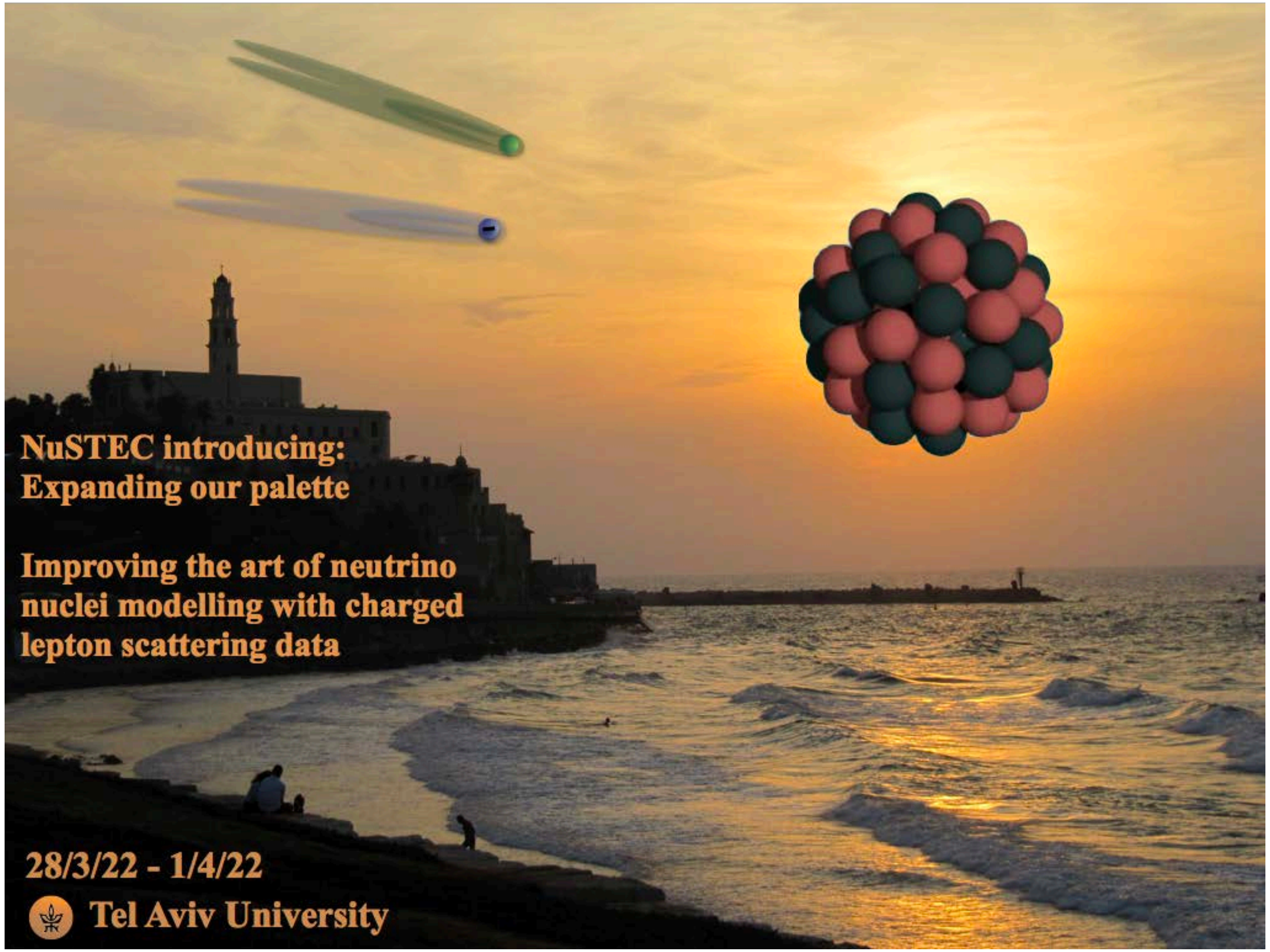
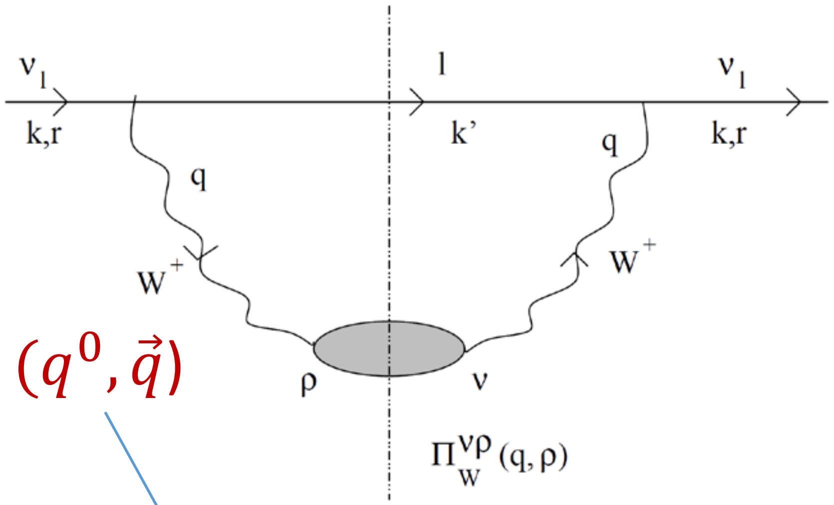


Inclusive and ~~(exclusive)~~ neutrino–nucleus cross sections and the reconstruction of the interaction kinematics

J. Nieves

IFIC (CSIC & UV)

Theoretical (many body) approach



$(q^0, \vec{q})$

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

For instance, charged current process

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

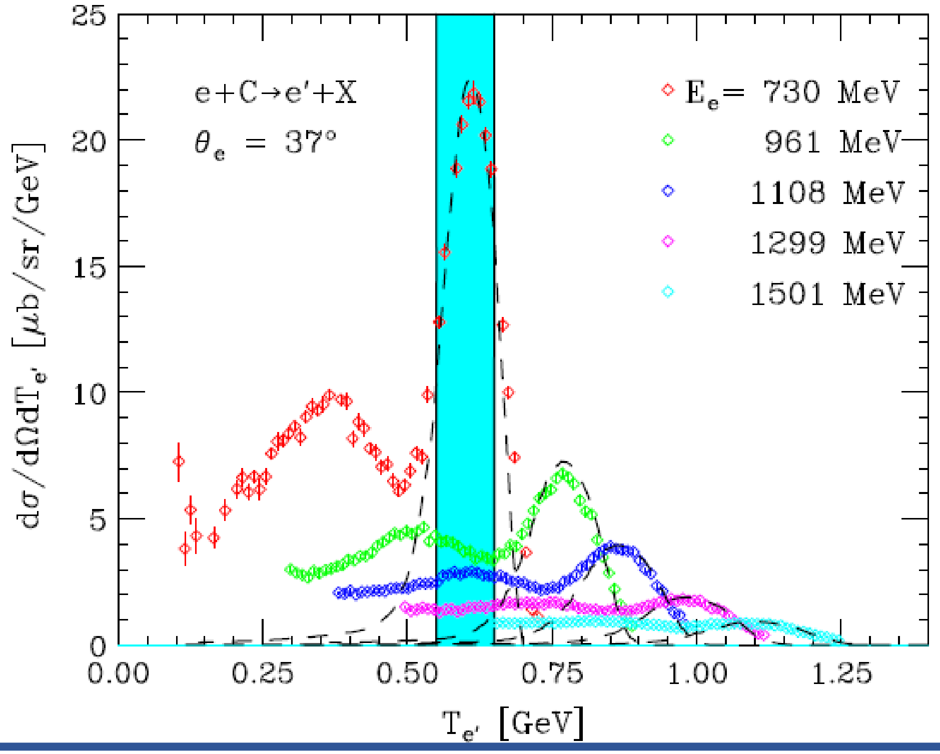
$$W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i} W_a^{\mu\sigma}$$

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

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

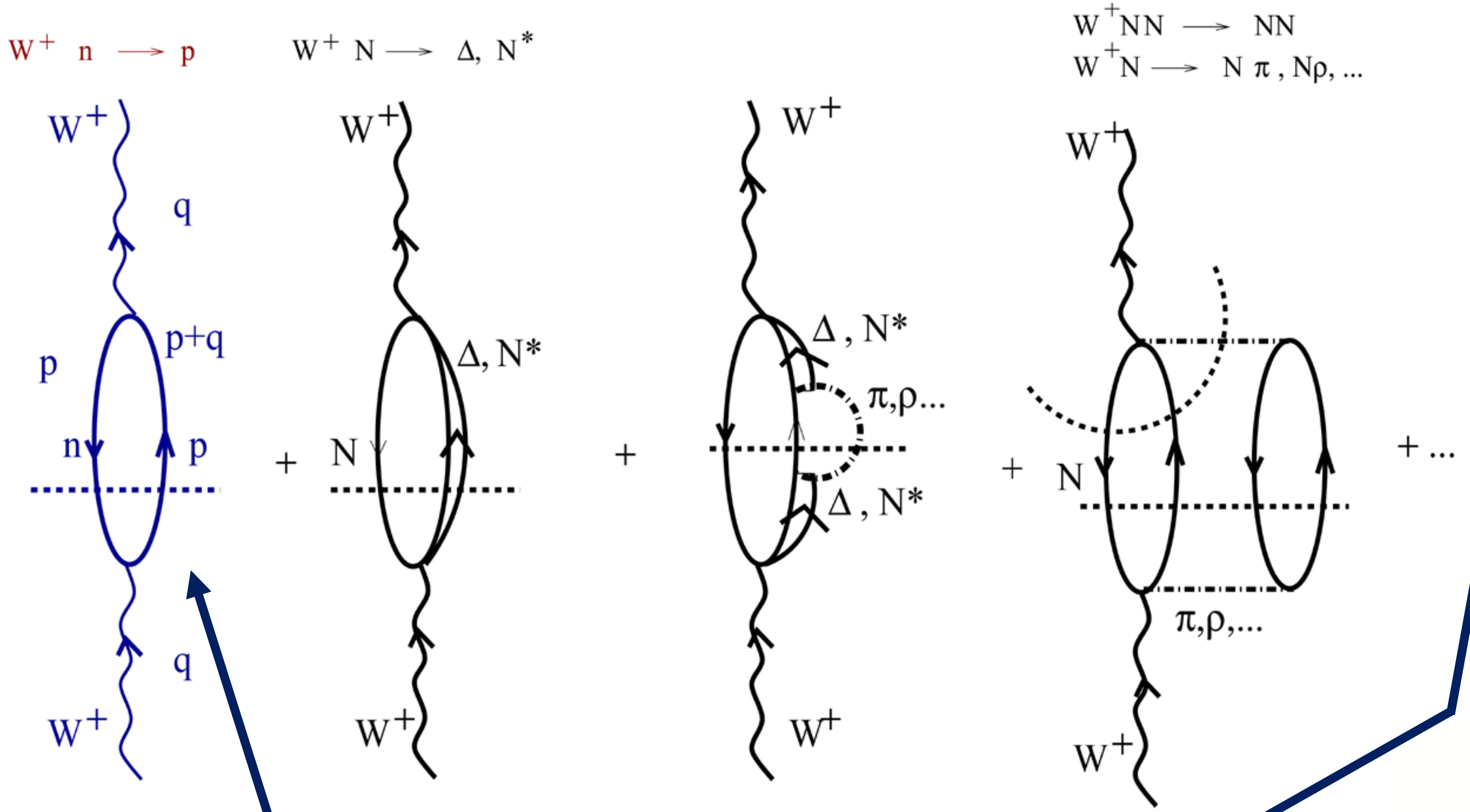
Basic object $\Pi^{\nu\rho}_{W,Z^0,\gamma}(q,\rho)$ $\equiv$ Selfenergy of the Gauge Boson $(W^\pm, Z^0, \gamma)$ inside of the nuclear medium. Perform a Many Body expansion, where the relevant gauge boson absorption modes should be systematically incorporated: absorption by one N, or NN or even 3N,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

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,



CONSISTENT MICROSCOPIC DESCRIPTION of the QE, DIP AND Δ , REGIONS BECOMES FUNDAMENTAL BECAUSE NEUTRINO BEAMS ARE NOT MONOCHROMATIC

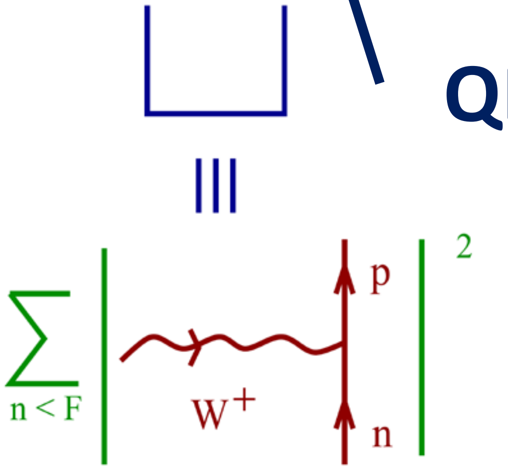
The energy bin corresponding to **the top of the QE peak at $E_e =$ 730 MeV receives significant contributions from** cross sections corresponding to different beam energies and **different mechanisms!**



$$p^2 \approx (p+q)^2$$

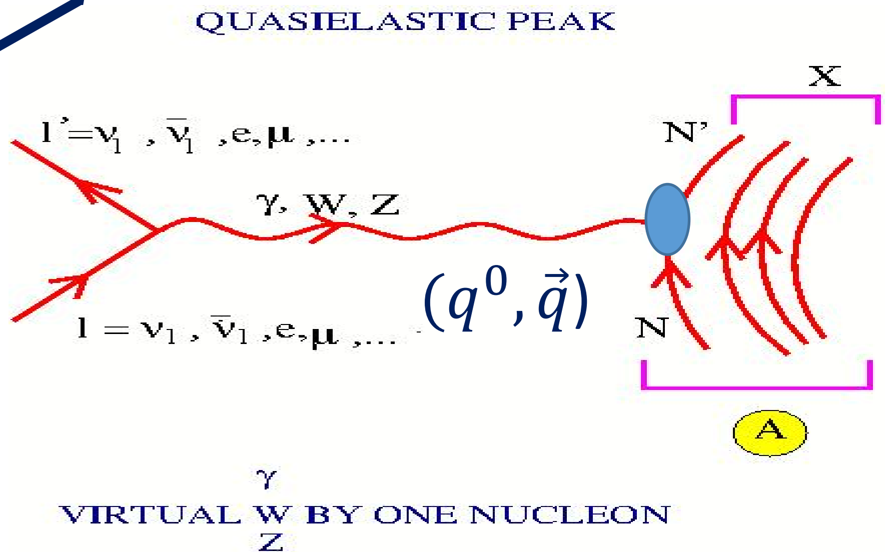
$$2pq + q^2 \approx 0$$

$$q^0 \approx -\frac{q^2}{2M} = \frac{|\vec{q}|^2 - (q^0)^2}{2M}$$



QE (1p1h) contribution

first ingredient $W^{\pm}NN'$ (or Z^0NN or γ^*NN) in **vacuum, after nuclear corrections should be included…..**



+NUCLEAR 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).

Spectral Functions: dressing the nucleon lines in the medium

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

Spectral Functions: modification of the dispersion relation of the nucleons inside of the nuclear medium

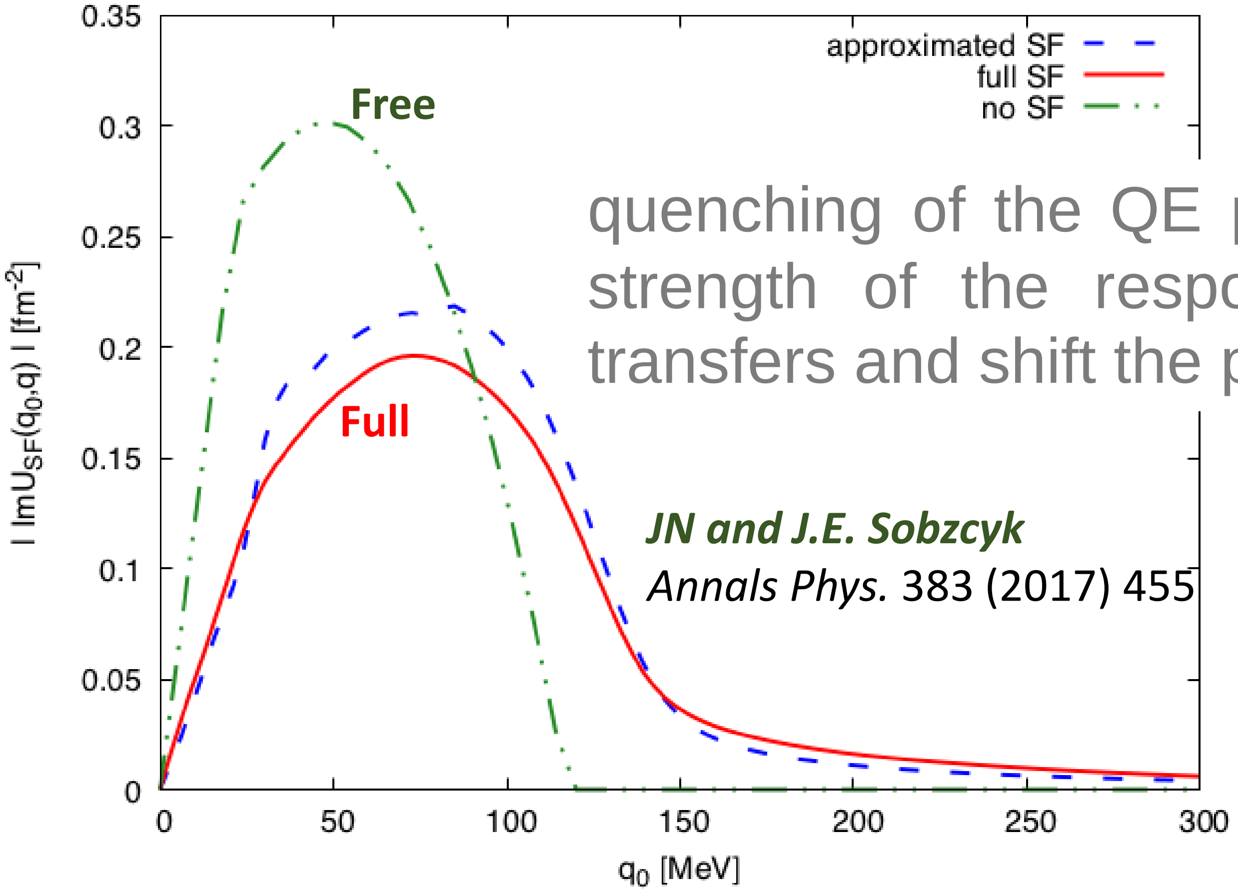
This nuclear effect is additional to those due to RPA (long range) correlations !!

PHYSICAL REVIEW C VOLUME 46, NUMBER 5 NOVEMBER 1992

Semiphenomenological approach to nucleon properties in nuclear matter

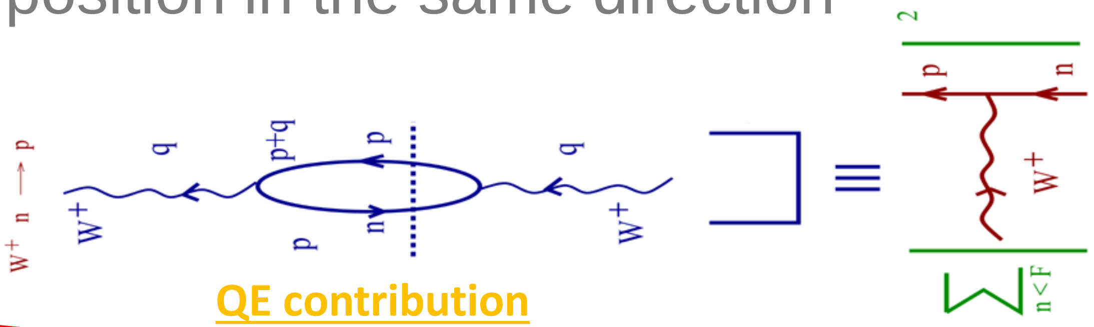
P. Fernández de Córdoba and E. Oset
Departamento de Física Teórica and Instituto de Física Corpuscular,
Centro Mixto Universidad de Valencia Consejo Superior de Investigaciones Científicas, 46100 Burjassot (Valenc
(Received 20 April 1992)

SF from effective NN interaction in the medium constructed from the experimental NN cross section + some medium corrections



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

JN and J.E. Sobczyk
Annals Phys. 383 (2017) 455



QE contribution

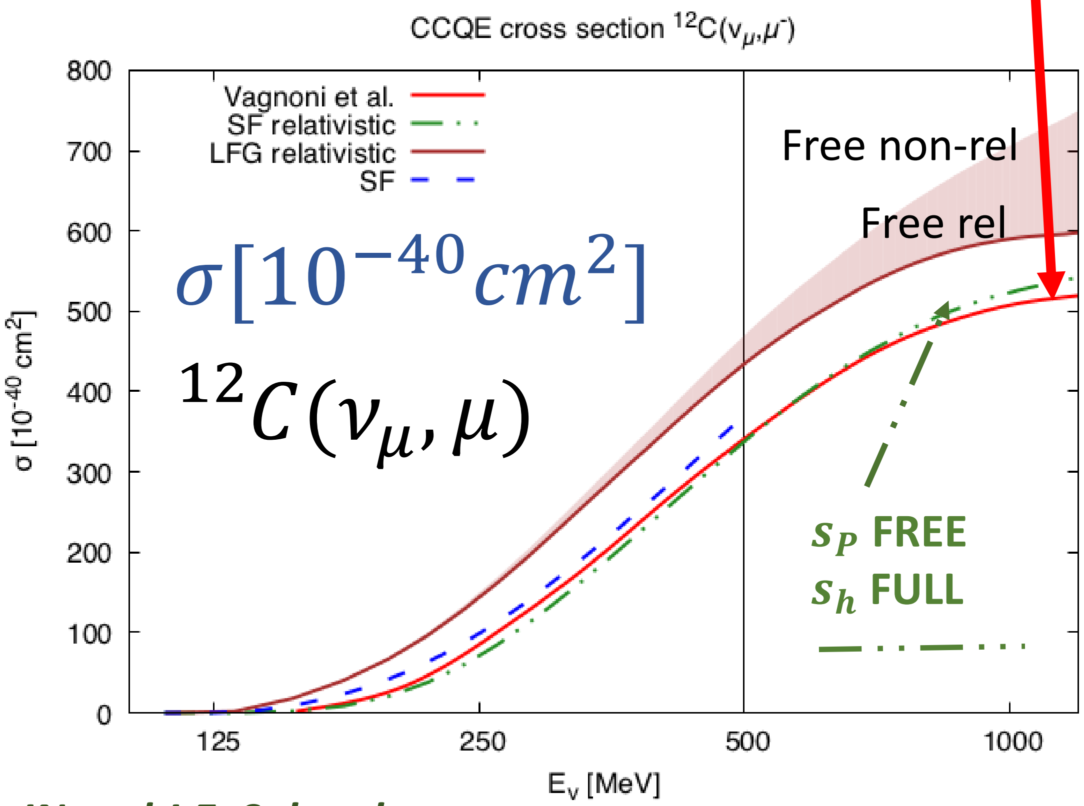
Imaginary part of the *ph* propagator (Lindhard function)

reasonable agreement !

