Review of theoretical developments in neutrino interaction modeling at the quasi-elastic peak

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International Workshop on Global Fits to Neutrino Scattering Data and Generator Tuning (NuTune2016), University of Liverpool, 11-15 July 2016

Neutrino interaction model that covers whole kinematical space available to our experiments (T2K, MicroBooNE, Nova, etc.)

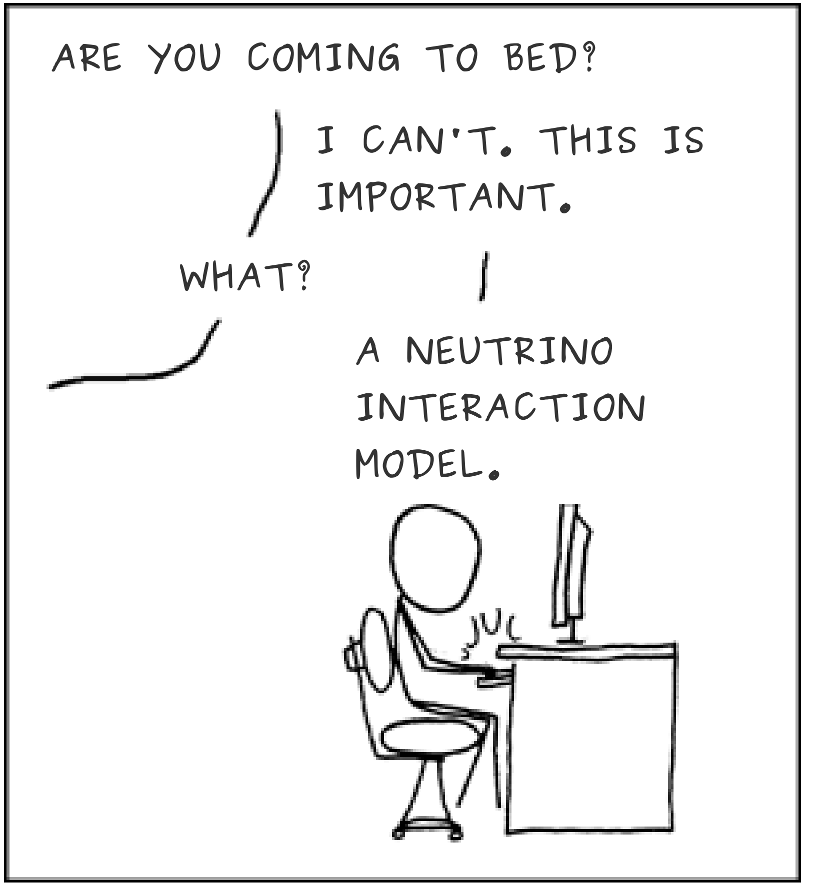
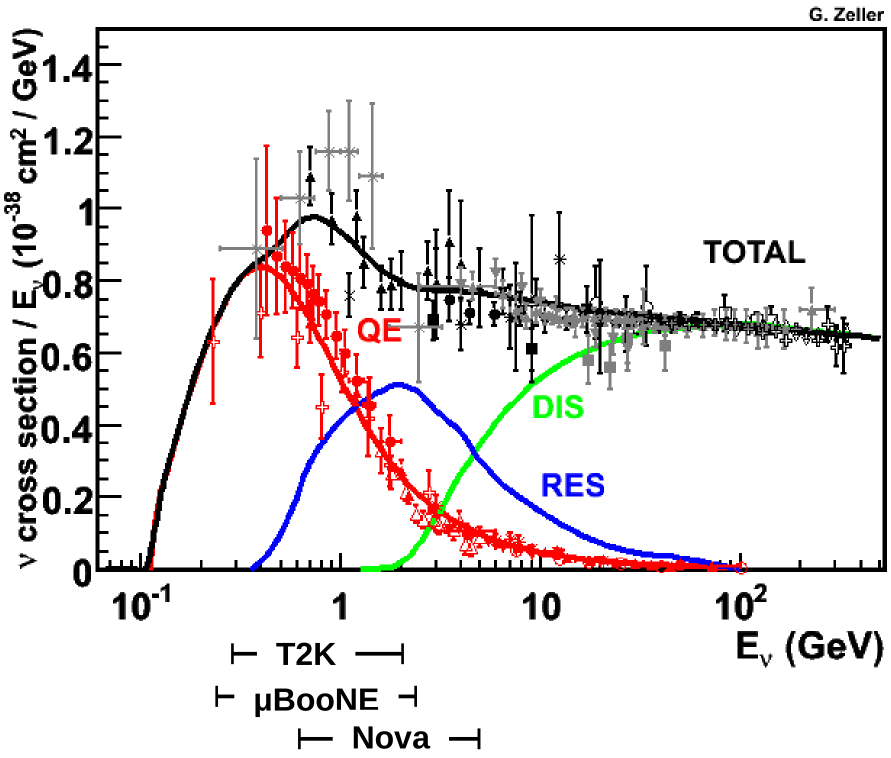


Image modified from xkcd

What neutrino brings: E_ν

Cross section (integrated over full phase-space) in terms of incoming neutrino energy E_ν.



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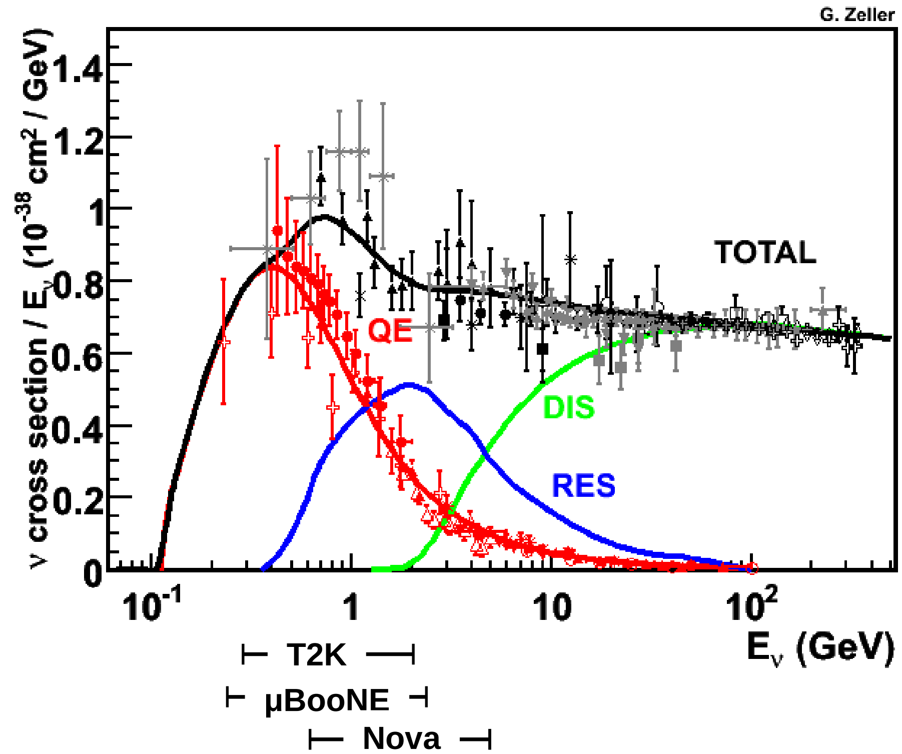
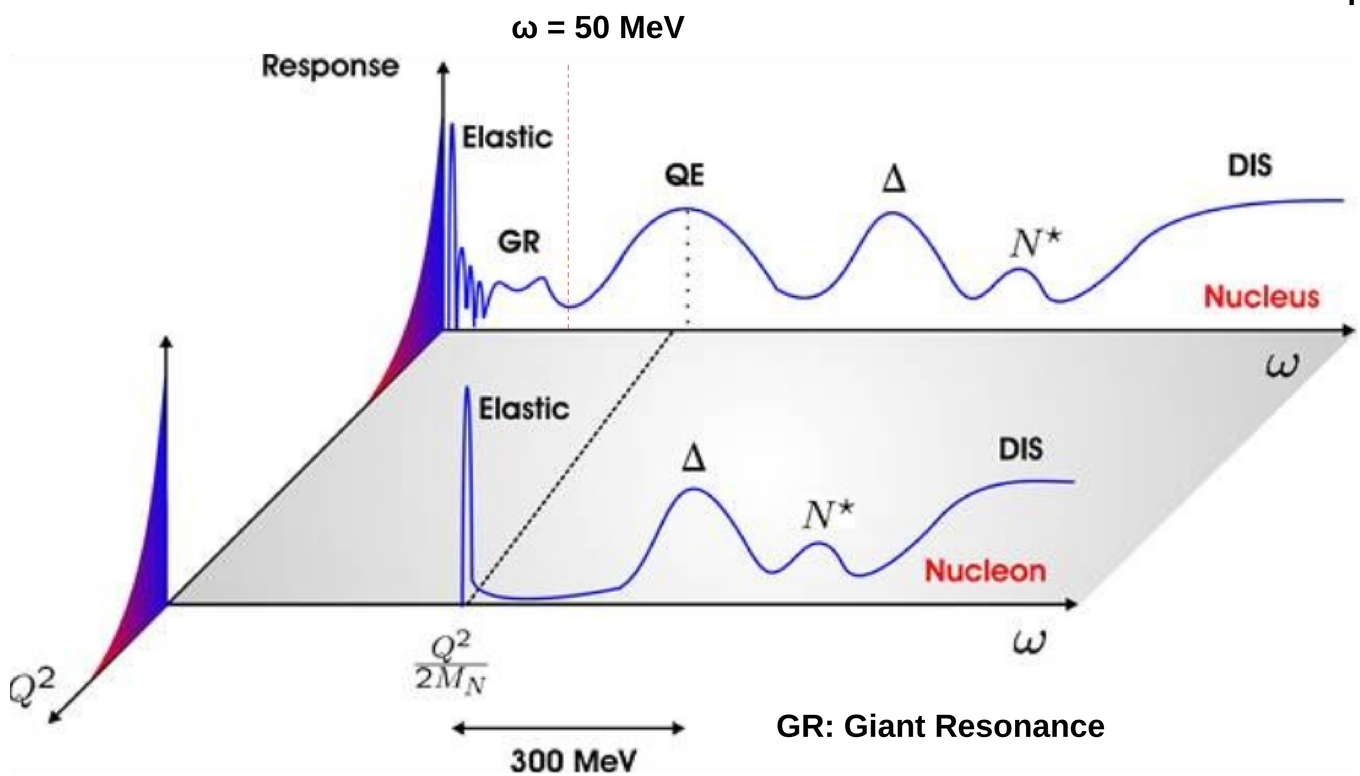




