Investigation of the MicroBooNE inclusive neutrino cross sections on argon

Marco Martini

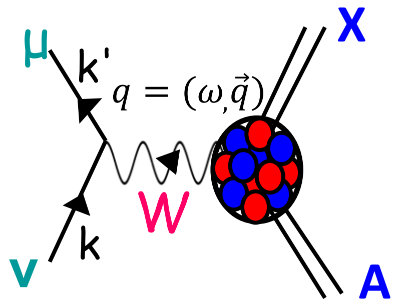
Based on: M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

Plan

- Brief review of our theoretical model
- Rapid review of our results for neutrino-carbon cross sections
- Investigation of the MicroBooNE inclusive $d^2\sigma/dp_\mu d\cos\theta$, $\sigma(E_\nu)$, $d\sigma/dE_\mu$ and $d\sigma/d\omega$ on argon
- Summary

Brief review of our theoretical model

Neutrino-nucleus cross section



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

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

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

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 cross section in terms of the response functions R(q,ω):

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

Nucleon properties → Form factors: Electric G_E, Magnetic G_M, Axial G_A

Nuclear dynamics → Nuclear Response Functions R(q,ω) ↔ Nuclear Matrix elements

Isovector R_τ (τ); Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$(τ σ•q); Isospin Spin Transverse $R_{\sigma\tau(T)}$(τ σxq)

Our theoretical model for Nuclear Response Functions

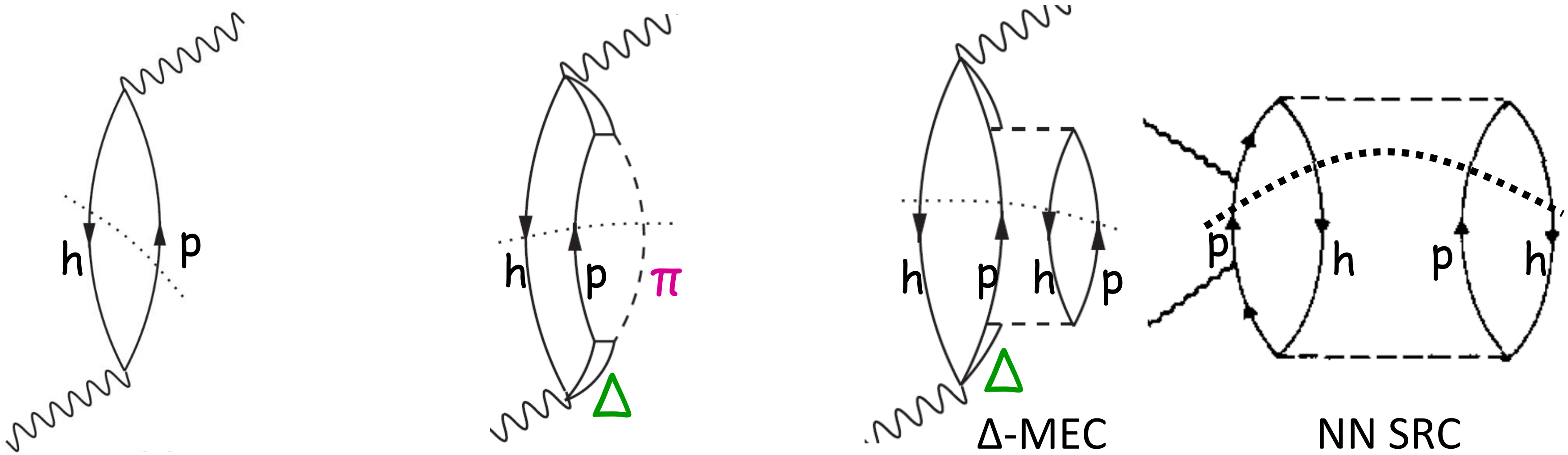
$$R_\alpha = \sum_{n \neq 0} |\langle n|\hat{O}_{(\alpha)}|0\rangle|^2 \; \delta[\omega - (E_n - E_0)]$$

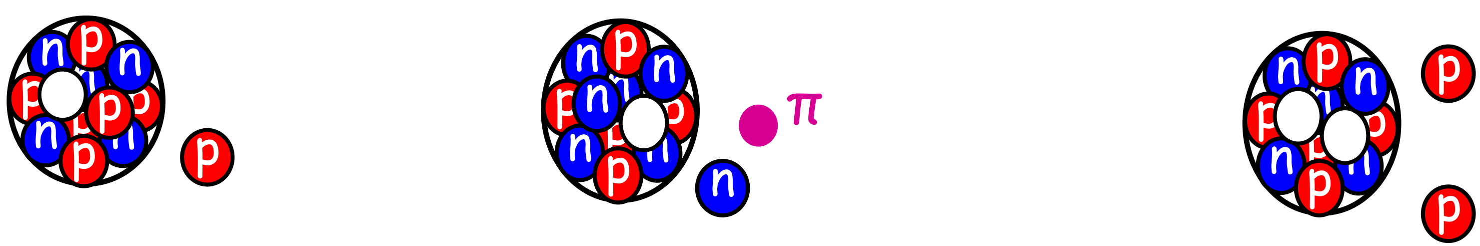
$$R(\omega, q) = -\frac{\mathcal{V}}{\pi} \mathrm{Im}[\Pi(\omega, q, q)]$$

1p-1h
Quasielastic

1p-1h
(Δ→πN) 1π production

2p-2h:
two examples



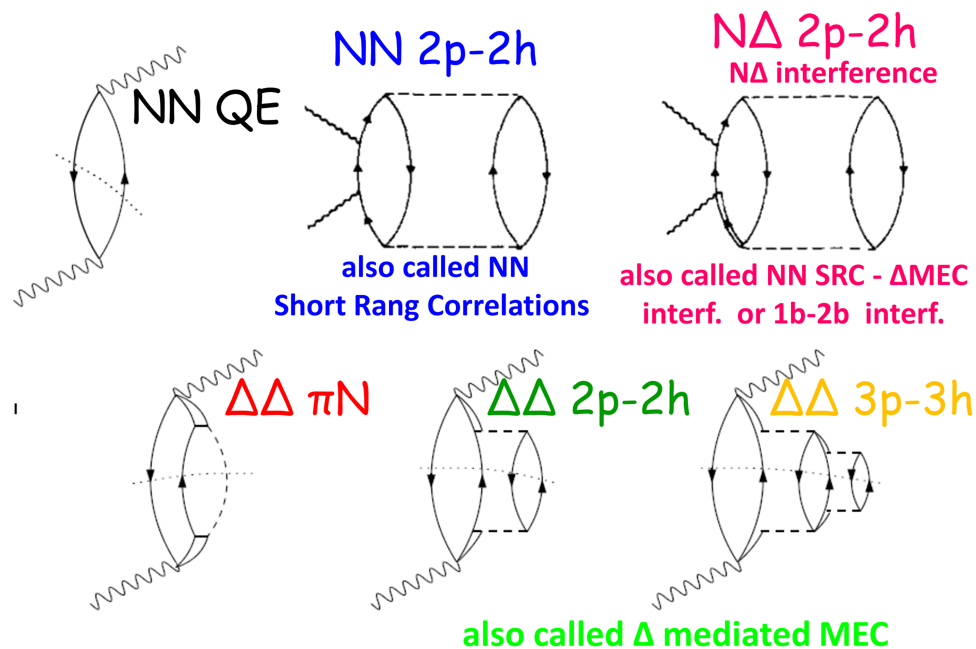


Unified description of several channels

Bare responses in semi-classical approximation – local Fermi gas

$$\Pi^0(\omega, \boldsymbol{q}, \boldsymbol{q}') = \int d\boldsymbol{r} e^{-i(\boldsymbol{q}-\boldsymbol{q}')\cdot\boldsymbol{r}} \Pi^0\left[\omega, \frac{1}{2}(\boldsymbol{q}+\boldsymbol{q}'), r\right]$$

$$\Pi^0\left(\omega, \frac{\boldsymbol{q}+\boldsymbol{q}'}{2}, \boldsymbol{r}\right) = \Pi^0_{k_F(r)}\left(\omega, \frac{\boldsymbol{q}+\boldsymbol{q}'}{2}\right)$$

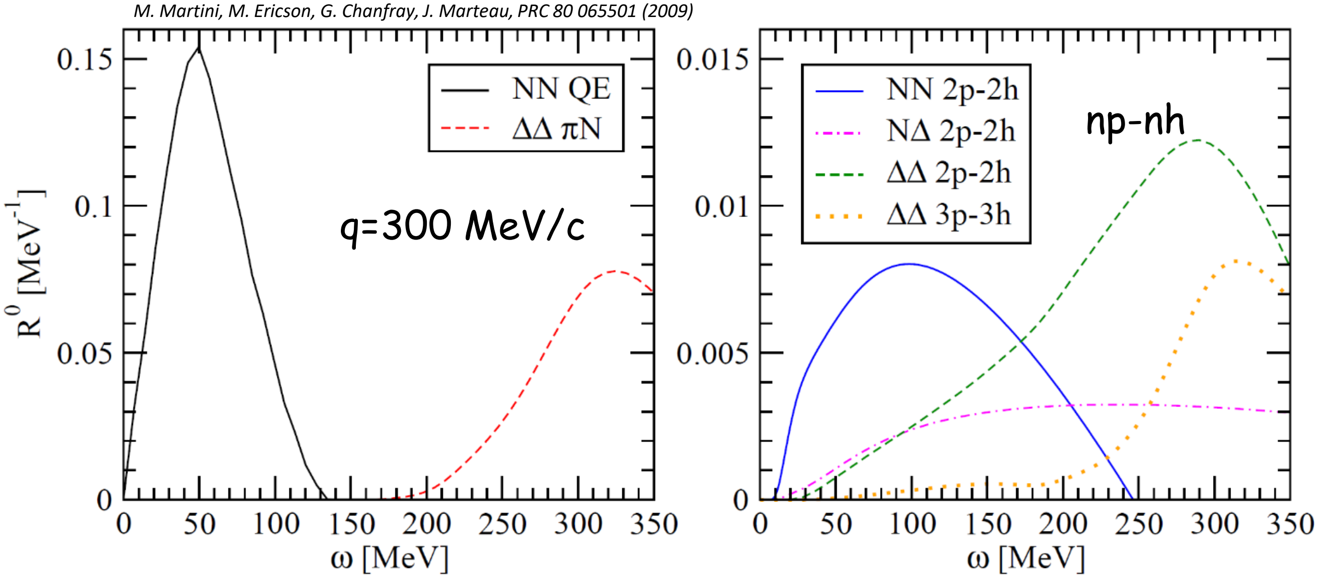


Local Density Approximation (LDA)

$$k_F(r) = [3/2\ \pi^2 \rho(r)]^{1/3}$$

Density profiles taken from experimental nuclear charge density distribution

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

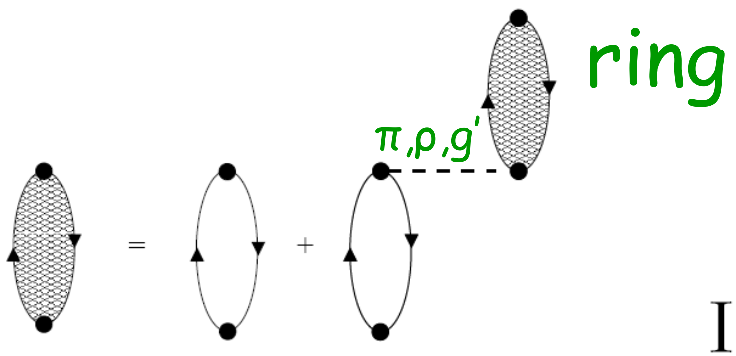


Several partial components

- QE (1 nucleon knock-out)
- Pion production
- Multinucleon excitation

Switching on the interaction: random phase approximation (RPA)

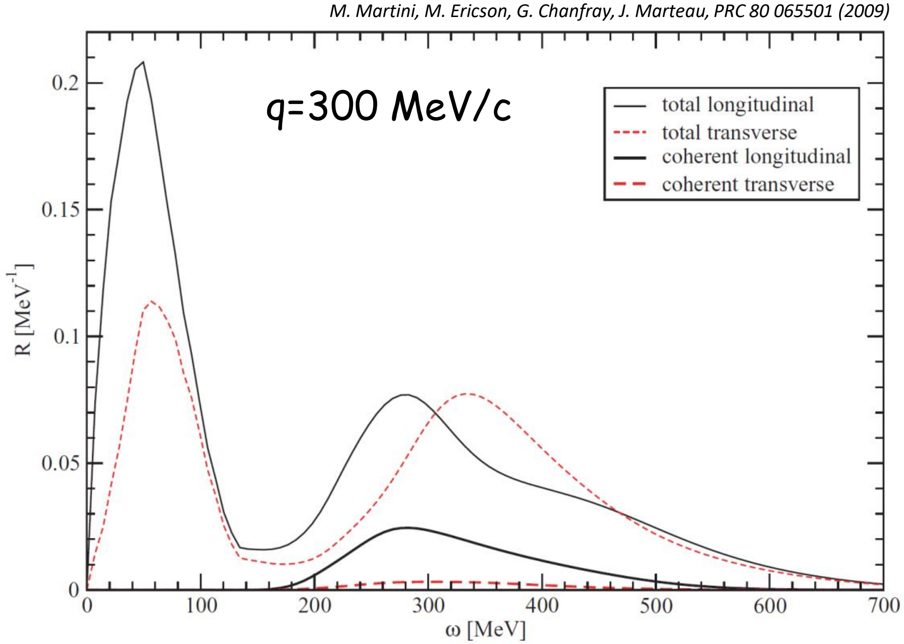
- External force acting on one nucleon is transmitted to the neighbors via the interaction
- The nuclear response becomes collective