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

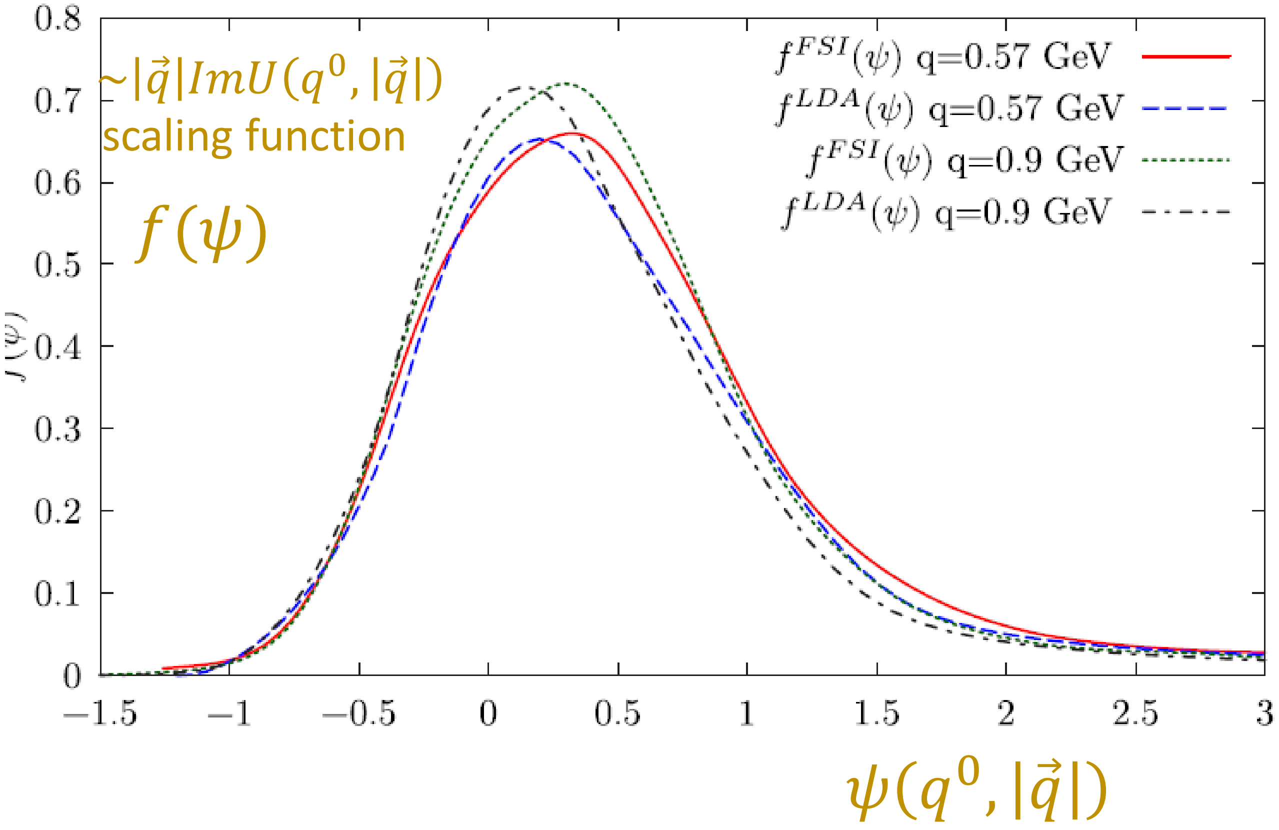
Inelastic Neutrino-Nucleus Interactions within the Spectral Function Formalism

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



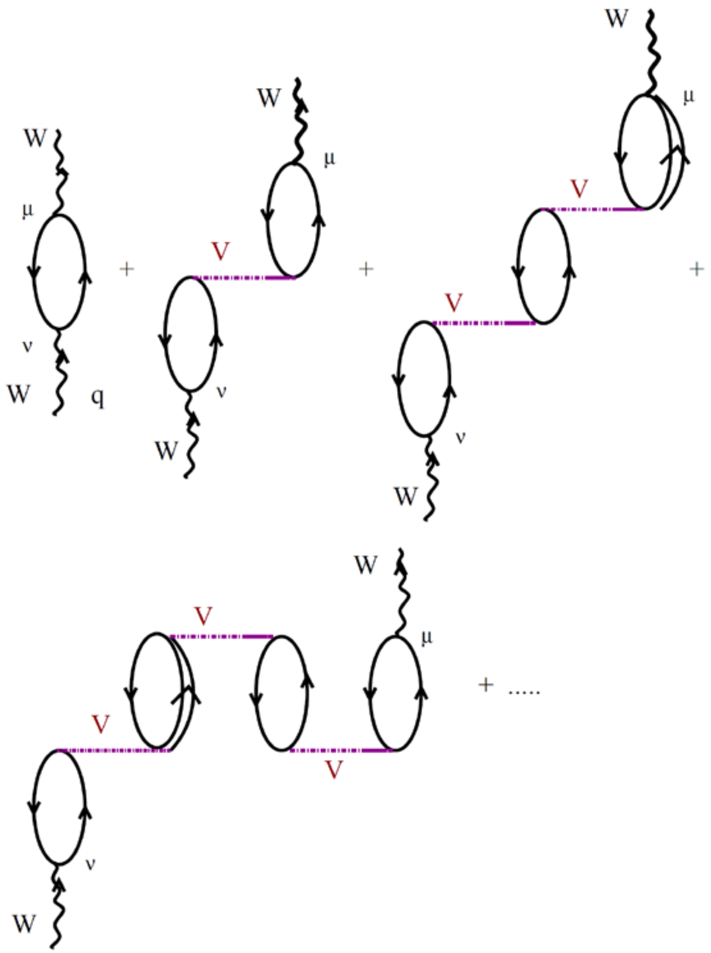
JN and J.E. Sobczyk
Annals Phys. 383 (2017) 455

J. E. Sobczyk, N. Rocco, A. Lovato and JN
PRC 97 (2018) 035506



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 **(SRC)**

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

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

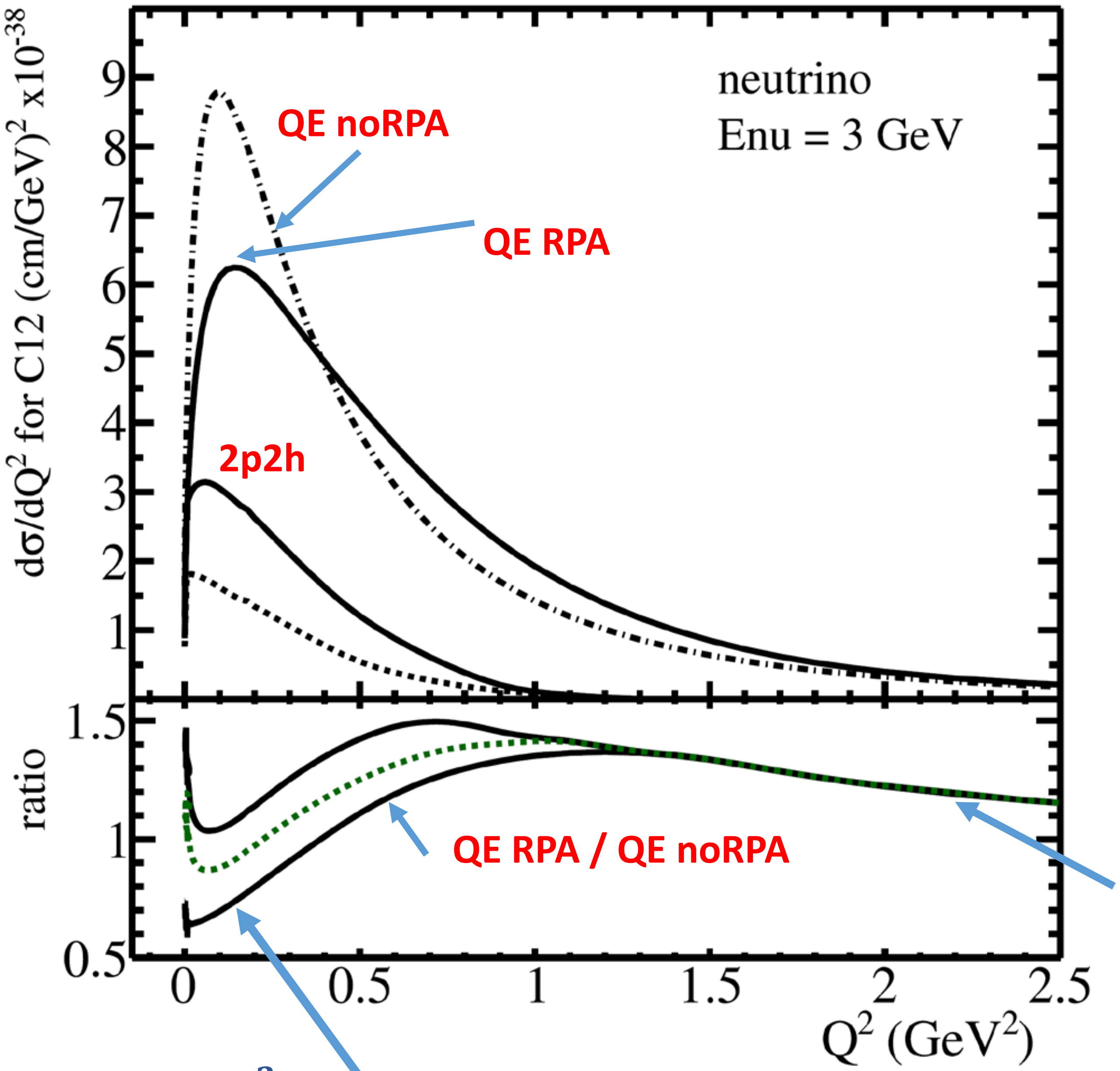
2. $S=T=1$ channel of the ph–ph interaction $\rightarrow$ s longitudinal (π) and transverse (ρ) + **SRC**

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

(SRC)

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

3. Contribution of Δh excitations important

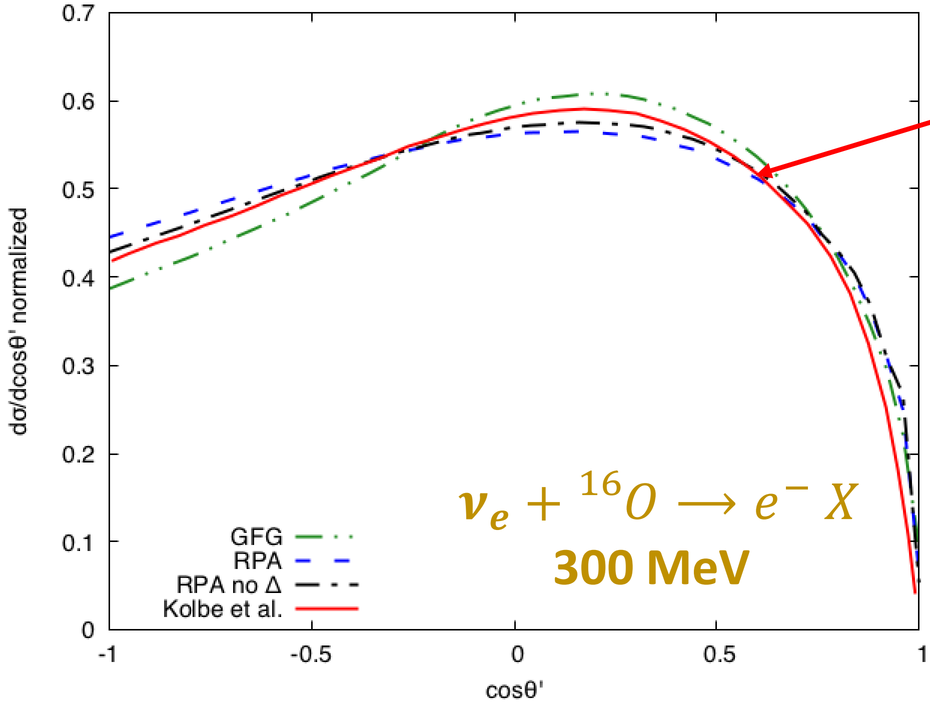


deplection at low Q^2 values

Gran+JN+Sánchez+Vicente-Vacas
*PRD*88 (2013) 113007

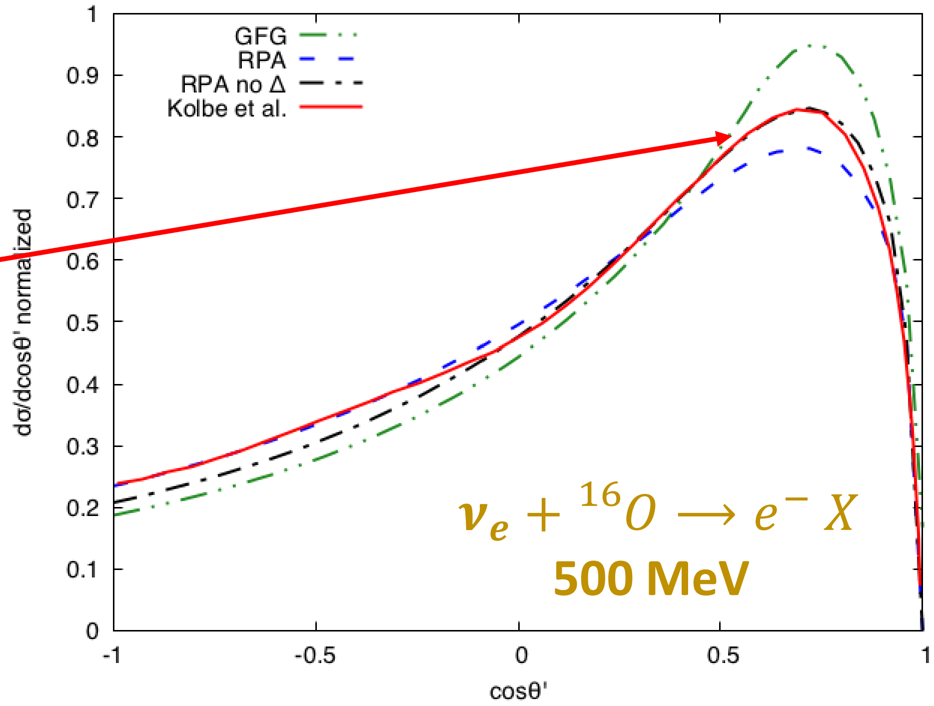
RPA (long range correlations) the weak probe interacts with the nucleus as a whole,

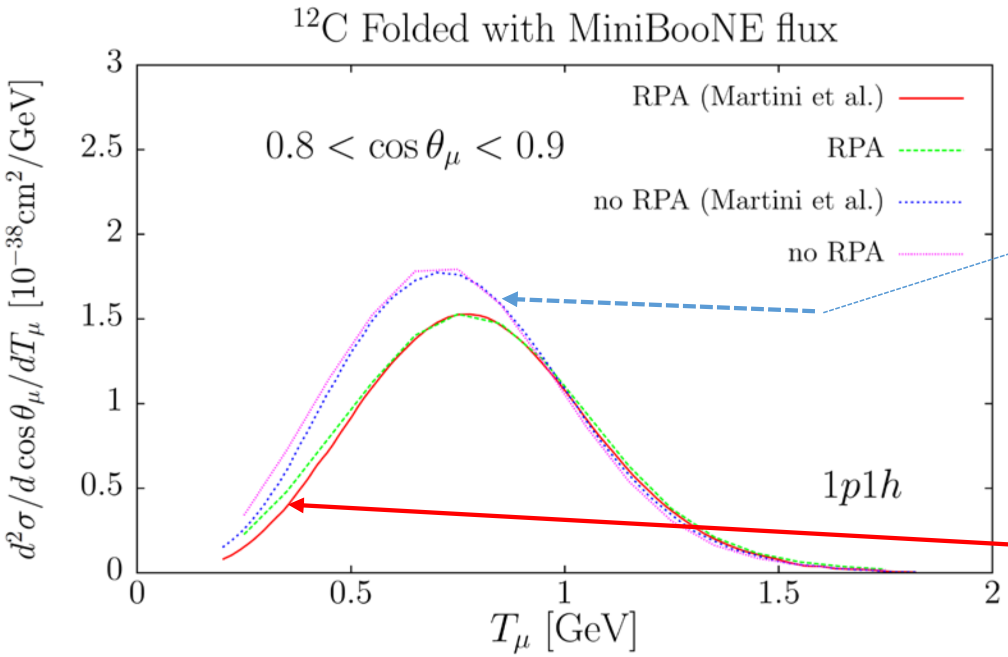
RPA effects → 0, when $1/\sqrt{Q^2} \ll$ <u>nuclear radius</u>, since then the probe would see the individual nucleons or even the partons



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

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



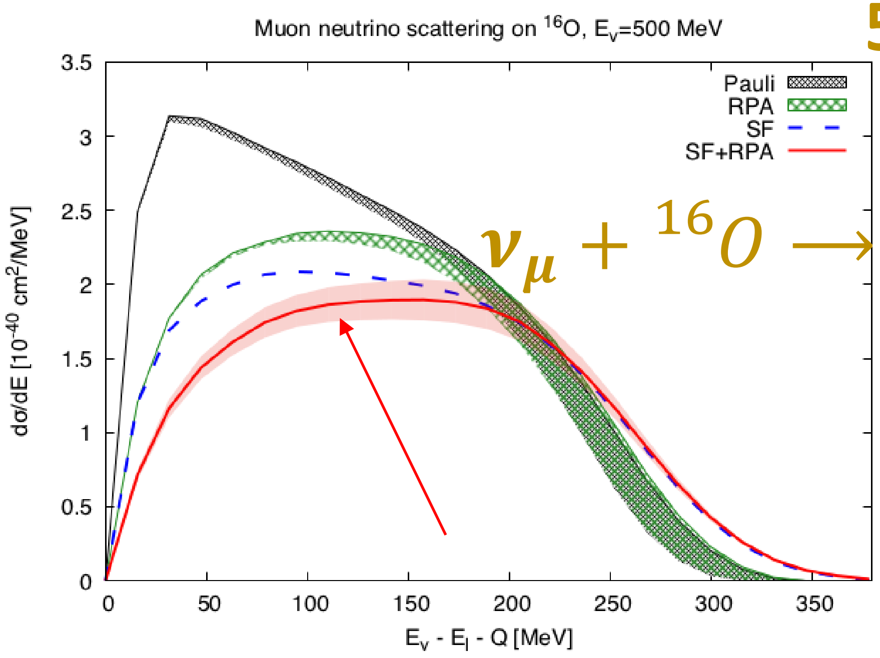


M. Martini, M. Ericson, and G. Chanfray, Phys.Rev. C84, 055502 (2011)

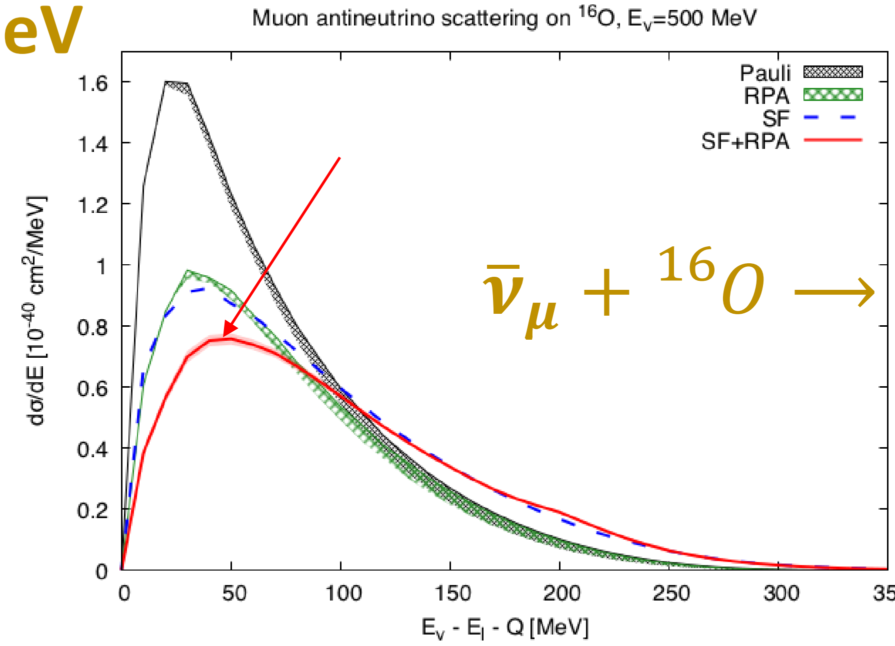
reasonable agreement !

JN and J.E. Sobzcyk
Annals Phys. 383 (2017) 455

500 MeV



$$\nu_\mu + {}^{16}O \longrightarrow \mu^- X$$

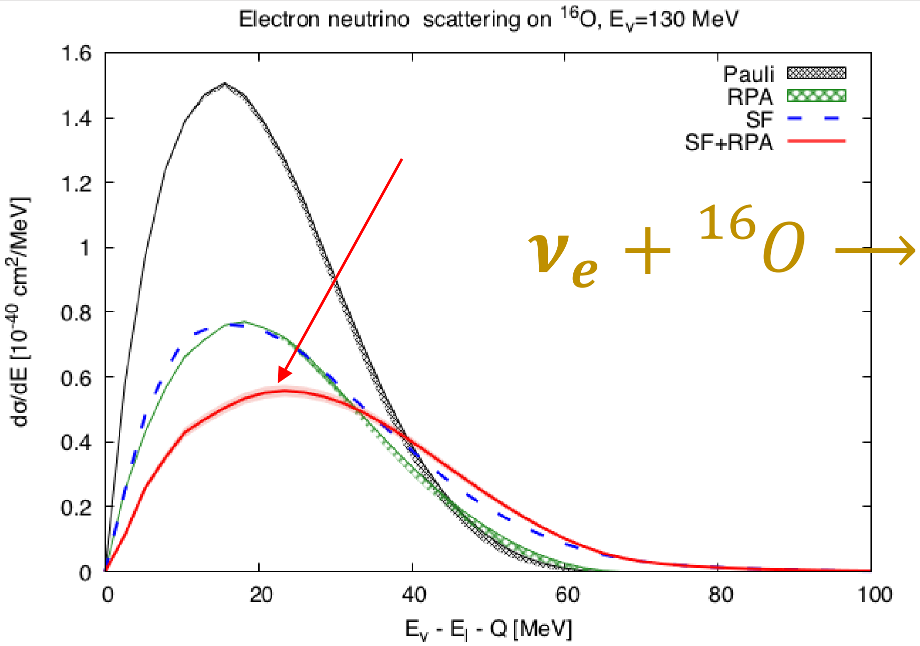


$$\bar{\nu}_\mu + {}^{16}O \longrightarrow \mu^+ X$$

QE: 1p1h

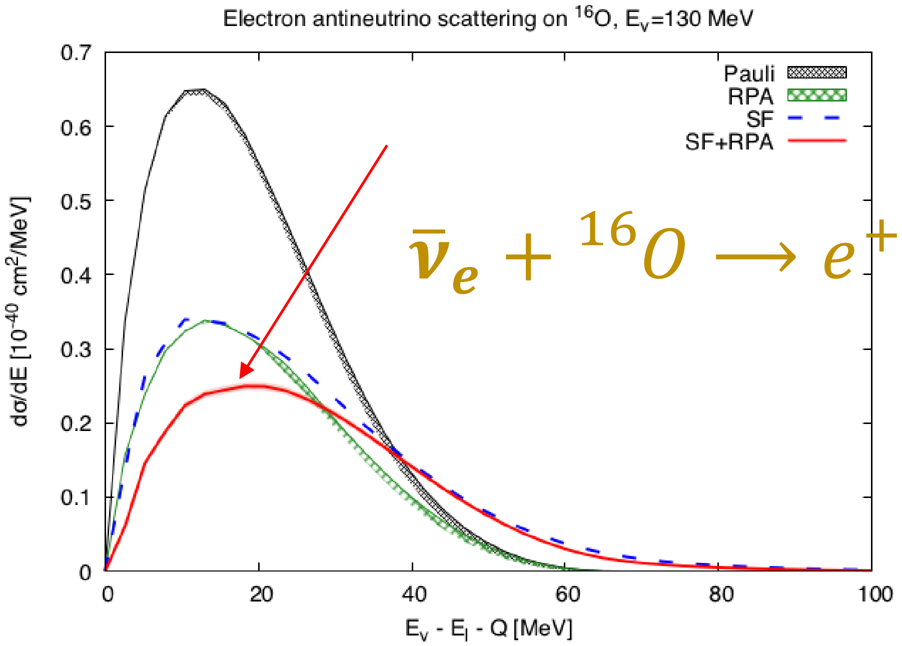
JN and J.E. Sobzcyk *Annals Phys.* 383 (2017) 455

RPA effects in integrated decay rates or cross sections become significantly smaller when SF corrections are also considered



$$\nu_e + {}^{16}O \longrightarrow e^- X$$

130 MeV



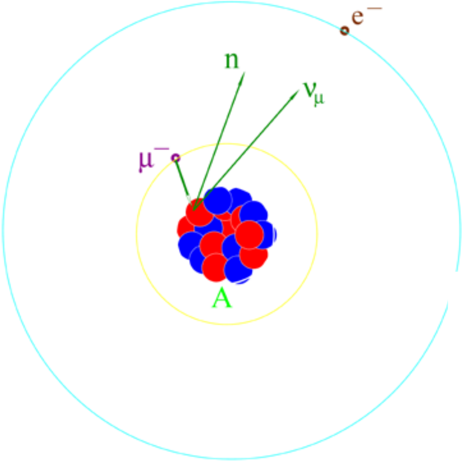
$$\bar{\nu}_e + {}^{16}O \longrightarrow e^+ X$$

SF+RPA

SF+RPA

Free

Free + RPA



JN and J.E. Sobzcyk
Annals Phys. 383 (2017) 455

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

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

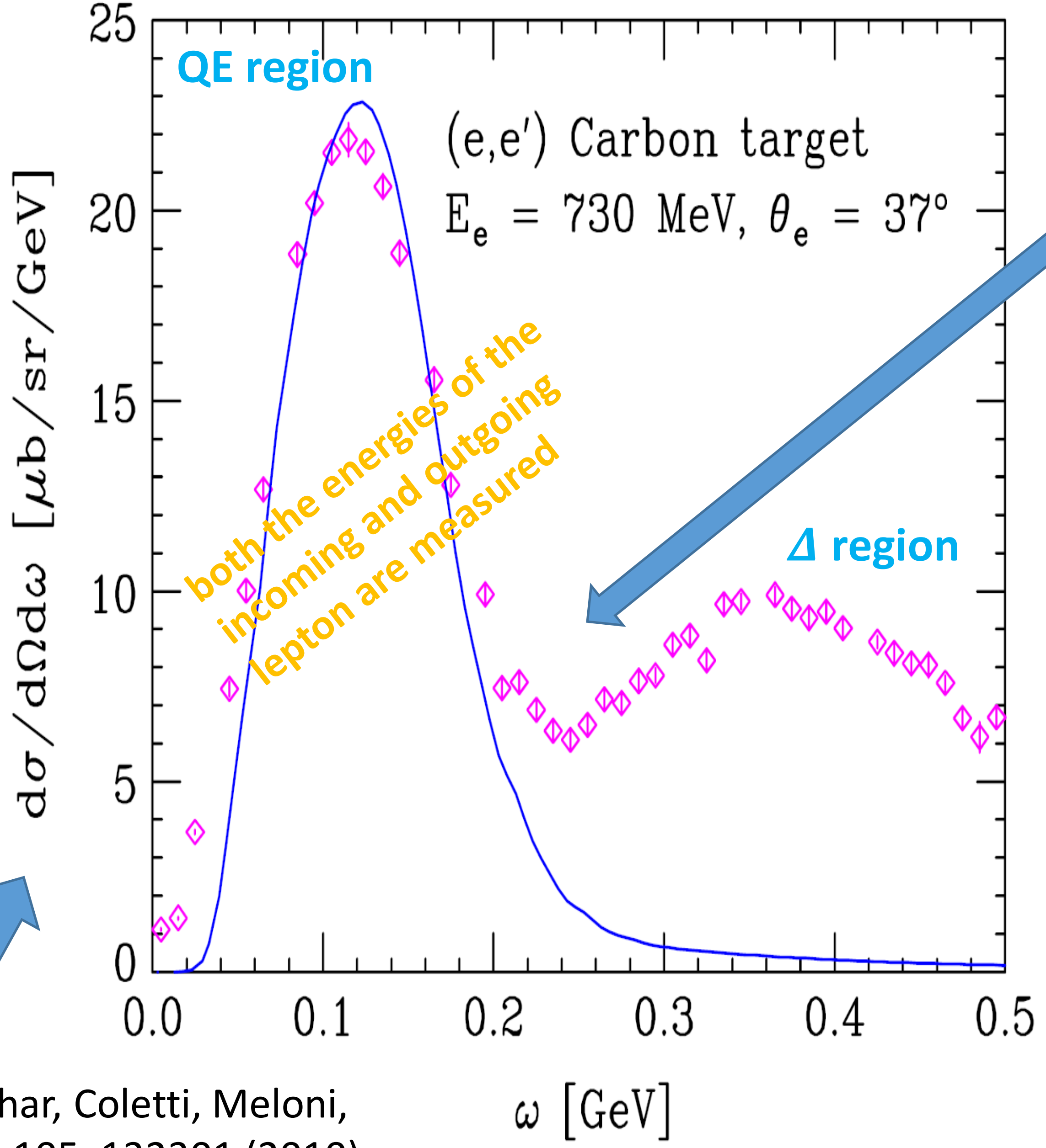
The inclusive ^{12}C$(\nu_\mu,\mu^-)X$ *and* ^{12}C$(\nu_e,e^-)X$ *reactions near threshold*

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

	Pauli	RPA	SF	SF+RPA	SM	SM	CRPA	Experiment		
					[125]	[44]	[45]	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

