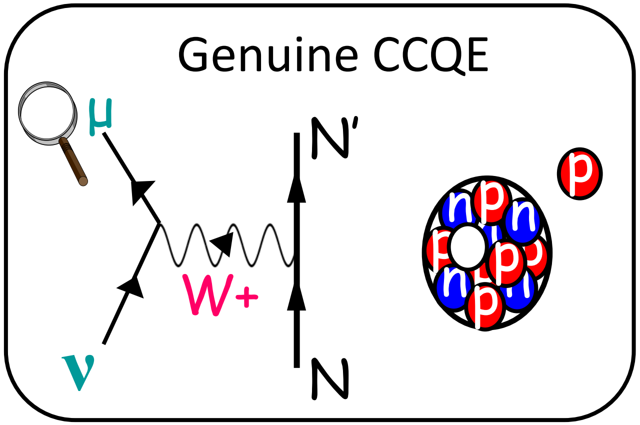


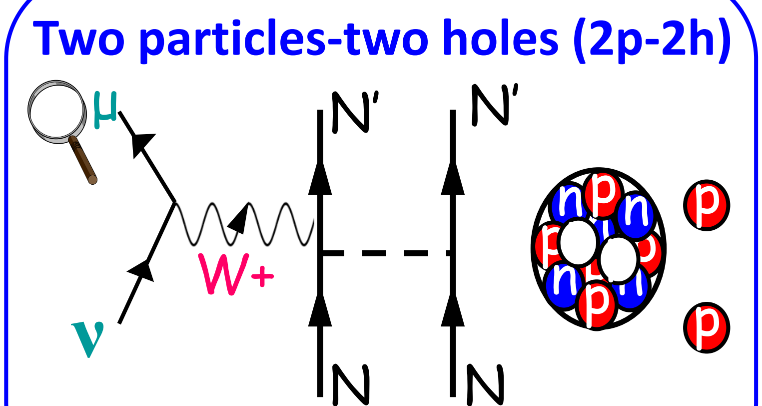
puzzle??

An explanation of this puzzle

Inclusion of the multinucleon emission channel
(np-nh = 2p-2h + 3p-3h)







CCQE-like = Genuine CCQE + np-nh

M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

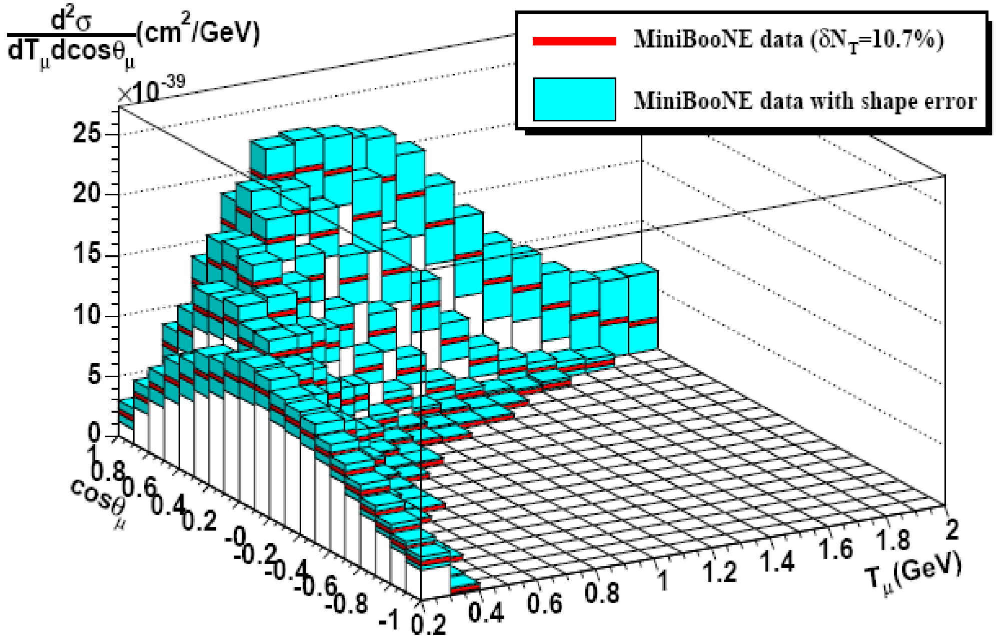
⇒ MiniBooNE measured CCQE-like, not genuine CCQE

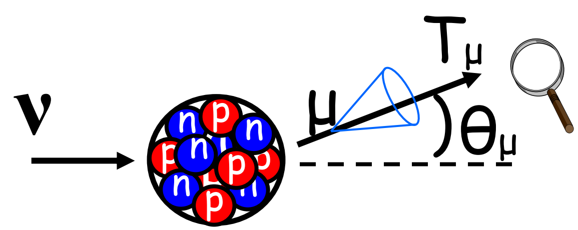
Flux-integrated double differential cross section

$$\left(\frac{d^2\sigma}{dT_l \cos\theta}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \epsilon_i \cdot (\Delta T_l, \Delta\cos\theta)_i}$$ (see slide 9)

PHYSICAL REVIEW D **81**, 092005 (2010)

First measurement of the muon neutrino charged current quasielastic double differential cross section





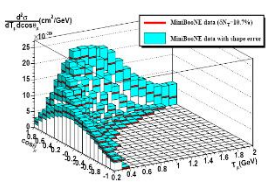
- Function of two measured variables
- Less model dependent than $\sigma(E_\nu)$: free from the neutrino energy reconstruction problem (see later)
- Flux dependent

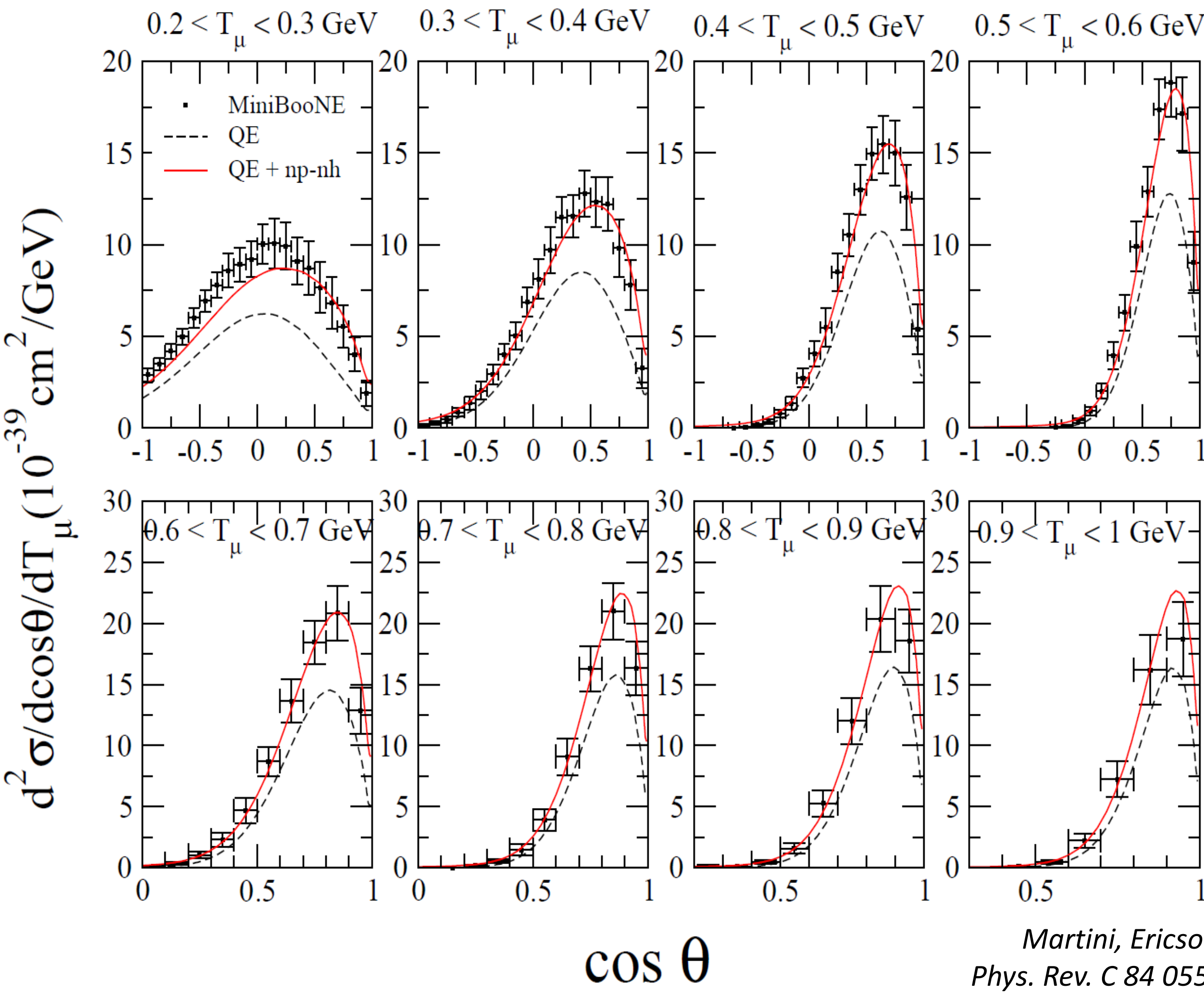
Flux-integrated differential cross section is where theorists and experimentalists meet for ν interaction

MiniBooNE CCQE-like flux-integrated double differential cross section

$$\frac{d^2\sigma}{dT_l\ d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\ dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\ d\cos\theta}\right]_{\omega=E_\nu - E_l} \Phi(E_\nu)$$

ν

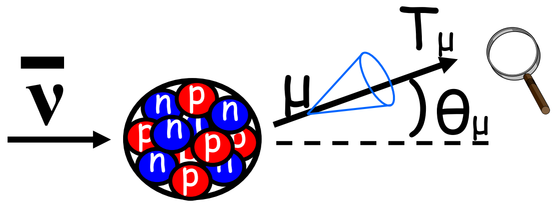




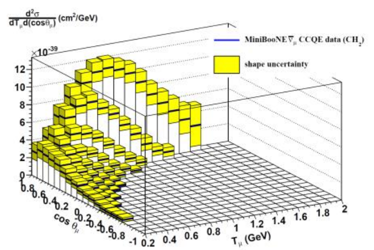
Martini, Ericson, Chanfray,
Phys. Rev. C 84 055502 (2011)

- Good agreement with data once multinucleon contributions are included
- Similar conclusions obtained by different theoretical calculations (see later)

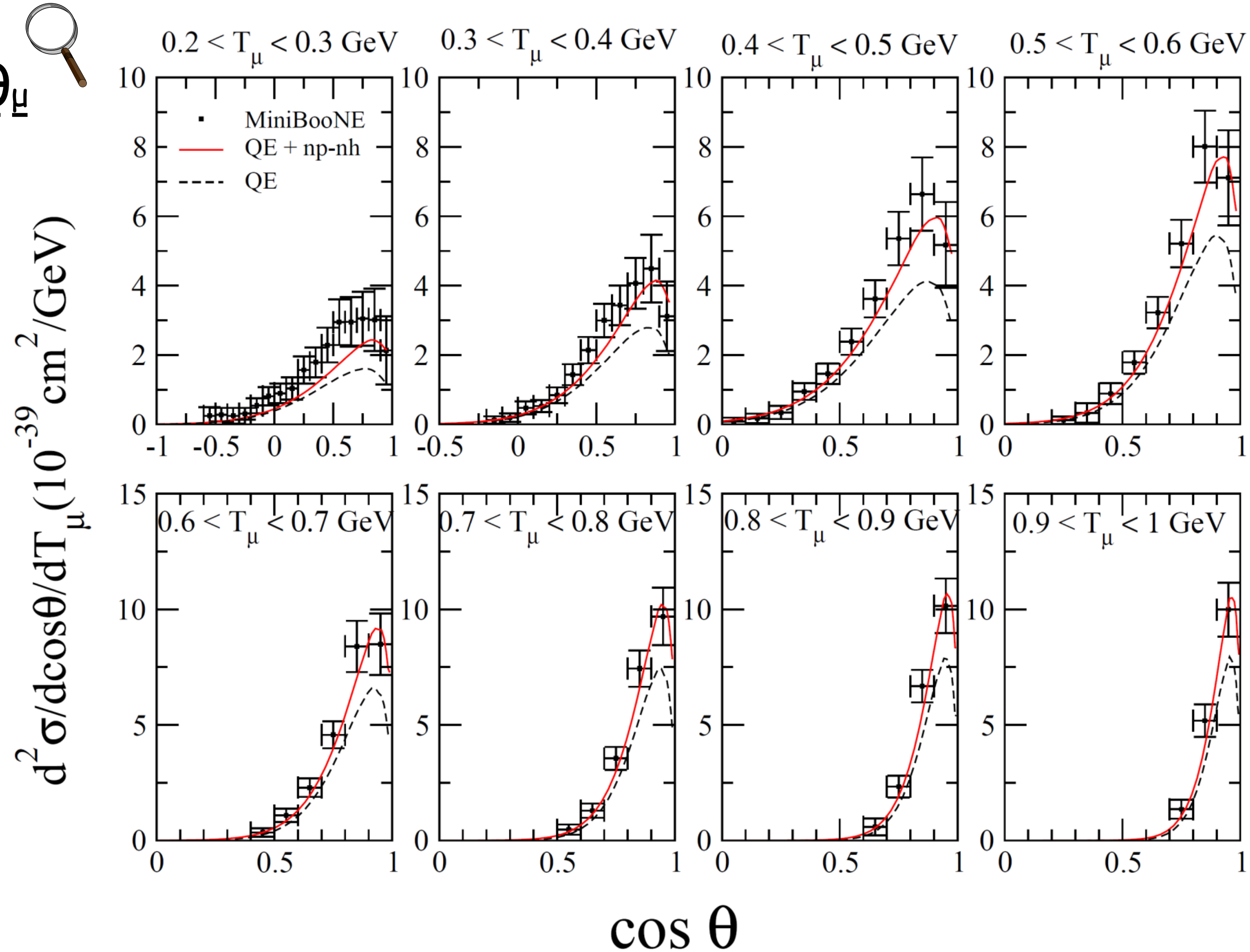
MiniBooNE CCQE-like flux-integrated double differential cross section



$\bar{\nu}$



MiniBooNE, Phys. Rev. D 88 032001 (2013)



Martini, Ericson, Phys. Rev. C 87 065501 (2013)

Similar conclusion also for the MiniBooNE CCQE-like antineutrino cross sections

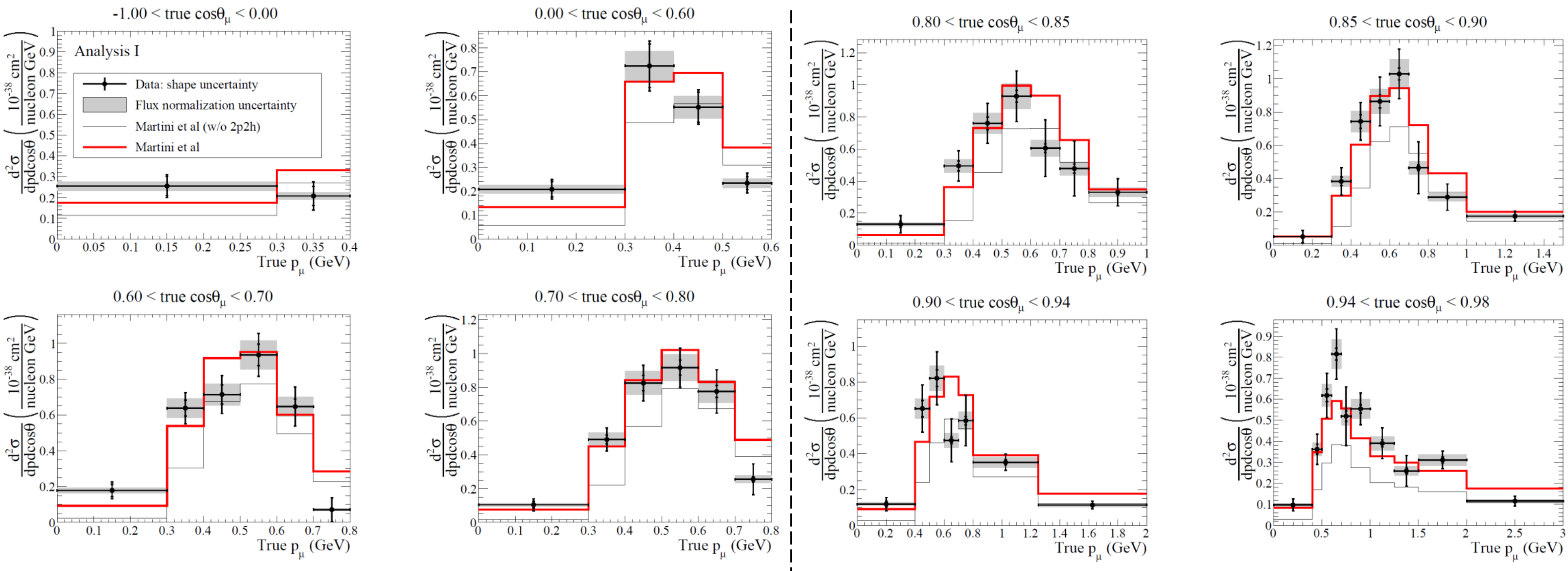
The **CC0π** measurement

After MiniBooNE, it has become more popular to present the data in terms of **final state** particles

CC0π = CCQE-like without subtraction of π absorption background (CC0π ≥ CCQE-like)

PHYSICAL REVIEW D **93,** 112012 (2016)

Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam



Including np-nh

Without np-nh

Better agreement including np-nh

The **CC0π** measurement

After MiniBooNE, it has become more popular to present the data in terms of final state particles

CC0π = CCQE-like without subtraction of π absorption background

PHYSICAL REVIEW D **93,** 112012 (2016)

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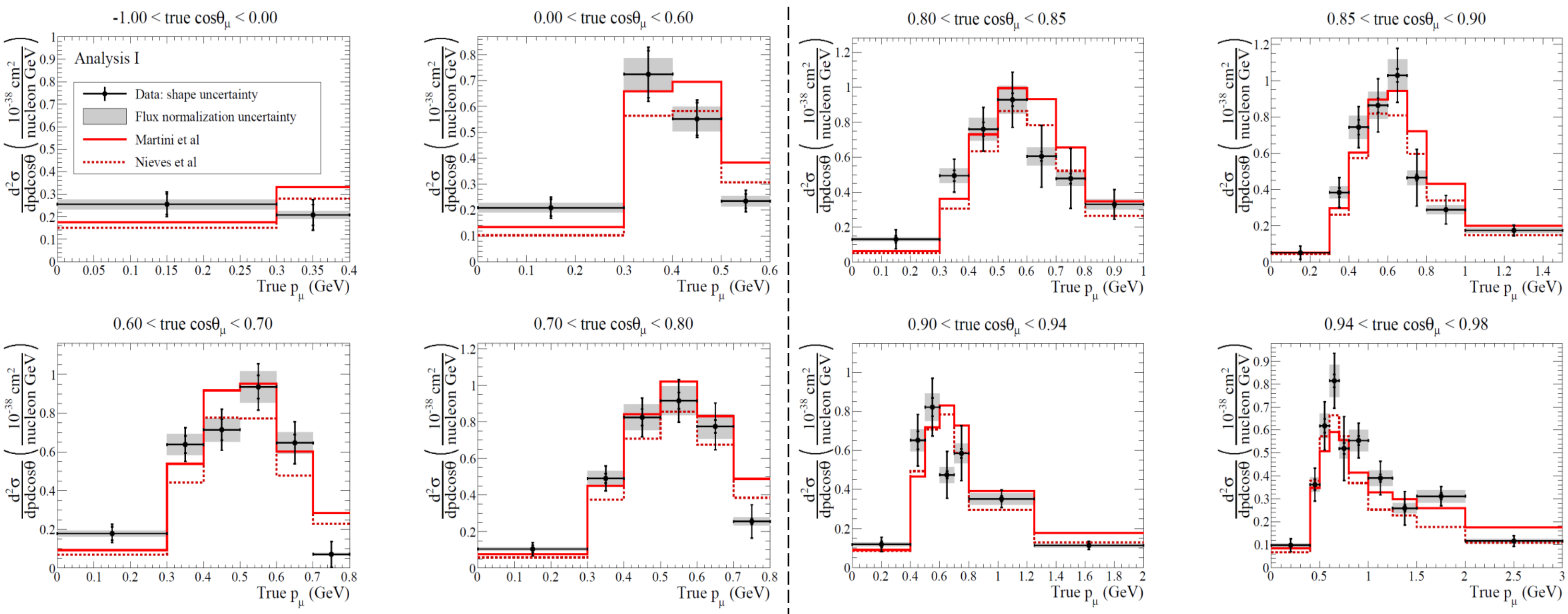


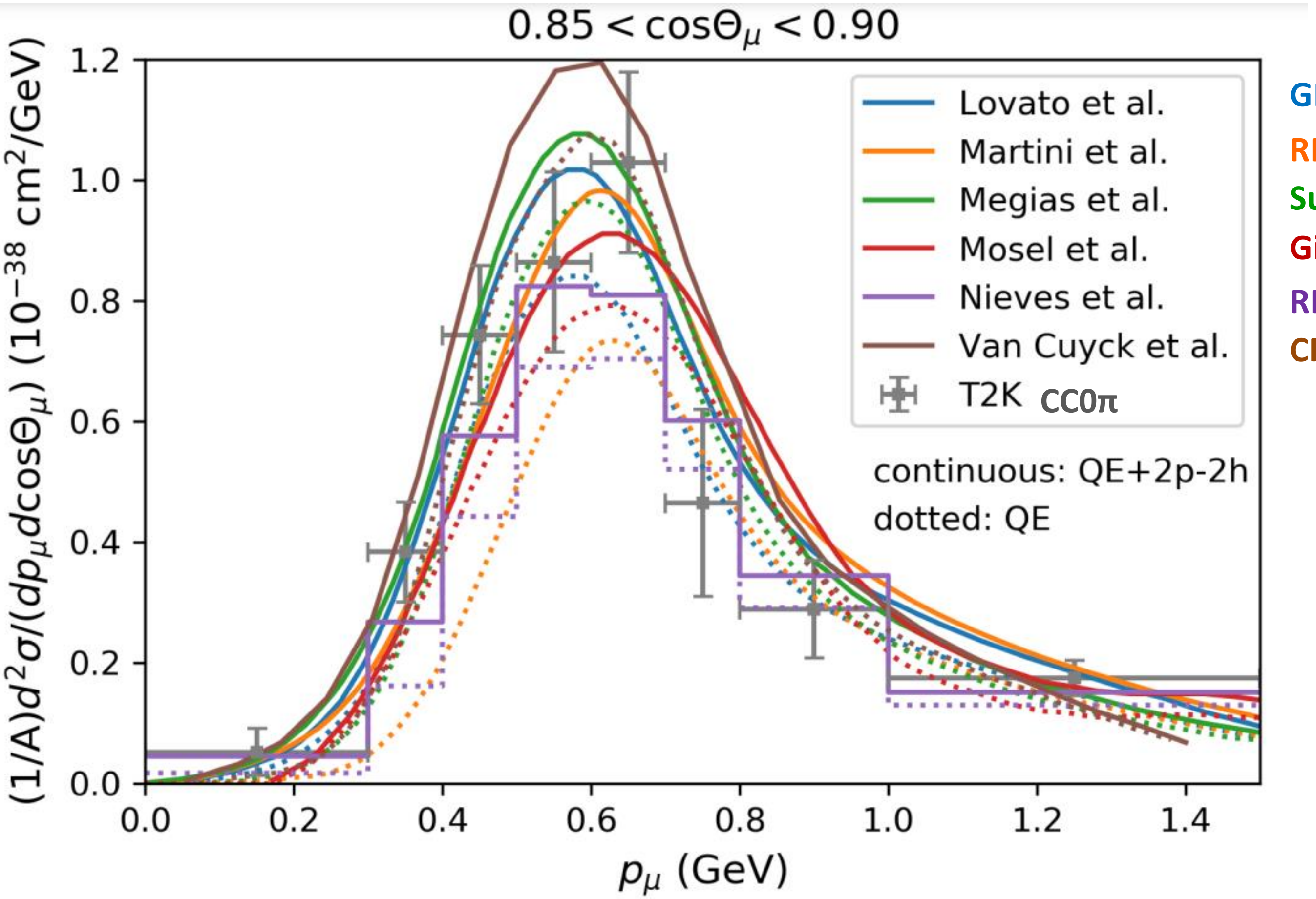
Martini et al.

Nieves et al.

Differences between models' predictions

Comparison between different CCQE+2p-2h theoretical predictions

A. Branca et al. Symmetry 13 (2021) 9, 1625



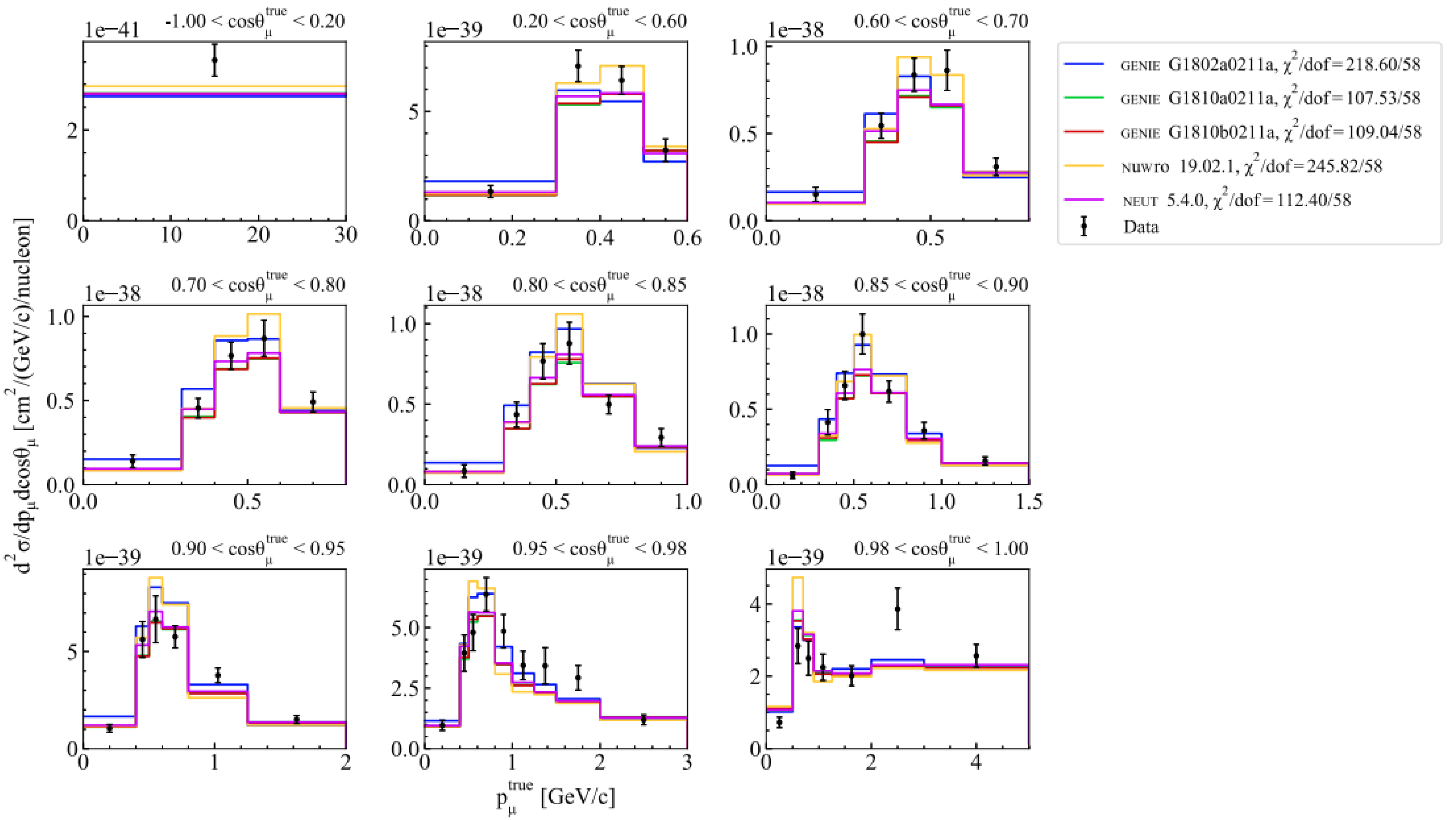
GFMC (Argonne, Los Alamos)
RPA (Lyon)
SuSAv2 (Granada, MIT,Sevilla, Torino)
GiBUU (Giessen)
RPA (Valencia)
CRPA (Ghent)

Several theoretical calculations agree on the crucial role of 2p-2h to reproduce data but there are discrepancies between the different models' predictions

⇨ **2p-2h are one of the most important source of the cross section uncertainties (systematic errors in oscillation experiments)**

The T2K **CC0π** data and the Monte Carlo predictions

M. BUIZZA AVANZINI *et al.* PHYS. REV. D **105**, 092004 (2022)



Differences in the MC predictions (CCQE, 2p-2h and π absorption modeling)

p.s. The effort to implement different 2p-2h models in several Monte Carlo is still in progress

Monte Carlo Event Generators

Monte Carlo event generators connects theoretical models to experimental measurements

Main Event Generators for neutrino interactions:

Genie — UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GiBUU

NEUT

NuWro — Wroclaw Neutrino Event Generator

L. Alvarez-Ruso et al., EPJ Spec. Top. 230, 4449 (2021)

O. Buss et al., Phys.Rept. 512 1-124 (2012)

Y. Hayato and L. Pickering, EPJ Spec. Top. 230, 4469 (2021)

T. Golan et al., NPB 229–232, 499 (2012)

PHYSICAL REVIEW D **105**, 092004 (2022)

Comparisons and challenges of modern neutrino-scattering experiments

M. Buizza Avanzini,[1] M. Betancourt,[2] D. Cherdack,[3] M. Del Tutto,[2,4] S. Dytman,[5] A. P. Furmanski,[6,7] S. Gardiner,[2] Y. Hayato,[8] L. Koch,[9] K. Mahn,[10] A. Mastbaum,[11] B. Messerly,[5,7] C. Riccio,[12,13] D. Ruterbories,[14] J. Sobczyk,[15] C. Wilkinson,[16] and C. Wret[14]

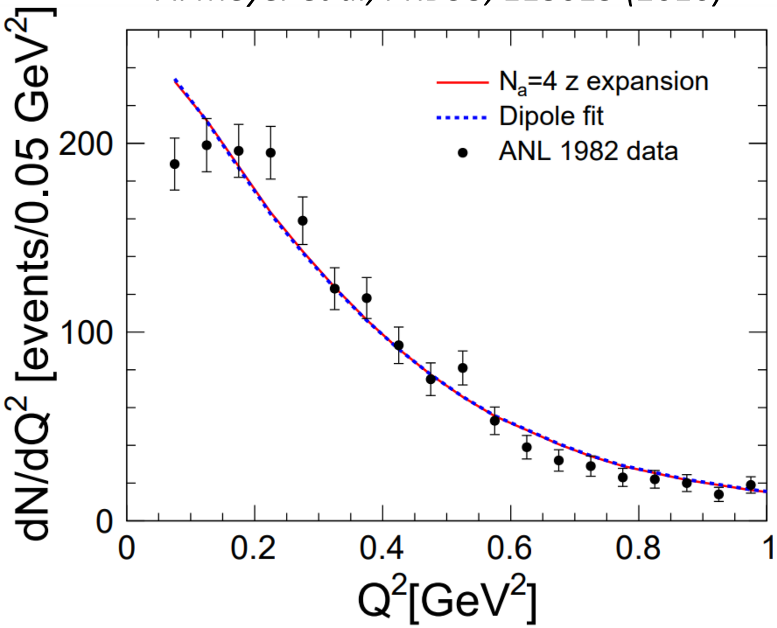
Main models implemented for the quasielastic and 2p-2h:

- Relativistic global and local Fermi Gas
- RPA
- Spectral Function
- SuperScaling (SuSAv2)

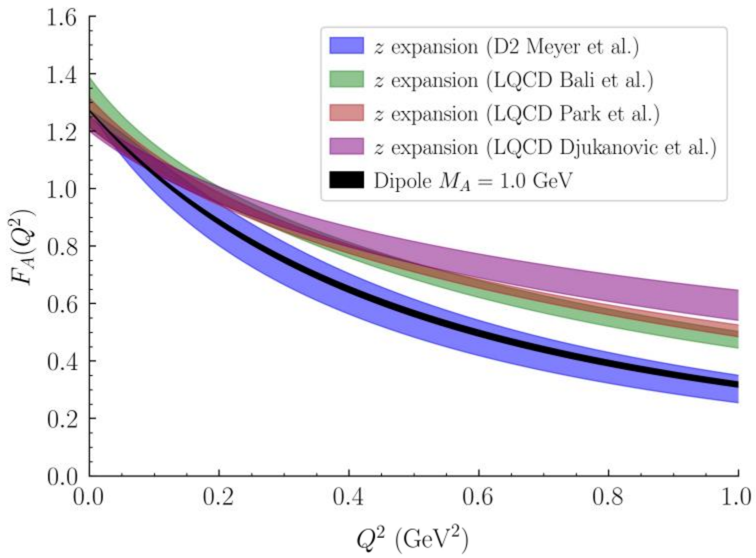
[For the illustration of the different models see for example the cross section lectures at the GIF school]

Axial Form factor and Lattice QCD predictions

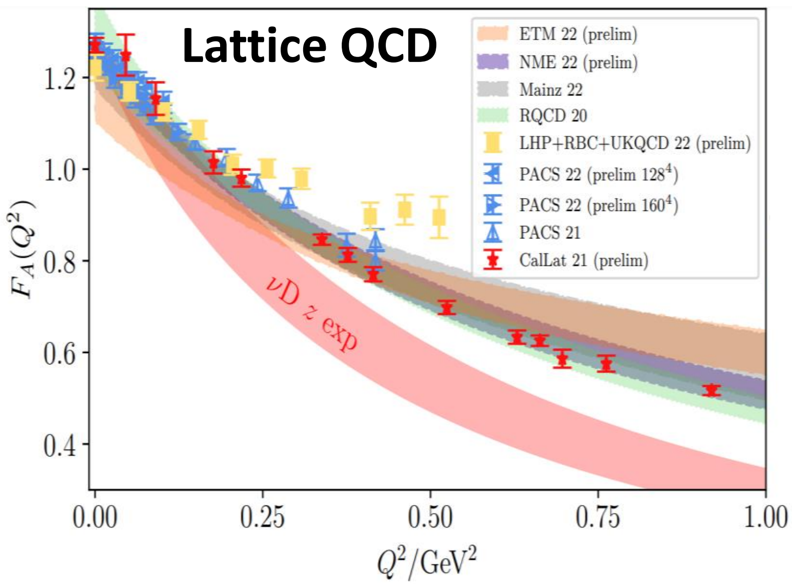
A. Meyer et al, PRD93, 113015 (2016)



D. Simons et al. 2210.02455



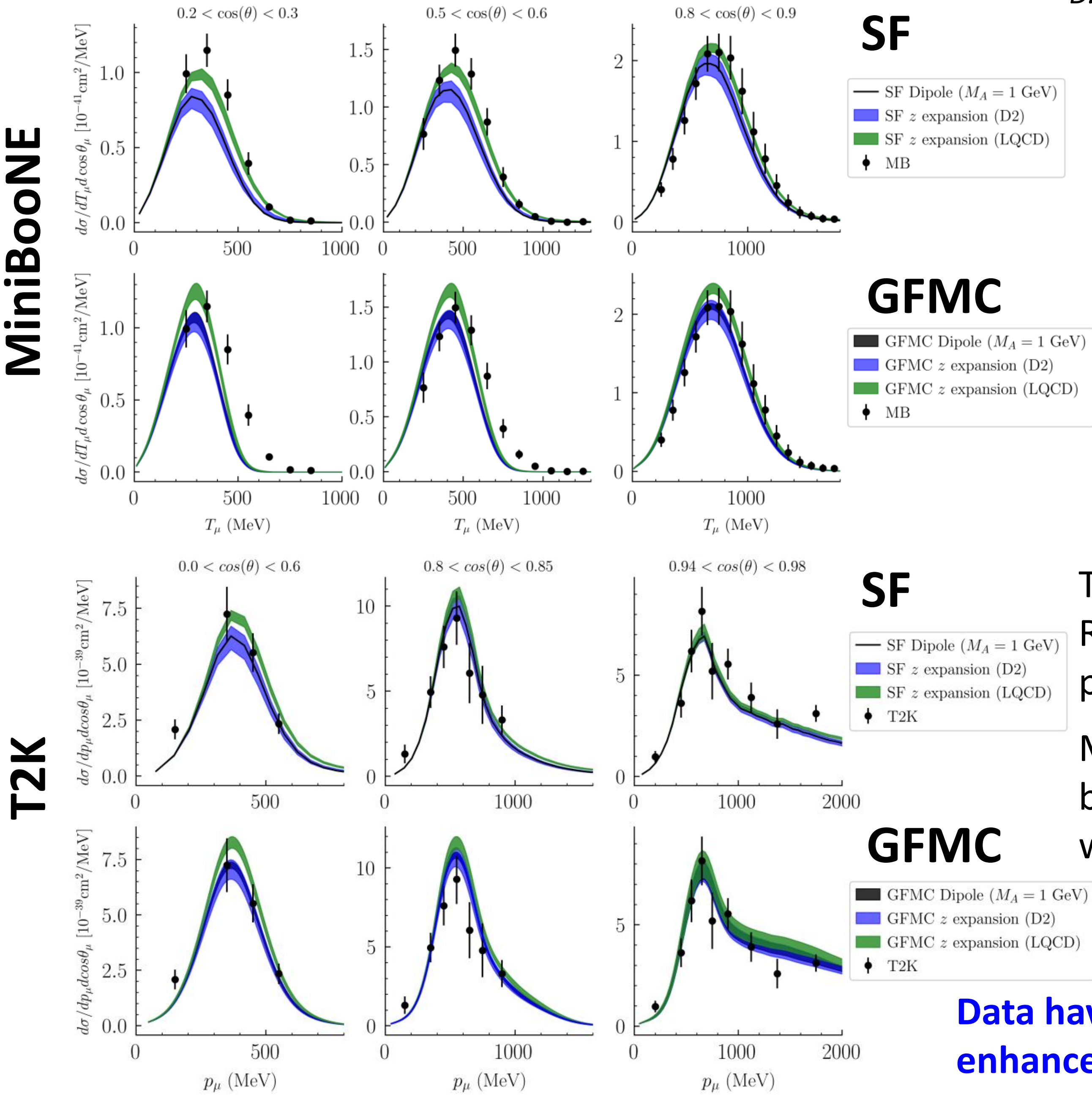
A. Meyer talk @ NUINT 2022; Ann.Rev.Nucl.Part.Sci. 72 (2022)



- Dipole parameterization underestimates uncertainties
- Meyer et al. z-expansion: similar to dipole parameterization but larger errors
- Lattice QCD calculations show evidence of slow Q^2 falloff
- LQCD: much larger normalization at $Q^2 > 0.3$ GeV^2

Impact of enhanced axial form factor from LQCD

D. Simons et al. 2210.02455



MiniBooNE:
Universal 10-20% increase in normalization with LQCD

T2K:
Results fairly independent of parameterization

Mostly due to T2K's lower beam energy hence lower Q^2 where form factors agree

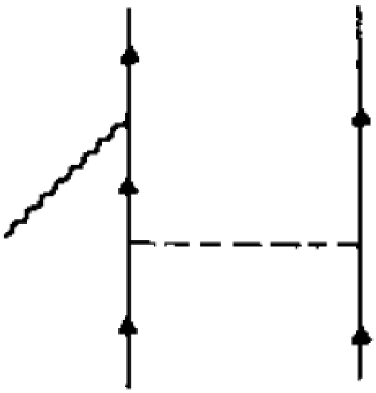
Data have room for both 2p-2h and enhanced axial form factor for LQCD

Some details on 2p-2h

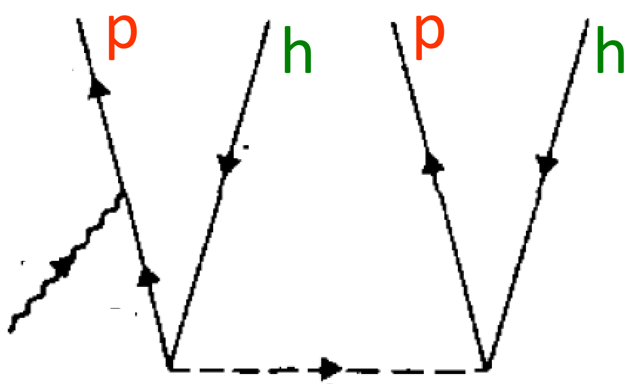
Two particle-two hole sector (2p-2h)

Three equivalent representations of the same process

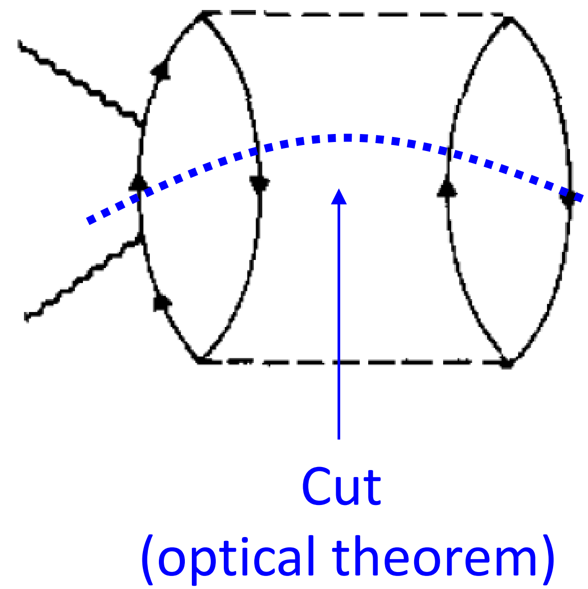
2 body current



2p-2h matrix element



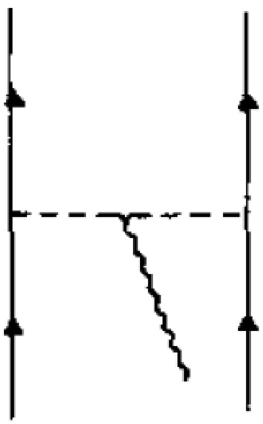
2p-2h response



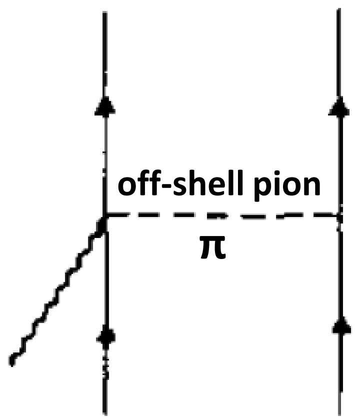
Final state: two particles-two holes

Diagrams for 2 body currents

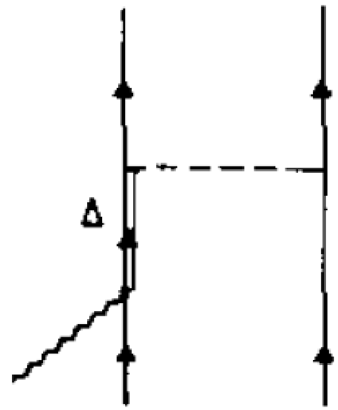
Meson Exchange Currents (MEC) J^{MEC}



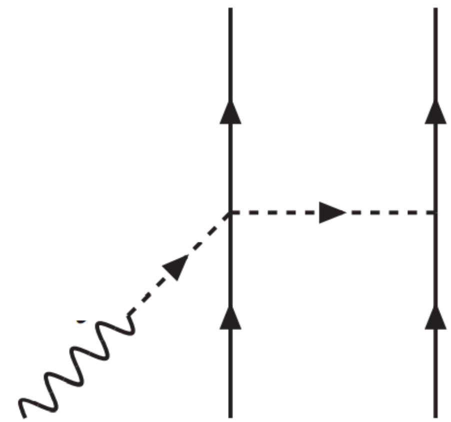
Pion in flight



Seagull or Contact

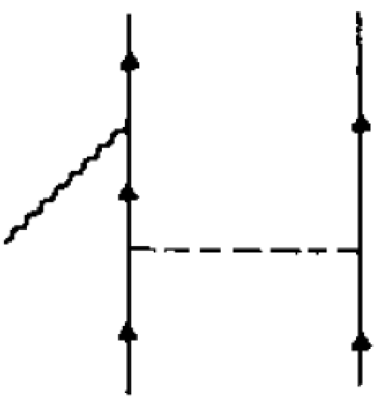


Delta



Pion pole (purely axial)

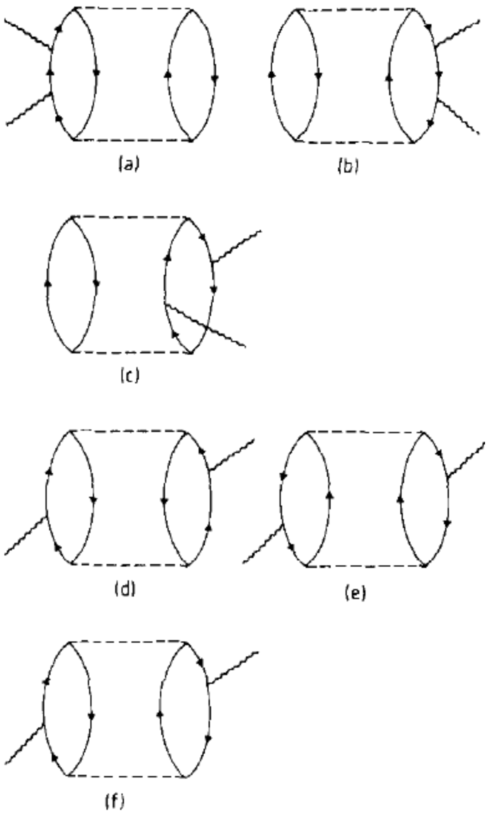
Nucleon-Nucleon Correlations (SRC) J^{corr}