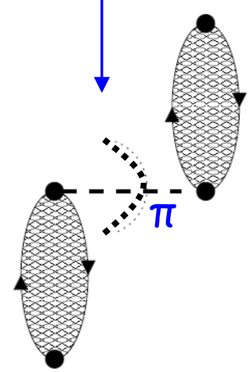


$$\Pi = \Pi^0 + \Pi^0\, V\, \Pi$$

$$\mathrm{Im}\Pi = |\Pi|^2\ \mathrm{Im}V\ + |1 + \Pi\, V|^2\ \mathrm{Im}\Pi^0$$

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





coherent π production

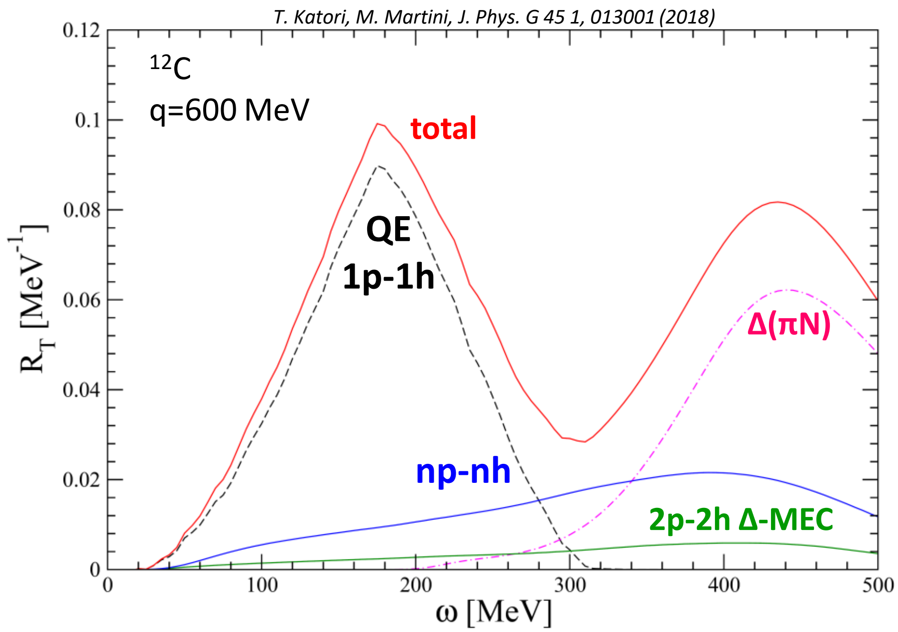
$$\Pi^0 = \sum_{k=1}^{N_k} \Pi^0_{(k)}$$

exclusive channels:
QE, 2p-2h, Δ→πN …

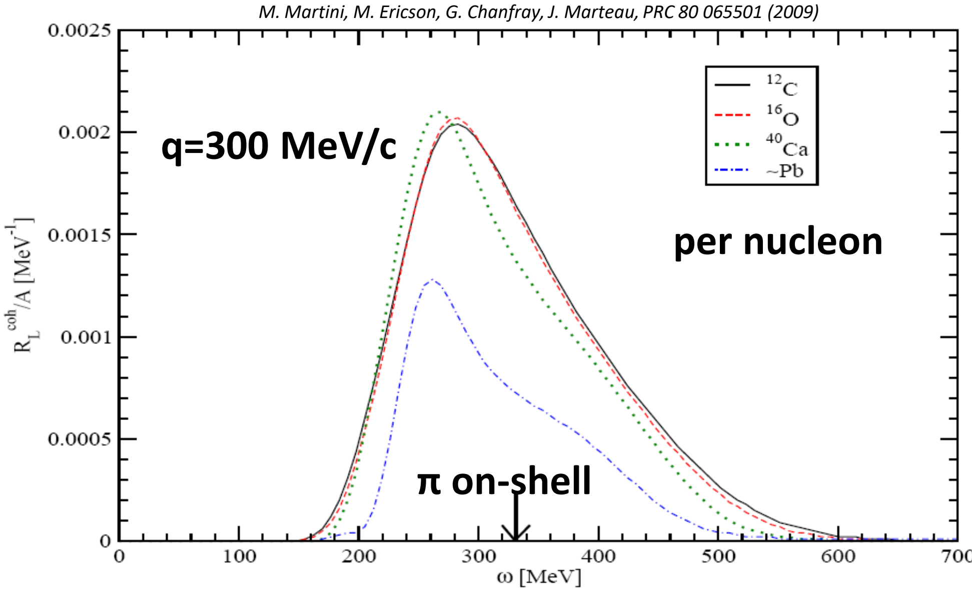
Several partial components treated in self-consistent and coupled way

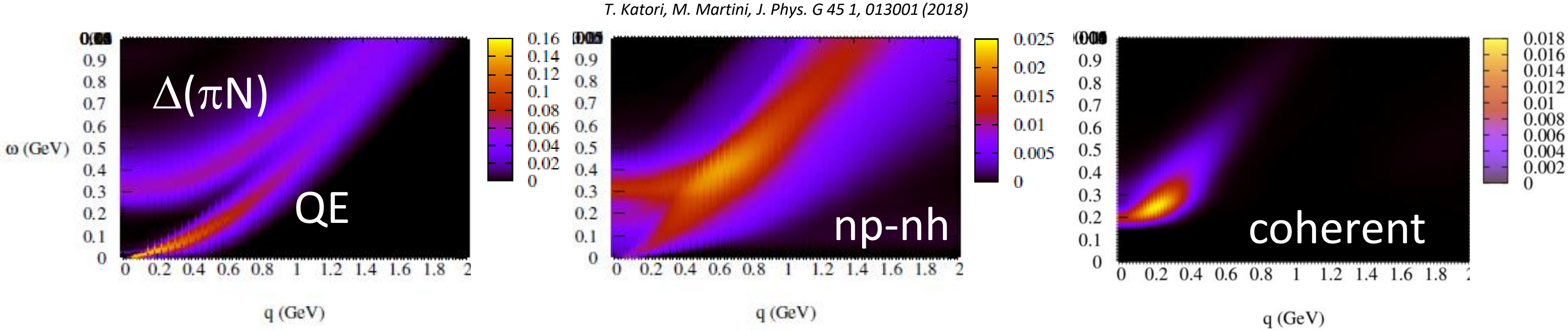
Examples of RPA nuclear responses

Isospin Spin Transverse $R_{\sigma\tau(T)}$



Isospin Spin Longitudinal $R_{\sigma\tau(T)}$ coherent

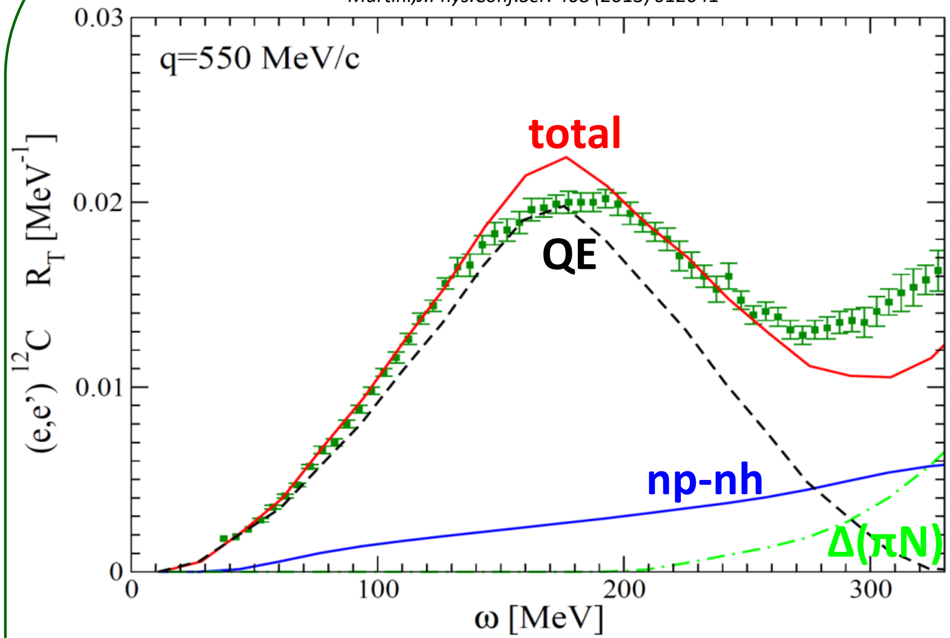


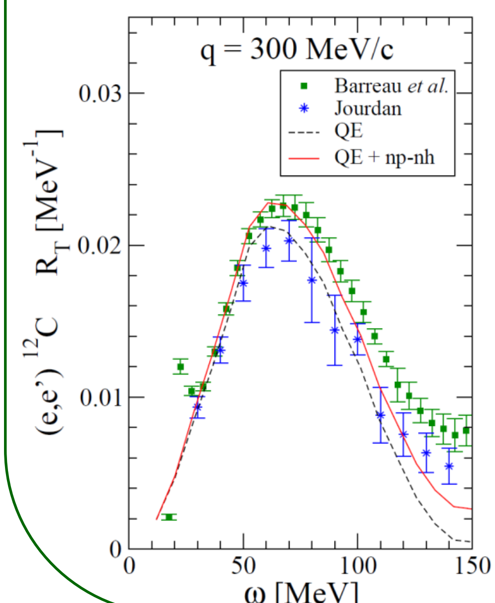


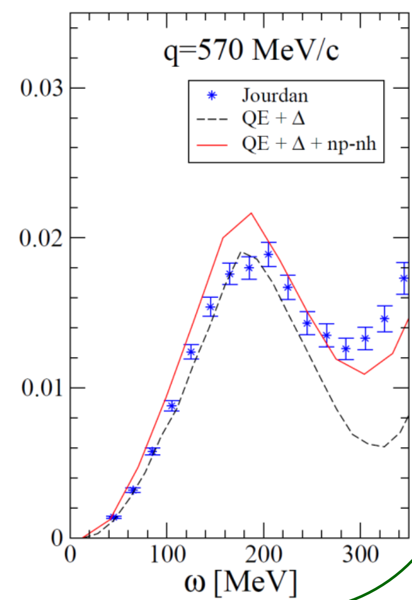
Testing our responses in other processes

Electron scattering

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

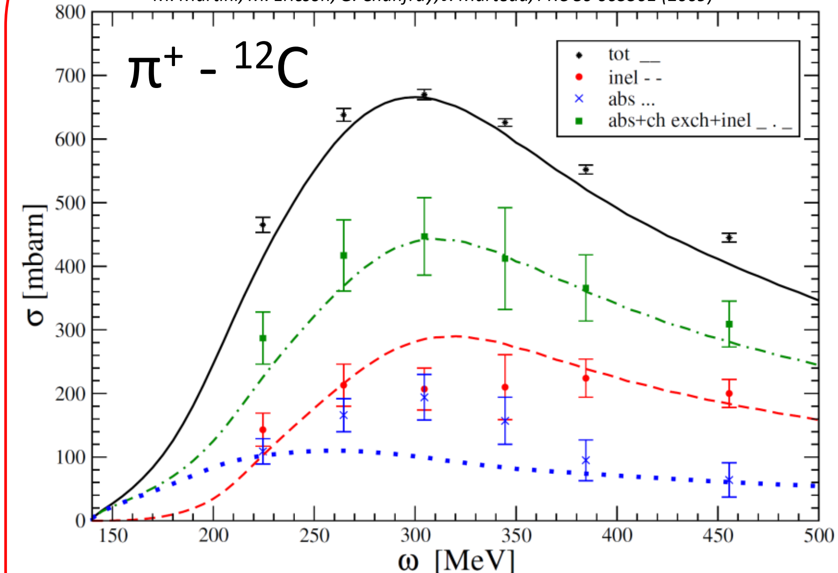


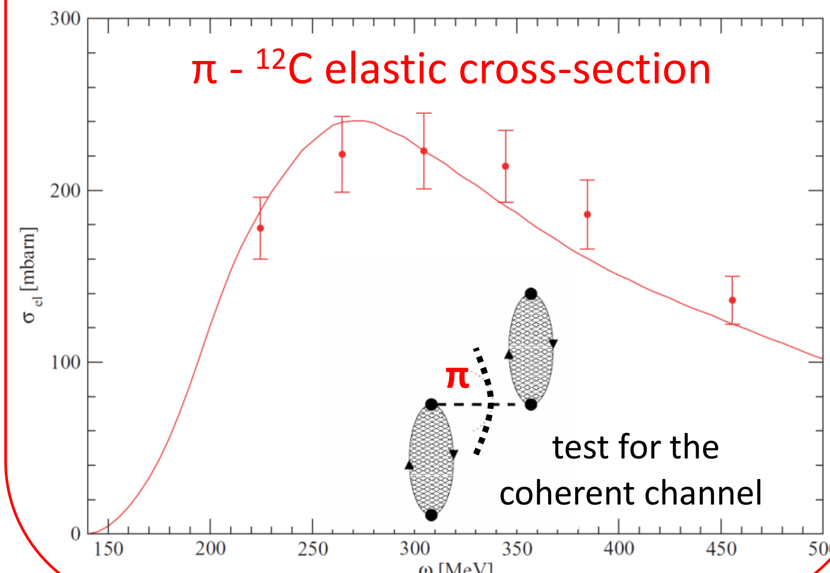




Pion scattering

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



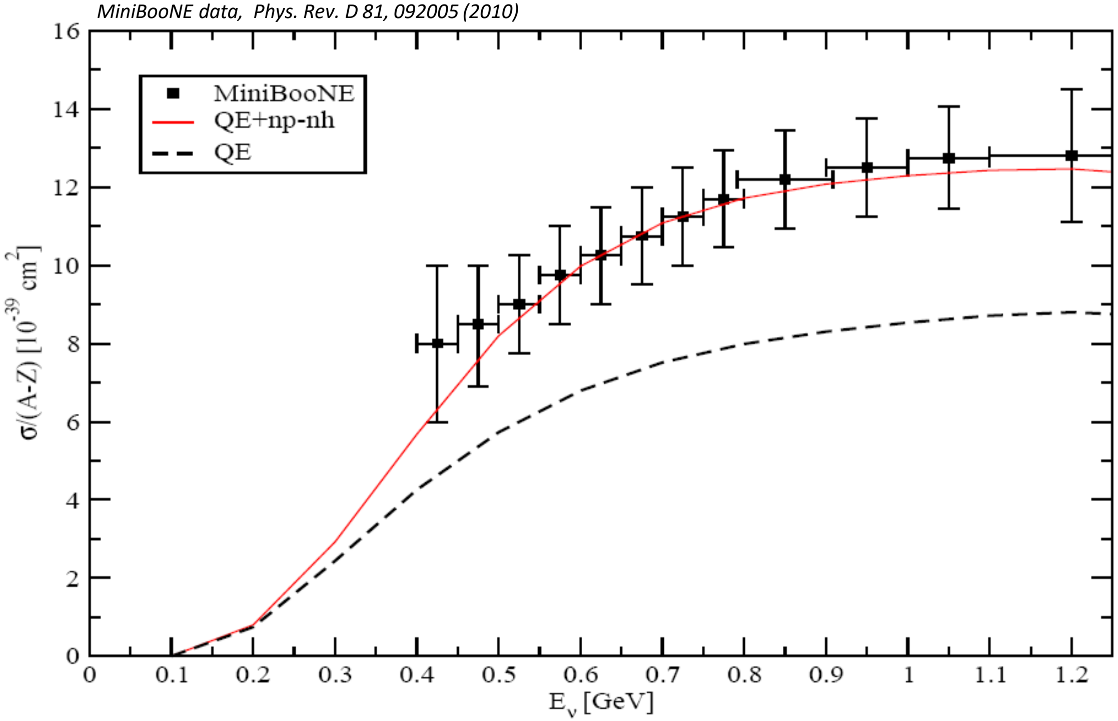


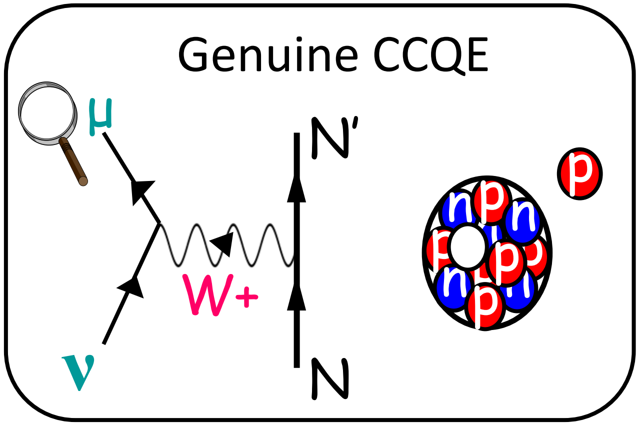
Rapid Review of our results related to neutrino cross sections on carbon

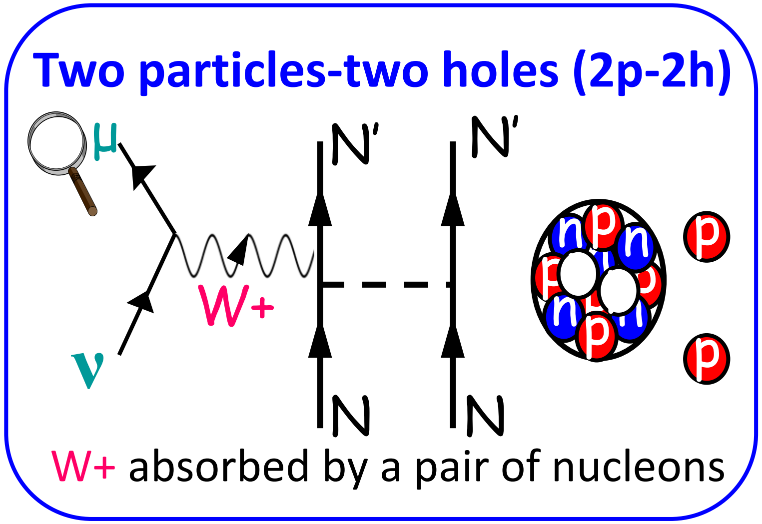
First explanation of the MiniBooNE CCQE-like cross section and M_A puzzle

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

MiniBooNE data, Phys. Rev. D 81, 092005 (2010)







