Sections efficaces neutrino-noyau aux énergies de MiniBooNE et T2K: un modèle théorique pour tous les différents canaux d'excitations

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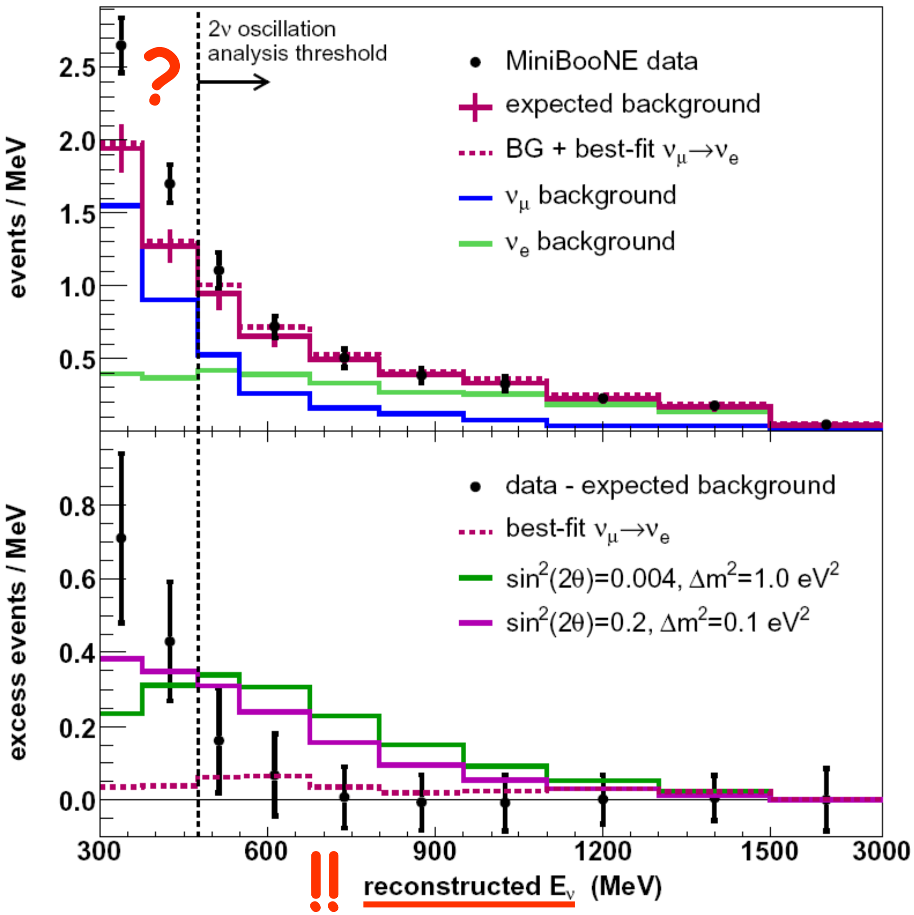
Outline

MiniBooNE $\nu_\mu \rightarrow \nu_e$

PRL 98, 231801 (2007)



- Introduction
  - relevant channels for accelerator exp.
  - link with ν oscillation physics
  - why nuclear physics is important?

- Our model: nuclear response functions

- Comparison with other microscopical models and with commonly used Monte Carlo

- Comparison with experimental results

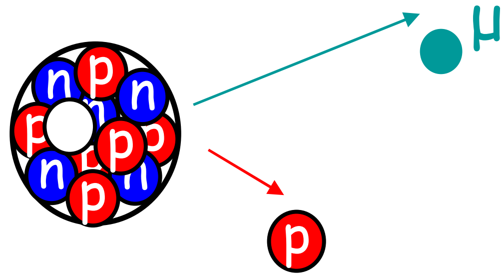
In collaboration with:

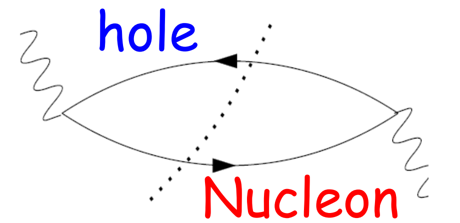
M. Ericson, G. Chanfray, J. Marteau, IPNL

Phys. Rev. C 80 065501 (2009)
Phys. Rev. C 81 045502 (2010)

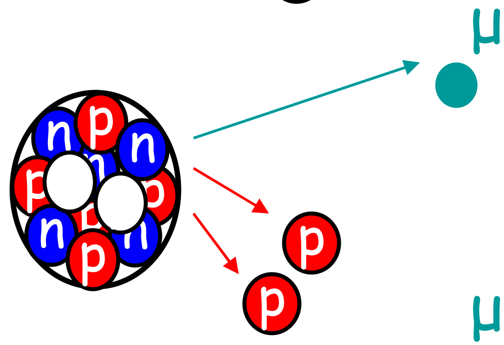
Neutrino - nucleus interaction @ $E_{\nu} \sim \mathcal{O}\,(1\ \mathrm{GeV})$

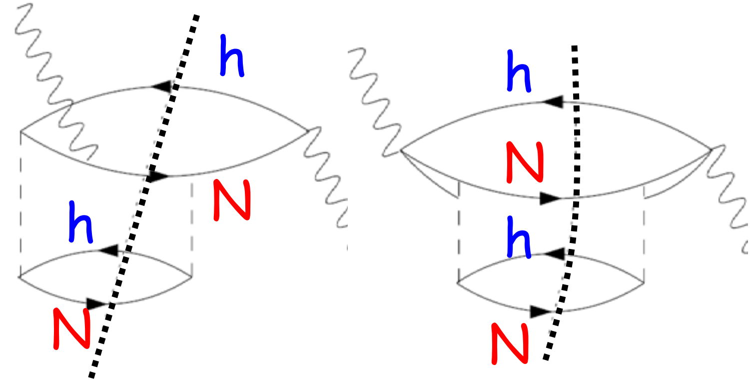
Quasielastic (QE)



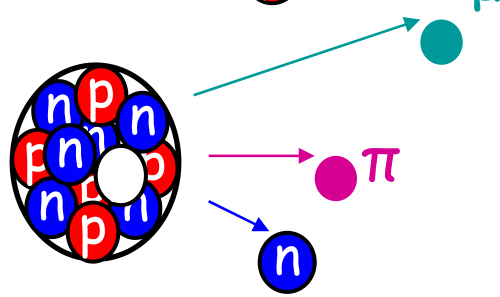


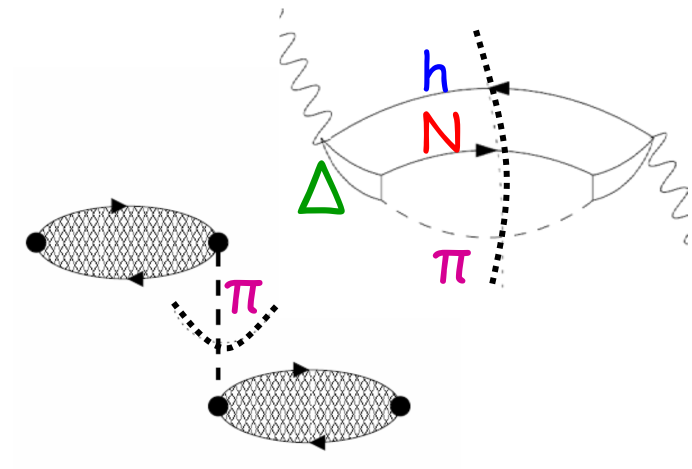
Two Nucleons knock-out (2p-2h)



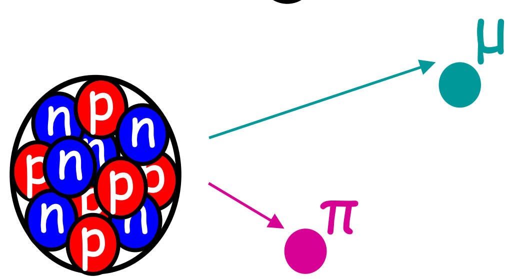


Incoherent π production





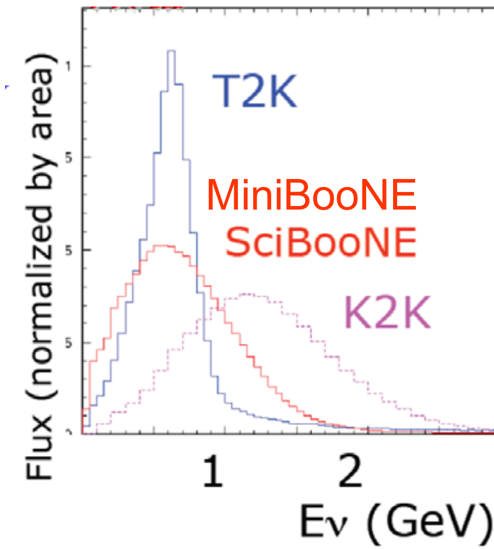
Coherent π production



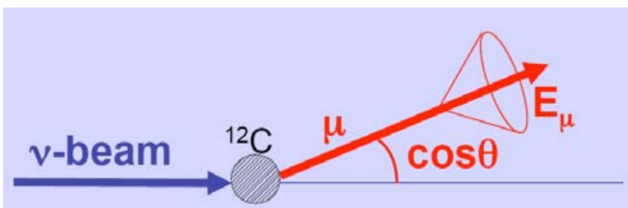
ν_μ Disappearance - 2-3 sector - Quasielastic channel

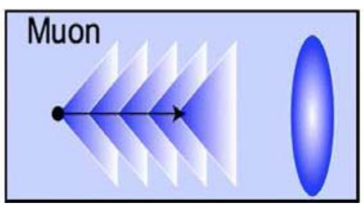
The measurement of θ_{23} and Δm^2_{23} is based on comparing the initial energy spectrum of ν_μ measured at a near detector to the final spectrum measured at a far detector

The ability to reconstruct neutrino energy, which is not known for broad fluxes, is crucial



E_ν from (ν_μ n $\rightarrow \mu^-$ p) CCQE





Cherenkov:
μ,π detected
n,p not detected

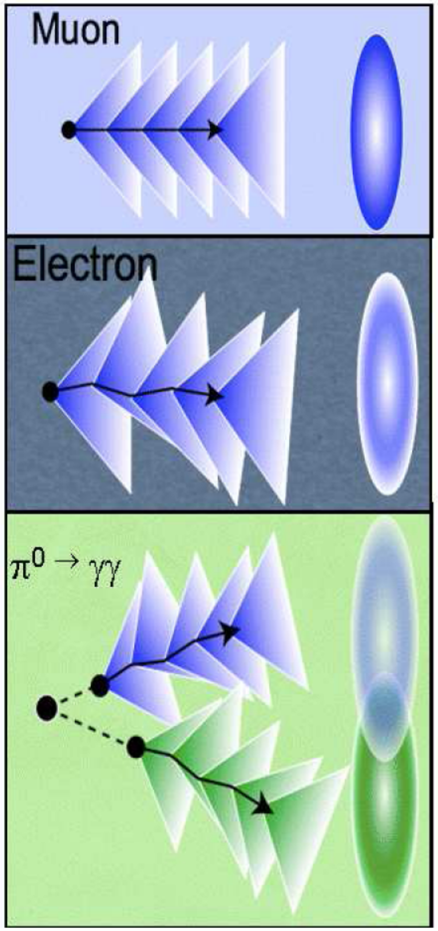
E_μ and θ_μ measured

E_ν reconstructed with two-body kinematics

but:

- This is exact only for free neutrons
- Detector are composed of nuclei
- E_ν is smeared due to momentum distribution of n
- Events not CCQE but look identical to them:
- Two nucleon knock-out
- CC1π production if π is not detected

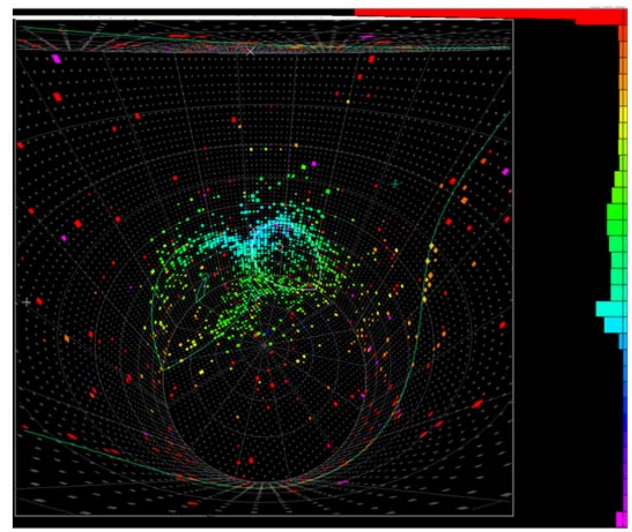
ν_e Appearance - 1-3 sector - NC π^0 production