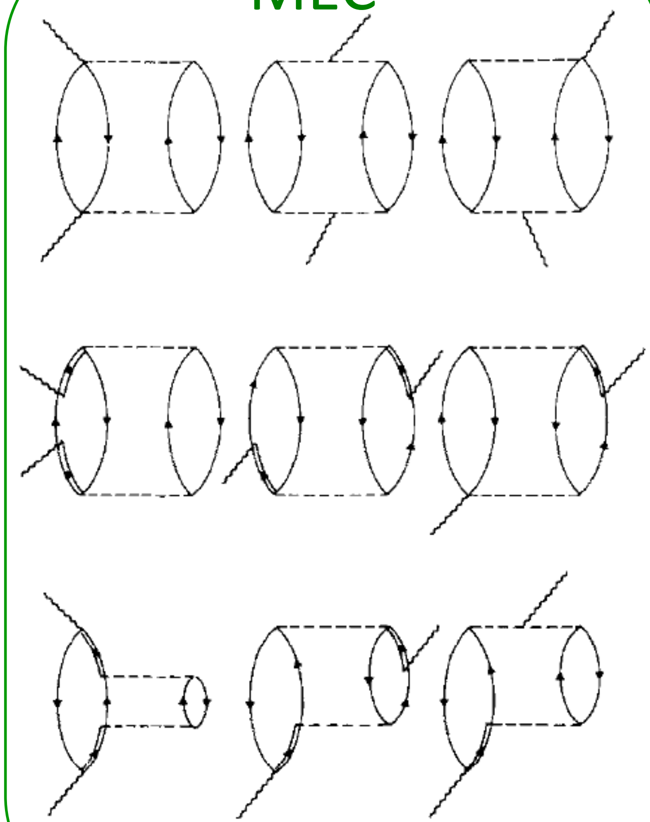
- An additional two-body current to be included in the framework of independent particle models for QE such as the Fermi Gas or Hartree-Fock.
- Absent in the approaches which start from the description of the nucleus in terms of correlated wave functions (such as CBF spectral function or GFMC) since the hadronic tensor of the one body current already includes this contribution.
- **There is a risk of a double counting of SRC in the Monte Carlo if different contributions to the neutrino cross sections are taken from different models.**

Some diagrams for 2p-2h responses

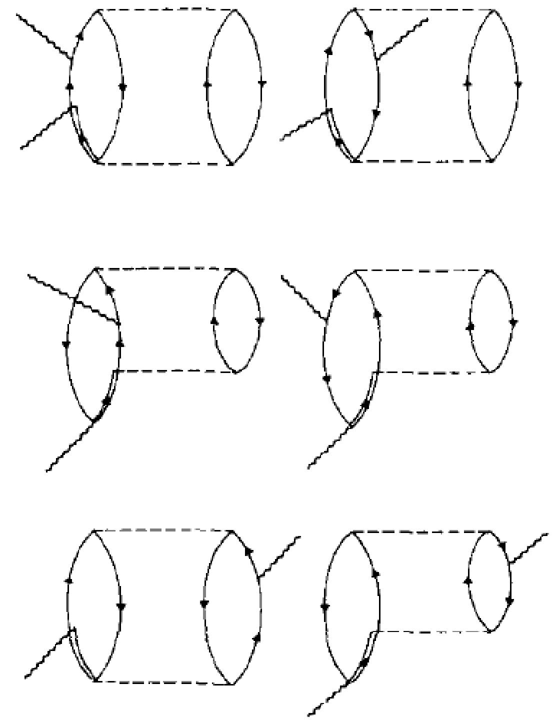
NN correlations



MEC



NN correlation-MEC interference



also called
1-body—2-body interference

Alberico, Ericson, Molinari, Ann. Phys. 154, 356 (1984)

Main difficulties in the np-nh sector

$$W^{\mu\nu}(\mathbf{q},\omega) = W^{\mu\nu}_{1p1h}(\mathbf{q},\omega) + W^{\mu\nu}_{2p2h}(\mathbf{q},\omega) + \cdots$$

$$W^{\mu\nu}_{2p-2h}(\mathbf{q},\omega) = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3p'_2 d^3h_1 d^3h_2 \frac{m_N^4}{E_1E_2E'_1E'_2}\theta(p'_2-k_F)\theta(p'_1-k_F)\theta(k_F-h_1)\theta(k_F-h_2)$$
$$\underbrace{\langle 0|J^\mu|\mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2\rangle\langle\mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2|J^\nu|0\rangle}_{\text{matrix elements}}\delta(E'_1+E'_2-E_1-E_2-\omega)\delta(\mathbf{p}'_1+\mathbf{p}'_2-\mathbf{h}_1-\mathbf{h}_2-\mathbf{q})$$

- 7-dimensional integrals $\int d^3h_1 d^3h_2\ d\theta'_1$ of thousands of terms
- Huge number of diagrams and terms
- Divergences (angular distribution; NN correlations contributions)
- Calculations for all the kinematics compatible with the experimental neutrino flux

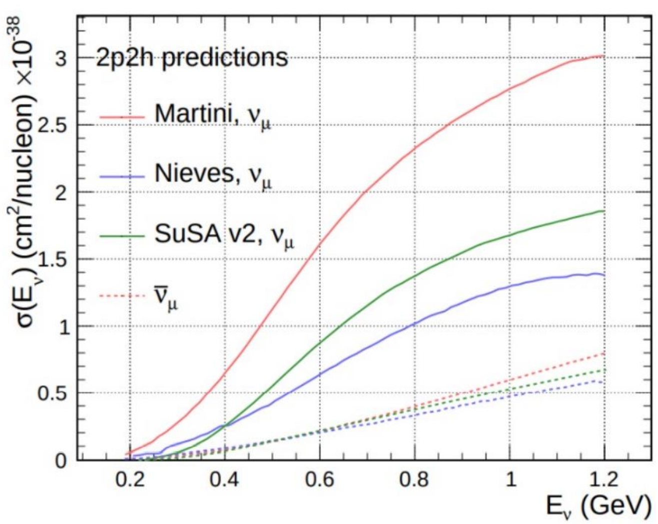
Computing very demanding

Hence different approximations by different groups:

- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D --> 2D if non relativistic; 7D -->1D if $h_1 = h_2 = 0$)

$\Rightarrow$ Different final results by different groups

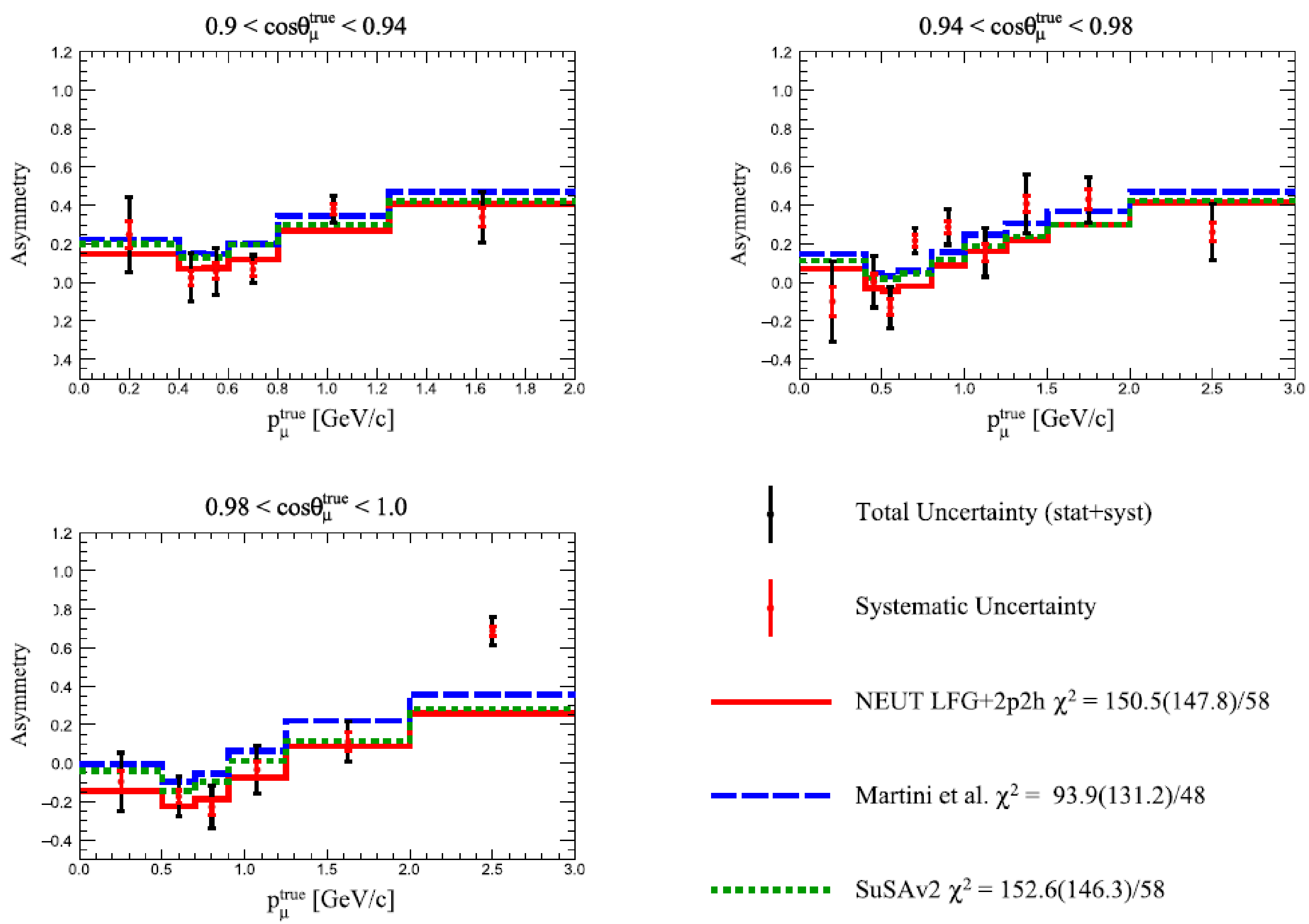
- **The relative role of np-nh for neutrinos and antineutrinos is different in different approaches**



PHYSICAL REVIEW D **101,** 112001 (2020)

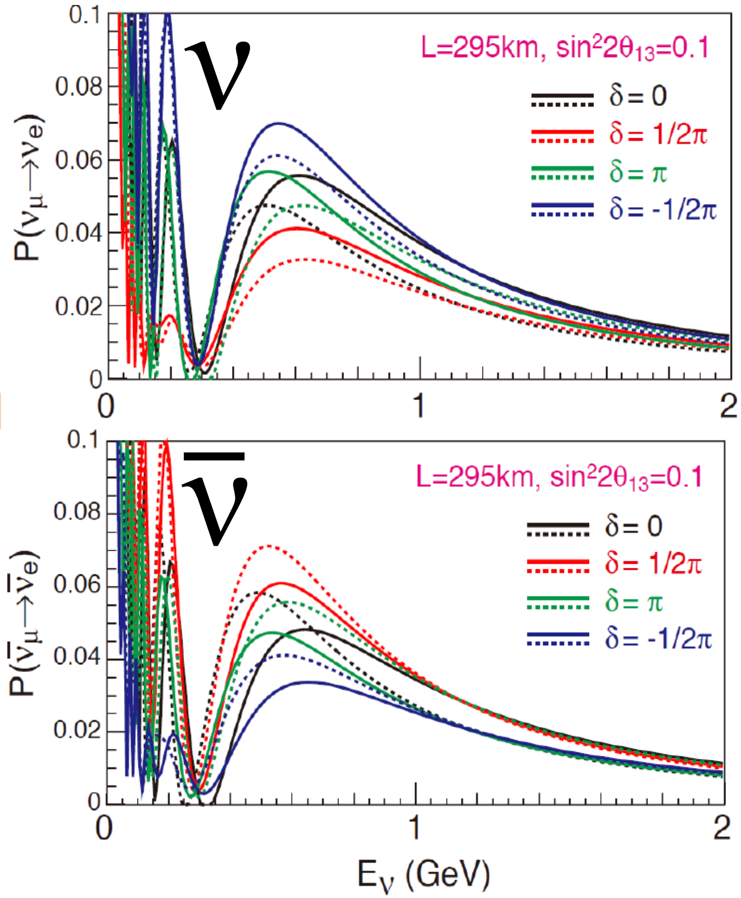
First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K

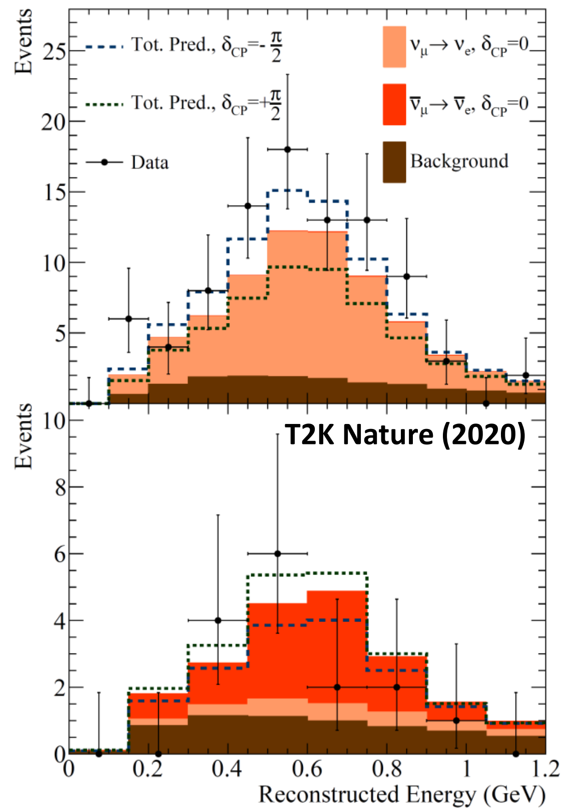
$$\frac{\nu - \bar{\nu}}{\nu + \bar{\nu}}$$



What about ν vs $\bar{\nu}$ interaction? And ν_μ vs ν_e?

$$P(\nu_\mu \rightarrow \nu_e) \overset{?}{\neq} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$





$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

A precise and simultaneous knowledge of the four cross sections is important in connection to the oscillation experiments aiming at the search for CP violation in the lepton sector (T2K, NOvA, Hyper-K, DUNE).

Non-trivial differences in the cross sections (see Appendix)

Neutrino energy reconstruction

Energy reconstruction in neutrino oscillation experiments

Reconstructed ν energy

True ν energy

$$N_{\nu_\beta}(\overline{E_\nu}) \sim \int \Phi_{\nu_\alpha}(E_\nu) P_{\nu_\alpha \to \nu_\beta}(E_\nu, L, \{\Theta\}) \sigma_{\nu_\beta}(E_\nu) \epsilon_{\text{det.}} d(E_\nu, \overline{E_\nu}) dE_\nu$$

Number of detected events

ν flux	ν oscillation probability	ν cross section	Detector efficiency	Migration matrix

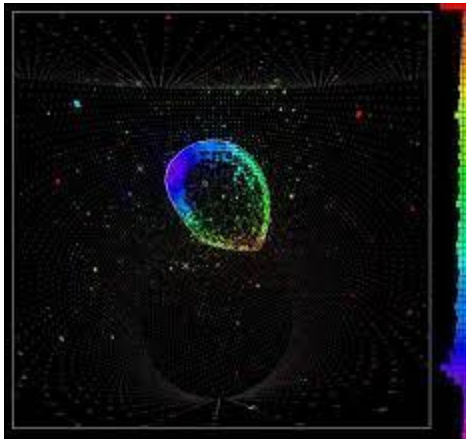
Two methods for ν energy reconstruction

Tracking detectors

- Use all the detected particles
- Calorimetric method

Cherenkov detectors

- Use only lepton (1 ring signal)
- Quasielastic-based method

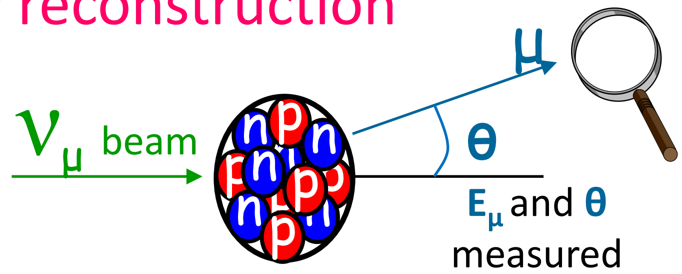


[For details see the cross section lectures at the GIF school]

Quasielastic-based neutrino energy reconstruction

Reconstructed neutrino energy

$$\overline{E_\nu} = \frac{m_p^2-(m_n-E_b)^2-m_\mu^2+2(m_n-E_b)E_\mu}{2(m_n-E_b-E_\mu+p_\mu \cos\theta_\mu)}$$

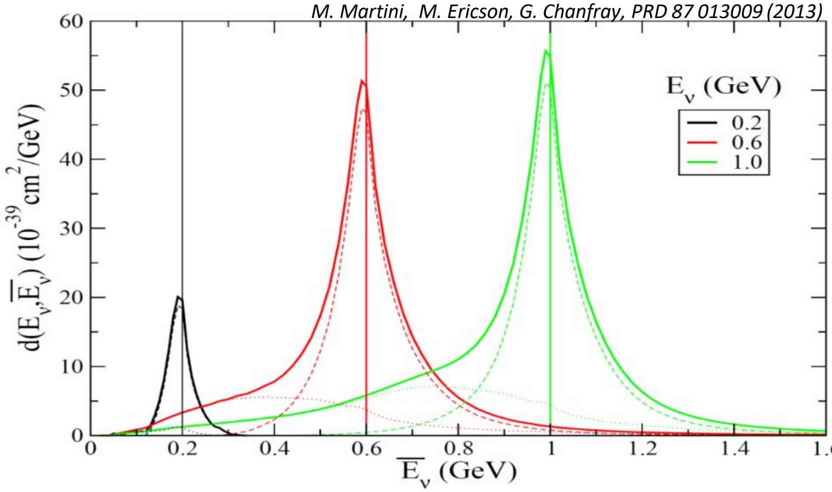


$\nu_\mu\, n \rightarrow \mu^-\, p$ via two-body kinematics

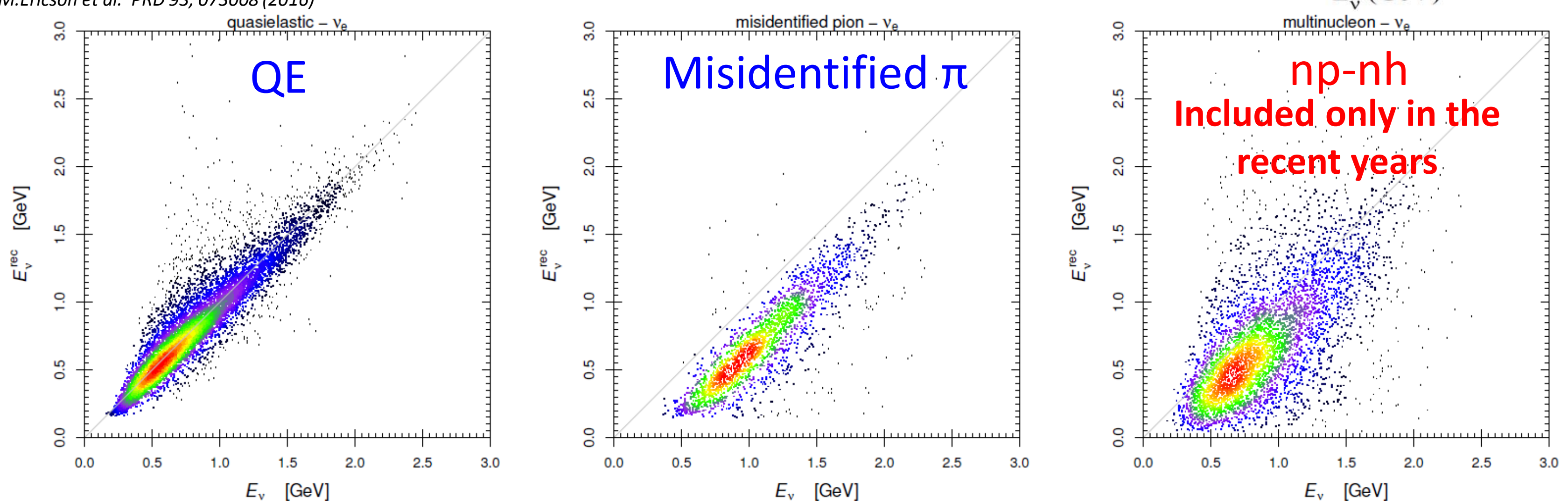
$\overline{E_\nu} = E_\nu$ exact only for CCQE with free nucleon

$d(E_\nu, \overline{E_\nu})$ Migration matrix: to take into account nuclear effects

M. Martini, M. Ericson, G. Chanfray, PRD 87 013009 (2013)

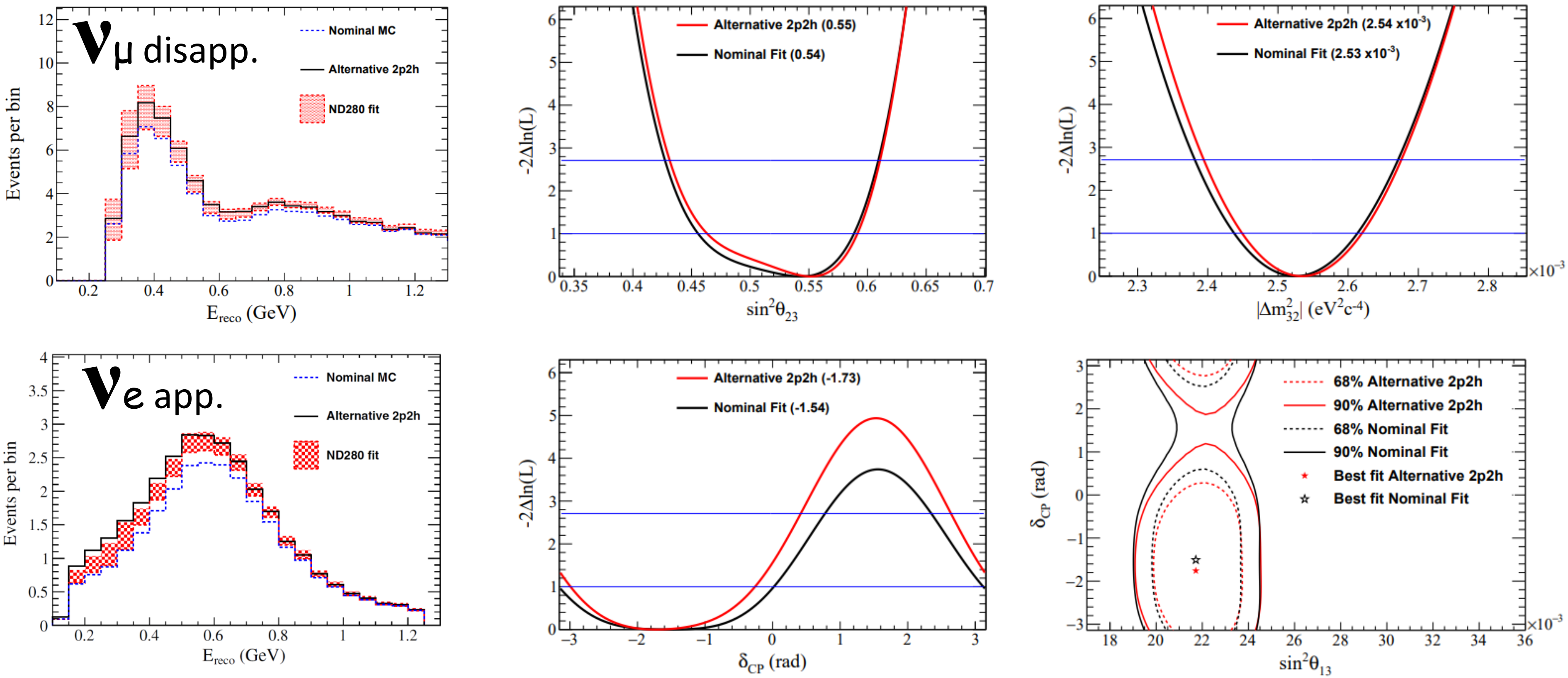


M.Ericson et al. PRD 93, 073008 (2016)

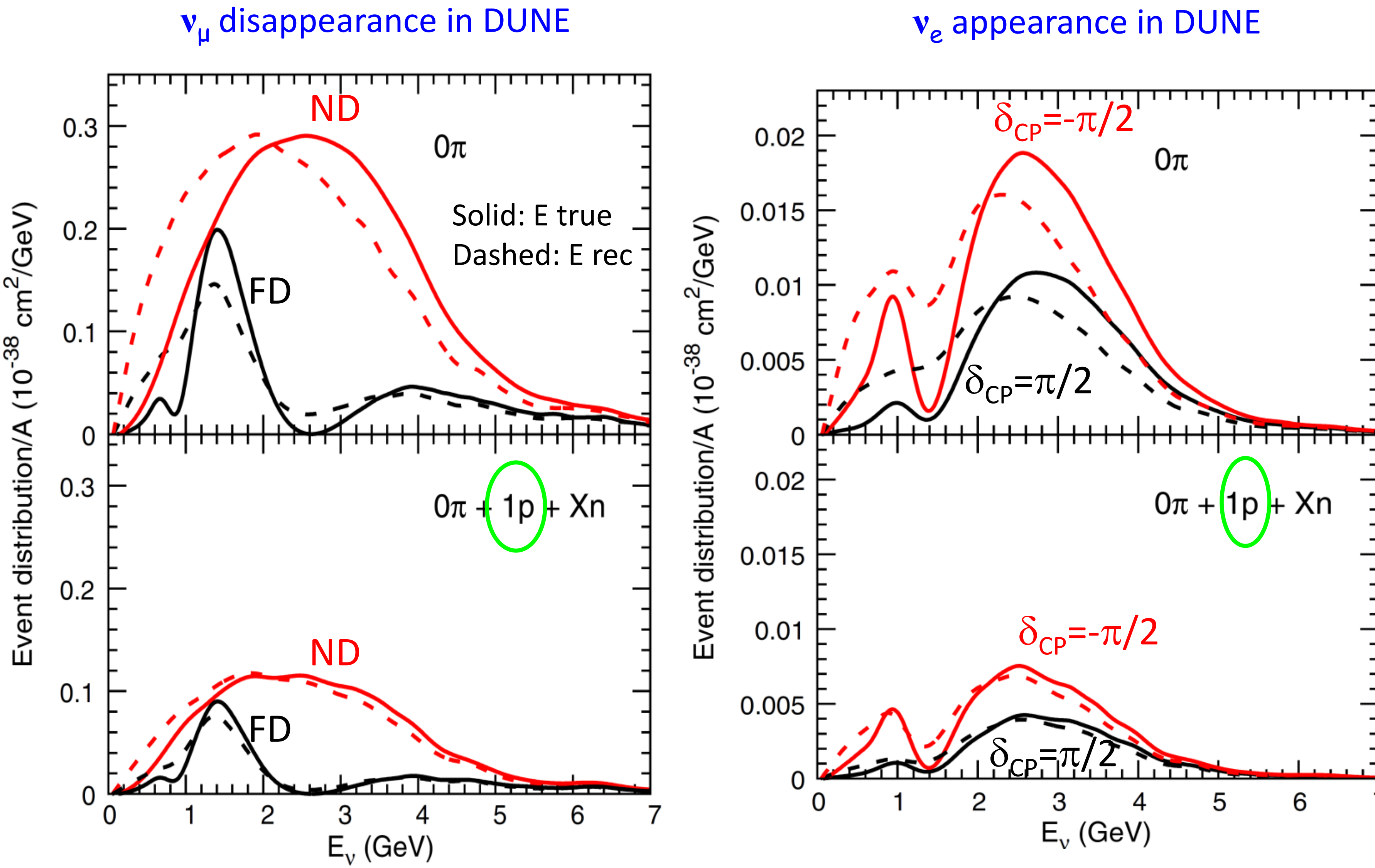


Impact of 2p-2h modeling on T2K oscillation analysis

T2K Phys.Rev.D 96 (2017) 9, 092006



QE-based E_ν reconstruction using proton information



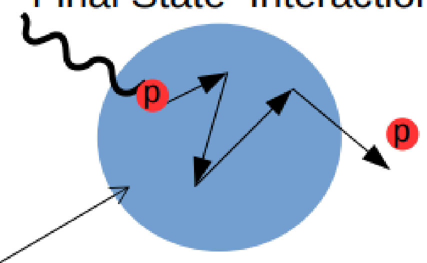
Major improvement in 0π **+ 1p** + Xn sample, events down by only factor 3

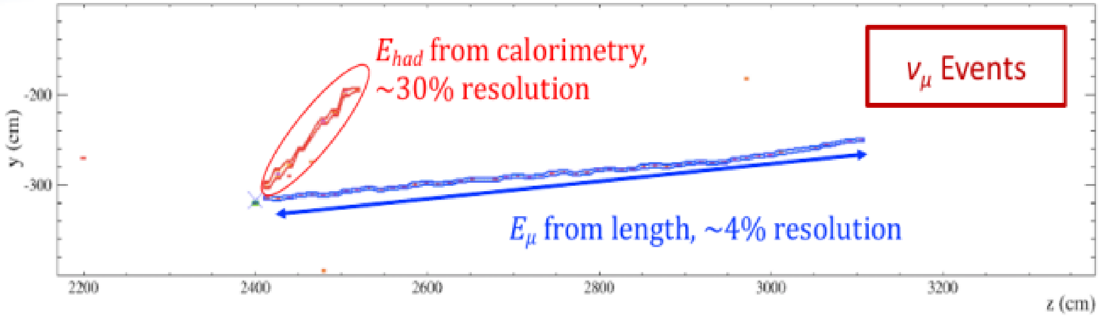
Mosel et al. Phys. Rev. Lett. 112 151802 (2014)

Eν reconstruction NOvA

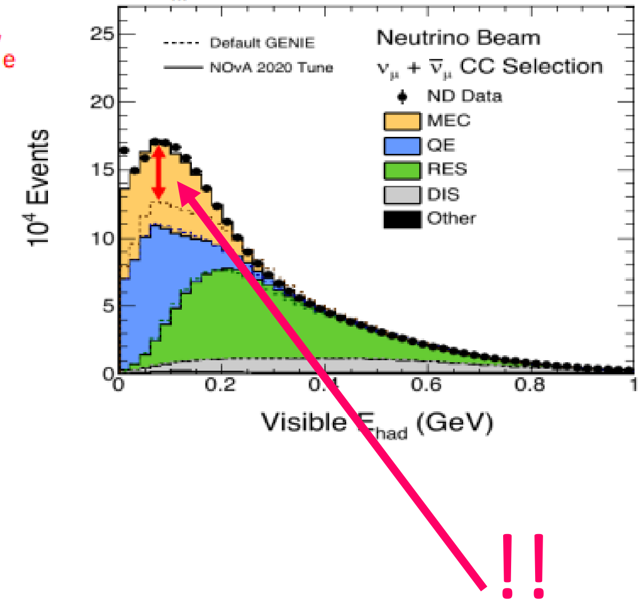
Calorimetric method

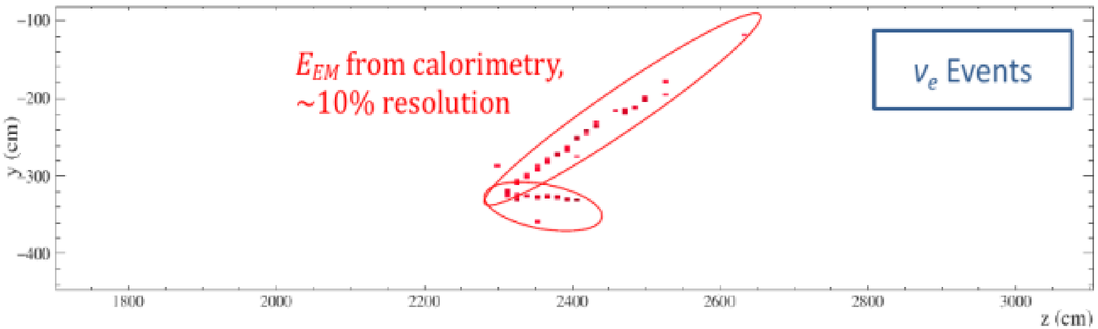
- **Eν reconstructed with hadronic deposits:**
  - important difference ν – ν̄: proton vs neutron (~undetected)
  - proton/pion energy smeared by Final State Interactions
- Different reconstruction and energy resolution for ν_μ and ν_e





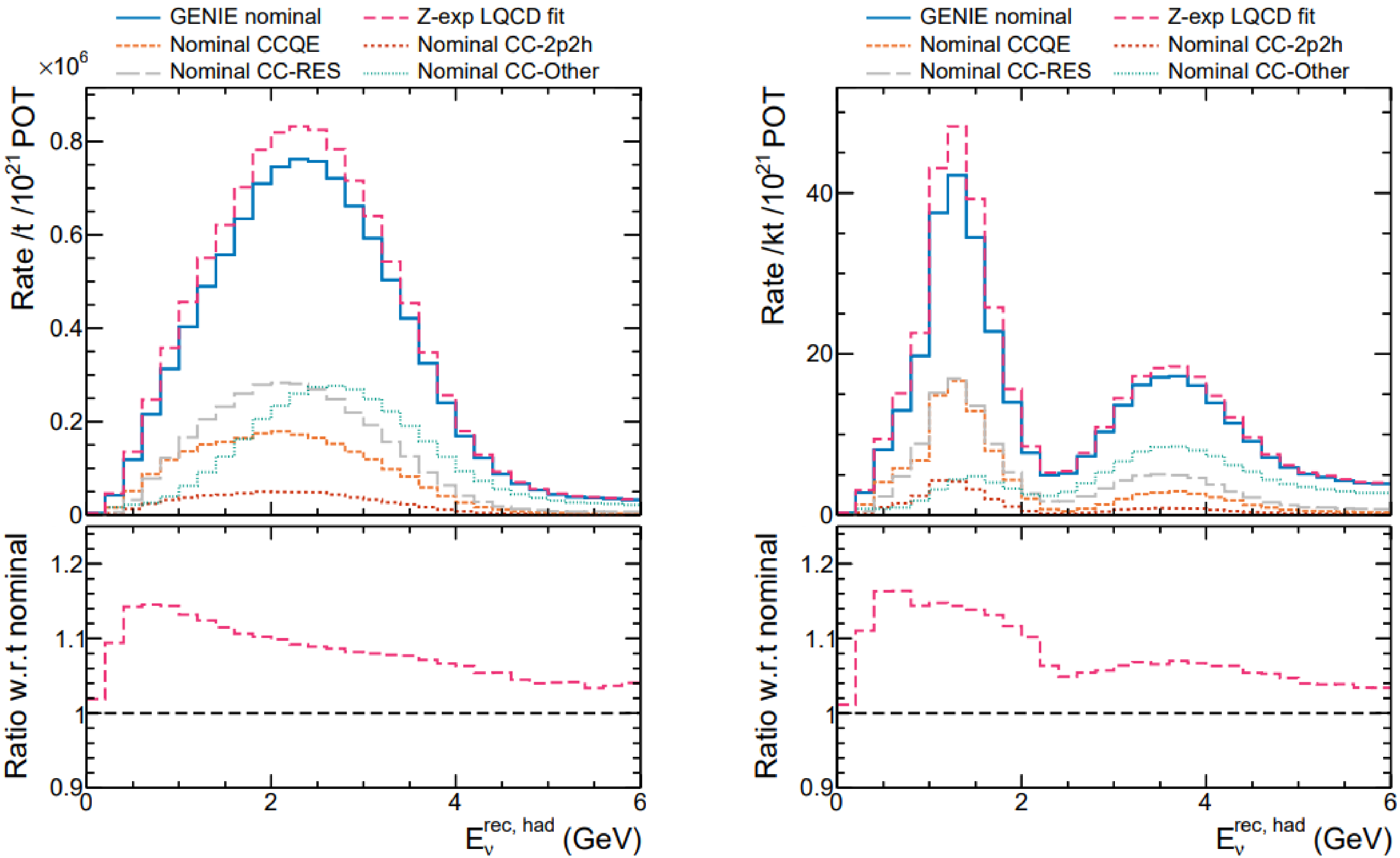
Important to tune model predictions for E_{had}





S. Bolognesi @ GIF school 119

GENIE predictions of ν_μ-^{40}Ar event rates at DUNE ND and FD

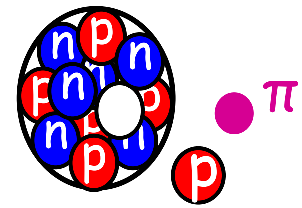


(a) ND (b) FD

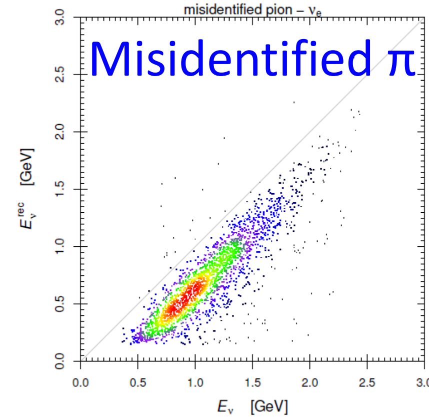
A. Meyer et al., Ann.Rev.Nucl.Part.Sci. 72 (2022)

1π production

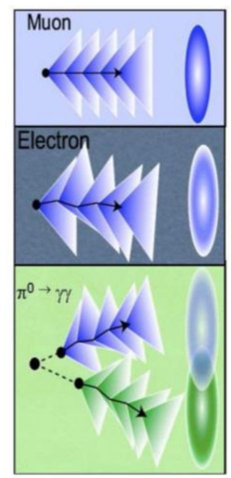
The one pion production channel



Important for several reasons:

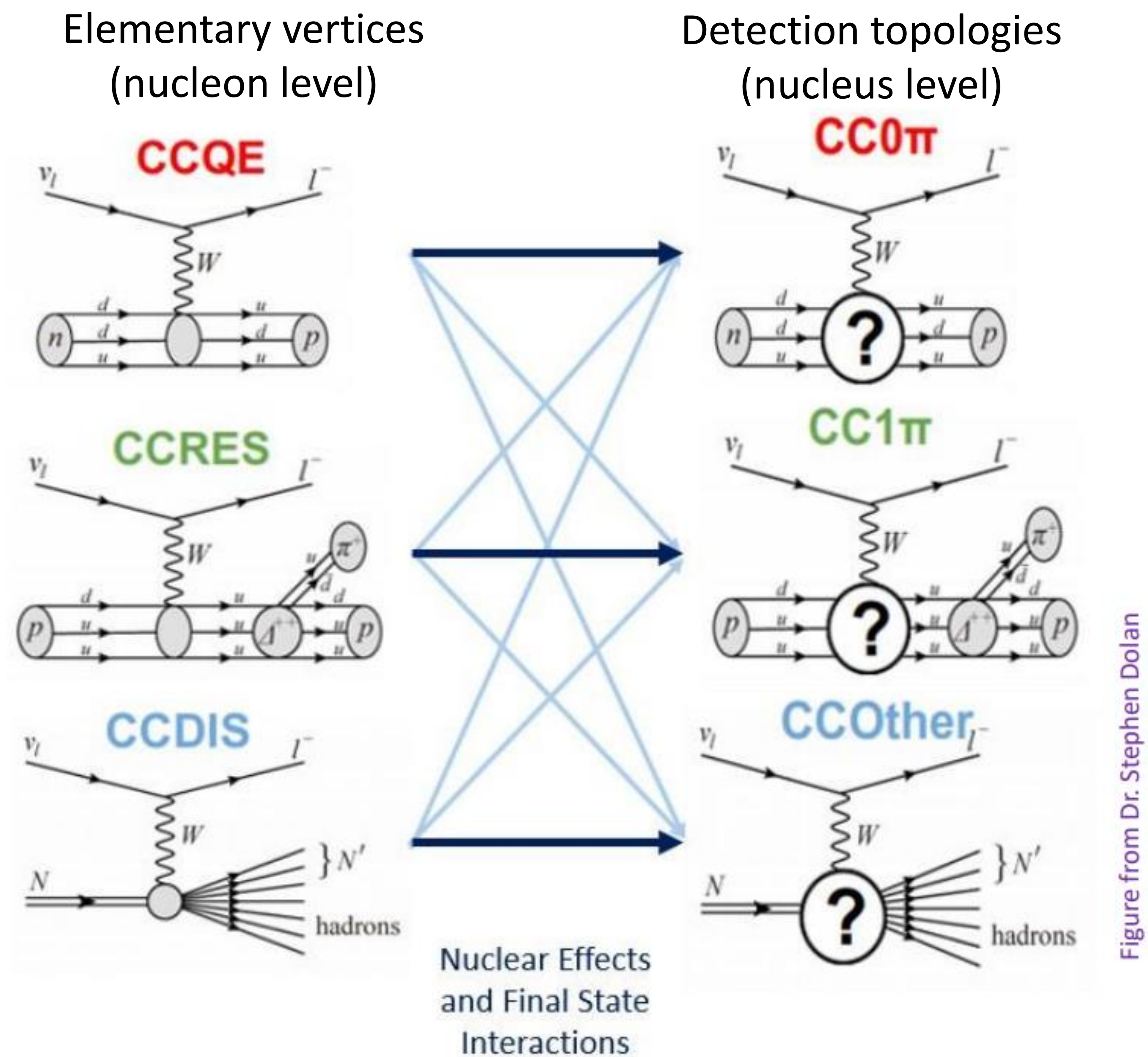


- Misidentified π is part of the ν energy migration matrix in QE-based method



- In Cherenkov detectors NC1π^0 can mimic electron-like signal in $\nu_\mu \to \nu_e$ oscillation search
- There is an increasing interest on CC 2-ring signal (charged lepton and π) at SK
- It is one of the dominant channels in DUNE

Elementary vertices .vs. detection topologies

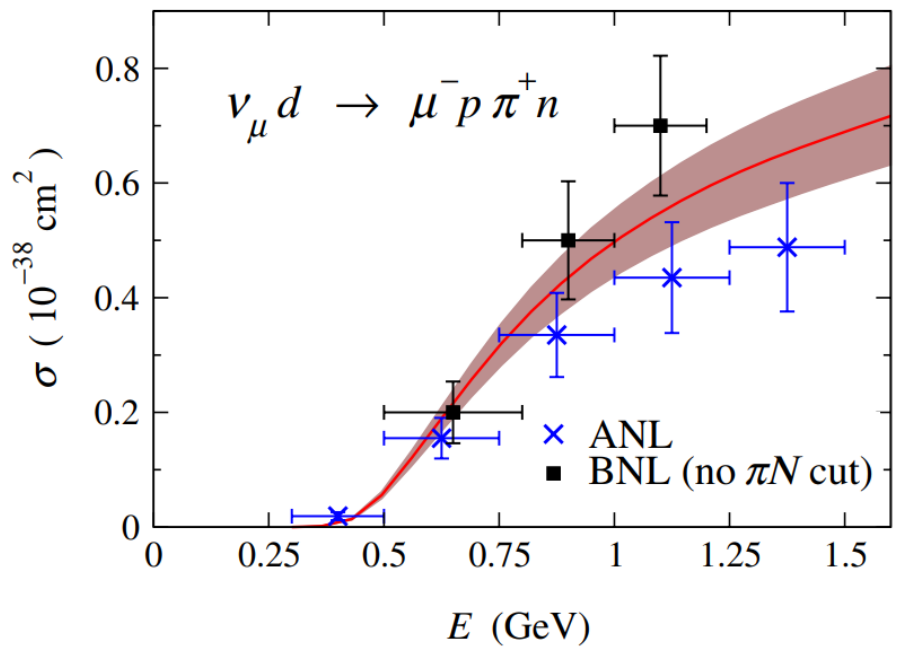


Different interaction vertices can lead to the same final state due to nuclear effects and FSI

1π production in neutrino-deuteron scattering

- Discrepancies between "old" deuteron bubble-chamber data (Argonne ANL and Brookhaven BNL)
- Both ANL and BNL data suffer from a large flux-normalization error

E. Hernandez et al. Phys. Rev. D 87, 113009 (2013)



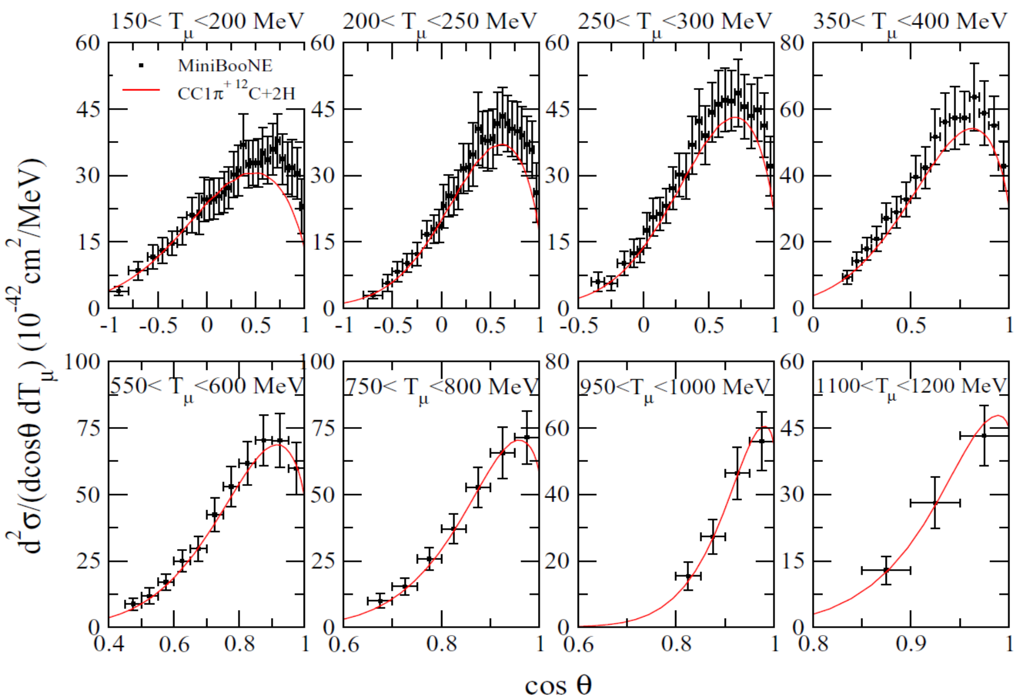
As for the CCQE, also for the 1π production there is a strong desire to repeat bubble-chamber experiments to better determine the axial form factors (in particular the C_5^A)

