XVII International Workshop on Neutrino Telescopes

Theory of Neutrino Cross Sections

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Outline

1. Motivation: Neutrino oscillations, neutrino detectors, nuclear cross sections
2. High energy cross sections: DIS
3. Intermediate energy cross sections
   a. Kaon production
   b. Multipion production
   c. Resonance production
   d. QE and QE-like processes: RPA & multinucleon mechanisms (MiniBooNE M_A puzzle)
4. Neutrino energy reconstruction
5. Conclusions

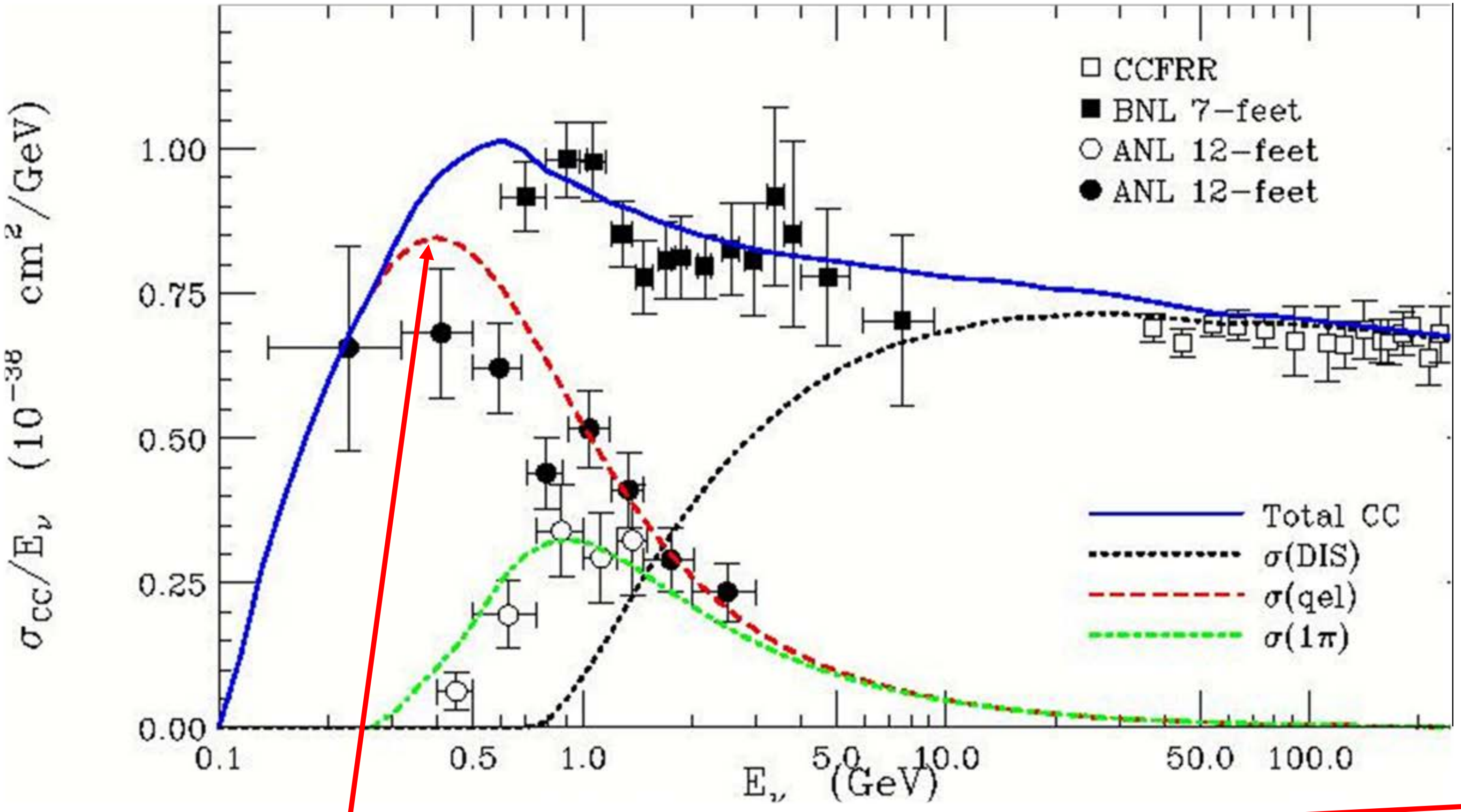
Bibliography:

- 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
- Formaggio J.A. and Zeller G.P.: *From eV to EeV: Neutrino cross sections across energy scales.: Rev. Mod. Phys. 84 (2012) 1307*
- Mosel U.: *Neutrino Interactions with Nucleons and Nuclei: Importance for Long-Baseline Experiments.:* Ann. Rev. Nucl. Part. Sci. 66, 171 (2016), arXiv:1602.00696 [nucl-th].
- Katori T. and Martini M.: *Neutrino-Nucleus Cross Sections for Oscillation Experiments.*: arXiv:1611.07770 [hep-ph].

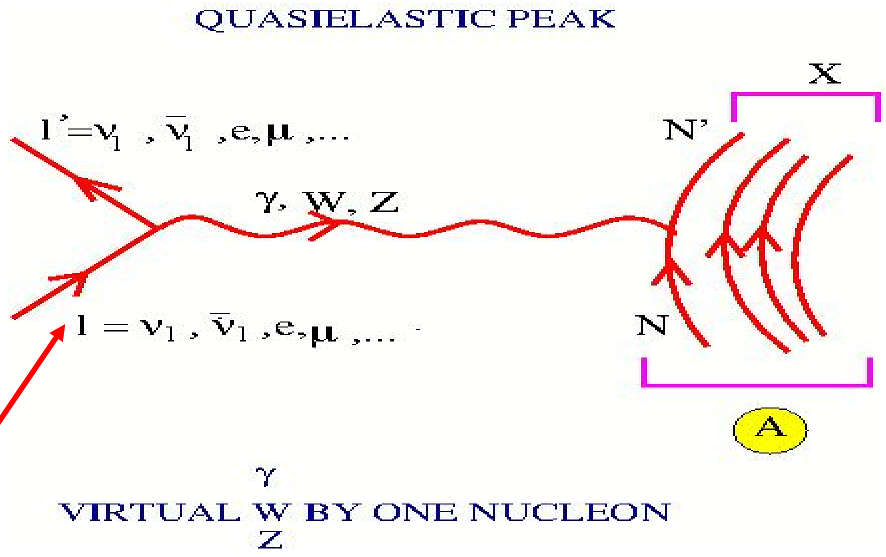
Motivation: Neutrino oscillations, neutrino detectors and nuclear cross sections

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

Theoretical knowledge of QE, 1π and DIS 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) ....

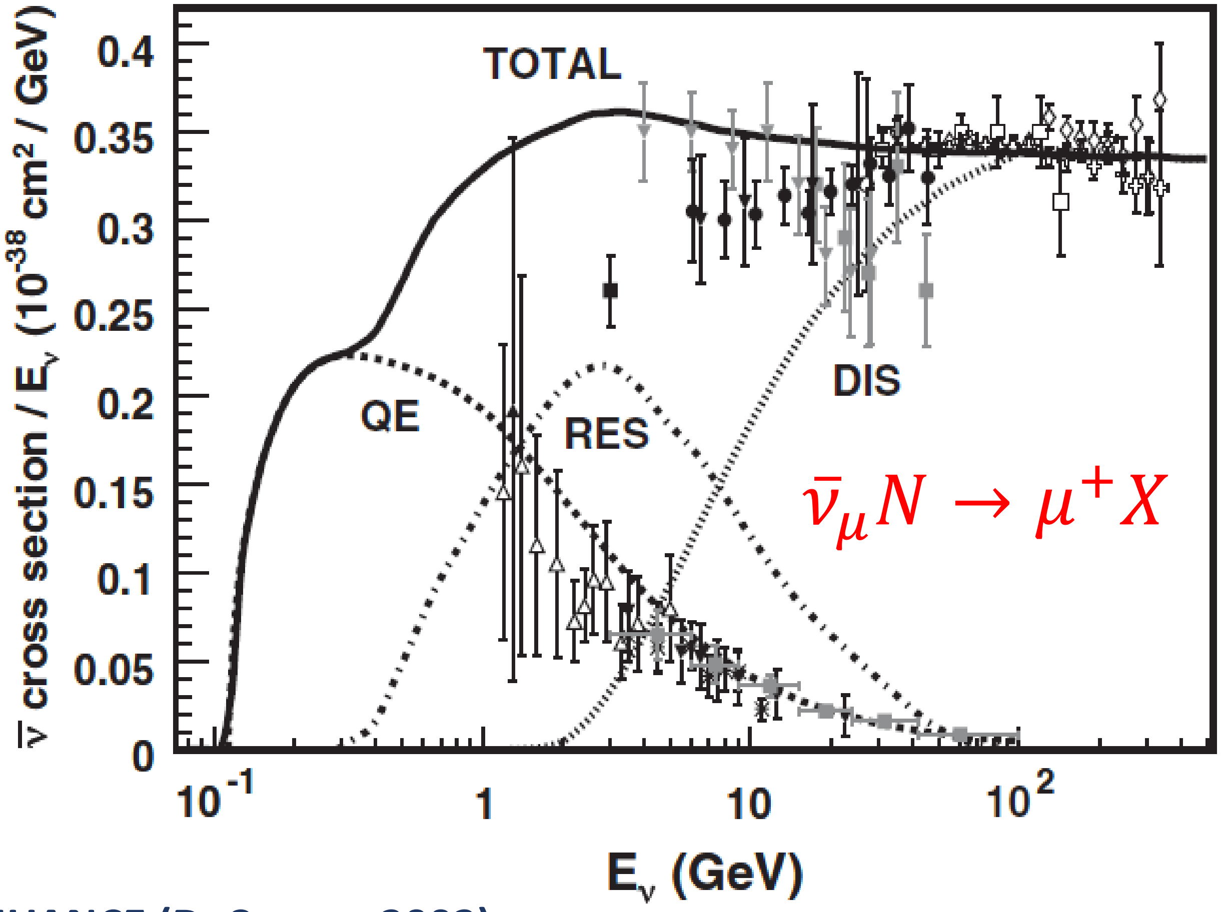


Th: NUANCE (D. Casper, 2002)

Juan Nieves, IFIC (CSIC & UV)

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

Neutrinos are detected through nuclear interactions



Th: NUANCE (D. Casper, 2002)

Theoretical knowledge of the neutrino-nucleus cross sections is important to carry out a precise neutrino oscillation data analysis...

^{12}C → Liquid scintillators
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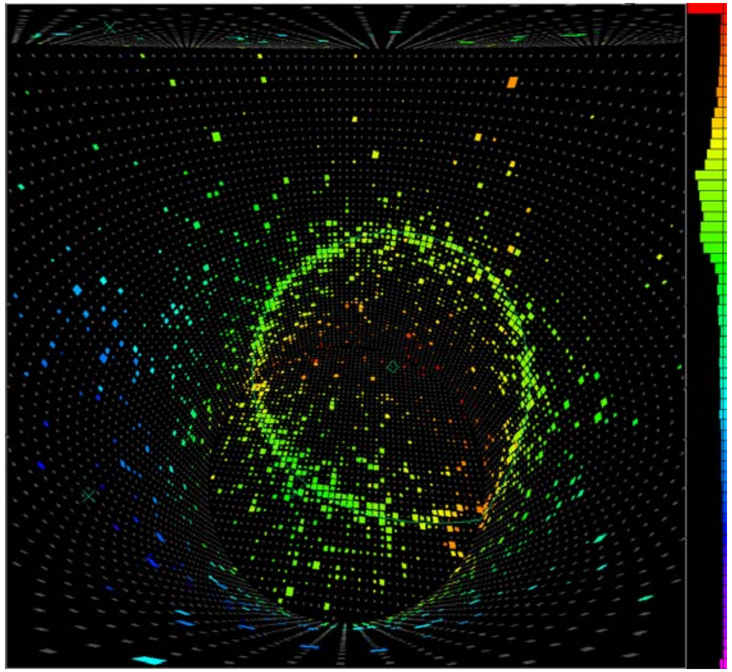
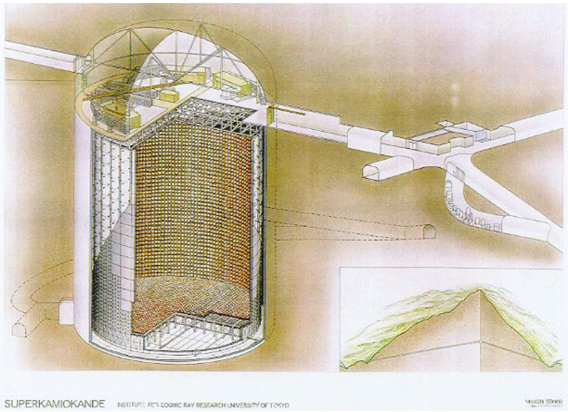
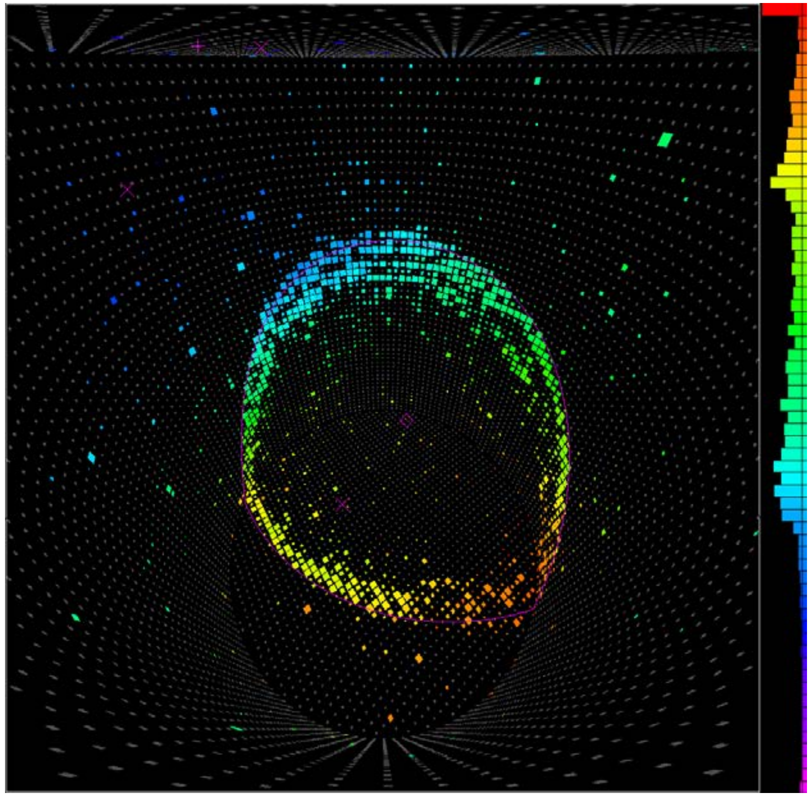
....



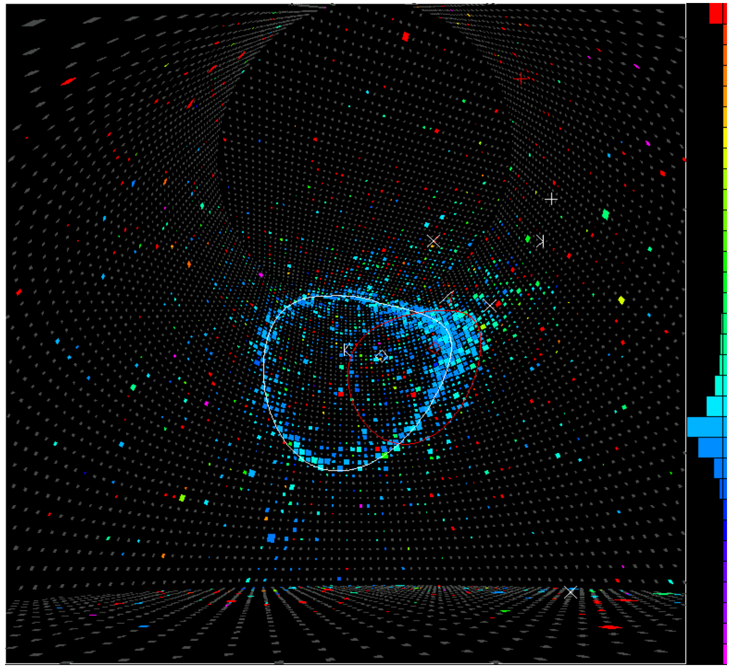
$\nwarrow$ e

SuperKamiokande





$\uparrow$ μ



$\leftarrow \pi^0$

$$\beta > \frac{1}{n} \rightarrow E_{\pi,\mu} > 200 - 300 \text{ MeV}$$

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Pion production → misidentification of 1 Cherenkov ring events that are assumed to be produced by Charged Current (CC) QE reactions $\nu_\alpha A \to l^\alpha$ A'

Even distinguishing between μ- and e-like rings

- Appearance Probability $P(\nu_\mu \to \nu_e)$: The CC QE signature $\nu_e A \to e\ A'$ used to identify ν_e can be confused with the NC 1π production $\nu_\mu A \to \nu_\mu A' \pi^0$
- Survival Probability $P(\nu_\mu \to \nu_\mu)$: The CC QE signature $\nu_\mu A \to \mu\ A'$ used to identify ν_μ can be confused with the CC or NC $\nu_{\mu,\tau} A \to (\nu_{\mu,\tau}\ or\ \mu, \tau) A' \pi$ when only one of the particles emits Cherenkov light. For instance, processes (ν_μ, μ, π) might produce an incorrect reconstruction of the neutrino energy E → L/E analysis ?

Nuclear cross sections are crucial to reduce the systematic errors of oscillation analysis !

There exist dedicated experiments as MINERνA (FermiLab), which **seeks to measure low energy neutrino interactions both in support of neutrino oscillation experiments and also to study the strong dynamics of the nucleon and nucleus that affect these interactions**

Neutrino Energy Reconstruction:

QE: $\nu_\mu + n \longrightarrow p\,\mu^-$ (bound in the nucleus)

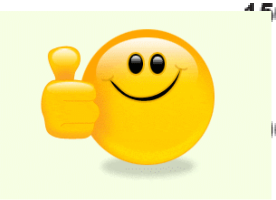
$$E_{\rm rec} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu|\cos\theta_\mu}$$

Exp

QE-like: problem absorbed or not detected pions and…

exp: only 1μ (from the lepton vertex). But, for instance if pions are produced:

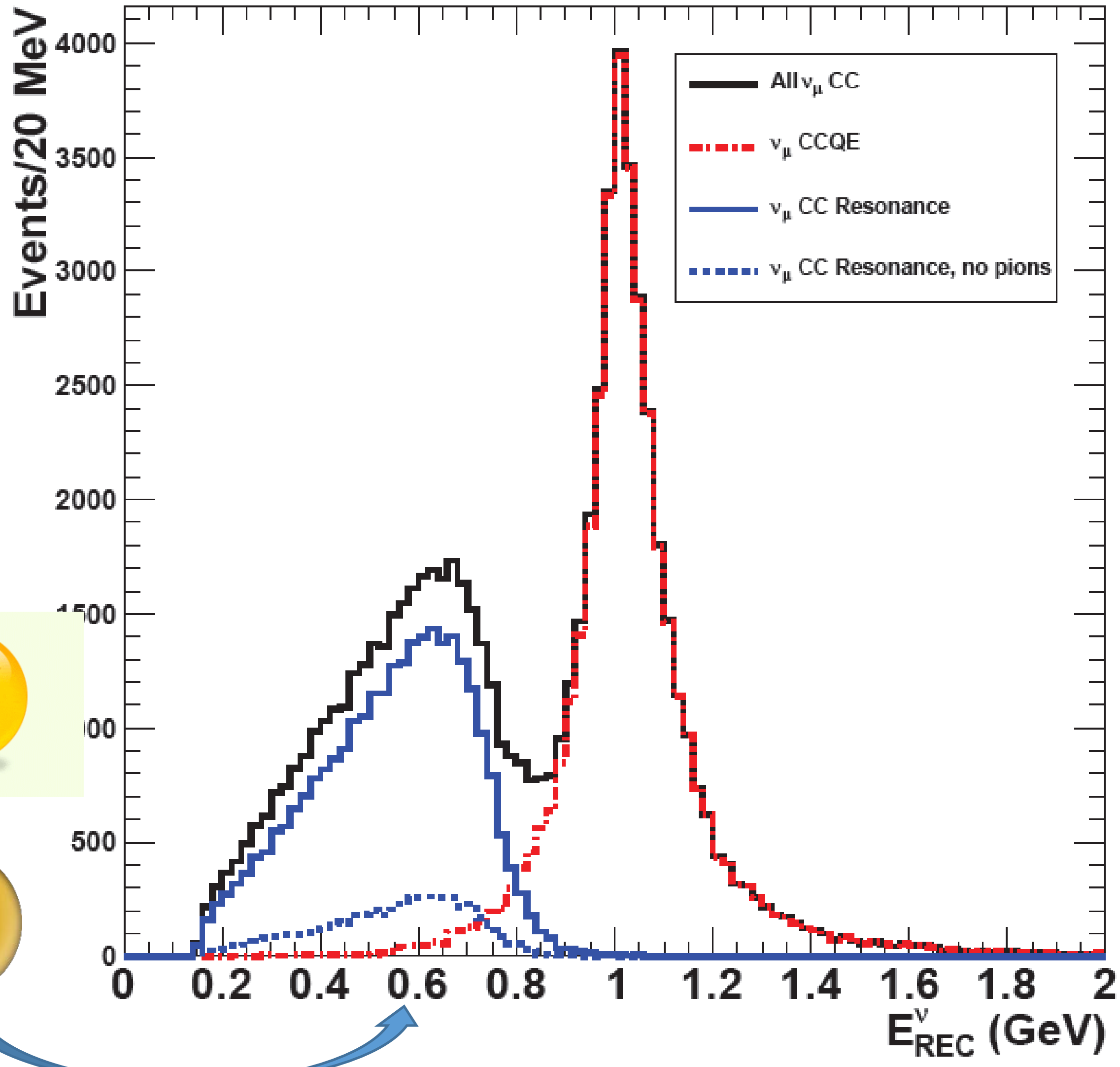
- pion decays and the extra muon is detected (2 muons in the final state)



- pion is absorbed or not detected

(MC corrected if the pion production cross section is well known…)

GENIE E_ν = 1 GeV



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Neutrino Energy Reconstruction:

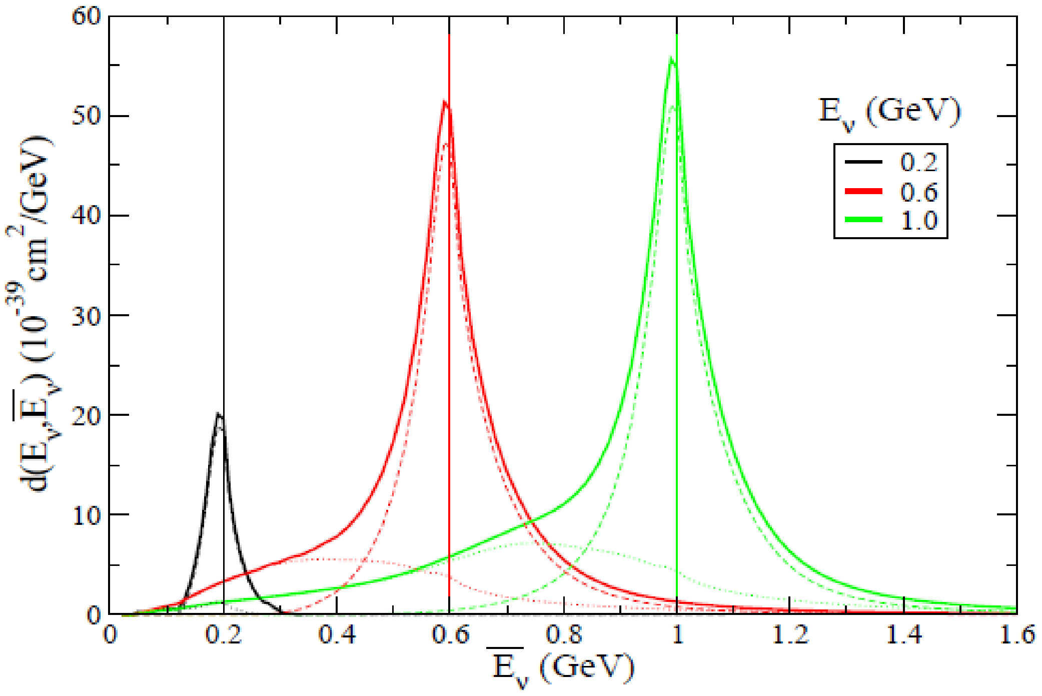
QE: $\nu_\mu + n \longrightarrow p\,\mu^-$ (bound in the nucleus)

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

Exp

QE-like: problem absorbed or not detected pions and 2p2h (nucl. effect)

M. Martini, M. Ericson, PRD 87 (2013)



QE Energy Reconstruction will be wrong !!

2p2h: $\nu_\mu + NN \longrightarrow N'N''\,\mu^-$

MC correct for this effect: ← cross section

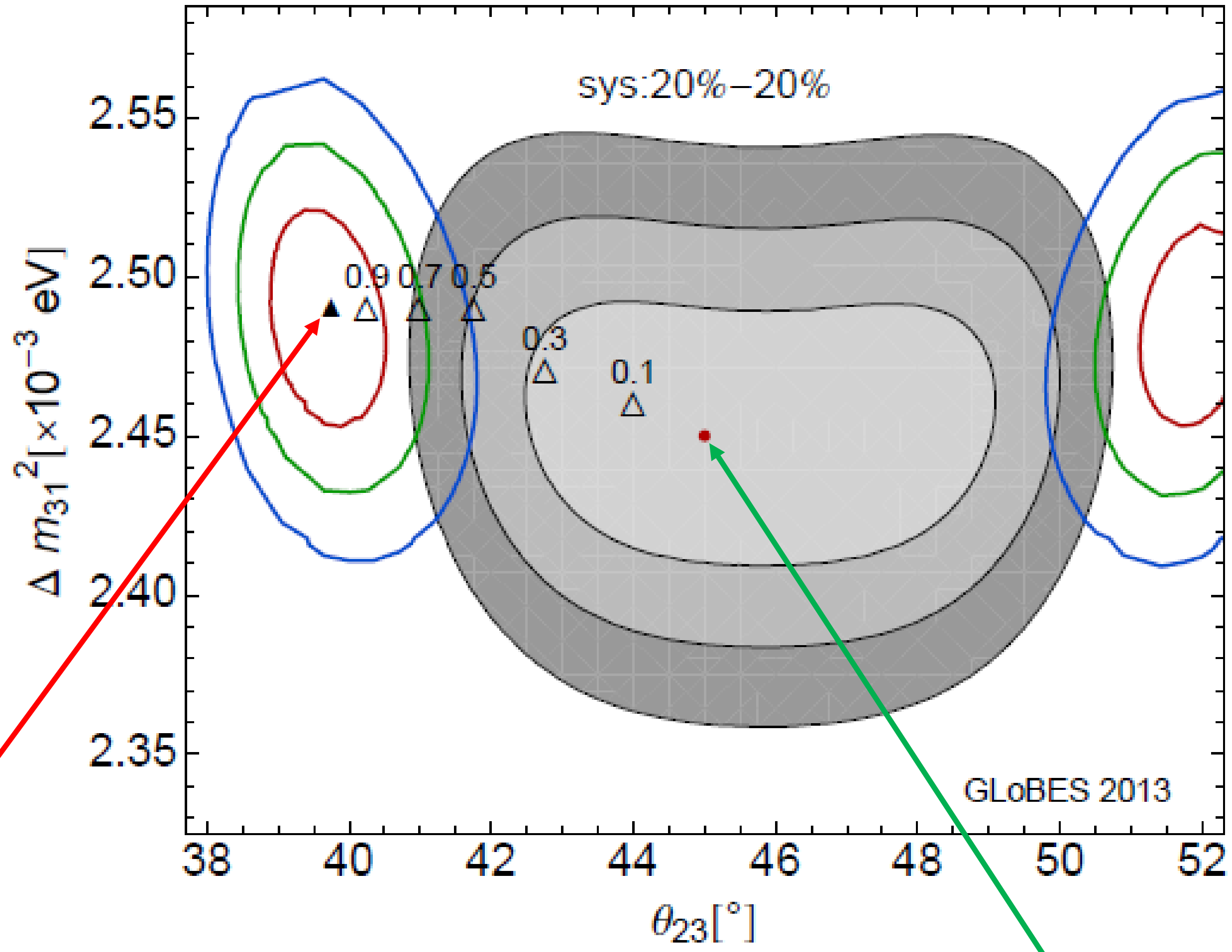
P. Coloma, P. Huber, PRL 111 (2013)

Quantitative impact in the determination of the oscillation parameters

Effects of a simple model for QE-like events ….

