IPPP/NuSTEC topical meeting on neutrino-nucleus scattering (Durham, April 2017)

Electro- and neutrino- nucleus interactions at intermediate energies

J. Nieves

IFIC (CSIC & UV)

Outline

1. Motivation: Neutrino oscillations, neutrino detectors, nuclear cross sections
2. Intermediate energies: QE and $\Delta(1232)$ peaks and the dip region
3. Many body approach
4. Neutrino-nucleus inclusive QE scattering: Multinucleon mechanisms, RPA correlations and MiniBooNE M_A puzzle
5. Neutrino energy reconstruction
6. Conclusions

Further details:

- **Alvarez-Ruso L., Hayato Y. and Nieves J., New J.Phys. 16 (2014) 075015**
- **Morfin J. G., Nieves J. and Sobzcyk J.T., Adv.High Energy Phys. 2012 (2012) 934597**
- **Nieves J., Sobzcyk J.E.: *In medium dispersion relation effects in nuclear inclusive reactions at intermediate and low energies.: arXiv: 1701.03628***
- arXiv:1307.8105: PRD 88 (2013) 113007 ($\nu, \bar{\nu}$ CCQE-like up to 10 GeV)
- arXiv:1106.5374: PLB 707 (2012) 72 (ν CCQE-like) & arXiv:1302.0703: PLB 721 (2013) 90 ($\bar{\nu}$ CCQE-like)
- arXiv:1204.5404: PRD 85 (2012) 113008 (E_ν reconstruct.)
- arXiv:1102.2777: PRC 83 (2011) 045501 (CCQE, 2p2h, ...)
- nucl-th/0408005: PRC 70 (2004) 055503 (CCQE) & hep-ph/0604042: PLB 638 (2006) 325 (Errors in CCQE) & hep-ph/0511204 : PRC 73 (2006) 025504 (NCQE & MC)
- arXiv:1612.02343: PRD 95 (2017) 053007 & arXiv: 1510.06266: PRD 93 (2016) 014016 & arXiv: 1001.4416: PRD 81 (2016) 085046 & hep-ph/0701149: PRD 76 (2007) 033005 ($\nu_l\, N \rightarrow l\, N'\pi$)
- arXiv: 1304.1320: PRD 87 (2013) 113009 ($\nu_l\, A \rightarrow l\, \pi\, X$)
- arXiv: 1007.3685: PRD 82 (2010) 077303 & arXiv: 0903.5285: PRD 80 (2009) 013003 & arXiv: 0811.1421: PRD 79 (2009) 013002 (coherent π production in nuclei)
- nucl-th/9711009 : NPA 627 (1997) 543 (inclusive *(e,e')*)
- nucl-th/9710070 : NPA 627 (1997) 599 (inclusive *(e,e'N), (e,e'NN), (e,e',π*)....

Reviews

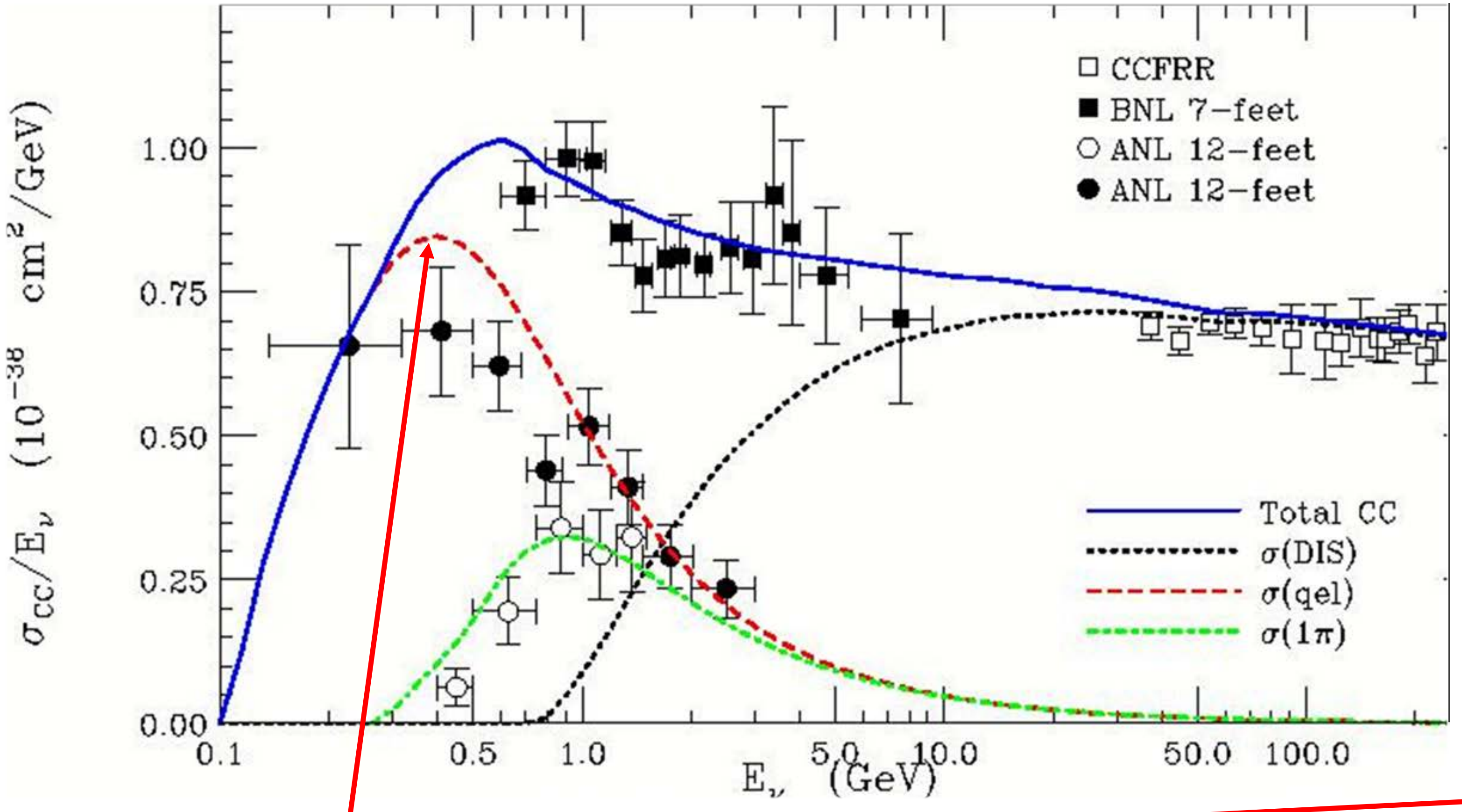
CCQE: latest work

CCQE & NCQE

π production

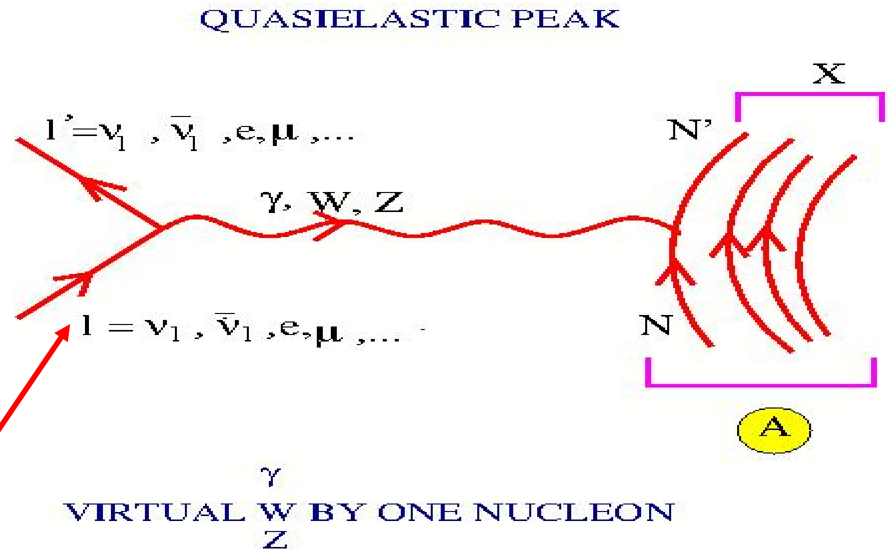
electron-nucleus

Motivation: Details on the axial structure of hadrons in the free space and inside of nuclei, and



Theoretical knowledge of QE and 1π cross sections is important to carry out a precise neutrino oscillation data analysis...

^{12}C → Liquid scintillators
^{16}O → Cerenkov detectors
^{40}A → TPC's (time projection chambers) ....



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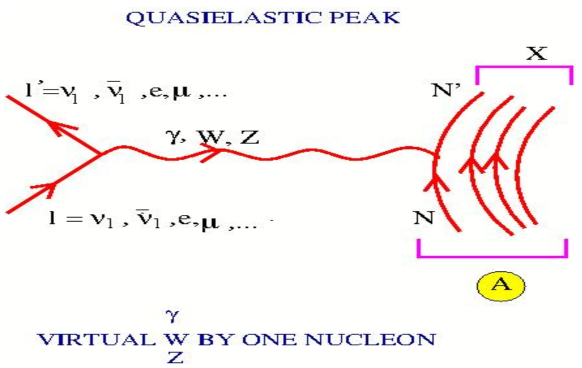
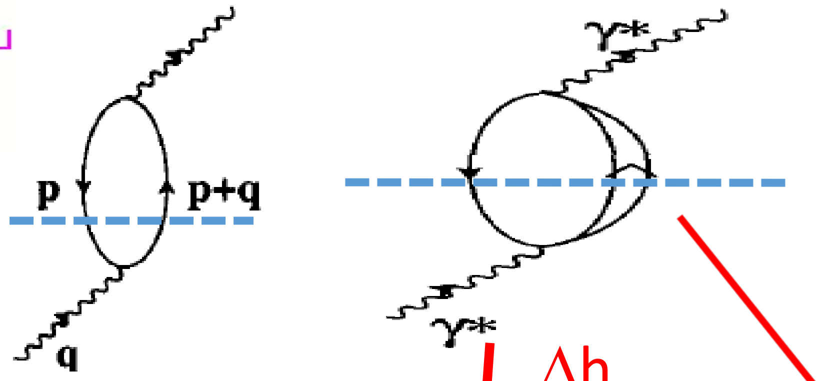
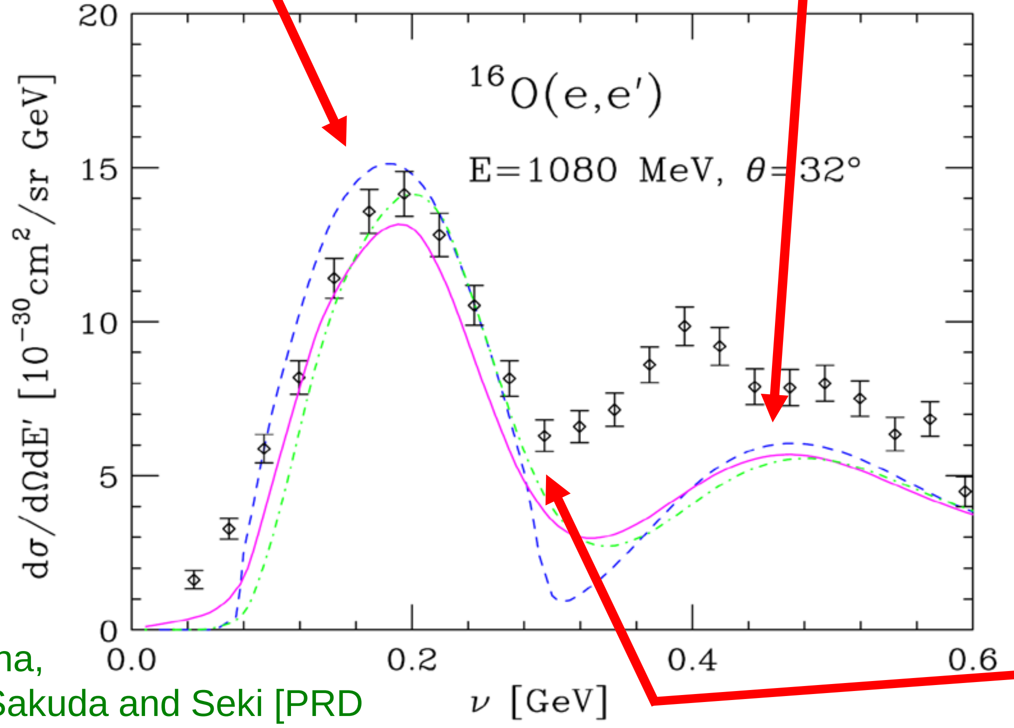
Intermediate energies: QE and Δ(1232) peaks and the dip region



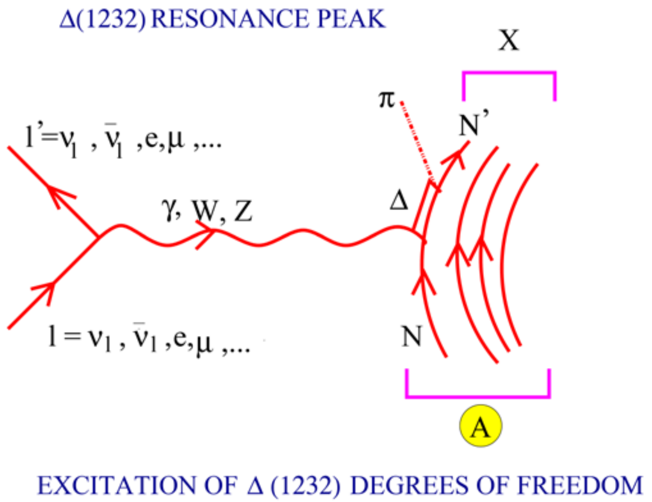


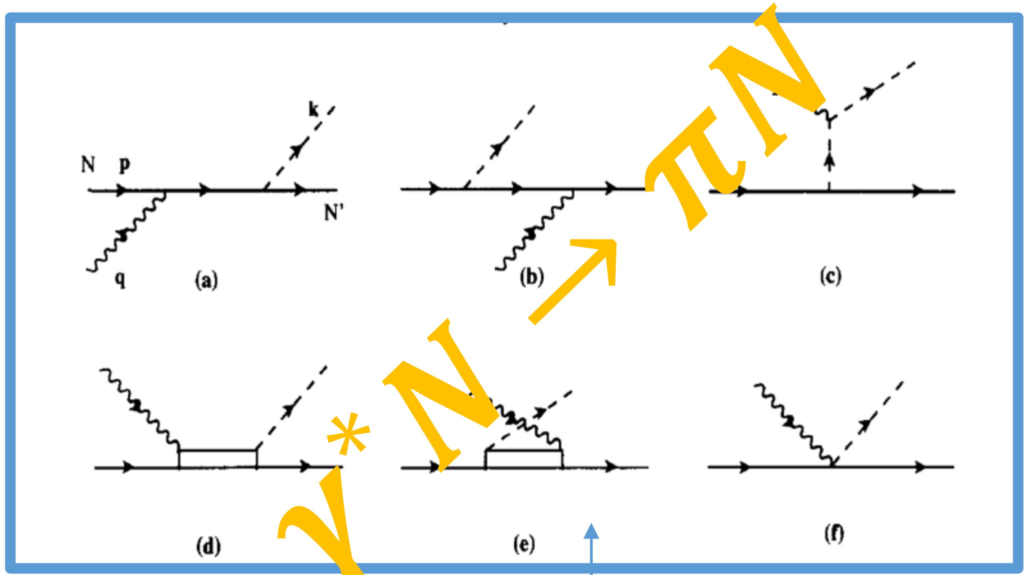
1p1h

Δh

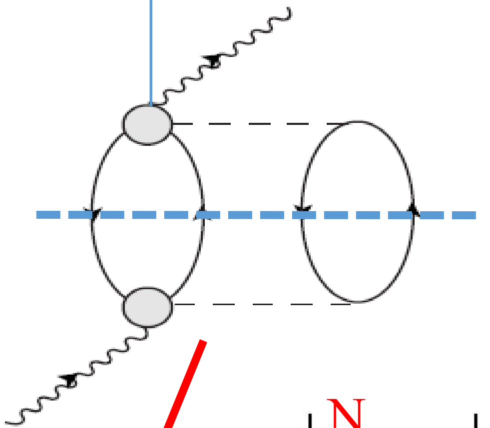


Benhar, Farina, Nakamura, Sakuda and Seki [PRD 72 (2005) 053005]



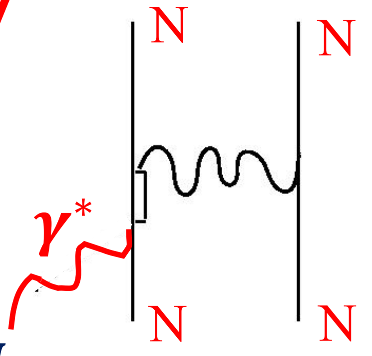


$\gamma^* N \rightarrow \pi N$



Dip region

2p2h



$\gamma^* NN \rightarrow NN$

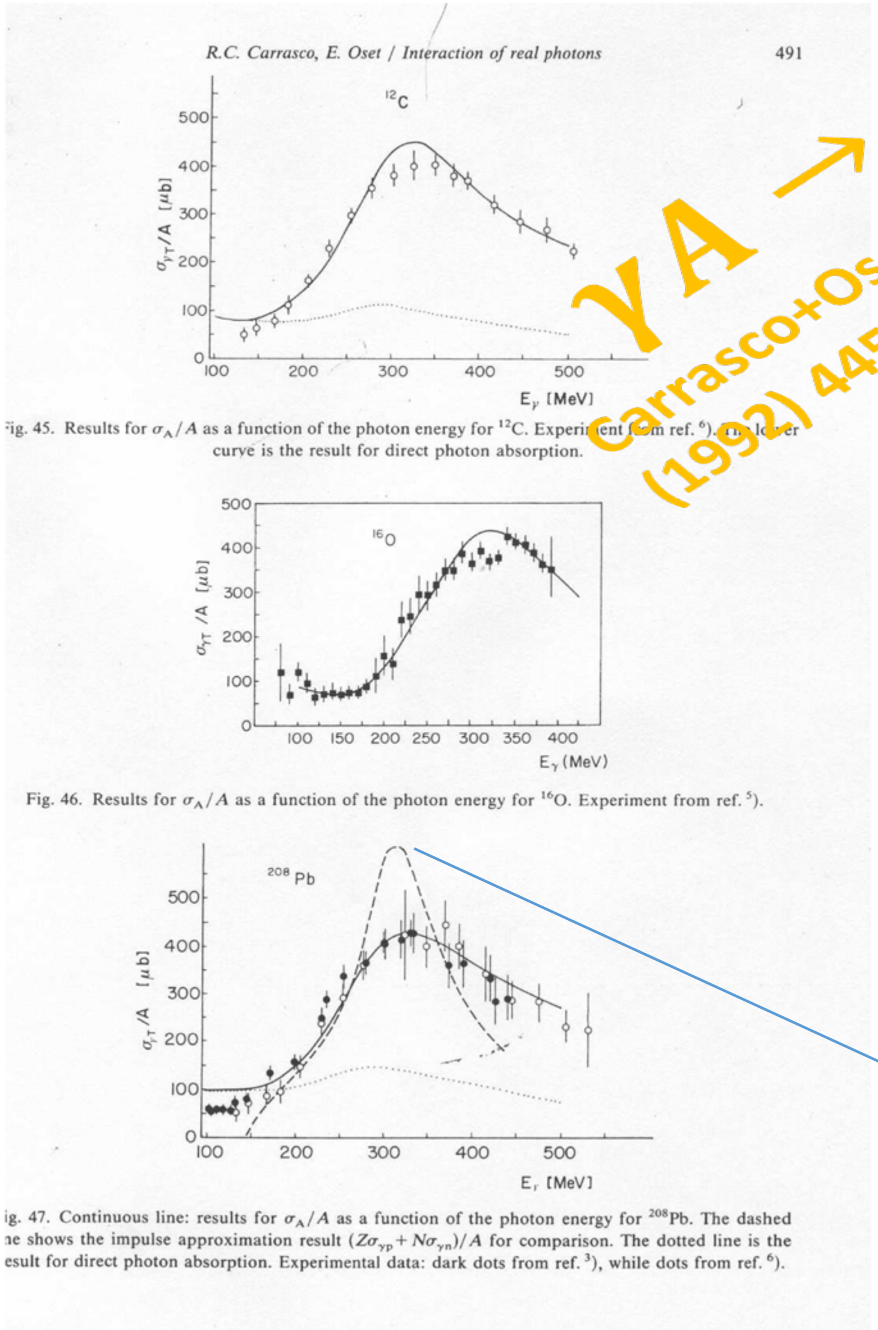

R.C. Carrasco, E. Oset / Interaction of real photons 491

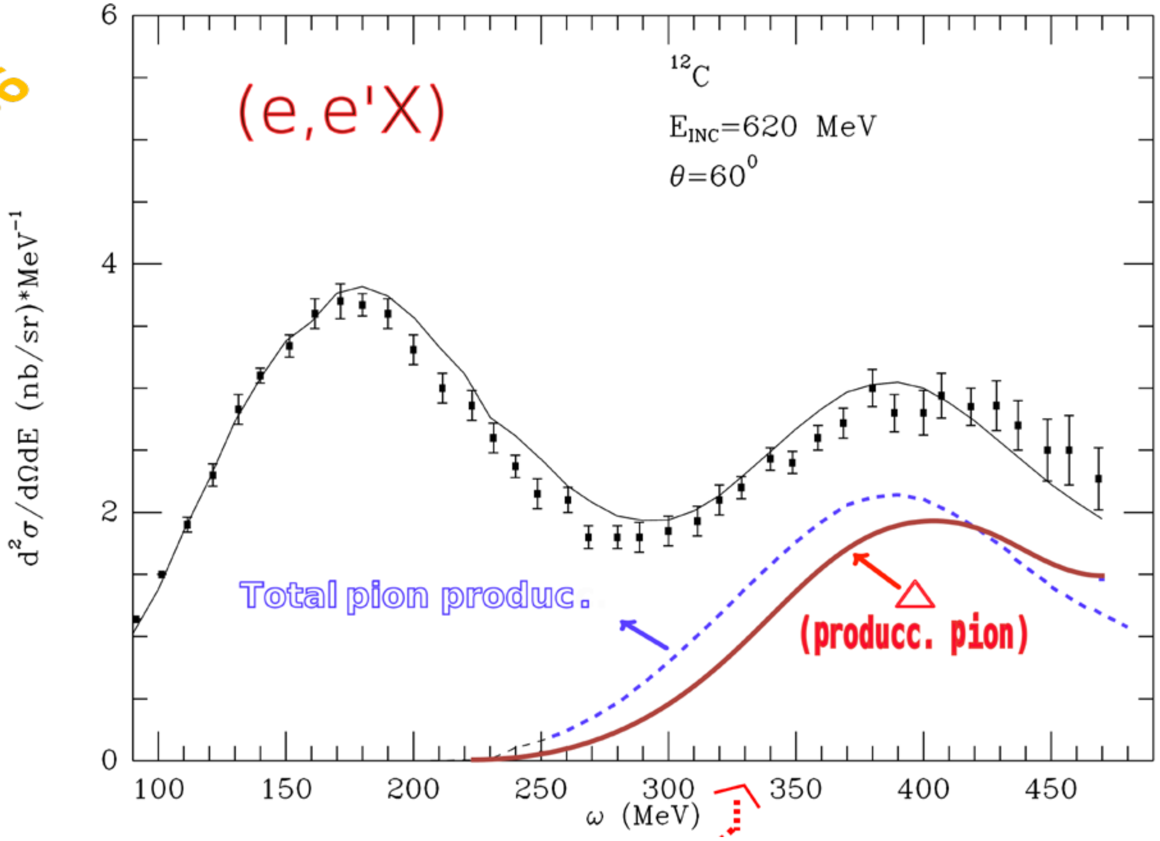
Fig. 45. Results for σ_A/A as a function of the photon energy for ^{12}C. Experiment from ref. [6]). The lower curve is the result for direct photon absorption.

Fig. 46. Results for σ_A/A as a function of the photon energy for ^{16}O. Experiment from ref. [5]).

Fig. 47. Continuous line: results for σ_A/A as a function of the photon energy for ^{208}Pb. The dashed line shows the impulse approximation result $(Z\sigma_{\gamma p}+N\sigma_{\gamma n})/A$ for comparison. The dotted line is the result for direct photon absorption. Experimental data: dark dots from ref. [3]), while dots from ref. [6]).

$\gamma A \rightarrow X$

Carrasco+Oset, NPA 536 (1992) 445



$eA \rightarrow e'X$

Gil+Nieves+Oset NPA 627 (1997) 543

Impulse approximation

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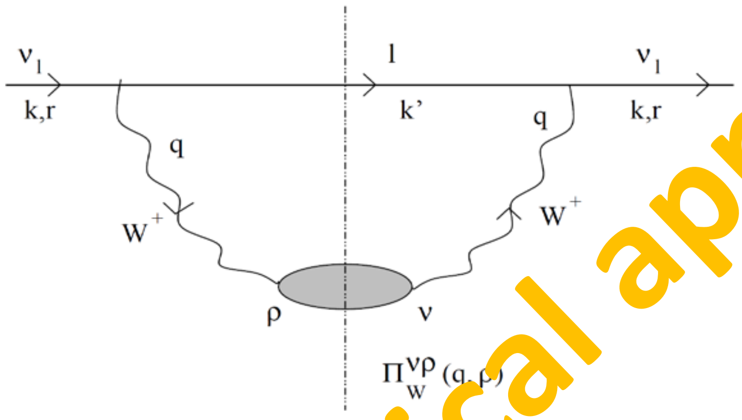
Many body approach

For instance, let's look at $\nu_l + A_Z \longrightarrow l + X$



$$\frac{d^2\sigma}{d\Omega(\hat{k}')dE'} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2} L_{\mu\sigma} W^{\mu\sigma}$$

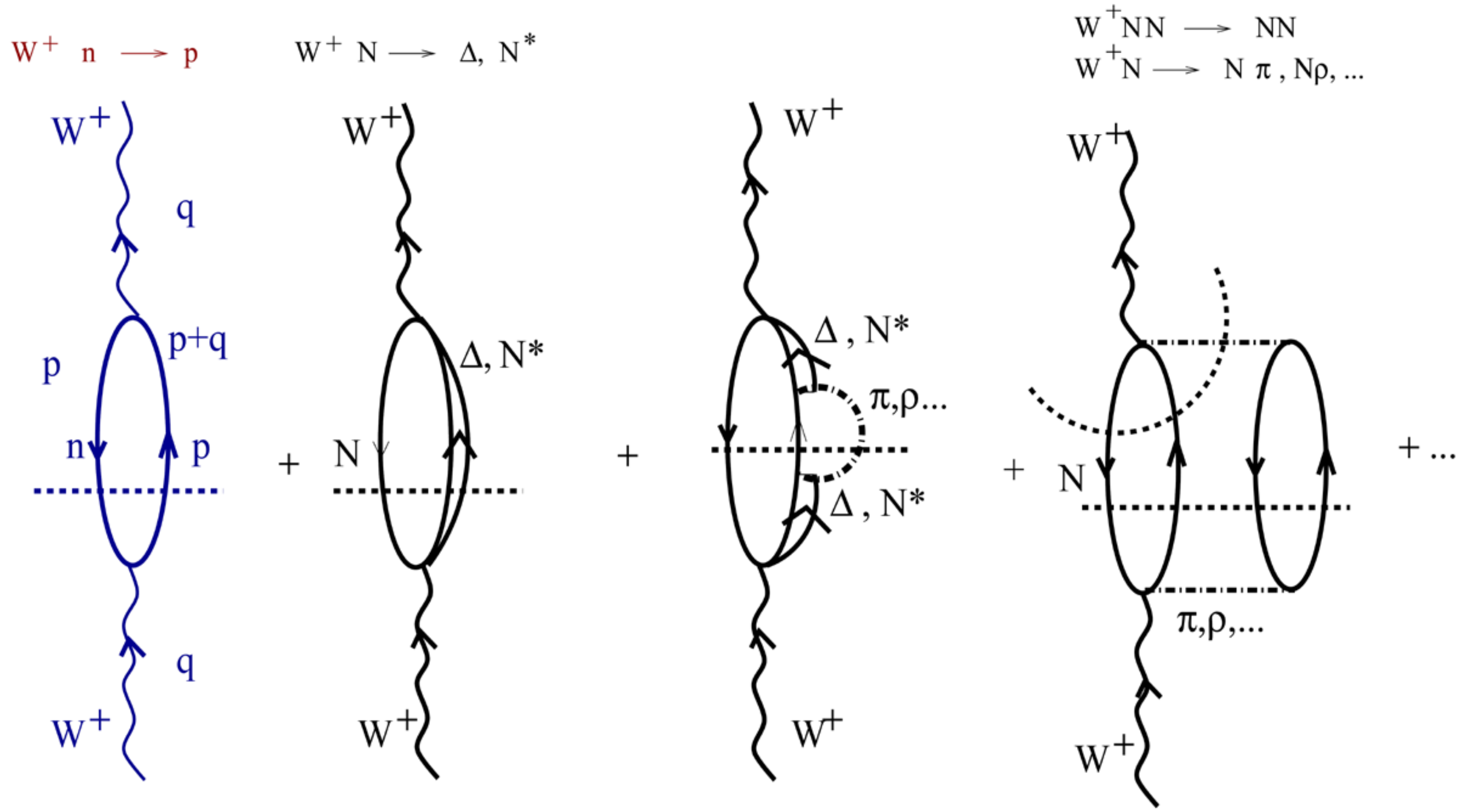
$$L_{\mu\sigma} = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma} k\cdot k' + \mathrm{i}\epsilon_{\mu\sigma\alpha\beta} k'^\alpha k^\beta$$

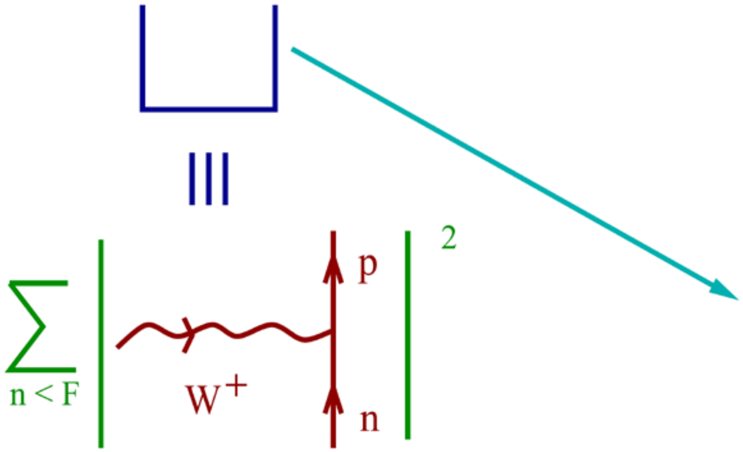
$$W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i} W_a^{\mu\sigma}$$

$$W_s^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\ \mathrm{Im}\ \left\{\Pi_W^{\mu\sigma}(q,\rho) + \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

$$W_a^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\ \mathrm{Re}\ \left\{\Pi_W^{\mu\sigma}(q,\rho) - \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

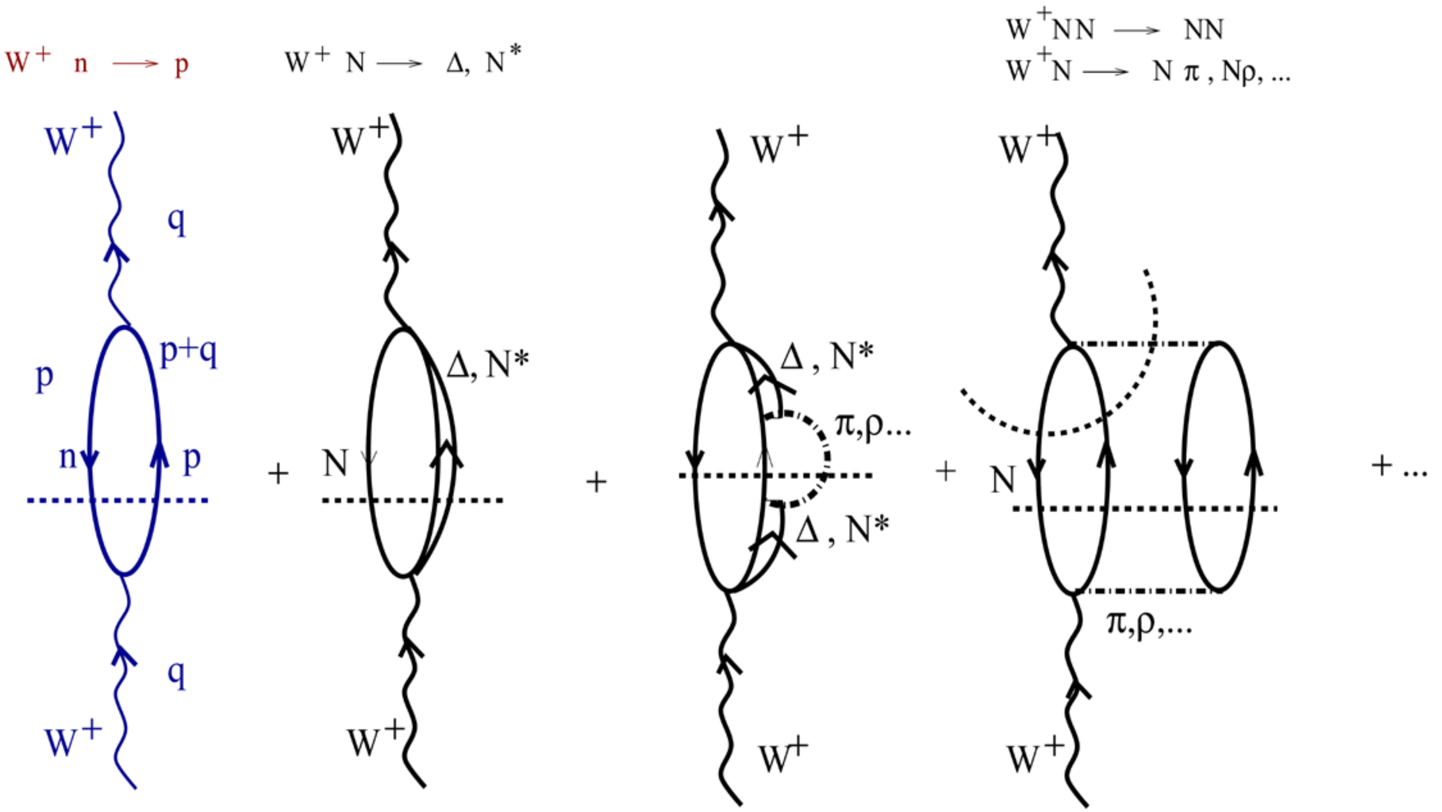
Basic object $\boxed{\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)}$ $\equiv$ Selfenergy of the Gauge Boson $(W^\pm, Z^0, \gamma)$ inside of the nuclear medium. Perform a Many Body expansion, where the relevant gauge boson absorption modes should be systematically incorporated: absorption by one N, or NN or even 3N, real and virtual (MEC) meson $(\pi,\ \rho,\ \cdots)$ production, Δ excitation, etc...

