The Impact of nuclear effects on accelerator-based neutrino-oscillation physics

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ECT* Doctoral Training Program, June 28, 2017, Trento, Italy

[Repetition helps]

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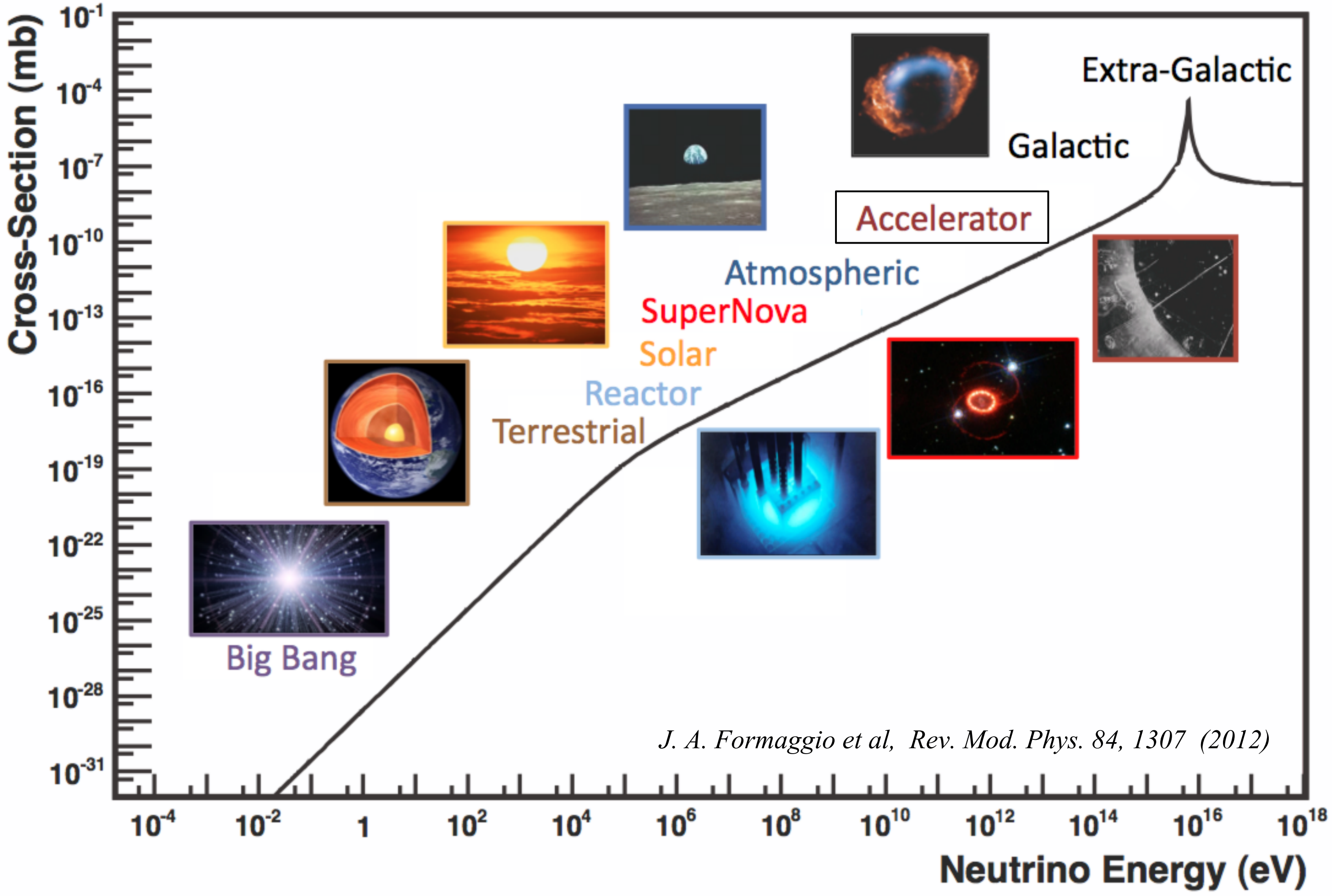
SED STUFANT

[But it’s boring]

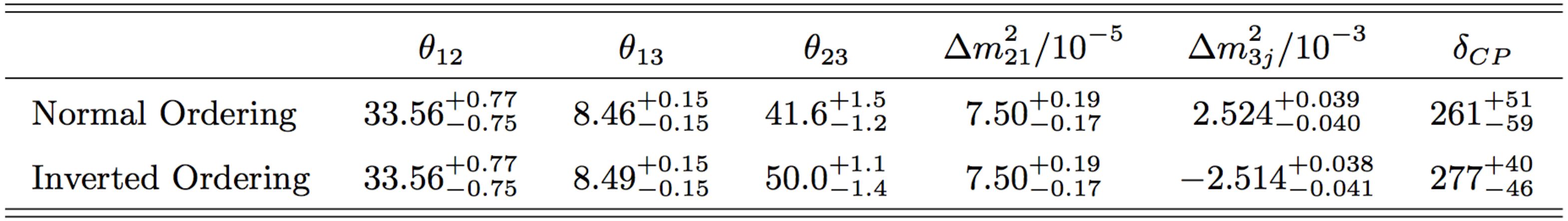
Neutrinos Everywhere!



J. A. Formaggio et al, Rev. Mod. Phys. 84, 1307 (2012)

Accelerator-based neutrino-oscillation experiments

Current knowledge:



	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

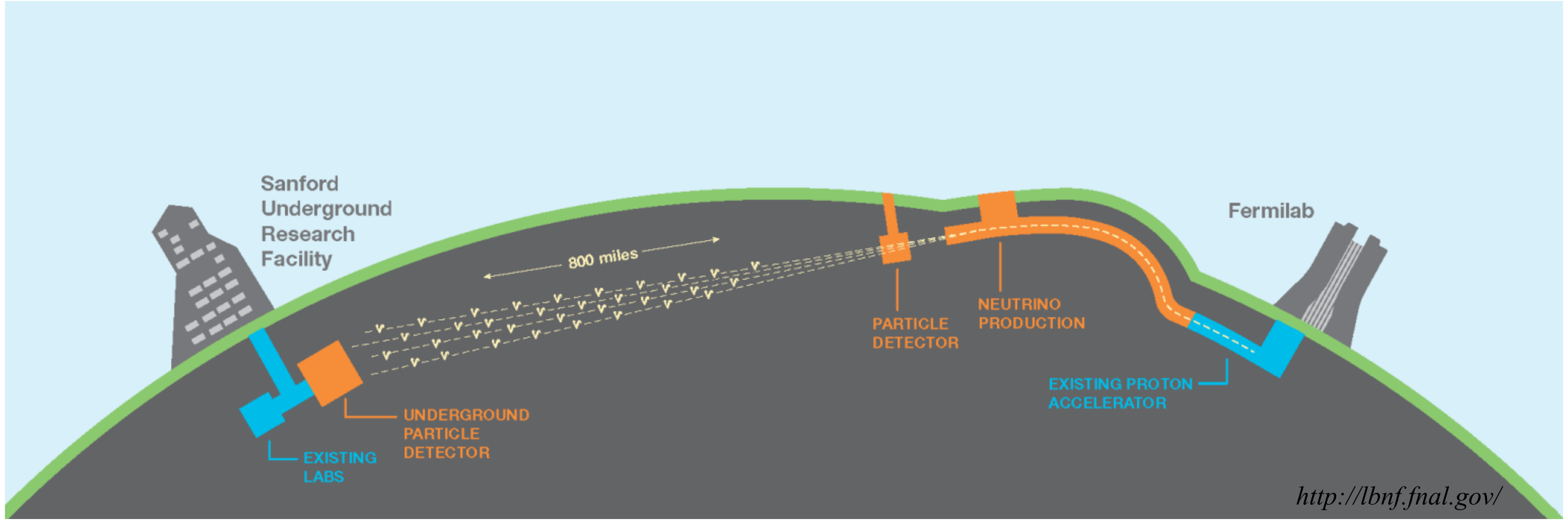
Current and future goals:

- Establish whether there is CP violation in the leptonic sector and, if so, measure δ_{CP}
- Improve the accuracy on θ_{23}
- Determine the neutrino mass ordering: $m_1 < m_2 < m_3$ or $m_3 < m_1 < m_2$

Many experiments:

- **MiniBooNE** (concluded), **NOvA** (running), etc.
- **SBN Program: MicroBooNE** (running), **ICARUS** (under construction), **SBND** (under construction); **DUNE** (under construction)
- **T2K** (running), **T2HK** (under construction)

Accelerator-based neutrino-oscillation experiments



http://lbnf.fnal.gov/

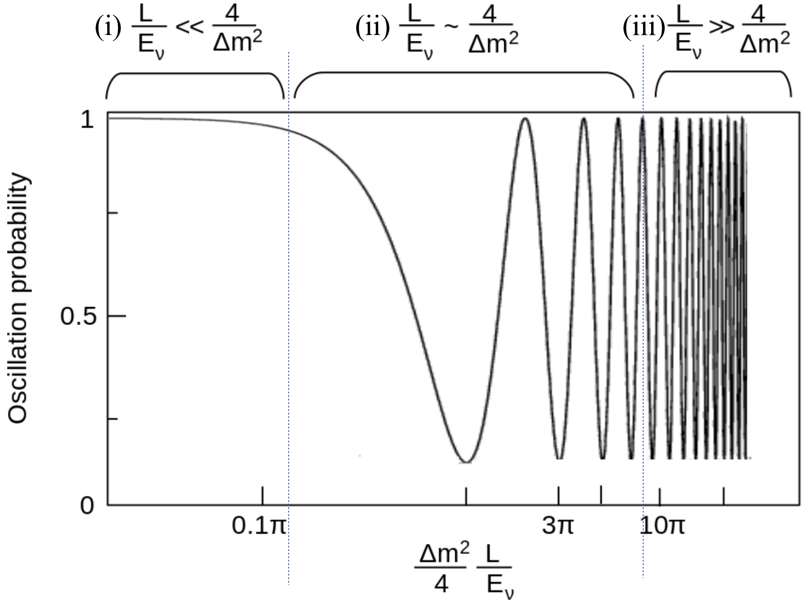
Oscillation Probability:

$$P(\nu_i \rightarrow \nu_j) \;=\; \sin^2 2\theta \;\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

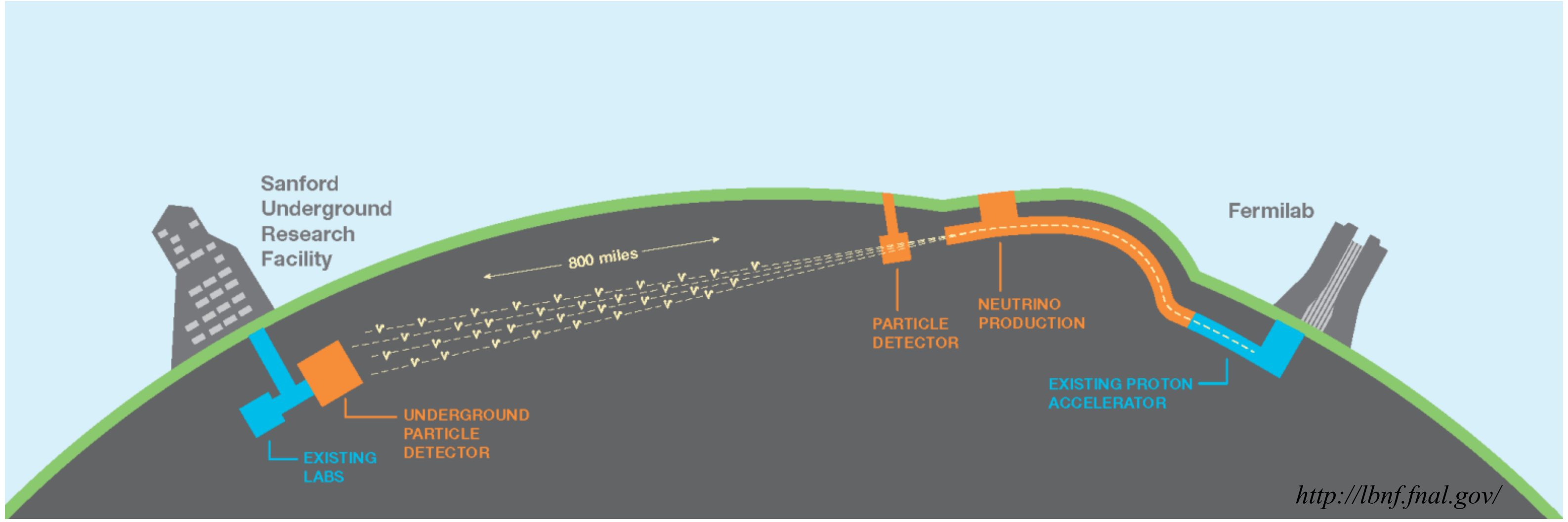
(i) Detector is too close to the source, no oscillation happened.

(ii) Necessary but most sensitive region to detect oscillations.

(iii) Several oscillations happened, only average oscillation probability can be measured.



Accelerator-based neutrino-oscillation experiments



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Oscillation Probability:

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Maximal sensitivity to oscillation probability:

- Maximize the baseline L ⟶ Neutrino beam diverges
- Minimize the beam energy E_ν ⟶ Cross section decreases

Optimal combination:

L ~ few 100s of km
E_ν ~ Intermediate energies

Event Rates:

$$\boxed{N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}};\boldsymbol{p}_{\mathrm{reco}})}$$

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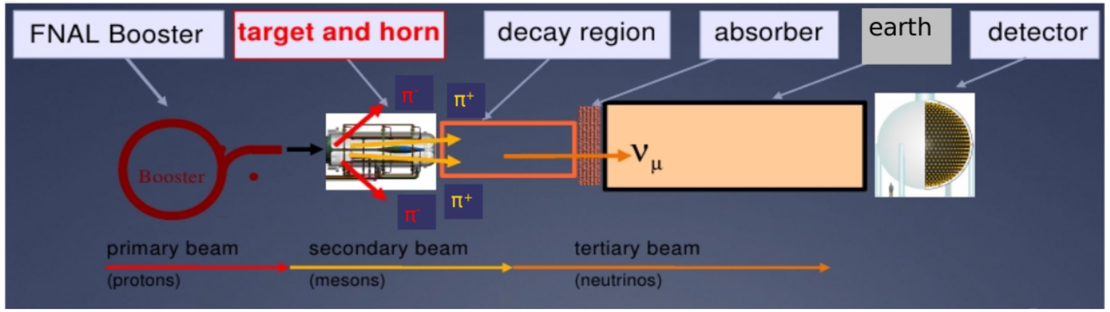
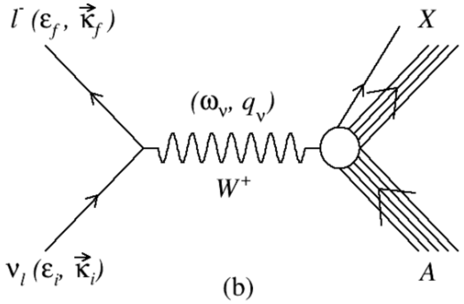
Energy reconstruction:



- Neutrino beams are part of tertiary beam – neutrino energy is not know.
- The neutrino energy is reconstructed based on the kinematics of the final state particles.
- Using the **nuclear model implemented in the Monte Carlo generator.**



Event Rates:

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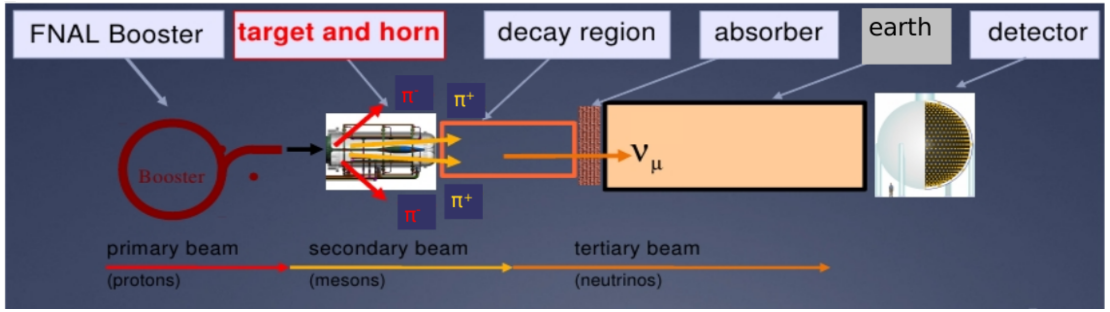

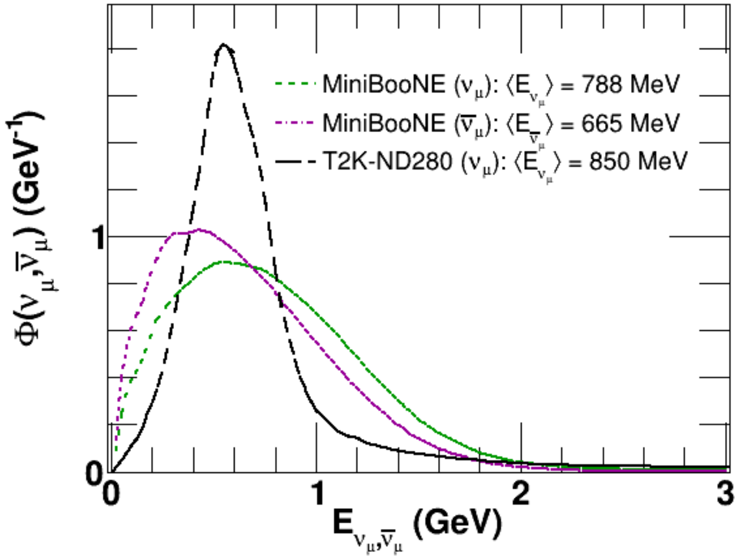

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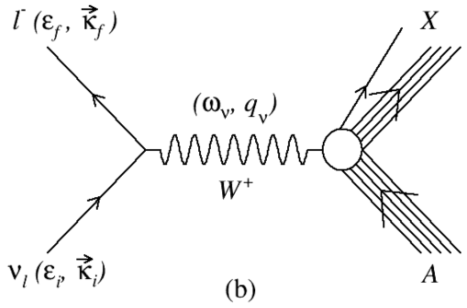