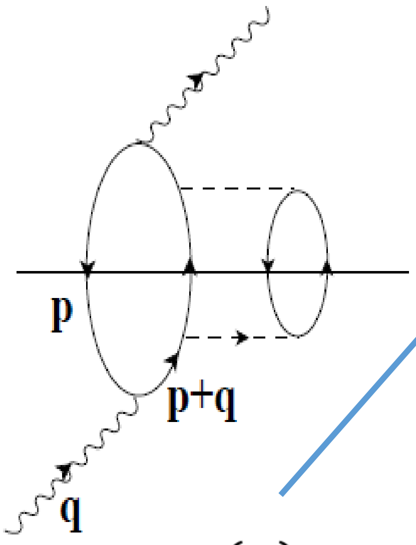
[125]: Hayes & Towner, PRC61, 044603;
[44]: Volpe et al., PRC62, 015501; [45]: Kolbe et al., J. Phys. G29, 2569

Spectral Functions (SRC) populate neither the **dip** nor the Δ regions



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)



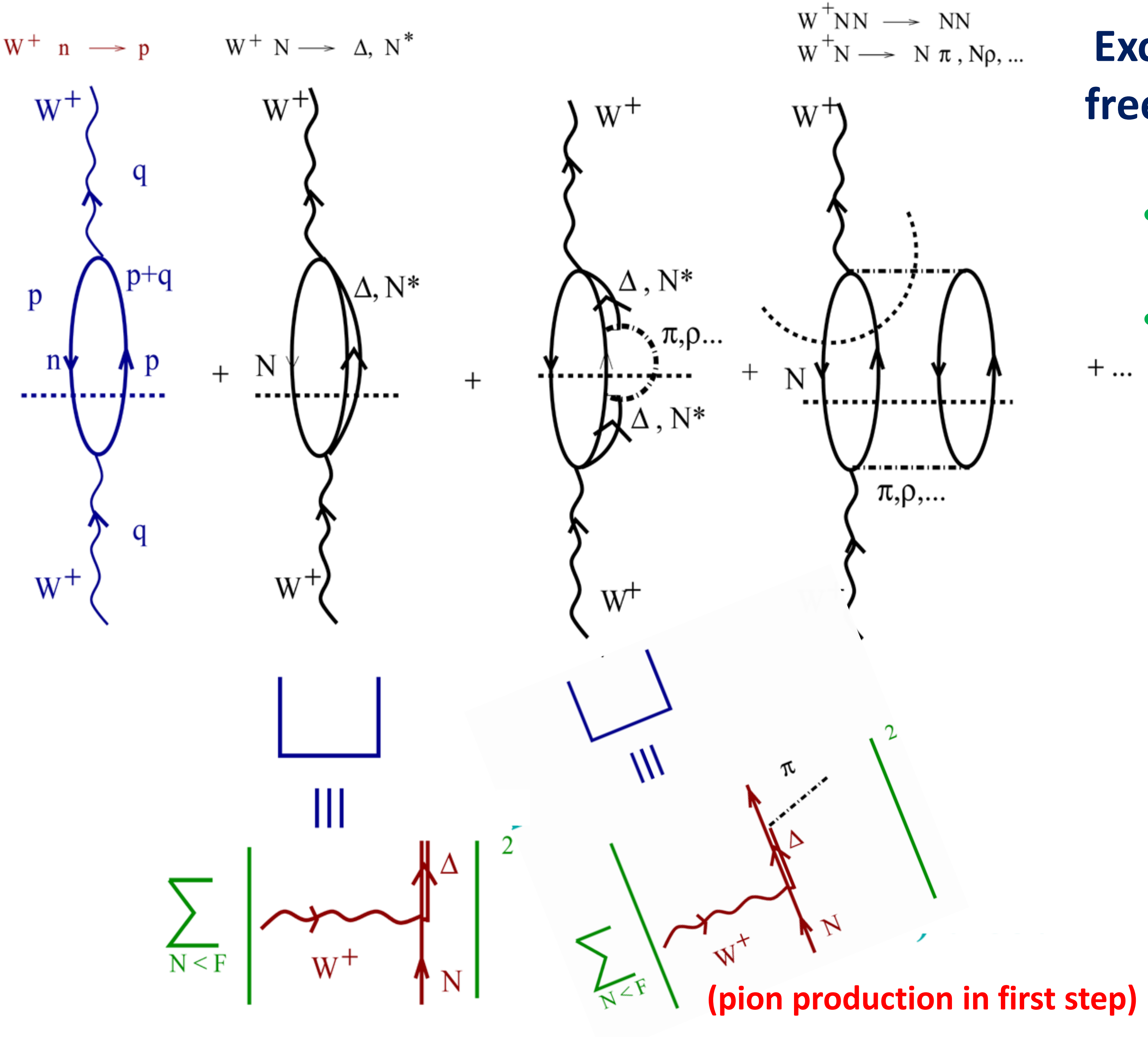
$$G(p) \to \int_{-\infty}^{\mu} d\omega \frac{S_h(\omega,\vec{p}\,)}{p^0-\omega-i\epsilon} + \int_{\mu}^{+\infty} d\omega \frac{S_p(\omega,\vec{p}\,)}{p^0-\omega+i\epsilon}$$

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

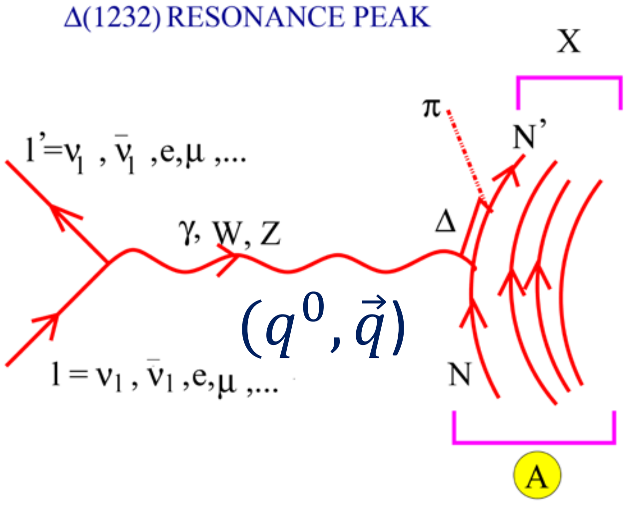
$$G(p) = \frac{n(\vec{p}\,)}{p^0-\varepsilon(\vec{p})-i\epsilon} + \frac{1-n(\vec{p}\,)}{p^0-\varepsilon(\vec{p})+i\epsilon}$$

Excitation of $\Delta(1232)$ degrees of freedom, $T = 3/2$ and $J^P = 3/2^+$

- energy transfer should be sufficiently large…
- because of the large $\pi N \Delta$ coupling, the <u>properties of pion and Δ inside of a nuclear medium become important</u>

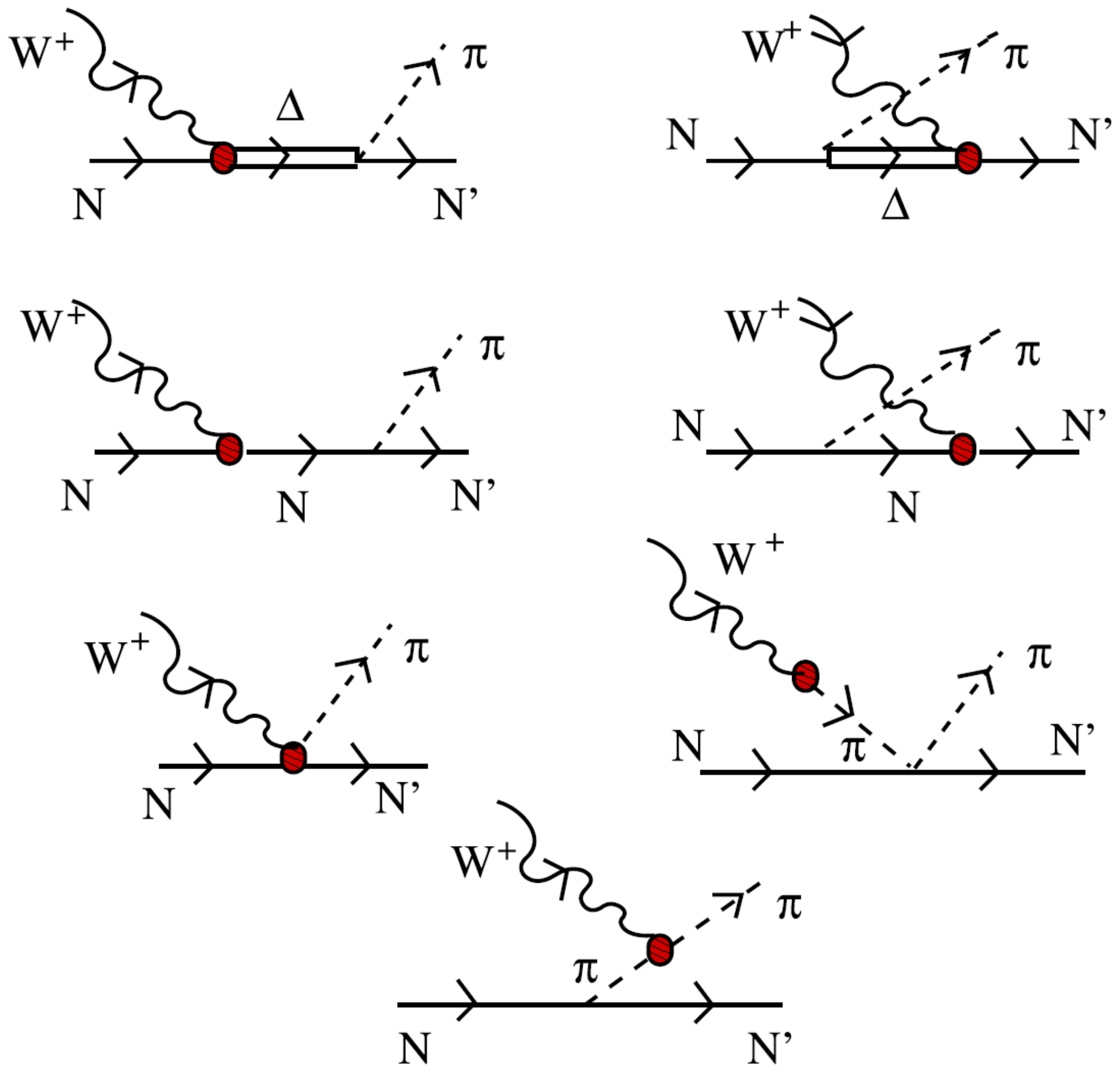


(pion production in first step)



Δh contribution

first ingredient $W^{\pm}N \longrightarrow N'\pi$ (or $Z^0N \longrightarrow N'\pi$ or $\gamma N \longrightarrow N'\pi$) in **vacuum, after nuclear corrections should be included…..**



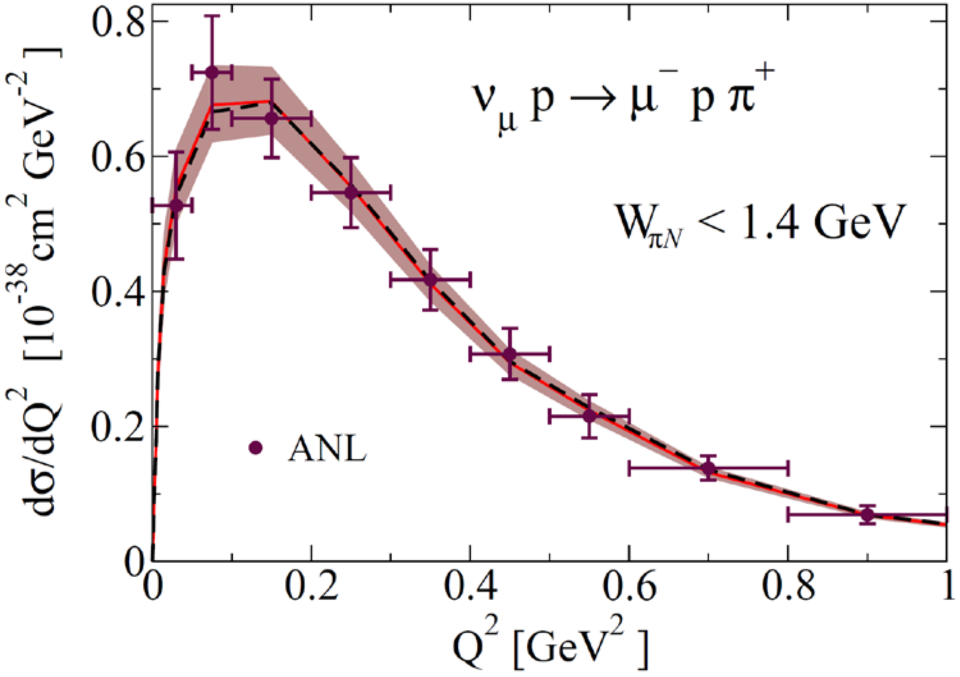
EFT involving pions and nucleons which implements:

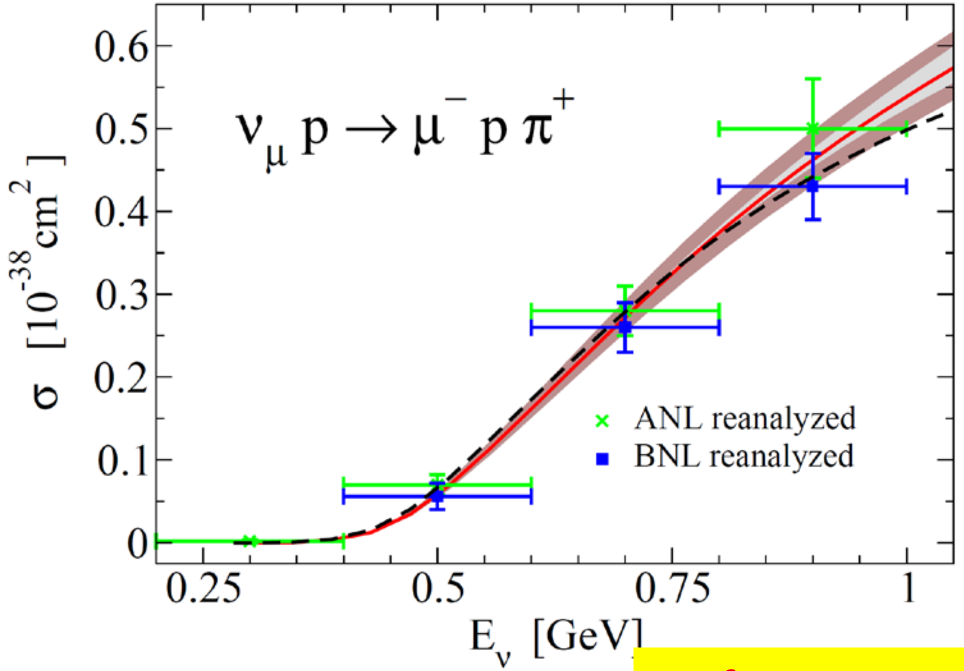
- **non-resonant background determined by chiral symmetry and its pattern of spontaneous breaking**
- **unitarity in the dominant multipoles**

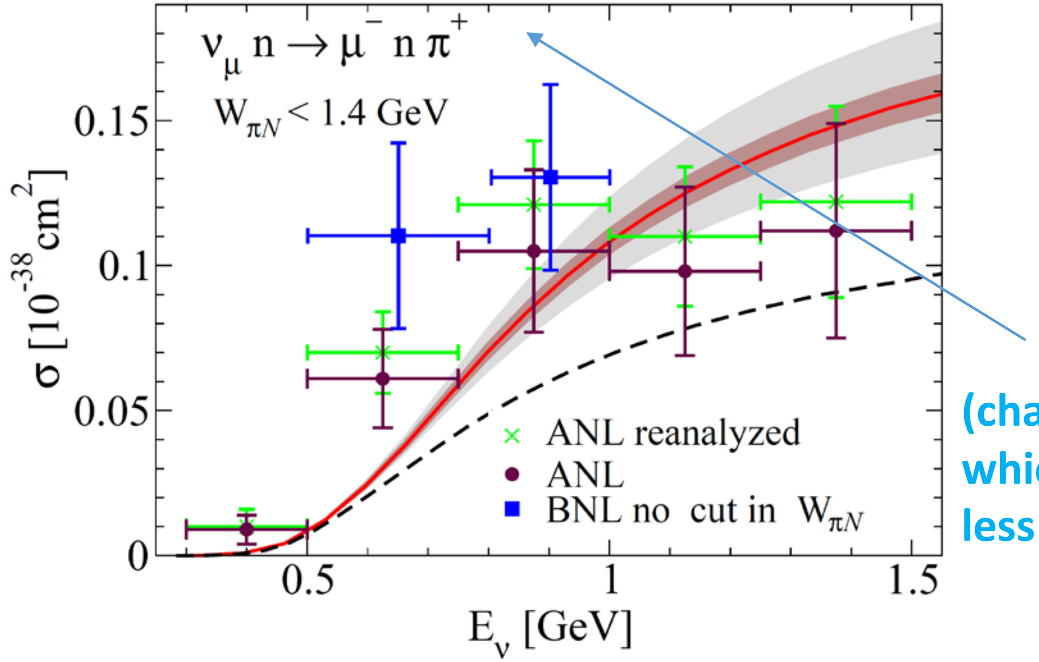
+ crossing symmetry+ N(1520)
+ phenomenological q^2 form-factors

Hernández+ JN+Valverde PRD76 (2007) 033005
PRD81 (2010) 085046 (deuteron effects in data)
PRD93 (2016) 014016 (Watson's theorem)
PRD95 (2017) 053007 (local terms and the $n\pi^+$channel)
PRD98 (2018) 073001 (comparison DCC model, T. Sato et al)

pion neutrino-production off nucleons







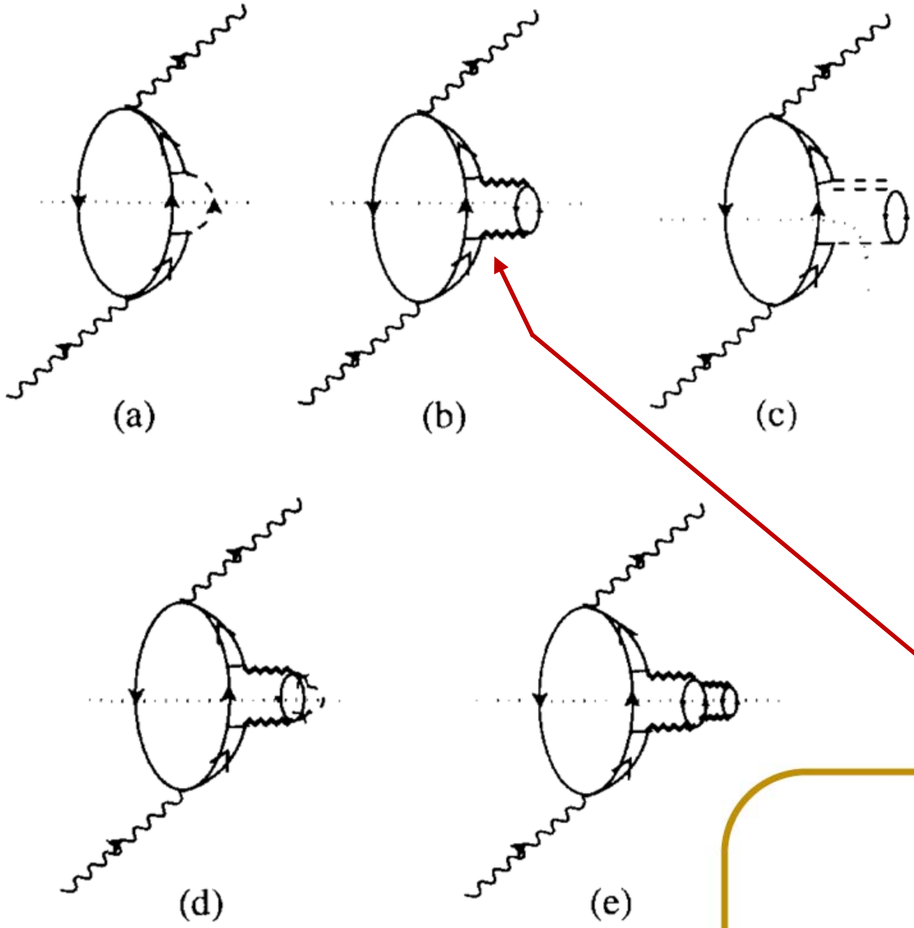
(channel for which the Δ is less dominant)

perfect agreement with the PCAC prediction ~1.2

$$C_5^A(q^2) = \underbrace{C_5^A(0)/(1-q^2/M_{A\Delta}^2)^2}$$

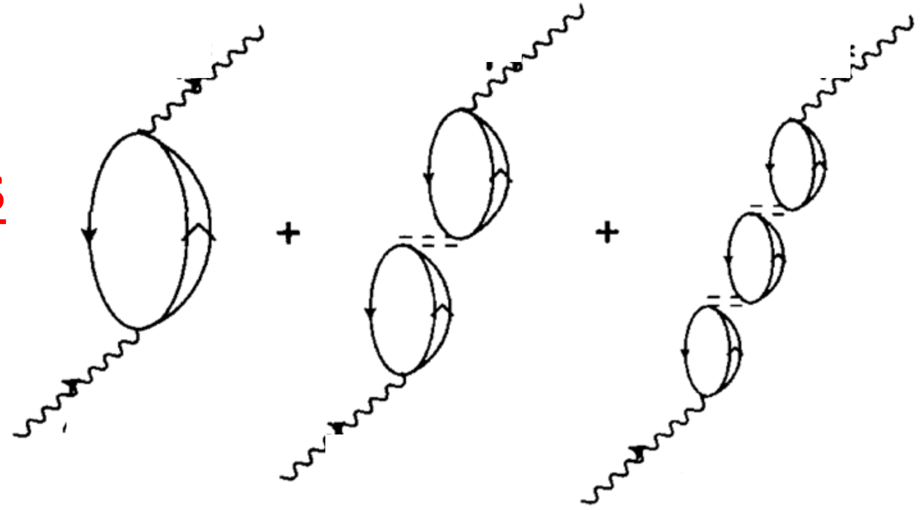
$C_5^A(0)=1.18\pm0.07$ $M_{A\Delta}=950\pm60$ MeV

(dominant WNΔ axial coupling)

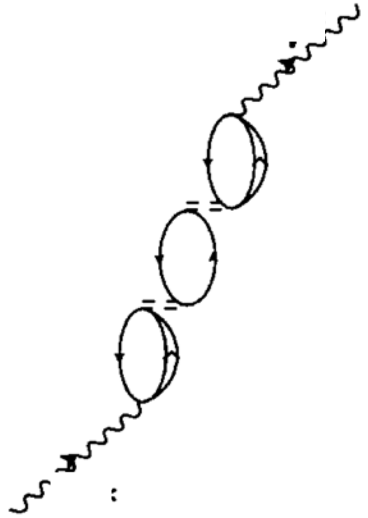


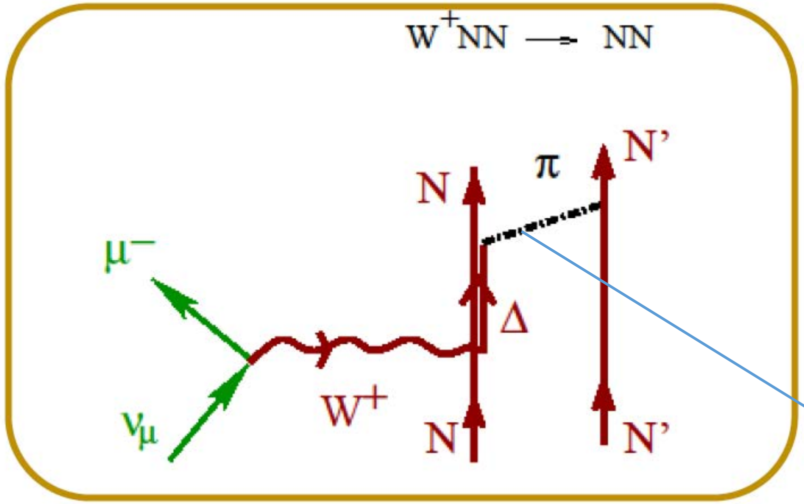
nuclear corrections

- Pauli blocking
- many body Δ decay modes: $\Delta N \to NN$
- RPA
- .....