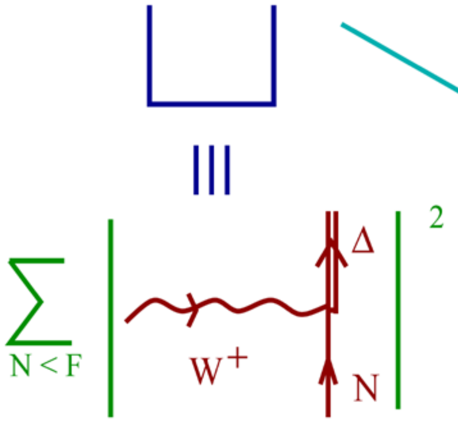




QE

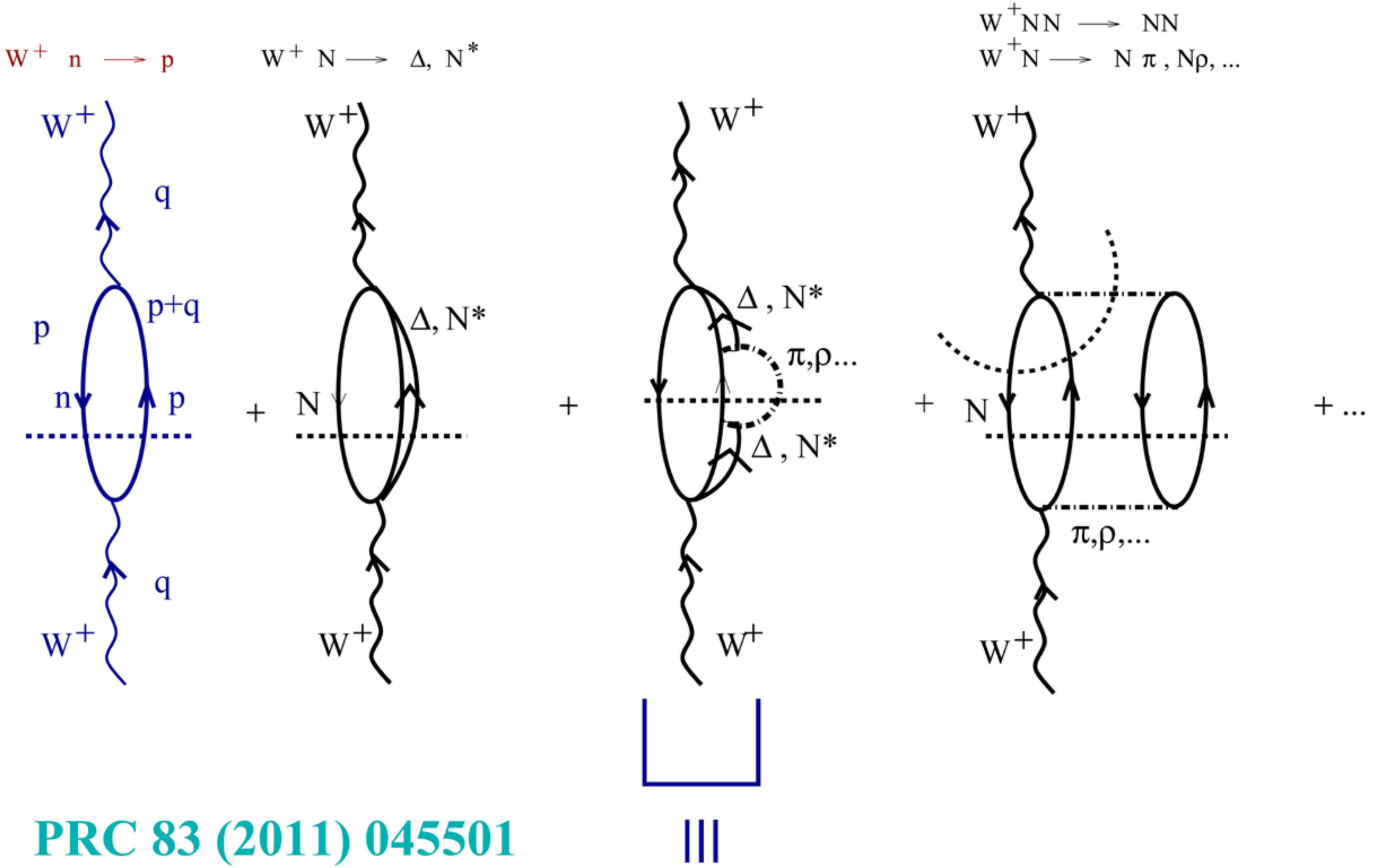
PRC 70 (2004) 055503 (CC)
PRC 73 (2006) 025504 (NC)





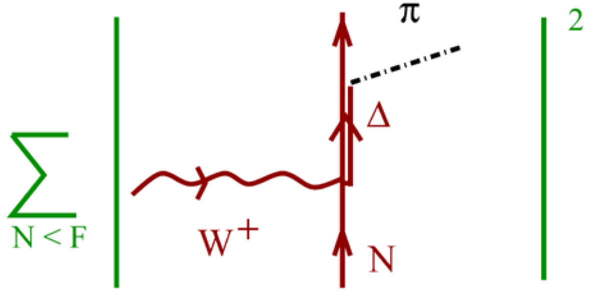
Δh prod.

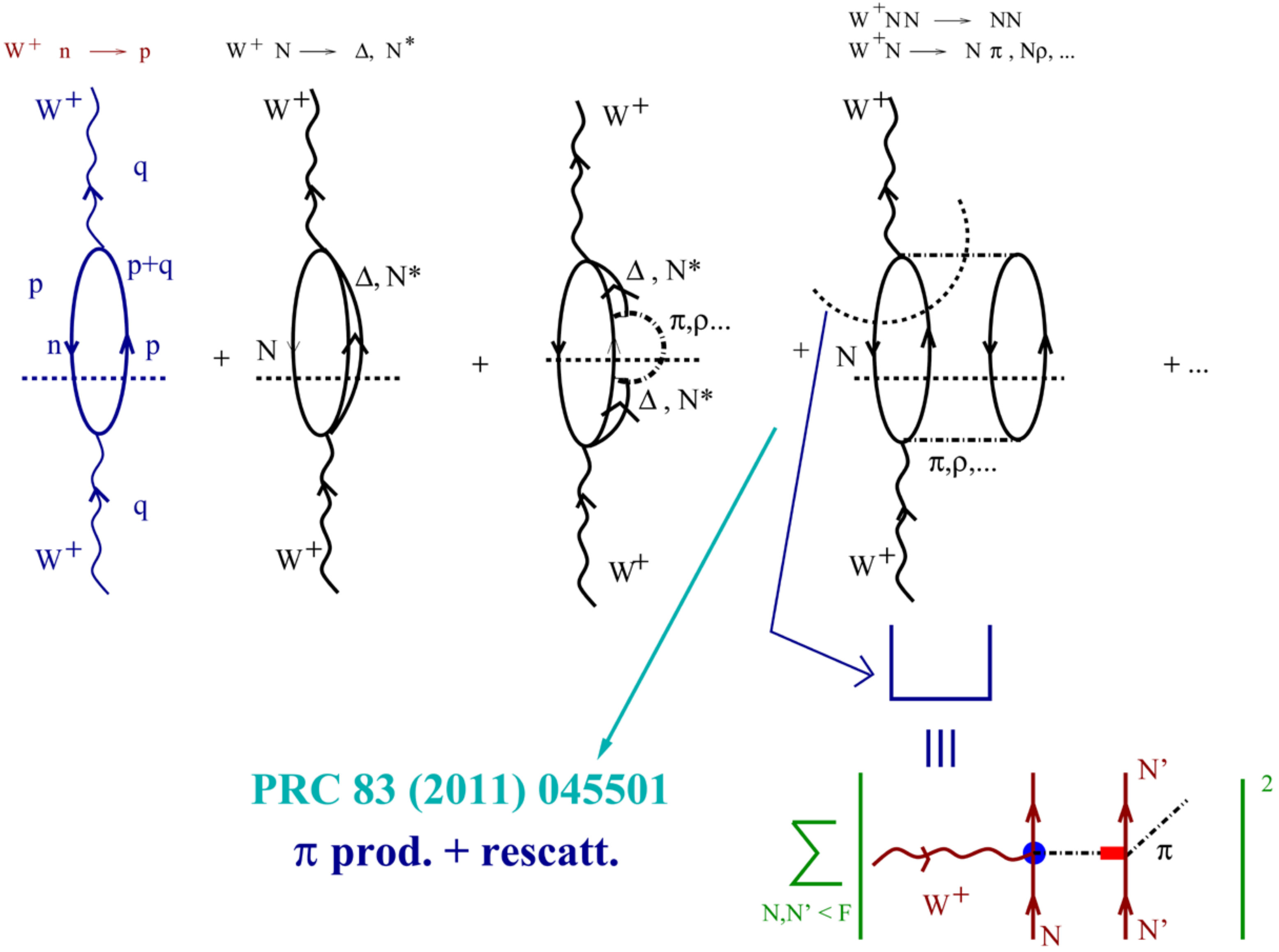
PRC 83 (2011) 045501



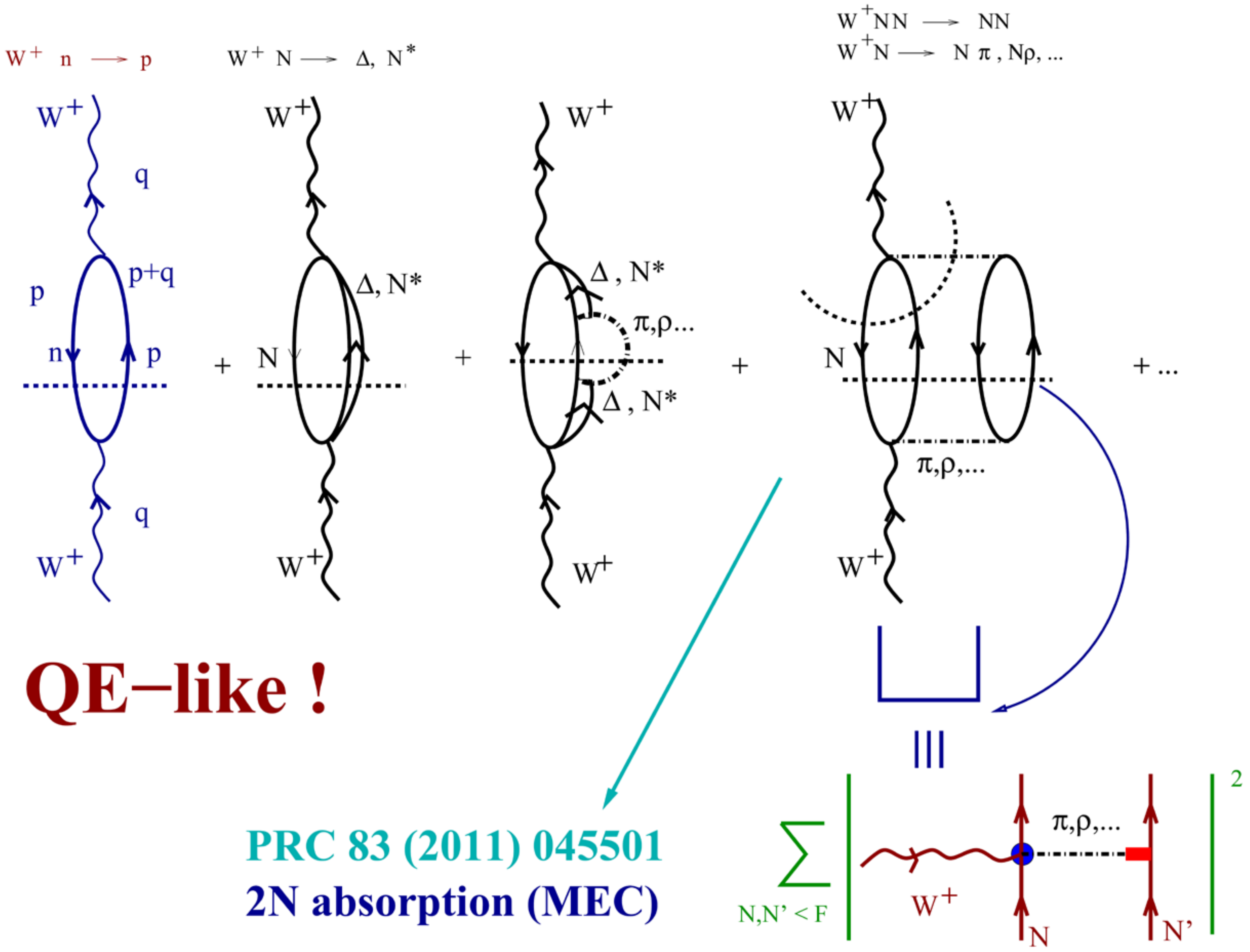
PRC 83 (2011) 045501

π prod.





$W^+ n \longrightarrow p$
$W^+ N \longrightarrow \Delta, N^*$
$W^+ NN \longrightarrow NN$
$W^+ N \longrightarrow N\pi, N\rho, \ldots$
W^+
q
p+q
p
n
p
Δ, N*
N
$\pi,\rho\ldots$
$\pi,\rho,\ldots$
+ ...
PRC 83 (2011) 045501
π prod. + rescatt.
N,N' < F
N'
N
π
2



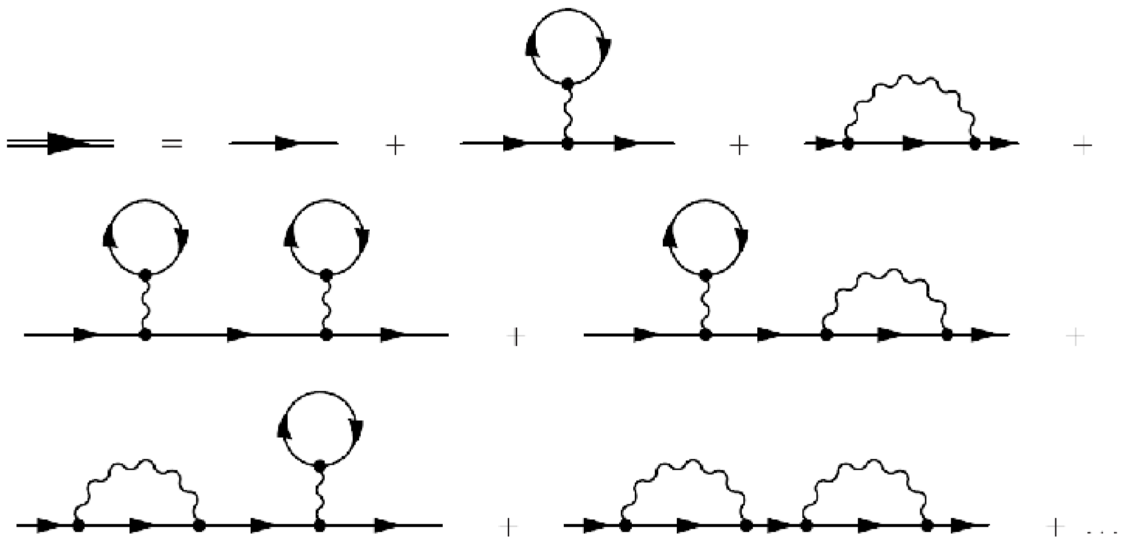
QE−like !

PRC 83 (2011) 045501

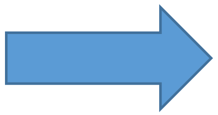
2N absorption (MEC)

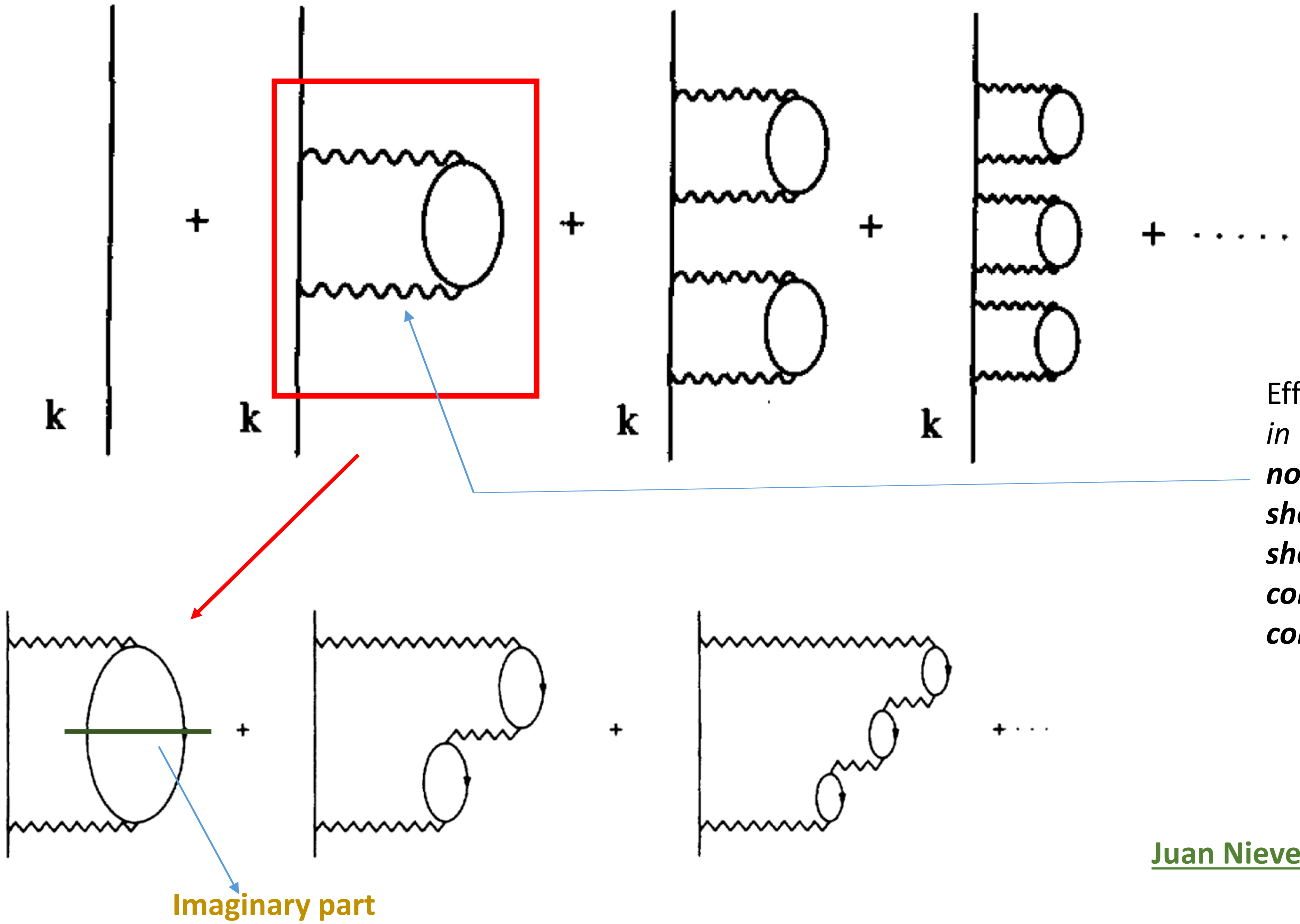
QE nuclear corrections

- **Spectral Functions: dressing the nucleon lines in the medium**



Beyond the Hartree-Fock approximation





Effective *NN interaction in the medium.* ***It is not just a pion and should account for short-range-correlations and RPA corrections***

$$S_{p,h}(\omega,\vec{p}) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(\omega,\vec{p}\,)}{[\omega^2-\vec{p}^2-M^2-\mathrm{Re}\Sigma(\omega,\vec{p})]^2+[\mathrm{Im}\Sigma(\omega,\vec{p})]^2}$$

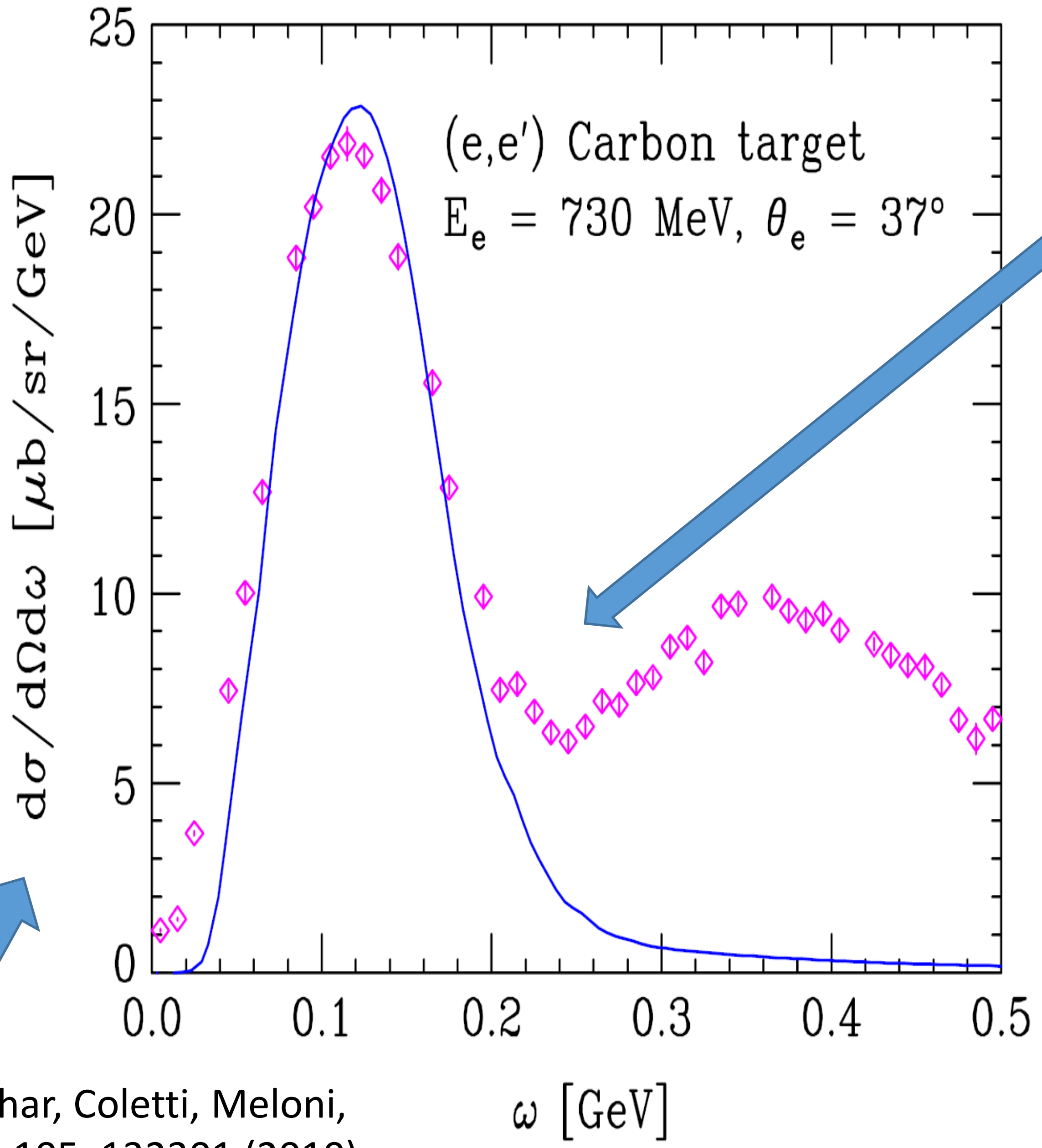
with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively (μ is the chemical potential).

Basic object: nucleon selfenergy in the medium: Σ (from realistic NN interactions in the medium).

This nuclear effect is additional to those due to RPA (long range) correlations !!

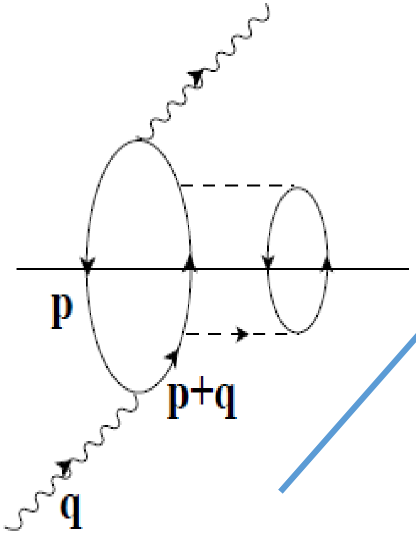
Nuclear medium dispersion relation effects: Spectral Functions

Spectral Function (SRC) do not populate the **dip region**



Benhar, Coletti, Meloni, PRL 105, 132301 (2010)

- Spectral Function (SF) + Final State Interaction (FSI): dressing up the nucleon propagator of the hole (SF) and particle (FSI) states in the *ph* excitation



– Change of nucleon dispersion relation:
  - ∗ hole ⇒ Interacting Fermi sea (SF)
  - ∗ particle ⇒ Interaction of the ejected nucleon with the final nuclear state (FSI)

$$G(p) \to \int_{-\infty}^{\mu} d\omega \frac{S_h(\omega,\vec{p}\,)}{p^0-\omega-\mathrm{i}\epsilon} + \int_{\mu}^{+\infty} d\omega \frac{S_p(\omega,\vec{p}\,)}{p^0-\omega+\mathrm{i}\epsilon}$$

The hole and particle spectral functions are related to nucleon self-energy Σ in the medium,

$$G(p) = \frac{n(\vec{p}\,)}{p^0-\varepsilon(\vec{p})-i\epsilon} + \frac{1-n(\vec{p}\,)}{p^0-\varepsilon(\vec{p})+i\epsilon}$$

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The simplest description $\Rightarrow$ relativistic Fermi Gas with

non interacting fermions $\boxed{\Sigma = 0}$,

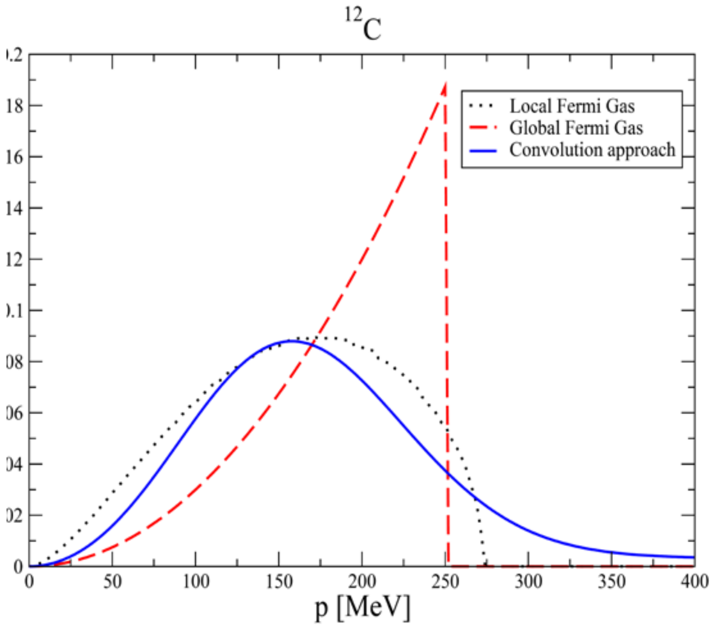
$$S_p(\omega,\vec{p}) = \frac{\theta(|\vec{p}\,| - k_F)}{2E(\vec{p})}\delta(\omega - E(\vec{p}))$$

$$S_h(\omega,\vec{p}) = \frac{\theta(k_F - |\vec{p}\,|)}{2E(\vec{p})}\delta(\omega - E(\vec{p}))$$

and only Pauli blocking is incorporated!!

Local vs Global Fermi Gas ?

$$k_F^{p,n}(r) = \left[3\pi^2\rho^{p,n}(r)\right]^{1/3} \text{ vs } k_F^{p,n} = \text{cte ?}$$



Local vs Global Fermi Gas ?

$$k_F(r) = \left[3\pi^2\rho(r)/2\right]^{1/3} \textbf{ vs } k_F \textbf{= cte ?}$$

$$S_h(\omega,\vec{p}) = \delta(\omega - E(\vec{p}))\theta(k_F - |\vec{p}\,|)/2\omega$$

$$n^{\rm RgFG}(|\vec{p}\,|) = \frac{4V}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) = \frac{3A}{4\pi k_F^3}\theta(k_F - |\vec{p}\,|)$$

$$n^{\rm LDA}(|\vec{p}\,|) = 4\int\frac{d^3r}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) = 4\int\frac{d^3r}{(2\pi)^3}\theta(\mathbf{k_F(r)} - |\vec{p}\,|)$$

$$\left(\int d^3p\, n(|\vec{p}\,|) = A\right)$$

Convolution approach: C. Ciofi degli Atti, S. Liuti, and S. Simula, PRC 53, 1689 (1996), provide realistic distribution due to short-range correlations !

PHYSICAL REVIEW C VOLUME 46, NUMBER 5 NOVEMBER 1992

Semiphenomenological approach to nucleon properties in nuclear matter

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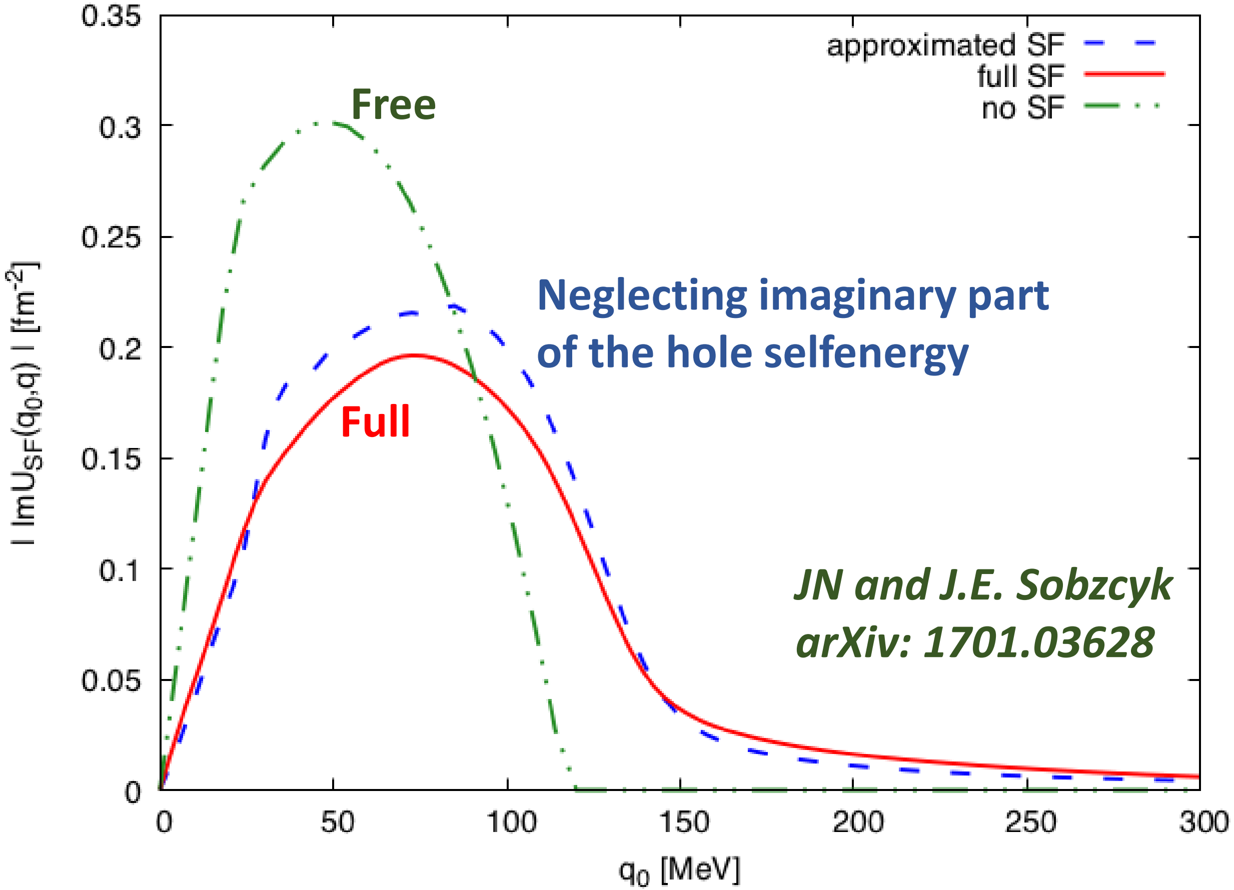
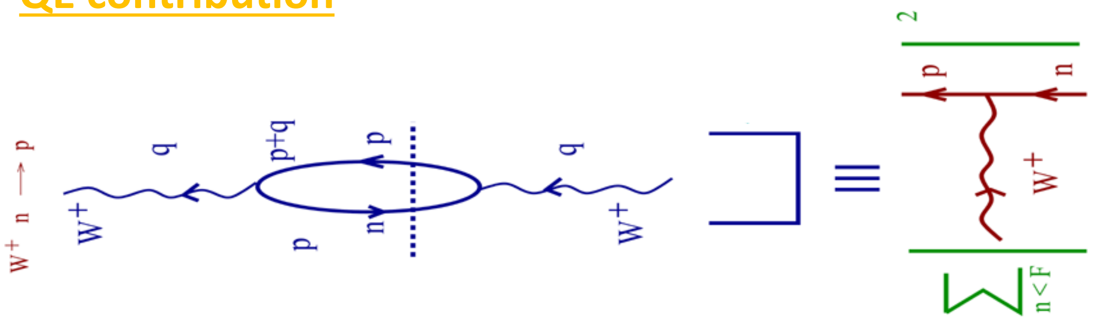
Departamento de Física Teórica and Instituto de Física Corpuscular,
Centro Mixto Universidad de Valencia Consejo Superior de Investigaciones Científicas, 46100 Burjassot (Valencia), Spain

(Received 20 April 1992)

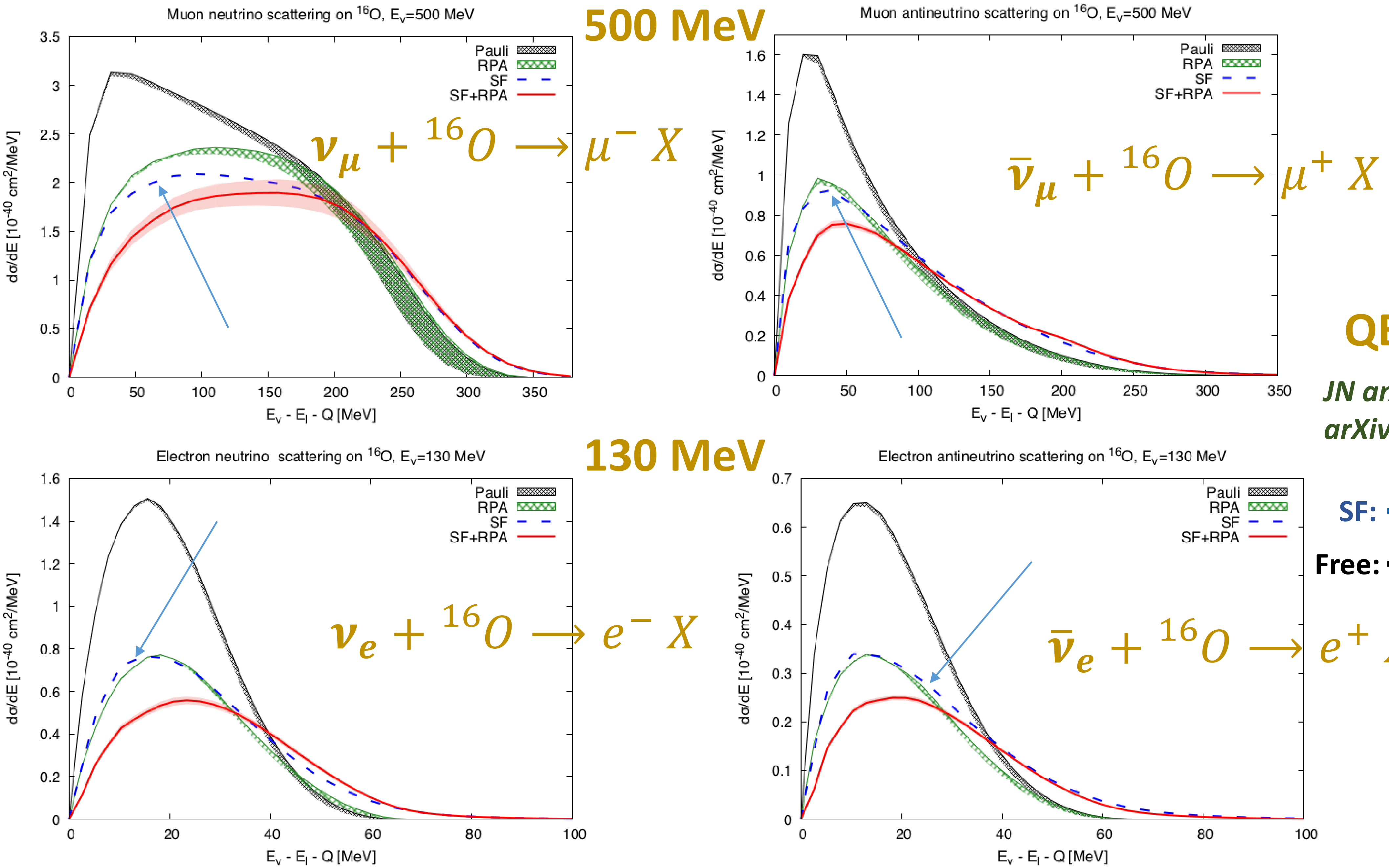


Effective *NN interaction in the medium constructed from the experimental NN cross section + some medium corrections*

QE contribution



Imaginary part of the *ph* propagator (Lindhard function)



QE: 1p1h

JN and J.E. Sobzcyk
arXiv: 1701.03628

SF: - - - -

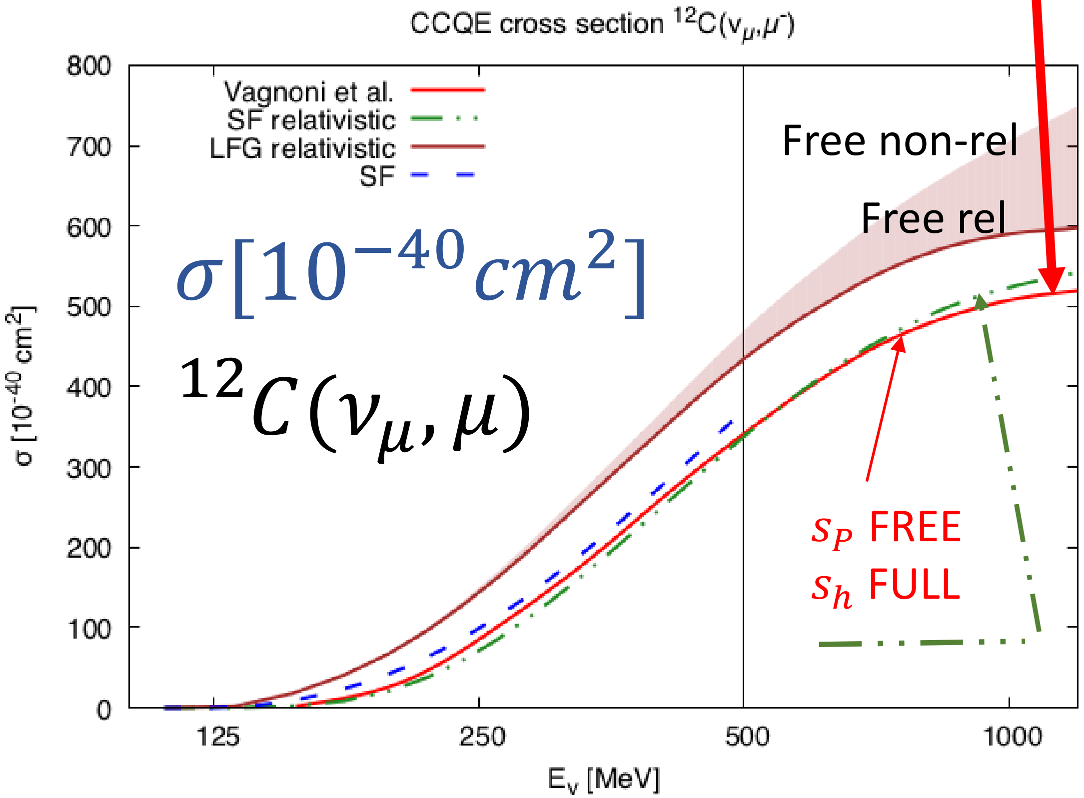
Free: ——

reasonable agreement !