High sensitivity searches for $\nu_\mu \to \nu_e$ appearance associated with θ_{13} and CP violation

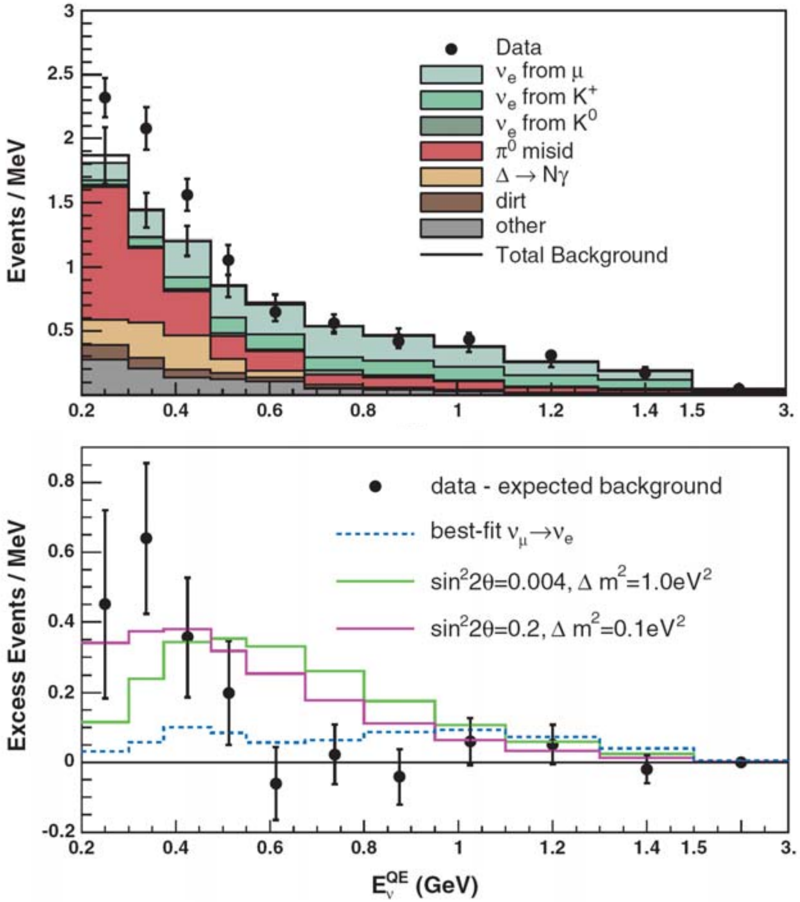
NC π^0 most important background

NC π^0 events can mimic CCQE ν_e signal events when 1 of the 2 γ associated with $\pi^0 \to \gamma\gamma$ decay is not detected



24/02/2010 First T2K event
seen is Super-Kamiokande

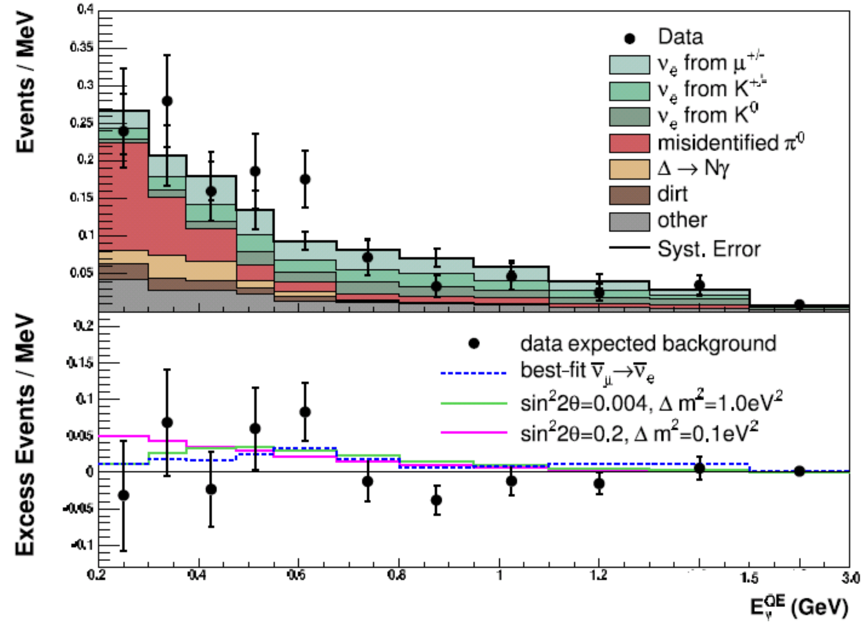
ν_e Appearance



MiniBooNE, PRL 102, 101802 (2009)

« MiniBooNE observes an unexplained excess of electronlike events in the energy region $200 < E_\nu^{QE} < 475$ MeV. These events are consistent with being either electron events produced by CC scattering or photon events produced by NC scattering. »

$\bar{\nu}_e$ Appearence

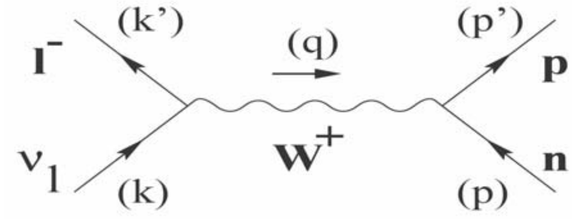


MiniBooNE, PRL 103, 111801 (2009)

« MiniBooNE observes no significant excess of $\bar{\nu}_e$ events in the low energy region $200 < E_\nu^{QE} < 475$ MeV. The absence of an excess at low energy in antineutrino mode should help distinguish between several hypotheses suggested as explanation for the low energy excess observed in neutrino mode. »

Neutrino-nucleus cross-section

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



lepton

$$\langle k', s' | l_\mu | k, s \rangle = e^{-iqx} \bar{u}(k', s') \, [\gamma_\mu (1 - \gamma_5)] \, u(k, s)$$

$$\langle p', s' | h^\mu | p, s \rangle \;=\; e^{iqx} \bar{u}(p', s') \, [F_1(t) \gamma^\mu \,+\, F_2(t) \sigma^{\mu\nu} \frac{i q_\nu}{2M_N} + G_A(t) \gamma^\mu \gamma_5 \,+\, G_P(t) \gamma_5 \frac{q^\mu}{2M_N}] \, u(p, s)$$

hadron

$$t = q^2 = \omega^2 - \boldsymbol{q}^2$$

$$G_A(t) = g_A \, [1 - \frac{t}{M_A^2}]^{-2}$$

After non-relativistic reduction:

$$\frac{\partial^2 \sigma}{\partial \Omega \, \partial k'} = \frac{G_F^2 \, \cos^2 \theta_c \, (\boldsymbol{k}')^2}{2\,\pi^2} \cos^2 \frac{\theta}{2} \Bigg[G_E^2 \, (\frac{q_\mu^2}{\boldsymbol{q}^2})^2 \, R_\tau^{NN}$$

charge nuclear response

$$+ \; G_A^2 \frac{(M_\Delta - M_N)^2}{2\,\boldsymbol{q}^2} R_{\sigma\tau(L)}^{N\Delta} + G_A^2 \frac{(M_\Delta - M_N)^2}{\boldsymbol{q}^2} R_{\sigma\tau(L)}^{\Delta\Delta}$$

isospin spin-longitudinal

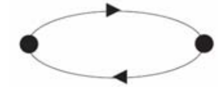
$$+ \; \left(G_M^2 \frac{\omega^2}{\boldsymbol{q}^2} + G_A^2 \right) \left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2 \tan^2 \frac{\theta}{2} \right) \left(R_{\sigma\tau(T)}^{NN} + 2 R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta} \right)$$

isospin spin-transverse

$$\begin{cases} + & (\nu) \\ - & (\bar{\nu}) \end{cases} \; \pm \; 2\, G_A \, G_M \frac{k + k'}{M_N} \tan^2 \frac{\theta}{2} \left(R_{\sigma\tau(T)}^{NN} + 2 R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta} \right) \Bigg]$$

interference V-A

Nuclear response functions

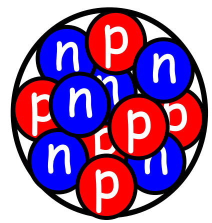


The nucleus is one of the multi-faceted many-body systems in the universe.
It exhibits a multitude of responses depending on the way one probes it.

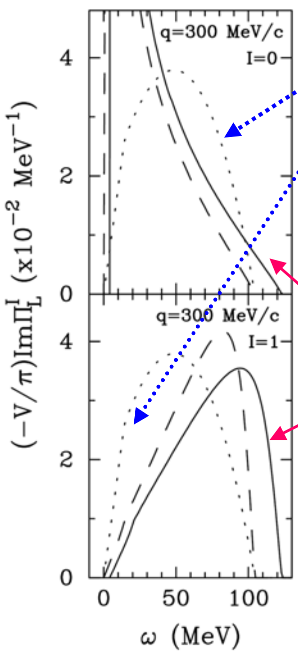
Ext. perturbation

$\gamma, W, Z^0, \pi, \ldots$

$(\mathbf{q}, \omega)$



Nucleus excitations
Nucleon excitations (e.g. Δ resonance)



NN interaction switched off

Nucleons respond individually

Nucleon at rest: $R \propto \delta(\omega - q^2/2M_N)$

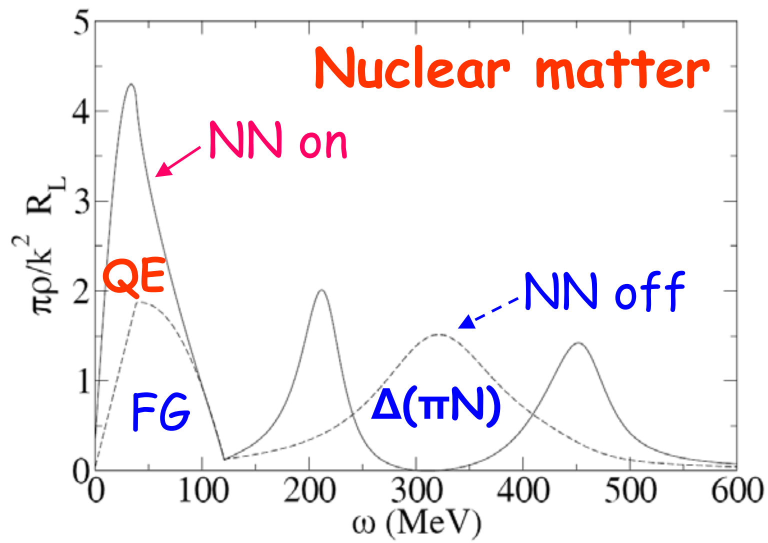
Fermi momentum spreads δ distribution (Fermi Gas)

NN interaction switched on (RPA)

Force acting on 1N is transmitted

The response R becomes collective

Decrease, increase, divergences,...

