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Electron versus Muon Neutrino Induced Cross Sections in Charged Current Quasielastic Processes

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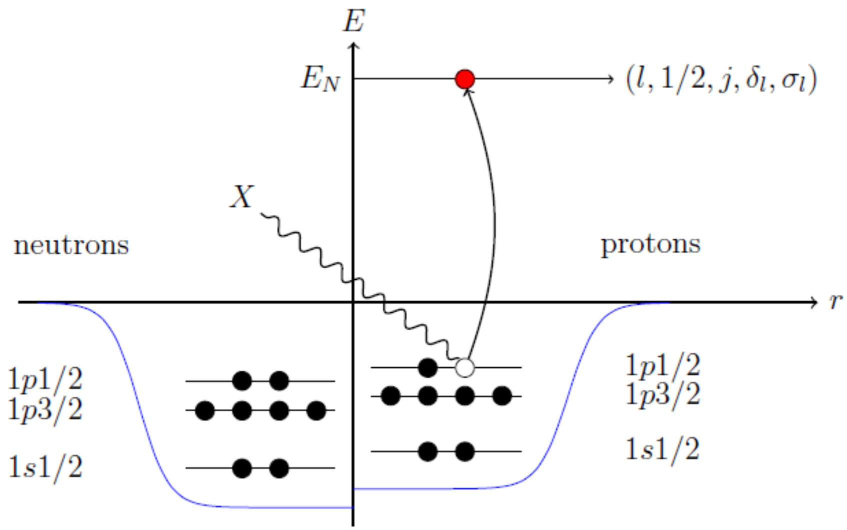
Outline:

I. Description of the mean field approach

II. Non trivial differences between electron and muon neutrino charged-current scattering on nuclei

III. The case for orthogonality and consistency

The mean field approach (briefly)



The mean field potential and bound states are obtained in a self-consistent Hartree-Fock calculation with a realistic nucleon-nucleon force

All bound and scattering states are obtained by solving the Schrödinger (or Dirac) equation in a central mean field potential.

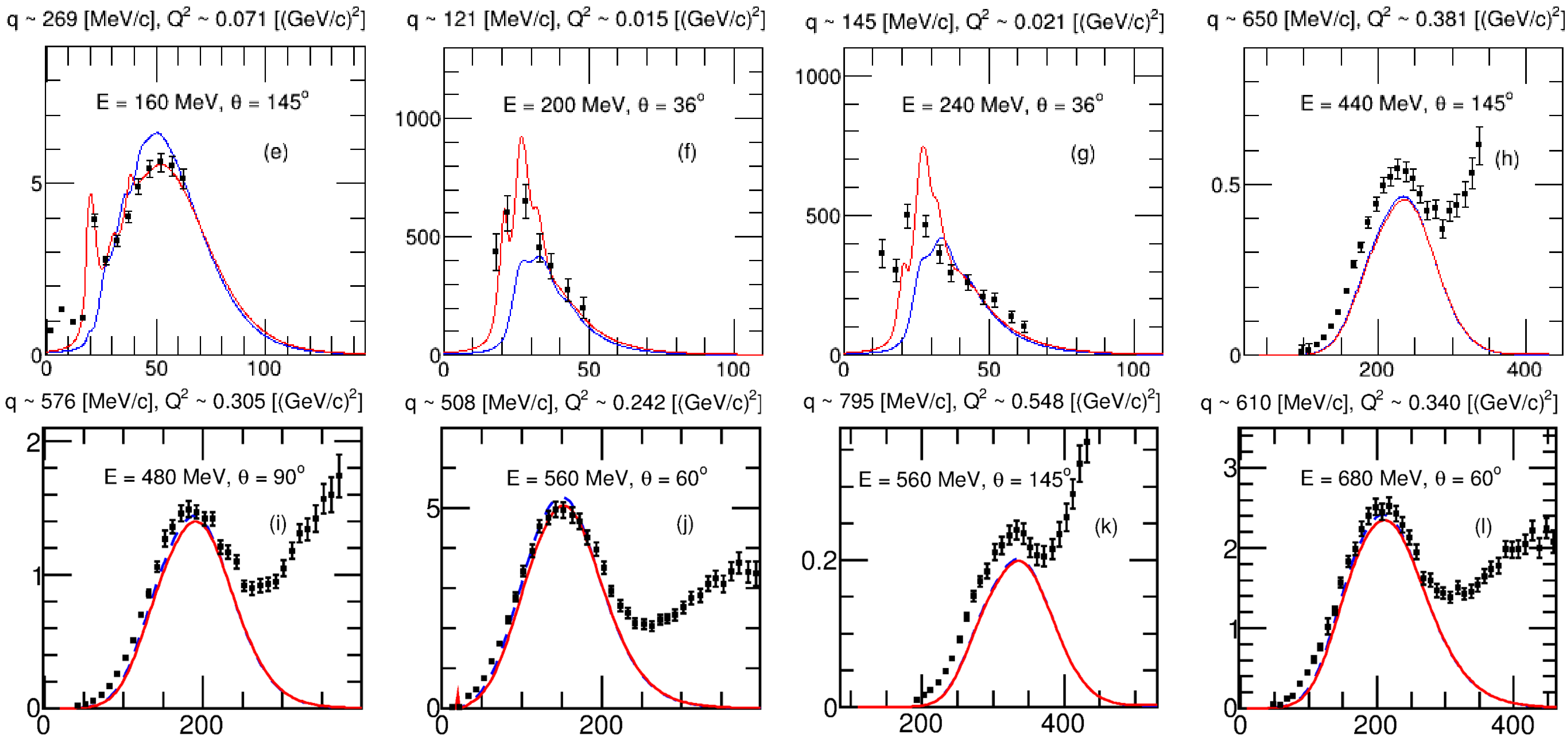
This means all states are consistent and orthogonal within this approach.

Naturally includes:

Binding
Fermi motion
Elastic Final state interactions
Pauli blocking
orthogonality

This approach captures the main nuclear effects in a consistent quantum mechanical way