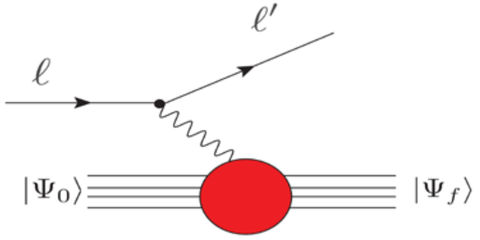
PRL **118,** 142502 (2017) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2017

Inelastic Neutrino-Nucleus Interactions within the Spectral Function Formalism

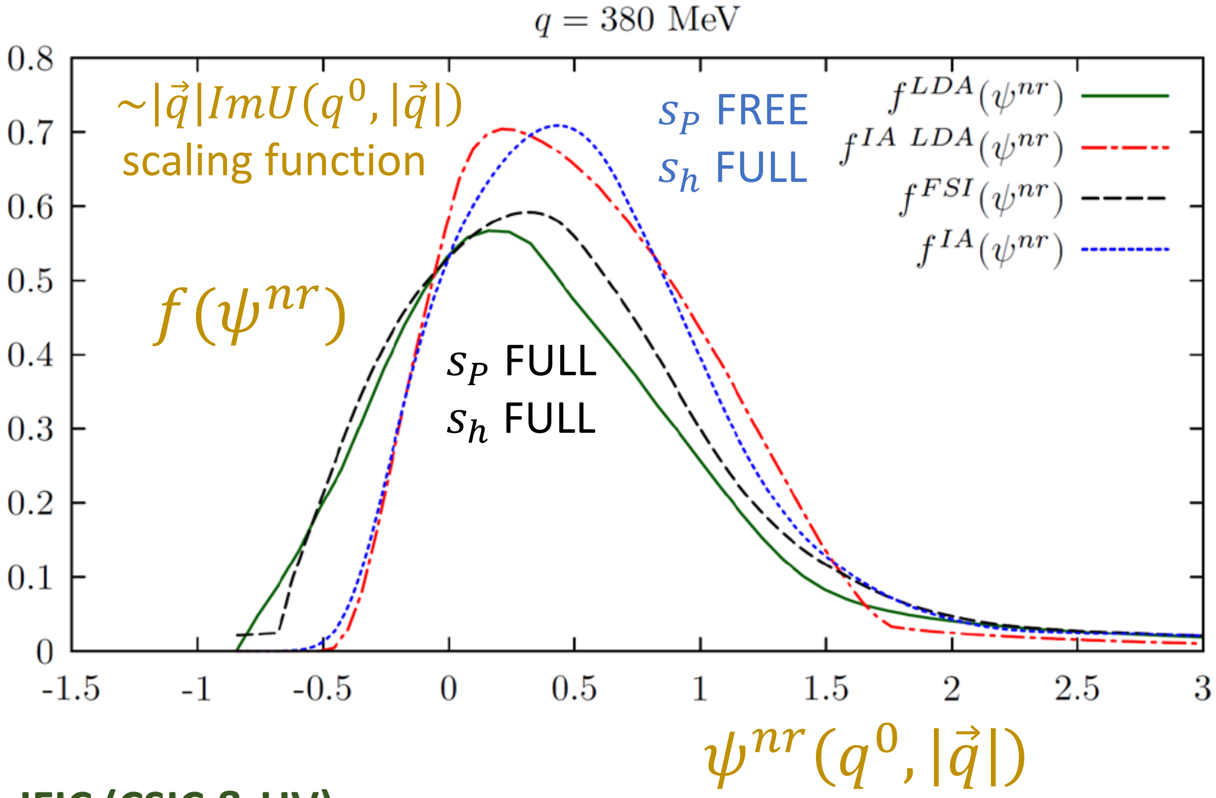
Erica Vagnoni,[1,*] Omar Benhar,[2,3,†] and Davide Meloni[1,‡]



Noemi Rocco



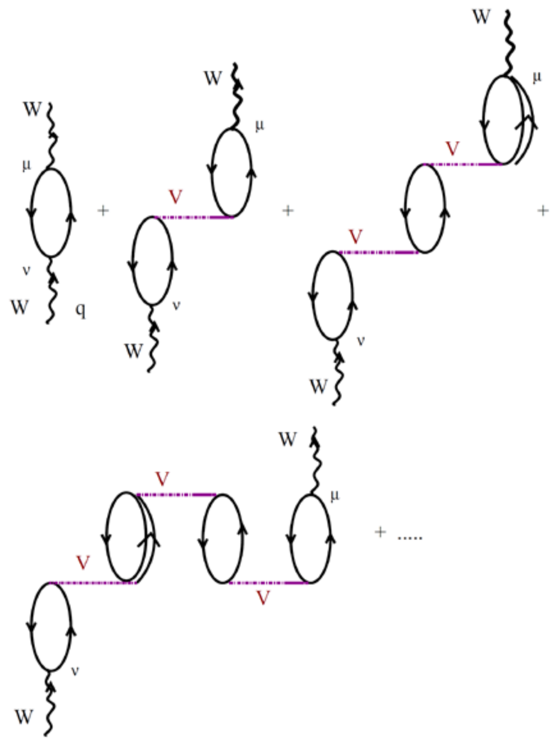
"FermiLab Theory Seminar" March 2nd 2017



QE nuclear corrections

- **RPA: long range correlations**

- Polarization (RPA) effects. Substitute the ph excitation by an RPA response: series of ph and Δh excitations.



1. Effective Landau-Migdal interaction

$$V(\vec{r}_1,\vec{r}_2) = c_0\delta(\vec{r}_1-\vec{r}_2)\left\{ \boxed{f_0(\rho)} + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + \boxed{g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2} + g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \right\}$$

Isoscalar terms $\boxed{}$ do not contribute to CC

2. $S=T=1$ channel of the ph–ph interaction → s longitudinal (π) and transverse (ρ) + **SRC**

$$g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \rightarrow [V_l(q)\hat{q}_i\hat{q}_j + V_t(q)(\delta_{ij}-\hat{q}_i\hat{q}_j)]\,\sigma_1^i\sigma_2^j\vec{\tau}_1\vec{\tau}_2$$

$$V_{l,t}(q) = \frac{f_{\pi NN,\rho NN}}{m^2_{\pi,\rho}}\left(F_{\pi,\rho}(q^2)\frac{\vec{q}^{\,2}}{q^2-m^2_{\pi,\rho}} + g'_{l,t}(q)\right)$$

3. Contribution of Δh excitations important

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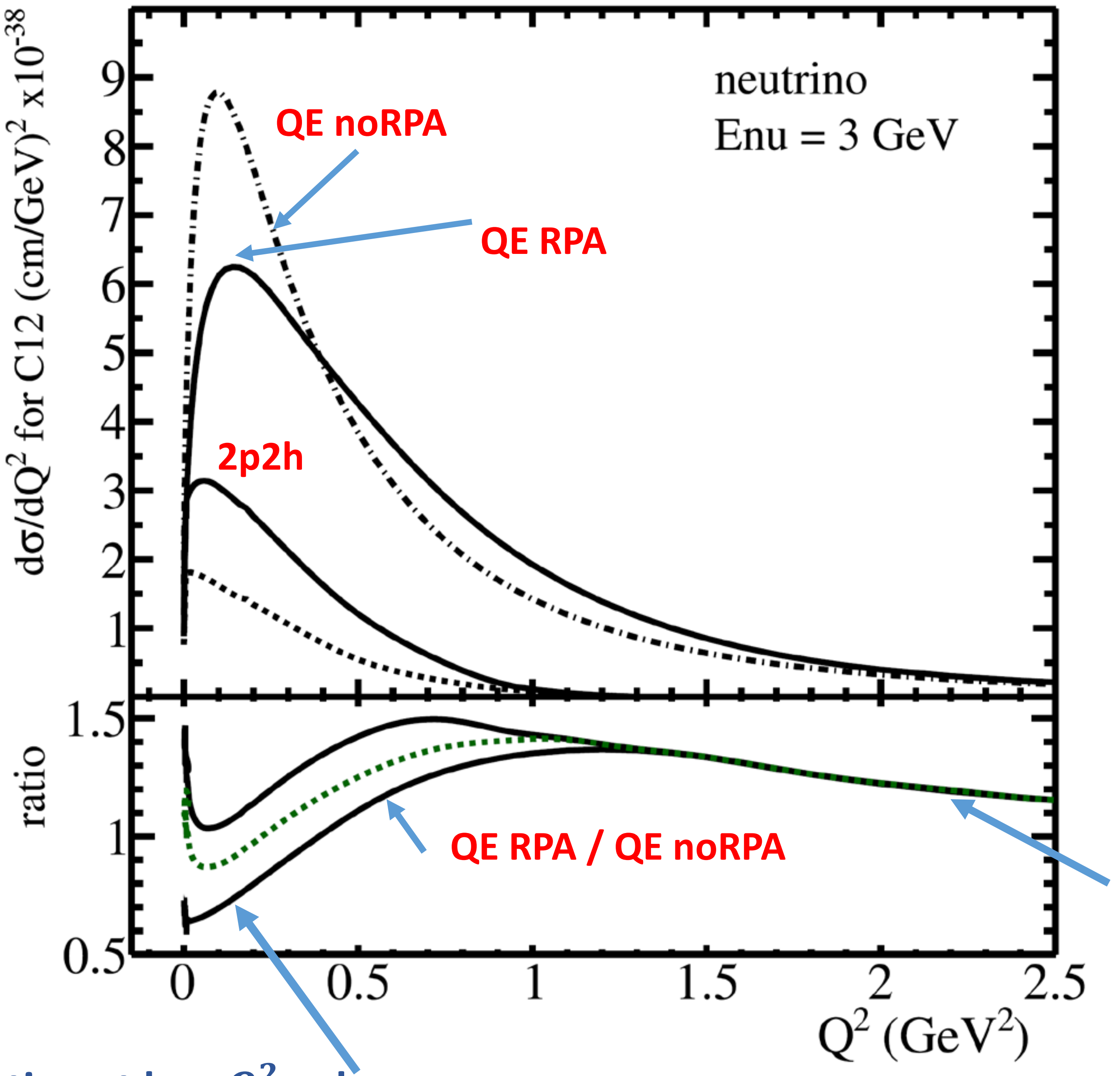
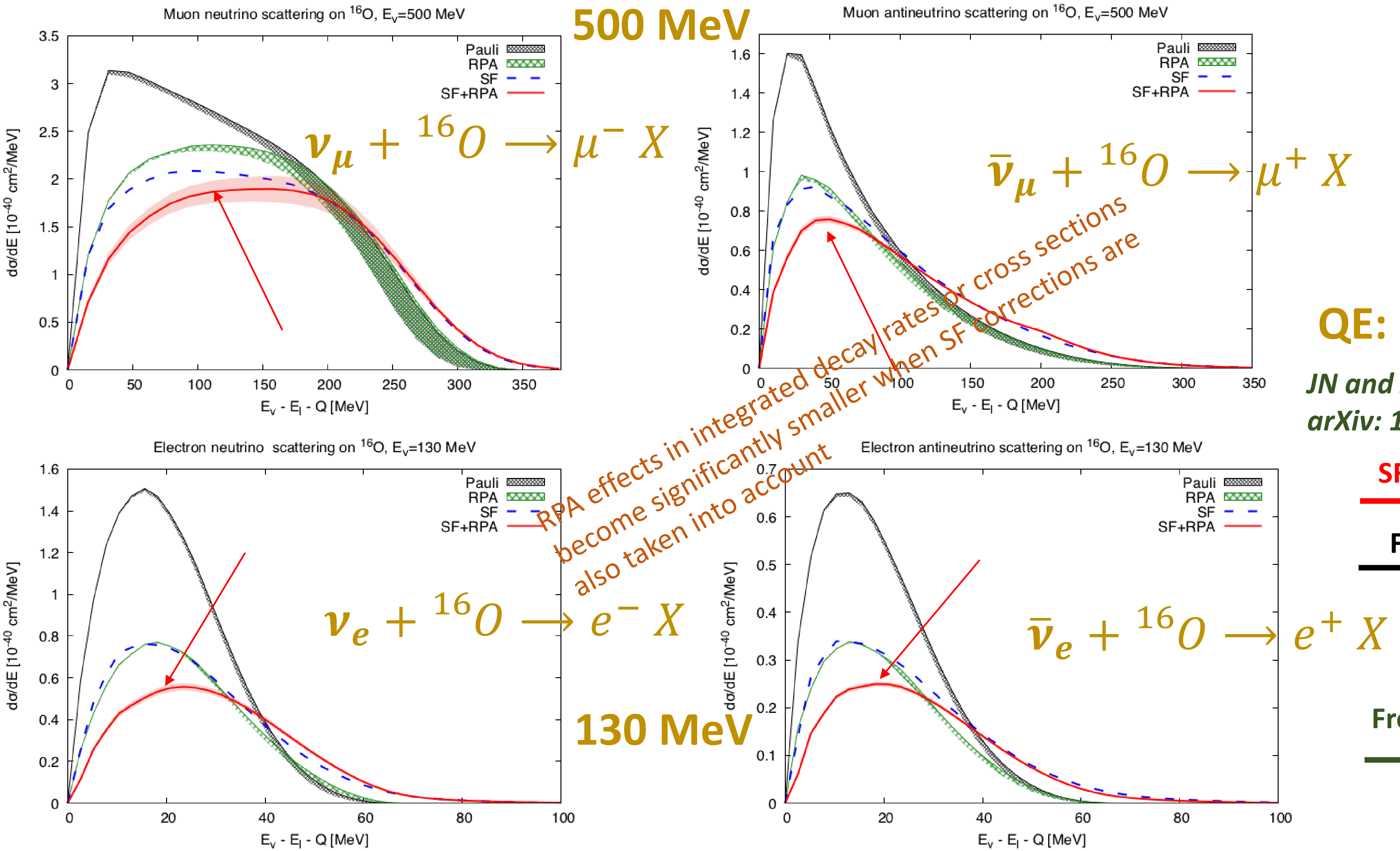


Deplection at low Q^2 values

RPA (long range correlations) the weak probe interacts with the nucleus as a whole,

RPA effects → 0, when $^1/_{\sqrt{Q^2}} \ll$ <u>nuclear radius</u>, since then the probe would see the individual nucleons or even the partons



QE: 1p1h

JN and J.E. Sobzcyk
arXiv: 1701.03628

SF+RPA

Free

Free+RPA

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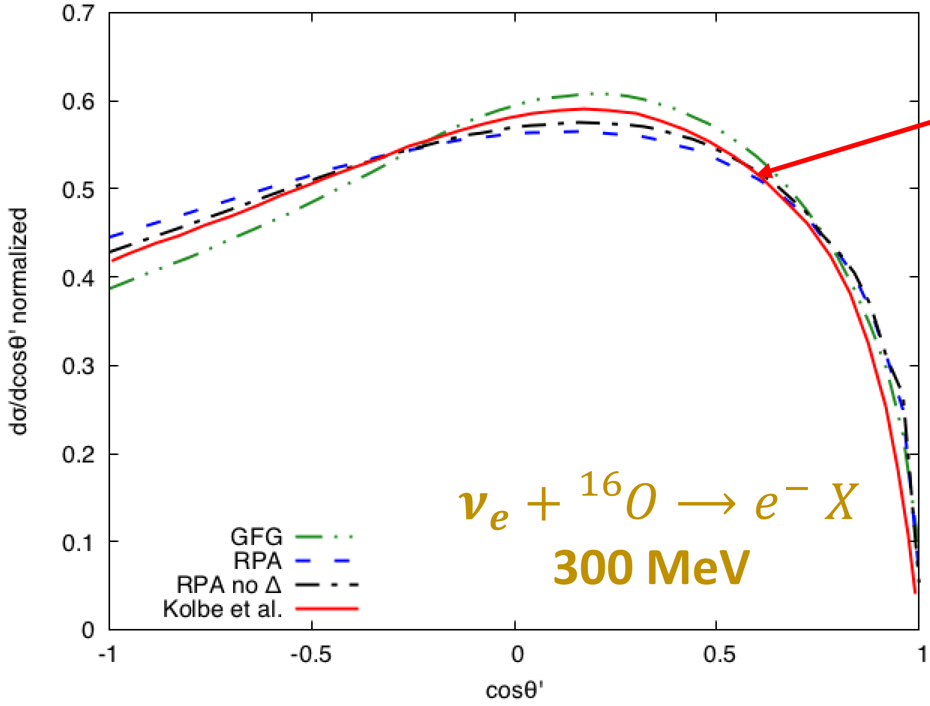
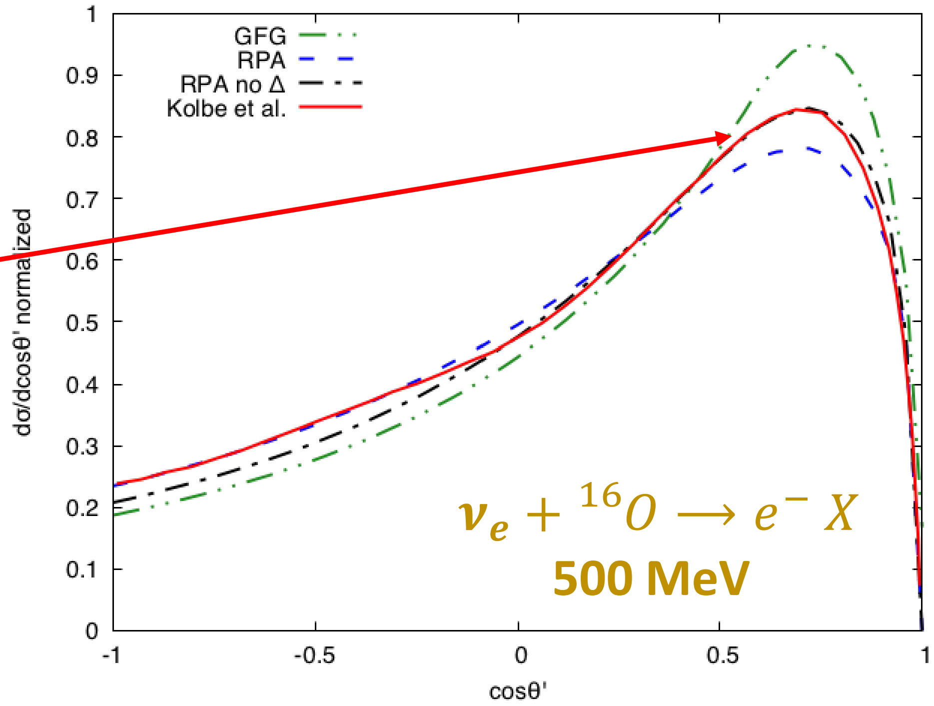
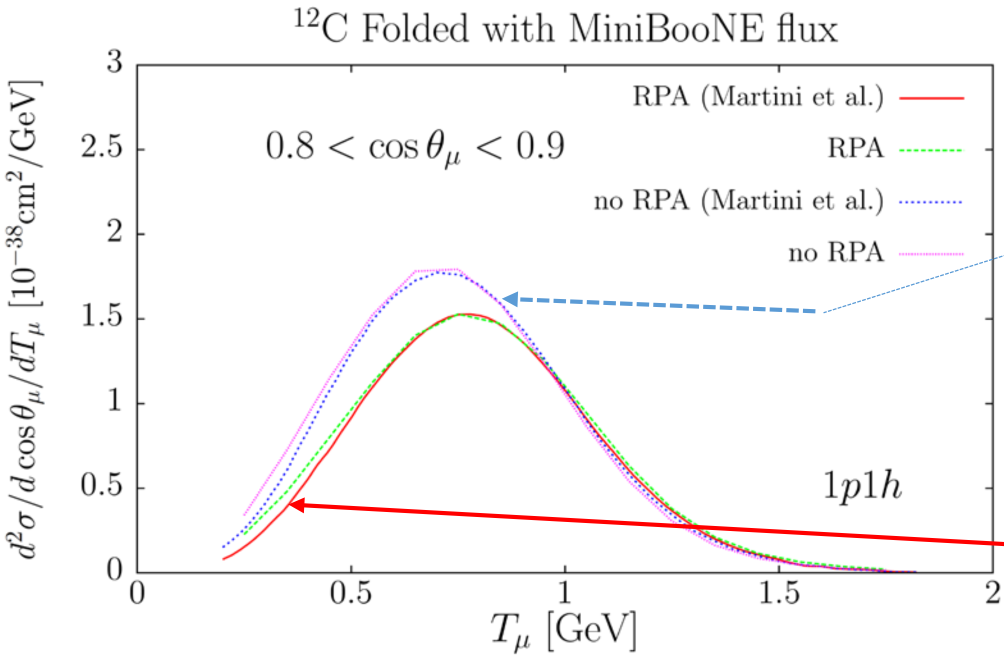


Kolbe, Langanke, Martinez-Pinedo, Vogel, J. Phys. G29, 2569 (2003)

$d\sigma / dcos(\theta')$





M. Martini, M. Ericson, and G. Chanfray, Phys.Rev. C84, 055502 (2011)

reasonable agreement !

JN and J.E. Sobzcyk arXiv: 1701.03628

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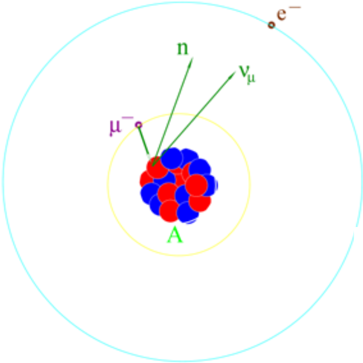


Inclusive Muon Capture: $\Gamma\left[(A_Z-\mu^-)^{1s}_{\rm bound}\right]$

JN and J.E. Sobzcyk
arXiv: 1701.03628

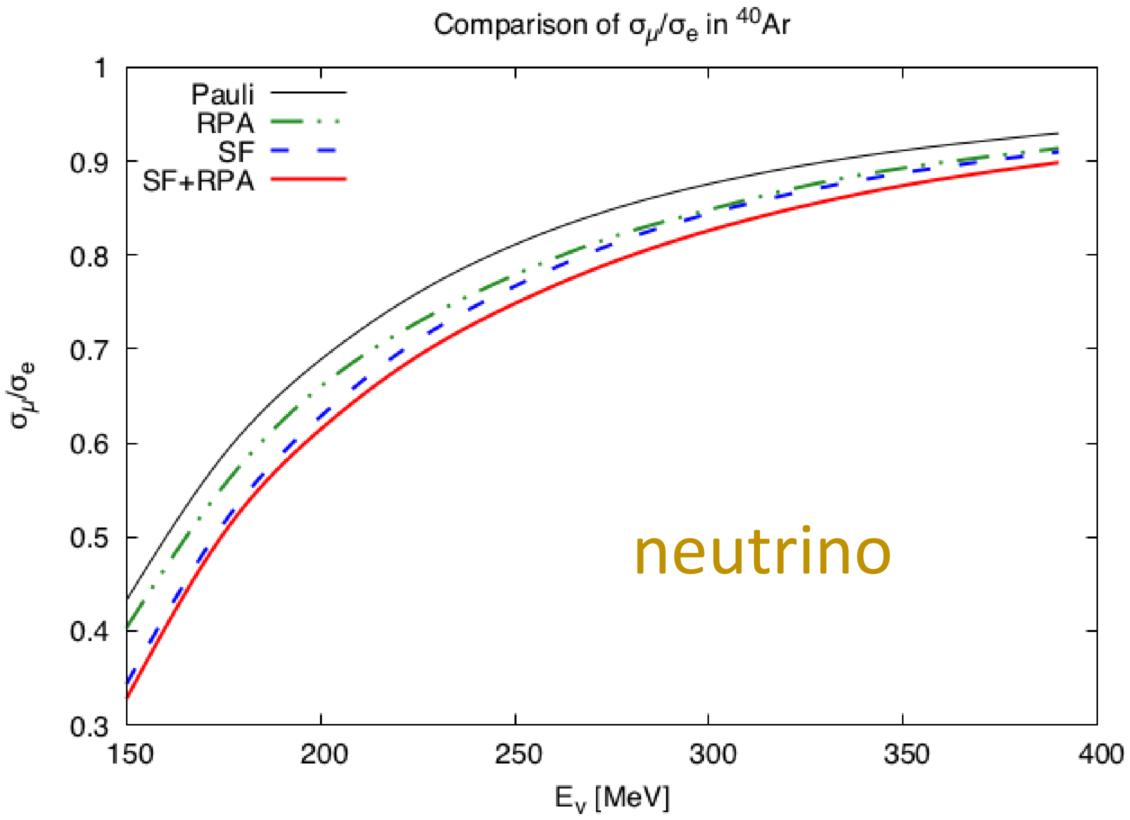
Nucleus	Pauli (10^4 s^{-1})	RPA (10^4 s^{-1})	SF (10^4 s^{-1})	SF+RPA (10^4 s^{-1})	Exp. (10^4 s^{-1})
^{12}C	5.76	3.37 ± 0.16	3.22	3.19 ± 0.06	3.79 ± 0.03
^{16}O	18.7	10.9 ± 0.4	10.6	10.3 ± 0.2	10.24 ± 0.06
^{18}O	13.8	8.2 ± 0.4	7.0	8.7 ± 0.1	8.80 ± 0.15
^{23}Na	64.5	37.0 ± 1.5	30.9	34.3 ± 0.4	37.73 ± 0.14
^{40}Ca	498	272 ± 11	242	242 ± 6	252.5 ± 0.6

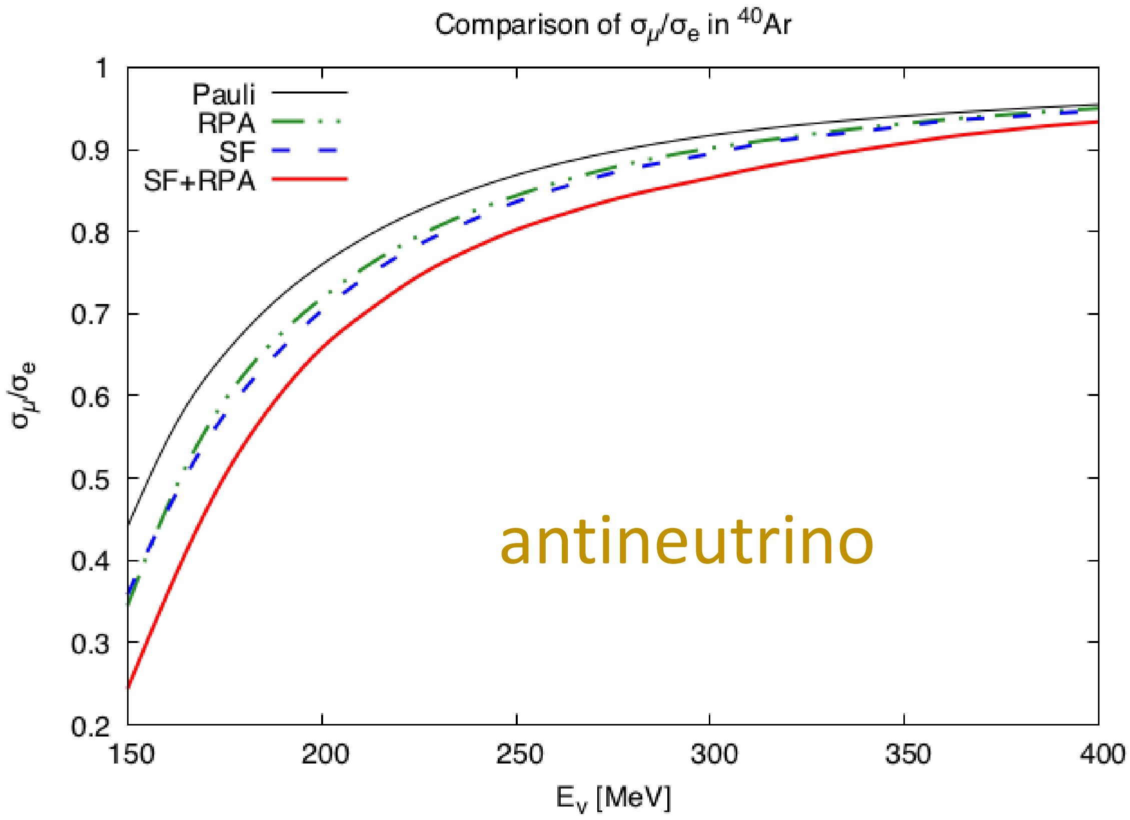
The inclusive ^{12}C$(\nu_\mu, \mu^-)X$ *and* ^{12}C$(\nu_e, e^-)X$ *reactions near threshold*

$10^{-40}\ cm^2$
Flux-averaged cross sections

	Pauli	RPA	SF	SF+RPA	SM [125]	SM [44]	CRPA [45]	Experiment		
								LSND [115]	LSND [116]	LSND [117]
$\bar\sigma(\nu_\mu, \mu^-)$	23.1	13.2 ± 0.7	12.2	9.7 ± 0.3	13.2	15.2	19.2	$8.3 \pm 0.7 \pm 1.6$	$11.2 \pm 0.3 \pm 1.8$	$10.6 \pm 0.3 \pm 1.8$
								KARMEN [120]	LSND [118]	LAMPF [119]
$\bar\sigma(\nu_e, e^-)$	0.200	0.143 ± 0.006	0.086	0.138 ± 0.004	0.12	0.16	0.15	$0.15 \pm 0.01 \pm 0.01$	0.15 ± 0.01	0.141 ± 0.023

[125]: Hayes & Towner, PRC61, 044603;
[44]: Volpe et al., PRC62, 015501; [45]: Kolbe et al., J. Phys. G29, 2569

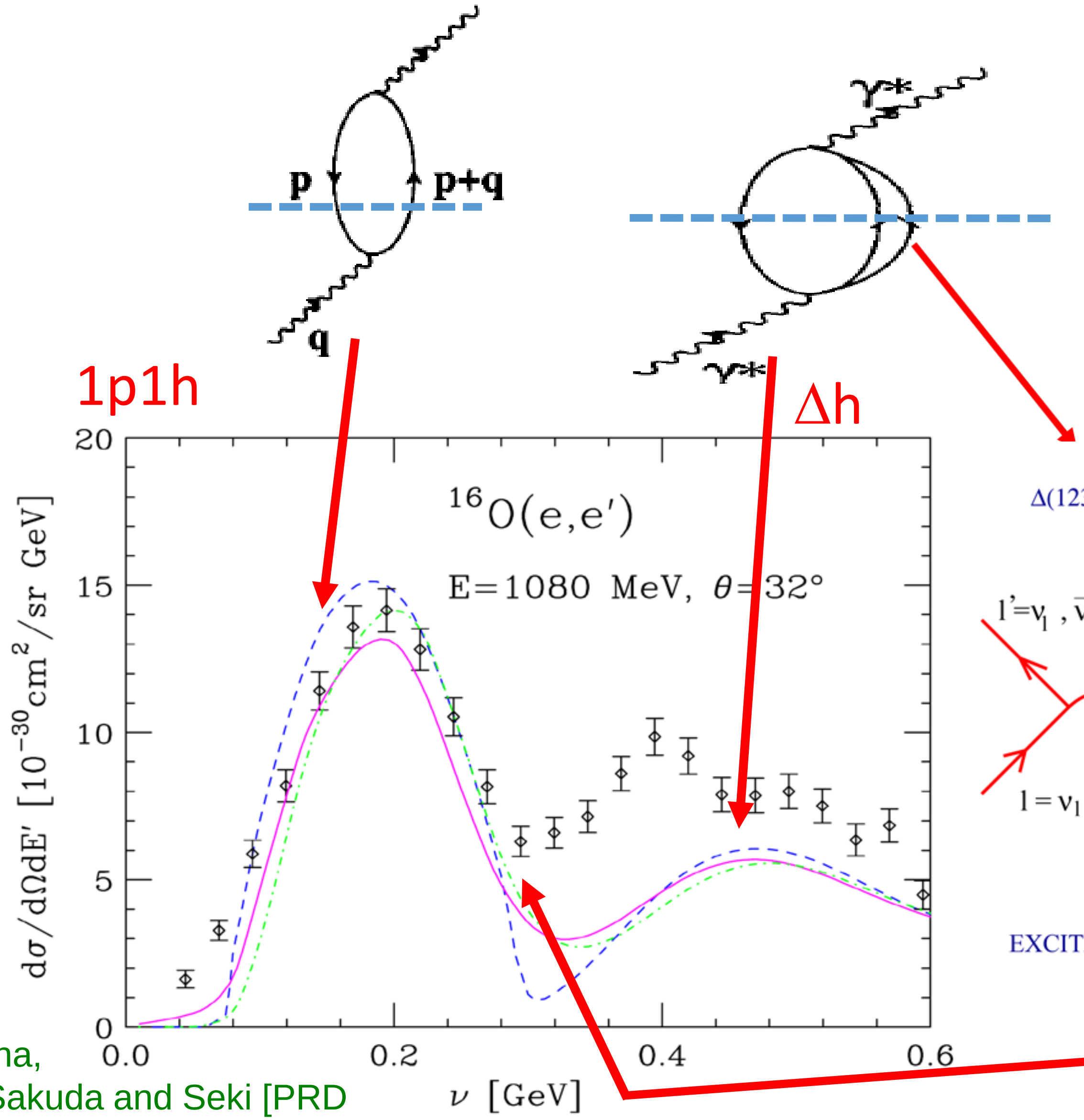


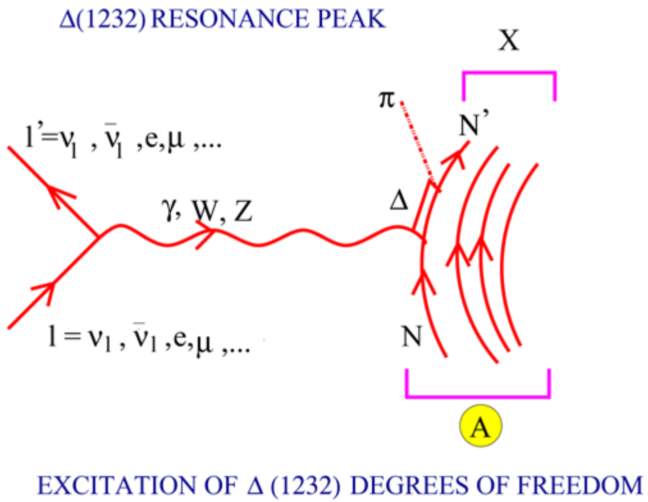


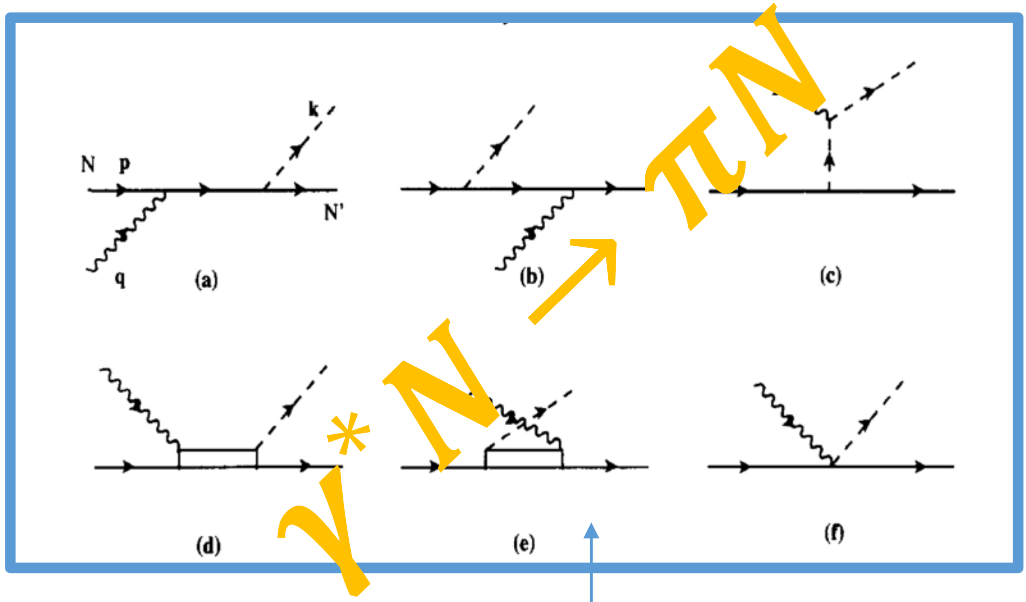
$^{40}Ar \quad {}^{\sigma_\mu}/_{\sigma_e}$

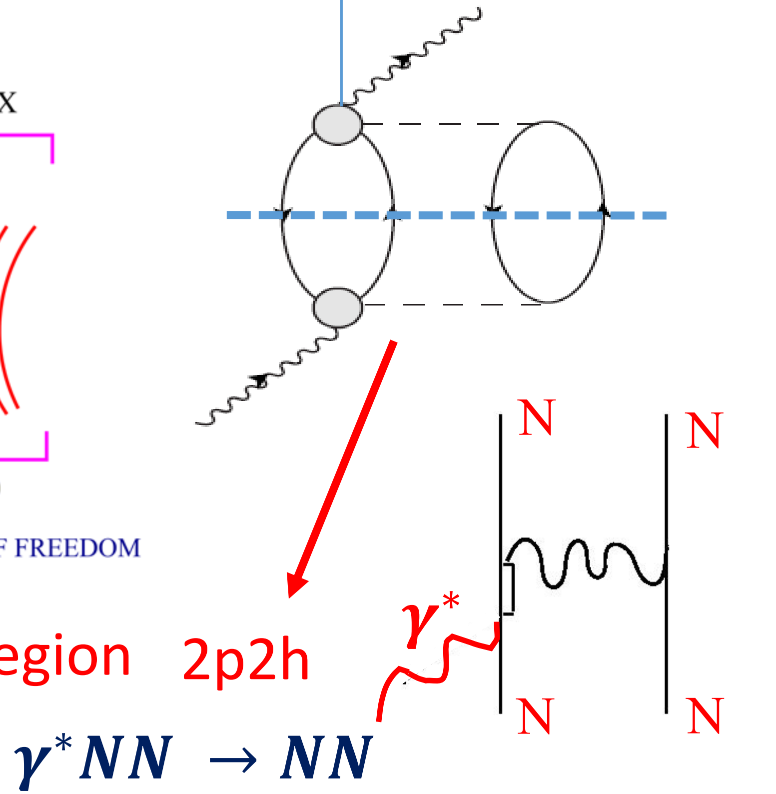
- Important deviations from 1 $(150\ MeV < E_\nu < 400\ MeV)$
- SFs & RPA effects strongly affect the ratio and become essential to perform a correct analysis of appearance neutrino oscillation events in LBE.