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/M_{A\Delta}^2)^2}$$

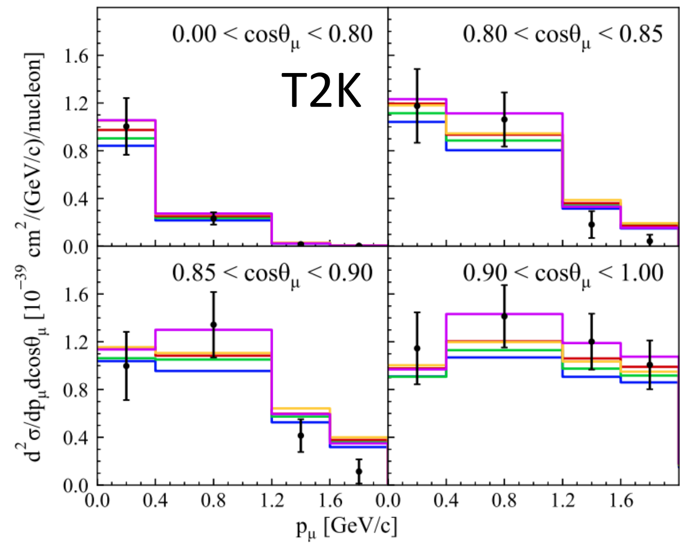
CC1π+ flux-integrated differential cross sections on carbon

Results in terms of muon variables

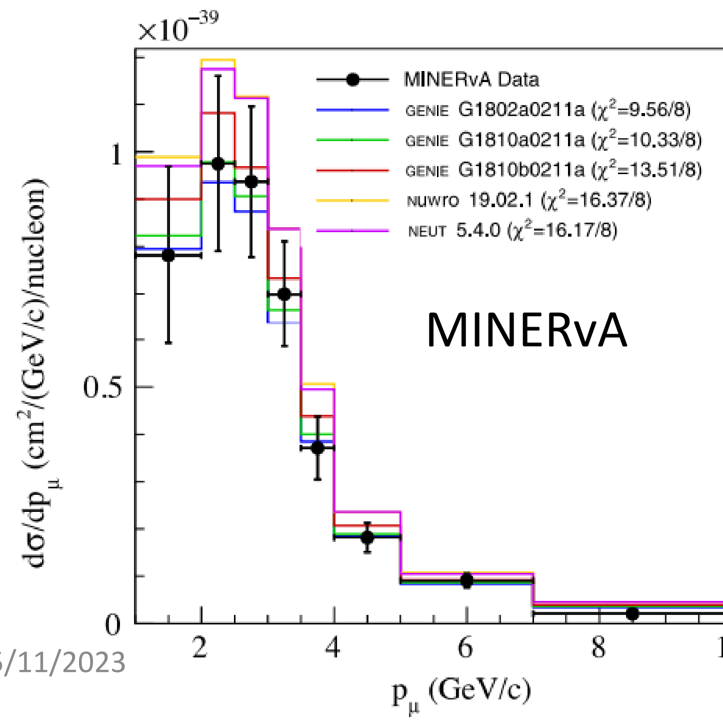
MiniBooNE



M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)



M. Buizza Avanzini et al. PRD 105, 092004 (2022)

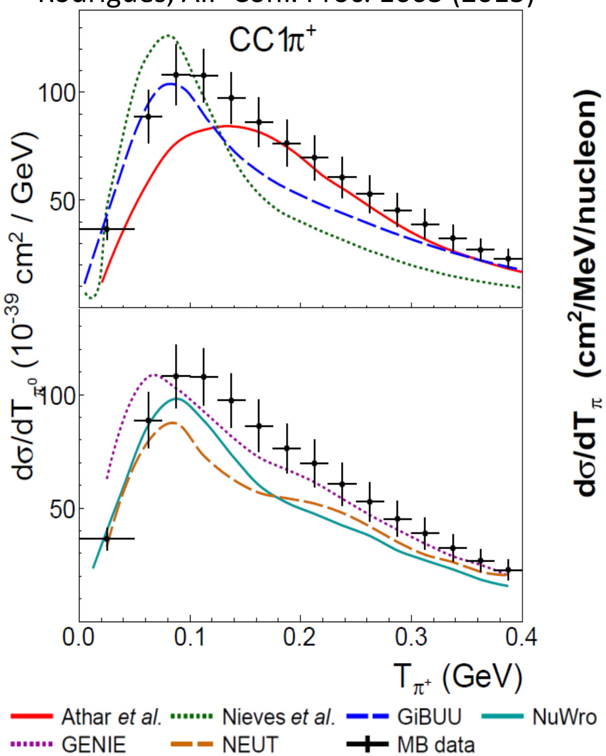


Reasonable agreement between models and data, in particular at MiniBooNE and T2K energies

CC1π results in terms of pion variables

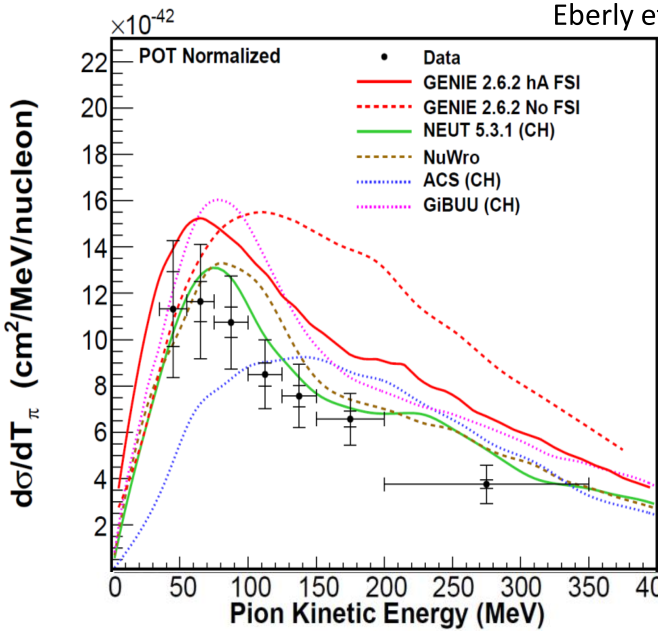
MiniBooNE

Rodrigues, AIP Conf. Proc. 1663 (2015)

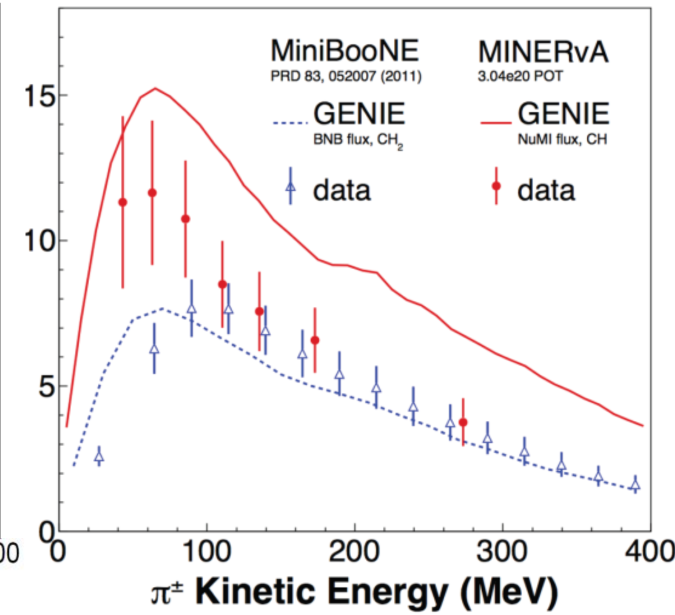


MINERvA

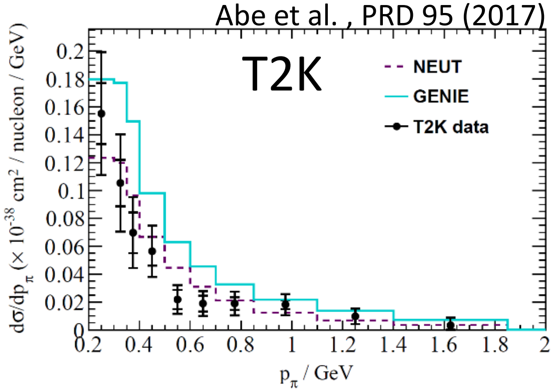
Eberly et al. , PRD 92 (2015)



MiniBooNE - MINERvA



Abe et al. , PRD 95 (2017)



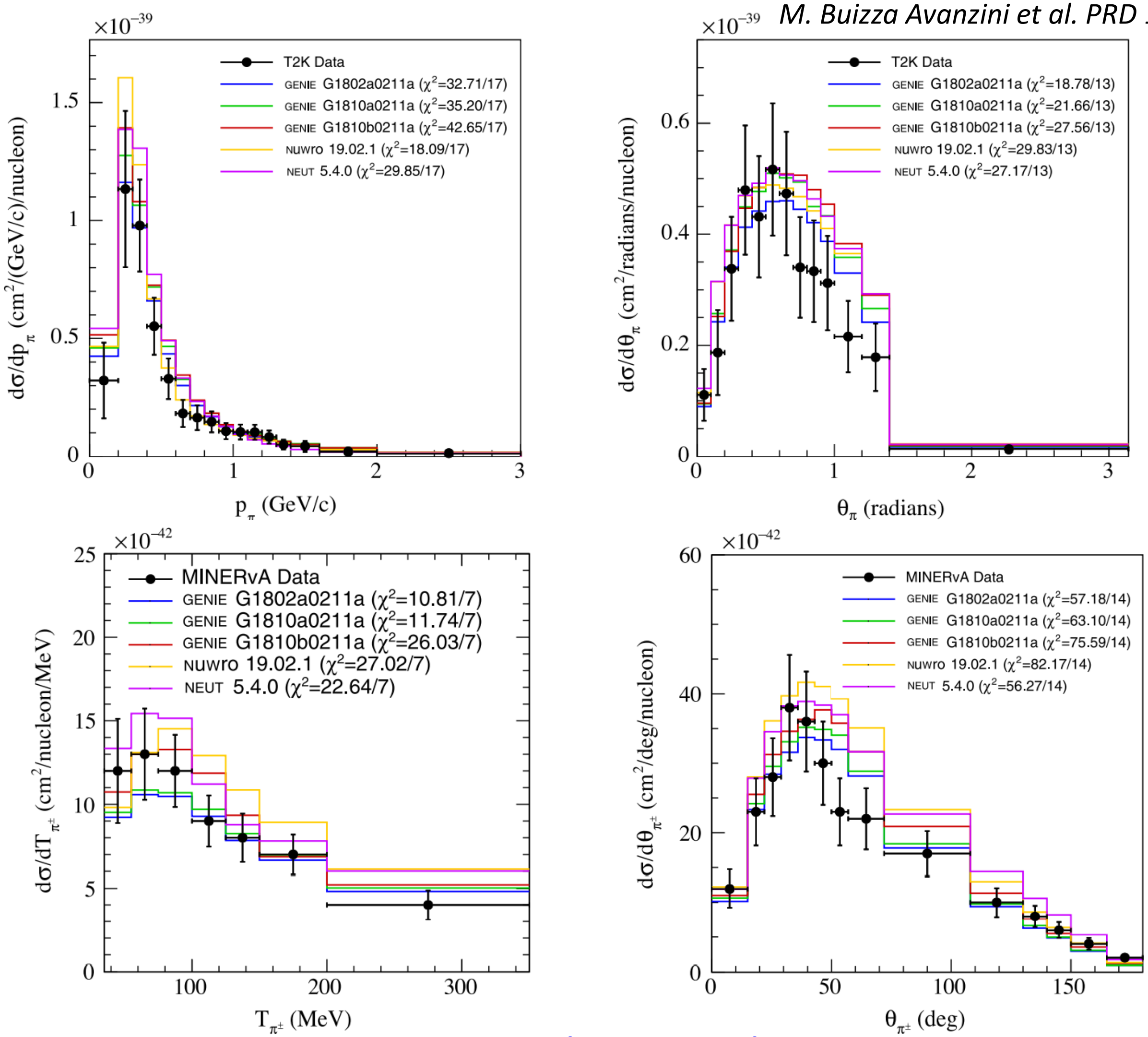
Historically many tensions

- models .vs. data ??
- models .vs. models??
- data .vs. data (through models)??

the 1π puzzle

Pion puzzle – T2K and MINERvA data .vs. Monte Carlo (2022)

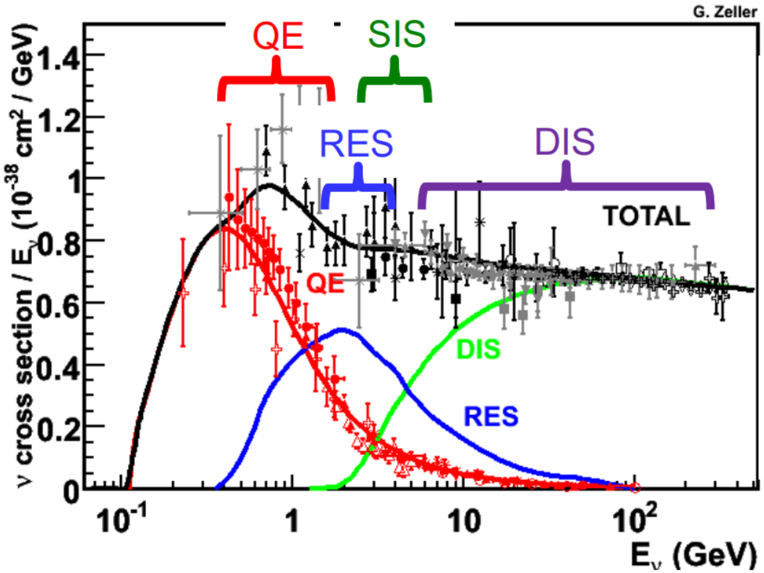
M. Buizza Avanzini et al. PRD 105, 092004 (2022)

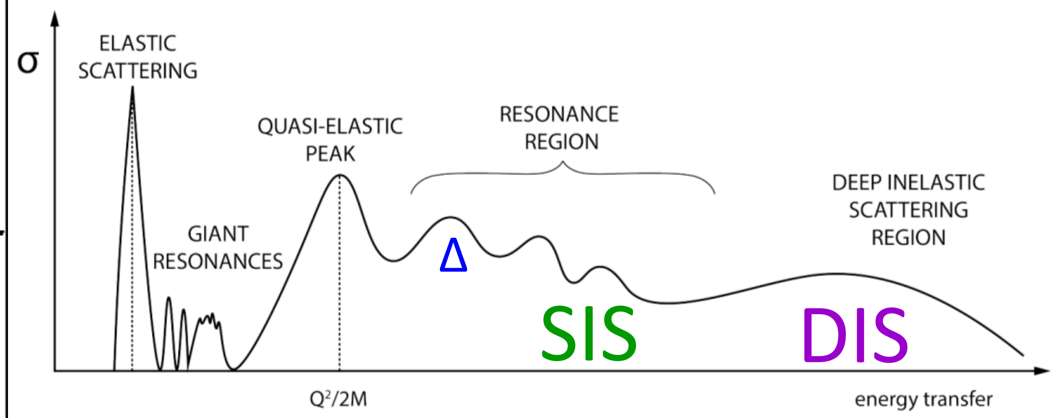


Tensions remain

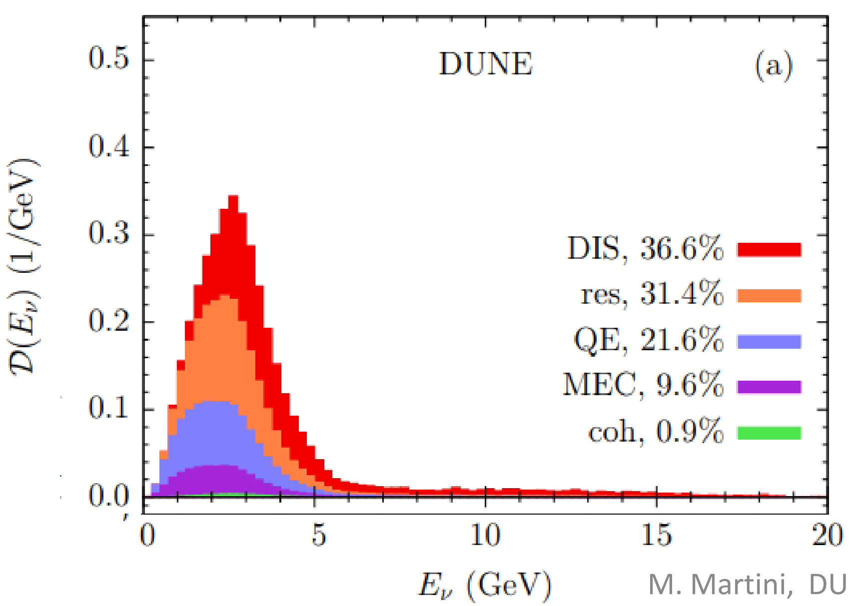
- The generators used to extract the cross section is often the one with the best description of the data
- Experimental collaborations have more advanced analyses in progress (T2K Vargas and MINERvA McFarland @ NuInt22)
- These Monte Carlo results are based on Δ dominated models
- None of the common event generators include nuclear medium effects for the Δ

Beyond Δ resonance





A. Ankowski



- The complications of pion data analyses lay not only on the modeling of primary production and pion FSI but also on the fact that **all hadronic processes** related to shallow inelastic scattering (SIS) and DIS regions **must be modeled correctly**
- **SIS and DIS have been minimally studied both experimentally and theoretically with neutrino scattering**
- **A major challenge, important in particular for DUNE**

T. Katori, M. Martini, J.Phys.G 45 1, 013001 (2018)
L. Alvarez-Ruso et al. Prog. Part. Nucl. Phys. 100, 1–68 (2018)
M. Sajjad Athar, J. G. Morfín, J.Phys. G 48, 034001 (2021)

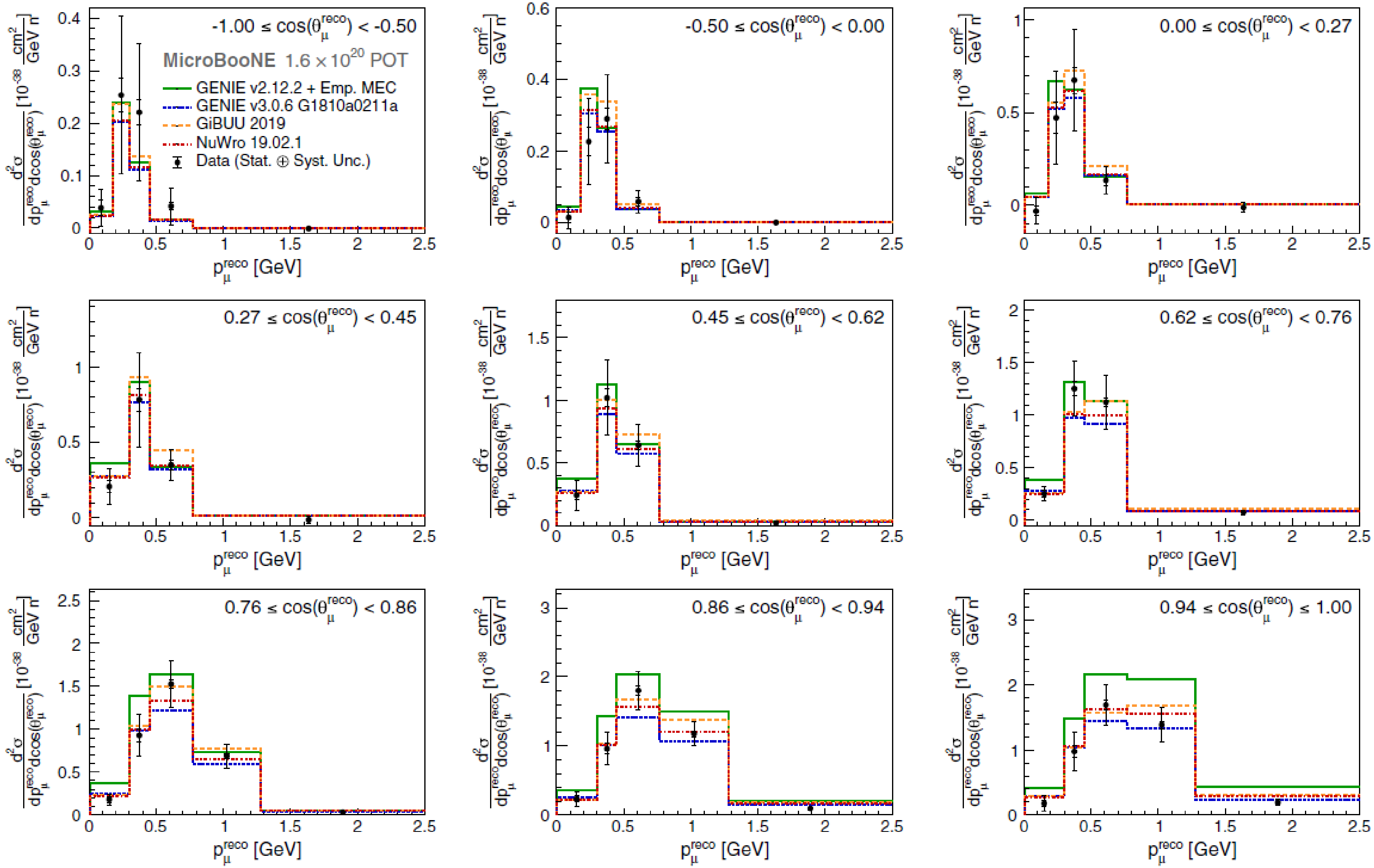
Recent cross sections results on Argon (MicroBooNE)

A) Inclusive measurements :
only the muon is detected

First MicroBooNE measurement on Argon: inclusive $d^2\sigma/dp_\mu d\cos\theta_\mu$

- CC Inclusive: only the charged lepton is detected. All reaction mechanisms contribute

PHYSICAL REVIEW LETTERS **123,** 131801 (2019)

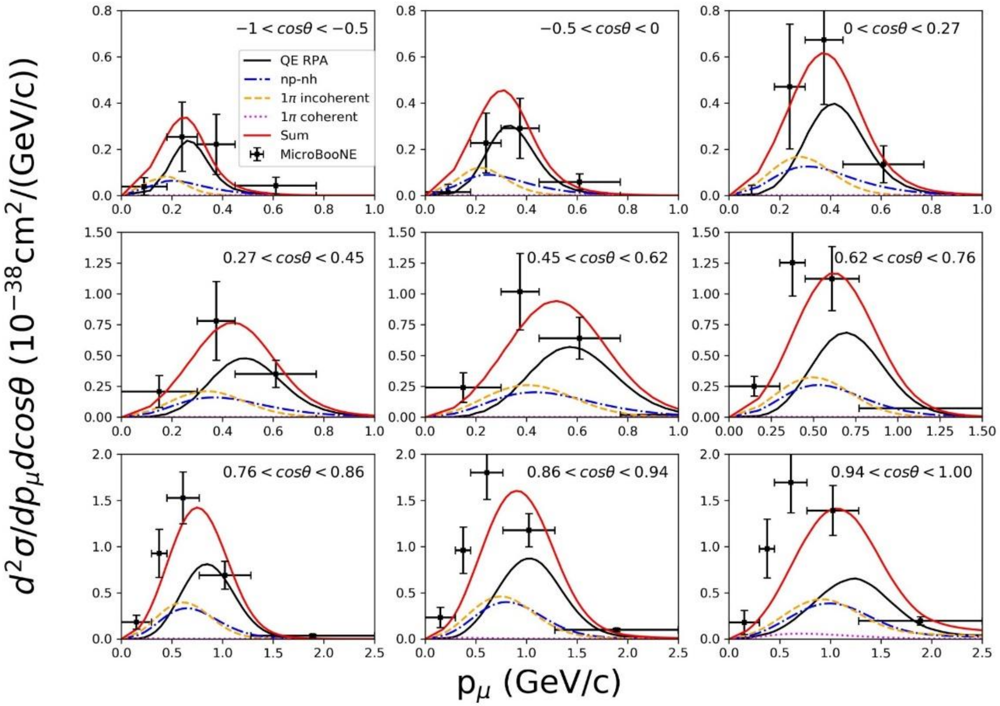


RPA and SuSAv2 calculations of MicroBooNE inclusive d$^2\sigma$ on argon

RPA

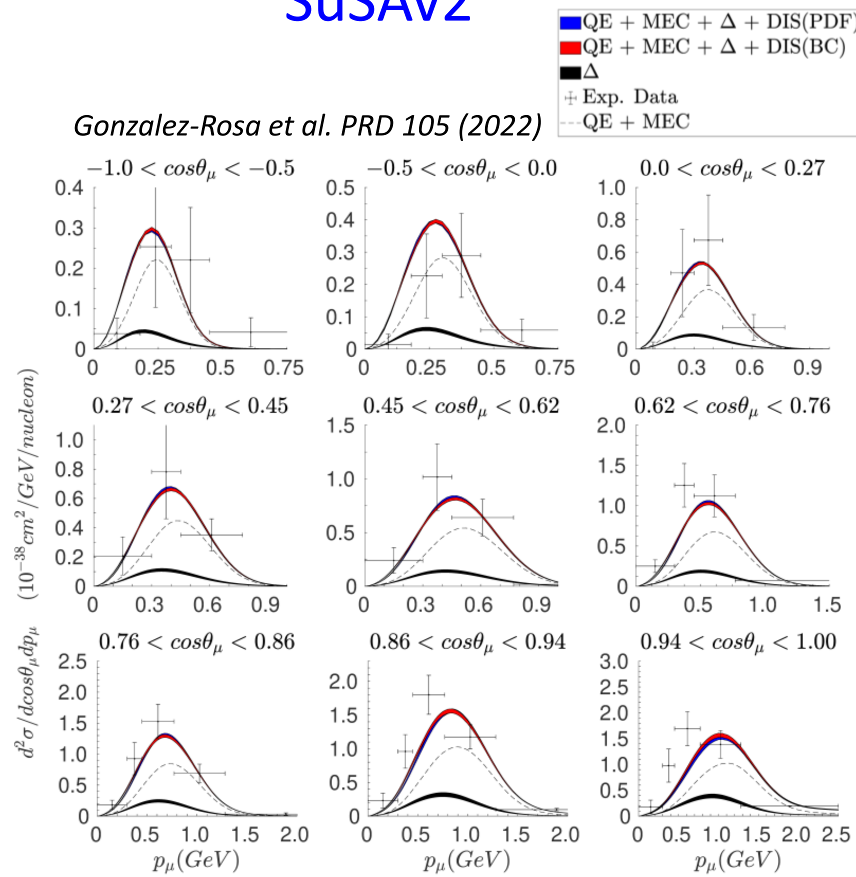
Total = QE + np-nh + 1π inc.+ 1π coh.

M. Martini, M. Ericson, G. Chanfray, PRC 106 (2022)



SuSAv2

Gonzalez-Rosa et al. PRD 105 (2022)



Results also with SuSA
Barbaro et al. Universe 7 (2021)

- Reasonable overall **agreement**, though **not as good as in the ^{12}C T2K** inclusive case (see next slide)
- At backward angles the predictions of the different models are slightly shifted to lower values of p_μ, whereas the reverse occurs at forward angles

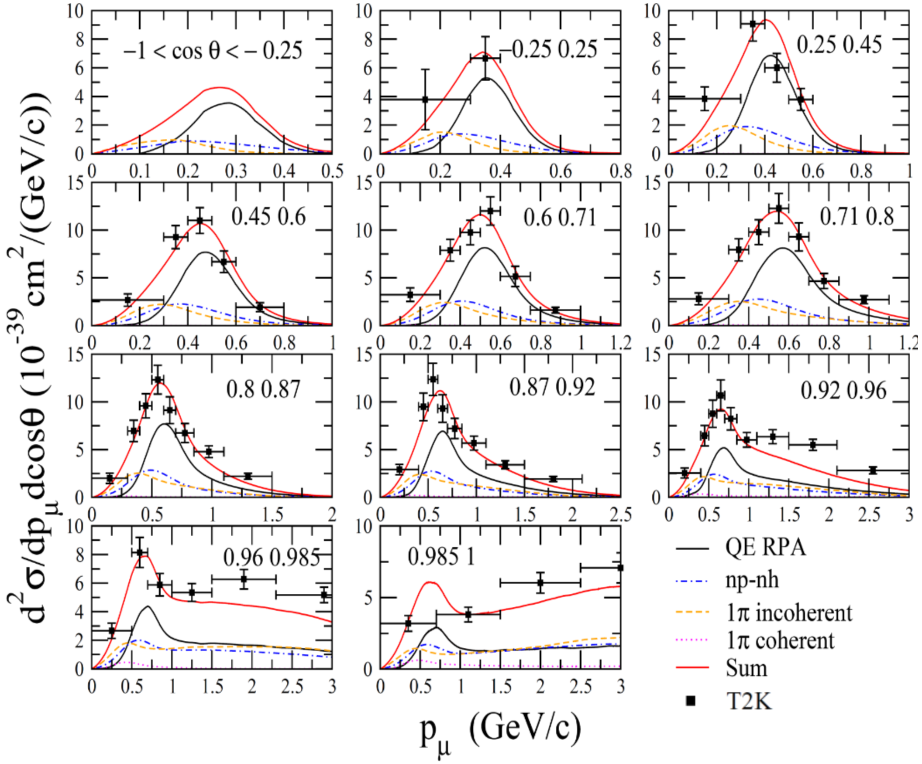
RPA and Monte Carlos calculations of T2K inclusive $d^2\sigma$ on carbon

PHYSICAL REVIEW D **98**, 012004 (2018)

Measurement of inclusive double-differential ν_μ charged-current cross section with improved acceptance in the T2K off-axis near detector

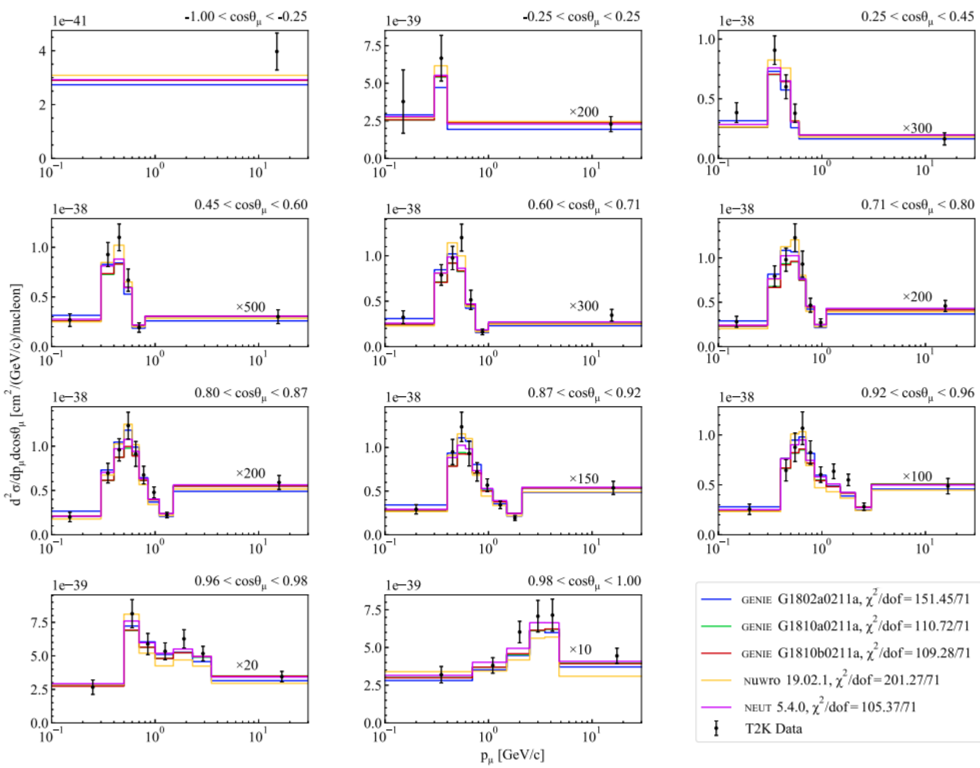
RPA

M. Martini, M. Ericson, G. Chanfray, PRC 106, 015503 (2022)



Monte Carlo

M. Buizza Avanzini et al. PRD 105, 092004 (2022)

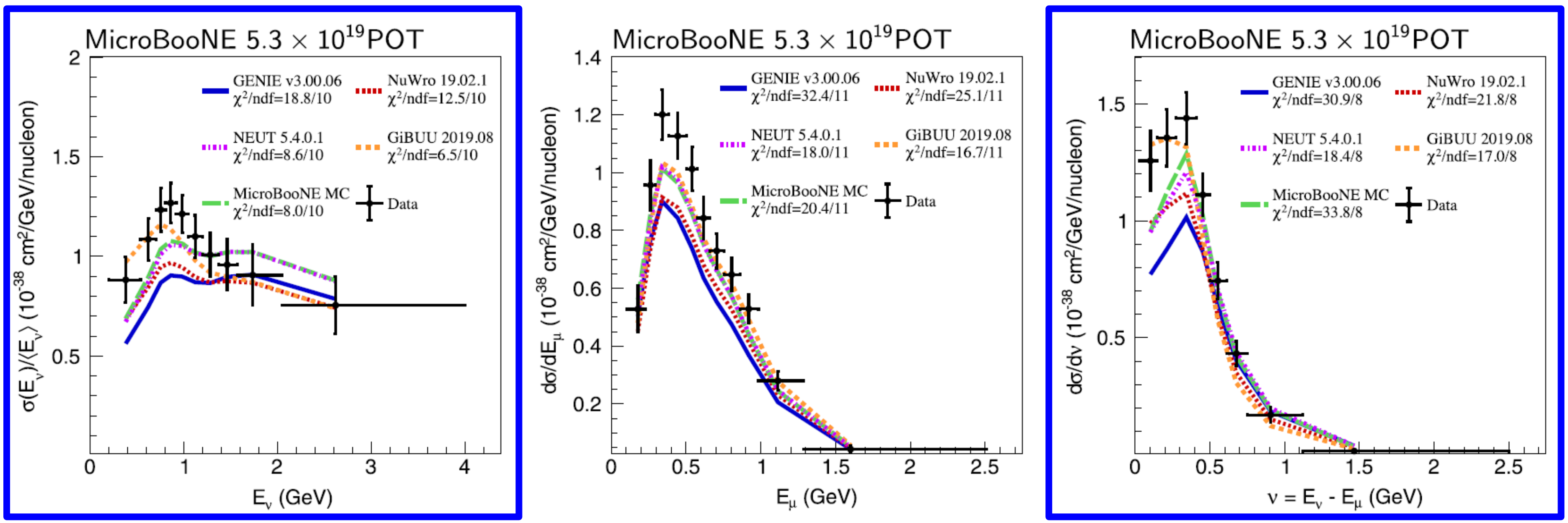


Remarkable agreement

Recent energy-dependent inclusive MicroBooNE cross sections on argon

PHYSICAL REVIEW LETTERS **128,** 151801 (2022)

First Measurement of Energy-Dependent Inclusive Muon Neutrino Charged-Current Cross Sections on Argon with the MicroBooNE Detector



Results presented for the first time as a function of true neutrino energy E_ν and transferred energy (ν or ω)

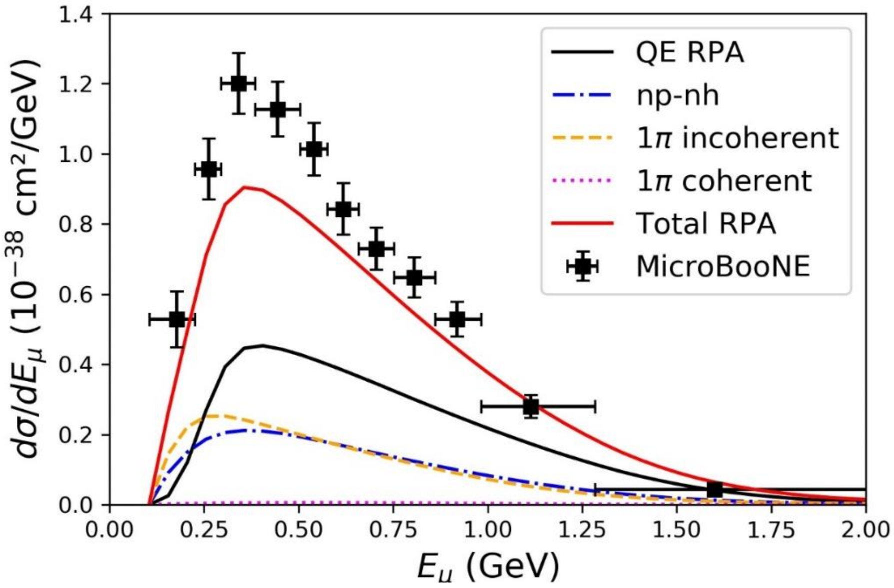
This has been made possible by a **new procedure**, **based on the comparison between the data and the Monte Carlo predictions constrained on the lepton kinematics**, allowing the mapping between the true E_ν and ω on one hand, and the reconstructed neutrino energy E_ν^{rec} and hadronic energy E_{had}^{rec} on the other hand

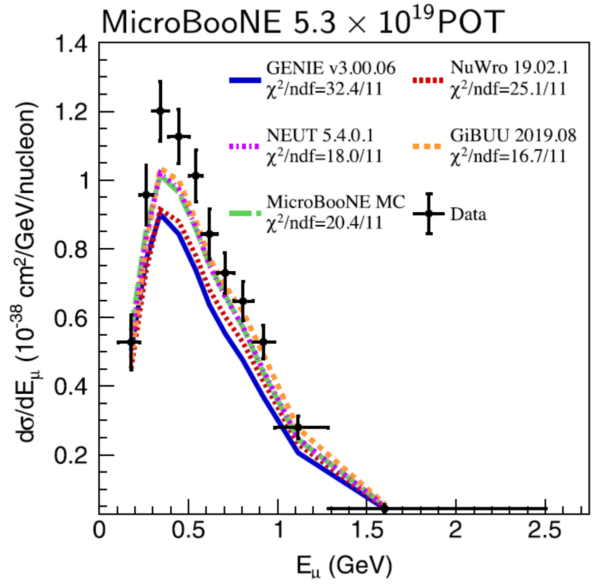
- Model dependence ?

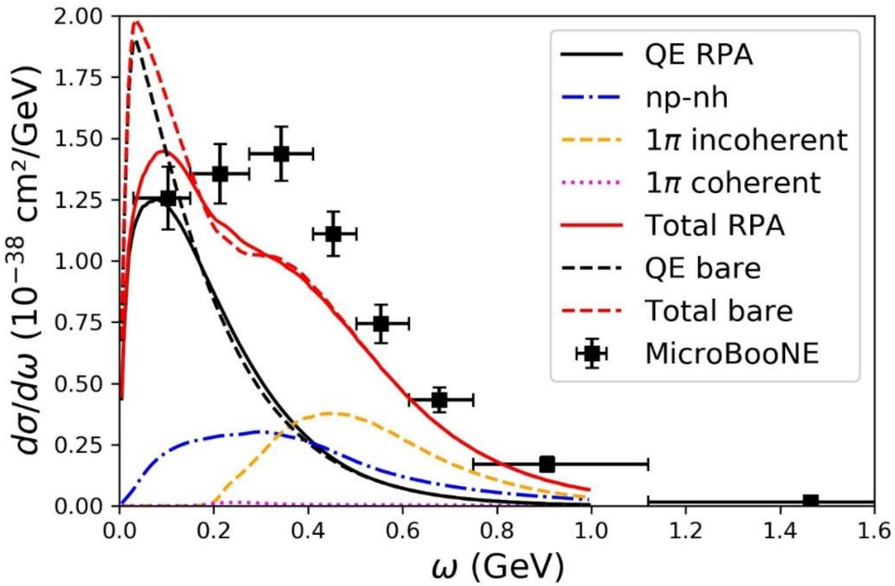
MicroBooNE flux-averaged inclusive $d\sigma/dE_\mu$ and $d\sigma/d\omega$ on argon

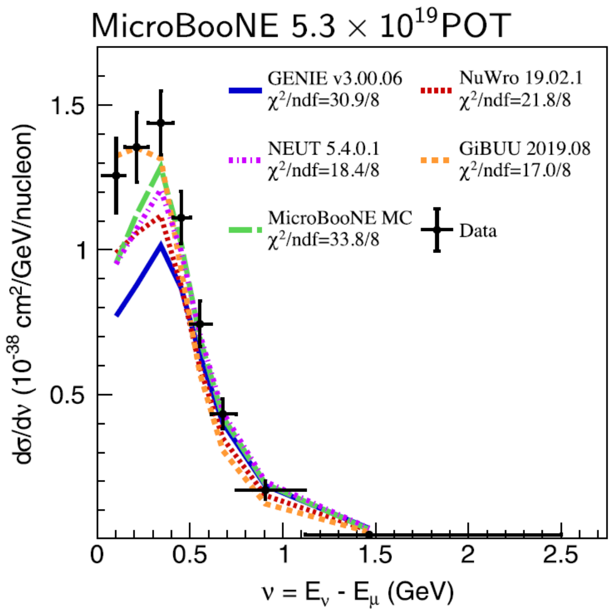
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

PRL 128, 151801 (2022)









In principle $d\sigma/d\omega$ allows a better separation of the different channels

Detector effects: unfolding measures and smearing theoretical models

Measured observables are always convoluted with detector effects.
Up to now neutrino cross sections (MiniBooNE, T2K, MINERvA,…) data have been presented after a deconvolution of these effects.
Such measurements are usually called **“unfolded”.**
Unfolded measurements can be easily compared with models

$$\left(\frac{d\sigma}{dx}\right)_j = \sum_i \frac{U_{ji}(N_i - B_i)}{\Phi T \epsilon_j (\Delta x)_j}$$

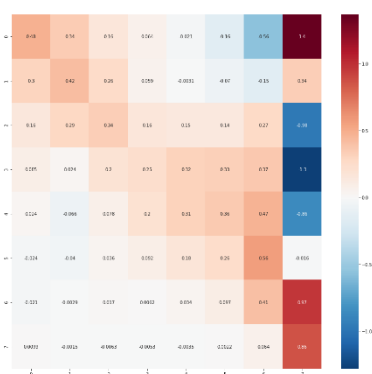
(see slide 9)

In the case of MicroBooNE the bias introduced in unfolding is captured in an **additional smearing matrix** that should be applied to every theoretical prediction.