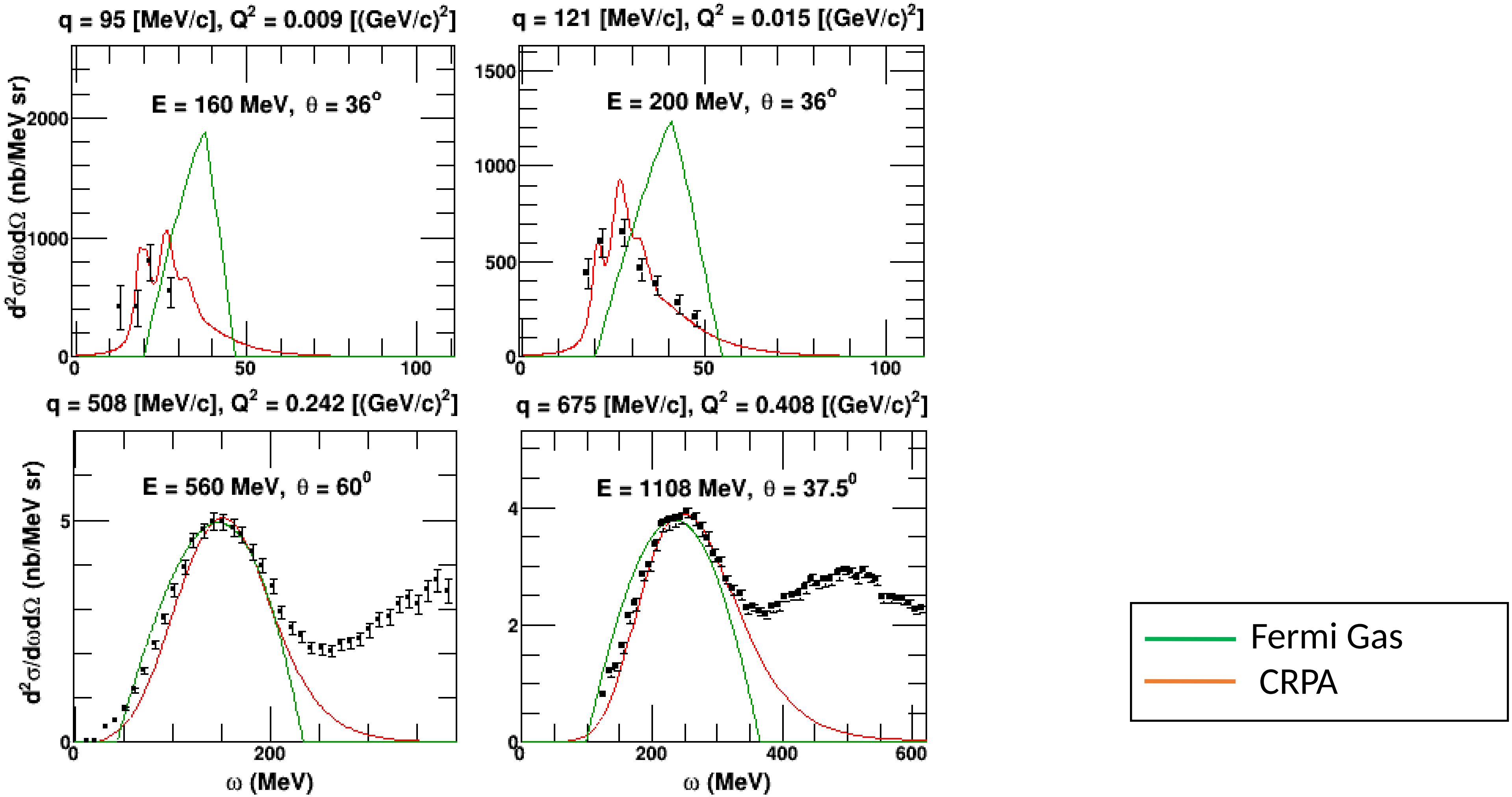
The mean field approach (briefly)



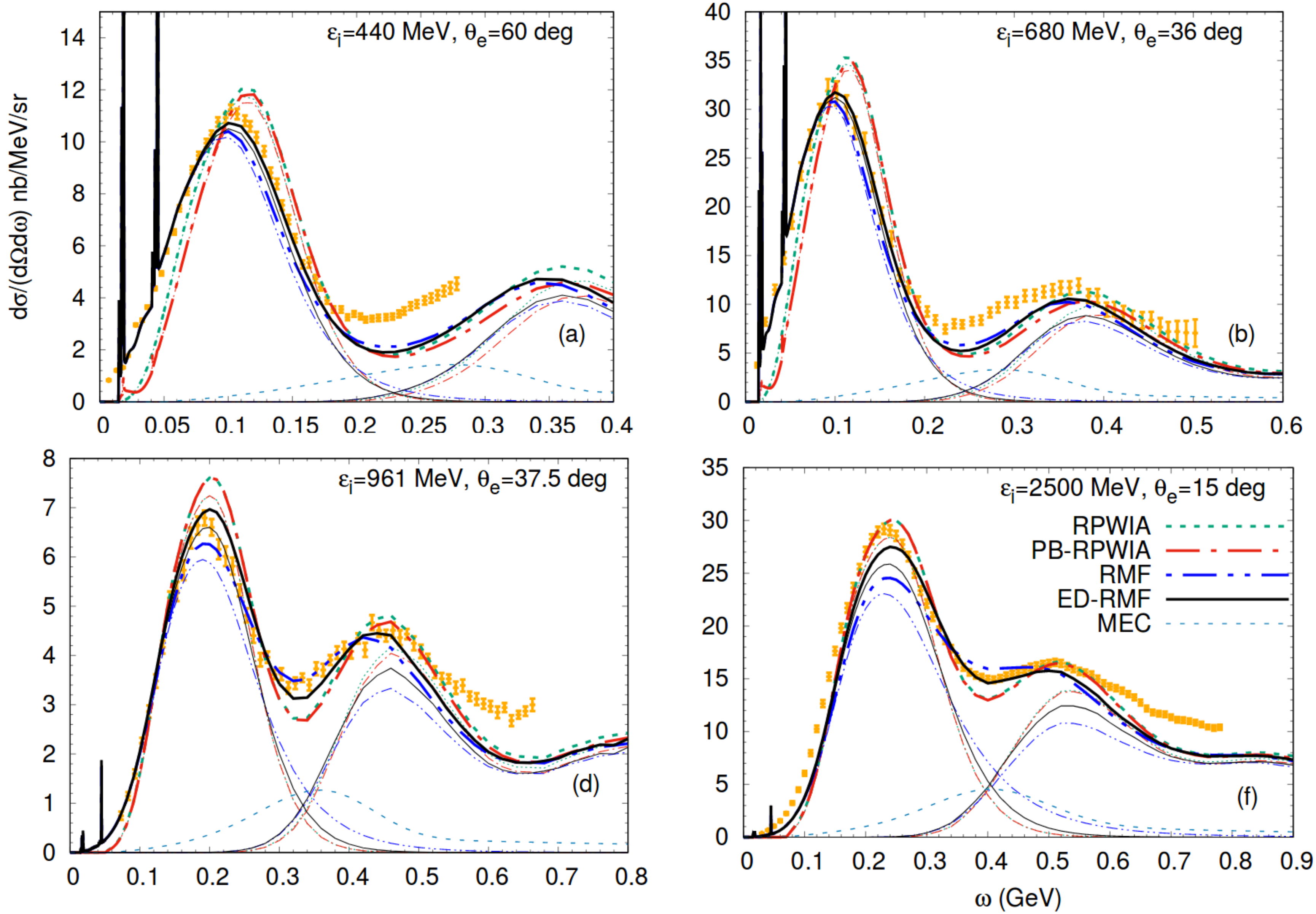
Comparison to (e,e') data from V. Pandey et al.
PRC 92, 024606 (2015)

The mean field approach (briefly)