CCQE-like = Genuine CCQE + np-nh

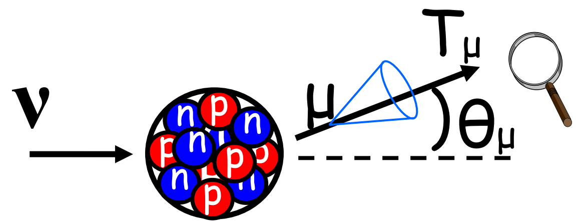
M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 80 065501 (2009)

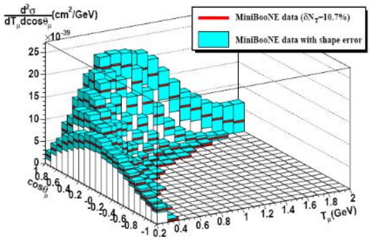
Agreement with MiniBooNE without increasing M_A

Starting from this result the 2p-2h attracted a lot of interest in the neutrino community

MiniBooNE CCQE-like flux-integrated double differential cross section

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

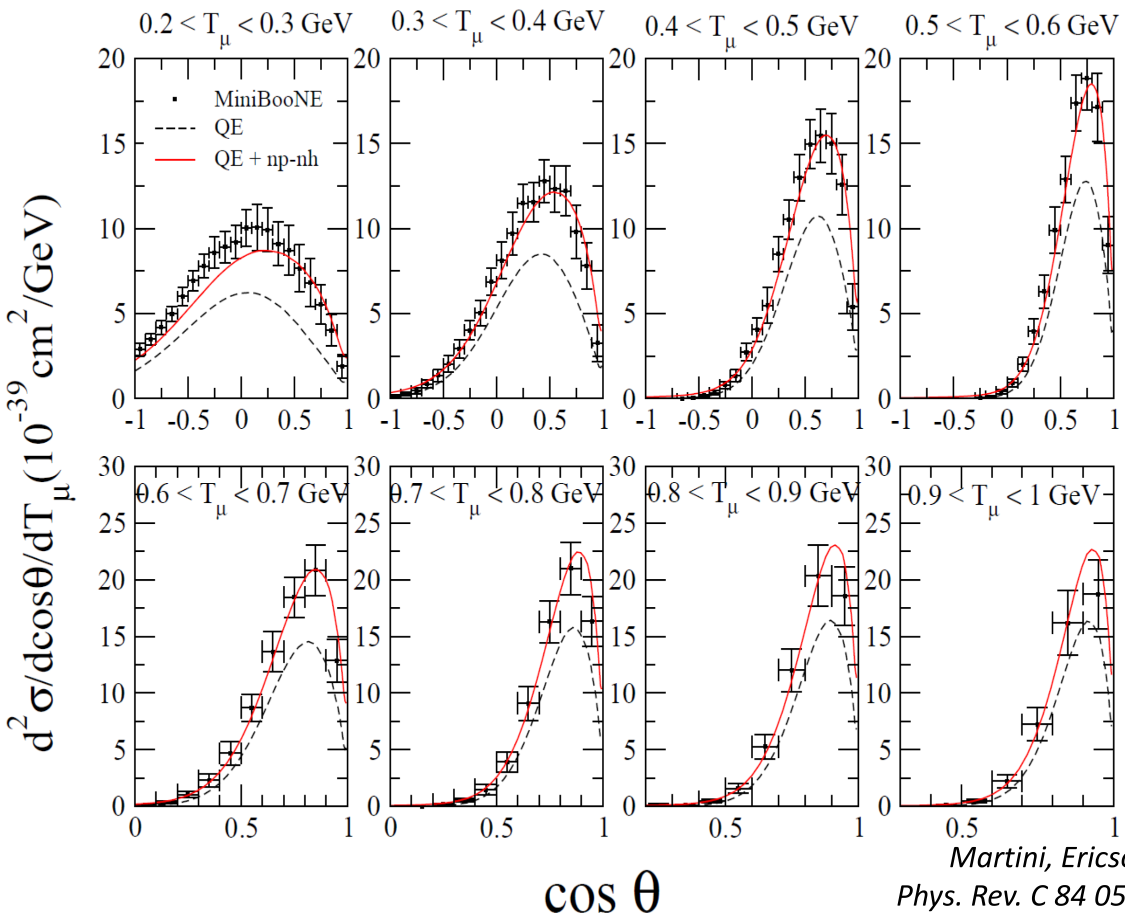




MiniBooNE, *Phys. Rev. D 81, 092005 (2010)*

- Less model dependent than $\sigma(E_\nu)$
- Flux dependent

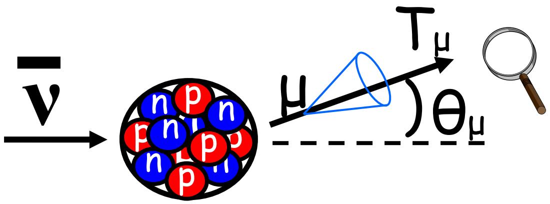
ν



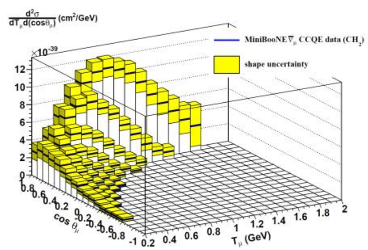
Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

Good agreement with data without increasing M_A once np-nh is included

MiniBooNE CCQE-like flux-integrated double differential cross section

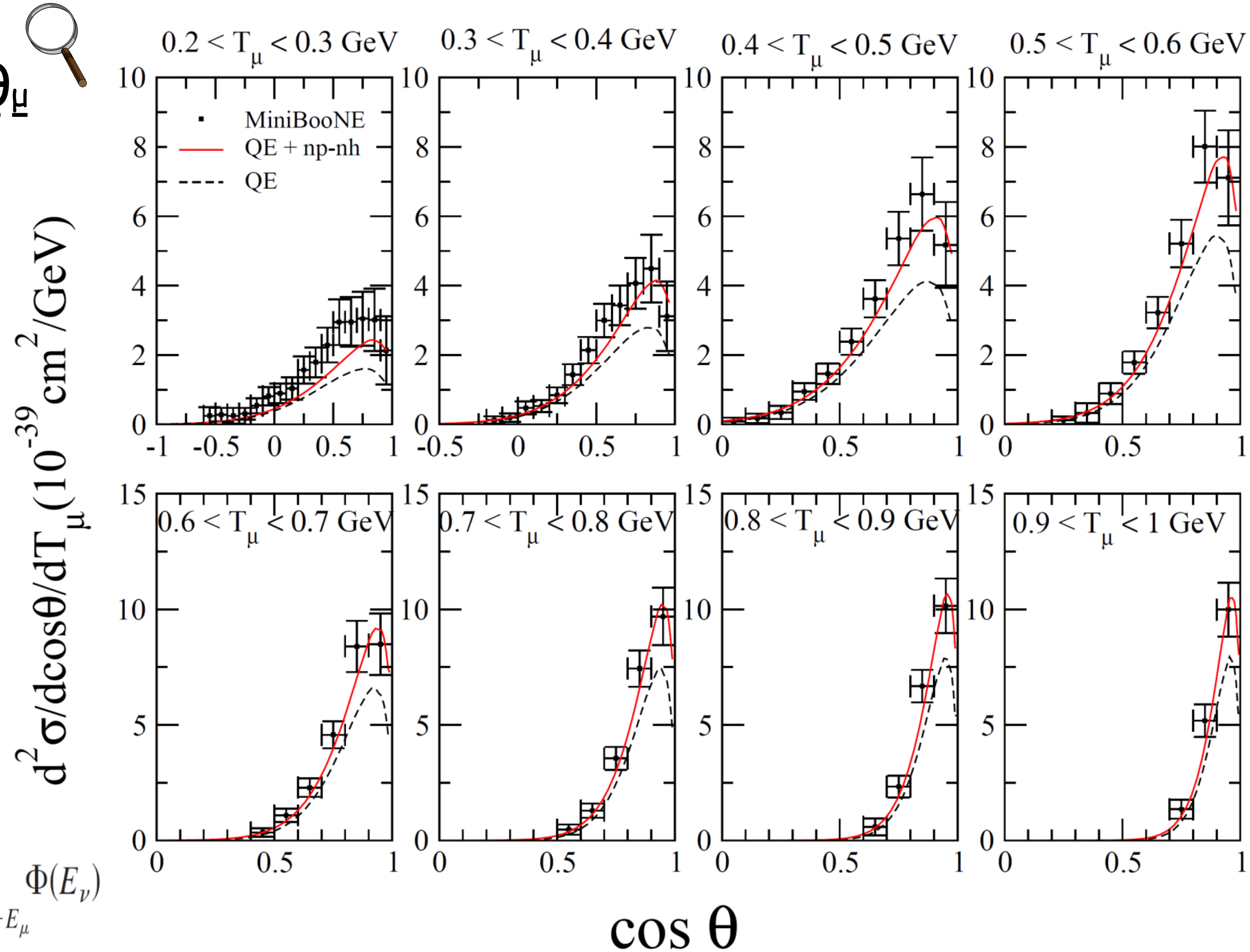


$\bar{\nu}$



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

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



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

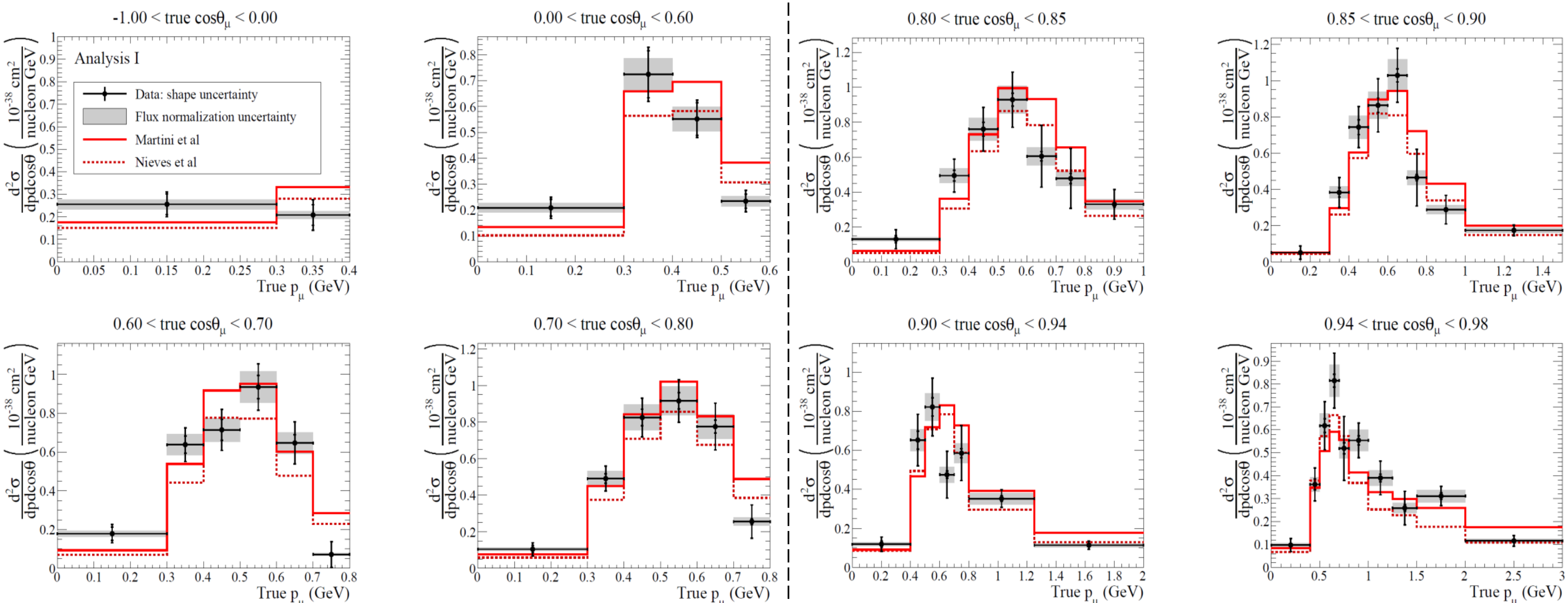
Similar agreement also for antineutrino scattering

The T2K $d^2\sigma$ CC0π measurement on ^{12}C

CC0π = CCQE-like without subtraction of π absorption background

In the last years it has become more popular to present the data in terms of final state particles (e.g. 1μ, 0π)

T2K collaboration: Abe et al. Phys. Rev. D 93 11012 (2016)



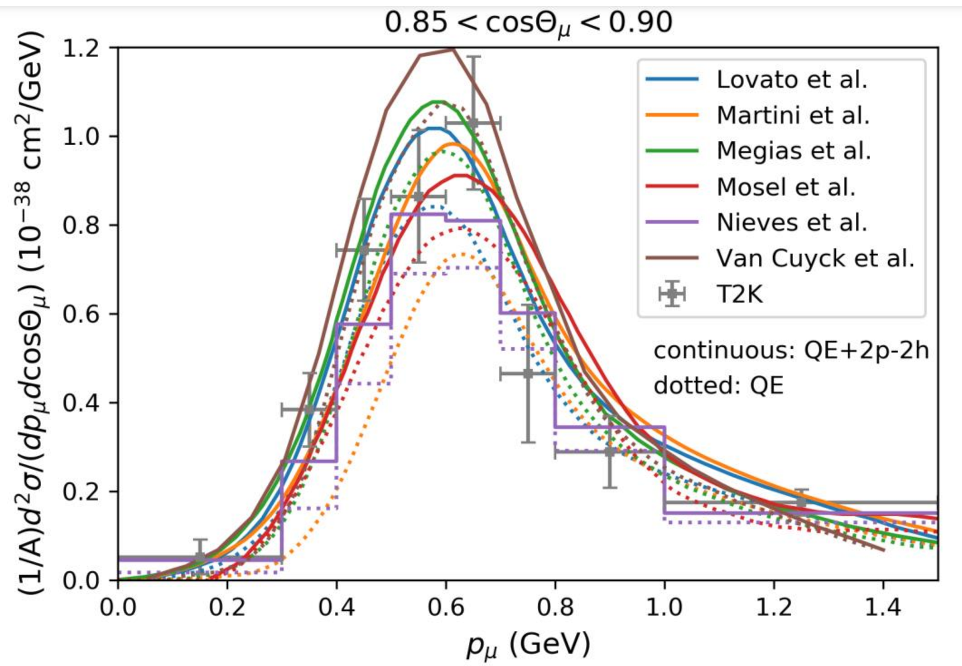
Martini et al.

Nieves et al.