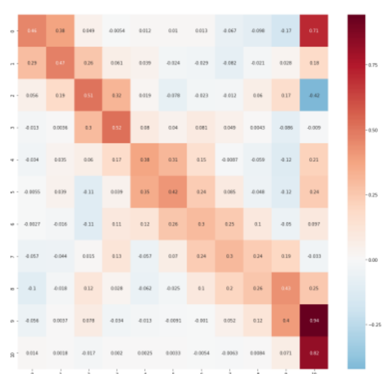
$$\sigma_{smeared} = M_{add\_smr} \times \sigma_{model}$$

For quantitative analysis additional smearing and covariant matrices are hence shared by MicroBooNE

Additional Smearing Matrices

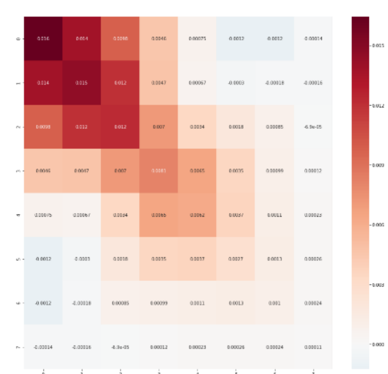


$d\sigma/d\omega$

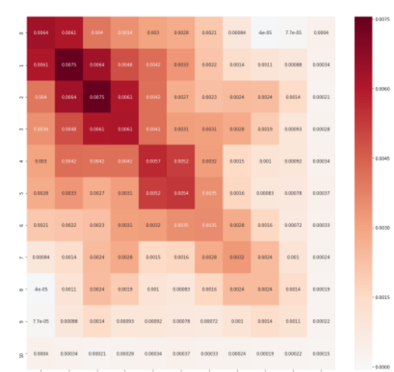


$d\sigma/dE_\mu$

Covariant Matrices



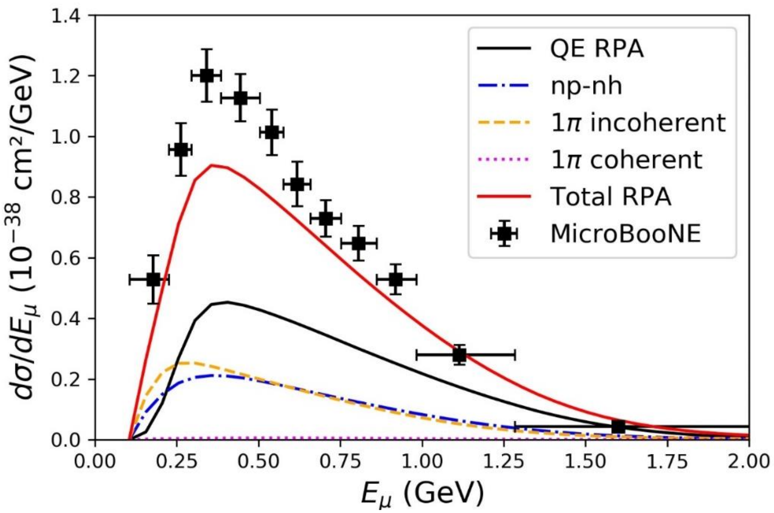
$d\sigma/d\omega$



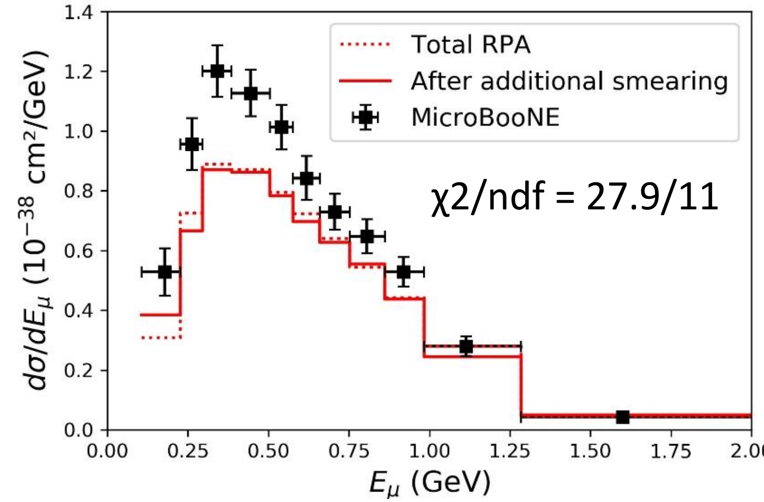
$d\sigma/dE_\mu$

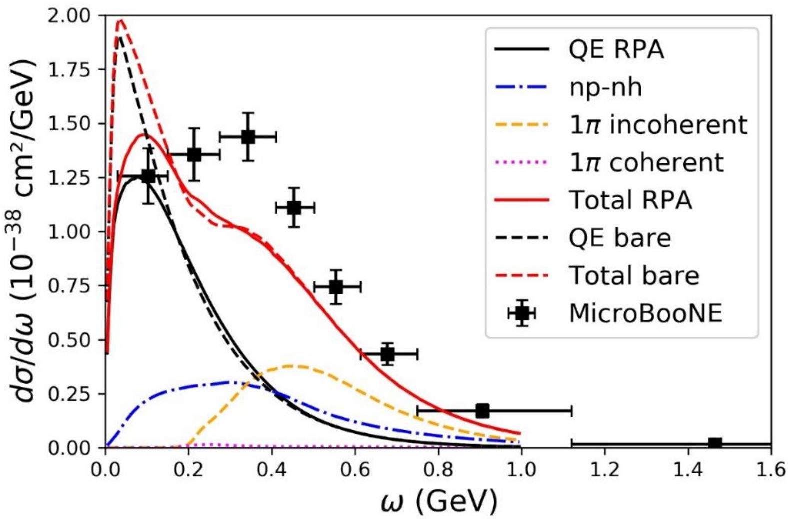
Theoretical results before and after the additional smearing

M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

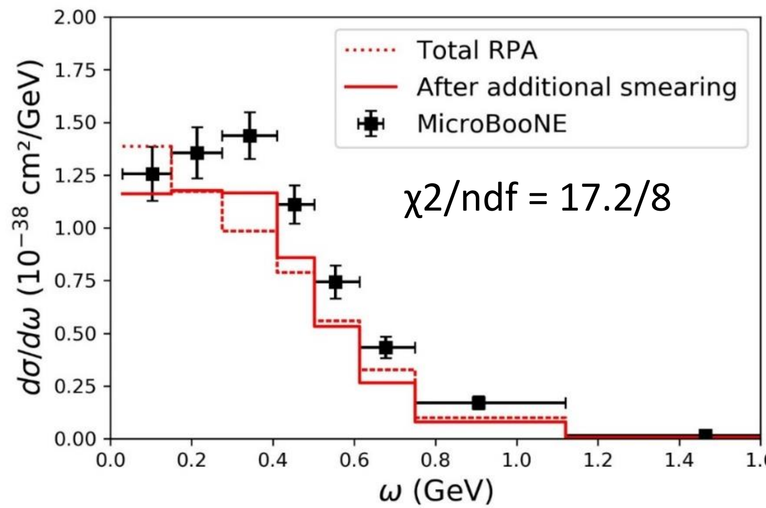


$d\sigma/dE_\mu$





$d\sigma/d\omega$



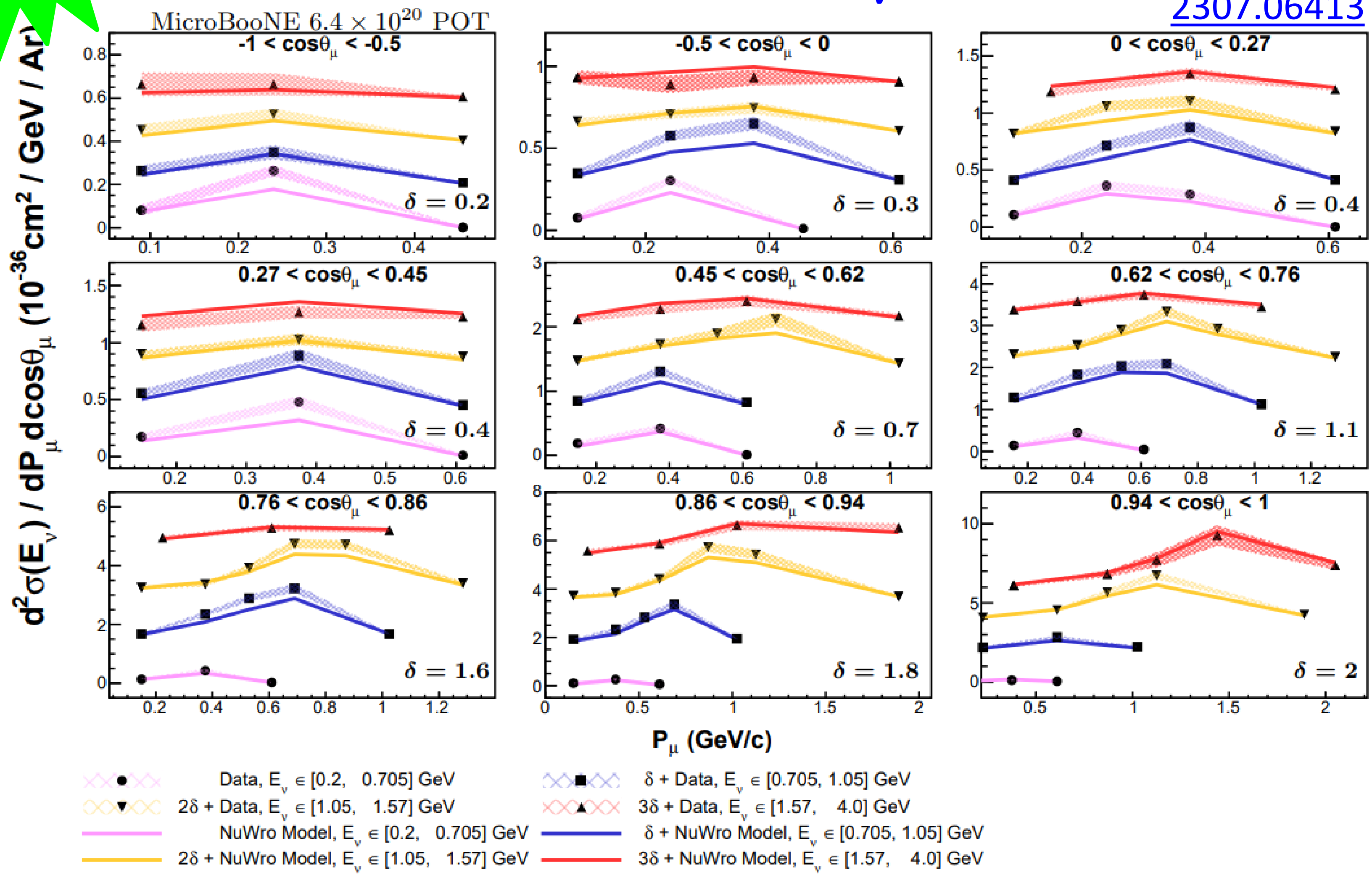
- The impact of the smearing is larger for $d\sigma/d\omega$ than for the $d\sigma/dE_\mu$
- The smearing produces a redistribution of the strength which is more important when the cross section is peaked, such as in the quasielastic channel

NEW

MicroBooNE triple-differential CC inclusive cross section

Results for 4 different E_ν slices

2307.06413



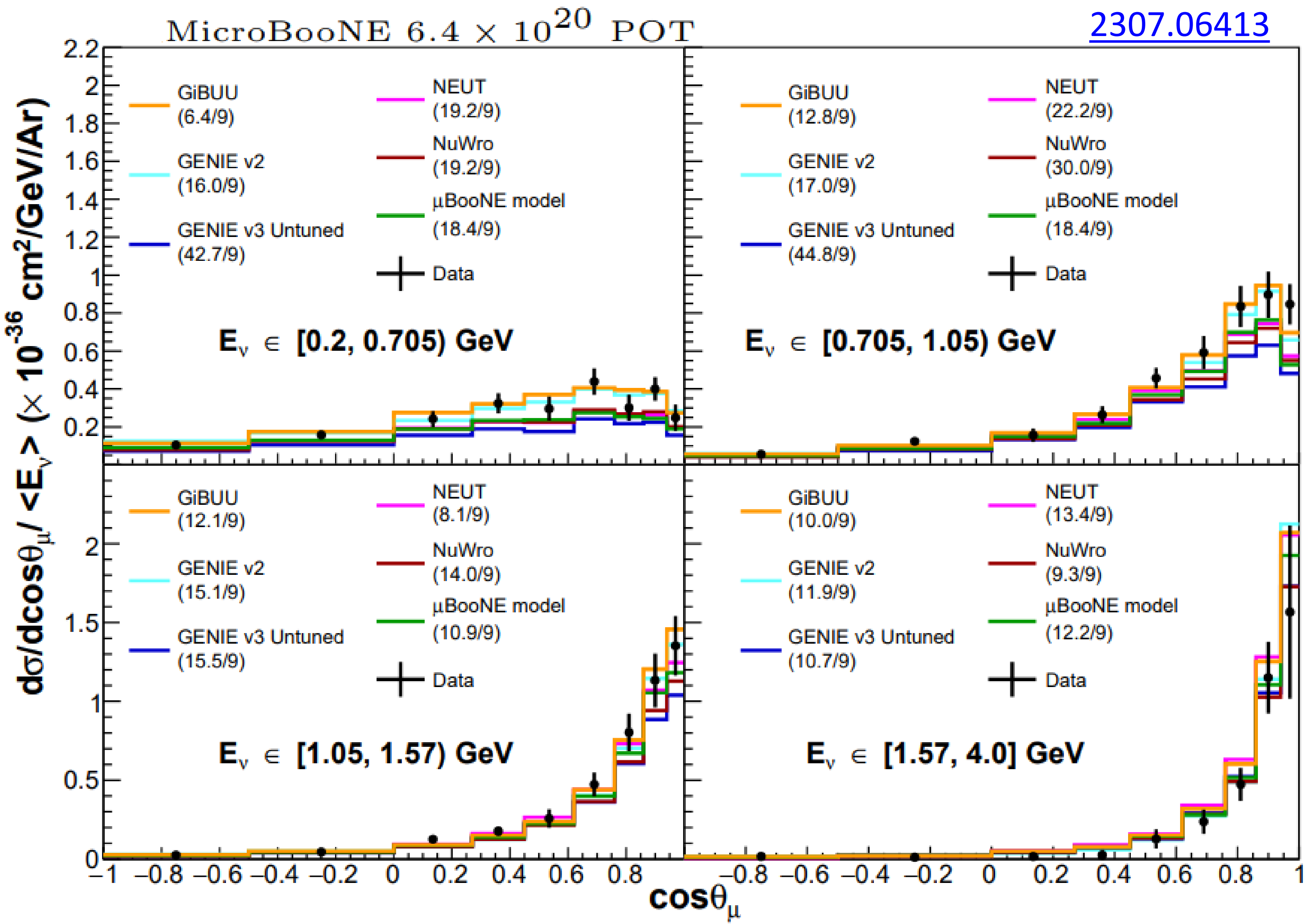
First time that this kind of results are available for neutrino cross sections

- No flux dependence!
- Model dependence ?

MicroBooNE double-differential CC inclusive cross section

After integrating over the muon momentum

2307.06413



Recent cross sections results on Argon (MicroBooNE)

B) Semi-inclusive processes: muon + proton(s) are detected

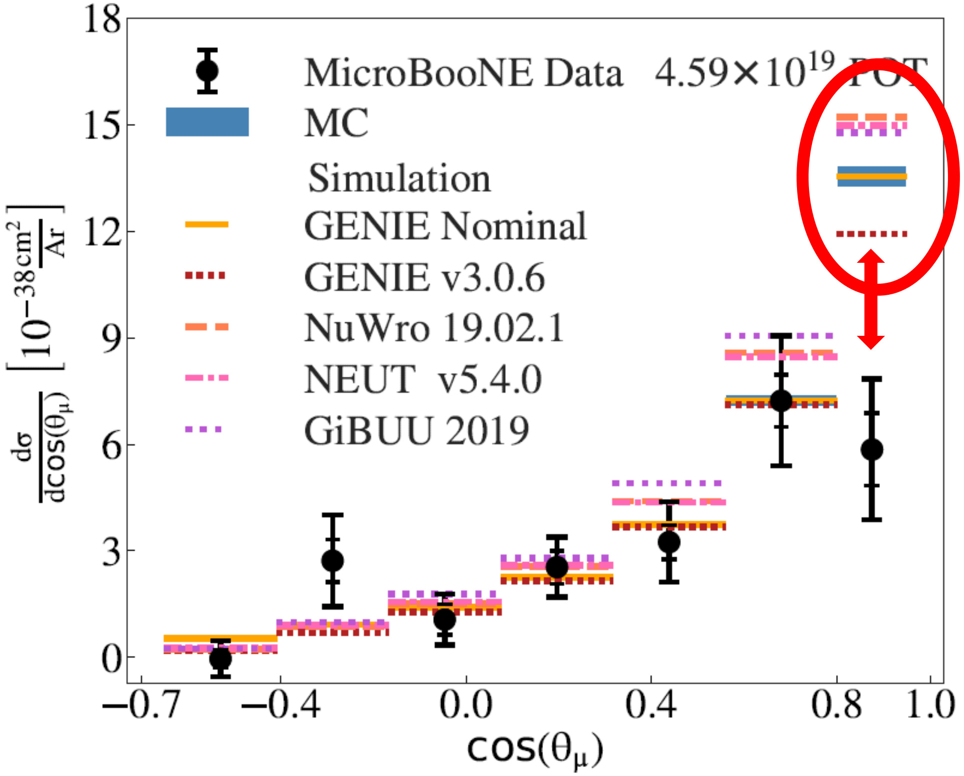
MicroBooNE **semi-inclusive CC0π1p** on argon

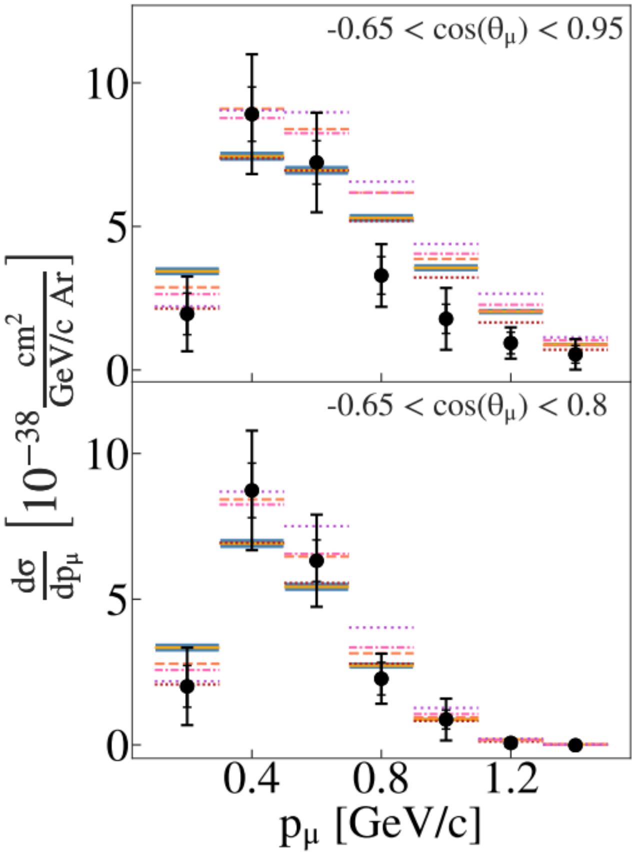
PHYSICAL REVIEW LETTERS **125**, 201803 (2020)

First Measurement of Differential Charged Current Quasielasticlike ν_μ-Argon Scattering Cross Sections with the MicroBooNE Detector

?! CCQE-like with another meaning than in the past

Results versus muon variables

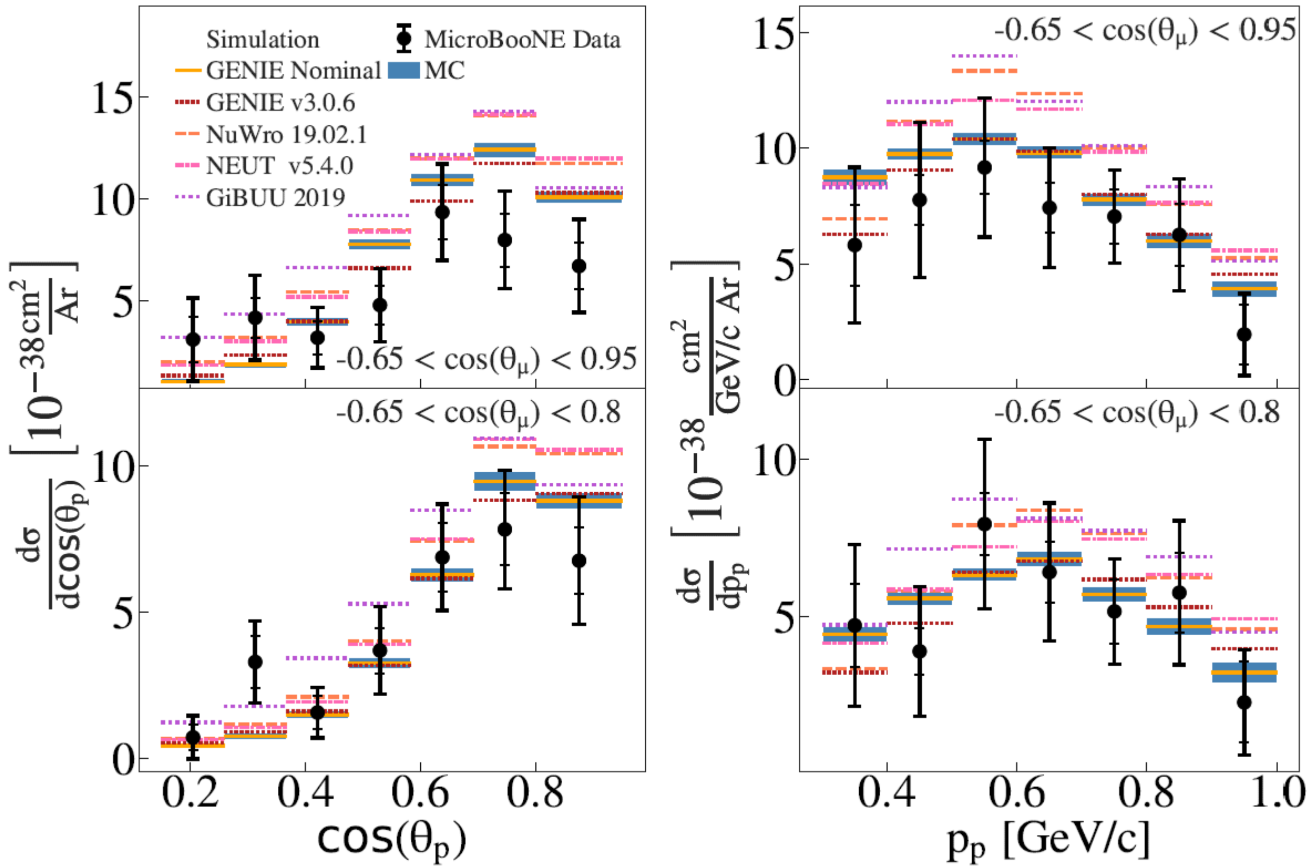




Overestimation of Monte Carlo predictions in the muon forward direction

MicroBooNE semi-inclusive CC0π1p on argon versus proton variables

MicroBooNE PRL 125(2020)

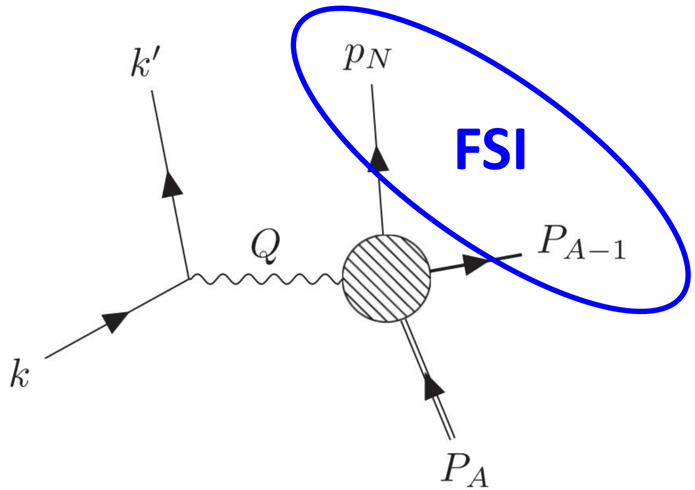


- Poor Monte Carlo – data agreement
- Spread of Monte Carlo predictions

How good are the current approximations (use "inclusive" models, factorization,…) of the Monte Carlos for the semi-inclusive processes?

Final State Interactions

FSI between the knocked-out particle(s) and the residual nucleus



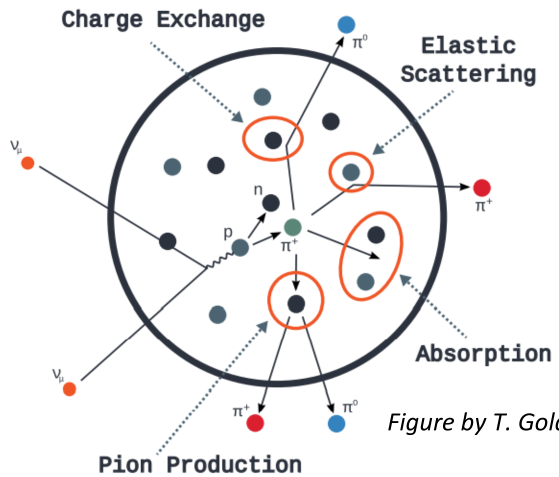


Figure by T. Golan

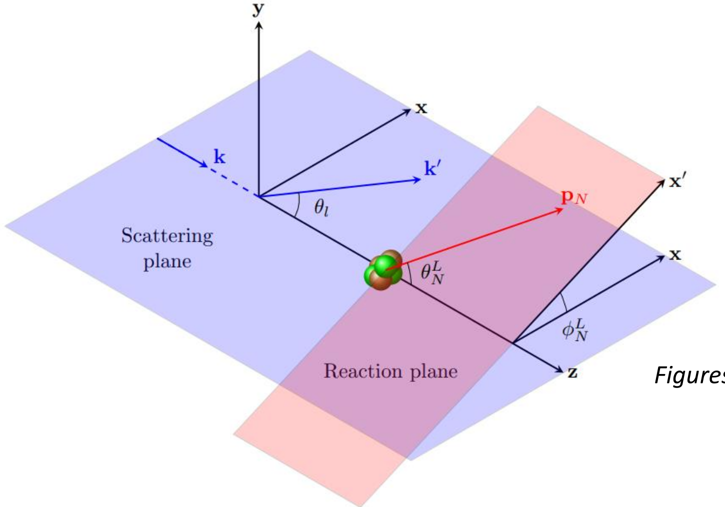
- Monte Carlo event generators include different models of intra-nuclear cascades: particles are assumed to be classical and move along a straight line
- FSI between the knocked-out nucleon and the residual nucleus can be microscopically treated using different approaches: Optical Potential, RMF, Energy-Dependent RMF

The inclusion of FSI effects is extremely important for the description of semi-inclusive data

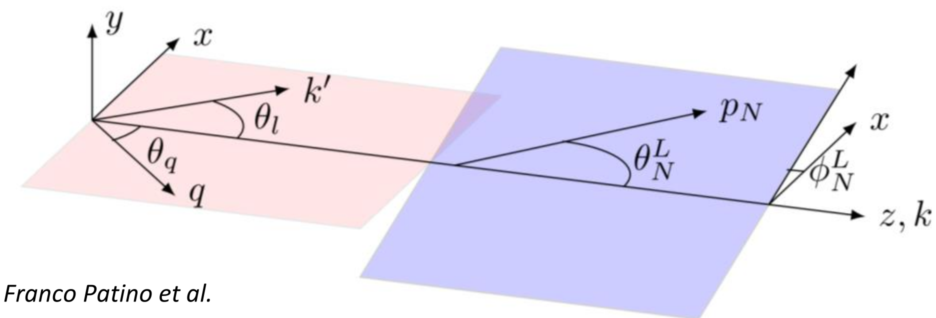
[Some recent references: *R. Gonzalez-Jimenez et al., PRC 101, 015503 (2020) ; J. Isaacson et al., PRC 103 015502 (2021); A. Nikolakopoulos et al. PRC 105, 054603 (2022); A. Ershova et al., PRD 106 032009 (2022)]*

The semi-inclusive neutrino cross section

There is an increasing interest on semi-inclusive cross sections



Figures by J. M. Franco Patino et al.



M. B. Barbaro talk @NUFACT 2021

$$\mathcal{F}_\chi^2 = L_{\mu\nu} W^{\mu\nu}$$
$$= V_{CC}R^{CC} + 2V_{CL}R^{CL} + V_{LL}R^{LL} + V_T R^T + V_{TT}R^{TT} + V_{TC}R^{TC} + V_{TL}R^{TL} + \chi\left(V_{T'}R^{T'} + V_{TC'}R^{TC'} + V_{TL'}R^{TL'}\right)$$

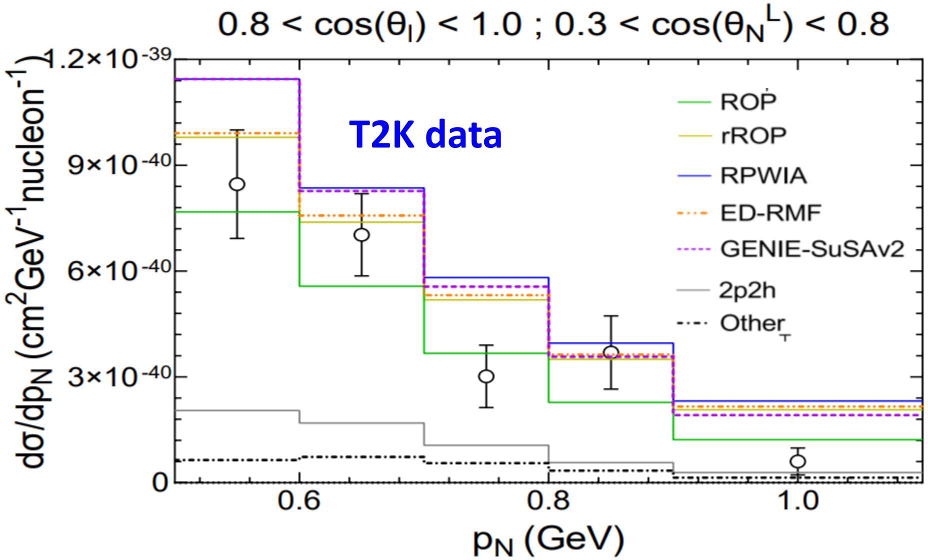
The $(\nu_\mu, \mu p)$ cross section is decomposed in **10 independent response functions** of **5 variables** $(\omega, q, \mathbf{p_N})$.
More complex structure than in the **inclusive** (ν_μ, μ) case: **5 new responses**, which vanish after integration over the final nucleon variables

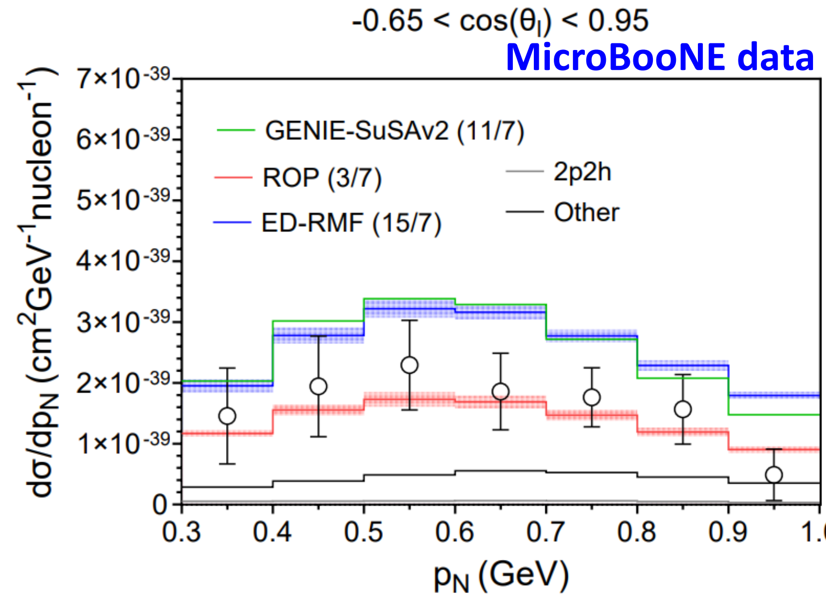
$$R^{TT,TC,TL,TC',TL'} \propto \cos(\phi), \cos(2\phi)$$ ϕ outgoing nucleon azimuthal angle

Semi-inclusive —> Inclusive (but not viceversa!)

Theoretical situation:
- few models and papers for genuine CCQE [*J. M. Franco Patino et al, PRC 102 (2020); PRD 104 (2021), PRD 106 (2022), 2304.01916;* A. V. Butkevich *PRC 105 (2022)]*
- one (incomplete due to the absence of Δ-MEC) model for 2p-2h [T. Van Cuyck et al. PRC 94 (2016); PRC 95 (2017)]

Semi-inclusive CC0π1p cross section: role of proton FSI

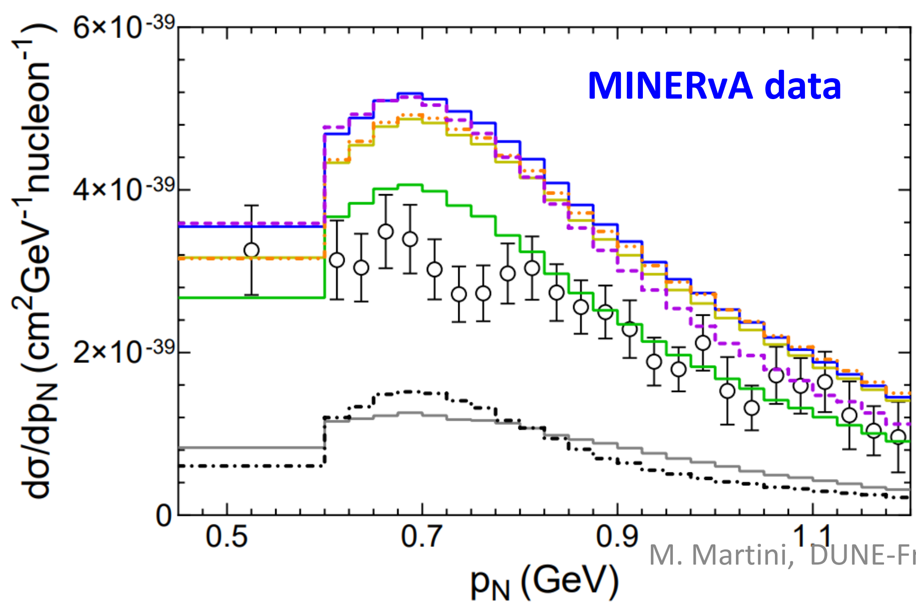




RPWIA: no FSI

GENIE-SuSAv2: include FSI but from inclusive model (factorization)

ED-RMF, **rROP**, **ROP**: different theoretical approaches for FSI



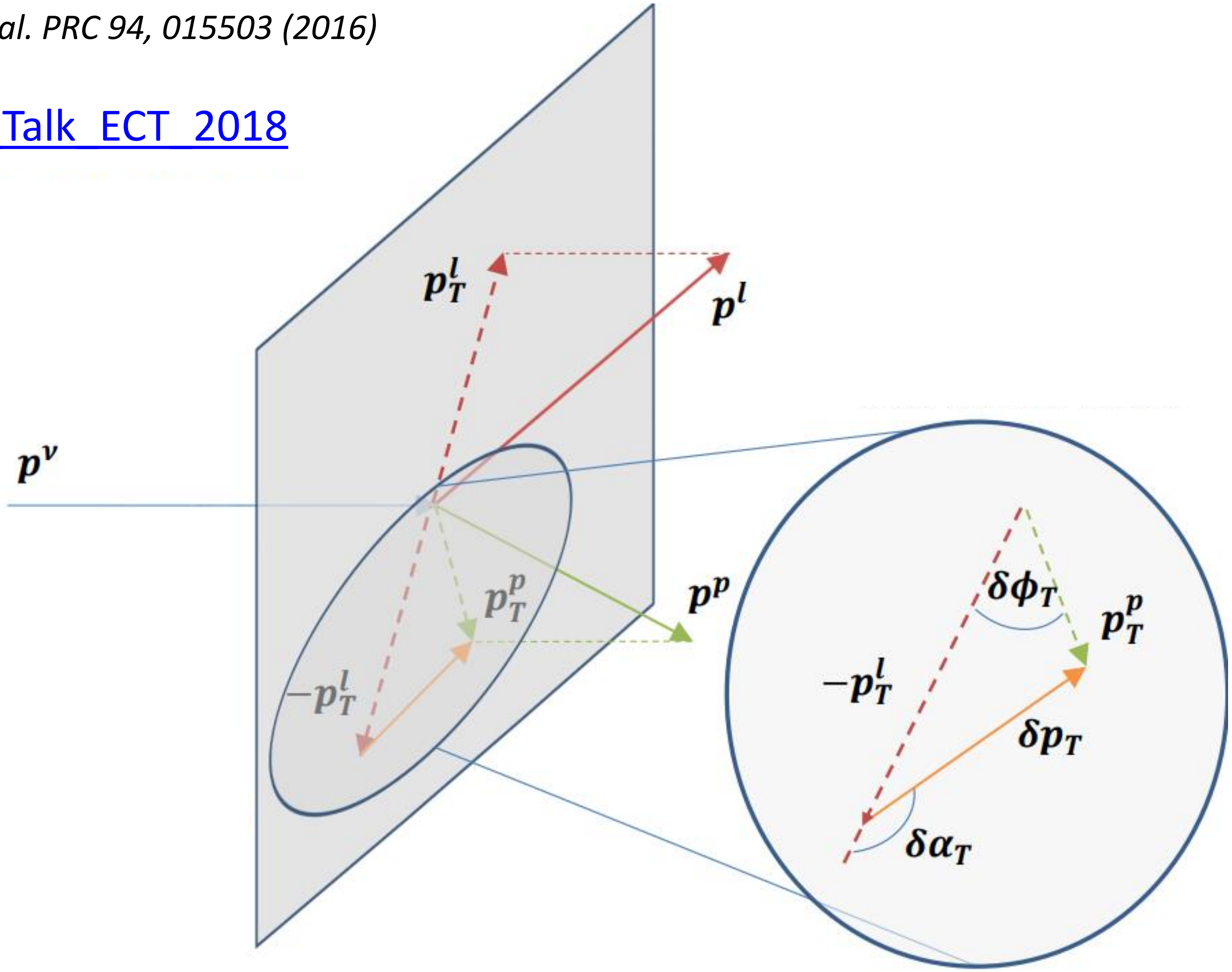
J. M. Franco Patino et al, PRD 106 (2022); 2304.01916

- FSI improve the agreement with data with respect to the RPWIA (no FSI) prediction
- Large differences between different FSI models

Single Transverse Kinematic Imbalance (STKI) variables (STV)

X. –G. Lu et al. PRC 94, 015503 (2016)

[S_Dolan_Talk_ECT_2018]



Scattering on a free nucleon at rest: $\vec{p}_T^{\,p} = -\vec{p}_T^{\,l}$

$\delta p_T = 0$; $\delta\phi_T = 0$ ⟶ peaked distributions

$\delta\alpha_T$ undefined ⟶ flat distribution

Deviations (imbalance) from these behaviors "measure" nuclear effects

Several recent MicroBooNE studies using Kinematic Imbalance Variables

NEW

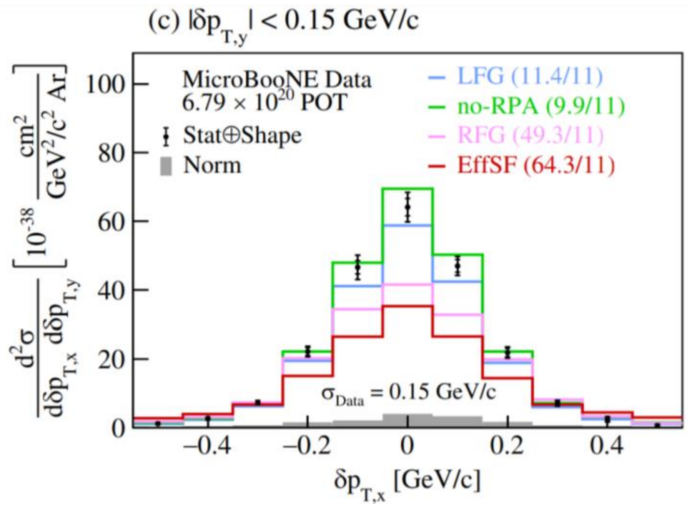
2D results for the first time on any neutrino target

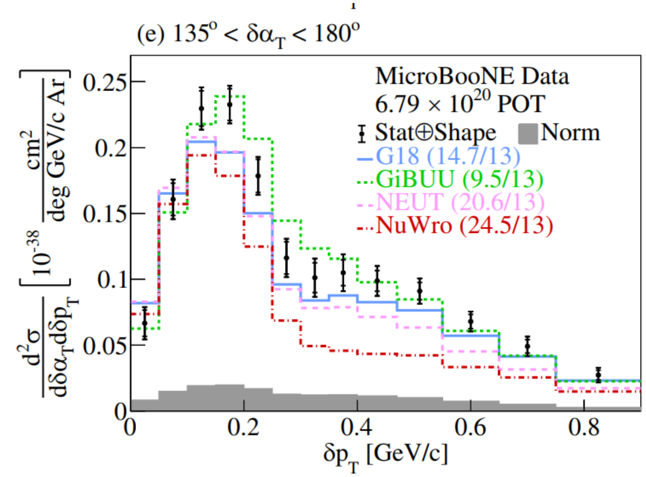
PHYSICAL REVIEW LETTERS **131,** 101802 (2023)

First Double-Differential Measurement of Kinematic Imbalance in Neutrino Interactions with the MicroBooNE Detector

PHYSICAL REVIEW D **108,** 053002 (2023)

Multidifferential cross section measurements of ν_μ-argon quasielasticlike reactions with the MicroBooNE detector





2310.06082

Measurement of nuclear effects in neutrino-argon interactions using generalized kinematic imbalance variables with the MicroBooNE detector

"These measurements allow us to demonstrate that the treatment of CCQE interactions in GENIEv2 is inadequate to describe data. Further, they reveal tensions with more modern generator predictions particularly in regions of phase space where FSI are important."

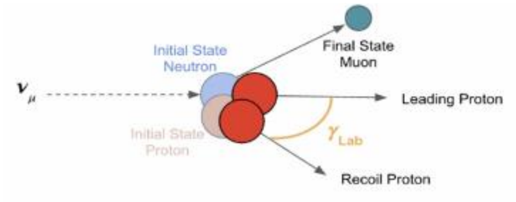
This is not a surprise since the generators implement "inclusive" microscopic models and "classical" cascade for FSI

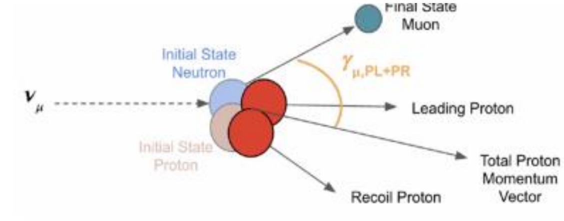
MicroBooNE semi-inclusive CC0π**2p** on argon

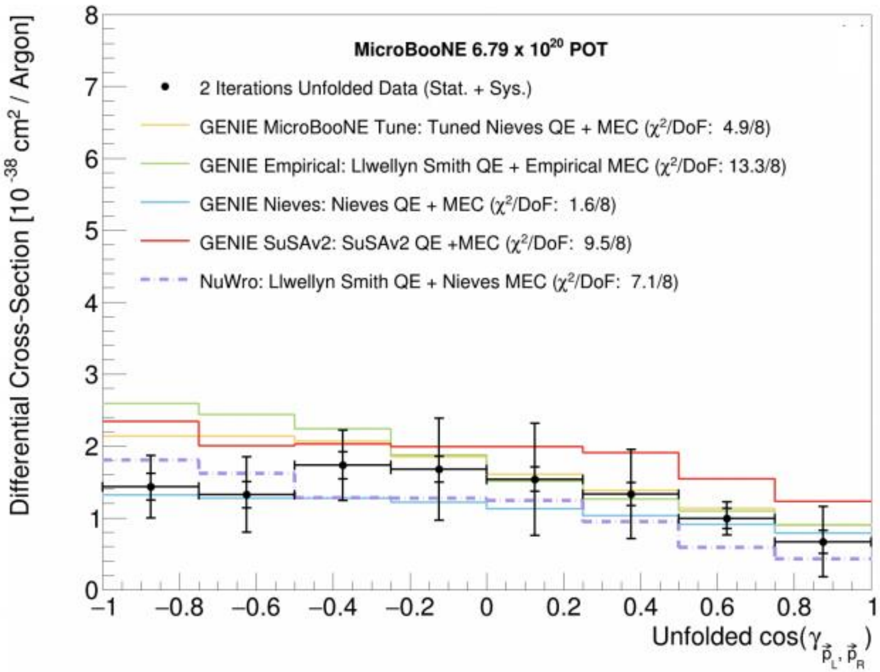
First Measurement of Differential Cross Sections for Muon Neutrino Charged Current Interactions on Argon with a Two-proton Final State in the MicroBooNE Detector

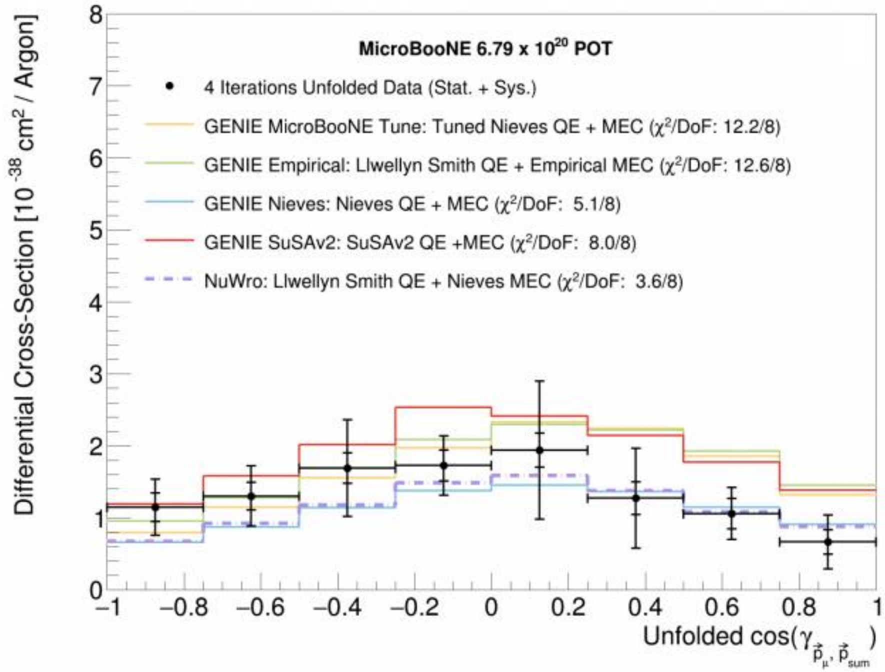
2211.03734

NEW







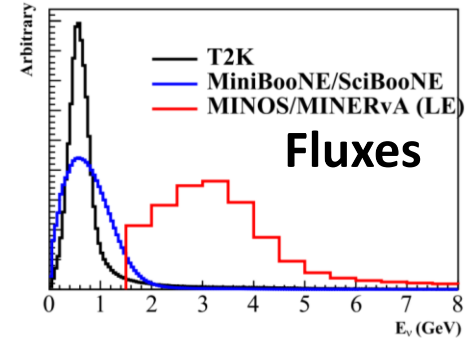


- Spread of Monte Carlo predictions
- How good are the current approximations of the MC for the semi-inclusive processes?

