2p2h excitations, MEC, nucleon correlations and other sources of QE-like events

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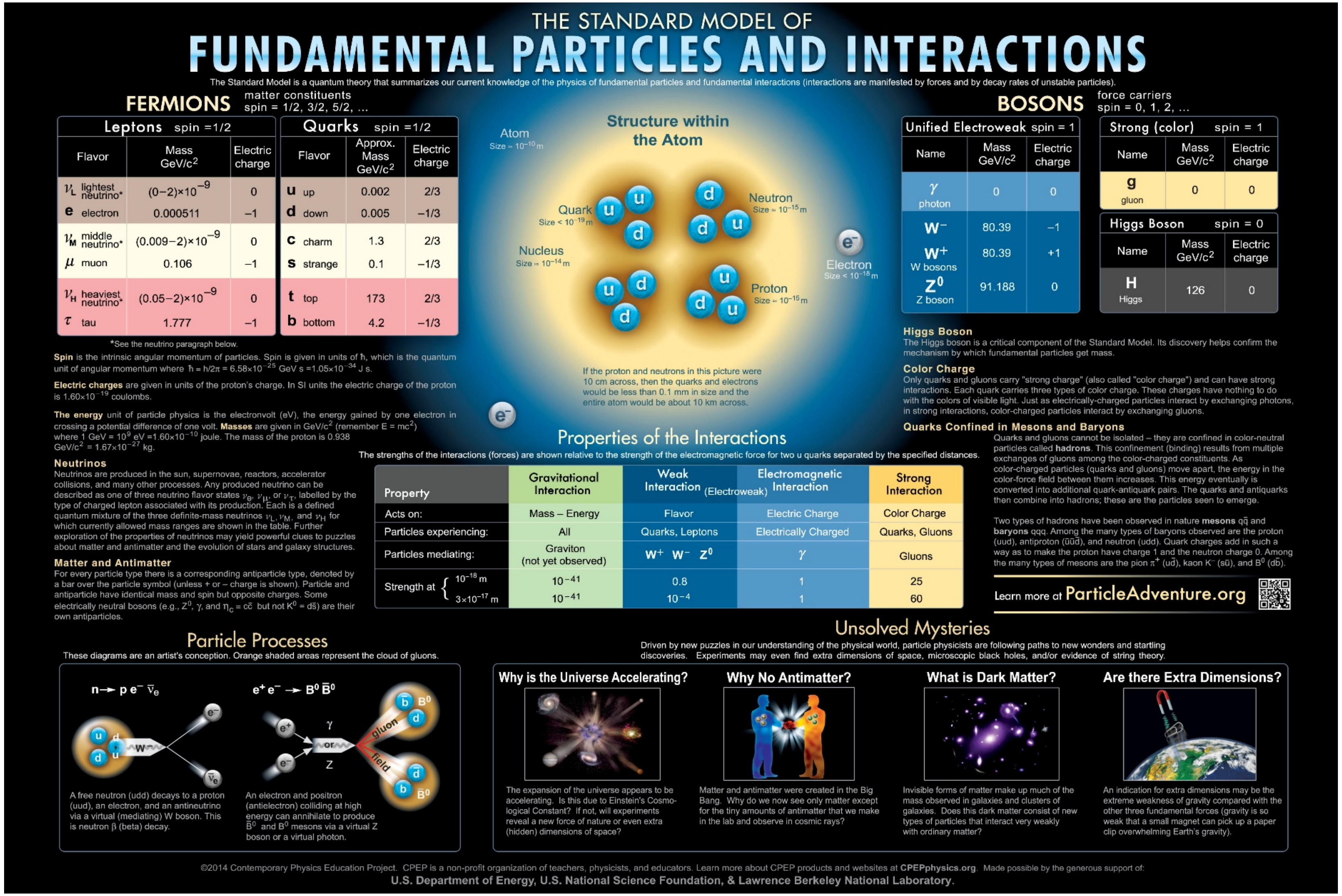
Outline

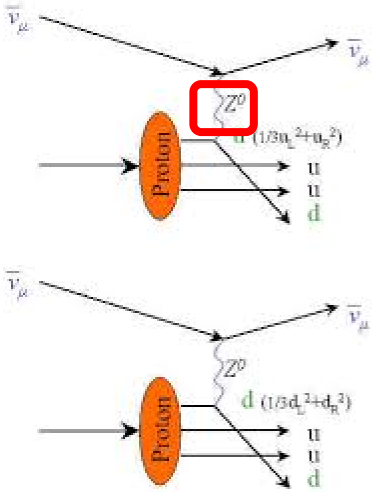
1. Motivation: Neutrino oscillations, neutrino detectors, nuclear cross sections
2. Neutrino-nucleus inclusive QE scattering: Multinucleon mechanisms, RPA correlations and MiniBooNE M_A puzzle
3. Neutrino energy reconstruction
4. Conclusions

Further details:

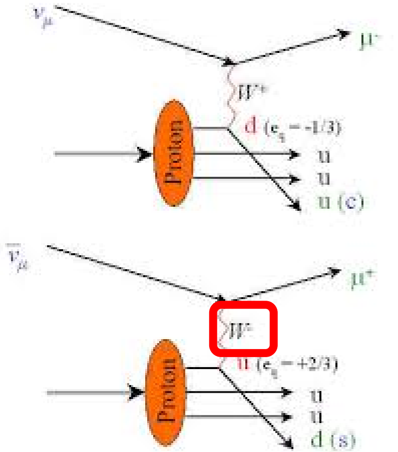
- **Alvarez-Ruso L., Hayato Y. and Nieves J.: *Progress and open questions in the physics of neutrino cross sections.:* New J.Phys. 16 (2014) 075015**
- **Morfin J. G., Nieves J. and Sobzcyk J.T.: *Recent Developments in Neutrino/Antineutrino - Nucleus Interactions.:* Adv.High Energy Phys. 2012 (2012) 934597**
- arXiv:1307.8105: PRD 88 (2013) 113007 ($\nu, \bar{\nu}$ CCQE-like up to 10 GeV)
- arXiv:1302.0703: PLB 721 (2013) 90 ($\bar{\nu}$ CCQE-like)
- arXiv:1204.5404: PRD 85 (2012) 113008 (E_ν reconstruct.)
- arXiv:1106.5374: PLB 707 (2012) 72 (ν CCQE-like)
- 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)

1. Motivation: Neutrino oscillations, neutrino detectors and nuclear cross sections





Neutral Current (NC)



Charged Current (CC)

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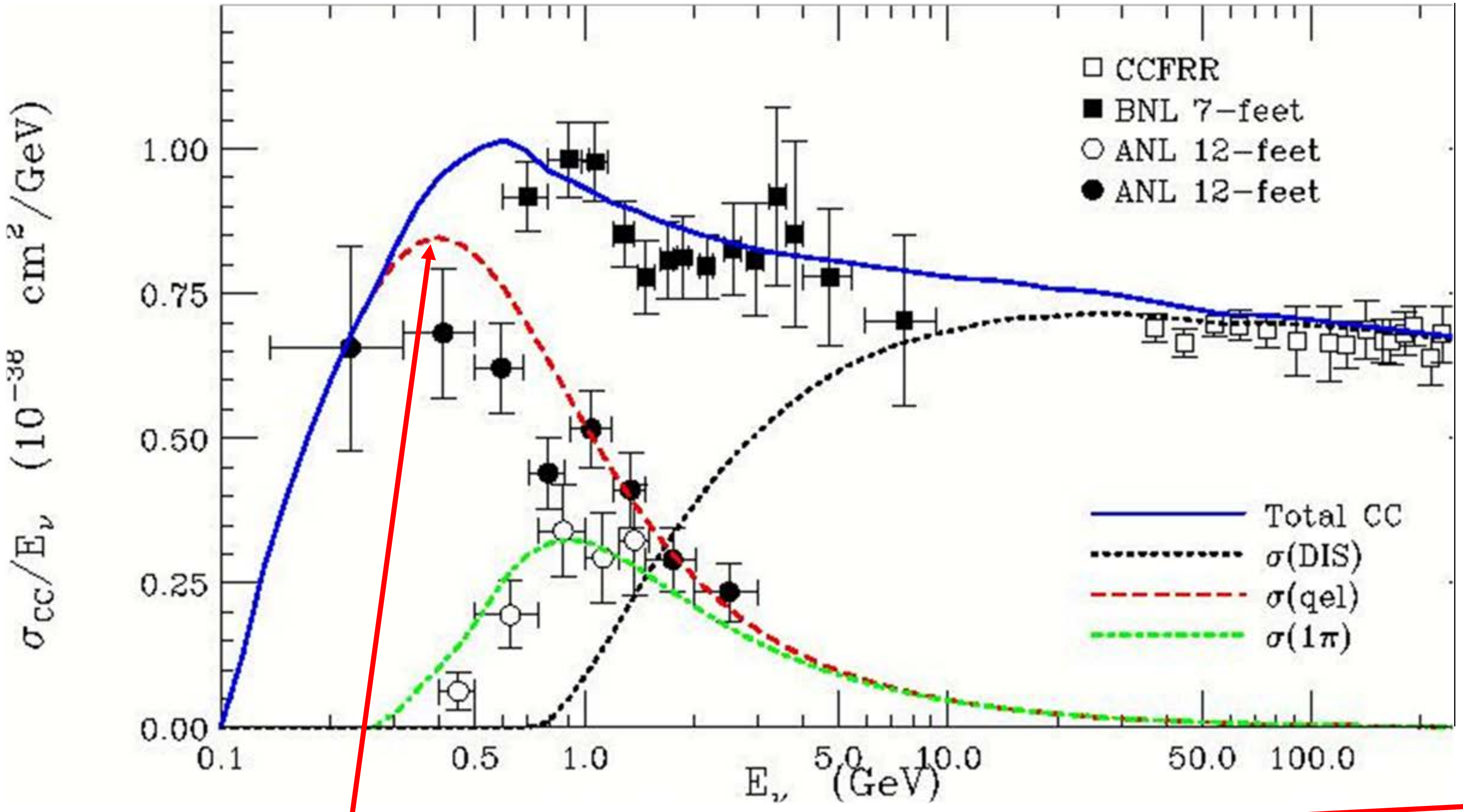
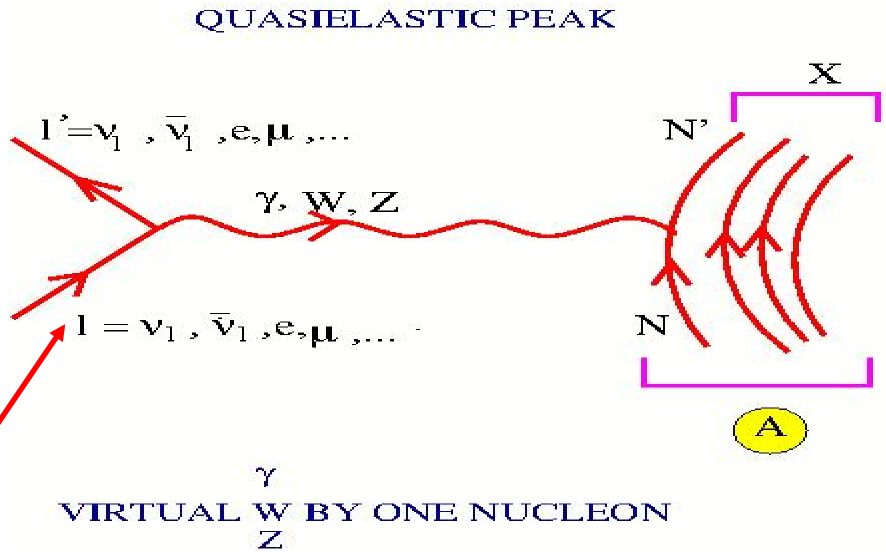
Motivation: Details on the axial structure of hadrons in the free space and inside of nuclei, and

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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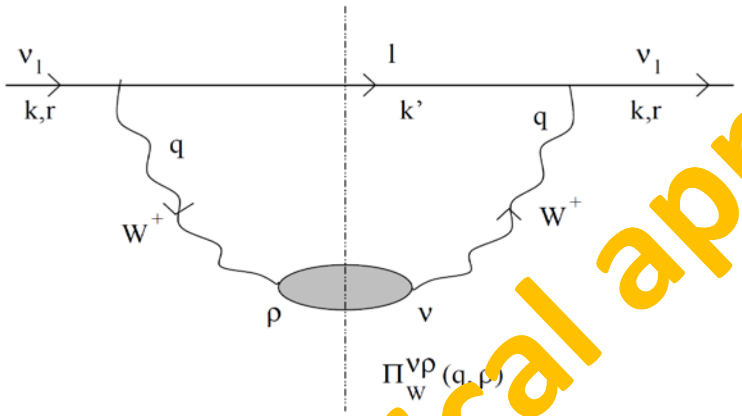
Theoretical approach

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



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

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

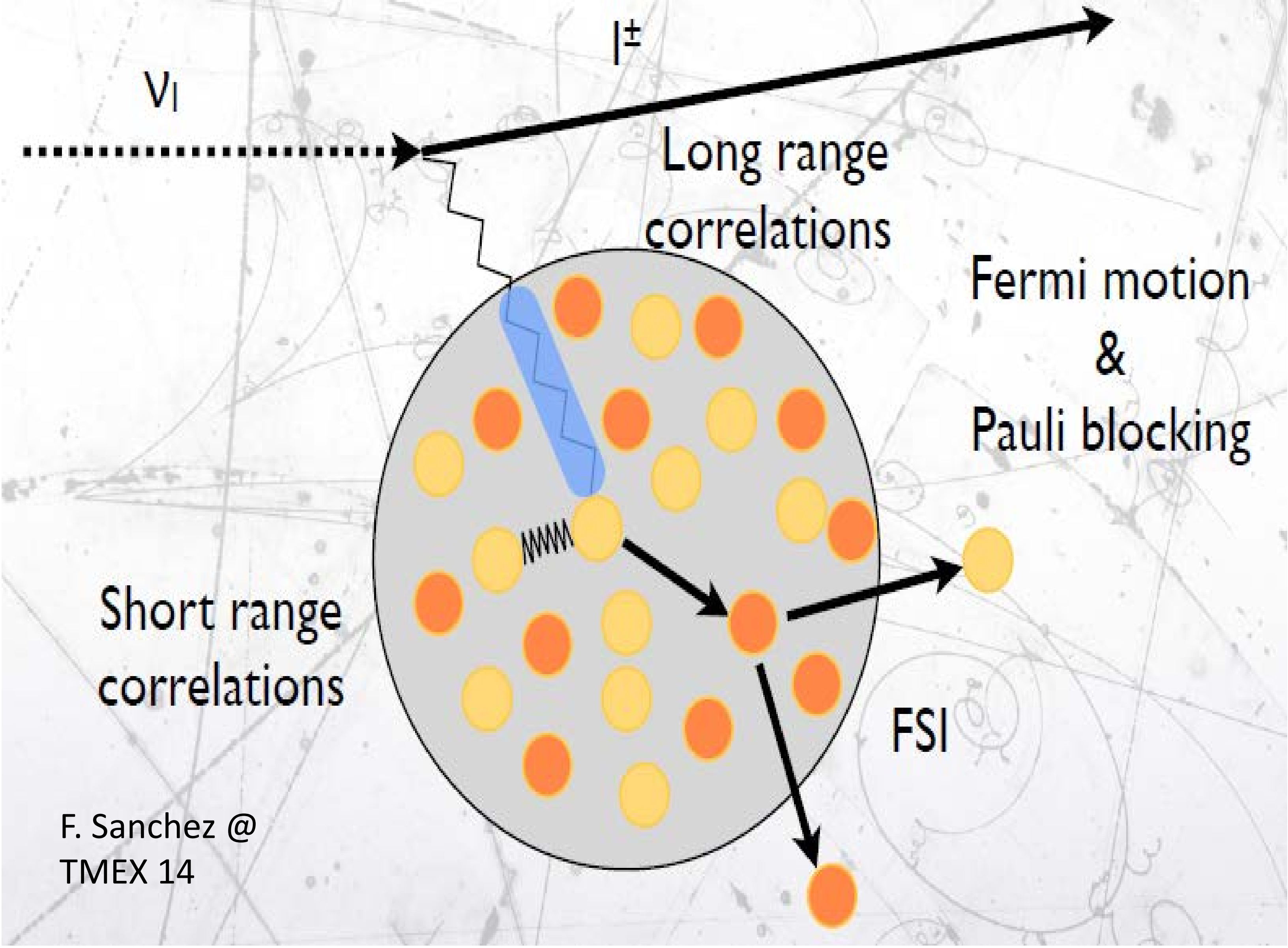
$$W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i}W_a^{\mu\sigma}$$

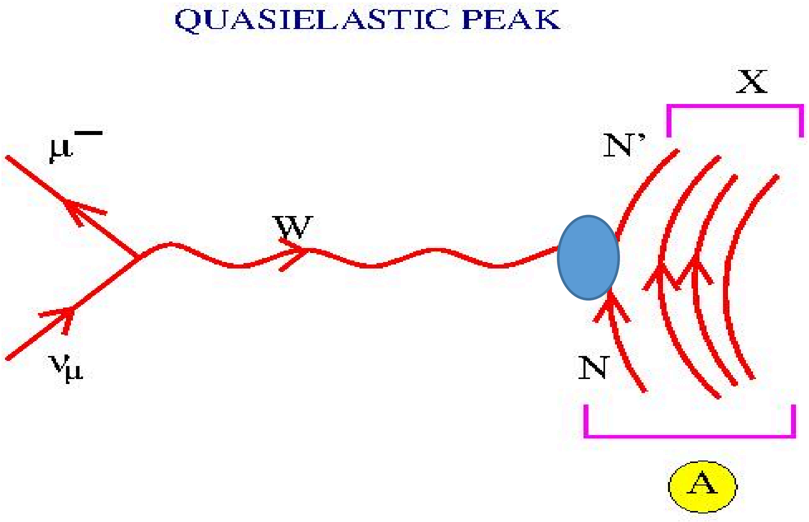
$$W_s^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\,\mathrm{Im}\,\left\{\Pi_W^{\mu\sigma}(q,\rho) + \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

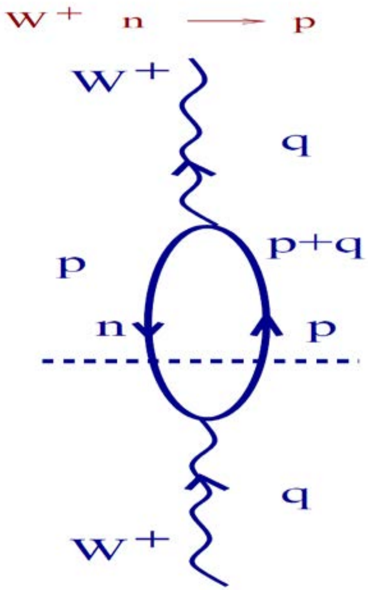
$$W_a^{\mu\sigma} \propto \int \frac{d^3r}{2\pi}\,\mathrm{Re}\,\left\{\Pi_W^{\mu\sigma}(q,\rho) - \Pi_W^{\sigma\mu}(q,\rho)\right\}\Theta(q^0)$$

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...