What nucleus cares: ω

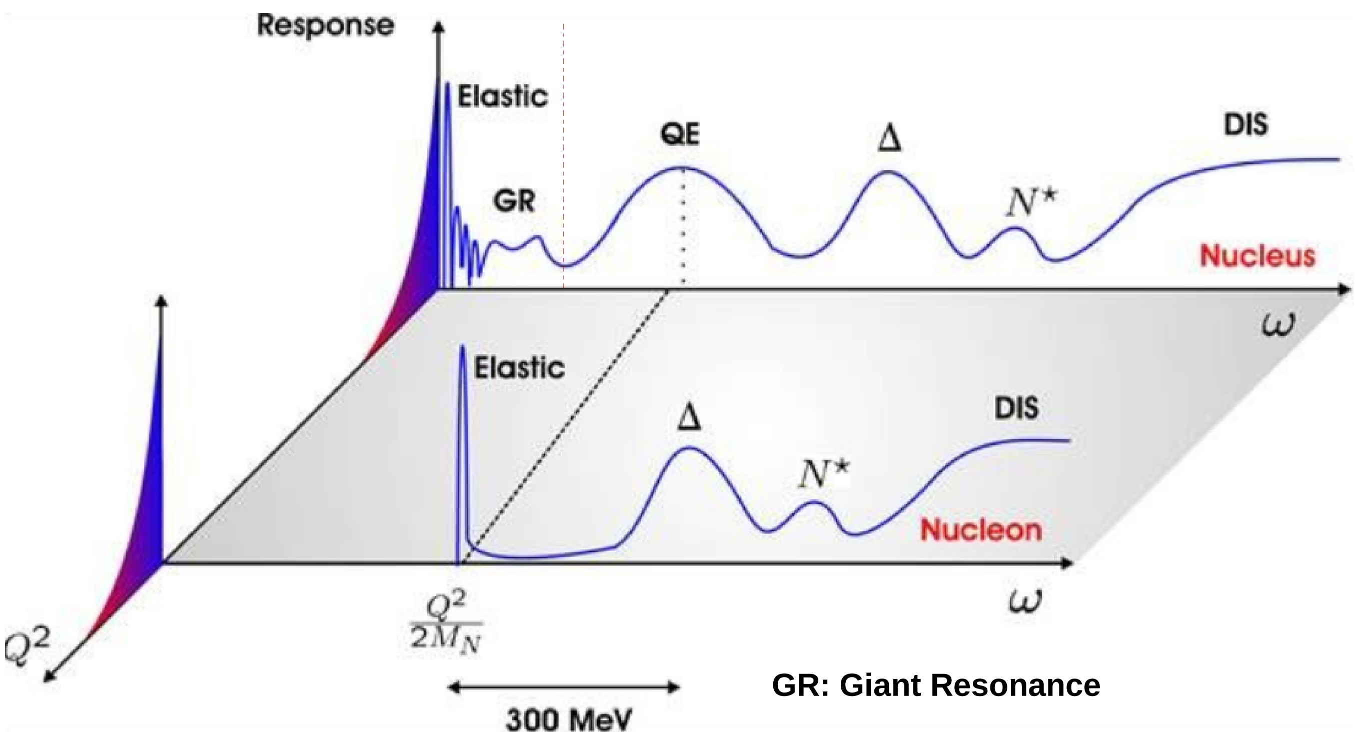
i.e. how much energy is transferred to the nucleus (ω).

For a given E_ν, it depends on other factors, such as on lepton scattering angle.

What is missed in the translation.

Does it matter in the kinematics of our interest?

ω = 50 MeV



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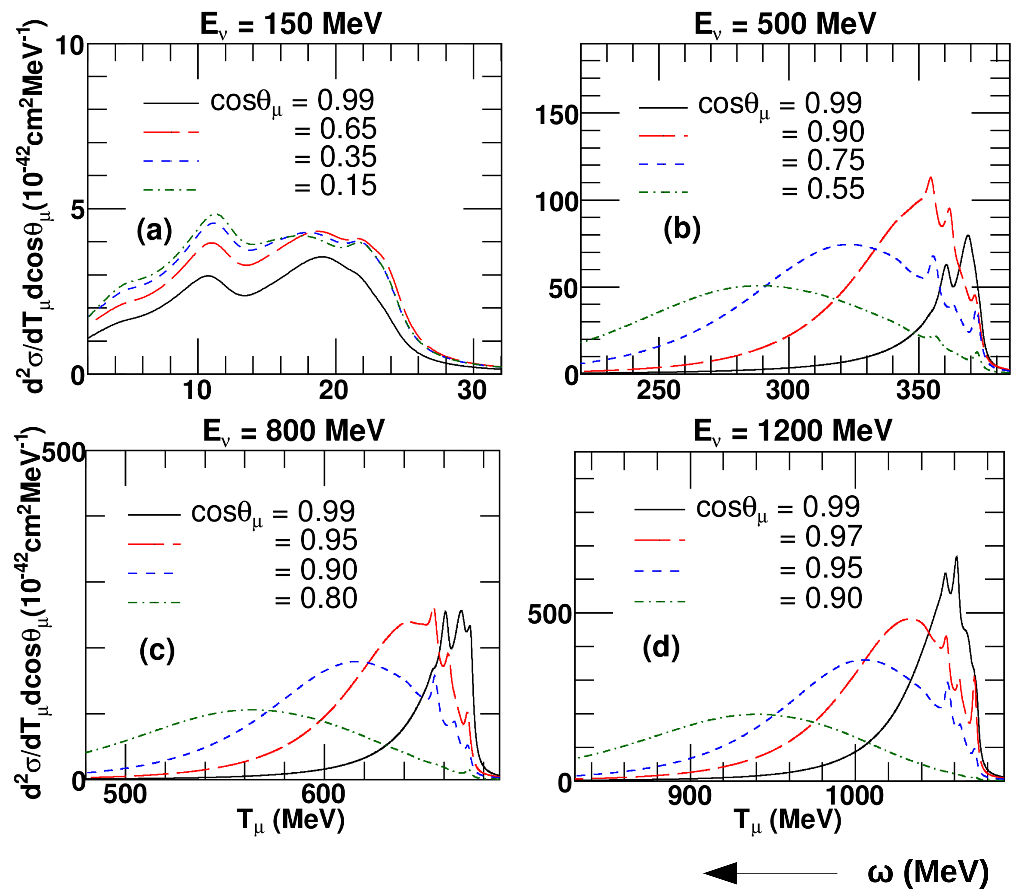
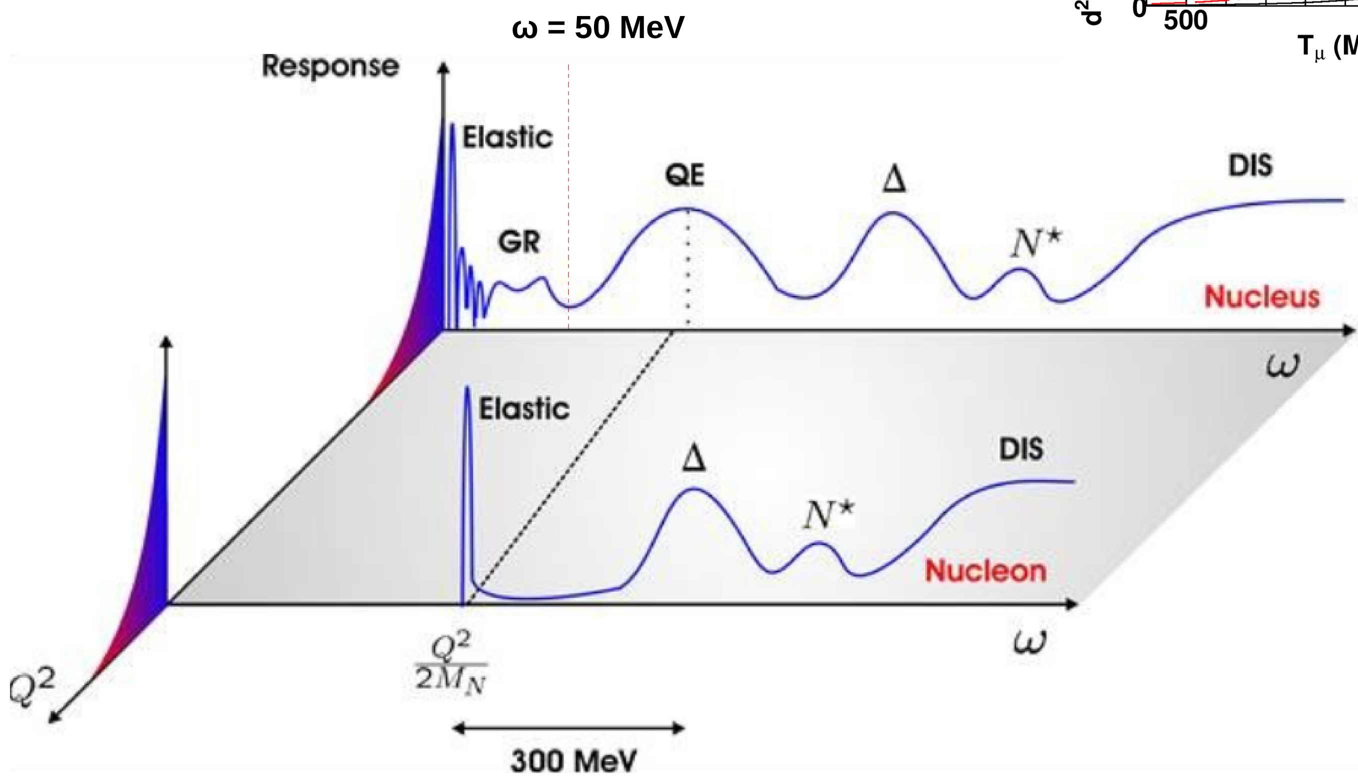
Low E_ν : cross section is dominated by low-energy excitations.

E_ν at the peak of T2K flux, forward scattering receive contribution from low-energy excitations.