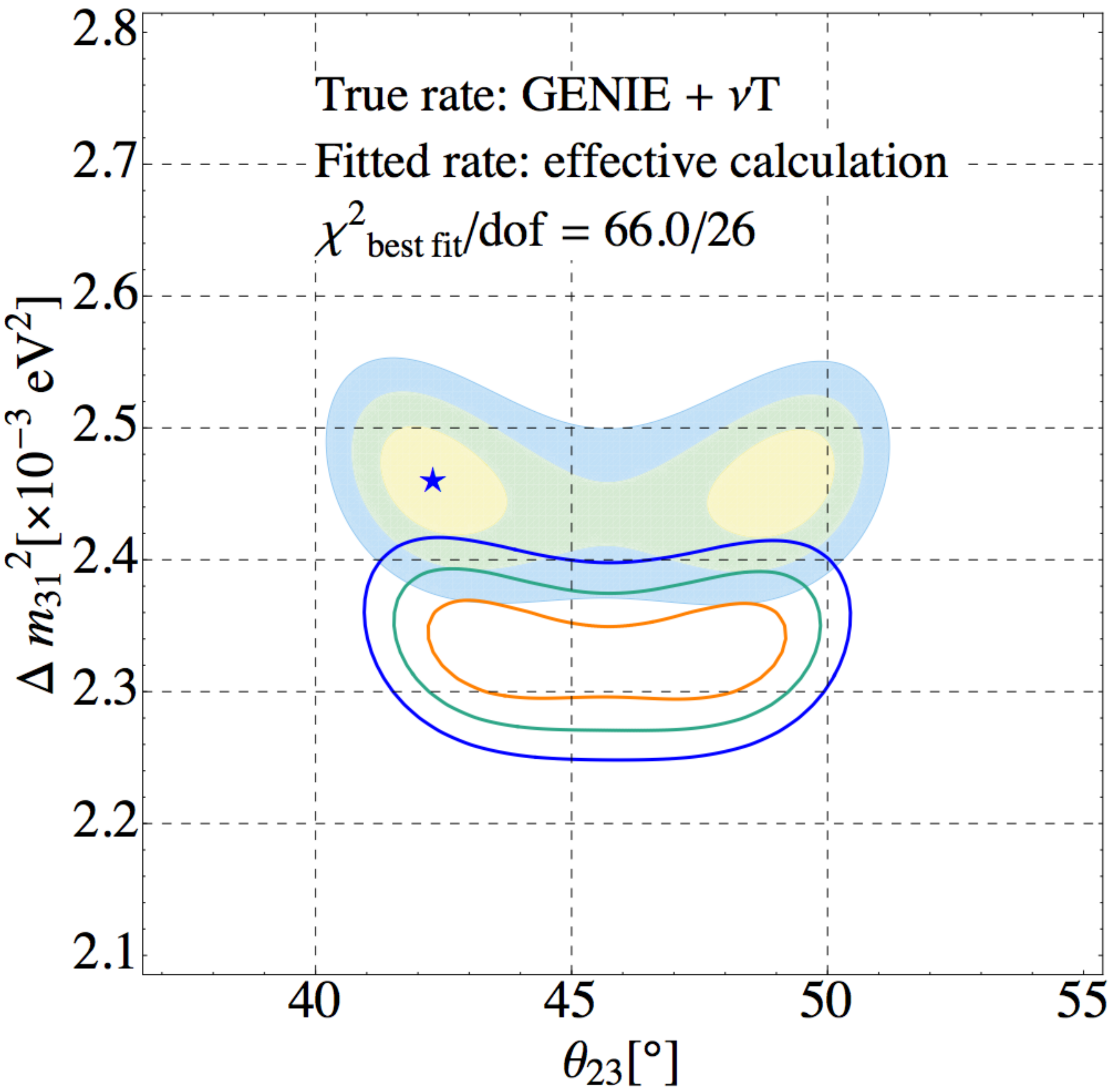
$$N_i^{\rm test}(\alpha) = \alpha \times N_i^{\rm QE} + (1-\alpha) \times N_i^{\rm QE\text{-}like}$$

α parametrizes the fraction of two-nucleon absorption that is neglected in the fit



Reconstructed from naive QE dynamics

true



Systematic uncertainties in long-baseline neutrino-oscillation experiments,
Artur M Ankowski and Camillo Mariani,
arXiv: 1609.00258

$\nu_l(\mathrm{k}) + A_Z \to l(k') + X, \qquad l = l^-, \nu_l$

$\bar{\nu}_l(\mathrm{k}) + A_Z \to l(k') + X, \qquad l = l^+, \bar{\nu}_l$

LAB frame
$$\frac{d^2\sigma_{\nu_l l, \bar{\nu}_l l}}{d\Omega(\widehat{k'})dE'_l} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G_F^2}{4\pi^2\eta\left(1-q^2/M_{W,Z}^2\right)^2} L_{\mu\sigma}^{(\nu,\bar{\nu})} W^{\mu\sigma}, \quad \eta = 1\,(CC), 4\,(NC)$$

$$L_{\mu\sigma}^{(\nu)} = L_{\sigma\mu}^{(\bar{\nu})} = L_{\mu\sigma}^s + iL_{\mu\sigma}^a = k'_\mu k_\sigma + k'_\sigma k_\mu - g_{\mu\sigma} k\cdot k' + i\epsilon_{\mu\sigma\alpha\beta}k'^\alpha k^\beta$$

$$W^{\mu\sigma} = \frac{1}{2M_i}\overline{\sum_f}(2\pi)^3\delta^4\left(P'_f - P - q\right)\langle f|j^\mu_{CC\pm,NC}(0)|i\rangle\langle f|j^\sigma_{CC\pm,NC}(0)|i\rangle^*$$

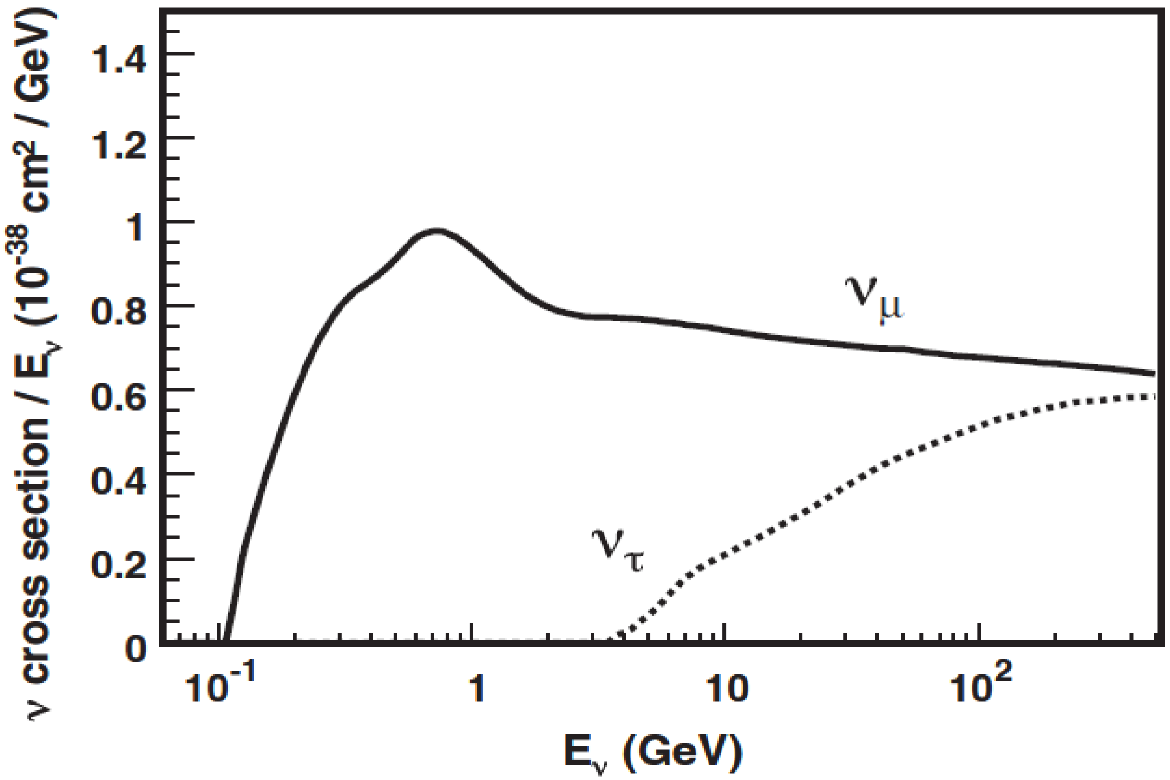
$$\frac{W^{\mu\nu}}{2M_i} = -g^{\mu\nu}W_1 + \frac{P^\mu P^\nu}{M_i^2}W_2 + i\frac{\epsilon^{\mu\nu\gamma\delta}P_\gamma q_\delta}{2M_i^2}W_3 + \frac{q^\mu q^\nu}{M_i^2}W_4 + \frac{P^\mu q^\nu + P^\nu q^\mu}{2M_i^2}W_5 + i\frac{P^\mu q^\nu - P^\nu q^\mu}{2M_i^2}W_6.$$

$W_i(q^2, q\cdot P)$

structure functions

$q = k - k', P^\mu = (M_i, \vec{0})$

I will focus on $\nu_\mu N$ scattering; In the case of $CC\ \nu_\tau N$ the τ mass produces large differences

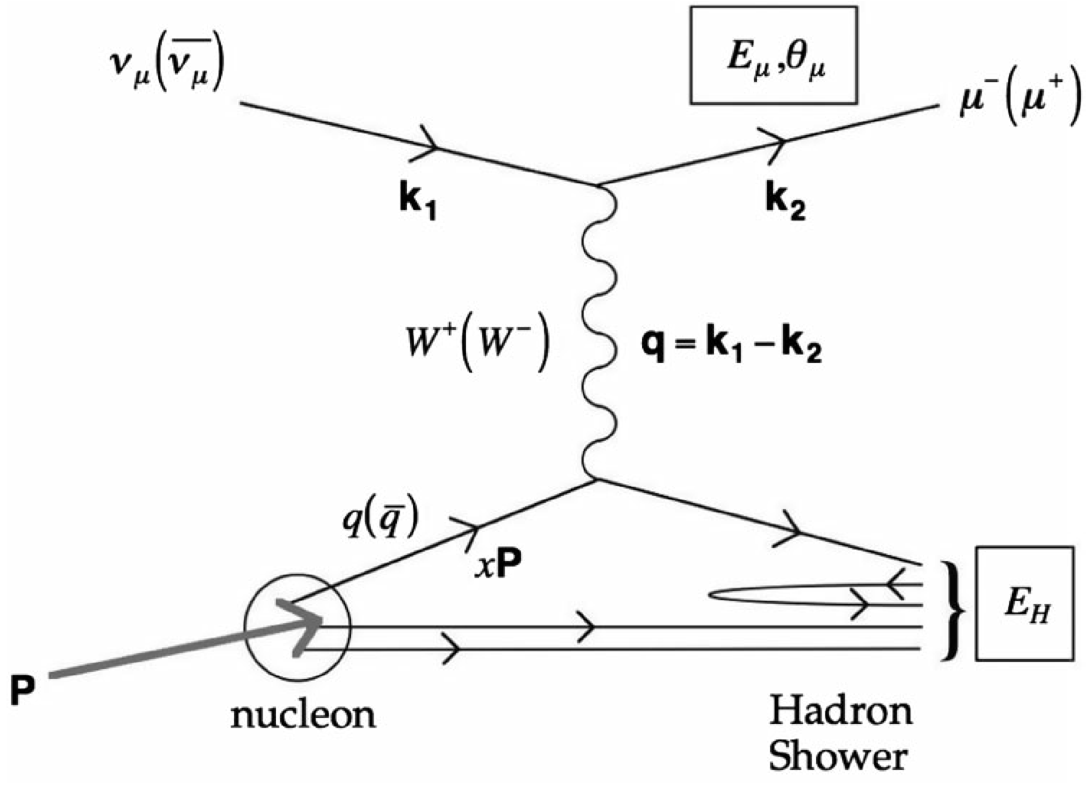


Formaggio & Zeller

Rev. Mod. Phys. 84 (2012) 1307

2. High energy cross sections $E_\nu \gg 1-5$ GeV, $Q^2 > 1\ \mathrm{GeV}^2$

At low energies the neutrino interacts with composite entities such as nucleons or nuclei. Given enough energy, the neutrino can actually begin to resolve the internal structure of the target: the neutrino can scatter off an individual quark inside the nucleon: **DIS (deep inelastic scattering) and manifests in the creation of a hadronic shower**



$$x = -\frac{q^2}{2M_N q^0}, \qquad y = \frac{q^0}{E_\nu} = \frac{E_{had}}{E_\nu}$$

The Bjorken scaling variable plays a prominent role in DIS, where the quark can carry a portion of the incoming momentum of the struck target

$$\frac{d^2\sigma_{\nu_l l,\bar{\nu}_l l}}{dxdy} = \frac{G_F^2 M_N E_\nu}{\eta\pi\left(1 - q^2/M_{W,Z}^2\right)^2}\left\{\left(1 - y - \frac{M_N x y}{2E_\nu}\right)F_2^{\nu,\bar{\nu}} + xy^2 F_1^{\nu,\bar{\nu}} \pm y\left(1 - \frac{y}{2}\right)xF_3^{\nu,\bar{\nu}}\right\}$$

$$x = -\frac{q^2}{2M_N q^0}, \qquad y = q^0/E_\nu$$

$$F_1(x,q^2) = 2M_N M_i W_1, \qquad F_2(x,q^2) = 2(q\cdot P)W_2, \qquad \frac{F_3(x,q^2)}{M_N} = -2(q\cdot P)\frac{W_3}{M_i}$$

Assuming the quark parton model, $F_i(x,q^2)$ can be expressed in terms of the quark composition of the target. Thus for instance in the simple case of scattering off nucleons..

PDFs

$$F_2(x,Q^2) = 2\sum_{i=u,d,\ldots}\left[xq(x,Q^2) + x\bar{q}(x,Q^2)\right],$$

$$xF_3(x,Q^2) = 2\sum_{i=u,d,\ldots}\left[xq(x,Q^2) - x\bar{q}(x,Q^2)\right],$$

xq $(x\bar{q})$ is the probability of finding a quark (antiquark) with a given momentum fraction

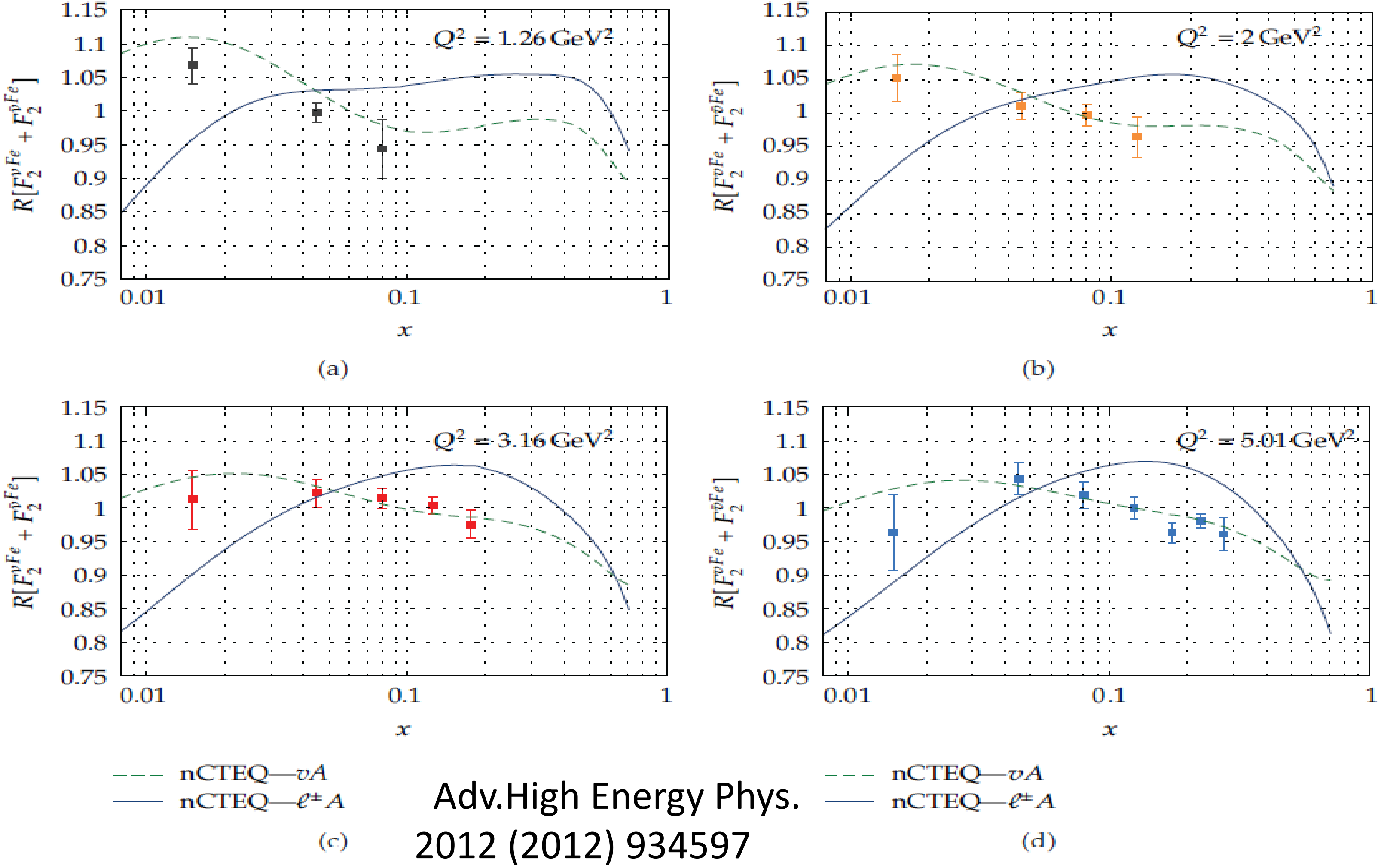
sum over all quark spices

and $F_2(x, Q^2) = \frac{1+R_L(x,Q^2)}{1+\frac{4M_N^2 x^2}{Q^2}} 2xF_1(x, Q^2)$, with $R_L(x, Q^2)$ the ratio of cross sections for scattering off longitudinally and transversely polarized exchange bosons

Neutrino scattering can play an important role in extraction of these fundamental parton distribution functions (PDFs) since only neutrinos via the weak interaction can resolve the flavor of the nucleon's constituents: ν interacts with d, s, $\bar{u}$ and $\bar{c}$ while the $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$. The weak current's unique ability to "taste" only particular quark flavors significantly enhances the study of parton distribution functions. High-statistics measurement of the nucleon's partonic structure, using neutrinos, could complement studies with electromagnetic probes.

Measurement of these structure functions has been the focus of many charged lepton and neutrino DIS experiments, which together have probed F_2, R_L and xF_3 over a wide range of x and Q^2 values both for neutrinos and antineutrinos.

Additional effects must be included in any realistic description of DIS processes: lepton masses, higher order QCD processes, heavy quark production, non perturbative higher twist effects, nuclear and radiative corrections. In general these contributions are typically well known and **do not add large uncertainties in the predicted cross sections**



Adv.High Energy Phys. 2012 (2012) 934597

Figure 7: Nuclear correction factor R for the average F_2 structure function in charged current νFe scattering at $Q^2 = 1.2, 2.0, 3.2$, and $5.0\,\text{GeV}^2$ compared to the measured NuTeV points. The green dashed curve shows the result of the nCTEQ analysis of νA (CHORUS, CCFR, and NuTeV) differential cross sections plotted in terms of the average F_2^{Fe} divided by the results obtained with the reference fit (free proton) PDFs. For comparison, the nCTEQ fit to the charged-lepton data is shown by the solid blue curve.

Some tension between charged-lepton $(l^{\pm}A)$ and the neutrino (νA) when comparing the same A

3. Intermediate energy cross sections (neutrino scatter off nucleons)

- Kaon production

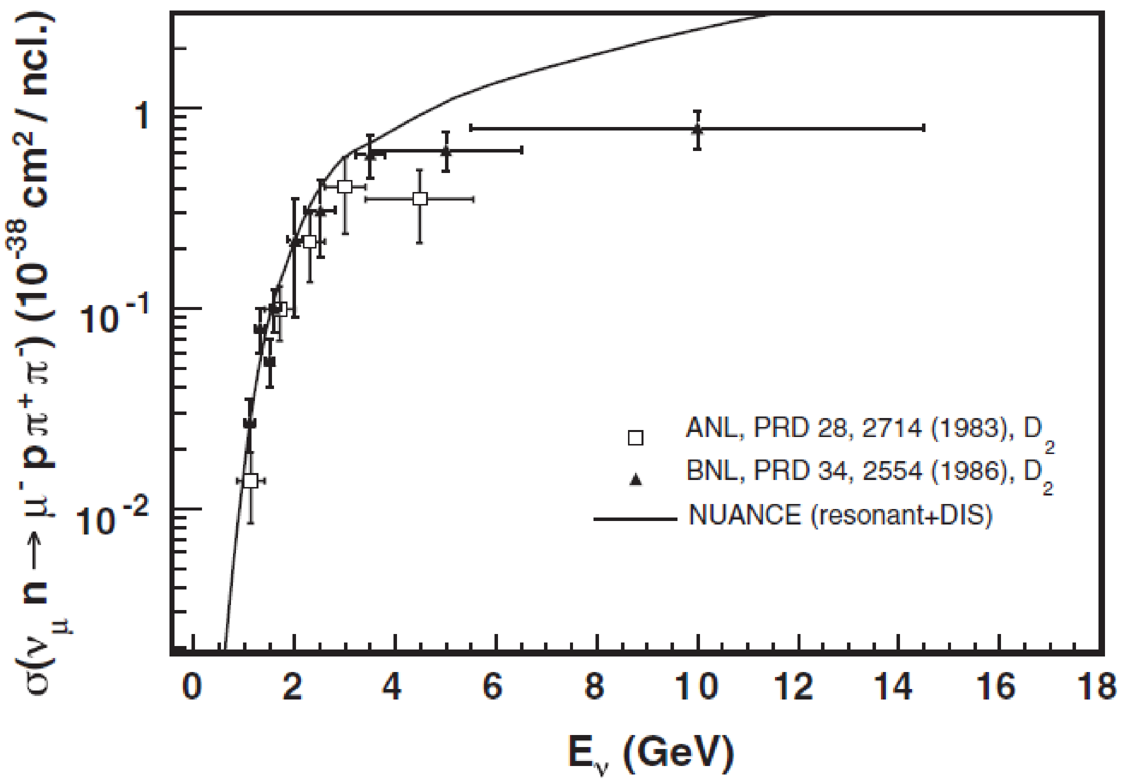
CC:	NC:
$\nu_\mu n \to \mu^- K^+ \Lambda^0$	$\nu_\mu p \to \nu_\mu K^+ \Lambda^0$
$\nu_\mu p \to \mu^- K^+ p$	$\nu_\mu n \to \nu_\mu K^0 \Lambda^0$
$\nu_\mu n \to \mu^- K^0 p$	$\nu_\mu p \to \nu_\mu K^+ \Sigma^0$
$\nu_\mu n \to \mu^- K^+ n$	$\nu_\mu p \to \nu_\mu K^0 \Sigma^+$
$\nu_\mu p \to \mu^- K^+ \Sigma^+$	$\nu_\mu n \to \nu_\mu K^0 \Sigma^0$
$\nu_\mu n \to \mu^- K^+ \Sigma^0$	$\nu_\mu n \to \nu_\mu K^+ \Sigma^-$
$\nu_\mu n \to \mu^- K^0 \Sigma^+$	$\nu_\mu n \to \nu_\mu K^- \Sigma^+.$

These reactions typically have small cross sections because the kaon channels are not enhanced by any dominant resonance

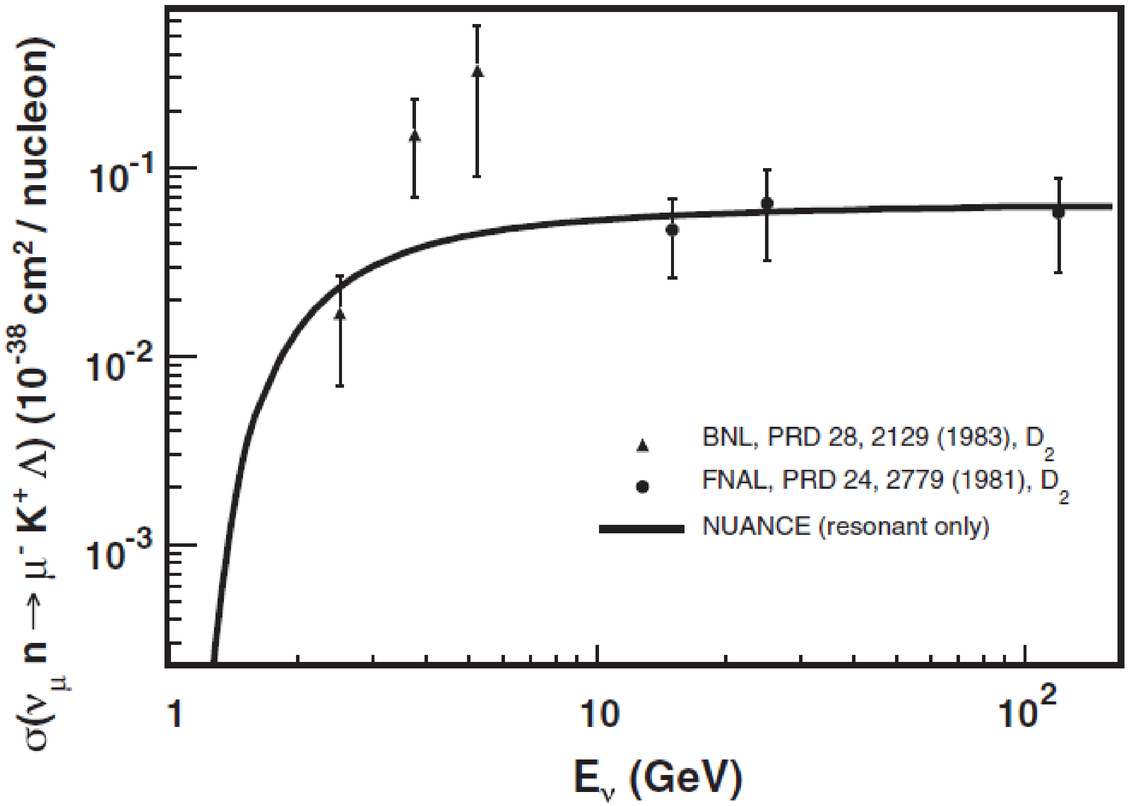
DIS can also produce mutipion and kaon final states

All of the existing measurements have been performed strictly using deuterium-filled bubble chambers

- Multipion production: Baryonic resonances created in neutrino-nucleon reactions can potentially decay into multipion final states.
- Resonance production
- QE & QE-like processes

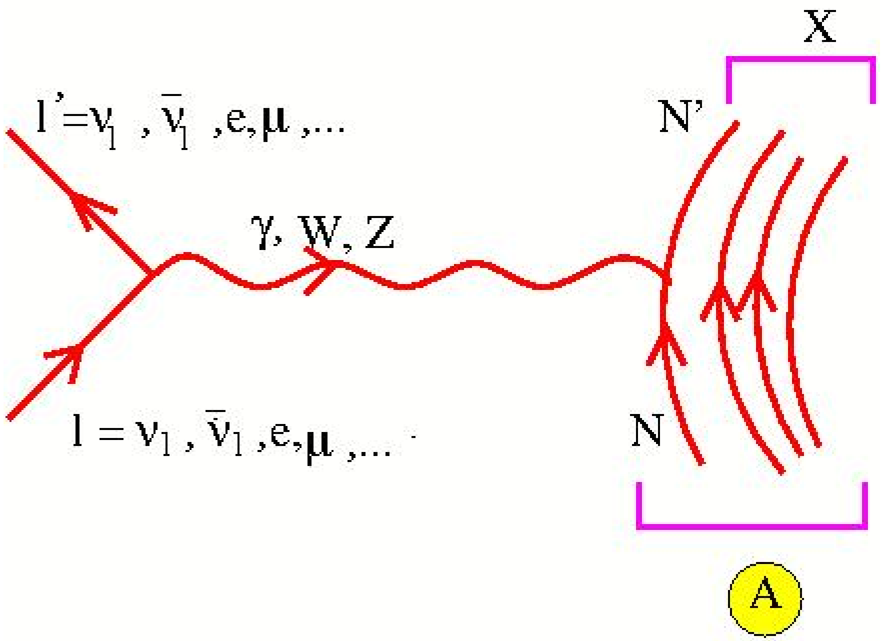


$\sigma(\nu_\mu n \to \mu^- p \pi^+ \pi^-)$ (10^{-38} cm^2 / ncl.)
1
10^{-1}
10^{-2}
0 2 4 6 8 10 12 14 16 18
E_ν (GeV)
ANL, PRD 28, 2714 (1983), D_2
BNL, PRD 34, 2554 (1986), D_2
NUANCE (resonant+DIS)



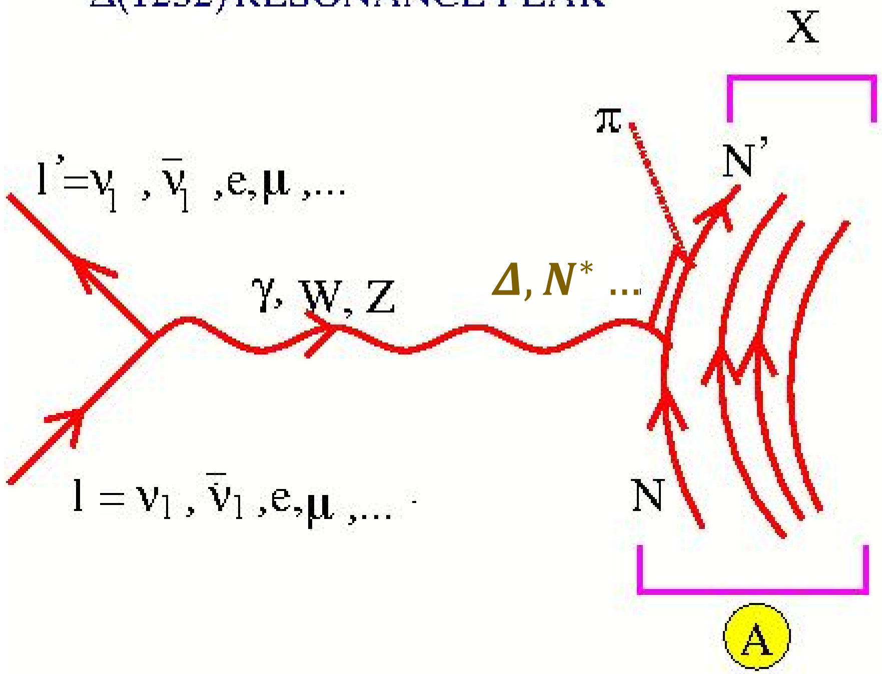
$\sigma(\nu_\mu n \to \mu^- K^+ \Lambda)$ (10^{-38} cm^2 / nucleon)
10^{-1}
10^{-2}
10^{-3}
1
10
10^2
E_ν (GeV)
BNL, PRD 28, 2129 (1983), D_2
FNAL, PRD 24, 2779 (1981), D_2
NUANCE (resonant only)

QUASIELASTIC PEAK



γ
VIRTUAL W BY ONE NUCLEON
Z

Δ(1232) RESONANCE PEAK

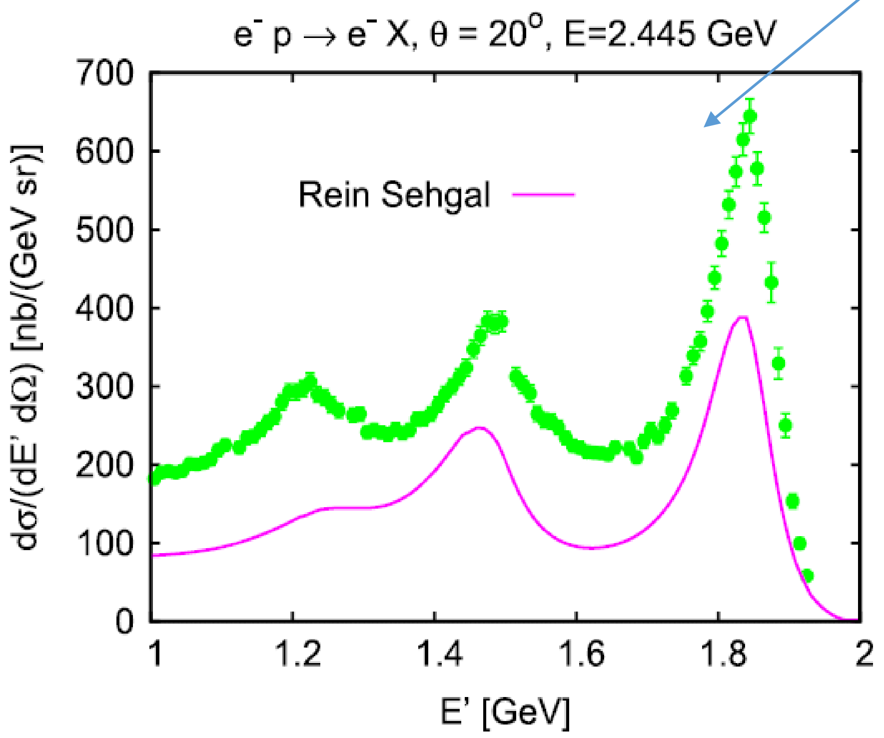


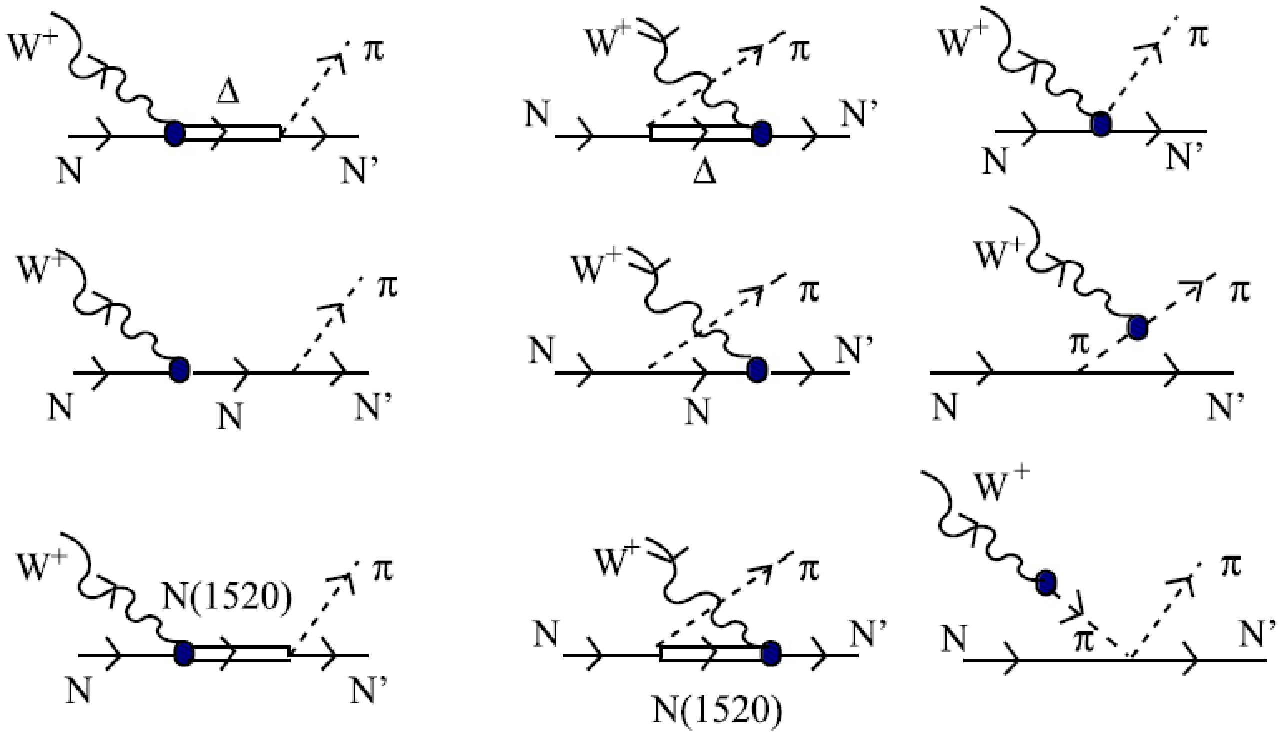
EXCITATION OF Δ, N^* ... DEGREES OF FREEDOM

Nuclear effects are relevant!