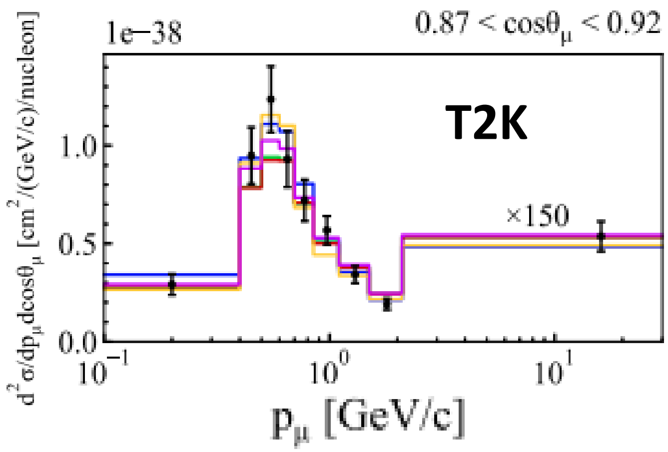
Complete semi-inclusive fully microscopic calculations of 2p-2h are not yet available

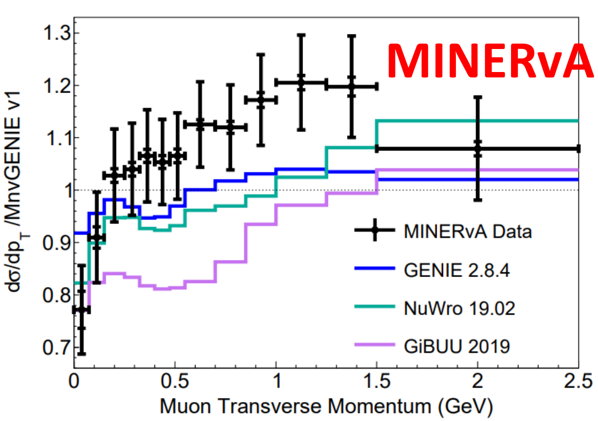
General considerations

1) The spread of the models increases with the neutrino energy

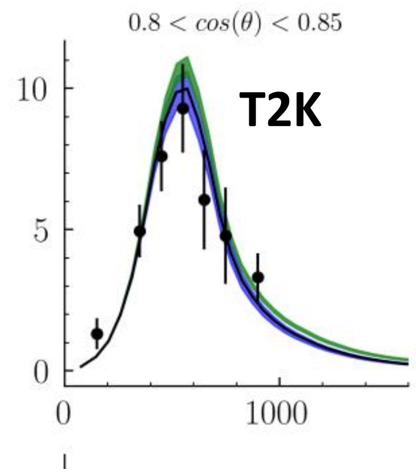


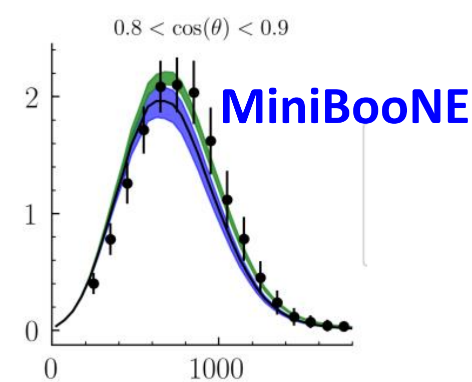
CC Inclusive



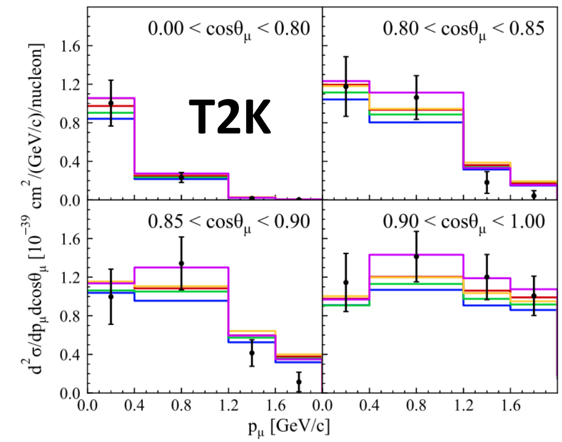


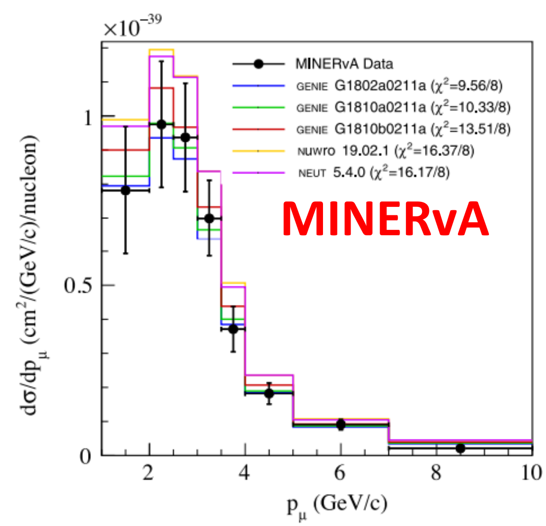
CC0π





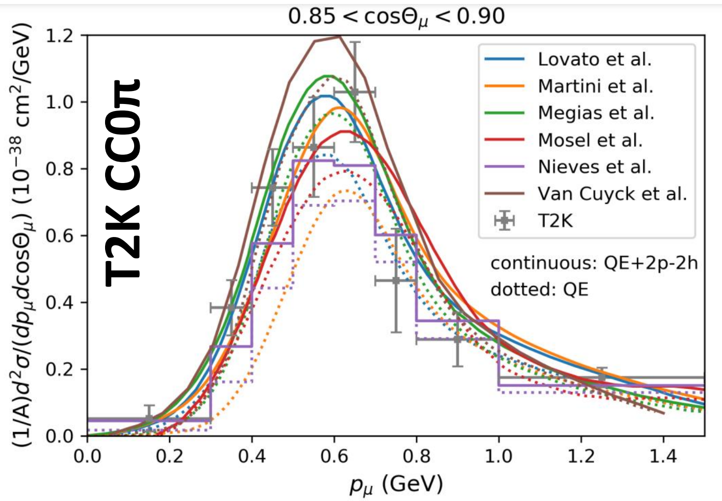
CC1π



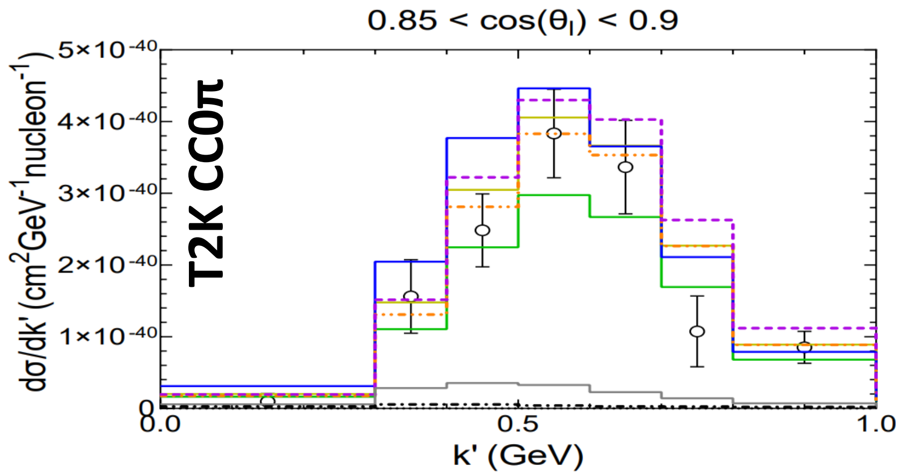


2) The spread of the models is larger in semi-inclusive processes

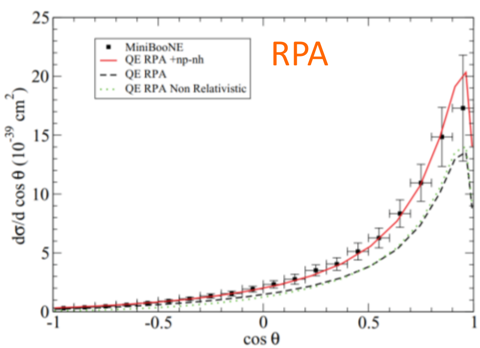
“Inclusive”

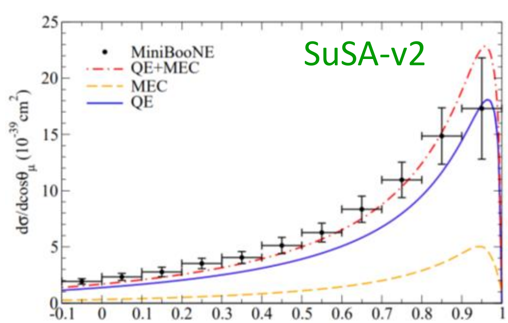


Semi-inclusive

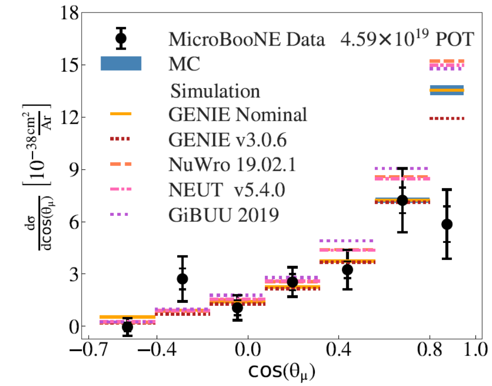


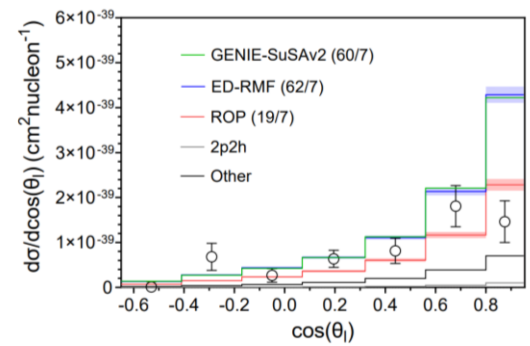
MiniBooNE “CCQE-like”





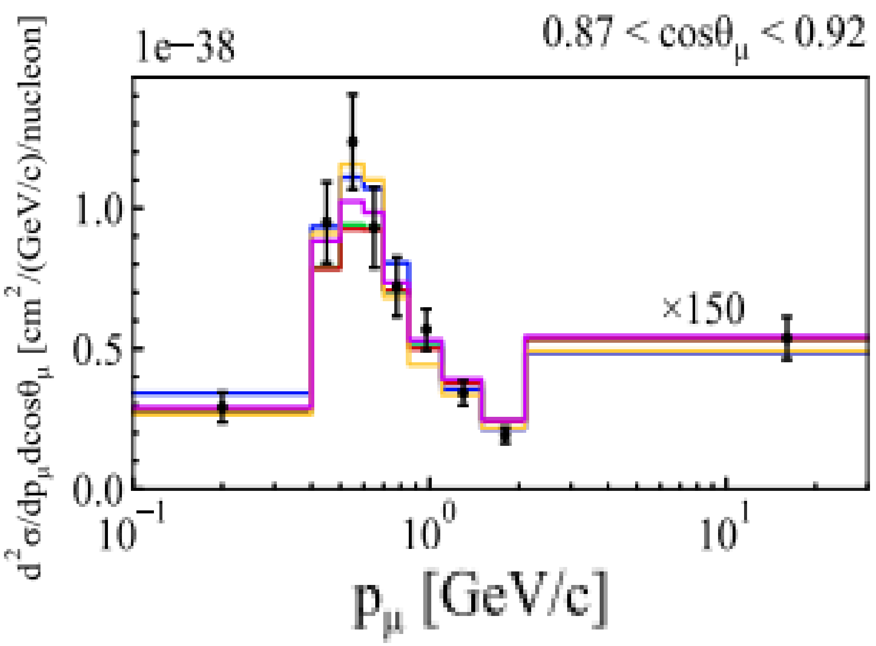
MicroBooNE CC0π1p





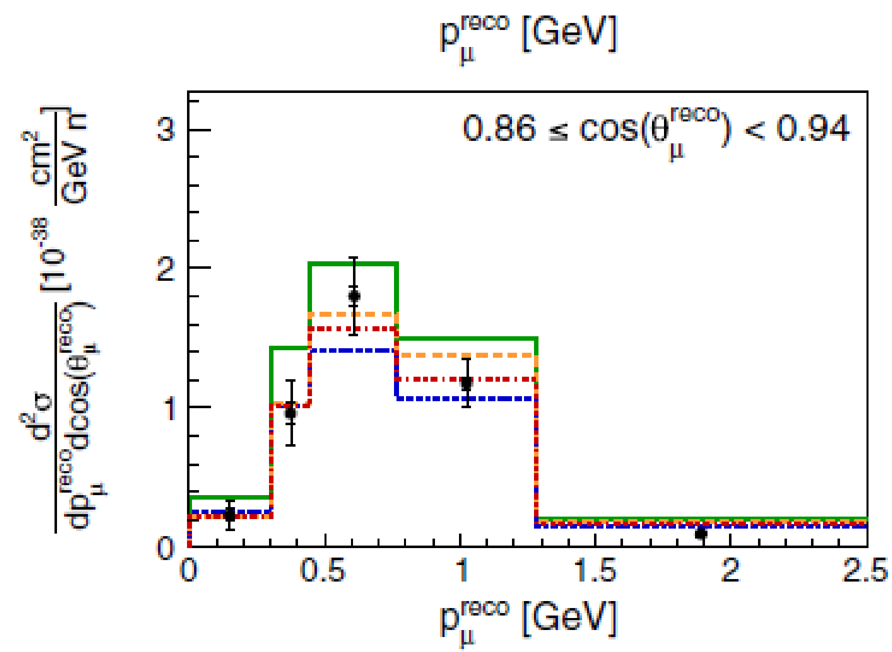
3) The spread of the models is larger for Argon than for Carbon

T2K Carbon



MicroBooNE Argon

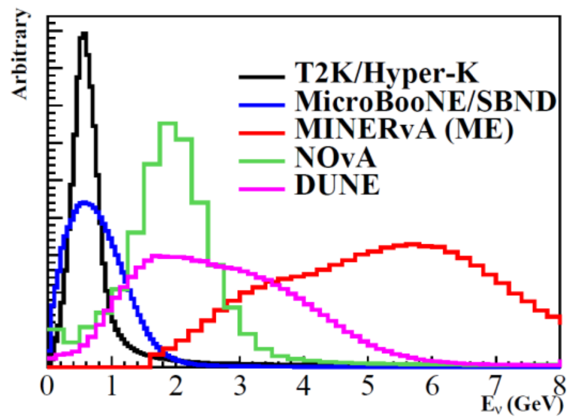
CC Inclusive



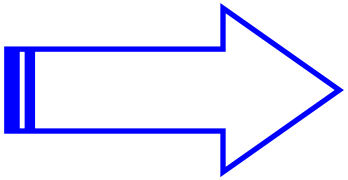
General comments

1) The spread of the models increases with the neutrino energy
2) The spread of the models is larger in semi-inclusive processes
3) The spread of the models is larger for Argon than for Carbon

This is not surprising since in the last 15 years the neutrino community focused on Carbon, on "inclusive" measurements as a function of the leptonic variables (Cherenkov detectors) and on "low" neutrino energy (MiniBooNE and T2K)



DUNE will be at larger energies, will use Argon detectors, will exploit semi-inclusive measurements as a function of leptonic and hadronic variables



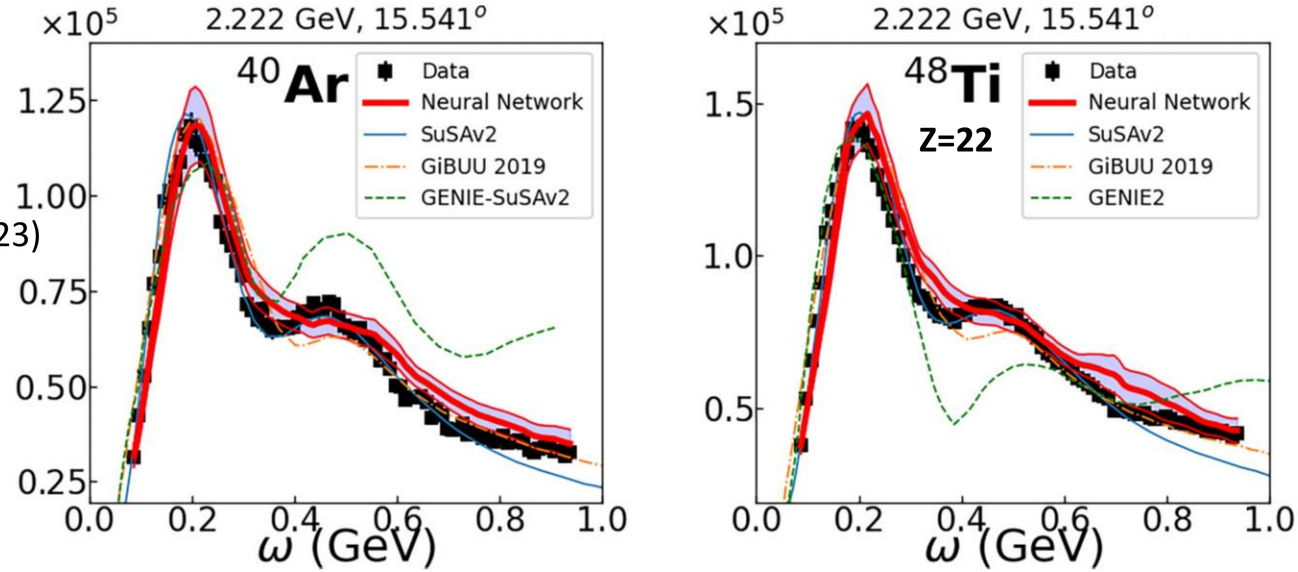
Many studies are needed!

Further elements for discussion

- Any model pretending to describe neutrino cross sections should first be validated by comparing its predictions with electron scattering data.
  Many data exists for N=Z nuclei (12C, 16O, 40Ca). Not so much for 40Ar (Z=18, N=22).

(e,e')

O. Al Hammal et al.
PRC 107, 065501 (2023)



- Many microscopic models have been initially developed for N=Z nuclei.
  - how good are their generalizations to asymmetric nuclei?
  - how reliable are in the Monte Carlo the approximations to obtain Argon predictions starting from microscopic models for Carbon?

- For the moment fully microscopic models for semi-inclusive processes are scarce and not yet implemented in Monte Carlo
  - what we learn by comparing semi-inclusive measurement as a function of hadronic variables with Monte Carlo predictions based on inclusive models?

Neutrino cross sections: summary of status and perspectives

A) Cross sections in terms of muon variables (CC inclusive, CC0π)

- **Significant progress in the last 15 years**
- Many experimental and theoretical results
- Still we have to tackle currently existing degeneracies:
  1. between cross sections and flux uncertainties
  2. between nucleon uncertainties and nuclear effects
  3. between different nuclear models and approximations

B) Cross sections in terms of hadronic variables (CC1π, CC0π1p, CC0πNp, CCOther)

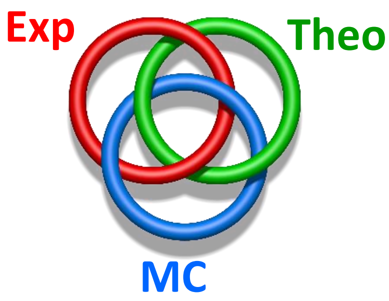
We are only at the beginning!

- Few experimental and theoretical results
- The one pion puzzle is still there
- SIS and DIS have been minimally studied
- Theoretical models and Monte Carlo implementation of semi-inclusive processes are needed

The DUNE and Fermilab SBN programs based on liquid argon detectors open new important and exciting perspectives on neutrino cross section measurements!

This is what is already happening in the case of MicroBooNE

It is important to establish the priorities in relation to the neutrino oscillation program



Close collaboration between theorists, experimentalists and generator developers is crucial

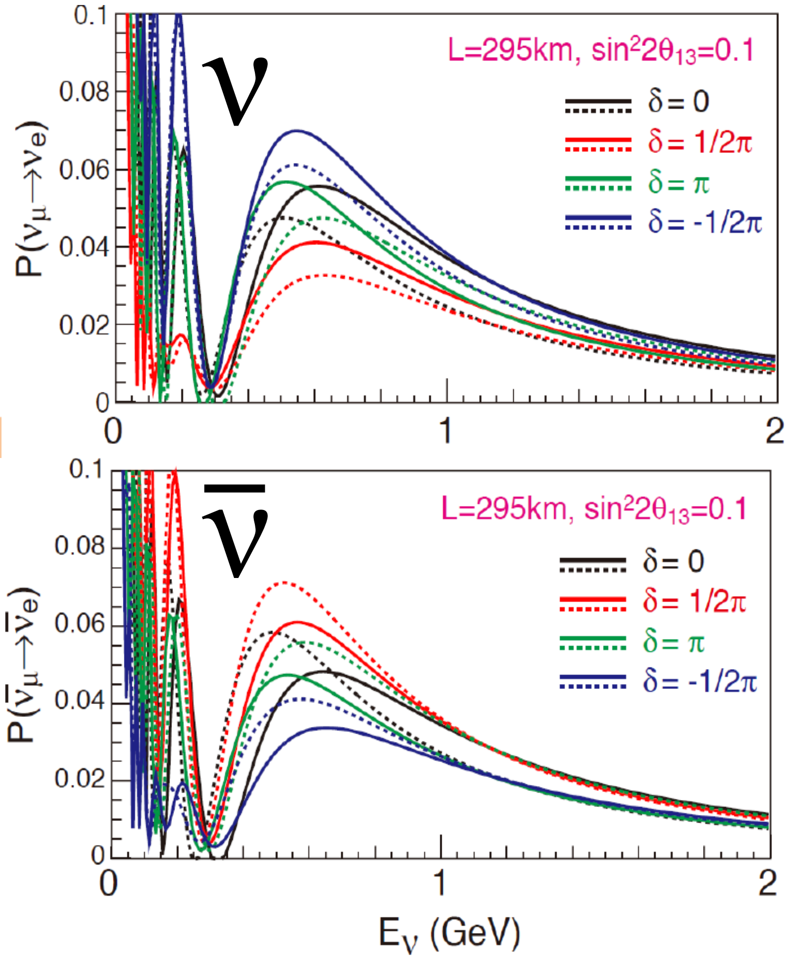
For the moment the community (at least theorists and generator developers) is not so large

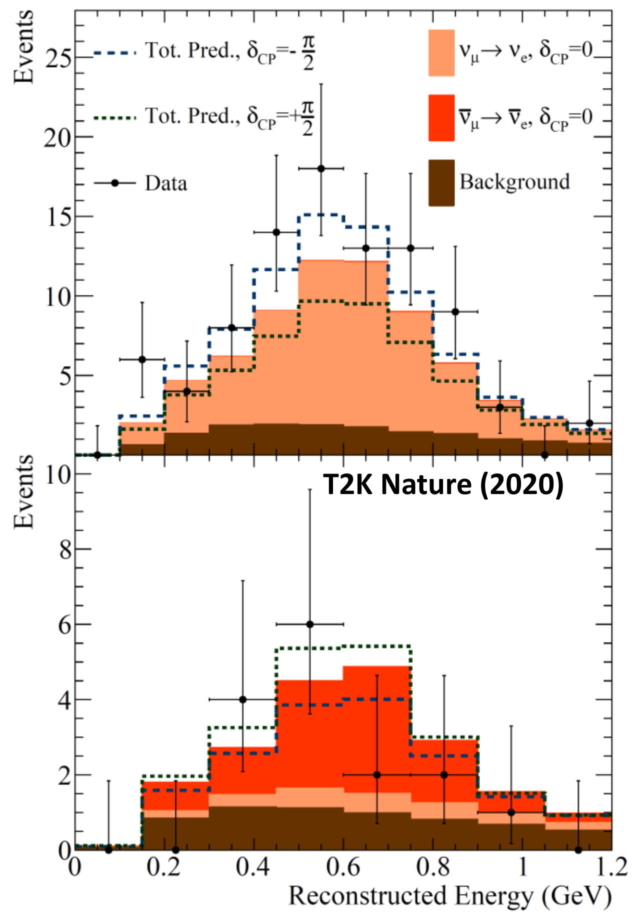
APPENDIX

ν .vs. $\bar{\nu}$ and ν_μ .vs. ν_e

ν oscillation and CP violation

$$P(\nu_\mu \to \nu_e) \overset{?}{\neq} P(\bar{\nu}_\mu \to \bar{\nu}_e) \iff \delta_{CP}$$





$$\nu_\mu \to \nu_e$$

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

A precise and simultaneous knowledge of the four cross sections is important in connection to the oscillation experiments aiming at the search for CP violation in the lepton sector.

Neutrino *vs* Antineutrino interactions

The ν and anti ν cross sections differ by the sign of the V-A interference term

$$\frac{d^2\sigma}{d\cos\theta d\omega} = \frac{G_F^2\cos^2\theta_c}{\pi}|\mathbf{k}'|E_l'\cos^2\frac{\theta}{2}\left[\frac{(\mathbf{q}^2-\omega^2)^2}{\mathbf{q}^4}G_E^2 R_\tau(\mathbf{q},\omega) + \frac{\omega^2}{\mathbf{q}^2}G_A^2 R_{\sigma\tau(L)}(\mathbf{q},\omega)\right.$$

$$\left. + 2\left(\tan^2\frac{\theta}{2}+\frac{\mathbf{q}^2-\omega^2}{2\mathbf{q}^2}\right)\left(G_M^2\frac{\mathbf{q}^2}{4M_N^2}+G_A^2\right)R_{\sigma\tau(T)}(\mathbf{q},\omega) \pm 2\frac{E_\nu+E_l'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}(\mathbf{q},\omega)\right]$$

Vector-Axial interference

$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases}$$

Vector-Axial interference:

basic asymmetry from weak interaction theory

different sign in the Leptonic tensor

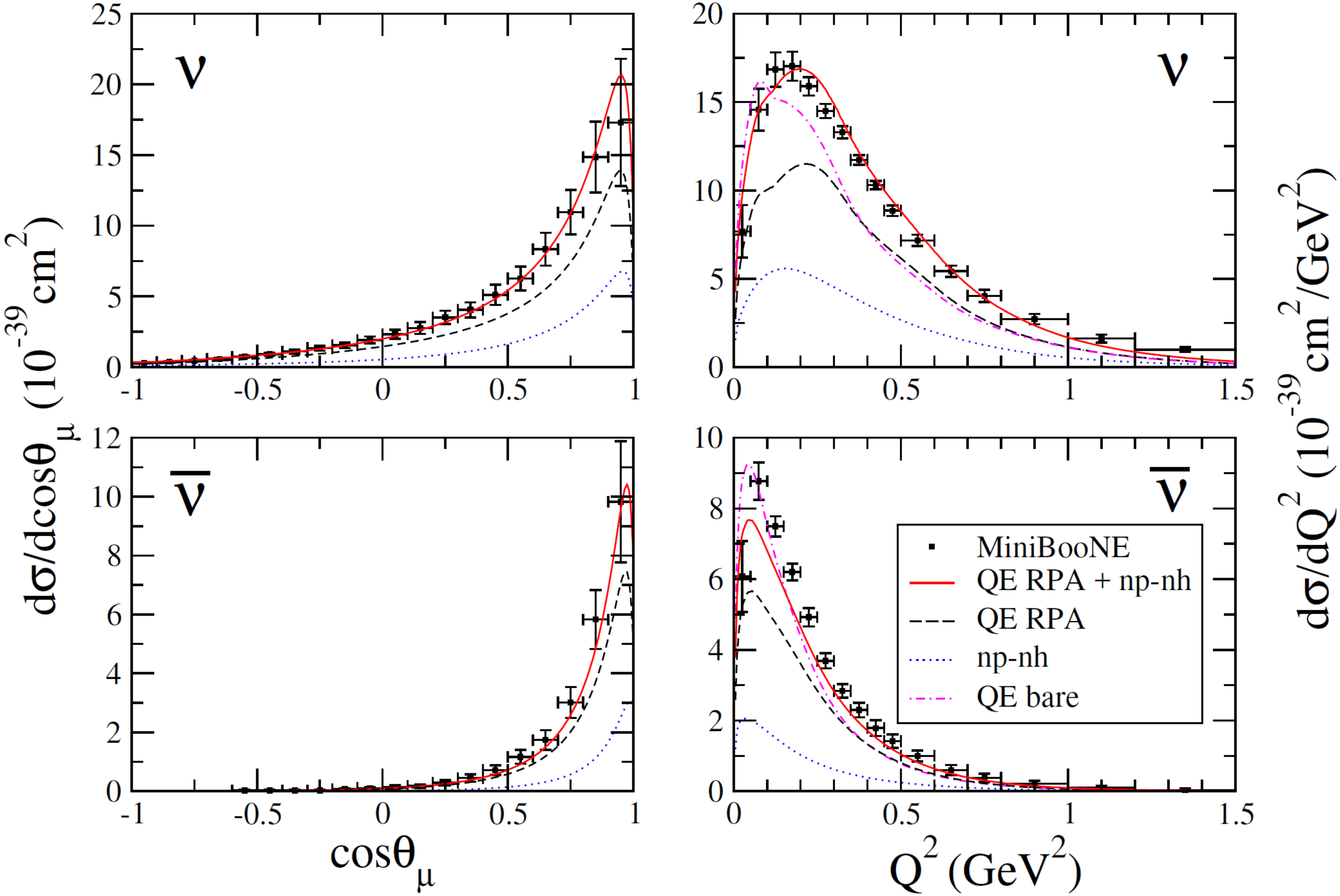
$$L_{\mu\nu} = k_\mu k'_\nu + k_\nu k'_\mu - g_{\mu\nu} k\cdot k' \mp i\varepsilon_{\mu\nu\alpha\beta}k^\alpha k'^\beta$$

($-$: ν; $+$: $\bar{\nu}$)

⇨ Even neglecting nuclear effects, the absolute value and the kinematic behavior of neutrino and antineutrino cross sections are different

dσ/dcosθ　　Q^2 distribution

T. Katori, M. Martini, J.Phys.G 45 (2018) 1, 013001



- Antineutrino cross section falls more rapidly than the neutrino one
- Antineutrino Q^2 distribution peaks at smaller Q^2 values than the neutrino one

Neutrino *vs* Antineutrino interactions and nuclear effects

$$\frac{d^2\sigma}{d\cos\theta\, d\omega} = \frac{G_F^2\cos^2\theta_c}{\pi}|\mathbf{k}'|E_l'\cos^2\frac{\theta}{2}\left[\frac{(\mathbf{q}^2-\omega^2)^2}{\mathbf{q}^4}G_E^2 R_\tau(\mathbf{q},\omega)+\frac{\omega^2}{\mathbf{q}^2}G_A^2 R_{\sigma\tau(L)}(\mathbf{q},\omega)\right.$$

$$\left.+\,2\left(\tan^2\frac{\theta}{2}+\frac{\mathbf{q}^2-\omega^2}{2\mathbf{q}^2}\right)\left(G_M^2\frac{\mathbf{q}^2}{4M_N^2}+G_A^2\right)R_{\sigma\tau(T)}(\mathbf{q},\omega) \pm 2\frac{E_\nu+E_l'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}(\mathbf{q},\omega)\right]$$

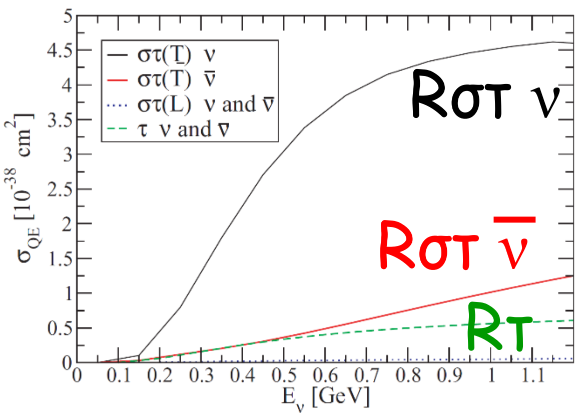
Vector-Axial interference

The ν and anti ν interactions differ by the sign of the V-A interference term

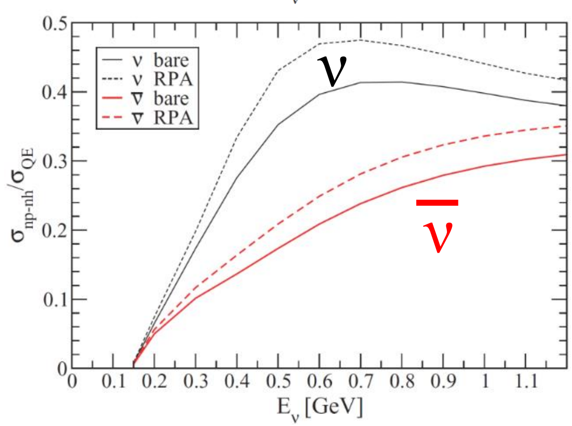
→the relative weight of the different nuclear responses is different for neutrinos and antineutrinos

→the relative role of np-nh contributions is different for neutrinos and antineutrinos

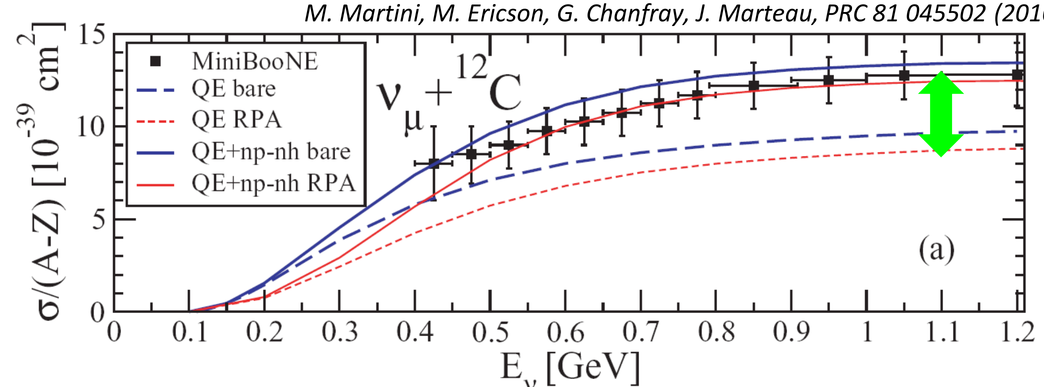
QE

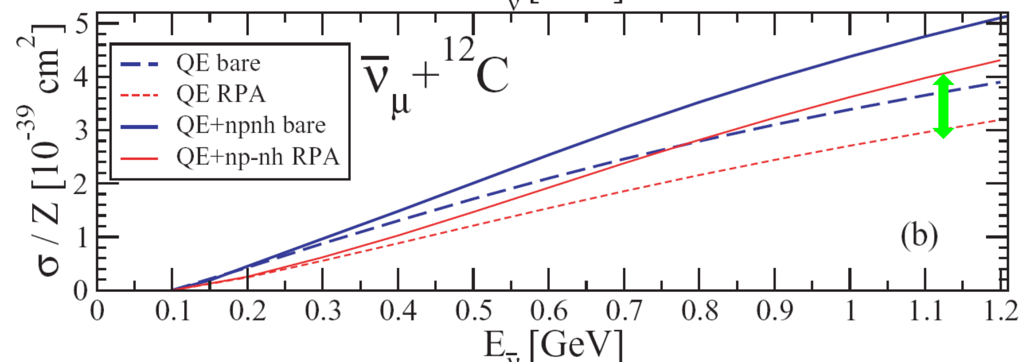


$\frac{np-nh}{QE}$



M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 81 045502 (2010)



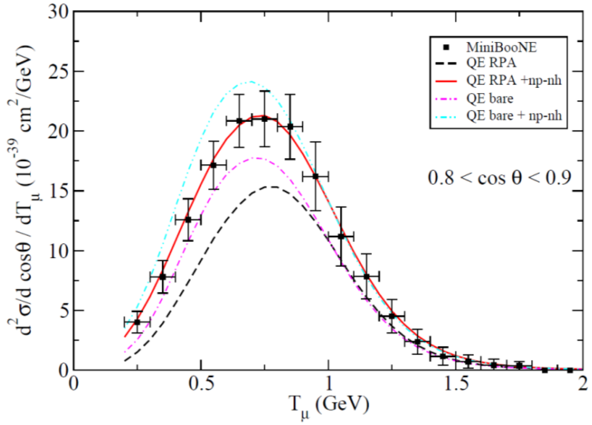


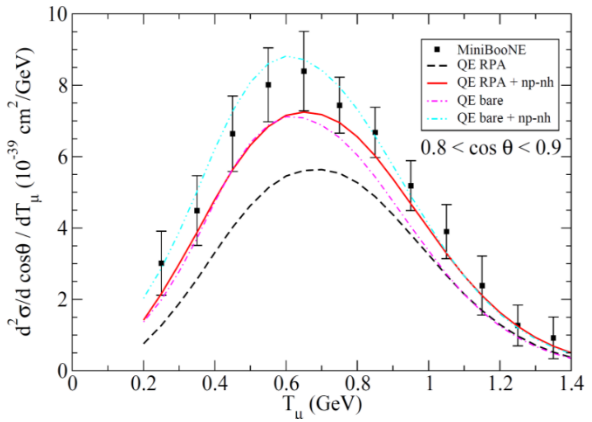
Nuclear effects generate an asymmetry unrelated to CP violation

ν **The relative role of np-nh for neutrinos and antineutrinos is different in different approaches** $\bar{\nu}$

Lyon RPA
Martini et al.

PRC 84 (2011)

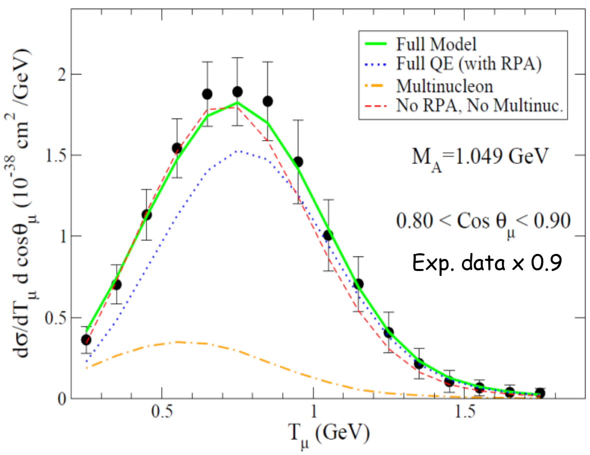


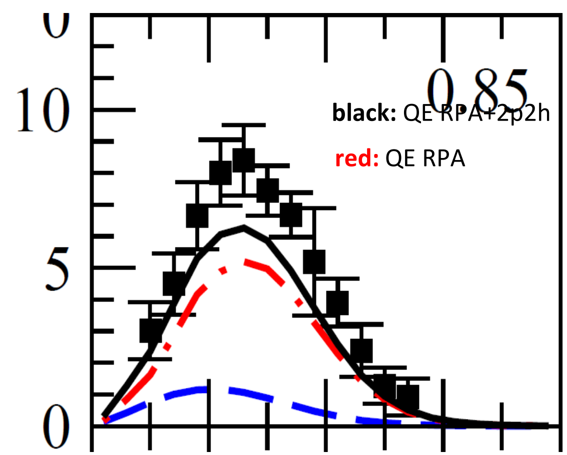


PRC 87 (2013)

Valencia RPA
Nieves et al.