VP, N. Jachowicz et al, PRC 92, 024606 (2015)



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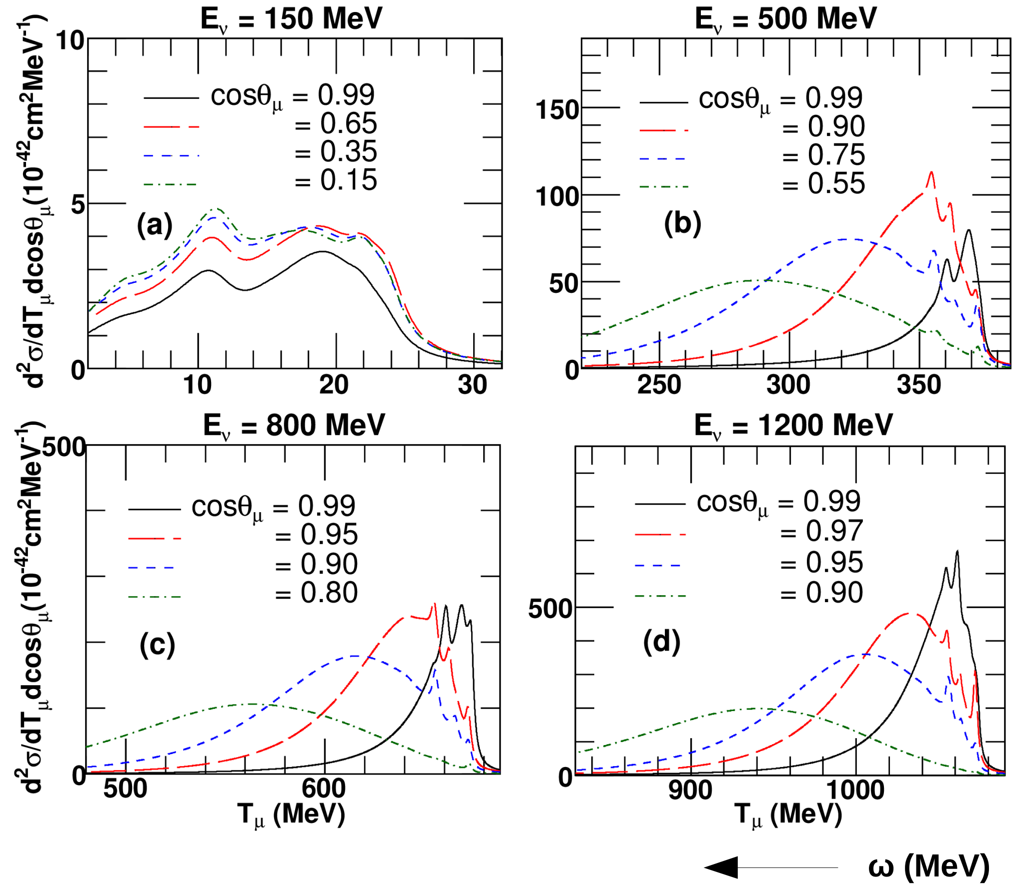
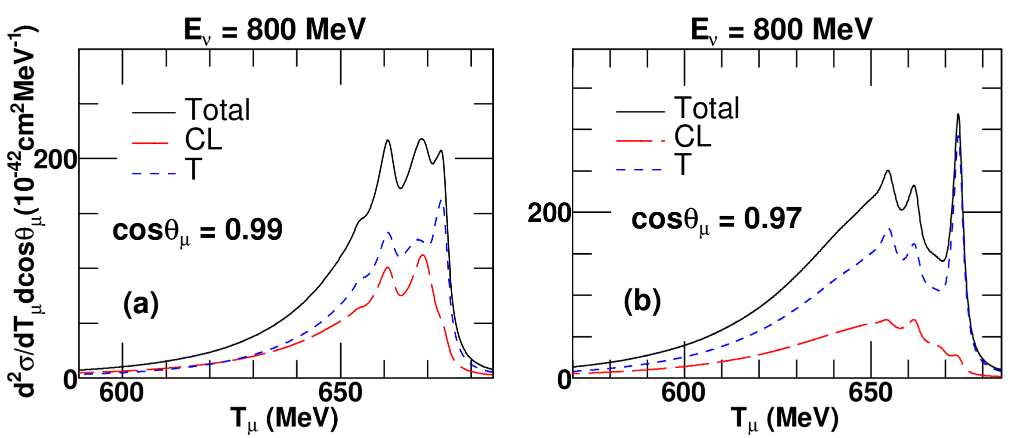


The forward we go in scattering angle, longitudinal contribution starts competing with the transverse one (at intermediate energy).

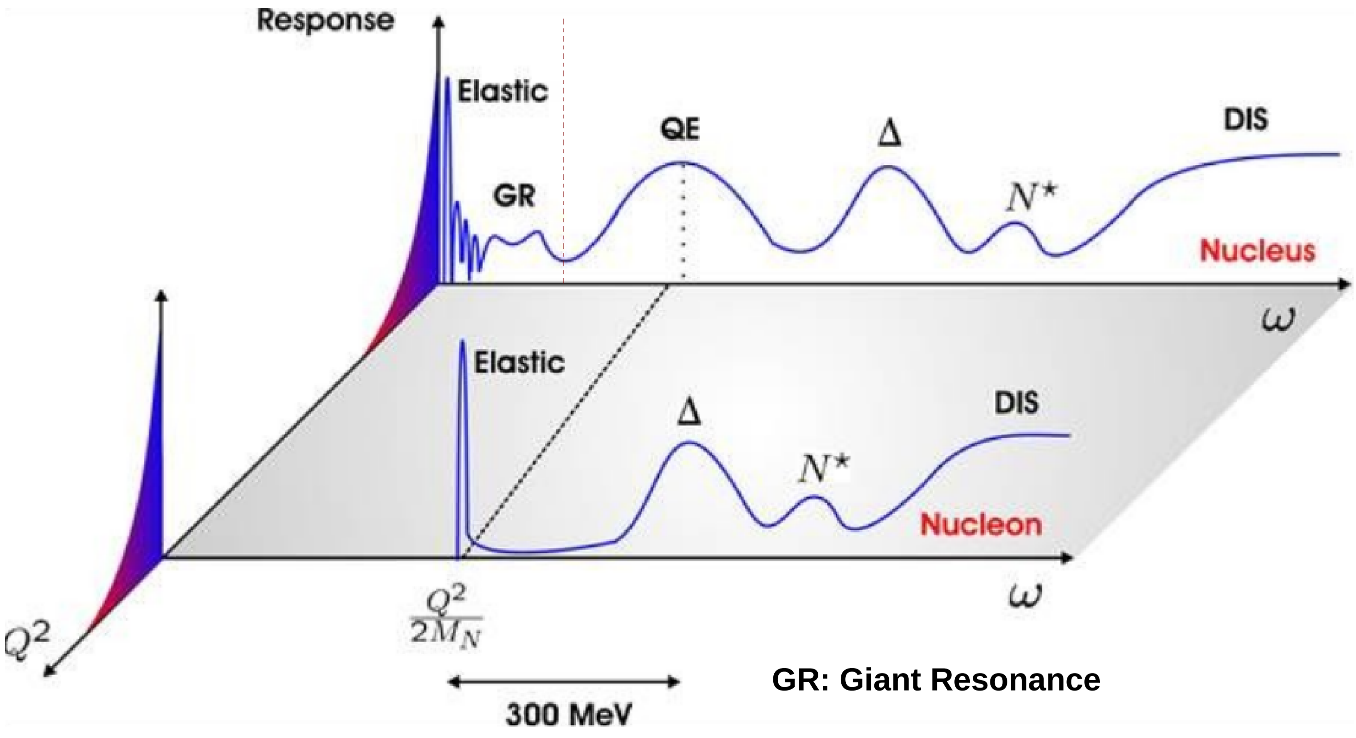
At low-energies and forward scattering, longitudinal response dominates over transverse one.



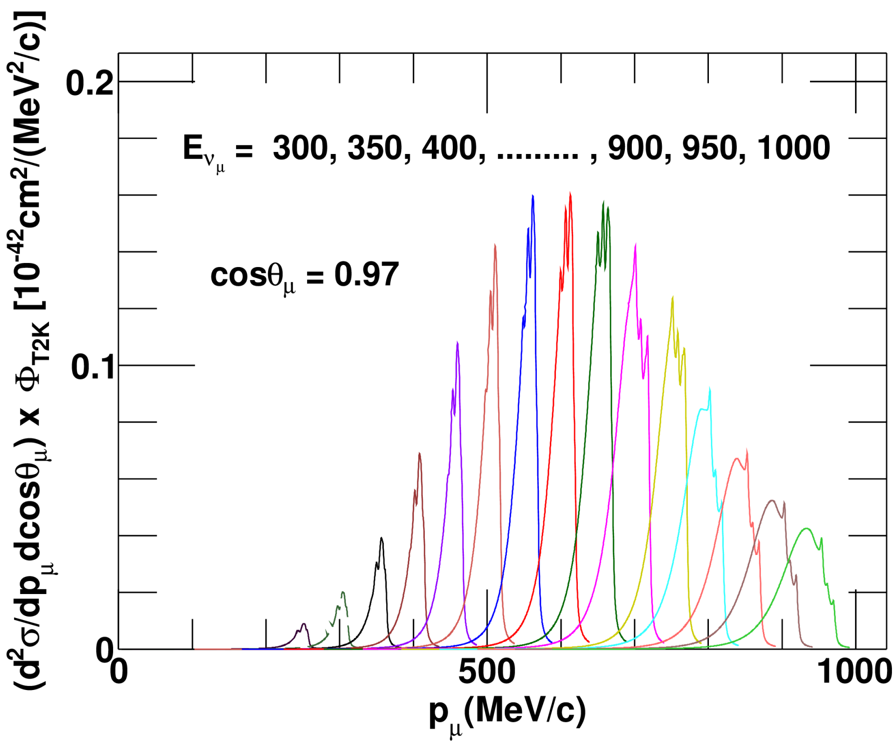
VP, N. Jachowicz et al, PRC 92, 024606 (2015)

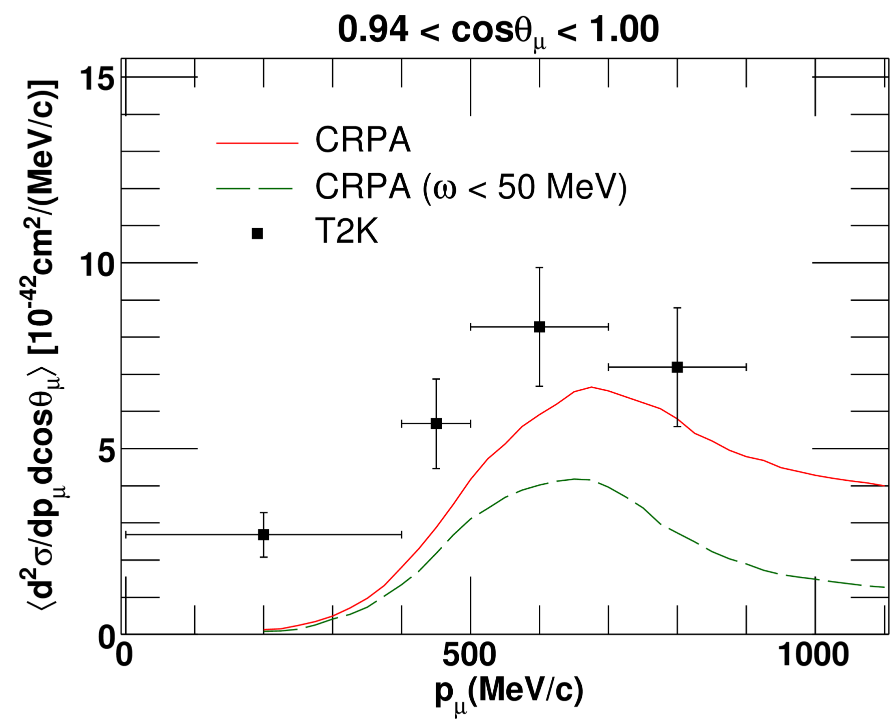
Does it affect the flux-folded cross section?
And how much?