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 !)

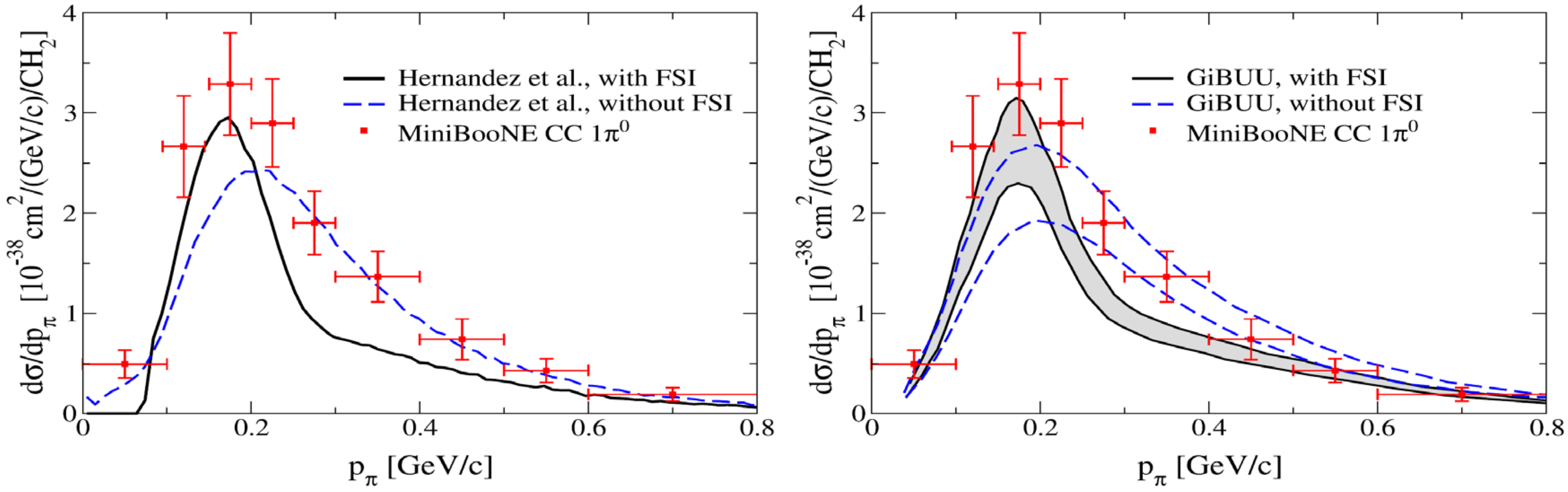
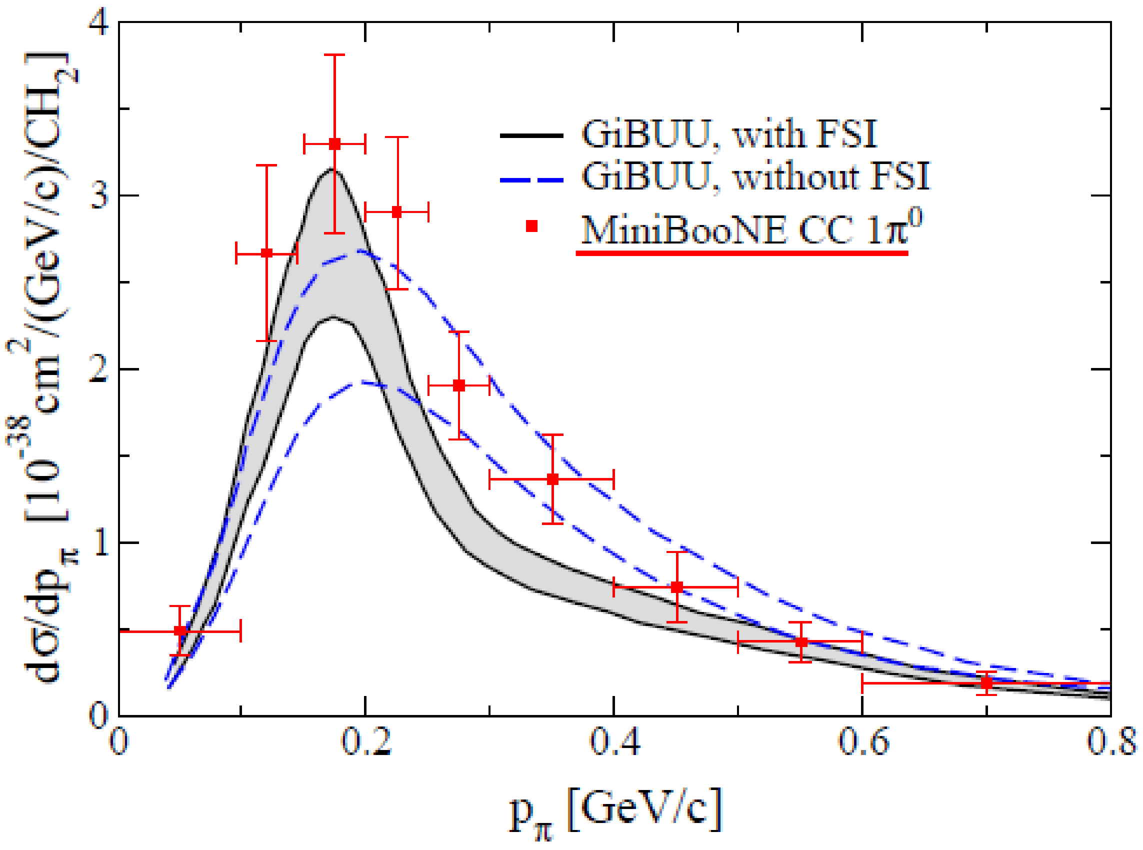
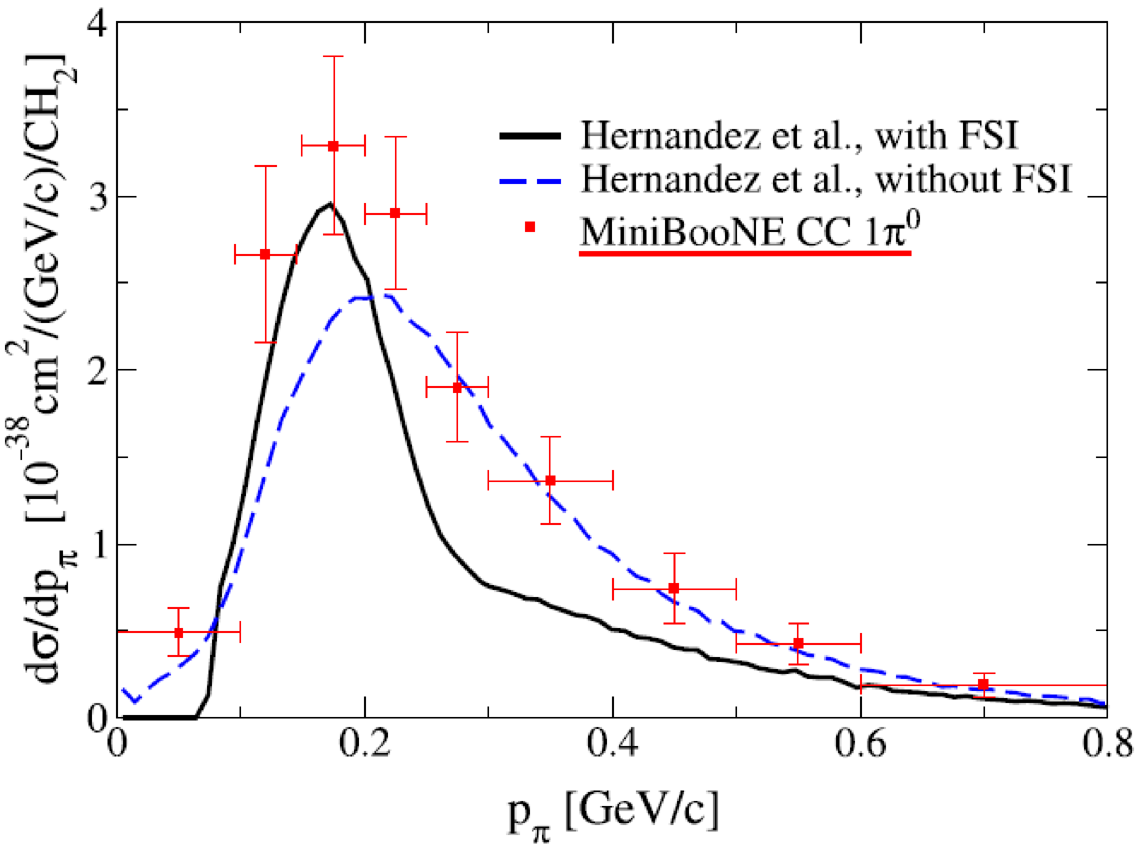


Figure 15. MiniBooNE flux-folded differential $d\sigma/dp_\pi$ cross section for $CC1\pi^0$ production by ν_μ in mineral oil. Data are from [27]. Left: predictions from the cascade approach of [184]. The solid curve corresponds to the full model and the dashed one stands for the results obtained neglecting 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.

There exist some discrepancies between theoretical predictions and data!

New J.Phys. 16 (2014) 075015

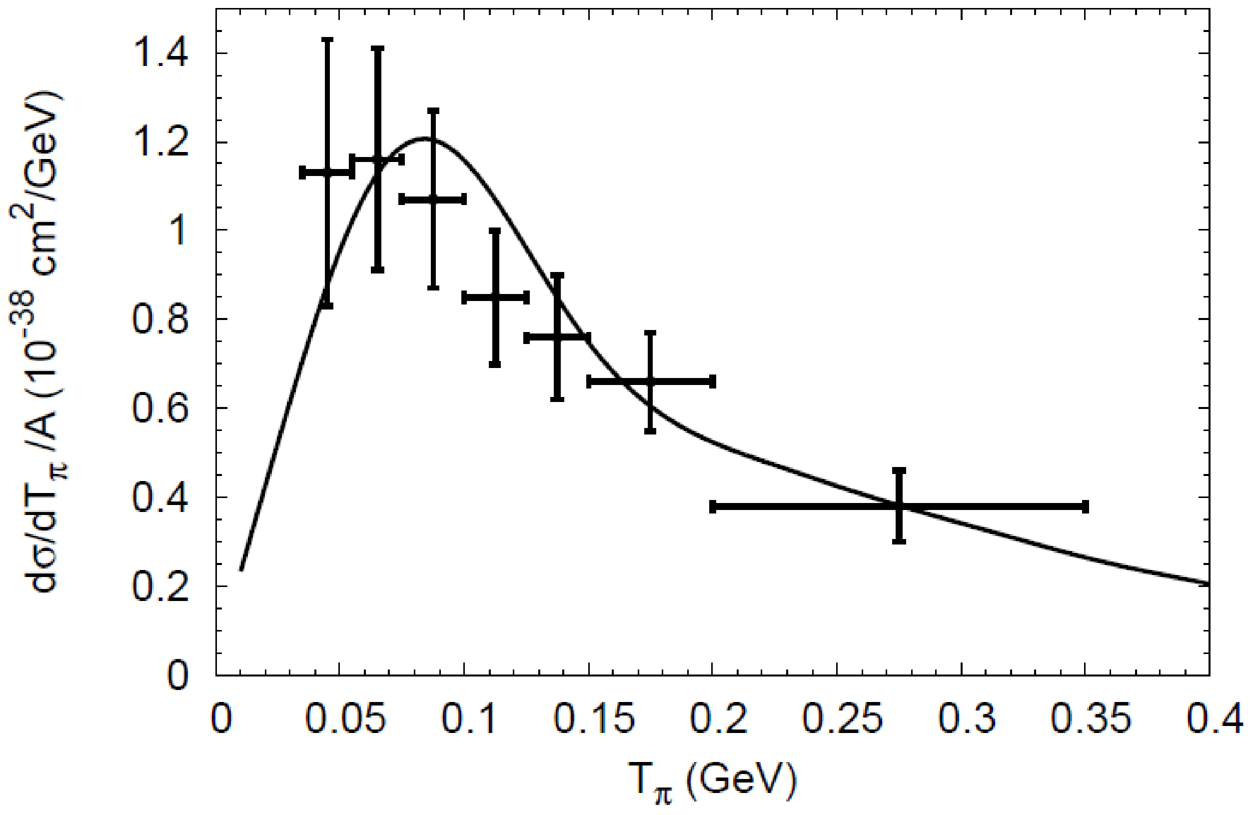


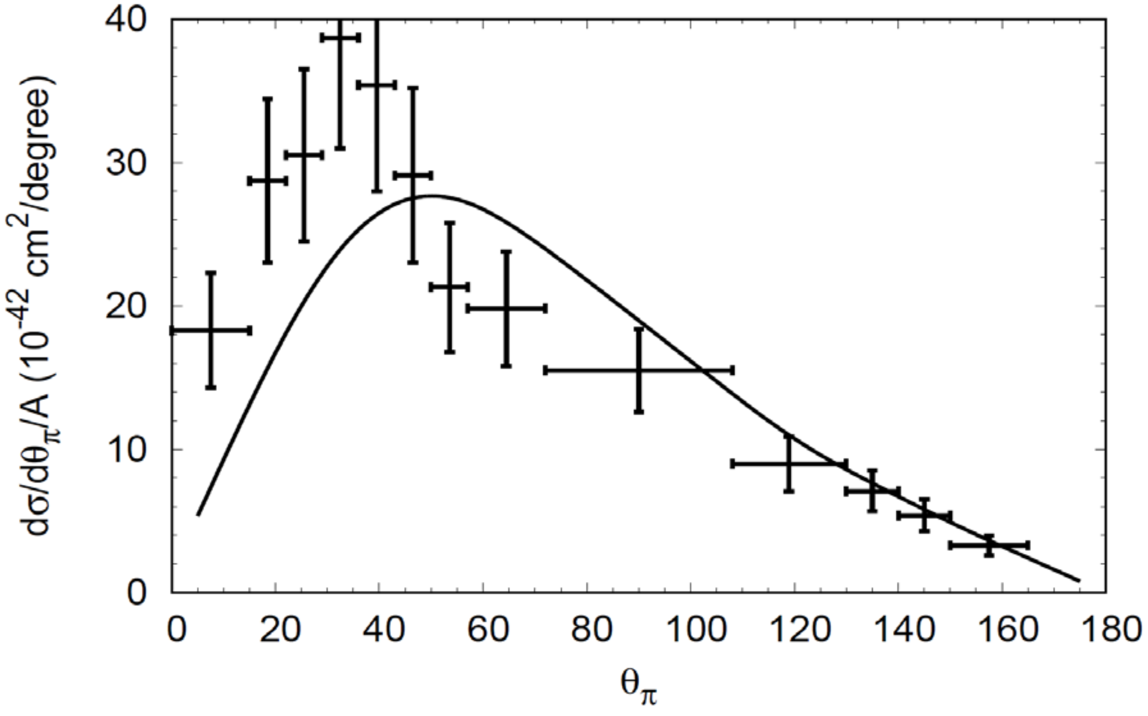


O. Lalakulich, U. Mosel, PRC 87 (2013)

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 ….

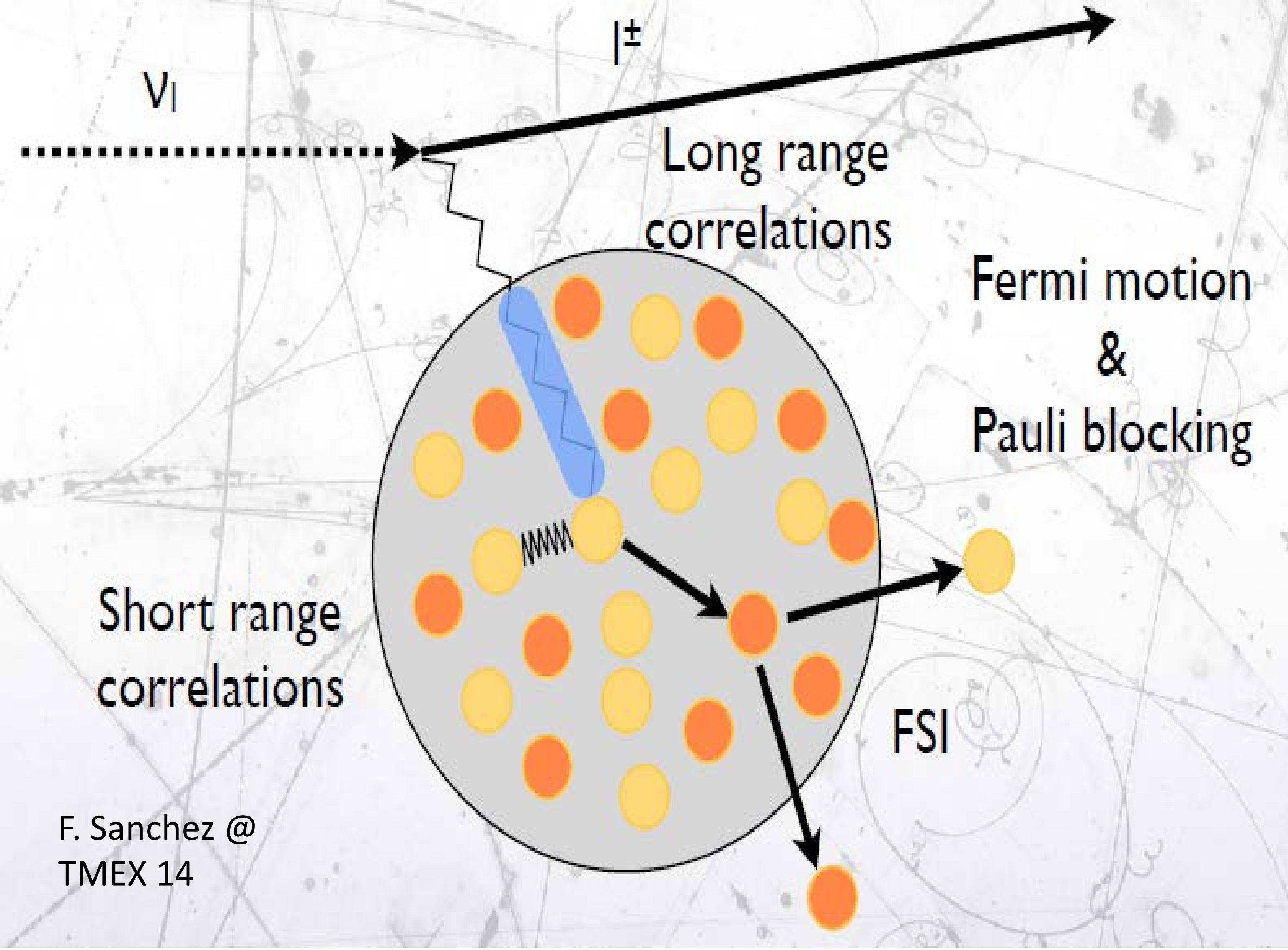


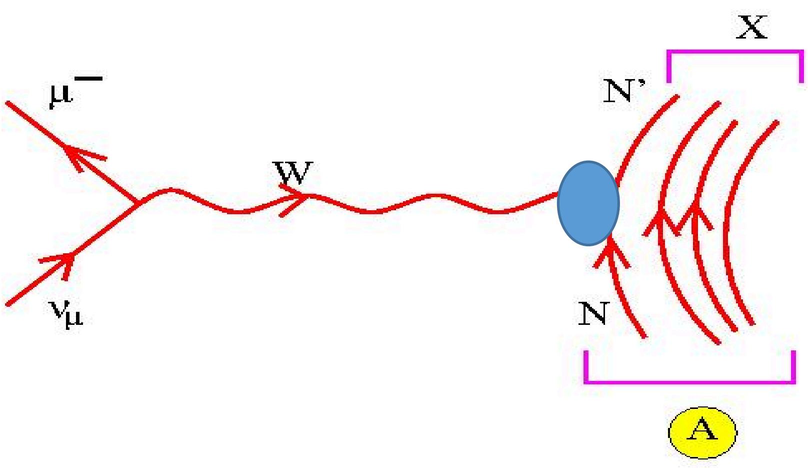


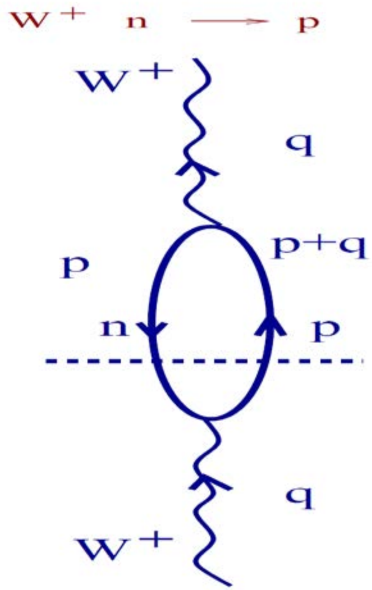
U. Mosel and K. Gallmeister (GiBUU), 1702.04932: Comparison to MINERνA data with $W_{\pi N} < 1.4$ GeV

MINERνA and MiniBooNE data compatible?

3.d) Neutrino-nucleus inclusive QE scattering : MiniBooNE M_A puzzle







1p1h excitation

Juan Nieves, IFIC (CSIC & UV)

Inclusive QE processes [f.i. (ν_l, l)]

$(W^\pm, Z^0$ absorption by one nucleon)

First ingredient: M.E. of the CC/NC current between nucleons.

$$< p; \vec{p}\,' = \vec{p} + \vec{q}\,|j^\alpha_{cc}(0)|n; \vec{p}\; > \;=\; \bar{u}(\vec{p}\,')\,[V^\alpha - A^\alpha]\,u(p)$$

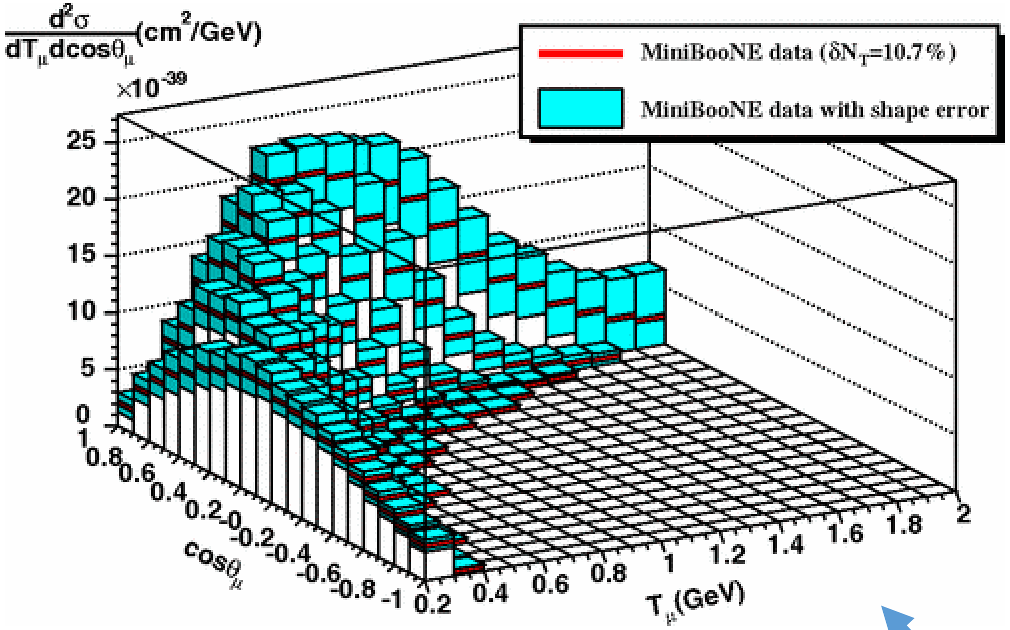
$$V^\alpha = 2\cos\theta_c \times \left(F_1^V(q^2)\gamma^\alpha + \mathrm{i}\mu_V \frac{F_2^V(q^2)}{2M}\sigma^{\alpha\nu} q_\nu \right)$$

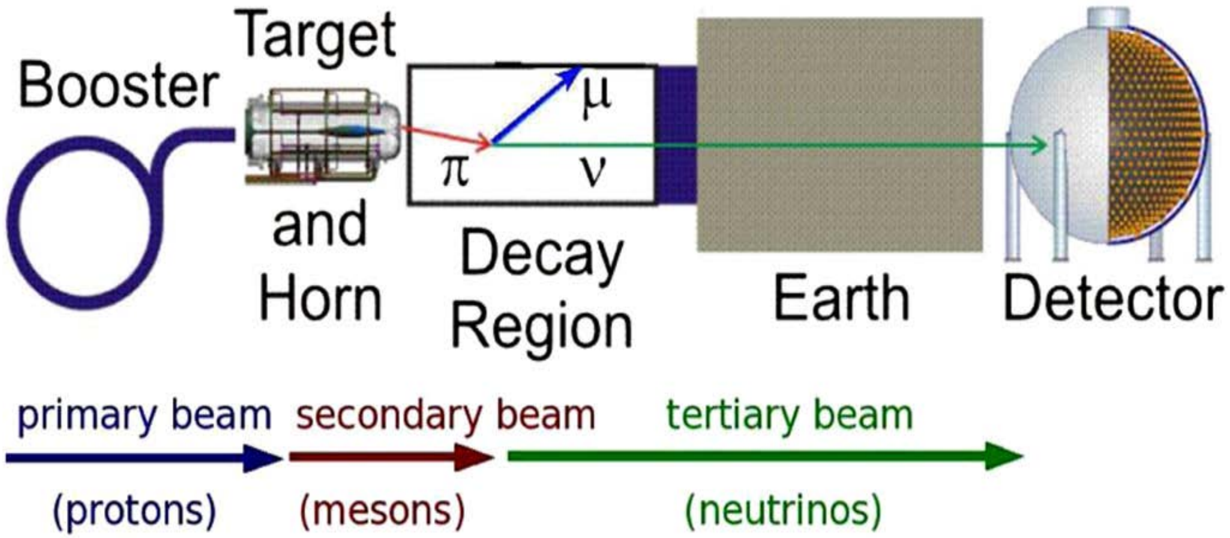
$$A^\alpha = \cos\theta_c G_A(q^2) \times \left(\gamma^\alpha\gamma_5 + \frac{2M}{m_\pi^2 - q^2} q^\alpha \gamma_5 \right) \quad \textbf{(PCAC)}$$

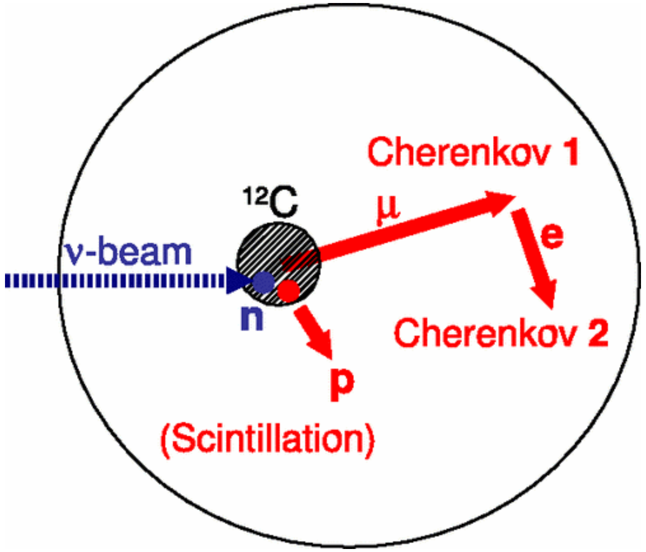
with vector form factors related to the electromagnetic ones and

$$G_A(q^2) = \frac{g_A}{(1 - q^2/\boxed{M_A^2})^2}, \quad g_A = 1.257$$

MiniBooNE CCQE (PRD 81, 092005)







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

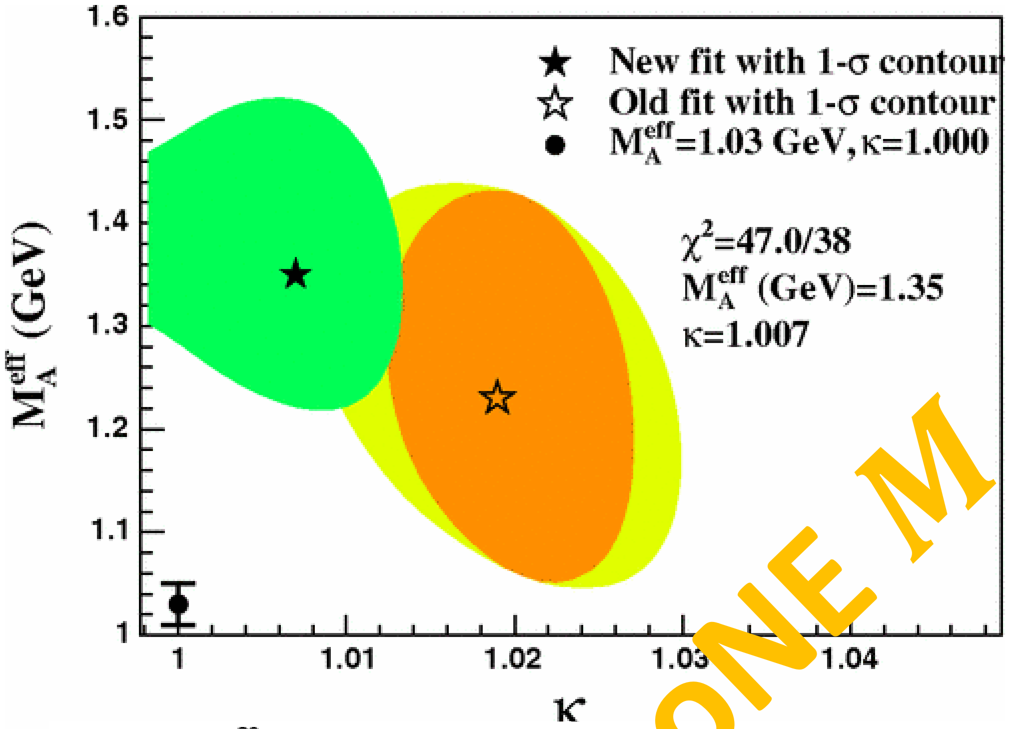
1 muon events !