Compared to commonly used RFG model:
Pauli-blocking important for low q



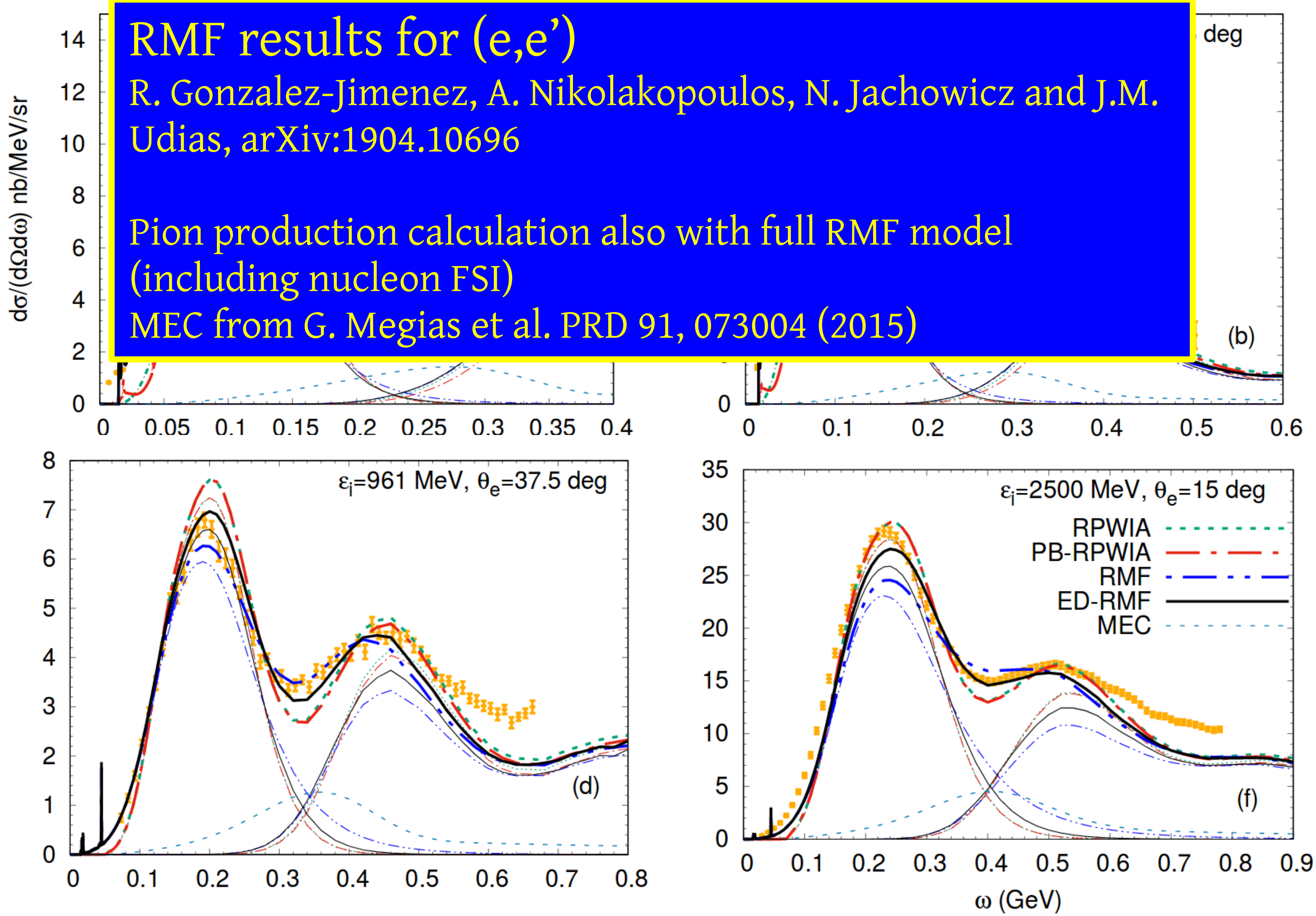
The mean field approach (briefly)



The mean field approach (briefly)

RMF results for (e,e’)
R. Gonzalez-Jimenez, A. Nikolakopoulos, N. Jachowicz and J.M. Udias, arXiv:1904.10696

Pion production calculation also with full RMF model (including nucleon FSI)
MEC from G. Megias et al. PRD 91, 073004 (2015)



Differences between e and μ CC scattering

Knowing the difference between these interactions is crucial for CP-violation searches in future experiments and for the interpretation of current appearance experiments.

T2K and MiniBooNE start with a muon-neutrino dominated beam
Used to 'calibrate' and verify the cross section model

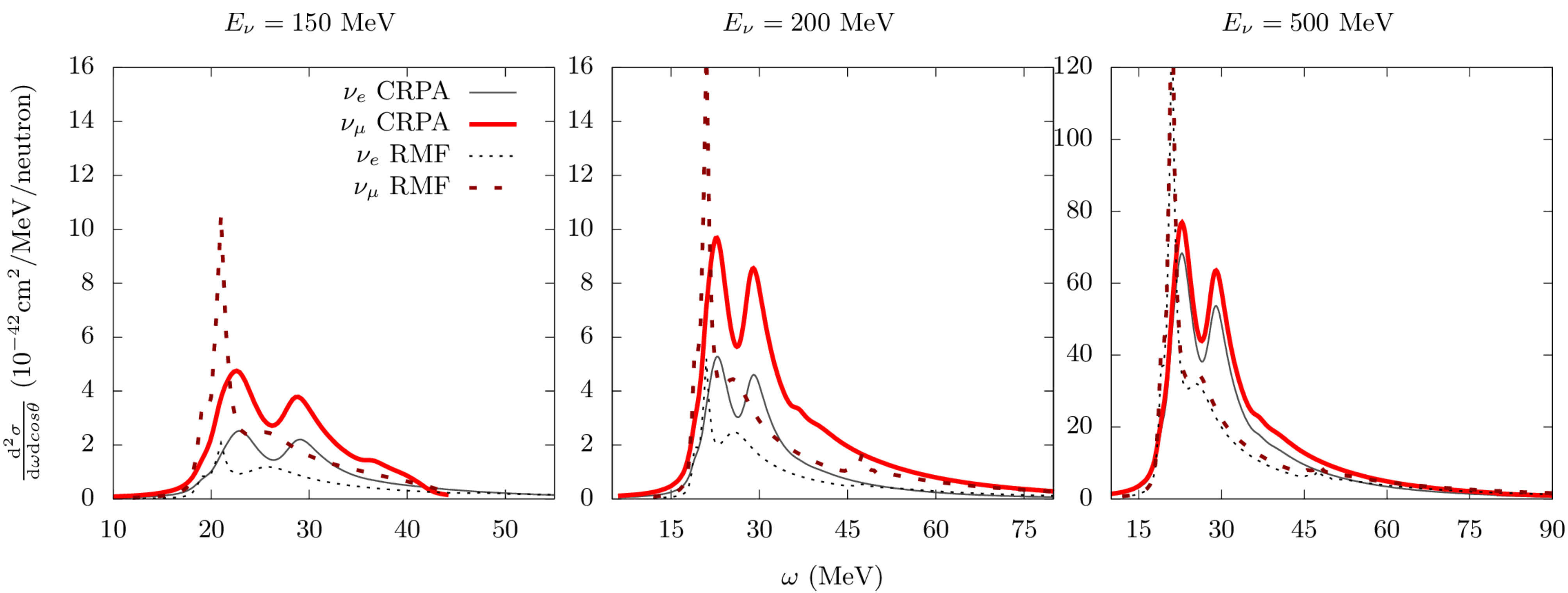
Appearance of electron-type neutrinos, which may behave differently

Theoretical and experimental interest over the last years:
Nuclear medium effects:
- J. Nieves and J.E. Sobczyk Annals Phys. 383 (2017) 455-496
- M. Martini, N. Jachowicz et al. Phys Rev C 94 015501 (2016)
- A. M. Ankowski Phys. Rev. C 96, 035501 (2017)