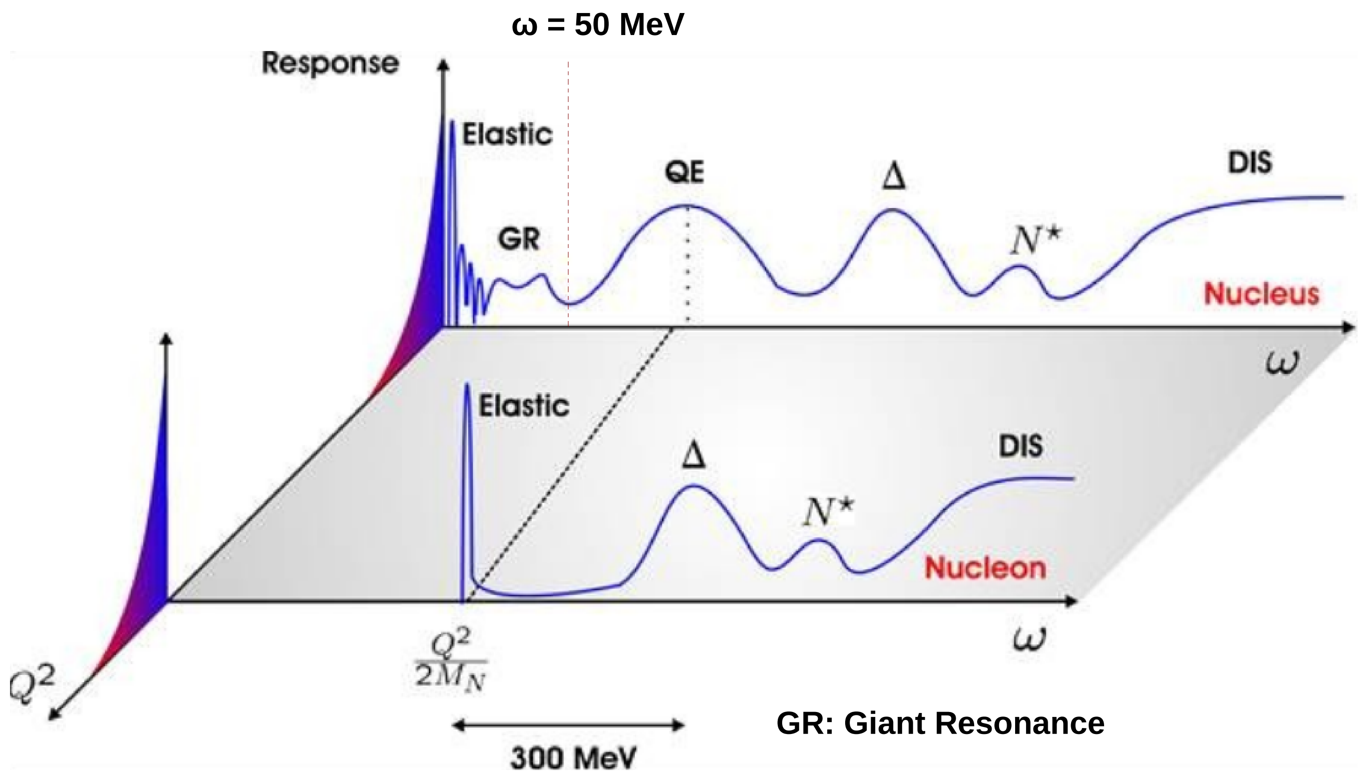
ω = 50 MeV



GR: Giant Resonance





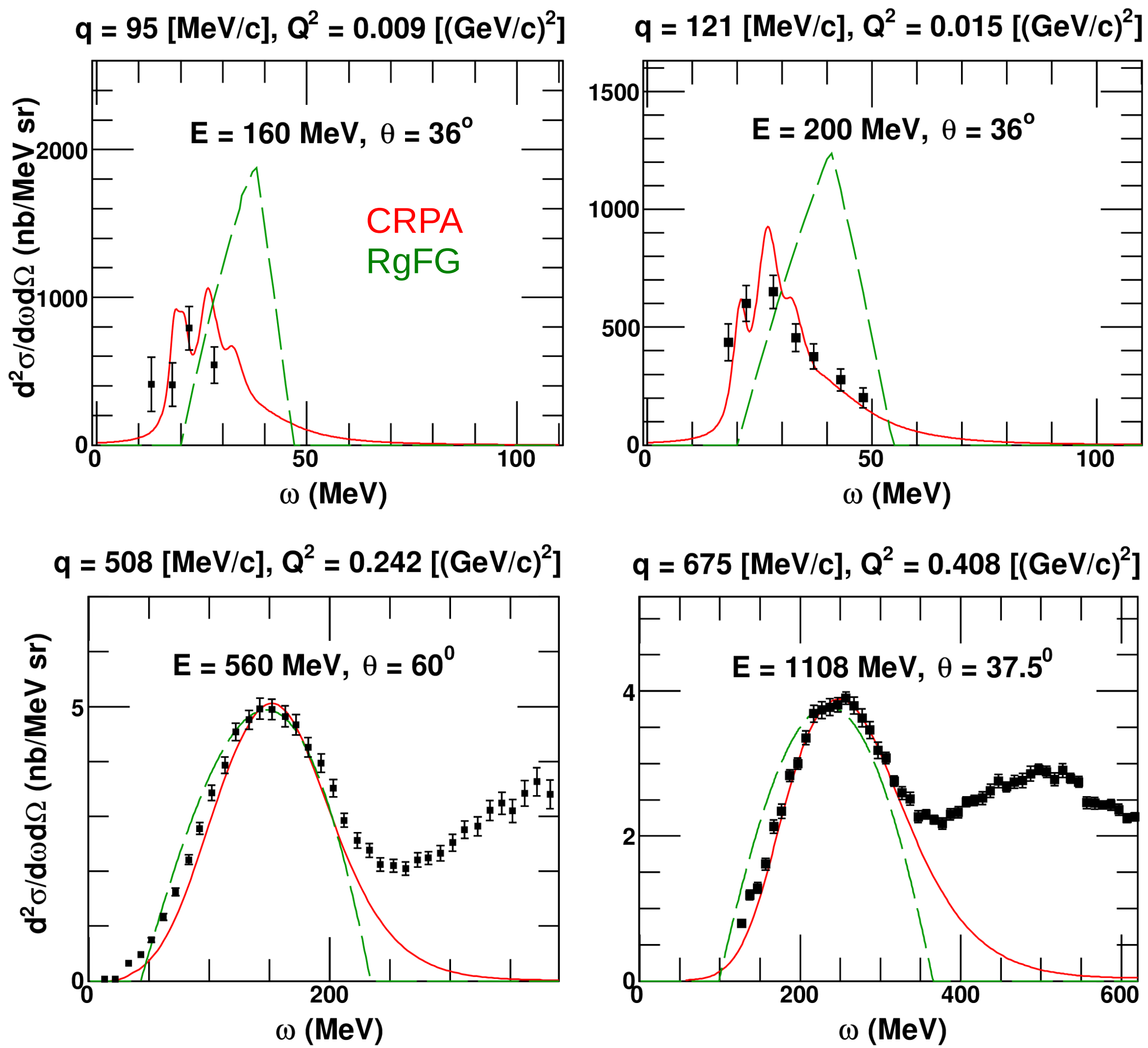


~ 50% of the flux folded cross section in this forward bin emerges from low-energy nuclear excitations.

VP, N. Jachowicz, arXiv:1607.01216 [nucl-th]