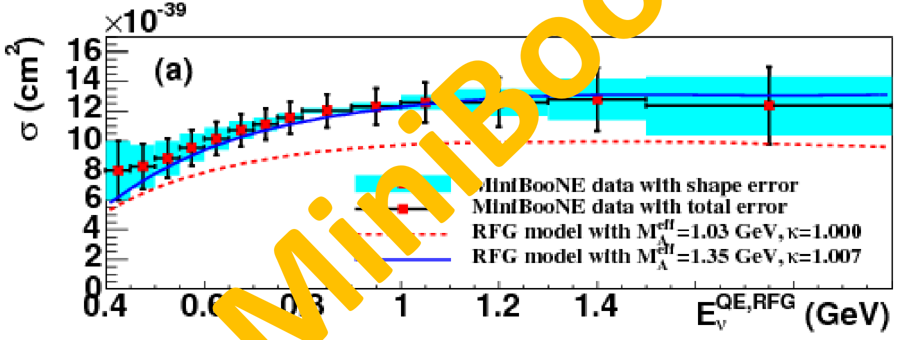
The largest background is from CC single pion production: CC1π^+

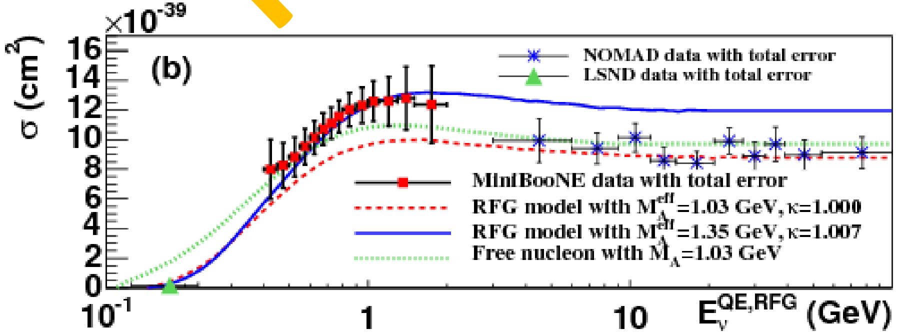
$$1:\ \nu_\mu + p(n) \to \mu^- + p(n) + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$2:\ \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$3:\ \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu.$$

2 muon events

MiniBooNE M_A puzzle





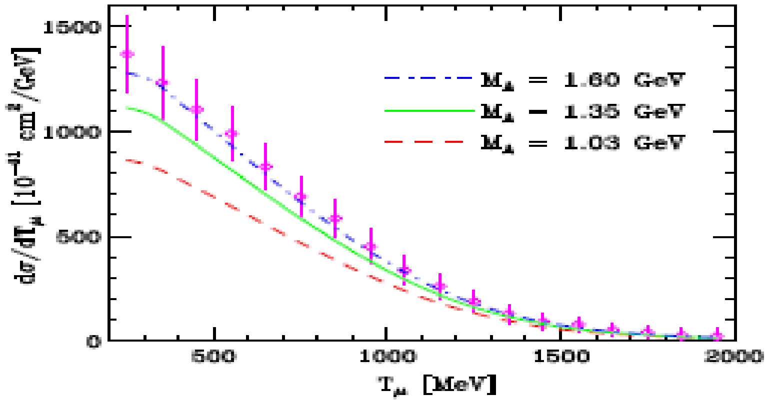


$M_A^{\rm eff} = 1.35$ GeV

vs

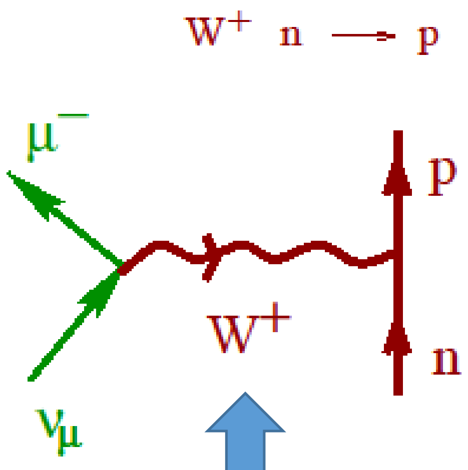
1.03 GeV (world avg)

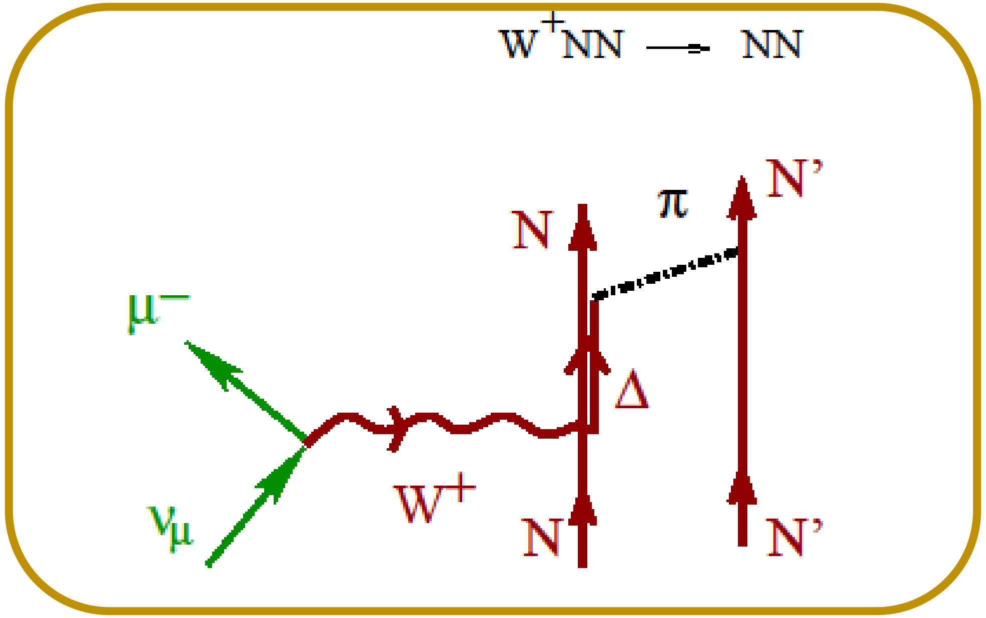
confirmed by many other groups, for instance by Benhar et al. (PRL 105, 132301)

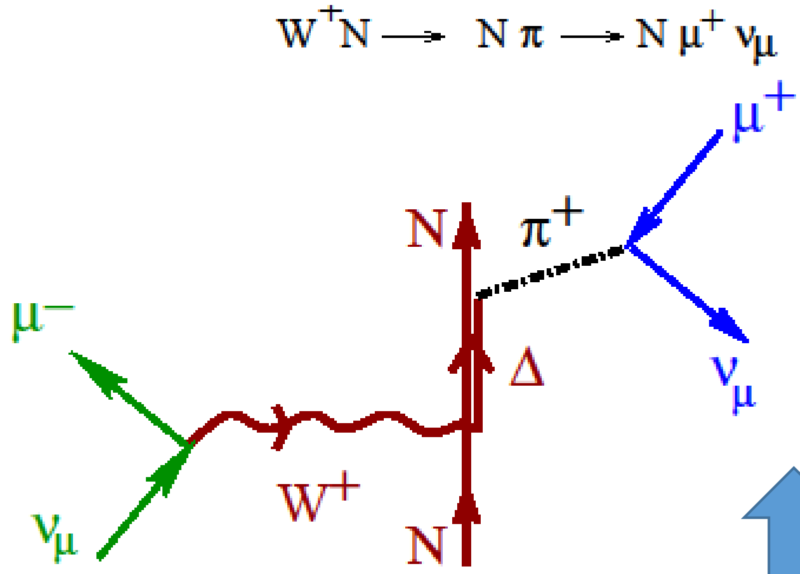


ChPT O(p^3) + single pion electroproduction data: $M_A = 1.014 \pm 0.016$ GeV (V. Bernard, N. Kaiser, and U. G.Meissner, PRL69, 1877 (1992))

- 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))



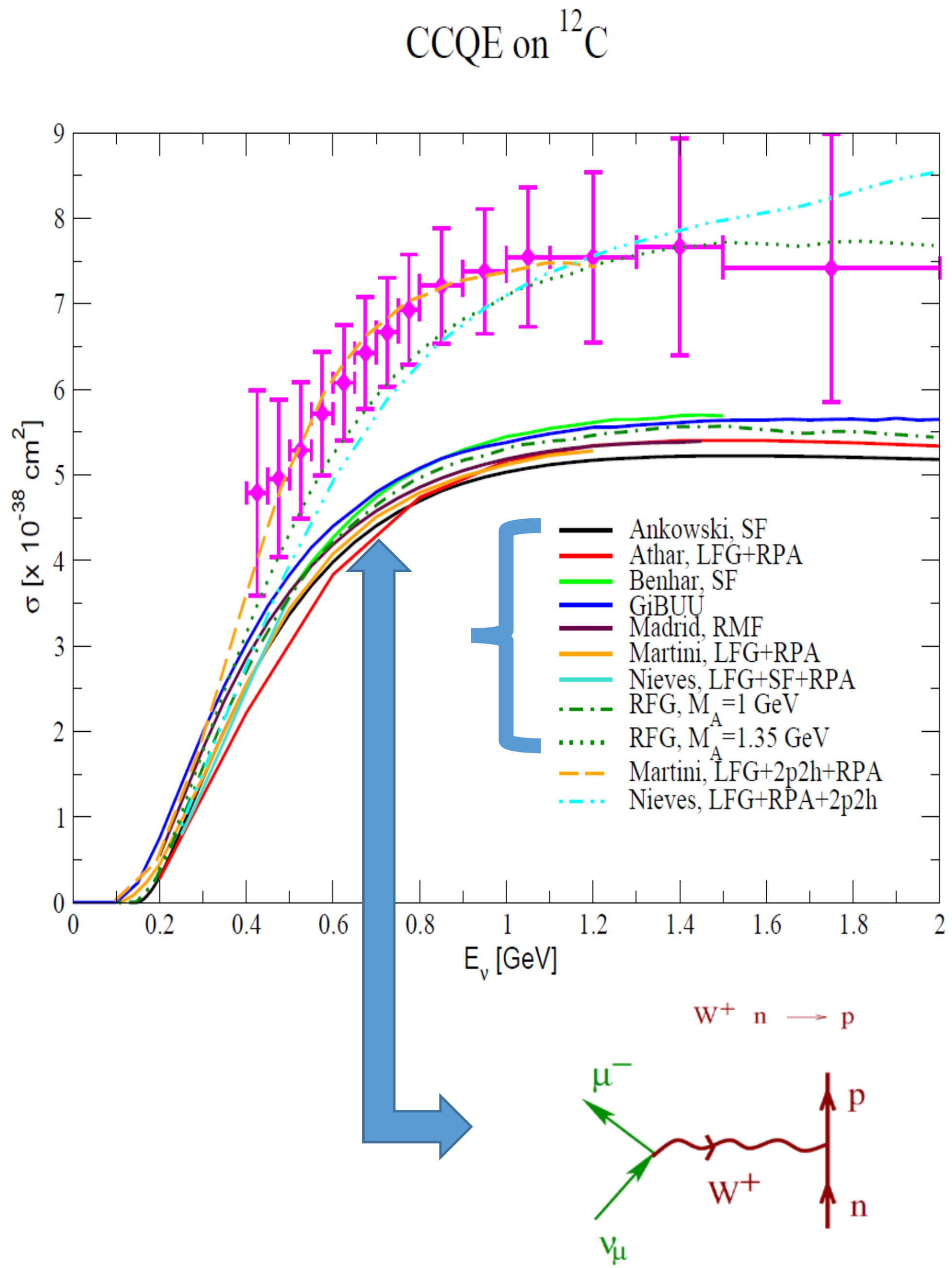




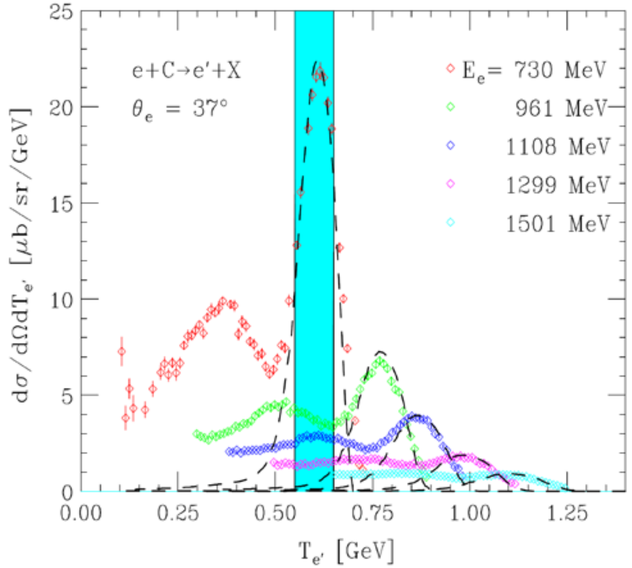
...but key observation (Martini et al., PRC 81, 045502): in most theoretical works QE is used for processes where the gauge boson $W^{\pm}$ or Z^{0} is absorbed by just one nucleon, which together with a lepton is emitted.

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).

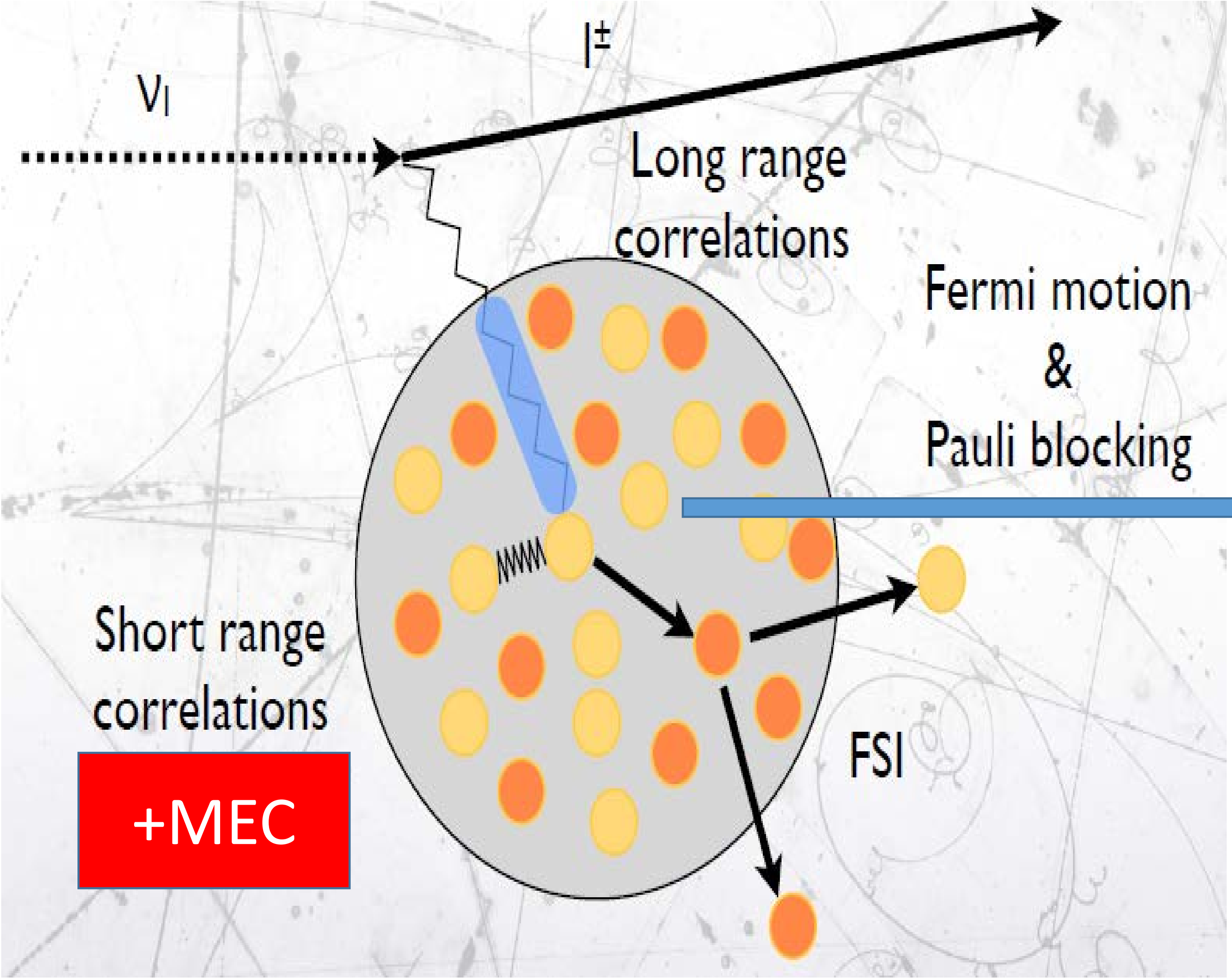


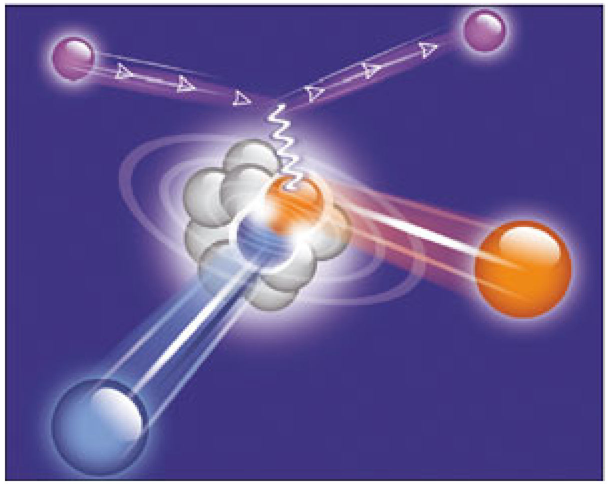
O. Benhar@NuFacT11: [arXiv : 1110.1835] measured electron-carbon scattering cross sections for a fixed outgoing electron angle $\theta = 37^o$ and different beam energies $\in [730, 1501]$ GeV, plotted as a function of E_e,



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!**

Juan Nieves, IFIC (CSIC & UV)



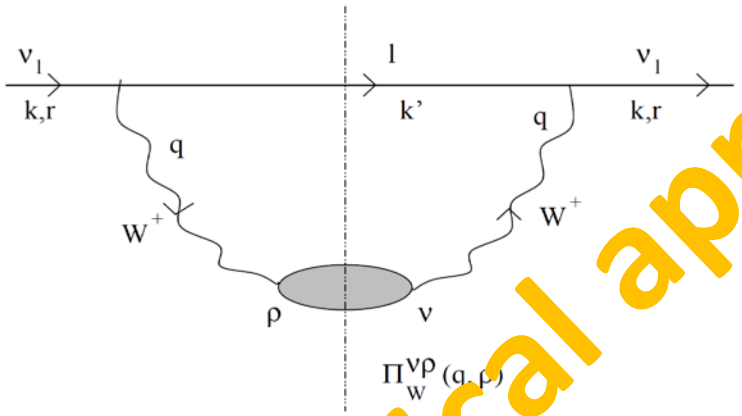


Solution:

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

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...

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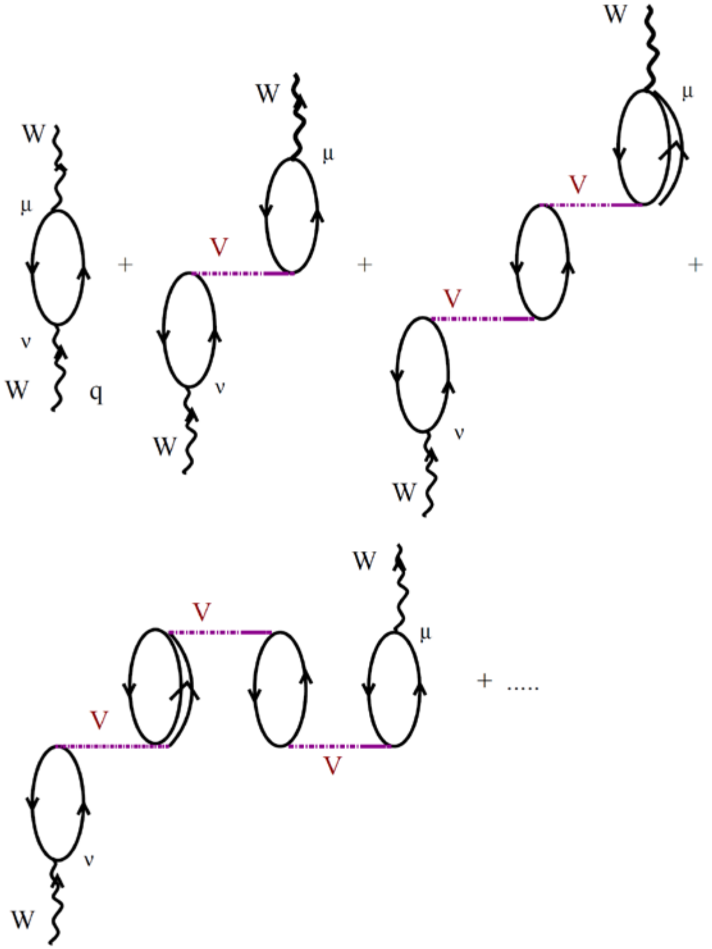
Polarization (RPA) effects. Substitute the ph excitation by an RPA response: series of ph and Δh excitations.



1. Effective Landau-Migdal interaction

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

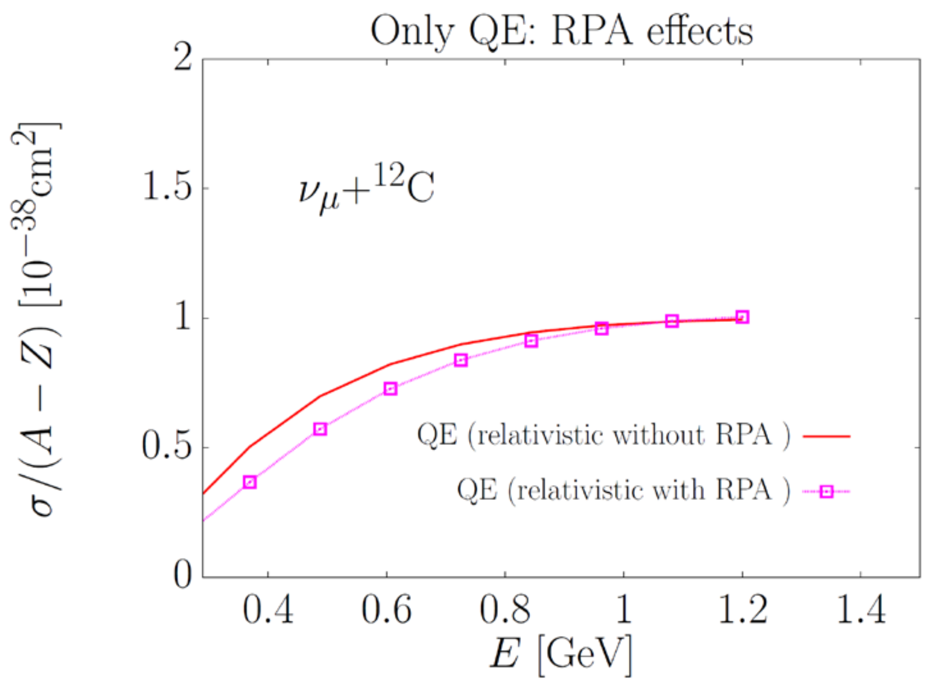
Isoscalar terms $\boxed{}$ do not contribute to CC

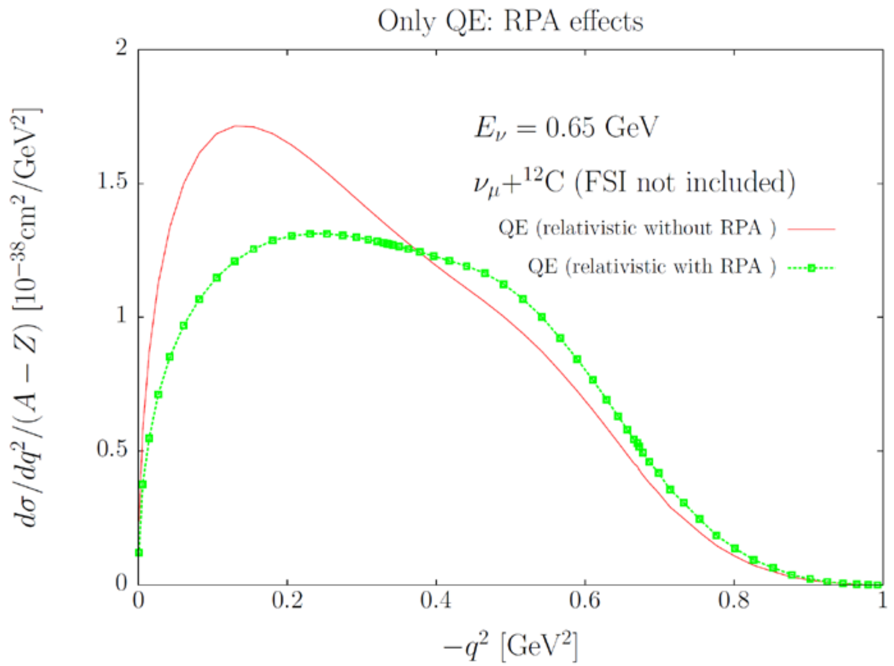
2. $S = T = 1$ channel of the ph–ph interaction → s longitudinal (π) and transverse (ρ) + **SRC**

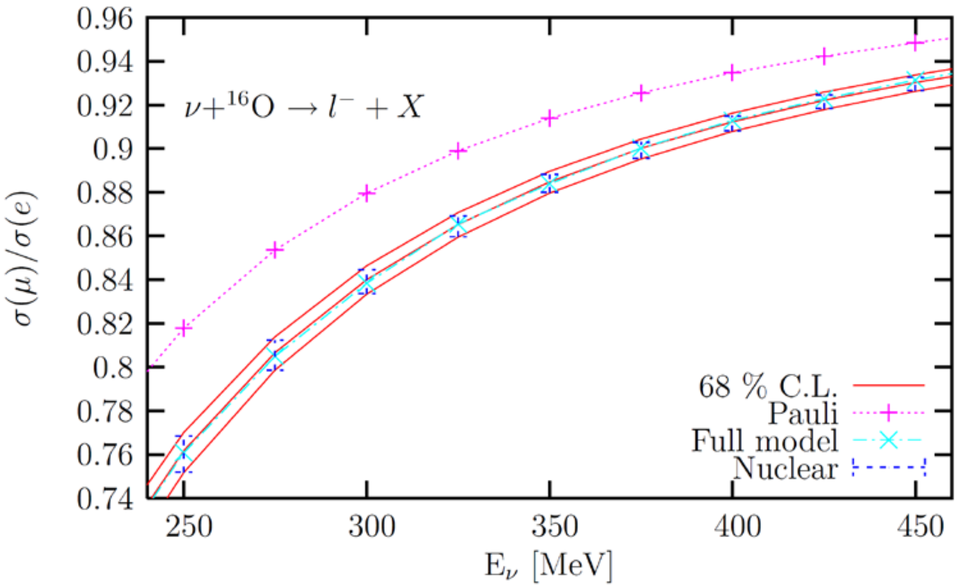
$$g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \rightarrow \left[V_l(q)\hat{q}_i\hat{q}_j + V_t(q)(\delta_{ij}-\hat{q}_i\hat{q}_j)\right]\sigma_1^i\sigma_2^j\vec{\tau}_1\vec{\tau}_2$$

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

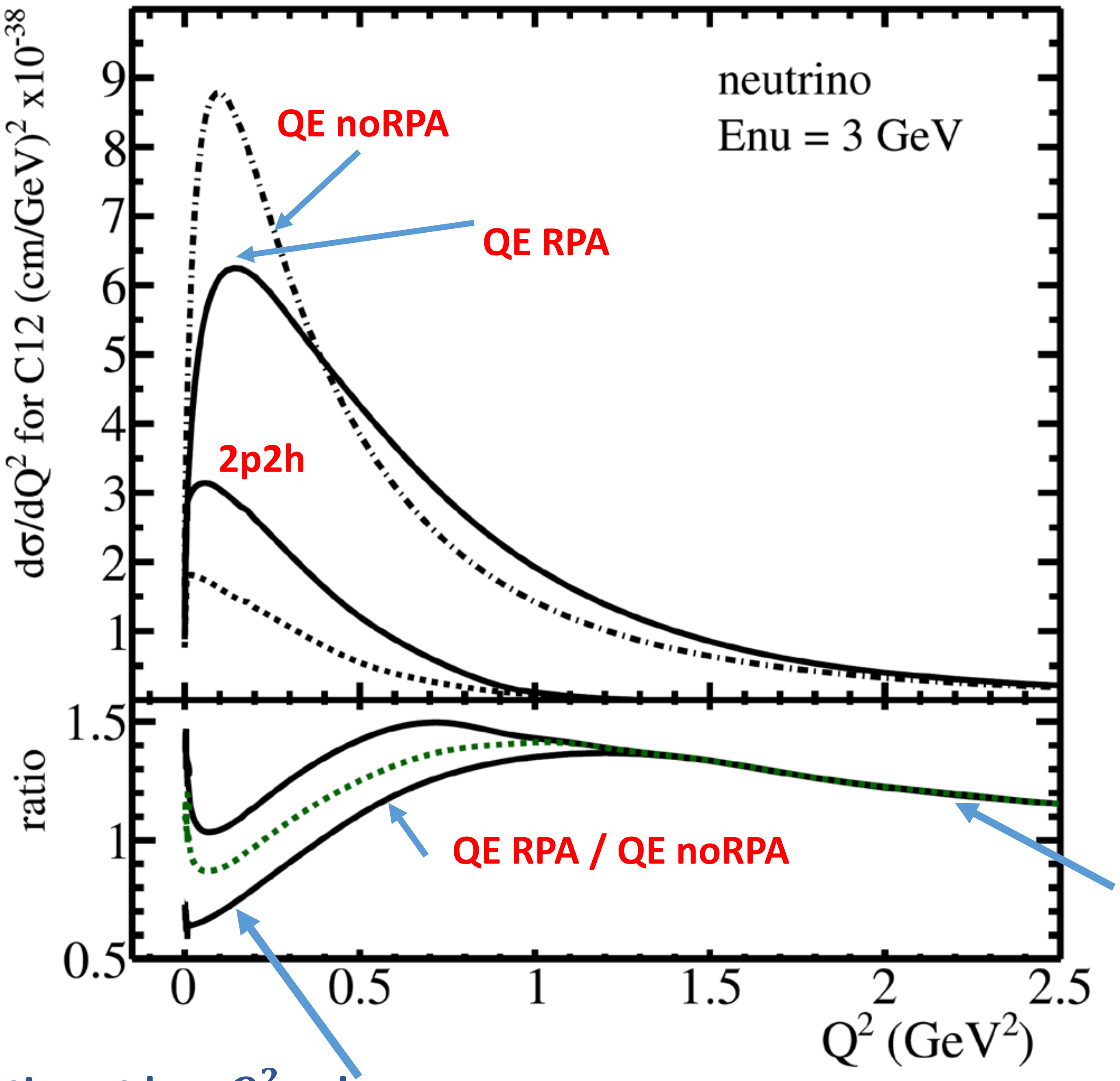
3. Contribution of Δh excitations important