Radiative corrections:
- M. Day and K. McFarland, Phys Rev D86 05300 (2012)

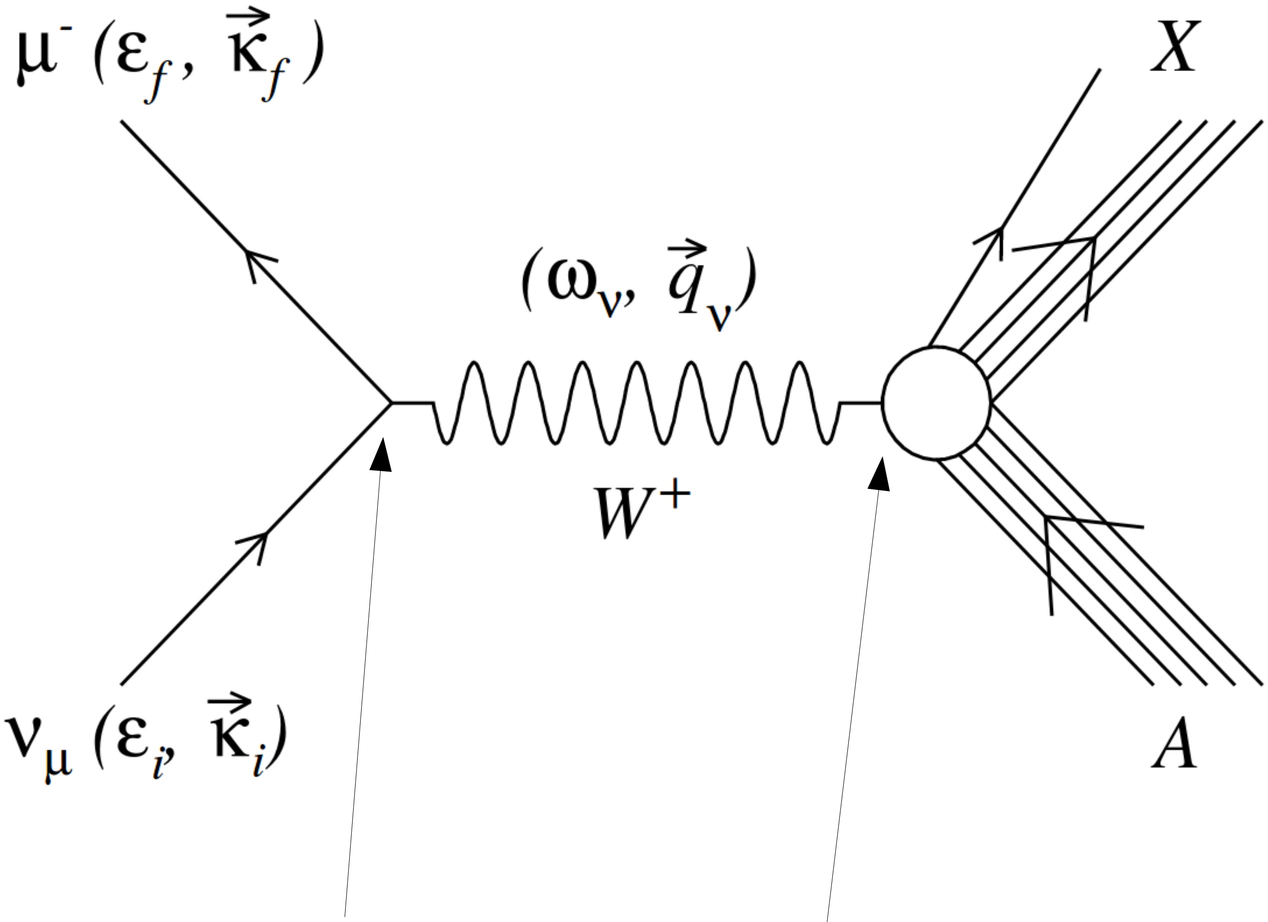
Differences between e and μ CC scattering

Mean field models lead to larger ν_μ than ν_e cross sections for low ω and q



This is counter-intuitive, from the lepton mass one expects the opposite

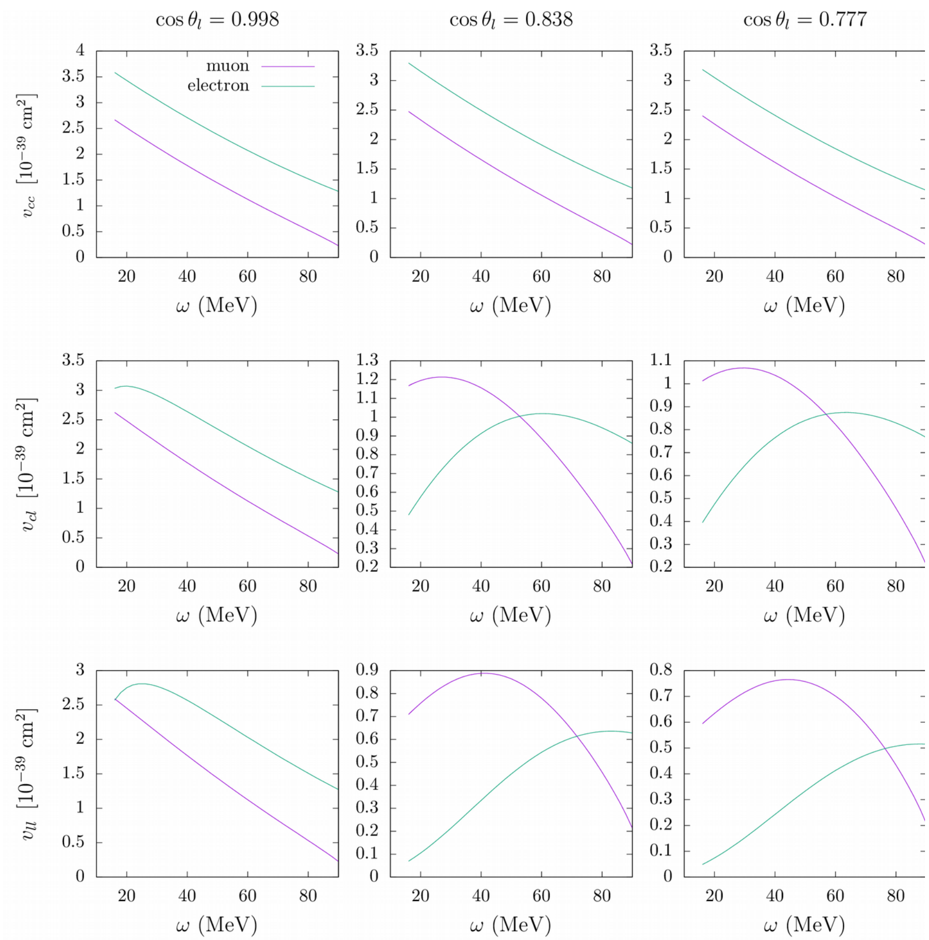
Differences between e and μ CC scattering