Also in this case our model including np-nh is compatible with data

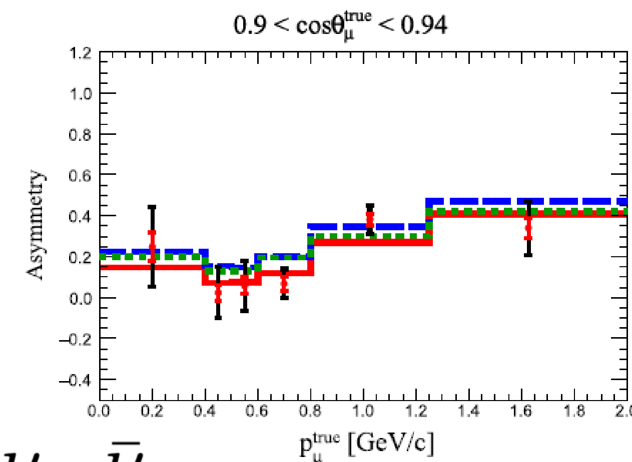
Some comparisons between models and T2K **CC0π** data

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

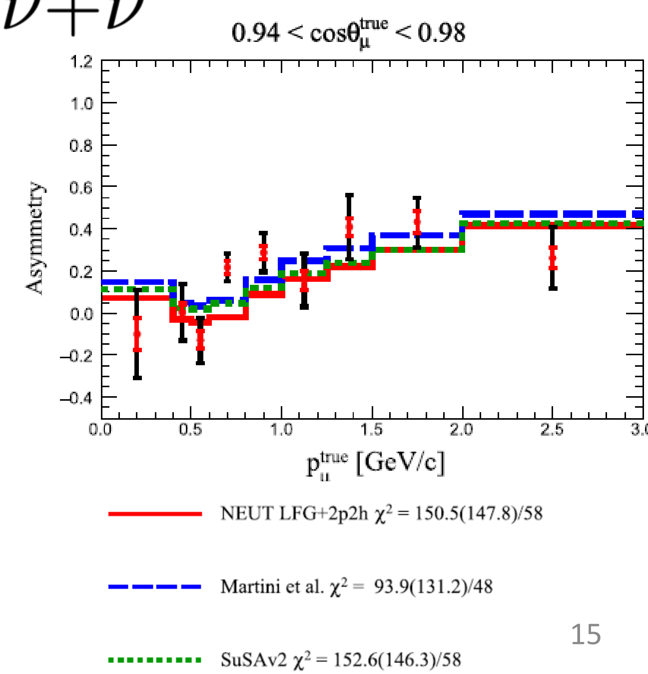


- Several theoretical calculations agree on the crucial role of 2p-2h but there are differences on the results obtained for this channel
- The different models including 2p-2h are compatible with data at present level of experimental accuracy

T2K, Phys. Rev. D 101 112001 (2020)



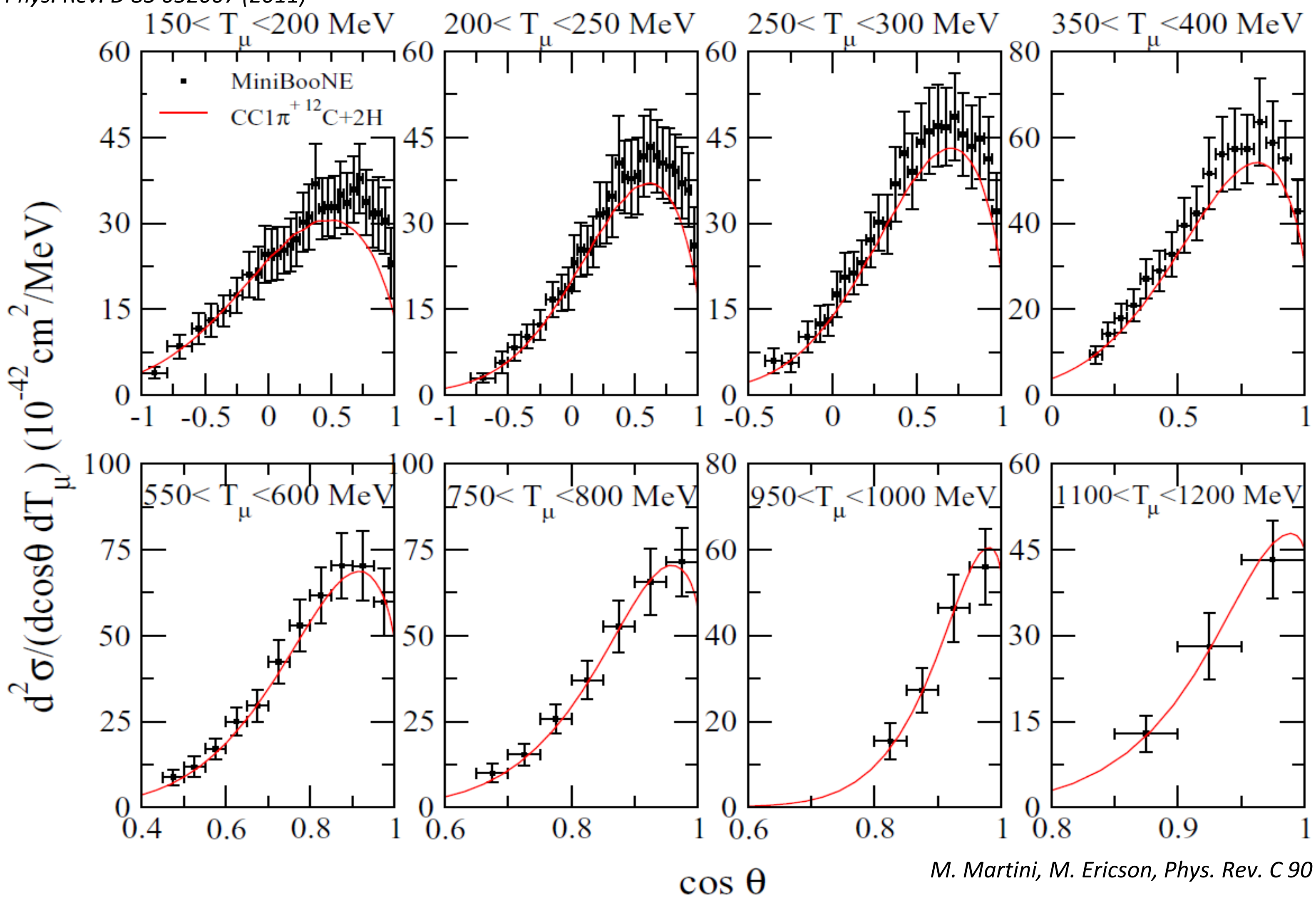
$$\frac{\nu - \bar{\nu}}{\nu + \bar{\nu}}$$



1π production channel

MiniBooNE flux-integrated CC1π+ $d^2\sigma$ in terms of μ variables

MiniBooNE Phys. Rev. D 83 052007 (2011)



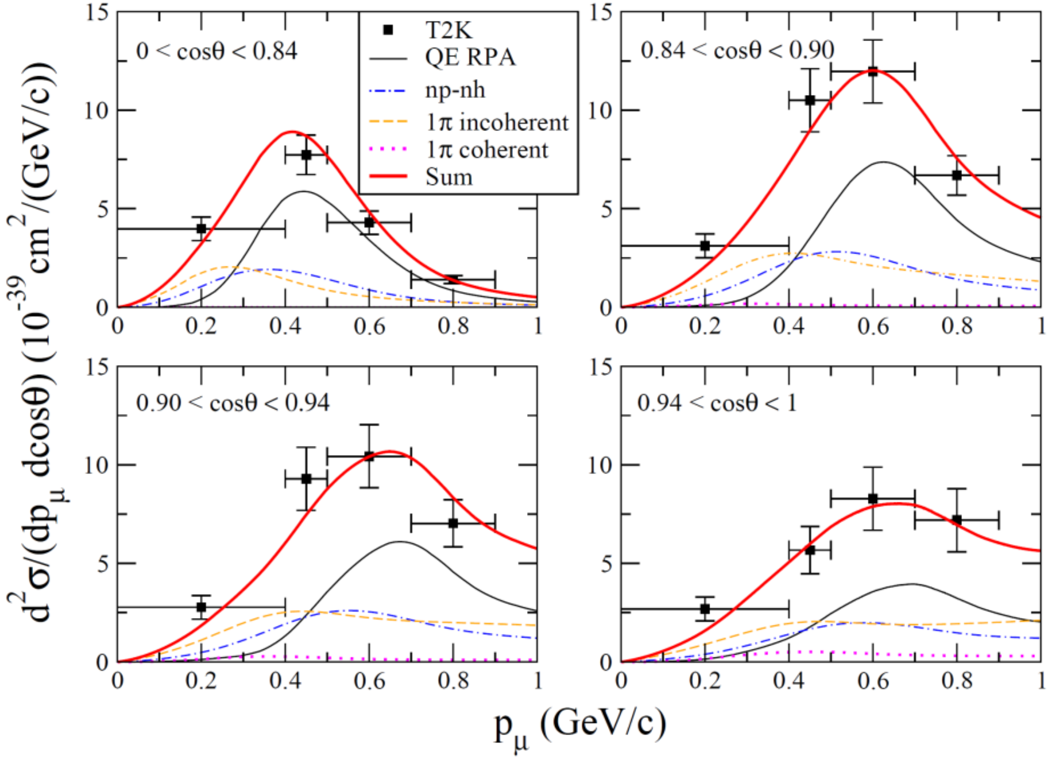
M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)

The general agreement between our evaluation and the data is good

T2K flux-integrated CC inclusive differential cross sections on carbon

ν_μ

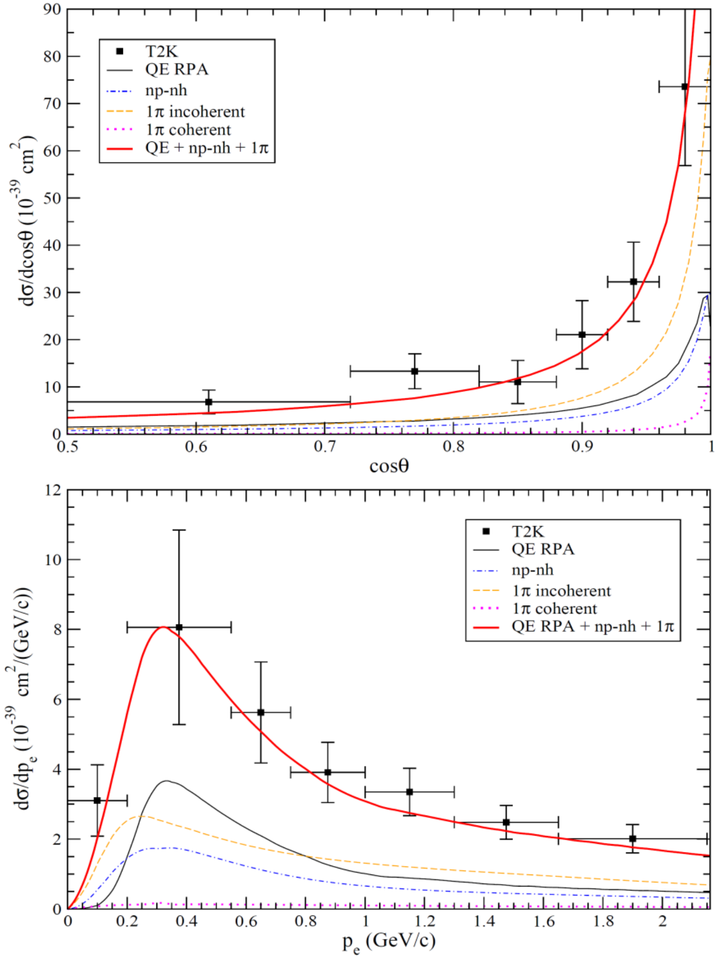
T2K data: *Phys. Rev. D 87, 092003 (2013)*



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

ν_e

T2K data: *PRL 113, 241803 (2014)*

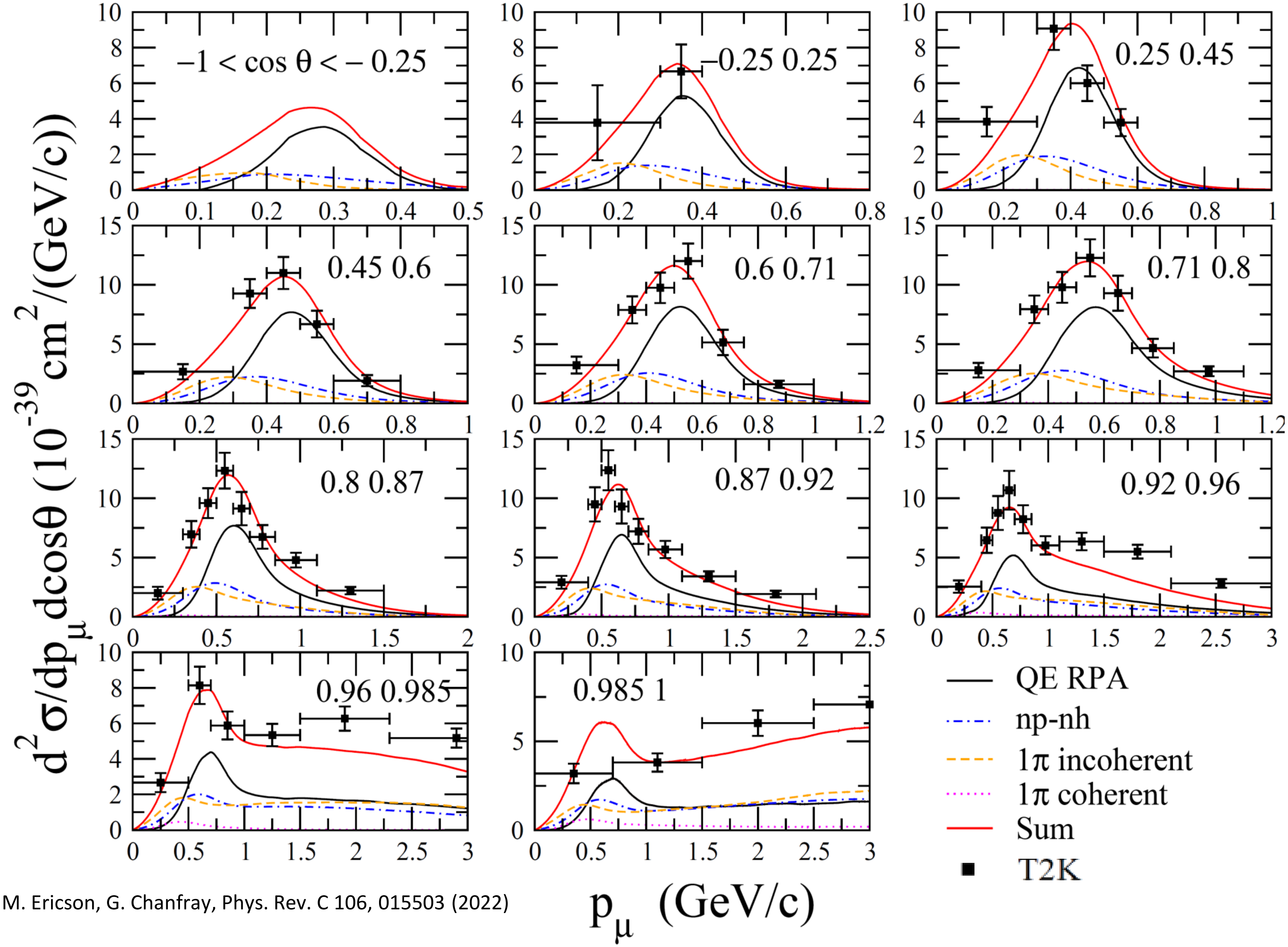


M. Martini et al., Phys. Rev. C 94 015501 (2016)

QE + np-nh + 1π incoherent + 1π coherent = agreement with T2K inclusive

T2K ν_μ CC inclusive data with increased angular acceptance and higher statistics

T2K data: *Phys. Rev. D 98, 012004 (2018)*



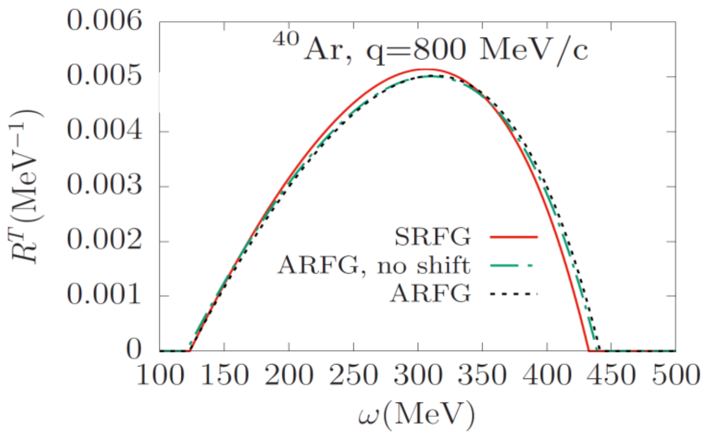
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

Remarkable agreement in all the analyzed bins; small deviations for cosθ>0.92 and p_μ>1.5 GeV