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 %)



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

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

Deplection at low Q^2 values

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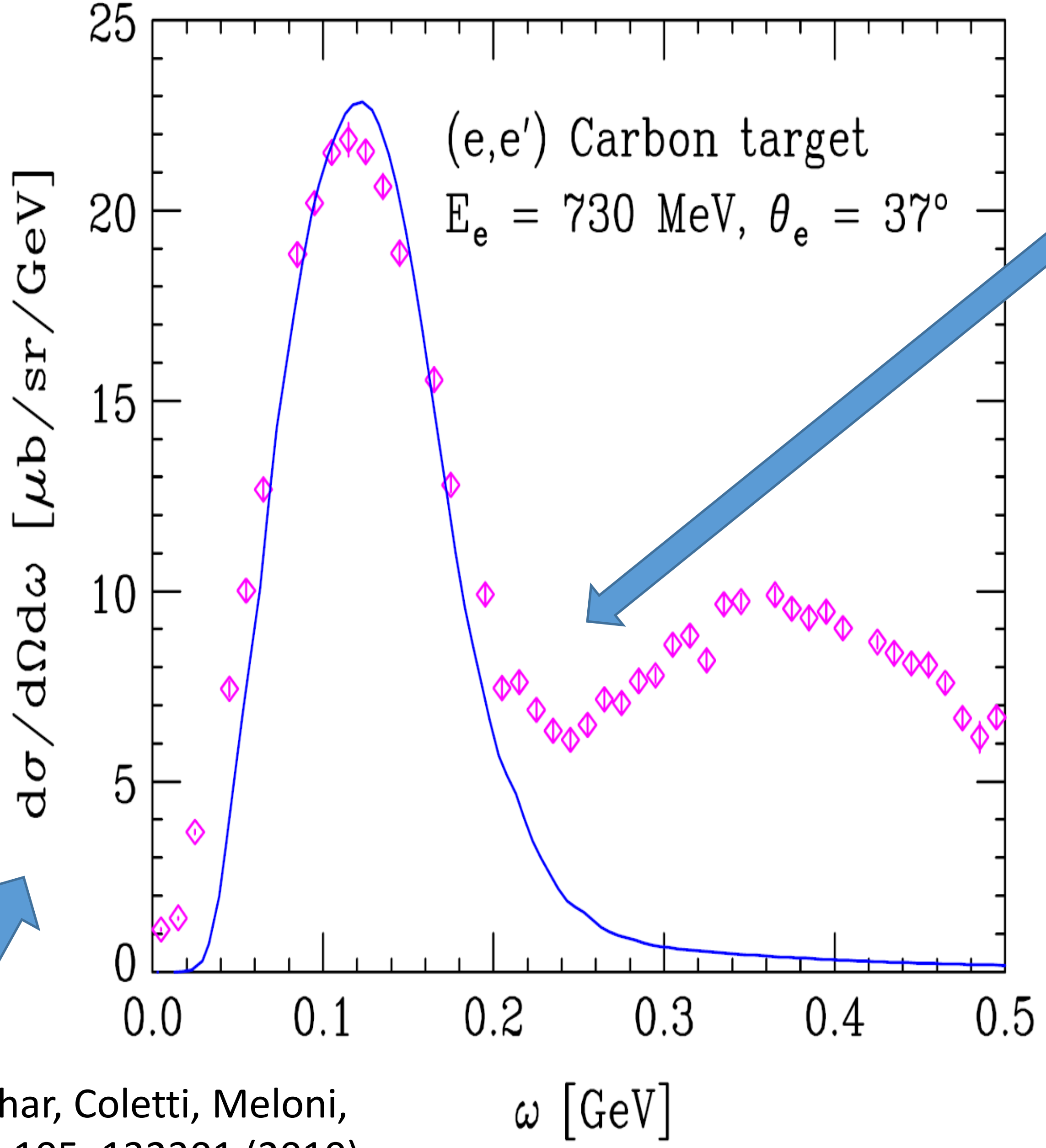
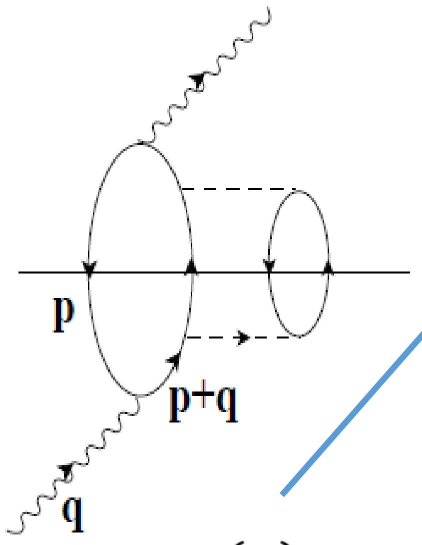
Spectral Function (SRC) do not populate the **dip region**



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)

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

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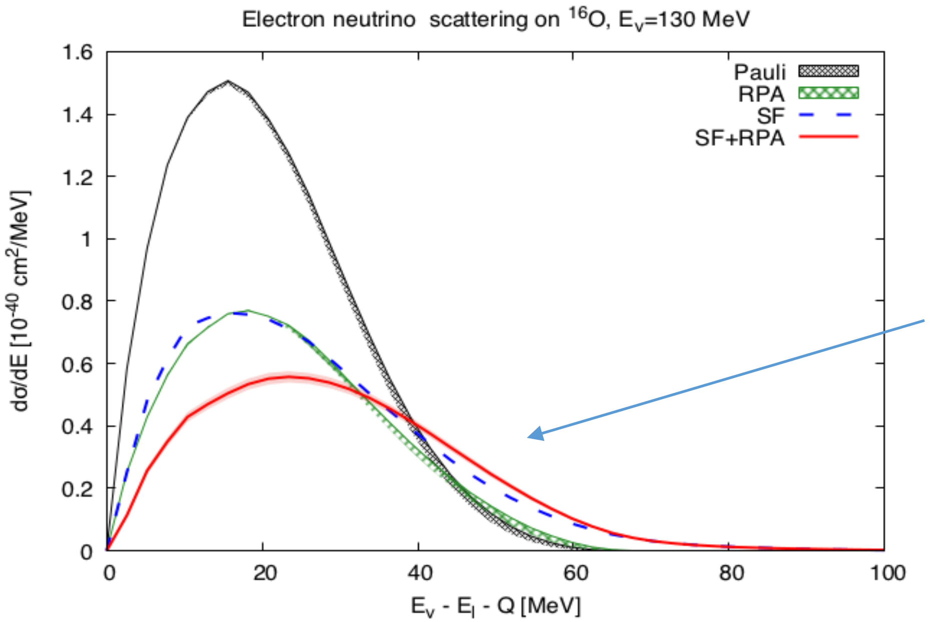
$$S_{p,h}(\omega,\vec{p}) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(\omega,\vec{p}\,)}{[\omega^2-\vec{p}^{\,2}-M^2-\mathrm{Re}\Sigma(\omega,\vec{p})]^2+[\mathrm{Im}\Sigma(\omega,\vec{p})]^2}$$

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).

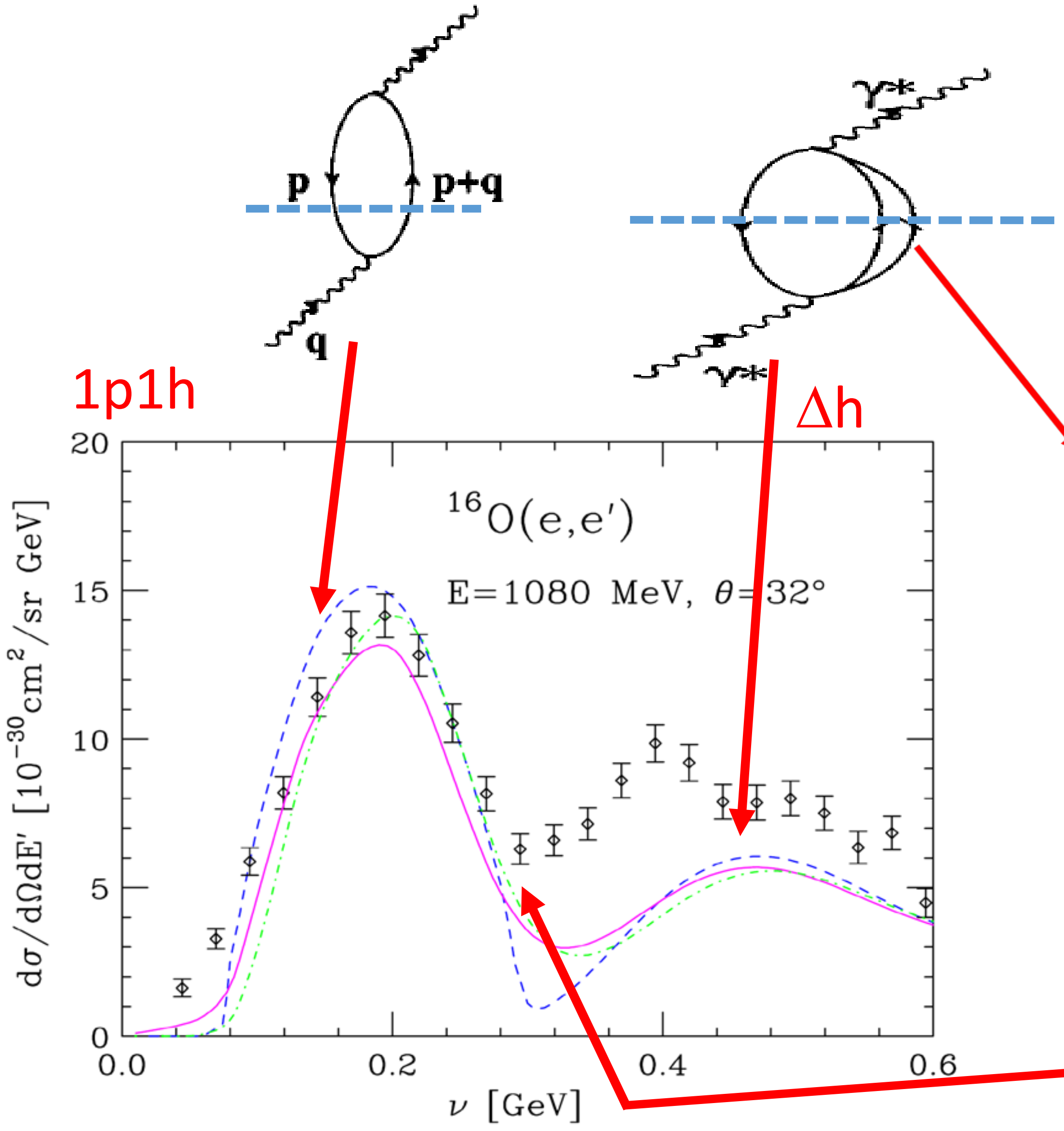
This nuclear effect is additional to those due to RPA (long range) correlations !!

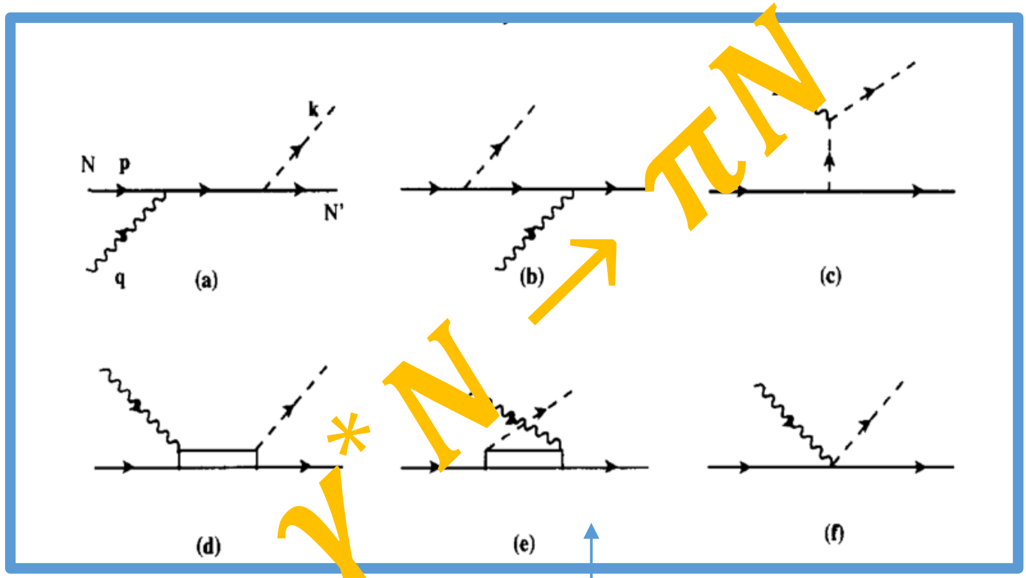


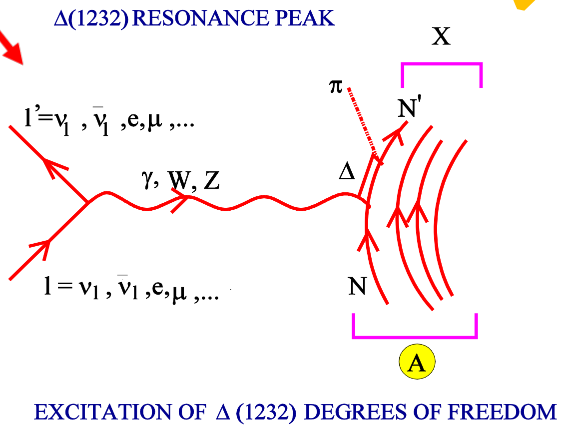
SF's produce a tail...

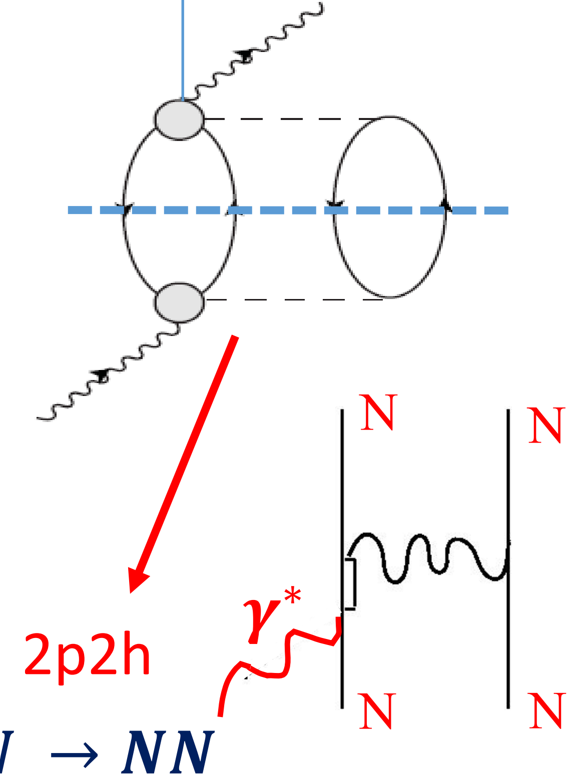
JN and J.E. Sobczyk, 1701.03628

2p2h: Inclusive electron-nucleus scattering









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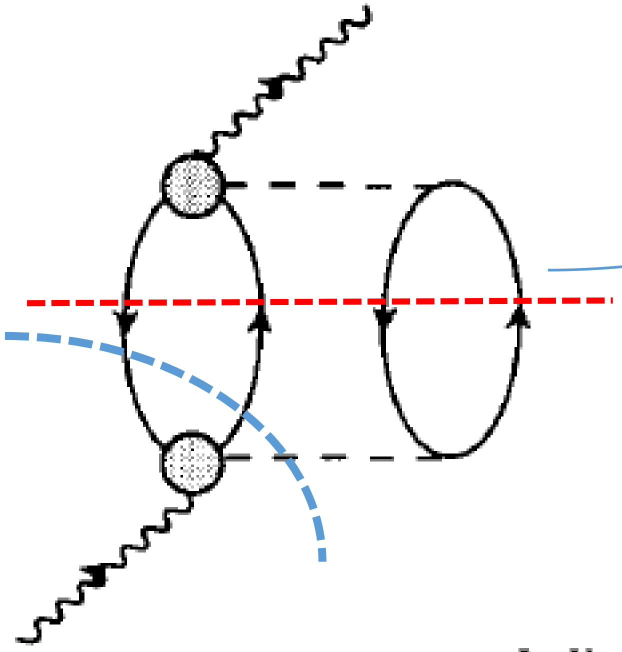
2p2h (two body absorption) contributions

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

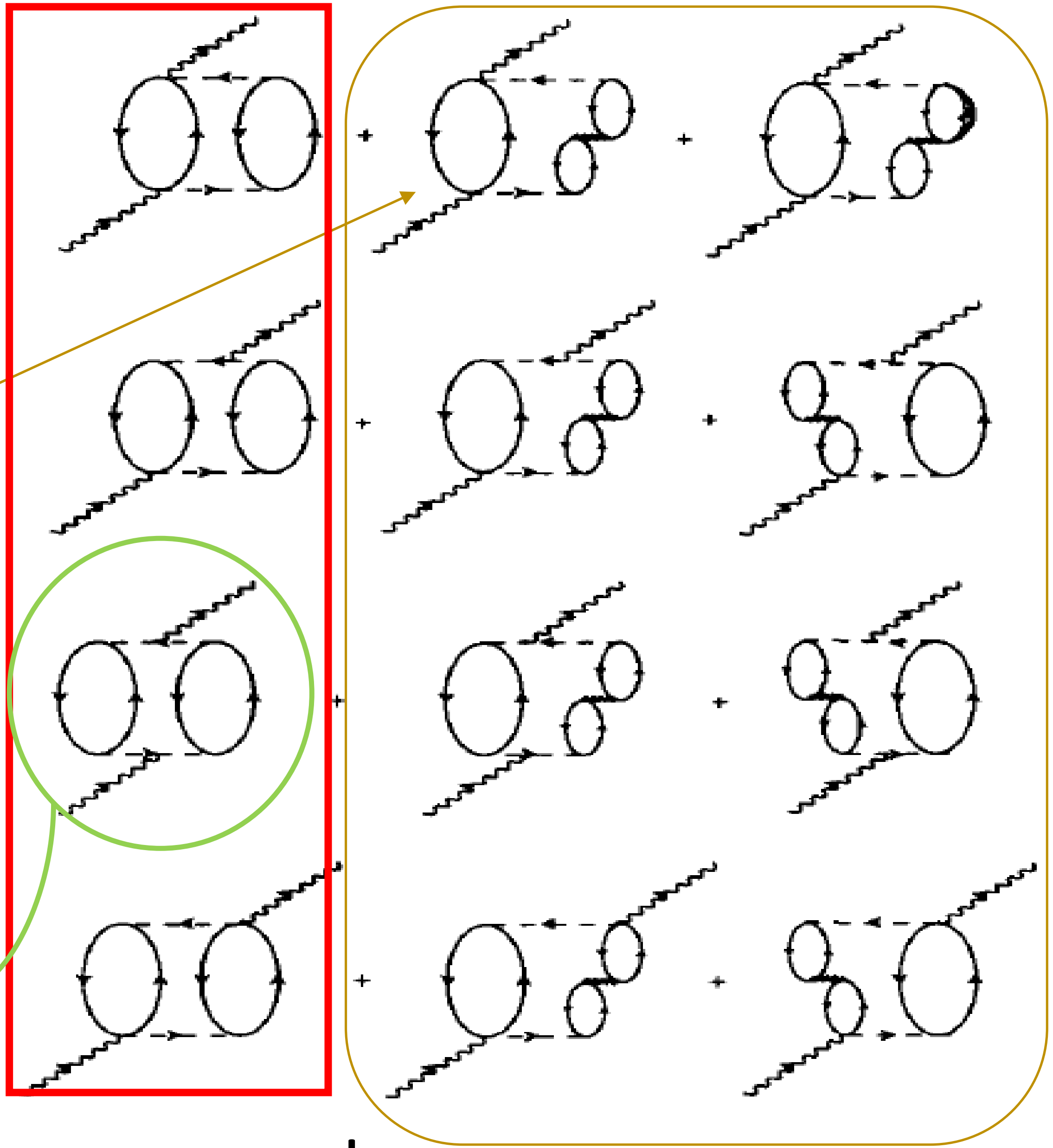


Two cuts: $\gamma^* NN \to NN$

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

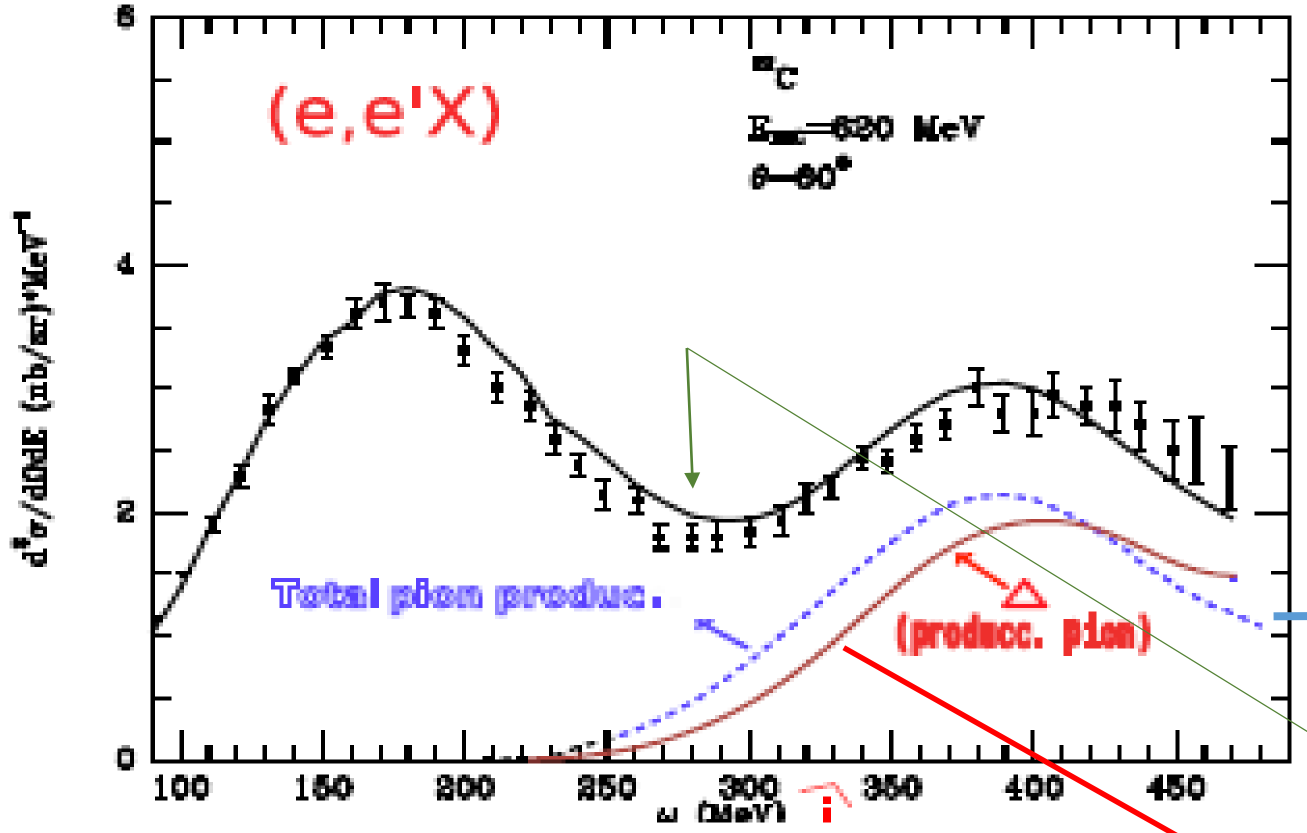
RPA corrections to 2p2h contributions

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

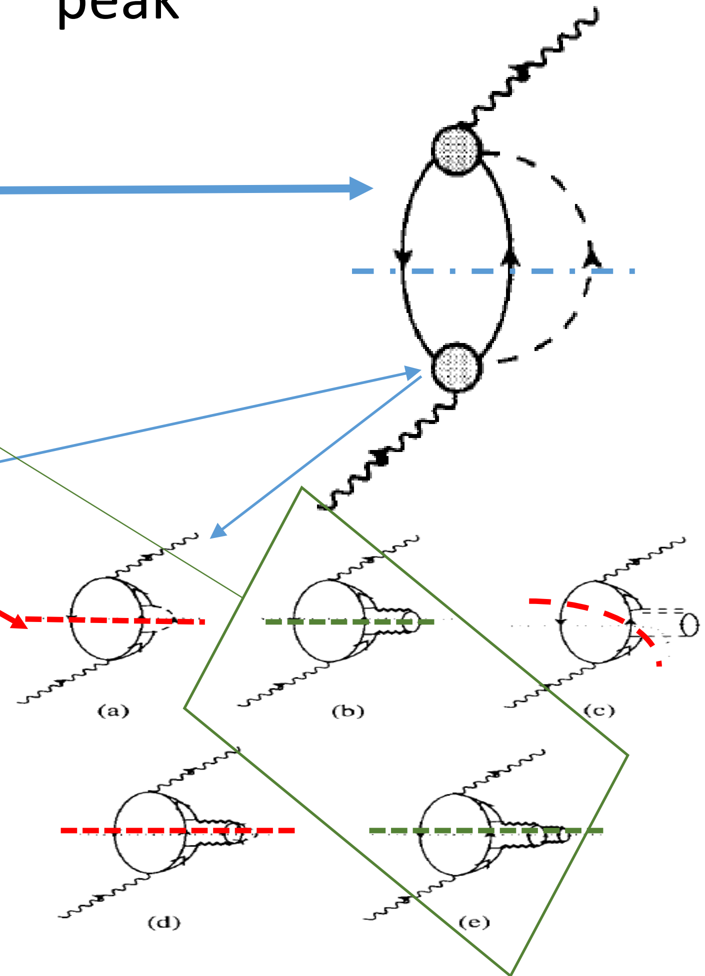


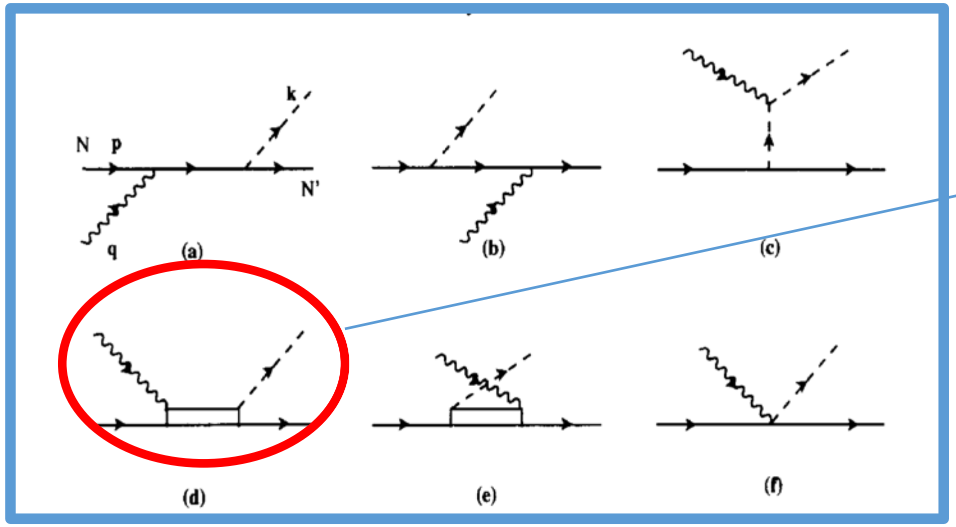
+.....