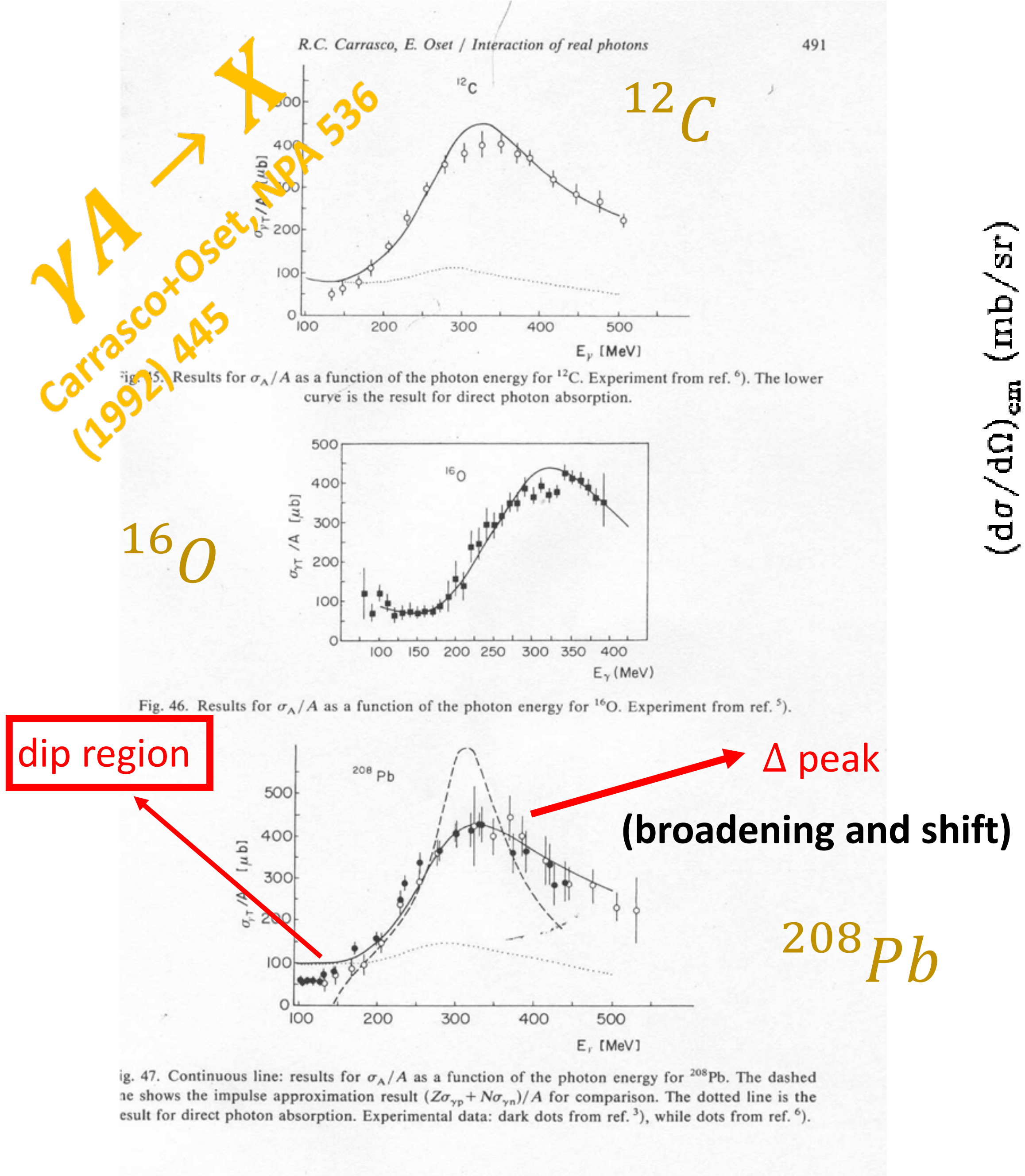
RPA corrections driven by an effective in medium ph-ph, ph-Δh and Δh-Δh interaction that includes SRC





Δ-selfenergy
Oset+Salcedo
NPA 468 (1987) 631

VIRTUAL pion
not only π: $\pi + \rho + \mathrm{SRC} + \mathrm{RPA} + \cdots$
(Effective NN interaction in the medium)

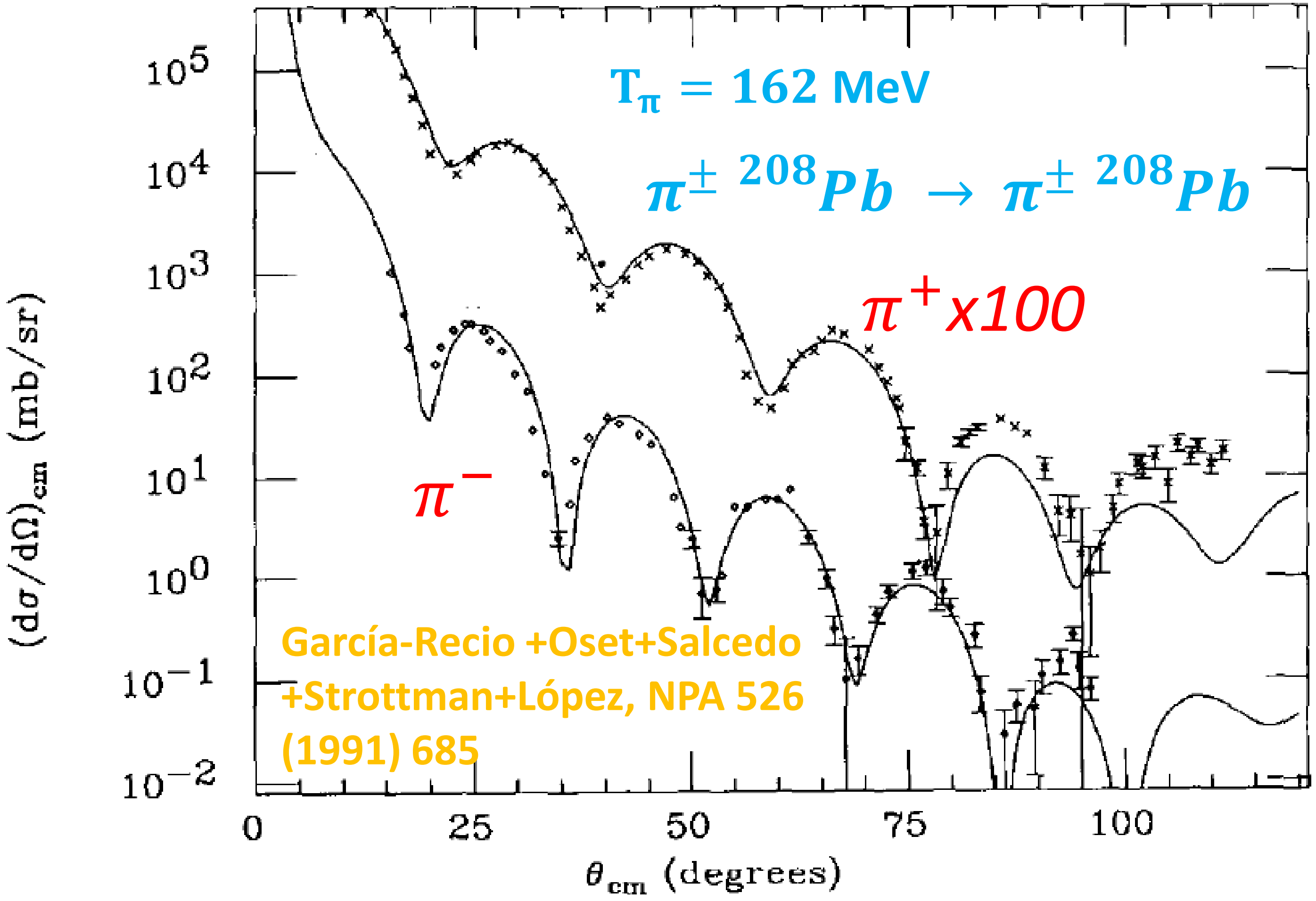


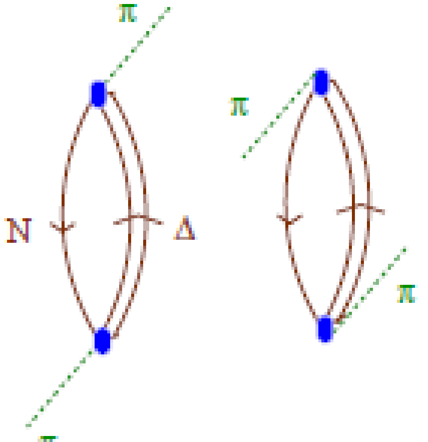
R.C. Carrasco, E. Oset / Interaction of real photons 491

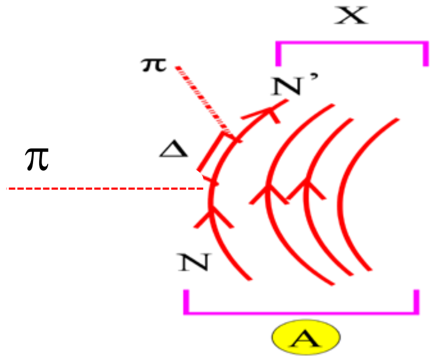
Fig. 45. Results for σ_A/A as a function of the photon energy for ^{12}C. Experiment from ref. [6]). The lower curve is the result for direct photon absorption.

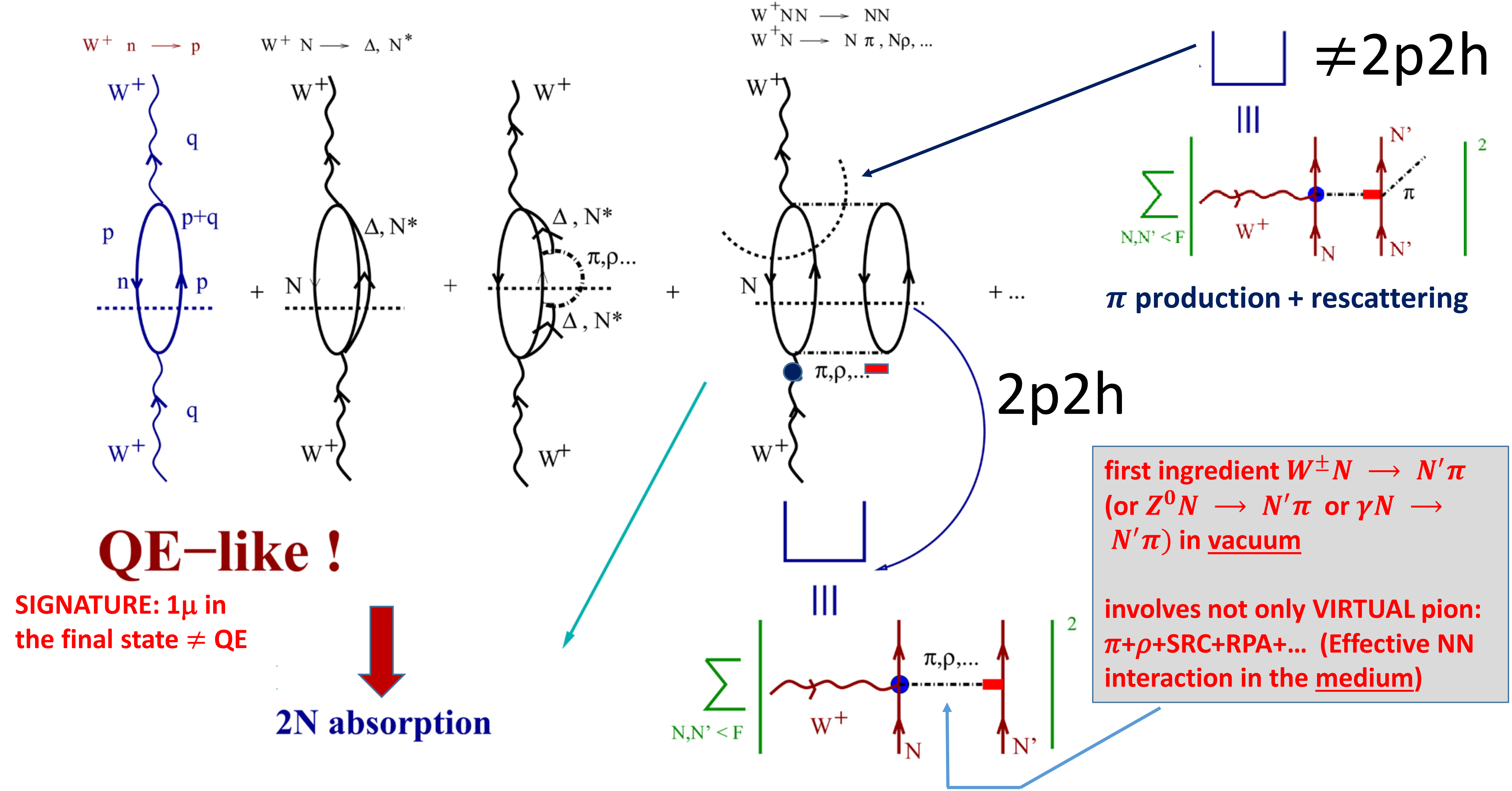
Fig. 46. Results for σ_A/A as a function of the photon energy for ^{16}O. Experiment from ref. [5]).

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]).



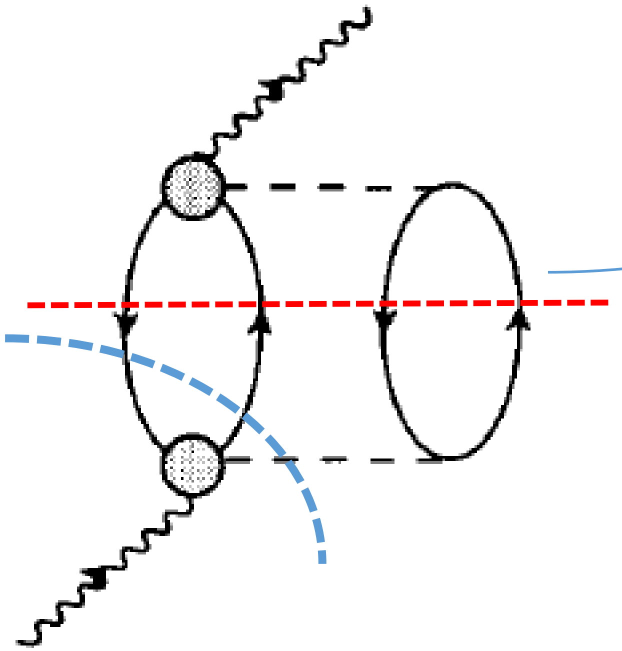


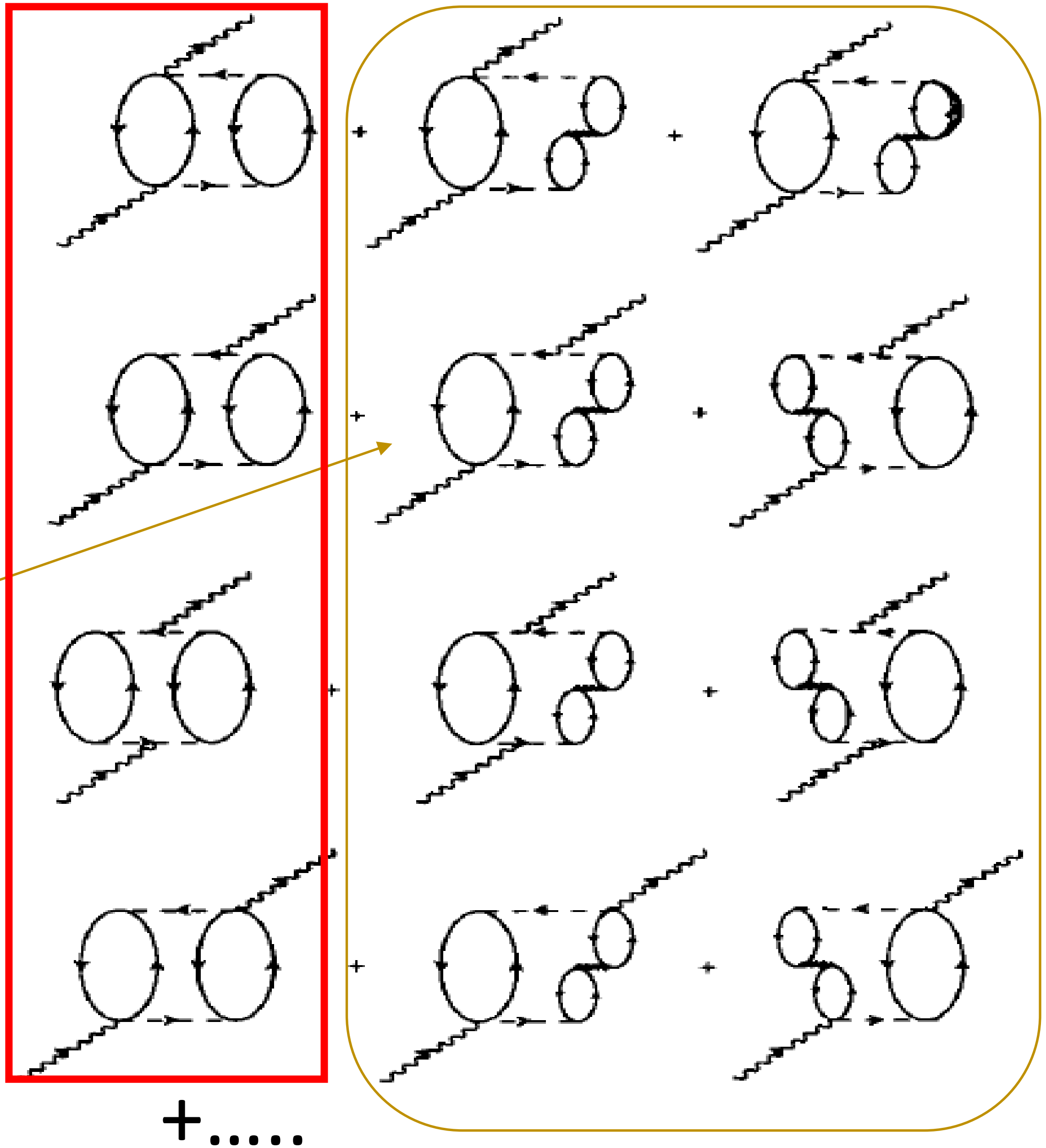




nuclear effect: populates the dip region and not dominated by the $\Delta(1232)$ driven mechanisms

2p2h (two body absorption) contributions





+.....

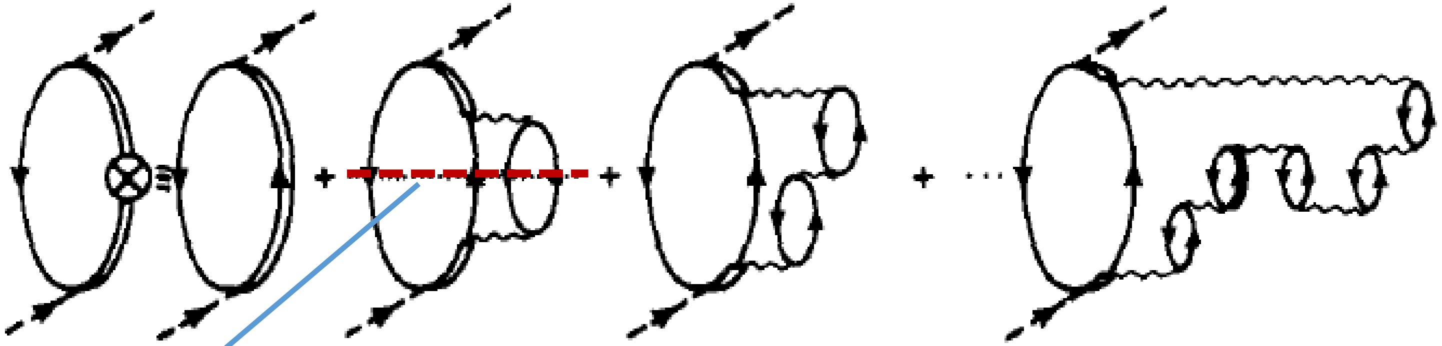
RPA corrections to 2p2h contributions

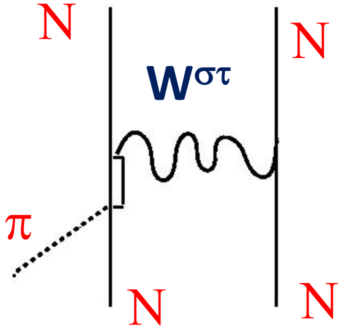
Two cuts: $\gamma^* NN \rightarrow NN$

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

Gil+Nieves+Oset.,NPA 627 (1997) 543 (extension of Carrasco+Oset NPA 536 (1992) 445 for real photons)

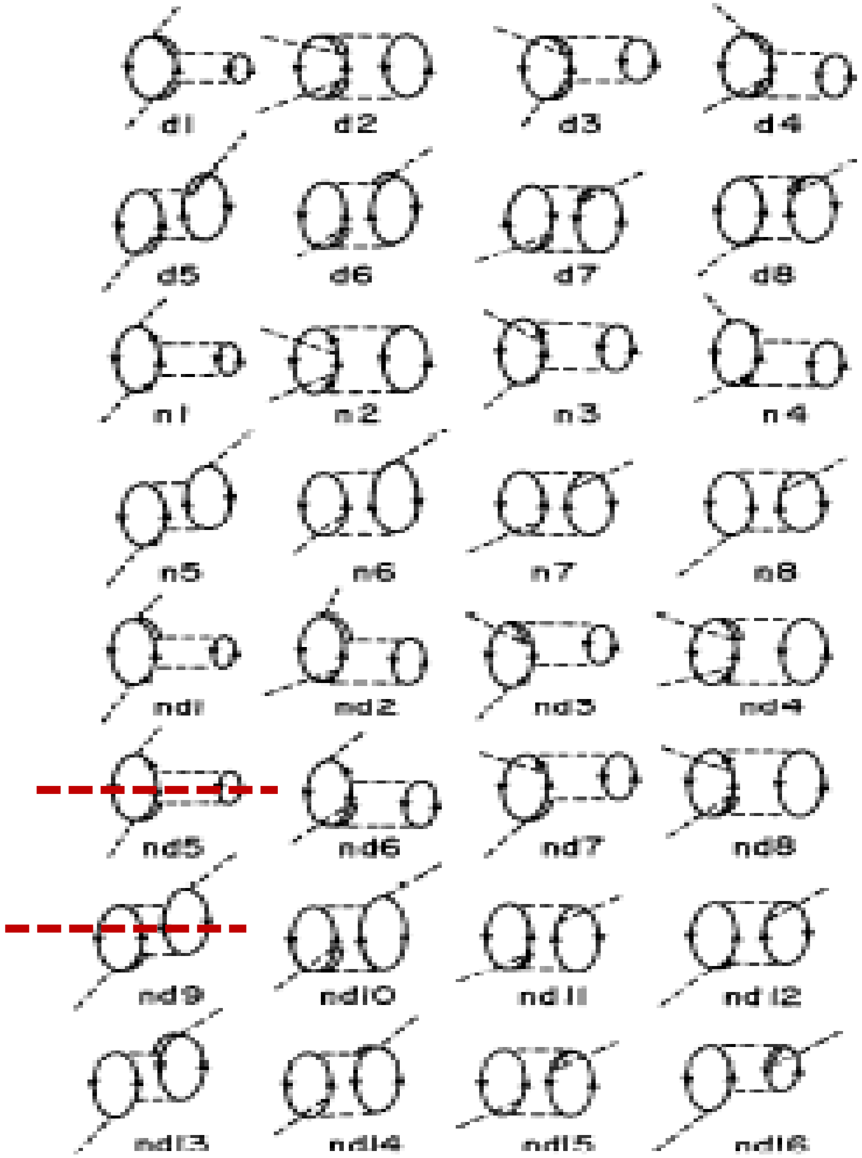
This work is the natural extension of previous work (1985-1993) in pion physics





$\pi NN \rightarrow NN$

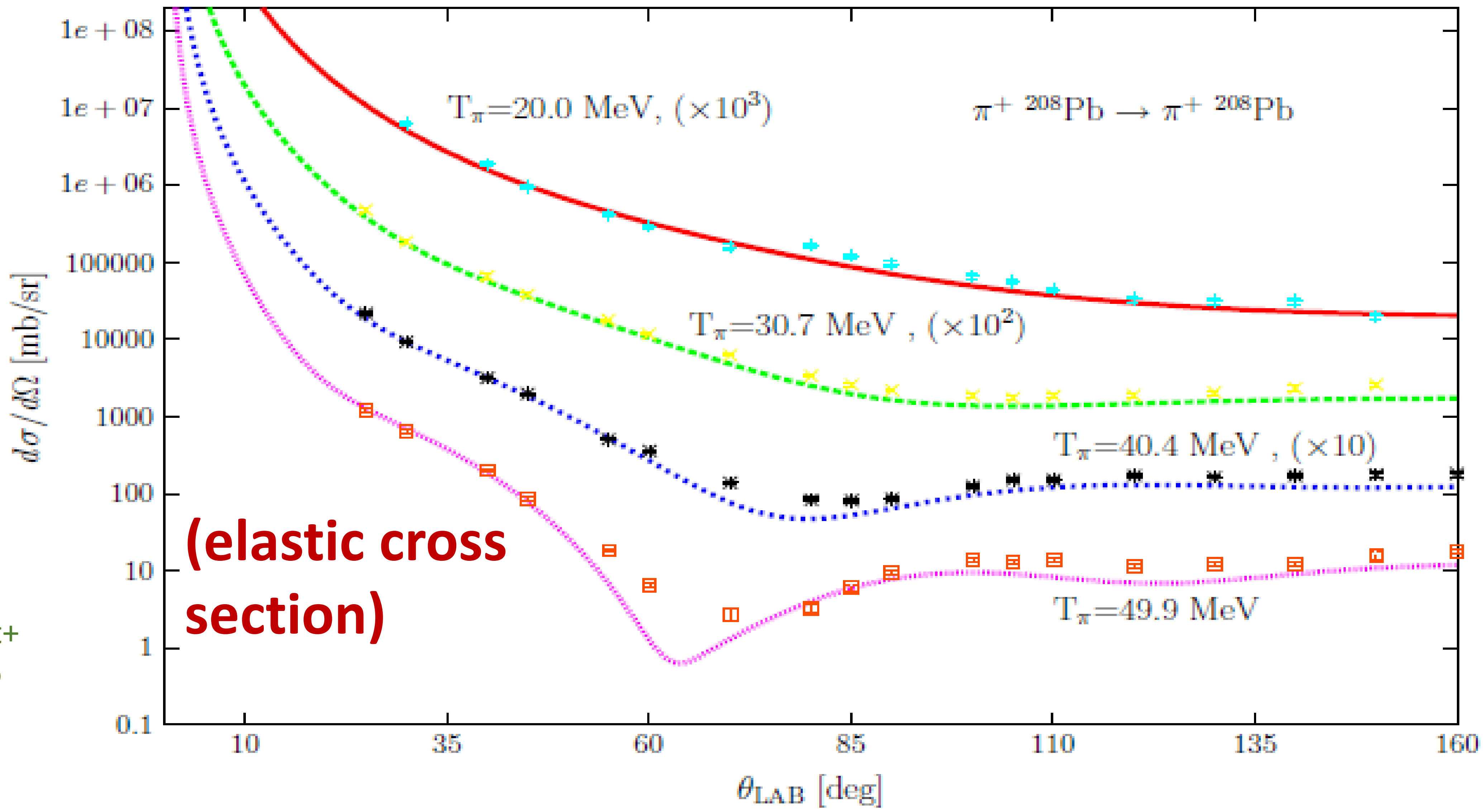
2p2h



$$2\omega V_1^{(s)}(\boldsymbol{r}) = -4\pi[(1+\varepsilon)(b_0+\Delta b_0(\boldsymbol{r}))f(T)\rho + (1+\varepsilon)b_1(\rho_n-\rho_p) + i(\mathrm{Im}\,B_0\,(1+\tfrac{1}{2}\varepsilon)2(\rho_p^2+\rho_p\rho_n) + \mathrm{Im}\,B_0^Q(T)(1+\tfrac{1}{2}\varepsilon)\rho^2)]$$

$$2\omega V_{\mathrm{opt}}^{(p)}(\boldsymbol{r}) = 4\pi\frac{M_N}{s}\left[\nabla\frac{P(\boldsymbol{r})}{1+4\pi g' P(\boldsymbol{r})}\nabla - \tfrac{1}{2}\varepsilon\Delta\left(\frac{P(\boldsymbol{r})}{1+4\pi g' P(\boldsymbol{r})}\right)\right]$$