Results for argon – Comparison with MicroBooNe CC inclusive

From ^{12}C to ^{40}Ar results passing through ^{40}Ca calculations

To keep our description close the one on ^{12}C, we perform the LFG+RPA calculations of nuclear responses by approximating the proton and neutron density profiles of ^{40}Ar by the proton density profile of ^{40}Ca



M. B. Barbaro et al. , Phys. Rev. C 98 035501 (2018)

Symmetric .vs. Asymmetric RFG calculations

small effects for ν CCQE transverse response

⇓

It may justify our approximation
to calculate the responses for the symmetric ^{40}Ca

Our approximation for the CC inclusive ν-40Ar cross section calculation

- QE rescaled according to the number of active nucleons (neutrons) $^{Ar}_{QE}\sigma = \frac{22}{20}\,^{Ca}_{QE}\sigma$
- No rescaling for 1π production since both p and n are active $^{Ar}_{1\pi}\sigma = \,^{Ca}_{1\pi}\sigma$
- 2p-2h and 3p-3h ΔΔ calculated for ^{40}Ca $^{Ar}_{\Delta\Delta}\sigma = \,^{Ca}_{\Delta\Delta}\sigma$
- 2p-2h NN and NΔ by rescaling the ^{12}C results (linear A-dependence) $^{Ar}_{NN}\sigma = \frac{40}{12}\,^{C}_{NN}\sigma$ $^{Ar}_{N\Delta}\sigma = \frac{40}{12}\,^{C}_{N\Delta}\sigma$

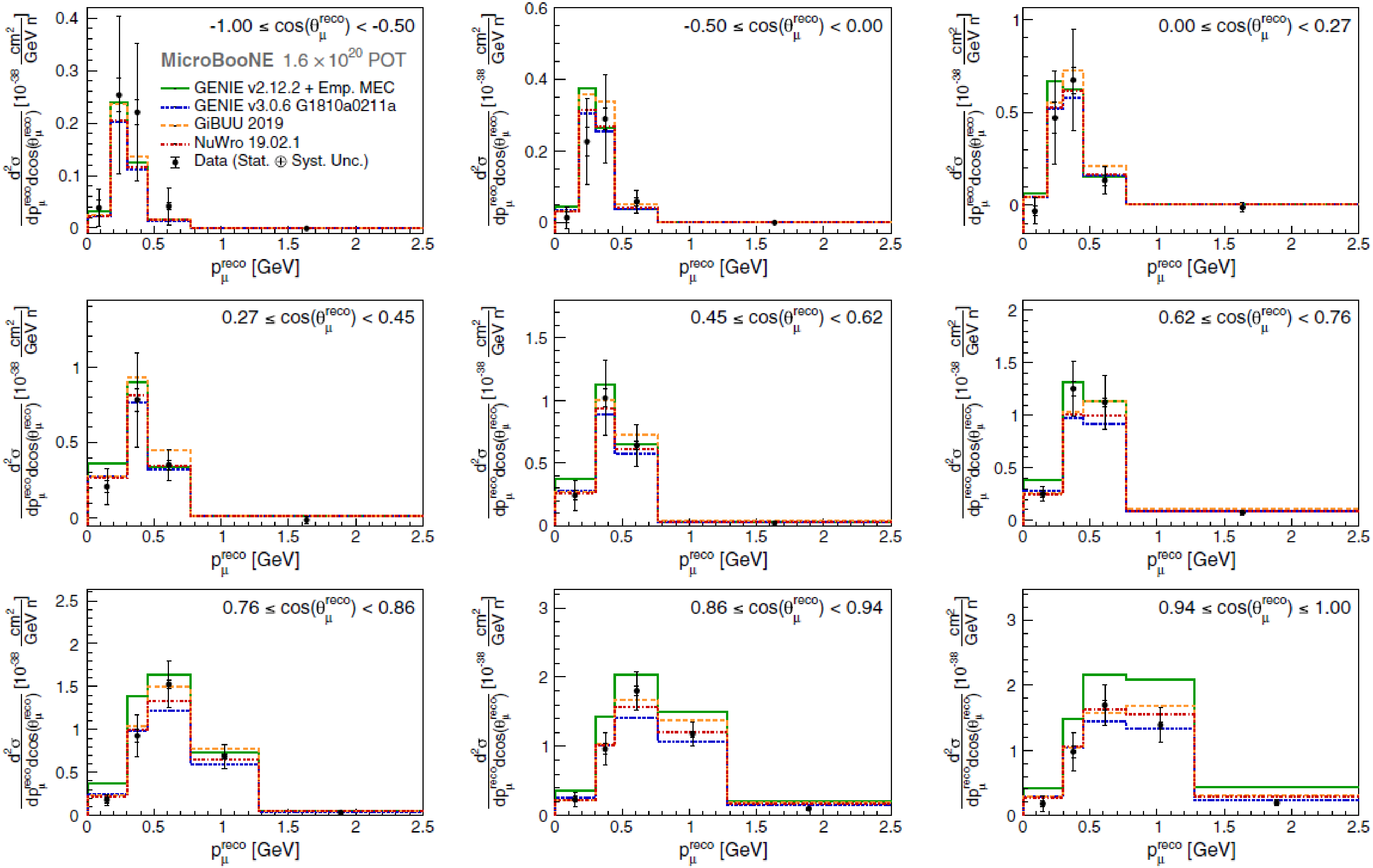
Quasi-deuteronic 2p-2h contribution $\sim \boldsymbol{\rho_p \rho_n}$

$$\rho_p\rho_n = \frac{Z}{V}\frac{N}{V} = \frac{18}{V}\frac{22}{V} = \frac{20-2}{V}\frac{20+2}{V} = \frac{400-4}{V^2} \Rightarrow$$

1% difference between ^{40}Ar and ^{40}Ca

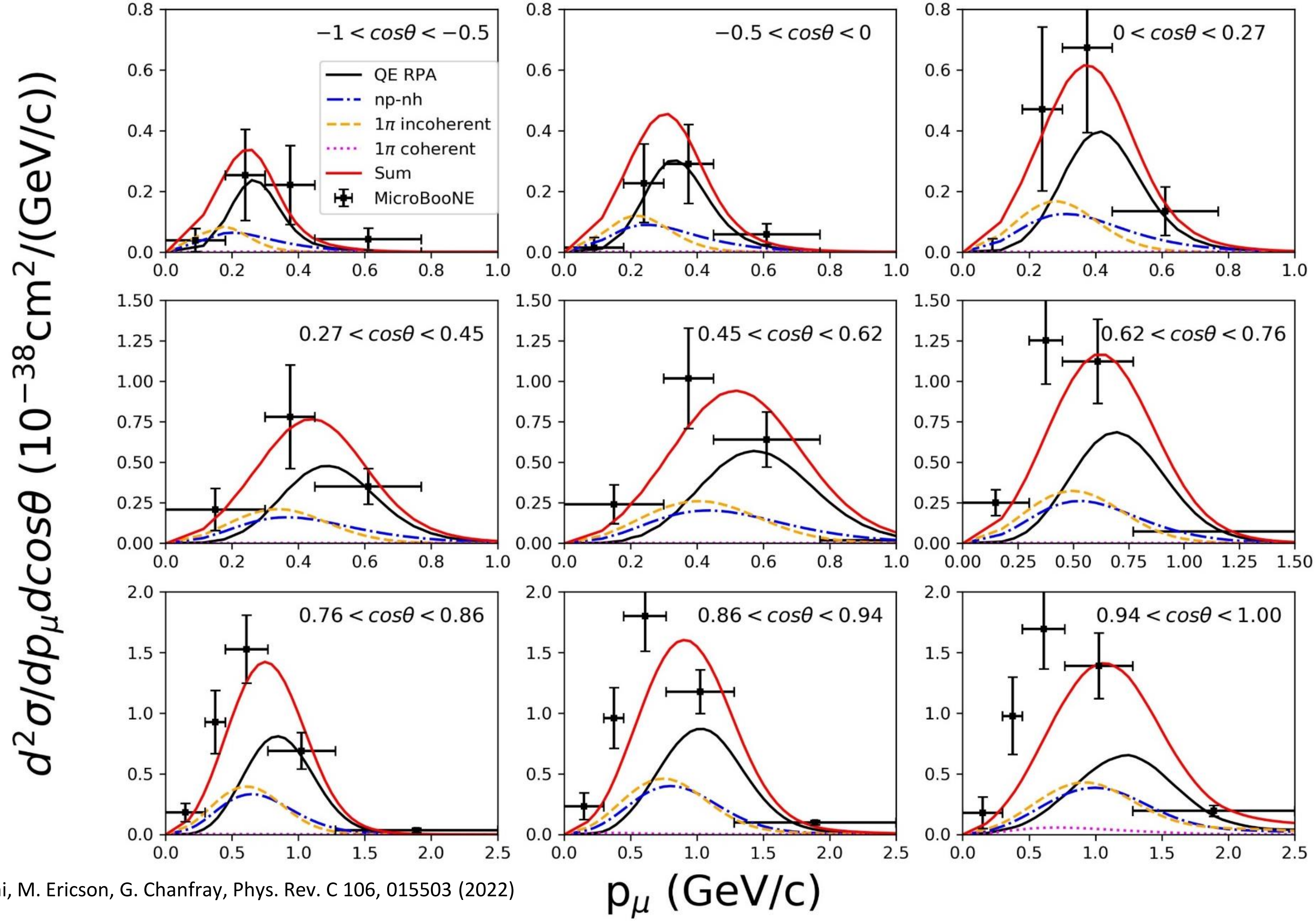
First MicroBooNE measurement: inclusive $d^2\sigma/dp_\mu d\cos\theta_\mu$

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



Our calculations of MicroBooNE flux-integrated inclusive $d^2\sigma$ on argon

MicroBooNE data: *PRL 123, 131801 (2019)*



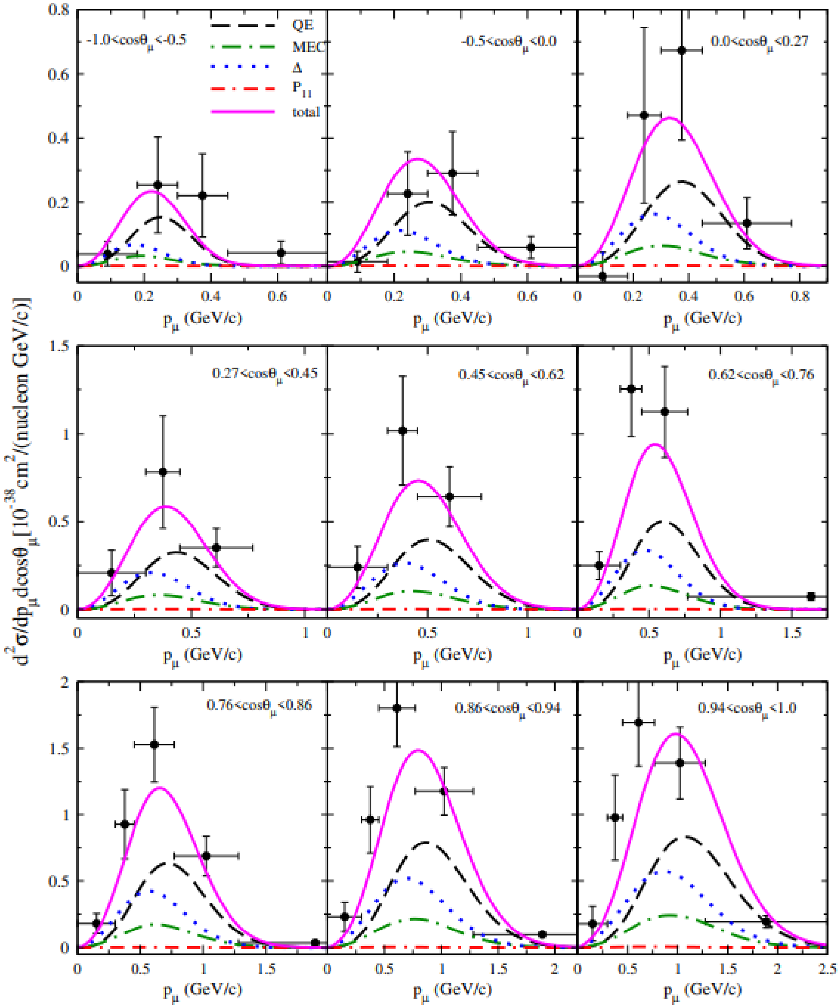
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

- The overall agreement is reasonable, though not as good as in the ^{12}C T2K inclusive case
- A disagreement shows up for low p_μ