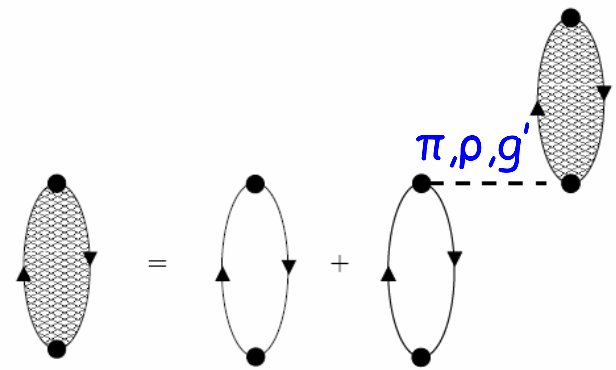


Nuclear responses in the random-phase approximation

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

RPA bare

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



RPA bare

ν-Nucleus

P, P' = N or Δ

$$\frac{\partial^2\sigma}{\partial\Omega_{k'}\partial k'} \propto f(R_\tau^{NN}, R_{\sigma\tau(L)}^{PP'}, R_{\sigma\tau(T)}^{PP'})$$

Several channels

isospin

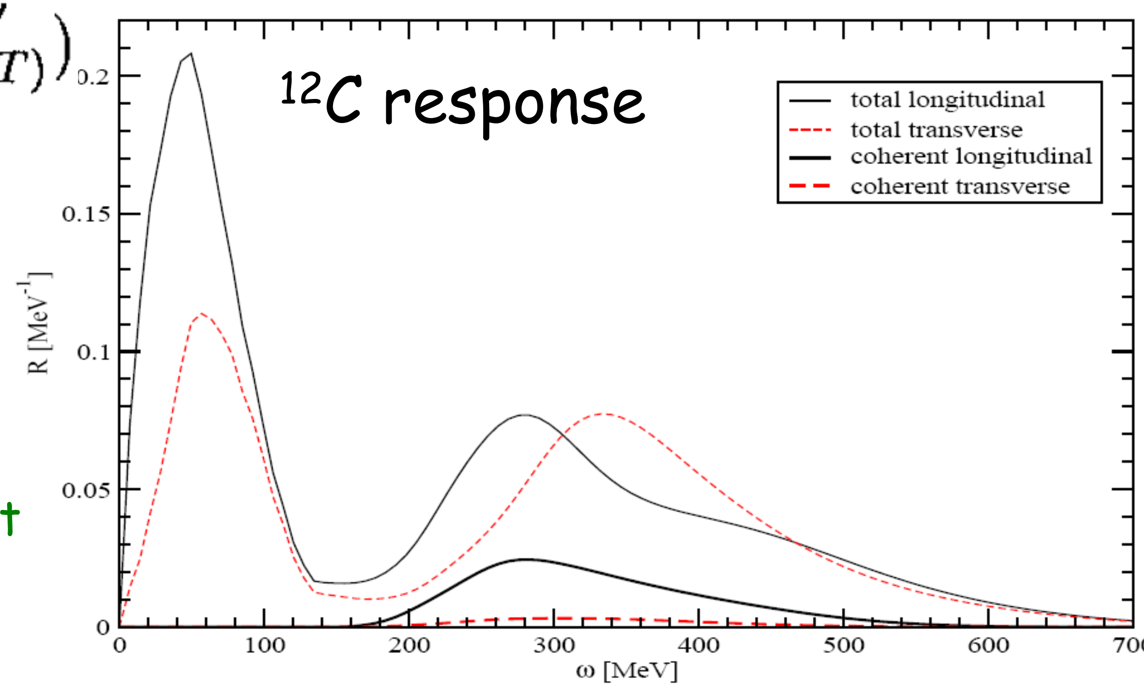
isospin spin-longitudinal

isospin spin-transverse

Several partial components

QE, 2p-2h,3p-3h, Δ→πN, π coherent

Treated in self-consistent, coupled and coherent way



V-Nucleus Quasielastic scattering

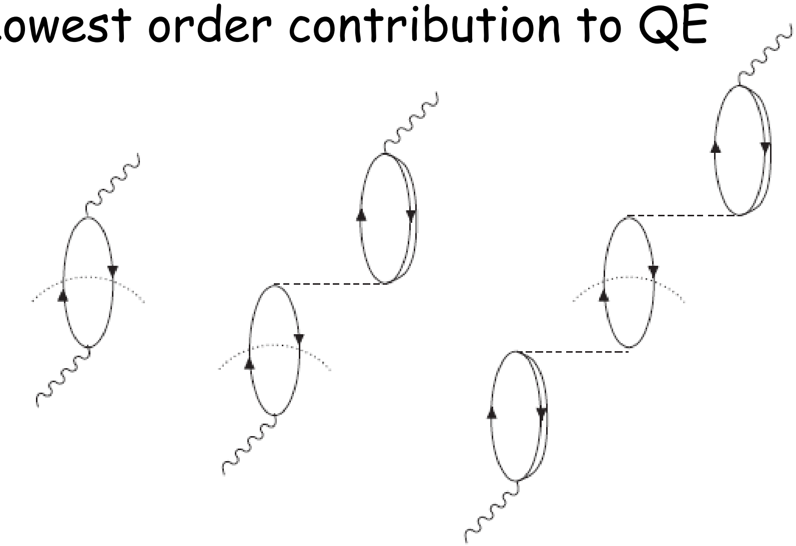
QE totally dominated by isospin spin-transverse response $R_{\sigma\tau(T)}$

RPA reduction

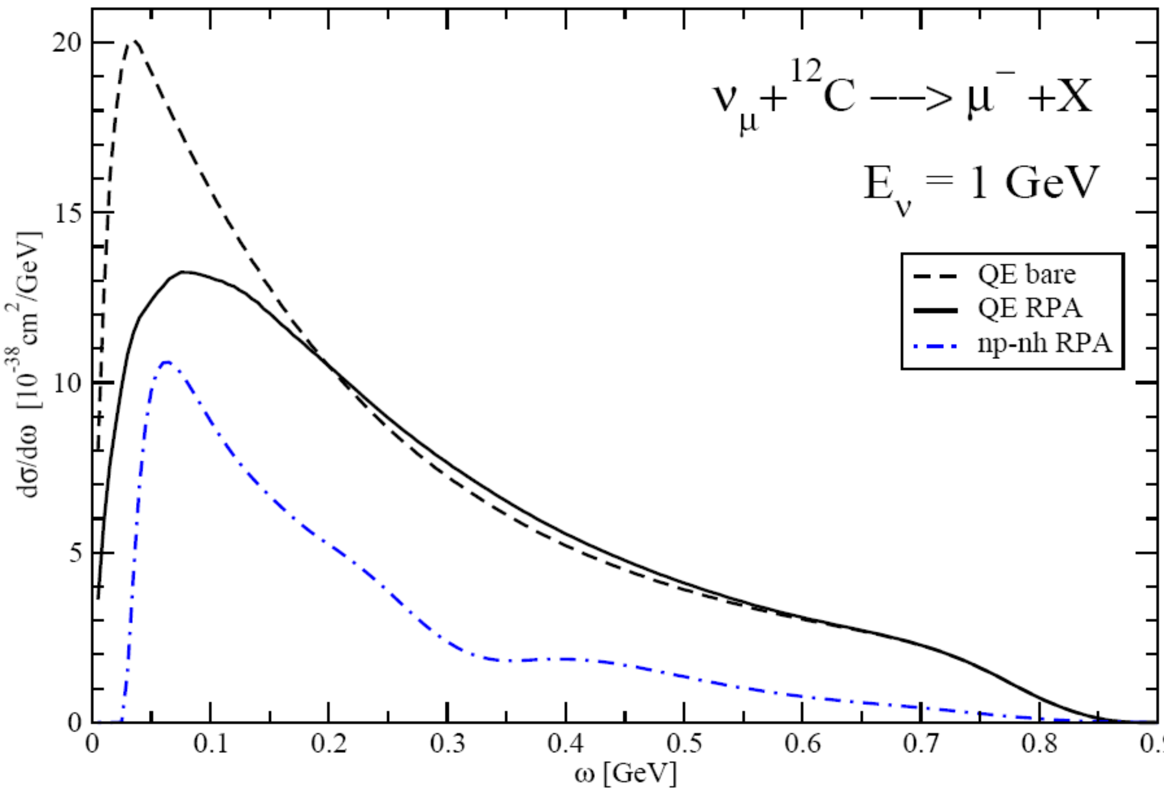
- expected from the repulsive character of p-h interaction in T channel
- mostly due to interference term $R^{N\Delta} < 0$

Test: electron-nucleus scattering

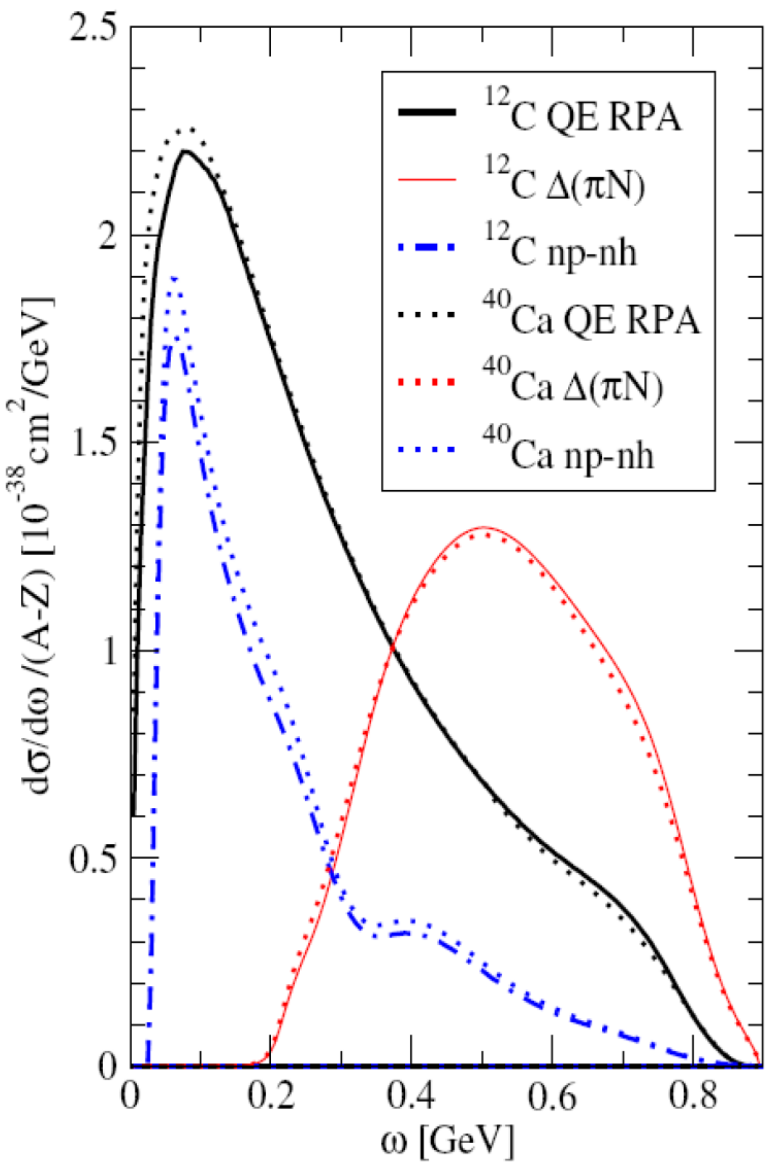
Lowest order contribution to QE



R^{NN}_{QE} $R^{N\Delta}_{QE}$ $R^{\Delta\Delta}_{QE}$



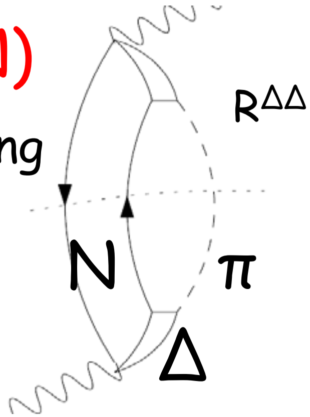
π production and np-nh ; nuclear mass dependence



Scaling with A

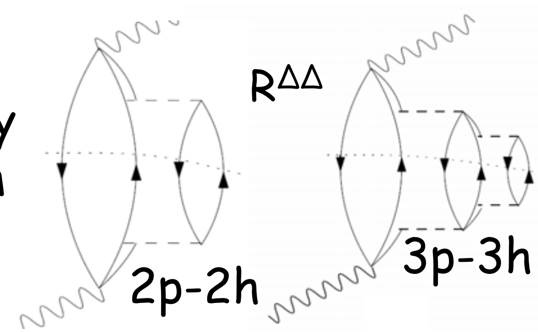
Pion production: Δ(πN)