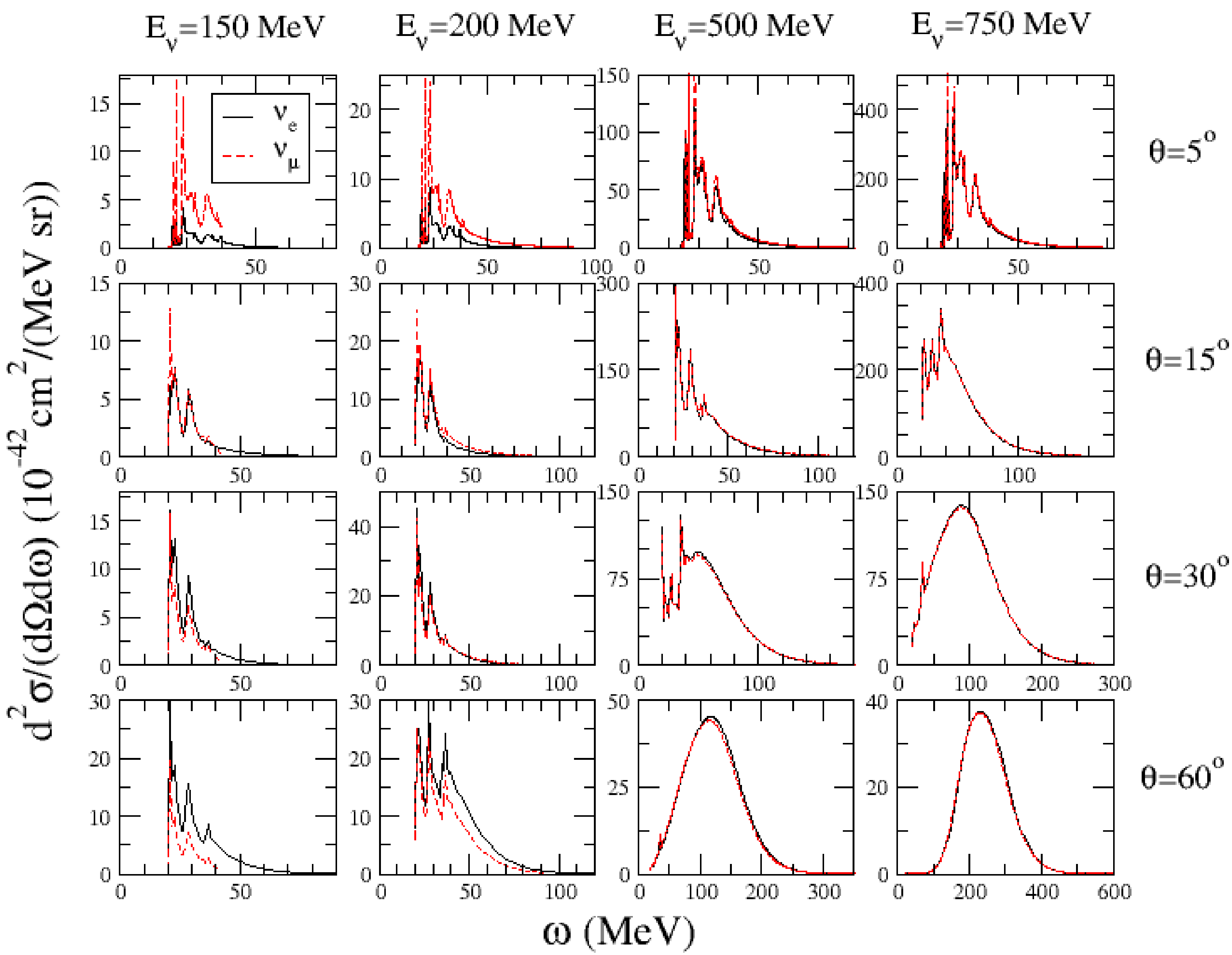
How does RgFG model describes low-energy excitations – it does not!

- Example from ^{12}C *(e,e')*



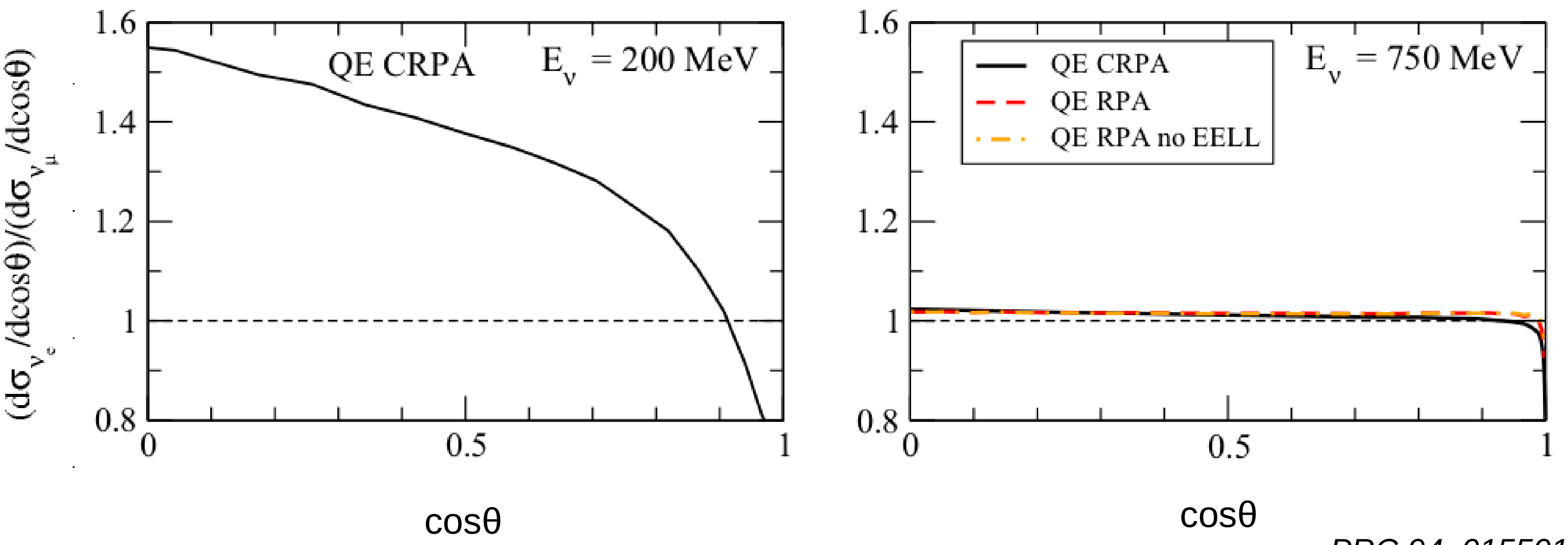
VP, PhD thesis (2016)

The effect of low-energy nuclear excitations on ν_e *vs* ν_μ cross section



PRC 94, 015501 (2016)

The effect of low-energy nuclear excitations on ν_e *vs* ν_μ cross section



PRC 94, 015501 (2016)

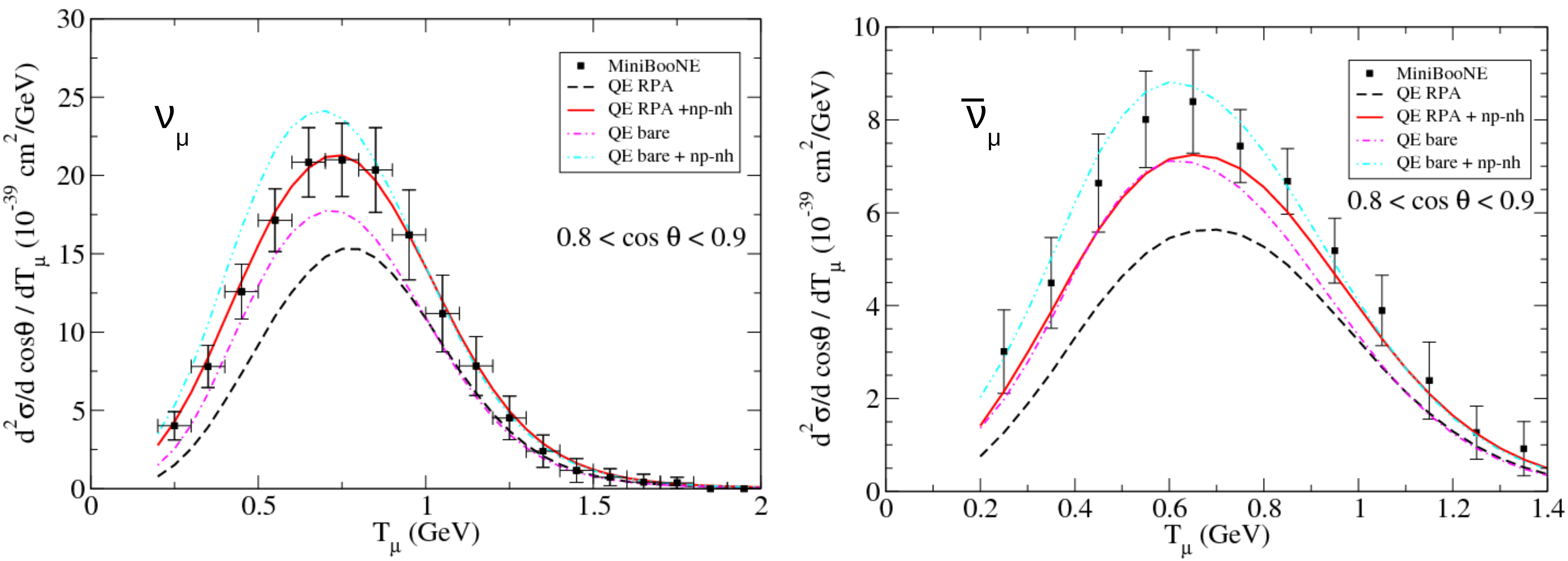
Low-energy nuclear excitations are vital
- At low E_ν
- At intermediate E_ν and forward scattering
- Differentiating between ν_e and ν_μ cross section (at low E_ν)

Martini, Ericson *et al.* (Saclay/Lyon) Model

- The nuclear ground state is a Fermi gas of non-interacting nucleons characterized by a Fermi momentum fixed according to the local density of protons and neutrons (**local Fermi gas model**).
- The **RPA** correlations are introduced through pion exchange, rho exchange, and contact Landau-Migdal parameters.

- First one to reproduce MiniBooNE CCQE cross section (with M_A~1 GeV) with the inclusion of np-nh channel.

<u>References</u>:
PRC 80, 065501 (2009); PRC 81, 045502 (2010); PRC 84, 055502 (2011); PRD 85, 093012 (2012); PRD 87, 013009 (2013); PRC 87, 065501 (2013); PRC 90, 025501 (2014); PRC 91, 035501 (2015); arXiv:1602.00230 [nucl-th], etc.