SuSA and SuSAv2 calculations display a similar trend

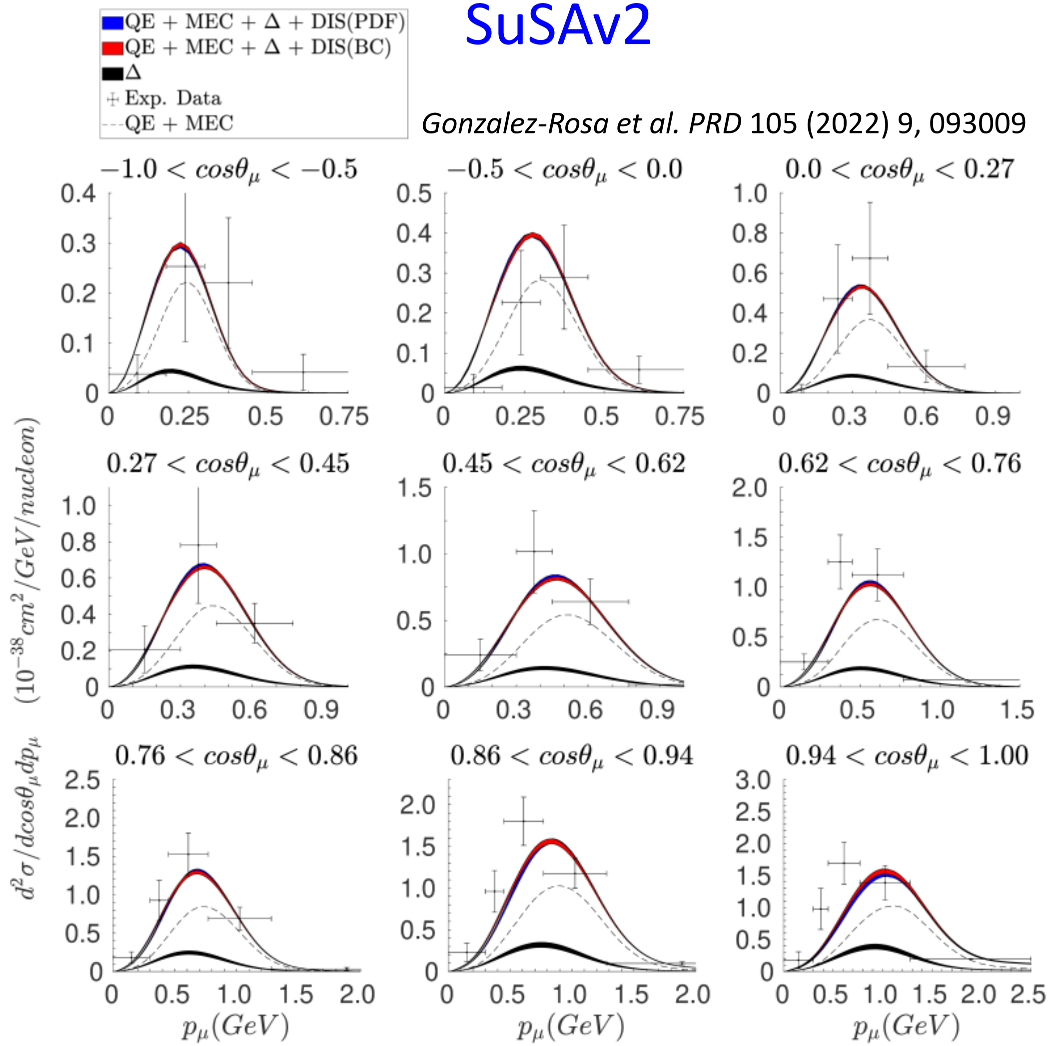
SuSA

Barbaro et al. Universe 7 (2021) 5, 140



SuSAv2

Gonzalez-Rosa et al. PRD 105 (2022) 9, 093009

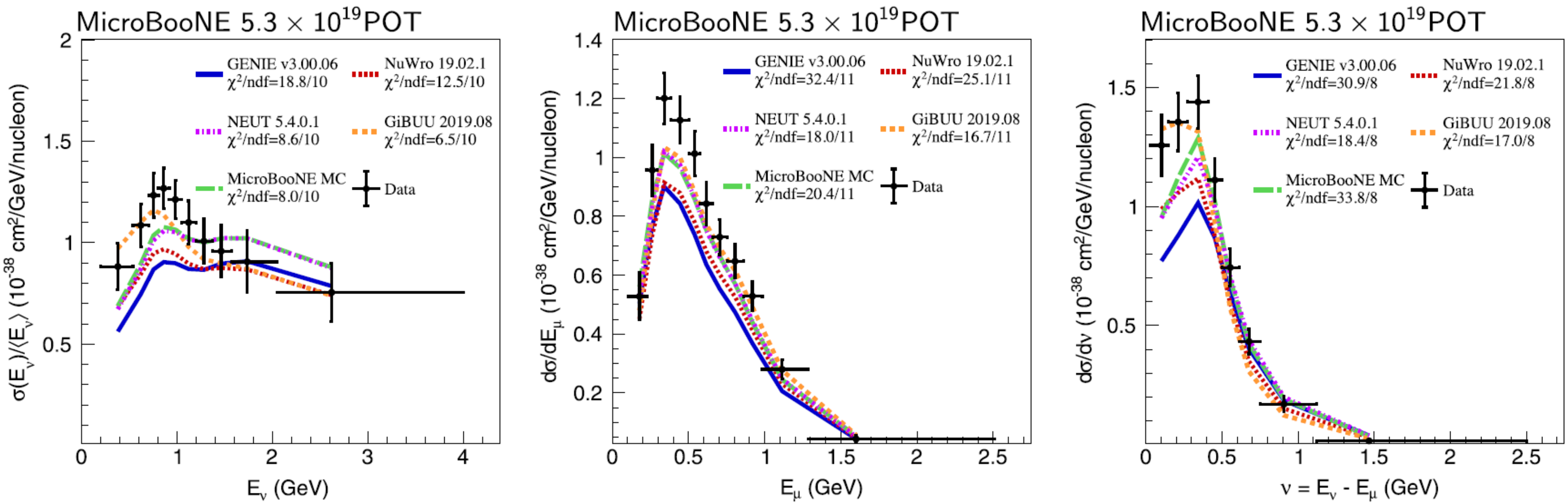


At backward angles the predictions of the different models are slightly shifted to lower values of p_μ, whereas the reverse occurs at forward angles

Recent energy-dependent MicroBooNE cross sections measurements

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

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

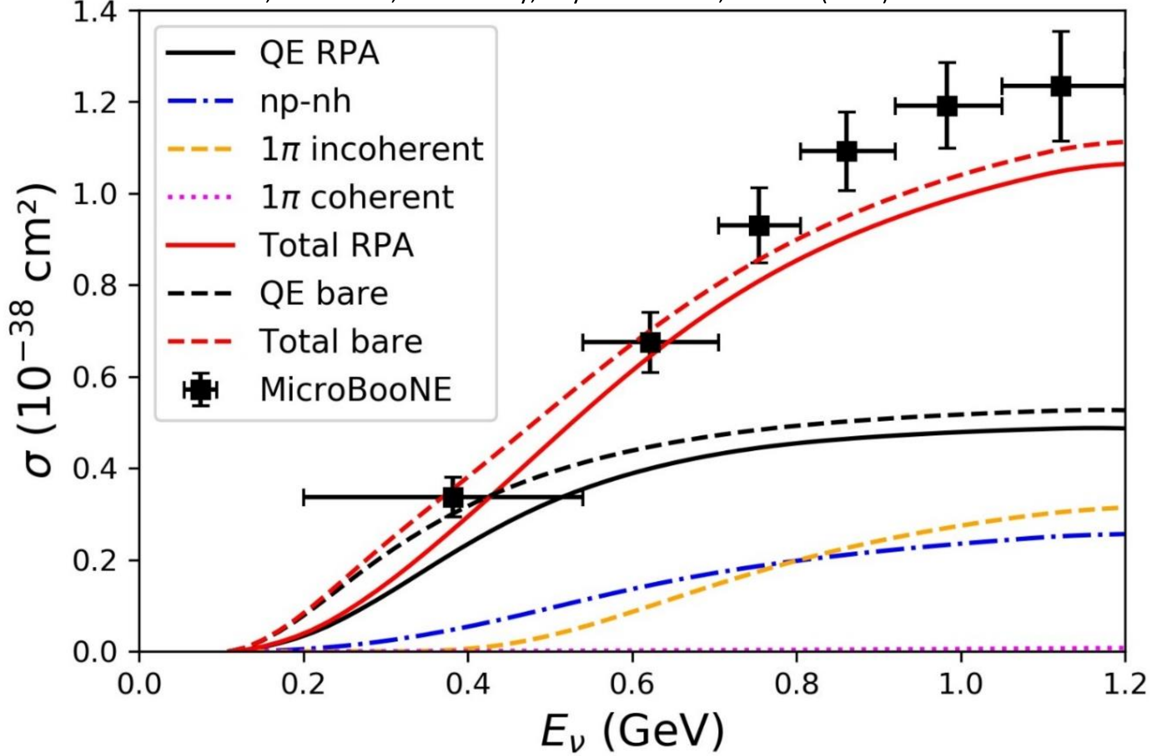


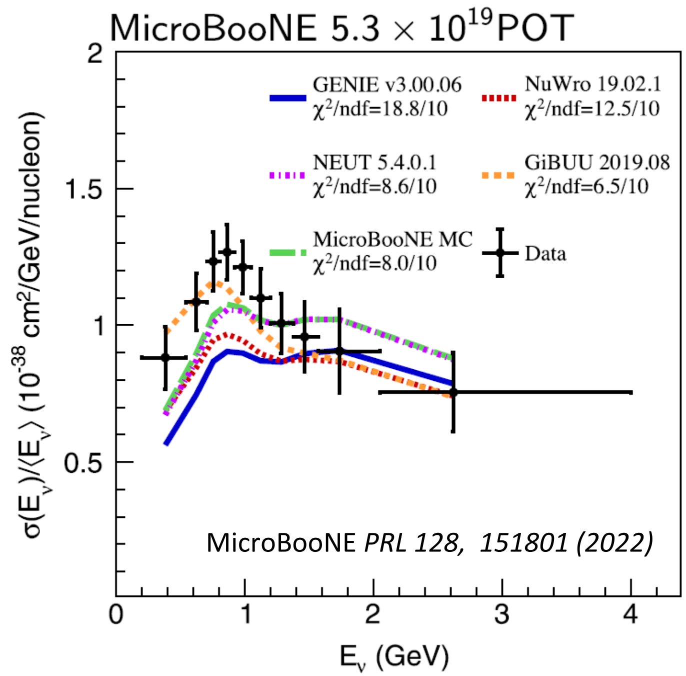
Experimental results presented for the first time as a function of true neutrino energy E_ν and transferred energy (ν or ω)

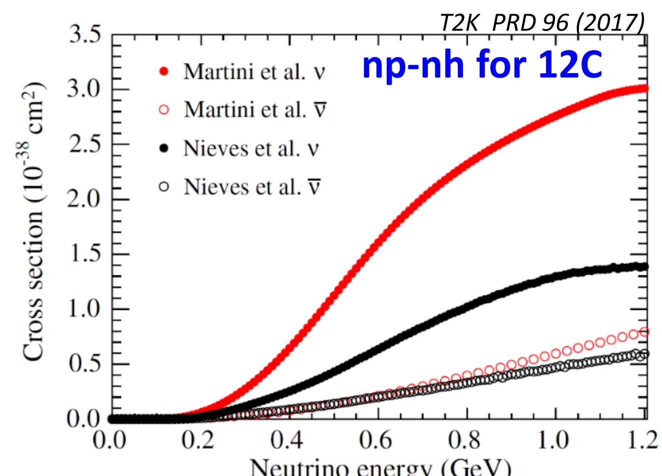
This has been made possible by a new procedure (based on the comparison between the data and the Monte Carlo predictions constrained on the lepton kinematics) allowing the mapping between the true E_ν and ω on one hand, and the reconstructed neutrino energy E_ν^{rec} and hadronic energy E_{had}^{rec}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

Inclusive total cross section as a function of the neutrino energy

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





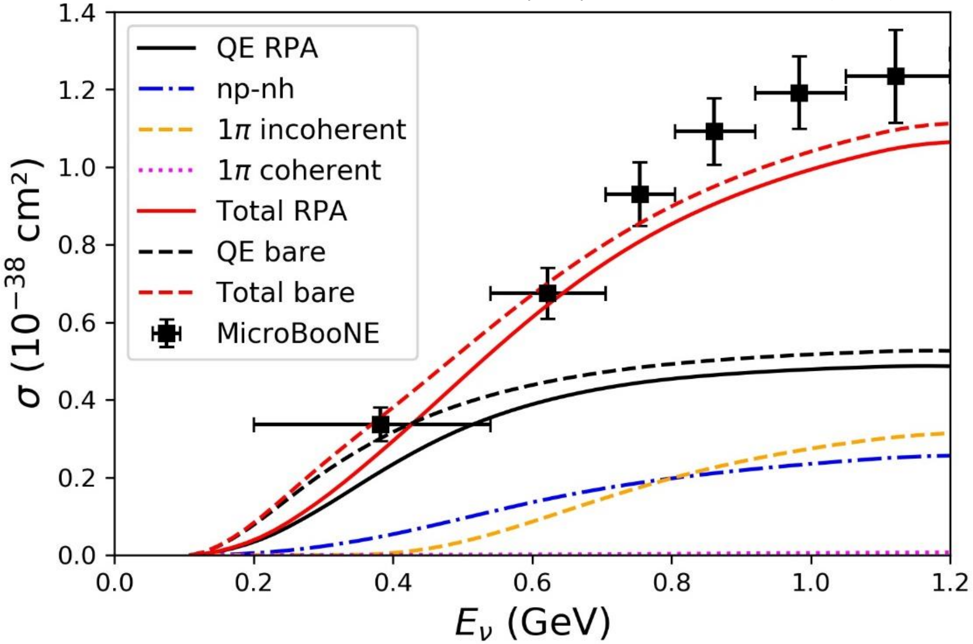


- Good agreement up to $E_\nu \approx 0.7$ GeV
- This is not the case of other models (GENIE v3, MicroBooNE MC, NEUT and NuWro) which underestimate the data
- A possible reason is that GENIEv3, MicroBooNE MC, NEUT and NuWro implement np-nh contribution deduced by Nieves et al. which is smaller than our by about a factor 2
- Beyond $E_\nu = 0.7$ GeV our evaluation as well underestimates the data

Comparison between argon (MicroBooNE) and carbon (SciBooNE) $\sigma(E_\nu)$

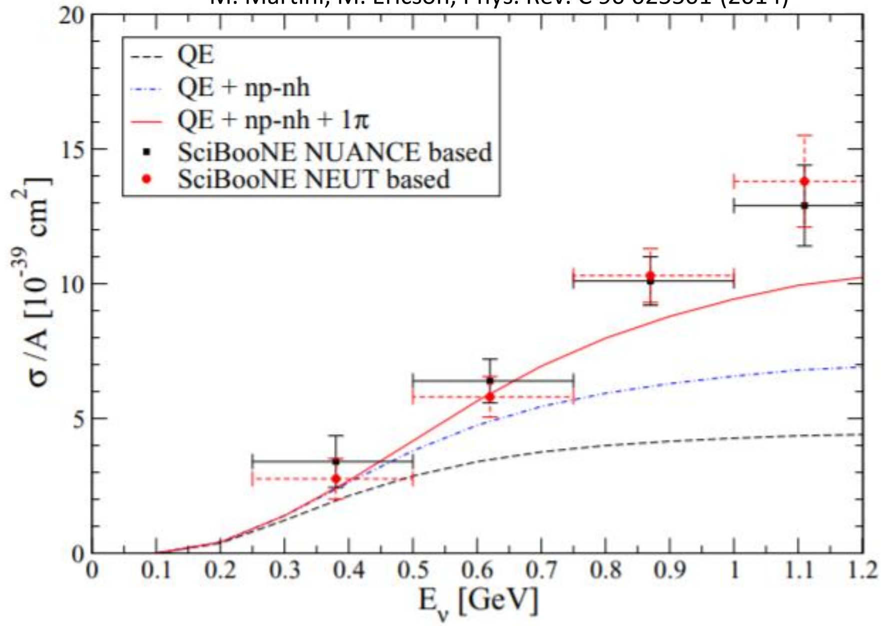
Argon - MicroBooNE

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



Carbon - SciBooNE

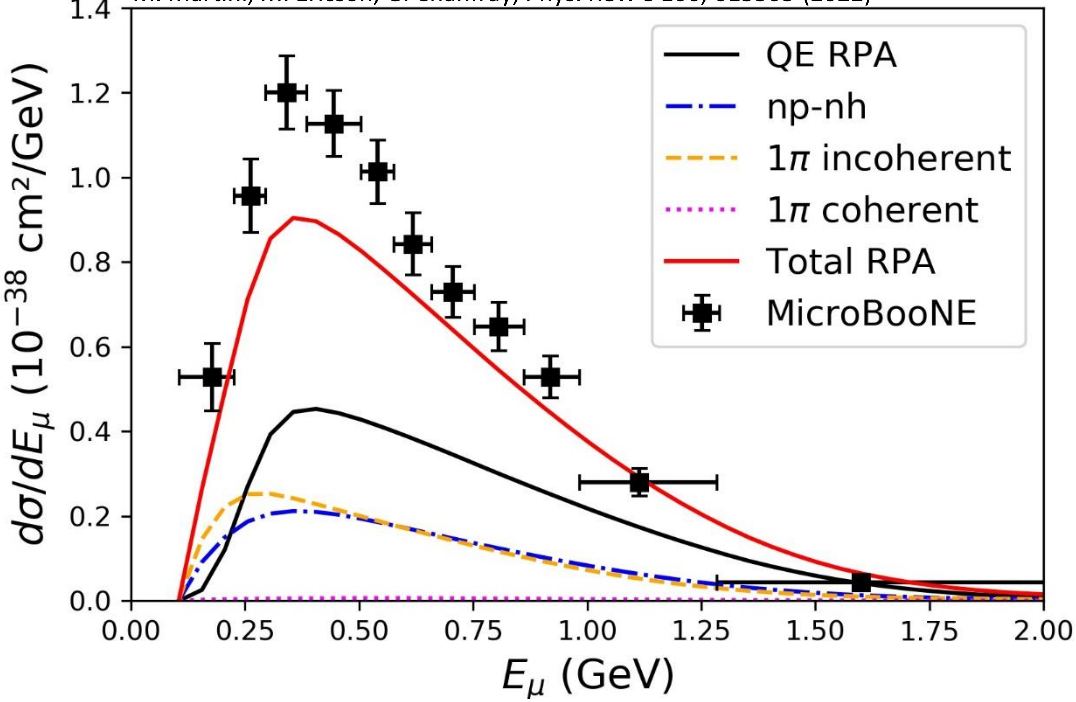
M. Martini, M. Ericson, Phys. Rev. C 90 025501 (2014)