- from π-A and γ-A scattering
- Test: π-A

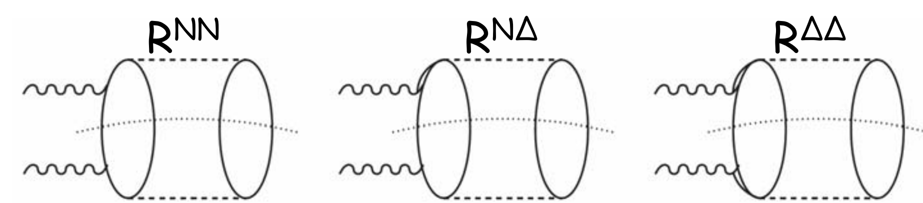


np-nh channel

- non pionic Δ decay in nuclear medium ΔN→NN

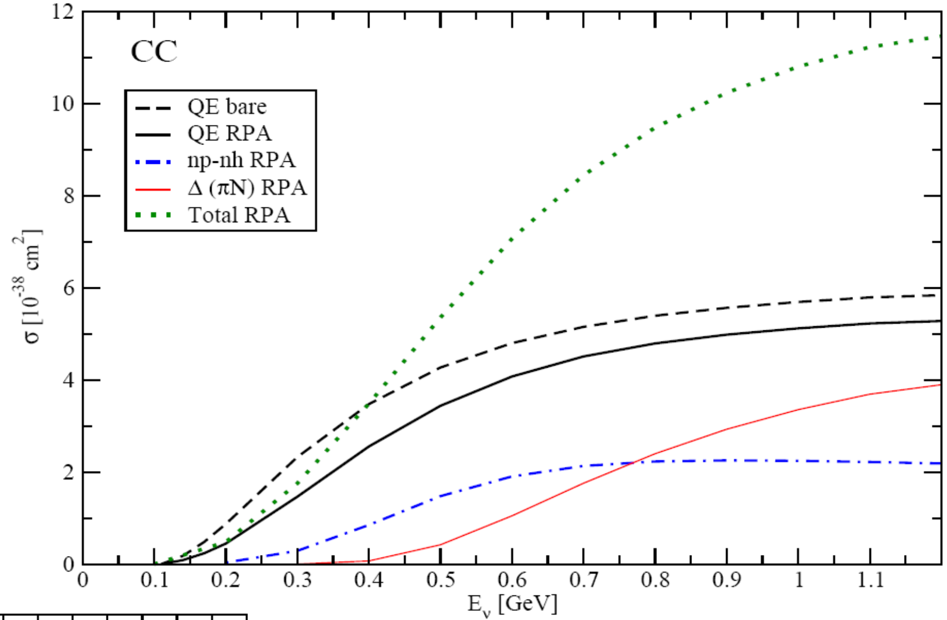


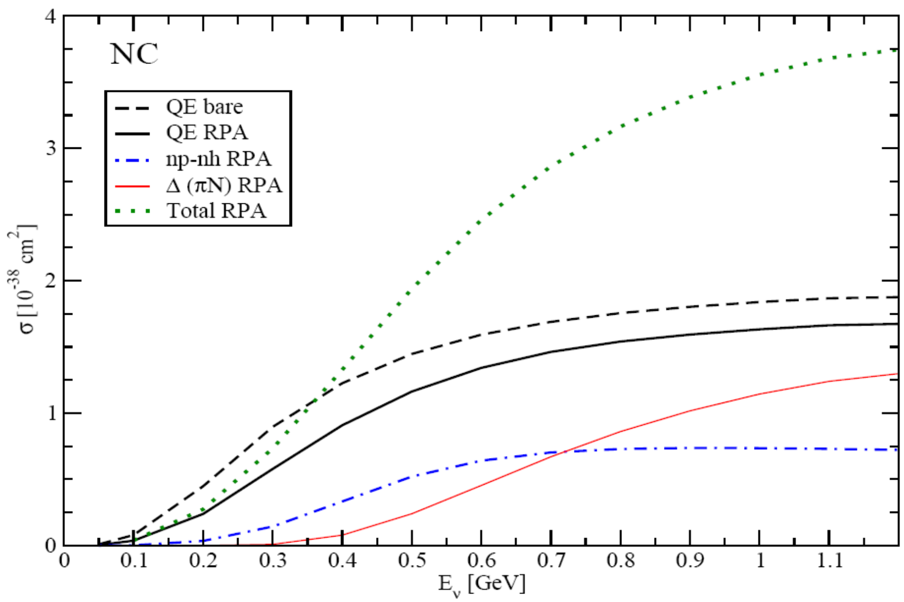
- Initial state nucleon correlation



Phenomenological parameterization from π absorption and electron scattering

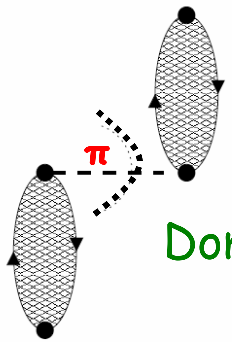
ν_μ-^{12}C Cross sections





as a function of ν energy

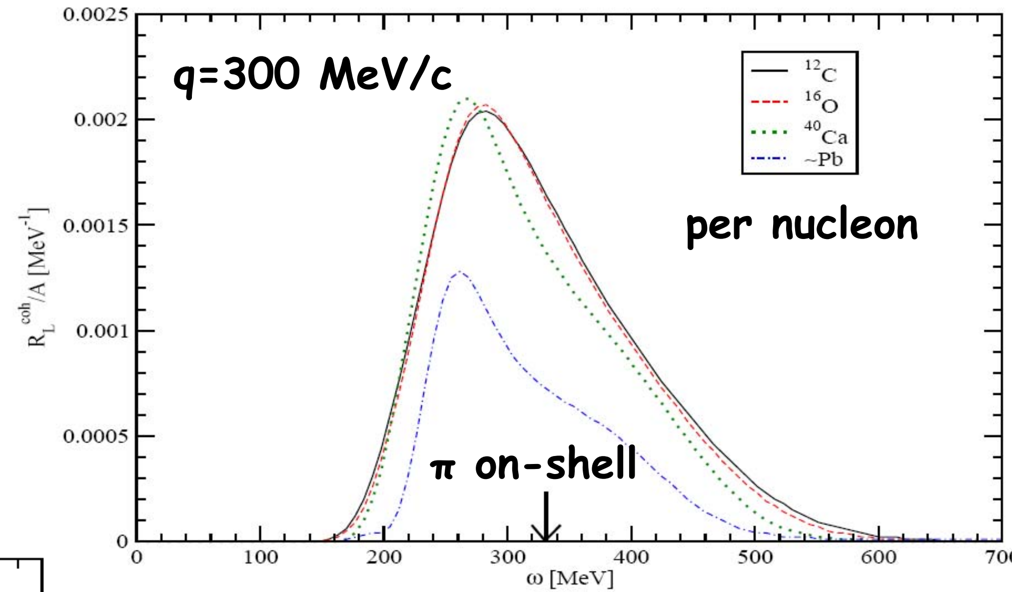
Coherent channel

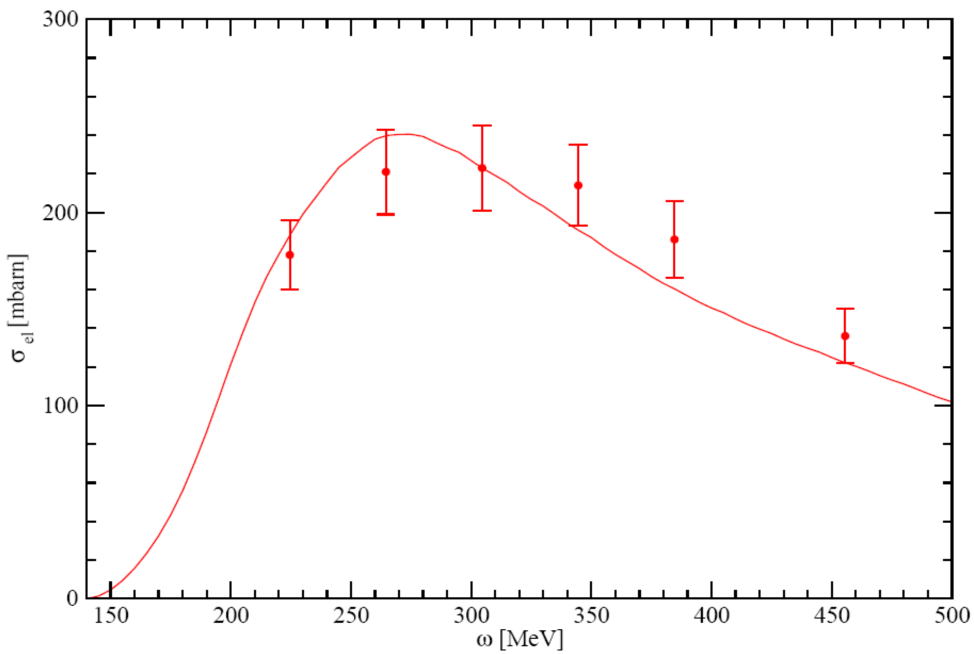


Dominated by $R_{\sigma\tau}$ longitudinal

Reshaped by collective effects

Softening of the responses





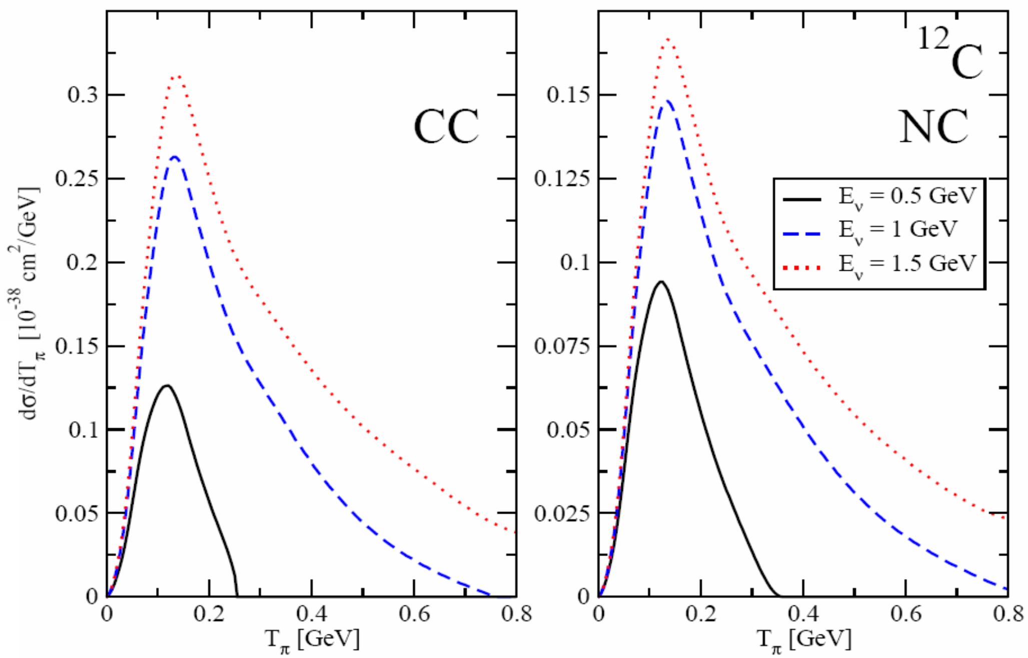
Test: π - ^{12}C elastic cross-section

$$\sigma^{elas}(\omega) = \left(\frac{g_r}{2M_N}\right)^2 \pi q_\pi \, R_L^{coh}(\omega, q_\pi)$$

$$q_\pi^2 = \omega^2 - m_\pi^2$$

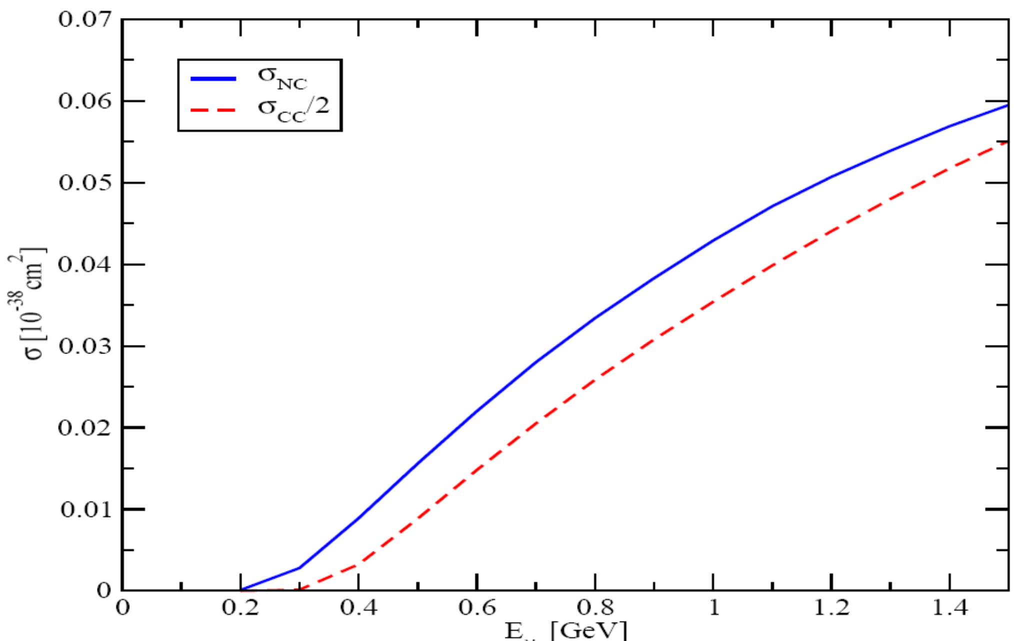
ν_μ induced coherent pion production off ^{12}C