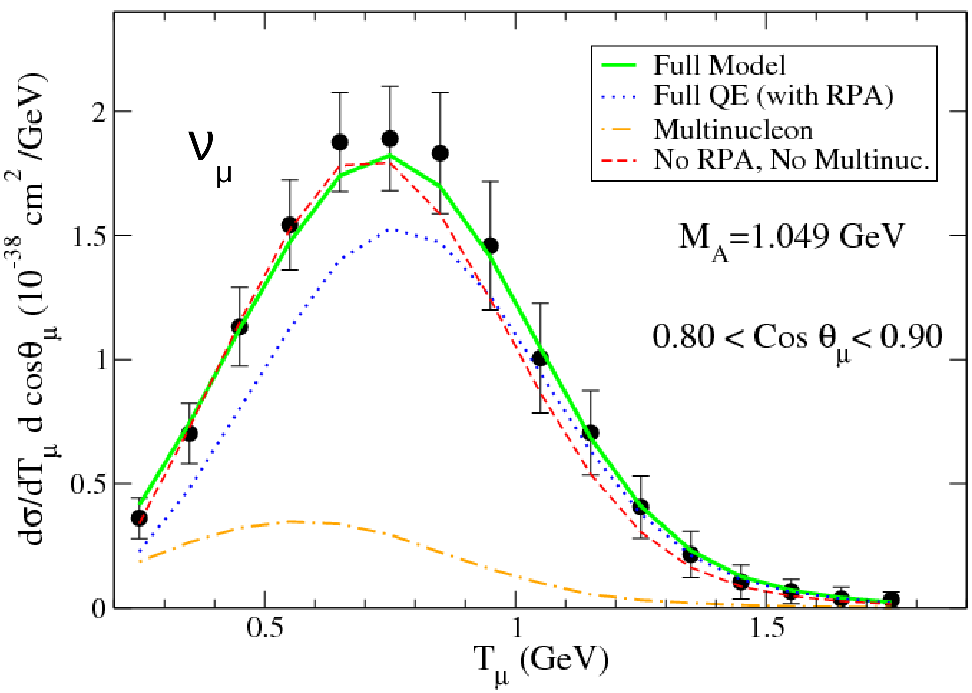


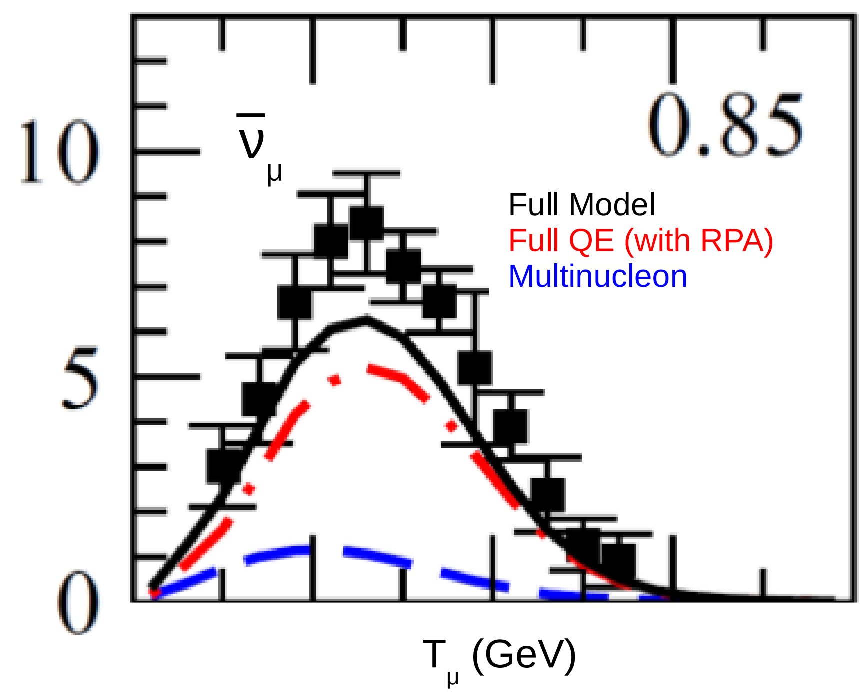
Nieves *et al.* (Valencia) Model

- The nuclear ground state is a Fermi gas of non-interacting nucleons characterized by a Fermi momentum fixed according to the local density of protons and neutrons (**local Fermi gas model**).
- The **RPA** correlations are introduced through pion exchange, rho exchange, and contact Landau-Migdal parameters.

- MiniBooNE data rescaled by a factor 0.9.

References:
PRC 83, 045501 (2011); PLB 707, 72 (2012);
PRD 85, 113008 (2012); PLB 721, 90 (2013);
PRD 88, 113007 (2013), etc.



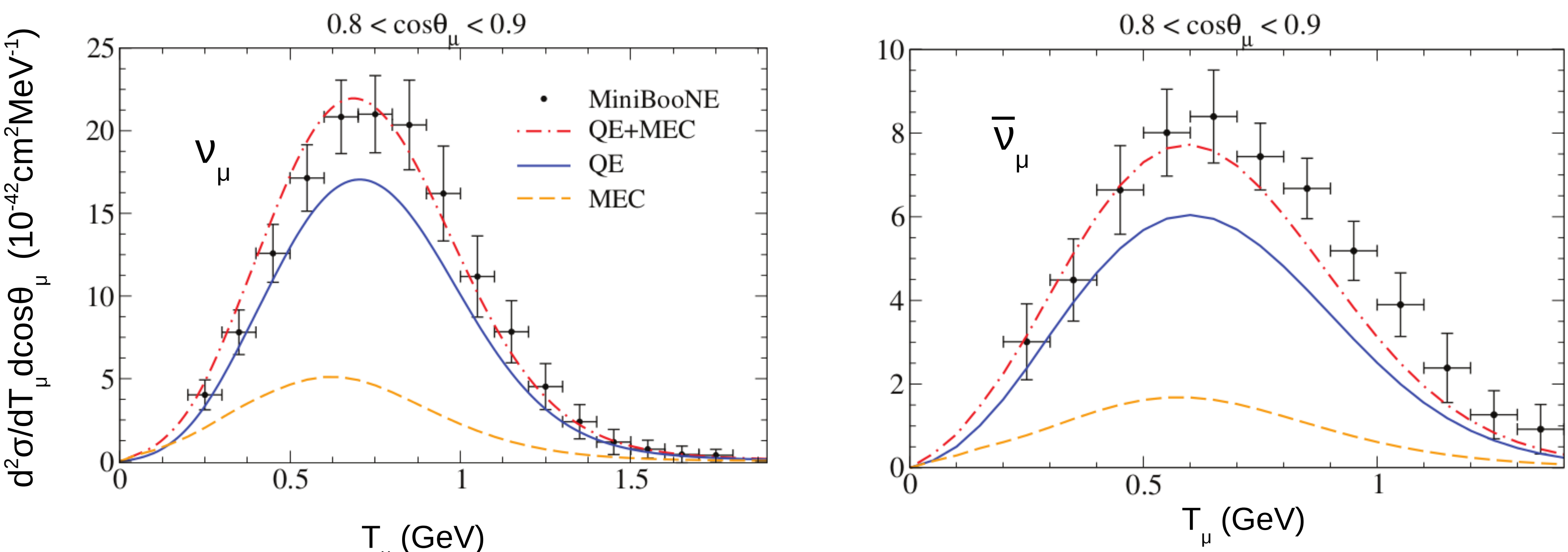


Super-Scaling Approach [SuSA] (Granada/MIT/Sevilla/Torino)

- The basic procedure consists of dividing the experimental (e, e′) data by an appropriate single-nucleon cross section to obtain the scaling function.

- The Super-scaling behavior of (e, e′) scattering is extended to neutrino scatterings.

<u>References</u>:
PLB 696, 151 (2011); PRD 84, 033004 (2011);
PRL 108, 152501 (2012); PLB725, 170 (2013);
PLB727, 265 (2013); PRD89, 093002 (2014);
PRD 90, 033012 (2014); PRD 90, 053010 (2014);
PRC90, 035501 (2014); PRD 91, 073004 (2015);
JPG 43, 045101 (2016), etc.

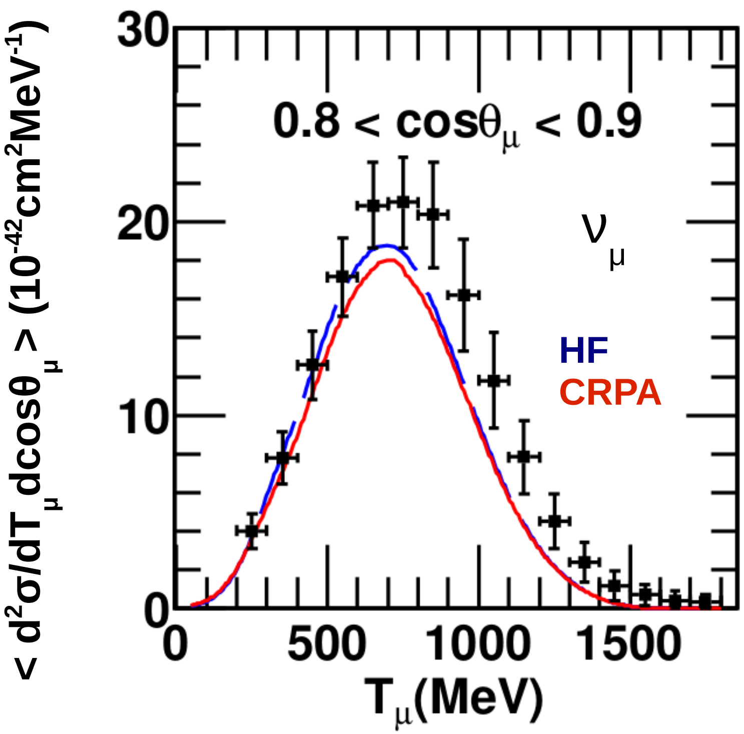


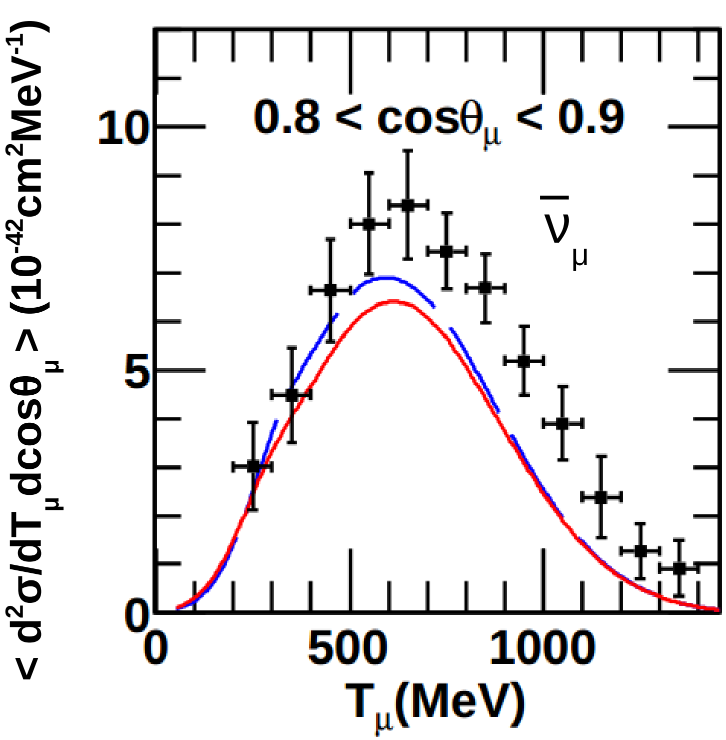
(preliminary) Megias Talk (Saclay-ESNT workshop)

Pandey, Jachowicz *et al.* (Ghent) Model

- The model takes the mean-field (MF) approach as the starting point, and solves Hartree-Fock (HF) equations using a Skyrme (SkE2) nucleon-nucleon interaction.
- Long-range nuclear correlations are taken into account by means of the continuum random-phase approximation (CRPA) framework.
- FSI is taken into account.
- Describes nuclear response from giant resonances to QE channel.