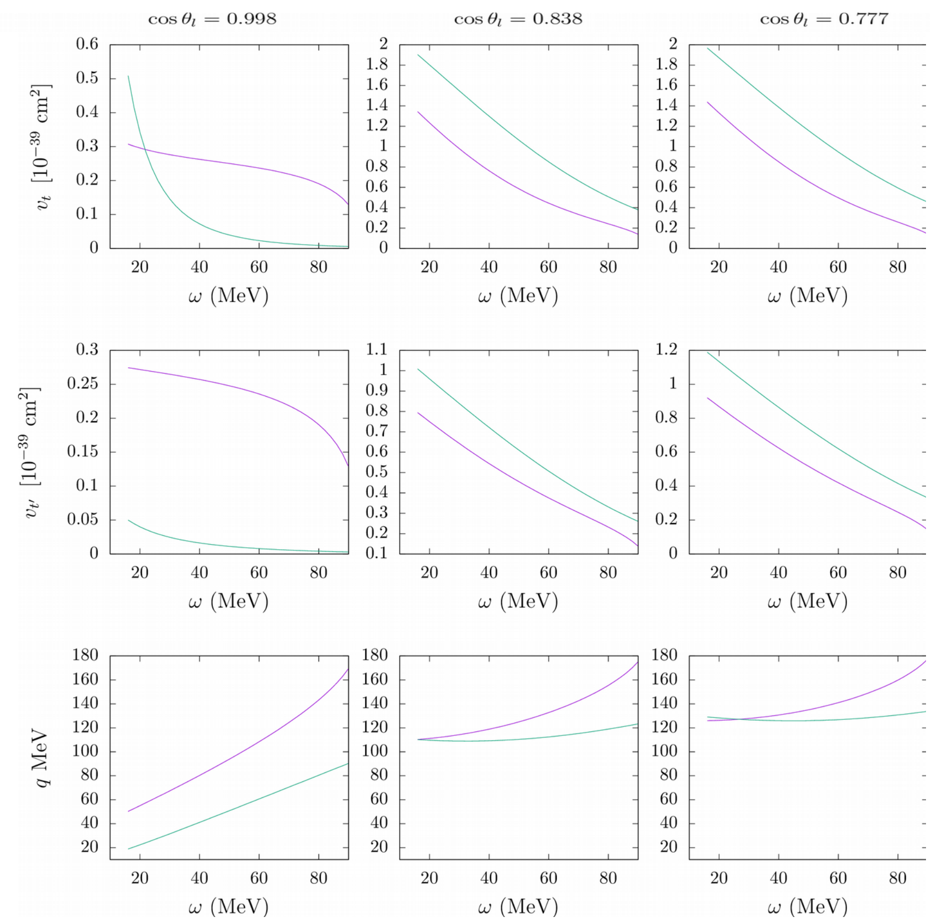
$$\sigma \sim \sum_i V_i(E_\nu, E_l, \cos\theta_l) \times R_i(\omega, q)$$

Leptonic prefactors

Longitudinal

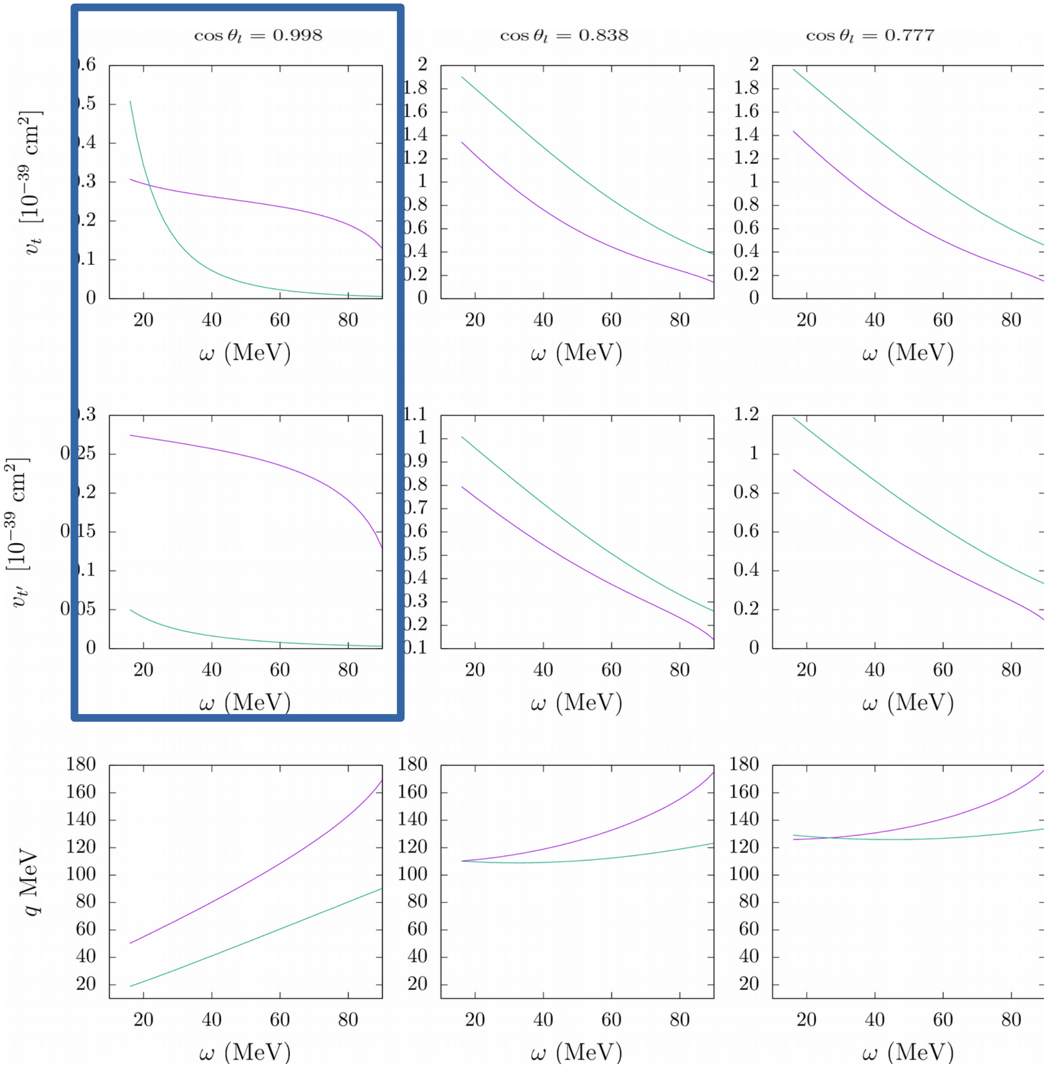


Transverse



From the leptonic vertex one expects the electron neutrino to dominate

Leptonic prefactors



Caveat: close to threshold the muon gets transverse contributions.