Differential cross section



pion kinetic energy

Total cross section



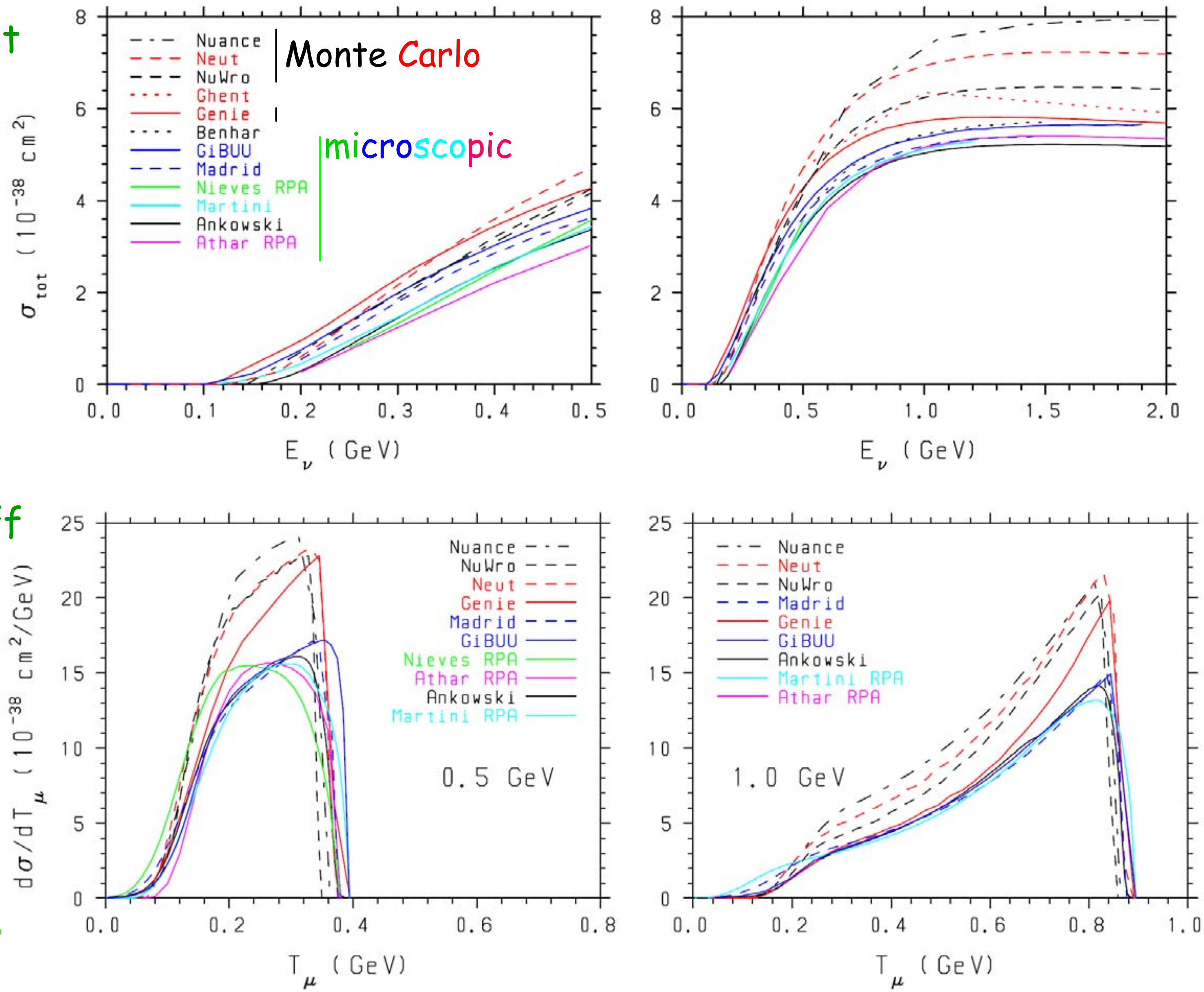
neutrino energy

Comparison of Models of Neutrino-Nucleus Interactions

S. Boyd*, S. Dytman†, E. Hernández**, J. Sobczyk‡ and R. Tacik§

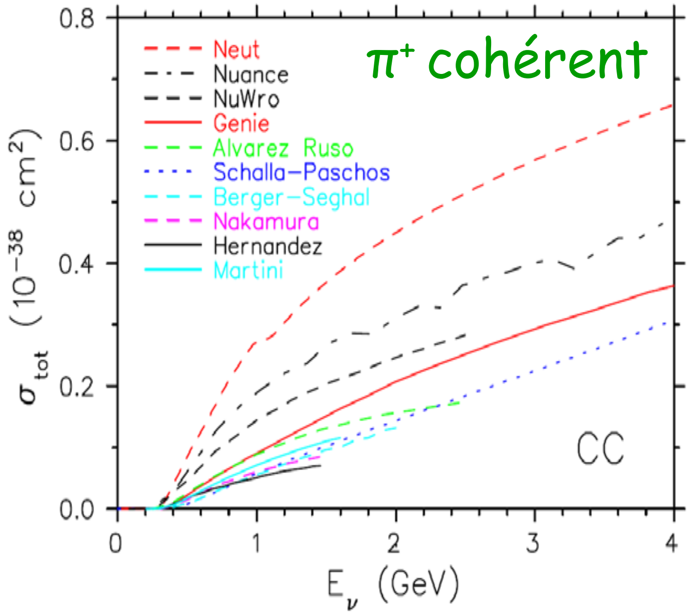
QE tot

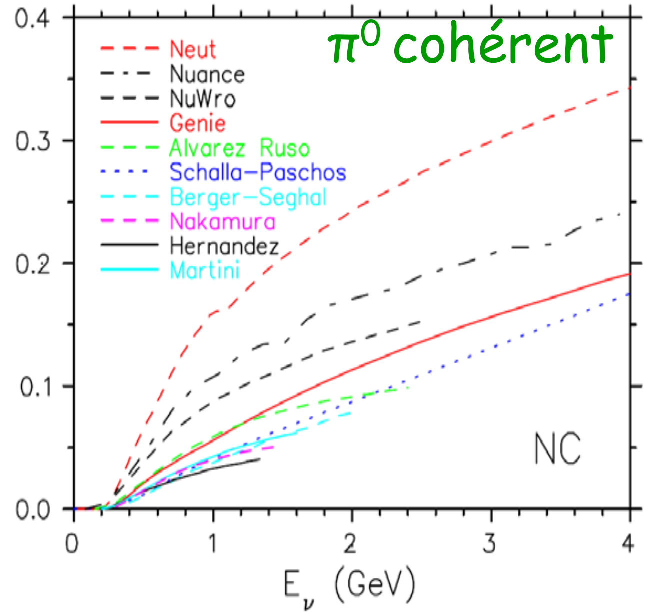
QE diff

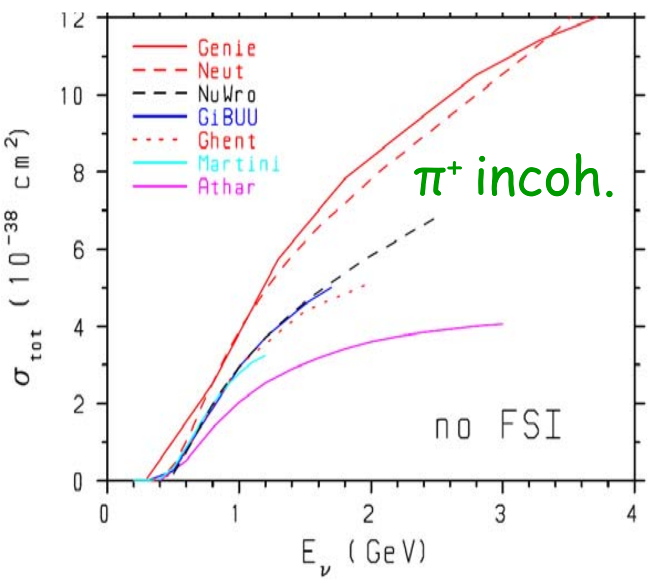


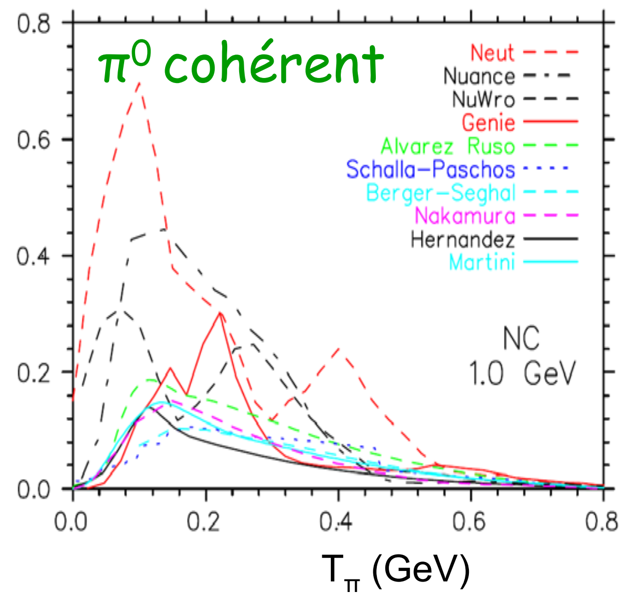
NUINT09

NUINT09









Monte Carlo

QE: Fermi Gas

π prod:Rein-Sehgal

- **Neut**: SuperKamiokande, K2K, T2K, SciBooNE
- Nuance: SuperKamiokande, MINOS, MiniBooNE
- **Genie**: T2K, MINOS, Minerva, NOvA, ArgoNEUT
- NuWro: Wroclaw theo. group

MC larger than microscopic models

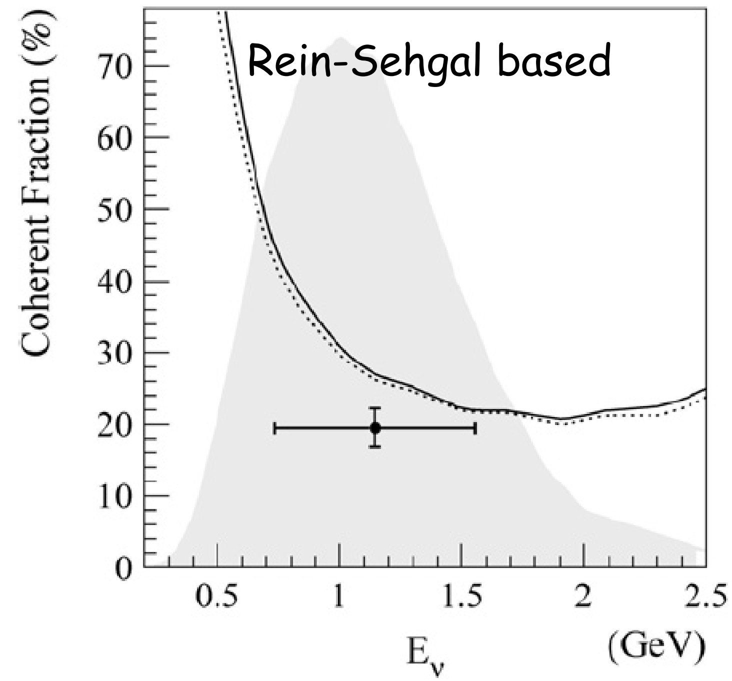
Comparison with data

- Ratios of cross sections
- Absolute cross sections (last months)

Neutral current coherent π^0 production

MiniBooNE, Phys. Lett. B 664, 41 (2008)

$$\frac{\sigma\ \pi^0_{\text{coherent}}}{\sigma\ \pi^0_{\text{total}}} = 19.5 \pm 1.1(\text{stat}) \pm 2.5(\text{sys})\ \%$$



Our ratio: 6%

Difficult to reconcile with data

A problem that other groups also face

Compatibility with π^+ coherent production ?