2. Neutrino-nucleus inclusive QE scattering : MiniBooNE M_A puzzle







1p1h excitation

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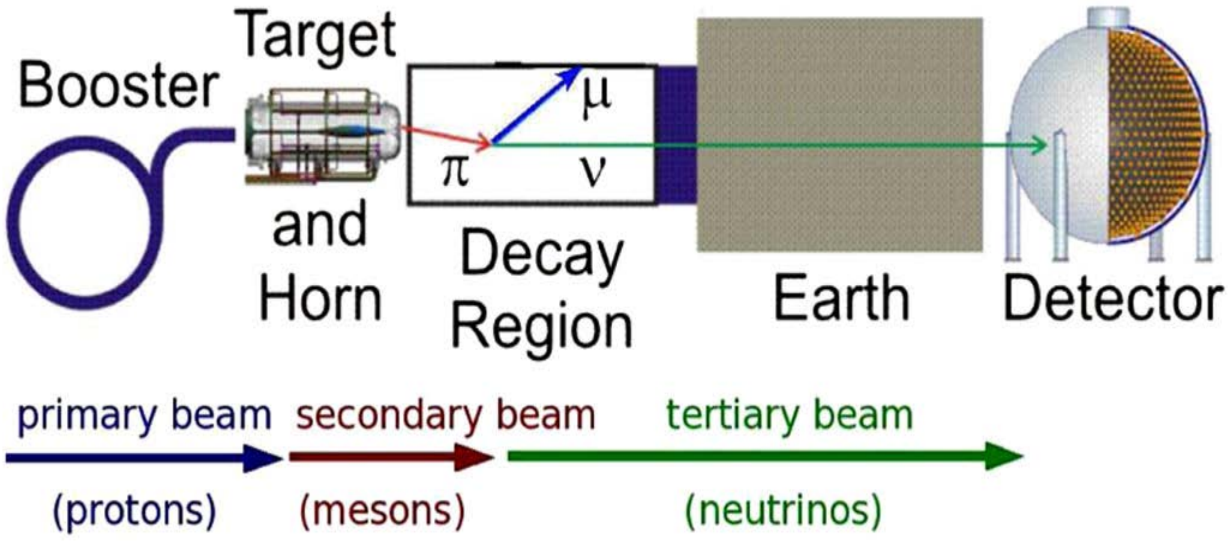
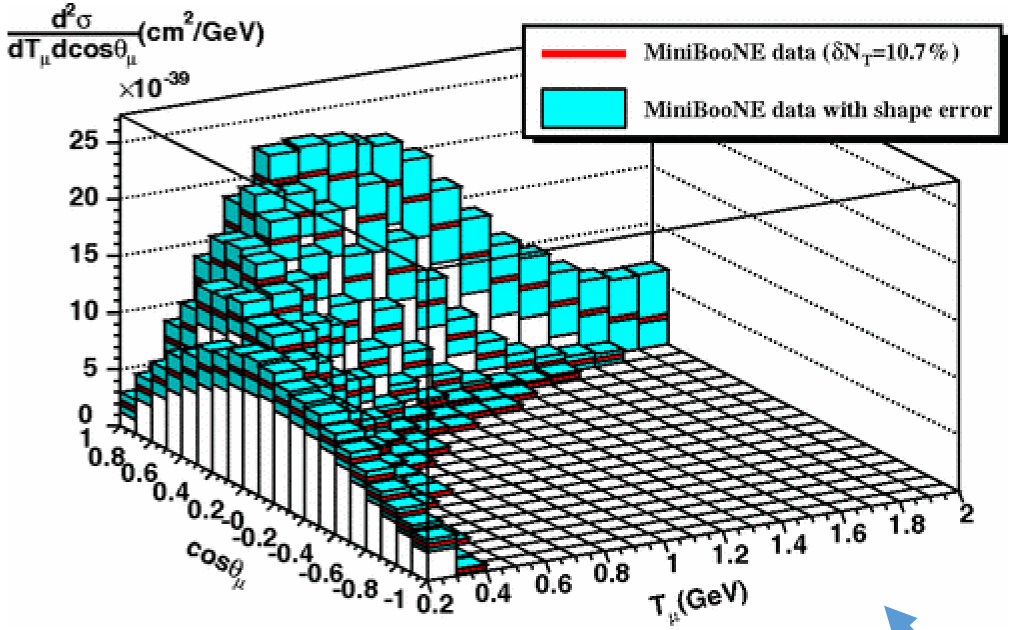
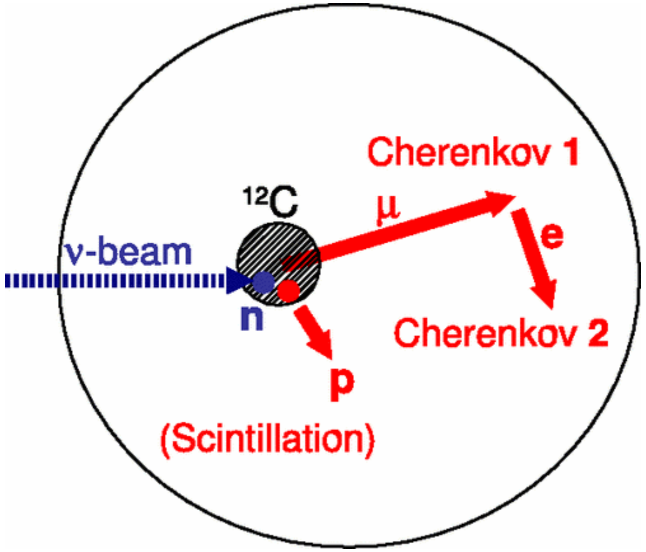
MiniBooNE CCQE (PRD 81, 092005)







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

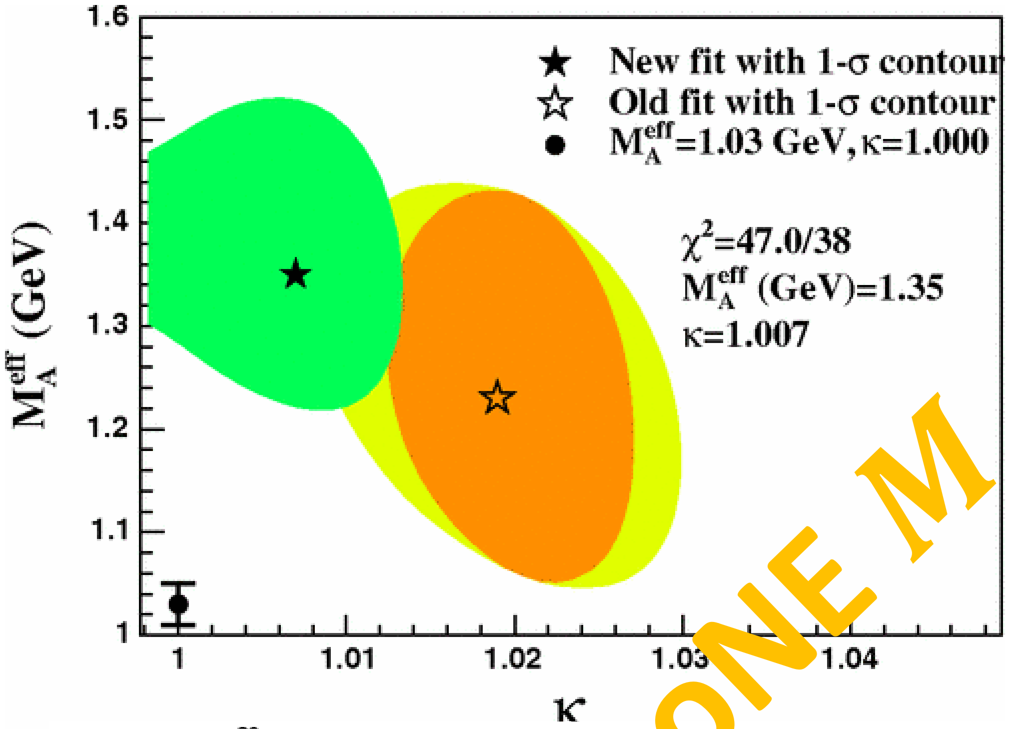
1 muon events !

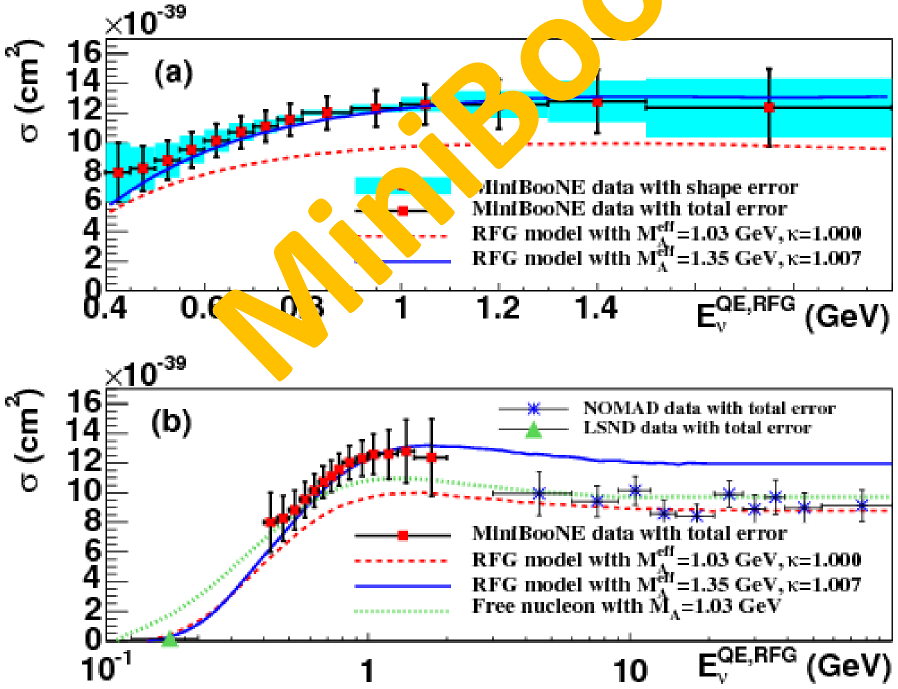
The largest background is from CC single pion production: CC1π^+

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

2 muon events

MiniBooNE M_A puzzle



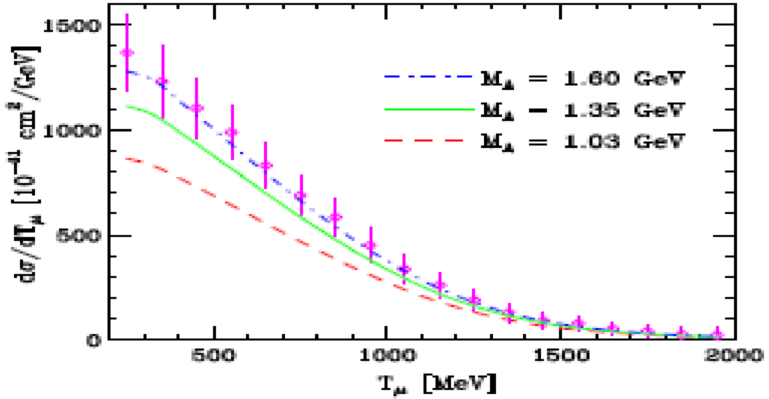


$M_A^{eff} = 1.35$ GeV

vs

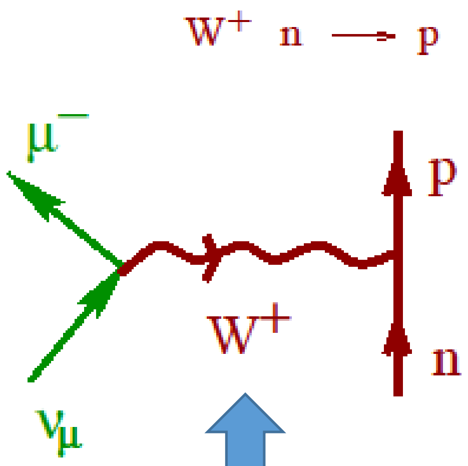
1.03 GeV (world avg)

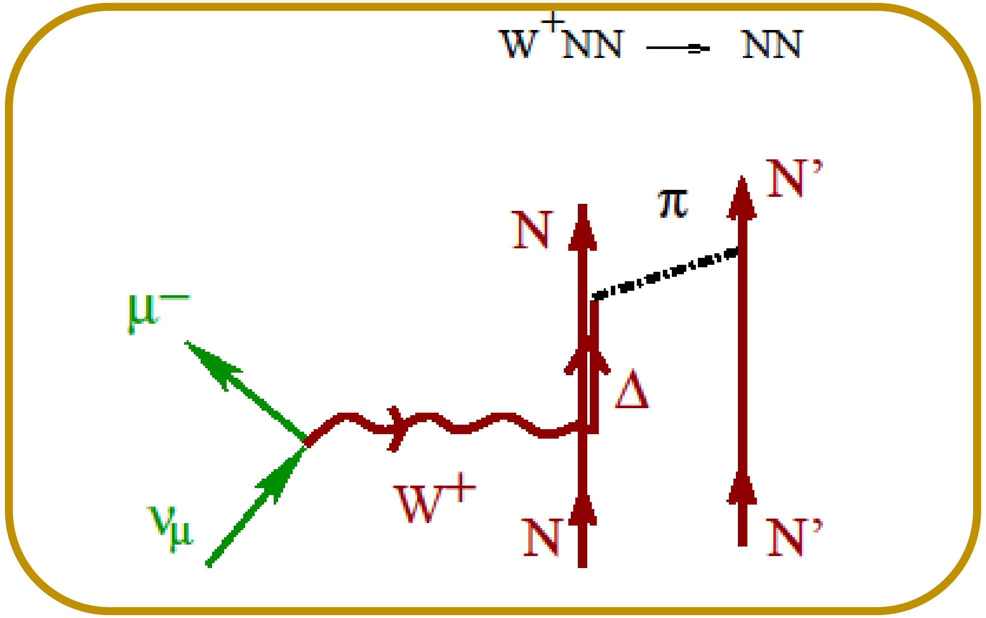
confirmed by many other groups, for instance by Benhar et al. (PRL 105, 132301)

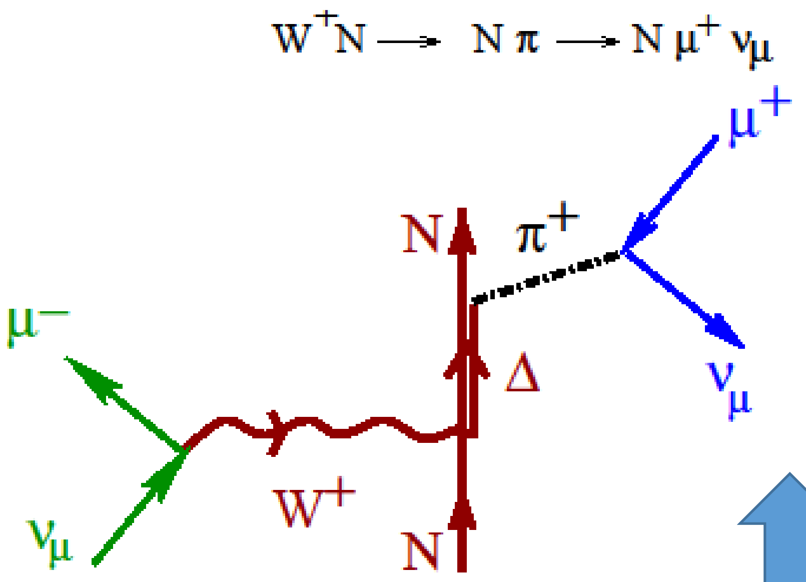


ChPT O(p^3) + single pion electroproduction data: $M_A = 1.014 \pm 0.016$ GeV (V. Bernard, N. Kaiser, and U. G.Meissner, PRL69, 1877 (1992))

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





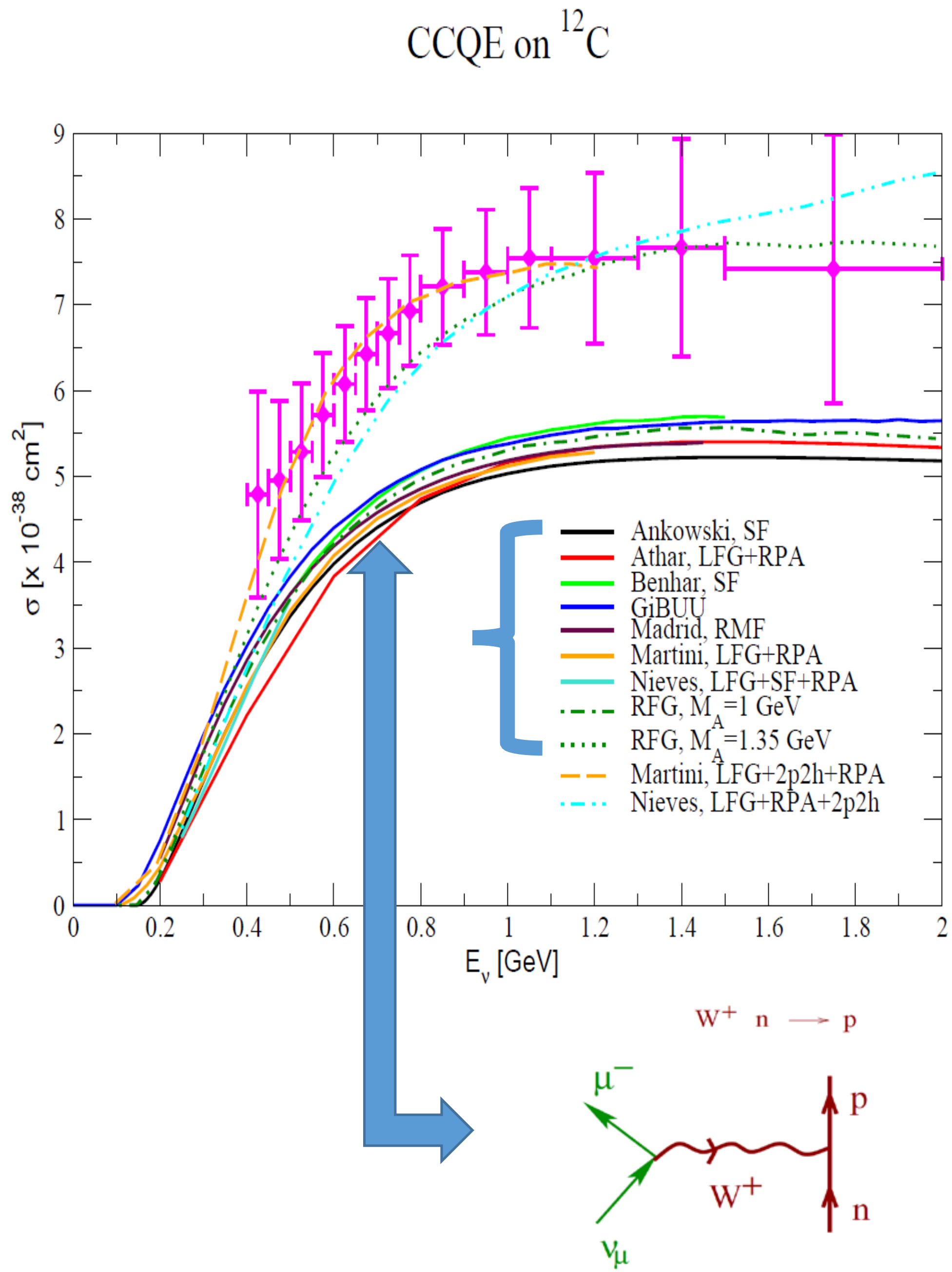


...but key observation (Martini et al., PRC 81, 045502): in most theoretical works QE is used for processes where the gauge boson $W^{\pm}$ or Z^{0} is absorbed by just one nucleon, which together with a lepton is emitted.