MEC 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

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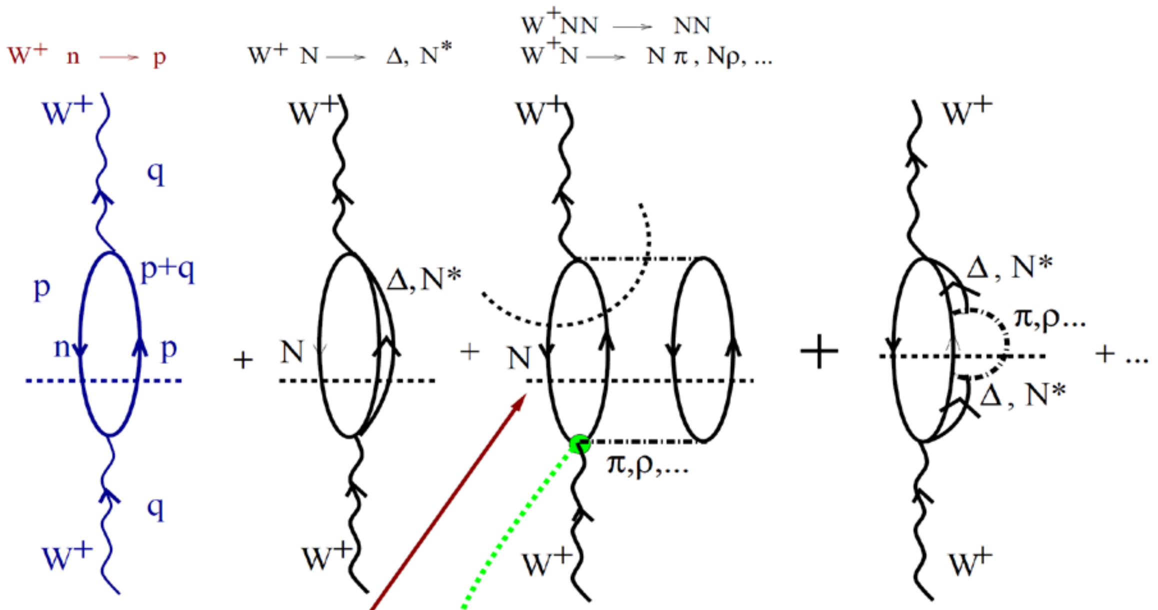
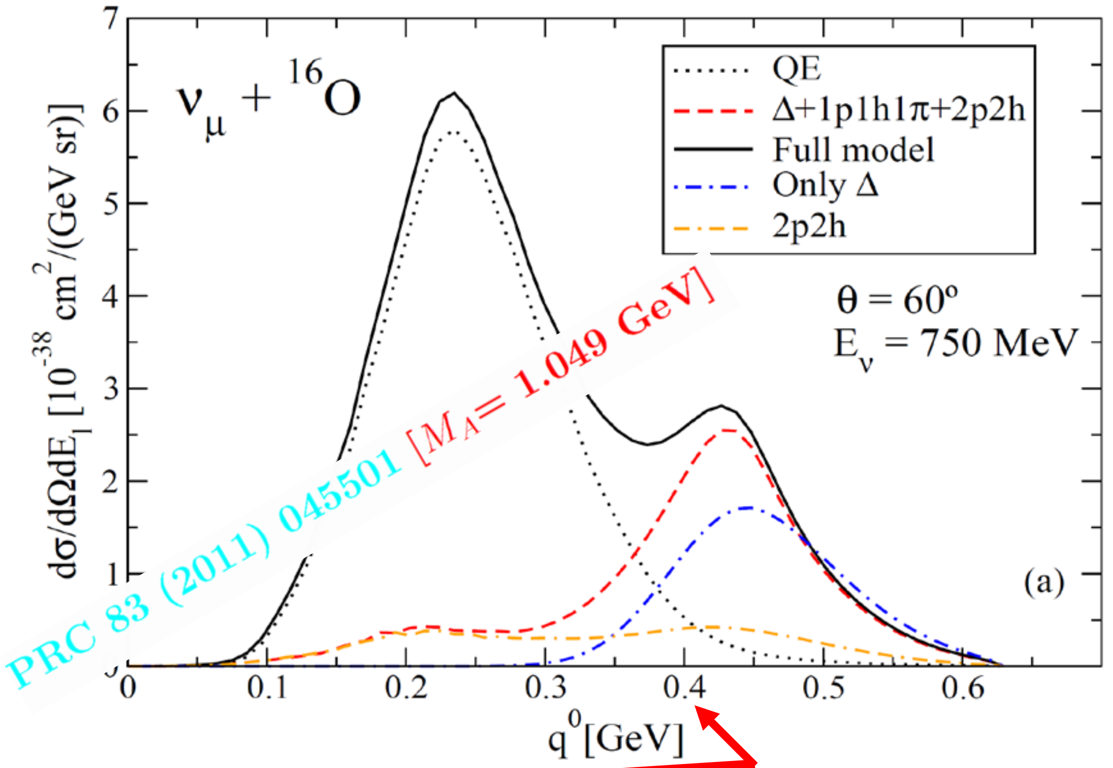
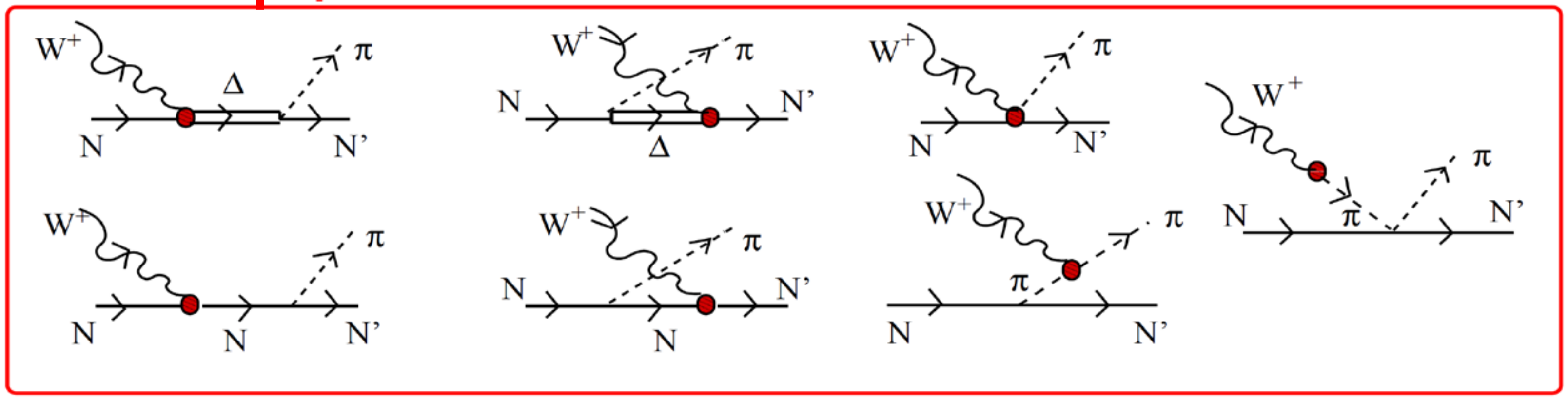
$\nu + A \rightarrow l + X$





MEC ⟶ QE like !

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



PRD93 (2016) 014016 (Watson's theorem) + 1612.02343
[PRD in print] (1/2 dof in Δ propagator)

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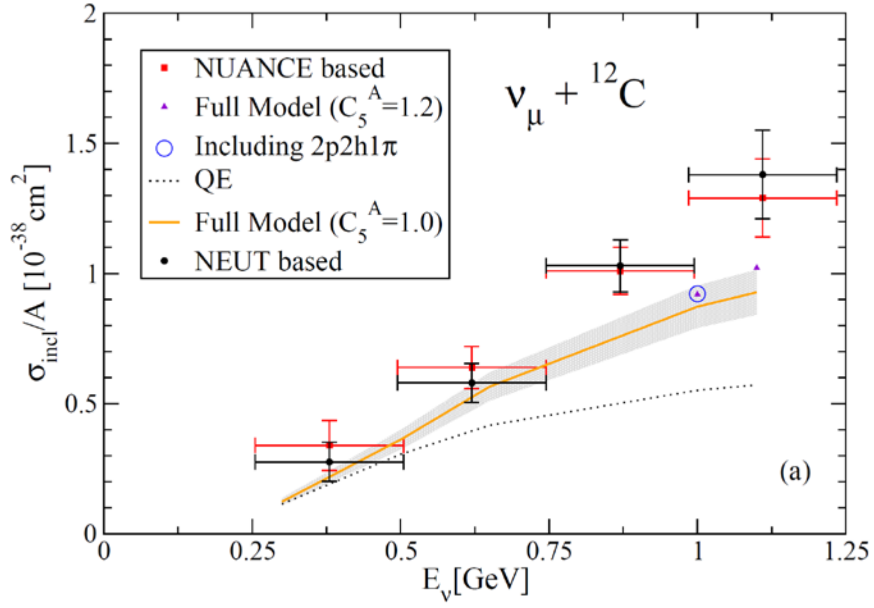
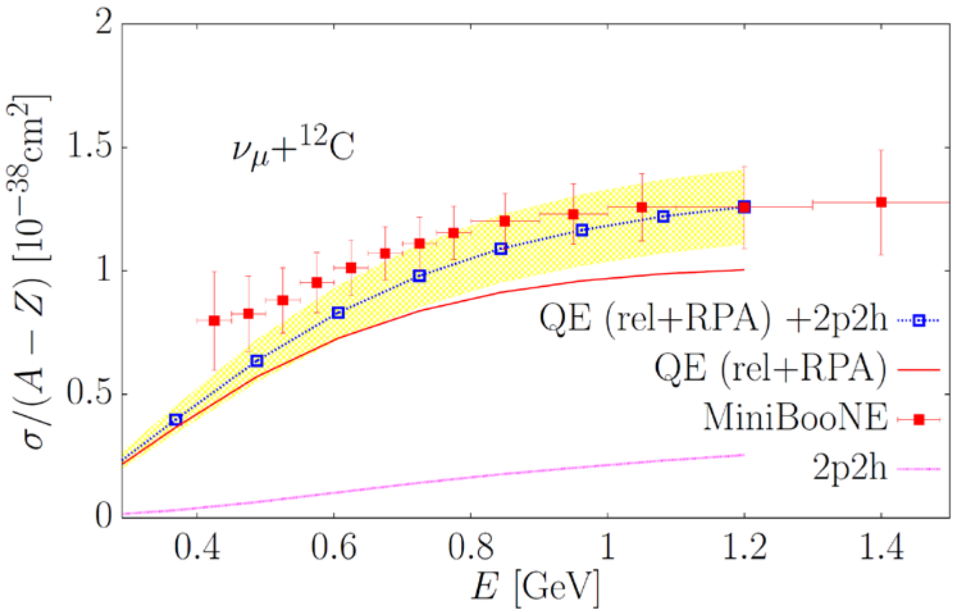




MiniBooNE CCQE-like double differential cross section $\frac{d^2\sigma}{dT_\mu d\cos\theta_\mu}$

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

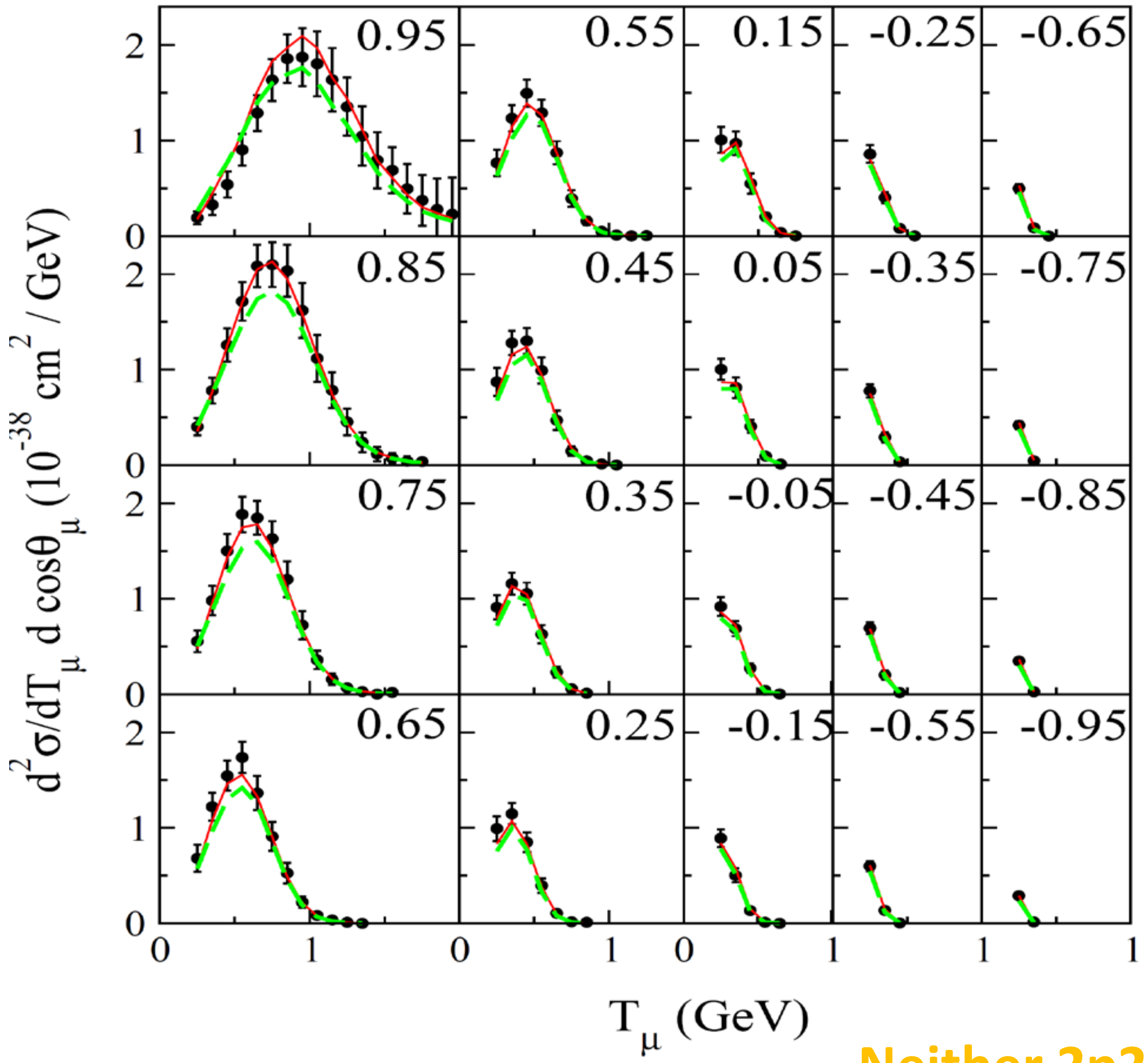
$$\chi^2 = \sum_{i=1}^{137} \left[\frac{\lambda \left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta} \right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta} \right)_i}{\lambda \Delta \left(\frac{d^2\sigma}{dT_\mu d\cos\theta} \right)_i} \right]^2 + \left(\frac{\lambda - 1}{\Delta\lambda} \right)^2,$$

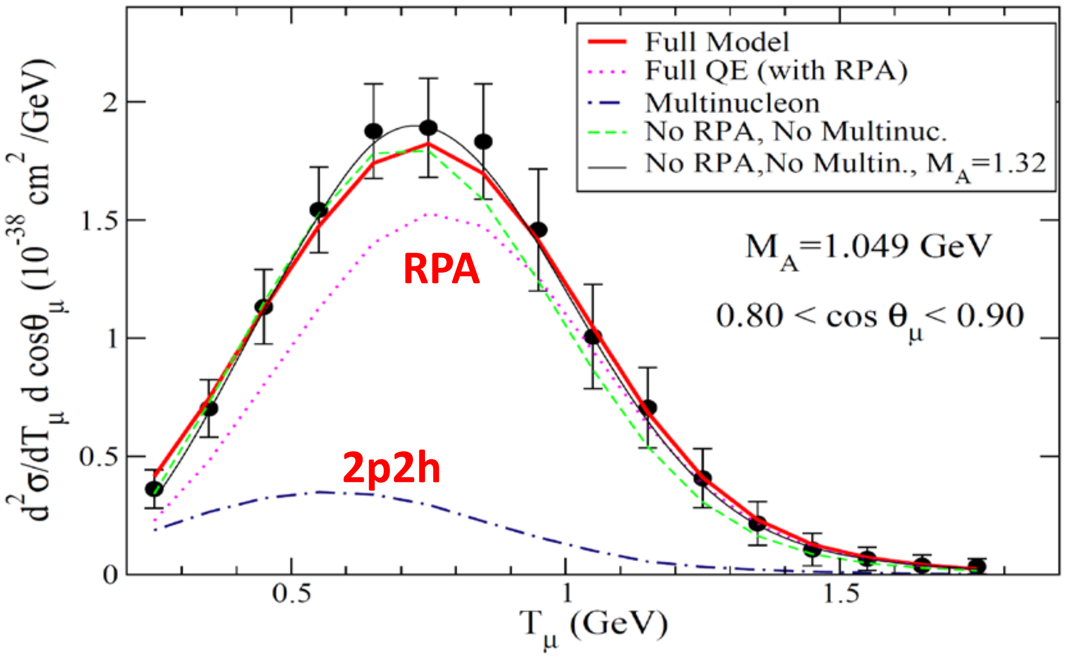
that takes into account the global normalization uncertainty ($\Delta\lambda = 0.107$) claimed by the MiniBooNE collaboration.

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

We obtain χ^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)	$\frac{\chi^2}{\#bins}$
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!

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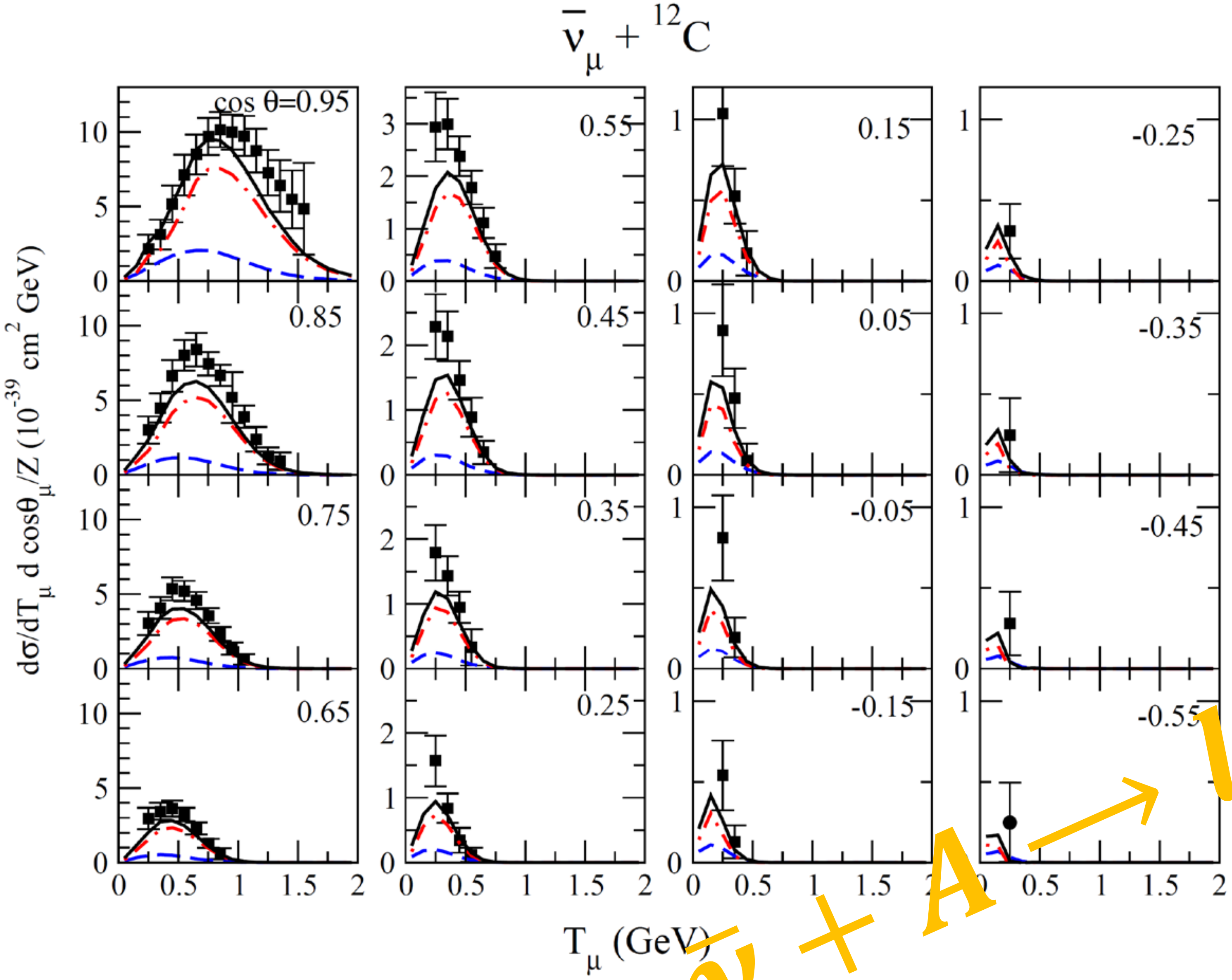
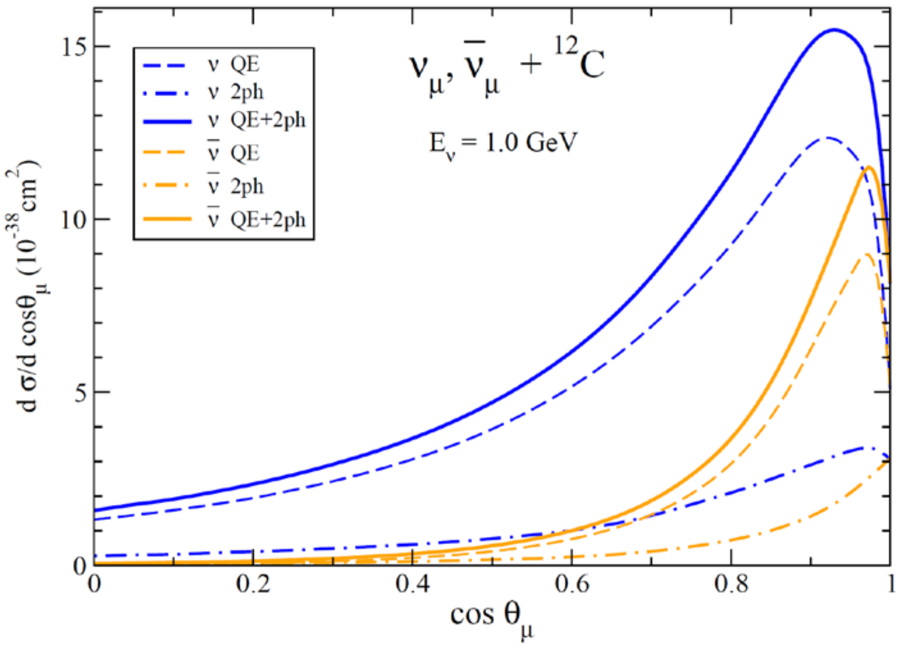
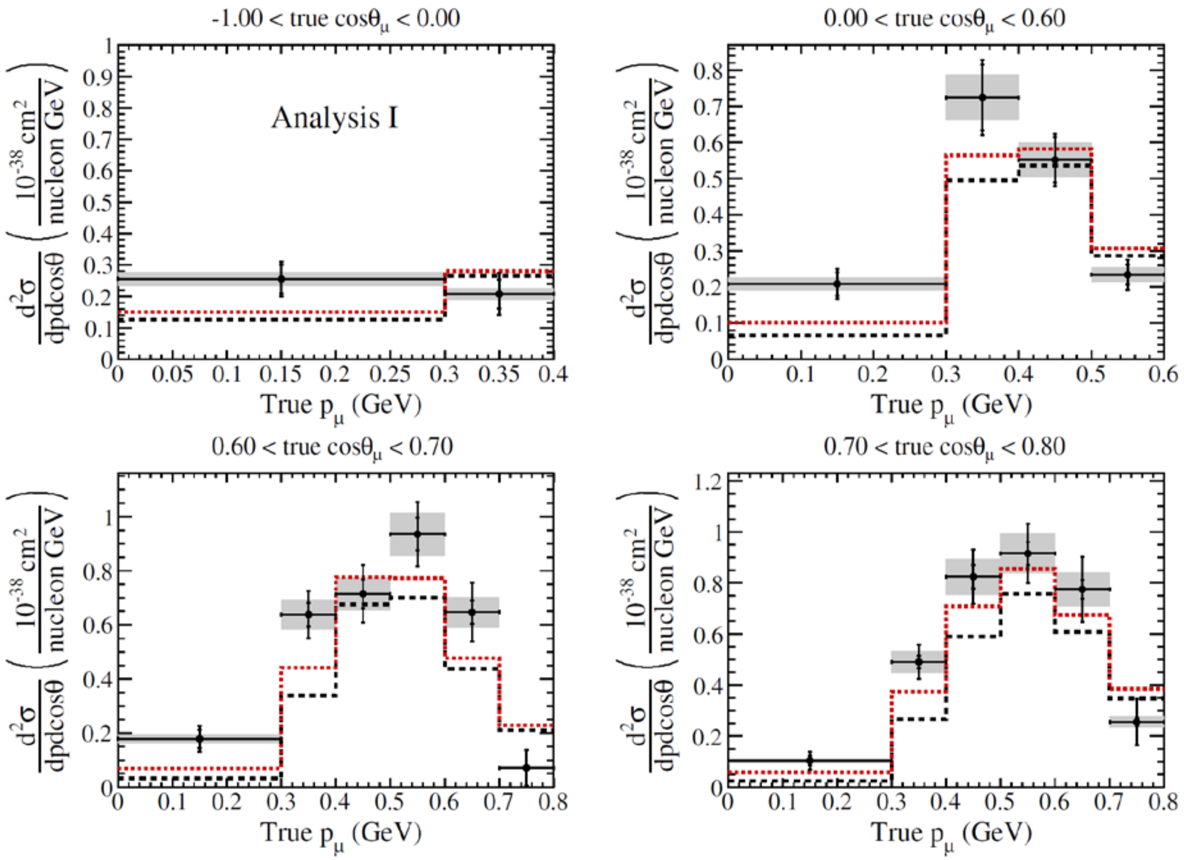
$M_A \sim 1.03$ GeV

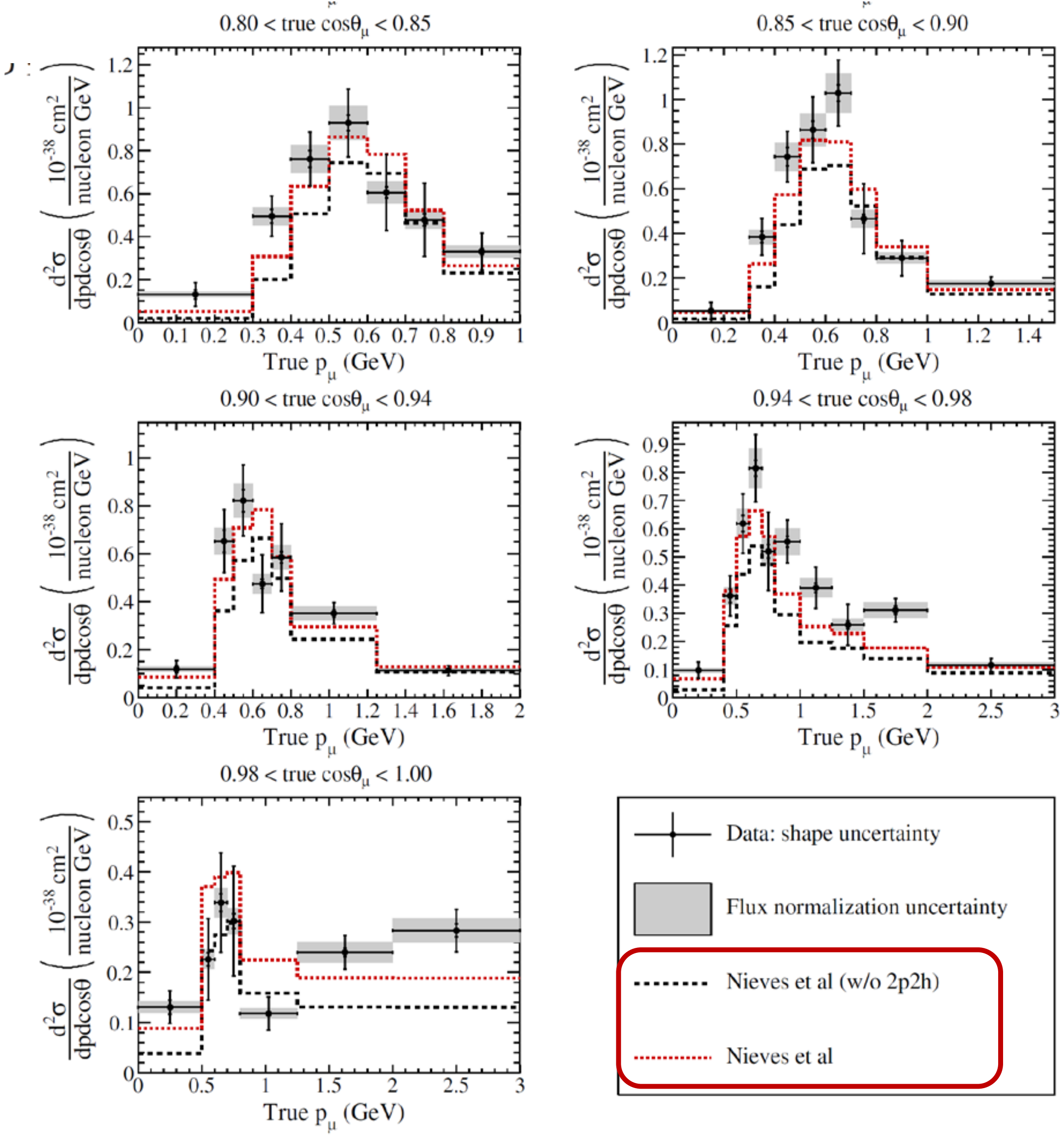




$\bar{\nu} + A \longrightarrow l + X$

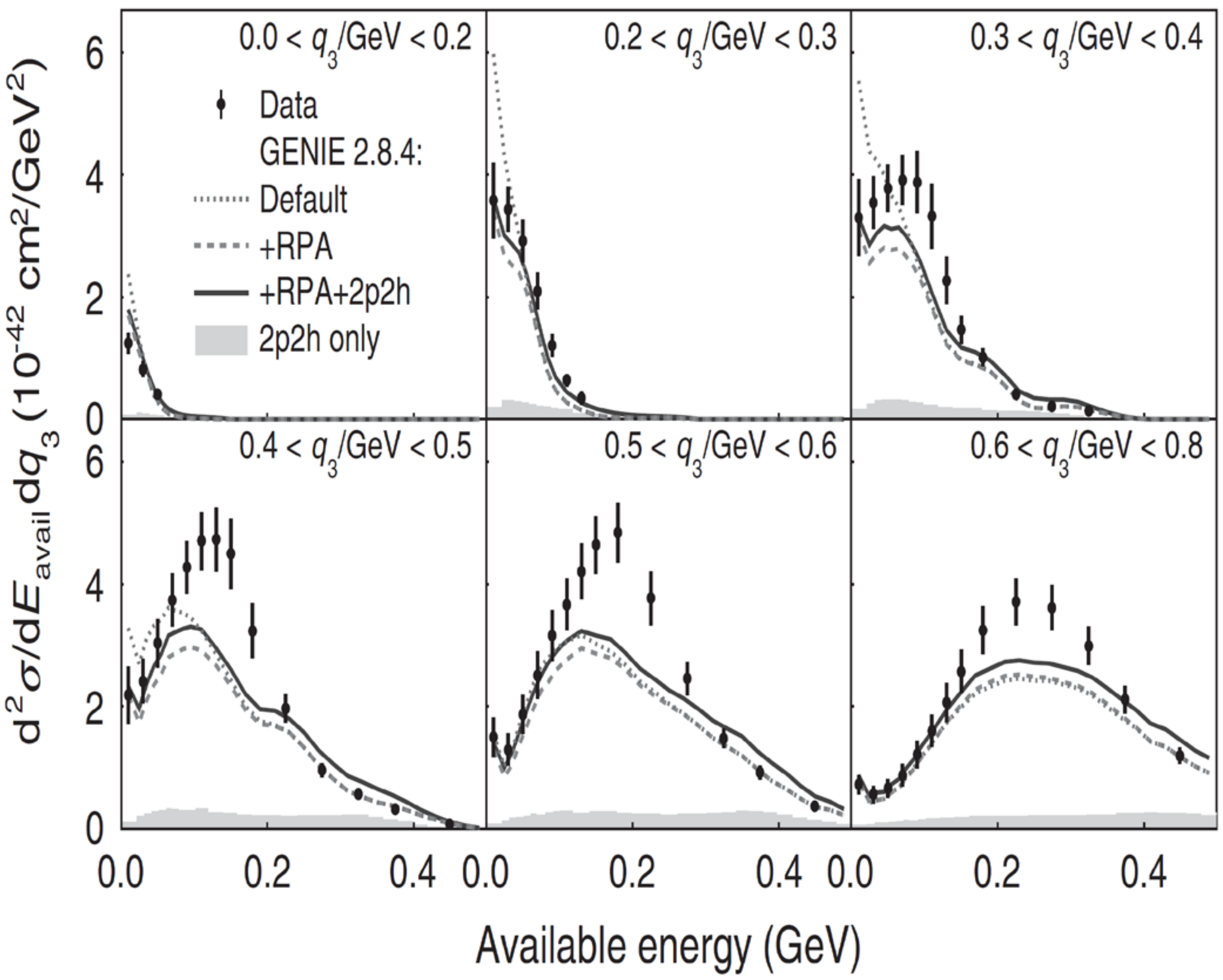
- **Antineutrino distributions are more forward peaked**
- **Relative importance of 2p2h contributions in ν and $\bar{\nu}$ are similar**





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); see also talk by A. Bravar

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

Unfolding procedure needs theoretical input!