Charged current coherent π^+ production

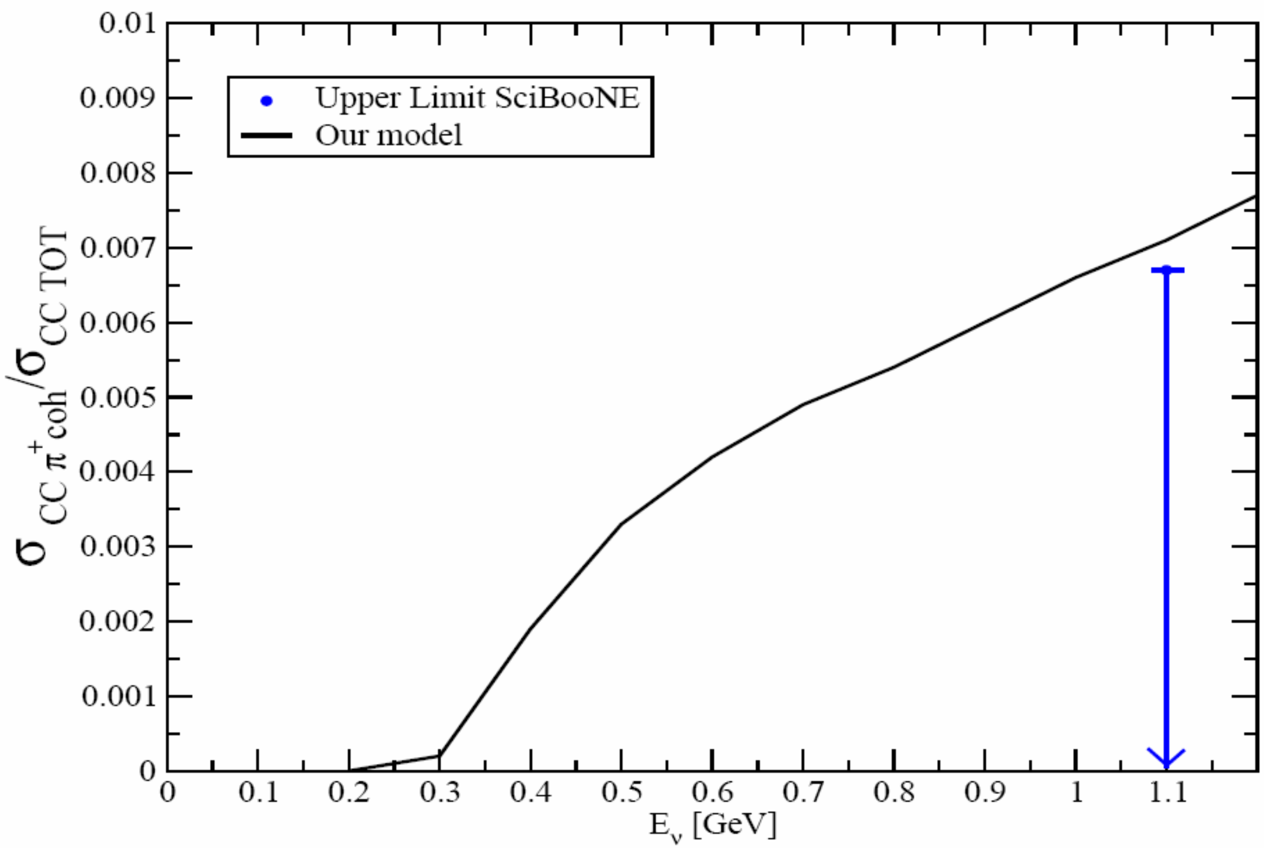
Upper limits

$$\frac{\sigma\ CC\ \pi^+_{coherent}}{\sigma\ CC\ total}$$

K2K: 0.60 10^{-2} averaged over ν flux $\langle E_\nu \rangle$ 1.3 GeV **PRL 95 252301 (2005)**

SciBooNE: 0.67 10^{-2} @ E_ν =1.1 GeV

1.36 10^{-2} @ E_ν =2.2 GeV **PRD 78 112004 (2008)**



Our model @ E_ν=1.1 GeV

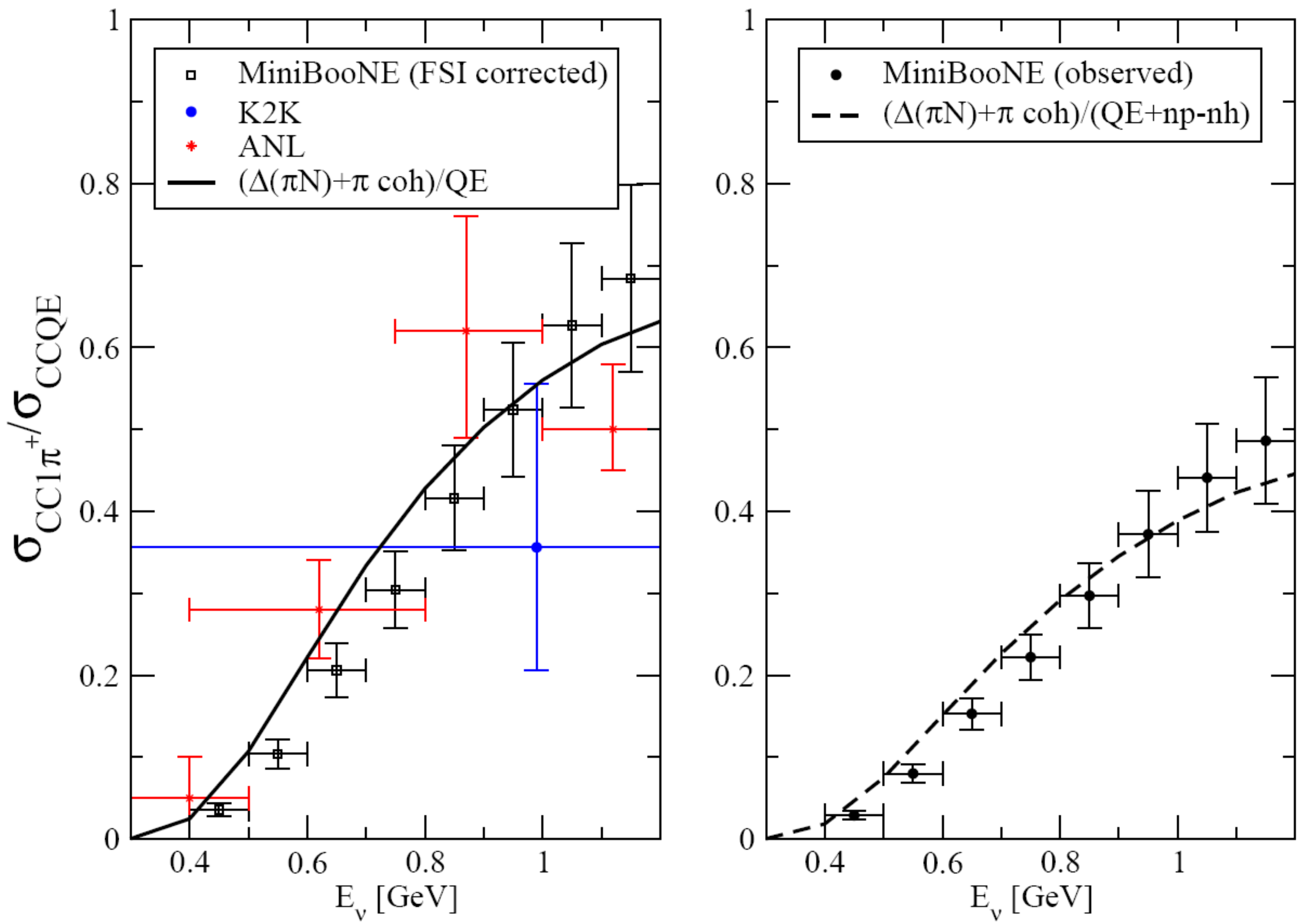
0.71 10^{-2}
Just compatible

Without np-nh in σ CC total

0.89 10^{-2}
Appreciably above u.l.

Charged current total $1\pi^+$ production over QE ratio

MiniBooNE, Phys. Rev. Lett. 103, 081801 (2009)



In our model π FSI are not included;
a reduction of ~ 15 % is expected

NC π^0 production over CC total cross-section

Total π^0

Phys. Rev. D 81, 033004 (2010)

$$\frac{\sigma(NC\ \pi_0)}{\sigma(CC_{TOT})} = (7.7 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \cdot 10^{-2}$$

SciBooNE @ E_ν = 1.1 GeV

Our model

$$\frac{\sigma(NC\ \pi_0)}{\sigma(CC_{TOT})} = 7.9 \cdot 10^{-2}$$

Suppressing np-nh in $\sigma\ CC_{TOT}$

$$\frac{\sigma(NC\ \pi_0)}{(\sigma(CC_{TOT}) - \sigma(CC_{np-nh}))} = 9.8 \cdot 10^{-2}$$

Coherent π^0

$$\frac{\sigma(NC\ \pi_0\ \mathrm{coh})}{\sigma(CC_{TOT})} = (0.7 \pm 0.4) \cdot 10^{-2}$$

SciBooNE @ E_ν = 1 GeV

Our model

$$\frac{\sigma(NC\ \pi_0\ \mathrm{coh})}{\sigma(CC_{TOT})} = 0.4 \cdot 10^{-2}$$

Suppressing np-nh in $\sigma\ CC_{TOT}$

$$\frac{\sigma(NC\ \pi_0\ \mathrm{coh})}{(\sigma(CC_{TOT}) - \sigma(CC_{np-nh}))} = 0.5 \cdot 10^{-2}$$

NC π^0 production absolute cross sections

Total cross section

	MiniBooNE σ [10^-40 cm^2/nucleon]	Our model σ [10^-40 cm^2/nucleon]
ν @ 808 MeV	4.76 ± 0.05 st ± 0.76 sy	5.42
$\bar{\nu}$ @ 664 MeV	1.48 ± 0.05 st ± 0.23 sy	1.37

Incoherent exclusive NC $1\pi^0$

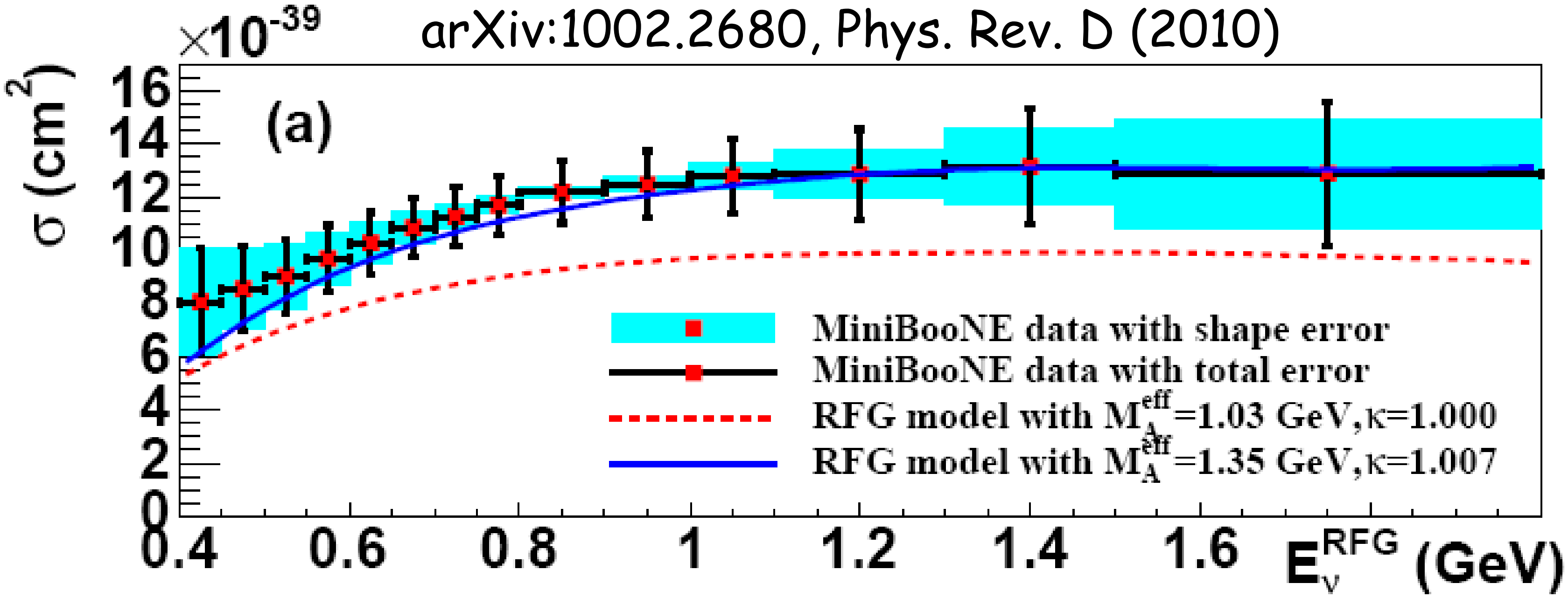
	MiniBooNE corrected for FSI effects	Our model
ν @ 808 MeV	5.71 ± 0.08 st ± 1.45 sy	5.14
$\bar{\nu}$ @ 664 MeV	1.28 ± 0.07 st ± 0.35 sy	1.17