$\pi^{\pm}$ − nucleus reactions at low energies

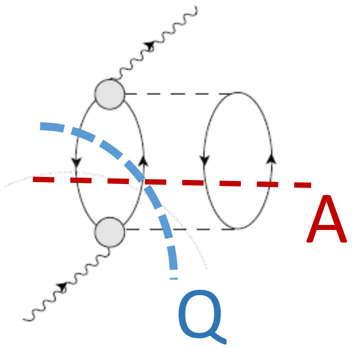


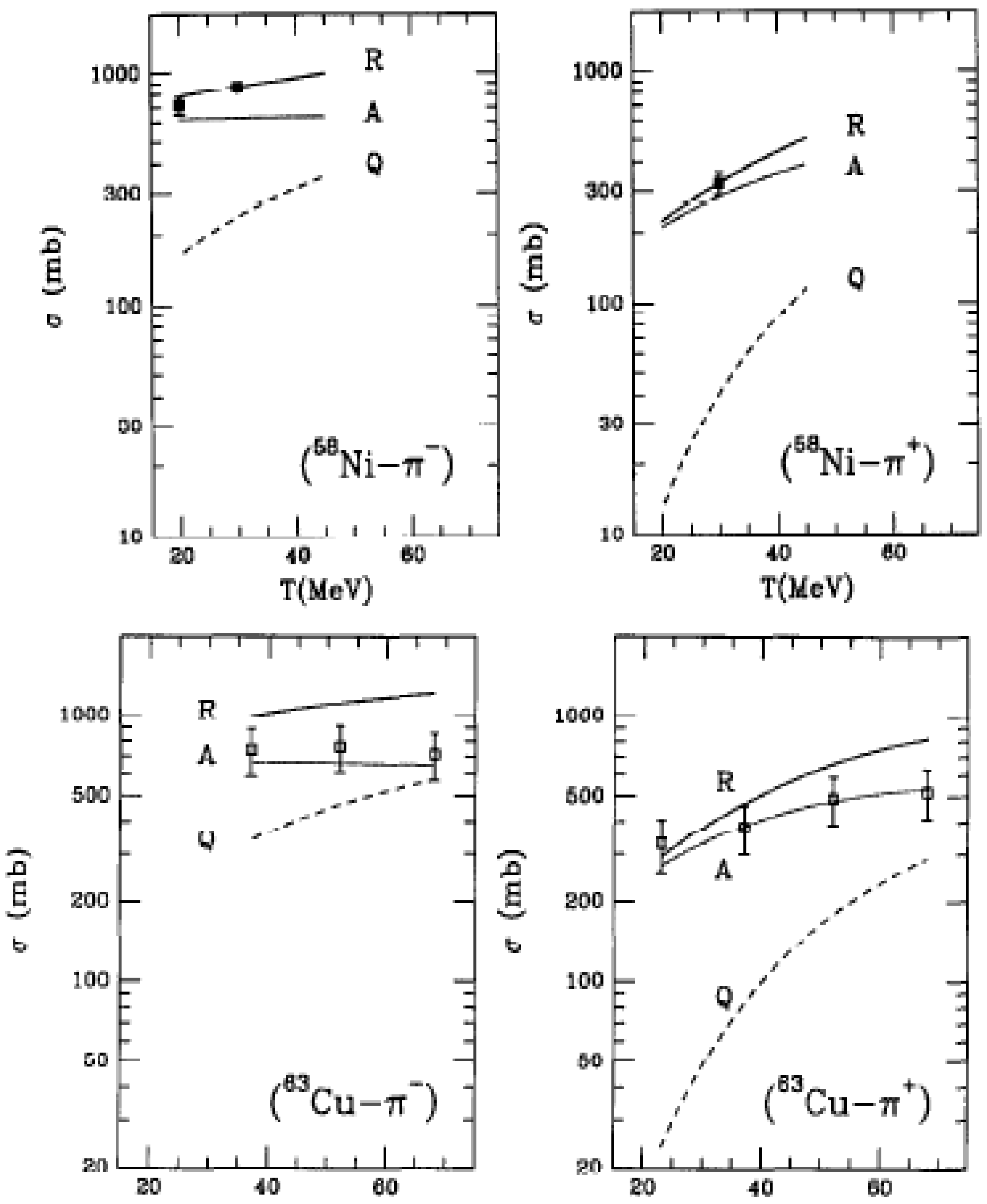
Nieves+Oset+
García-Recio
NPA 554
(1993) 554

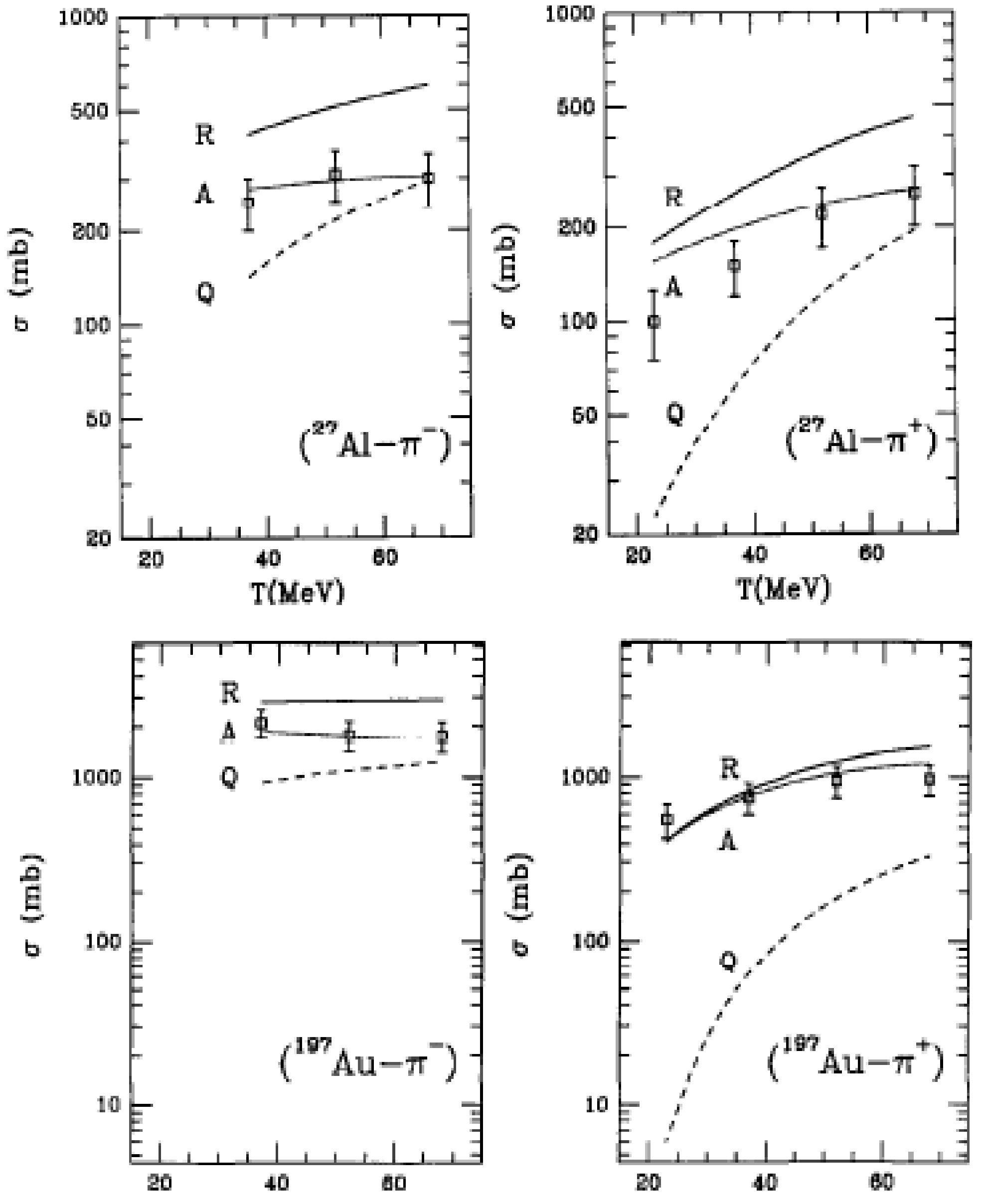
pions at these energies are non-resonant [kinetic energies well below production of $\Delta(1232)$]

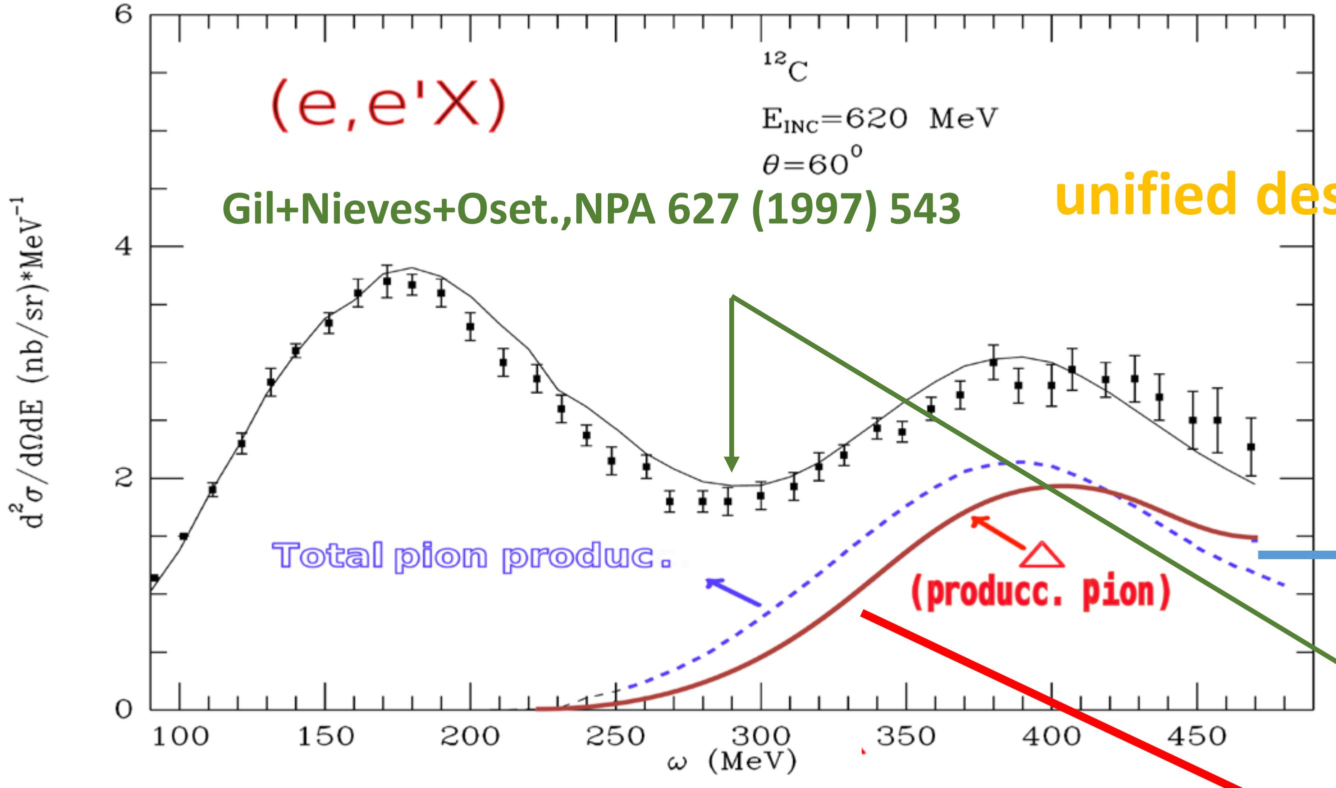
Absorption + Quasielastic= Reaction cross section

Q= pions which have changed either charge, energy or momentum



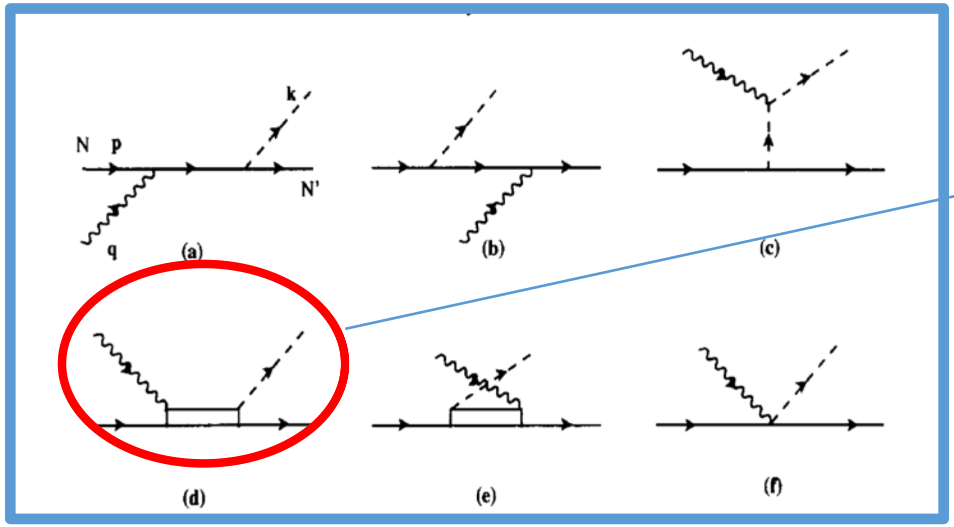




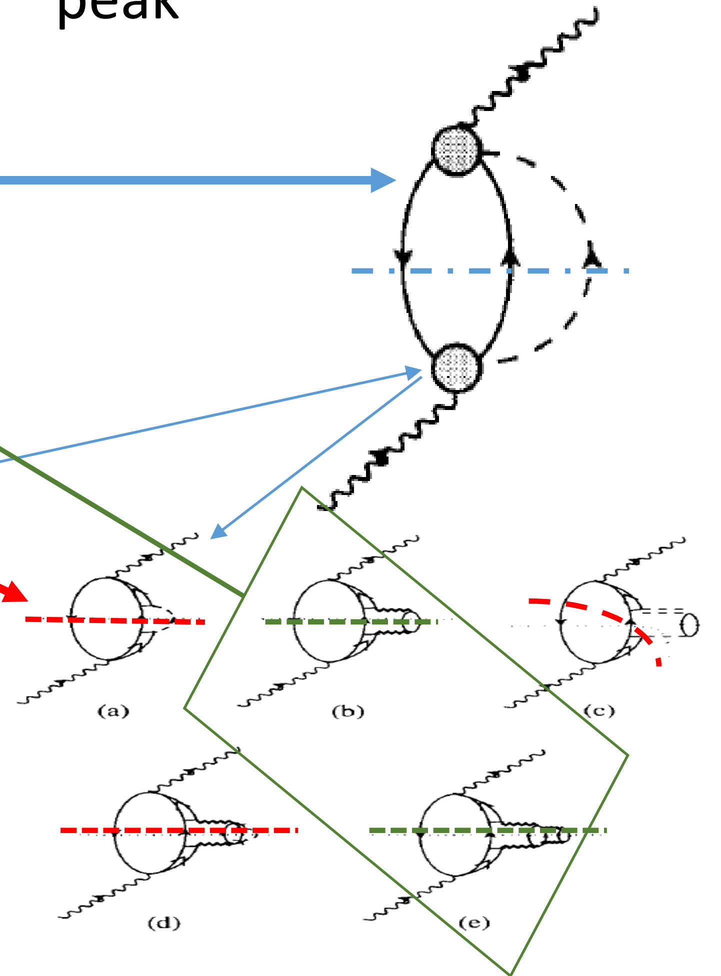


unified description

- 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

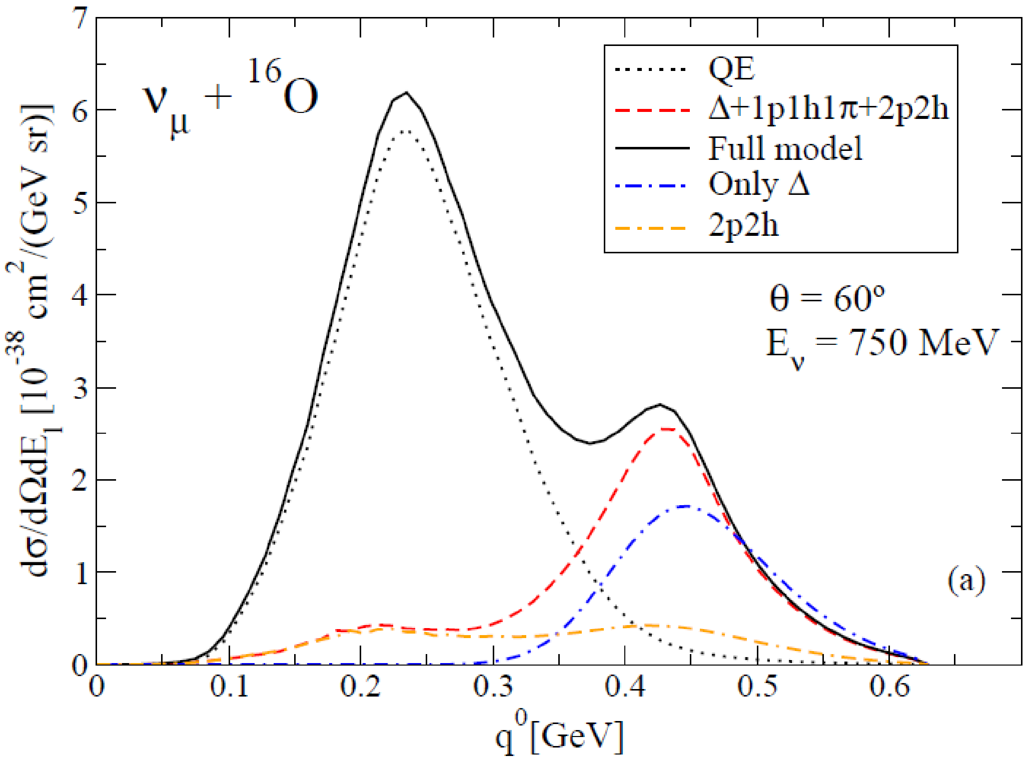


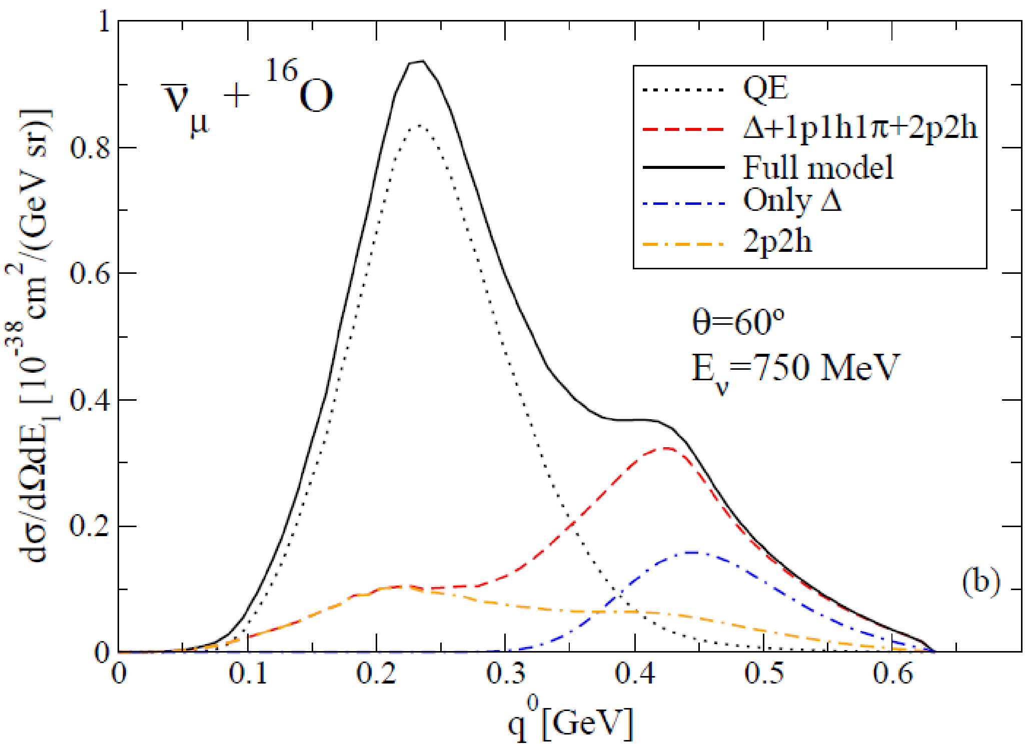
(ν_μ, μ^-) Results

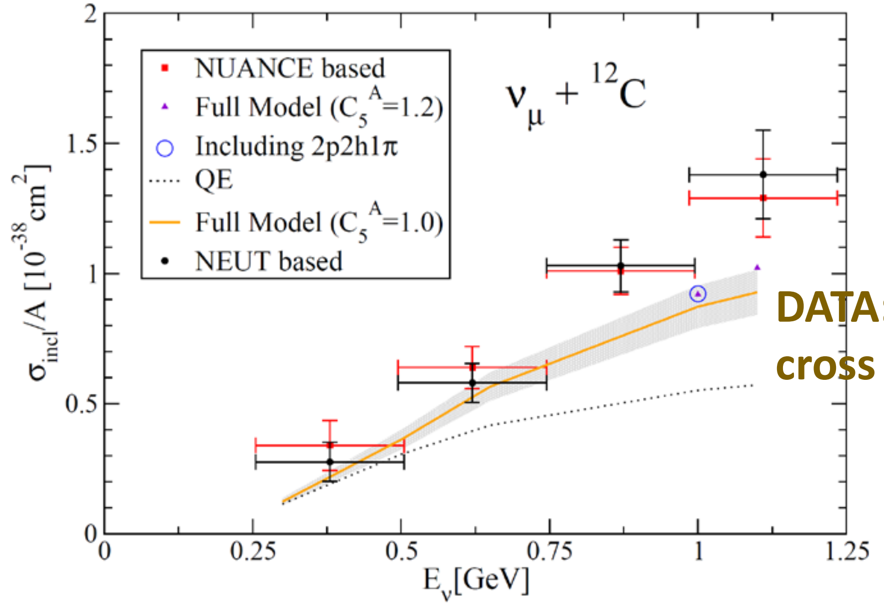
INCLUSIVE CROSS SECTION

PRC 83 (2011) 045501 [M_A= 1.049 GeV]

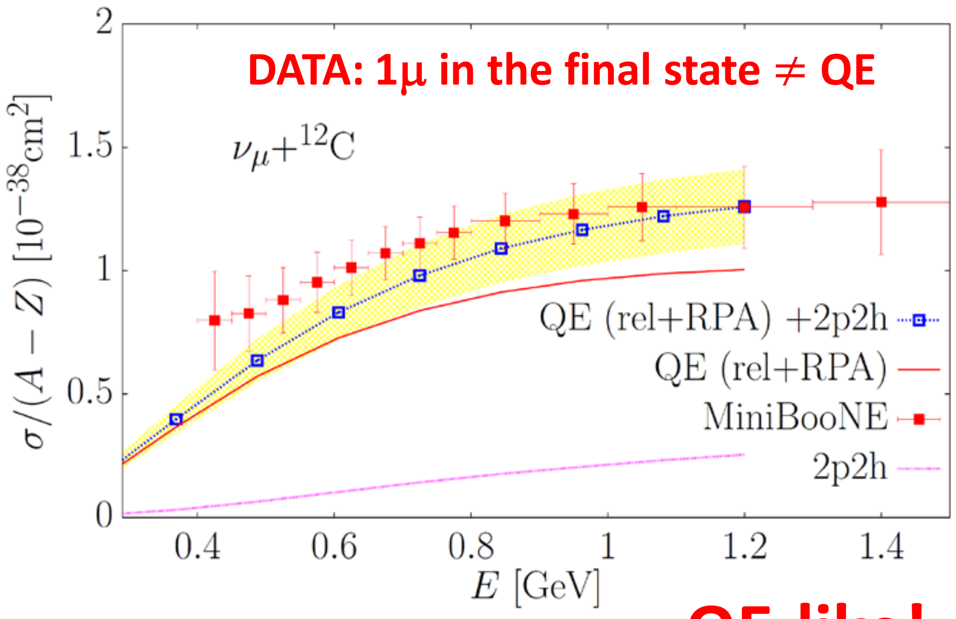
MICROSCOPIC MODEL: PREDICTIONS (NO FITTED PARAMETERS) FROM THE QE to the Δ PEAKS, INCLUDING THE DIP REGION







DATA: TOTAL inclusive cross section



DATA: 1μ in the final state ≠ QE

QE-like!