PLB 707 (2012)

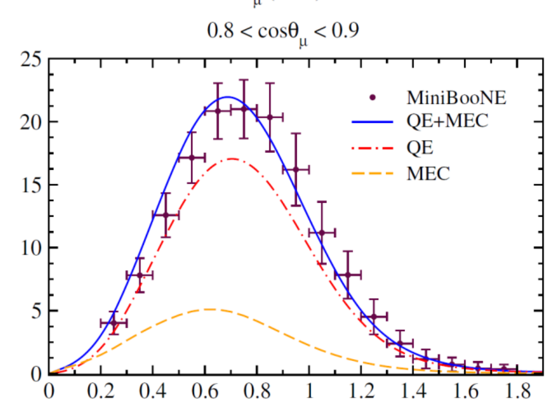


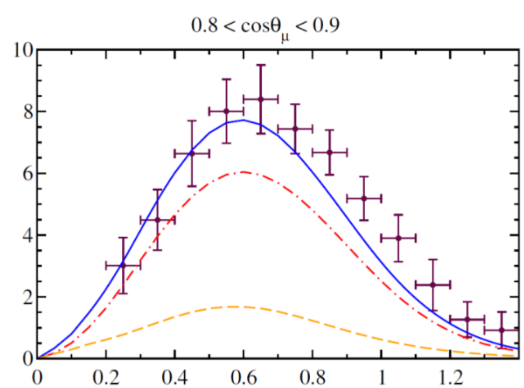


PLB 721 (2013)

SuSAv2

PRD 94 (2016)





PRD 94 (2016)

T. Katori, M. Martini, J.Phys.G 45 (2018) 1, 013001

Difference of ν and antiν cross sections and the VA interference term

$$d\sigma \sim d\sigma_L + d\sigma_T \pm d\sigma_{VA} \qquad\qquad d\sigma_\nu - d\sigma_{\bar\nu} \overset{?}{\leftrightarrow} 2d\sigma_{VA}$$

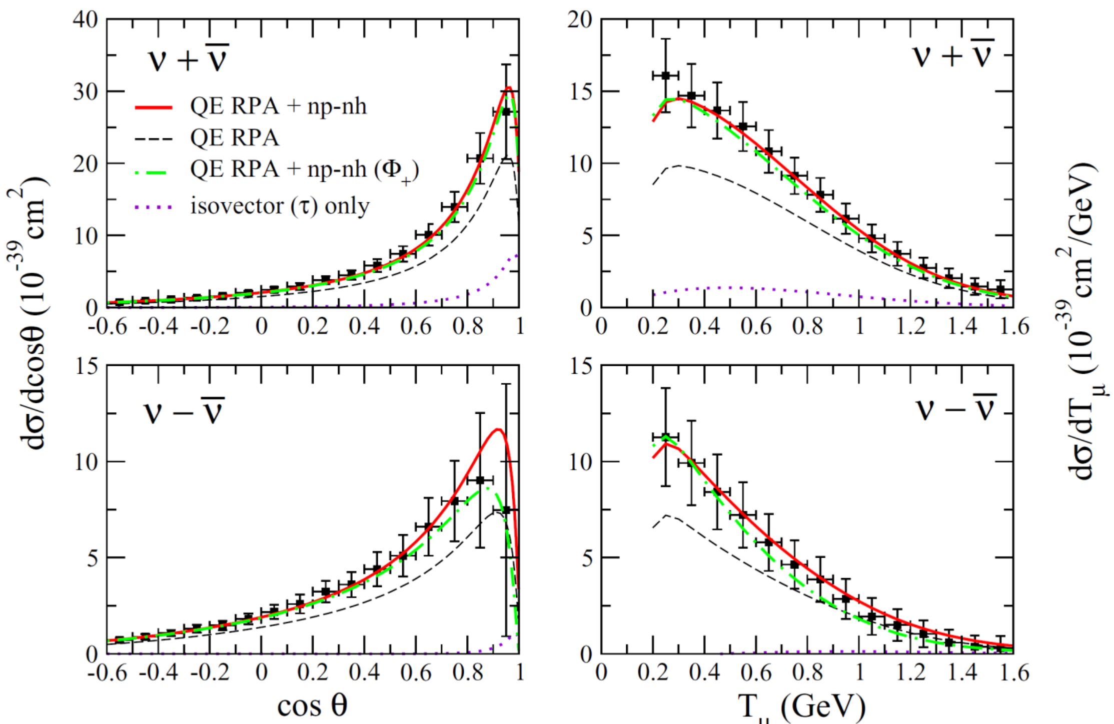
Difference gives only the VA term for identical ν and antiν flux

Problem: flux dependence of dσ $\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$

We introduce the **mean flux** $\Phi_+ = 1/2[\Phi_\nu + \Phi_{\bar\nu}]$

We calculate the sum and the difference using **real** and **mean** MiniBooNE fluxes results

M. Ericson, M. Martini Phys. Rev. C 91 035501 (2015)



The mean flux contribution is dominant

⇓

The VA interference term is experimentally accessible in MBdata

⇓

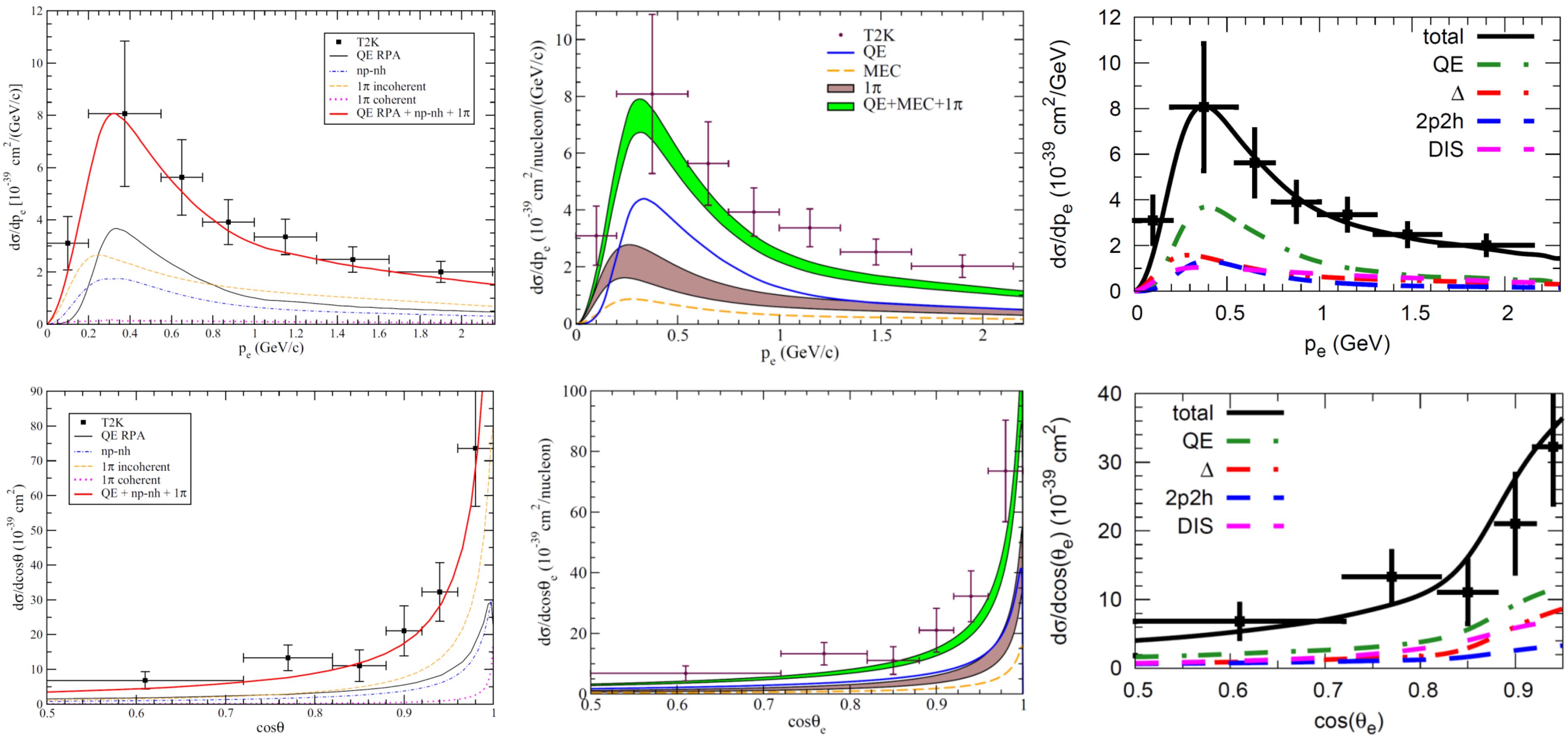
Need for the **multinucleon** component in the **VA interference**

ν_e cross sections

- There are few published results on ν_e cross sections. This is essentially due the relatively small component of ν_e fluxes with respect to the ν_μ ones hence to small statistics.
- The ν_e experimental published results essentially concern inclusive cross sections

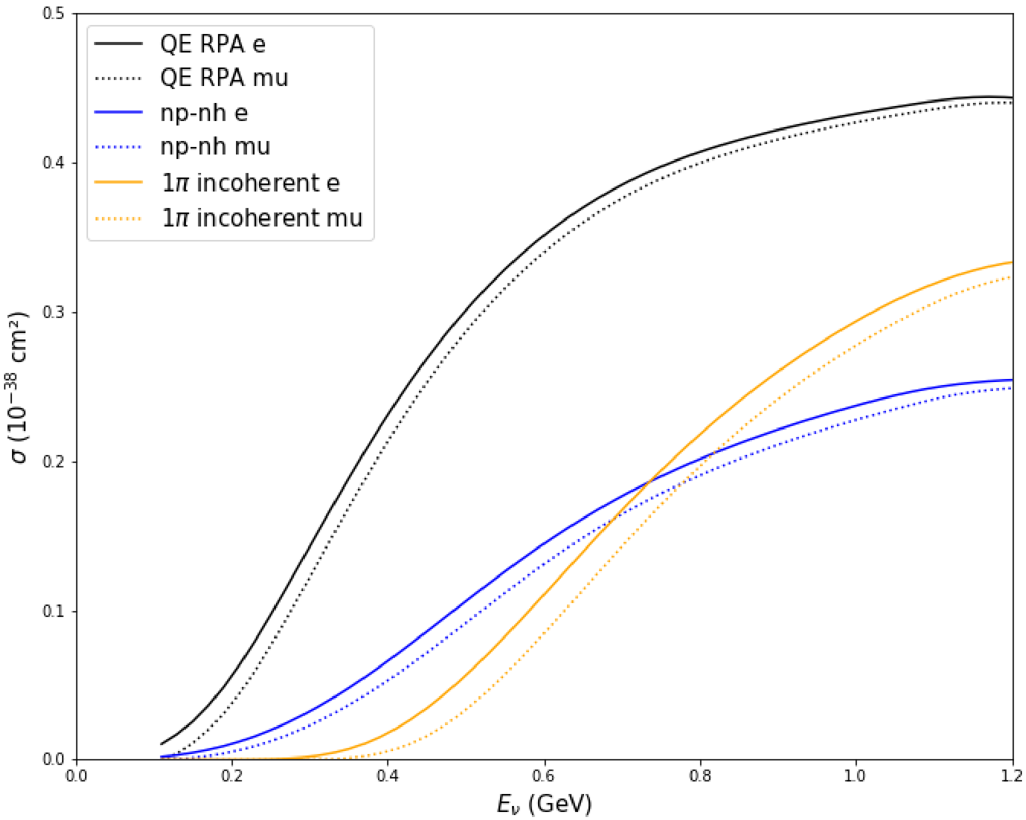
T2K flux-integrated ν_e CC inclusive differential cross sections on carbon

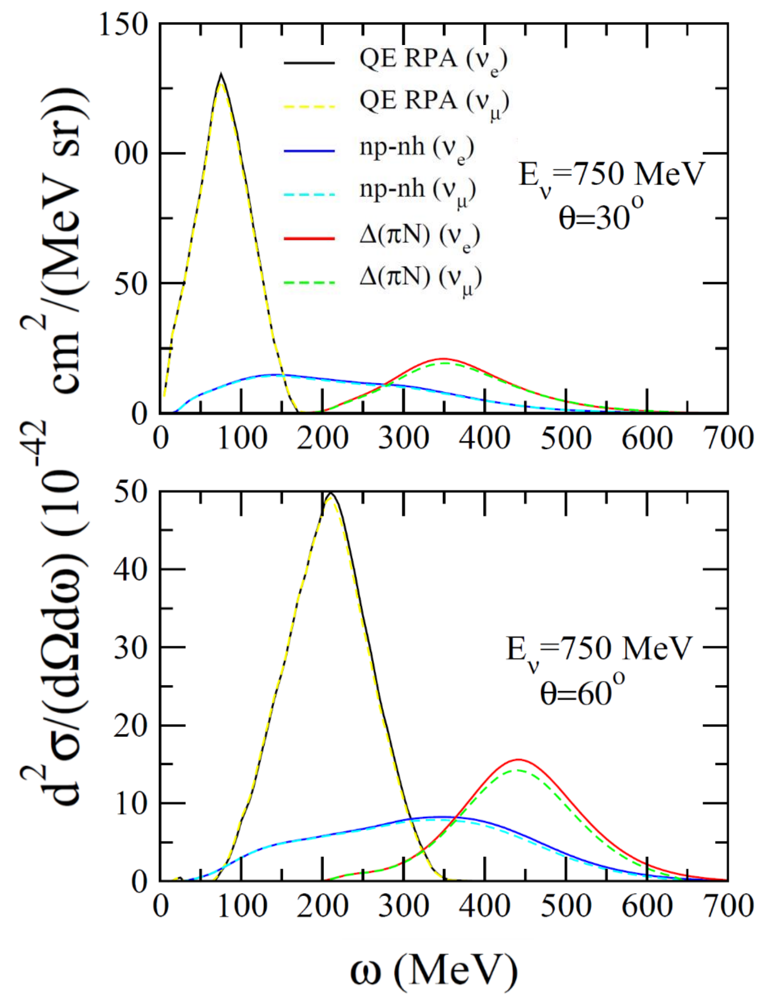
Martini et al., PRC 94 (2016) ***Megias et al., PRD 94 (2016)*** ***Gallmeister et al.PRC 94(2016)***



- Theoretical results agree with data
- Similarity of the theoretical results for the inclusive dσ

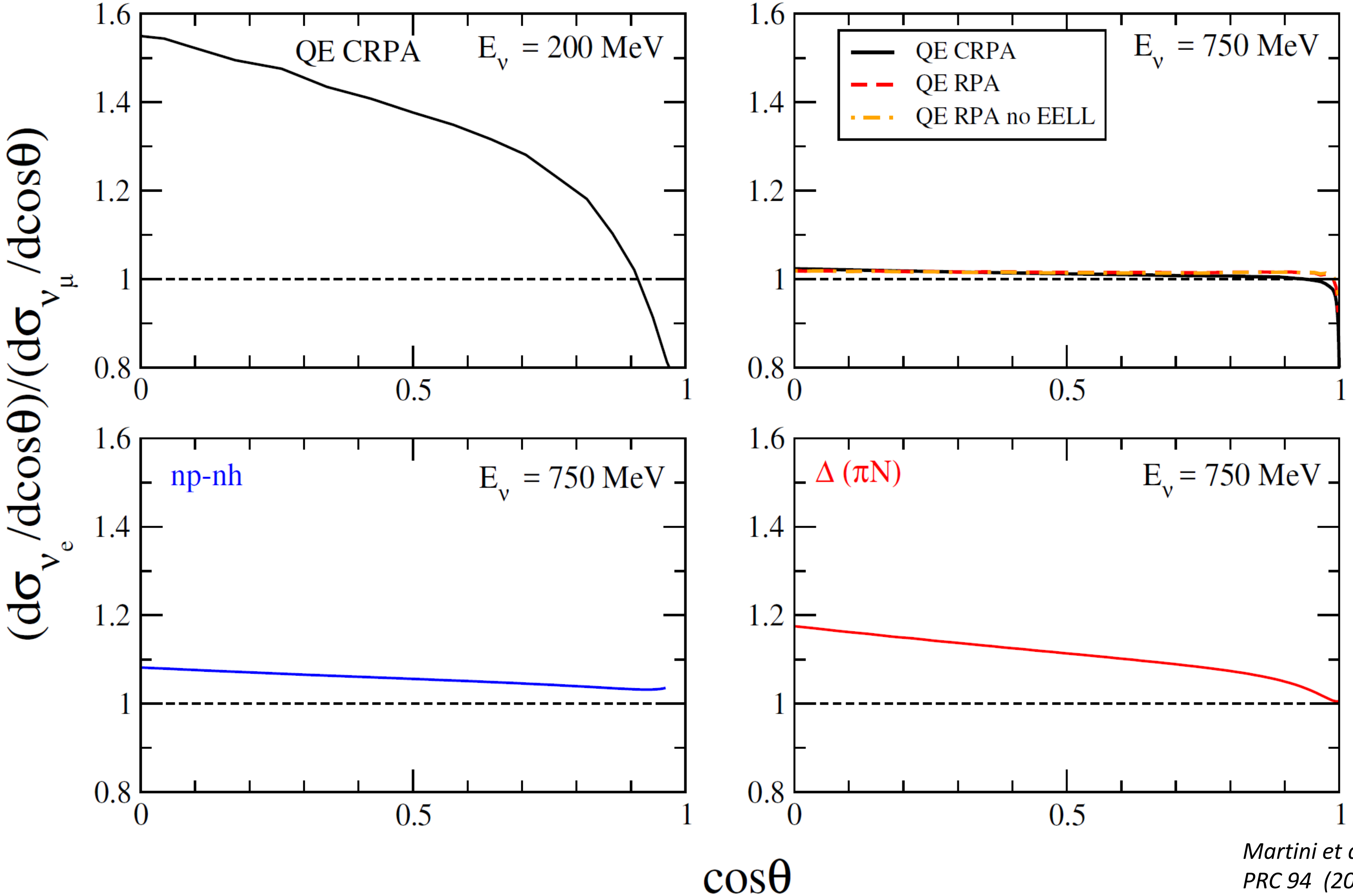
ν_e and ν_μ total and double differential cross sections





Due to the different kinematic limits, the ν_e cross sections are expected to be larger than the ν_μ ones

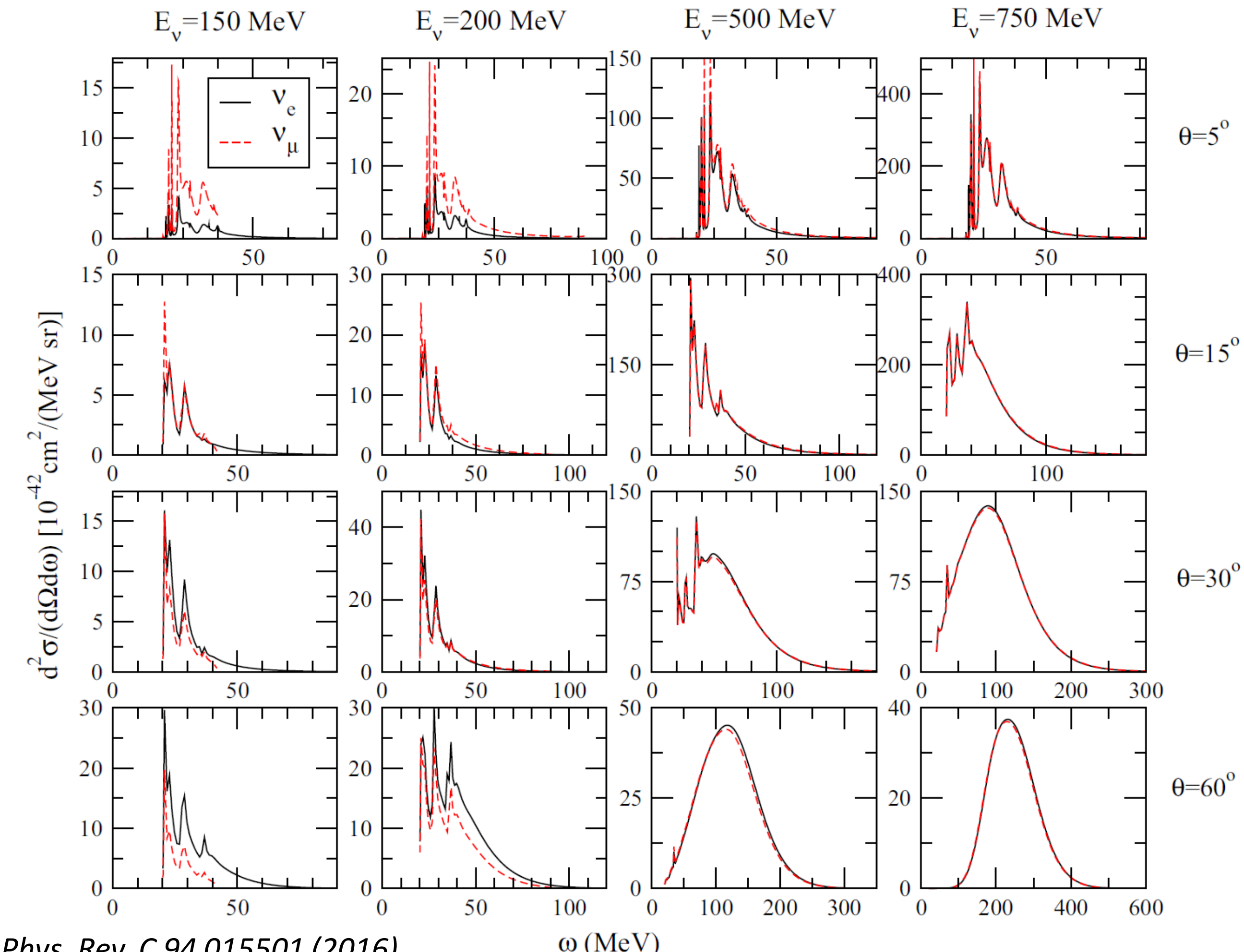
Ratio ν_e/ν_μ for $d\sigma/d\cos\theta$ in different channels



Martini et al., PRC 94 (2016)

Due to the different kinematic limits, the ν_e cross sections are expected to be larger than the ν_μ ones.
However for forward scattering angles this hierarchy is opposite in the QE channel.

A theoretical study (HF+CRPA Ghent) of the ν_μ and ν_e $d^2\sigma$



M. Martini et al., Phys. Rev. C 94 015501 (2016)

Due to the different kinematic limits, the ν_e cross sections are expected to be larger than the ν_μ ones. However for forward scattering angles this hierarchy is opposite.

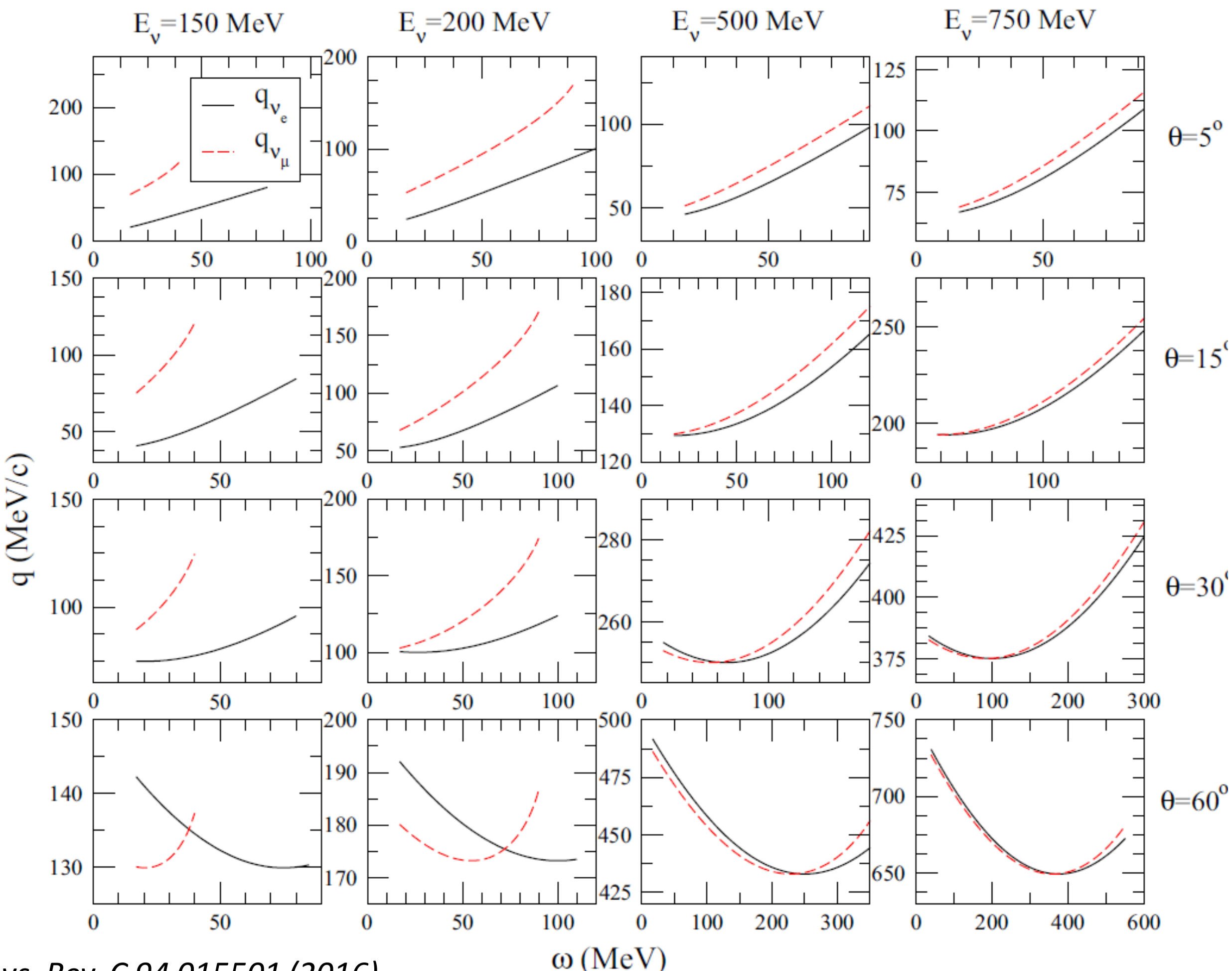
The only difference between ν_μ and ν_e cross sections is the mass of the outgoing lepton.

But the mass affects the three momentum transfer which enters into the kinematics as well as the dynamics of the nuclear model

Further studies: A Nikolakopoulos et al. , PRL 123, 052501 (2019); R. González-Jiménez, PRC, 100, 045501 (2019)

Momentum transfer q versus transferred energy ω for ν_μ and ν_e $d^2\sigma$

Kinematical conditions of the previous slide



M. Martini et al., Phys. Rev. C 94 015501 (2016)

$$q^2 = E_\nu^2 + p_l^2 - 2E_\nu p_l \cos\theta \qquad p_l^2 = E_l^2 - m_l^2 = (E_\nu - \omega)^2 - m_l^2$$

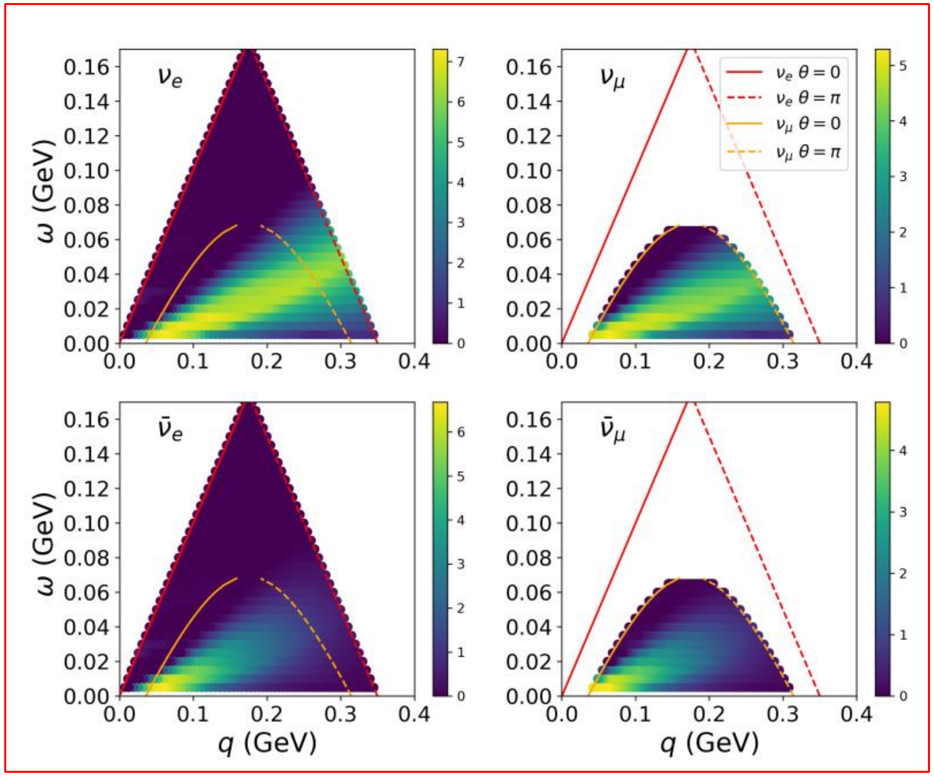
The only difference between ν_μ and ν_e cross sections is the mass of the outgoing lepton.
But the mass affects the three-momentum transfer which enters into the kinematics as well as the dynamics of the nuclear model

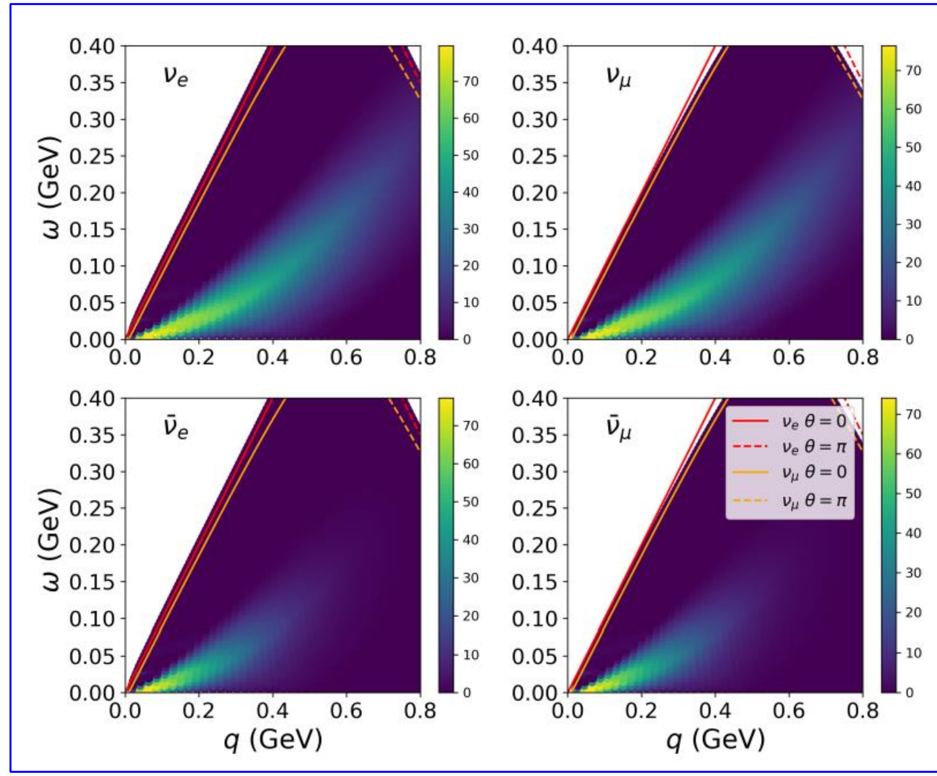
Projection of ν_μ and ν_e $d^2\sigma$ on (q,ω) plane

Martini, Ericson, Chanfray 2310.06388

Eν = 175 MeV

Eν = 575 MeV





For neutrino and antineutrino scattering the θ = 0 muon and electron lines explore in the (q, ω) plane two different regions, the muon one corresponding to larger quasielastic cross sections

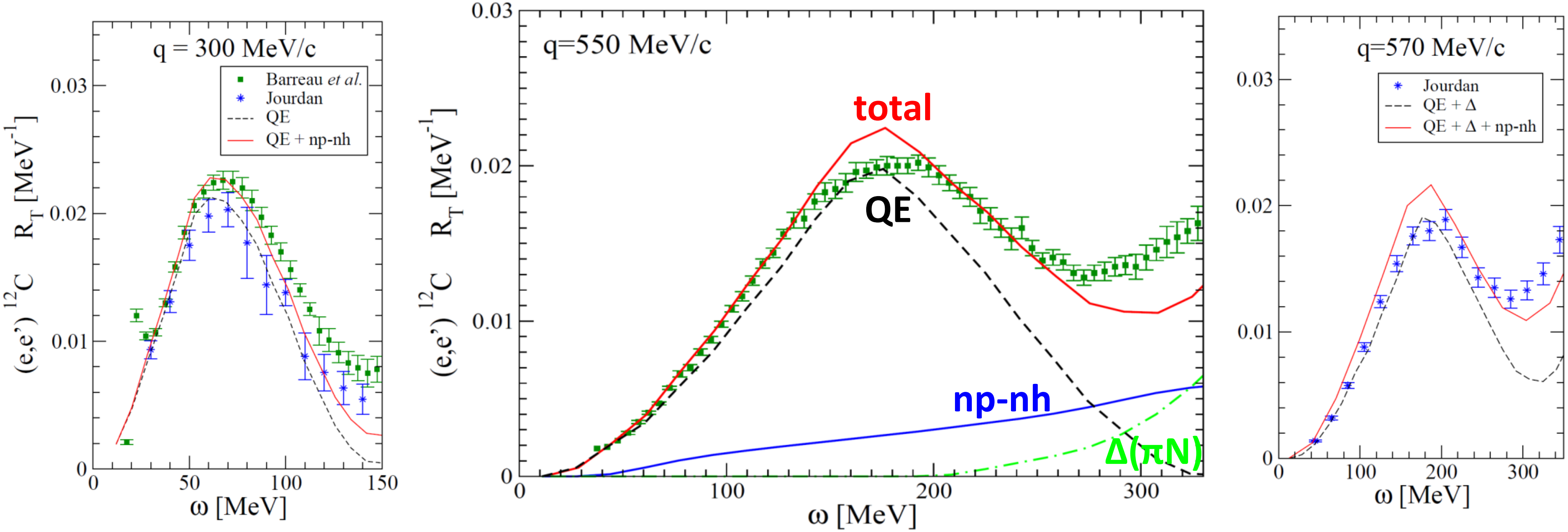
By increasing the neutrino energies the difference between the muon and electron θ = 0 lines decreases and the two curves explore more and more similar region in the (q, ω) plane

Testing the responses in other processes

Electron scattering

$$\frac{d^2\sigma}{d\theta\, d\omega} = \sigma_M \left\{ \frac{(\omega^2 - q^2)^2}{q^4} R_L(\omega, q) + \left[\tan^2\left(\frac{\theta}{2}\right) - \frac{\omega^2 - q^2}{2q^2} \right] \boxed{R_T(\omega, q)} \right\}$$

M. Martini, J.Phys.Conf.Ser. 408 (2013) 012041

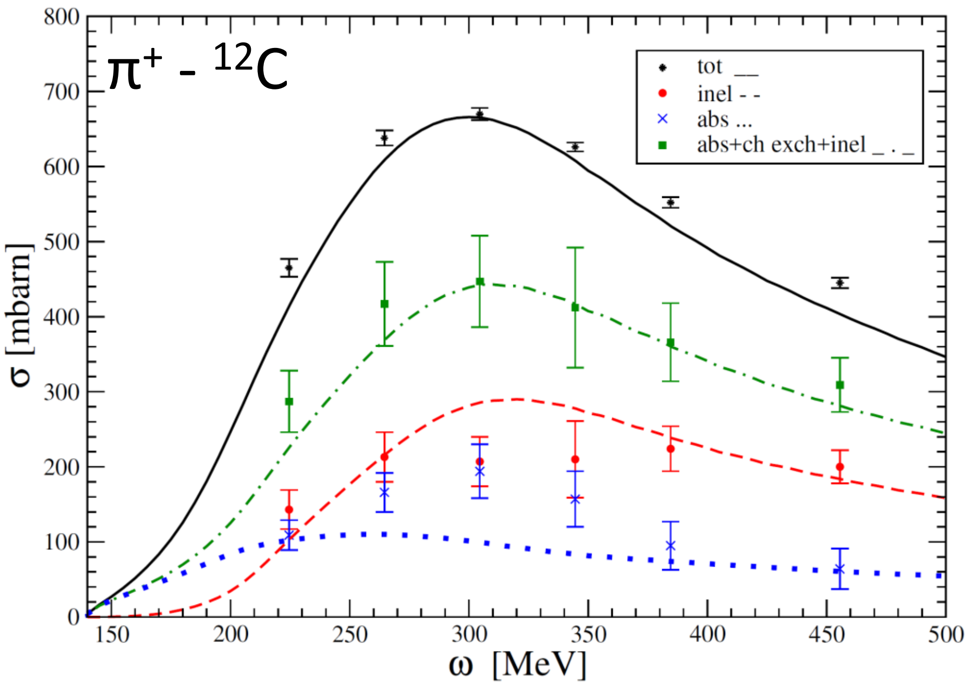


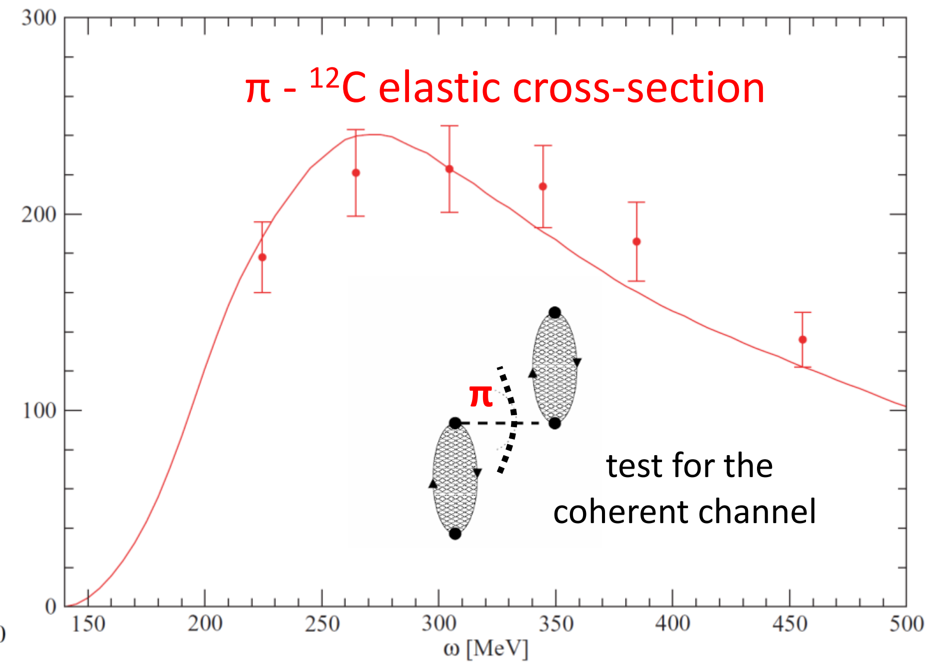
Pion scattering

$$\sigma^{tot}(\omega) = \left(\frac{g_r}{2M_N}\right)^2 \pi q_\pi \, R_L(\omega, q_\pi)$$

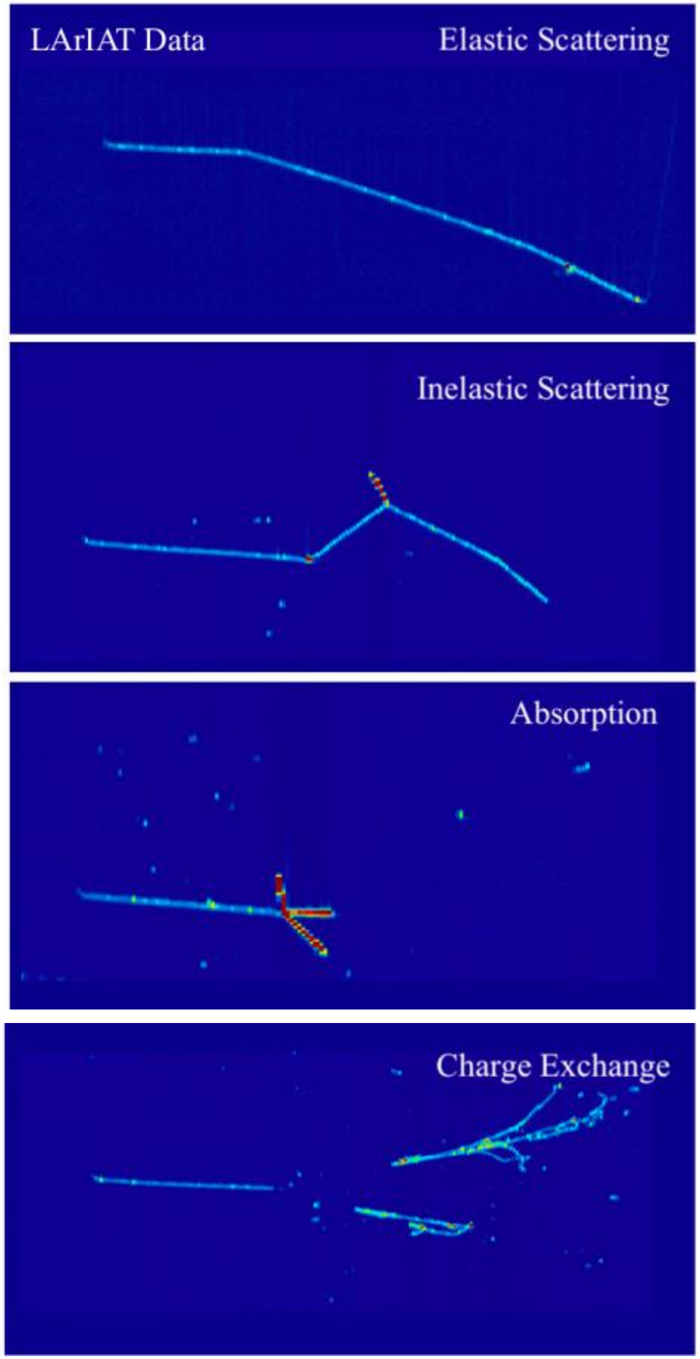
$$q_\pi^2 = \omega^2 - m_\pi^2$$

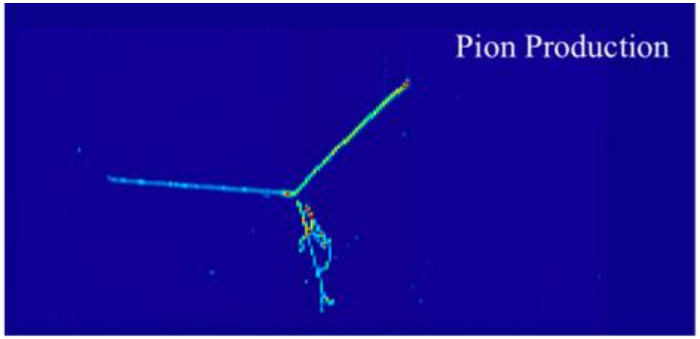
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



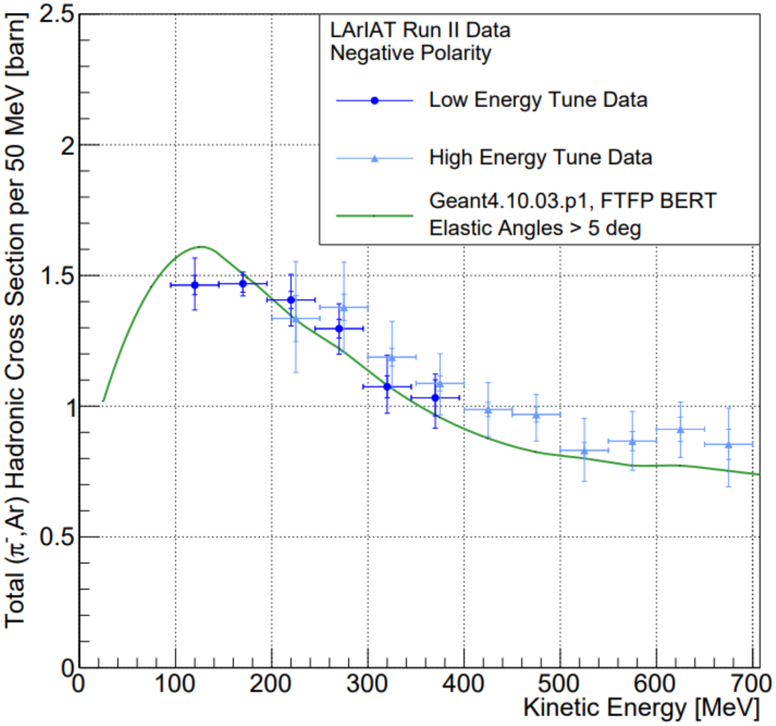


π-Ar cross section: LArIAT experiment

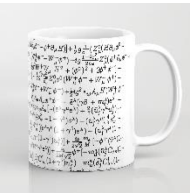




Phys.Rev.D 106 (2022) 5, 052009



SPARES

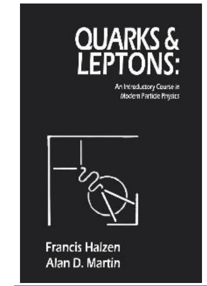


Standard Model of electroweak interaction

Electroweak interaction Lagrangian

$$\mathcal{L}_{\text{int}} = -eJ^{\mu}_{\text{EM}}A_{\mu} - \frac{g}{2\sqrt{2}}\left(J^{\mu}_{\text{CC}}W_{\mu}{}^{\dagger} + \text{h. c.}\right) - \frac{g}{2\cos\theta_W}J^{\mu}_{\text{NC}}Z_{\mu}$$

Feynman Rules

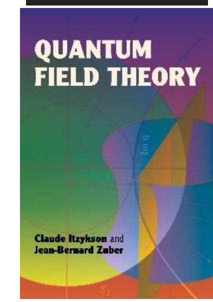


Gauge Bosons Propagators

- Photon (γ) $\quad \frac{\mathrm{i}}{q^2}(-g^{\mu\nu})$

- Massive vector bosons (W,Z)

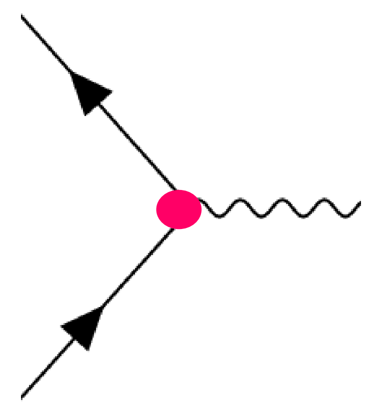
$$\frac{\mathrm{i}}{q^2 - M_V^2}\left(-g^{\mu\nu} + \frac{q^{\mu}q^{\nu}}{M_V^2}\right) \xrightarrow{|q^2| \ll M_V^2} \frac{\mathrm{i}\,g^{\mu\nu}}{M_V^2}$$



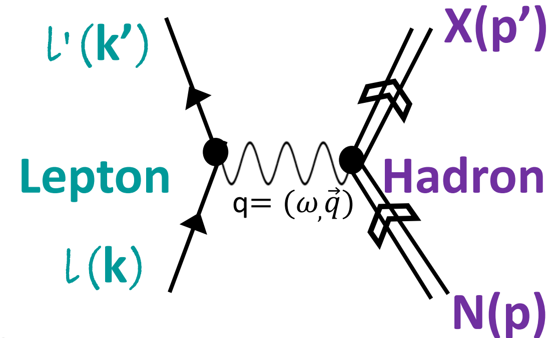
Fermion Vertices

- Electromagnetic $\quad -\mathrm{i}eQ_f\gamma_{\mu}$
  - $Q_{e-} = -1, Q_{up} = 2/3, \ldots$

- Weak (W exchange) $\quad -\mathrm{i}\frac{g}{\sqrt{2}}c\,\gamma_{\mu}\frac{1-\gamma^5}{2}$
  - c = 1 for leptons
  - c = Cabibbo-mixing matrix element for quarks



Electroweak transition matrix elements



Electromagnetic transition $\ell^- N \to \ell^- X$

$$-i\mathcal{M} = -(ie)^2 \underbrace{\bar{u}(k')\gamma_\mu u(k)}_{\text{e.m. lepton current}} \frac{-ig^{\mu\nu}}{q^2} \left\langle X(p'_f) \middle| J_\nu(0) \middle| N(p) \right\rangle$$

hadronic current (Vector)

Charged current transition $\nu N \to \ell^- X$

$$-i\mathcal{M} = \left(\frac{-ig}{2\sqrt{2}}\right)^2 \cos\theta_C \underbrace{\bar{u}(k')\gamma_\mu(1-\gamma^5)u(k)}_{\text{weak lepton current}} \frac{ig^{\mu\nu}}{M_W^2} \left\langle X(p'_f) \middle| J_\nu(0) \middle| N(p) \right\rangle$$

hadronic current (Vector-Axial)

θ_C

Cabibbo angle

$$\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$$

Fermi coupling constant

The single nucleon electroweak current

Electromagnetic current - Electron scattering

$$J^{\mu}_{s's}(\mathbf{p}',\mathbf{p}) = \overline{u}_{s'}(\mathbf{p}')\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)i\sigma^{\mu\nu}\frac{q_{\nu}}{2m_N}\right]u_s(\mathbf{p})$$

$$Q^2 = -q^2 \quad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^{\mu},\gamma^{\nu}]$$

Weak current – CC neutrino scattering

$$J^{\mu} = V^{\mu} - A^{\mu}$$

Vector – Axial

Vector $V^{\mu}_{s's}(\mathbf{p}',\mathbf{p}) = \overline{u}_{s'}(\mathbf{p}')\left[2F_1^V\gamma^{\mu} + 2F_2^V i\sigma^{\mu\nu}\frac{q_{\nu}}{2m_N}\right]u_s(\mathbf{p})$

Conserved Vector Current (CVC) $q_{\alpha}V^{\alpha} = 0$ and isospin symmetry $\Rightarrow$ $F_i^V = F_i^p - F_i^n$

Axial $A^{\mu}_{s's}(\mathbf{p}',\mathbf{p}) = \overline{u}_{s'}(\mathbf{p}')\left[G_A\gamma^{\mu}\gamma_5 + G_P\frac{q^{\mu}}{2m_N}\gamma_5\right]u_s(\mathbf{p})$

Partially Conserved Axial Current (PCAC) and pion-pole dominance $\Rightarrow$ $G_P = \frac{4m_N^2}{m_{\pi}^2 + Q^2}G_A$

$$q_{\alpha}A^{\alpha} = i(m_u + m_d)\bar{q}_u\gamma_5 q_d \to 0$$

Some two-body currents

Electromagnetic

- Seagull or contact:

$$j_{\rm s}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\mathrm{i}\epsilon_{3ab}\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\frac{F_1^{\rm V}}{K_1^2-m_\pi^2}\,\overline{u}(\mathbf{p}_2')\tau_b\gamma_5\gamma^\mu u(\mathbf{p}_2)+(1\leftrightarrow 2)\,.$$

- Pion-in-flight:

$$j_{\rm p}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\mathrm{i}\epsilon_{3ab}\frac{F_\pi(K_1-K_2)^\mu}{(K_1^2-m_\pi^2)(K_2^2-m_\pi^2)}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\overline{u}(\mathbf{p}_2')\tau_b\gamma_5 \not{K}_2 u(\mathbf{p}_2)\,.$$