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Cross section:

Event Rates:

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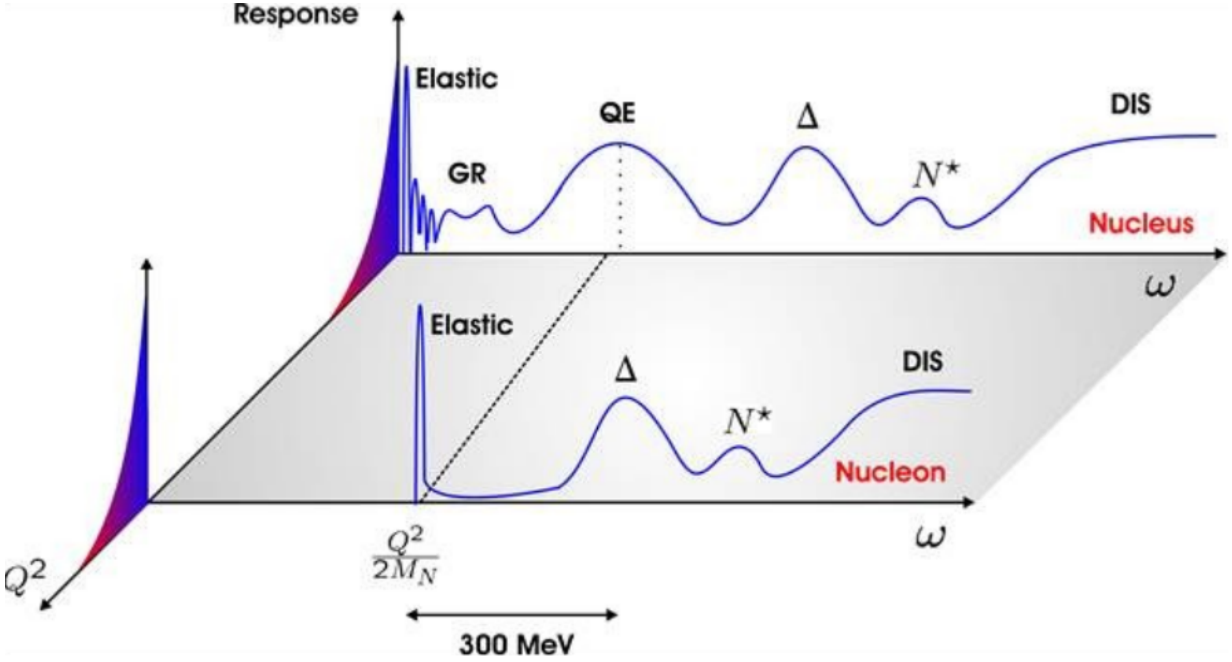

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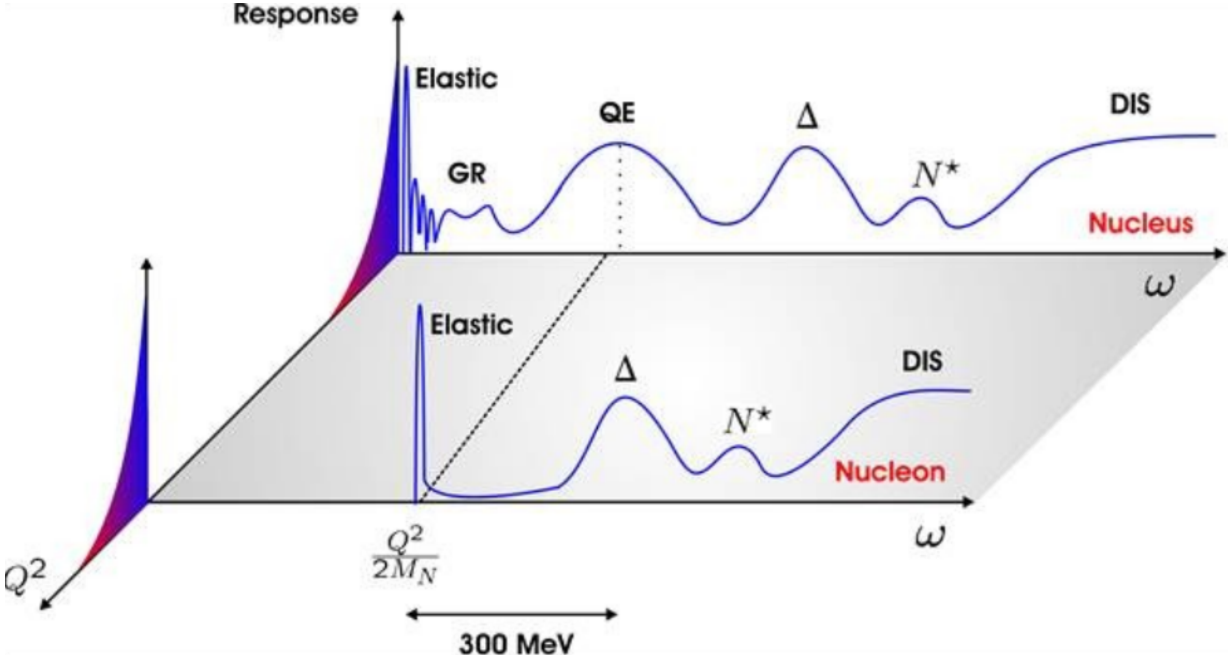
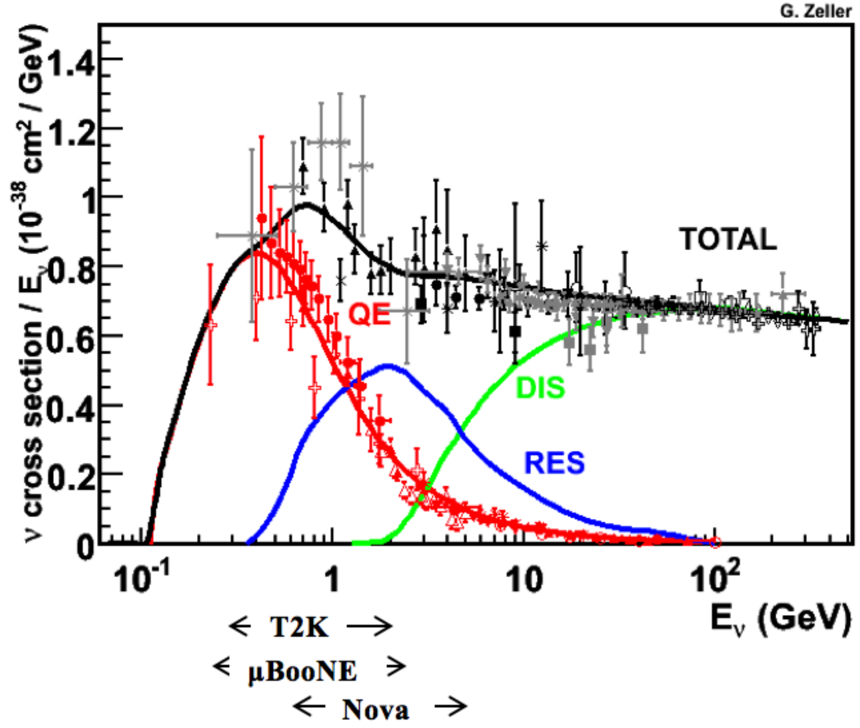
Cross section:





- Cross section is calculated using the **nuclear model implemented in the Monte Carlo generator.**

- Monte Carlo generators should consists of a realistic nuclear model that can describe accurately the neutrino-nucleus scatterings at the kinematics relevant for these experiments.

- Current status: Monte Carlo generators, e.g. GENIE, are primarily based on Fermi-gas based Model of the nucleus.

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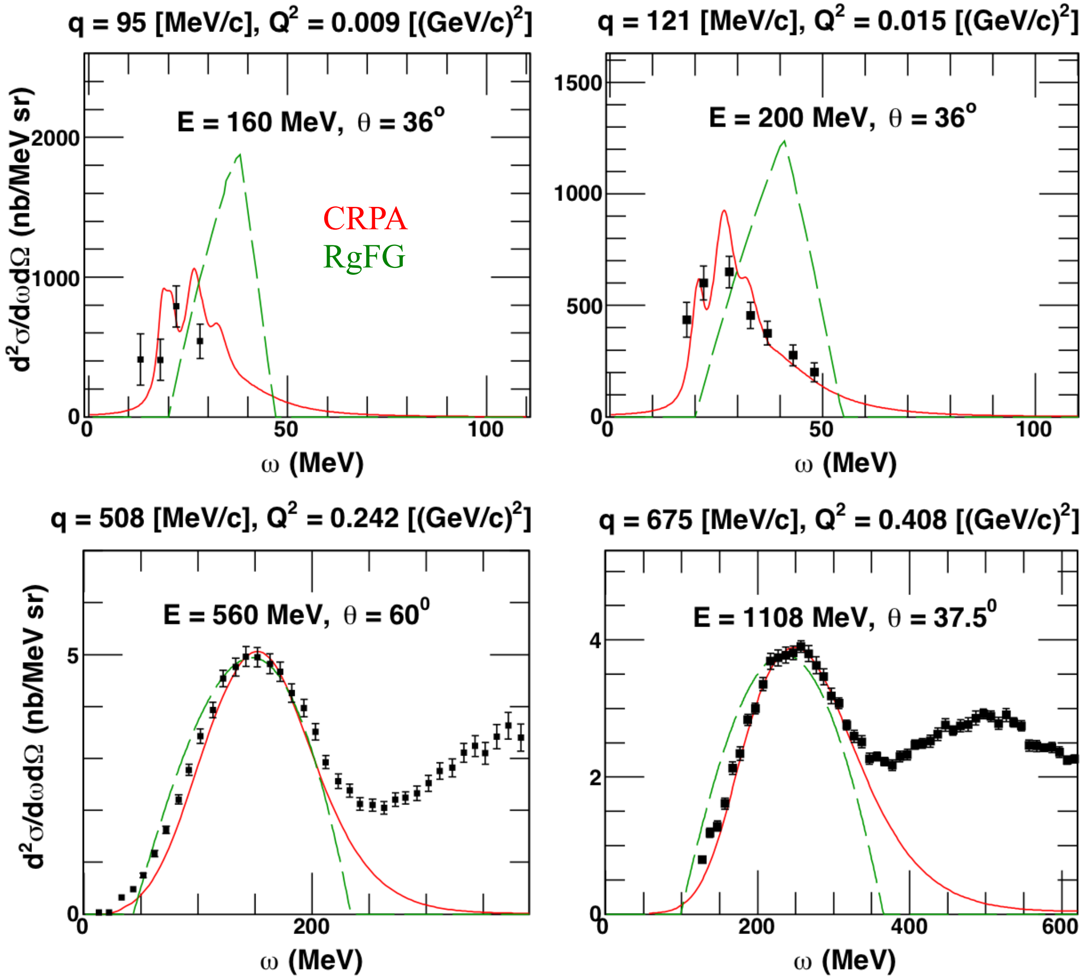
Example from ^{12}C *(e,e')*



VP, PhD thesis (2016)

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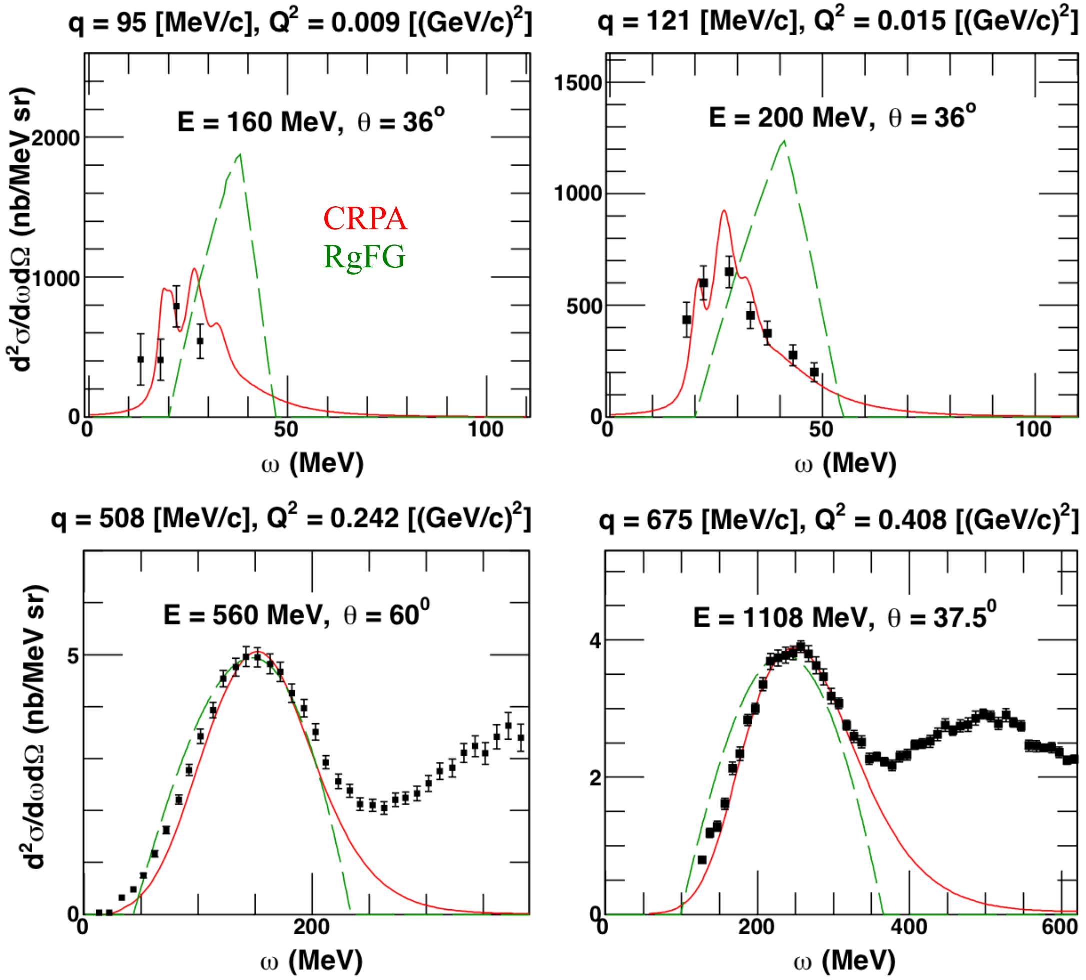
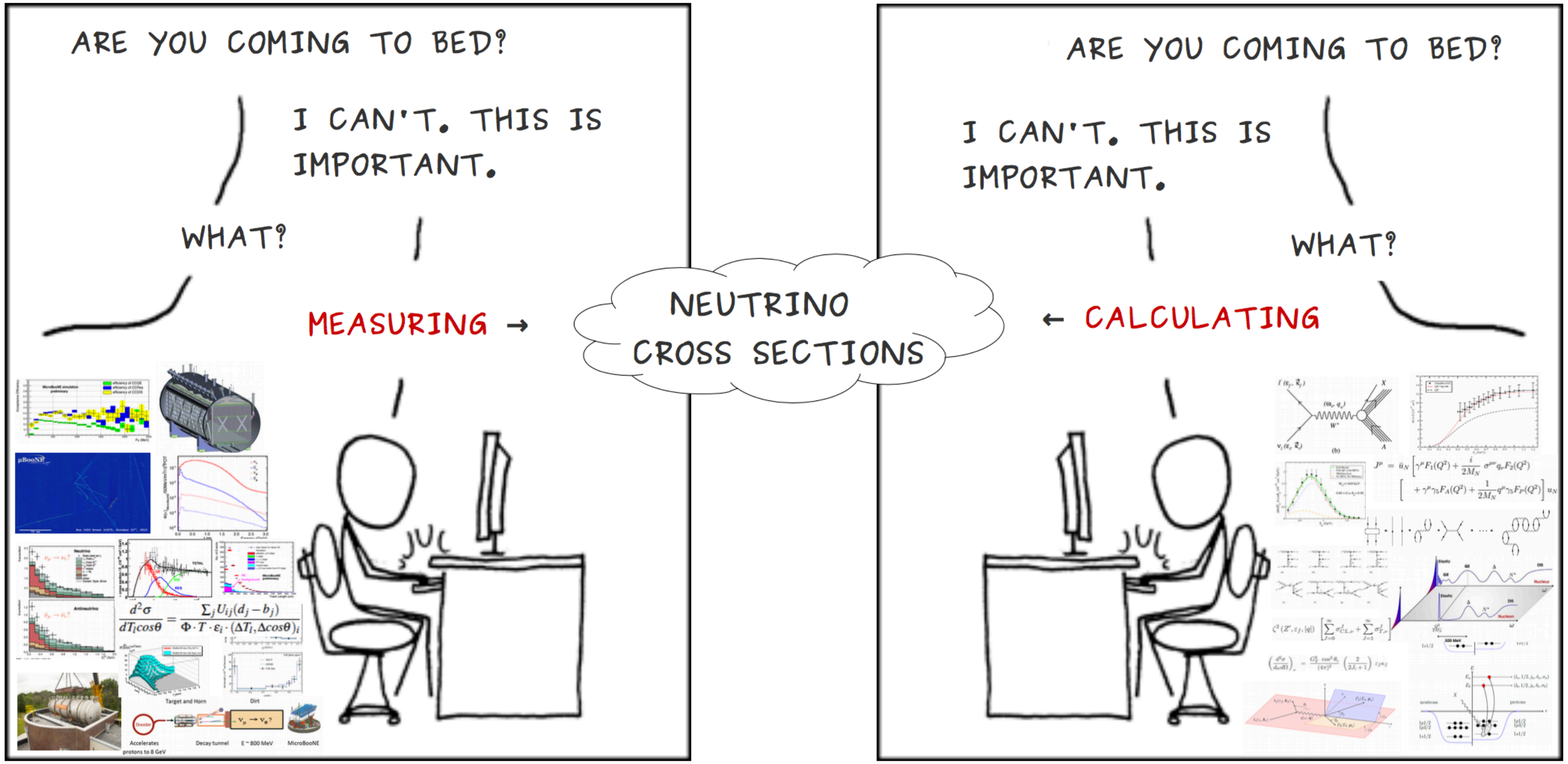


VP, PhD thesis (2016)

- **The uncertainties in the measurements, mainly owing to inadequate nuclear models in generators, is ~ 10-15 % - No Surprize!**

Neutrino Experimentalist's Desk

Nuclear Theorist's Desk



- Need better models to reduce systematic uncertainties to eventually make precise measurements

- Need precise data to test and validate the assumptions and approximations to eventually improve the model

- **In an ideal world:** with strong collaboration between neutrino experimentalists and nuclear theorists - we all understand neutrino cross section with high accuracy and make precise oscillations measurements.