2p2h: Inclusive electron-nucleus scattering





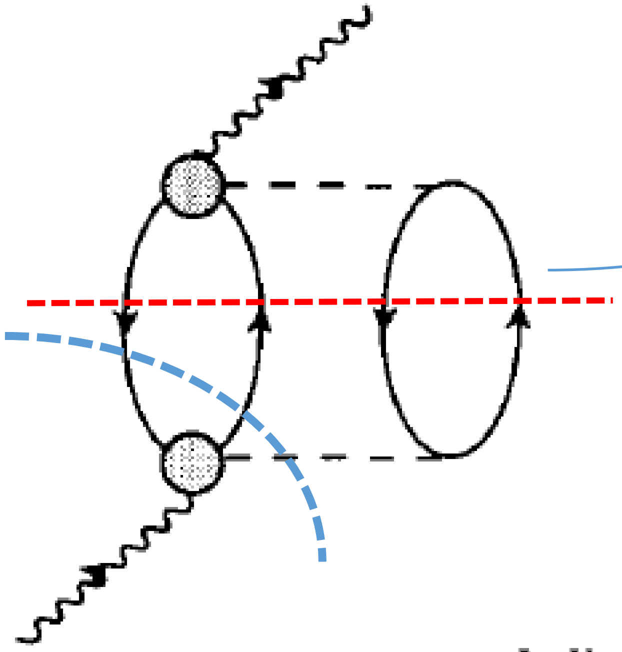


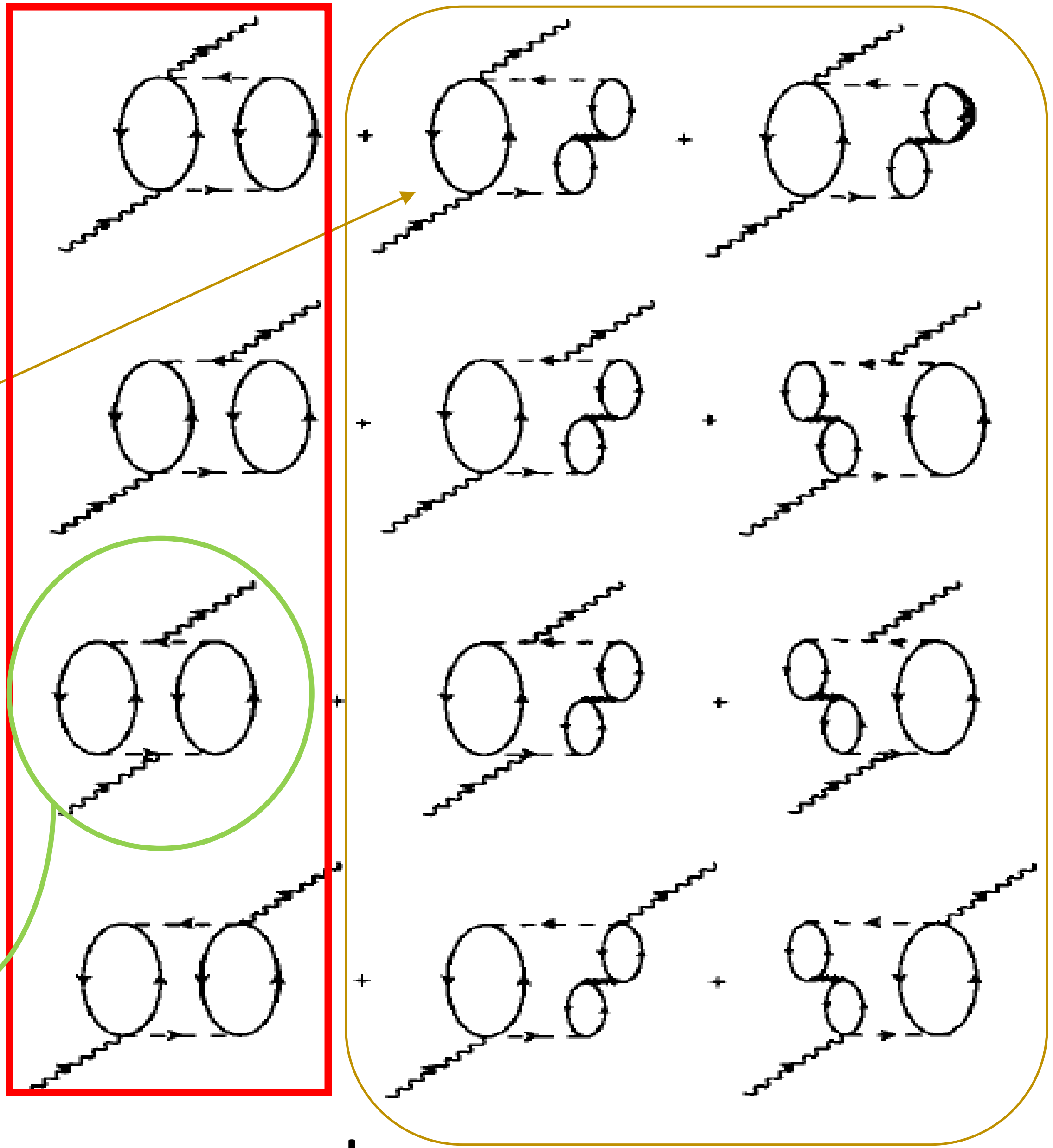


Benhar, Farina, Nakamura, Sakuda and Seki [PRD 72 (2005) 053005]

2p2h (two body absorption) contributions

[A. Gil et al.,NPA 627 (1997) 543; NPA 627 (1997) 599]





RPA corrections to 2p2h contributions

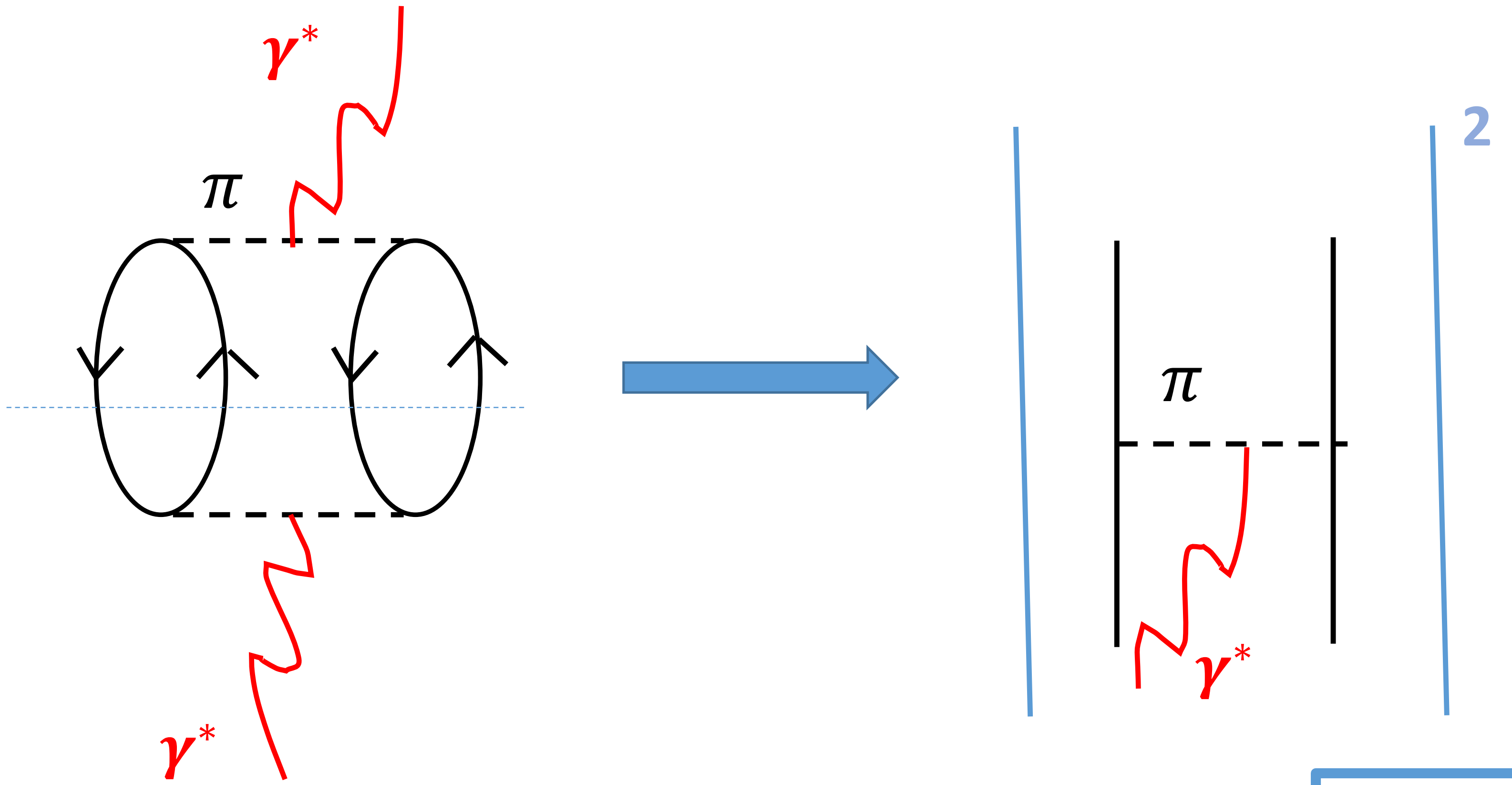
$$\mathrm{Im}\,U_N \to a\frac{\mathrm{Im}\,U_N}{|1-U_\lambda(q)V_l|^2}+b\frac{\mathrm{Im}\,U_N}{|1-U_\lambda V_t|^2}$$

+.....

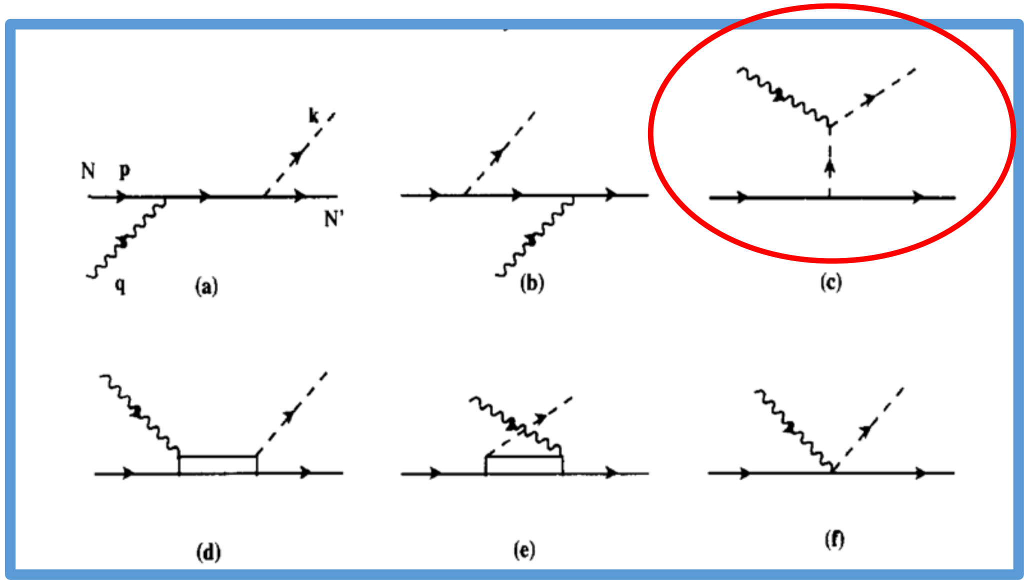
Two cuts: $\gamma^* NN \to NN$

$\gamma^* N \to N\pi\ (dressed)$

Juan Nieves, IFIC (CSIC & UV)

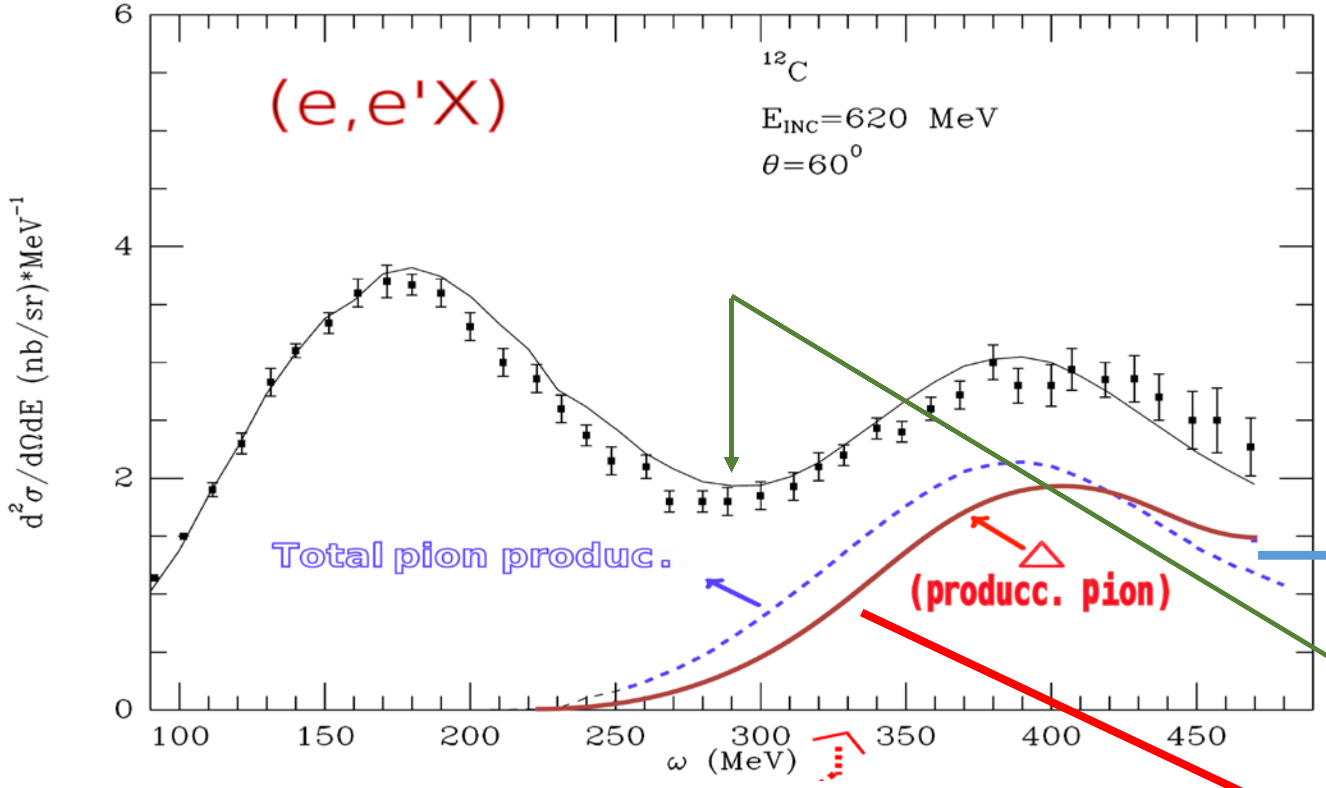


$\gamma^* N \rightarrow \pi N$

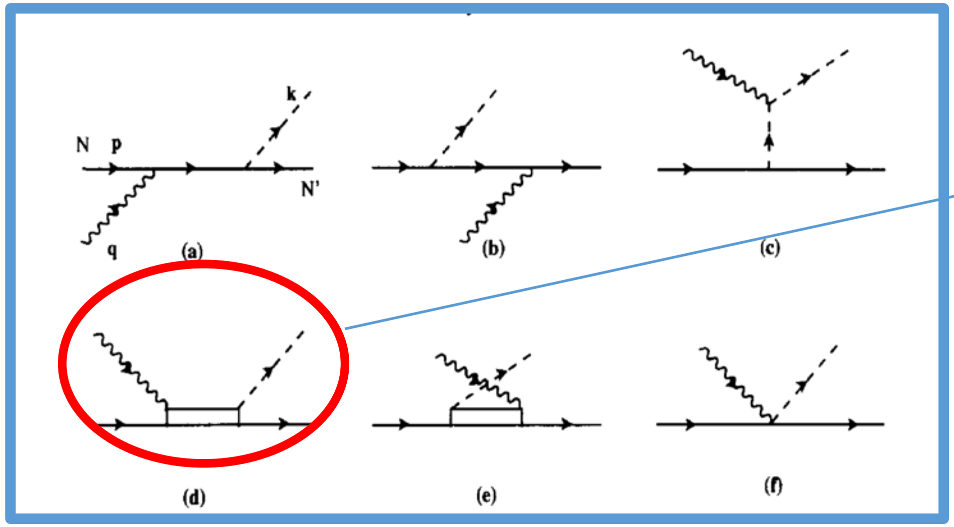


Meson Exchange Contribution

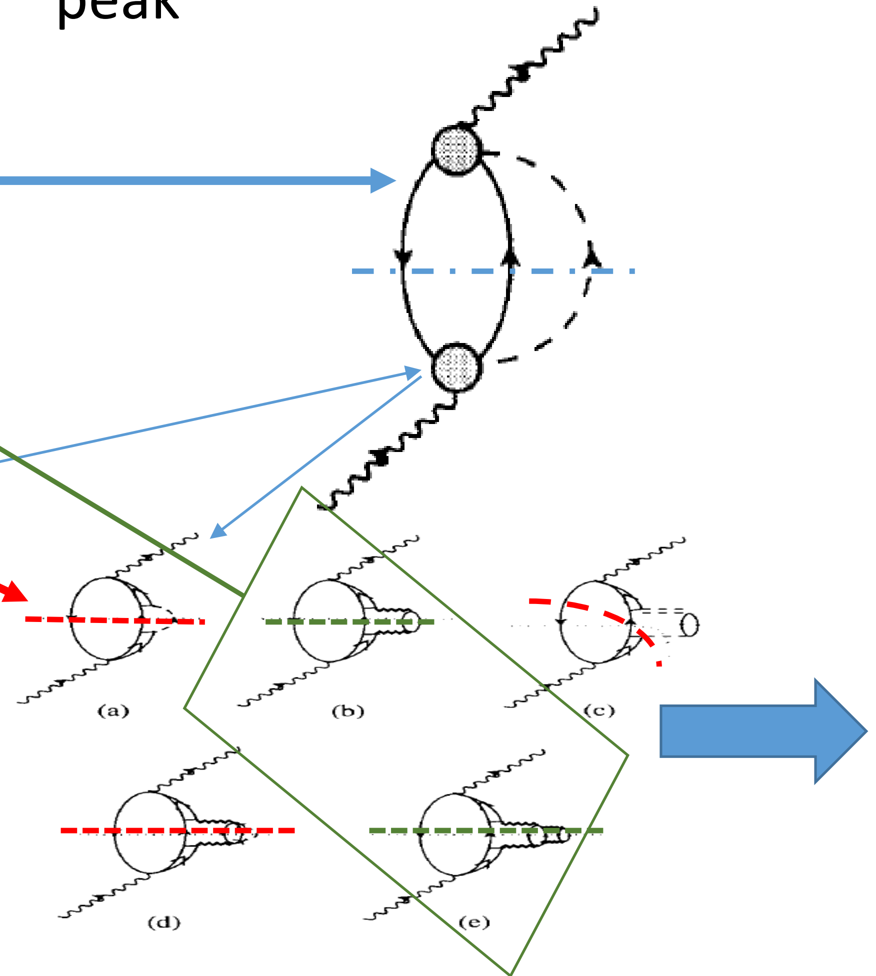
Juan Nieves, IFIC (CSIC & UV)



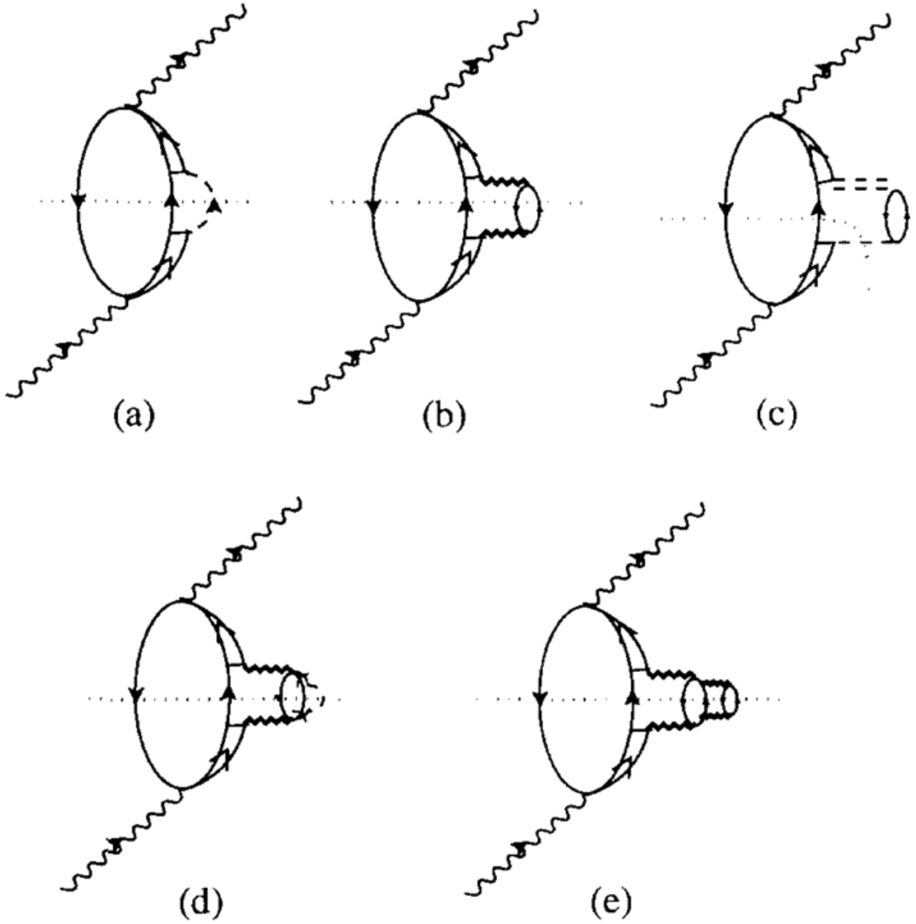
- Δ dominant component of the pion production contribution
- Missing strength both at the dip region and the Δ peak

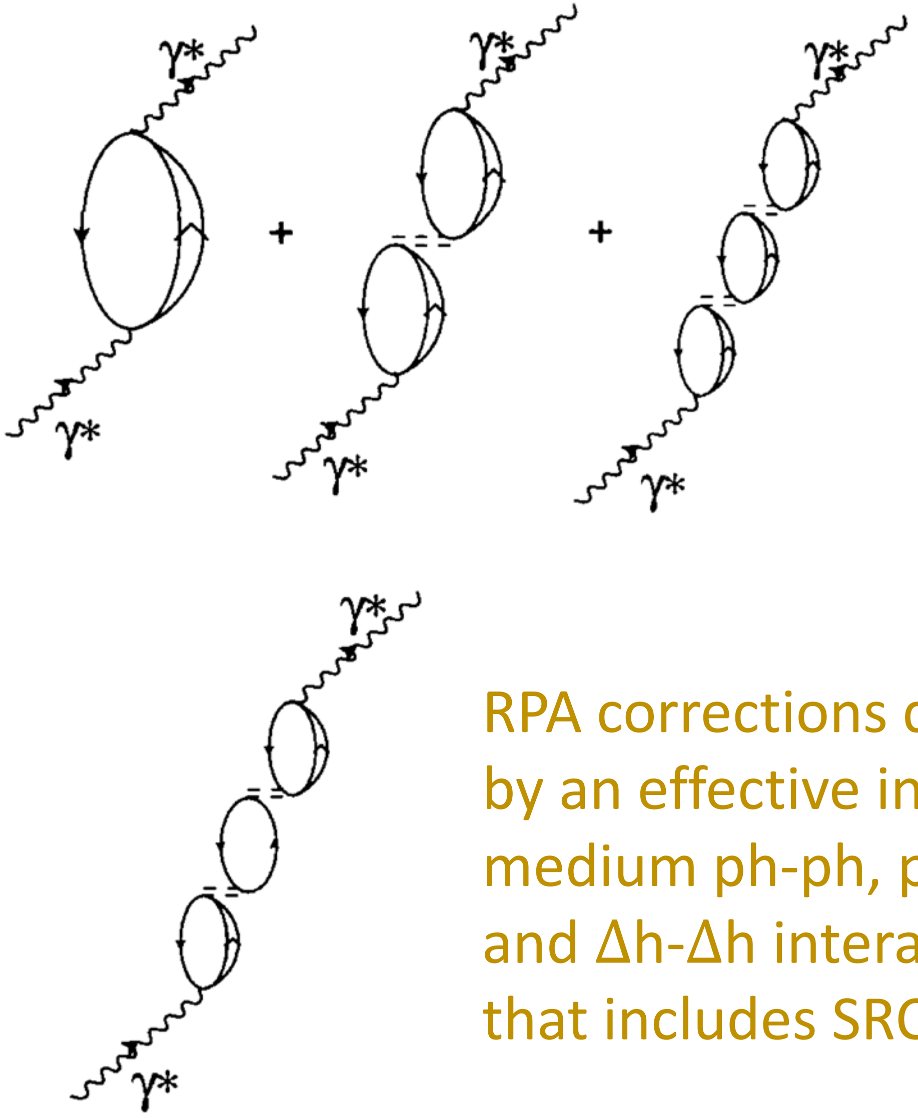


one of the terms generates the Δ contribution



Juan Nieves, IFIC (CSIC & UV)

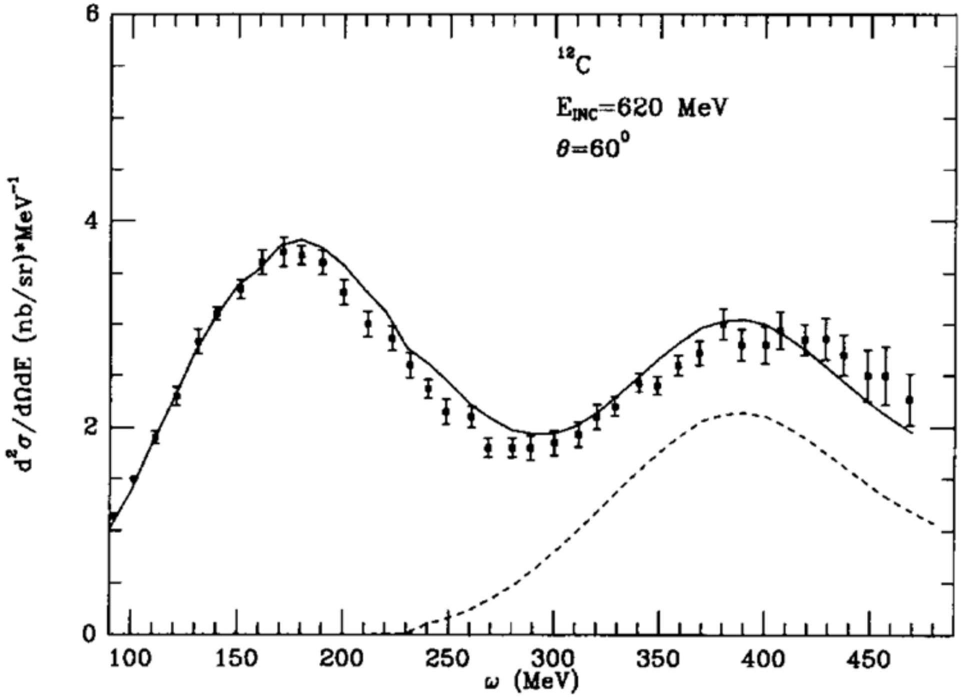




RPA corrections driven by an effective in medium ph-ph, ph-Δh and Δh-Δh interaction that includes SRC

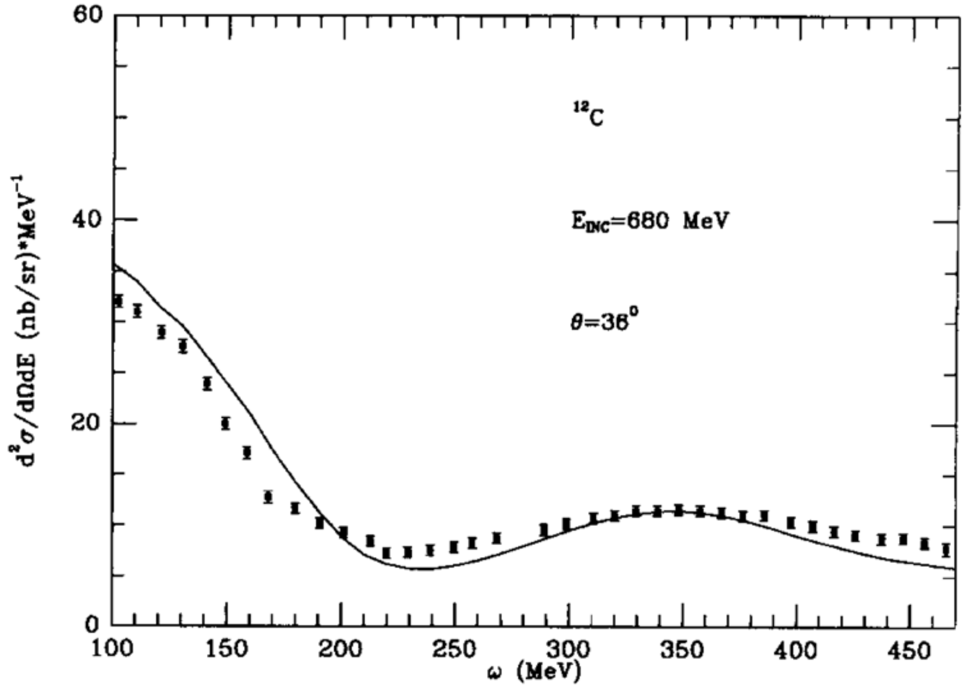
pionless Δ decay modes:
Oset+Salcedo, NPA 468 (1987) 631

Juan Nieves, IFIC (CSIC & UV)

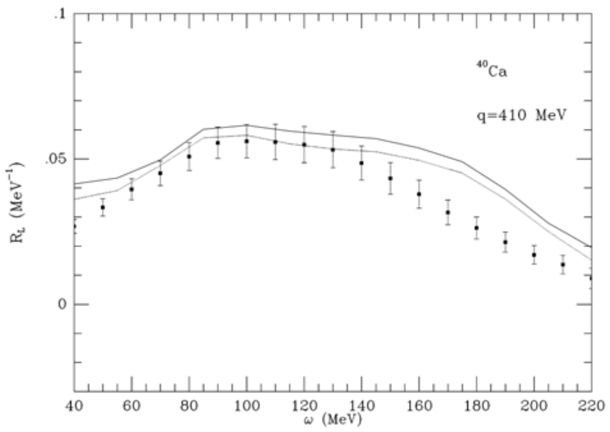


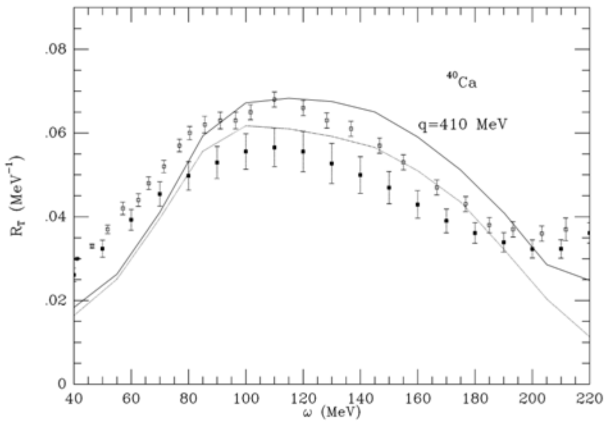
Gil, Nieves, Oset,
NPA 627 (1997) 543

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

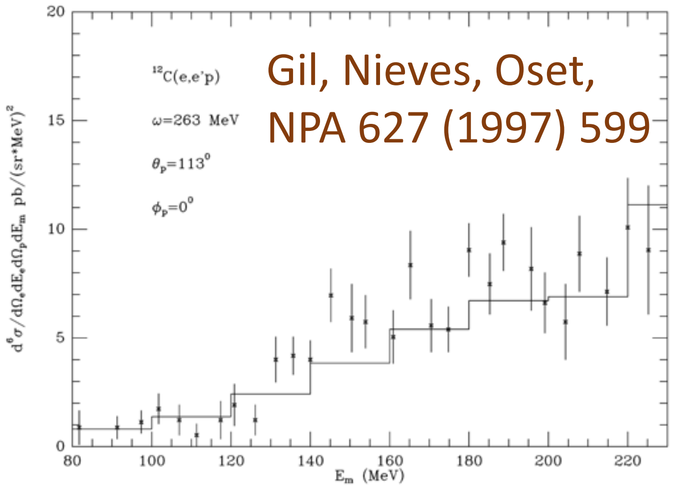


and by means of a Monte Carlo simulation we obtain cross sections for the processes $(e, e'N)$, $(e, e'NN)$, $(e, e'\pi)$, ...