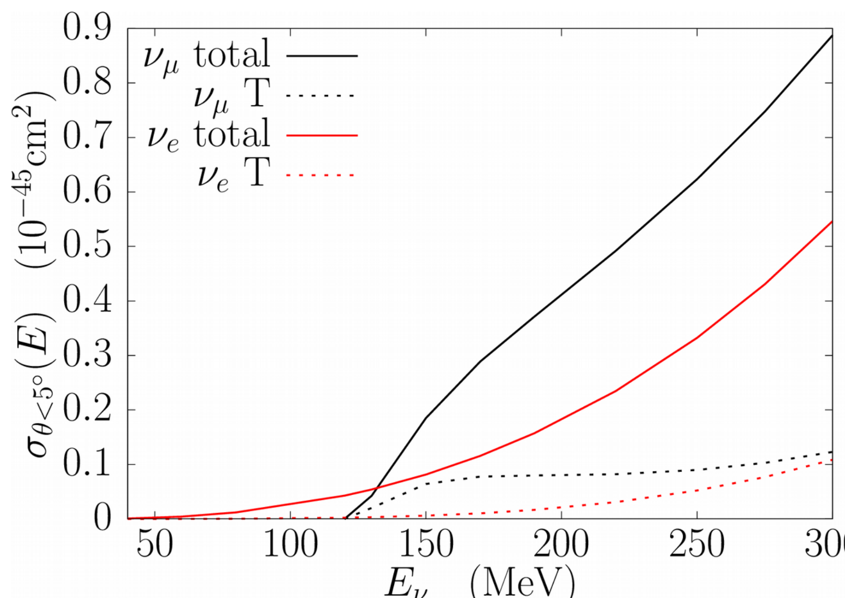
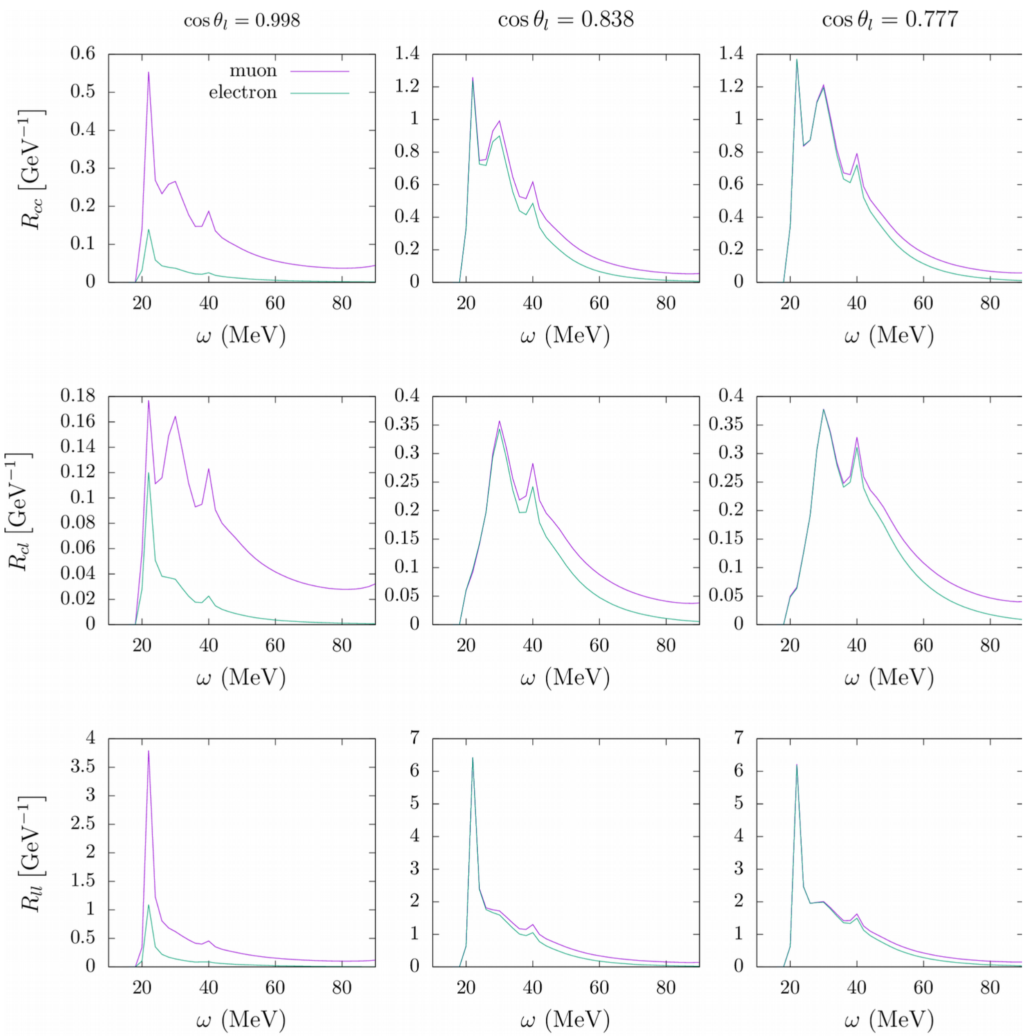


Fig. from arXiv:1904.10696

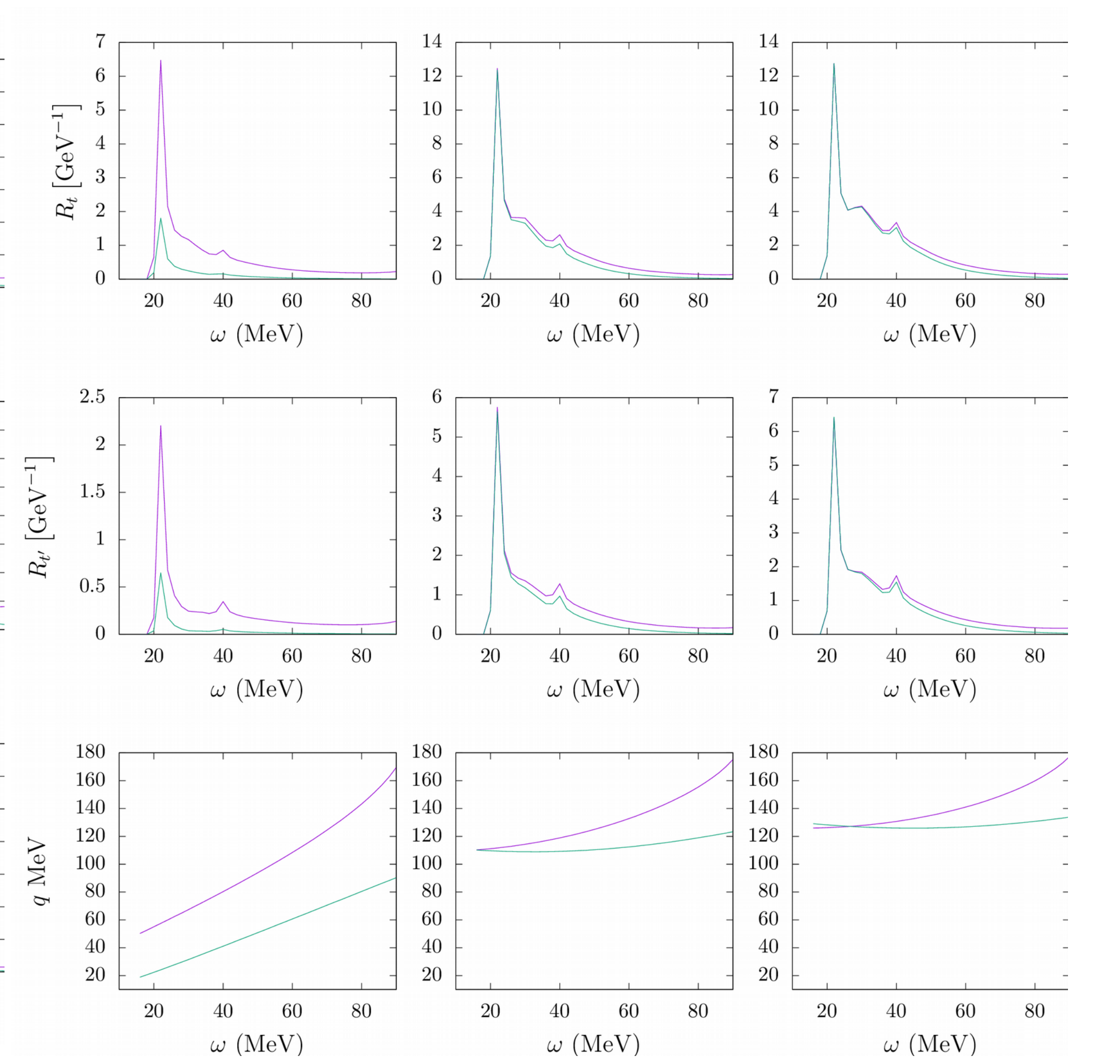
Not enough to explain the difference when the neutrino energy increases.