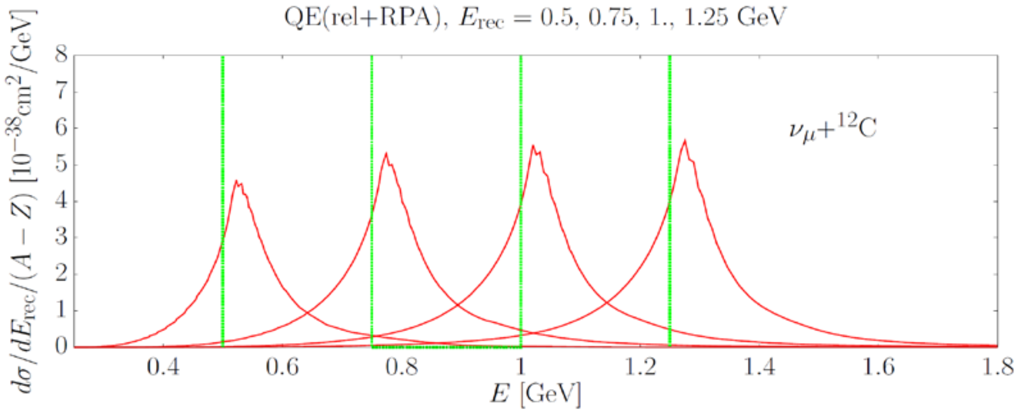
$$P_{\rm true}(E) = \int dE_{\rm rec}\, \underbrace{P_{\rm rec}(E_{\rm rec})}_{\rm EXP}\, \underbrace{P(E|E_{\rm rec})}_{theory!}$$

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

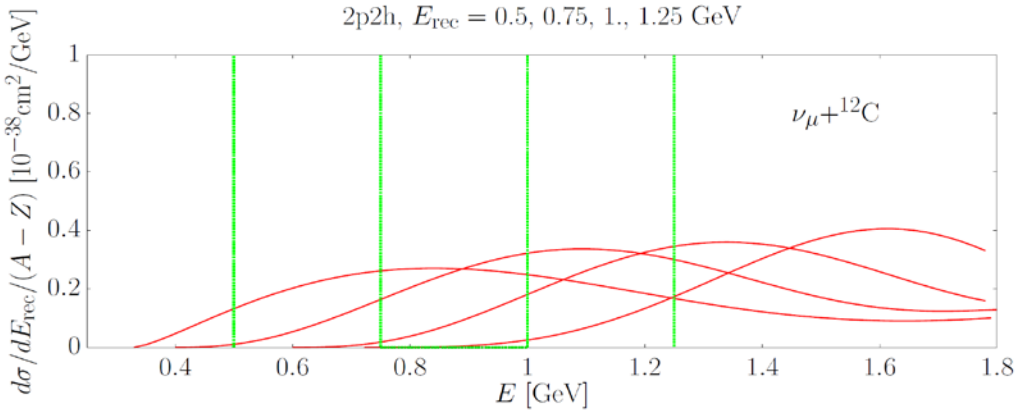
Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section



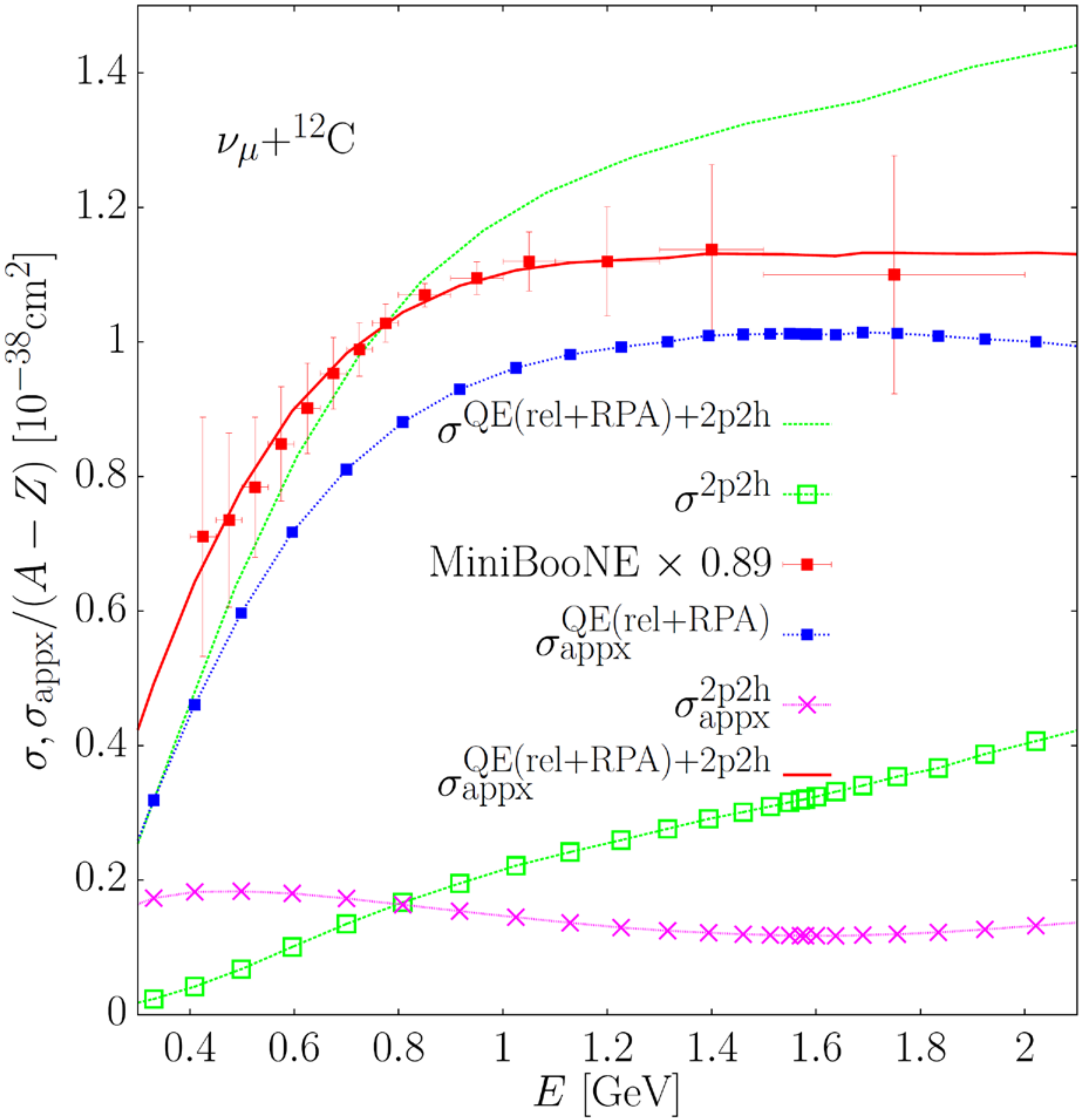
(qualitatively in agreement with Martini et al., PRD85 093012)

theory !

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



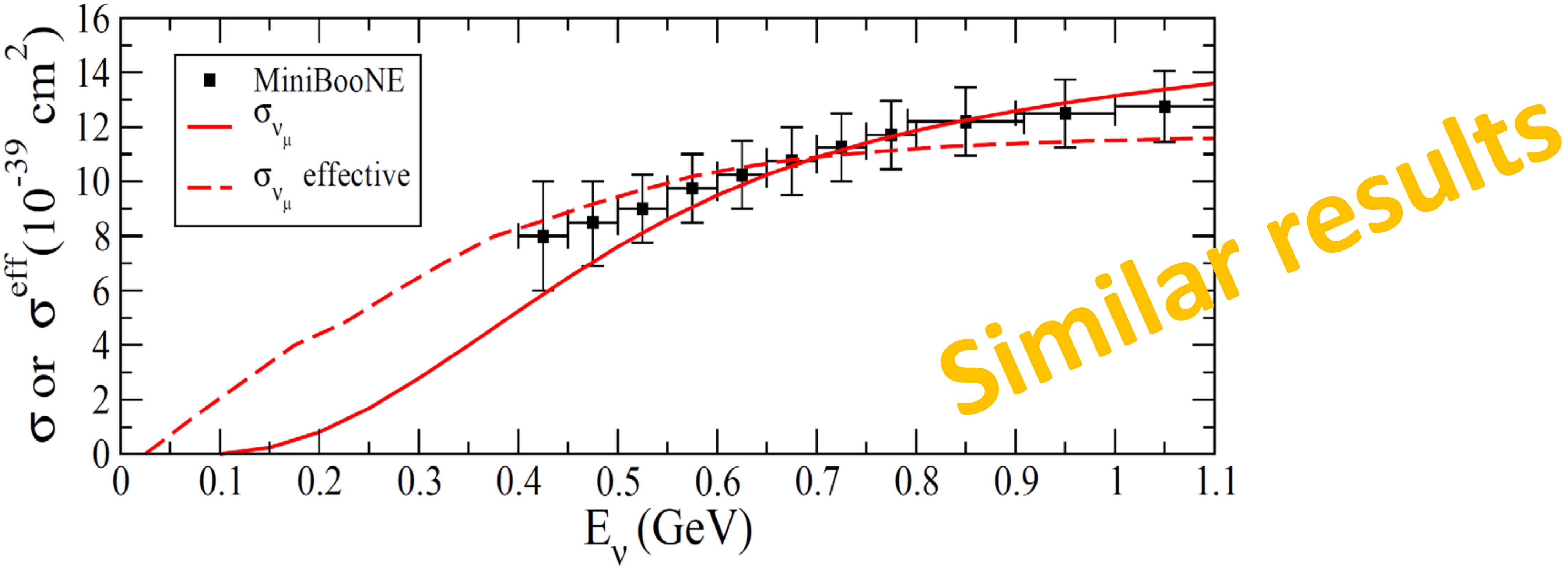
For each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$.



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

... 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

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

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

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Conclusions II

- 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.**

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

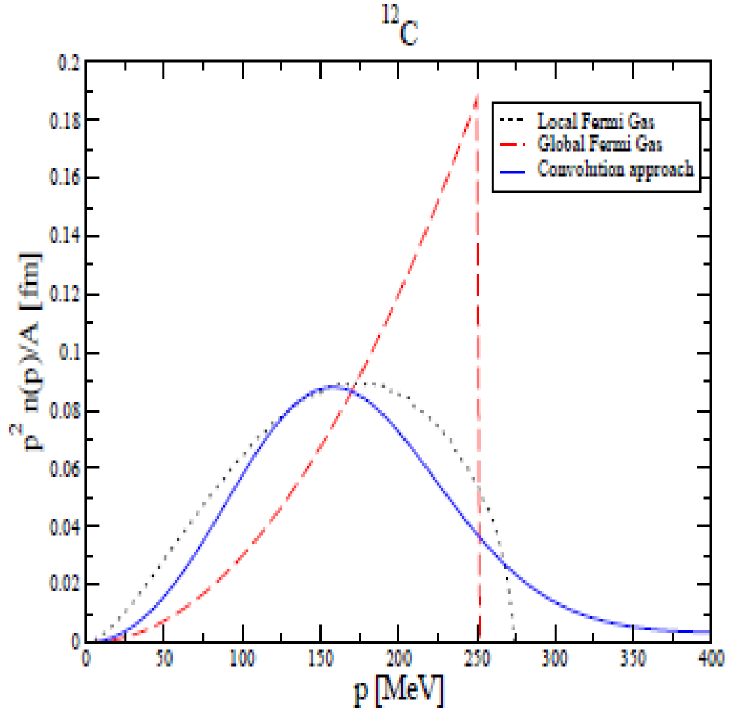
$$S_p(\omega,\vec{p}) = \frac{\theta(|\vec{p}\,| - k_F)}{2E(\vec{p})}\delta(\omega - E(\vec{p}))$$

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

and only Pauli blocking is incorporated!!

Local vs Global Fermi Gas ?

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



Local vs Global Fermi Gas ?

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

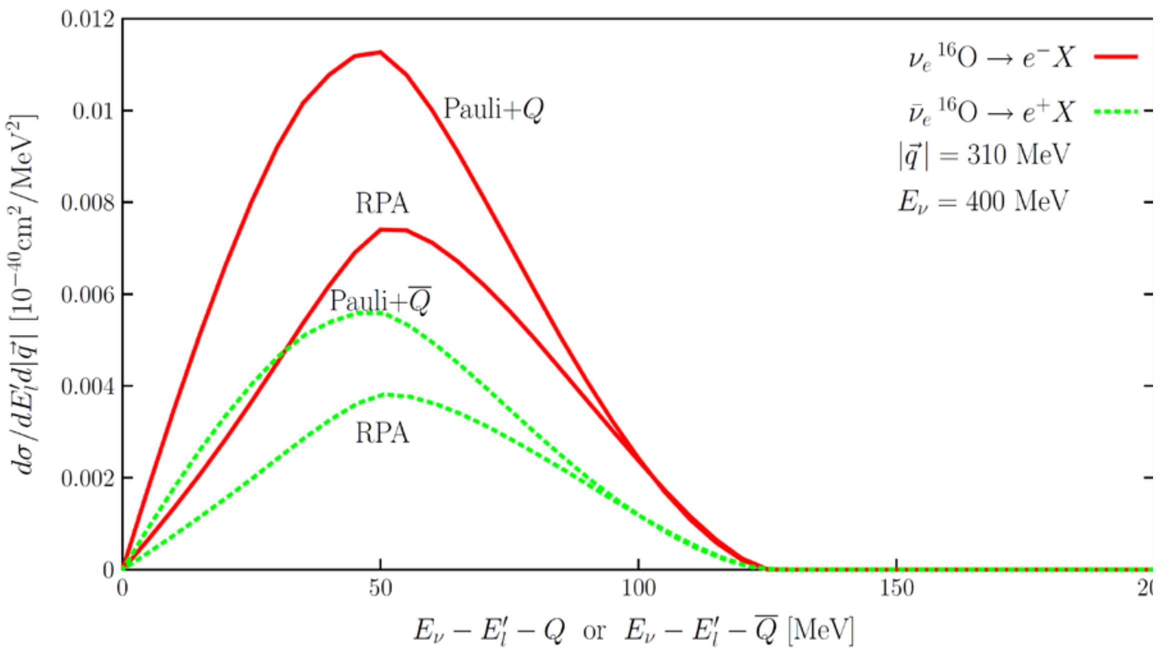
$$S_h(\omega,\vec{p}) = \delta(\omega - E(\vec{p}))\theta(k_F - |\vec{p}\,|)/2\omega$$

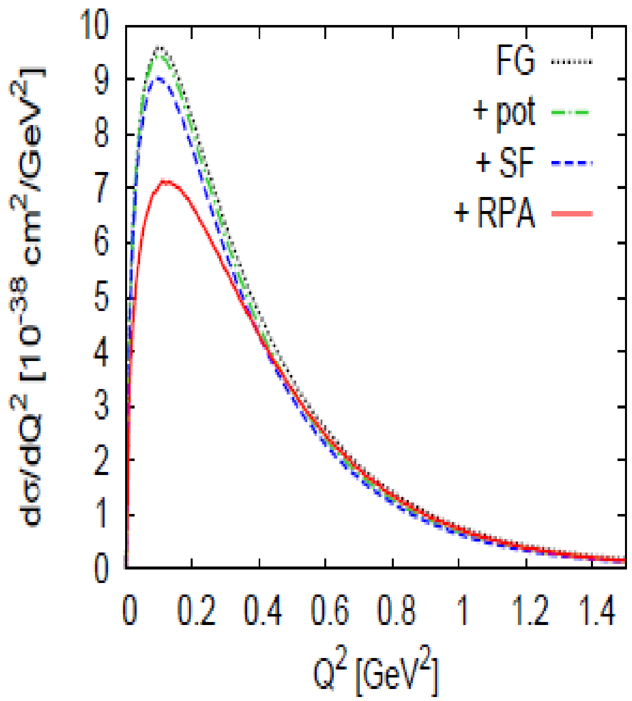
$$n^{\rm RgFG}(|\vec{p}\,|) = \frac{4V}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) = \frac{3A}{4\pi k_F^3}\theta(k_F - |\vec{p}\,|)$$

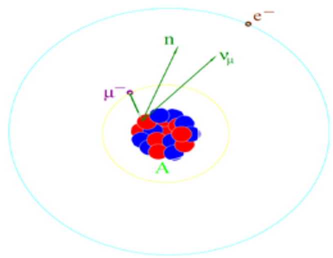
$$n^{\rm LDA}(|\vec{p}\,|) = 4\int\frac{d^3r}{(2\pi)^3}\int d\omega 2\omega S_h(\omega,\vec{p}) = 4\int\frac{d^3r}{(2\pi)^3}\theta(\mathbf{k_F}(\mathbf{r}) - |\vec{p}\,|)$$

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

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







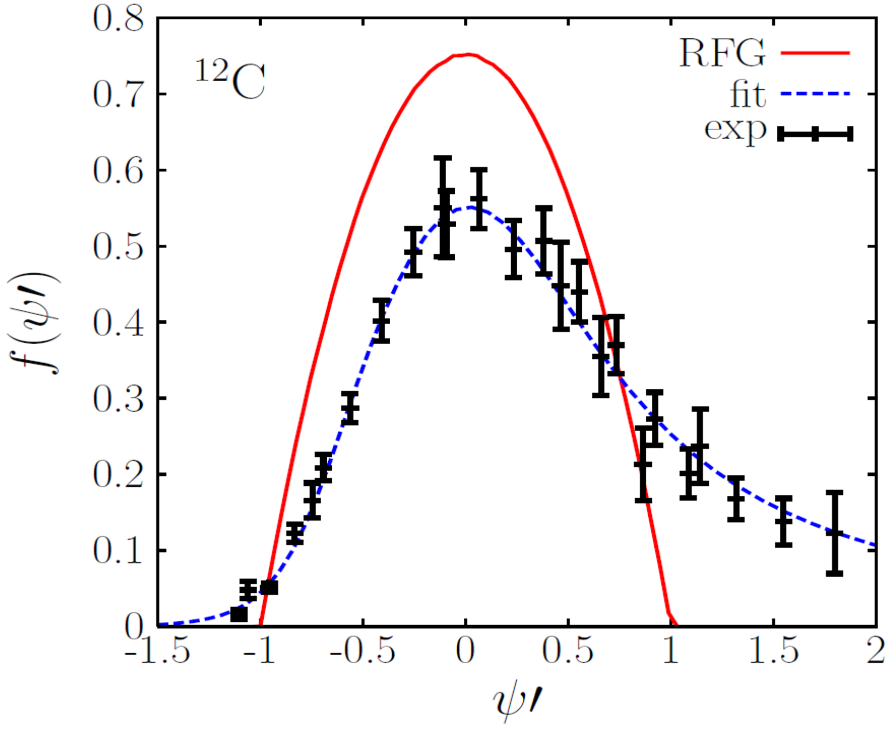
Inclusive Muon Capture: $\Gamma\left[(A_Z - \mu^-)^{1s}_{\rm bound}\right]$

	Pauli [$10^4\ s^{-1}$]	RPA [$10^4\ s^{-1}$]	Exp [$10^4\ s^{-1}$]	$\left(\Gamma^{\rm Exp} - \Gamma^{\rm Th}\right)/\Gamma^{\rm Exp}$
^{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 !



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.

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

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

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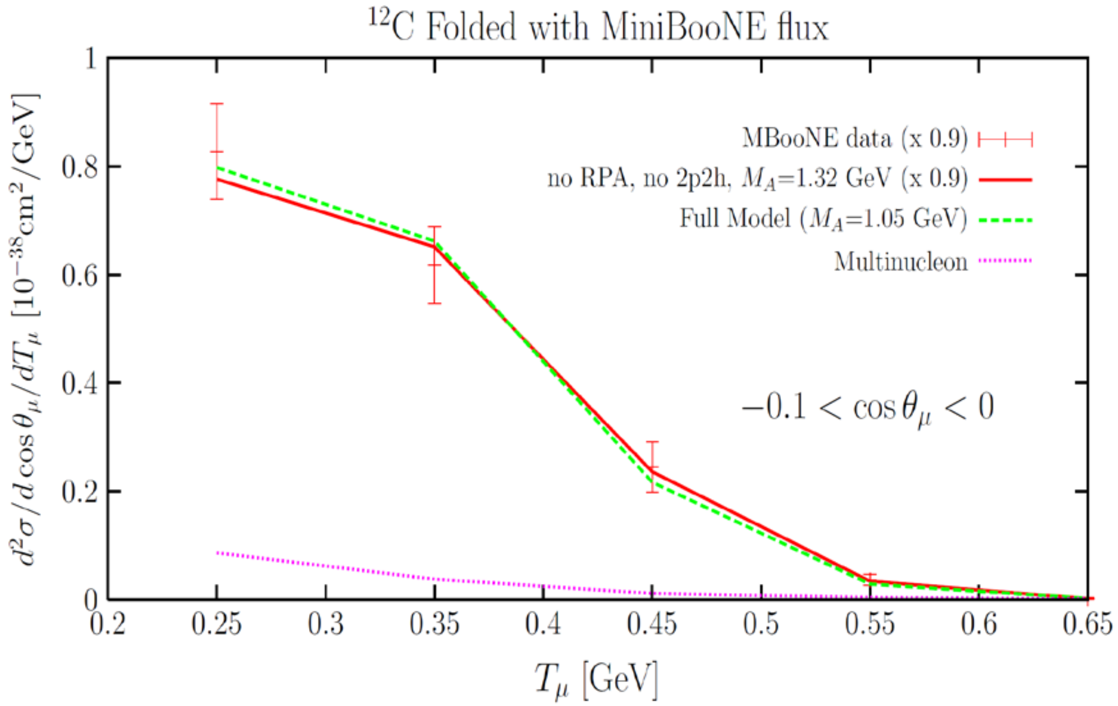
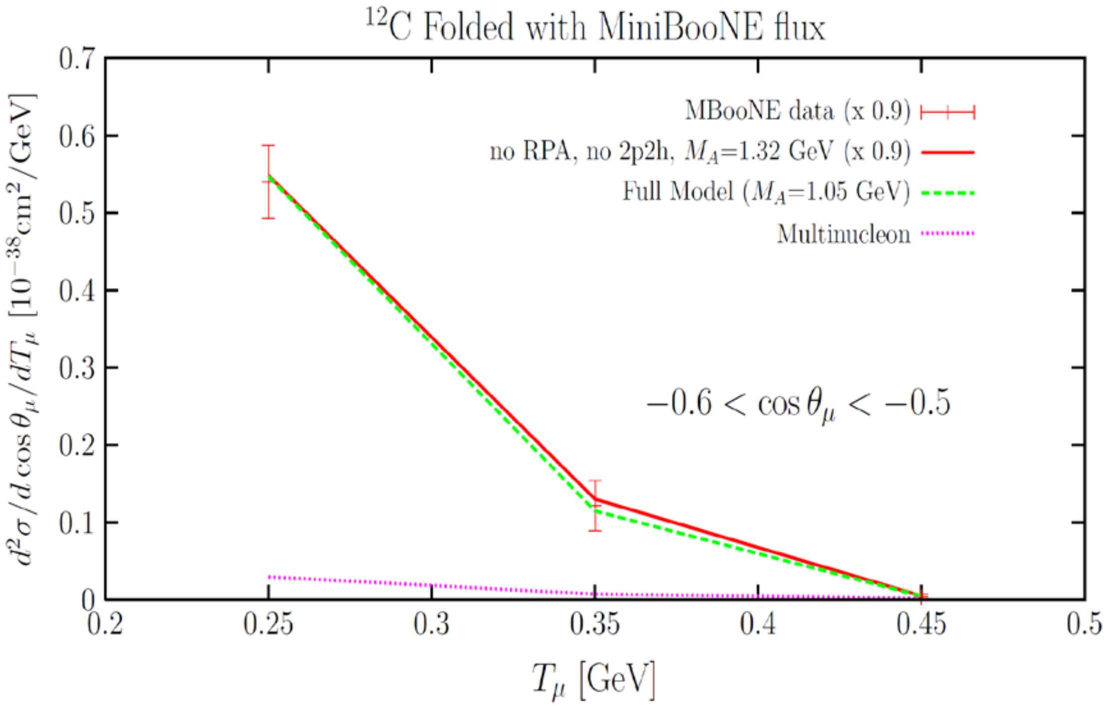
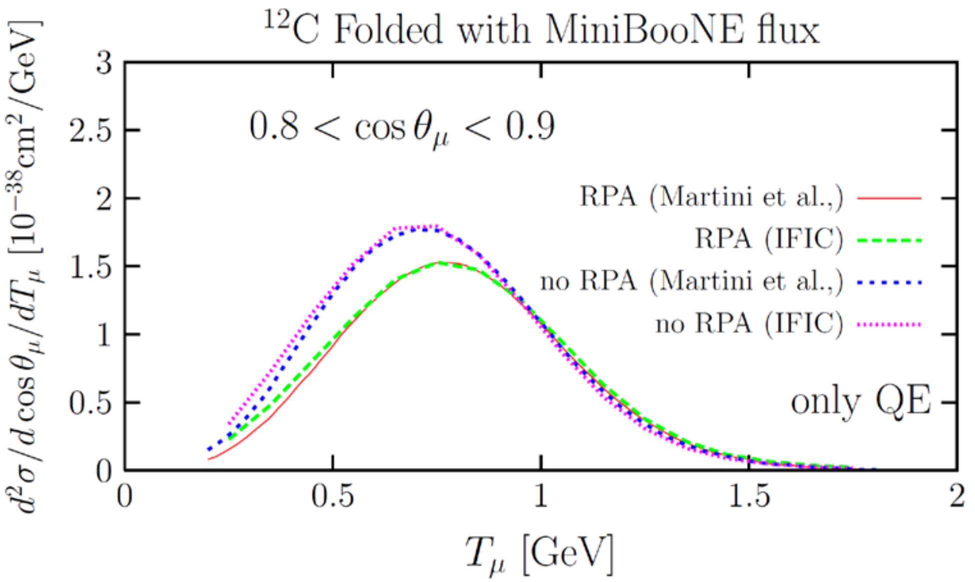
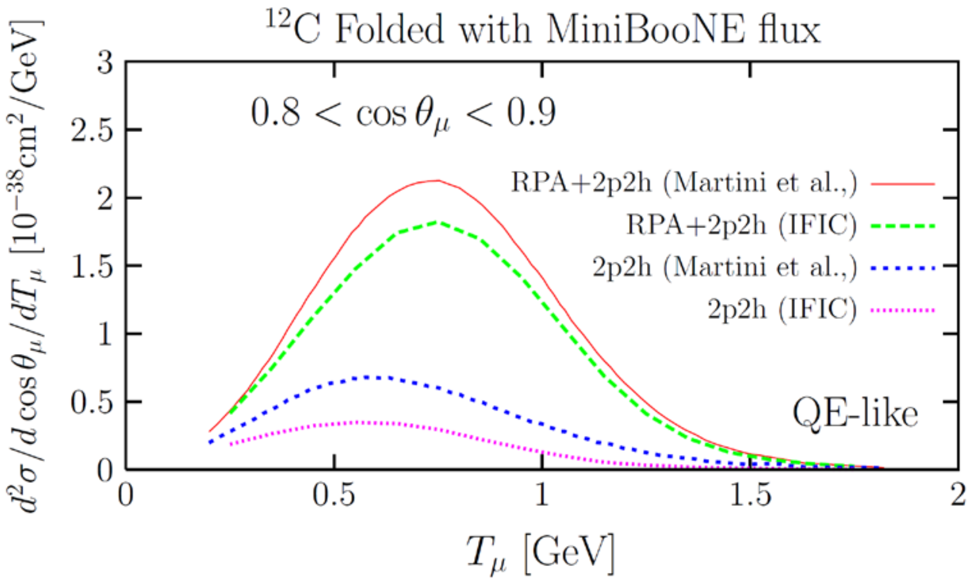
Dependence of the 2p2h contribution on $\cos\theta_\mu$







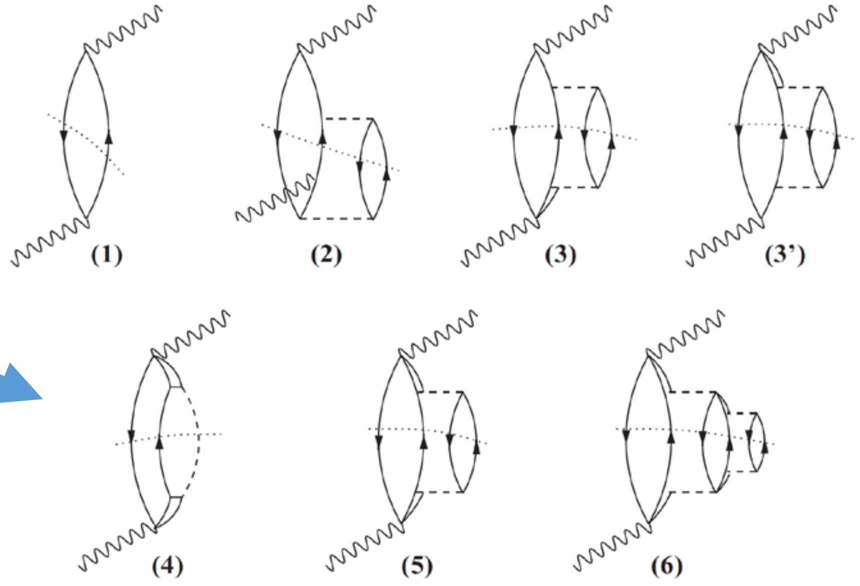
We compare rather well with Martini et al., PRC 84, 055502 for bare QE and QE+RPA



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

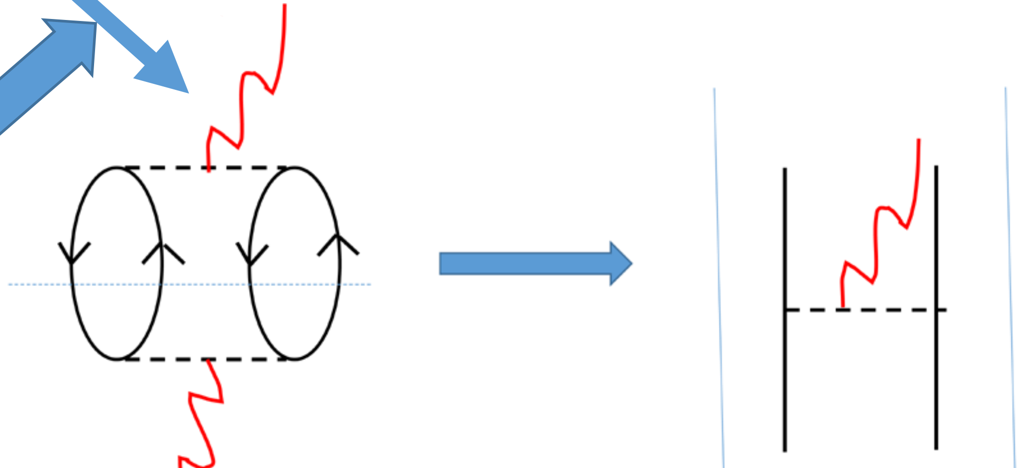
Differences with the work of Martini et al. (PRC80,065501)

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



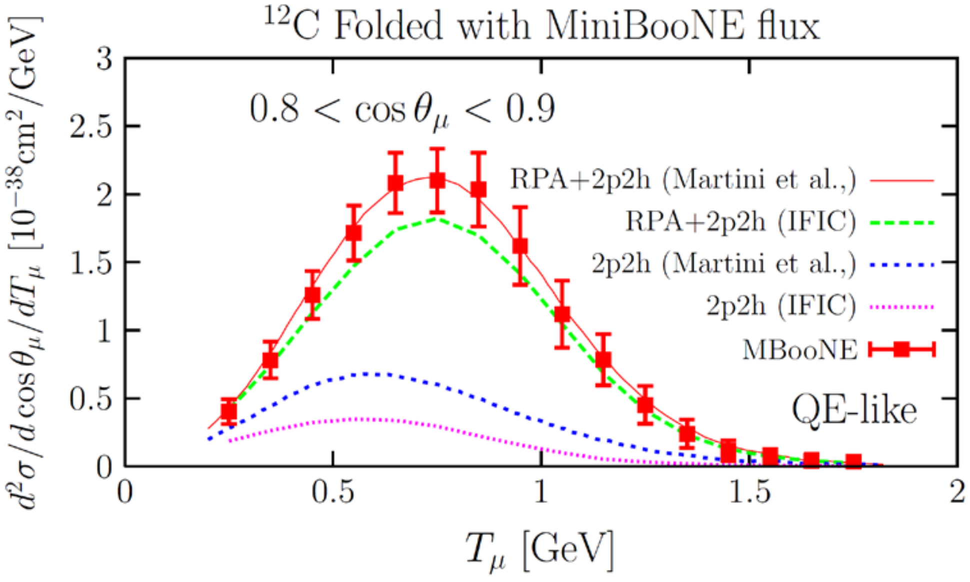
2. Martini et al. do not consider 2p2h contributions driven by contact, pion pole and pion in flight terms.