R_L and R_T QE response functions for $e + {}^{40}\mathrm{Ca} \to e' + X$



Gil, Nieves, Oset,
NPA 627 (1997) 599

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

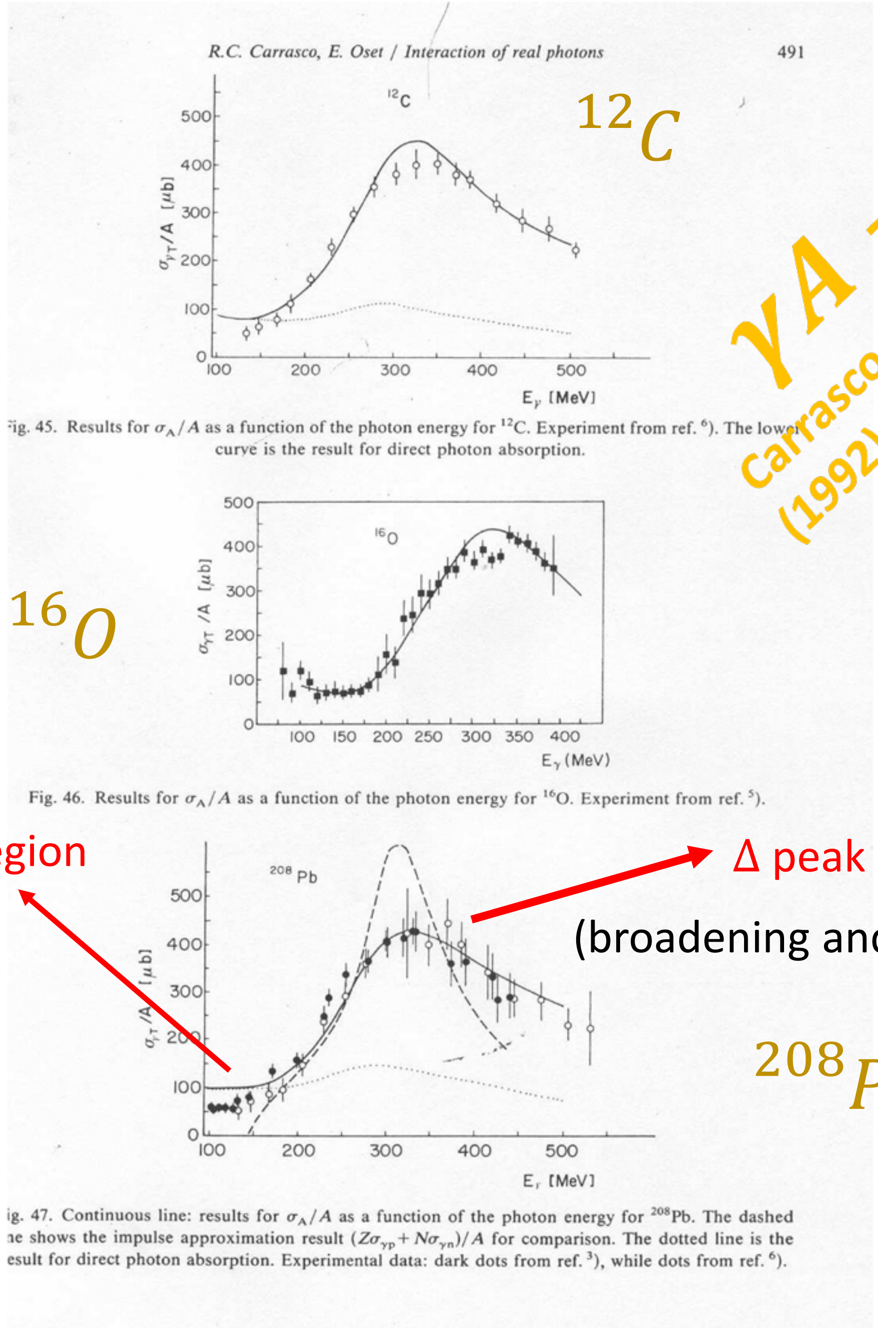


Fig. 45. Results for σ_A/A as a function of the photon energy for ^{12}C. Experiment from ref. [6]). The lower curve is the result for direct photon absorption.

Fig. 46. Results for σ_A/A as a function of the photon energy for ^{16}O. Experiment from ref. [5]).

Fig. 47. Continuous line: results for σ_A/A as a function of the photon energy for ^{208}Pb. The dashed line shows the impulse approximation result $(Z\sigma_{\gamma p} + N\sigma_{\gamma n})/A$ for comparison. The dotted line is the result for direct photon absorption. Experimental data: dark dots from ref. [3]), while dots from ref. [6]).

^{12}C

^{16}O

^{208}Pb

dip region

Δ peak

(broadening and shift)

$$\gamma A \to X$$

Carrasco+Oset, NPA 536 (1992) 445

$$\frac{d^2\sigma}{d\Omega dp}$$

Carrasco+Oset+Salcedo, NPA 541 (1992) 583

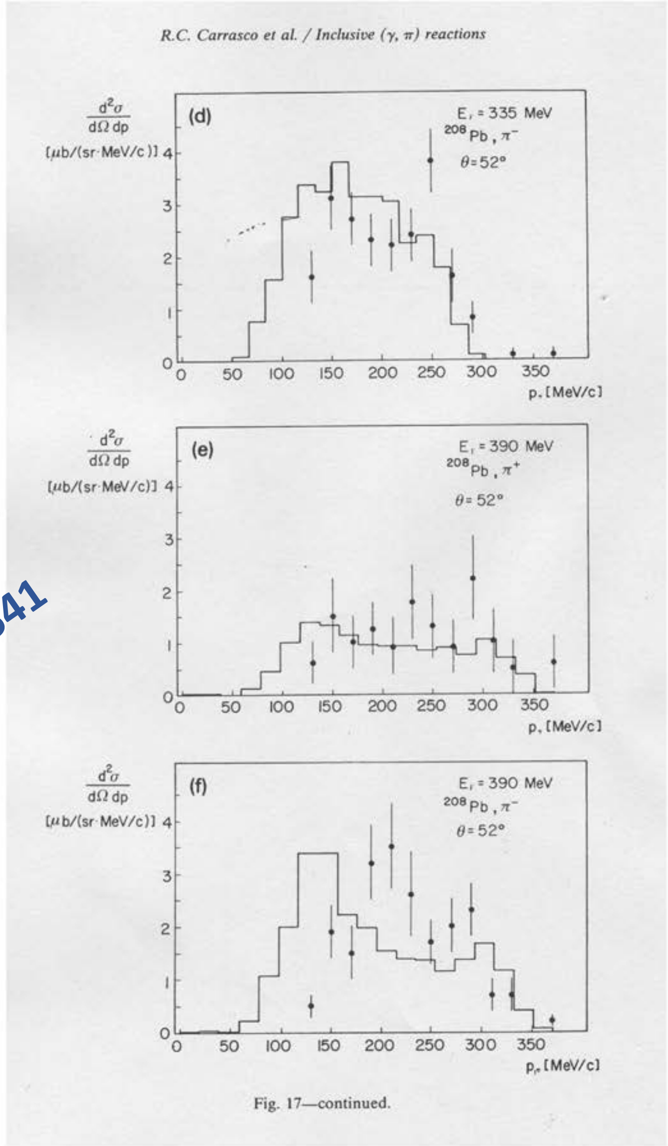
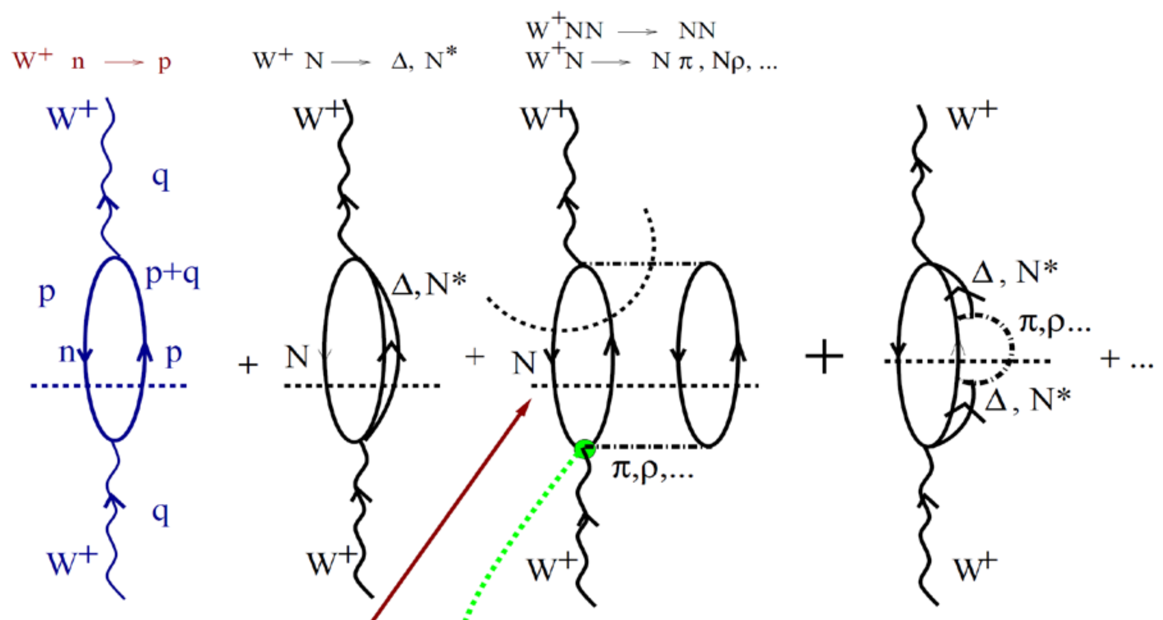
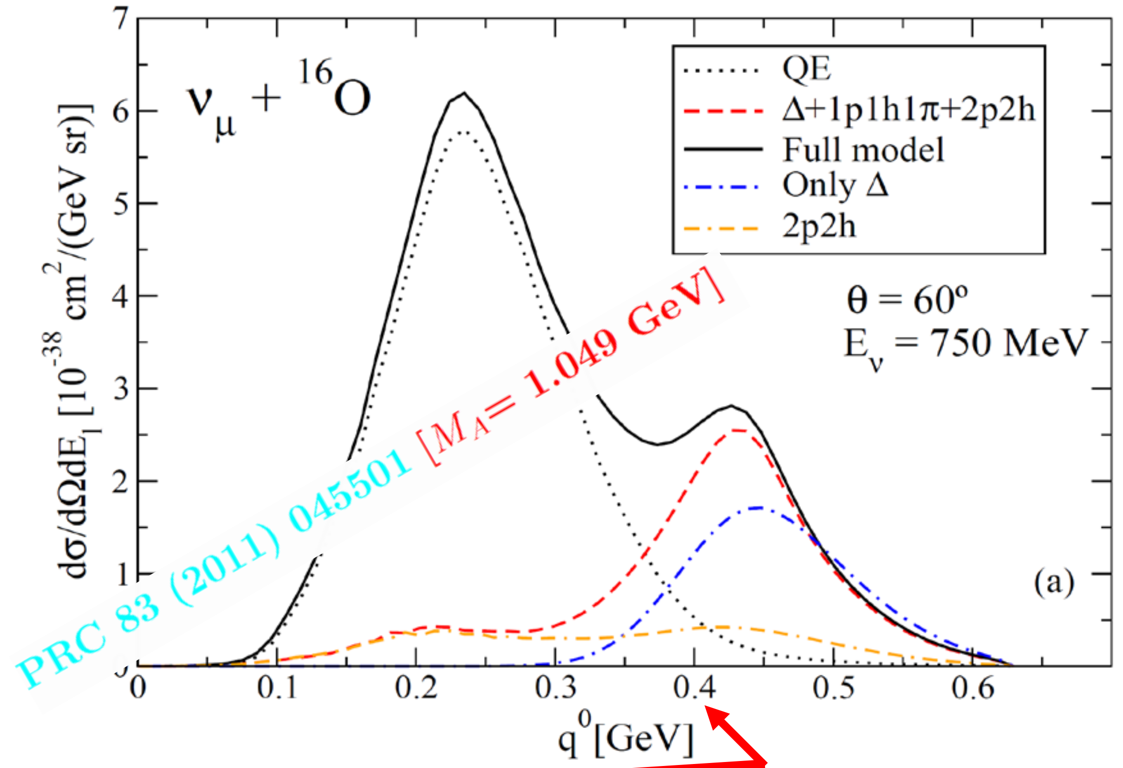


Fig. 17—continued.

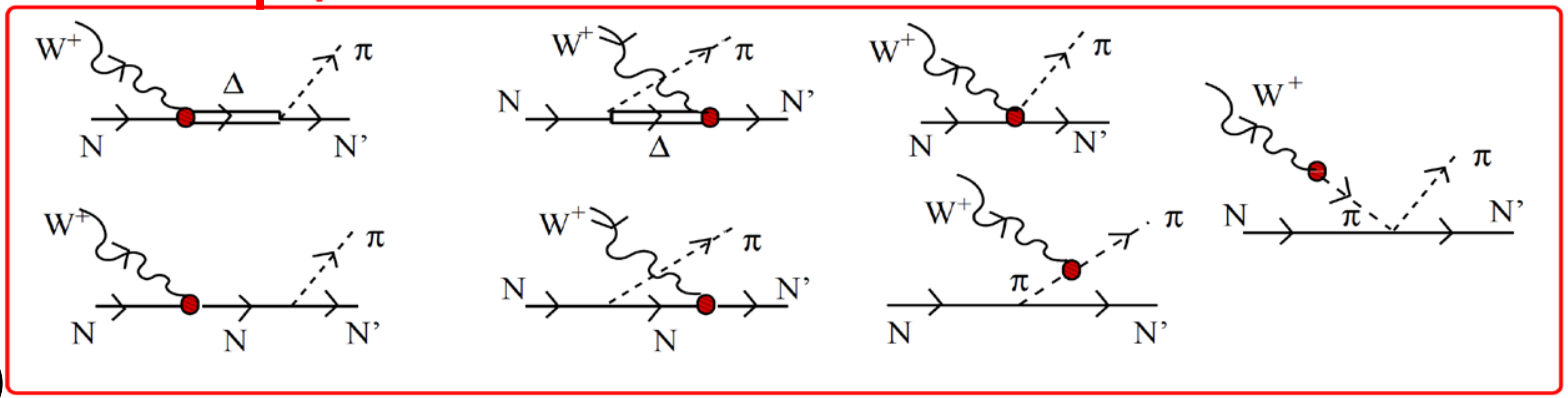
$$\gamma + {}^{208}\mathrm{Pb} \to X + \pi^\pm$$

$\nu + A \rightarrow l + X$





MEC ⟶ QE like !



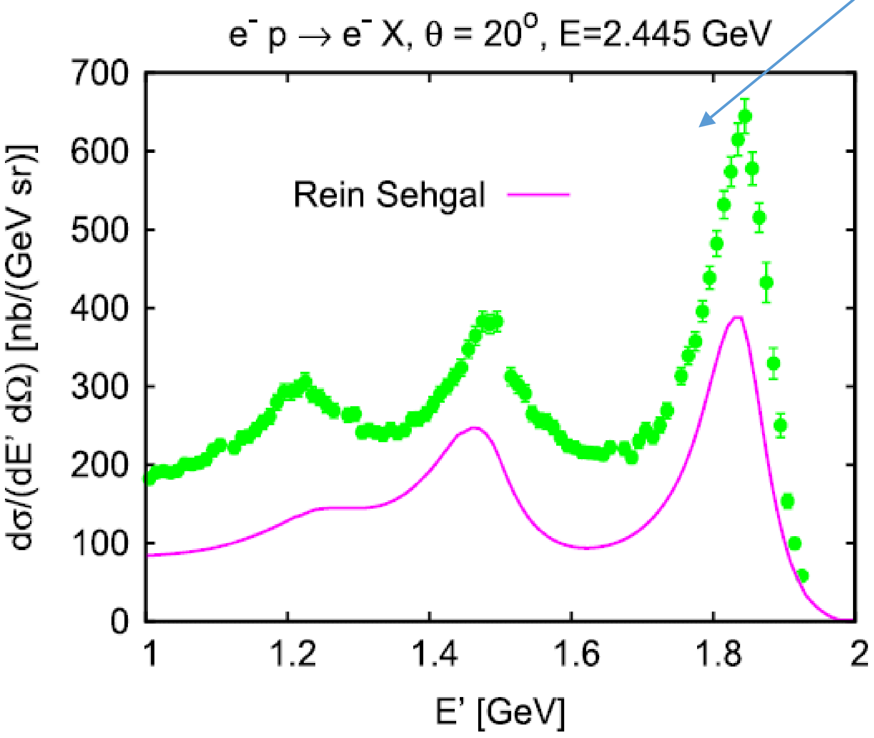
PRD D76 (2007) 033005
PRD D81 (2010) 085046

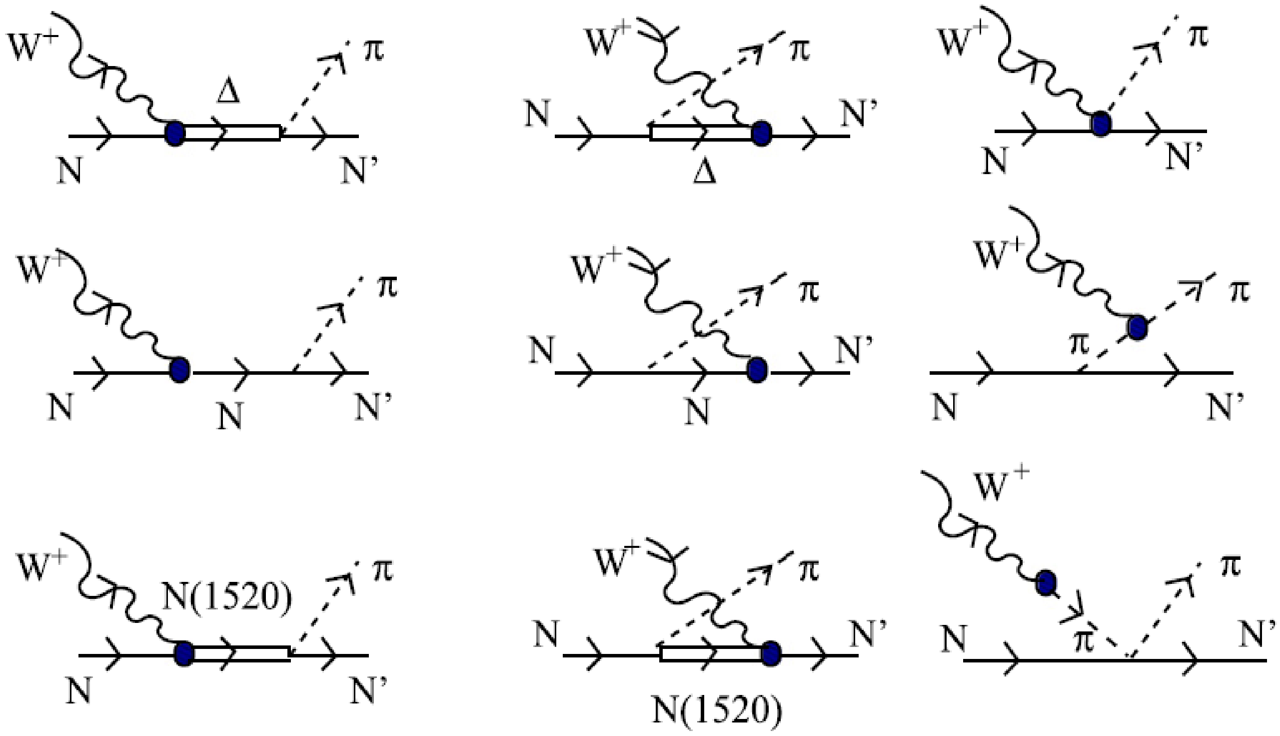
+ PRD 93 (2016) 014016 (Watson's theorem)
+ PRD 95 (2017) 053007 (local terms in Δ propagator)

Juan Nieves, IFIC (CSIC & UV)

Neutrino Resonance Production

Deficiencies of the Rein Sehgal model ! ⇒ **Improved models**





Electron data ⇒ Resonance vector form factors !
PCAC ⇒ Resonance axial form factors !
Background: chiral symmetry (when possible !)

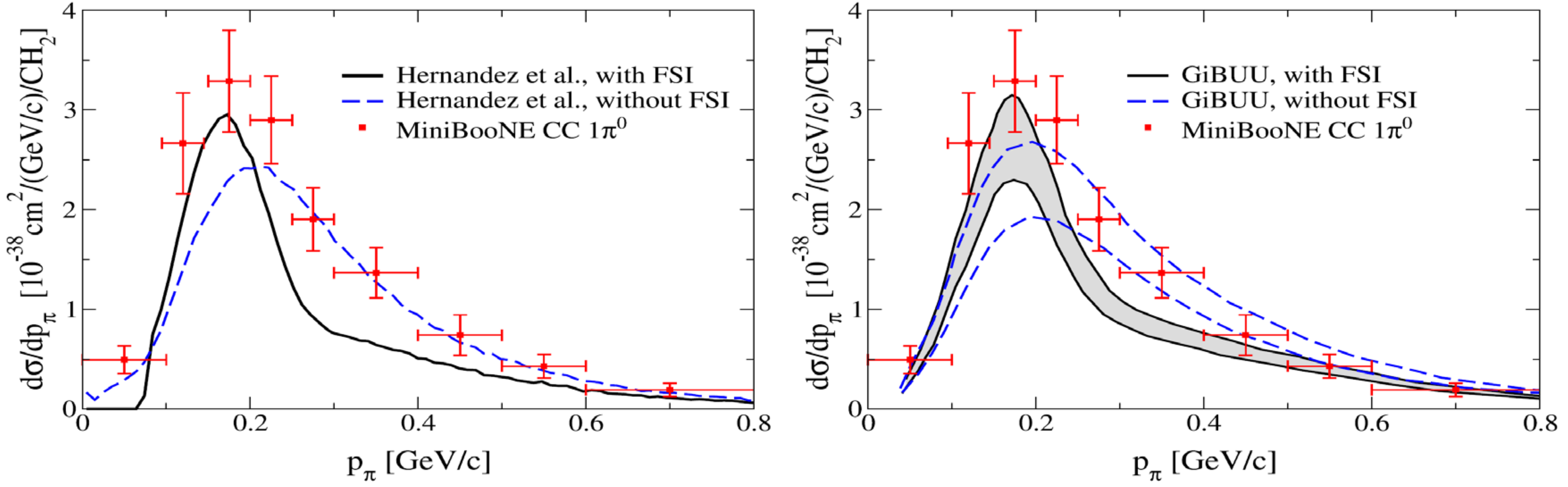
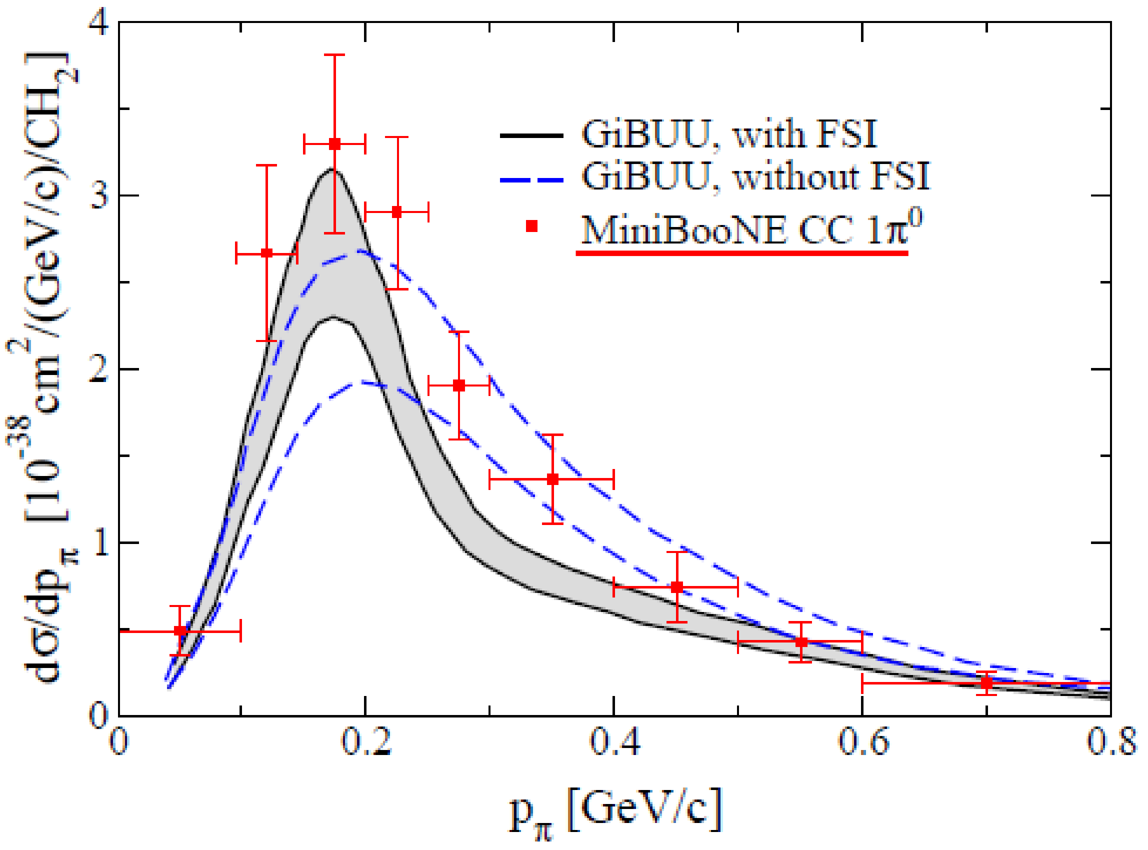


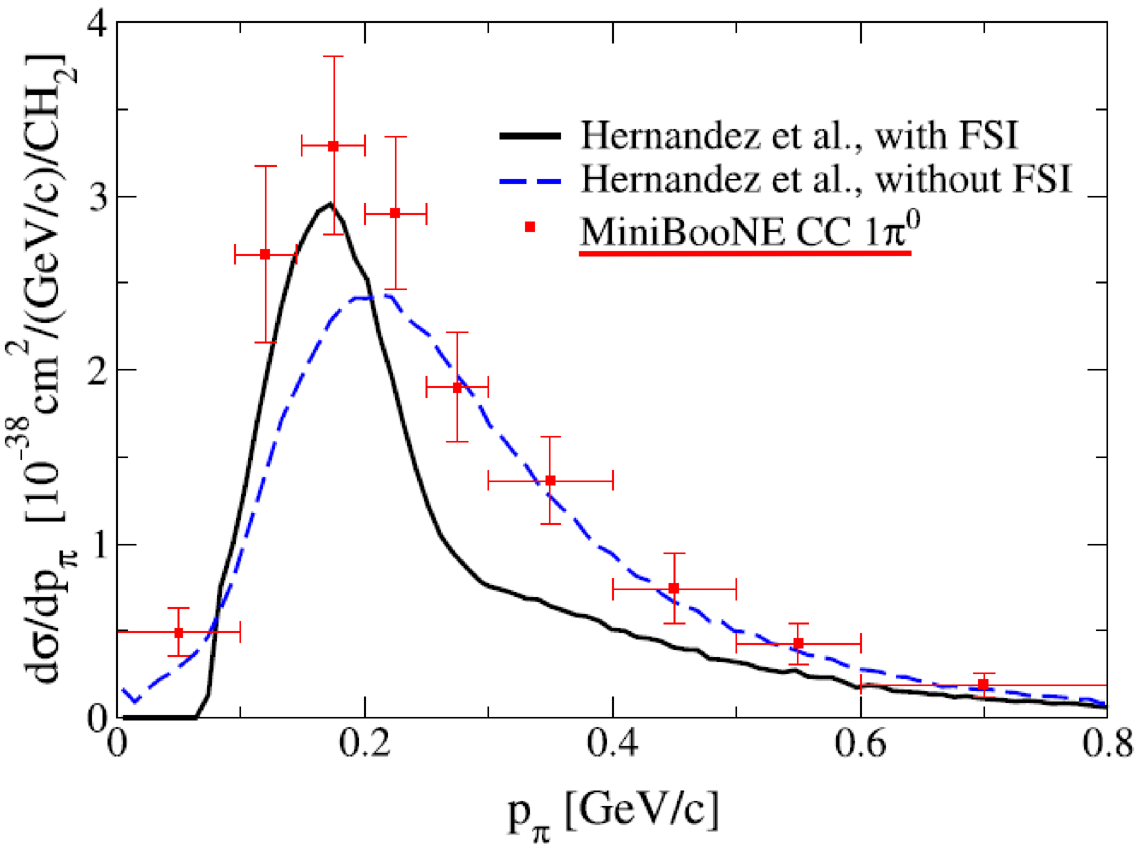
Figure 15. MiniBooNE flux-folded differential $d\sigma/dp_\pi$ cross section for $CC1\pi^0$ production by ν_μ in mineral oil. Data are from [27]. Left: predictions from the cascade approach of [184]. The solid curve corresponds to the full model and the dashed one stands for the results obtained neglecting FSI effects. Right: predictions from the GiBUU transport model of [207]. The dashed curves give the results before FSI, the solid curves those with all FSI effects included. Two different form factors $C_5^A(q^2)$, tuned to the ANL and BNL data-sets have been employed and give rise to the systematic uncertainty bands displayed in the figure.

New J.Phys. 16 (2014) 075015

There exist some discrepancies between theoretical predictions and data!

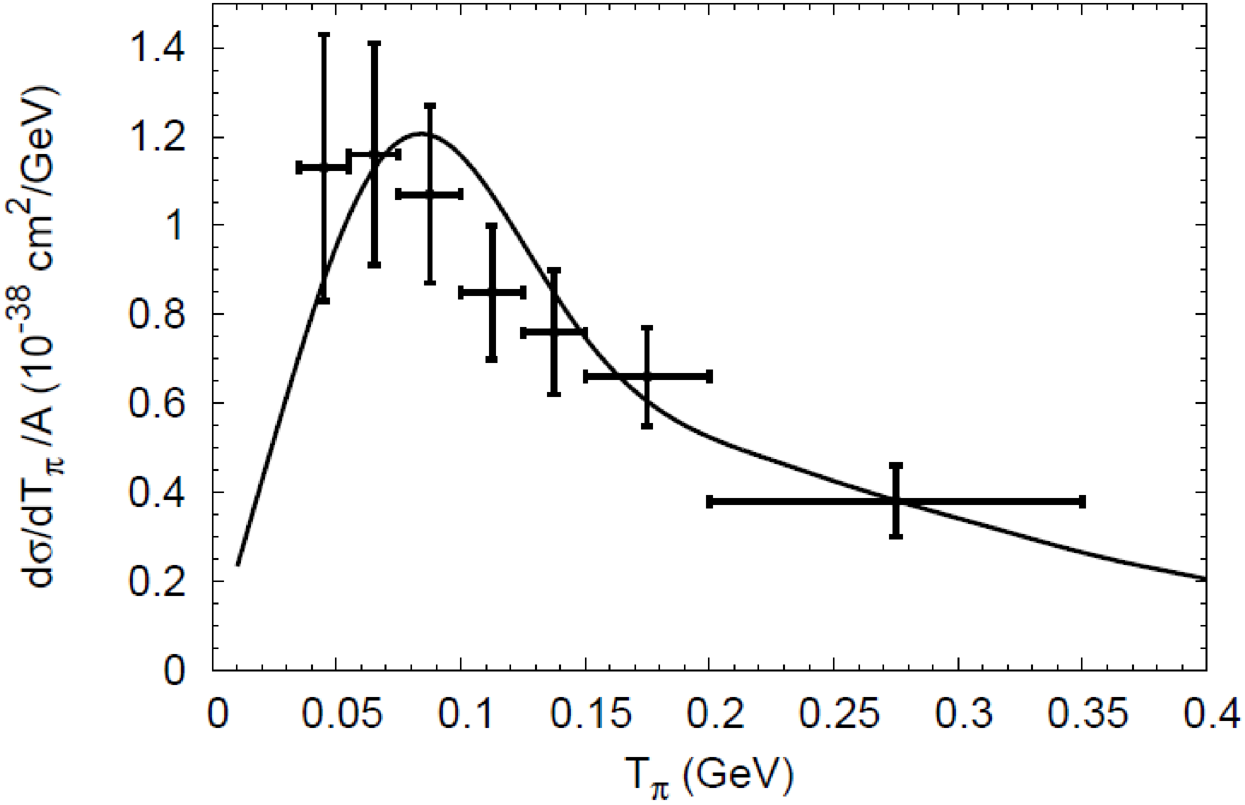


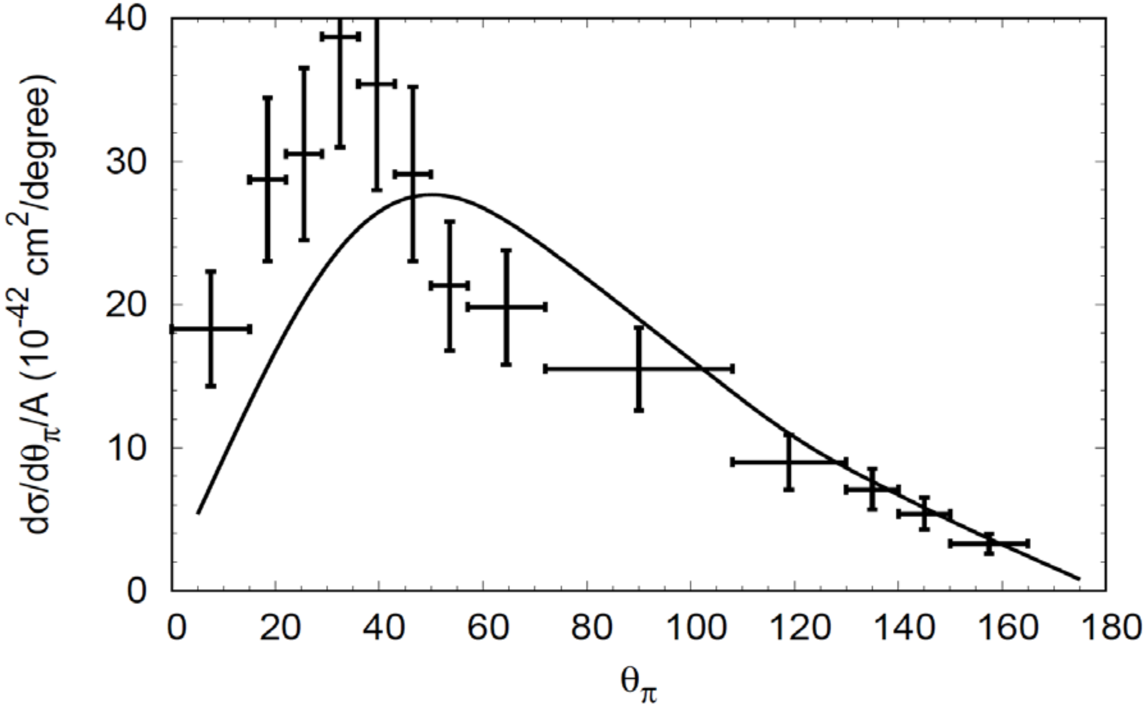
O. Lalakulich, U. Mosel, PRC 87 (2013)



E. Hernandez, J. Nieves M.J. Vicente-Vacas, PRD 87 (2013)

Problems to describe pion production in nuclei (FSI, coherent production …) → MINERνA and T2K will shed light ….

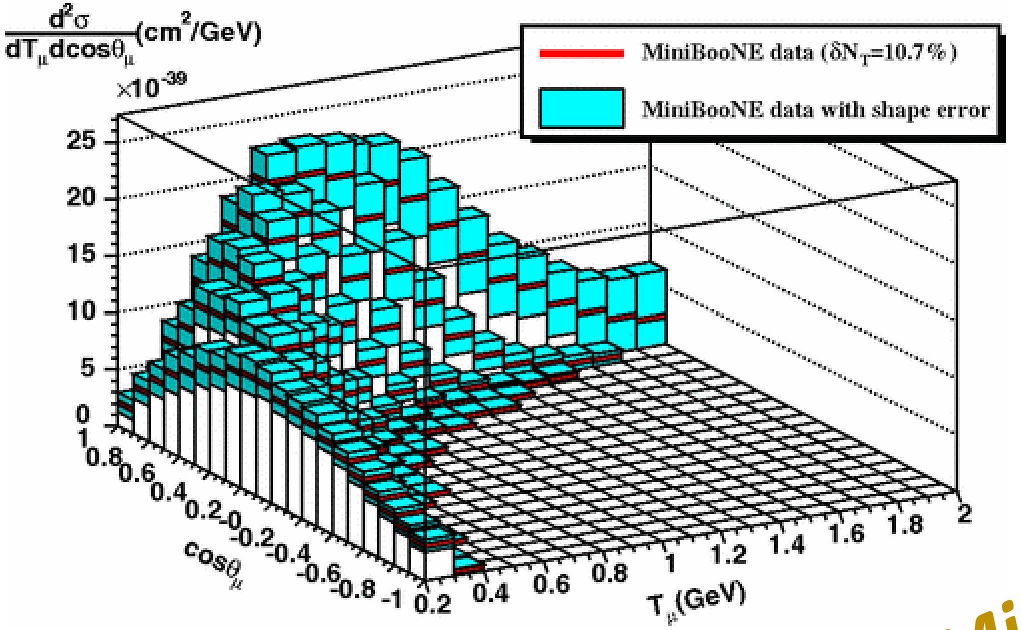


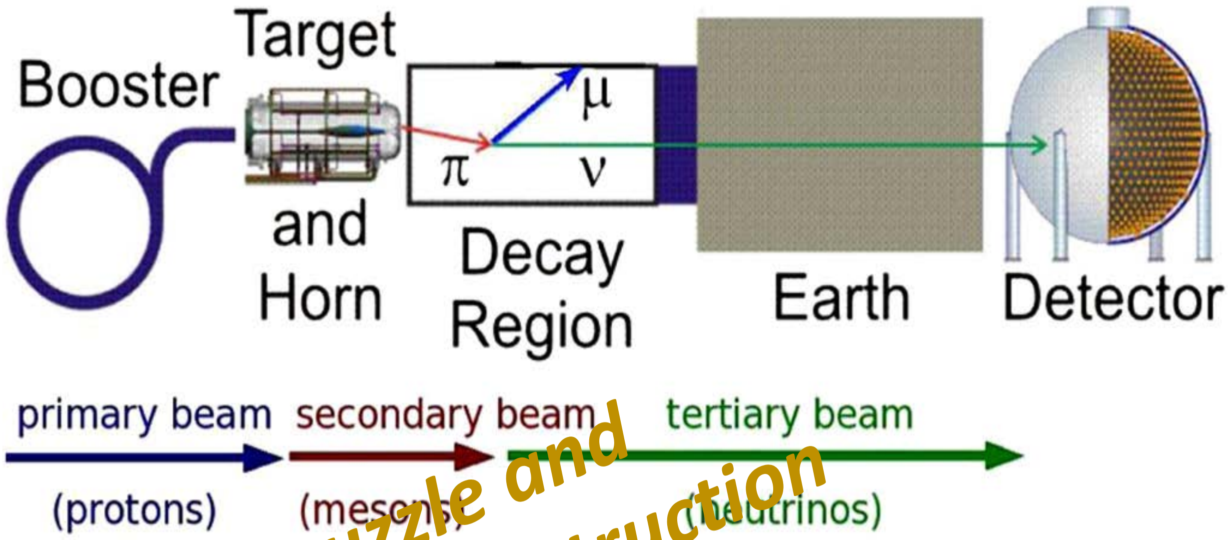


U. Mosel and K. Gallmeister (GiBUU), 1702.04932: Comparison to MINERνA data with $W_{\pi N} < 1.4$ GeV

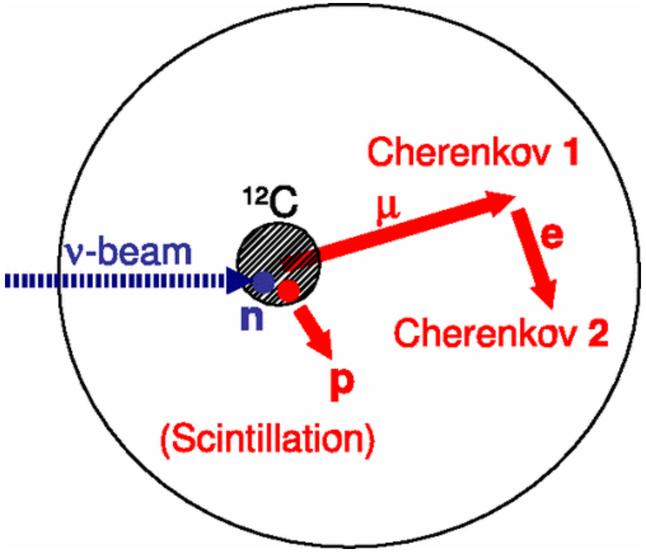
MINERνA and MiniBooNE data compatible?