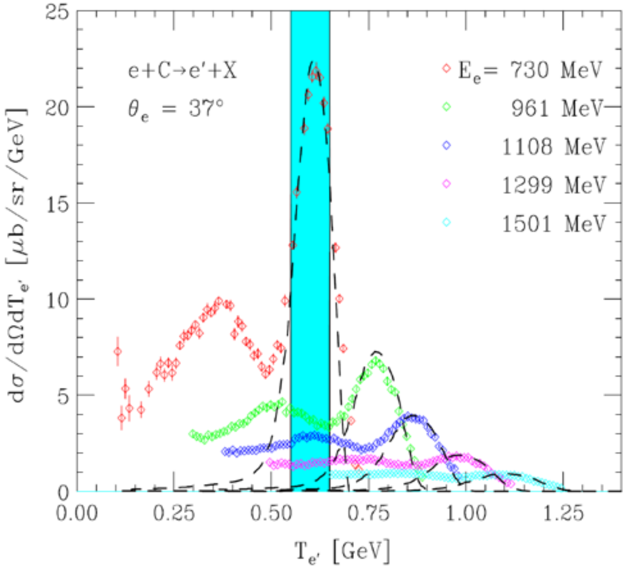
However in the recent MiniBooNE measurements, QE is related to processes in which only a muon is detected (ejected nucleons are not detected !) ≡ **CCQE-like**

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!**

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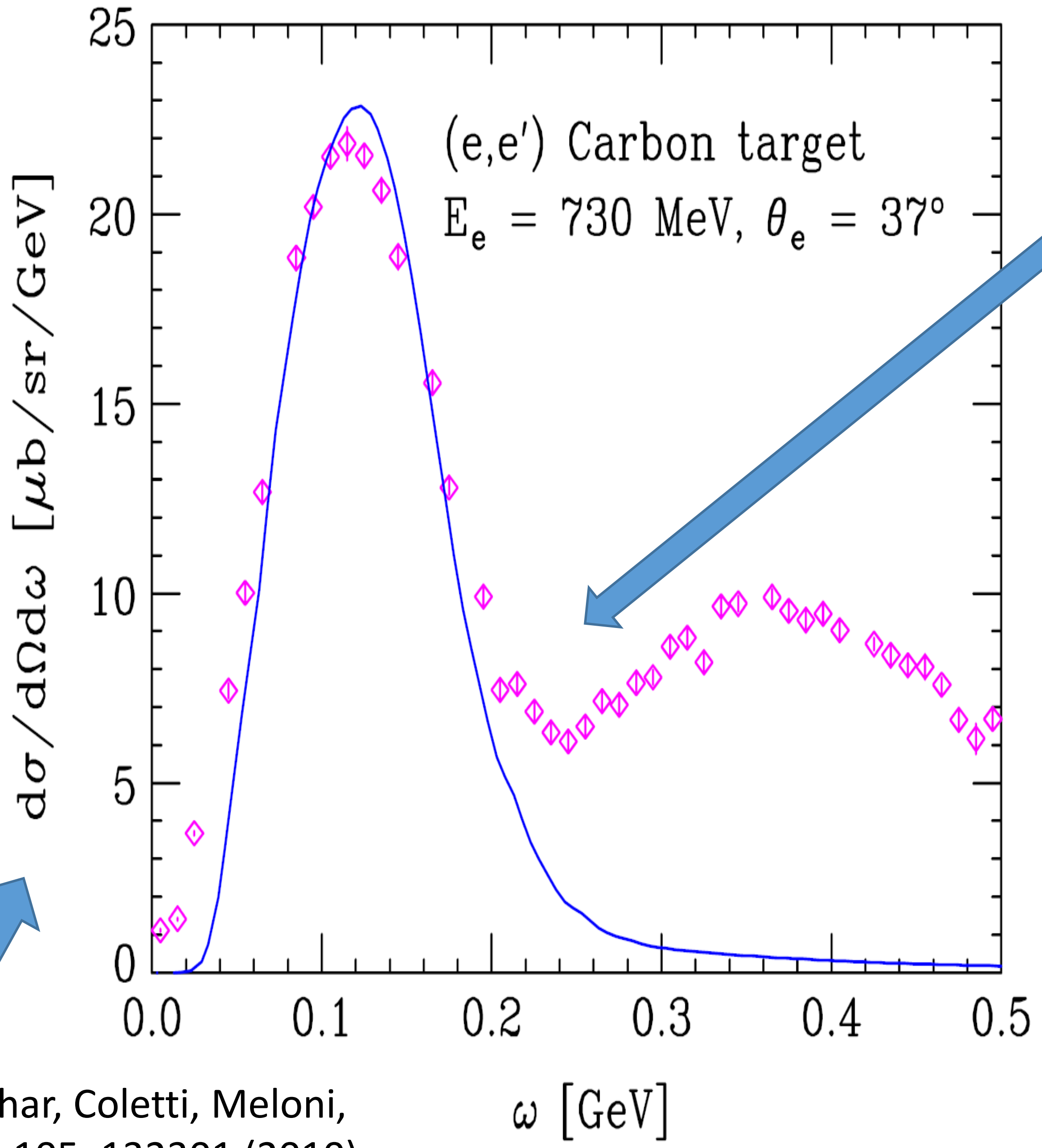
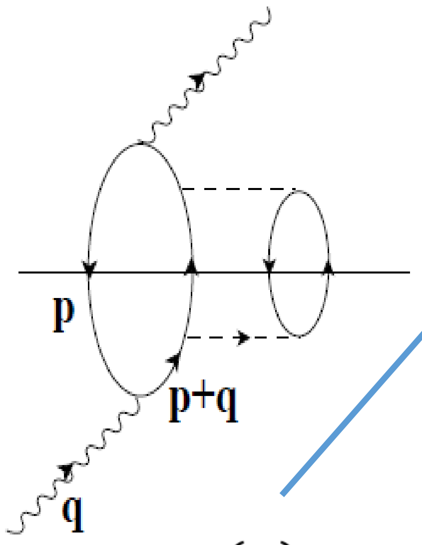


Benhar, Coletti, Meloni,
PRL 105, 132301 (2010)

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

- 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)



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

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

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 !!

The simplest description ⇒ relativistic Fermi Gas with non interacting fermions $\boxed{\Sigma = 0}$,

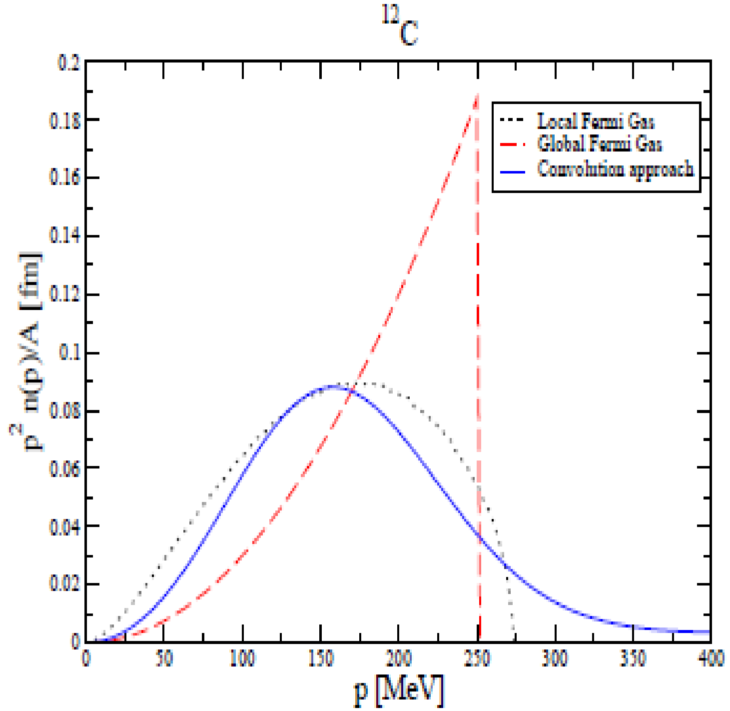
$$S_p(\omega,\vec{p}) = \frac{\theta(|\vec{p}\,| - k_F)}{2E(\vec{p})}\delta(\omega - E(\vec{p}))$$

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

and only Pauli blocking is incorporated!!

Local vs Global Fermi Gas ?

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



Local vs Global Fermi Gas ?

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

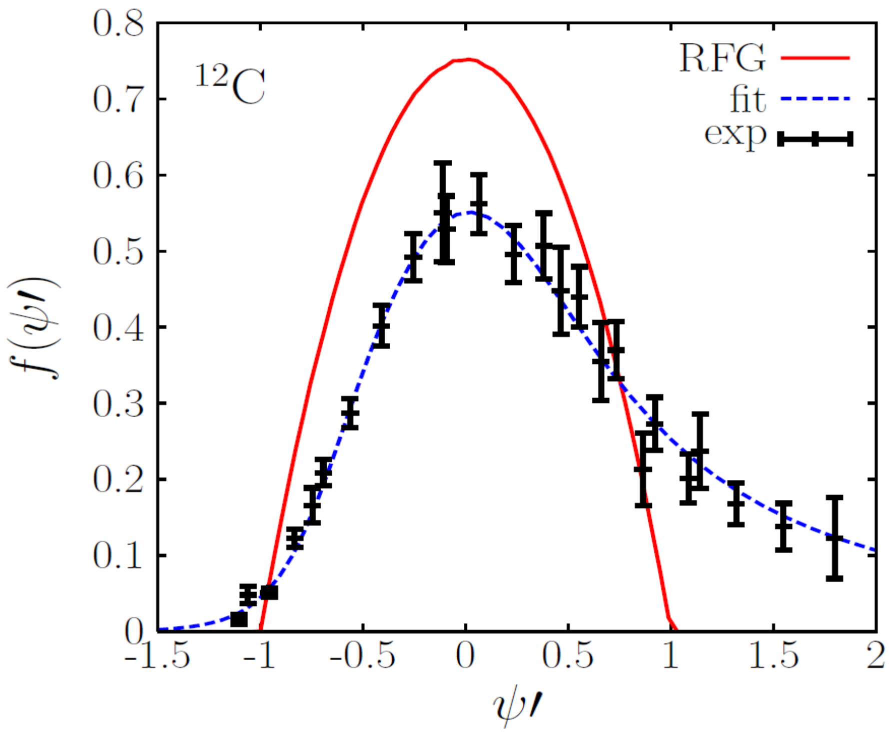
$$S_h(\omega,\vec{p}) = \delta(\omega - E(\vec{p}))\theta(k_F - |\vec{p}\,|)/2\omega$$

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

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

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

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



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** $f_{RgFG} \to f_{\exp}$.

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

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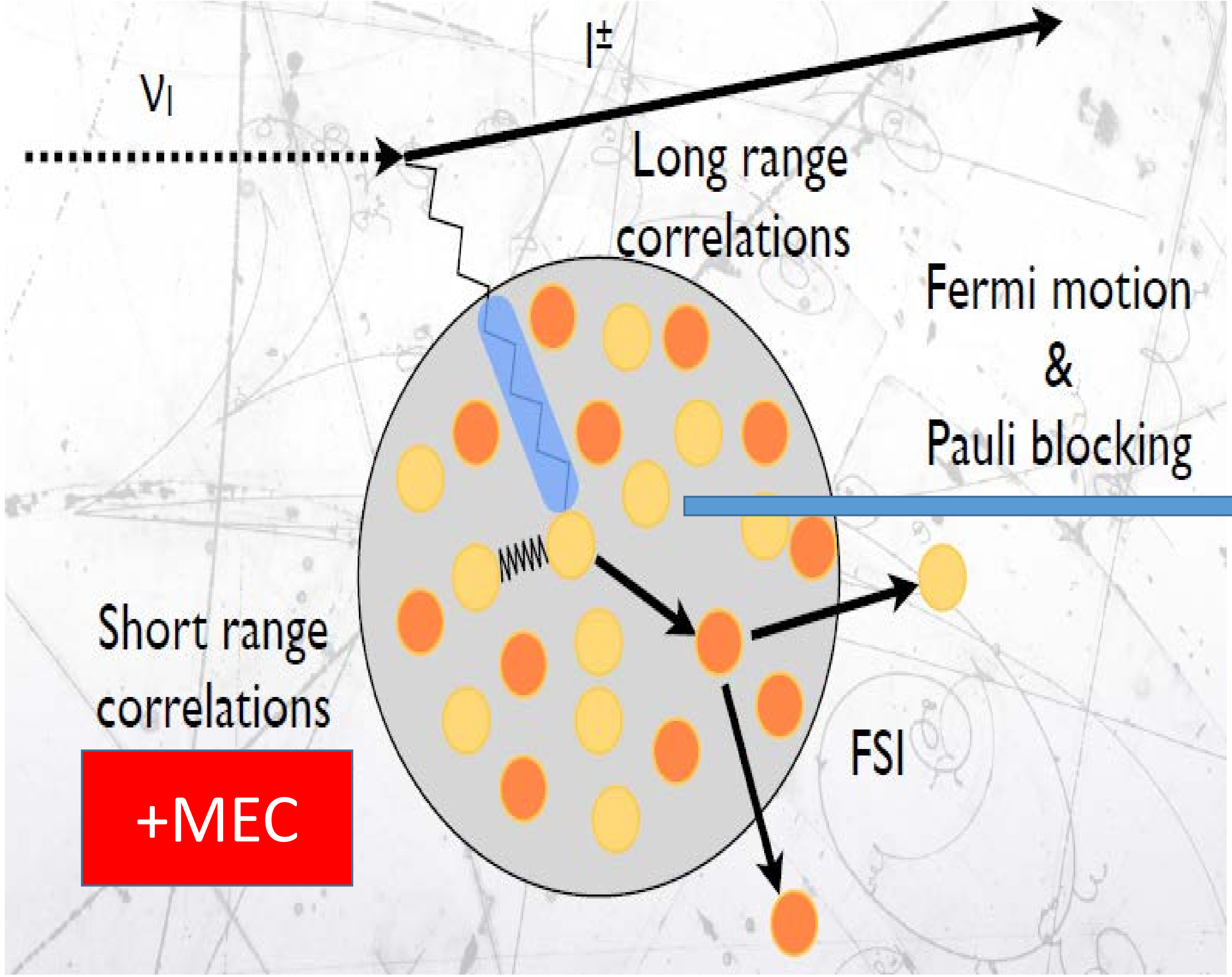
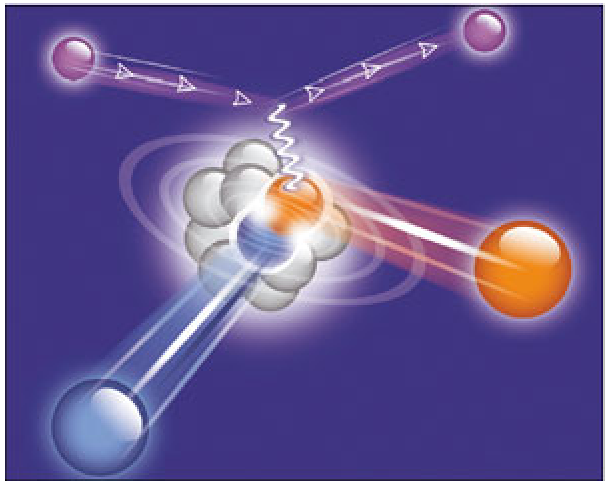
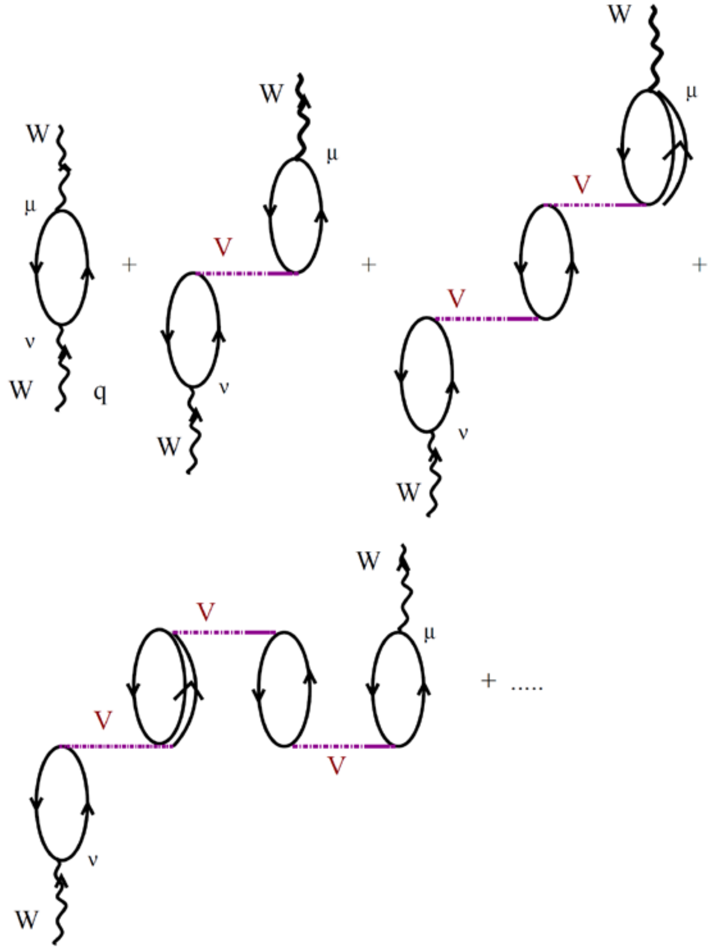




Solution:

Multinucleon mechanisms and Long range RPA correlations (renormalization of the interactions inside of a nuclear medium...)

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



1. Effective Landau-Migdal interaction

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

Isoscalar terms □ do not contribute to CC

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

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

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

3. Contribution of Δh excitations important

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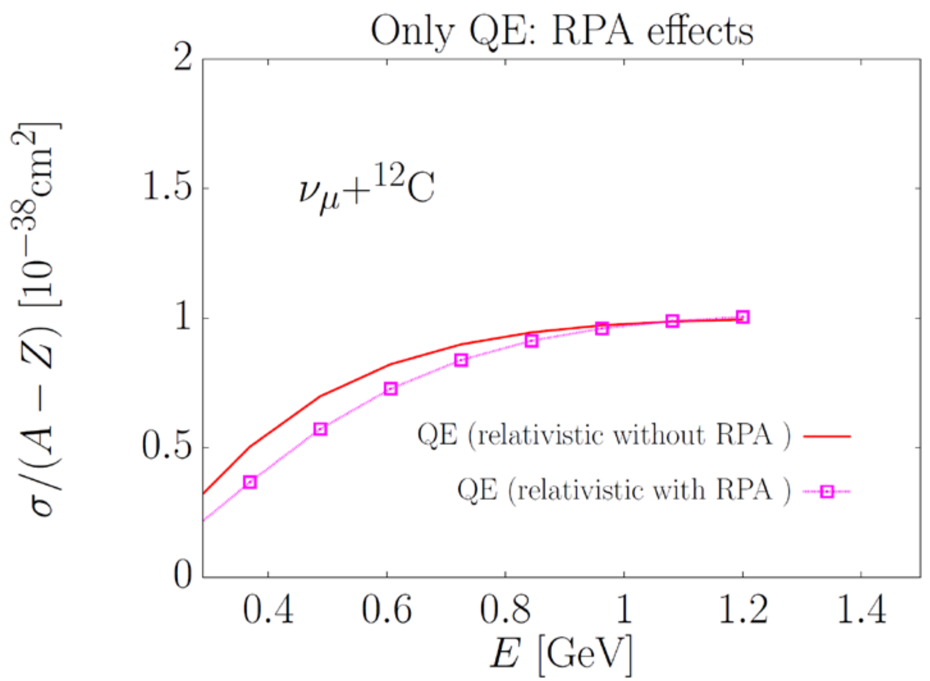

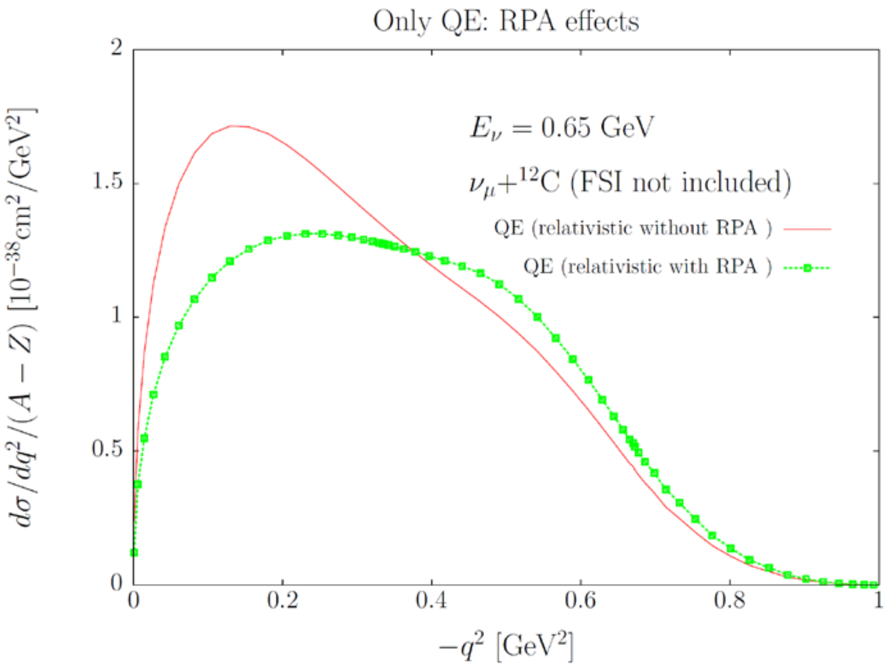

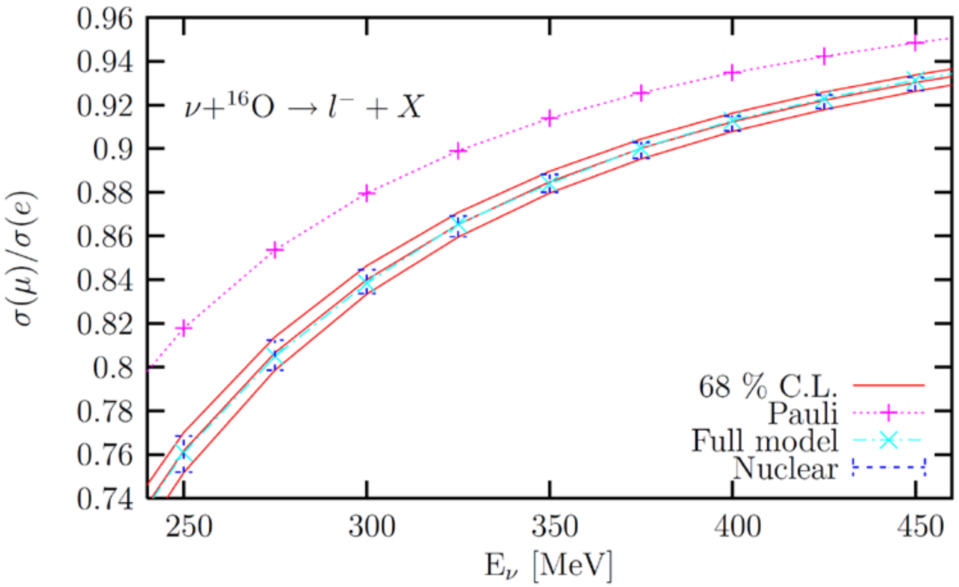

RPA corrections strongly decrease as the neutrino energy increases. However, their effects might account for a low Q^2 deficit of CCQE events and affect the σ_μ/σ_e ratio (~ 5 %)