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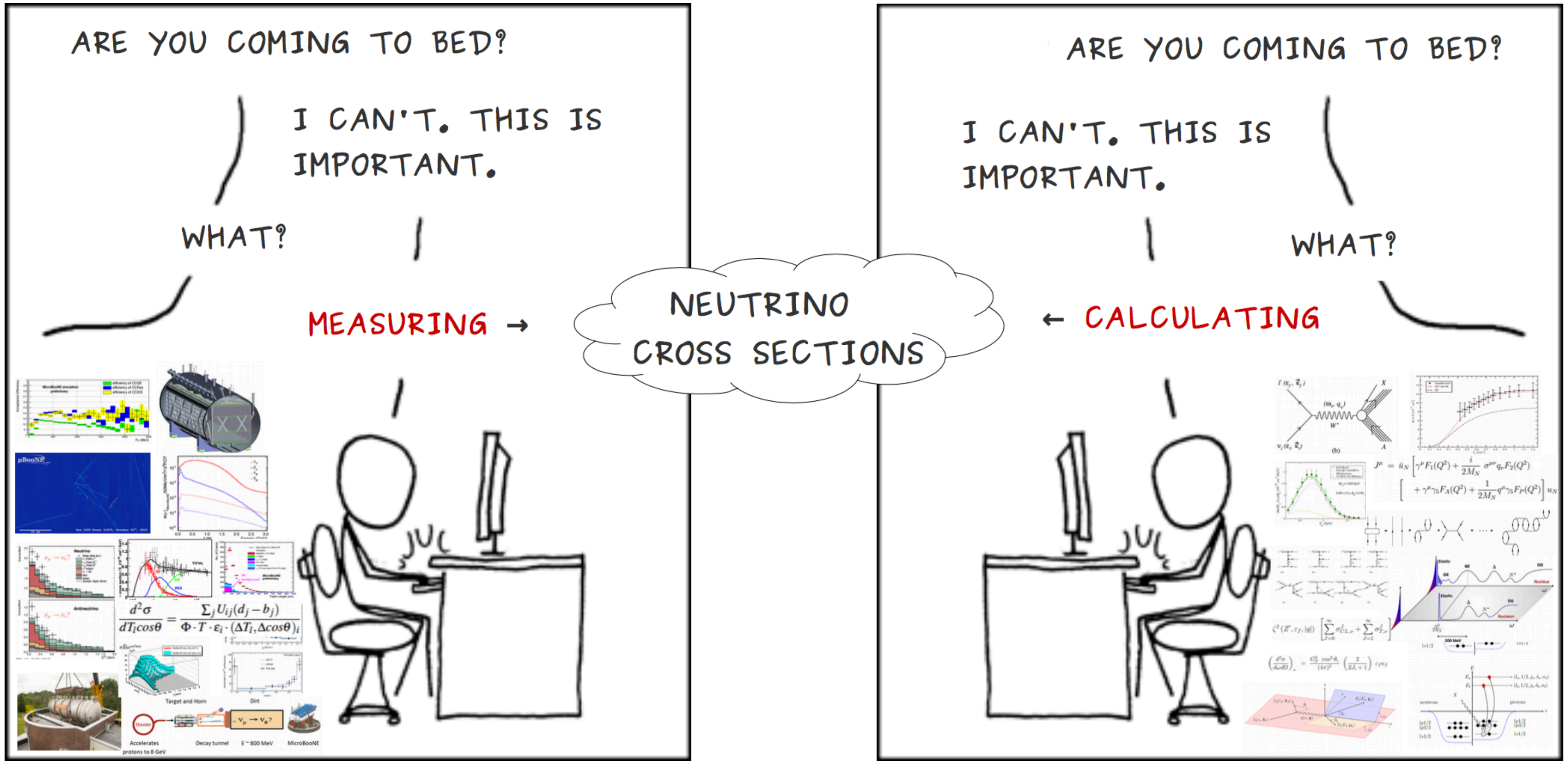
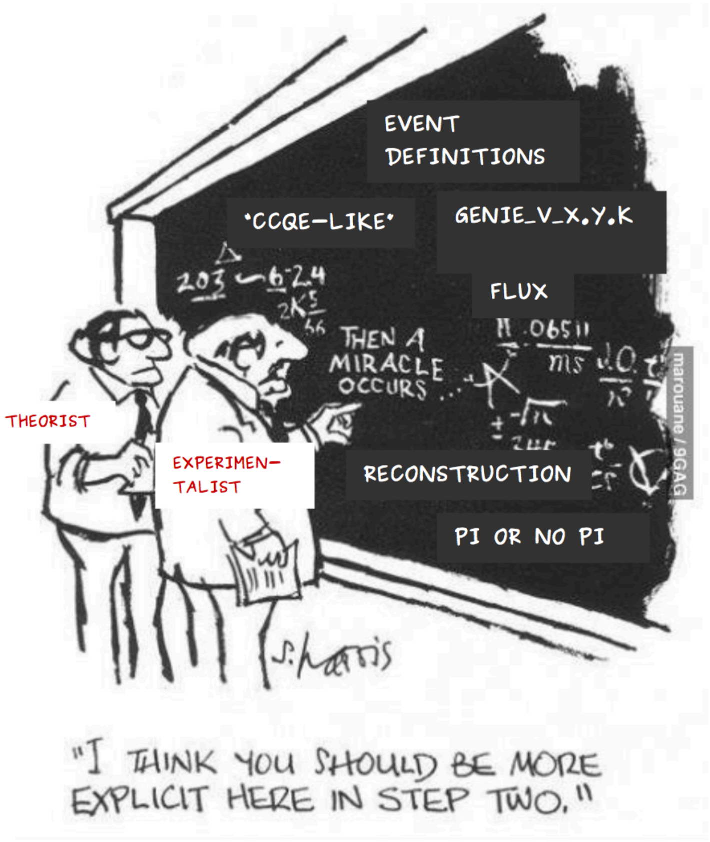
Nuclear Theorist's Desk



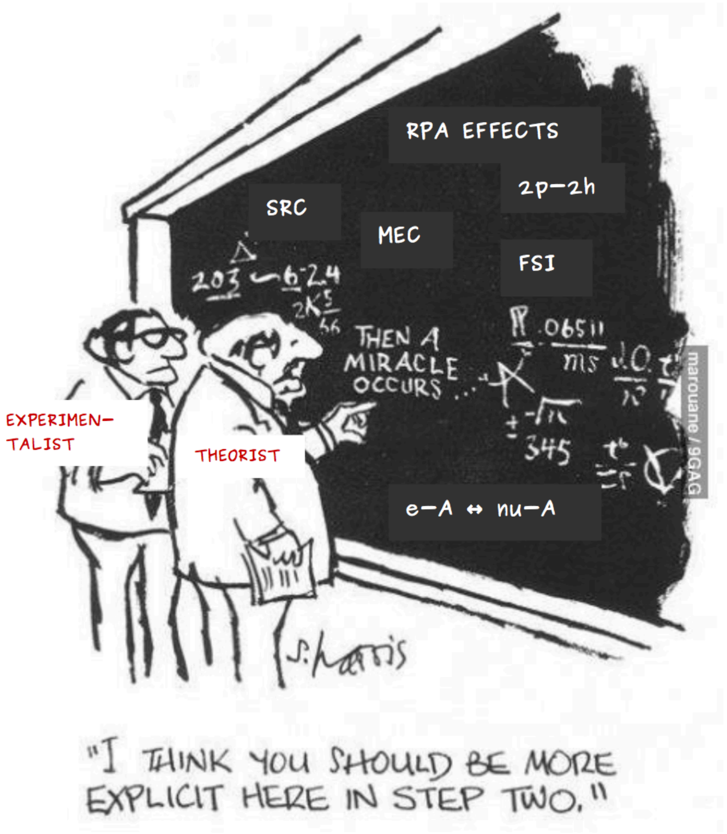
And they lived happily ever after…

- **In real world:** things are a bit messy!

When nuclear theorists talk to neutrino experimentalists



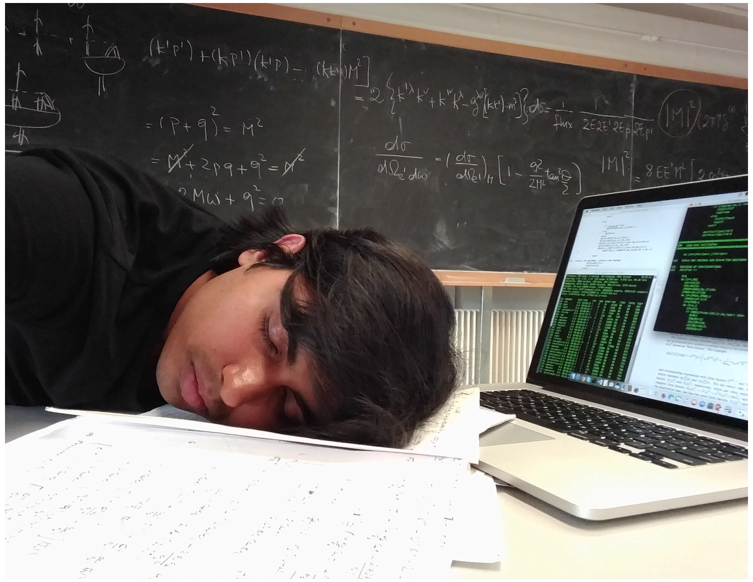
When neutrino experimentalists talk to nuclear theorists



State of art, unfortunately :-/

My Neutrino Experimentalist’s Desk

My Nuclear Theorist’s Desk



There’s no such thing as multi-tasking – just doing lots of things badly. The correct term is multi-failing.

General cross section formalism:

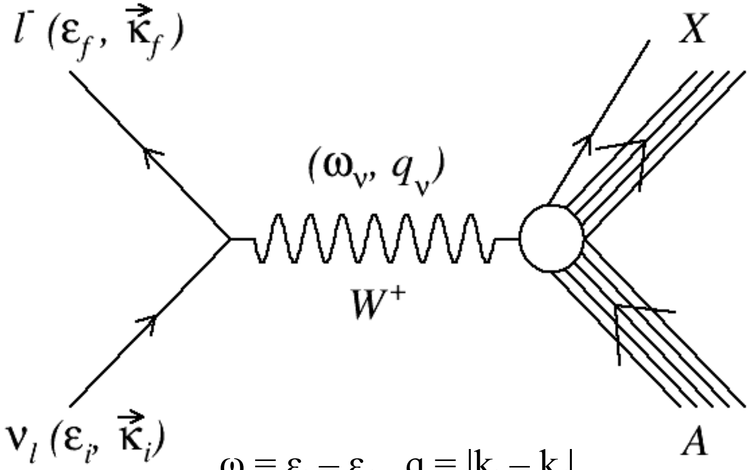
Leptonic current

$$J_\mu = \bar{\nu}_l\ \gamma_\mu(1-\gamma_5)\ l$$
$$= \bar{\nu}_l\ \gamma_\mu\ l - \bar{\nu}_l\ \gamma_\mu\gamma_5\ l$$

Hadronic current

$$J^\mu = \bar{u}_N \left[\gamma^\mu F_1(Q^2) + \frac{i}{2M_N}\ \sigma^{\mu\nu} q_\nu F_2(Q^2) + \gamma^\mu\gamma_5 F_A(Q^2) + \frac{1}{2M_N} q^\mu \gamma_5 F_P(Q^2)\right] u_N$$

CCQE scattering



$\omega = \varepsilon_i - \varepsilon_f$, $q = |k_i - k_f|$

$Q^2 = q^2 - \omega^2$

Propagator

$$\approx \frac{1}{Q^2 - M_W^2}\ , \quad Q^2 \ll M_W^2$$

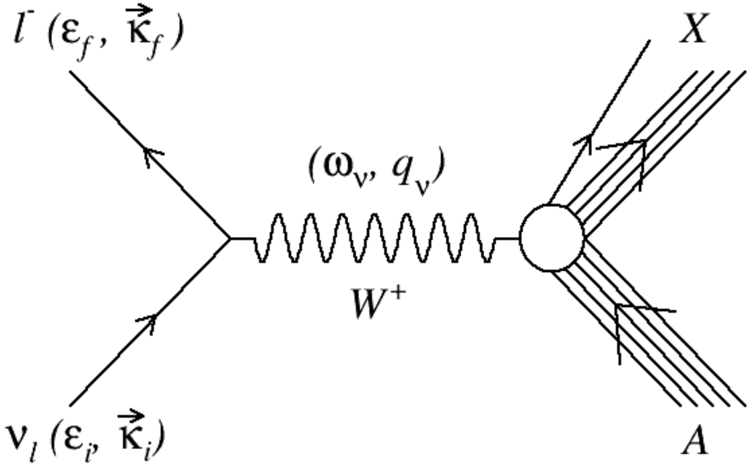
$$\left(\frac{d^2\sigma}{d\omega d\Omega}\right)_\nu = \frac{G_F^2\ \cos^2\theta_c}{(4\pi)^2} \left(\frac{2}{2J_i+1}\right) \varepsilon_f \kappa_f\ \ \zeta^2(Z', \varepsilon_f, |q|) \left[\sum_{J=0}^{\infty} \sigma^J_{CL,\nu} + \sum_{J=1}^{\infty} \sigma^J_{T,\nu}\right]$$

$$\sigma^J_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + \ 2\ v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right] \qquad \sigma^J_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\ v_\nu^{TT} R_\nu^{TT}\right]$$

+/- sign is the only difference between ν and anti-ν

General cross section formalism:

QE ν-A scattering



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$$\times\ \zeta^2\left(Z',\varepsilon_f,q_\nu\right)\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu}+\sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$$

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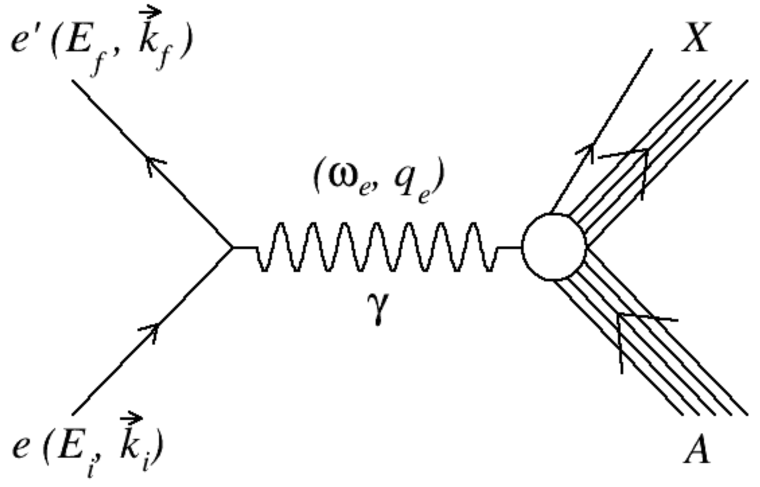
v’s → Leptonic coefficients → Purely kinematical → Easy to calculate

R’s → Response functions → Nuclear dynamics → **Need nuclear models to calculate!**

General cross section formalism:

QE e-A scattering

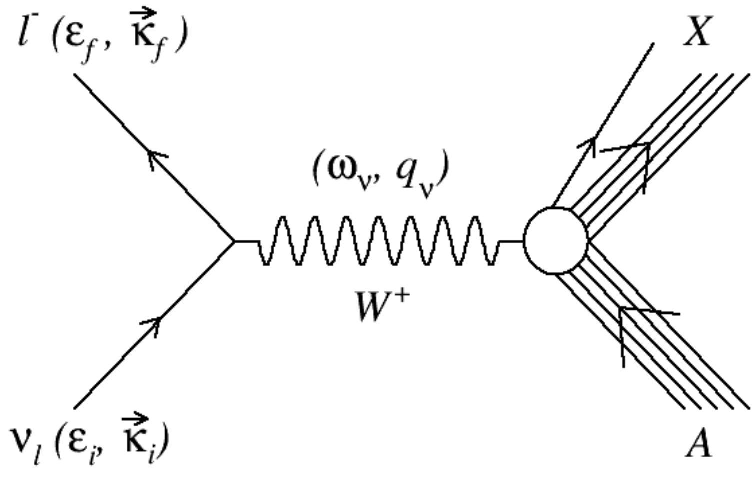


$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2\left(Z', E_f, q_e\right)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e}+\sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