MiniBooNE CCQE (PRD 81, 092005)





MiniBooNE M_A puzzle and Neutrino energy reconstruction



$$1:\ \nu_\mu + n \rightarrow \mu^- + p$$
$$2:\ \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu.$$

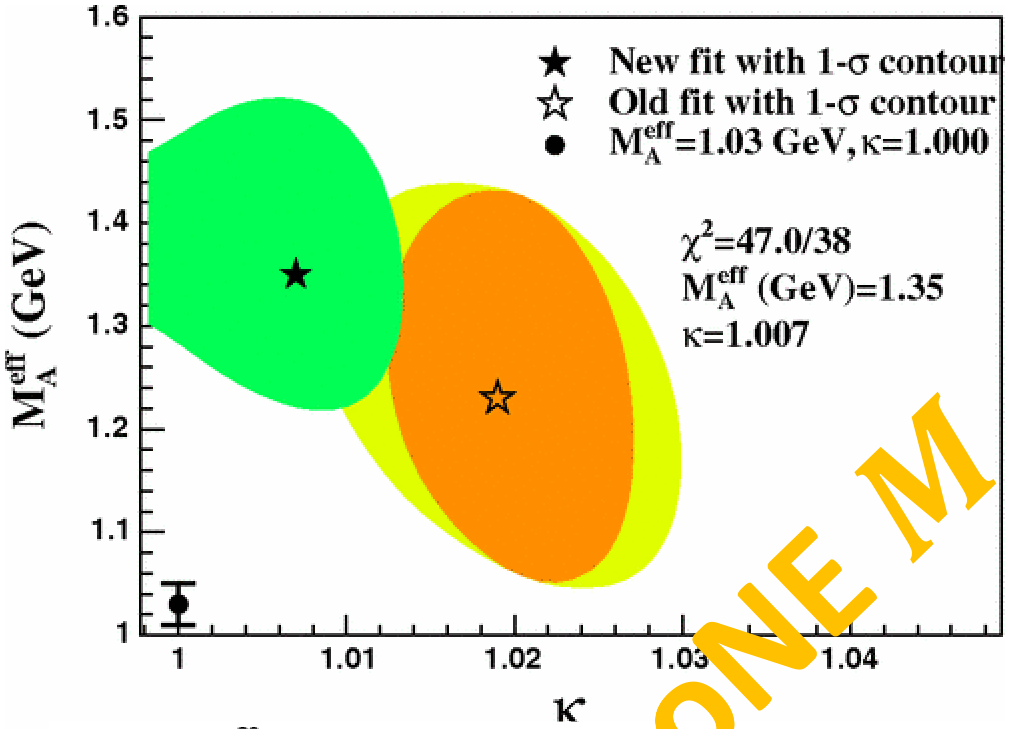
<u>**1 muon events !**</u>

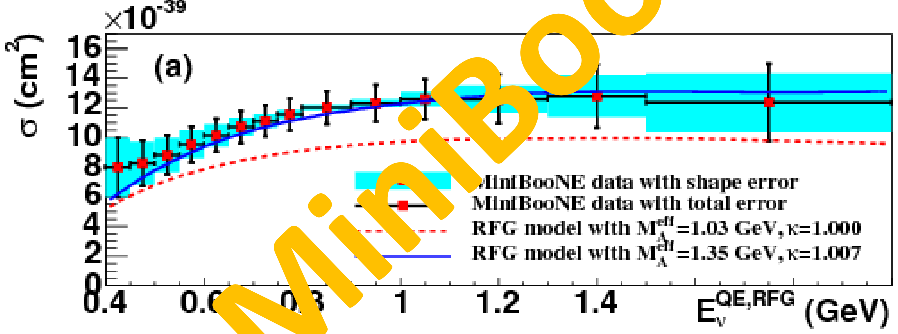
The largest background is from CC single pion production: CC1π^+

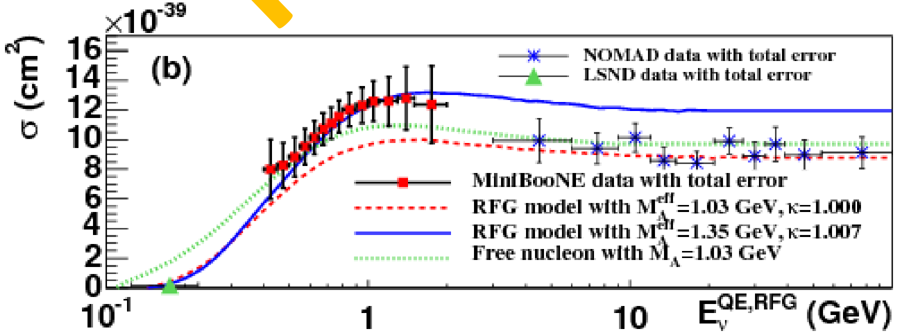
$$1:\ \nu_\mu + p(n) \rightarrow \mu^- + p(n) + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$2:\ \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$3:\ \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$

<u>**2 muon events**</u>

MiniBooNE M_A puzzle





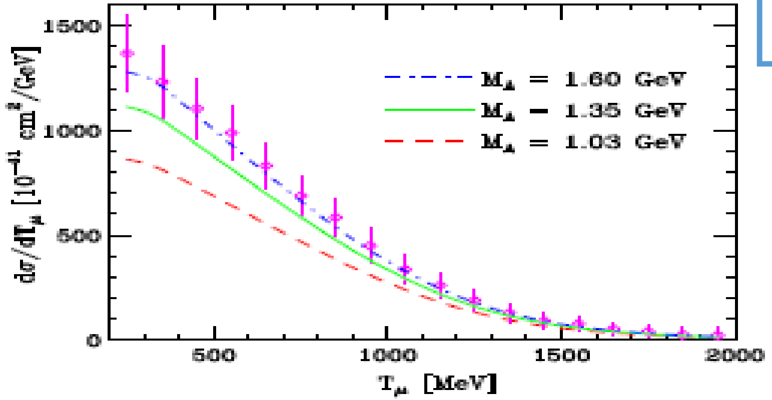


$$M_A^{\rm eff} = 1.35 \text{ GeV}$$

vs

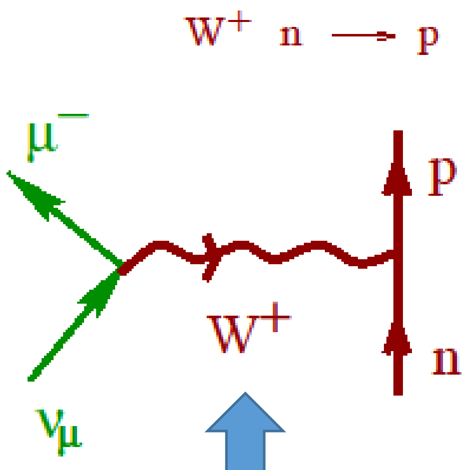
1.03 GeV (world avg)

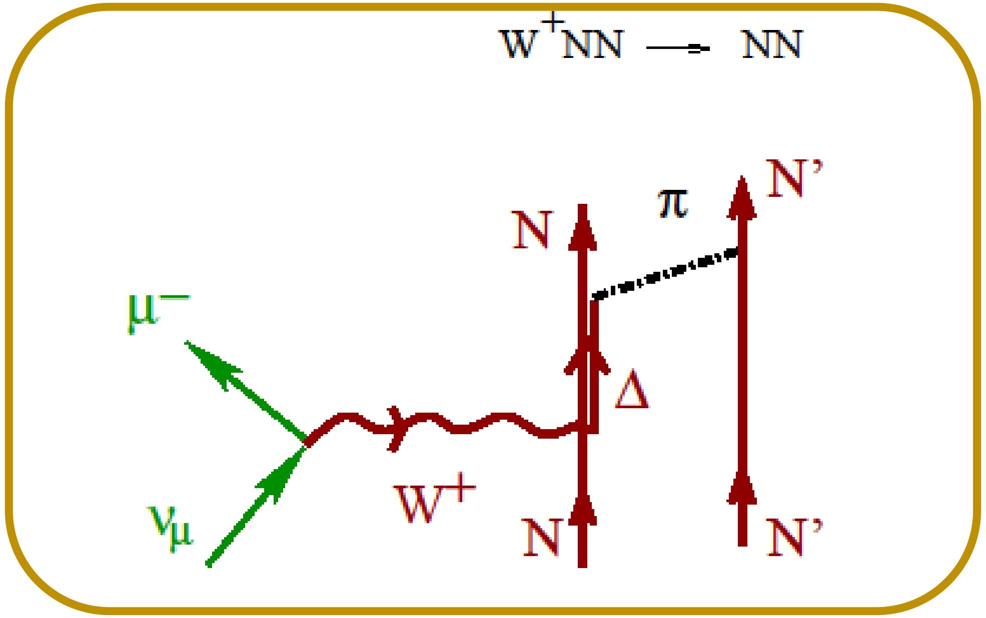
confirmed by many other groups, for instance by Benhar et al. (PRL 105, 132301)

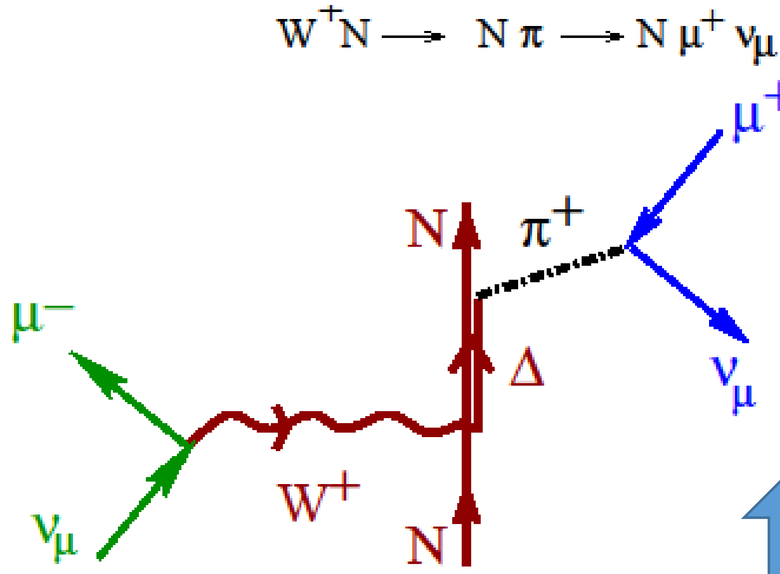


ChPT O(p^3) + single pion electroproduction data: M_A = 1.014± 0.016 GeV (V. Bernard, N. Kaiser, and U. G.Meissner, PRL69, 1877 (1992))

- CCQE measurements on deuterium and, to lesser extent, hydrogen targets is M_A = 1.016 ± 0.026 GeV (A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, EPJC 53, 349 (2008))





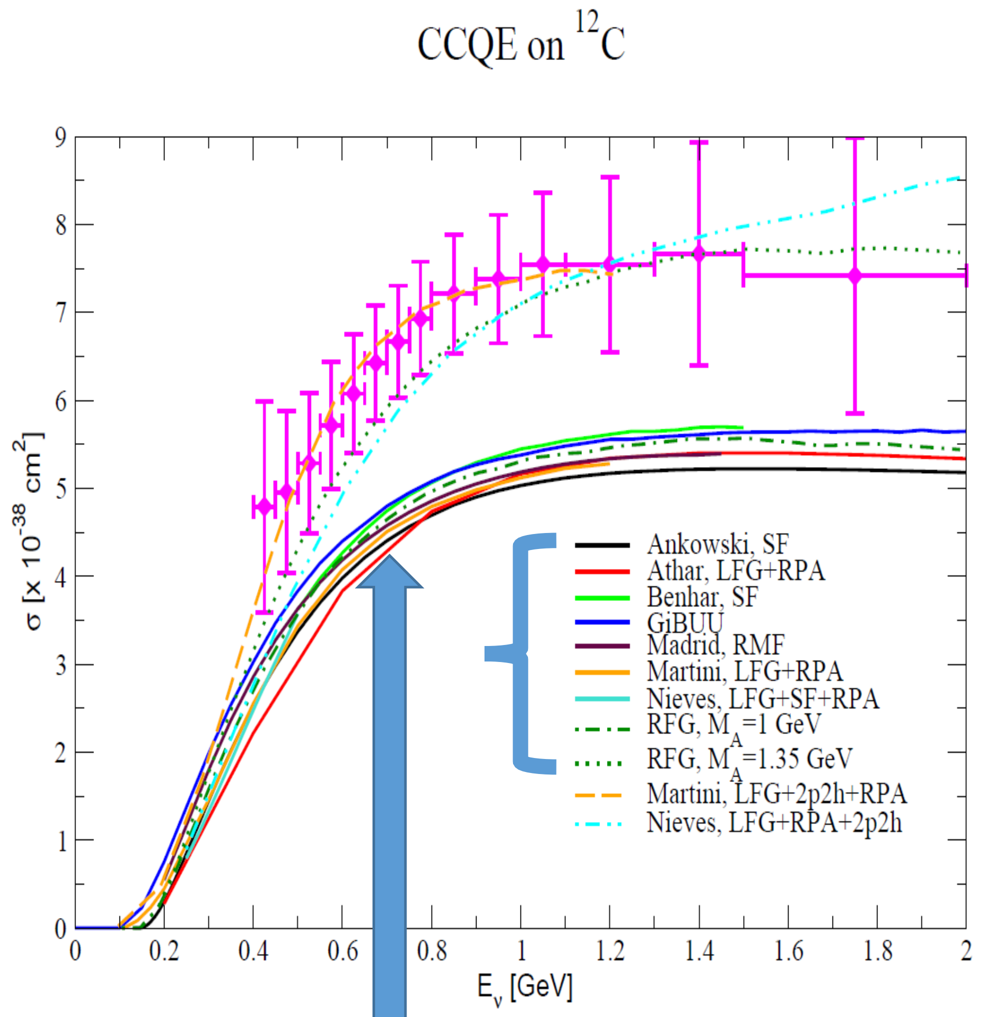


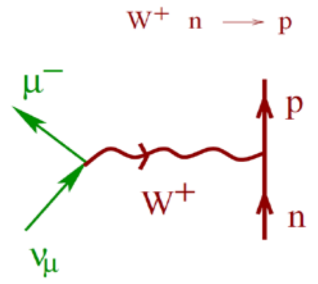
...but key observation (Martini et al., PRC 81, 045502): in most theoretical works QE is used for processes where the gauge boson $W^{\pm}$ or Z^{0} is absorbed by just one nucleon, which together with a lepton is emitted.

However in the recent MiniBooNE measurements, QE is related to processes in which only a muon is detected (ejected nucleons are not detected !) ≡ **CCQE-like**

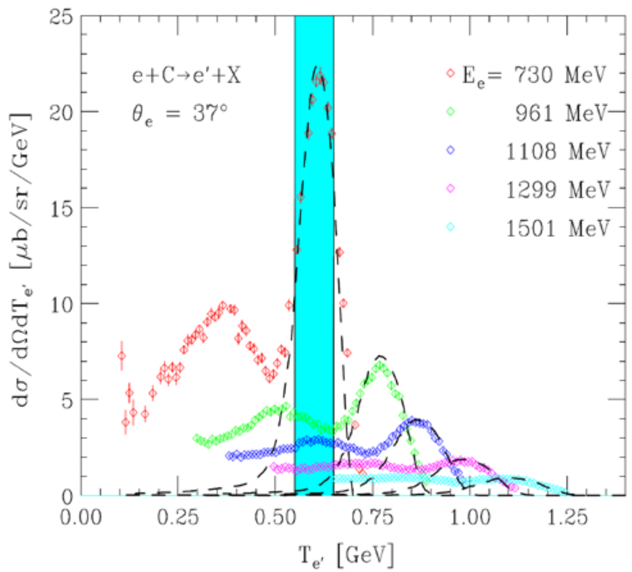
It discards pions coming off the nucleus, since they will give rise to additional leptons after their decay.

It includes multinucleon processes and others like π production followed by absorption (MBooNE analysis Monte Carlo corrects for these latter events).

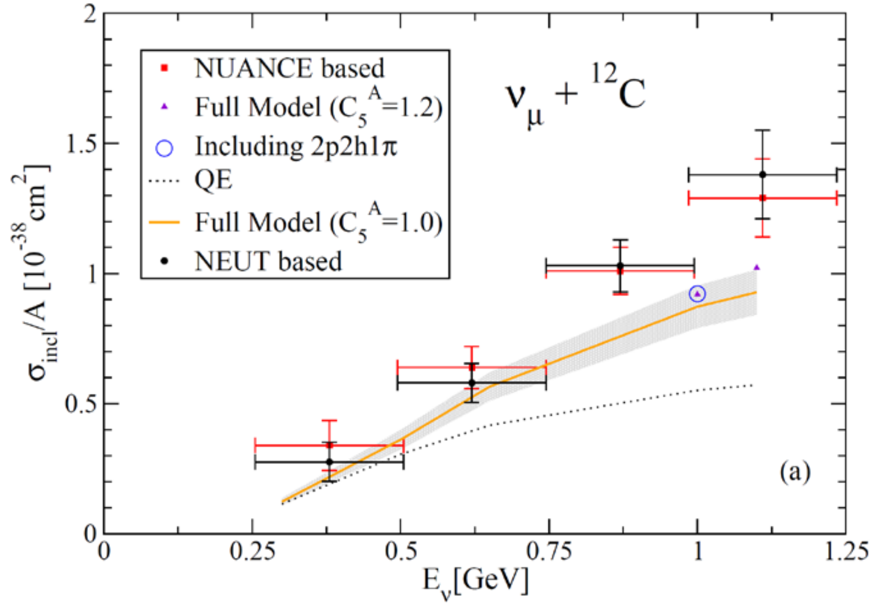


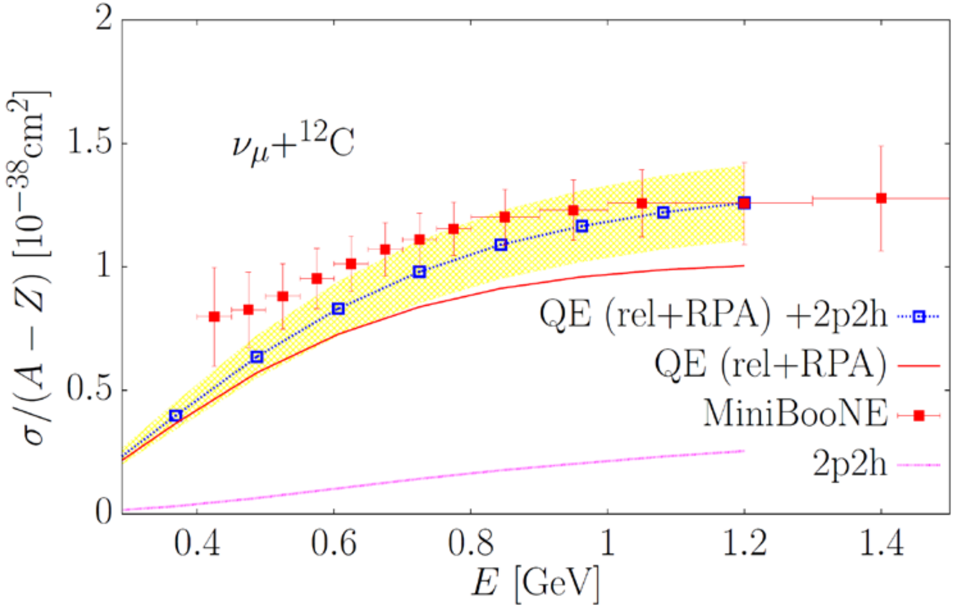


O. Benhar@NuFacT11: [arXiv : 1110.1835] measured electron-carbon scattering cross sections for a fixed outgoing electron angle $\theta = 37^o$ and different beam energies $\in [730, 1501]$ GeV, plotted as a function of E_e,



The energy bin corresponding to **the top of the QE peak at $E_e =$ 730 MeV receives significant contributions from** cross sections corresponding to different beam energies and **different mechanisms!**





MiniBooNE CCQE-like double differential cross section $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$

We define a **merit function** and consider our **QE+2p2h results**

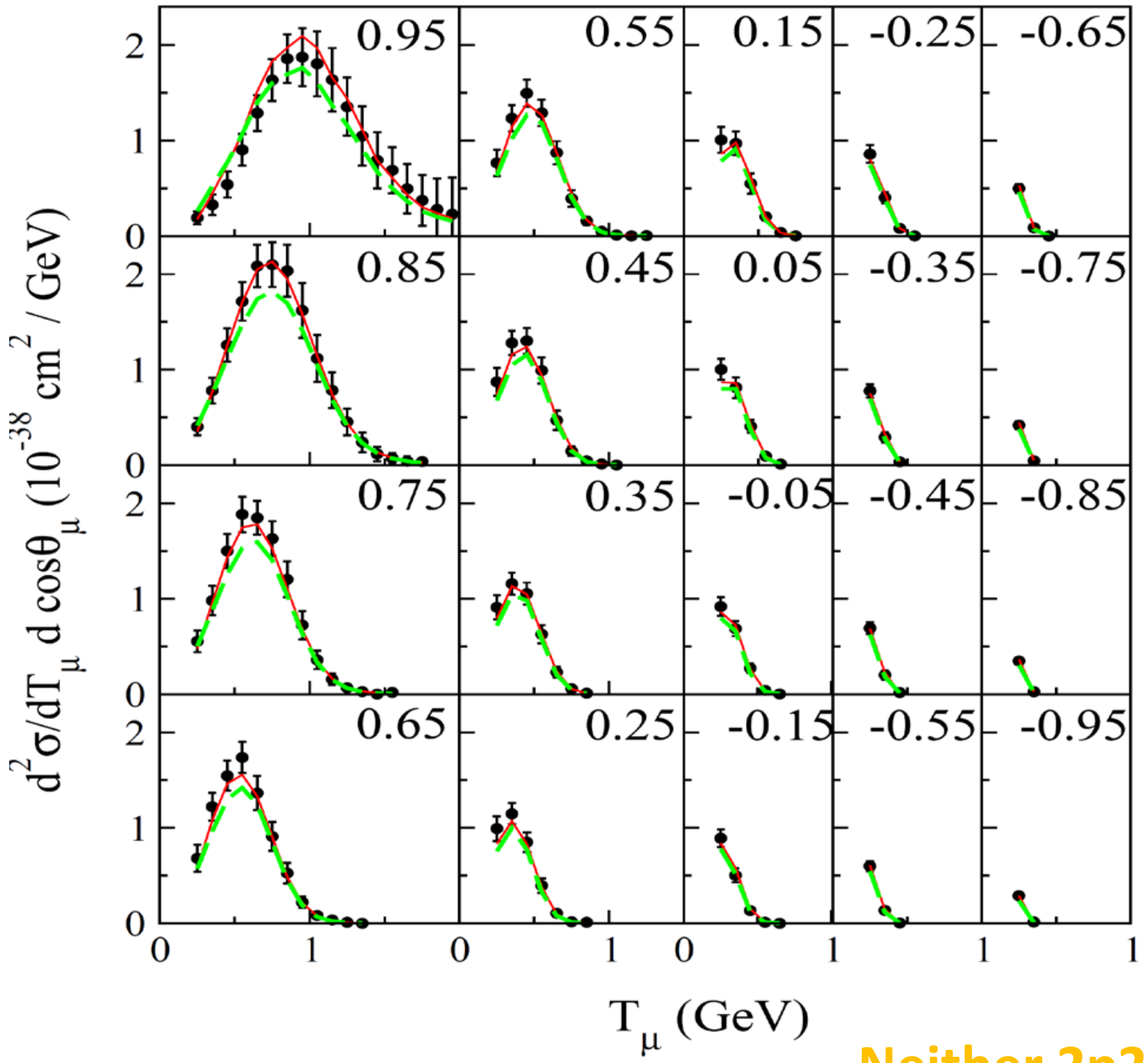
$$\chi^2 = \sum_{i=1}^{137} \left[\frac{\lambda \left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta}\right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta}\right)_i}{\lambda\Delta\left(\frac{d^2\sigma}{dT_\mu d\cos\theta}\right)_i} \right]^2 + \left(\frac{\lambda - 1}{\Delta\lambda}\right)^2,$$

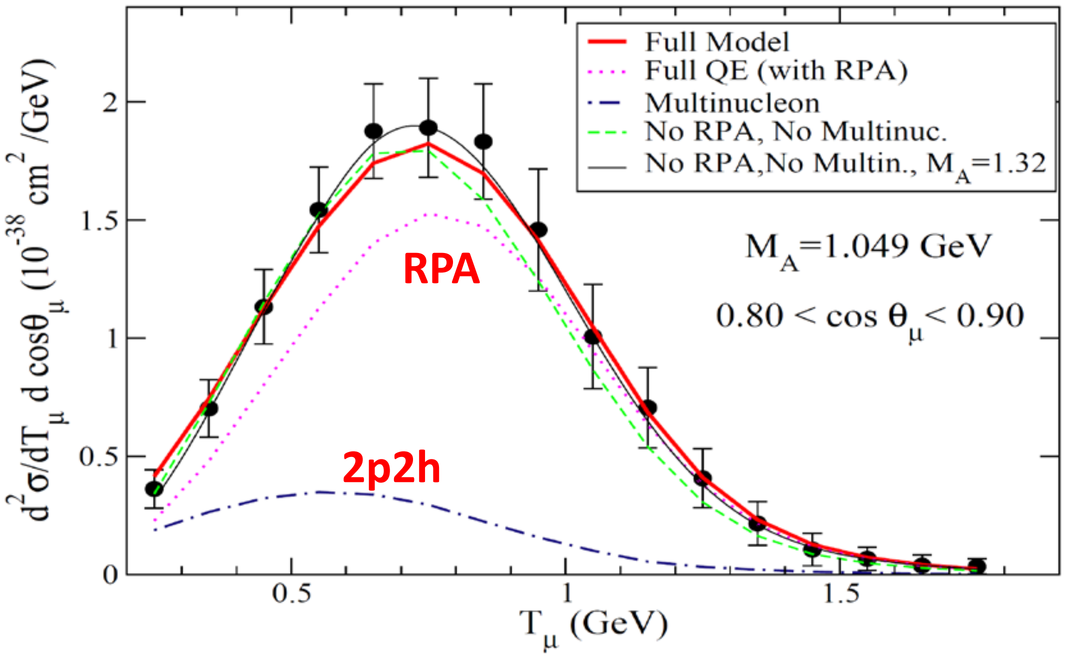
that takes into account the **global normalization uncertainty** ($\Delta\lambda = 0.107$) claimed by the MiniBooNE collaboration.

We fit λ to data with a fixed value of M_A (=1.049 GeV).

We obtain $\chi^2/\#$ bins =52/137 with $\lambda = 0.89 \pm 0.01$.

The microscopical model, with no free parameters, agrees remarkably well with data! The shape is very good and χ^2 strongly depends on λ, which is strongly correlated with M_A.





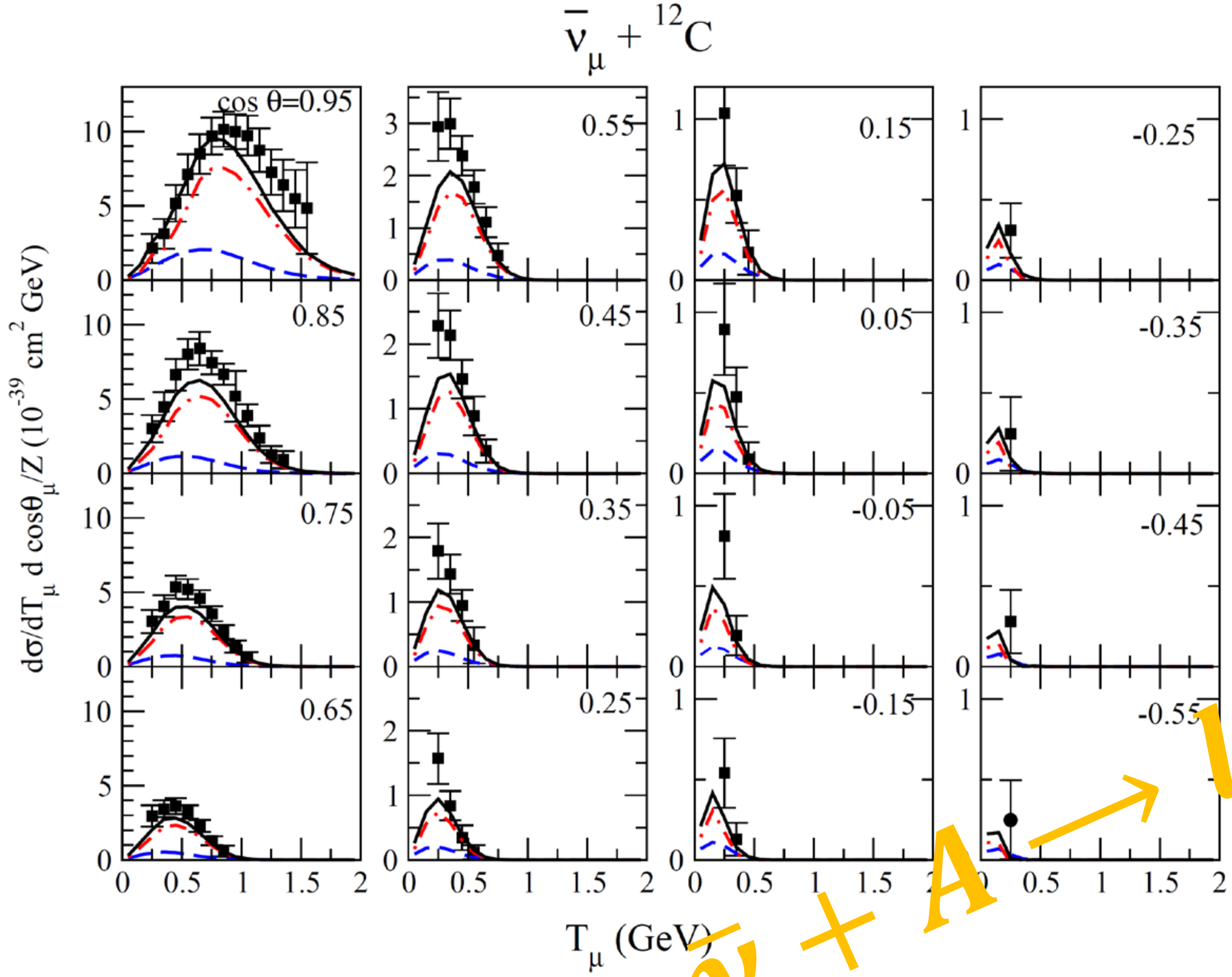
Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#\text{bins}}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	**0.92±0.03**	**1.08±0.03**	**50/137**
Full $\lvert q\rvert > 0.4^\dagger$ GeV	0.83±0.04	1.01±0.03	30/123

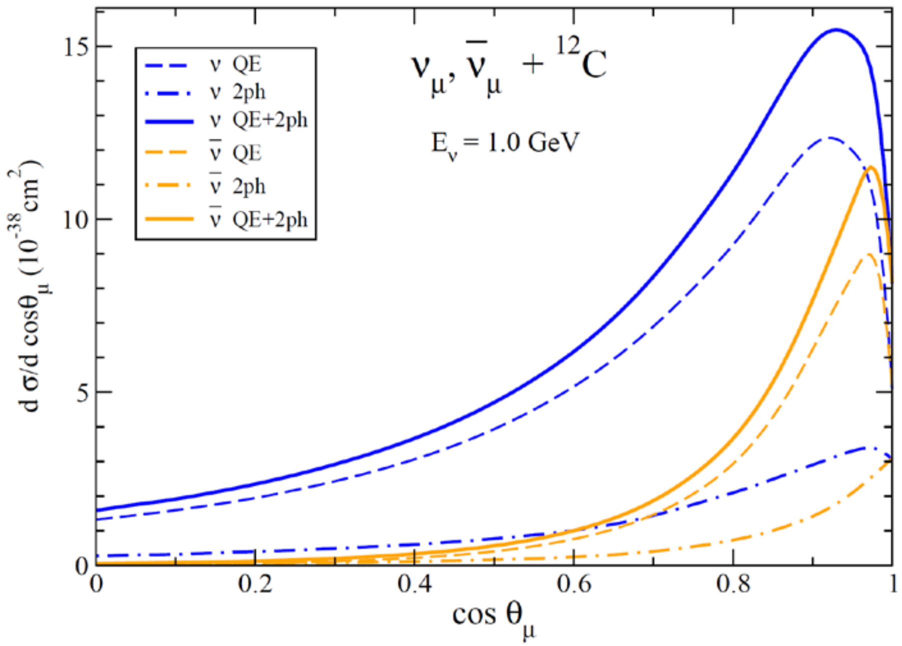
† : As suggested by Sobczyk et al. PRC 82, 045502

Neither 2p2h contributions nor RPA effects alone describe the MB 2D dataset, which is however described by the combination of both nuclear mechanisms!