MiniBooNE, Phys. Rev. D 81, 013005 (2010)

P.S. Our model: $\Delta N \rightarrow NN$ absorption process, but not absorption once π_{inco} is placed on-shell

Quasielastic cross section

MiniBooNE,
AIP Conf. Proc. 1189: 139-144 (2009);
arXiv:1002.2680, Phys. Rev. D (2010)



Comparison with a prediction based on RFG with M_A=1.03 GeV (standard value) reveals a discrepancy

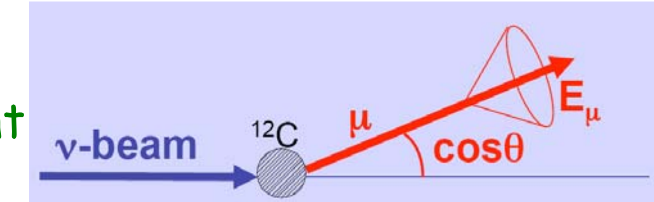
In RFG an axial mass of 1.35 GeV is needed to account for data

The introduction of a realistic spectral function does not alter this conclusion (Benhar and Meloni, Phys. Rev. D80: 073003, 2009)

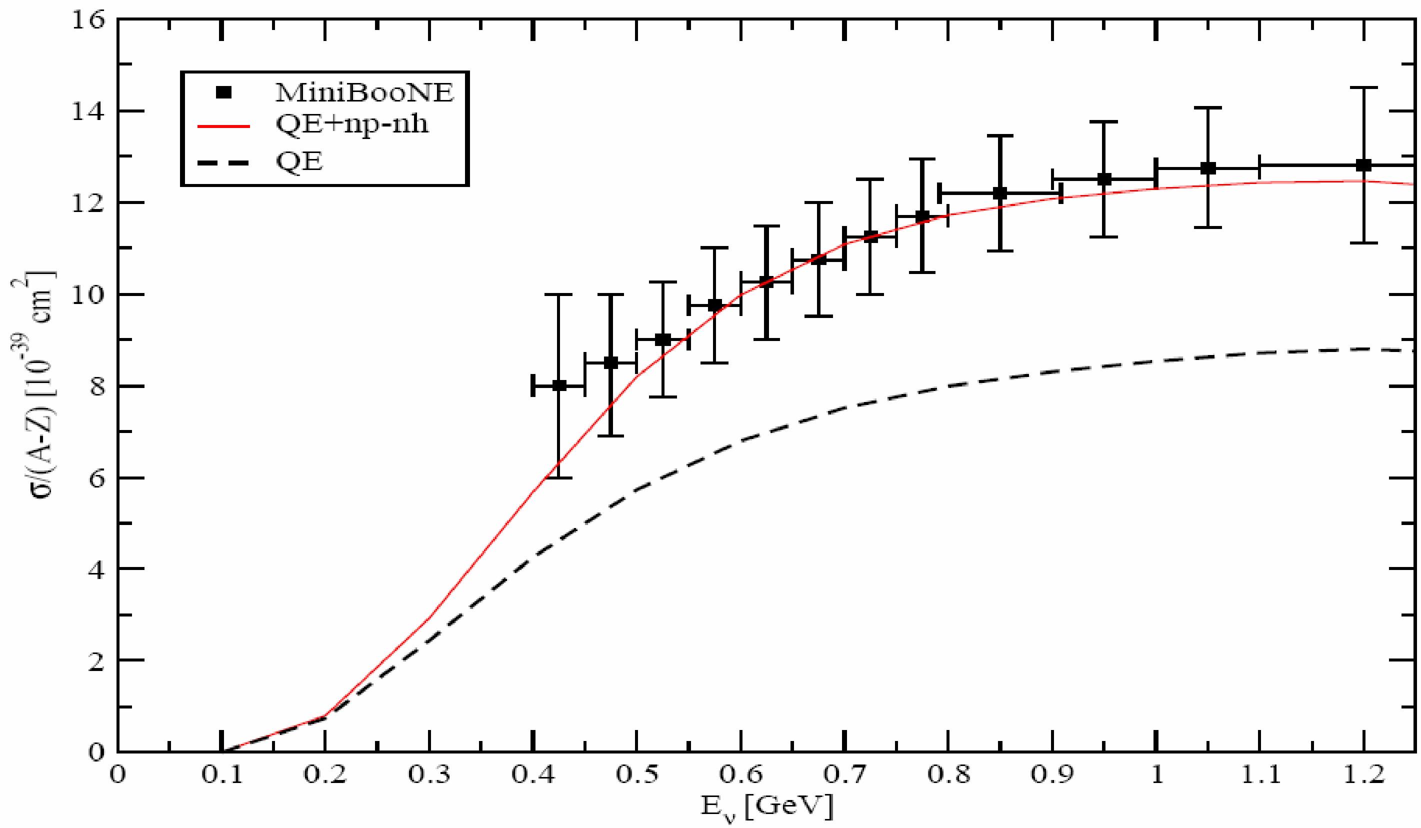
We propose a possible alternative interpretation…

"Quasielastic" events if just μ is detected

• Ejection of a single nucleon (1N): "genuine" QE event



•Events involving a correlated nucleon pair: 2N ejected



Flux averaged:

MiniBooNE

$9.4\ 10^{-39} cm^2 \pm 11\%$

Our model QE+np-nh

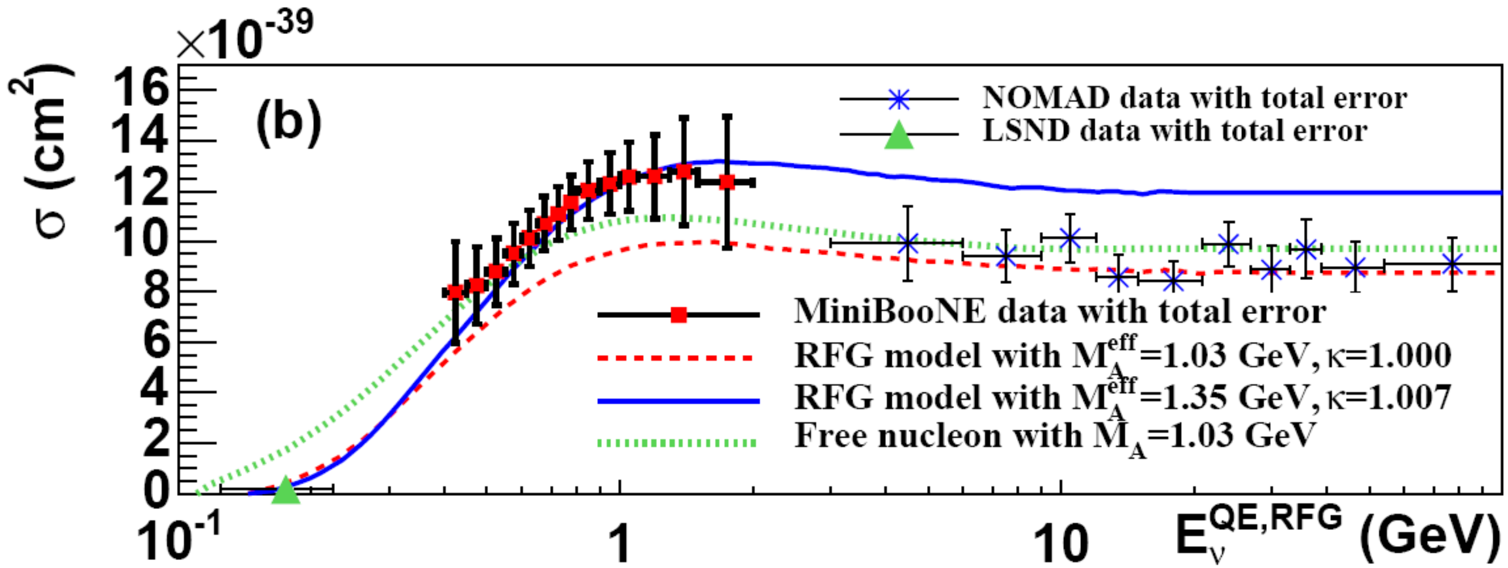
$9.1\ 10^{-39}\ cm^2$

Our model QE

$6.3\ 10^{-39}\ cm^2$

Observed increase of the quasielastic cross section

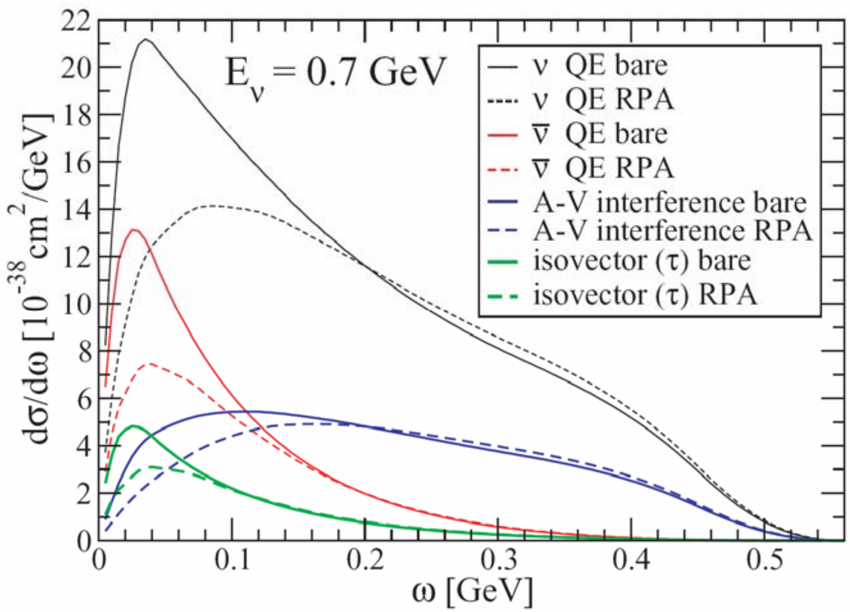
might reflect the underlying nuclear (rather than nucleon's) physics

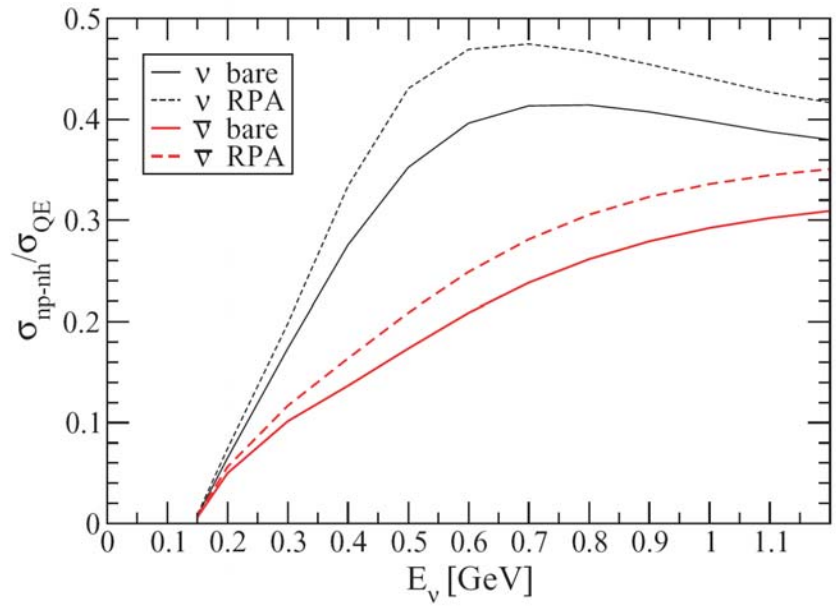


It is interesting that the MiniBooNE measurement is also larger than this free nucleon value (at least at higher energies). This may indicate a significant contribution from neglected mechanisms for CCQE-like scattering from a nucleus such as multi-nucleon processes (for example, Ref. [17]). This may explain both the higher cross section and the harder Q^2 spectrum, but has not yet been explicitly tested. It may also be relevant for the difference between these results and those of NOMAD (or other experiments) where the observation of recoil nucleons enter the definition of a CCQE event.