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].

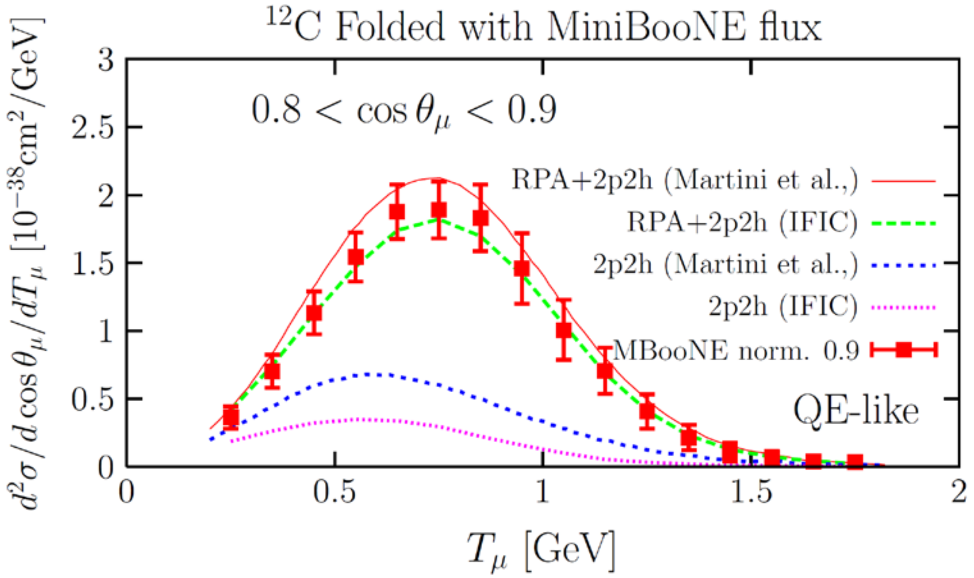


This 2p2h parametrization includes MEC effects driven by the vector current !

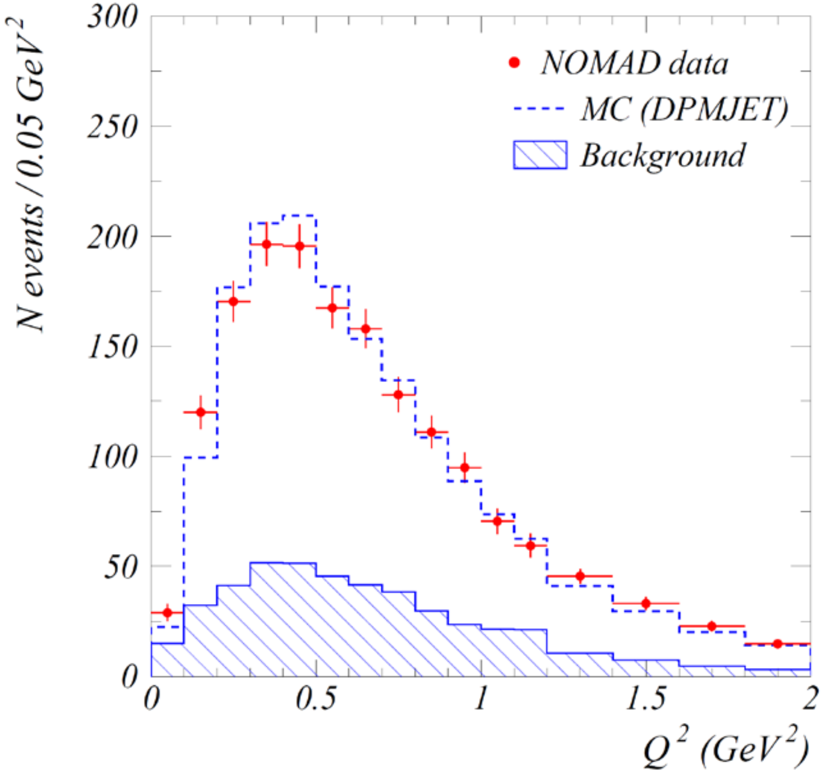
Martini et al. model does not account for all axial and axial-vector interference contributions !



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!**

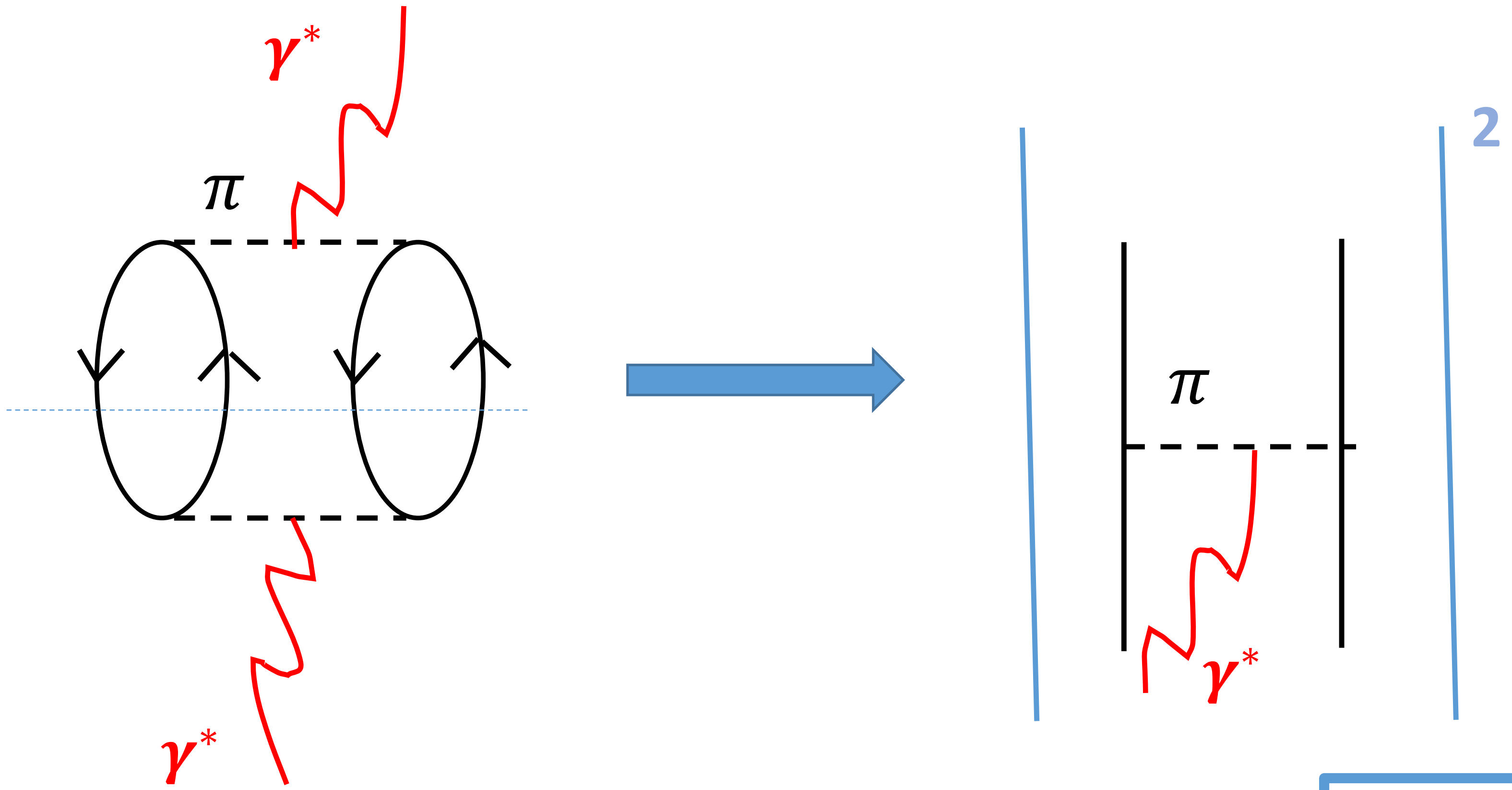


...however our predictions for the 2p2h contribution would favor a global normalization scale of about 0.9. This would be consistent with the MiniBooNE estimate of a total normalization error of 10.7%.

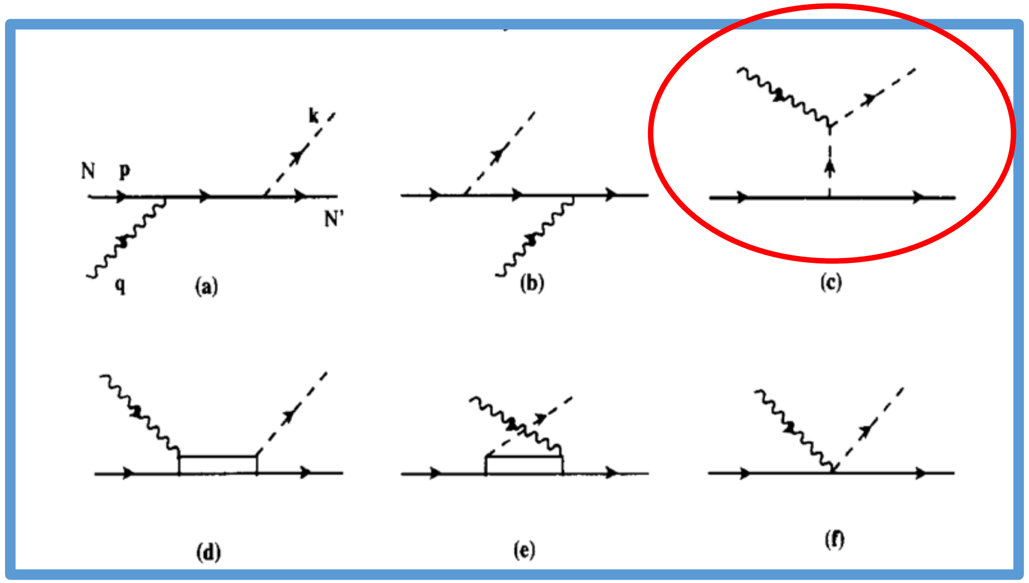


V. Lyubushkin et al. **(NOMAD Collaboration)**, Eur. Phys. J. C 63, 355 (2009). In the **two-track sample**, which is primarily Q^2 above 0.3 GeV^2, a **large fraction of the 2p2h component**, as well as QE and pion production where the hadrons rescattered as they exited the nucleus, are **rejected.**

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.



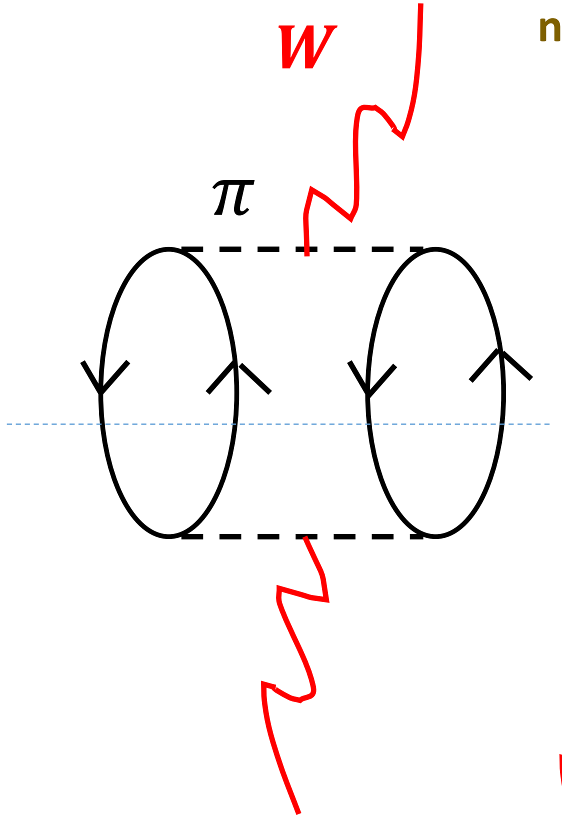
$$\gamma^* N \to \pi N$$

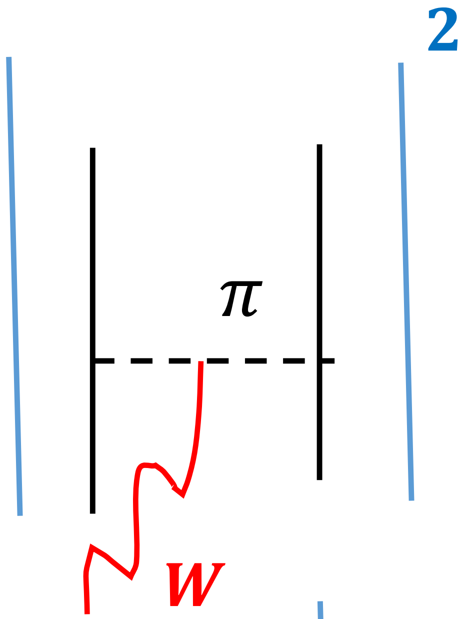


Meson Exchange Contribution

MEC & FSC & ISC

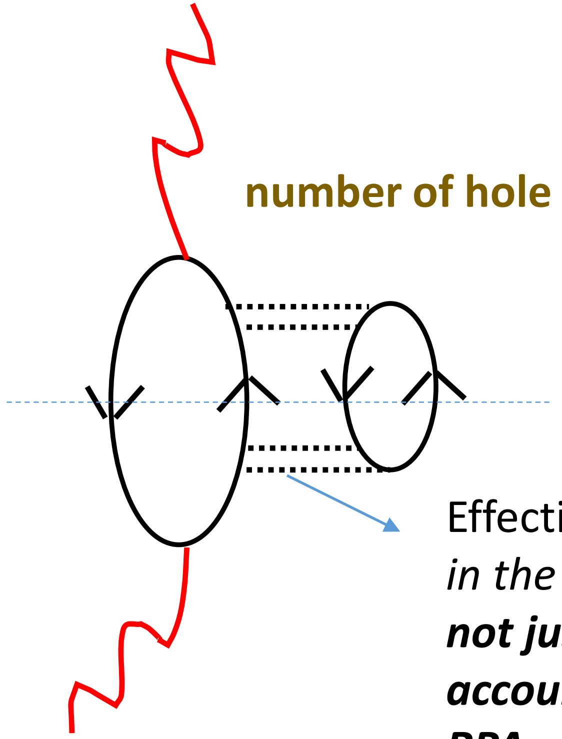
number of hole lines (density) = 2



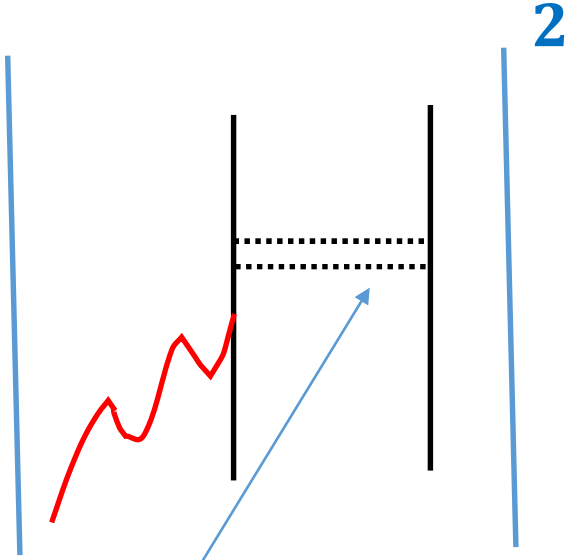


MEC term

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***



MEC/FSC term

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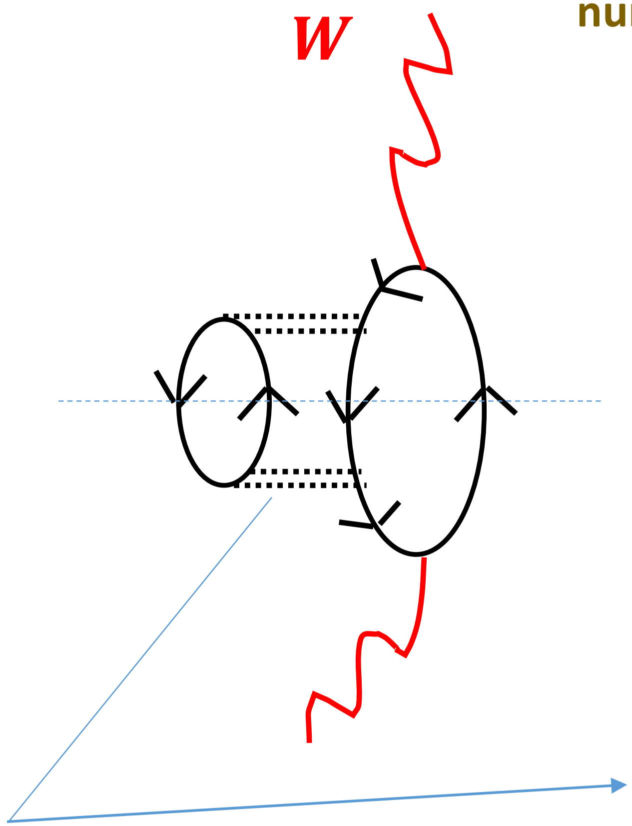
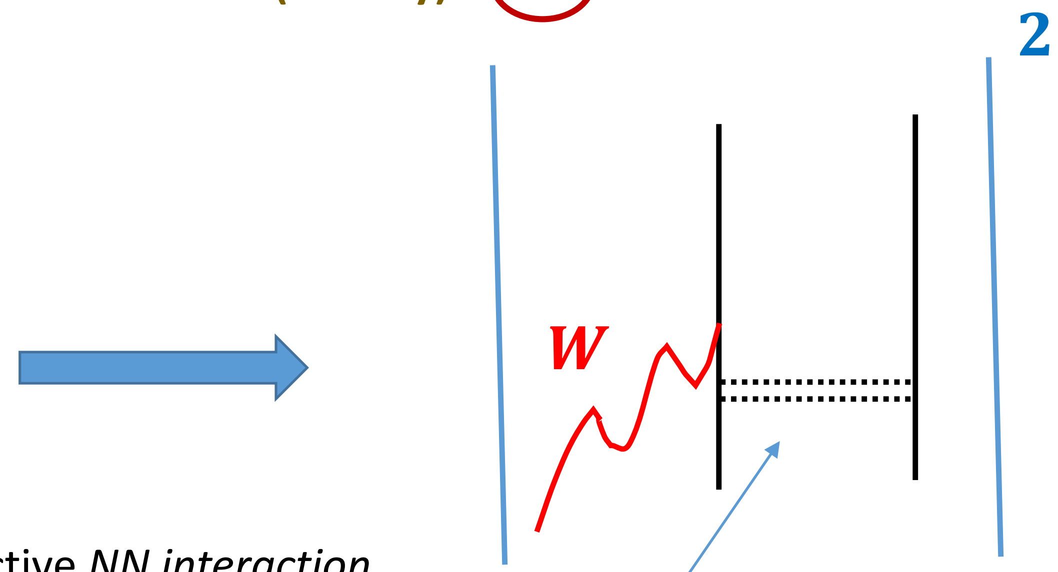
number of hole lines (density) = 4

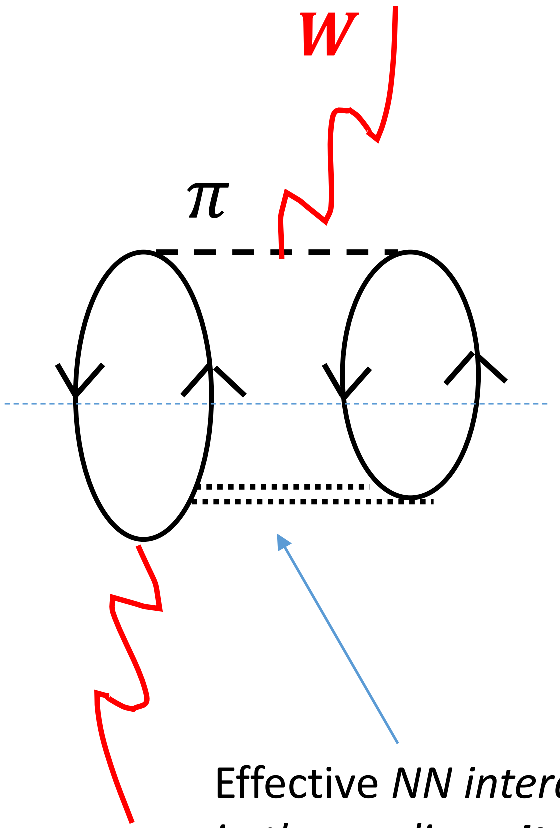




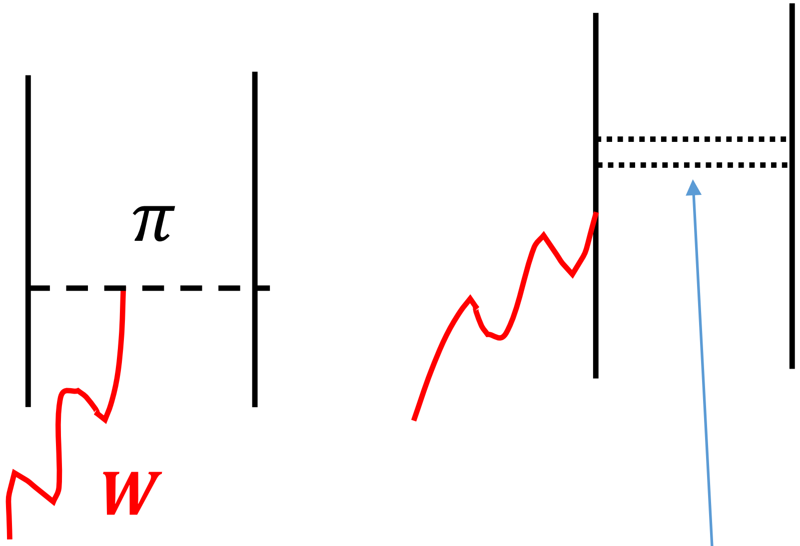
Effective *NN interaction* *in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

MEC/ISC term

number of hole lines (density) = 2



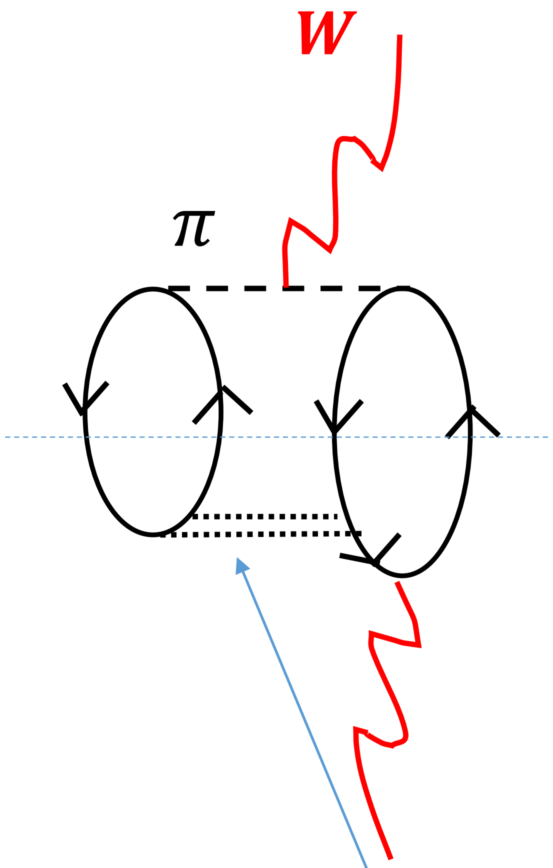
Effective *NN interaction in the medium.* ***It is not just a pion and accounts for SRC and RPA correlations***

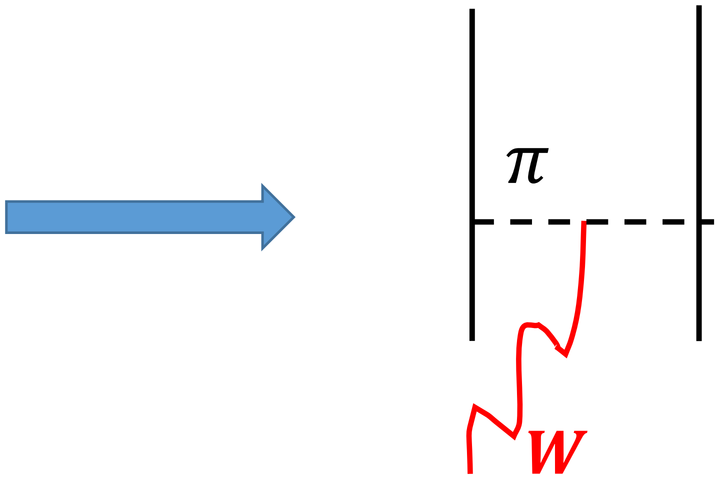


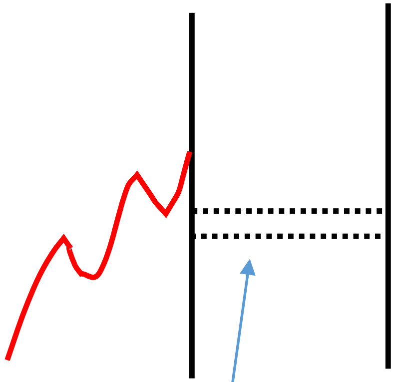
FSC-MEC interference term

MEC-ISC interference term

number of hole lines (density) = 3





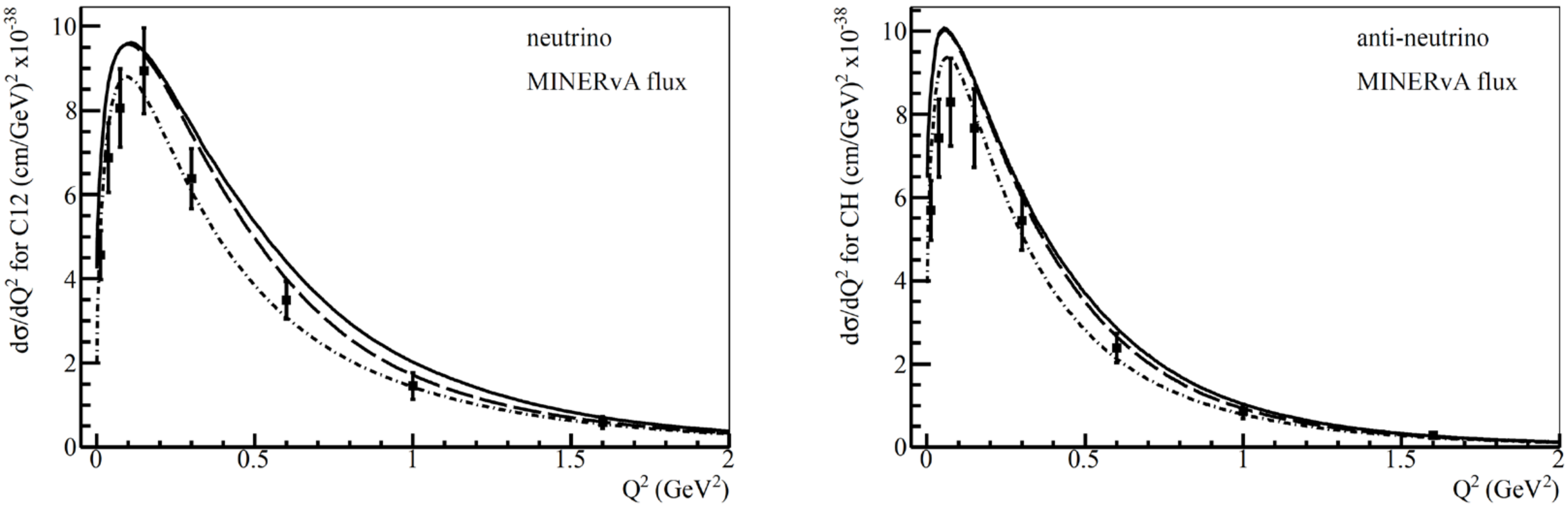


Important ?
Benhar, Lovato, Rocco [PRC 92 (2015) 024602]

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)**

MINERνA



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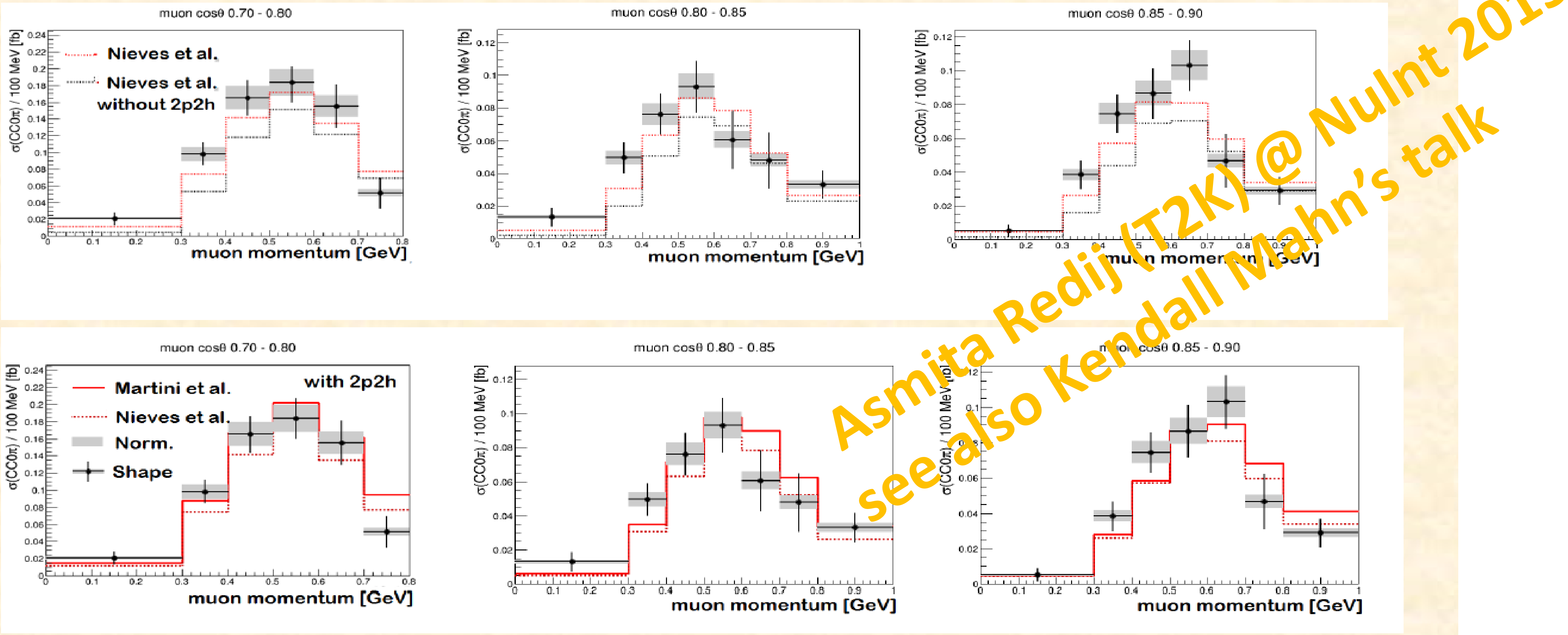
Comparison with nuclear models



Measurement favor presence of 2p2h interactions.