Juan Nieves, IFIC (CSIC & UV)

$M_A \sim 1.03$ GeV

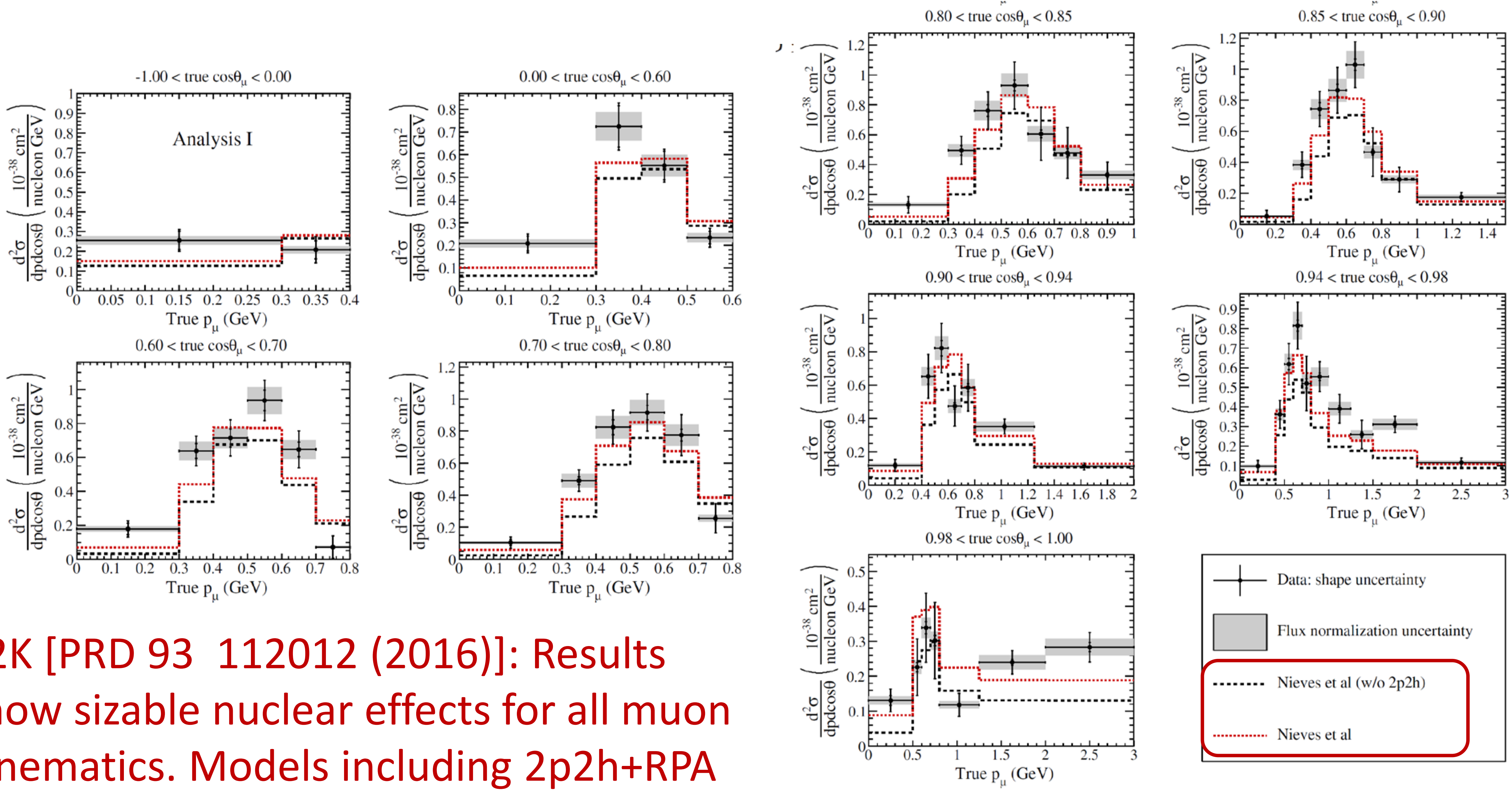




$\bar{\nu} + A \longrightarrow l + X$

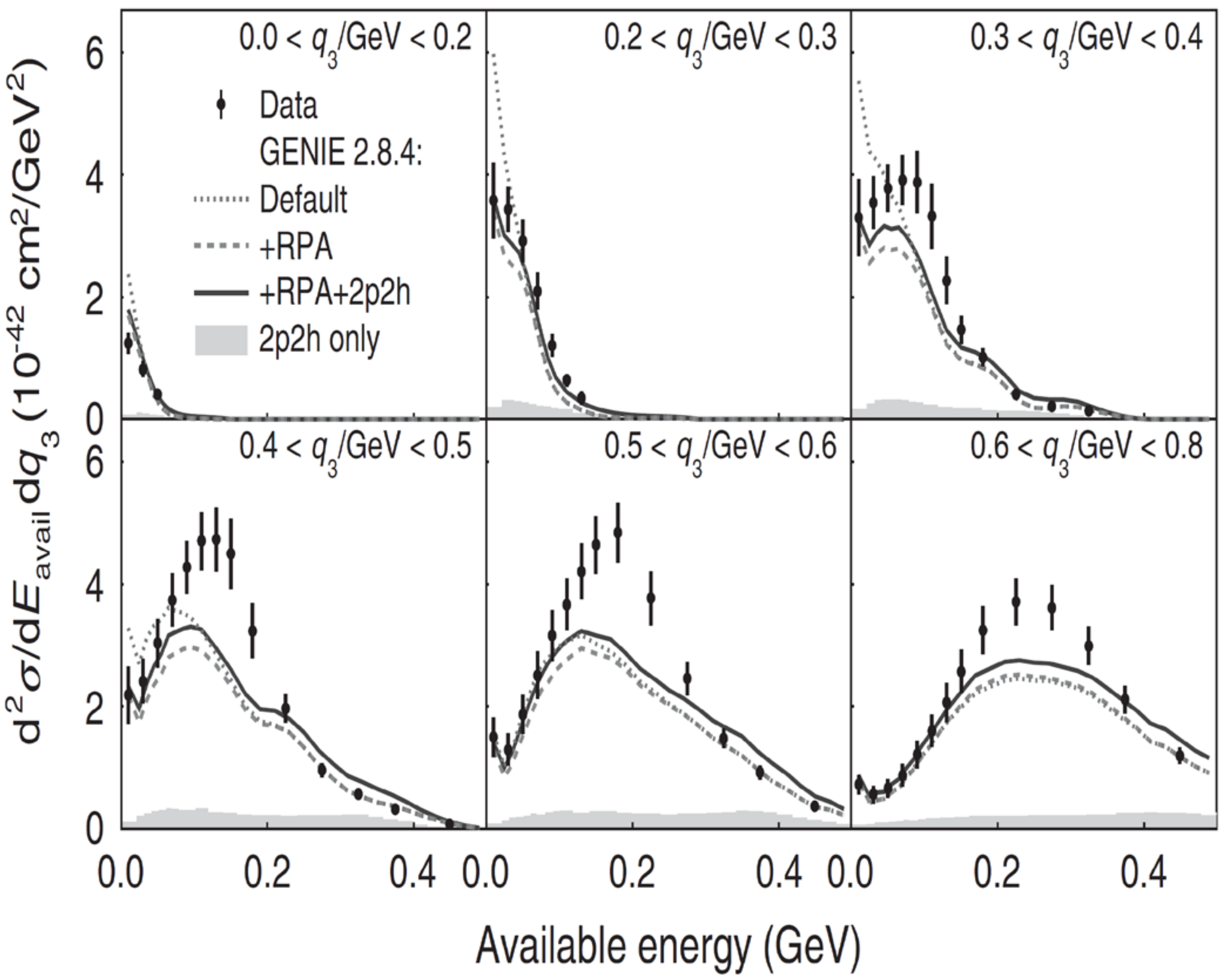
- **Antineutrino distributions are more forward peaked**
- **Relative importance of 2p2h contributions in ν and $\bar{\nu}$ are similar**

Juan Nieves, IFIC (CSIC & UV)



T2K [PRD 93 112012 (2016)]: Results show sizable nuclear effects for all muon kinematics. Models including 2p2h+RPA contributions agree well with the data

T2K: CCQE-like



The data make clear two distinct multinucleon effects that are essential for complete modeling of neutrino interactions at low momentum transfer. The $2p2h$ model tested in this analysis improves the description of the event rate in the region between QE and Δ peaks, and the rate for multiproton events, but does not go far enough to fully describe the data. Oscillation experiments sensitive to energy reconstruction effects from these events must account for this event rate. The cross section presented here will lead to models with significantly improved accuracy.

MINERνA: CCQE-like

PRL 116, 071802 (2016)

3. Neutrino energy reconstruction

Neutrino beams ARE NOT monochromatic. For QE-like events, only the charged lepton is observed and the only measurable quantities are then its direction (scattering angle θ_μ with respect to the neutrino beam direction) and its energy E_μ. The energy of the neutrino that has originated the event is unknown. Assuming QE dynamics is defined a "reconstructed" energy

$$E_{\rm rec} = \frac{M E_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu| \cos\theta_\mu}$$

(genuine quasielastic event on a nucleon at rest, ie. $E_{\rm rec}$ is determined by the QE-peak condition $q^0 = -q^2/2M$). Note that each event contributing to the flux averaged double differential cross section $d\sigma/dE_\mu d\cos\theta_\mu$ defines unambiguously a value of $E_{\rm rec}$. The actual ("true") energy, E, of the neutrino that has produced the event will not be exactly $E_{\rm rec}$.

Flux-folded $d\sigma/dT_\mu d\cos\theta_\mu \overset{?}{\leftrightarrow}$ CCQE-like unfolded $\sigma(E)$

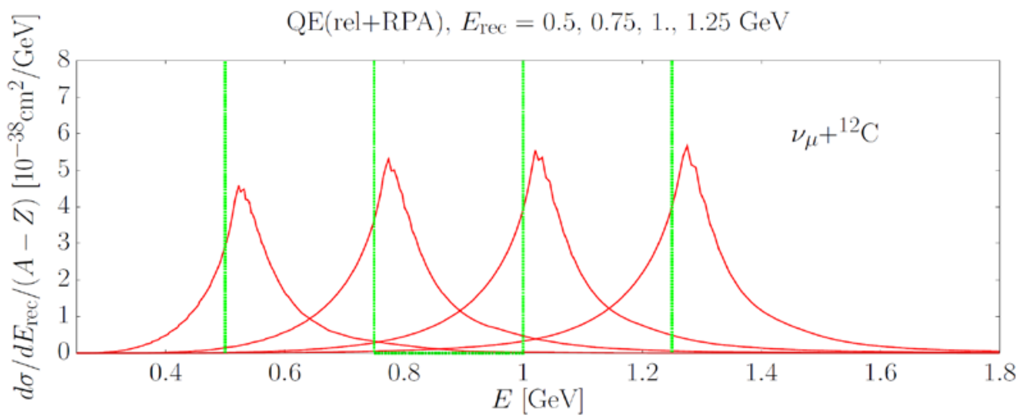
Unfolding procedure needs theoretical input!

$$P_{\rm true}(E) = \int dE_{\rm rec} \underbrace{P_{\rm rec}(E_{\rm rec})}_{\rm EXP} \underbrace{P(E|E_{\rm rec})}_{theory!}$$

$P_{\rm rec}(E_{\rm rec})$ is the *pd* of measuring an event with reconstructed energy $E_{\rm rec}$. $P(E|E_{\rm rec})$ is, given an event of reconstructed energy $E_{\rm rec}$, the conditional *pd* of being produced by a neutrino of energy E.

...using Bayes's theorem $P(E|E_{\rm rec})$ could be related to

$P(E_{\rm rec}|E)$ is determined by $\displaystyle\frac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec})$

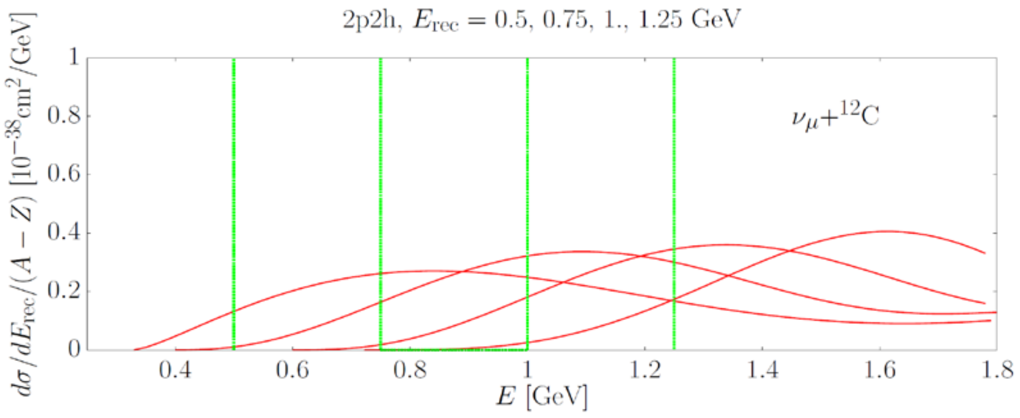


Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section

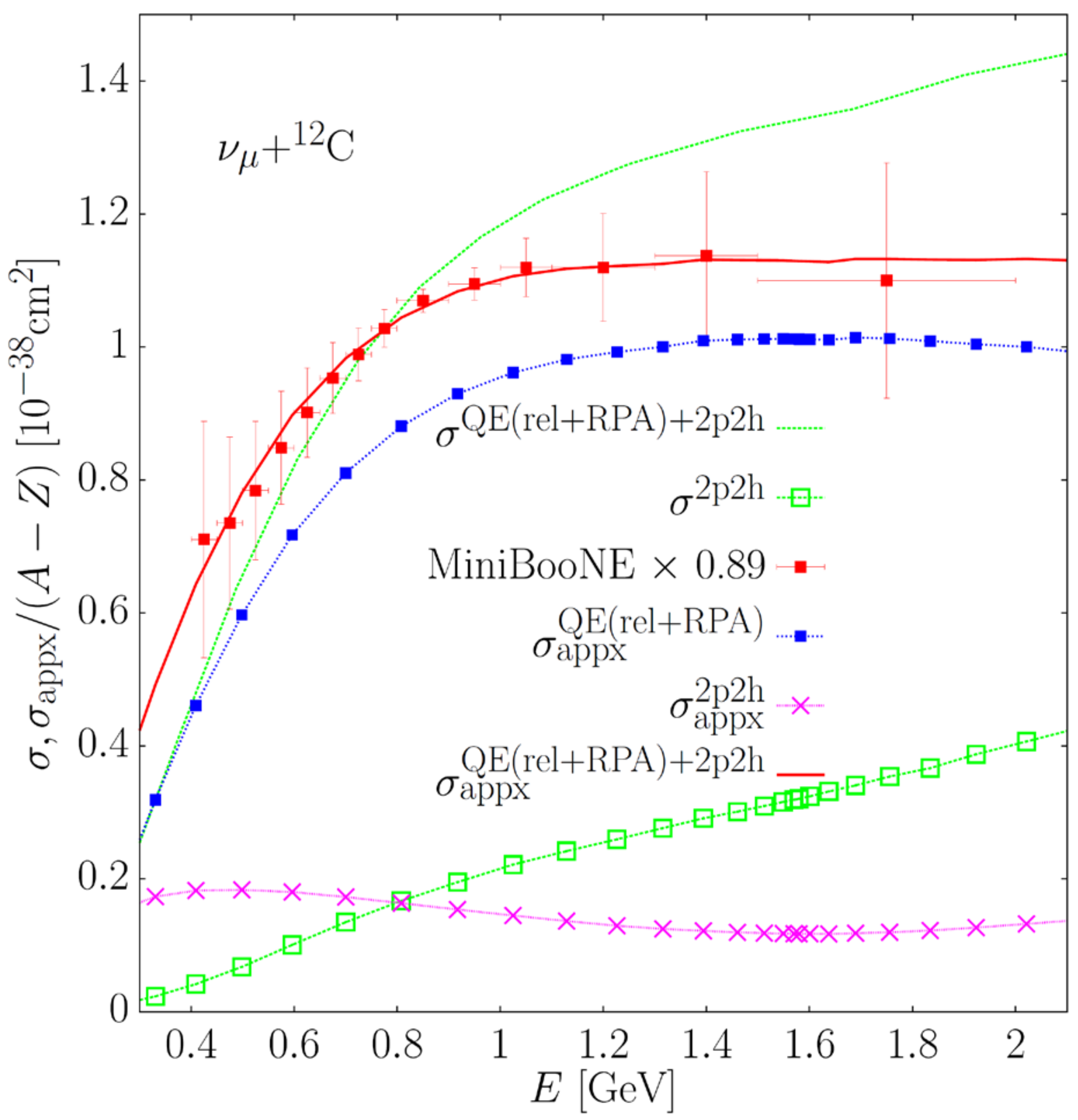
(qualitatively in agreement with Martini et al., PRD85 093012)

theory !

$$\frac{d\sigma}{dE_{\rm rec}}(E;E^0_{\rm rec}) = \int_{m_\mu}^{E} dE_\mu \frac{d^2\sigma}{dE_{\rm rec}dE_\mu}(E;E^0_{\rm rec}) = \int_{m_\mu}^{E} dE_\mu \left|\frac{\partial(\cos\theta_\mu)}{\partial E_{\rm rec}}\right| \frac{d^2\sigma}{d(\cos\theta_\mu)dE_\mu}(E;E^0_{\rm rec})$$



For each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$.

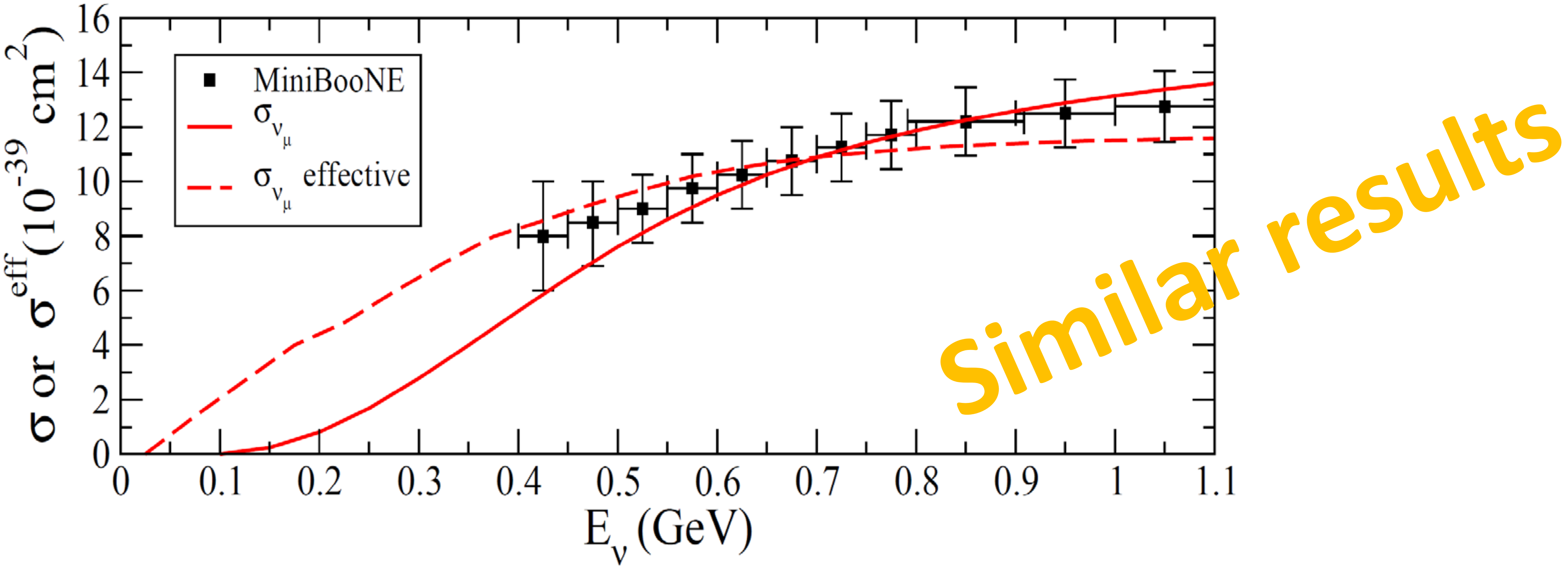


$$\Big[\langle\sigma\rangle P_{\mathrm{rec}}(E_{\mathrm{rec}})\Big]_{\mathrm{Exp}} \sim$$

$$\int \left(\frac{d\sigma}{dE_{\mathrm{rec}}}(E'; E_{\mathrm{rec}})\Big|^{M_A=1.049\ \mathrm{GeV}}_{\mathrm{QE+RPA},} + \frac{d\sigma^{\mathrm{2p2h}}}{dE_{\mathrm{rec}}}(E'; E_{\mathrm{rec}}) \right) \Phi(E') dE'$$

... and

$$\underbrace{\left[\frac{d\sigma/dE_{\mathrm{rec}}(E; E_{\mathrm{rec}})}{\int dE'' \Phi(E'') d\sigma/dE_{\mathrm{rec}}(E''; E_{\mathrm{rec}})} \right]}_{\text{ONLY QE },\mathrm{M_A}=1.32\ \text{GeV and noRPA}}$$



Martini, Ericson, Chanfray [Phys.Rev. D87 (2013), 013009]

Conclusions

- We have presented a theoretical description of effects produced by the inclusion of SFs, which account for the change of the dispersion relations of the interacting nucleons embedded in a nuclear medium.

- SFs are responsible for the quenching of the QE peak, produce a spreading of the strength of the response functions to higher energy transfers and shift the peak position in the same direction. The overall result is a decrease of the integrated cross sections and a considerable change of the differential shapes.

- RPA effects in integrated decay rates or cross sections become significantly smaller when SF corrections are also taken into account, in sharp contrast to the case of a free LFG where they lead to large reductions, even of around 40%.

- We have analyzed the MiniBooNE CCQE 2D cross section data using a theoretical model that has proved to be quite successful in the analysis of nuclear reactions with electron, photon and pion probes and contains no additional free parameters.

- RPA and multinucleon knockout have been found to be essential for the description of the data.

- MiniBooNE ν and $\bar{\nu}$ CCQE-like data are fully compatible with former determinations of M_A in contrast with several previous analyses. We find, $M_A = 1.08 \pm 0.03$ GeV.

- The MiniBooNE ν_μ flux could have been underestimated ($\sim$ 10%).

- Because of the multinucleon mechanism effects, the algorithm used to reconstruct the neutrino energy is not adequate when dealing with QE-like events.

- The inclusion of nucleon-nucleon correlation effects in the RPA series yields a much larger shape distortion toward relatively more high-q^2 interactions, with the 2p2h component filling in the suppression at very low q^2.

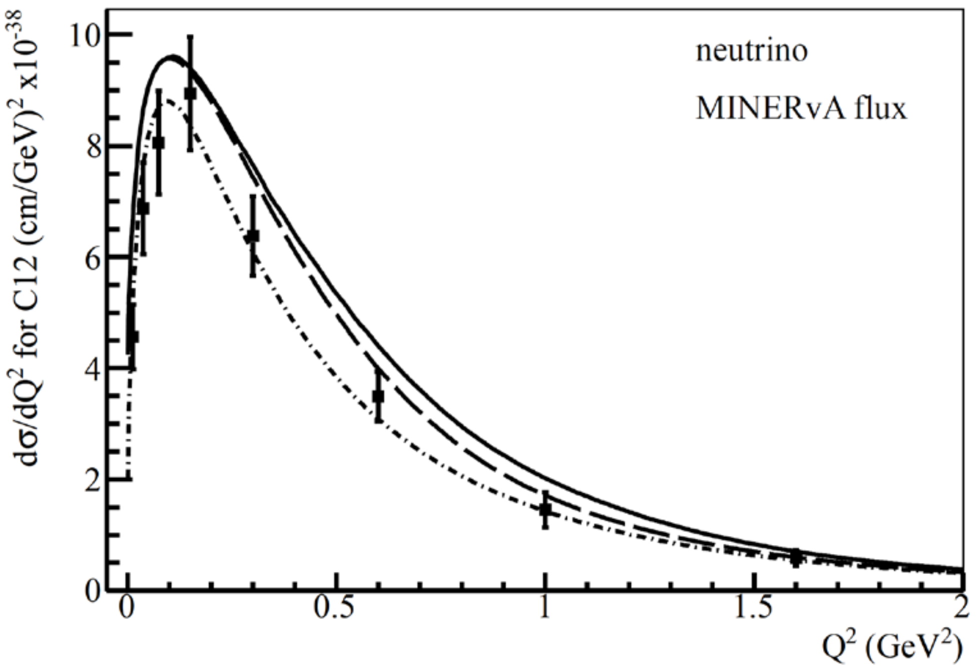
Final remark:

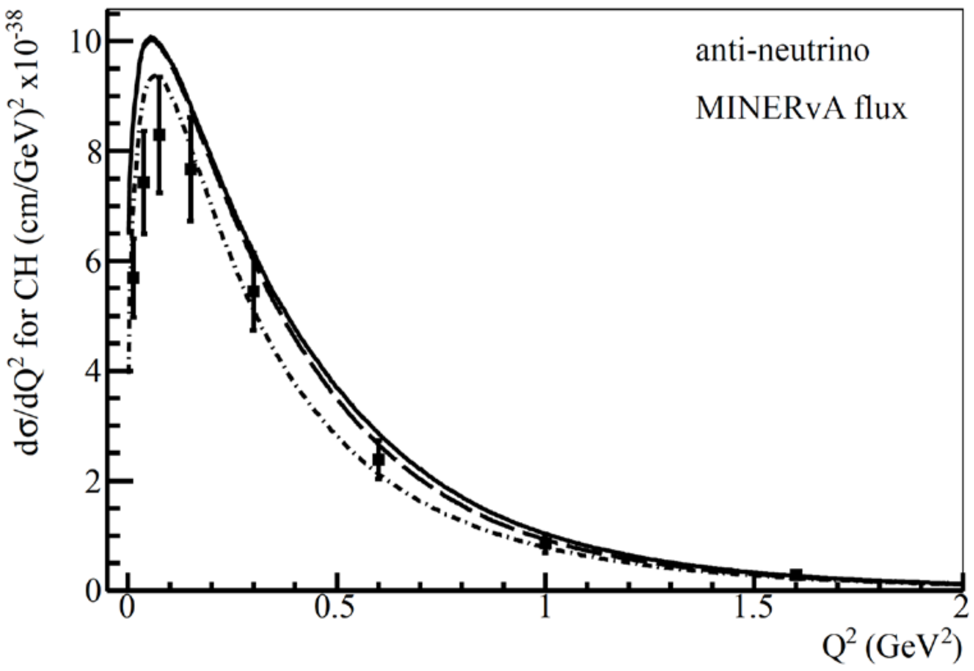
Nuclear effects lead to sizable uncertainties on the neutrino nucleus cross sections at low $-q^2 = Q^2 < 1\,\mathrm{GeV}^2$

It is important to incorporate these effects in event generators (GENIE, etc..)

Back up Slides

MINERνA





PHYSICAL REVIEW D 88, 113007 (2013)

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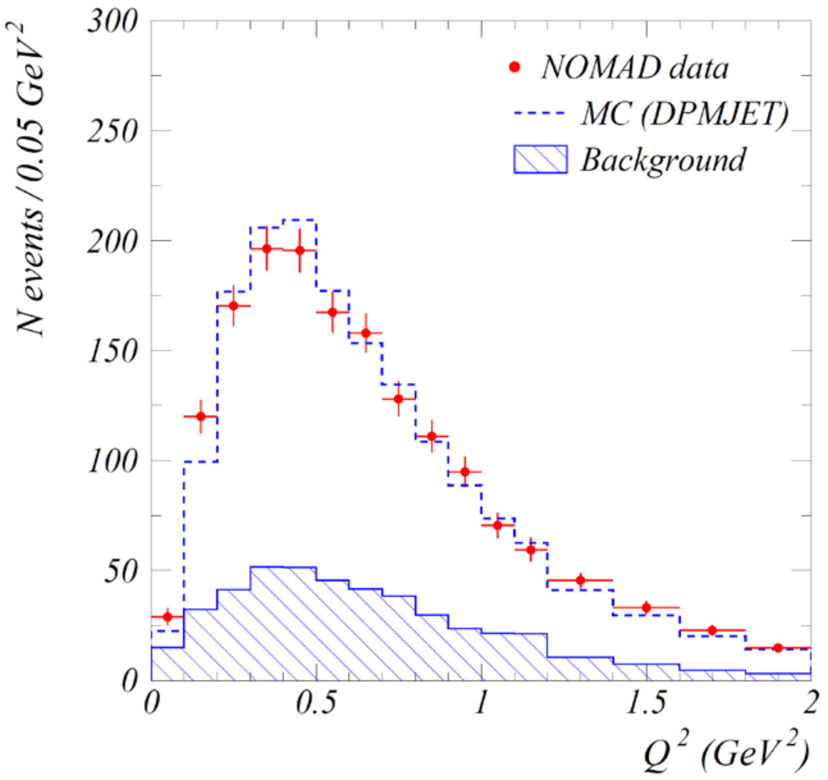
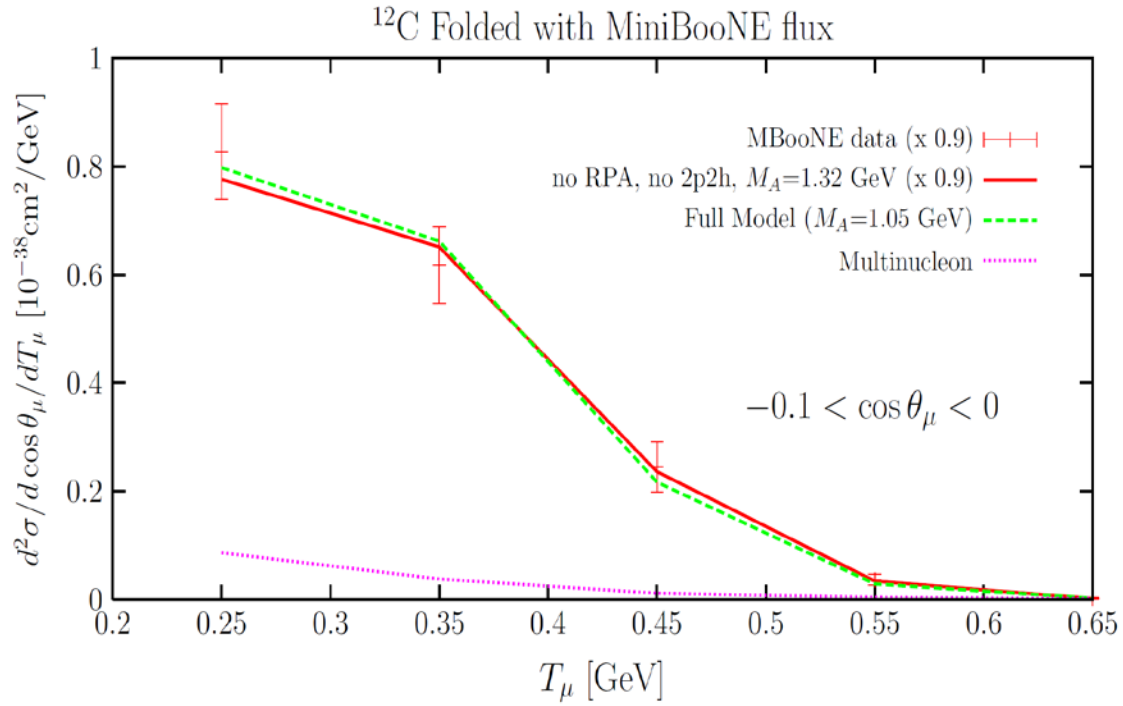
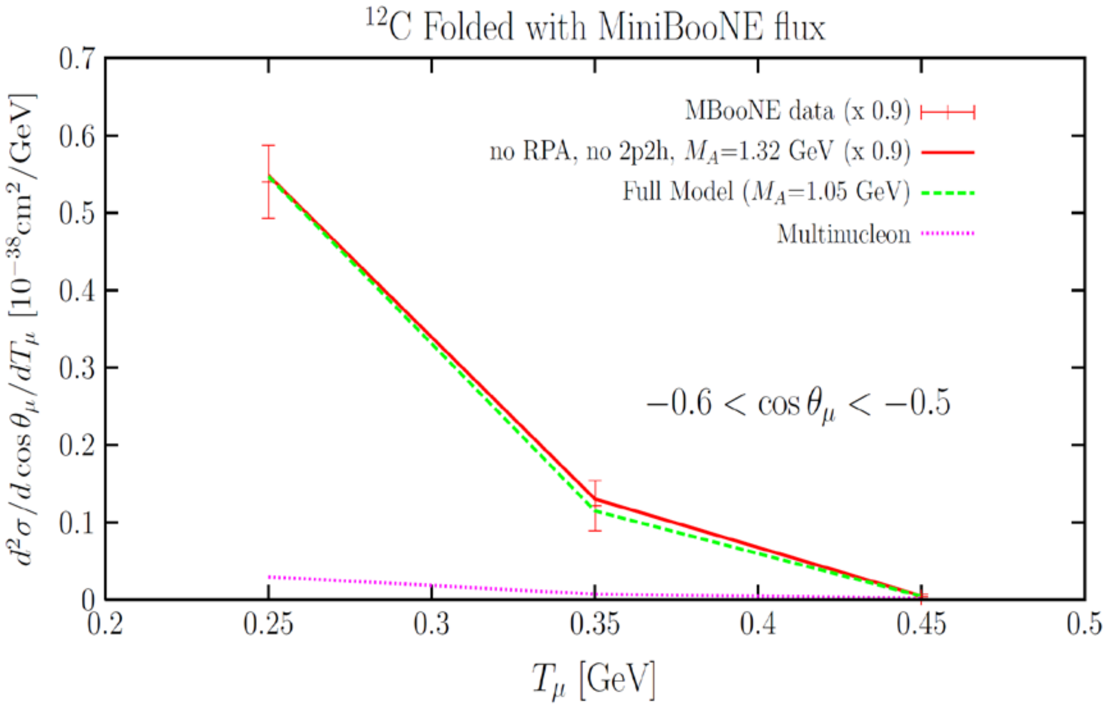


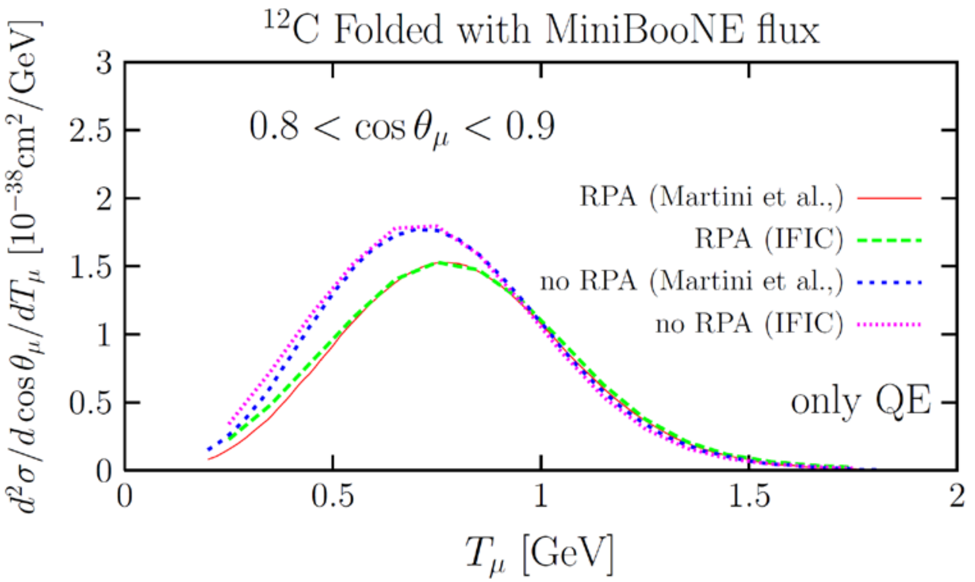
V. Lyubushkin et al. **(NOMAD Collaboration)**, Eur. Phys. J. C 63, 355 (2009). In the **two-track sample**, which is primarily Q^2 above 0.3 GeV^2, a **large fraction of the 2p2h component**, as well as QE and pion production where the hadrons rescattered as they exited the nucleus, are **rejected.**

It is observed a relative **deficit at $Q^2 = 0.3$ and excess at 1.5 GeV^2 compared to QE without RPA**. If the first two or three points are eliminated, the distribution will be consistent with $M_A \sim 1.2$ GeV.

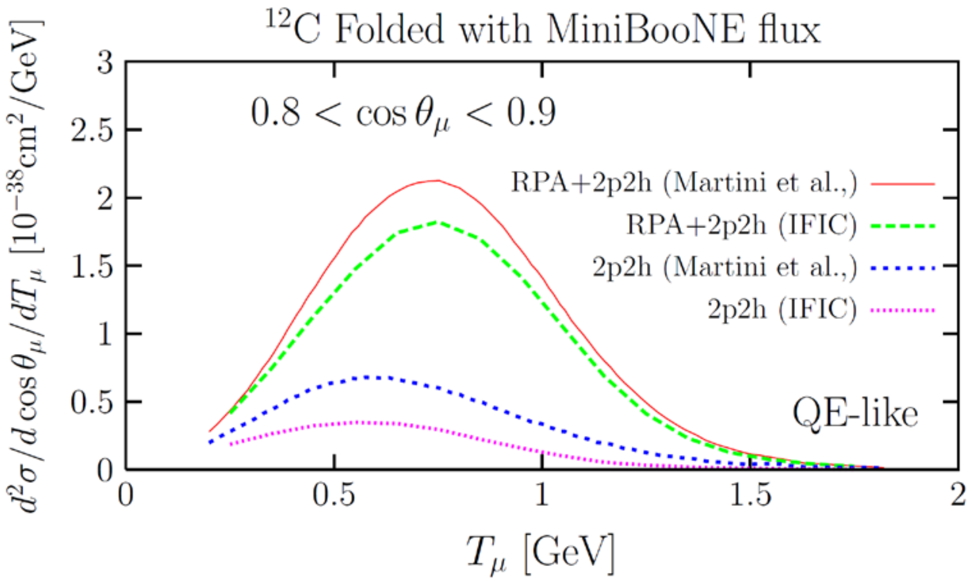
Dependence of the 2p2h contribution on $\cos\theta_\mu$







We compare rather well with Martini et al., PRC 84, 055502 for bare QE and QE+RPA

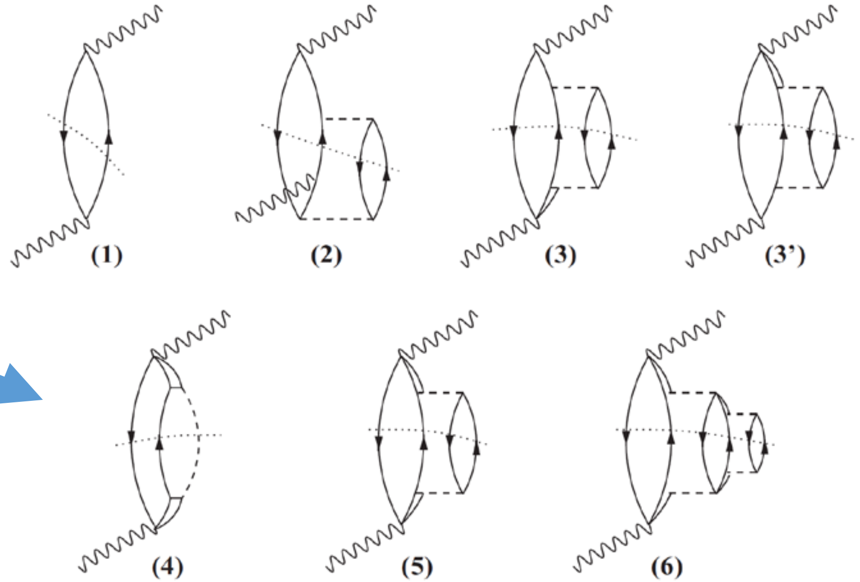


...however our 2p2h contribution is about a factor of 2 smaller!