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**

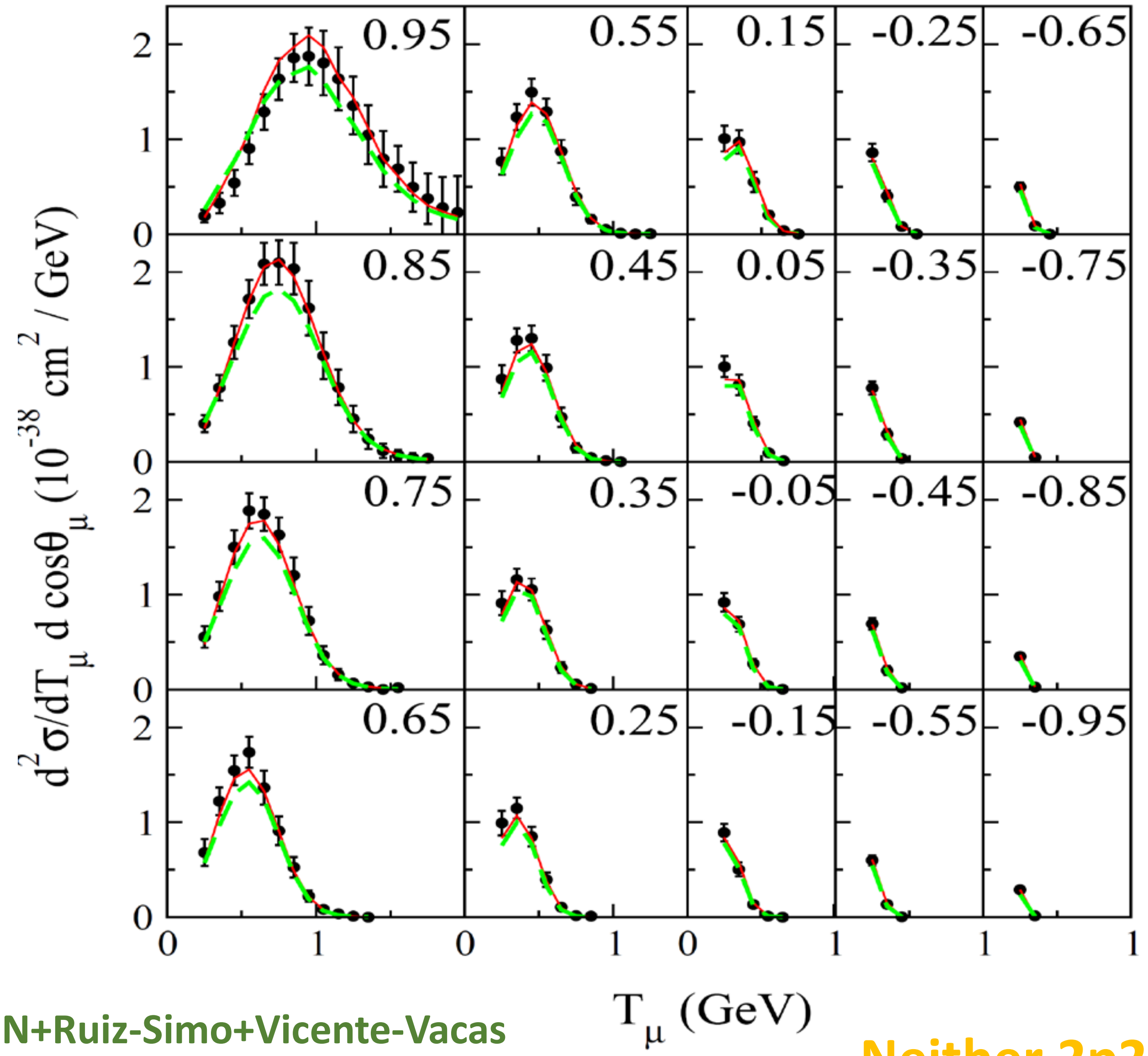
$$\chi^2 = \sum_{i=1}^{137} \left[\frac{\lambda \left(\frac{d^2\sigma^{exp}}{dT_\mu d\cos\theta}\right)_i - \left(\frac{d^2\sigma^{th}}{dT_\mu d\cos\theta}\right)_i}{\lambda\Delta\left(\frac{d^2\sigma}{dT_\mu d\cos\theta}\right)_i} \right]^2 + \left(\frac{\lambda-1}{\Delta\lambda}\right)^2,$$

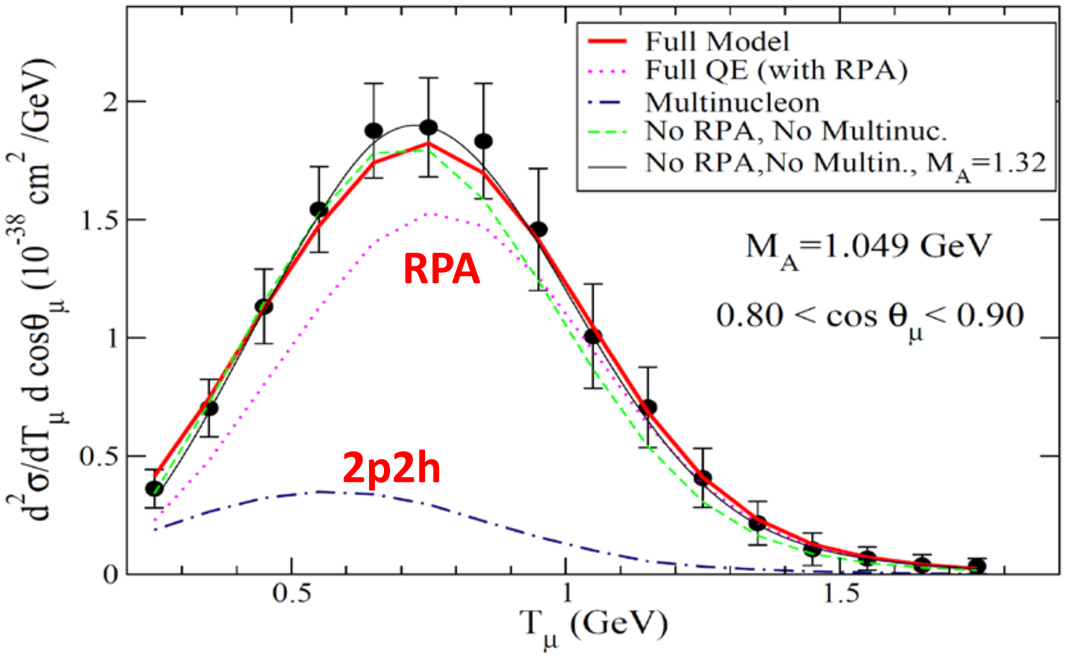
that takes into account the global normalization uncertainty ($\Delta\lambda = 0.107$) claimed by the MiniBooNE collaboration.

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)	$\frac{\chi^2}{\#bins}$
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

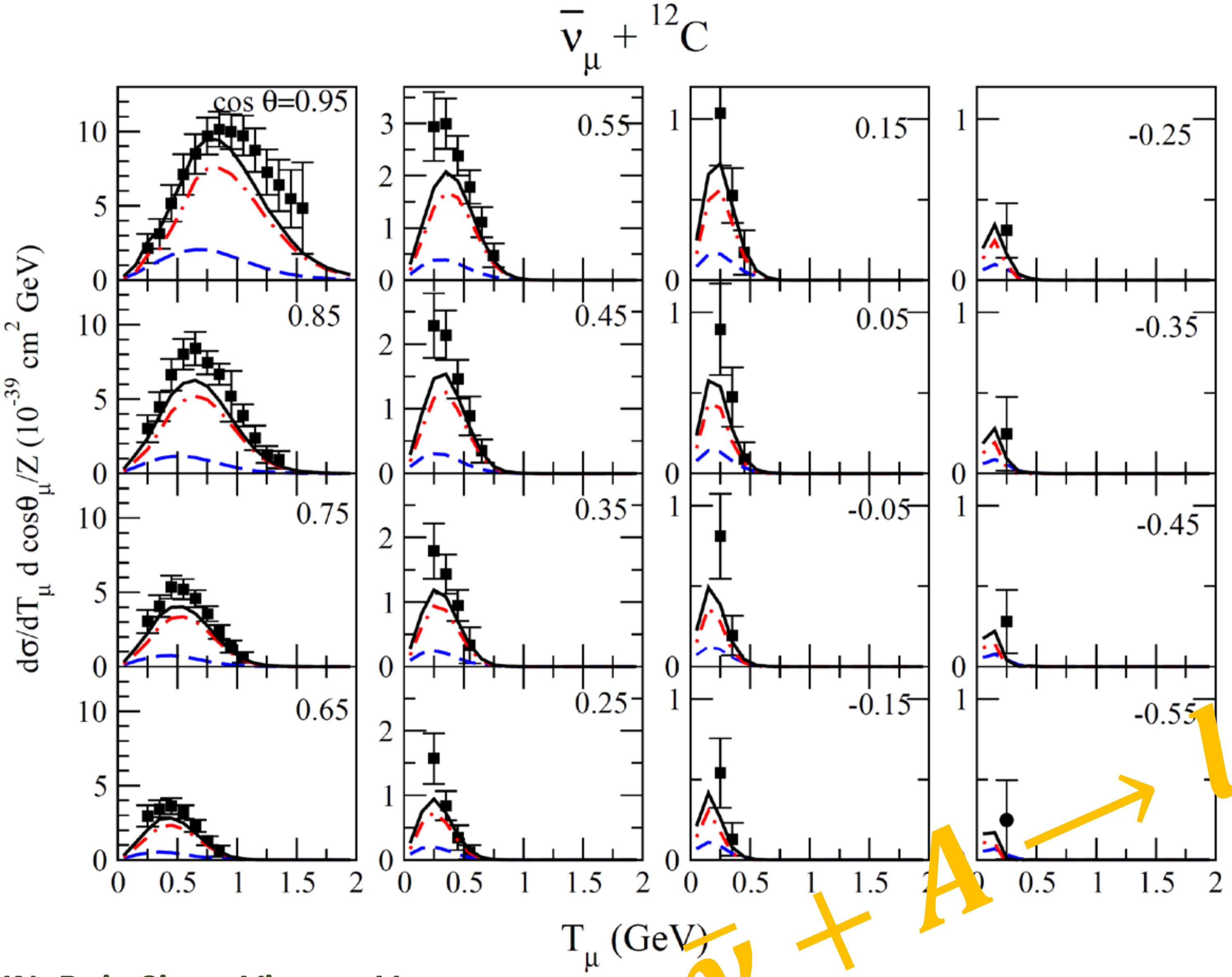
MB estimate of total normalization error 10.7%

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

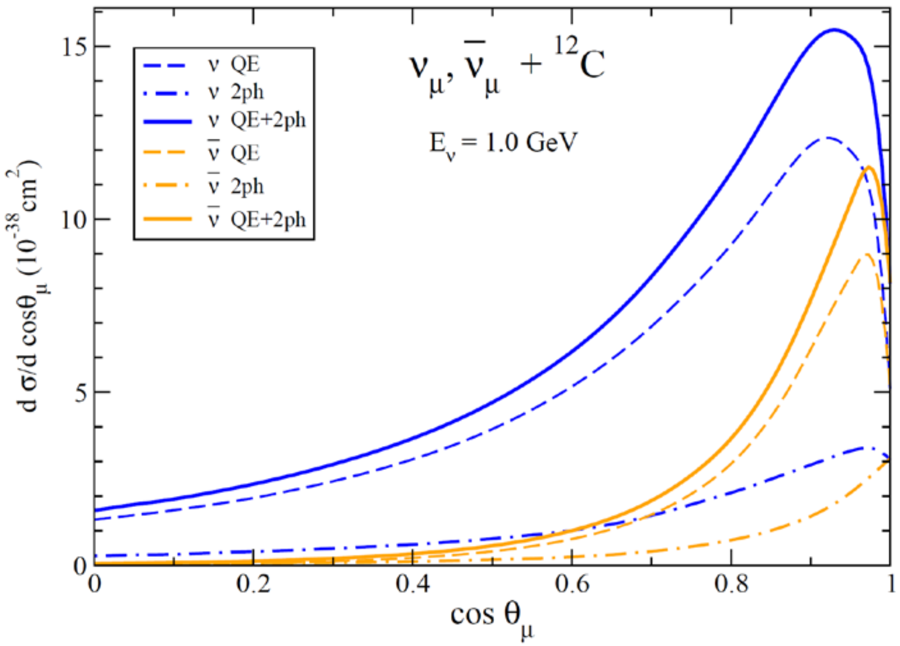
JN+Ruiz-Simo+Vicente-Vacas
PLB 707 (2012) 72

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

$M_A \sim 1.03$ GeV

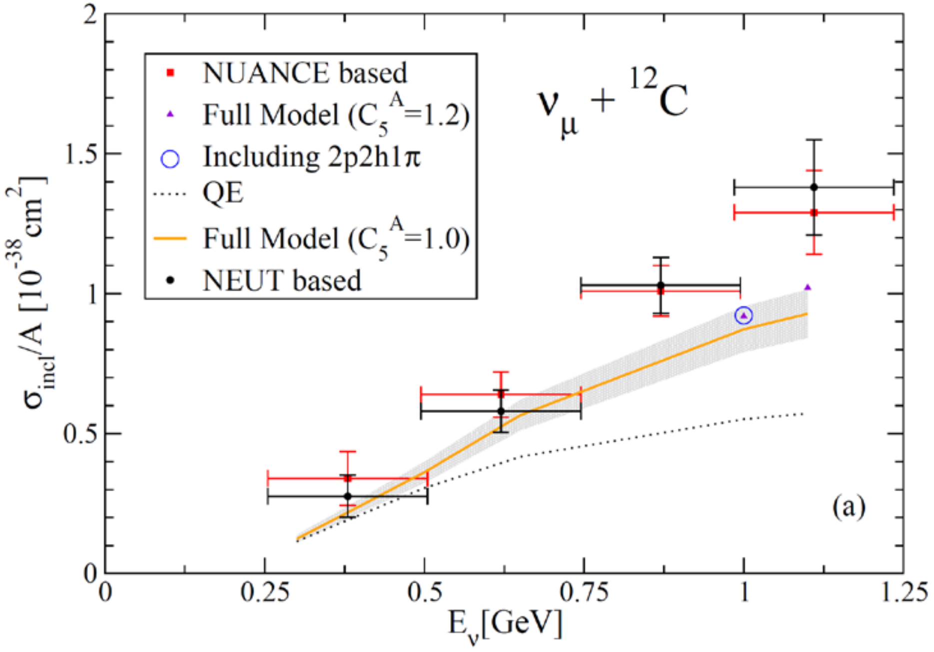


$\bar{\nu} + A \rightarrow l + X$



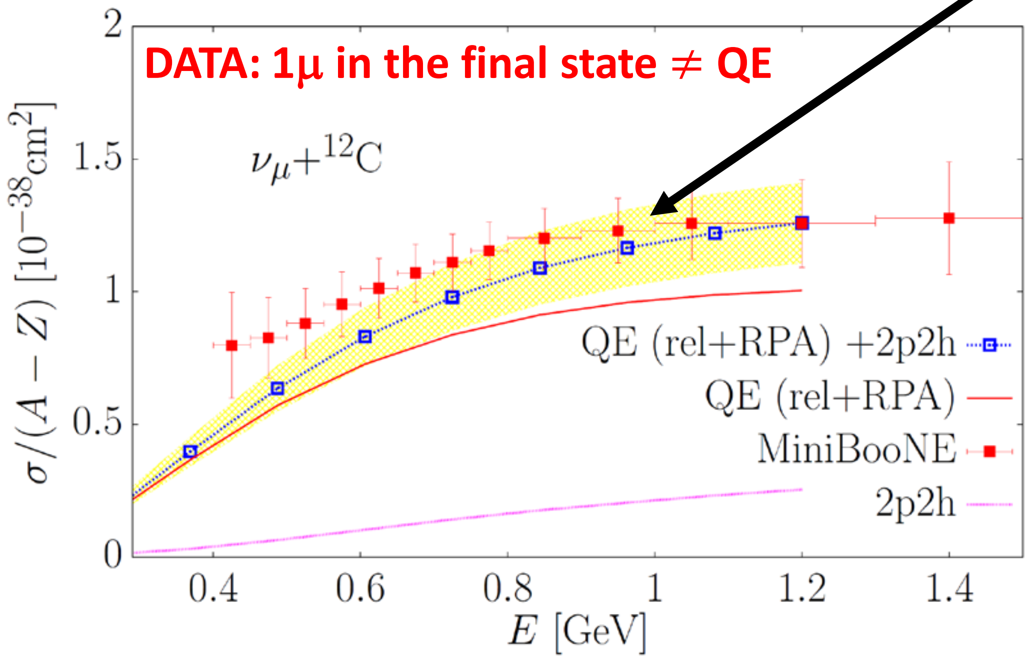
- **Antineutrino distributions are more forward peaked**
- **Relative importance of 2p2h contributions in ν and $\bar{\nu}$ are similar**

JN+Ruiz-Simo+Vicente-Vacas
Phys.Lett.B 721 (2013) 90



Inclusive

some discrepancies between QE+2p2h and MiniBooNE flux-unfolded cross section caused by the **neutrino energy reconstruction procedure used to pass from flux-folded to flux-unfolded data**



MB neutrino and antineutrino 2D dataset is, however, reasonably described by the combination of both nuclear mechanisms

QE-like!

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!

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

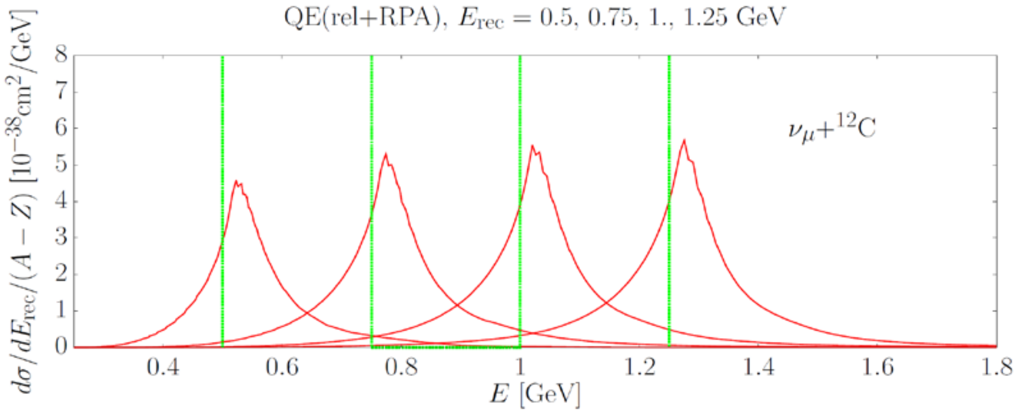
$P_{\rm rec}(E_{\rm rec})$ is the *pd* of measuring an event with reconstructed energy $E_{\rm rec}$. $P(E|E_{\rm rec})$ is, given an event of reconstructed energy $E_{\rm rec}$, the conditional *pd* of being produced by a neutrino of energy E.

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

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

given a true neutrino energy E, there is a distribution of reconstructed energies E_{rec} .....

QE

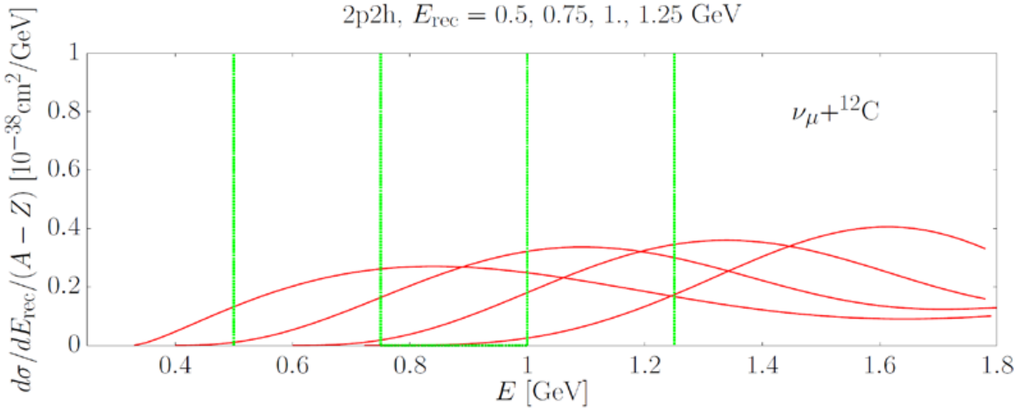


Neutrino Energy Reconstruction and the Shape of the CCQE-like Total Cross Section

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

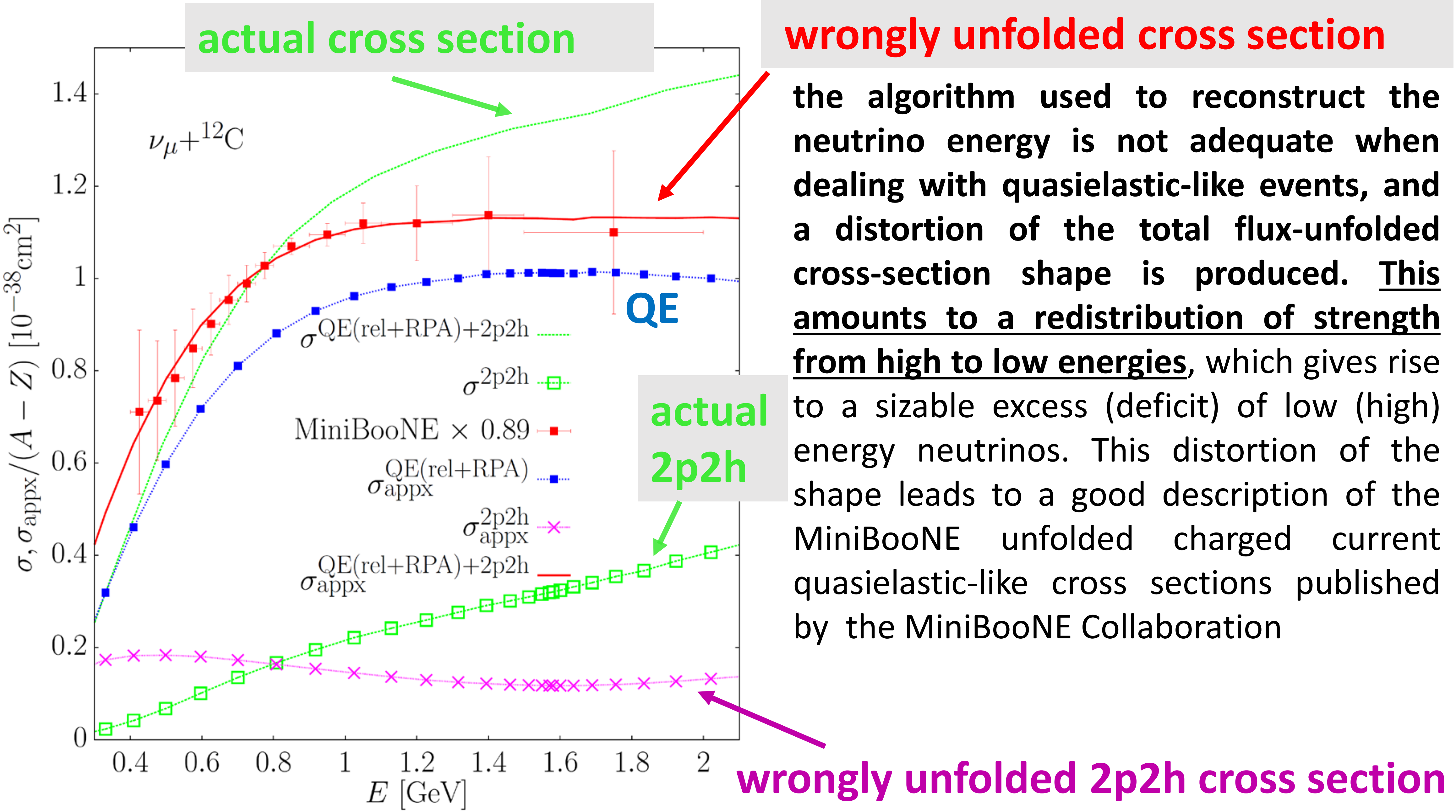
theory !

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



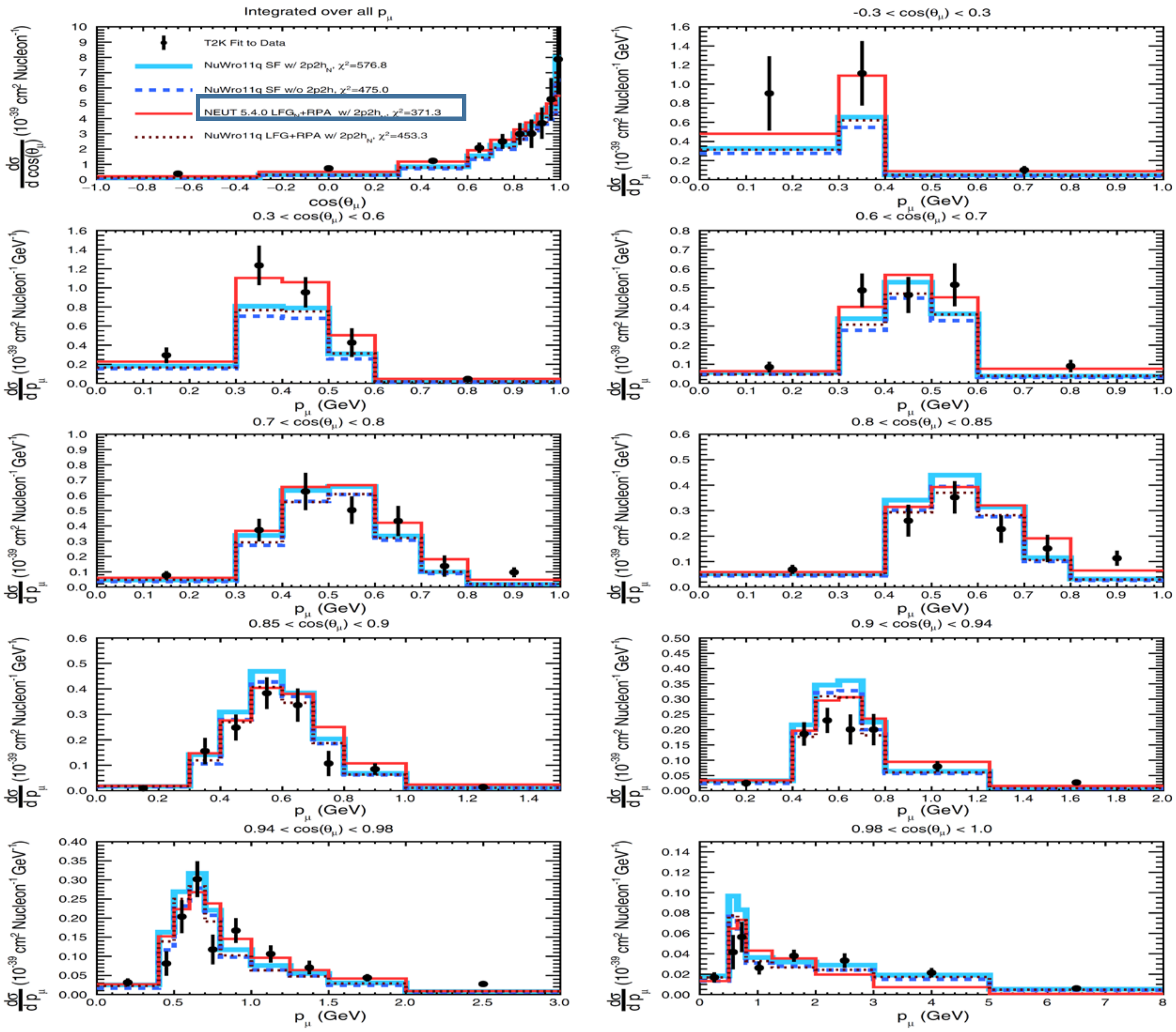
For each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose muon kinematics would lead to the given value of $E_{\rm rec}$.