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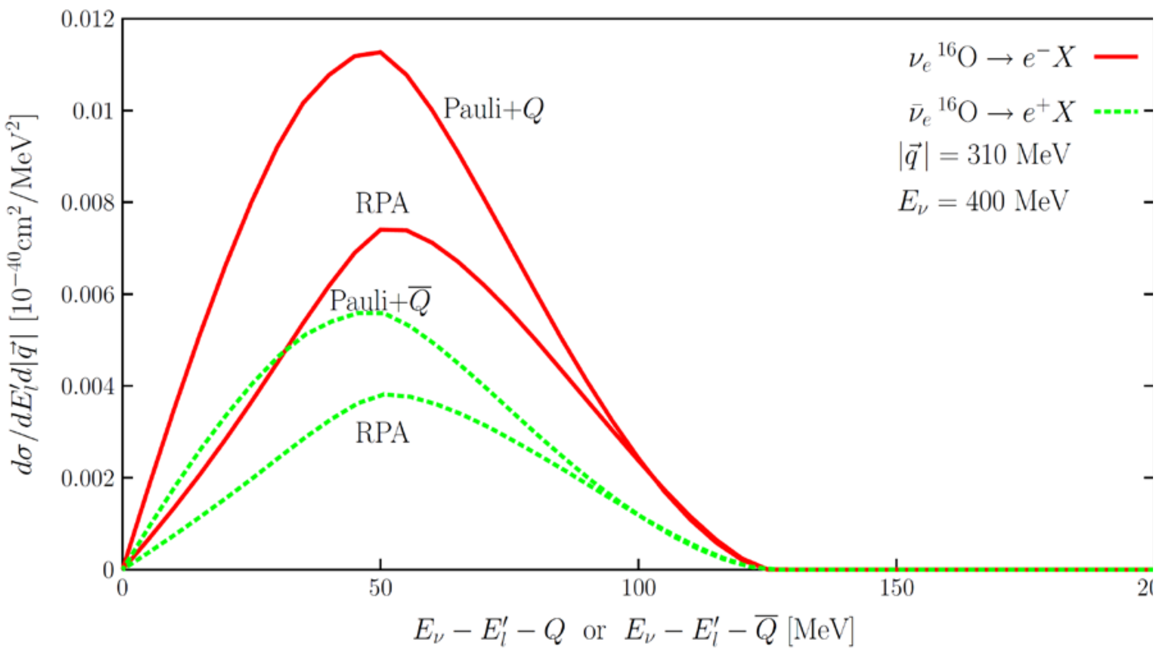
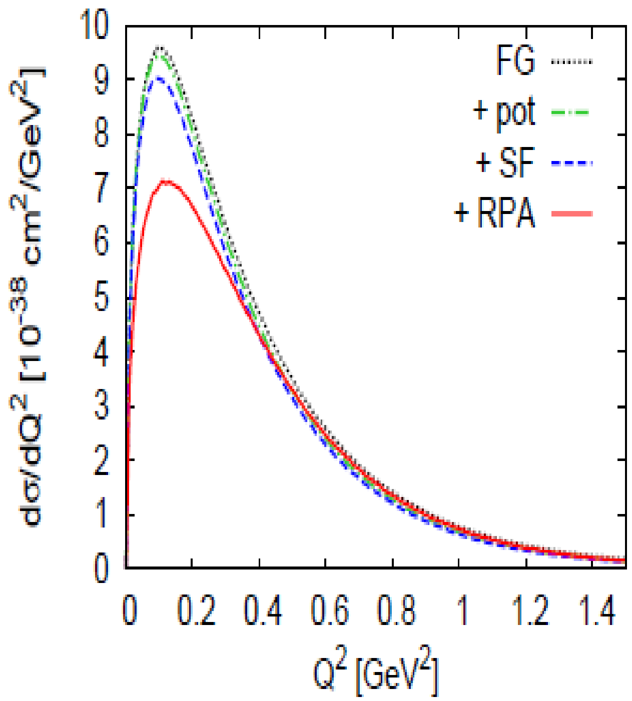
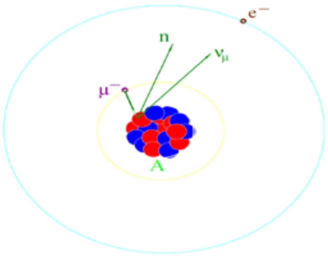






Inclusive Muon Capture: $\Gamma\left[(A_Z - \mu^-)^{1s}_{\mathrm{bound}}\right]$

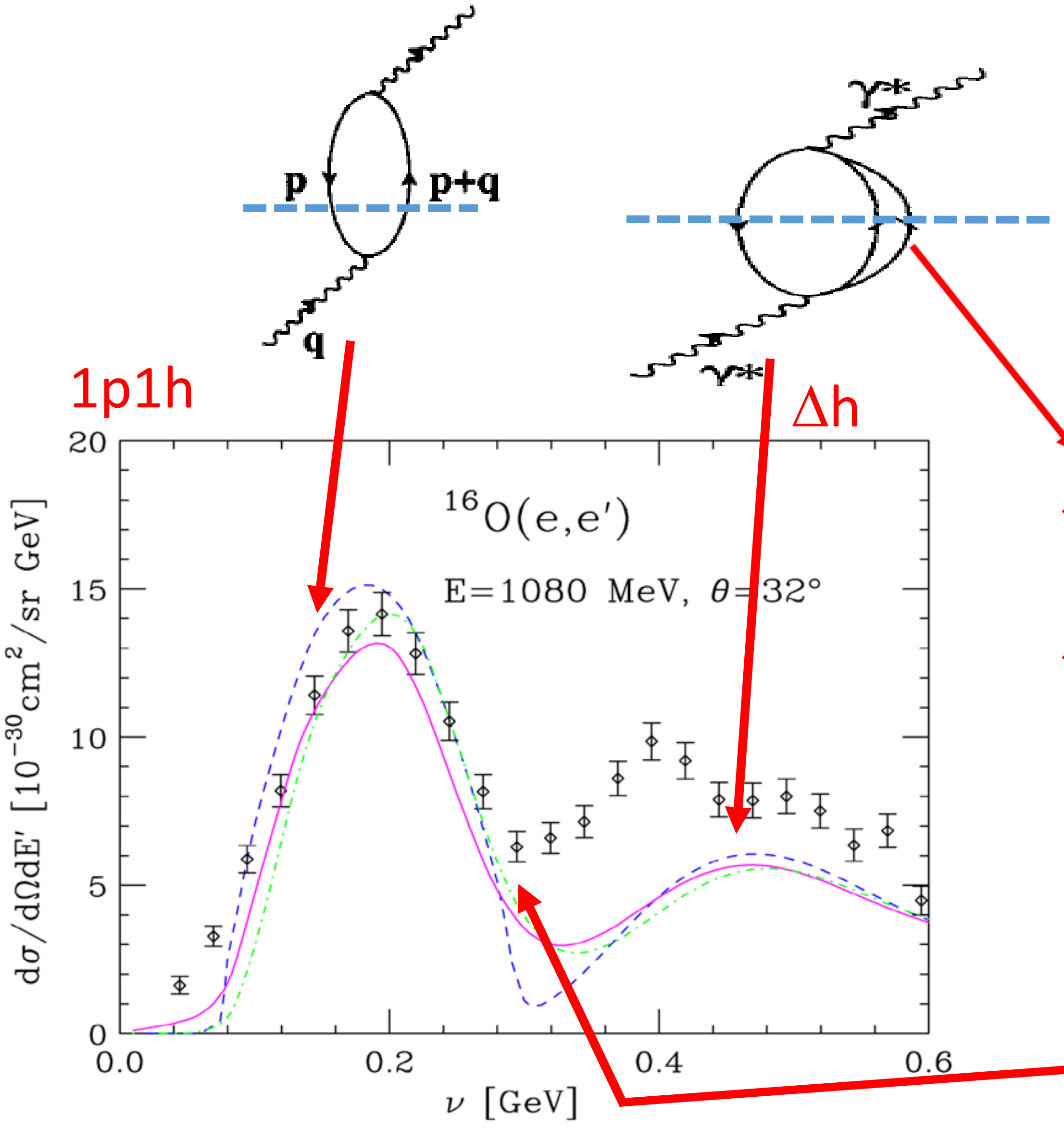
	Pauli $[10^4\ s^{-1}]$	RPA $[10^4\ s^{-1}]$	Exp $[10^4\ s^{-1}]$	$\left(\Gamma^{\mathrm{Exp}} - \Gamma^{\mathrm{Th}}\right)/\Gamma^{\mathrm{Exp}}$
^{12}C	5.42	3.21	3.78 ± 0.03	0.15
^{16}O	17.56	10.41	10.24 ± 0.06	-0.02
^{18}O	11.94	7.77	8.80 ± 0.15	0.12
^{23}Na	58.38	35.03	37.73 ± 0.14	0.07
^{40}Ca	465.5	257.9	252.5 ± 0.6	-0.02
^{44}Ca	318	189	179 ± 4	-0.06
^{75}As	1148	679	609 ± 4	-0.11
^{112}Cd	1825	1078	1061 ± 9	-0.02
^{208}Pb	1939	1310	1311 ± 8	0.00

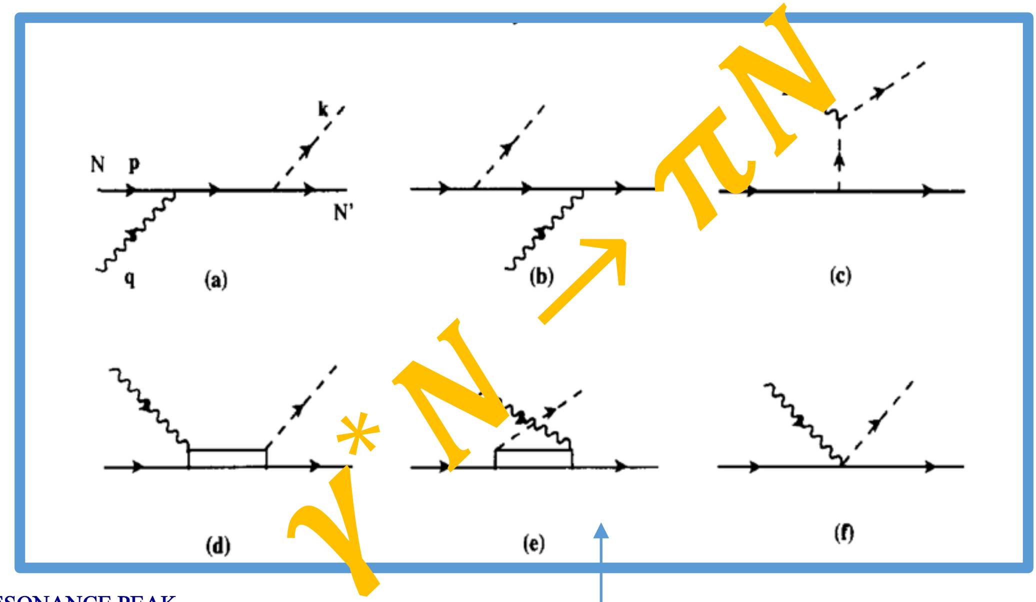
RPA vs SF effects: Differential cross sections for the CCQE reaction on ^{12}C averaged over the MiniBooNE flux (Alvarez-Ruso L et al., 2009 AIP Conf. Proc. 1189 151)

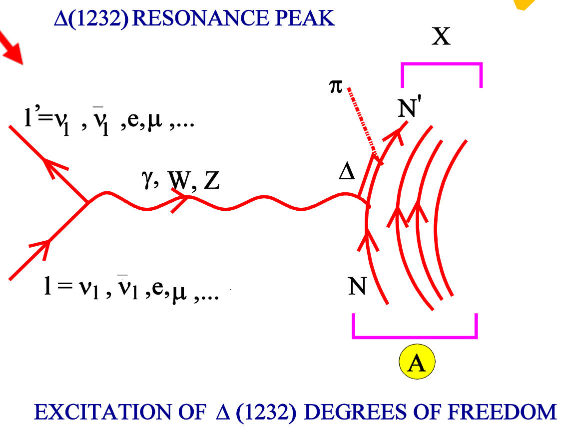
RPA $\gg$ SF

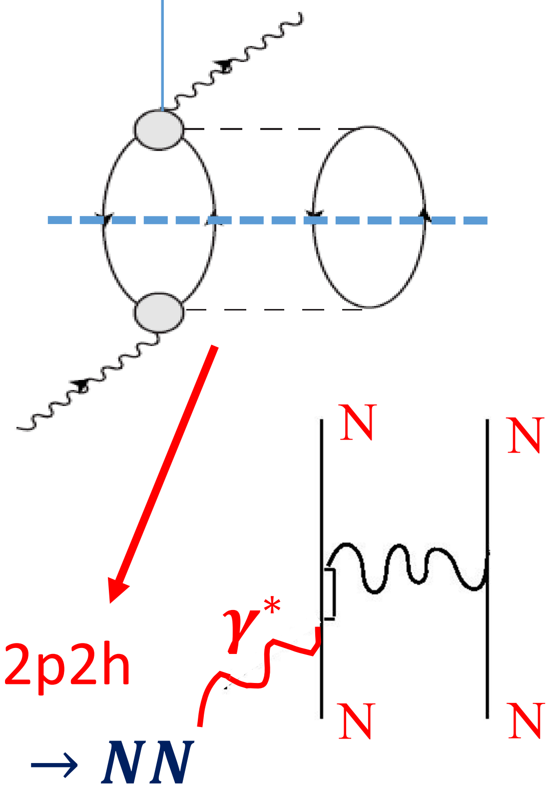
It depends on the specific kinematics and observable !

2p2h: Inclusive electron-nucleus scattering



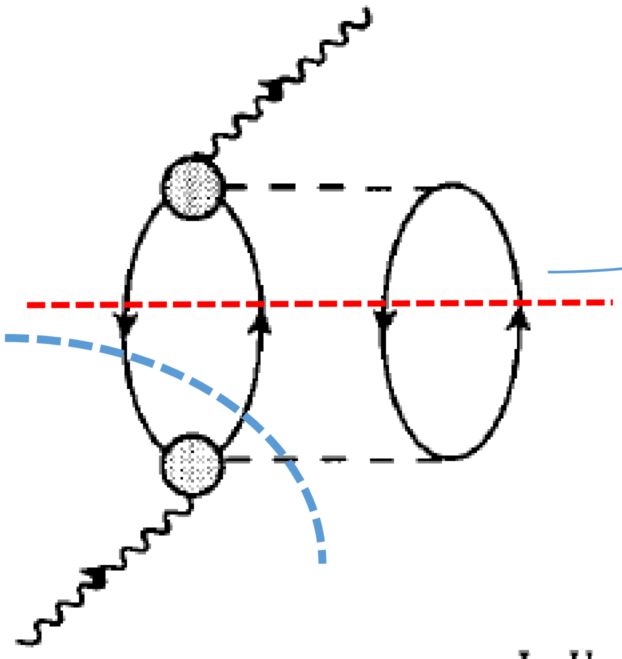






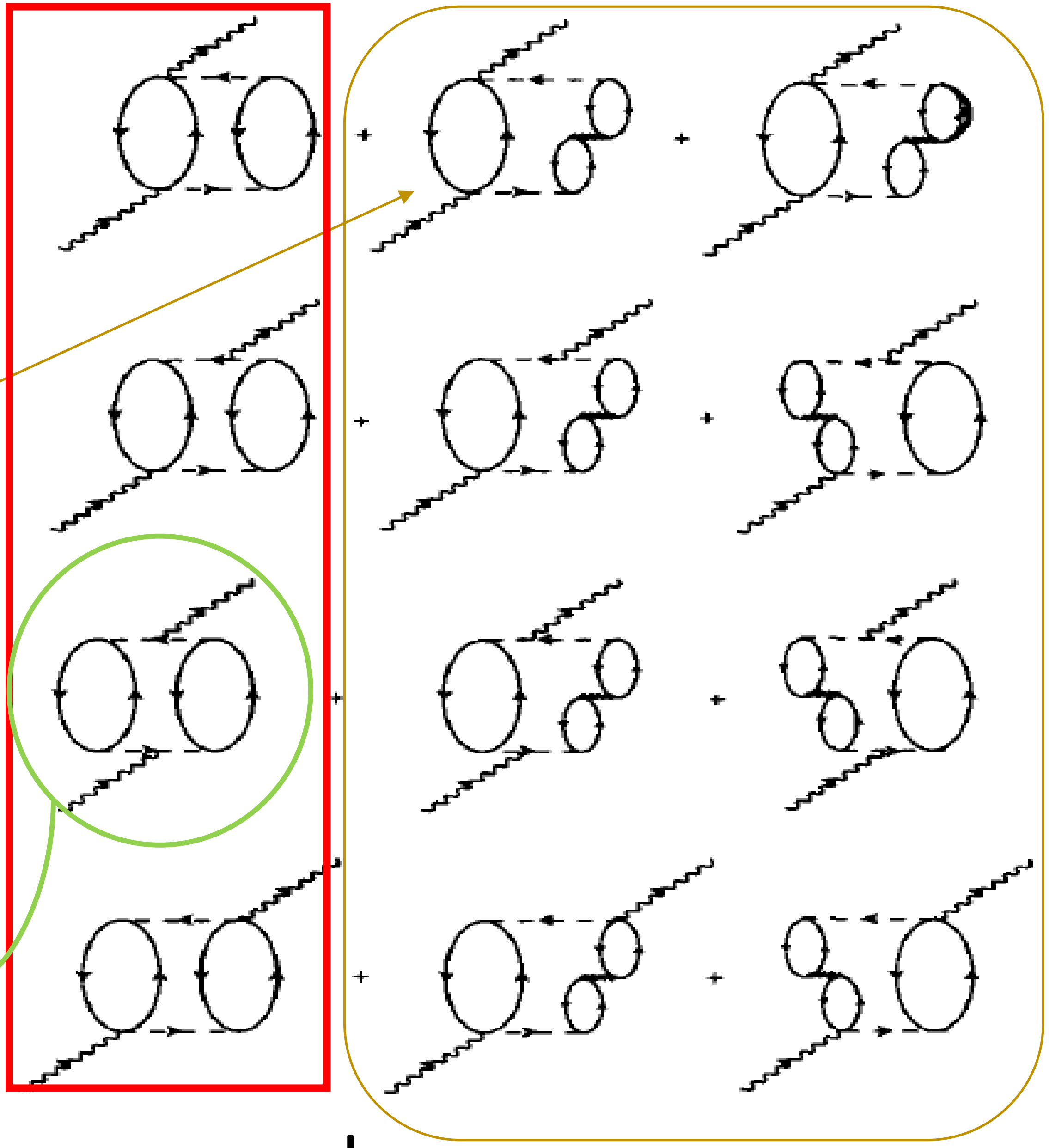
2p2h (two body absorption) contributions