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

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

QE ν-A scattering



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

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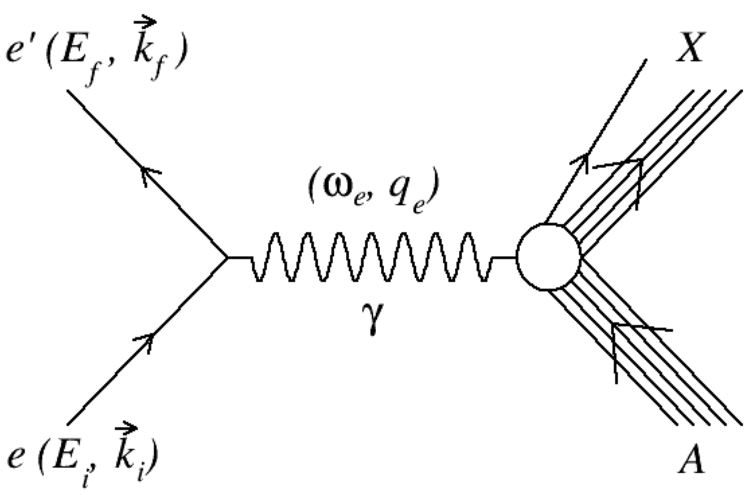
***e*-A to ν-A cross section**

QE e-A scattering



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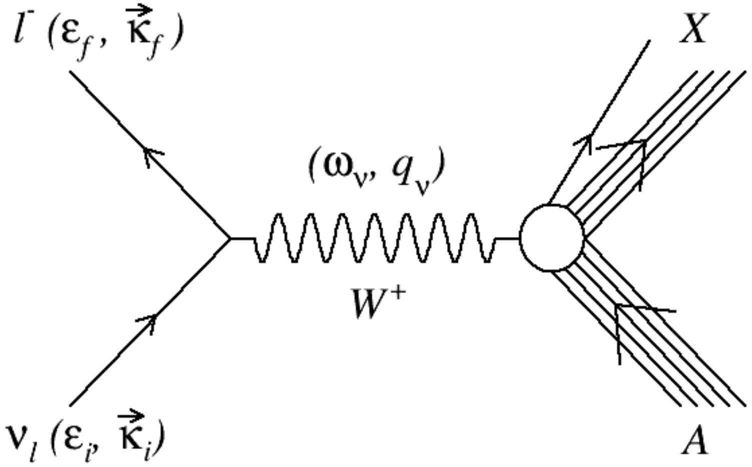


CAUTION: CHALLENGES AHEAD

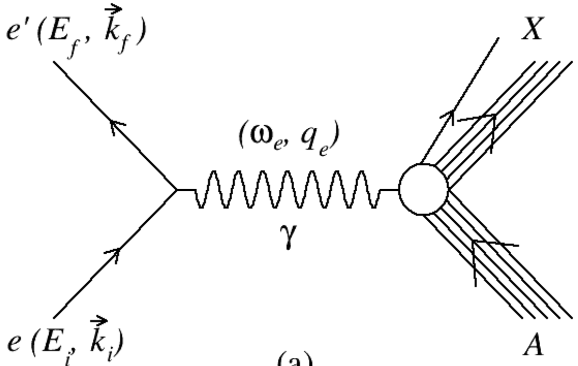
- Monoenergetic beams (E_e known precisely; ω, q can be calculated)
- Hence, different reaction channels can be separated

- E_ν has to be reconstructed → wide flux
- Hence, difficult to distinguish different reactions channels.
- What experimentalist's measure:

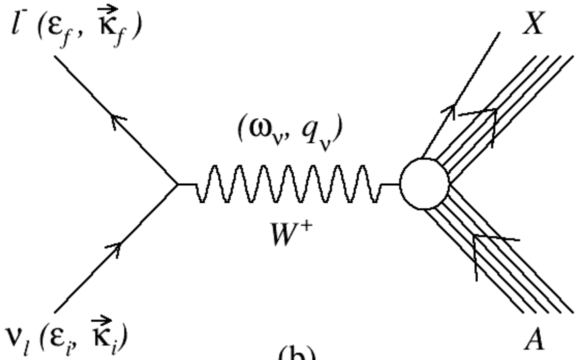
$$\frac{d^2\sigma}{dT_l cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

- What theorist's calculate:

$$\frac{d^2\sigma}{dT_l \, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$



(a)



(b)

- Start with some basic description of nucleus. Add some ingredient, make some approximation, etc. to take into account several nuclear effects.

- Test each of those ingredient, and approximation against e-A scattering data*.

- If it all successfully describes the e-A scattering data over wide range of kinematics (and possibly over several nuclei).

- *Congratulations madam, you rock!* your model is validated. Please extended the model (with few relatively simpler steps) into ν-A scattering.

- Implement the model in MC. Validate implementation against e-A data.

- **Ready to use by experiments!**

- If it doesn't work for e-A scattering (*sorry sir, you suck!*), its highly unlikely to work for ν-A scattering.

*There is plenty of data available for e-A scattering over wide range of kinematics and for several nuclei.

Few (many) models:

- RFG+RPA (Martini, Ericson, *et al*)
- RFG+RPA (Nieves, *et al*)
- HF+CRPA (Pandey, Jachowicz *et al*)
- Spectral Function Formalism (Benhar, Rocco, Ankowski, *et al.*)
- Super-Scaling approach (Amaro, Barbaro, Caballero, Donnelly, Megias, *et al.*)
- Relativistic Green's Function Model (Meucci, Giusti *et al.*)
- Green’s Function Monte Carlo Approach (Lovato, Gandolfi, Carlson, *et al.)*
- *..., etc.*

References:
PRC 89, 024601 (2014); PRC 92, 024606 (2015); PRC 94, 015501 (2016);
PRC 94, 024611 (2016); PRC 94, 054609 (2016);
arXiv:1612.05511 [nucl-th] (accepted in PRD); arXiv:1704.07817 [nucl-th]

Formalism: HF-CRPA Approach

- We start by describing the nucleus with a Hartree-Fock (HF) approximation. The mean-field (MF) potential is obtained by solving the HF equations and using a Skyrme (SkE2) two-body interaction.
- Once we have bound and continuum single-nucleon wave functions, we introduce long-range correlations between the nucleons through a continuum Random Phase Approximation (CRPA).
- The propagation of particle-hole pairs in the nuclear medium is described by the polarization propagator. In the Lehmann representation, this particle-hole Green's function is given by

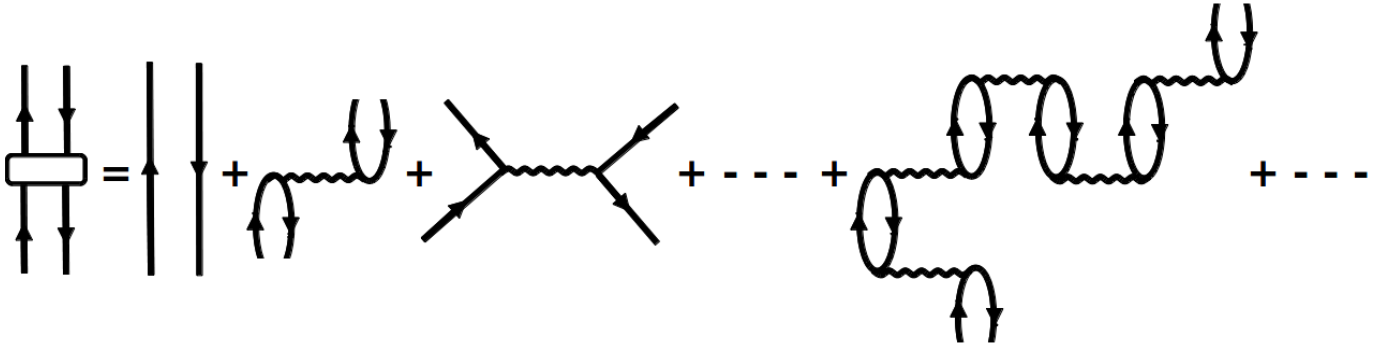
$$\begin{aligned}\Pi(x_1,x_2,x_3,x_4;E_x) \quad &= \quad \hbar \sum_n \left[\frac{\langle\Psi_0|\hat{\psi}^\dagger(x_2)\hat{\psi}(x_1)|\Psi_n\rangle\langle\Psi_n|\hat{\psi}^\dagger(x_3)\hat{\psi}(x_4)|\Psi_0\rangle}{E_x-(E_n-E_o)+i\eta} \right. \\ &\left. - \frac{\langle\Psi_0|\hat{\psi}^\dagger(x_3)\hat{\psi}(x_4)|\Psi_n\rangle\langle\Psi_n|\hat{\psi}^\dagger(x_2)\hat{\psi}(x_1)|\Psi_0\rangle}{E_x+(E_n-E_o)-i\eta} \right]\end{aligned}$$

- RPA equations are solved using a Green's function approach.

Formalism: HF-CRPA Approach

- The RPA-polarization propagator

$$\Pi^{(RPA)}(x_1, x_2; E_x) = \Pi^{(0)}(x_1, x_2; E_x) + \frac{1}{\hbar}\int dx dx' \ \Pi^0(x_1, x; E_x) \times \tilde{V}(x, x') \ \Pi^{(RPA)}(x', x_2; E_x)$$



- The Skyrme (SkE2) nucleon-nucleon interaction, which was used in the HF calculations, is also used to perform CRPA calculations. That makes this approach self-consistent.

Formalism: Folding procedure

A limitation of RPA formalism at lower energies:

- → energy position of the giant resonances is generally well predicted
- → width is underestimated
- → height is overestimated

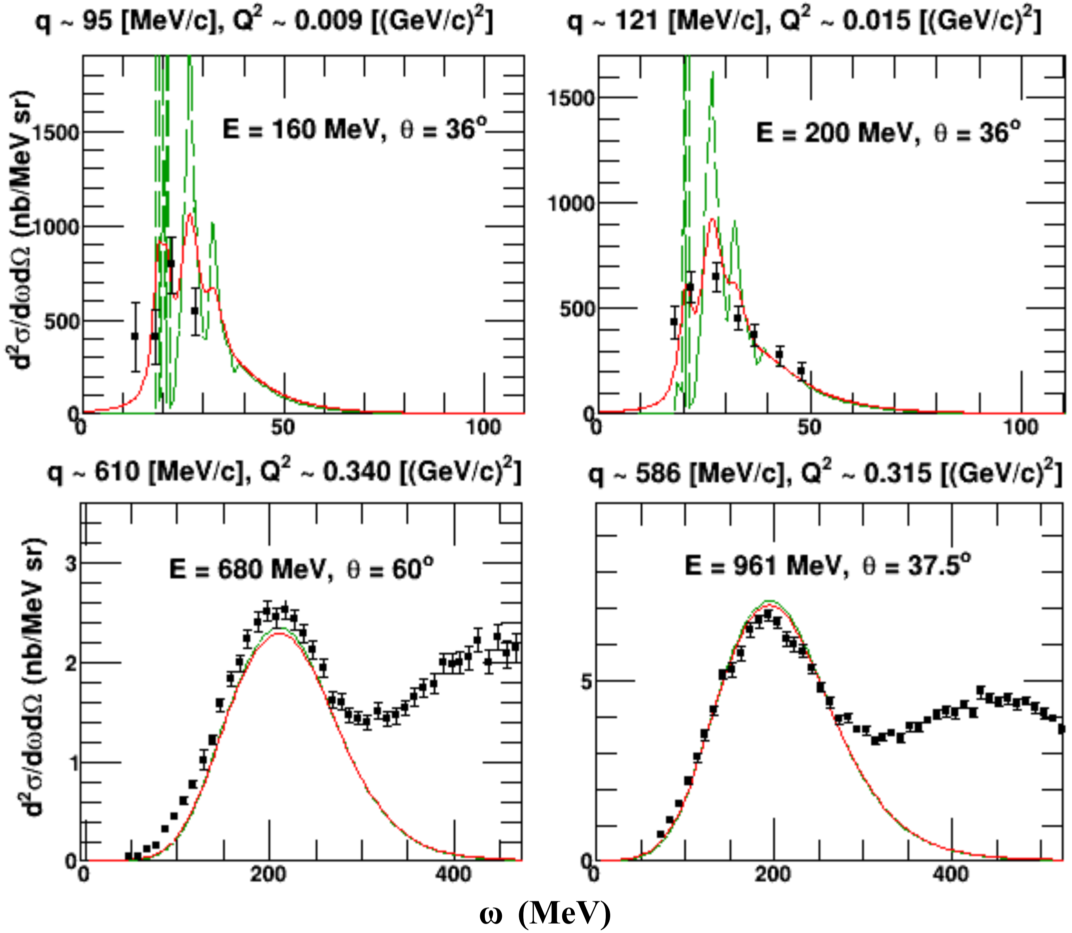
Folding

$$R'(q,\omega') = \int_{-\infty}^{\infty} d\omega R(q,\omega) L(\omega,\omega')$$

$$L(\omega,\omega') = \frac{1}{2\pi}\left[\frac{\Gamma}{(\omega-\omega')^2+(\Gamma/2)^2}\right]$$

$\Gamma = \ 3\ MeV$

CRPA: Without Folding, CRPA: With Folding



Formalism: Relativistic corrections

Non-relativistic model

'Semi-relativistic' modeling

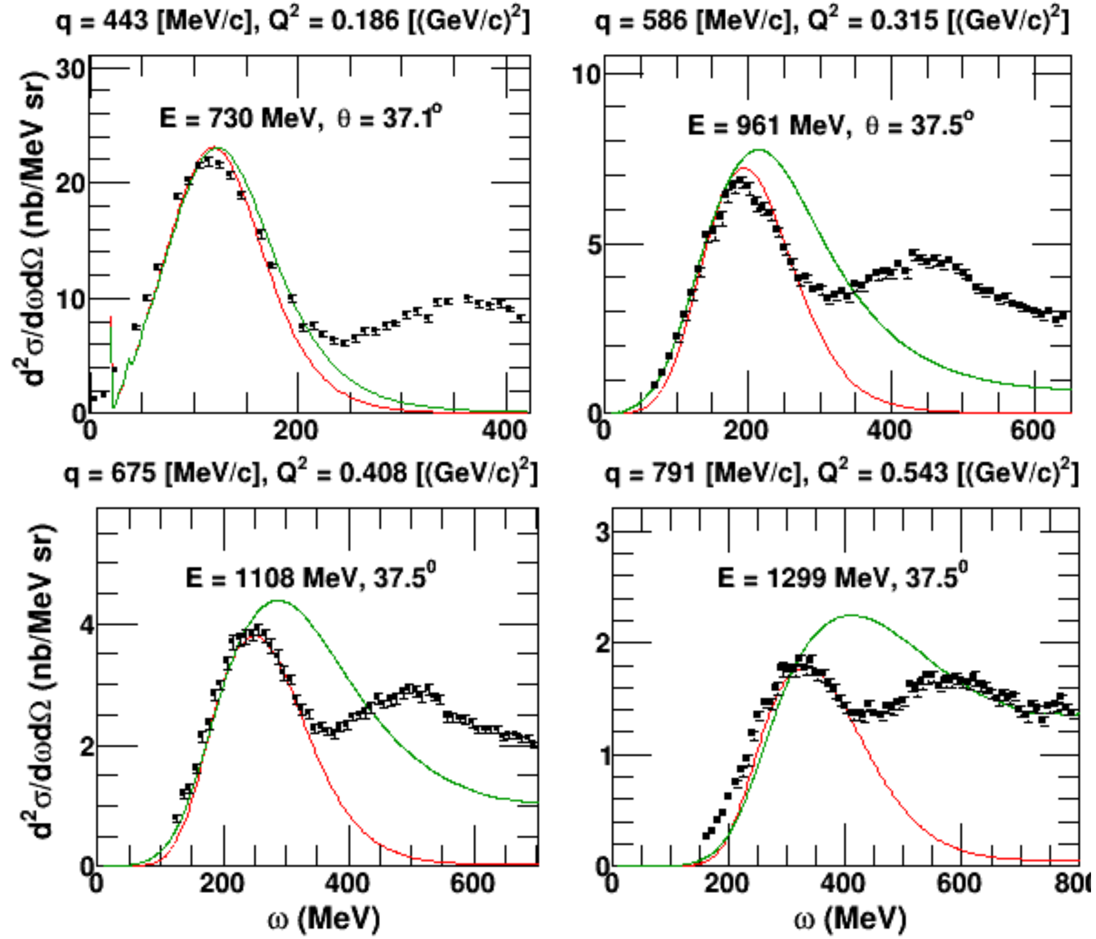
(S. Jeschonnek and T. W. Donnelly, PRC57, 2438 (1998))

Kinematic effects:

$\lambda \rightarrow \lambda\,(1+\lambda), \quad \lambda = \omega/2M_N$

QE peak: $\omega = q^2/2M_N \Rightarrow Q^2/2M_N$

CRPA: Non-relativized, CRPA: Relativized

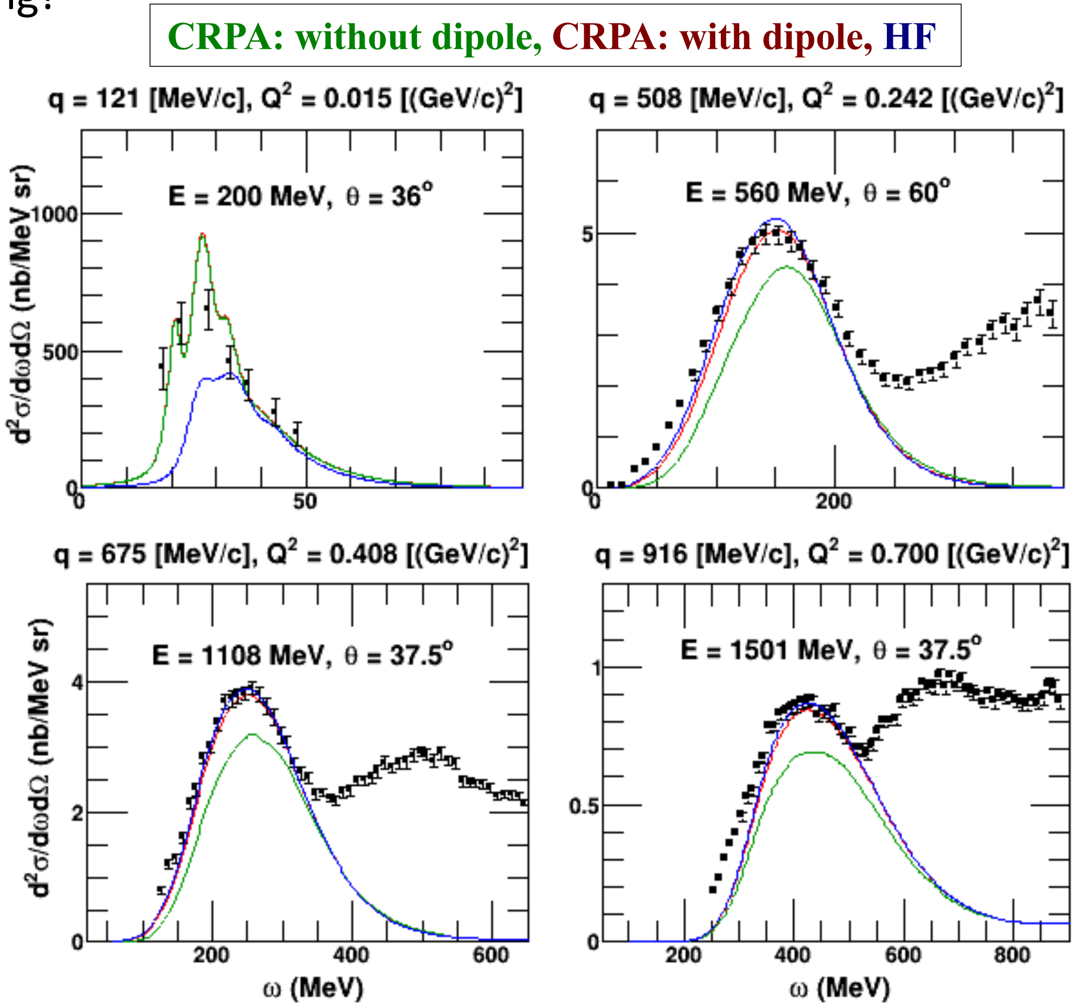


Formalism: Regularization of the residual interaction

SkE2 interaction → optimized against ground-state and
low-excitation energy properties
→ at higher Q^2, unrealistically strong!

$$V(Q^2) \;= V(Q^2=0)\,\frac{1}{(1+\frac{Q^2}{\Lambda^2})^2}$$

With Λ = 455 MeV, optimized with a χ^2 fitting of theory-experiment comparison from low ω up to the QE peak, over broad set of available data on *A(e,e')* scattering.



Formalism: Coulomb correction

Effect of coulomb potential of the nucleus on the charged lepton:

→ Low energies: Fermi function $F(Z', E) = \dfrac{2\pi\eta}{1 - e^{-2\pi\eta}}$ $\eta \sim \mp Z'\alpha$

→ High energies:

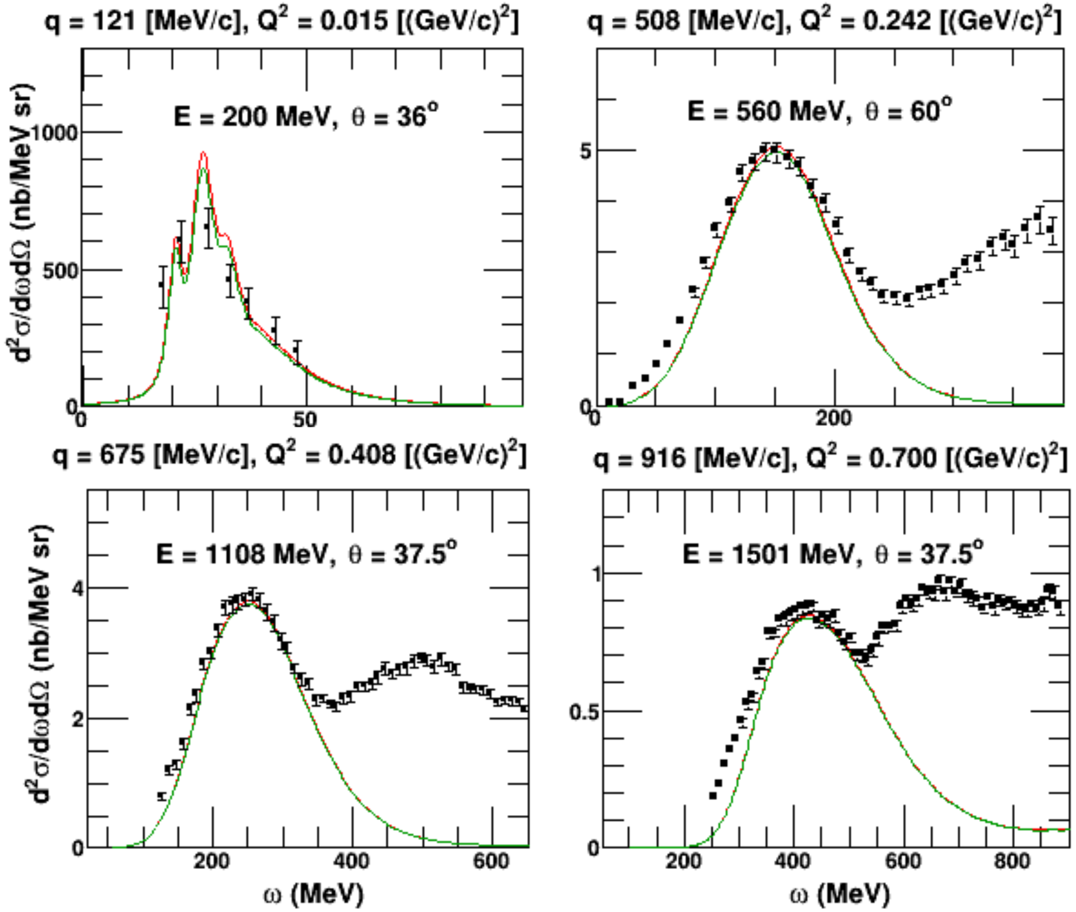
Modified effective momentum approximation

(J. Engel, PRC57,2004 (1998))

$$q_{\text{eff}} = q + 1.5\left(\frac{Z'\alpha\hbar c}{R}\right)$$

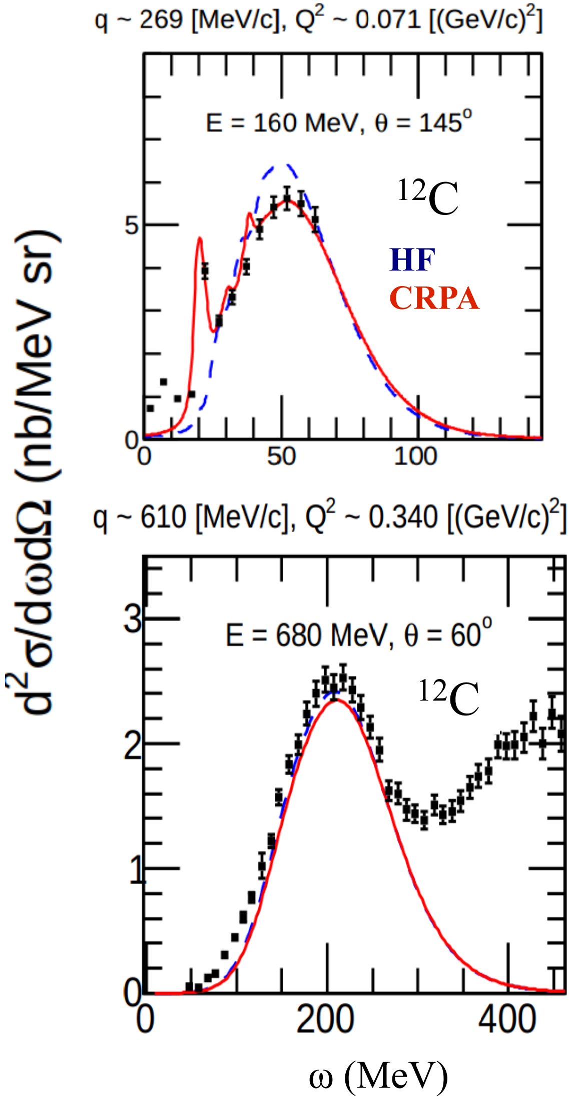
$$\zeta(Z', E, q) = \sqrt{\frac{q_{\text{eff}} E_{\text{eff}}}{q E}}$$

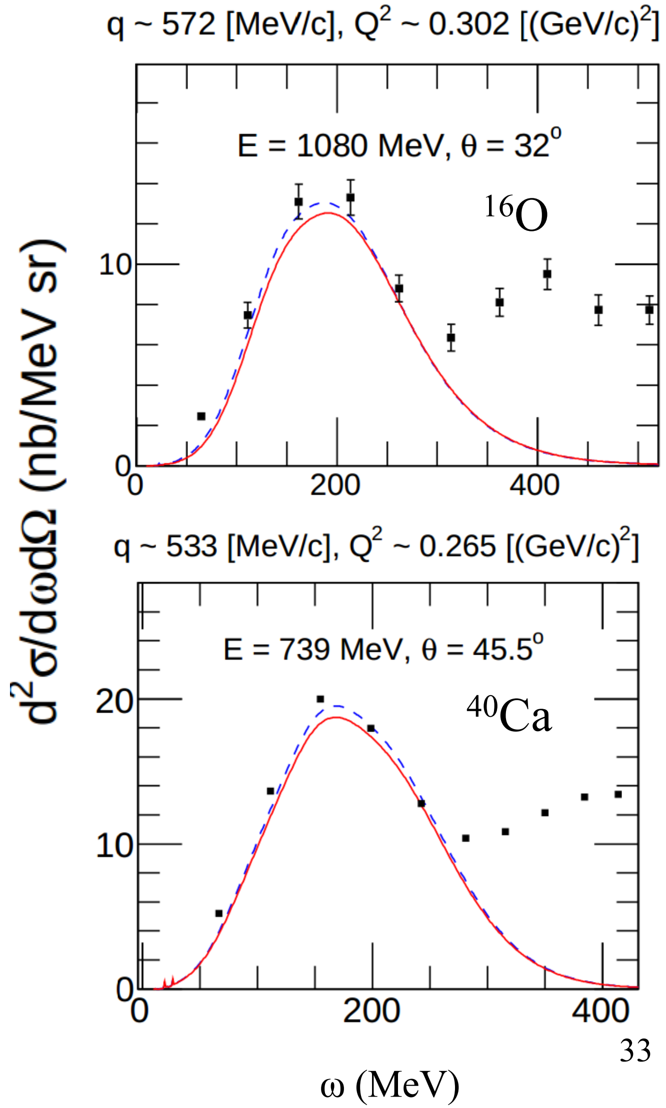
CRPA: without MEMA, CRPA: with MEMA



Comparison with (e,e') data for ^{12}C, ^{16}O, ^{40}Ca

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

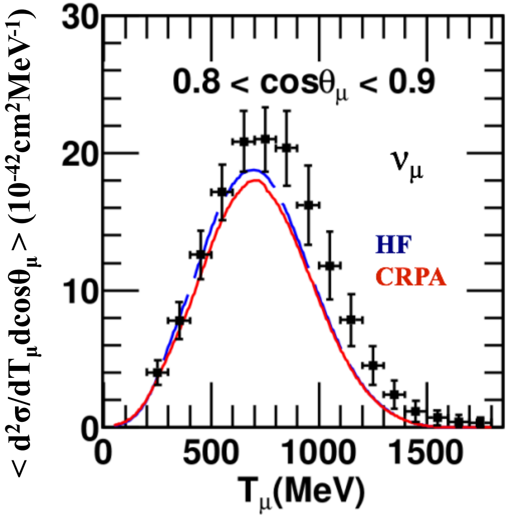




Comparison with neutrino data

VP, N. Jachowicz, PRC 94, 054609 (2016)

MiniBooNE DATA



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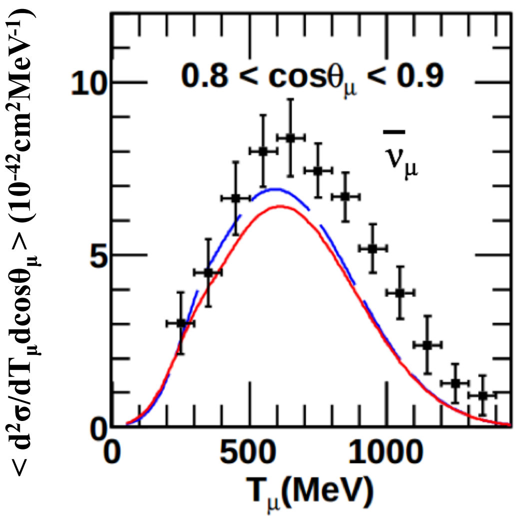
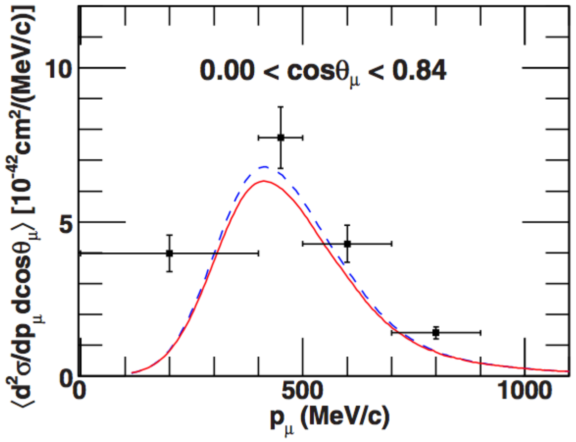


T2K ND280 DATA



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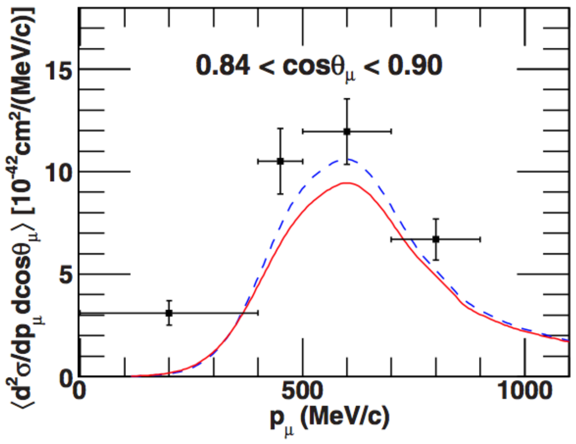

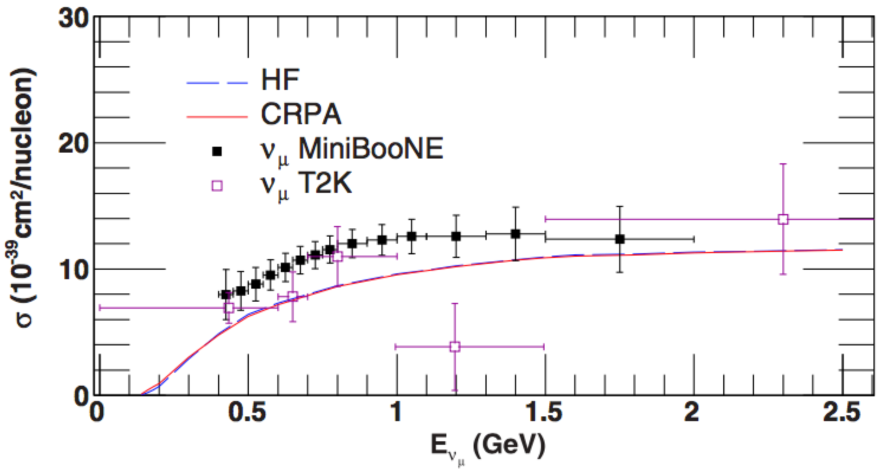

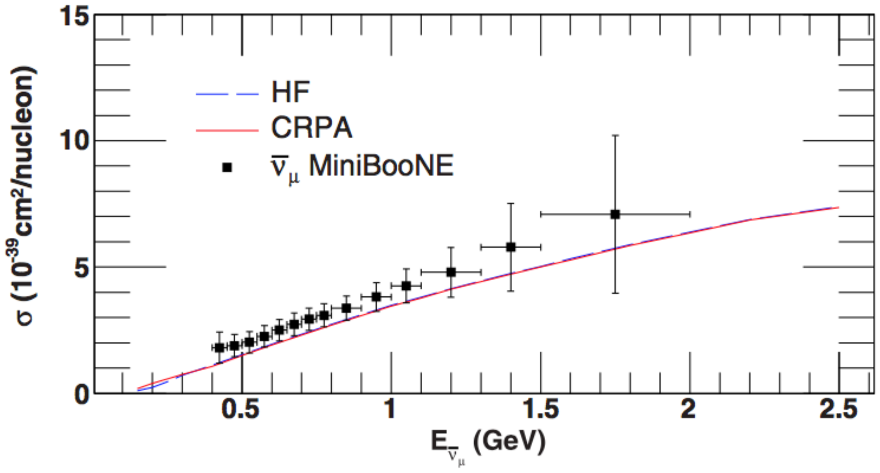

Comparing RPA-based models

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

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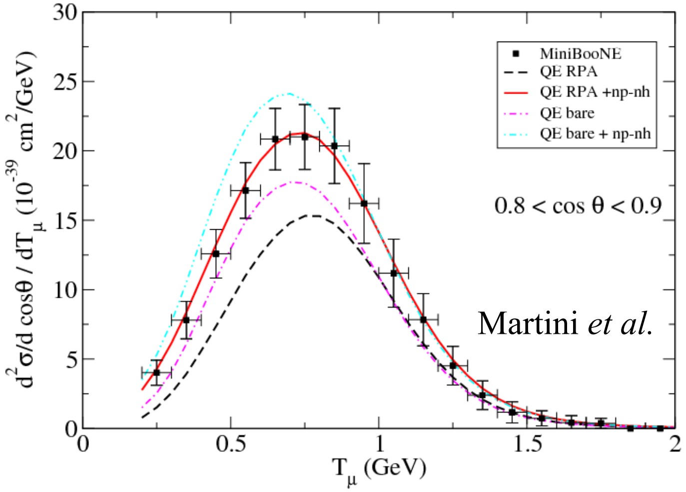
RPA polarization propagator:

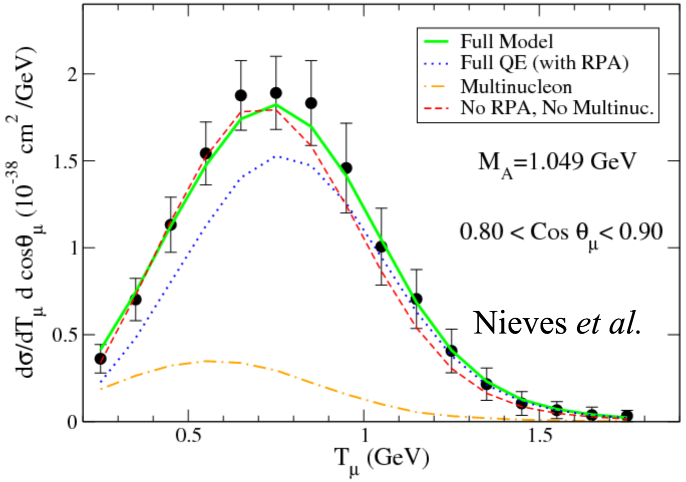
$$\Pi = \Pi^0 + \Pi^0 \, V \, \Pi$$

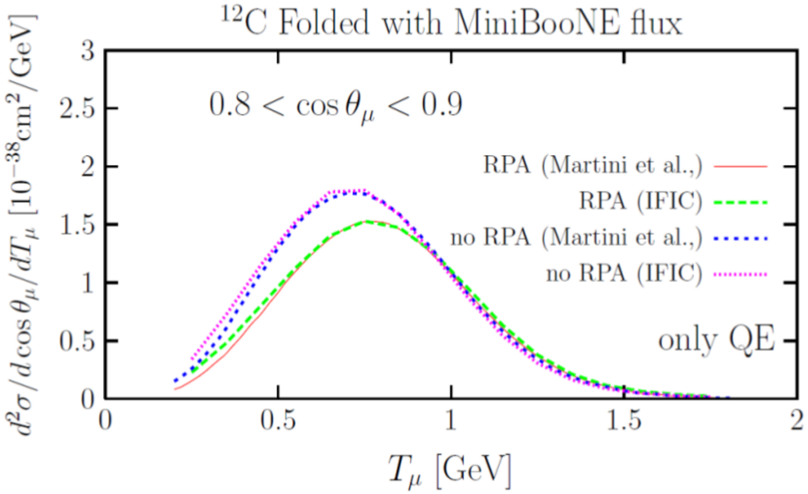
[Martini *et al.* and Nieves *et al.*]

Bare Propagatoor (RlFG)

π exchange, ρ exchange,
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

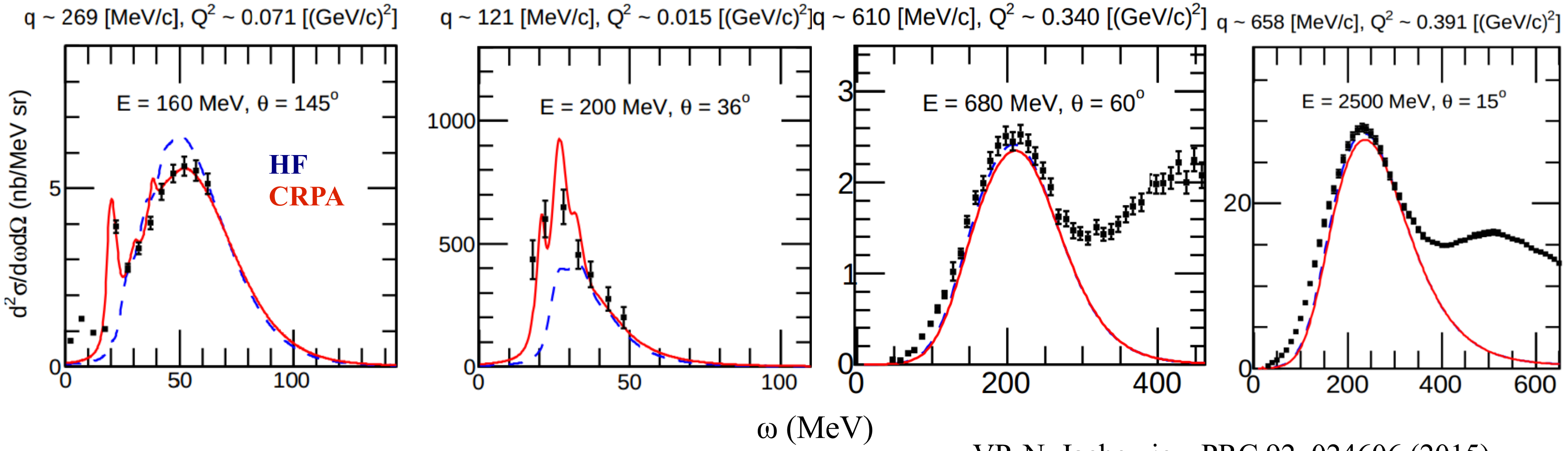
RPA polarization propagator:

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

HF

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)*

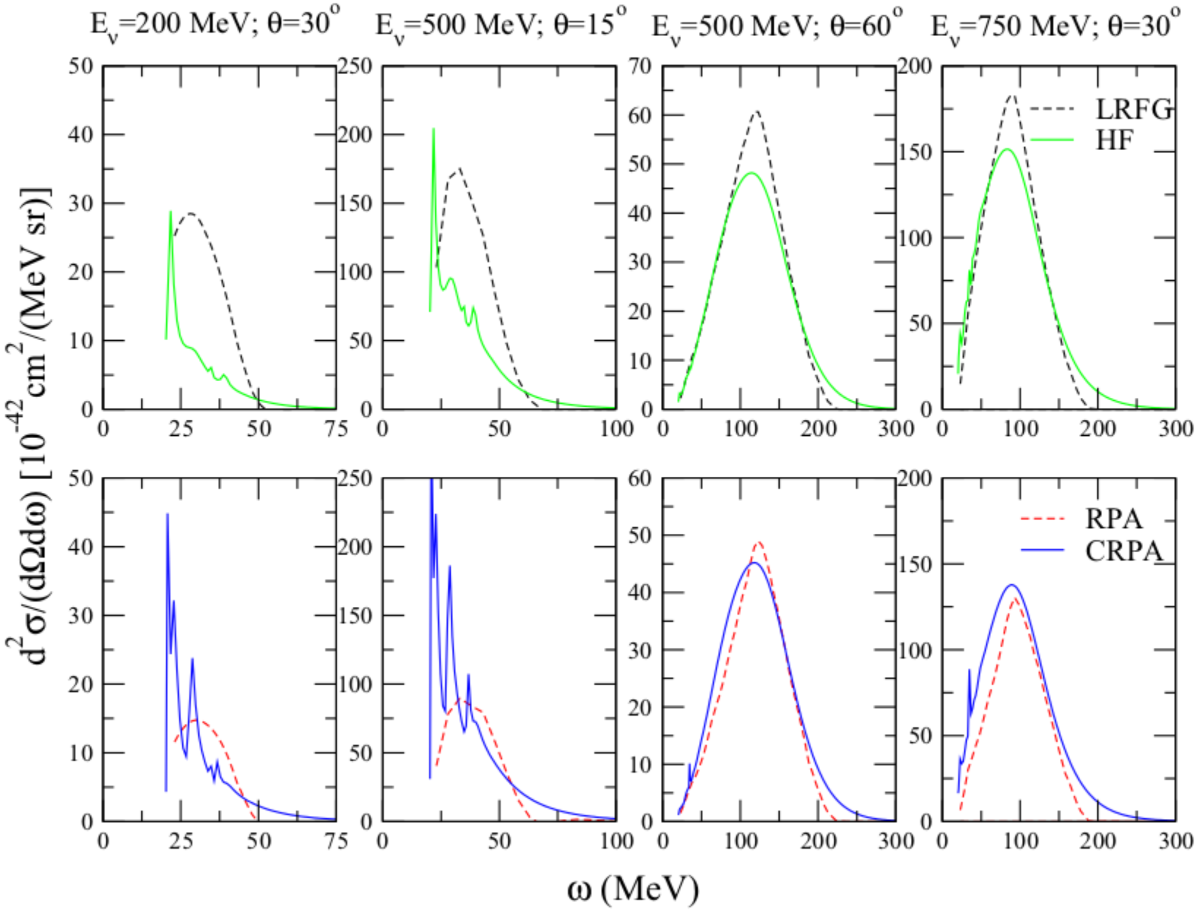
LRFG, RPA: Martini, Ericson *et al.*

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

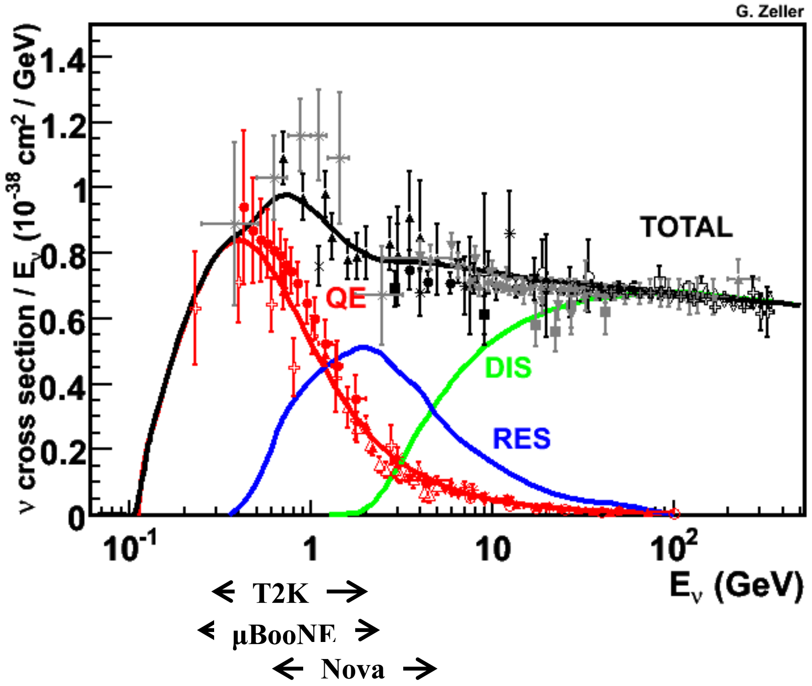
- Significant differences between RPA and CRPA approach, at both ends of the (one-body) ω spectrum.

*Lorentz-Lorentz-Ericson-Ericson effect: accounts for the possibility of a Δ-hole excitation in the RPA chain

Impact of low-energy excitations

What neutrino brings: E_ν

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



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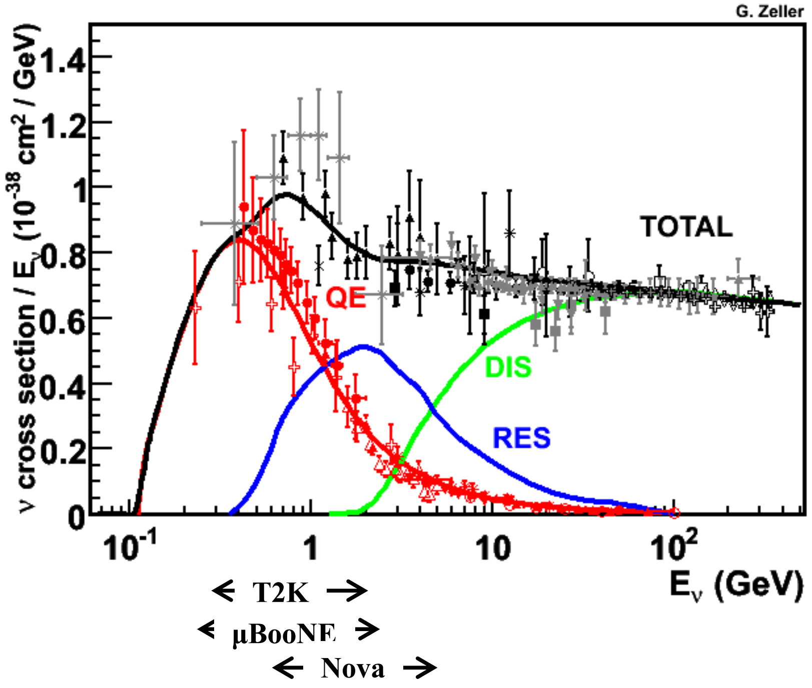
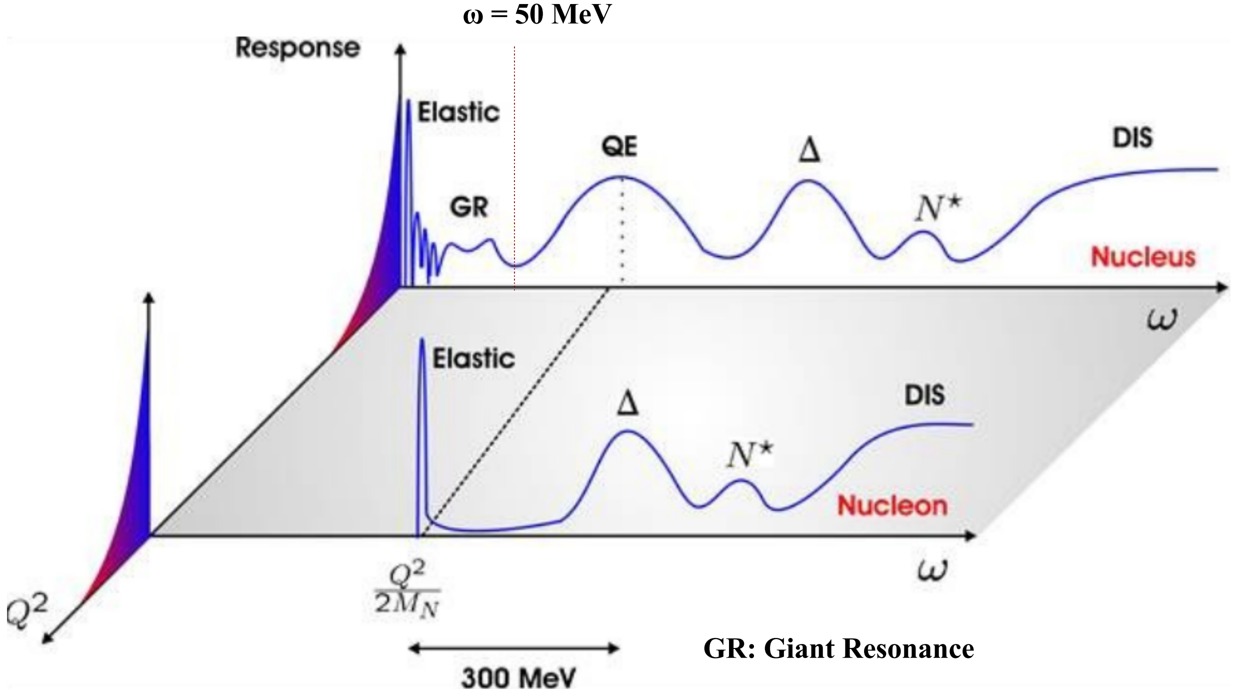




What nucleus cares: ω

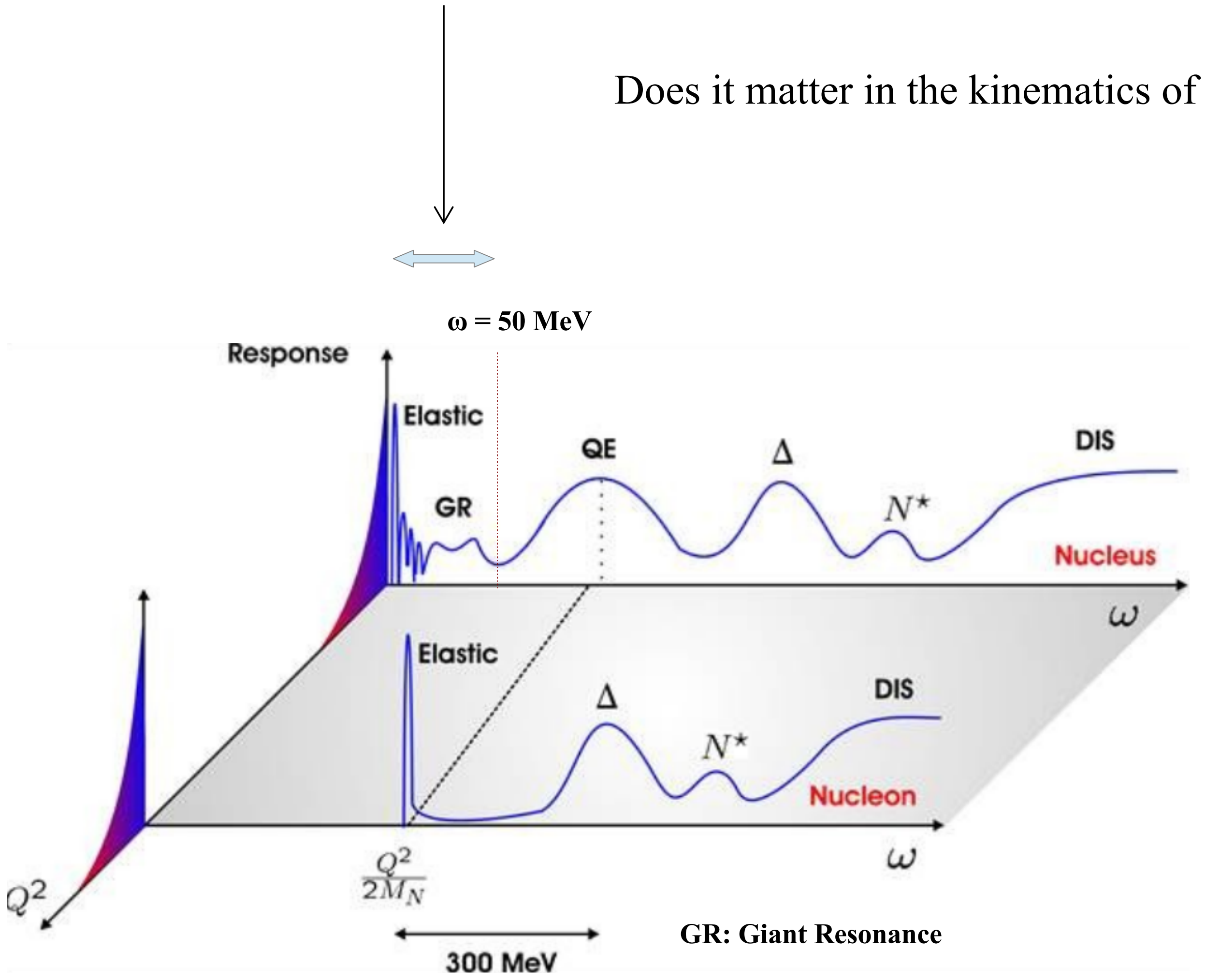
i.e. how much energy is transferred to the nucleus (ω).