- Correlation:

$$j_{\rm cor}^{\mu}(\mathbf{p}_1',\mathbf{p}_2',\mathbf{p}_1,\mathbf{p}_2)=\frac{f^2}{m_\pi^2}\,\overline{u}(\mathbf{p}_1')\tau_a\gamma_5 \not{K}_1 u(\mathbf{p}_1)\frac{1}{K_1^2-m_\pi^2}\overline{u}(\mathbf{p}_2')[\tau_a\gamma_5 \not{K}_1 S_{\rm F}(P_2+Q)\Gamma^\mu(Q)$$

$$+\Gamma^\mu(Q)S_{\rm F}(P_2'-Q)\tau_a\gamma_5 \not{K}_1]u(\mathbf{p}_2)+(1\leftrightarrow 2)\,.$$

Amaro et al. Phys.Rev.C 82 044601 (2010)

Weak

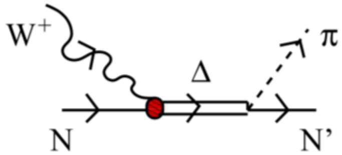
- CC Seagull

$$j_s^\mu(\mathbf{p}_1',\mathbf{p}_2',\mathbf{h}_1,\mathbf{h}_2)=$$

$$(\tau_0\otimes\tau_{+1}-\tau_{+1}\otimes\tau_0)\frac{f}{m_\pi}\frac{1}{\sqrt{2}f_\pi}\overline{u}(\mathbf{p}_1')\gamma_5\ \not{K}_1 u(\mathbf{h}_1)\ \frac{\overline{u}(\mathbf{p}_2')\left[g_A F_1^V(Q^2)\gamma_5\gamma^\mu+F_\rho(K_2^2)\gamma^\mu\right]u(\mathbf{h}_2)}{K_1^2-m_\pi^2}-(1\leftrightarrow 2)$$

Ruiz-Simo et al. Phys.Rev.D 90 033012 (2014); J.Phys.G 44 065105 (2017)

The 1π production via Δ(1232) resonance excitation and decay



At energies of our interest, it is the dominant mechanism of the reaction $WN \to N'\pi$

E. Hernandez et al. Phys. Rev. D 76, 033005 (2007)

$W^+ n \to \Delta^+$ **Hadron matrix element** $\langle \Delta^+; p_\Delta = p+q \,|j^\mu_{cc+}(0)|n;p\rangle = \bar{u}_\alpha(\vec{p}_\Delta)\Gamma^{\alpha\mu}(p,q)\,u(\vec{p})\cos\theta_C$

Electroweak vertex

$$\Gamma^{\alpha\mu}(p,q) = \left[\frac{C_3^V}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p_\Delta^\mu) + \frac{C_5^V}{M^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu) + C_6^V g^{\mu\alpha}\right]\gamma_5$$
$$+ \left[\frac{C_3^A}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p_\Delta^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2}q^\mu q^\alpha\right], \quad p_\Delta = p+q$$

Vector form factors $C^V_{3,4,5,6}$ can be extracted from single-pion electro-production data

Axial form factors $C^A_{3,4,5,6}$ $\quad C_5^A(Q^2) = \frac{C_5^A(0)}{(1+Q^2/M_{A\Delta}^2)^2}$ $\quad C_6^A = M^2/(m_\pi^2+Q^2)\cdot C_5^A$ PCAC $\quad C_4^A = -1/4\cdot C_5^A$ Adler $\quad C_3^A$ Small, usually neglected

Δ propagator

$$G^{\mu\nu}(p_\Delta) = \frac{P^{\mu\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta}$$

Spin 3/2 projection operator

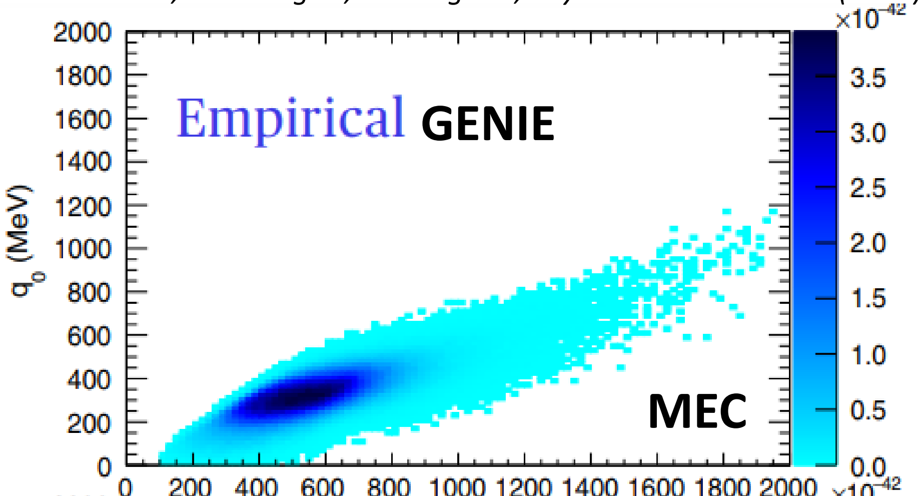
$$P^{\mu\nu}(p_\Delta) = -(\not{p}_\Delta + M_\Delta)\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{2}{3}\frac{p_\Delta^\mu p_\Delta^\nu}{M_\Delta^2} + \frac{1}{3}\frac{p_\Delta^\mu\gamma^\nu - p_\Delta^\nu\gamma^\mu}{M_\Delta}\right]$$

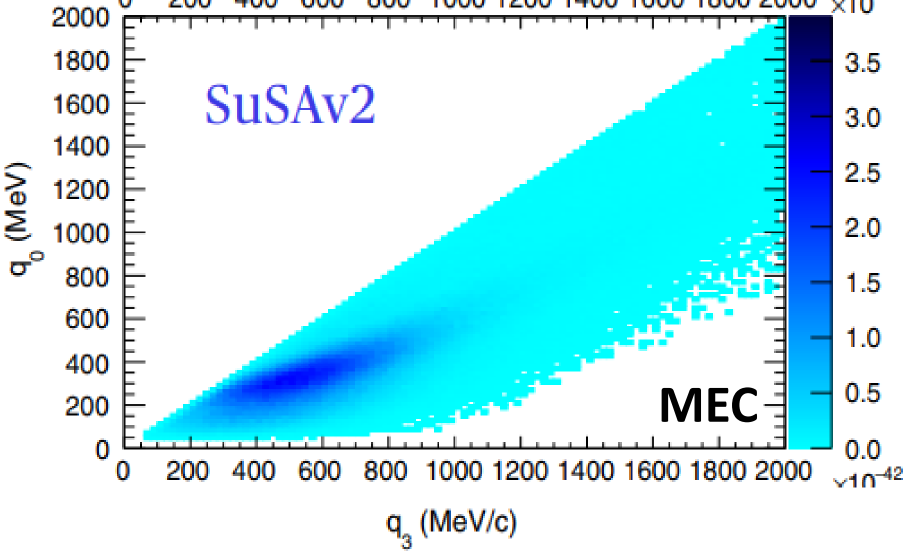
NΔπ coupling

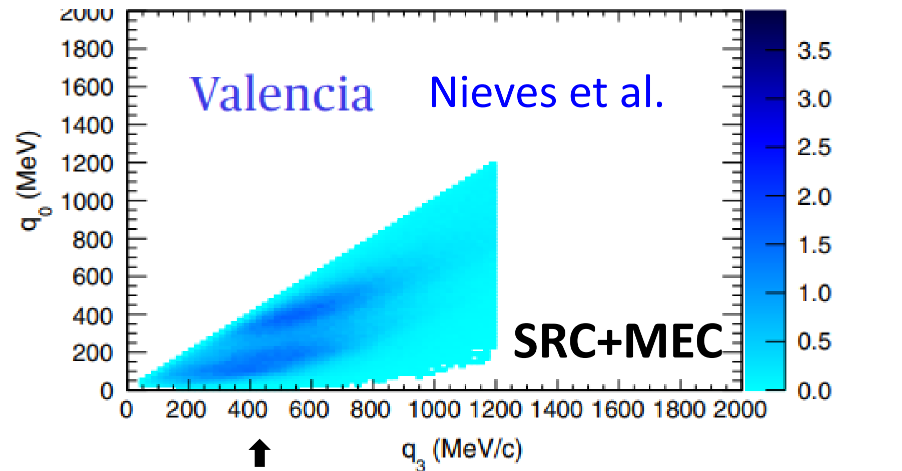
$$\mathcal{L}_{\pi N\Delta} = \frac{f^*}{m_\pi}\bar{\Psi}_\mu \vec{T}^\dagger(\partial^\mu\vec{\phi})\Psi + \text{h.c.}$$

Example of different results for 2p-2h in the (q,ω) or (q_0,q_3) plane

S. Dolan, G.D. Megias, S. Bolognesi, Phys.Rev.D 101 033003 (2020)

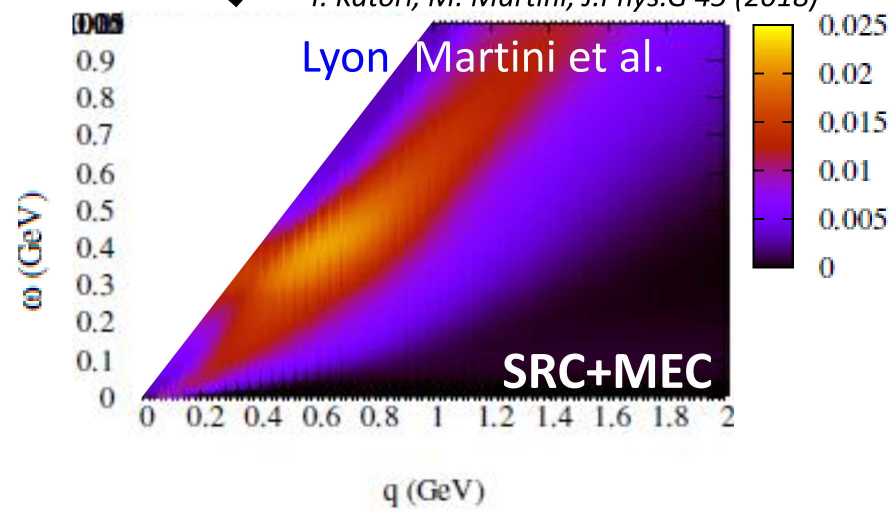






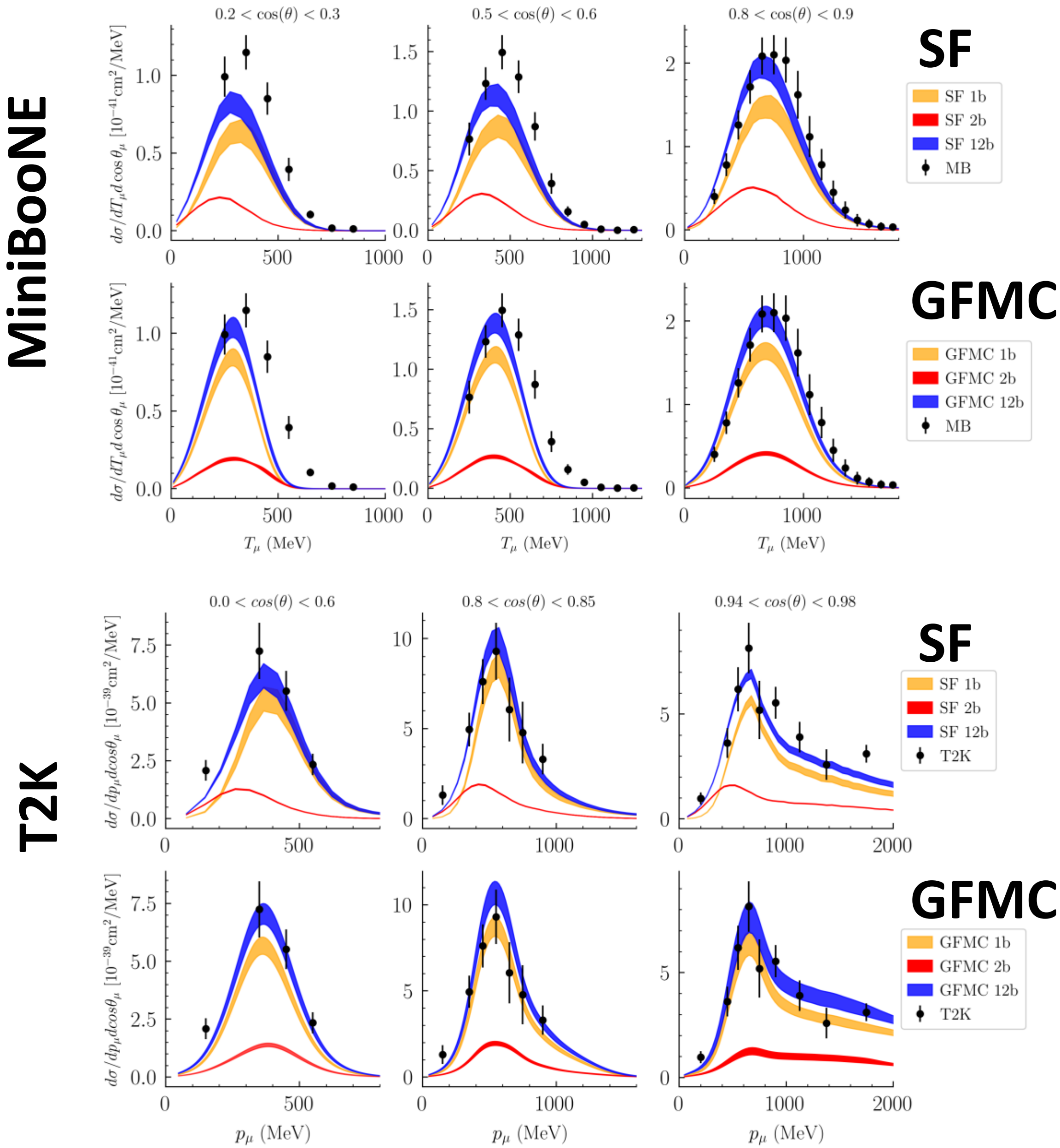
RPA-based

T. Katori, M. Martini, J.Phys.G 45 (2018)



N.B. A one-to one correspondence between different exclusive channel’s contributions can be misleading
[e.g. NN SRC contributions are part of the 2p-2h channel in RPA-based approaches while they are included in QE in SuSA.]

Example of different results in recent Spectral Function and Green's Function Monte Carlo (ab-initio) calculations



D. Simons et al. 2210.02455

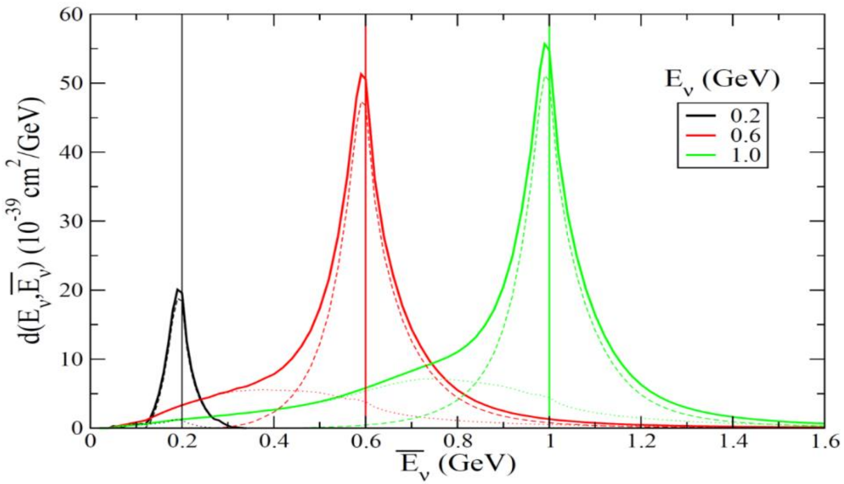
N. Steinberg talk @ NUINT 2022

SF and GFMC 2-body contributions shifted

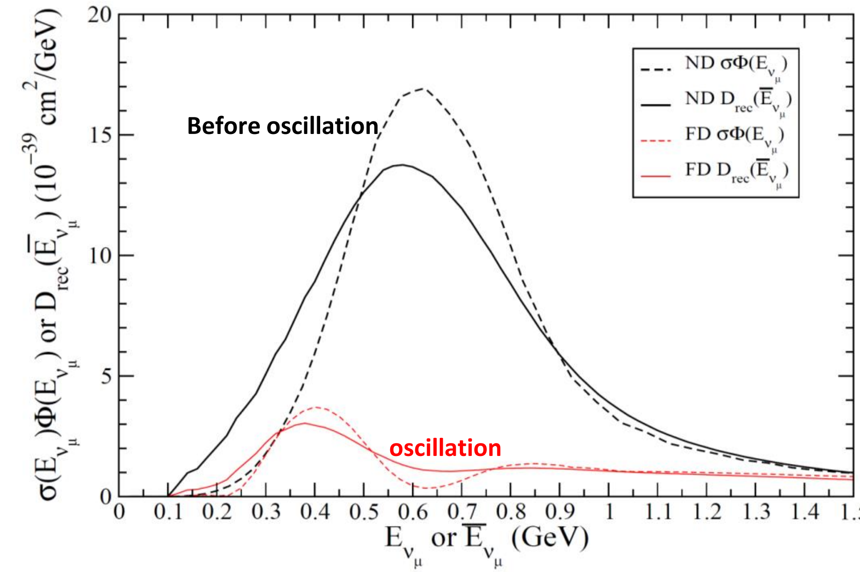
because of different 1 body – 2 body interference effects

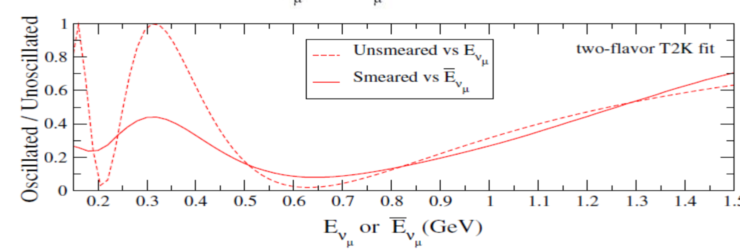
QE-based neutrino energy reconstruction and neutrino oscillations

ν energy migration matrix

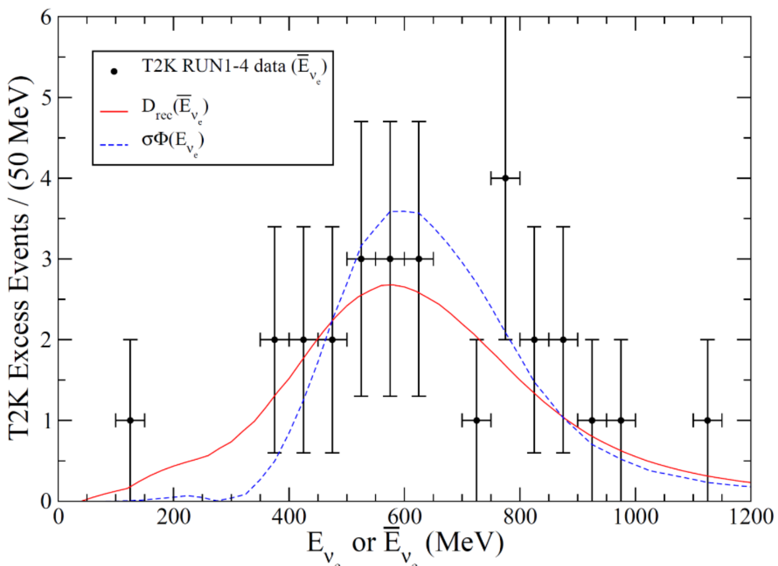


ν_μ disappearance T2K





ν_e appearance T2K

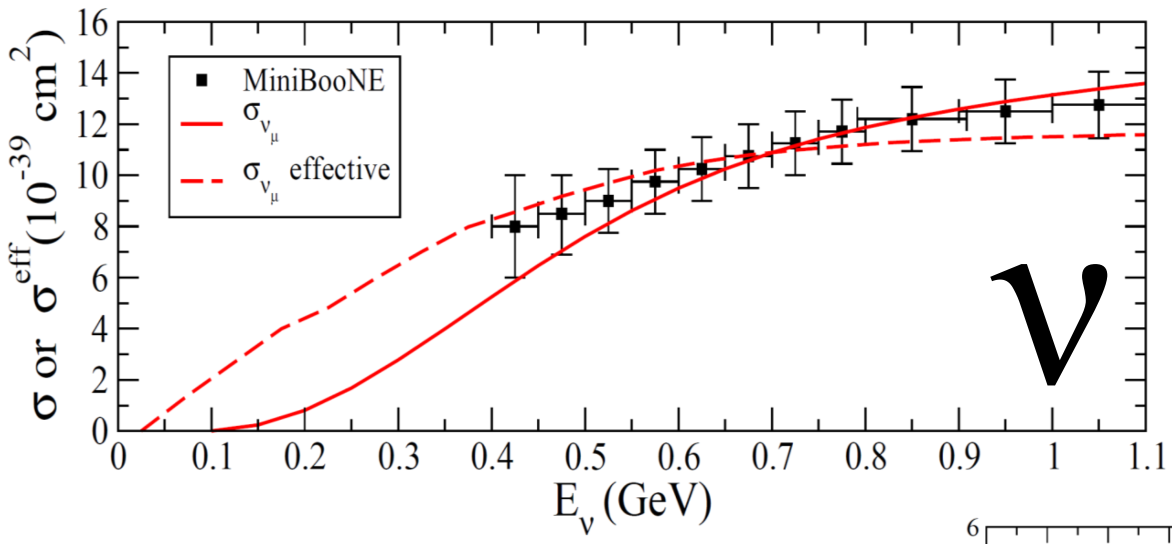


M. Martini, M. Ericson, G. Chanfray
Phys. Rev. D 85 093012 (2012); Phys. Rev. D 87 013009 (2013)

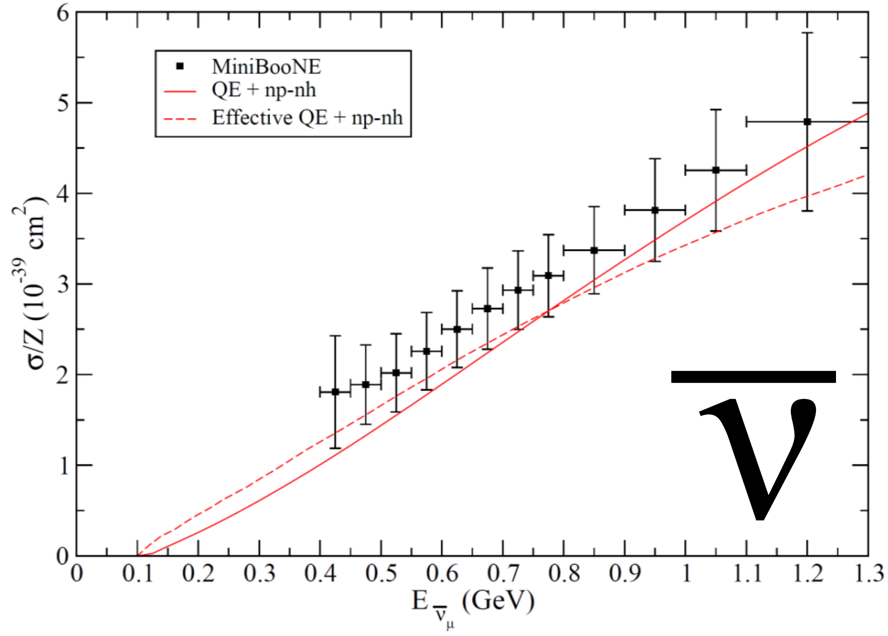
Similar results in:
Nieves et al. PRD 85 113008 (2012);
Lalakulich et al. PRC 86 054606 (2012)

Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

CCQE-like cross sections as a function of real (continuous line) and reconstructed (dashed line) neutrino energy

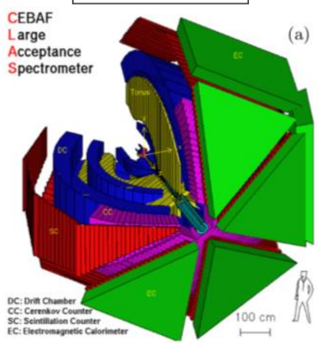


M. Martini, M. Ericson, G. Chanfray, Phys. Rev. D 87 013009 (2013)

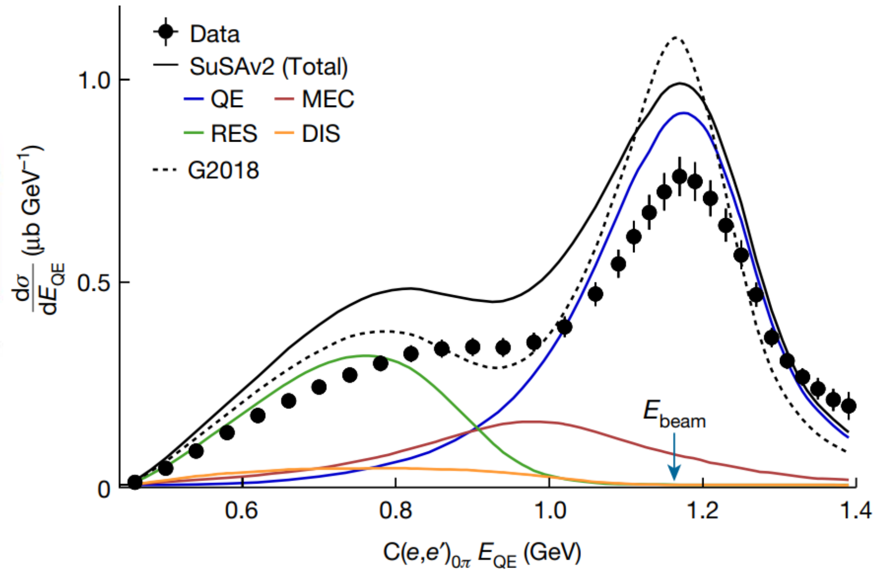


Martini, Ericson, Phys. Rev. C 87 065501 (2013)

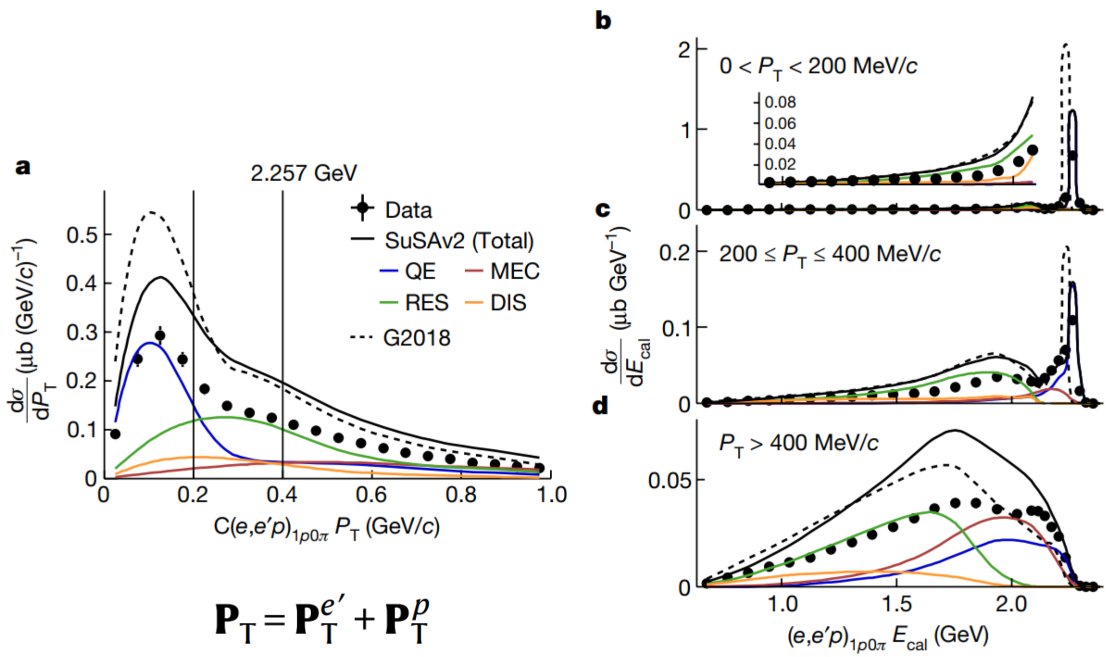
Electron-beam energy reconstruction for ν oscillation measurements



Nature 599 (2021) 7886, 565-570



QE-based (e,e')



$$\mathbf{P}_T = \mathbf{P}_T^{e'} + \mathbf{P}_T^{p}$$

Calorimetric -based (e,e'p)

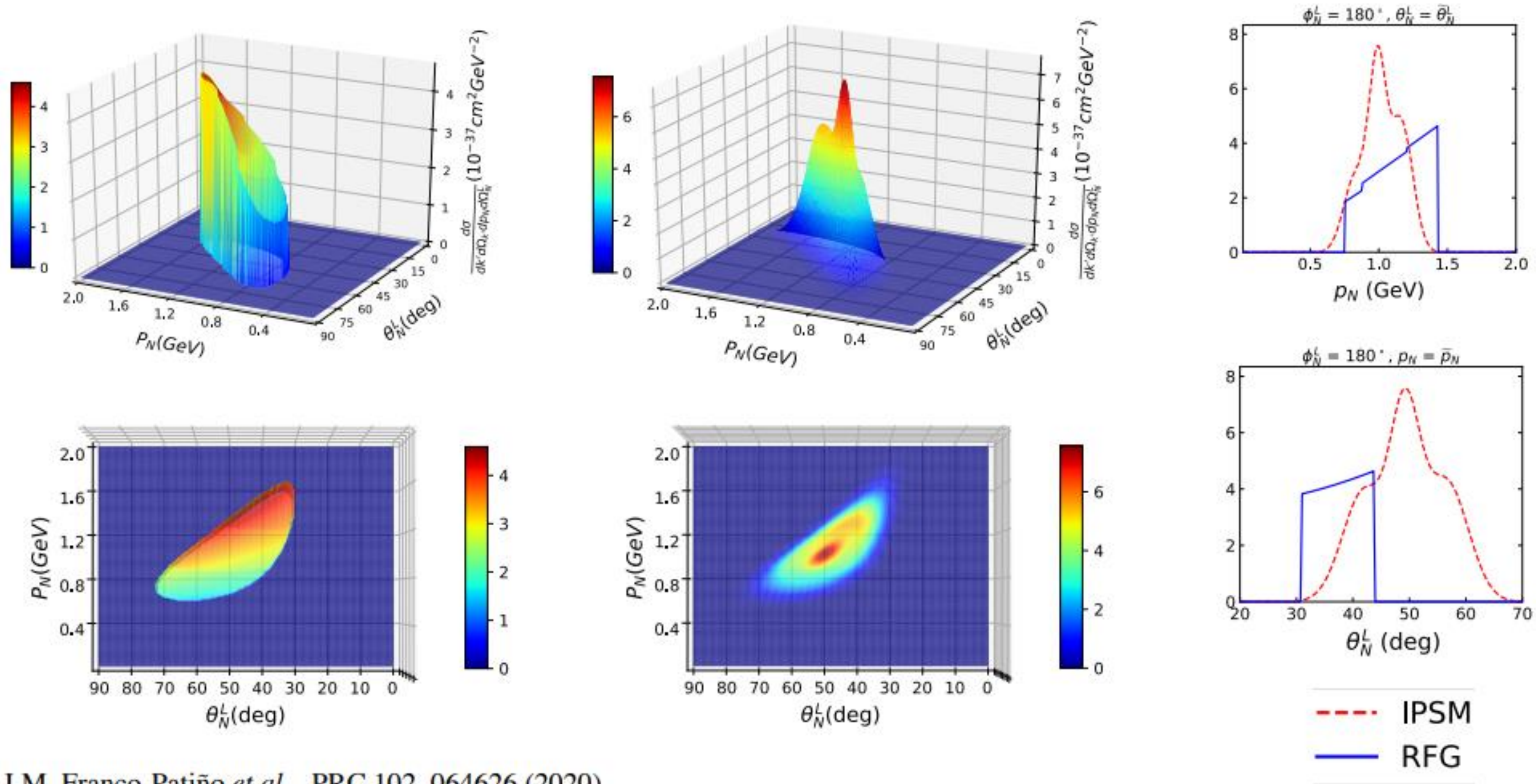
Semi-inclusive cross section: impact of different initial state modeling

M. Barbaro talk @IPSA 2022

6-differential semi-inclusive cross section $(\nu_\mu, \mu p)$ nucleon knock-out

$^{40}Ar(\nu_\mu,\mu^- p)^{39}Cl$ DUNE flux $k' = 1.5\,\text{GeV}, \theta_\mu = 30^0, \phi_N^L = \pi$

Relativistic Fermi Gas **Independent Particle Shell Model**



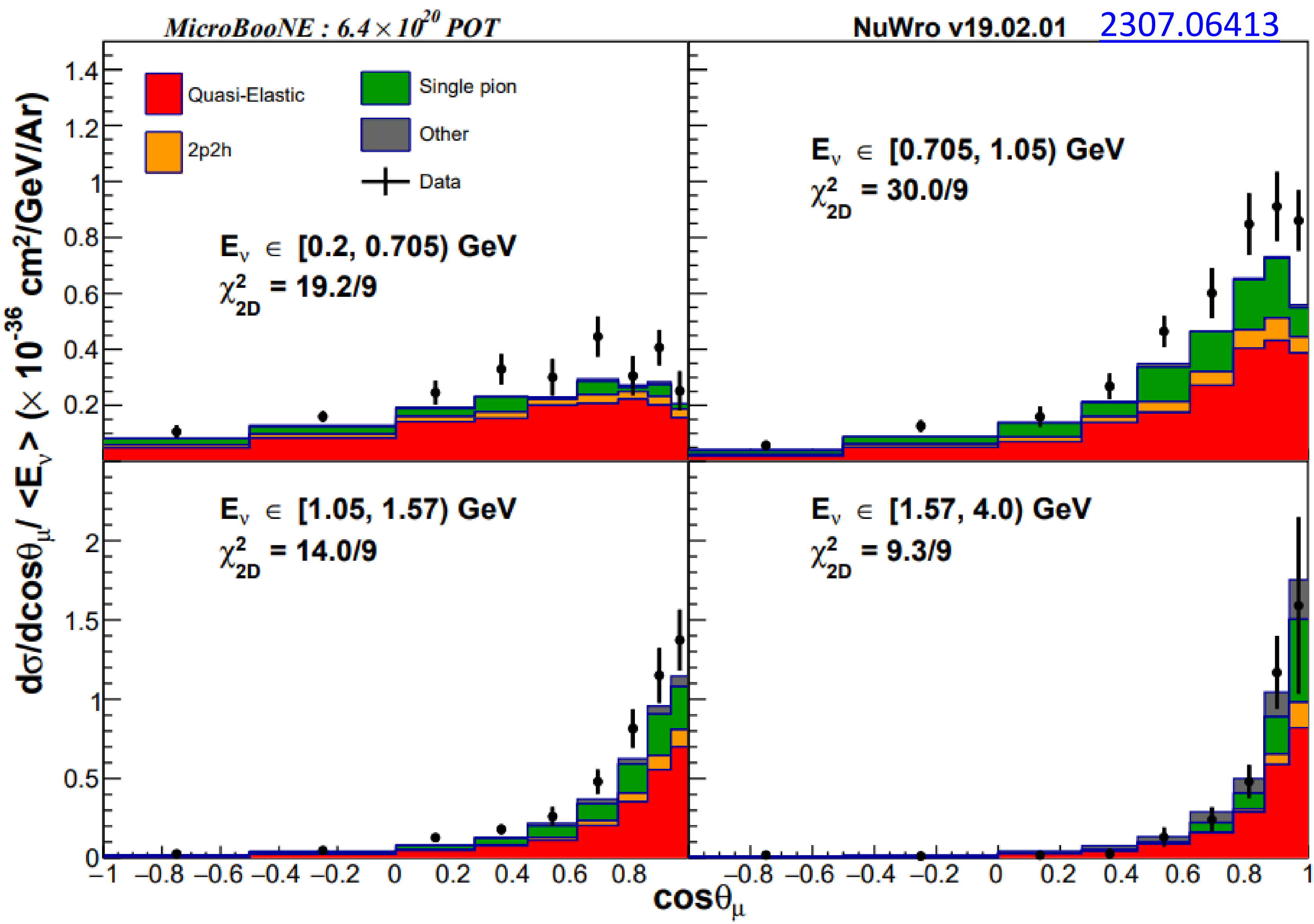
J.M. Franco-Patiño *et al.*, PRC 102, 064626 (2020)

Relativistic Plane Wave Impulse Approximation (no FSI included)

Striking differences in the cross section due to initial state physics described by different spectral functions.
The precise knowledge of the SF is crucial for a reliable modelling of semi-inclusive reactions.

MicroBooNE double-differential CC inclusive cross section

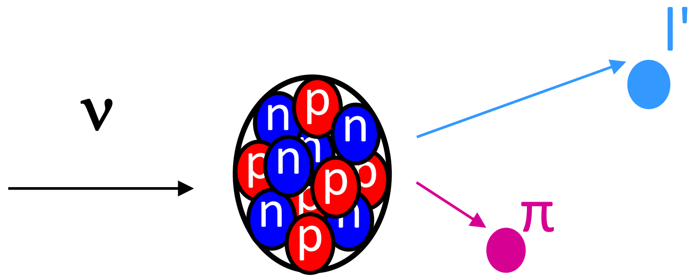
NuWro estimation of interaction channels breakdown

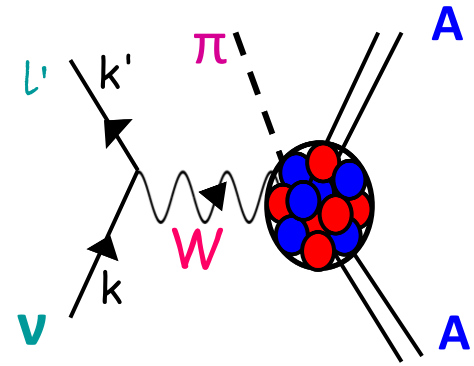


The coherent 1π production

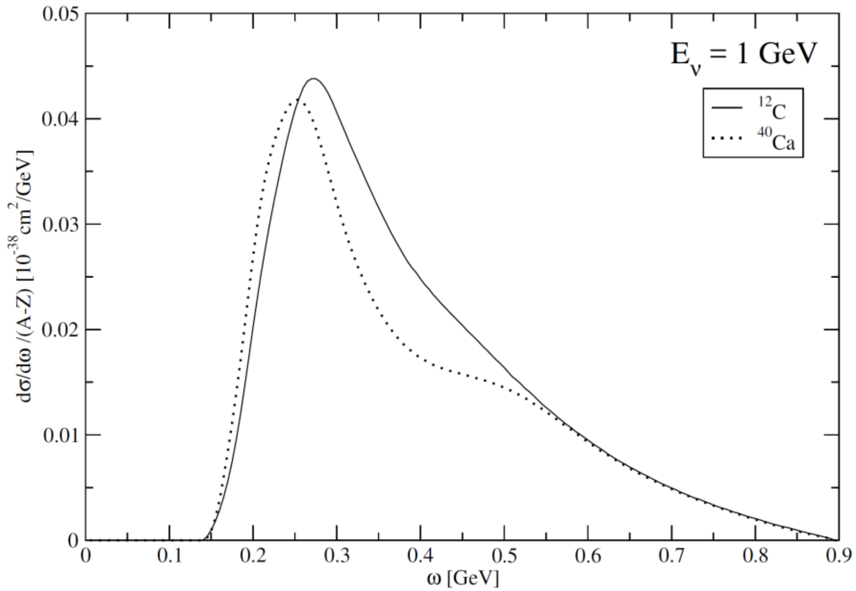
Production of 1 pion with the nucleus remaining in its ground state

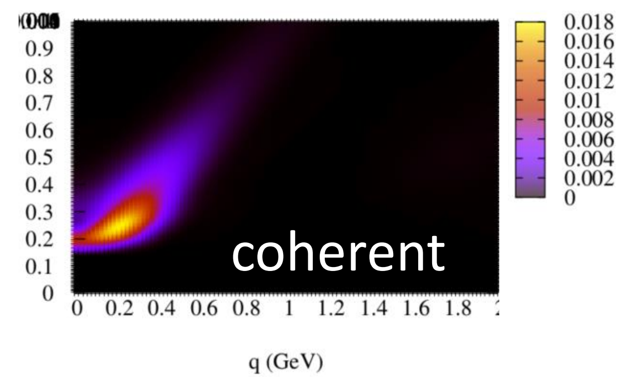
Relatively rare interaction channel, but can mimic oscillation signals

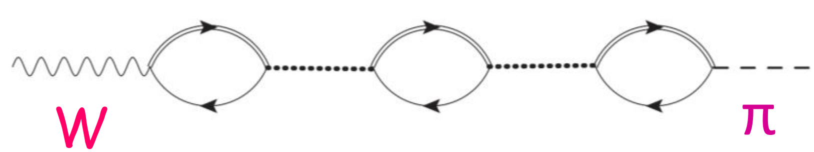




M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)







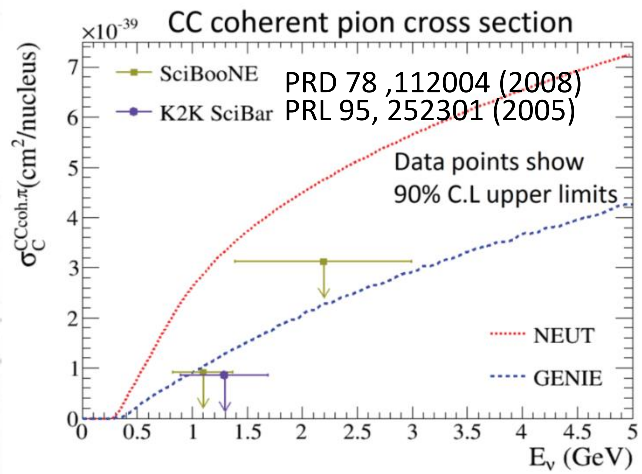
Cross sections reshaped by nuclear collective effects

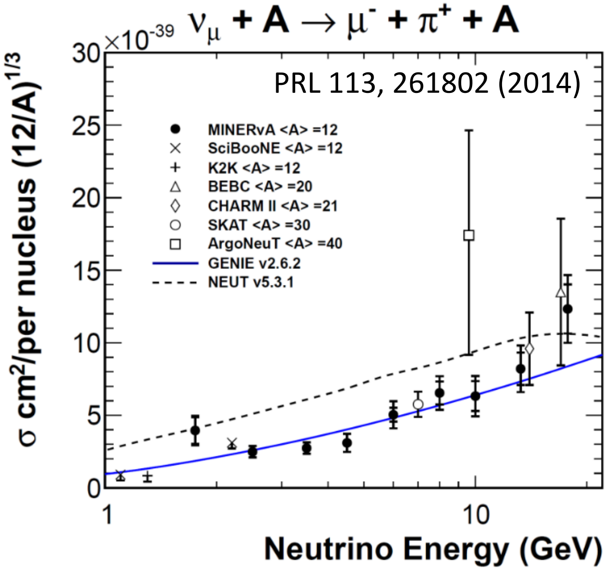
Coherent 1π production experimental results

K2K and SciBooNE did not observe coherent π^+ production at neutrino energies ~1GeV

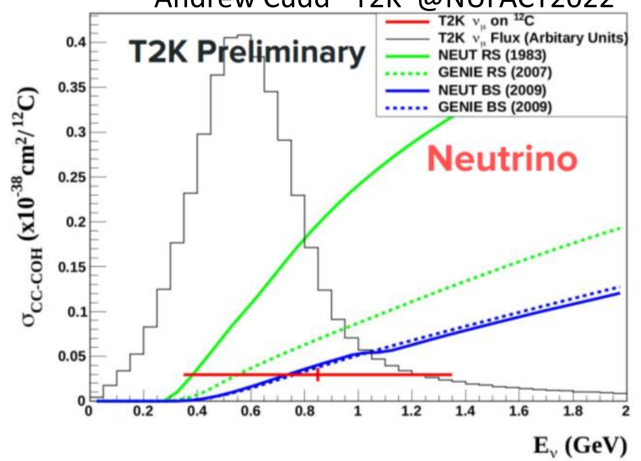
MINERνA and ArgoNeut see evidence for CC coherent pion production

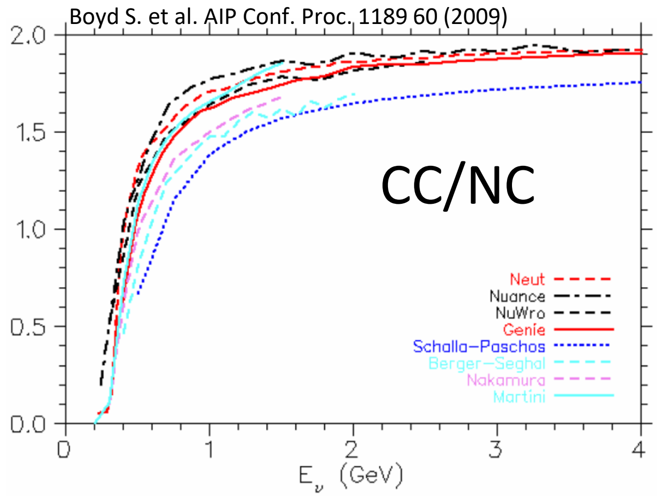
Preliminary T2K cross section measurement: coherent π+ production at neutrino energies ~1GeV





Andrew Cudd –T2K @NUFACT2022





Coherent puzzle at $E_\nu \sim 1$ GeV

Theoretical models:

$$\frac{\pi+\text{ coh. CC}}{\pi 0\text{ coh. NC}} = 1.5 \sim 2$$

SciBooNE:

$$\frac{\pi+\text{ coh. CC}}{\pi 0\text{ coh. NC}} = 0.14^{+0.30}_{-0.28}$$

Kurimoto et al, PRD 81 (2010)