MiniBooNE, arXiv:1002.2680, Phys. Rev. D 2010

Neutrino vs Antineutrino QE scattering



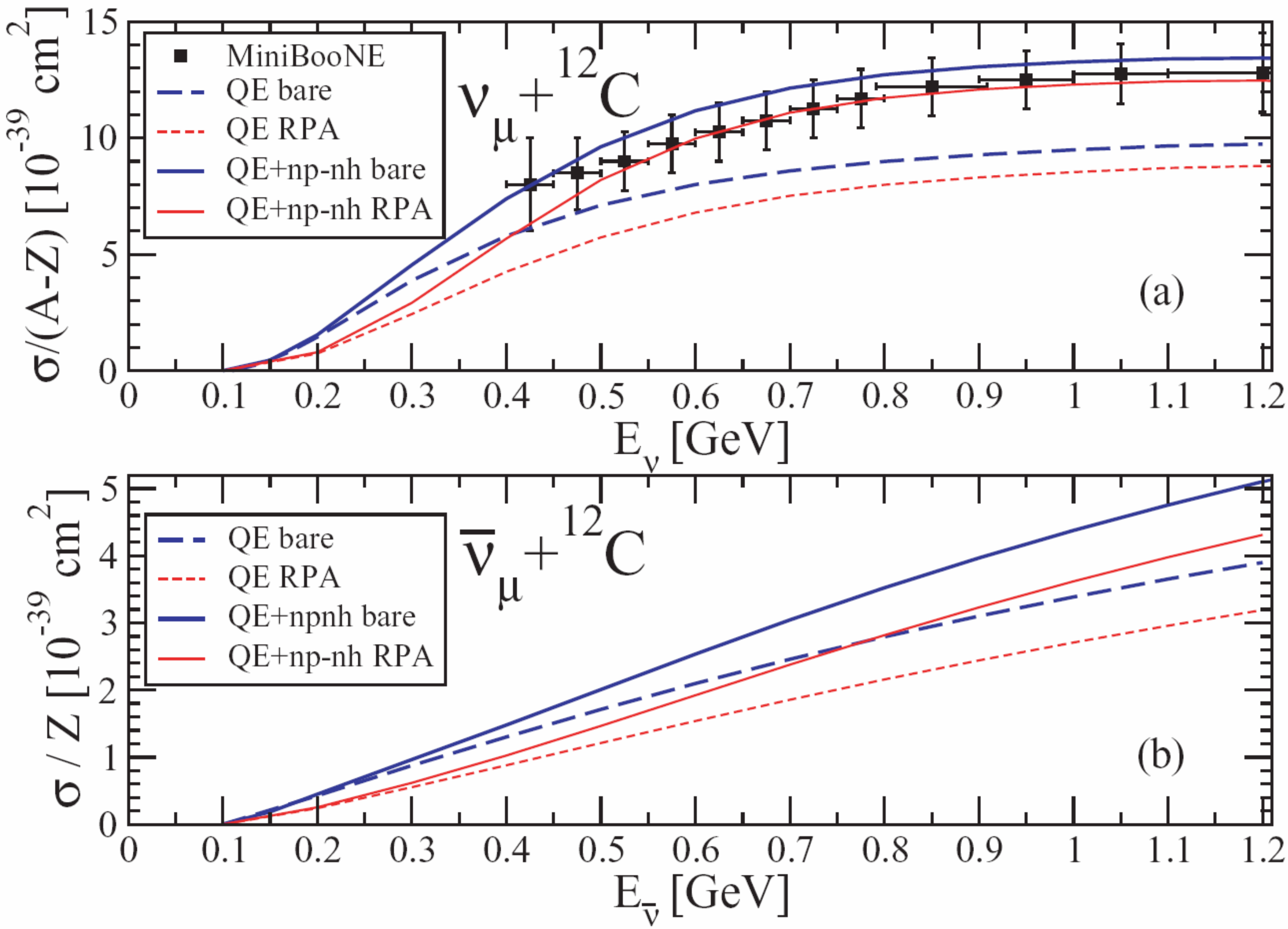


$$\begin{aligned}\frac{\partial^2\sigma}{\partial\Omega\,\partial k'} = {} & \frac{G_F^2\cos^2\theta_c\,(\boldsymbol{k}')^2}{2\,\pi^2}\cos^2\frac{\theta}{2}\left[G_E^2\left(\frac{q_\mu^2}{\boldsymbol{q}^2}\right)^2 R_\tau^{NN}\right. \\ & + G_A^2\,\frac{(M_\Delta-M_N)^2}{2\,\boldsymbol{q}^2}\,R^{N\Delta}_{\sigma\tau(L)} + G_A^2\,\frac{(M_\Delta-M_N)^2}{\boldsymbol{q}^2}R^{\Delta\Delta}_{\sigma\tau(L)} \\ & + \left(G_M^2\,\frac{\omega^2}{\boldsymbol{q}^2}+G_A^2\right)\left(-\frac{q_\mu^2}{\boldsymbol{q}^2}+2\tan^2\frac{\theta}{2}\right)\left(R^{NN}_{\sigma\tau(T)}+2R^{N\Delta}_{\sigma\tau(T)}+R^{\Delta\Delta}_{\sigma\tau(T)}\right) \\ & \left.\pm\ 2\,G_A\,G_M\,\frac{k+k'}{M_N}\tan^2\frac{\theta}{2}\left(R^{NN}_{\sigma\tau(T)}+2R^{N\Delta}_{\sigma\tau(T)}+R^{\Delta\Delta}_{\sigma\tau(T)}\right)\right]\end{aligned}$$

np-nh only affects magnetics and axial responses; no isovector

Interference: suppression for $\bar{\nu}$

Test of "Quasielastic" anomaly: antineutrino scattering



The role of the np-nh is smaller for antineutrinos

Summary

Theory of neutrino interactions with nuclei

Nuclear responses treated in RPA

Unified description of several channels:

- Quasielastic ⇔ E_ν reconstruction
- Pion production ⇔ CC1π backgr. of CCQE; NC π^0 backgr. of Ve appearance
- Multi-nucleon emission ⇔ QE like scattering

Evolution with the mass number (12→40): partial cross-sections scales with *A*

Collective effects in the coherent channel

Successful comparison to the available experimental data (K2K, MiniBooNE, SciBooNE)

Multi-nucleon component quite relevant for the interpretation of the experiments, in particular for the QE of MiniBooNE

Test of "Quasielastic" anomaly: antineutrino scattering

Spares

Bare particle-hole polarization propagators

Nucleon-hole

$$\Pi^0(\vec{q},\omega) = g \int \frac{\mathrm{d}\vec{k}}{(2\pi)^3} \left[\frac{\theta(|\vec{k}+\vec{q}| - k_F)\theta(k_F - k)}{\omega - (\omega_{\vec{k}+\vec{q}} - \omega_{\vec{k}}) + i\eta} - \frac{\theta(k_F - |\vec{k}+\vec{q}|)\theta(k - k_F)}{\omega + (\omega_{\vec{k}} - \omega_{\vec{k}+\vec{q}}) - i\eta} \right]$$

→ Quasielastic

Delta-hole

$$\Pi_{\Delta-h}(q) = \frac{32\tilde{M}_\Delta}{9} \int \frac{d^3k}{(2\pi)^3} \theta(k_F - k) \left[\frac{1}{s - \tilde{M}_\Delta^2 + i\tilde{M}_\Delta \Gamma_\Delta} - \frac{1}{u - \tilde{M}_\Delta^2} \right]$$

→ Pion Production

RPA

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

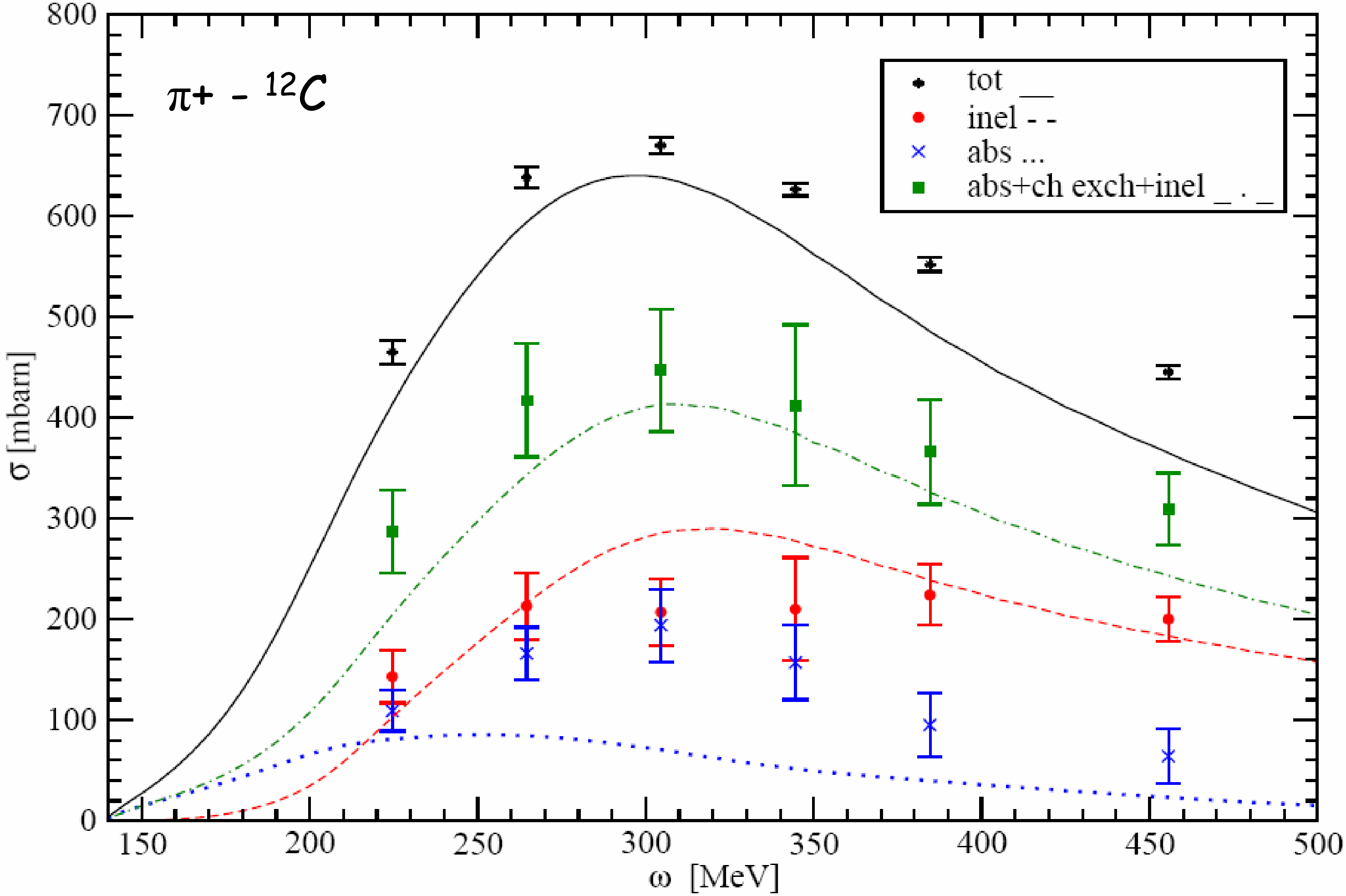
Several partial components

QE, 2p-2h, $\Delta \to \pi N$ ...

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

Pion-nucleus cross-section

$$\sigma^{tot}(\omega) = \left(\frac{g_r}{2M_N}\right)^2 \pi q_\pi \, R_L(\omega, q_\pi)$$



Overestimation of inelastic ch. in the peak region

Underestimation of absorption

Absence of π FSI

ν_μ induced coherent pion production