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



RPA corrections to 2p2h contributions

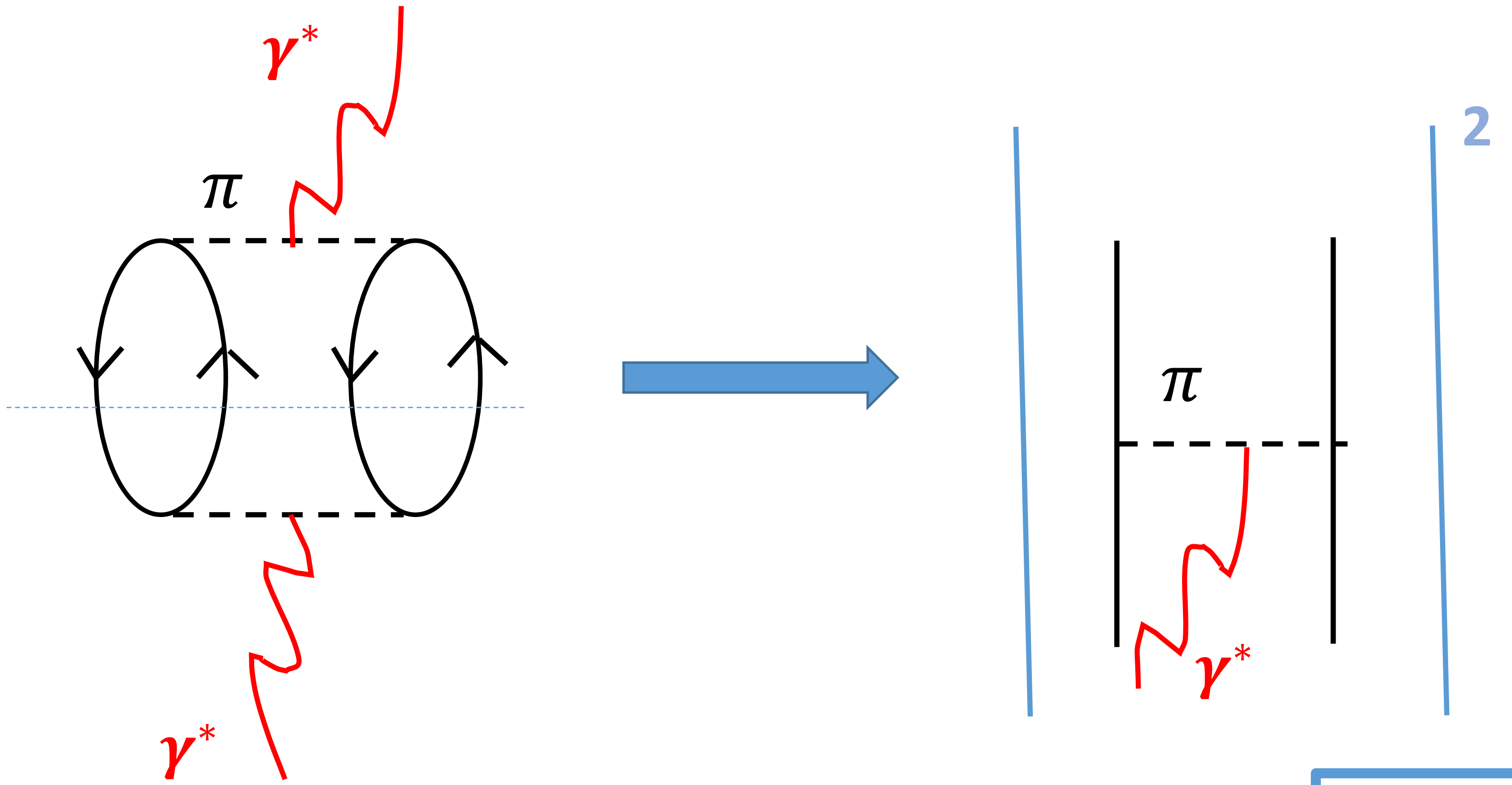
$$\mathrm{Im}\,U_N \to a\frac{\mathrm{Im}\,U_N}{|1-U_\lambda(q)V_l|^2} + b\frac{\mathrm{Im}\,U_N}{|1-U_\lambda V_t|^2}$$



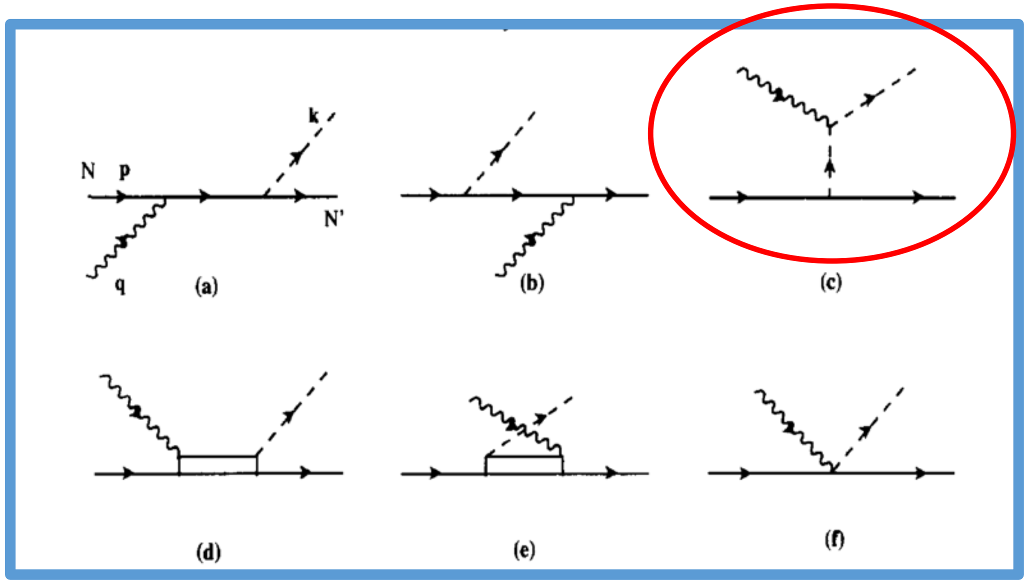
+.....

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

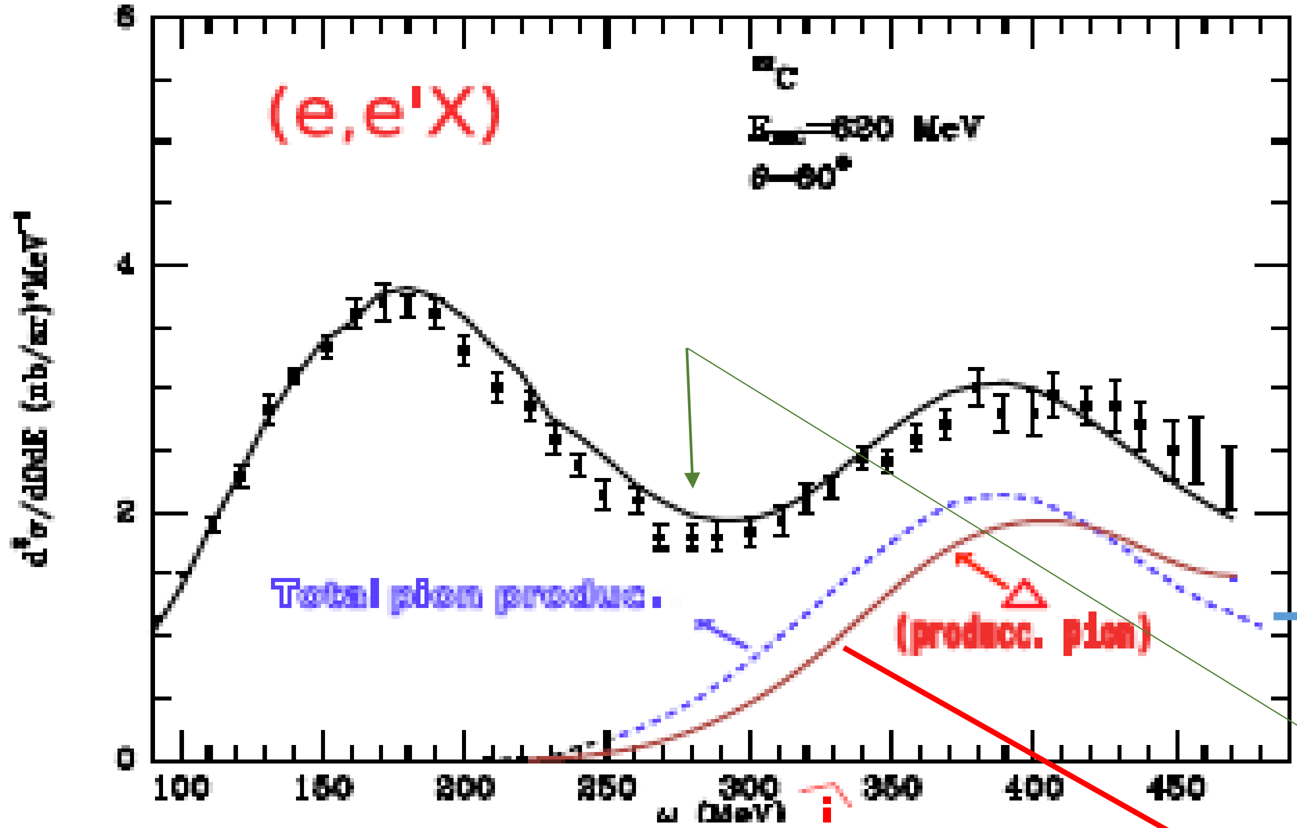
$\gamma^* N \to N\pi$ (dressed)



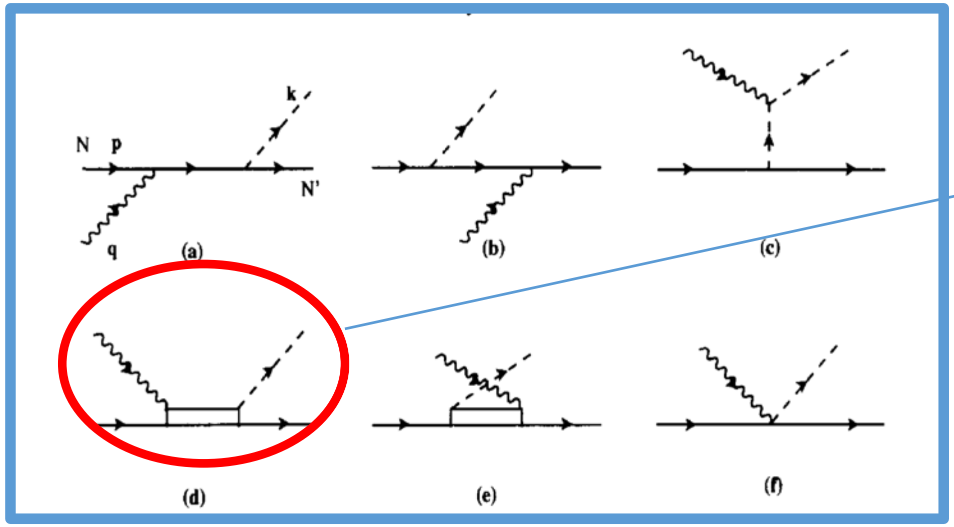
$\gamma^* N \to \pi N$

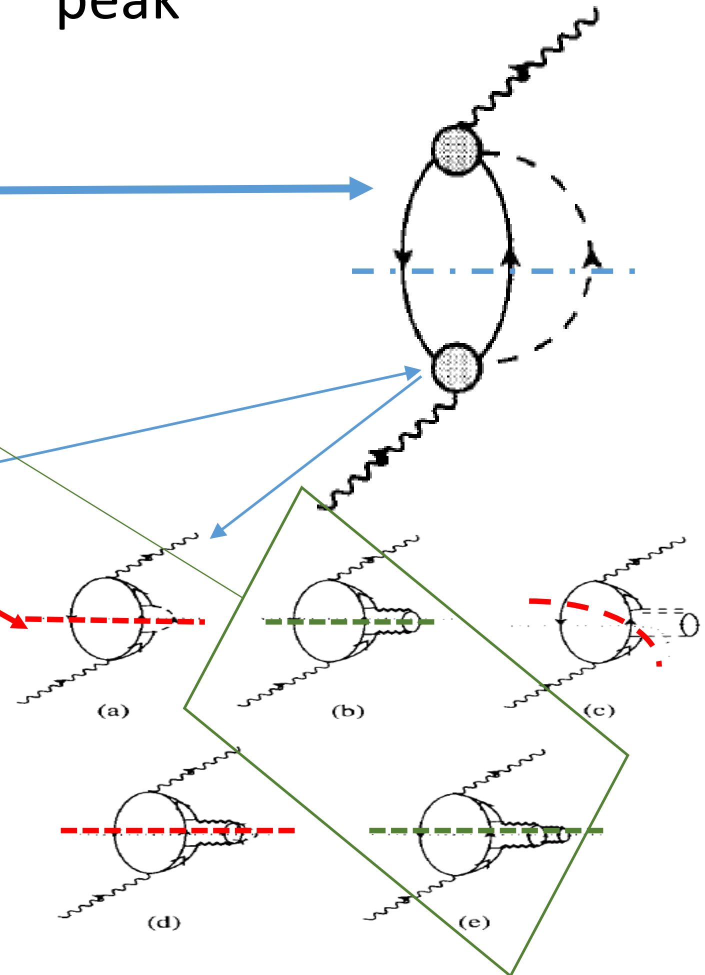


Meson Exchange Contribution



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

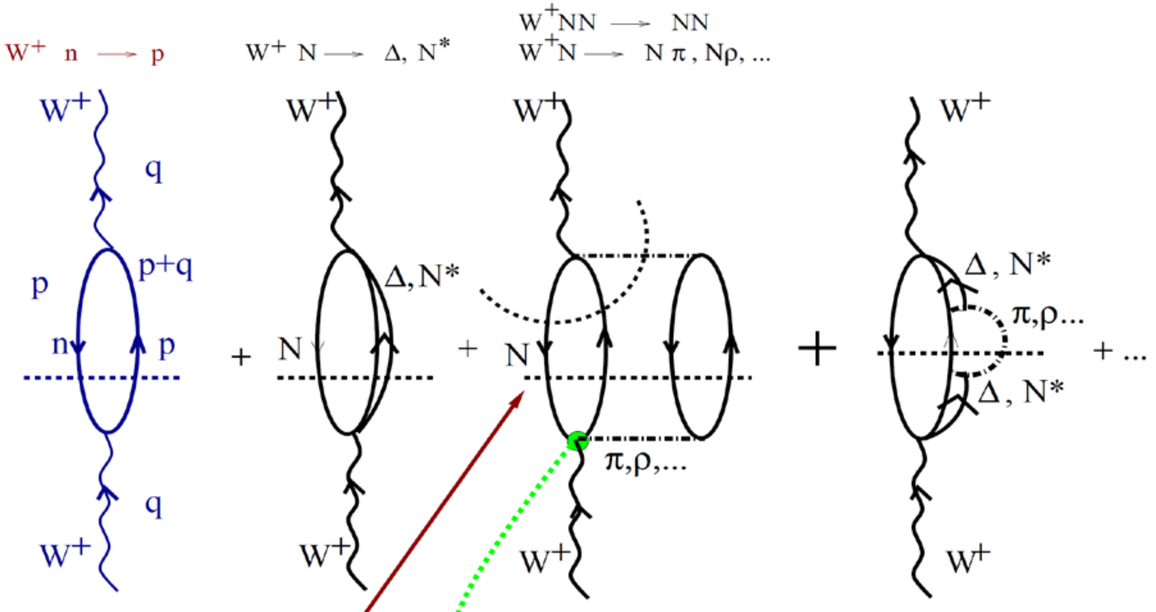


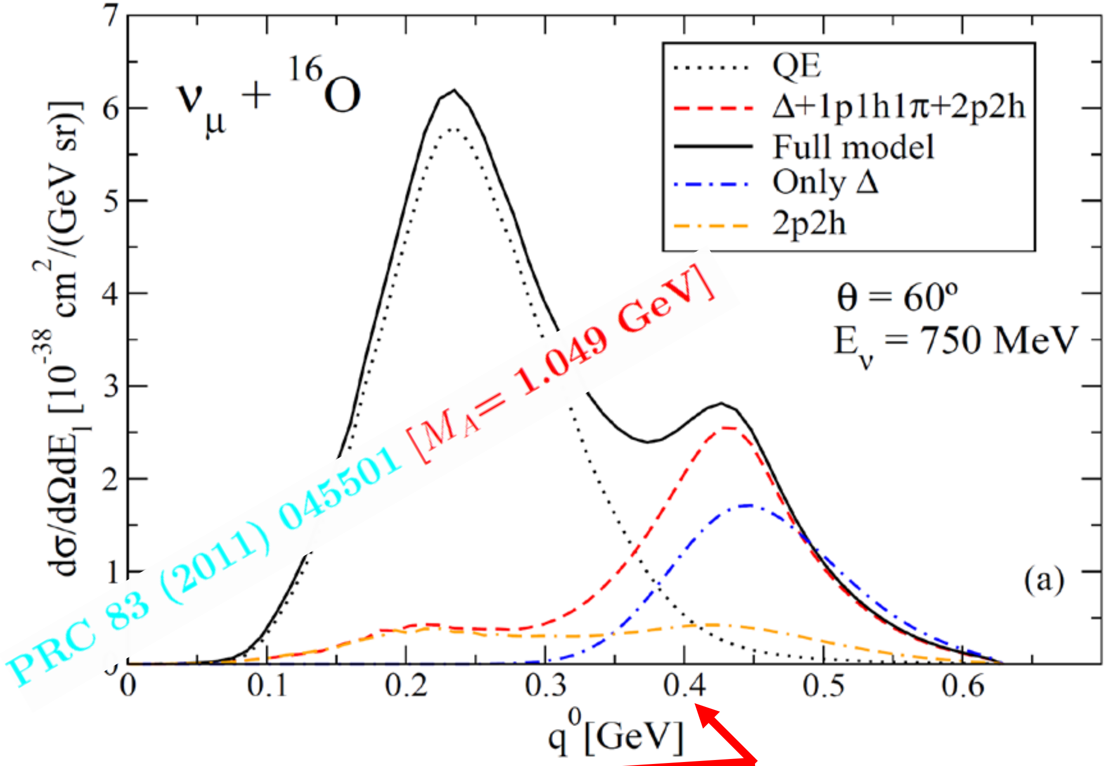


one of the terms generates the Δ contribution

Juan Nieves, IFIC (CSIC & UV)

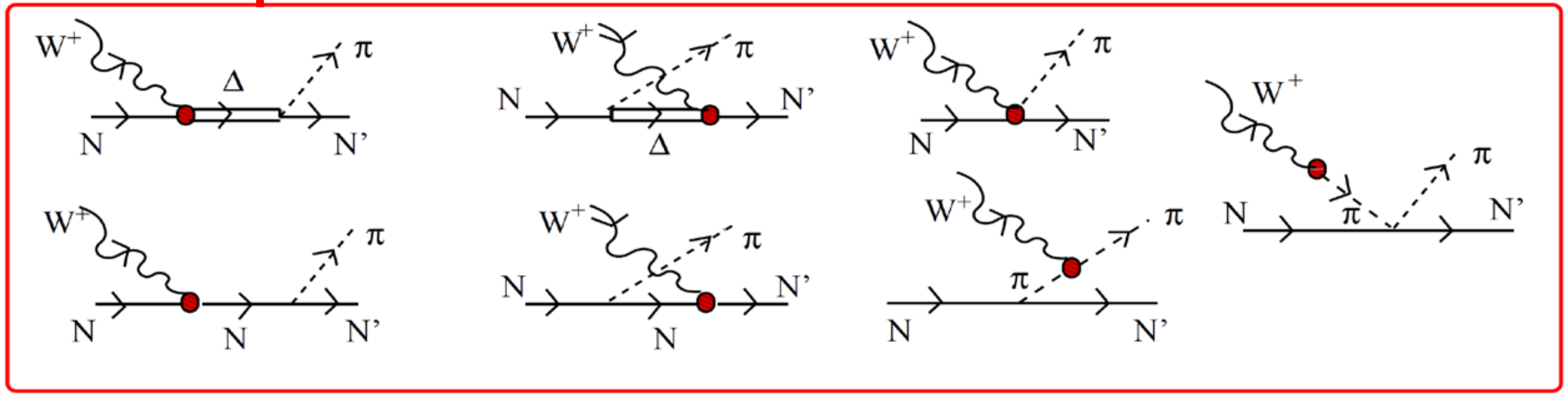
$\nu + A \rightarrow l + X$





MEC → QE like !