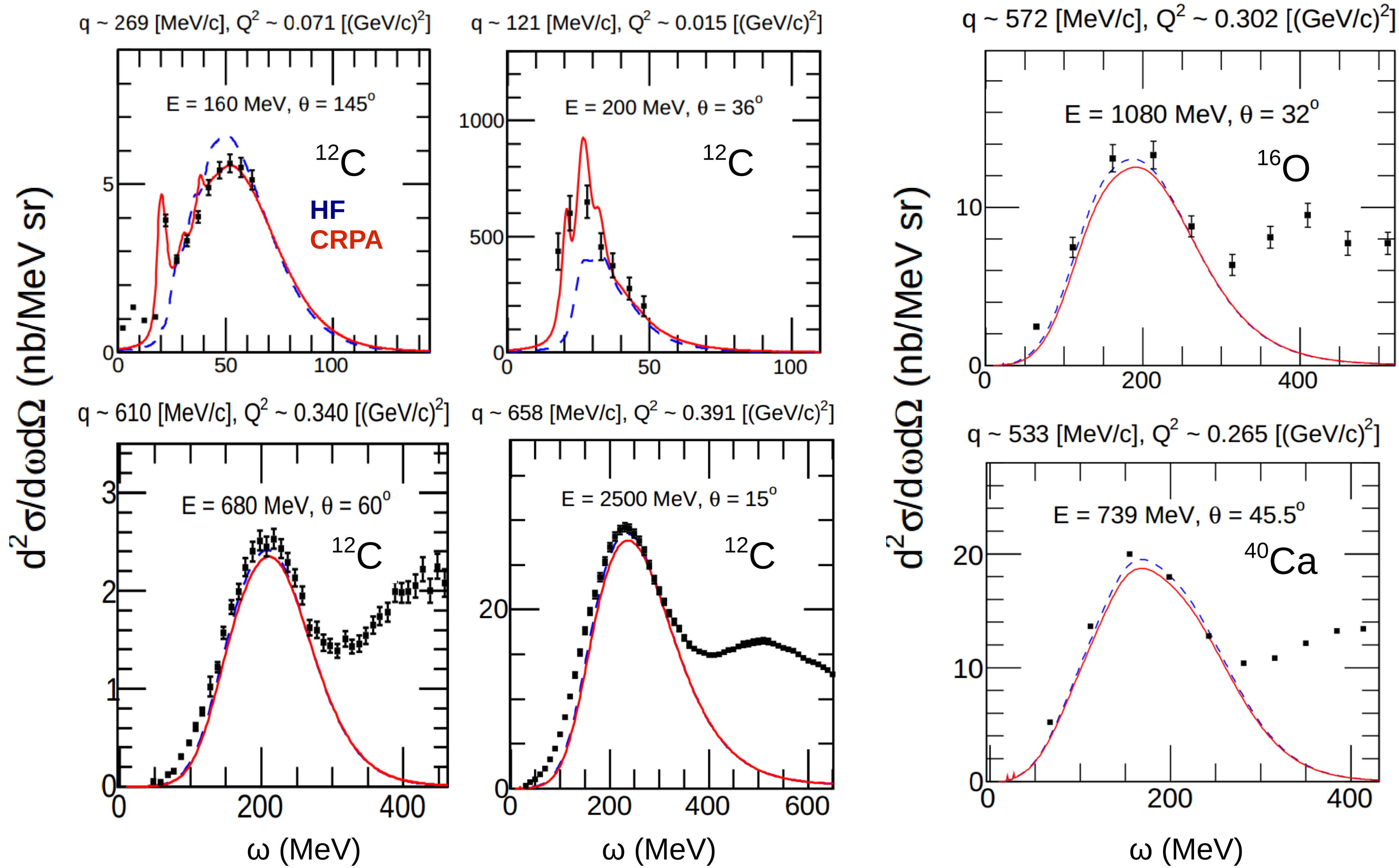
References:
PRC 89, 024601 (2014); PRC 92, 024606 (2015); PRC 94, 015501 (2016); arXiv:1606.00273 [nucl-th]; arXiv:1607.01216 [nucl-th]





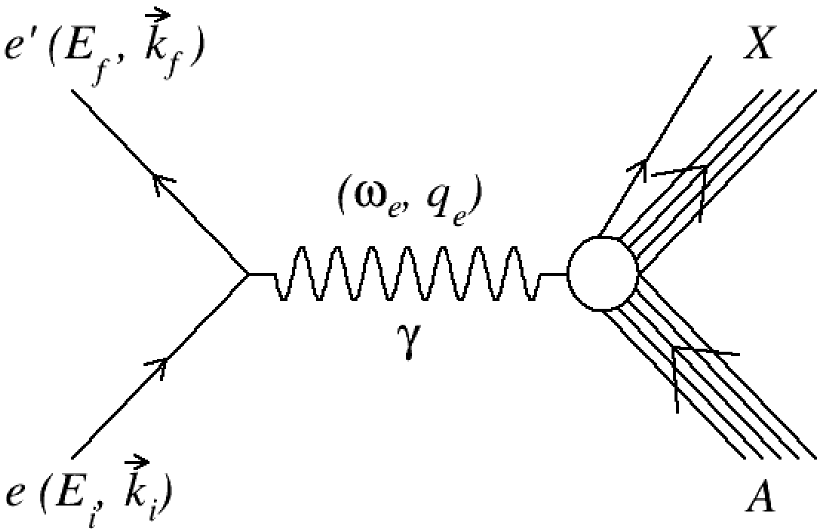
Pandey, Jachowicz *et al.* (Ghent) Model

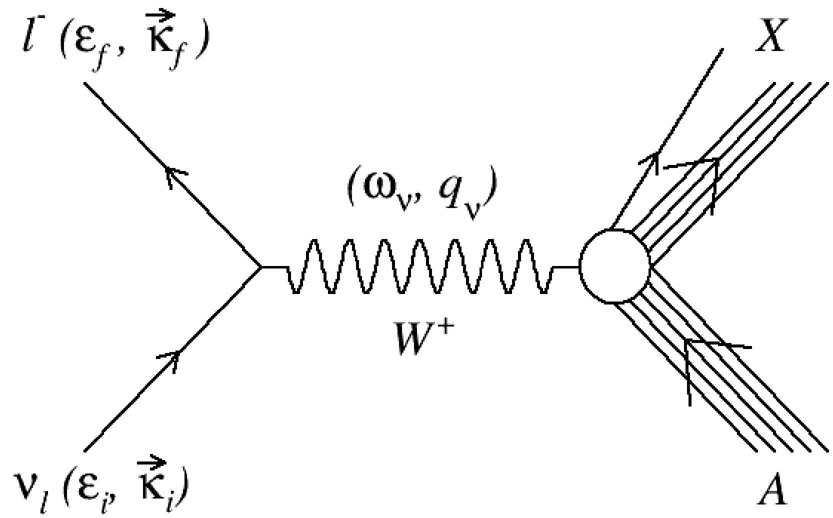
- Compared with (e,e') data for ^{12}C, ^{16}O, ^{40}Ca
- VP, N. Jachowicz, PRC 92, 024606 (2015)



Pandey, Jachowicz *et al.* (Ghent) Model

- Same ν code, in few simple steps, can be adapted to e⁻ code (no tuning, etc. involved)





$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma_{L,e}^J + \sum_{J=1}^{\infty}\sigma_{T,e}^J\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

$$\sigma_{T,e} = v_e^T R_e^T$$

$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2 \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f \kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma_{CL,\nu}^J + \sum_{J=1}^{\infty}\sigma_{T,\nu}^J\right]$$

$$\sigma_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

$$\sigma_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

Relativistic Green's Function Model (Meucci, Giusti *et al.*)

PRL 107, 172501 (2011): PRD 84, 113003 (2011);
PRD 85, 093002 (2012); PRD 88, 013006 (2013);
PRD 89, 057302 (2014); PRD 89, 117301 (2014);
PRD 91, 093004 (2015), etc.

Spectral Function Formalism (Benhar *et al.*)

PRL 105, 132301 (2010); PRD 82, 013002 (2010);
PRD 91 033005, (2015); Phys. Rev. C 92, 024602 (2015);
PRL 116, 192501 (2016), etc.

Green's Function Monte Carlo Approach (ANL/ LANL/ Jlab)

PRL 112, 182502 (2014); PRC 91, 062501 (2015), etc.