Differences with the work of Martini et al. (PRC80,065501)

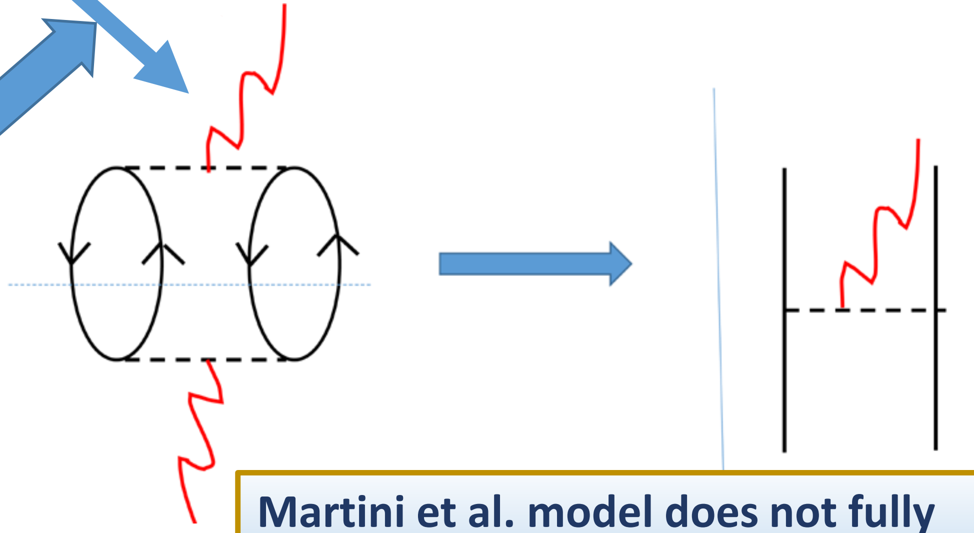
only for vector current driven processes

1. Similar for the 2p2h contributions driven by Δh excitation (both groups use the same model for the $\Delta-$selfenergy in the medium).



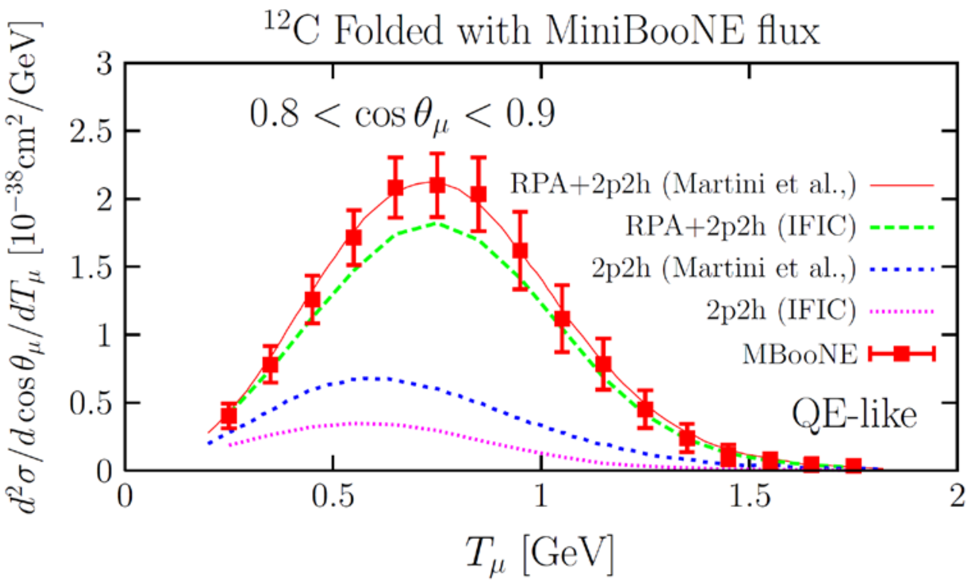
2. Martini et al. do not consider 2p2h contributions driven by contact, pion pole and pion in flight terms.

3. Martini et al. give approximate estimates (no microscopical calculation) for the rest of 2p2h contributions [relate them to the absorptive part of the $p-$wave pion-nucleus optical potential at threshold or to a microscopic calculation by Alberico et al. (Annals Phys. 154, 356) specifically aimed at the evaluation of the 2p-2h contribution to the isospin spin-transverse response, measured in inclusive (e, e') scattering].

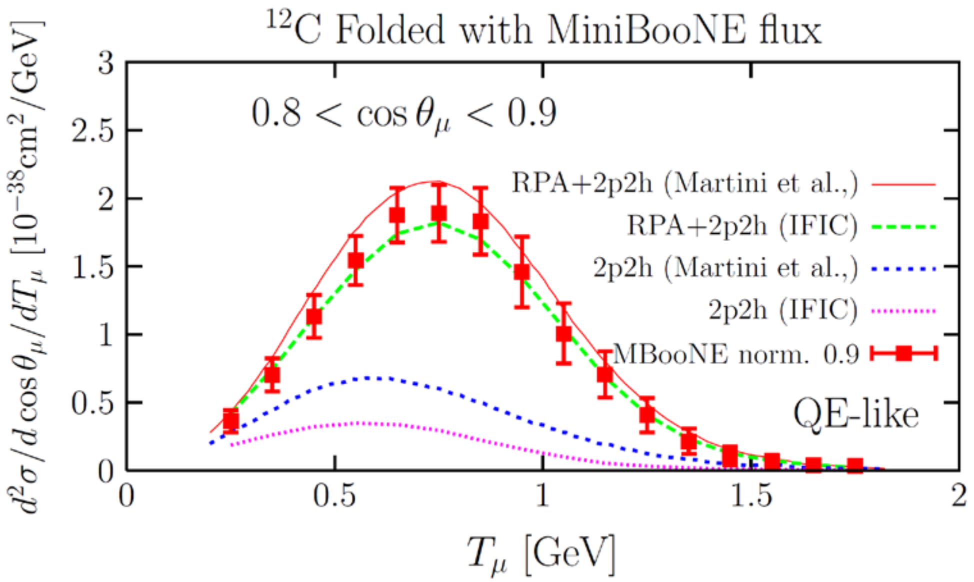


This 2p2h parametrization includes MEC effects driven by the vector current !

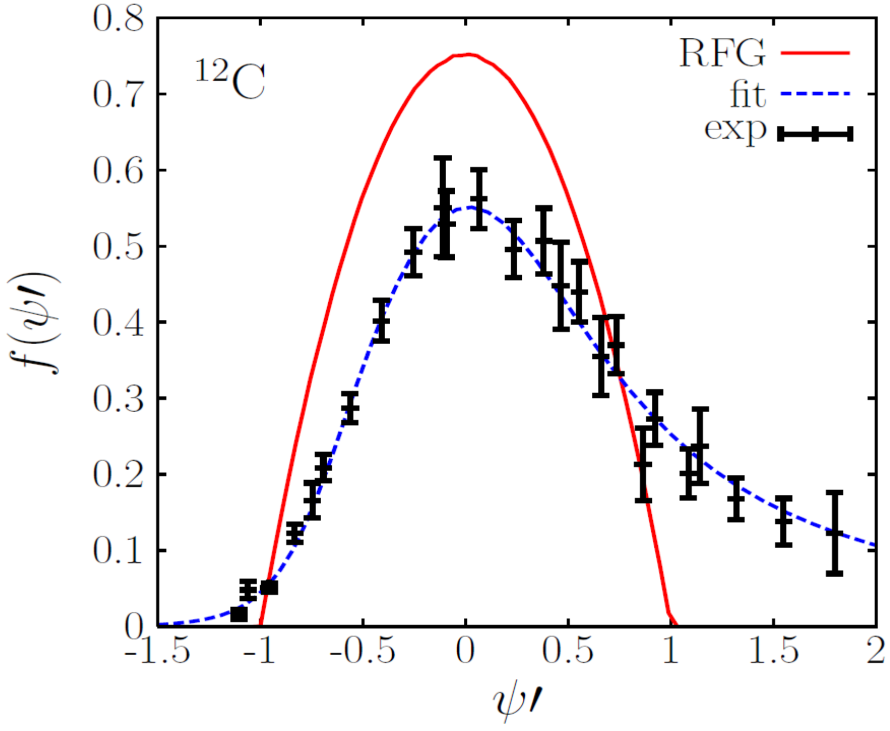
Martini et al. model does not fully account for the axial and axial-vector interference contributions !



Martini et al., predictions look consistent with MiniBooNE data ..., **but their estimate rely on some computation of the 2p2h mechanisms for (e, e') (Alberico et al.,) $\Rightarrow$ no info on axial part of the interaction!**



...however our predictions for the 2p2h contribution would favor a global normalization scale of about 0.9. This would be consistent with the MiniBooNE estimate of a total normalization error of 10.7%.



Superscaling approach: Inclusive electron scattering data exhibit interesting systematics that can be used to predict (anti)neutrino-nucleus cross sections (T. Donnelly and I. Sick, PRL 82, 3212 (1999)),

$$f = k_F \frac{\frac{d\sigma}{d\Omega' dE'}}{Z\sigma_{ep} + N\sigma_{en}}$$

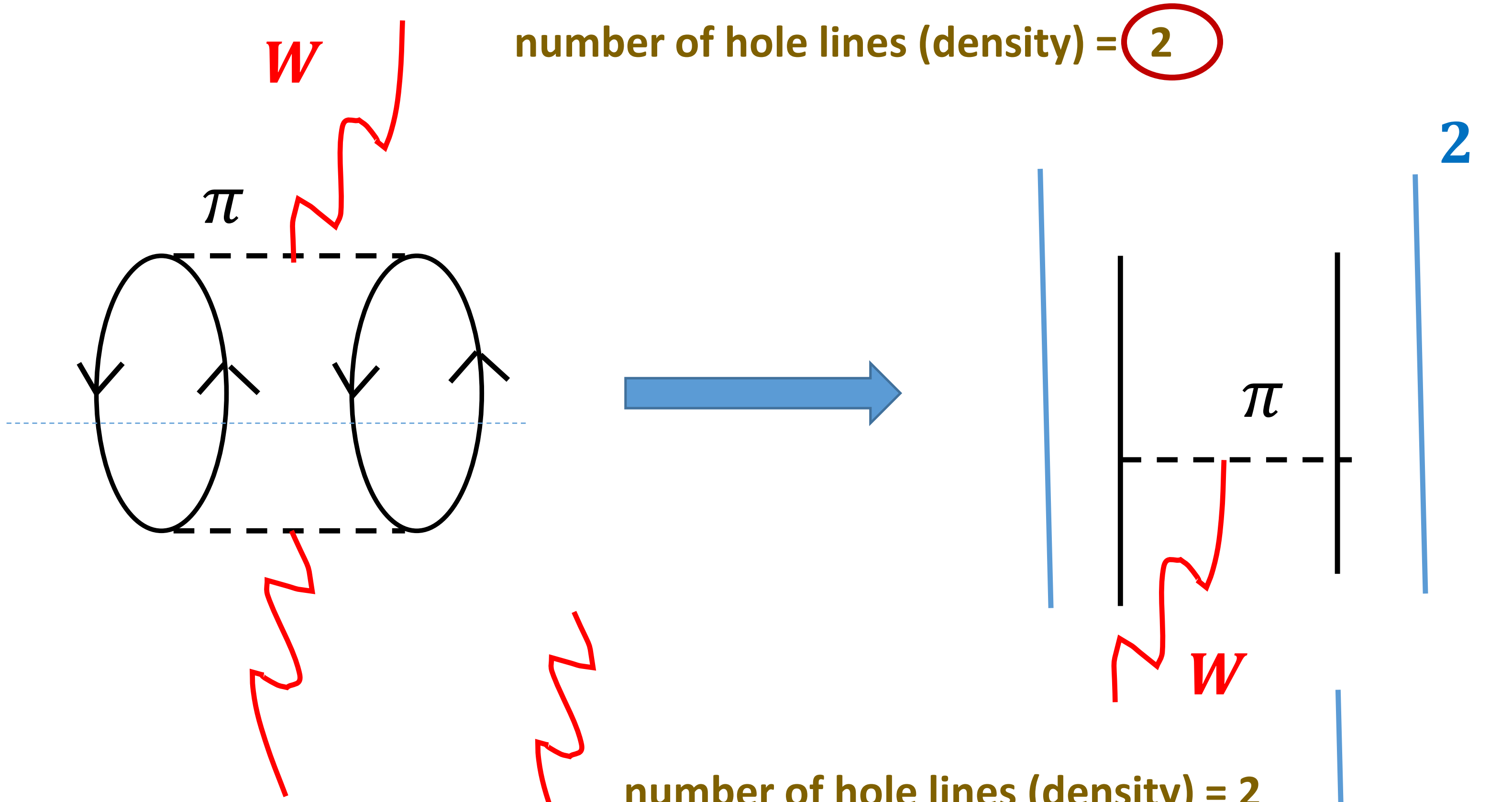
- $f = f(\psi')$, **with** $\psi' = \psi'(q^0, |\vec{q}\,|)$
- f **is largely independent of the specific nucleus**

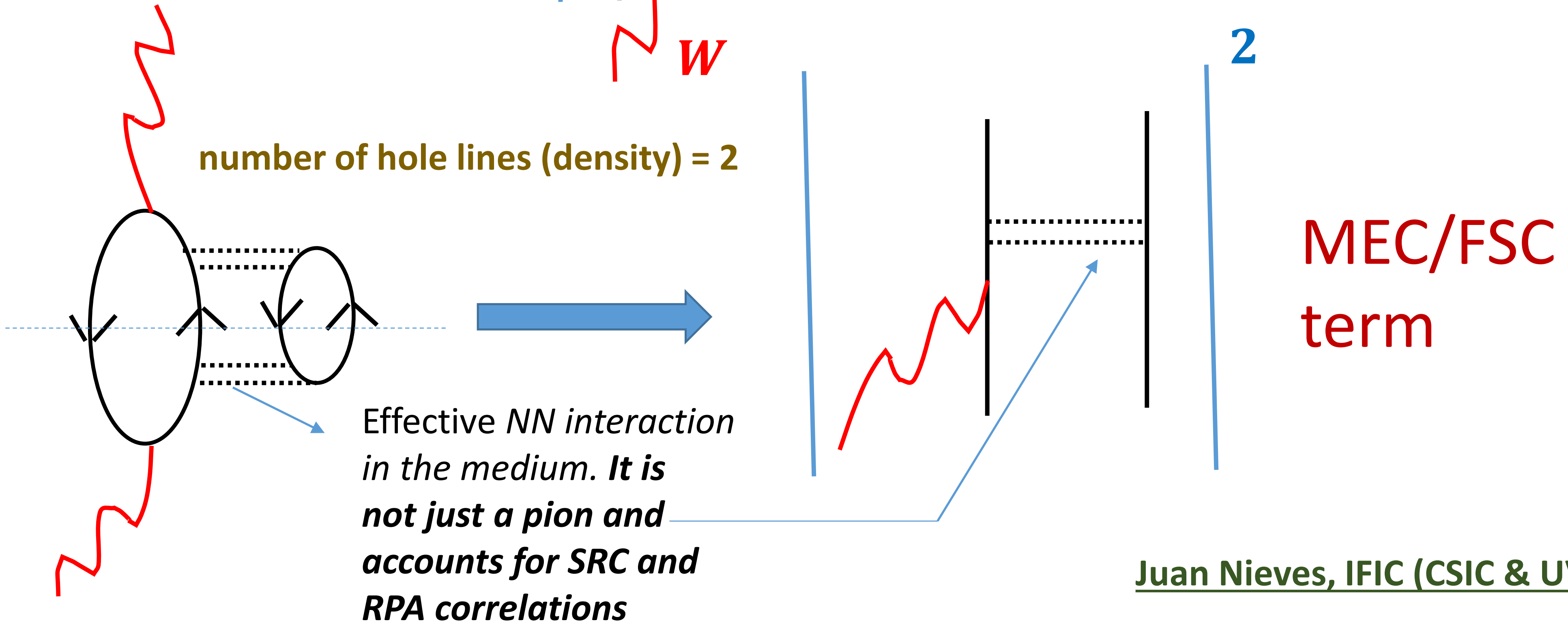
Scaling violations reside mainly in R_T: excitation of resonances, meson production, 2p2h mechanisms and even the tail of DIS. An experimental scaling function $f(\psi')$ could be reliably extracted by fitting the data for R_L.

ν QE cross sections can be calculated with the simple RgFG model followed by the replacement $f_{RgFG} \rightarrow f_{\exp}$.

Superscaling function does not take into account **dip region events**

MEC & FSC & ISC





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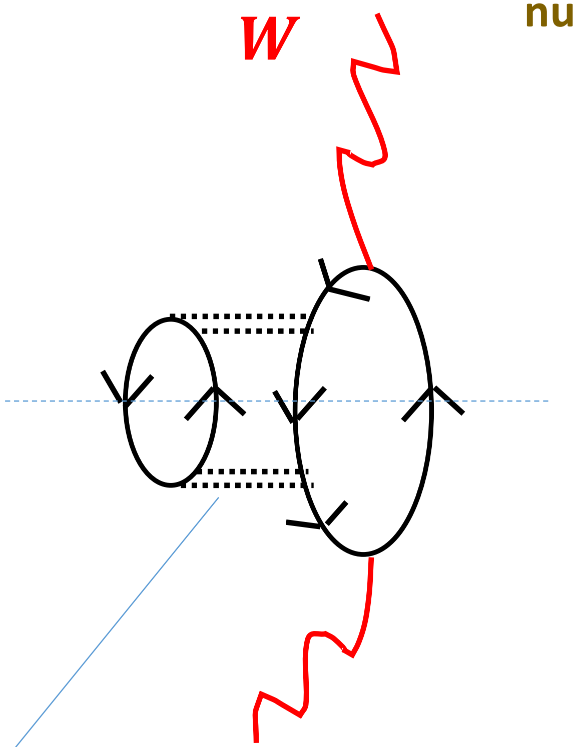
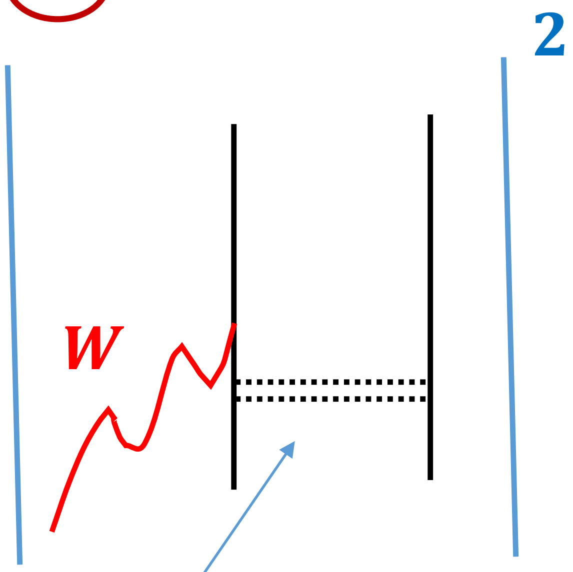
number of hole lines (density) = 4

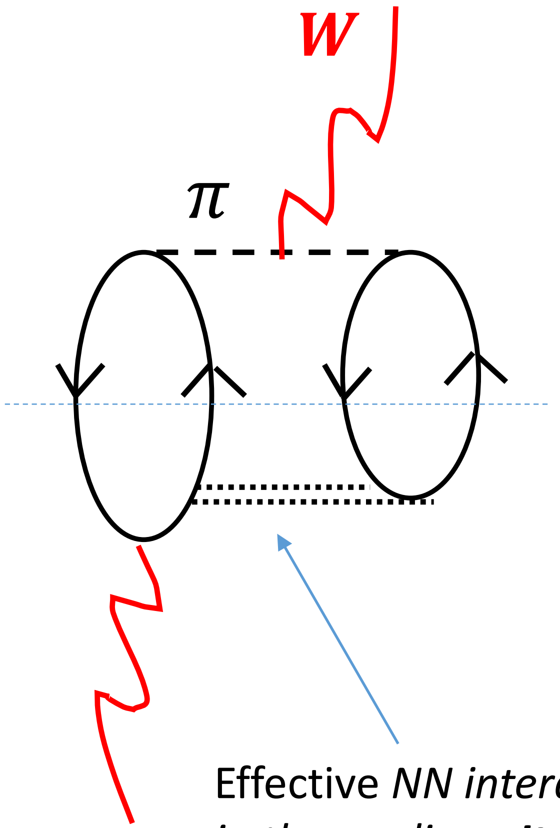




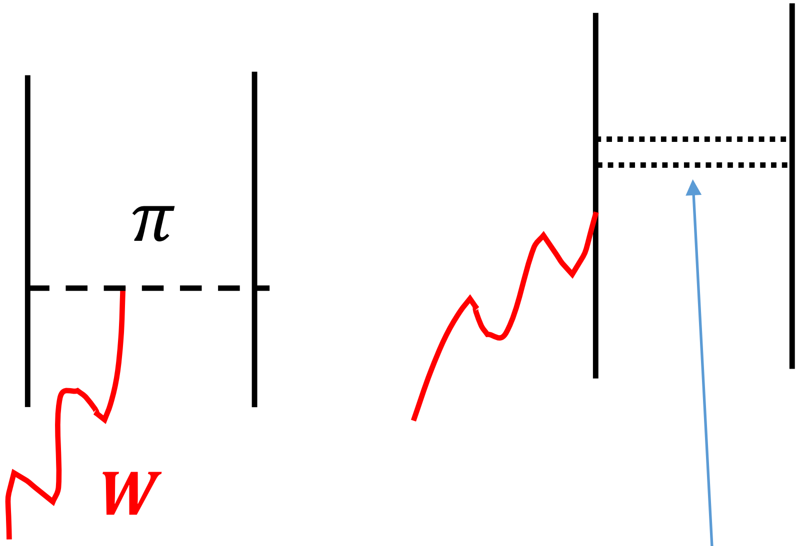
Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

MEC/ISC term

number of hole lines (density) = 2



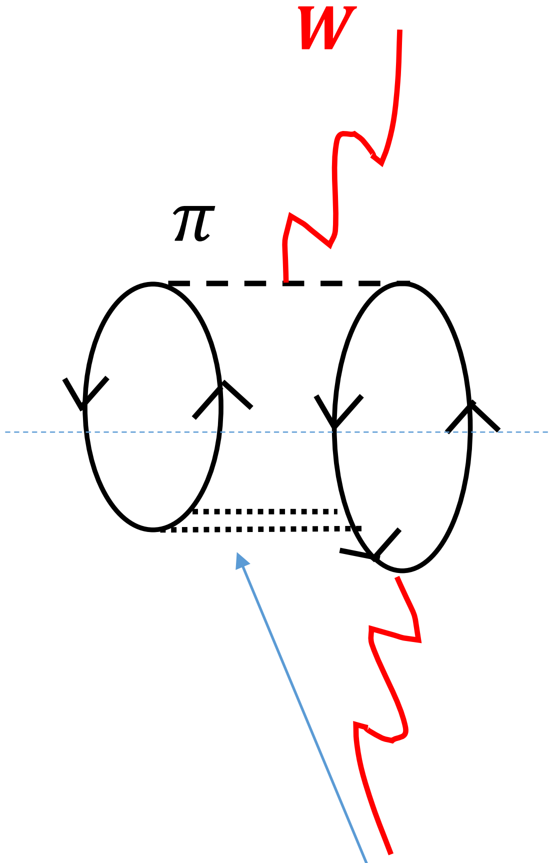
Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

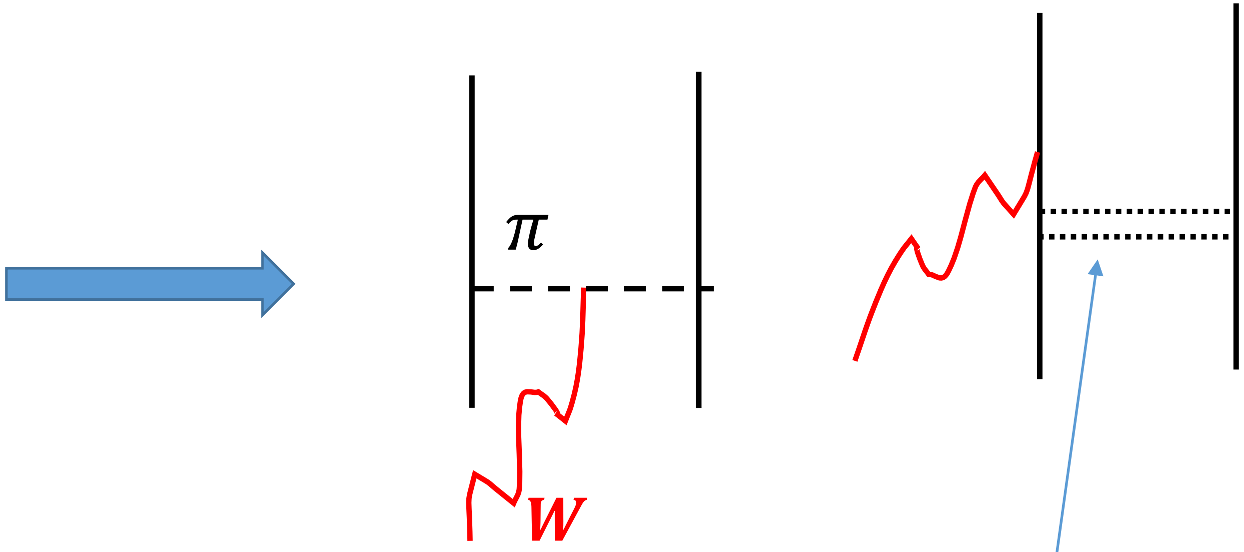


FSC-MEC interference term

MEC-ISC interference term

number of hole lines (density) = 3

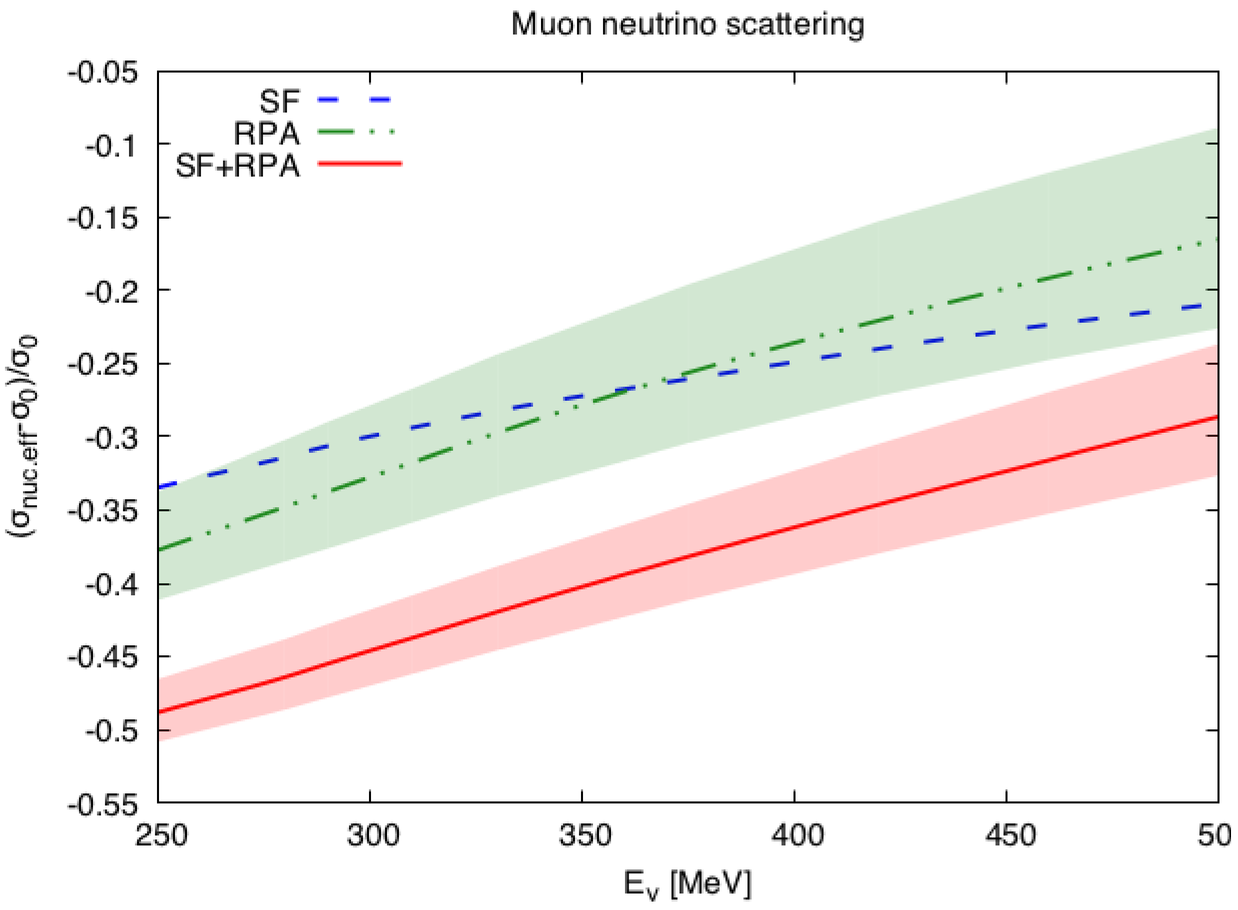




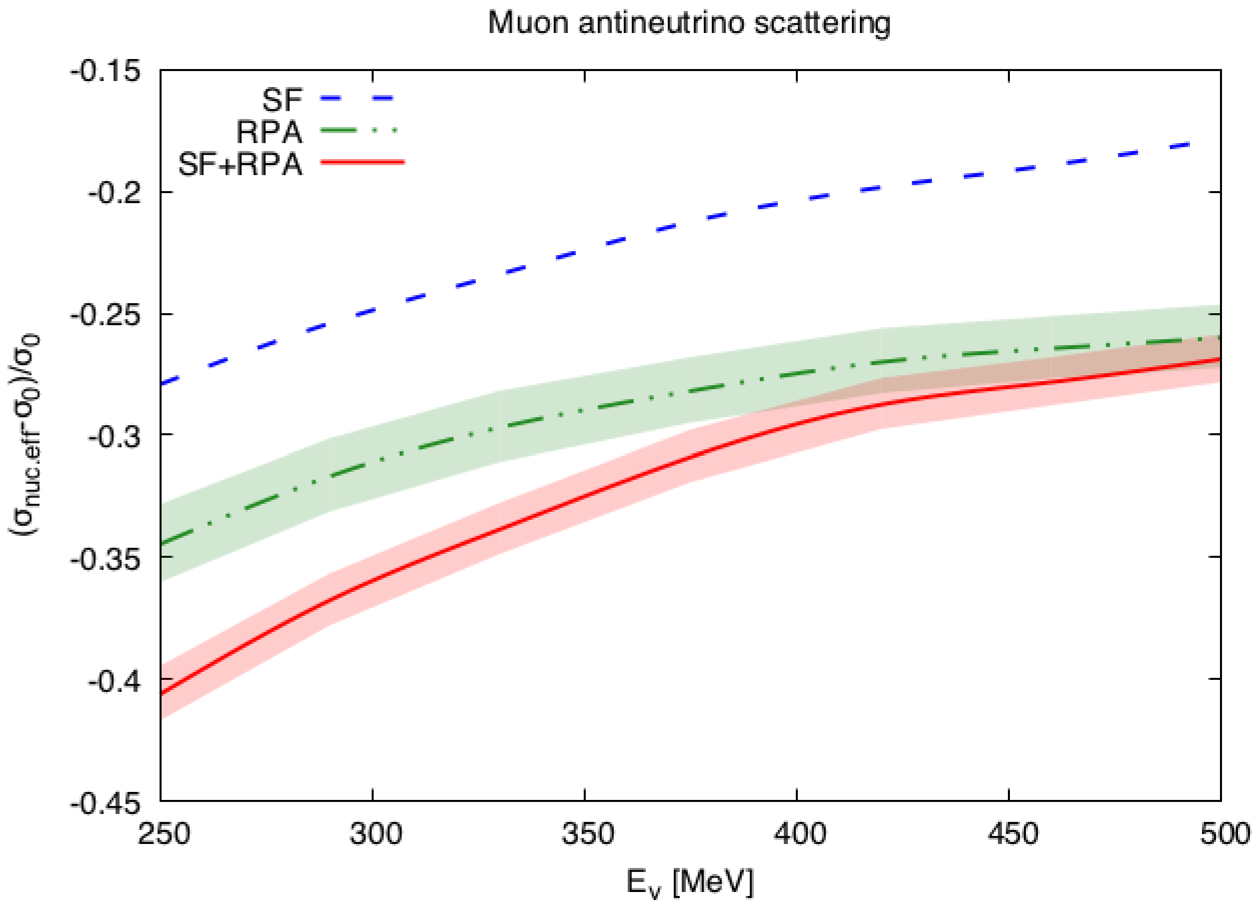
Important ?
Benhar, Lovato, Rocco [PRC 92 (2015) 024602]

Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

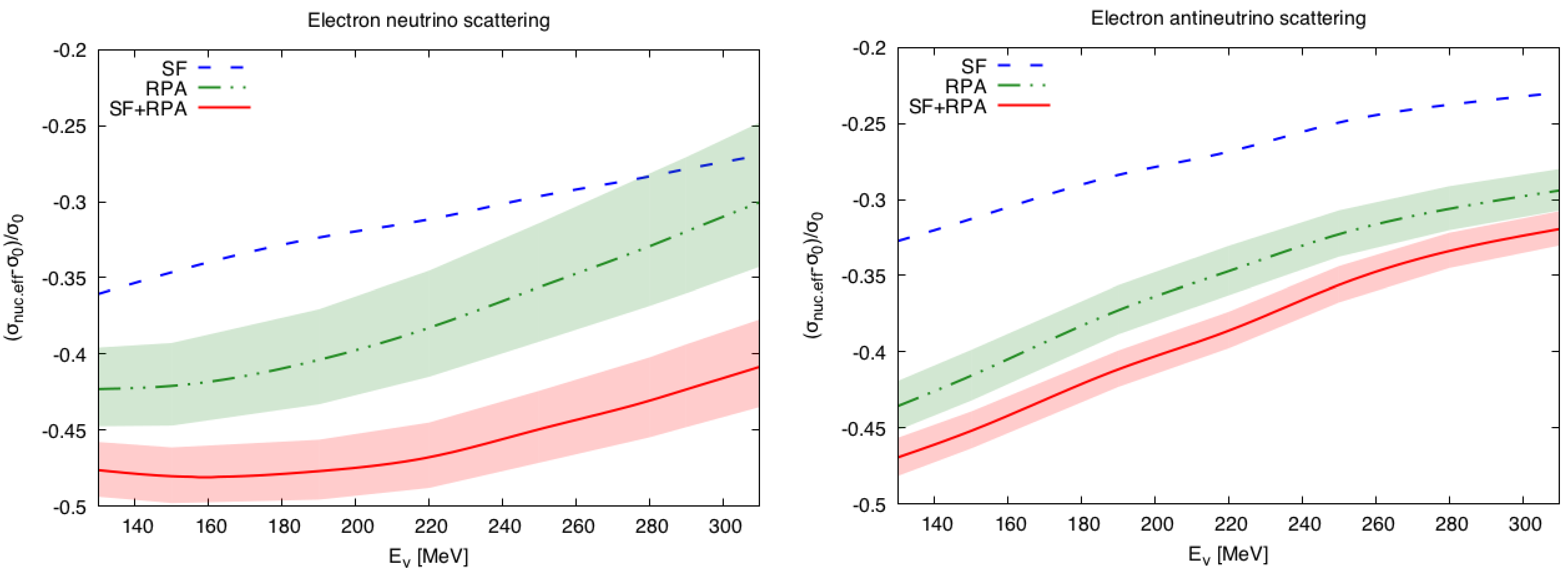
- **IFIC 2p2h calculation does not incorporate these terms.**
- **Martini et al. predictions are based on a 2p2h calculation for $(e, e'X)$ [Alberico et al.,] that accounts for such contributions (only vector current)**



Muon neutrino scattering
SF
RPA
SF+RPA
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
-0.55
250
300
350
400
450
50
$(\sigma_{nuc.eff}-\sigma_0)/\sigma_0$
E_ν [MeV]



Muon antineutrino scattering
SF
RPA
SF+RPA
-0.15
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
250
300
350
400
450
500
$(\sigma_{nuc.eff}-\sigma_0)/\sigma_0$
E_ν [MeV]


Electron neutrino scattering
SF
RPA
SF+RPA
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
140
160
180
200
220
240
260
280
300
E_ν [MeV]
$(\sigma_{nuc.eff}-\sigma_0)/\sigma_0$
Electron antineutrino scattering
SF
RPA
SF+RPA
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
140
160
180
200
220
240
260
280
300
E_ν [MeV]
$(\sigma_{nuc.eff}-\sigma_0)/\sigma_0$