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



+ arXiv:1510.06266
(Watson's theorem)

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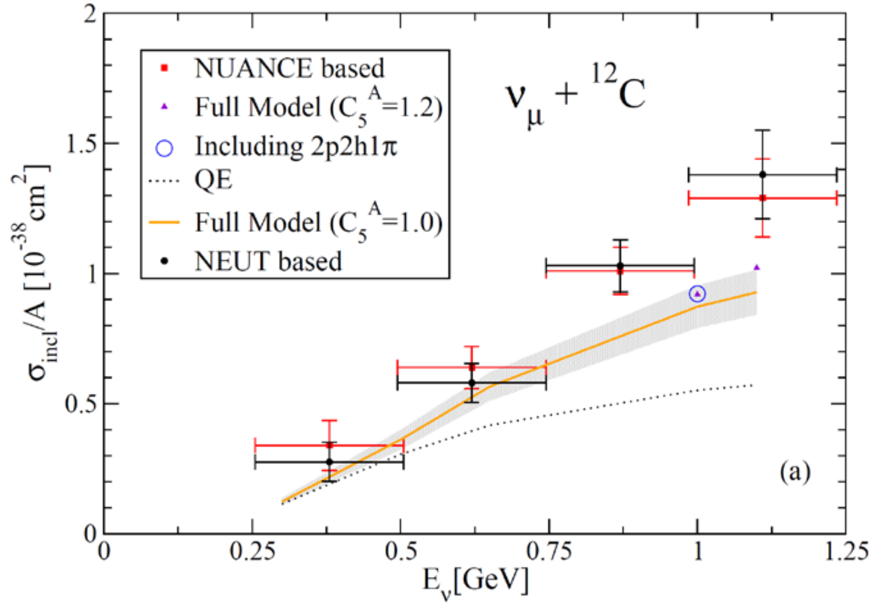
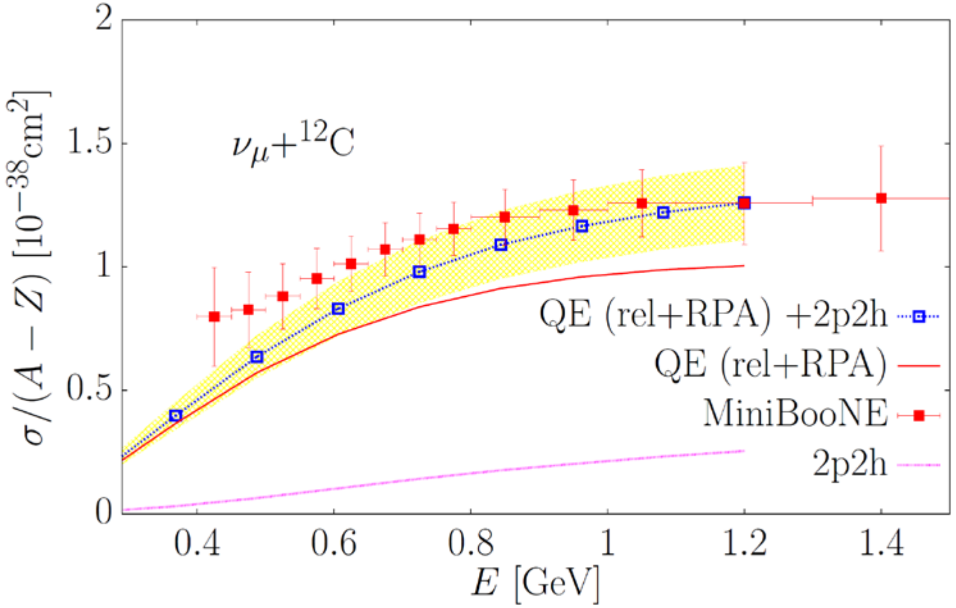




MiniBooNE CCQE-like double differential cross section $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$

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

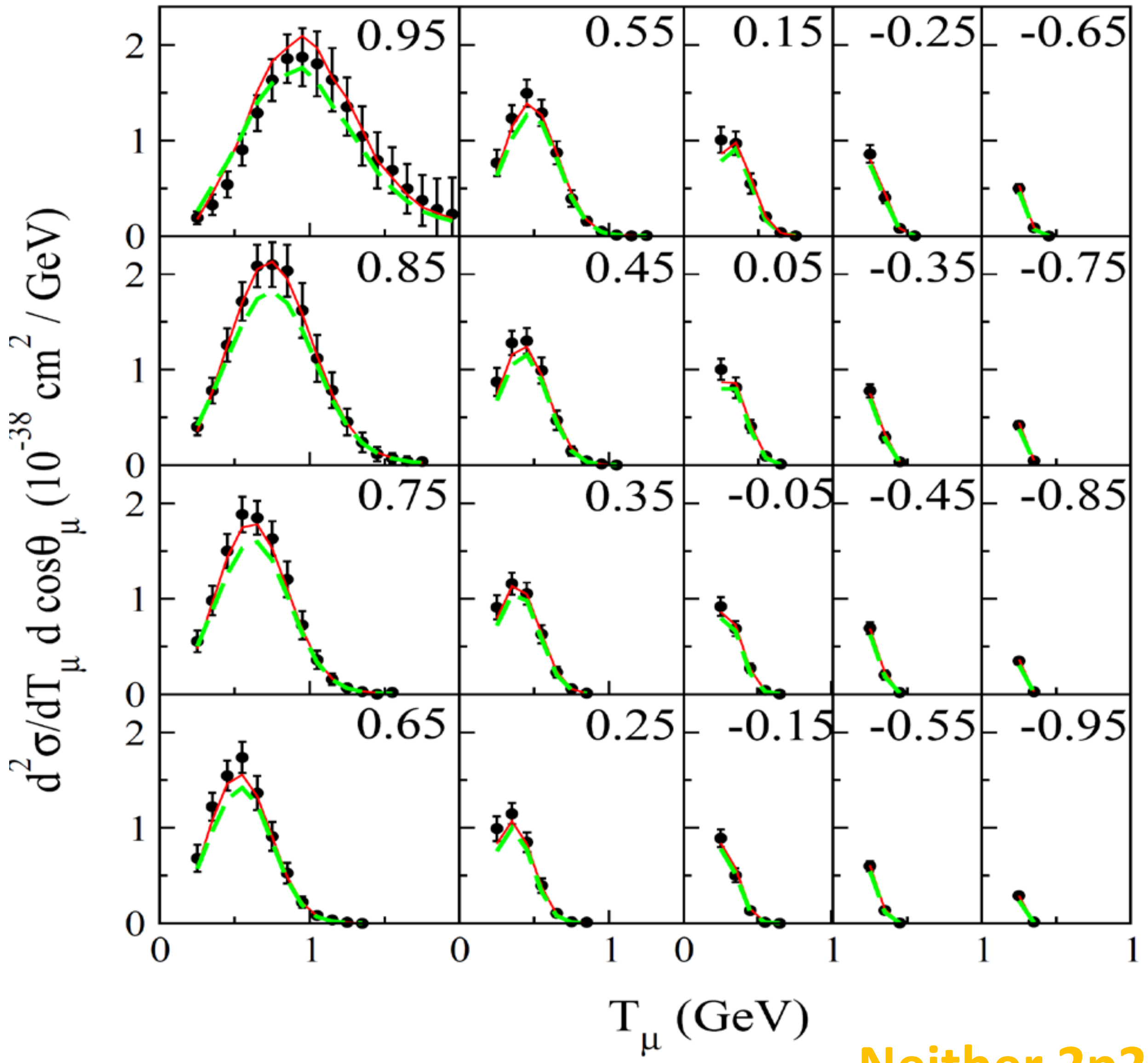
$$\chi^2 = \sum_{i=1}^{137}\left[\frac{\lambda\left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta}\right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta}\right)_i}{\lambda\Delta\left(\frac{d^2\sigma}{dT_\mu d\cos\theta}\right)_i}\right]^2 + \left(\frac{\lambda-1}{\Delta\lambda}\right)^2,$$

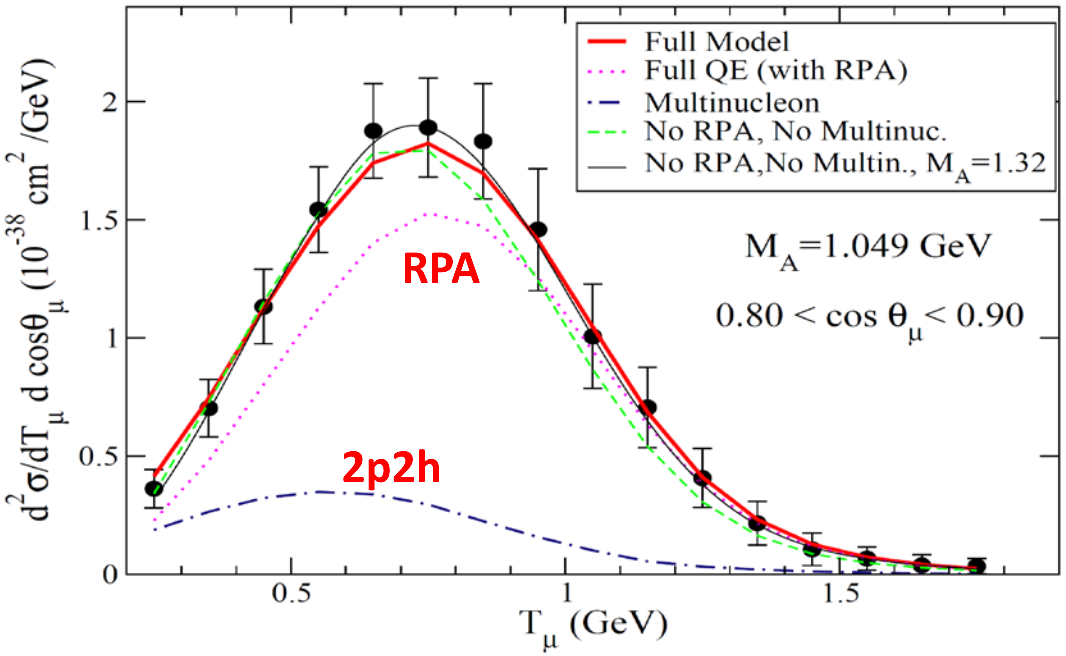
that takes into account the global normalization uncertainty ($\Delta\lambda = 0.107$) claimed by the MiniBooNE collaboration.

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.



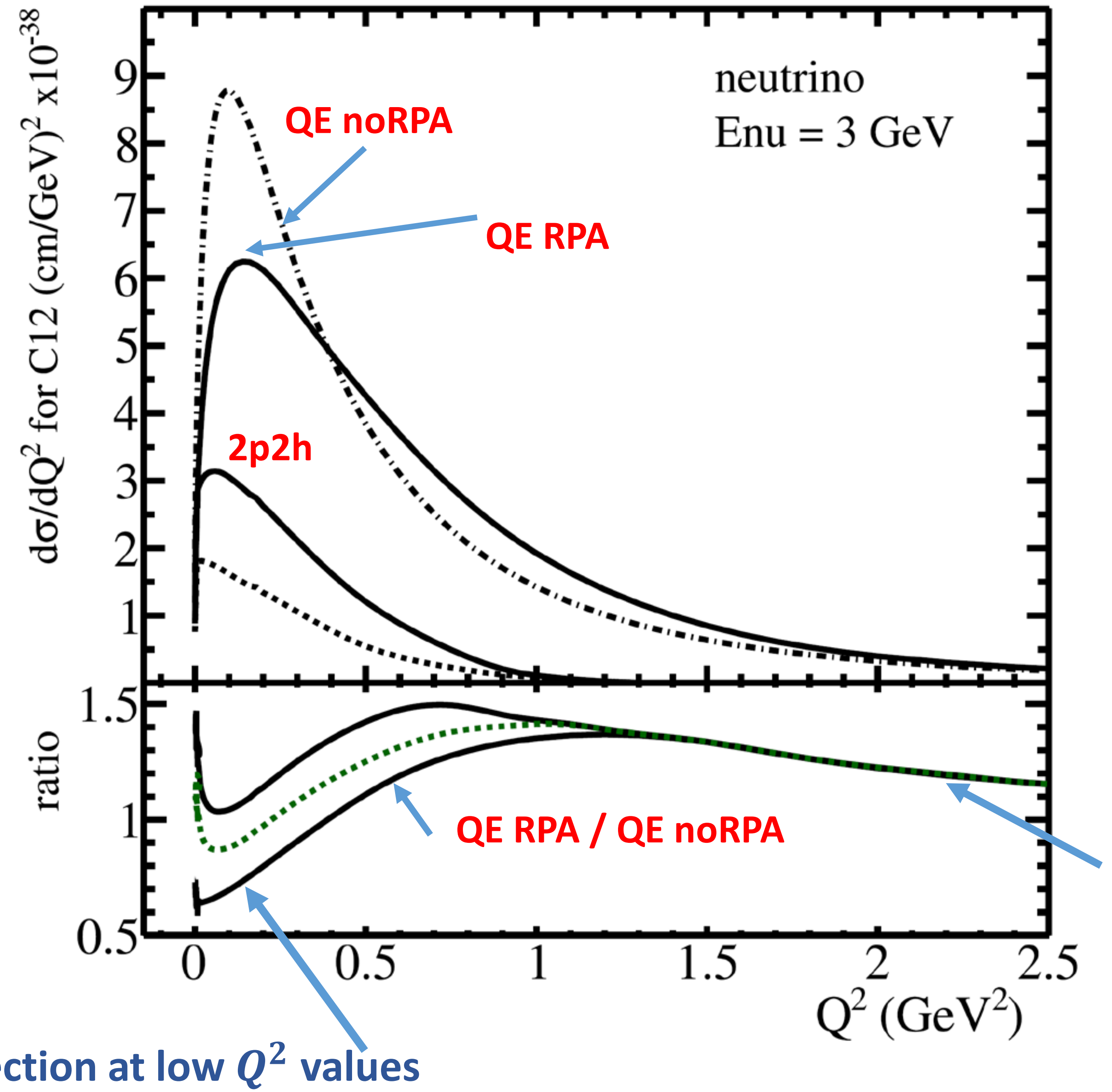


Model	Scale	M_A (GeV)	$\frac{\chi^2}{\#\text{bins}}$
LFG	0.96±0.03	1.32±0.03	35/137
Full	**0.92±0.03**	**1.08±0.03**	**50/137**
Full $\lvert q \rvert > 0.4^{\dagger}$ GeV	0.83±0.04	1.01±0.03	30/123

† : 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!

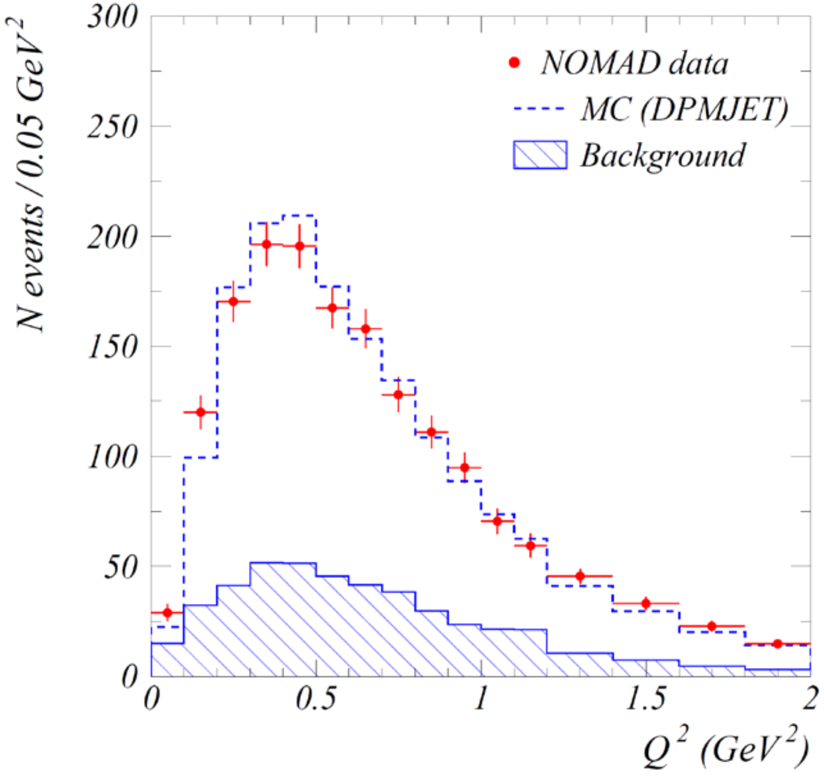
Juan Nieves, IFIC (CSIC & UV)



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

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

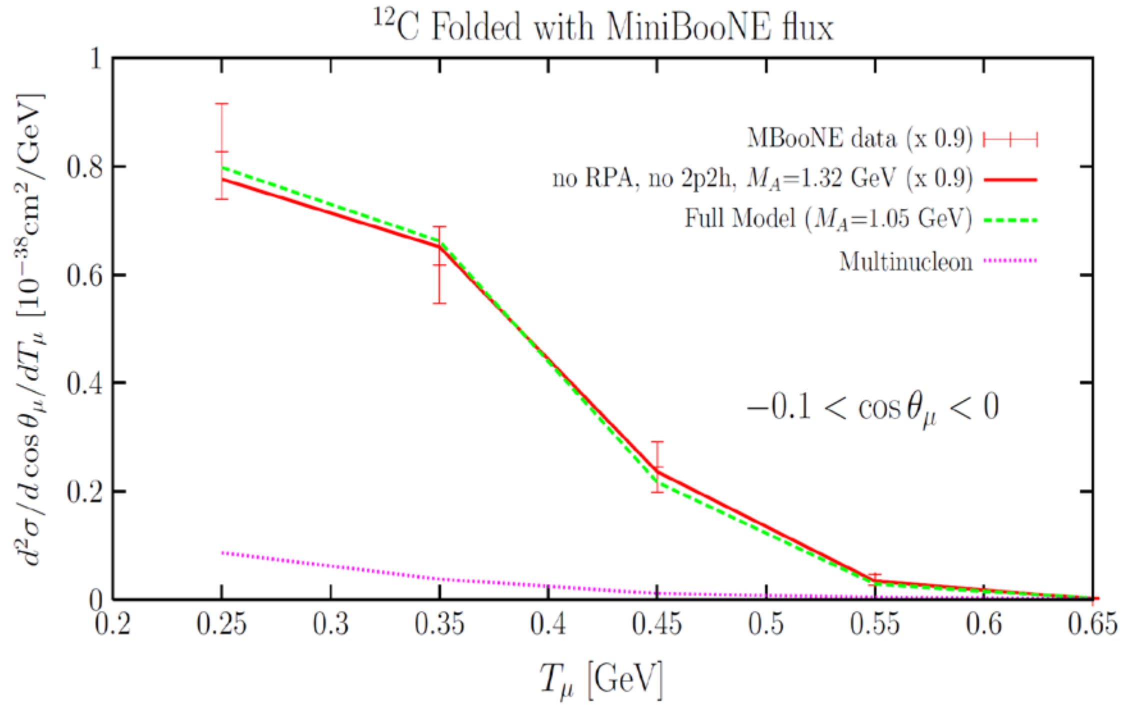
Juan Nieves, IFIC (CSIC & UV)

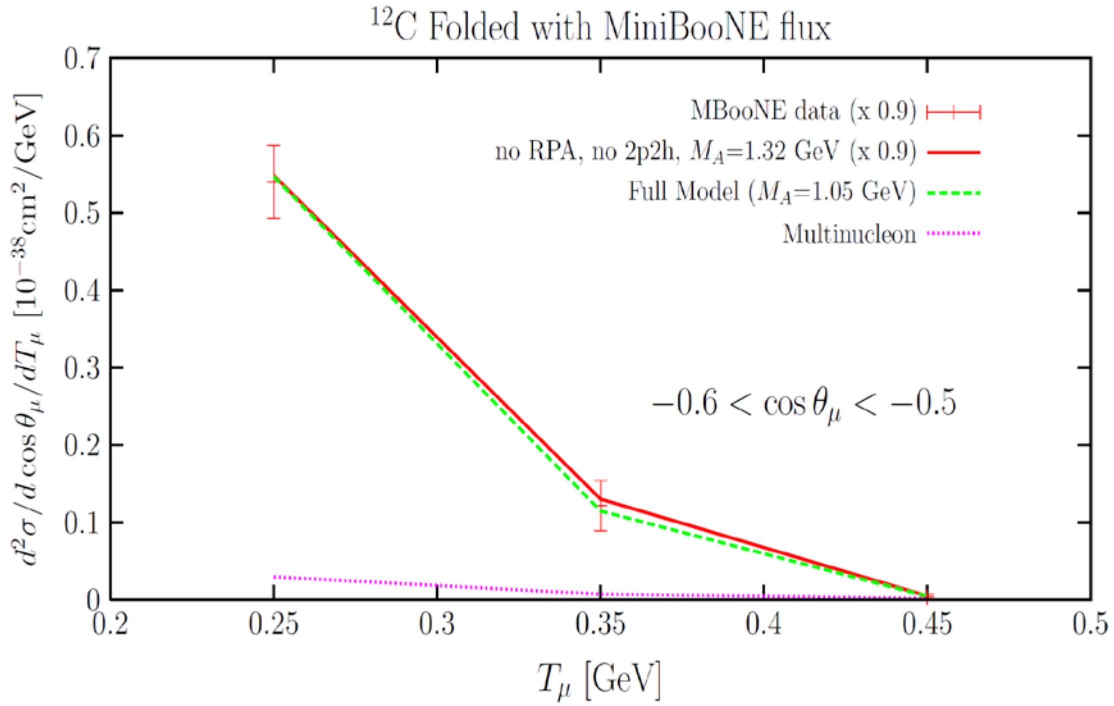


V. Lyubushkin et al. **(NOMAD Collaboration)**, Eur. Phys. J. C 63, 355 (2009). In the **two-track sample**, which is primarily Q^2 above 0.3 GeV^2, a **large fraction of the 2p2h component**, as well as QE and pion production where the hadrons rescattered as they exited the nucleus, are **rejected.**