Comparing RPA-based models

RPA polarization propagator: $\Pi = \Pi^0 + \Pi^0 \, V \, \Pi$

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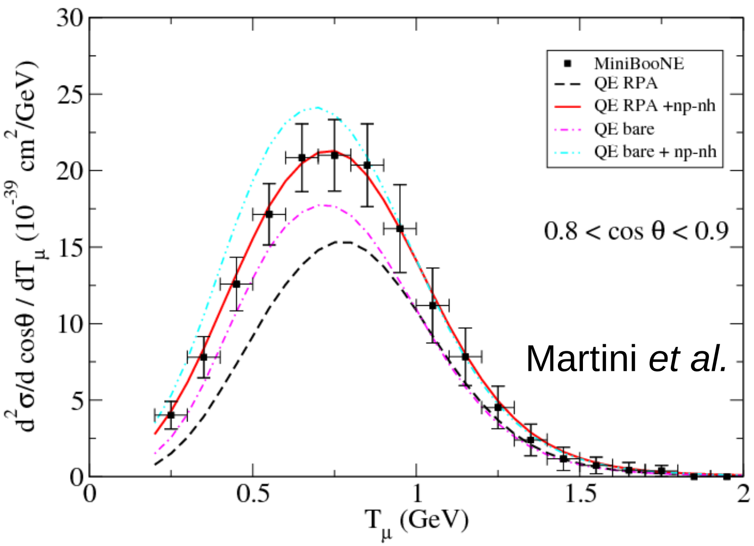
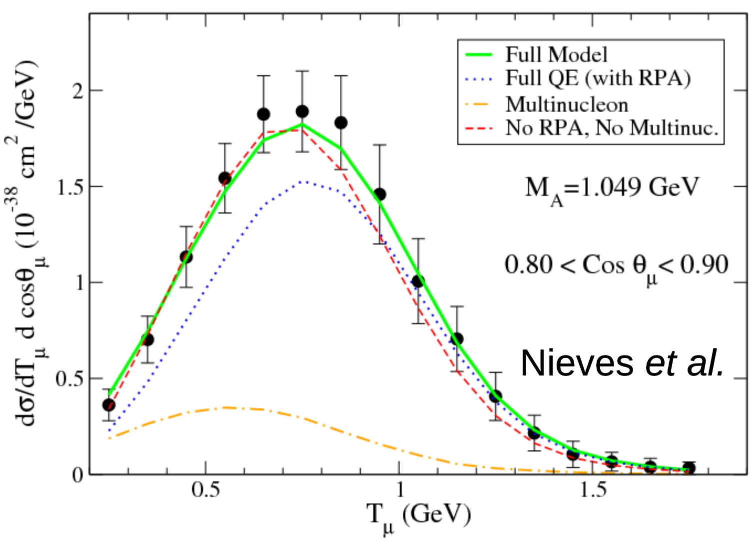
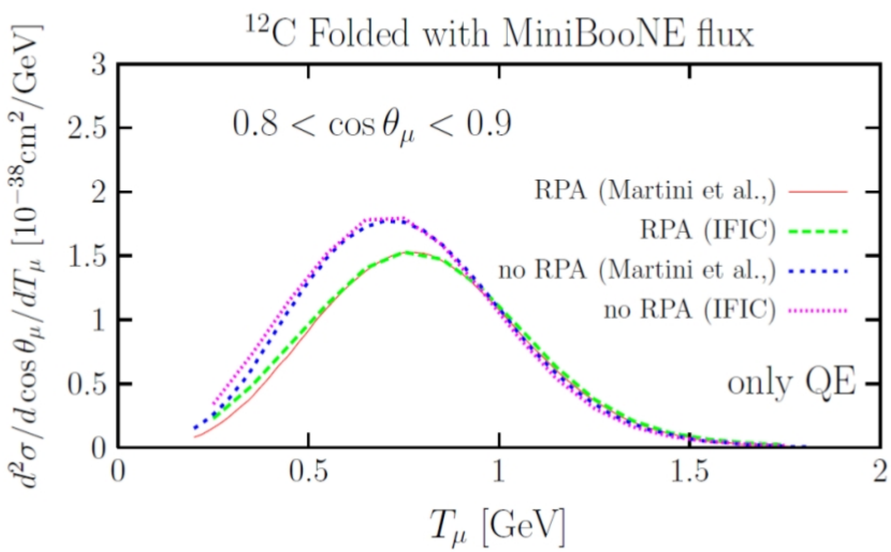
[Martini *et al.* and Nieves *et al*.]

Bare Propagatoor (RlFG)

π exchnage, ρ exchnage, contact Landau-Migdal parametrs







- Significant RPA quenching in both approaches.
- Genuine QE bare (RlFG) and RPA very similar in both approaches.

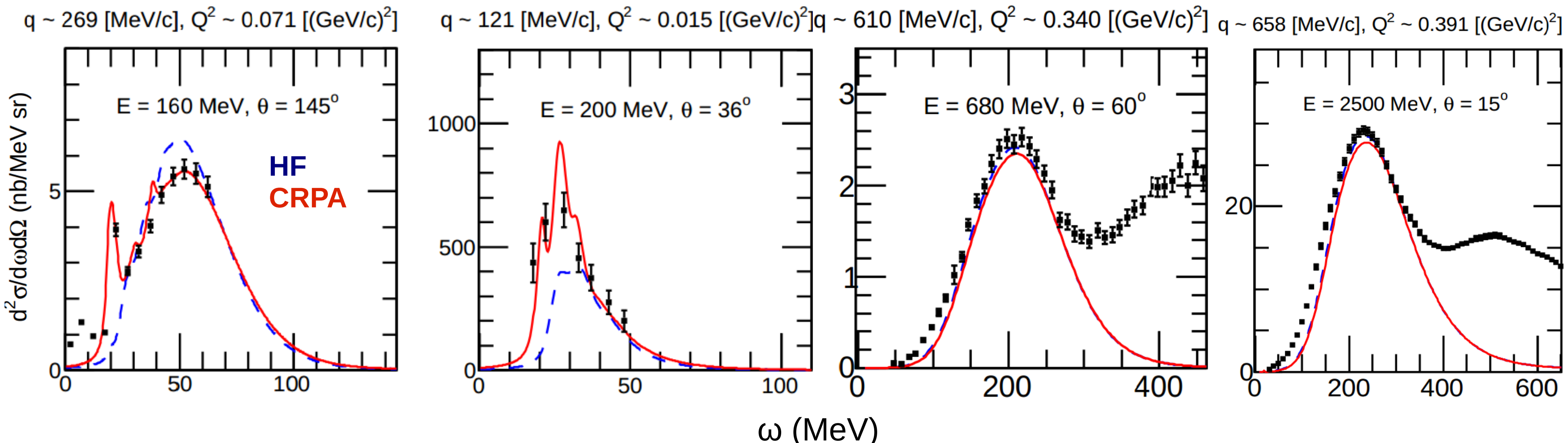
Comparing RPA-based models

RPA polarization propagator: $$\Pi = \Pi^0 + \Pi^0 \, V \, \Pi$$

Π^0 → HF

V → Skyrme (SkE2)

[Pandey, Jachowicz *et al*.]



VP, N. Jachowicz, PRC 92, 024606 (2015)

- At low ω, RPA (long-range correlations) describes the collective behavior of the nucleus (low-energy excitations).
- At high ω, RPA effects are smaller.
- Approach compares well with the (e,e') cross section.

Comparing RPA-based models

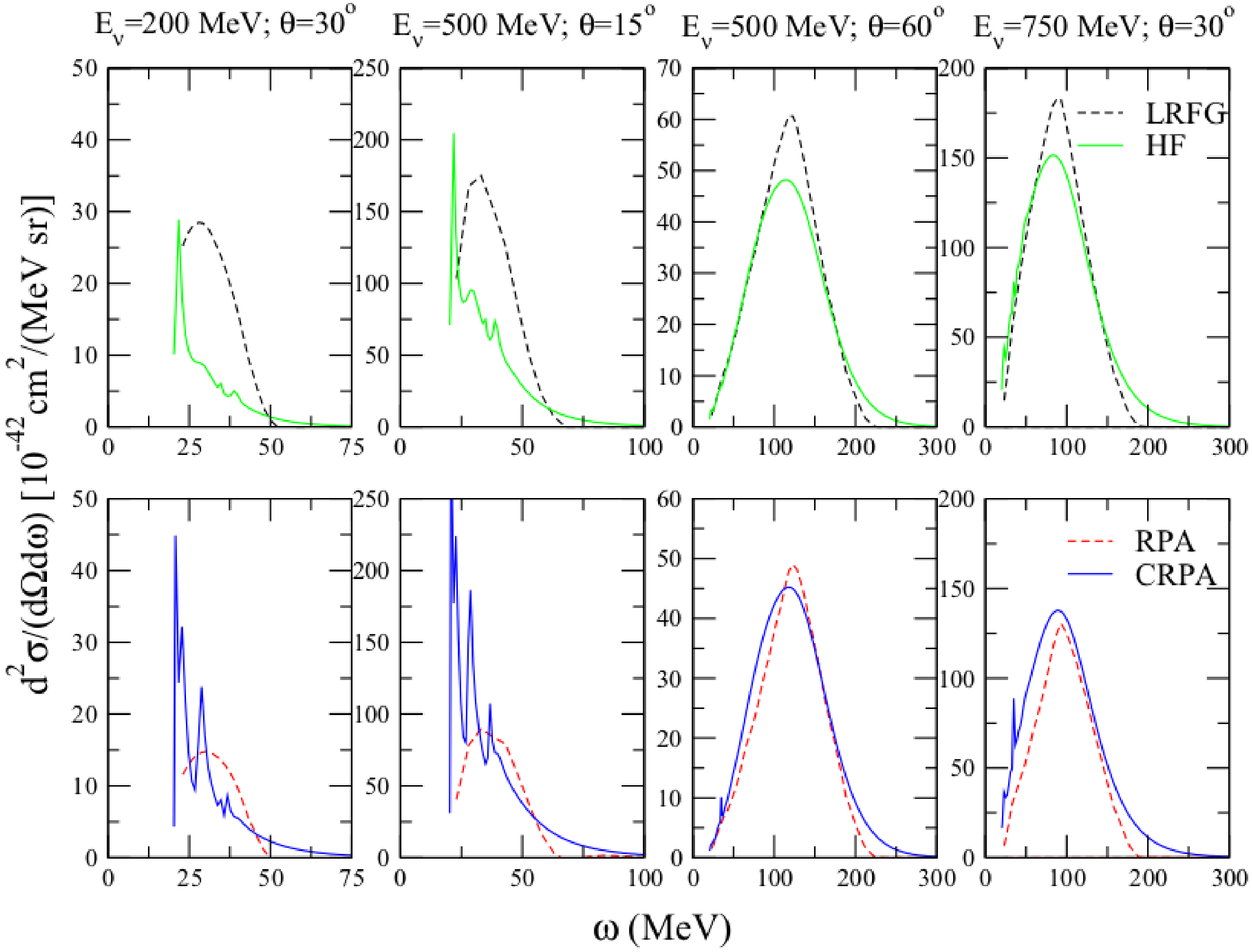
For more details: M. Martini, N. Jachowicz, M. Ericson, and VP *et al., PRC 94, 015501 (2016)*

- LRFG, RPA: Martini, Ericson *et al.*
- HF, CRPA: Pandey, Jachowicz *et al.*

➢ Important differences at both ends of the spectrum

→ Low-energy excitations at low ω

→ High ω tail



Comparing RPA-based models

Model	Shell Effects	Low-energy excitations & Giant Resonance	RPA effect	Starting point	N-N interaction
Martini, Ericson *et al.*	No	No	Significant suppression (LLEE effect)	Local Fermi Gas	Meson -exhange (π,ρ,g')
Nieves *et al.*	No	No	Significant suppression (LLEE effect)	Local Fermi Gas	Meson -exhange (π,ρ,g')
Pandey, Jachowicz *et al.*	Yes	Yes	Describe low ω physics, not much effects at higher ω	Hartree-Fock	Skyrme

- Significant differences between RPA and CRPA approach, at both ends of the (one-body) ω spectrum.

Final Remarks

- Different model describe one-body part differently, they use different ingredients and approximations.
- These ingredients and approximations have different range of validity – should be assessed may be against electron scattering data. [Extrapolation is dangerous!]
- In principle, any code predicting neutrino scattering can be very easily converted into electron scattering code.
- If generators could be adapted to electron scattering – would be great!