2p2h



the algorithm used to reconstruct the neutrino energy is not adequate when dealing with quasielastic-like events, and a distortion of the total flux-unfolded cross-section shape is produced. <u>This amounts to a redistribution of strength from high to low energies</u>, which gives rise to a sizable excess (deficit) of low (high) energy neutrinos. This distortion of the shape leads to a good description of the MiniBooNE unfolded charged current quasielastic-like cross sections published by the MiniBooNE Collaboration

JN, F. Sánchez, I Ruiz-Simo, M.J. Vicente-Vacas PD85 (2012) 113008

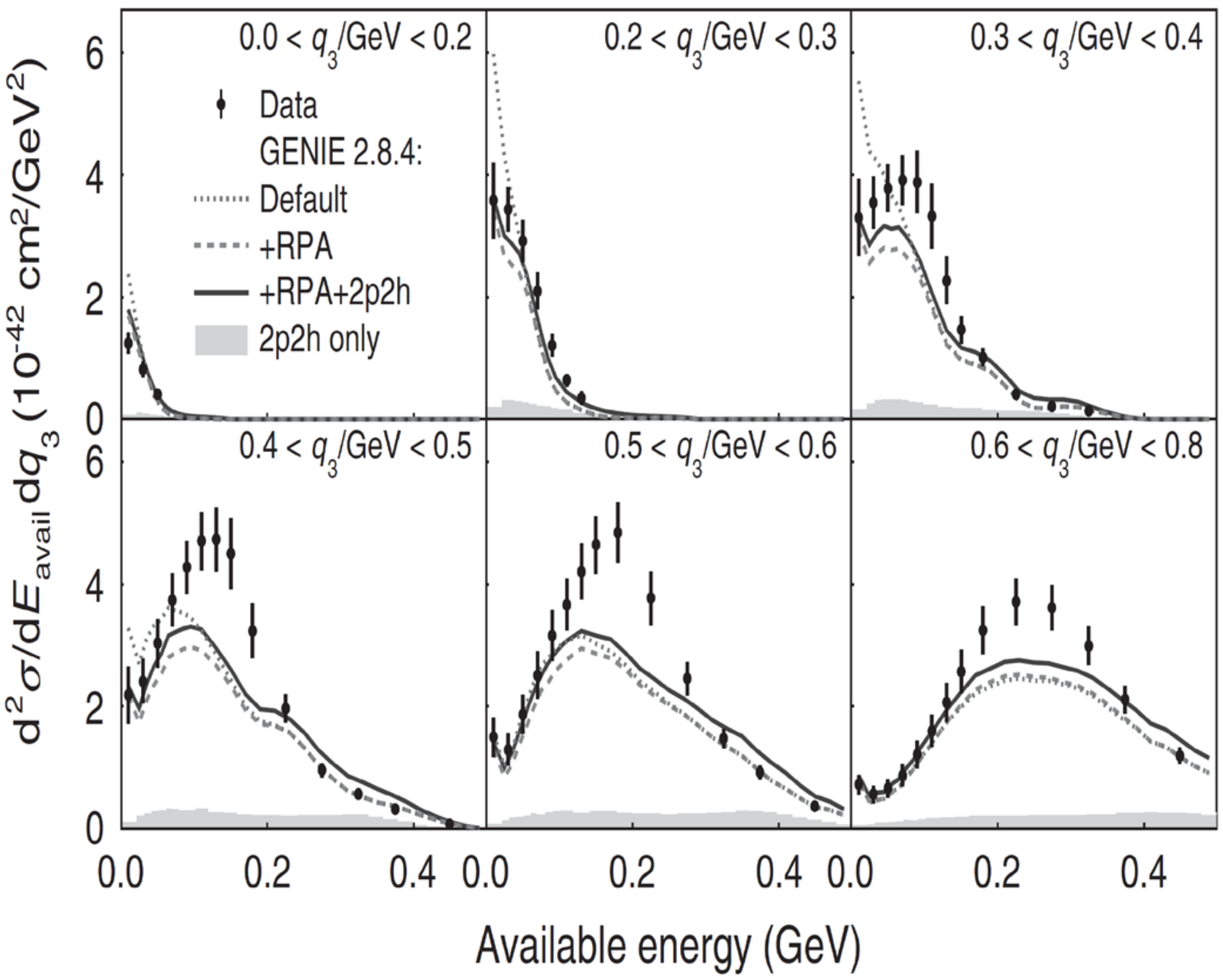


NEUT 5.4.0 LFG$_N$+RPA w/ 2p2h$_N$, χ^2=371.3

Measurement of the cross section as a function of the muon kinematics when there are no protons (with momenta above 500 MeV).

good agreement with T2K data!

T2K: PRD 98 032003 (2018)



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 (hadron calorimetry)

PRL 116, 071802 (2016)

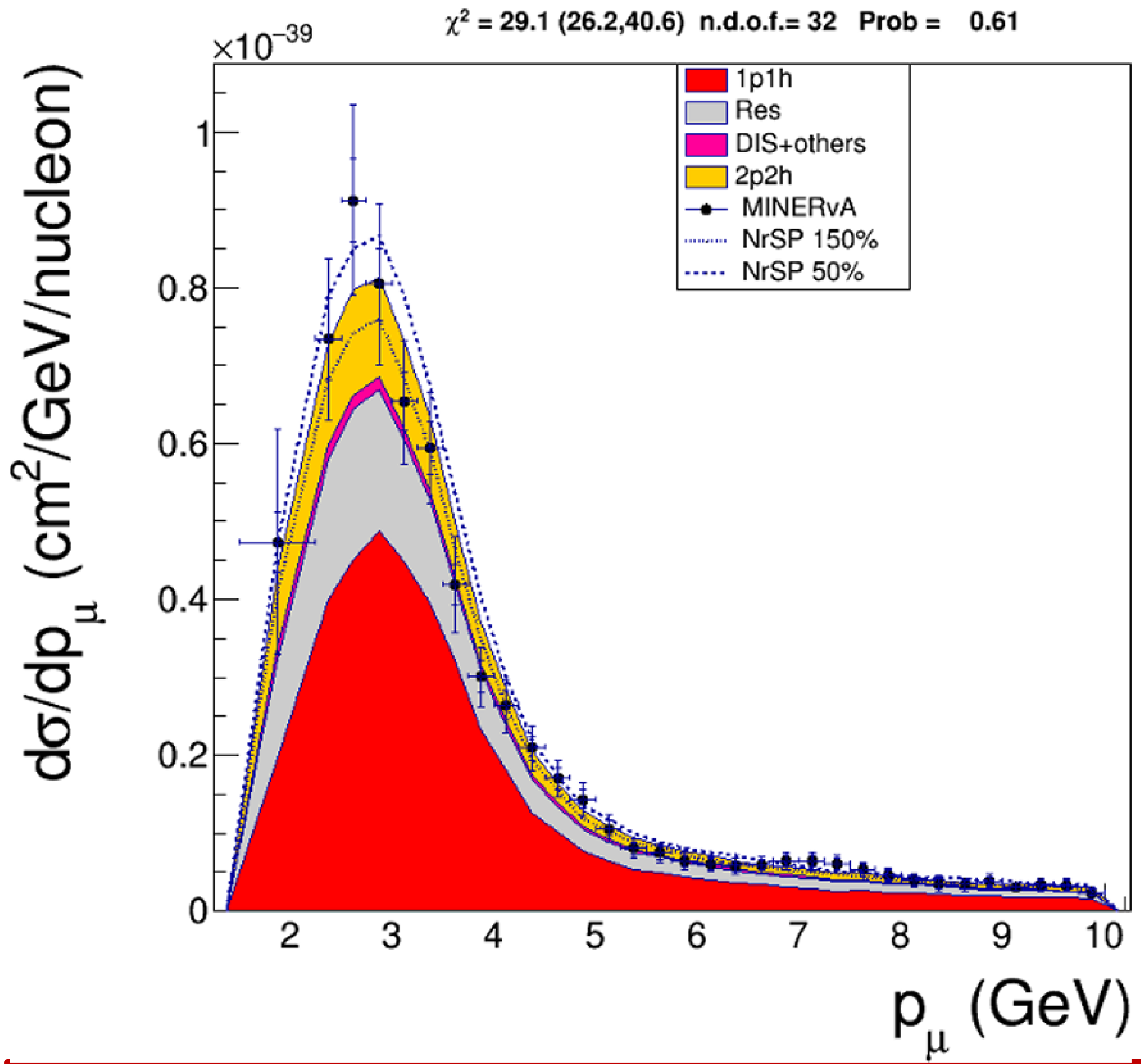
Hadronic energy spectrum: **The IFIC Valencia 2p2h model increases the predicted event rates, but not enough.** This process is increased further with an empirical enhancement based on MINERνA inclusive neutrino data. The additional events are from weighting up the generated 2p2h events according to a two-dimensional Gaussian in true q0, q3, whose six parameters are fit to the neutrino data version of these distributions. This enhancement adds 50% to the predicted 2p2h strength, but it targets the event rate in the kinematic region between the CCQE and Δ peaks where the rate doubles.

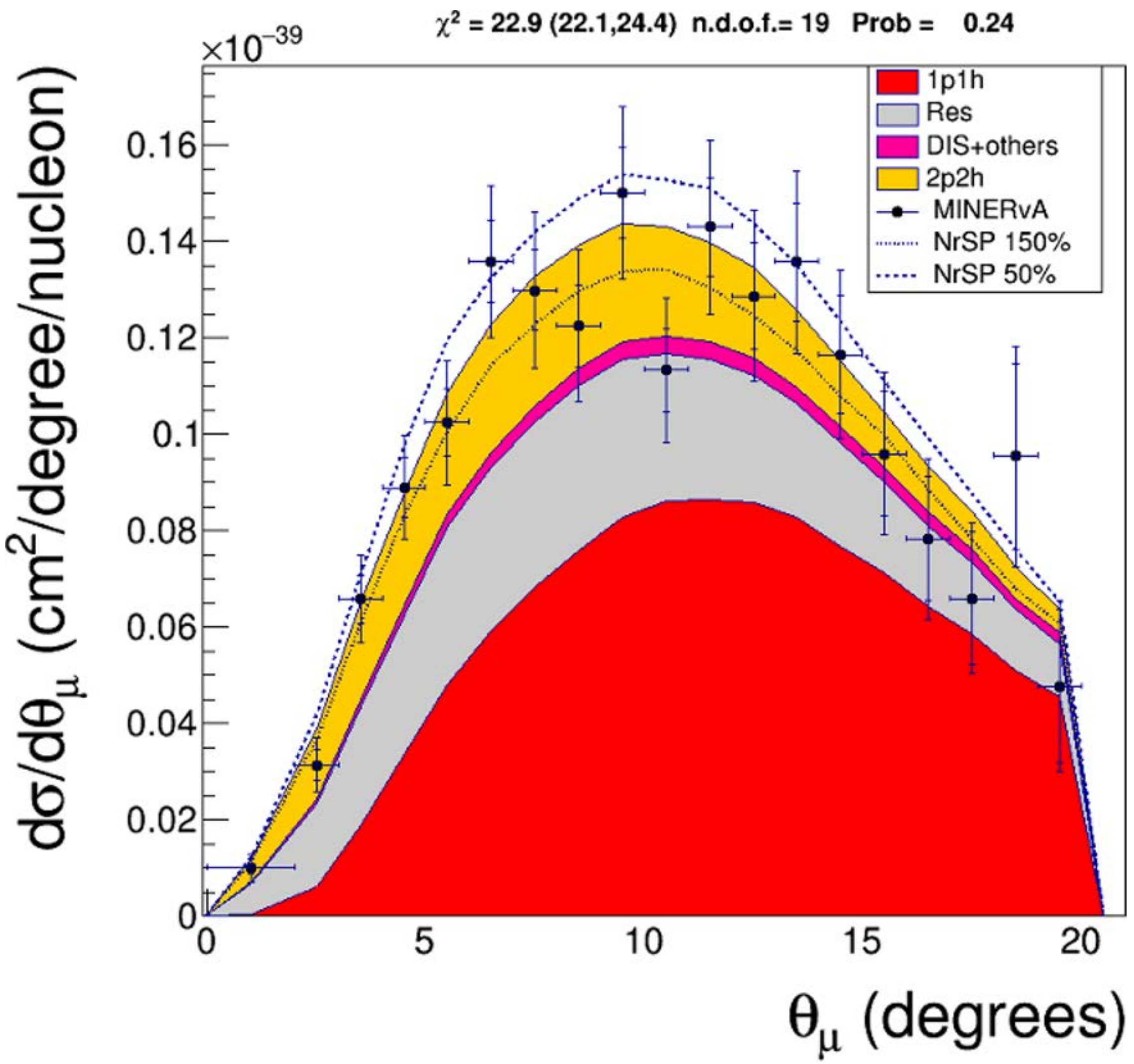
MINERνA (Antineutrino Charged-Current Reactions on Hydrocarbon with Low Momentum Transfer): PRL (2018) 221805

We therefore enhance the 2p2h prediction from the Nieves model in a specific region. Integrated overall phase space the rate of 2p2h is increased by 53%.

MINERνA (Measurement of Quasielastic-Like Neutrino Scattering at $\langle E_\nu \rangle \sim$ 3.5 GeV on a Hydrocarbon Target) Phys.Rev.D 99 (2019) 1, 012004

however……

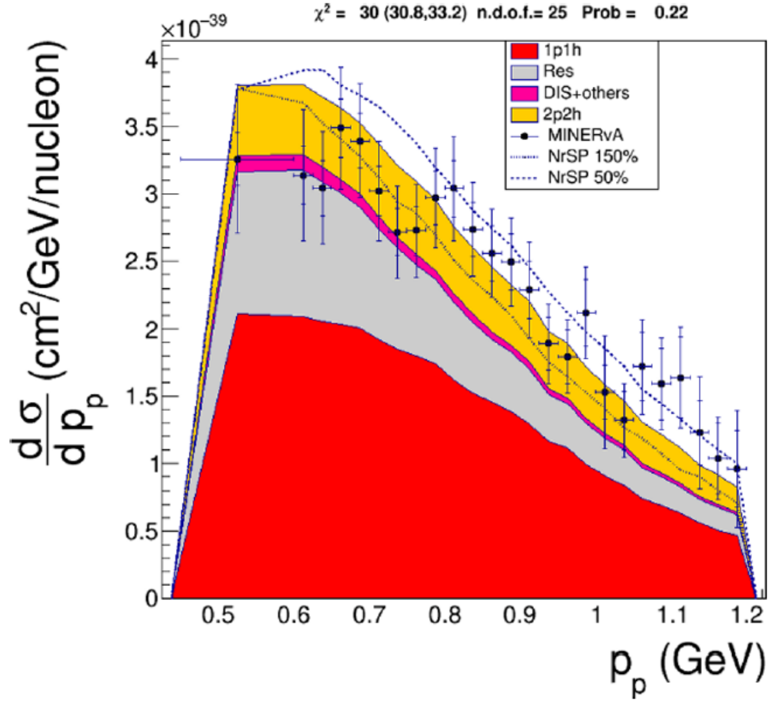


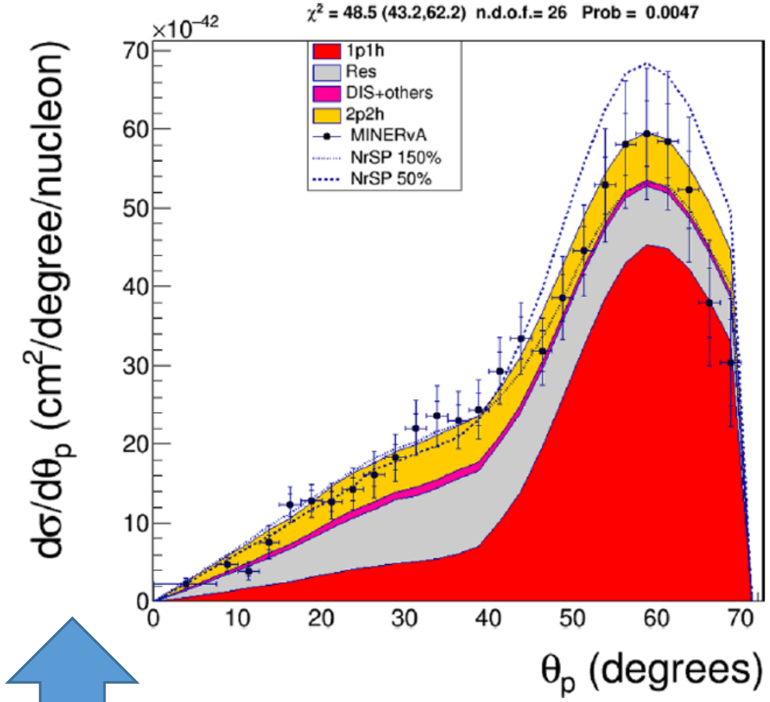


MINERνA CC0π1p

Bourguille B., Nieves J. and Sánchez F.: Inclusive and exclusive neutrino-nucleus cross sections and the reconstruction of the interaction kinematics, JHEP 04 (2021) 004 (results obtained with NEUT)

MINERνA CC0π1p



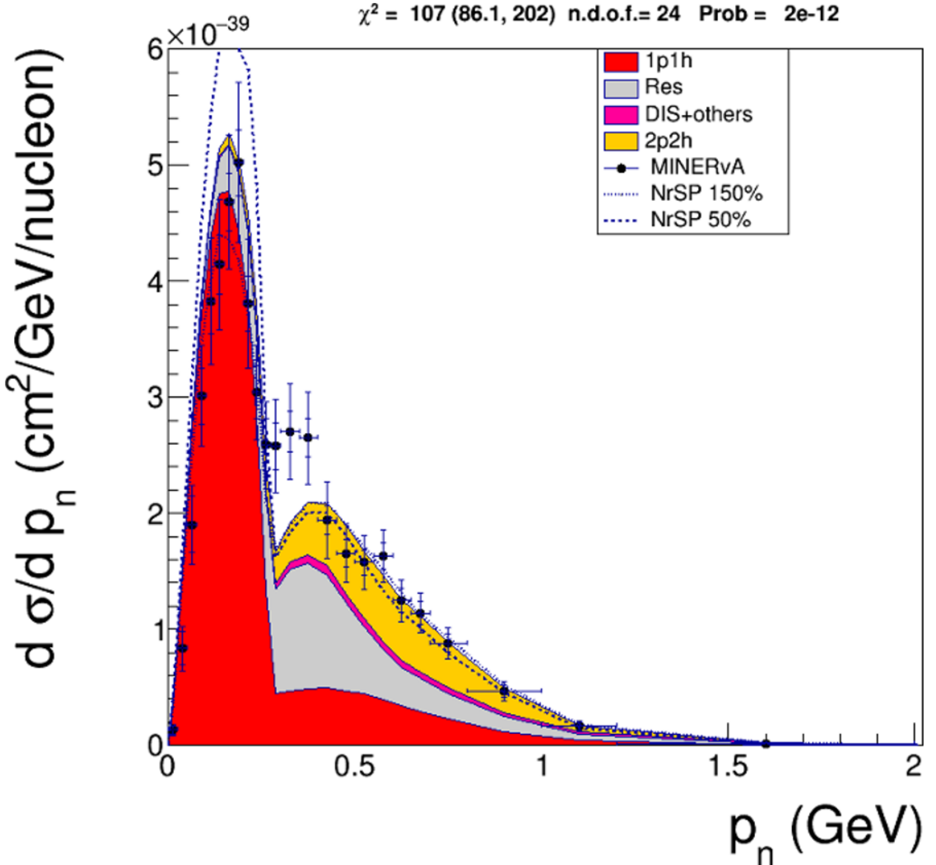


visible proton in the final state

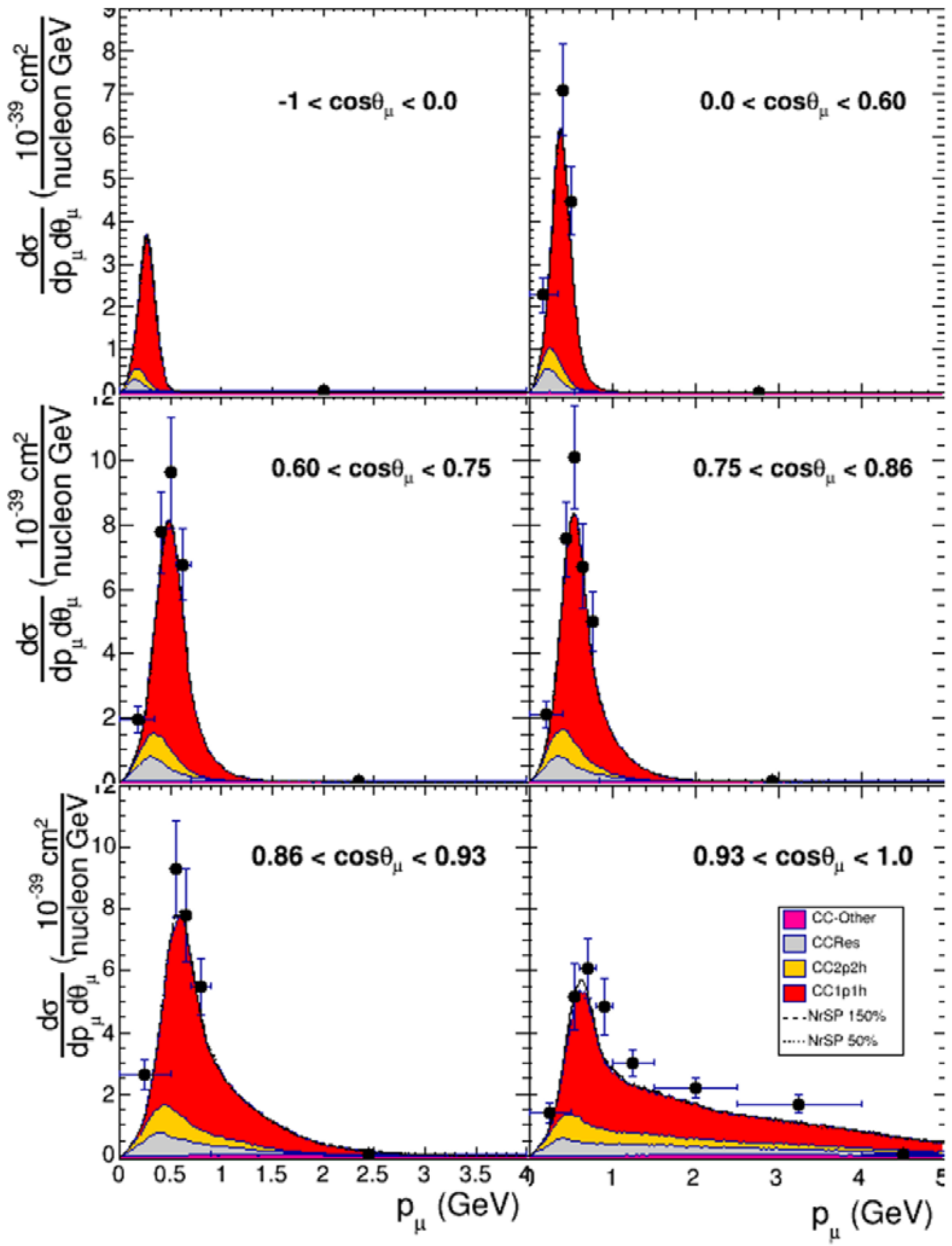
QE: $\nu_\mu + n \longrightarrow p\, \mu^-$

(bound in the nucleus)

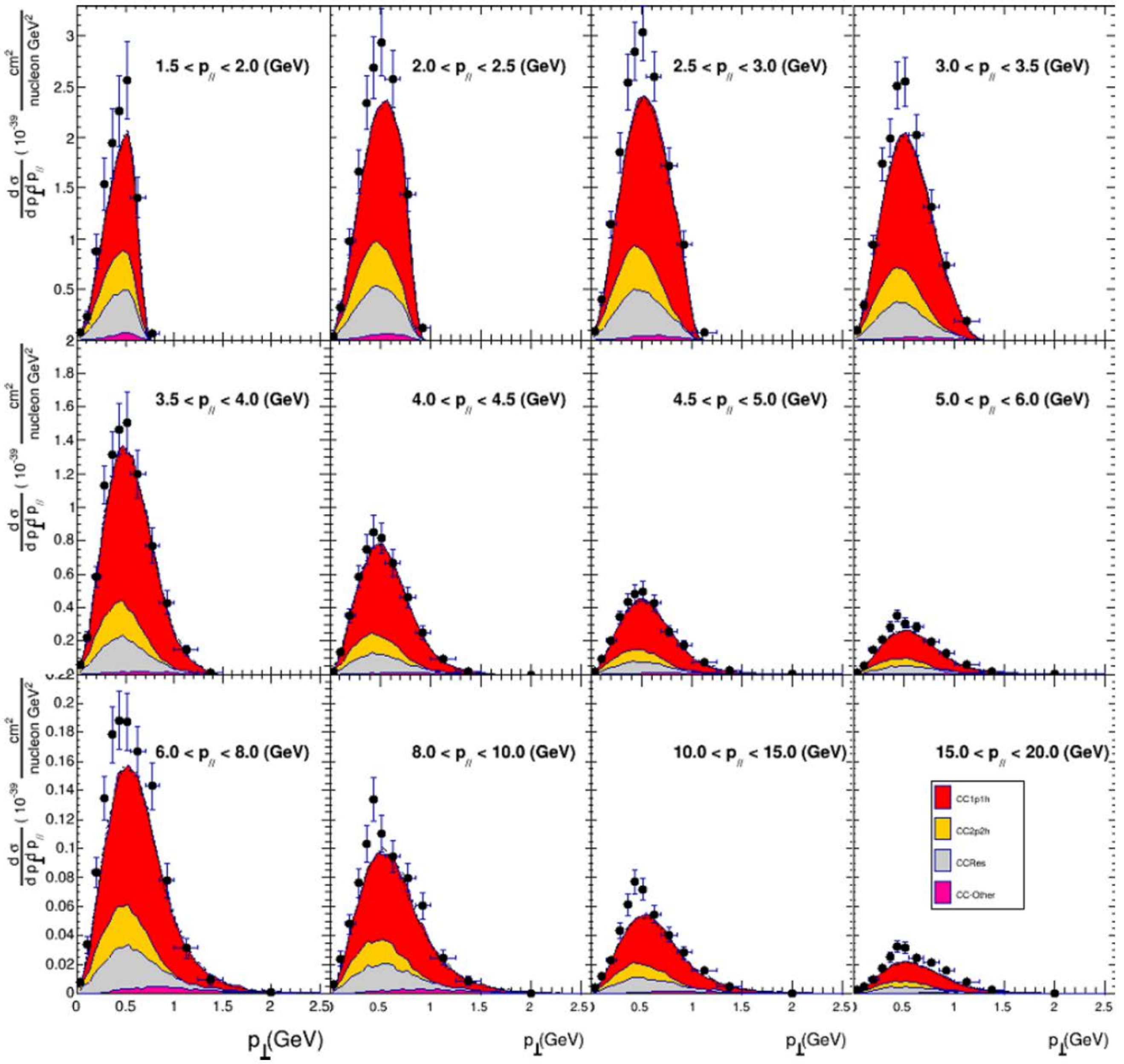
reconstructed neutron in the initial state