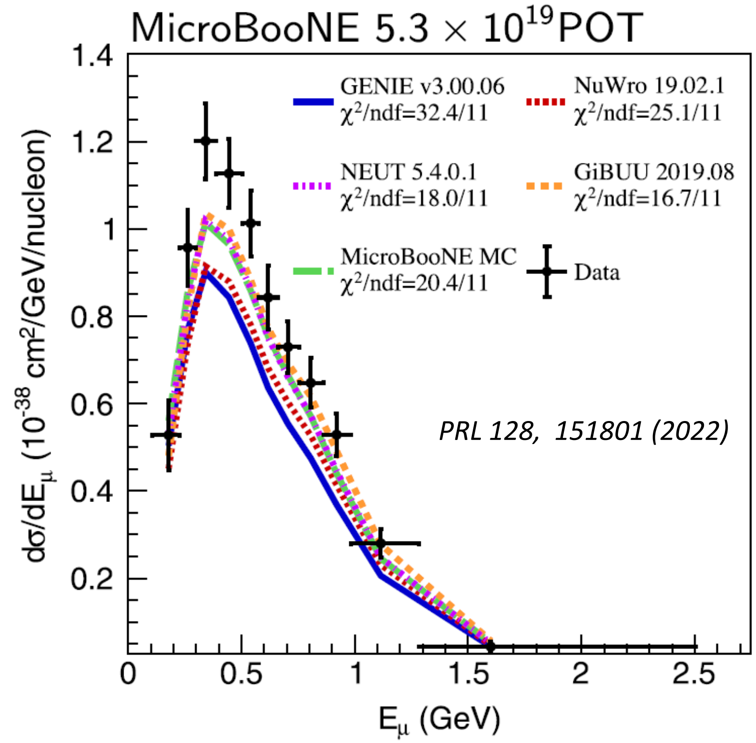


- Similar behavior
- Good agreement up to $E_\nu \approx 0.7$ GeV
- Underestimation of the data for $E_\nu > 0.7$ GeV
- This underestimation is due to inelastic channels missing in our description such as 2π production

MicroBooNE flux-averaged differential cross sections $d\sigma/dE_\mu$

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



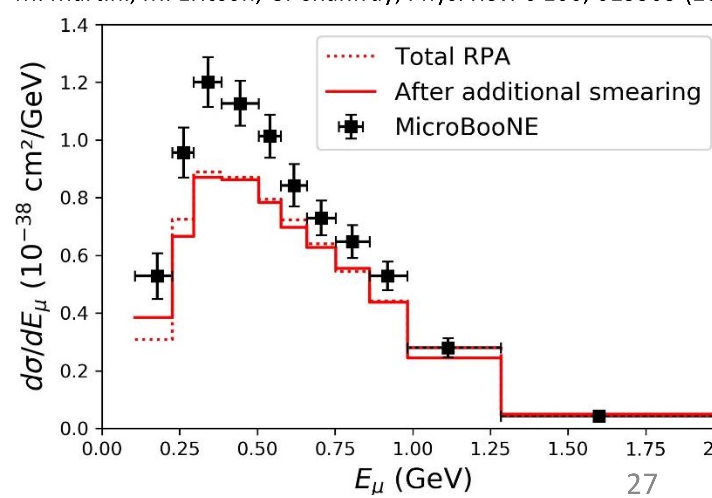


- Lack of strength. It appears in the same muon kinematical region as the one of $d^2\sigma/dp_\mu d\cos\theta$ previously shown
- Also the other models underestimate the data

More quantitative analysis by applying an **additional smearing** (result of regularization in the data unfolding) and by calculating the **χ2** (smearing and covariant matrices shared by MicroBooNE):

- The effect of the smearing is small
- χ2\ndf=27.9/11. Larger than the one of most of the other models. Probably due to the absence in our model of inelastic channels (2π,…,DIS) included in the Monte Carlo

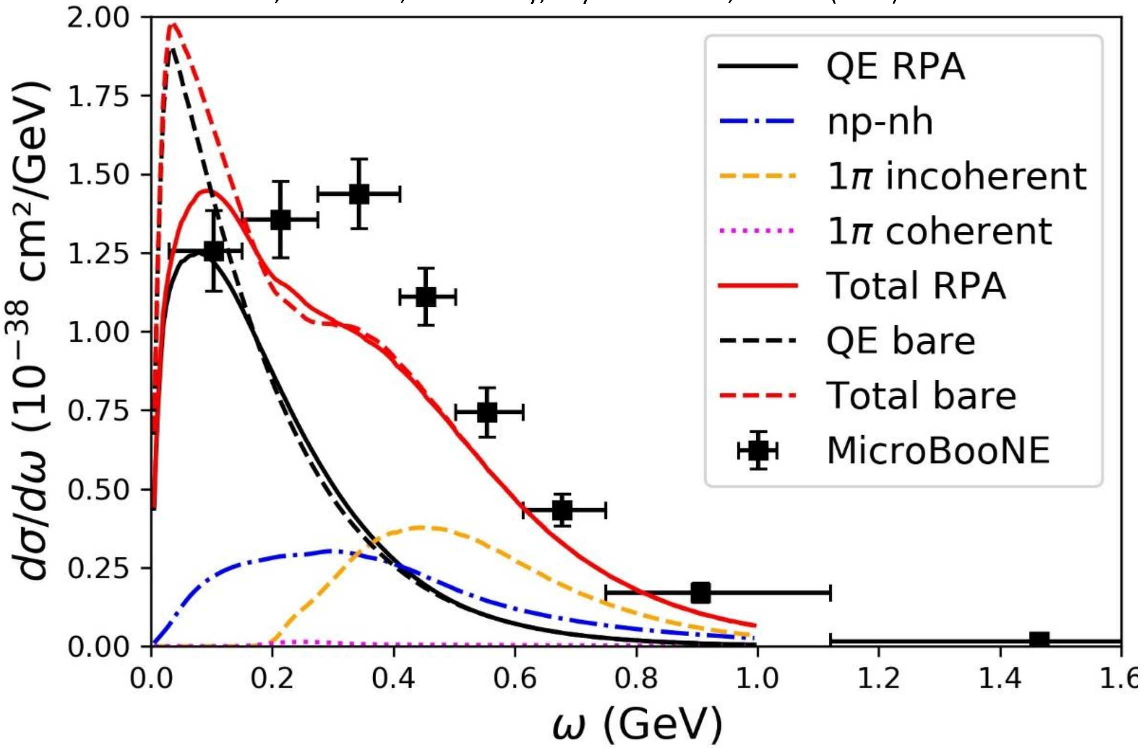
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 106, 015503 (2022)

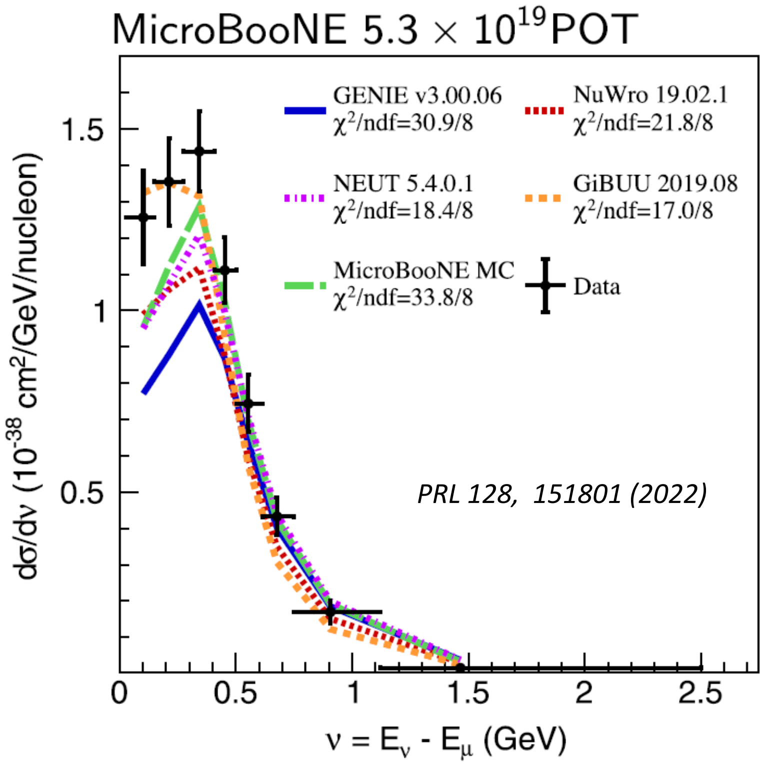


MicroBooNE flux-averaged differential cross sections dσ/dω

A new type of measurement for neutrinos

The cross section function of the transferred energy allows a better separation of the different channels

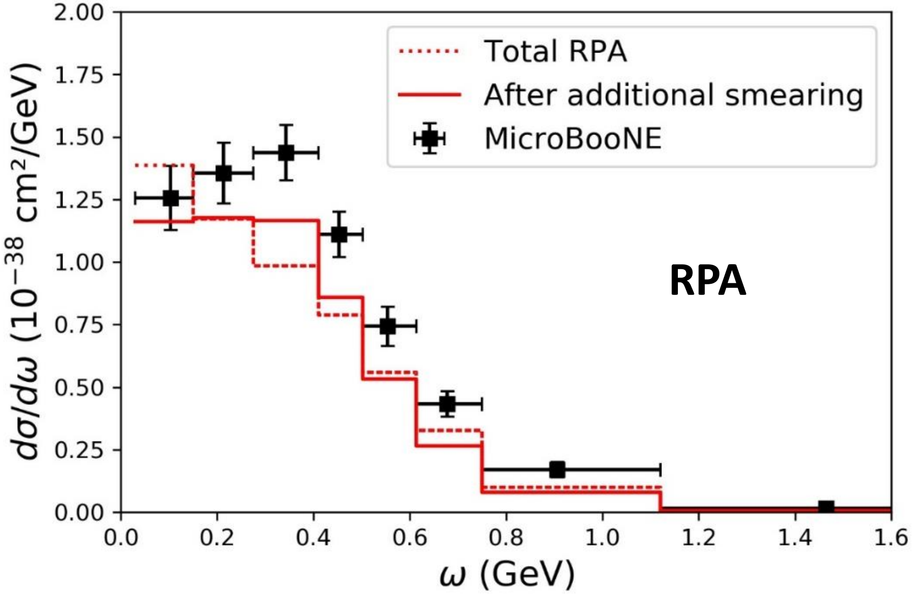


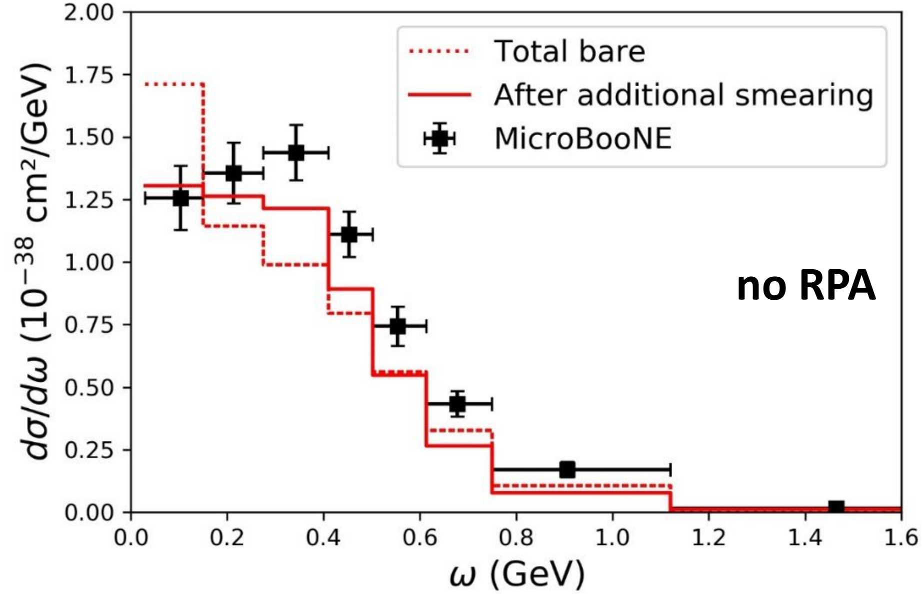


- At low energy transfer the cross section is dominated by the quasielastic channel which is quenched by RPA effects in our theoretical calculations
- A lack of strength shows up for 0.2 < ω < 0.6 GeV but the additional smearing should be applied to our curves before drawing any conclusions

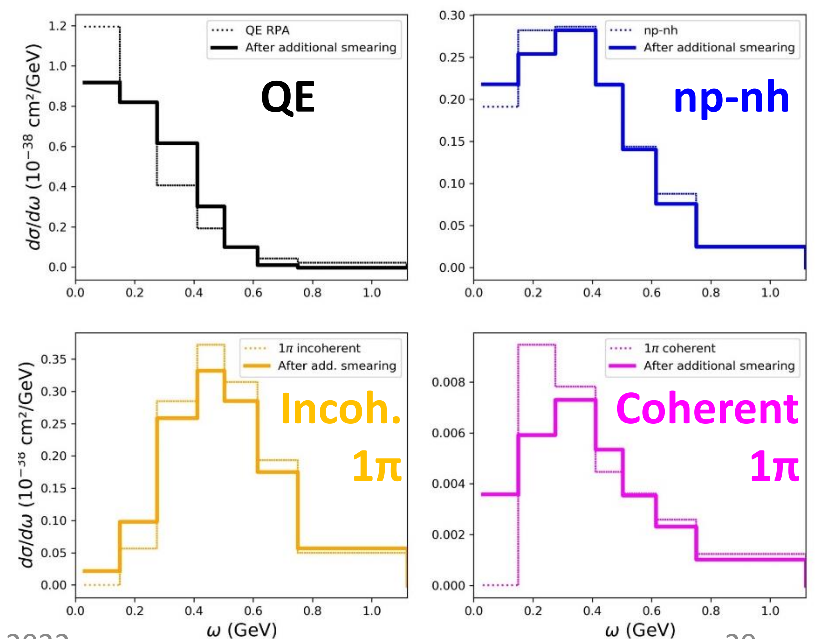
dσ/dω before and after the additional smearing

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

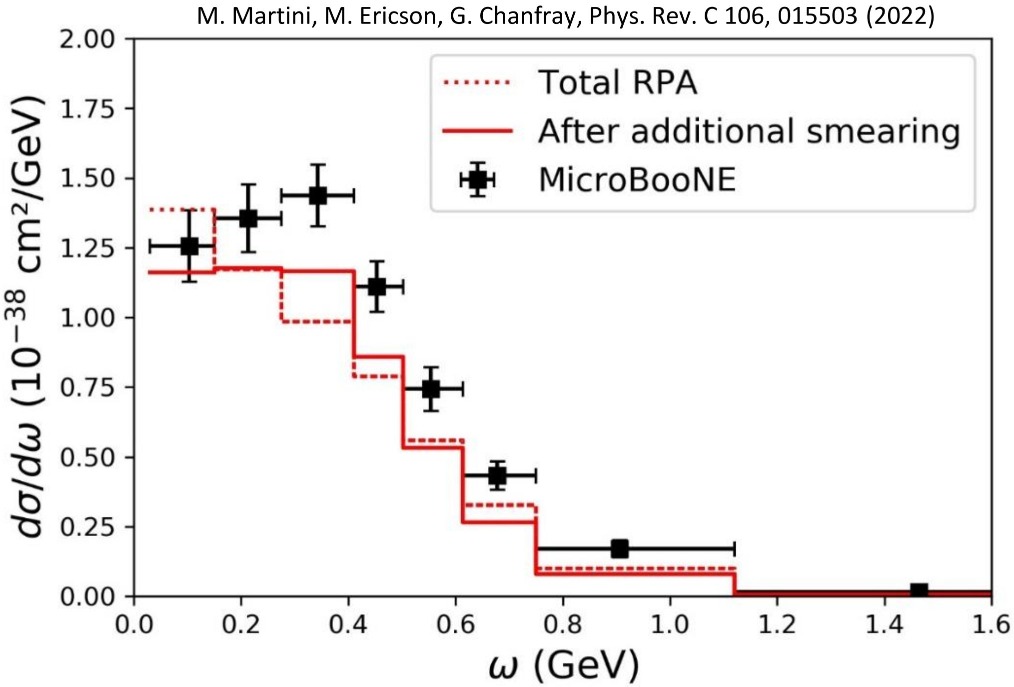


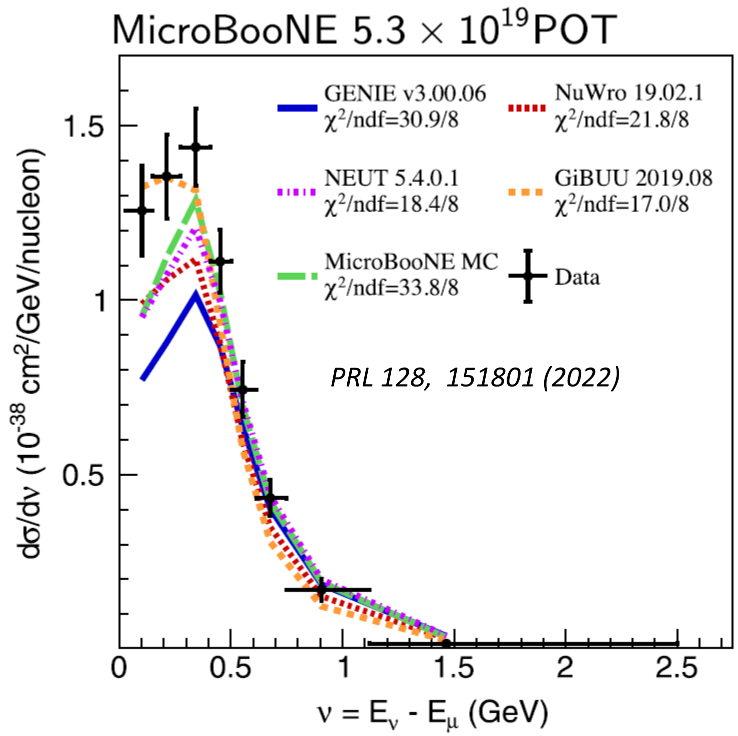


- The impact of the smearing is larger for dσ/dω than for the dσ/dE_μ
- The smearing reduces the difference between the results with and without RPA
- The smearing produces a redistribution of the strength which is more important when the cross section is peaked, such as the quasielastic or the pion production