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

Impact of low-energy excitations

What is missed in the translation.

Does it matter in the kinematics of our interest?



GR: Giant Resonance

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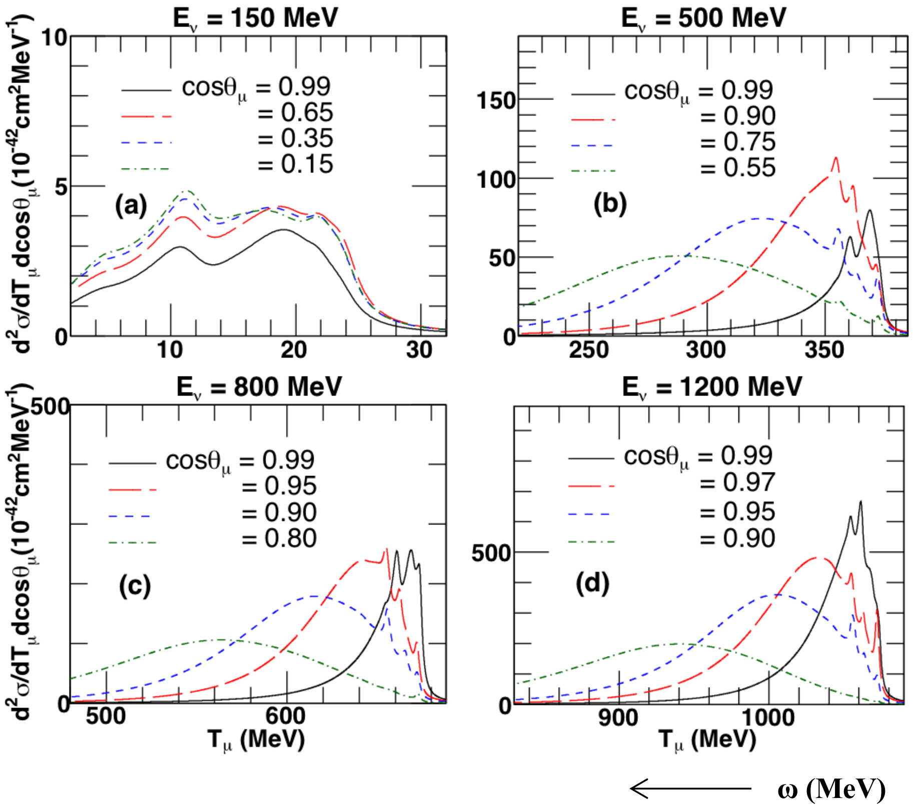
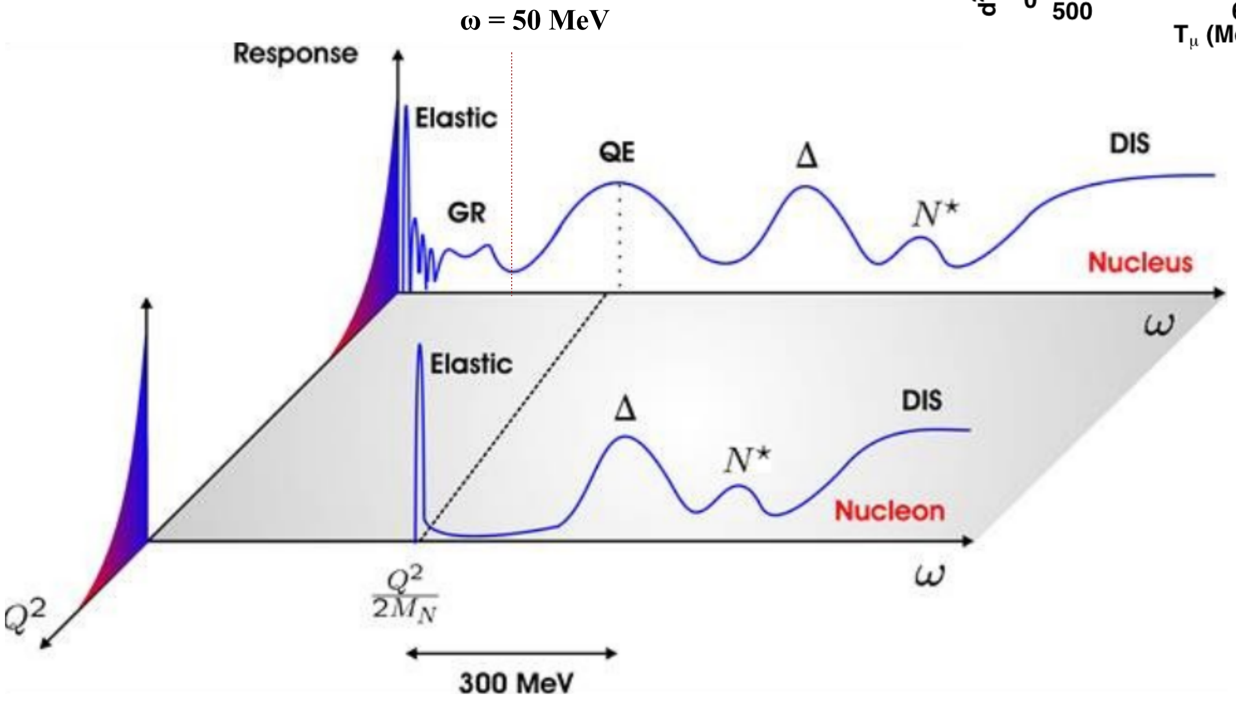
Impact of low-energy excitations

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

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



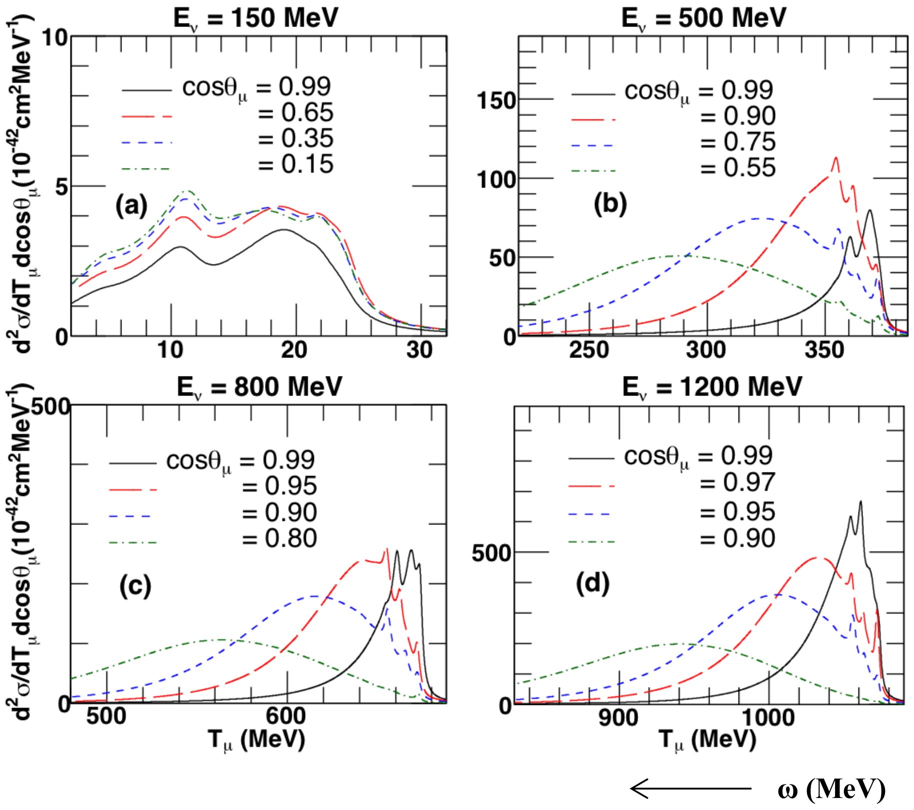
VP, N. Jachowicz et al, PRC 92, 024606 (2015)



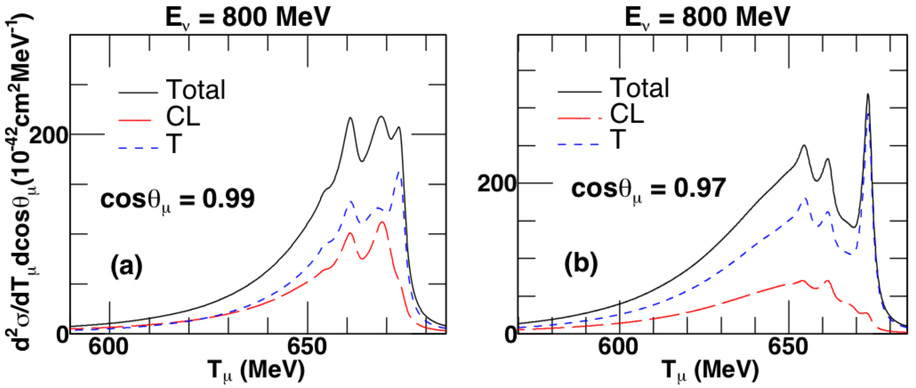
Impact of low-energy excitations

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.



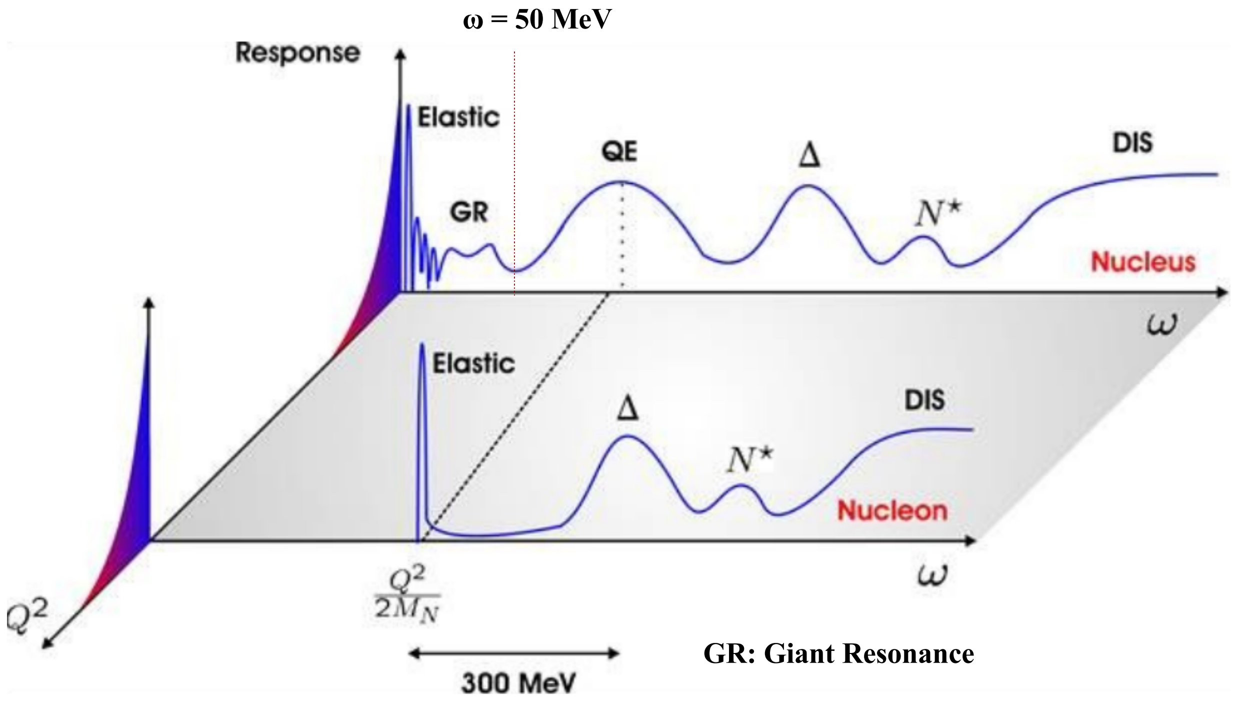
- The forward we go in scattering angle, longitudinal contribution starts competing with the transverse one (at intermediate energy).
- At low-energies and forward scattering, longitudinal response dominates over transverse one.



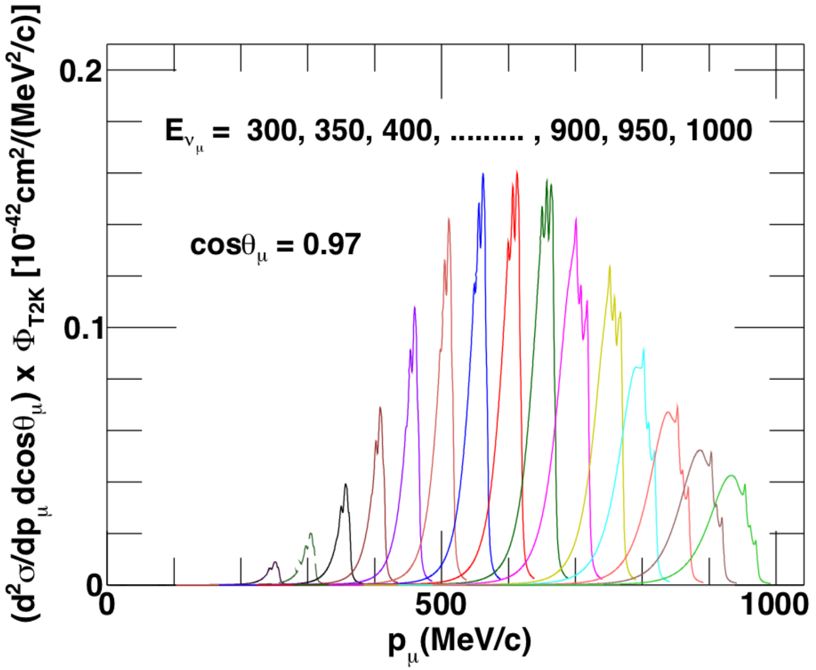
VP, N. Jachowicz et al, PRC 92, 024606 (2015)