Nuclear targets of present and future LBL oscillation experiments

Present

Future

Carbon: T2K(ND) and NOvA

Oxygen (water): T2K (SuperK) and Hyper-K

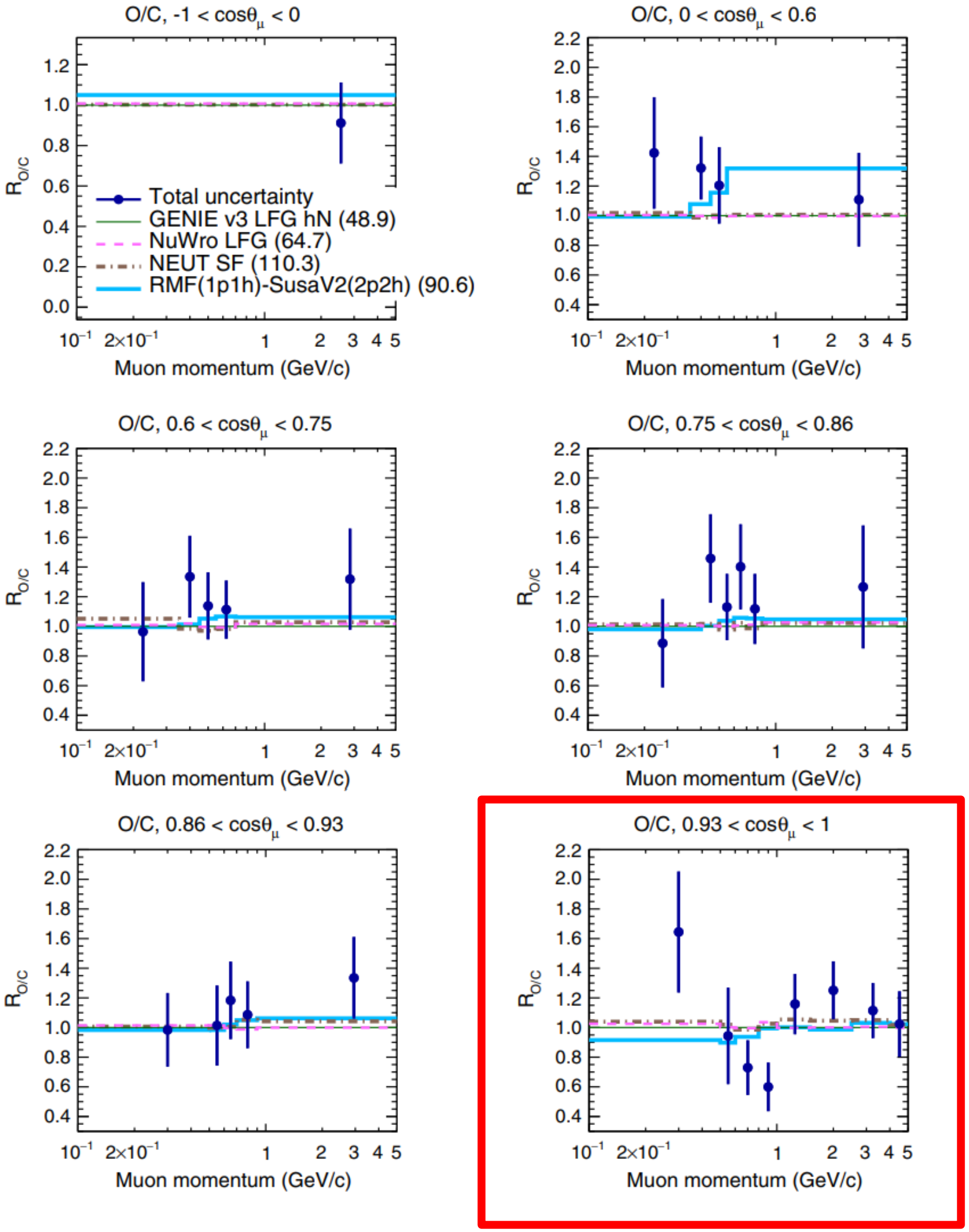
Argon: DUNE

In the last 15 years many cross sections measurements and theoretical studies have been performed for Carbon (^{12}C). Less for Oxygen (^{16}O) and Argon (^{40}Ar)

T2K CC0π $d^2\sigma$ cross sections on oxygen and carbon

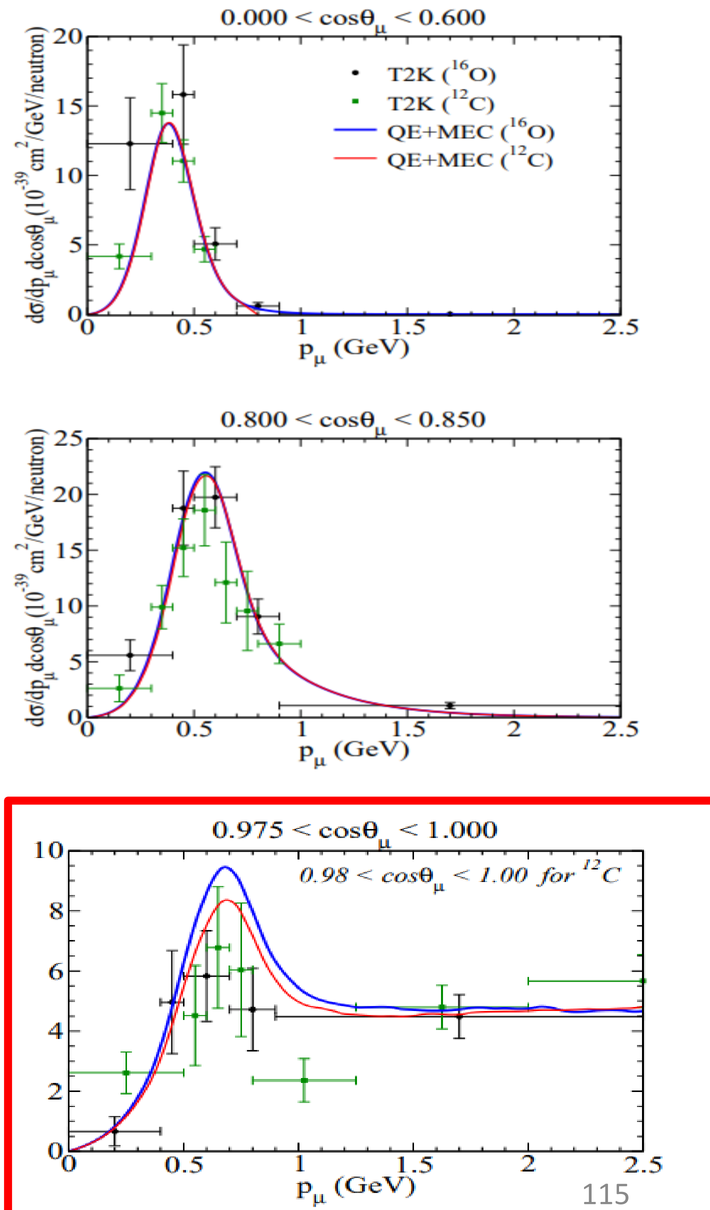
Ratio $^{16}O/^{12}C$ per nucleon

T2K PRD 101 (2020)

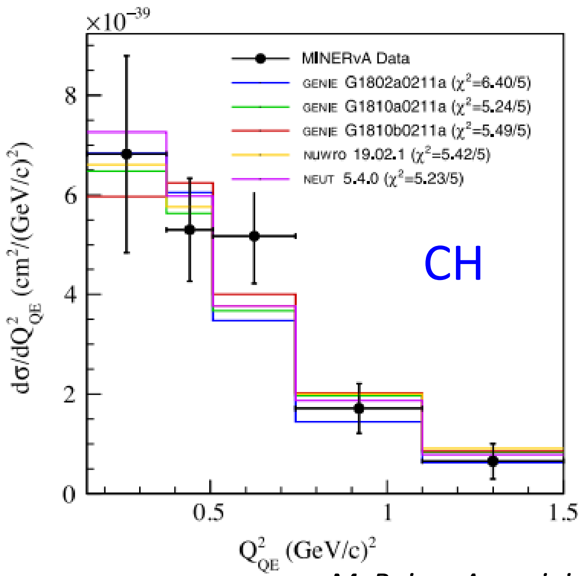


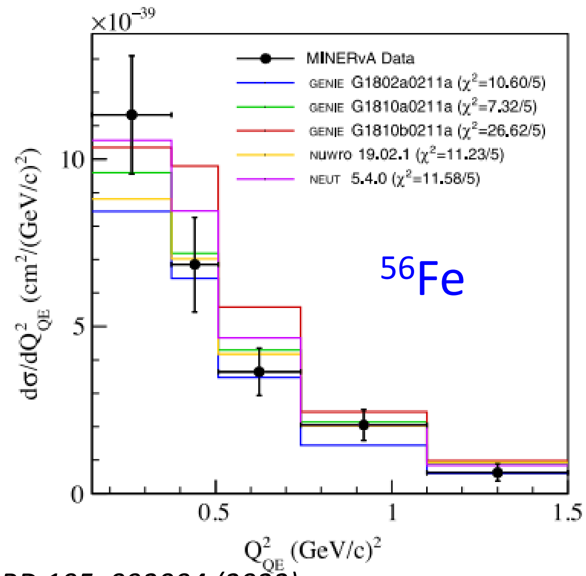
SuSAv2+MEC

Megias et al., JPG46 (2019)

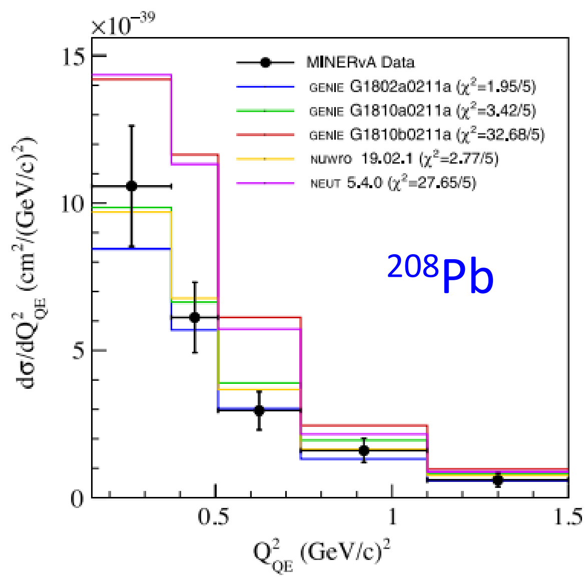


MINERvA CC0π1p(at least) Q^2distributions for carbon, iron, lead





M. Buizza Avanzini et al. PRD 105, 092004 (2022)

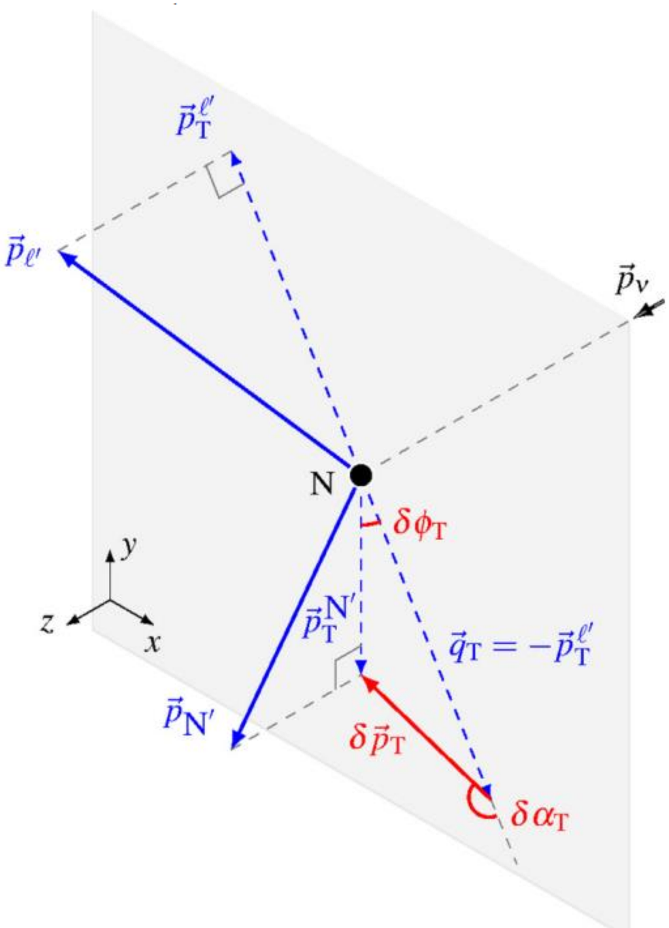


- The spread of distributions predicted by generators increases from carbon to lead
- Most significant deviations are at low Q^2 where nuclear effects are more important

PHYSICAL REVIEW C **94**, 015503 (2016)

Measurement of nuclear effects in neutrino interactions with minimal dependence on neutrino energy

X.-G. Lu,[1,*] L. Pickering,[2] S. Dolan,[1] G. Barr,[1] D. Coplowe,[1] Y. Uchida,[2] D. Wark,[1,3] M. O. Wascko,[2] A. Weber,[1,3] and T. Yuan[4]



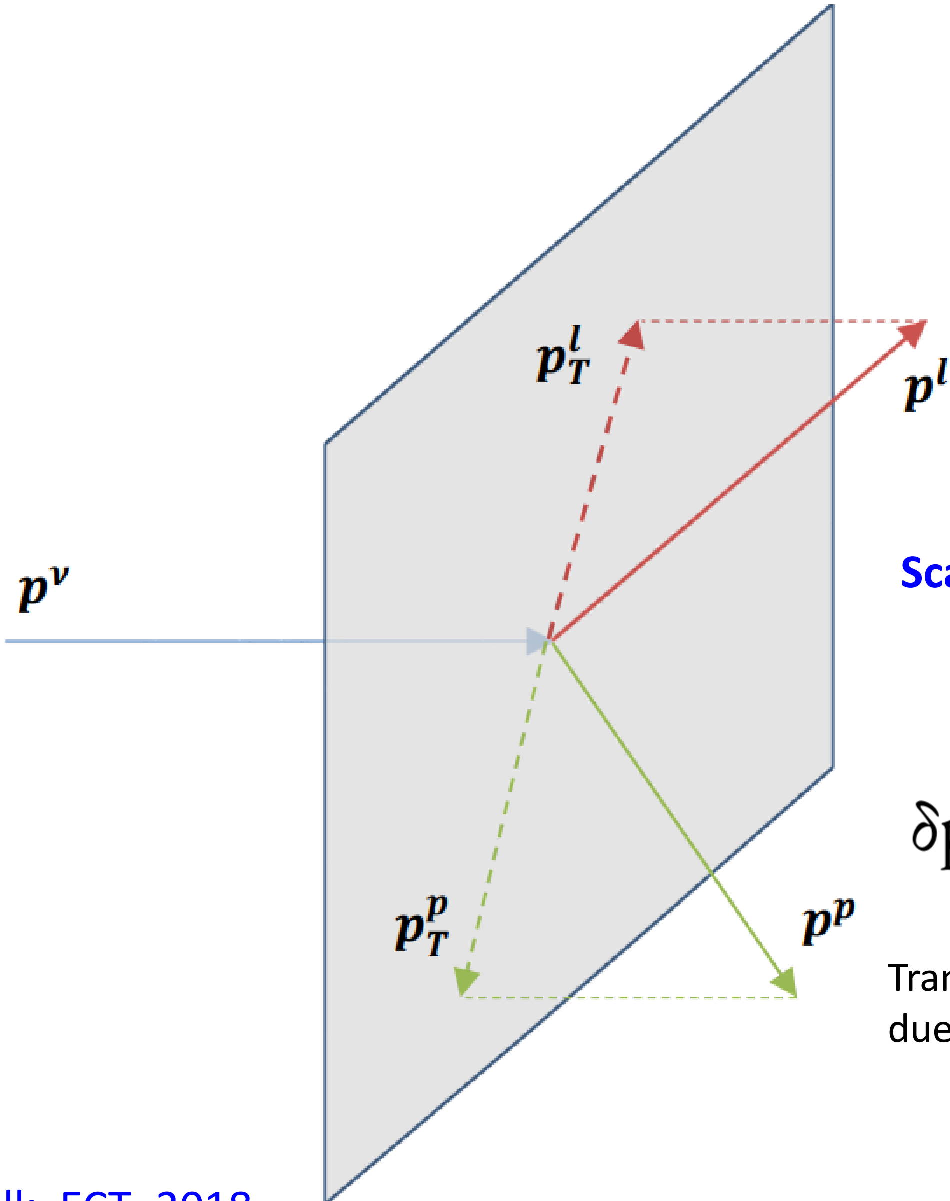
Single Transverse Variables (STV)

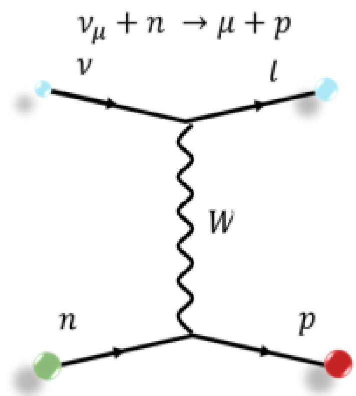
$$\delta\vec{p}_T \equiv \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'}$$

$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\delta\vec{p}_T}{p_T^{\ell'}\,\delta p_T}$$

$$\delta\phi_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\vec{p}_T^{\,N'}}{p_T^{\ell'}\,p_T^{N'}},$$

Single Transverse Kinematic Variables





No nuclear Effects

Scattering on a free nucleon at rest

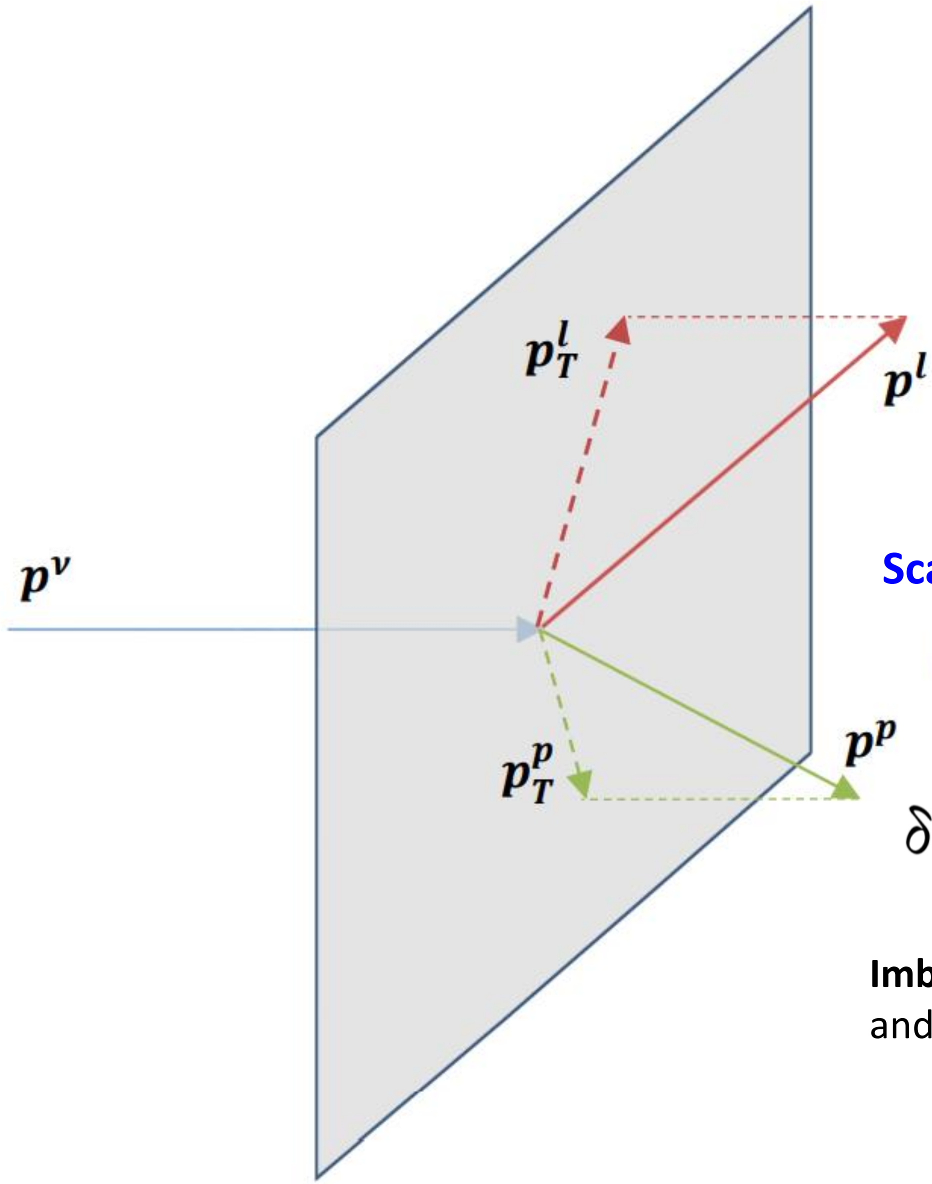
$$p_T^l = -p_T^p$$

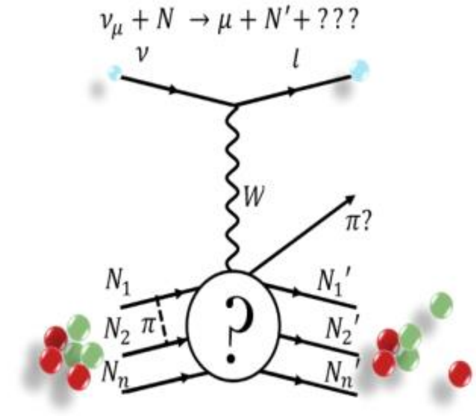
$$\delta p_T = |\, \mathbf{p_T}^{\mu} + \mathbf{p_T}^{\mathbf{p}} \,| = 0$$

Transverse projections equal and opposite due to momentum conservation

[S_Dolan_Talk_ECT_2018]

Single Transverse Kinematic imbalance (STKI)





With Nuclear Effects

Scattering on nucleus

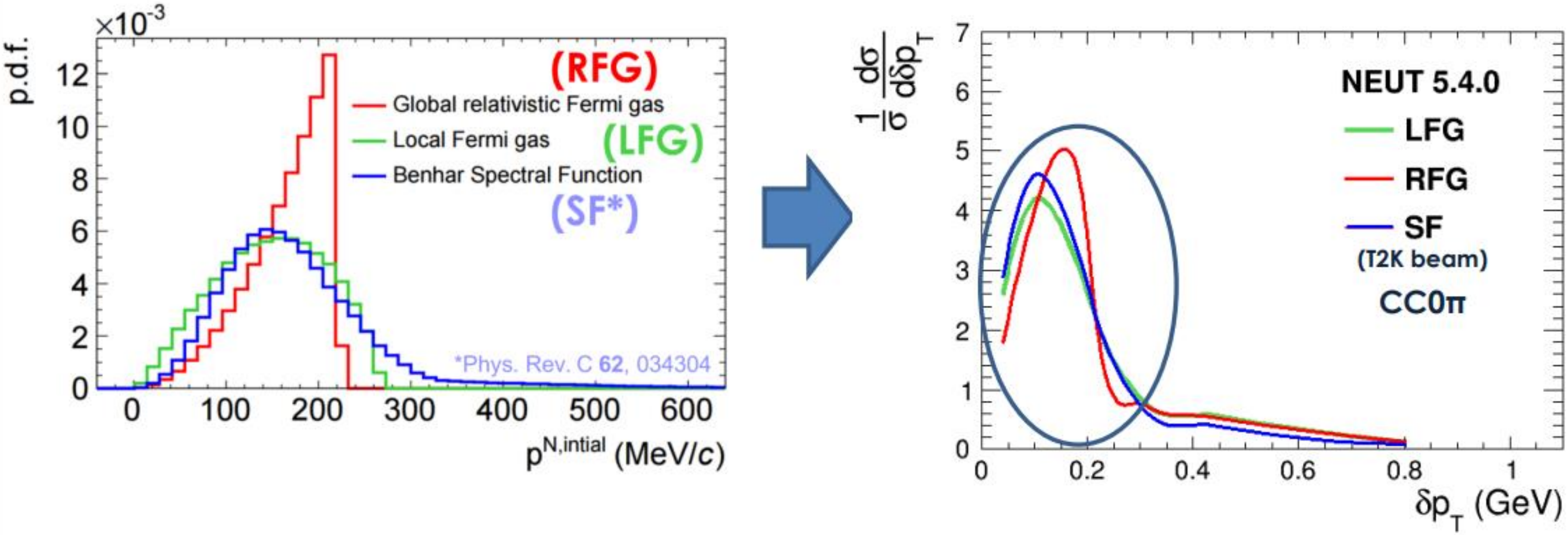
$$p_T^l \neq -p_T^p$$

$$\delta p_T = |\,\mathbf{p_T}^{\mu} + \mathbf{p_T}^{\mathbf{p}}\,| > 0$$

Imbalance due to initial nucleon motion and other nuclear effects

S Dolan Talk ECT 2018

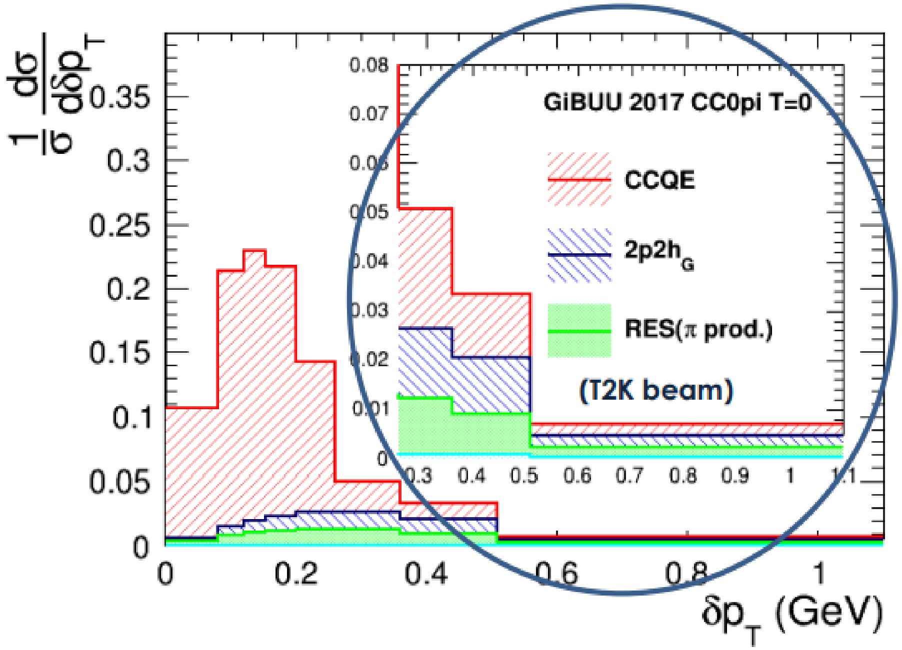
STV model discrimination - δp_T

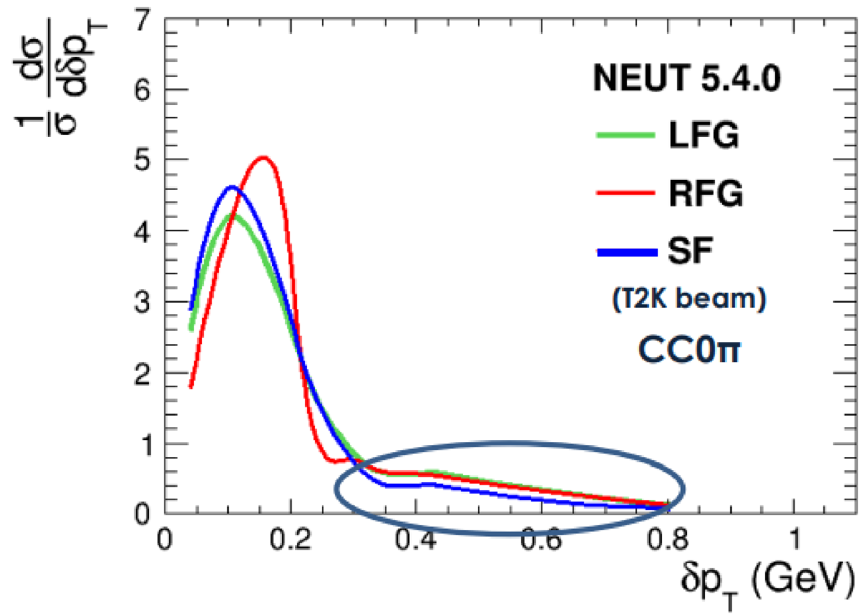


- In the absence of other nuclear effects, δp_T is the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion

S_Dolan_Talk_ECT_2018

STV model discrimination - δp_T

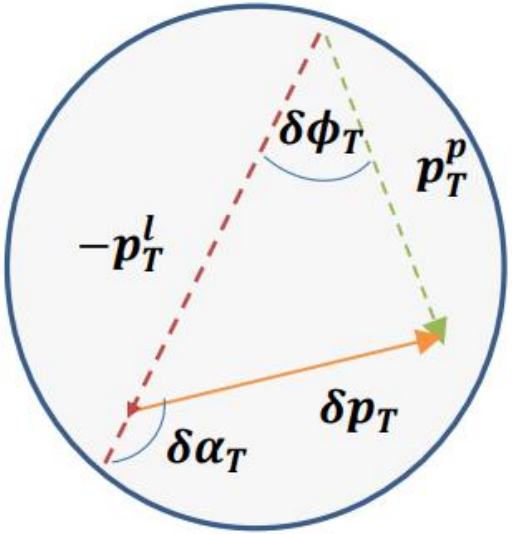




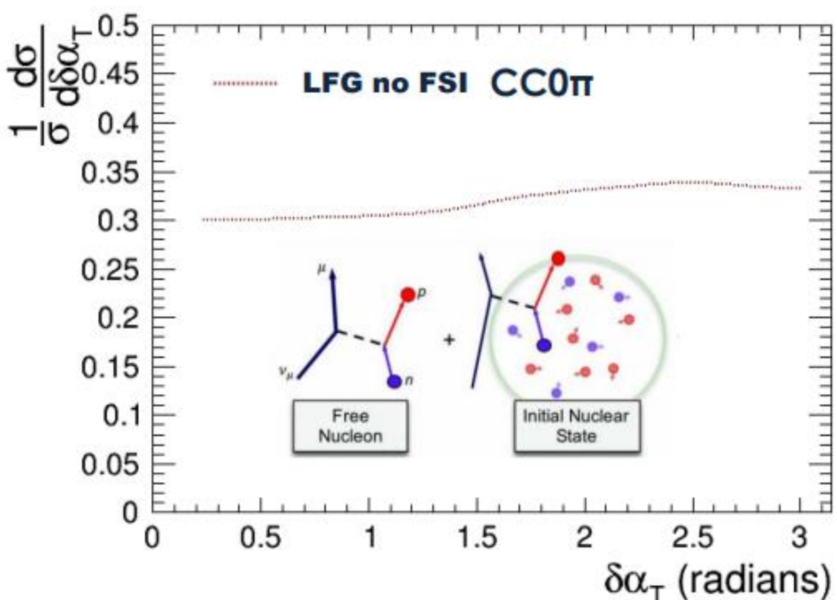
- In the absence of other nuclear effects, δp_T *is* the transverse projection of the Fermi motion.
- Since this motion is isotropic, $\delta p_T \rightarrow$ Fermi motion
- Cross section beyond the Fermi momentum must come from physics beyond RFG → 2p2h, FSI, SRCs …

S_Dolan_Talk_ECT_2018

STV model discrimination - $\delta\alpha_T$



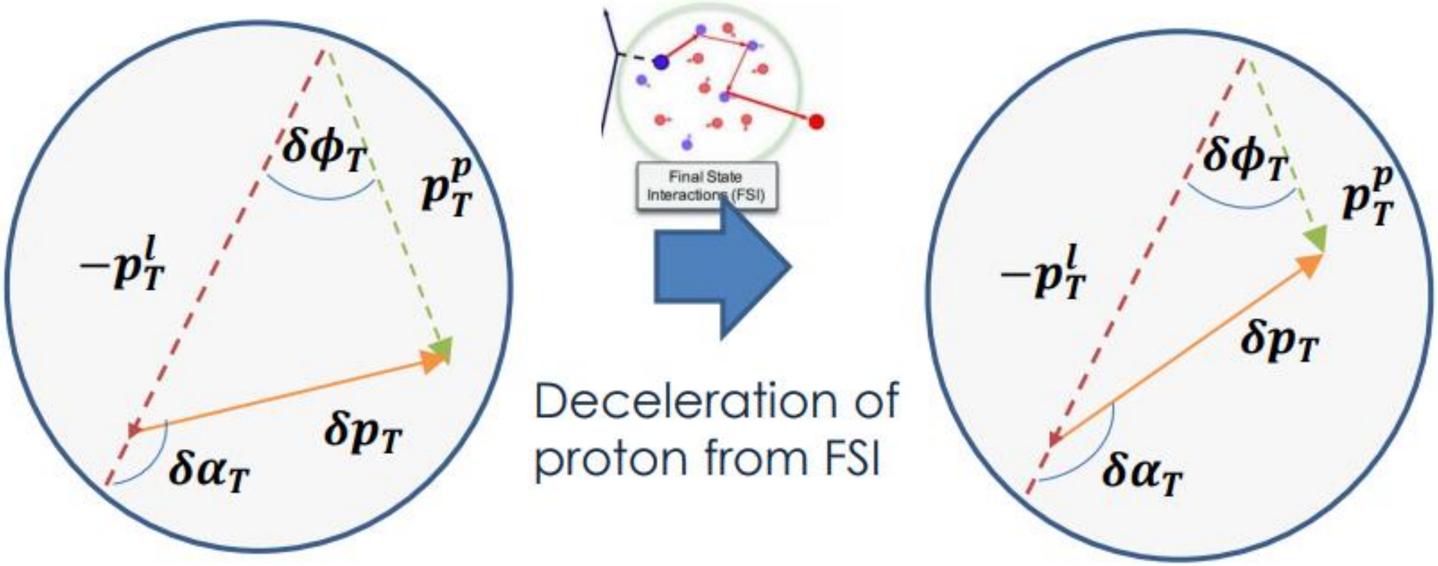
Consider imbalance from only Fermi motion



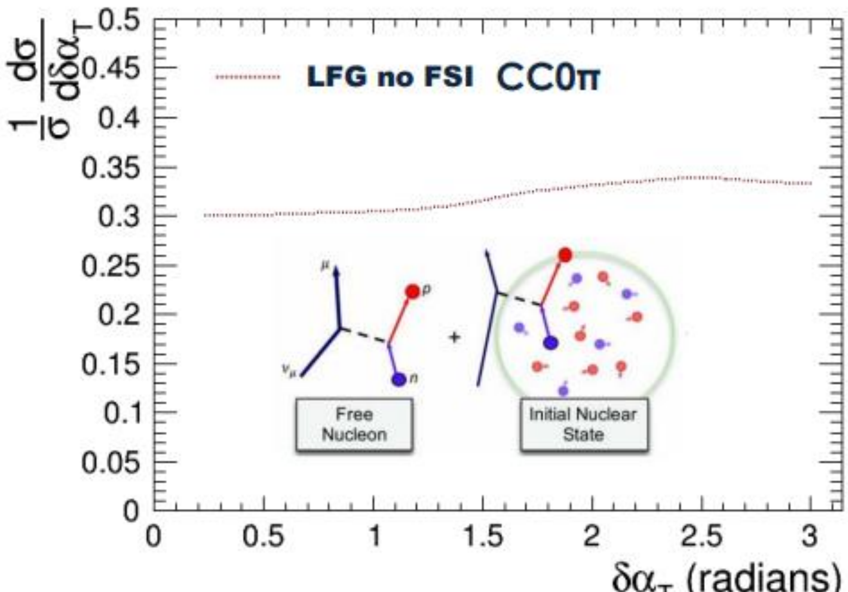
Fermi motion is isotropic so no preferred $\delta\alpha_T$ direction

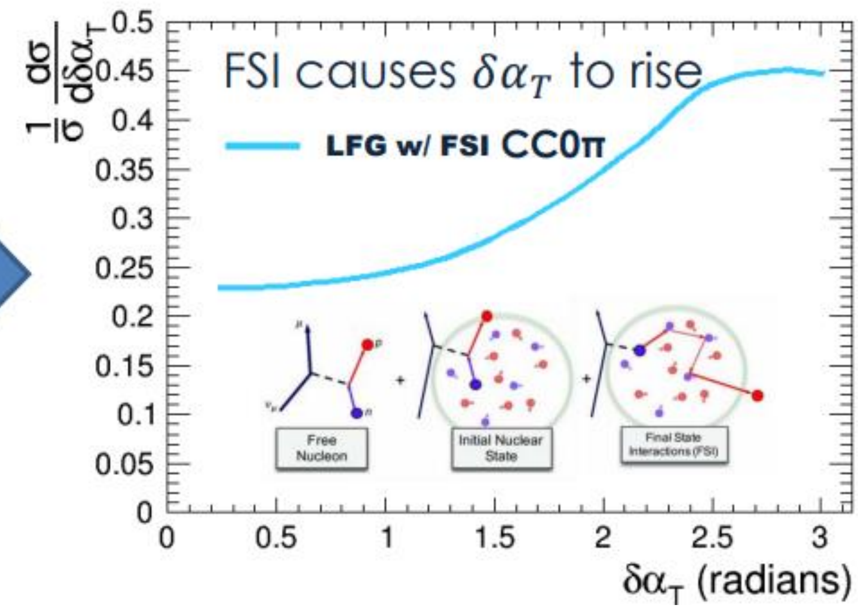
S_Dolan_Talk_ECT_2018

STV model discrimination - $\delta\alpha_T$



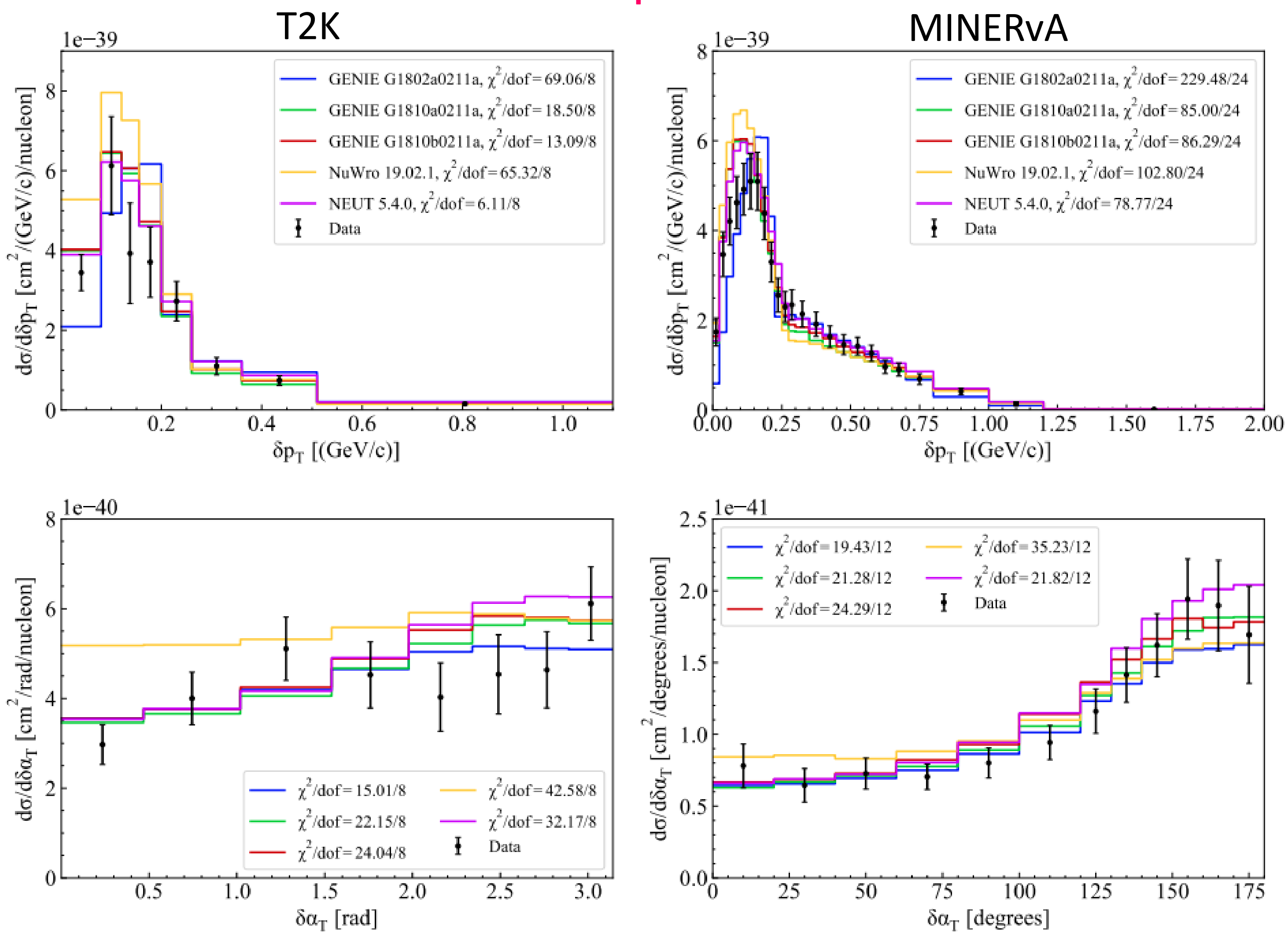
= larger $\delta\alpha_T$





S_Dolan_Talk_ECT_2018

Semi-inclusive CC0π dσ on carbon versus STKI Variables: Monte Carlo predictions



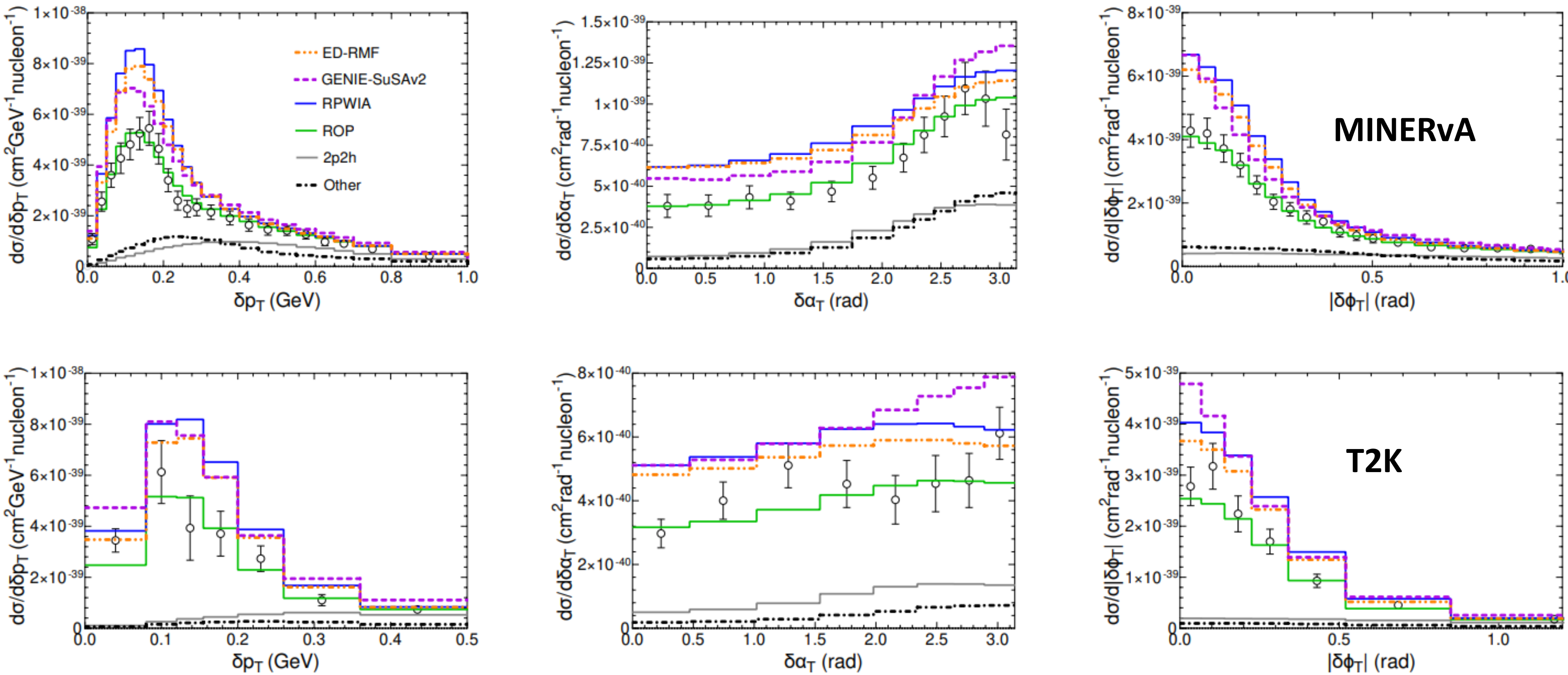
M. Buizza Avanzini et al. PRD 105, 092004 (2022)

None of the generators correctly reproduces all the data in the STKI variables without tuning

This is not a surprise since these generators implement "inclusive" microscopic models

Semi-inclusive CC0π dσ on carbon versus STKI Variables: discrimination of FSI microscopic modeling

J. M. Franco Patino et al, PRD 106 (2022)



RPWIA: no FSI
GENIE-SuSAv2: include FSI but from inclusive model (factorization)
ED-RMF, **rROP**, **ROP**: different theoretical approaches for FSI

- FSI improve the agreement with data respect to the RPWIA prediction
- STKI Variables helps to discriminate between different FSI models: data seem to prefer **ROP**
- 2p2h (from an inclusive-based model) give non-negligible contribution