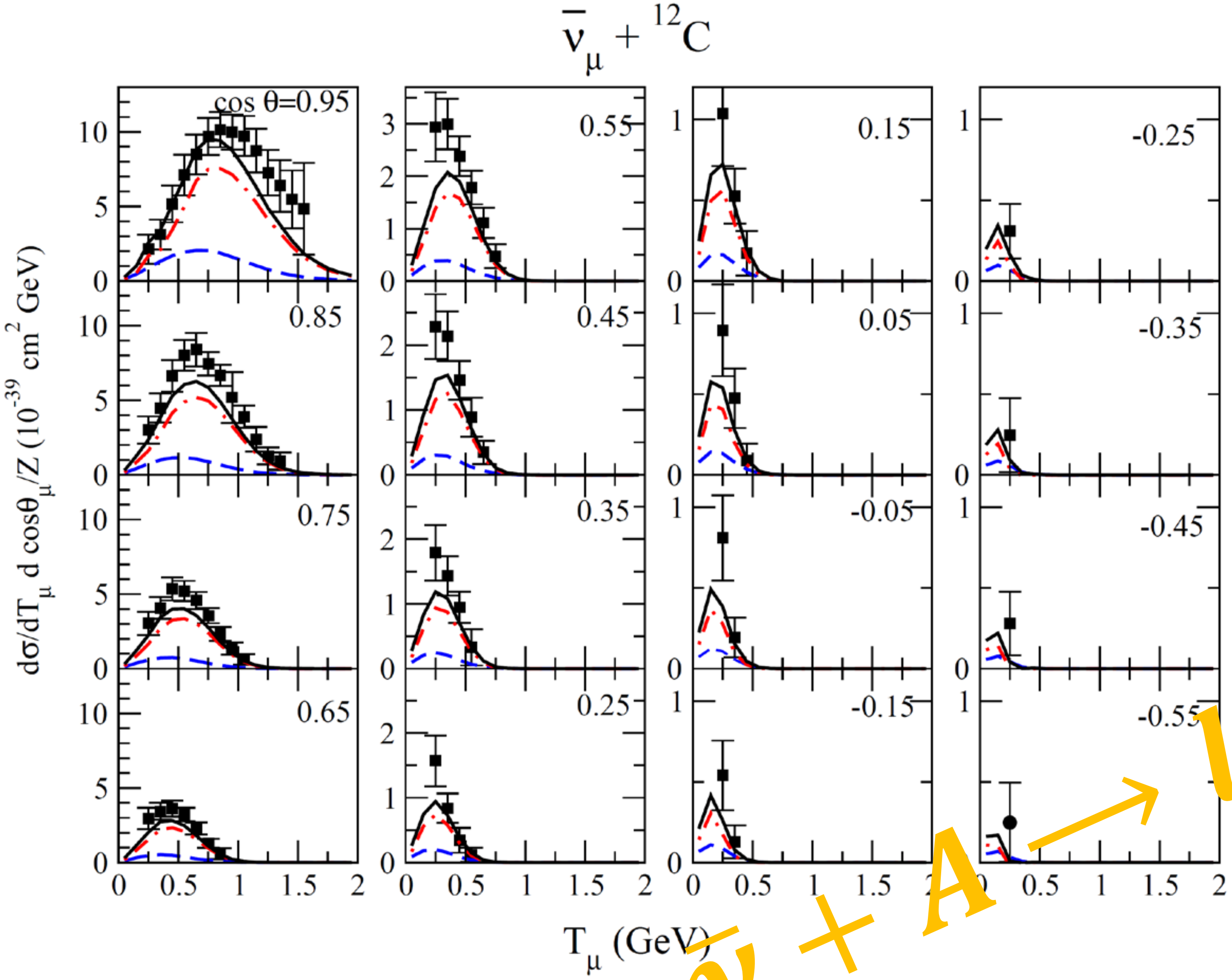
It is observed a relative **deficit at $Q^2 = 0.3$ and excess at 1.5 GeV^2 compared to QE without RPA**. If the first two or three points are eliminated, the distribution will be consistent with $M_A \sim 1.2$ GeV.

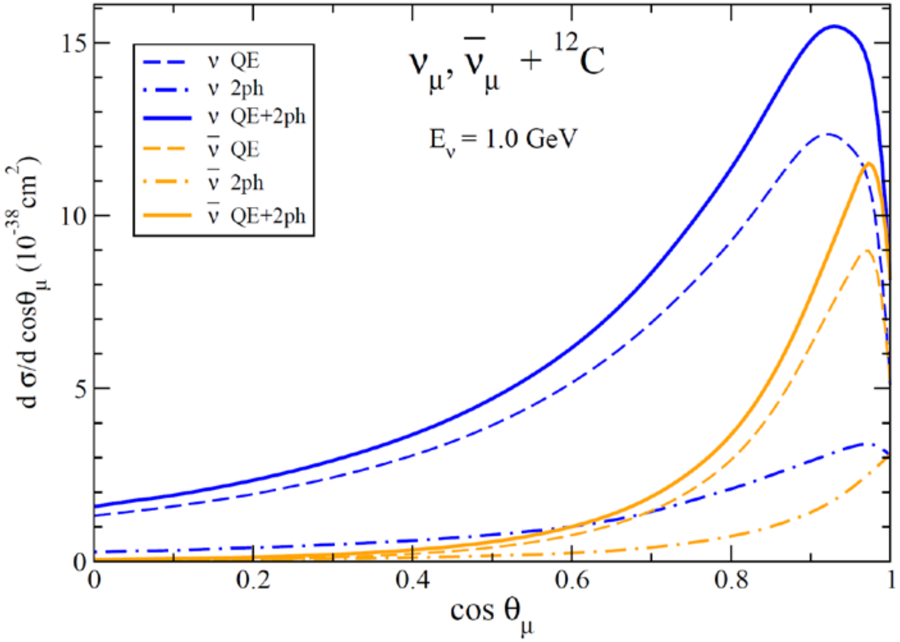
Dependence of the 2p2h contribution on $\cos\theta_\mu$





$M_A \sim 1.03$ GeV

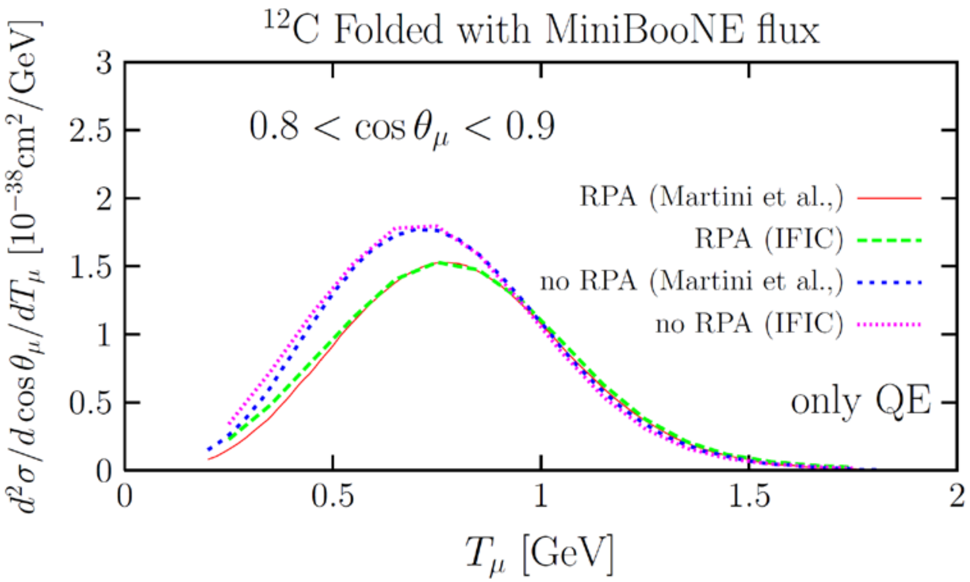




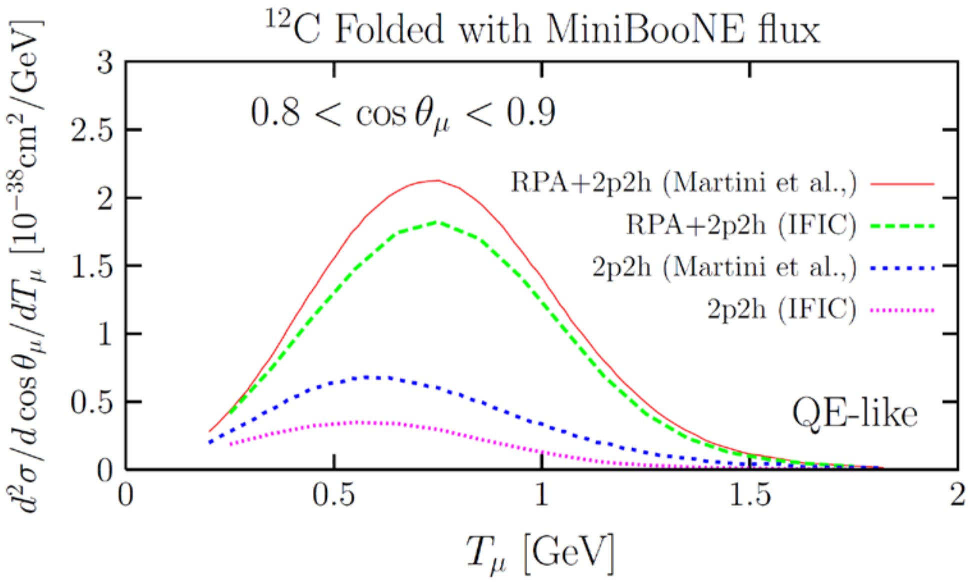
$\bar{\nu} + A \longrightarrow l+X$

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

Juan Nieves, IFIC (CSIC & UV)



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

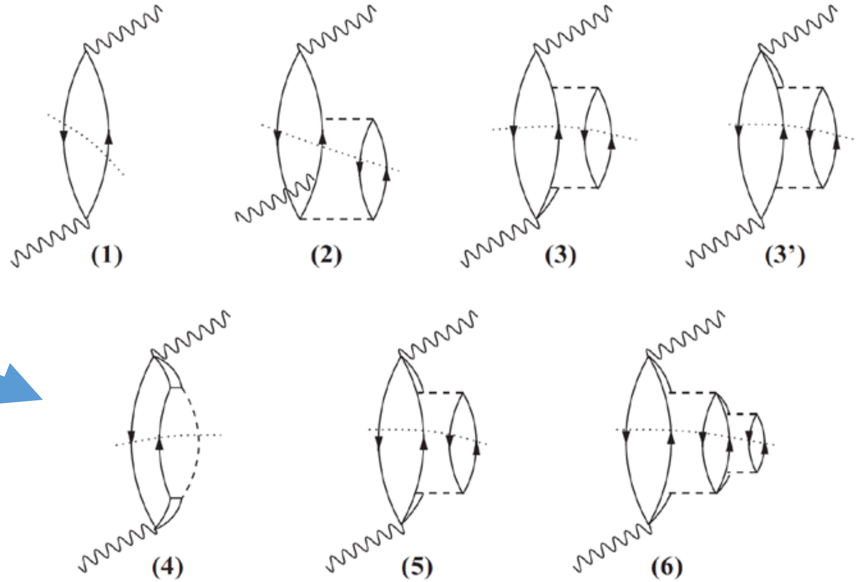


...however our 2p2h contribution is about a factor of 2 smaller!

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

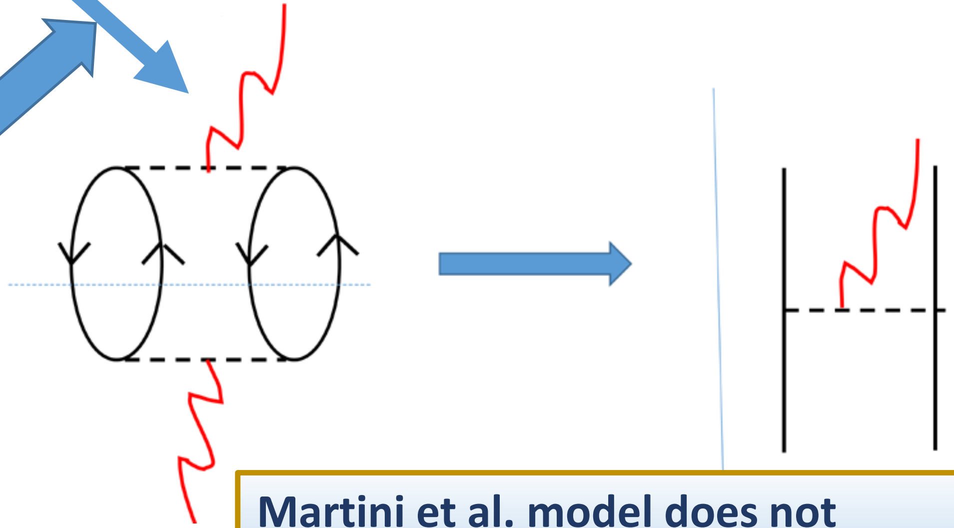
only for vector current driven processes

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



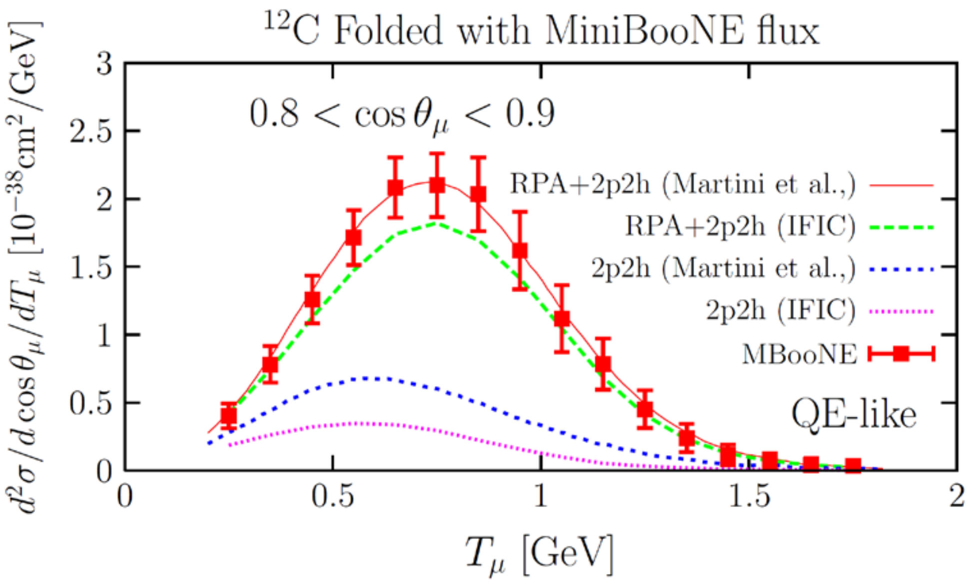
2. Martini et al. do not consider 2p2h contributions driven by contact, pion pole and pion in flight terms.

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].

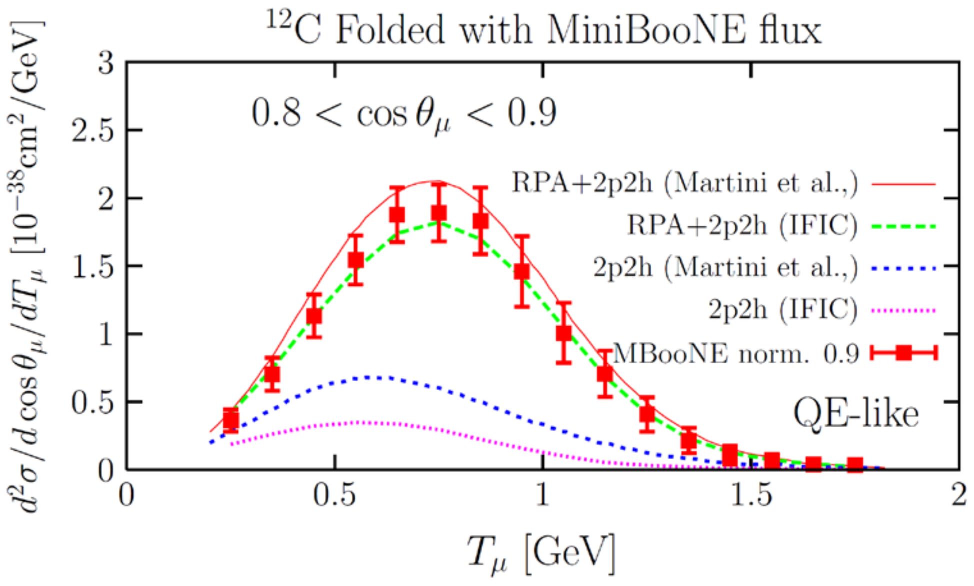


This 2p2h parametrization includes MEC effects driven by the vector current !

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



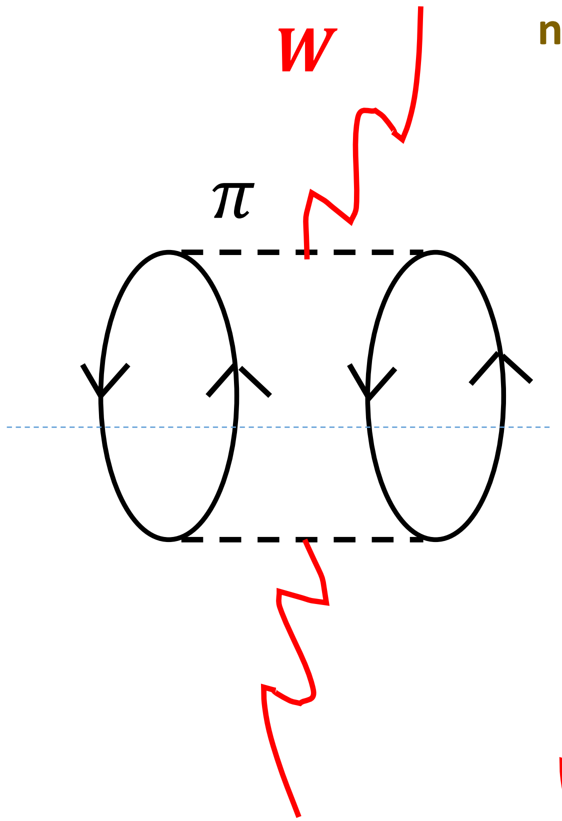
Martini et al., predictions look consistent with MiniBooNE data ..., **but their estimate rely on some computation of the 2p2h mechanisms for (e, e') (Alberico et al.,) $\Rightarrow$ no info on axial part of the interaction!**

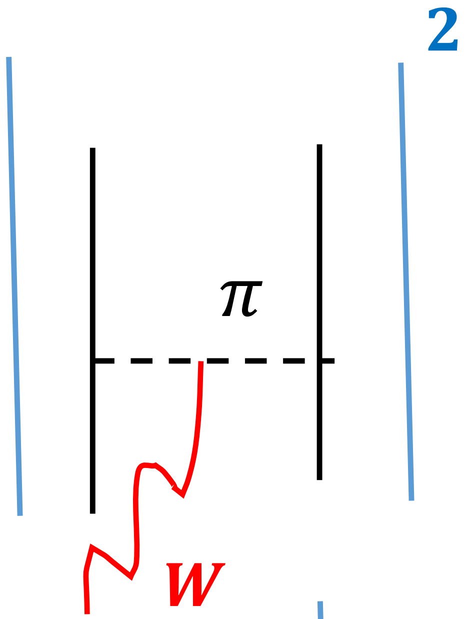


...however our predictions for the 2p2h contribution would favor a global normalization scale of about 0.9. This would be consistent with the MiniBooNE estimate of a total normalization error of 10.7%.