Responses

Longitudinal



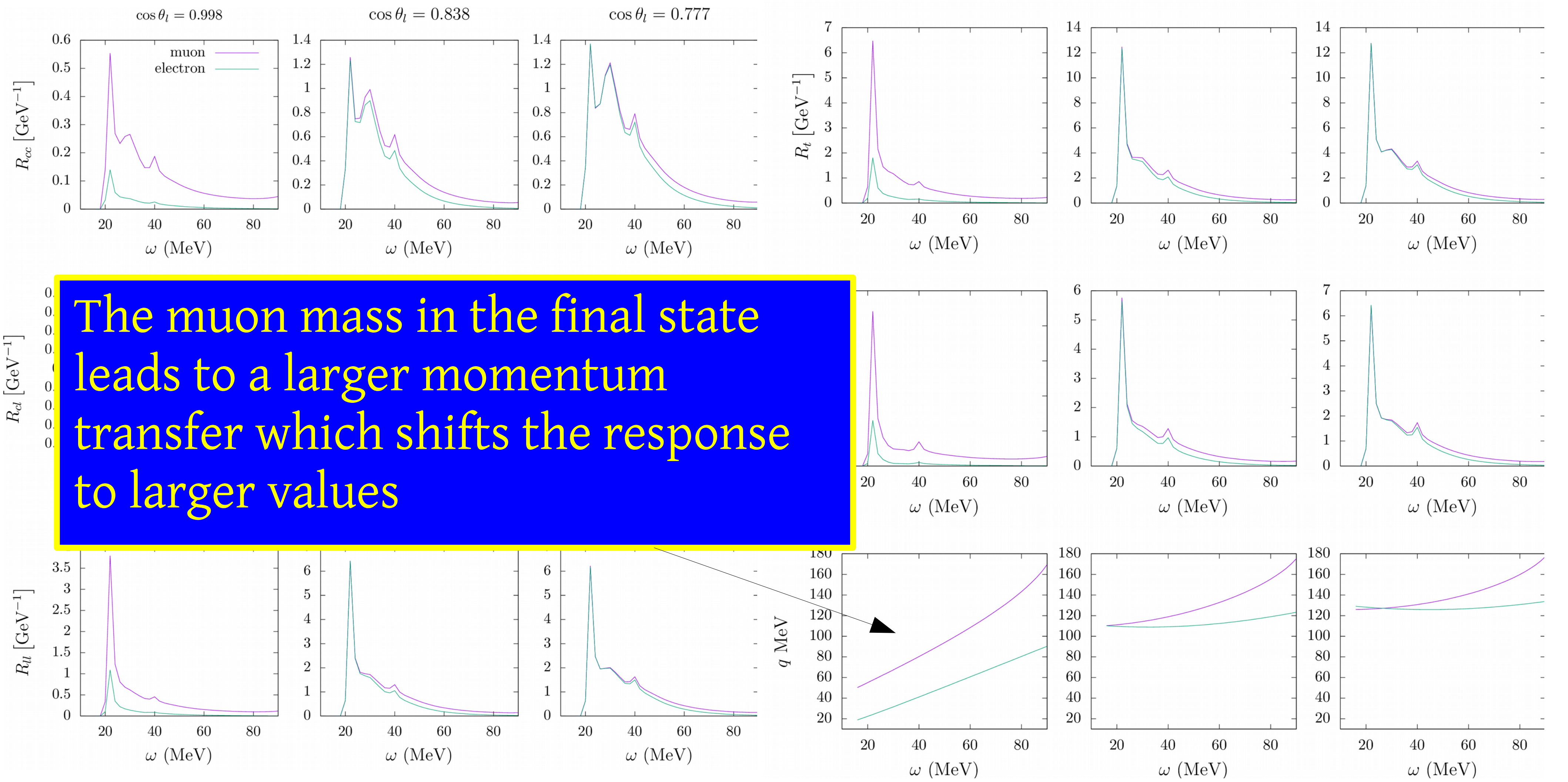
Transverse



Responses

Longitudinal

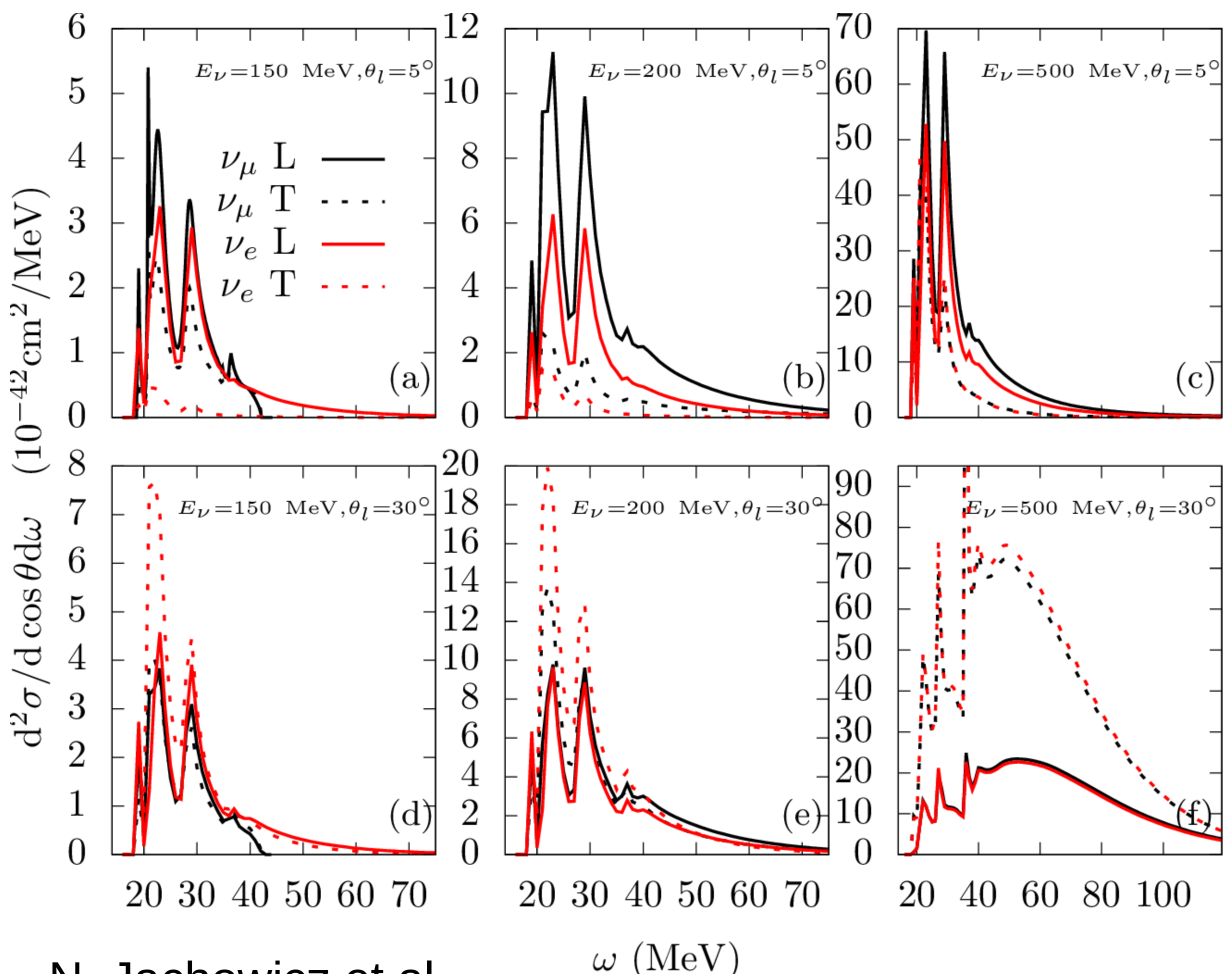
Transverse



The muon mass in the final state leads to a larger momentum transfer