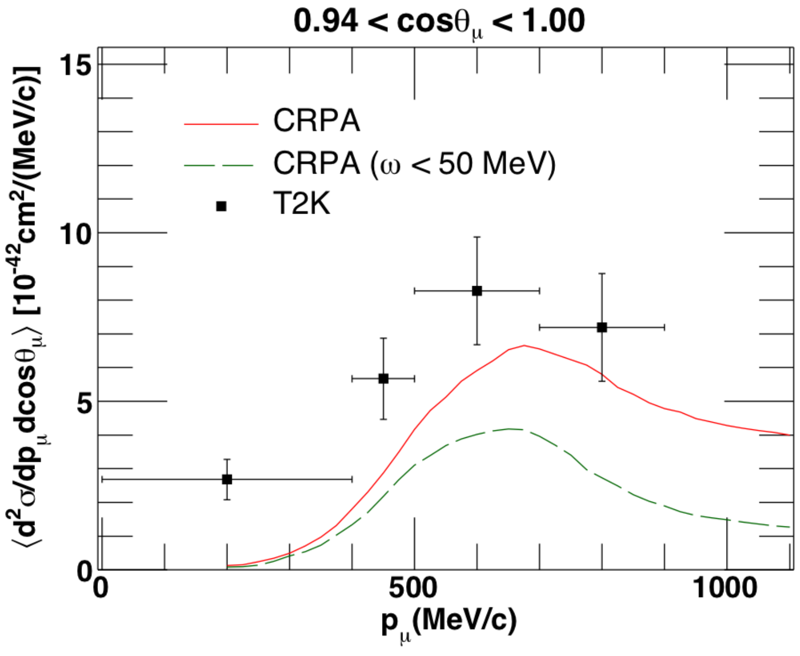
Impact of low-energy excitations

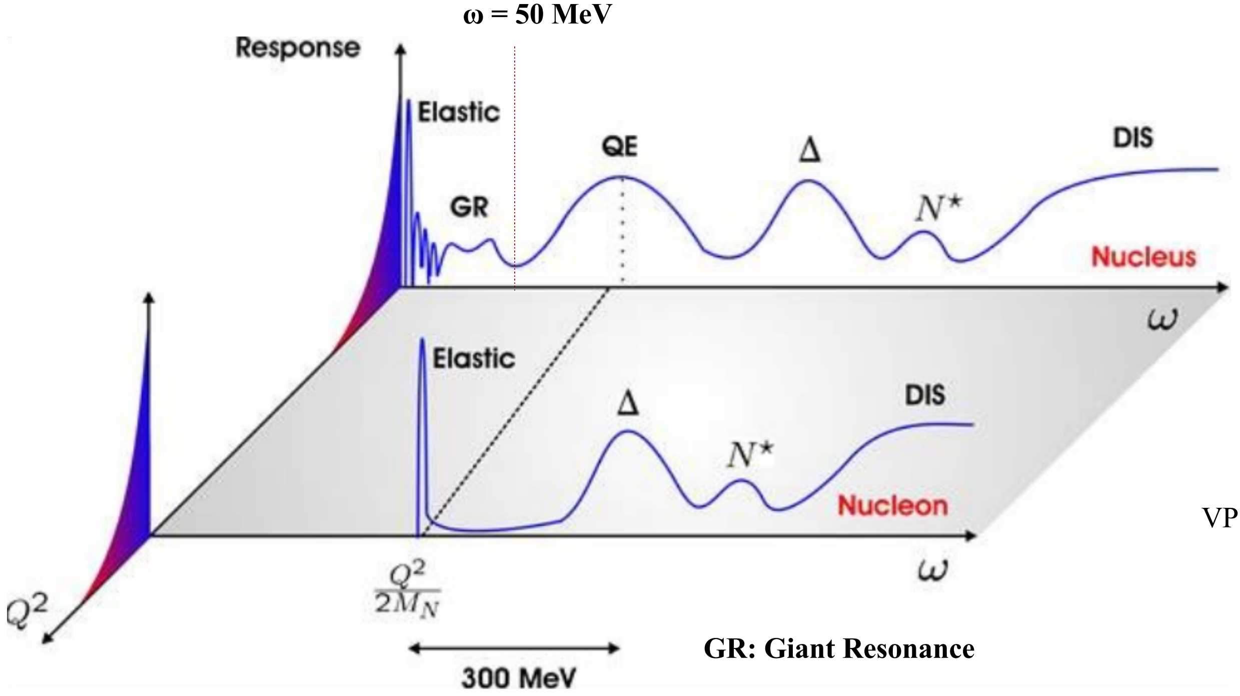
Does it affect the flux-folded cross section?
And how much?



GR: Giant Resonance







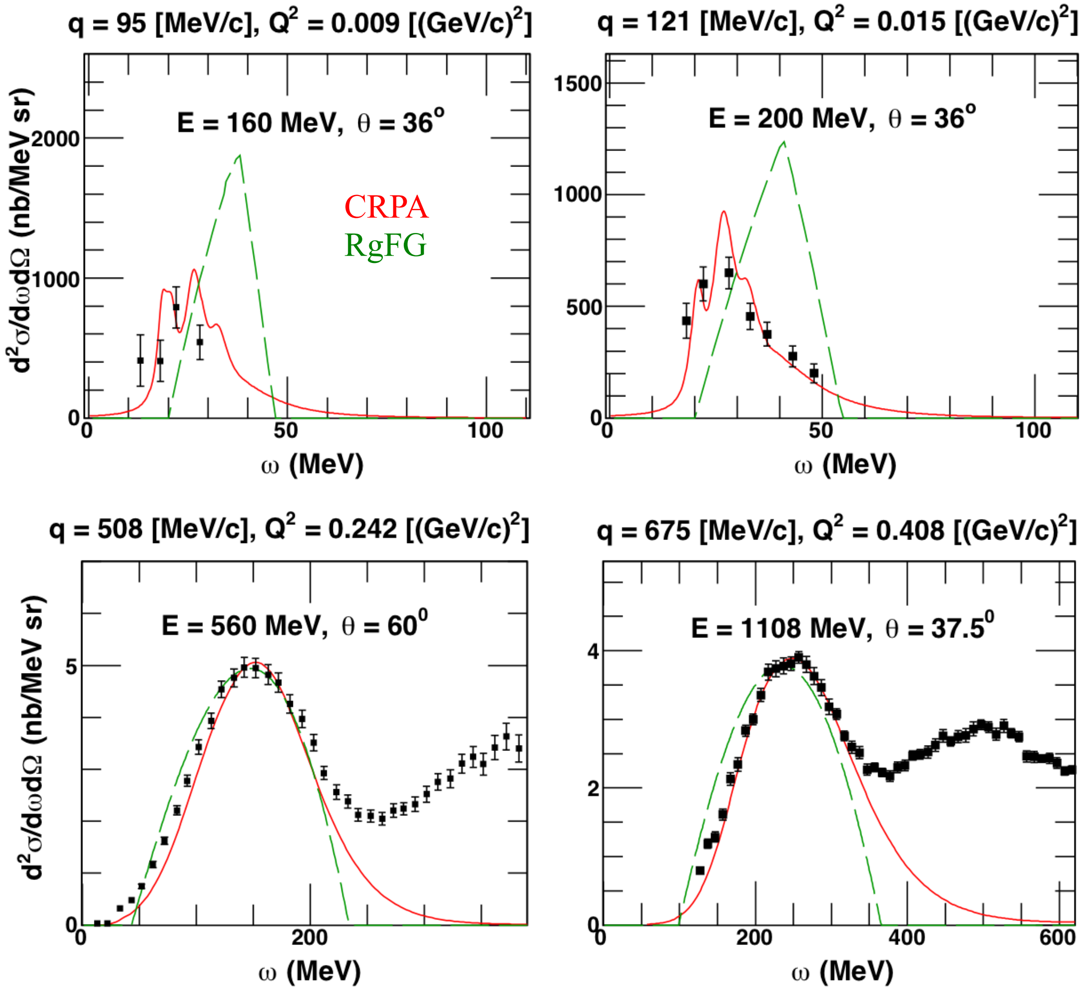
GR: Giant Resonance

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

VP, N. Jachowicz, Phys.Rev. C94, 054609 (2016).

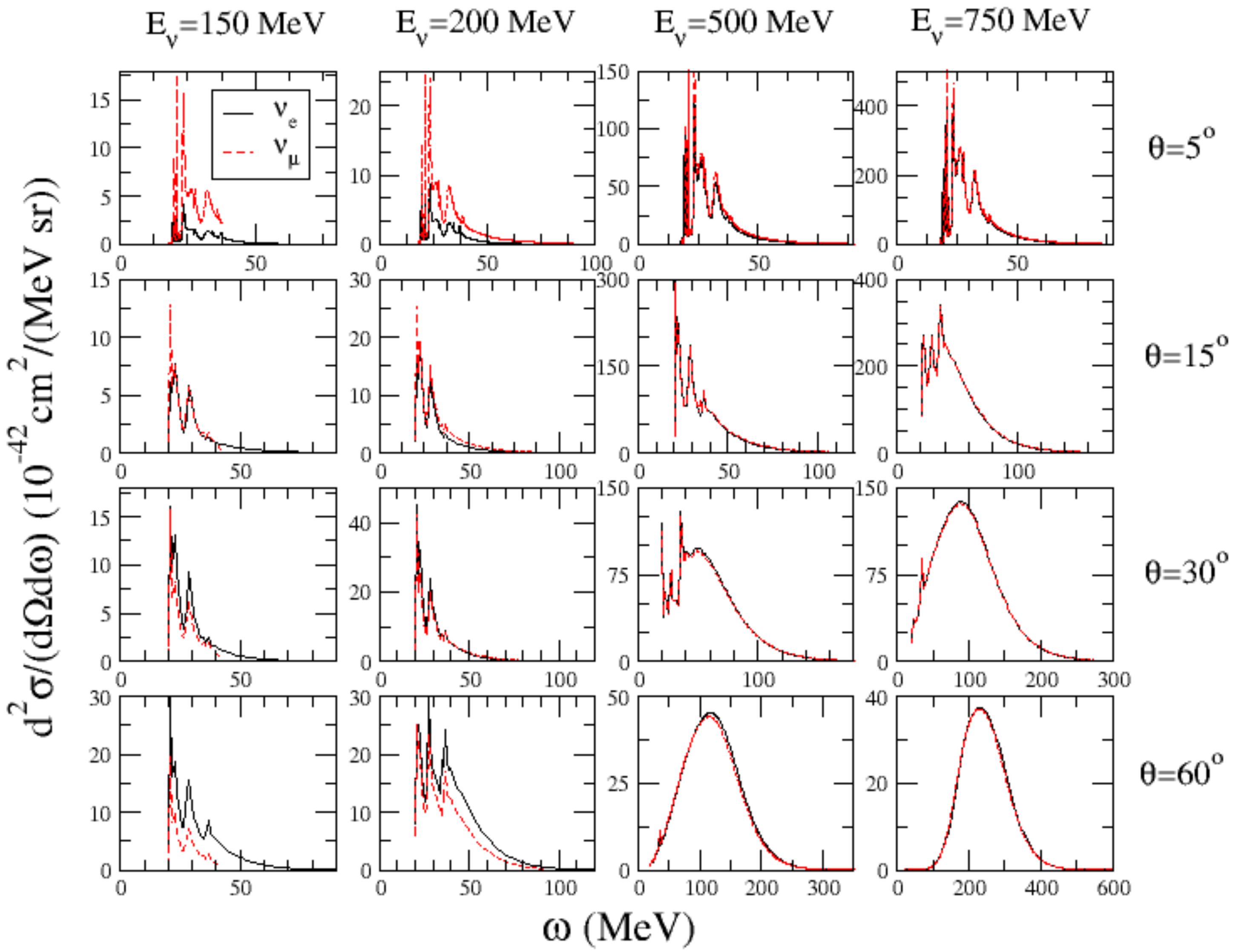
How does RgFG model describes low-energy excitations – it does not!

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



Impact of low-energy excitations

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



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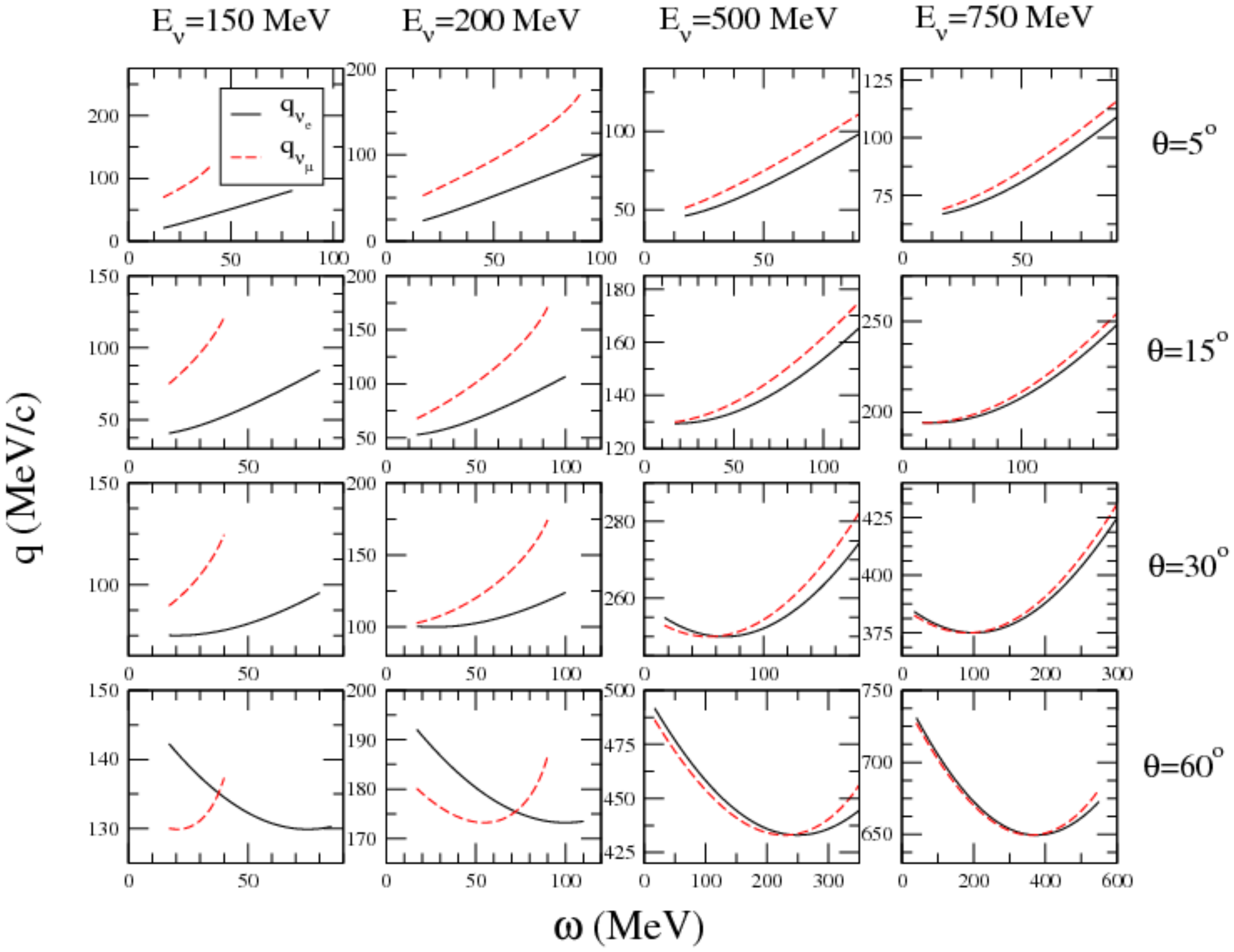

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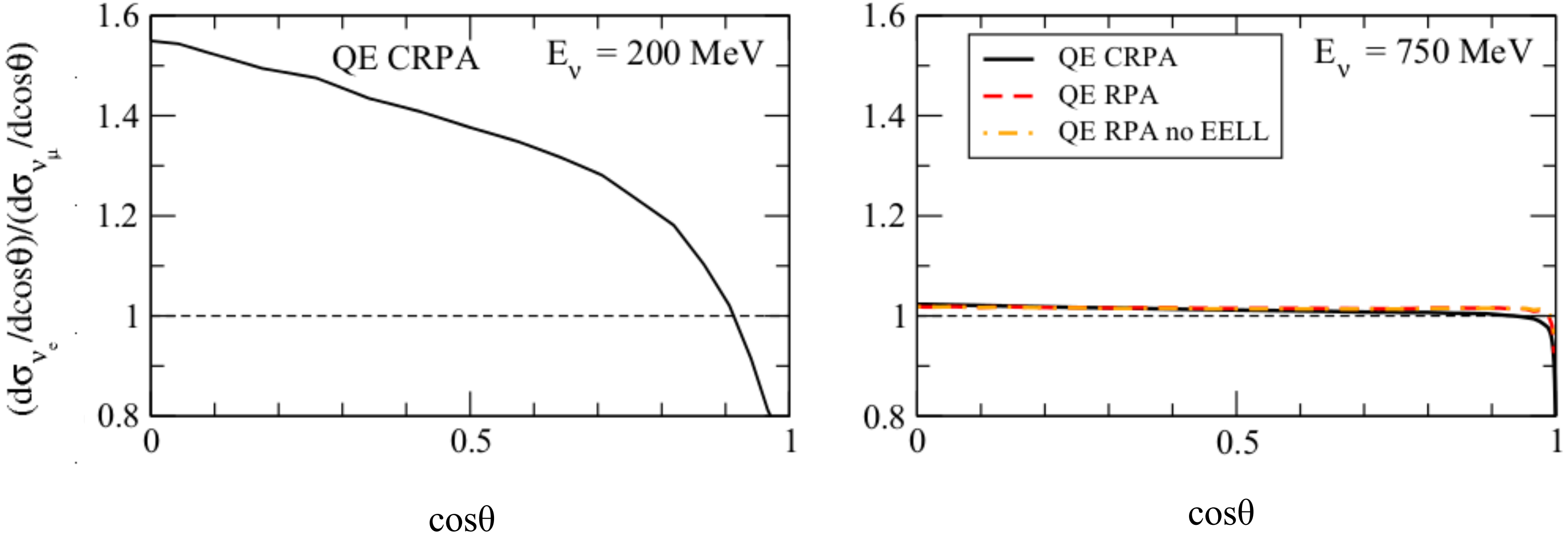

Low-energy nuclear excitations are vital
- At low E_ν
- At intermediate E_ν and forward scattering
- Differentiating between ν_e and ν_μ cross section (at low E_ν)

Summary

- Accelerator-based neutrino-oscillation program, for the precision measurement of neutrino oscillation parameters and hopefully establishing cp violation in leptonic sector, is moving with full steam.

- There are still major issues related to identification of basic processes contributing to the neutrino-nucleus signal in a detector and the reduction of systematic uncertainties.

Summary

The Impact of nuclear effects on accelerator-based neutrino-oscillation physics

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- A number of theoretical efforts to model neutrino-nucleus interactions at the kinematics relevant for the neutrino-oscillation experiments.

- The Monte-Carlo generators are still based on inadequate models and implementing new models into current generators is complex and slow.

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- Next generation experiments (MicroBooNE, ICARUS, SBND, and DUNE) employ LArTPC technology but a little (almost nonthing) is known about Ar nucleus and its electroweak response.

- A new Ar(e,e’p) experiment at Jlab (was recently approved and now also already finished collecting data) will provide spectroscopic factors and cross sections on Ar.