MEC & FSC & ISC

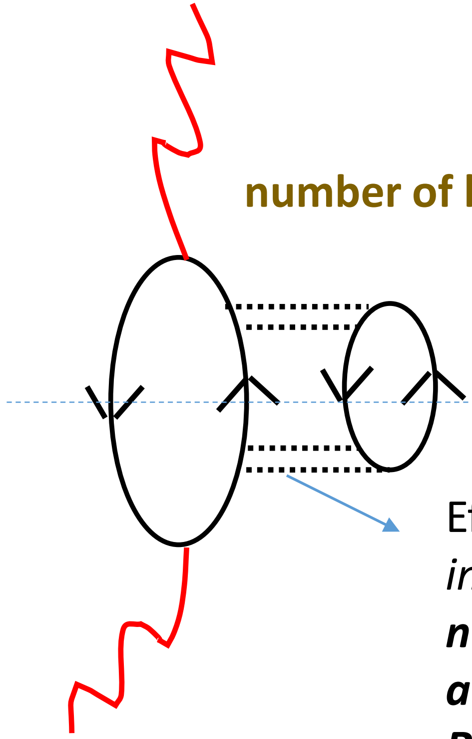
number of hole lines (density) = 2

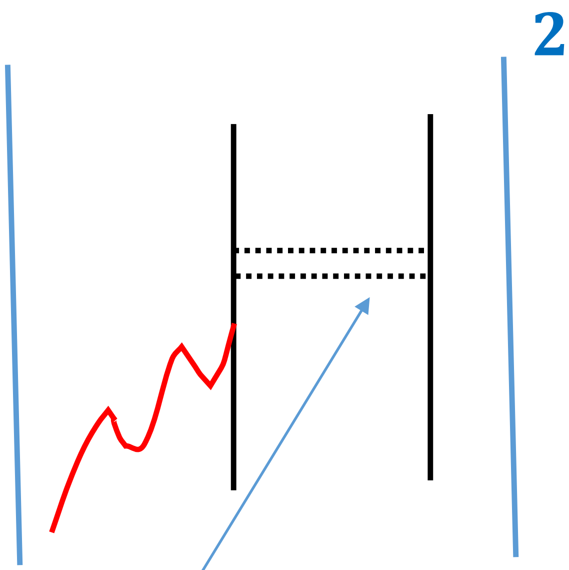




MEC term

number of hole lines (density) = 2



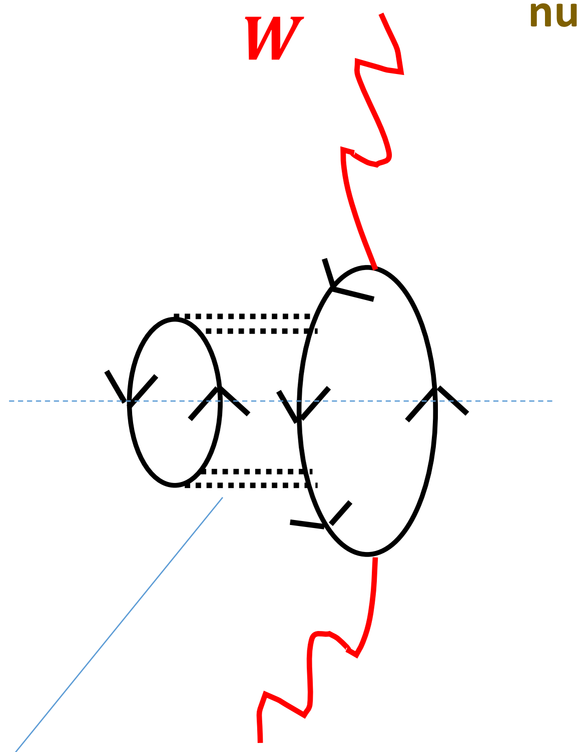


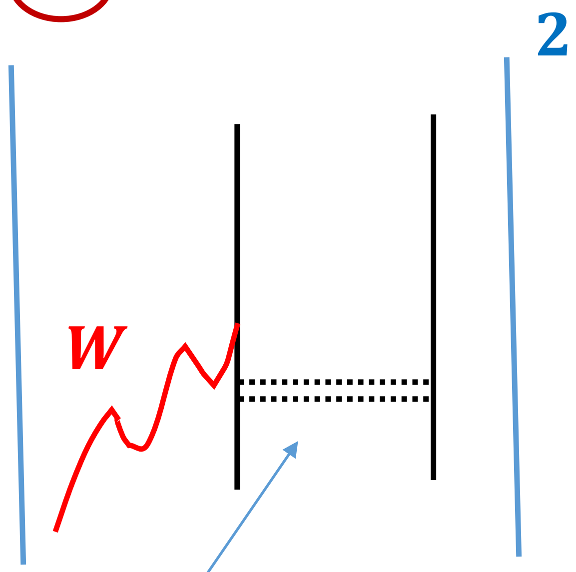
MEC/FSC term

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

Juan Nieves, IFIC (CSIC & UV)

number of hole lines (density) = 4

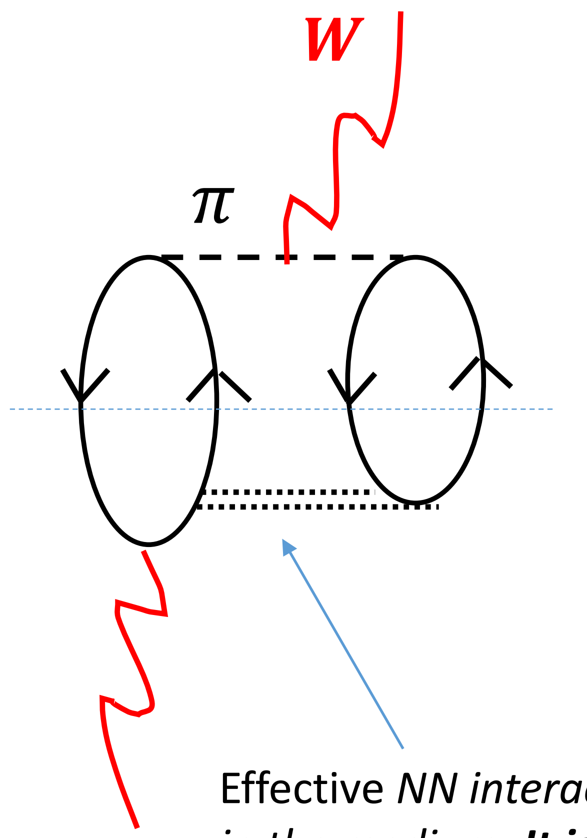




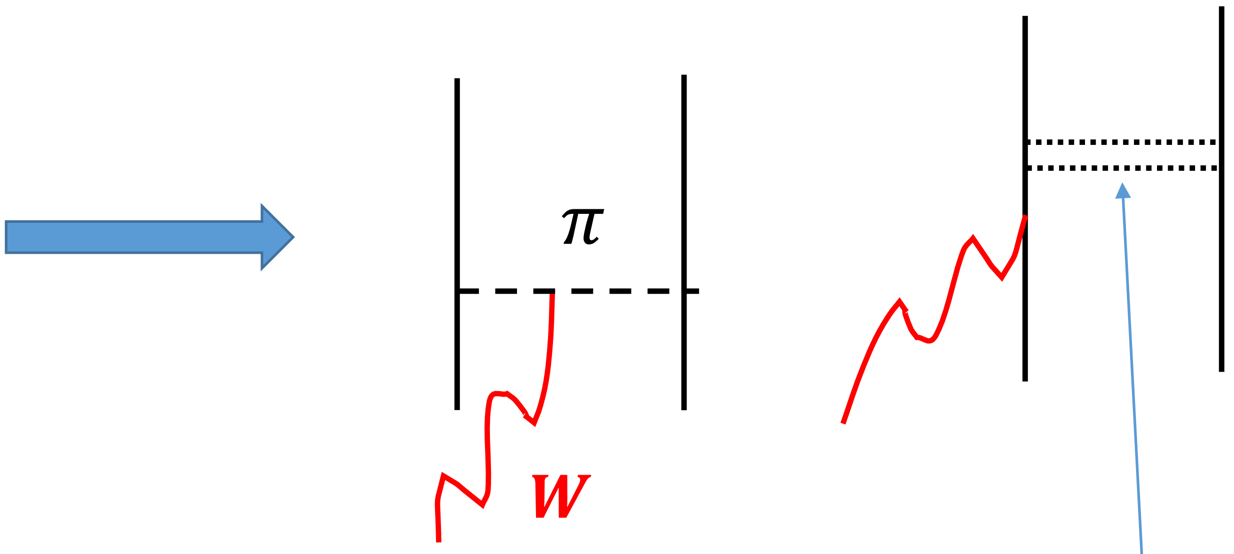
Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

MEC/ISC term

number of hole lines (density) = 2



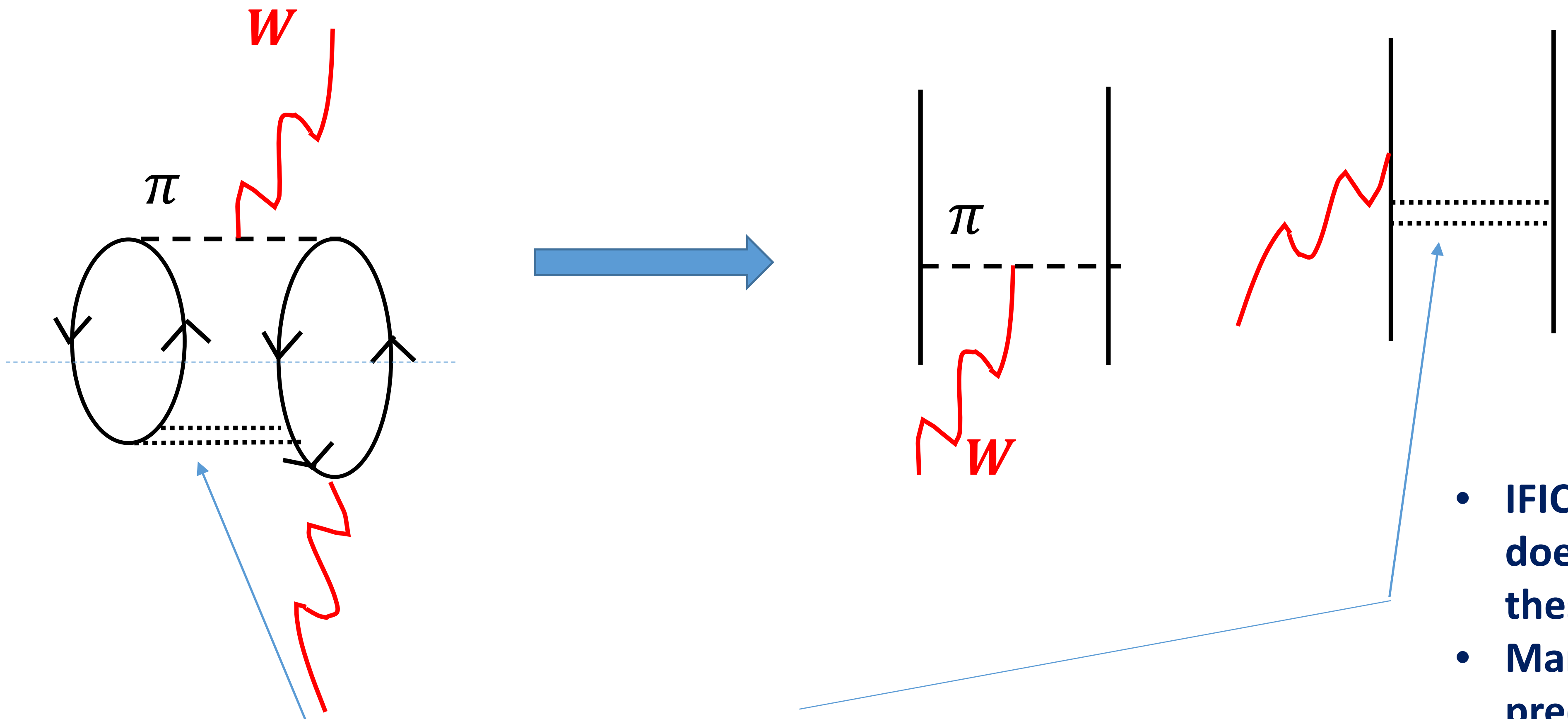
Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***



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)**

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

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

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

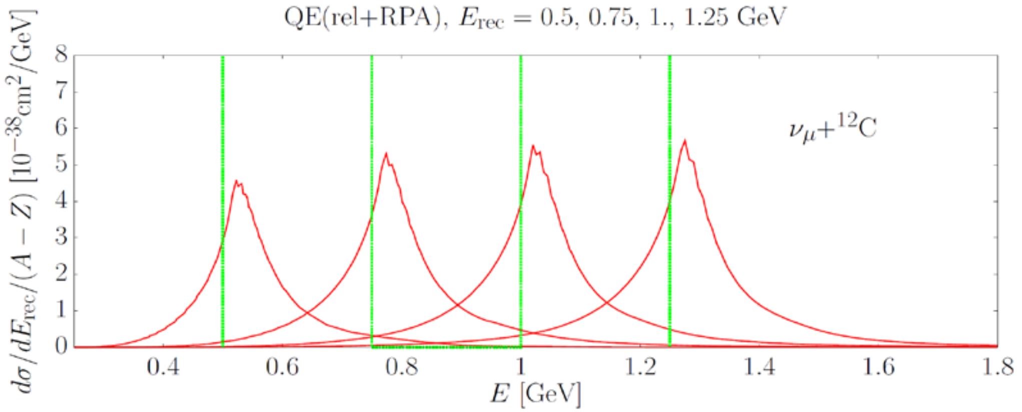
Unfolding procedure needs theoretical input!

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

$P_{\rm rec}(E_{\rm rec})$ 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 $\dfrac{d\sigma}{dE_{\rm rec}}(E; E_{\rm rec})$

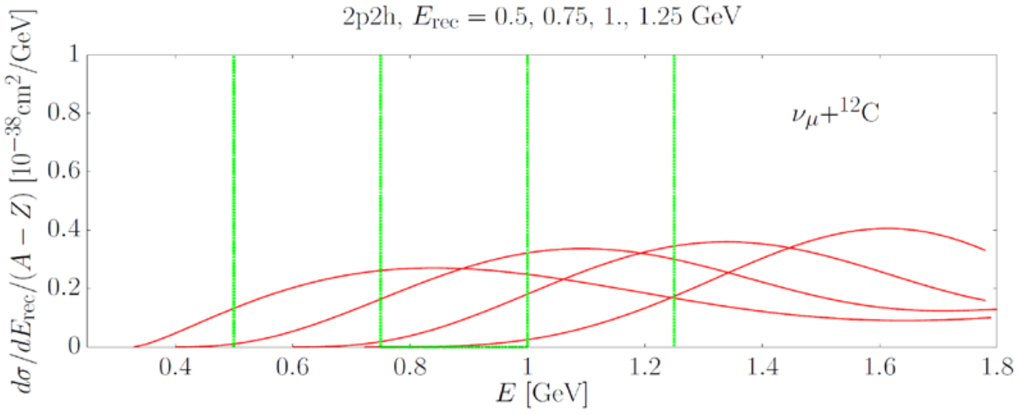


Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section

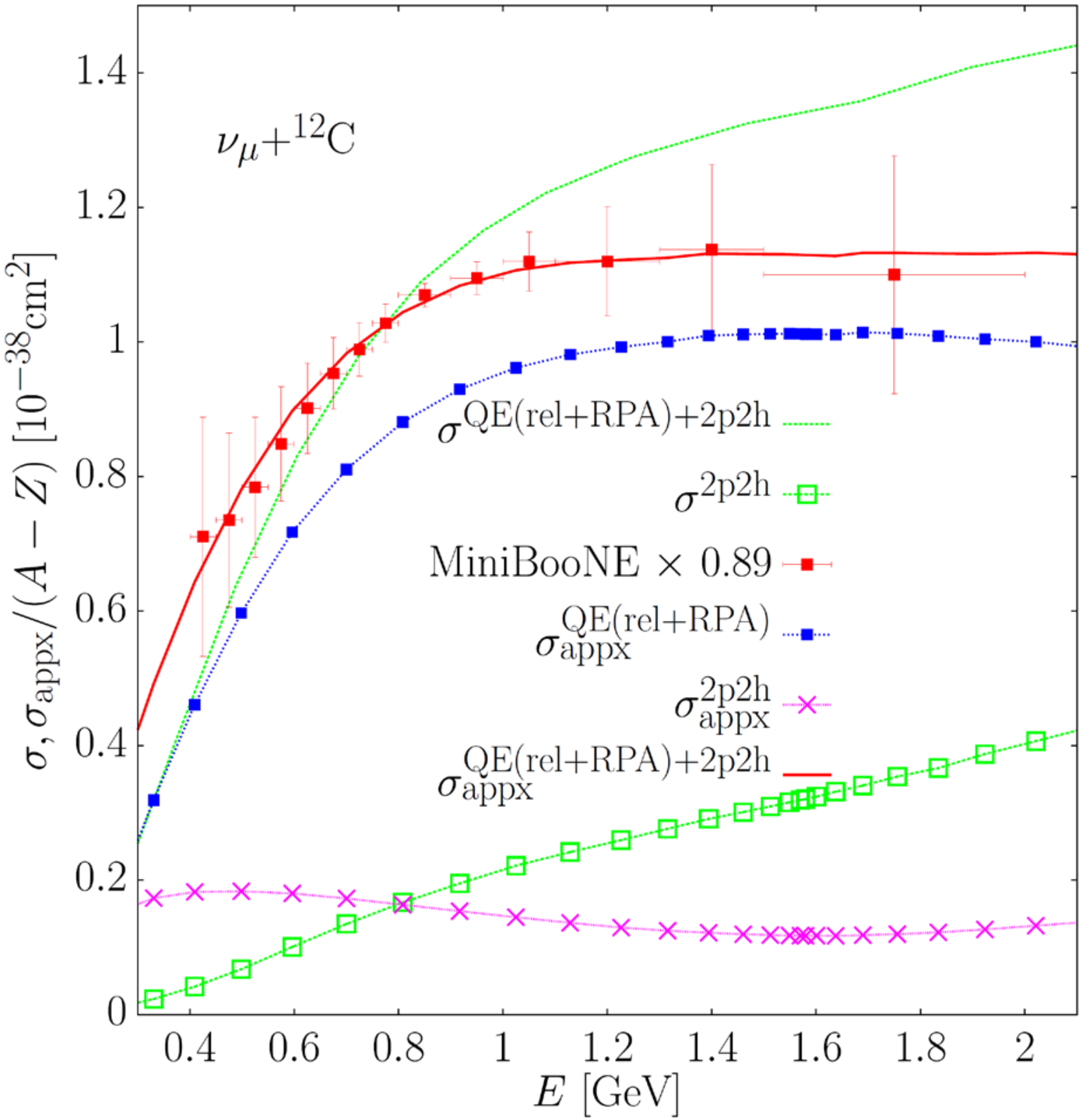
(qualitatively in agreement with Martini et al., PRD85 093012)

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 $E_{\rm rec}$.

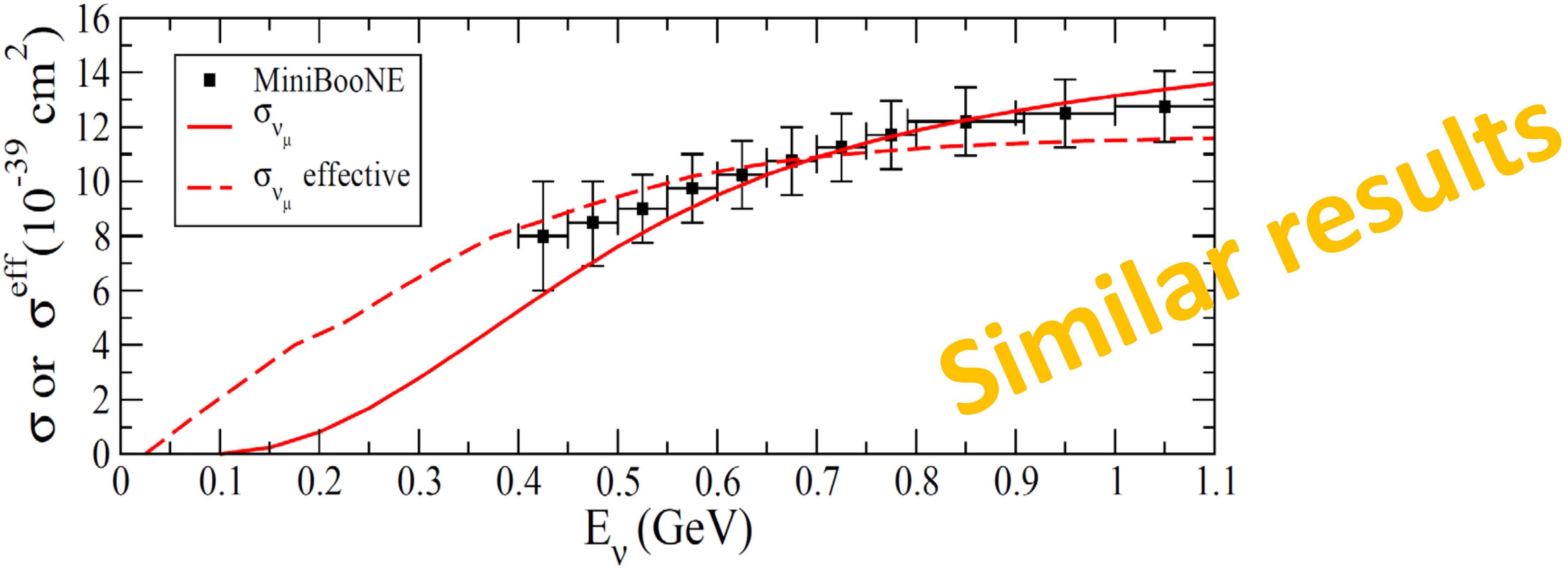


$$\left[\langle\sigma\rangle P_{rec}(E_{rec})\right]_{Exp} \sim$$

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

... and

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



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

Conclusions

- We have analyzed the MiniBooNE CCQE $\frac{d^2\sigma}{dT_\mu\, d\cos\theta_\mu}$ 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, $\boxed{M_A = 1.08 \pm 0.03}$.

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