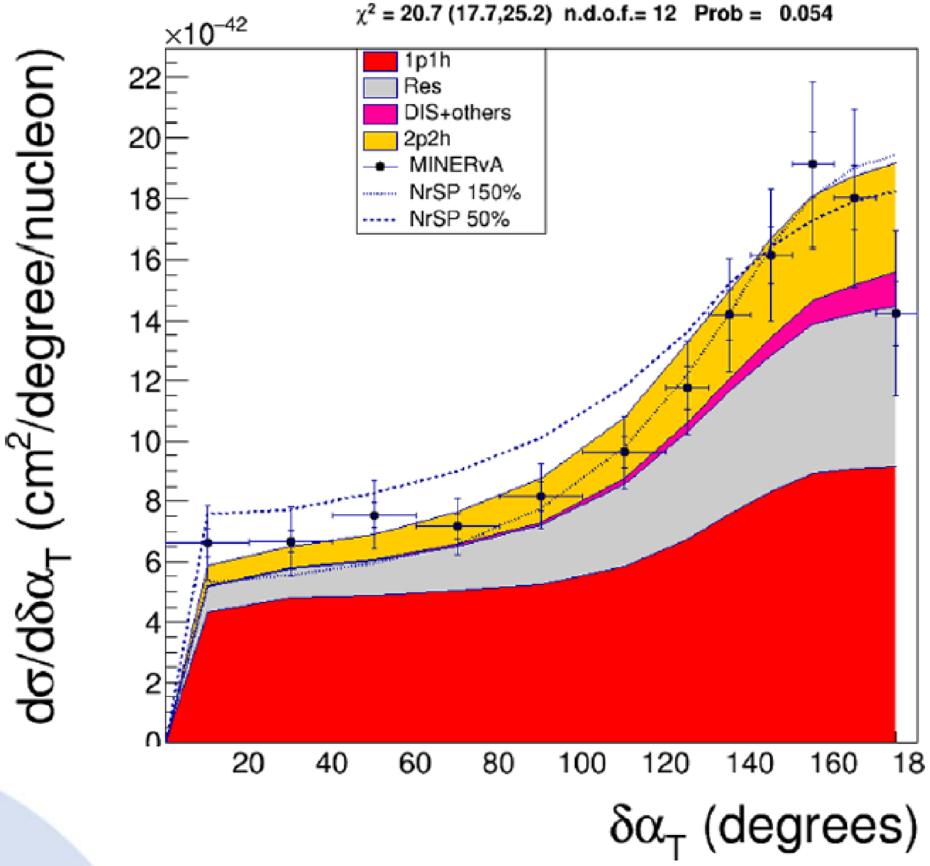
T2K CC0π



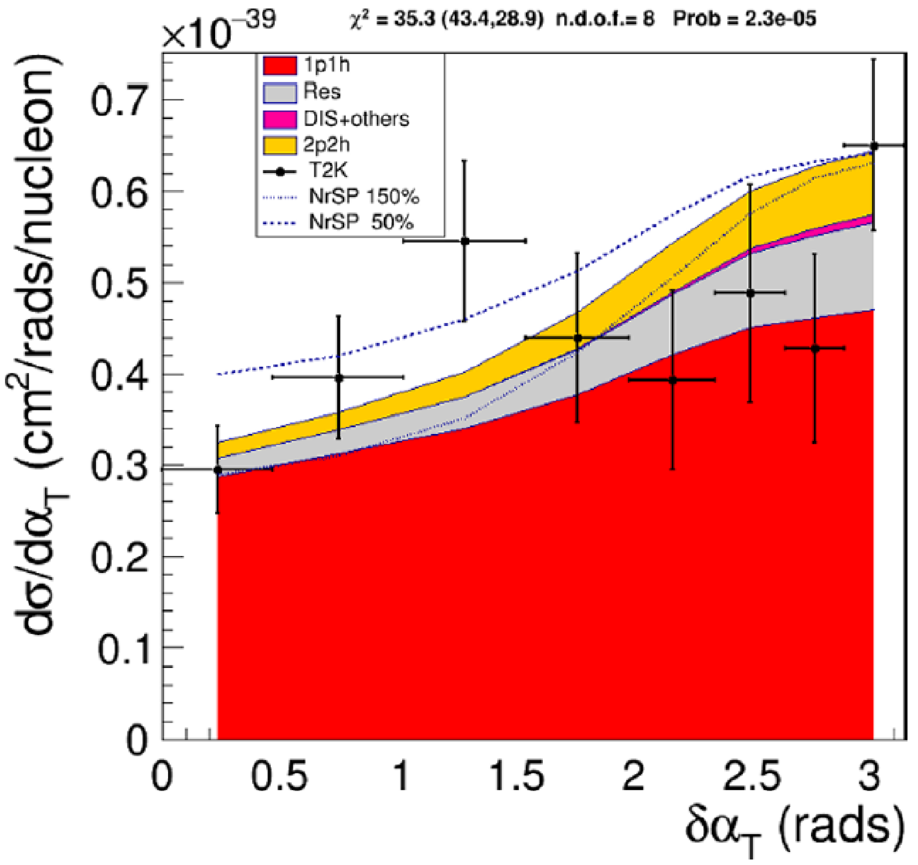
MINERνA CC0π



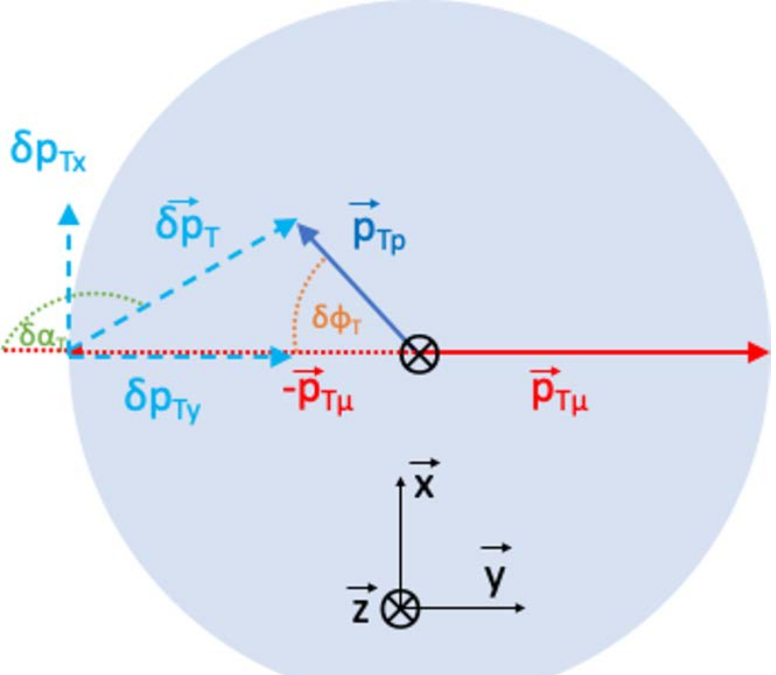
Angular and transverse momentum variables (neutrino perpendicular to the plane).



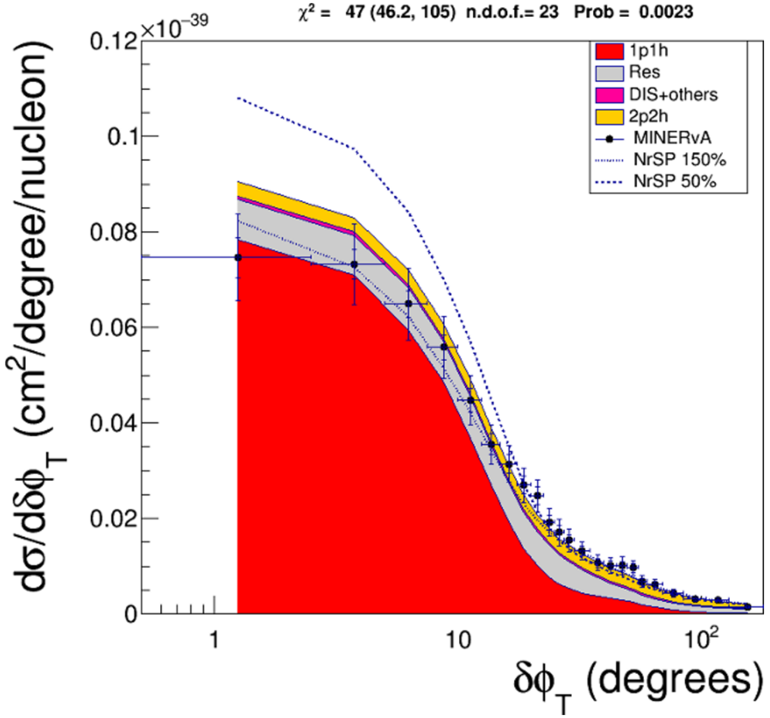
MINERνA CC$0\pi1p$

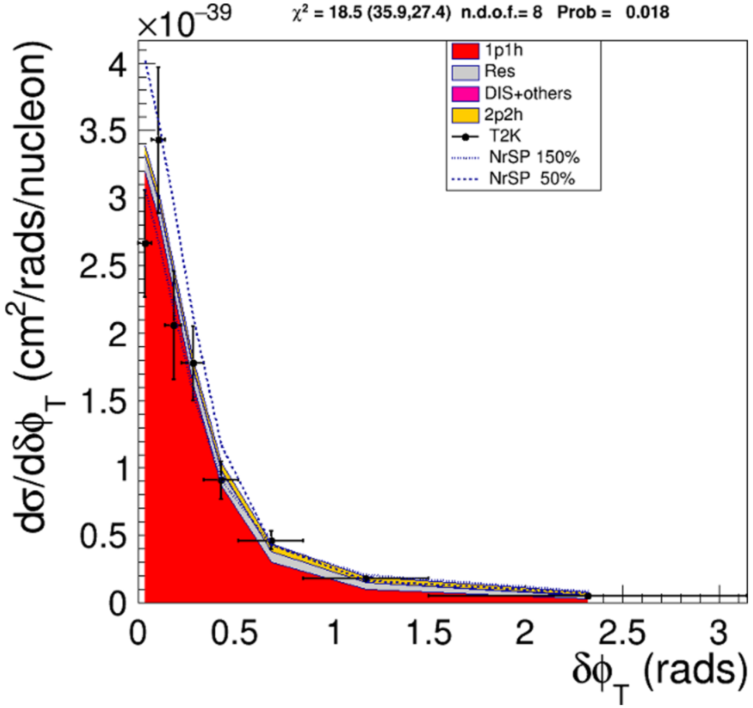


T2K CC$0\pi1p$



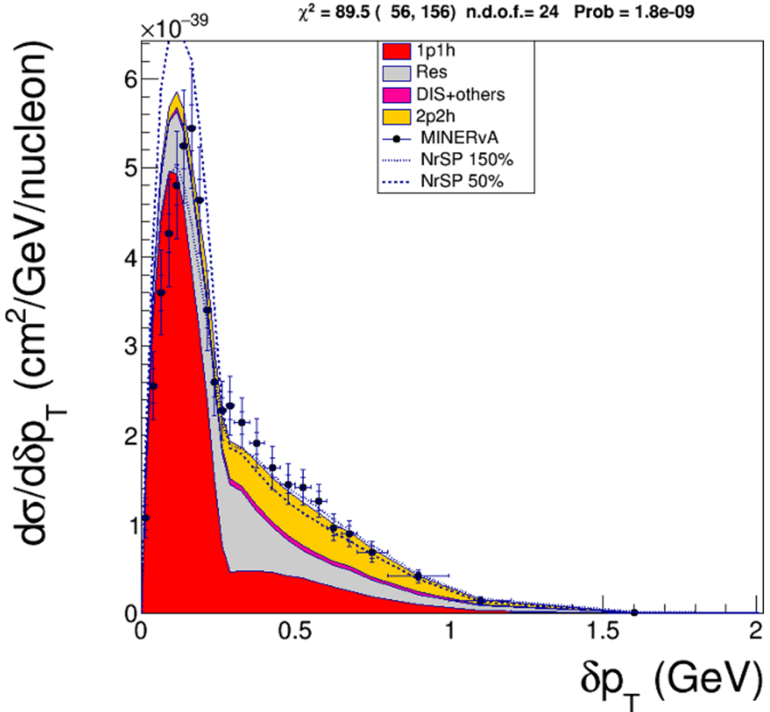
Transverse Kinematic Imbalance (TKI) variables



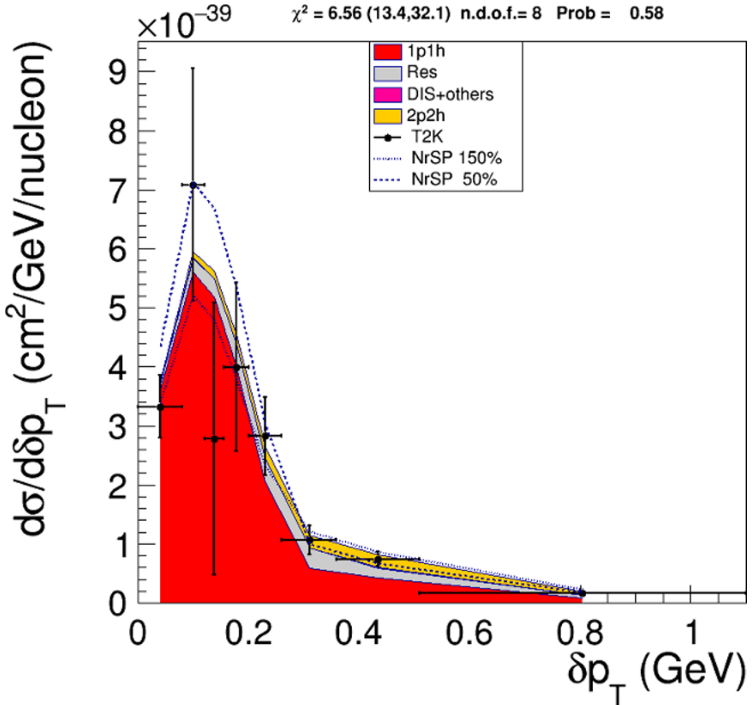


MINERνA & **T2K**

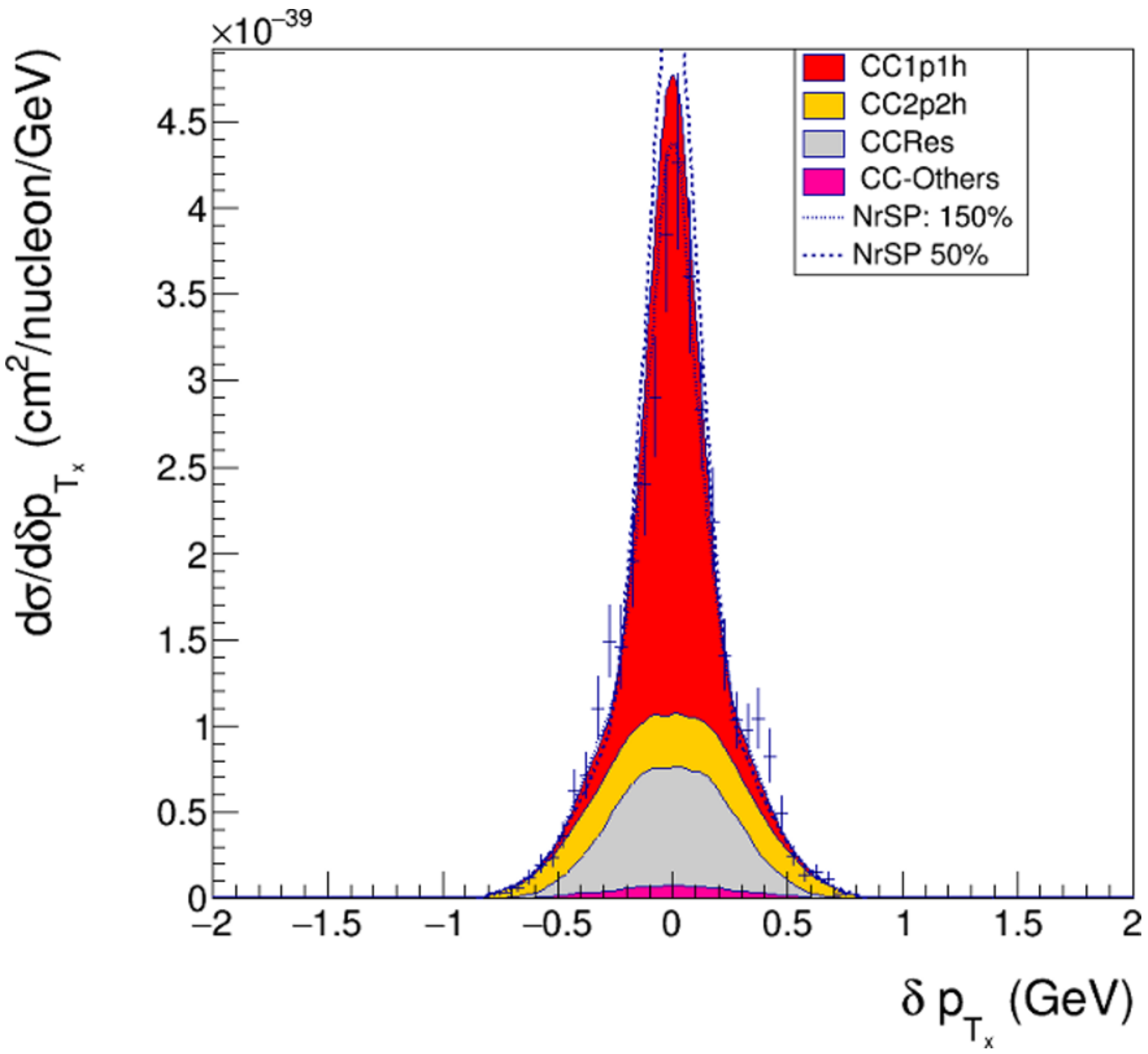
$CC0\pi1p$

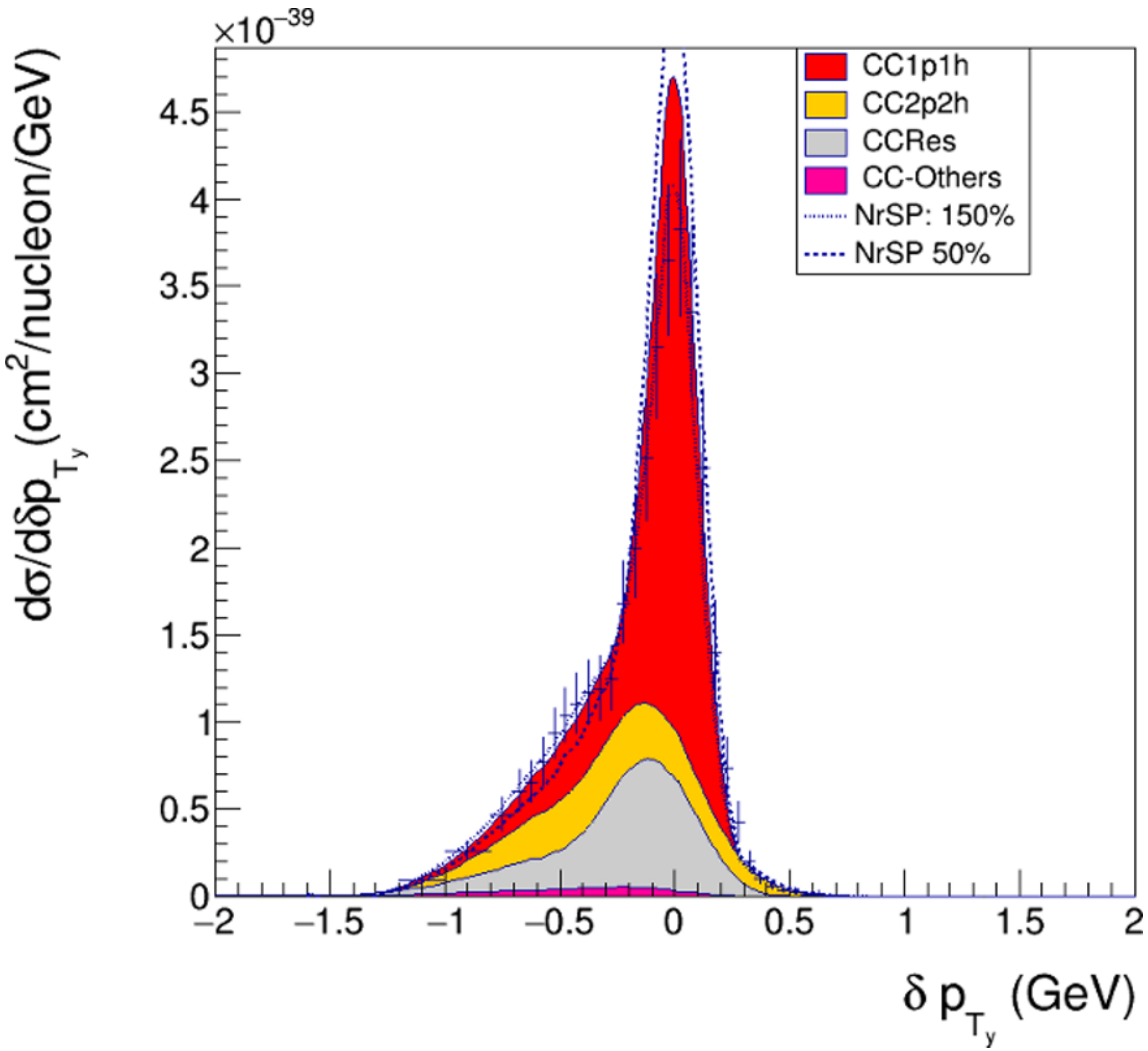


TKI distributions

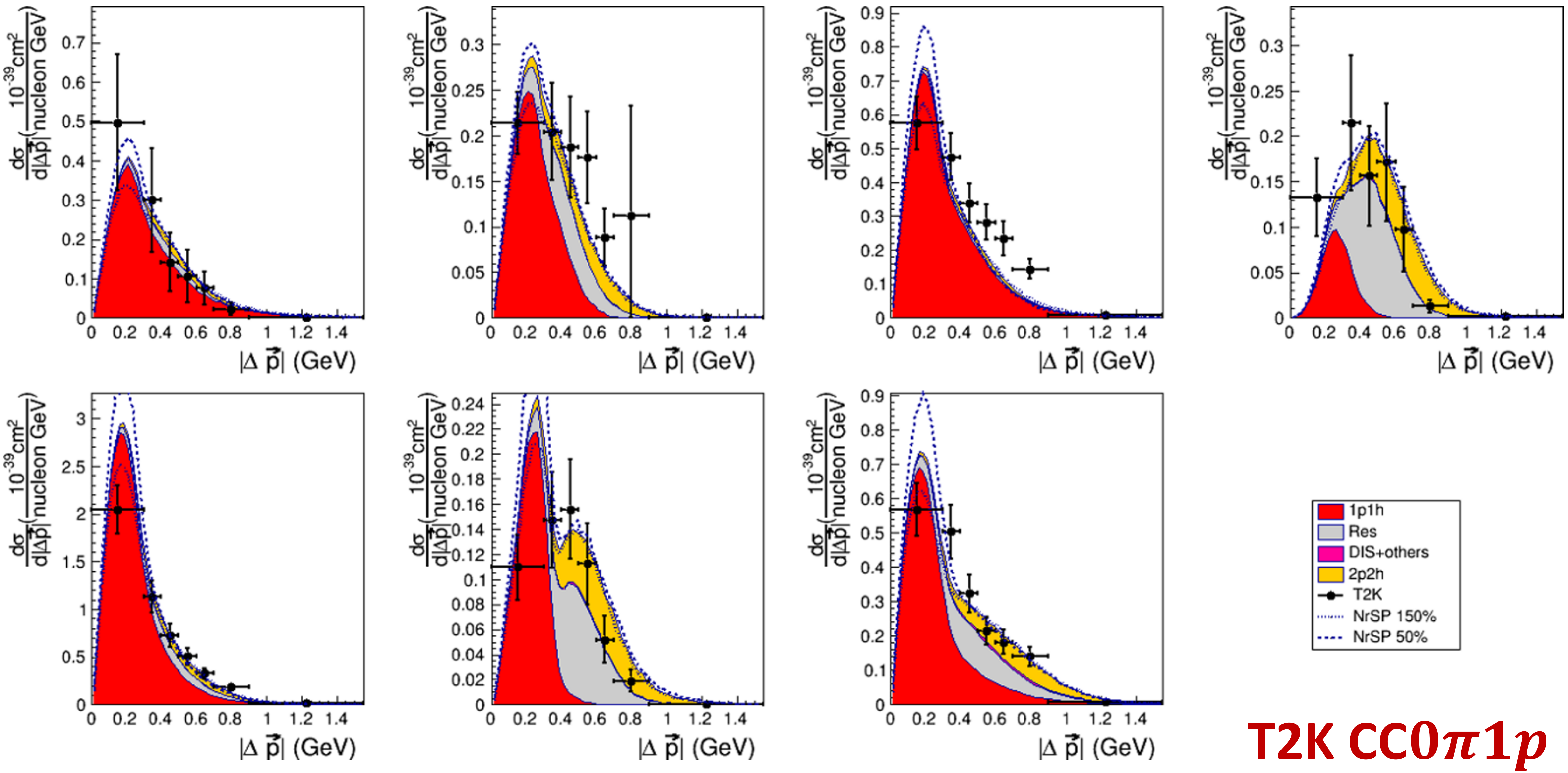


MINERνA CC0π1p





TKI distributions



T2K CC0π1p

$$|\Delta\vec{p}| = |\vec{p}_p^{\,\mathrm{inf}} - \vec{p}_p^{\,\infty}| \qquad \vec{p}_p^{\,\mathrm{inf}} = \vec{p}_\nu^{\,\mathrm{rec}} - \vec{p}_\mu$$

PHYSICAL REVIEW C **102**, 024601 (2020)

previous results are confirmed & distributions of momenta of the outgoing nucleons in the first step

Exclusive-final-state hadron observables from neutrino-nucleus multinucleon knockout

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[2] *Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*

[3] *Université de Genève, Faculté des Sciences, Département de Physique Nucléaire et Corpusculaire (DPNC) 24, Quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland*

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We present results of an updated calculation of the two particle two hole (2p2h) contribution to the neutrino-induced charge-current cross section. We provide also some exclusive observables, interesting from the point of view of experimental studies, e.g., distributions of momenta of the outgoing nucleons and of available energy, which we compare with the results obtained within the NEUT generator. We also compute, and separate from the total, the contributions of 3p3h mechanisms. Finally, we discuss the differences between the present results and previous implementations of the model in MC event generators, done at the level of inclusive cross sections, which might significantly influence the experimental analyses, particularly in the cases where the hadronic observables are considered.

Conclusions

- **CONSISTENT MICROSCOPIC DESCRIPTION of the QE, DIP AND Δ , REGIONS BECOMES FUNDAMENTAL BECAUSE NEUTRINO BEAMS ARE NOT MONOCHROMATIC**

  ✓ 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%.

  ✓ **2p2h: necessary ingredients i)** $W^{\pm}N \longrightarrow N'\pi$ **(or** $Z^0N \longrightarrow N'\pi$ **or** $\gamma N \longrightarrow N'\pi$**) in vacuum and ii) effective NN interaction in the medium:** π**+**ρ**+SRC+RPA+…**

  ✓ **properties of pions and Δ inside of a nuclear medium become essential to describe the resonance region**

- 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.**
- ✓ 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

2018-2021: 2p2h+RPA nuclear model describes fairly well MINERVA-T2K inclusive CC0π data. Problems with MINERνA persist in available hadron energy distributions (2p2h contributions need to be substantially enhanced!), perhaps related with pion production data…