Quantitative analysis of dσ/dω

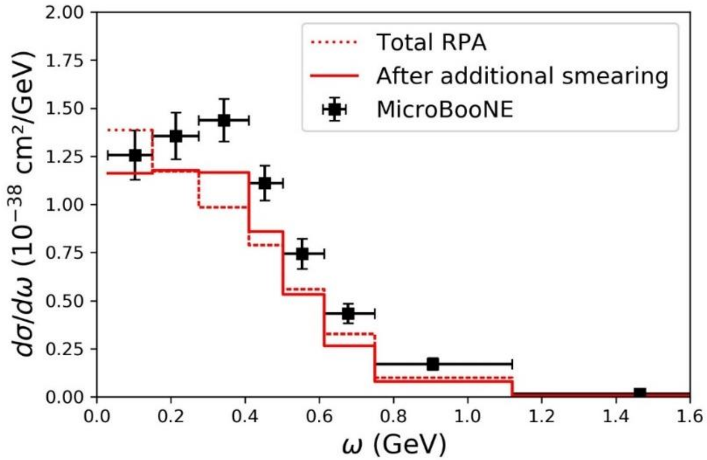


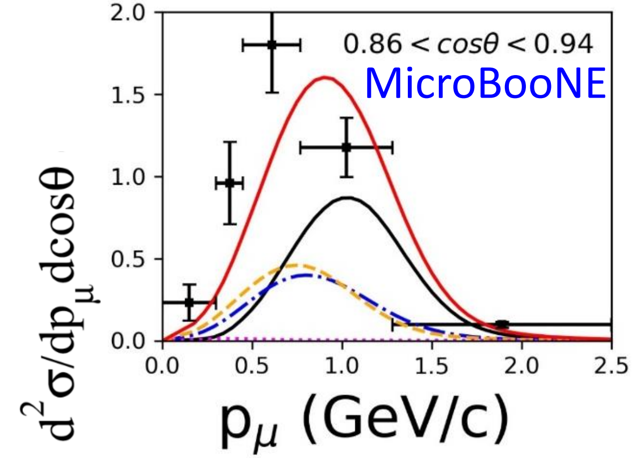


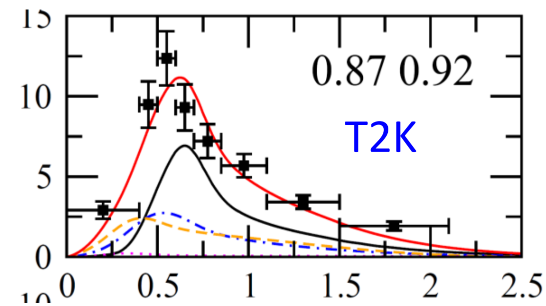
- Our model including RPA effects: χ2/ndf = 17.2/8
- Our χ2 comparable with the one of GiBUU and better than all the Monte Carlo predictions
- A possible reason is that GENIEv3, MicroBooNE MC, NEUT and NuWro implement np-nh contribution deduced by Nieves et al. which is smaller than our by about a factor 2 for neutrinos

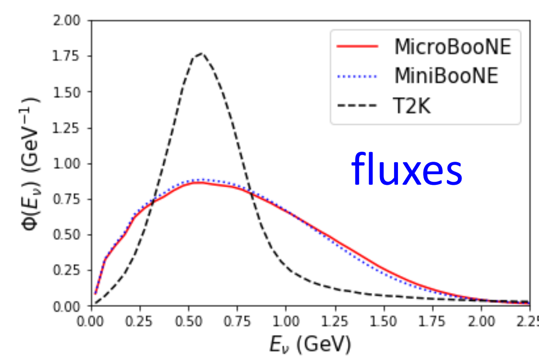
Impact of missing inelastic channels

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









- Our underestimation, which remains even after the additional smearing, seems to start at $\omega \approx 2m_\pi$
- It may signal the absence in our description of 2π production and other inelastic channels
- This absence could explain the underestimation of the inclusive MicroBooNE $d^2\sigma$ at low p_μ (previously shown)
- This underestimation does not appear for the inclusive T2K $d^2\sigma$ data (previously shown)
- The reason of this difference is related to the different neutrino energy profiles of MicroBooNE and T2K, the MicroBooNE one having a larger high energy contribution
- 2π production and other inelastic contributions are more relevant for MicroBooNE than for T2K

Investigation of the MicroBooNE inclusive neutrino cross sections on Ar

Summary

- We have compared the MicroBooNE inclusive $d^2\sigma/dp_\mu d\cos\theta$, $\sigma(E_\nu)$, $d\sigma/dE_\mu$ and $d\sigma/d\omega$ to our theoretical approach
- Overall we find an agreement with the data, in spite of a tendency of underestimation in some specific regions
- Our model is particularly efficient in the case of the $d\sigma/d\omega$ data, a new type of measurement
- These data allow a better separation of the different reaction channels, even after the additional smearing needed for comparing models and data
- The low ω region is dominated by the quasielastic. At larger ω our predictions underestimate the data
- The two pions production and other inelastic contributions which are not taken into account in our description are the natural candidates to explain this underestimation
- These channels are more relevant for MicroBooNE than for T2K, due to the different energy profiles of these neutrino beams

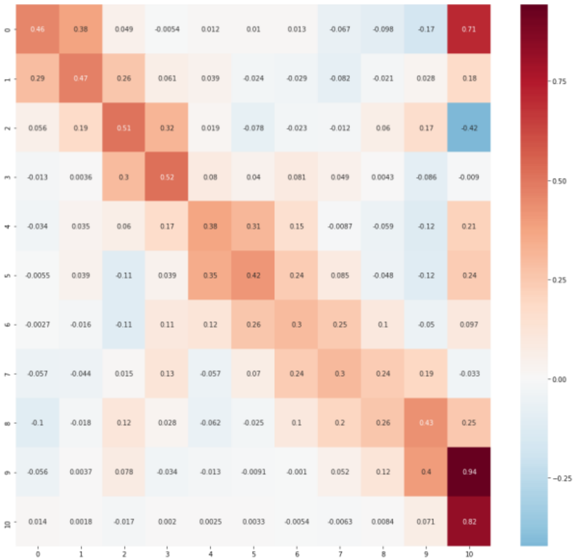
BACKUP

Smearing Matrices

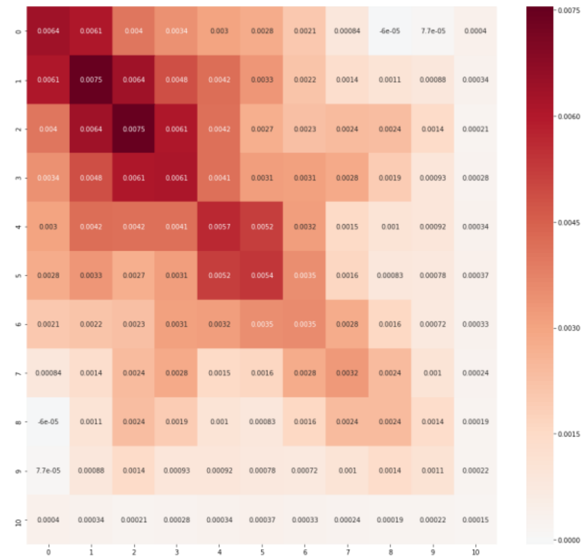
$$\sigma_{smeared} = M_{add\_smr} \times \sigma_{model}$$

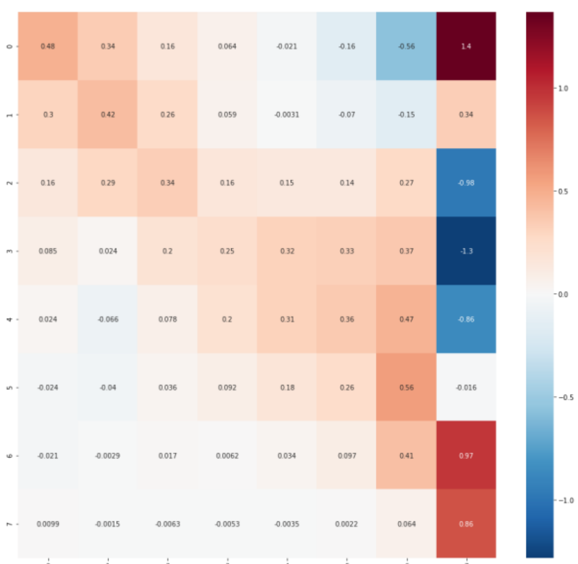
Covariant Matrices

$$\chi^2 = (M - P)^T \times Cov_{full}^{-1}(M, P) \times (M - P)$$

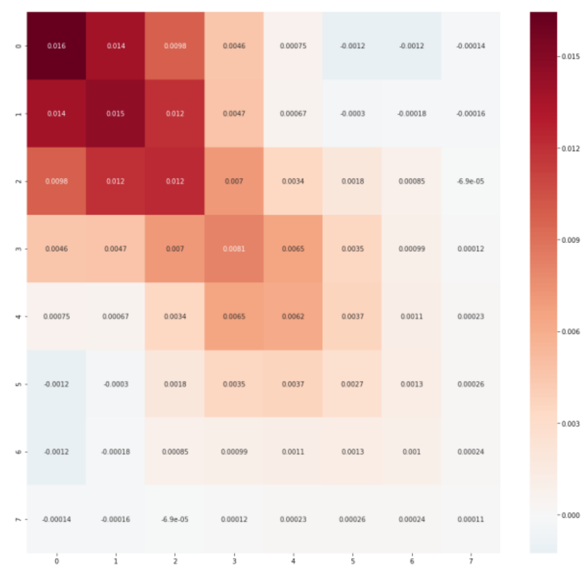


$d\sigma/dE_{\mu}$





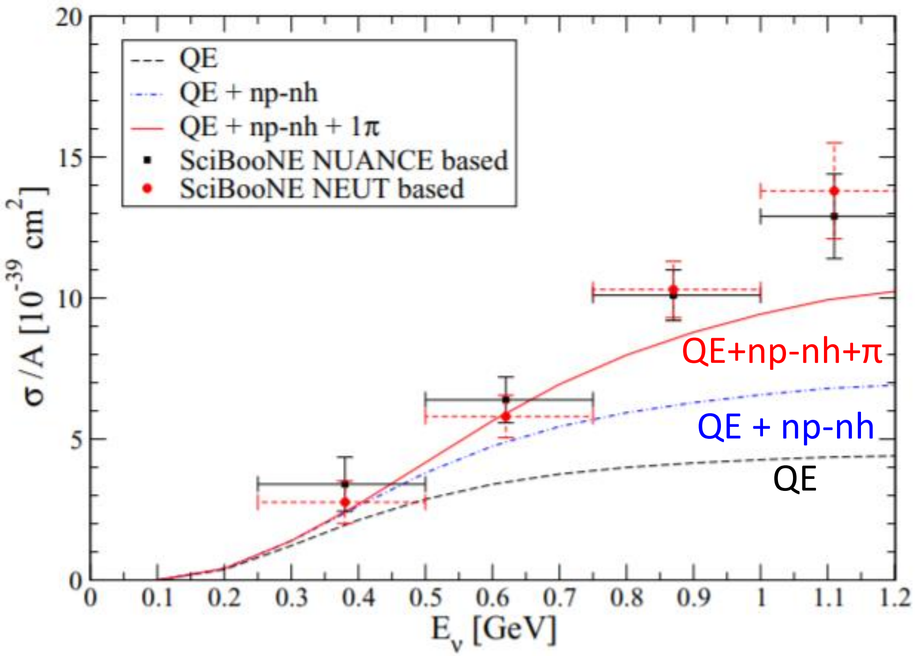
$d\sigma/d\omega$



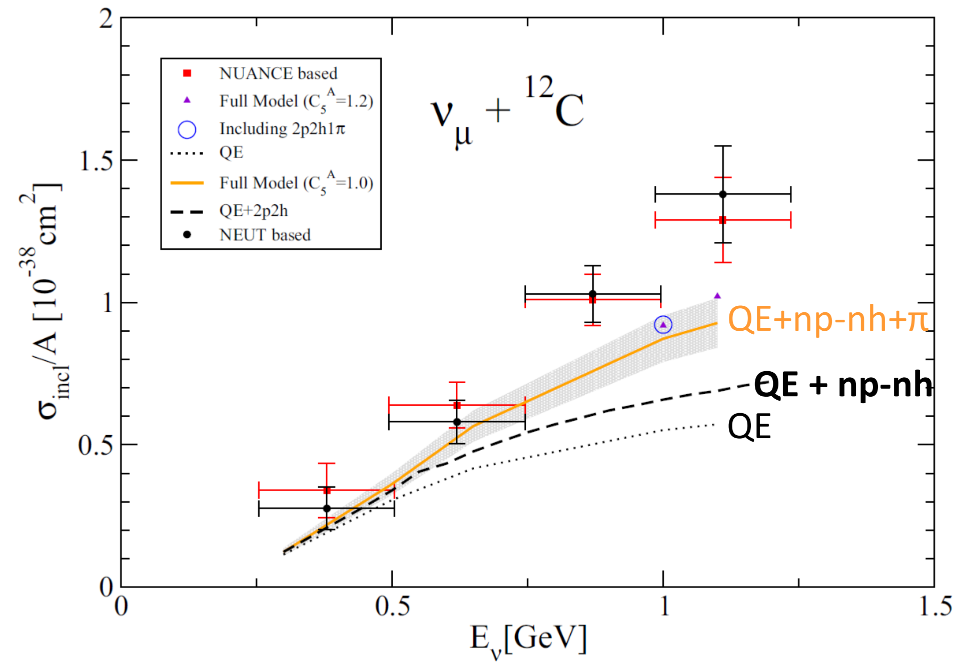
Supplemental material of MicroBooNE *PRL 128, 151801 (2022)*

Inclusive CC cross section on Carbon

SciBooNE, *Phys. Rev. D. 83, 012005 (2011)*



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



J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas
Phys. Rev. C 83 045501 (2011)