which shifts the response to larger values

Leptonic x Responses

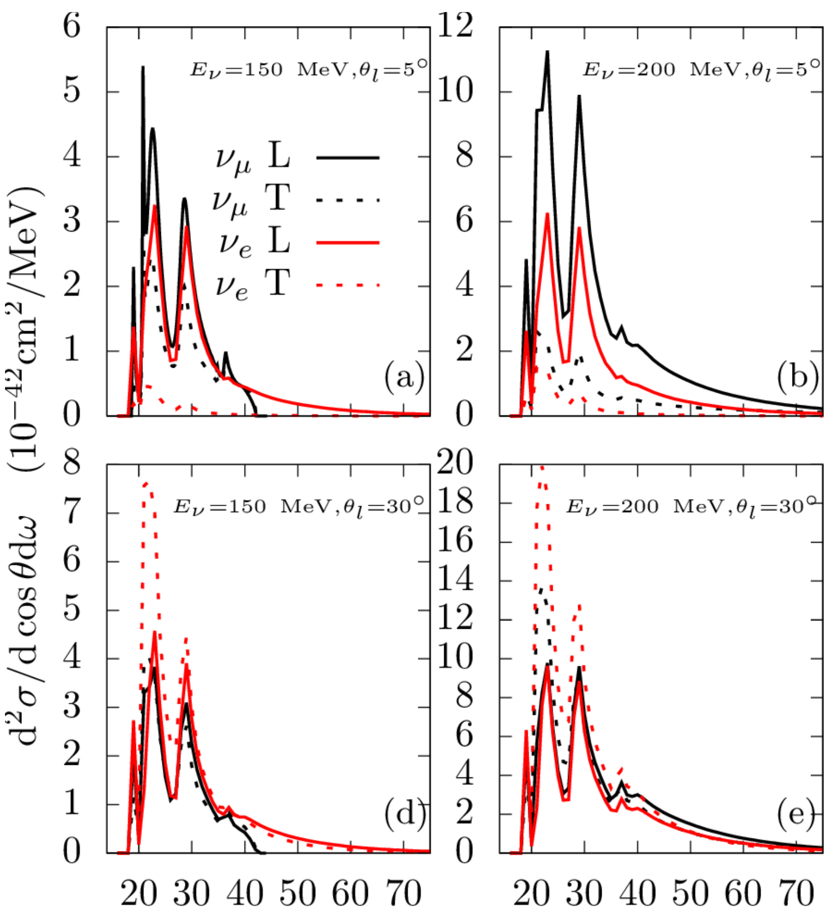
CRPA



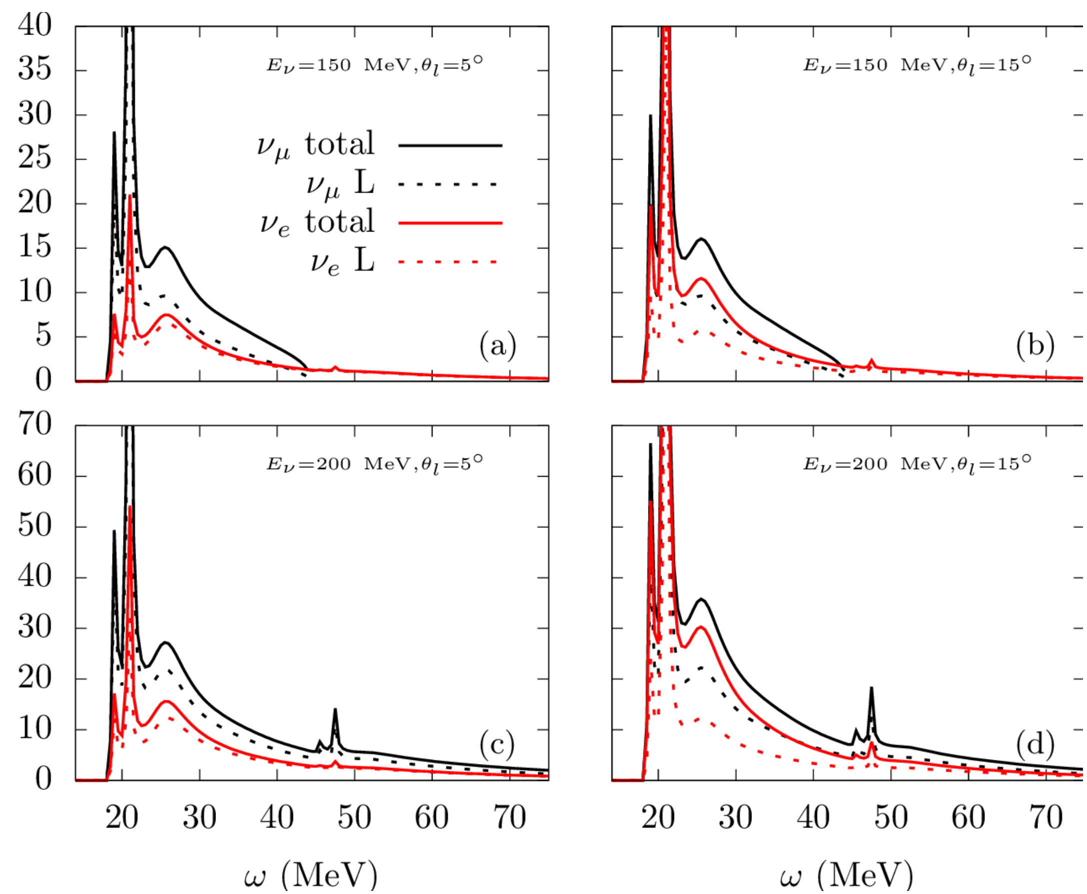
N. Jachowicz et al.
J. Phys. G 46, number 8

Leptonic x Responses

CRPA



RMF

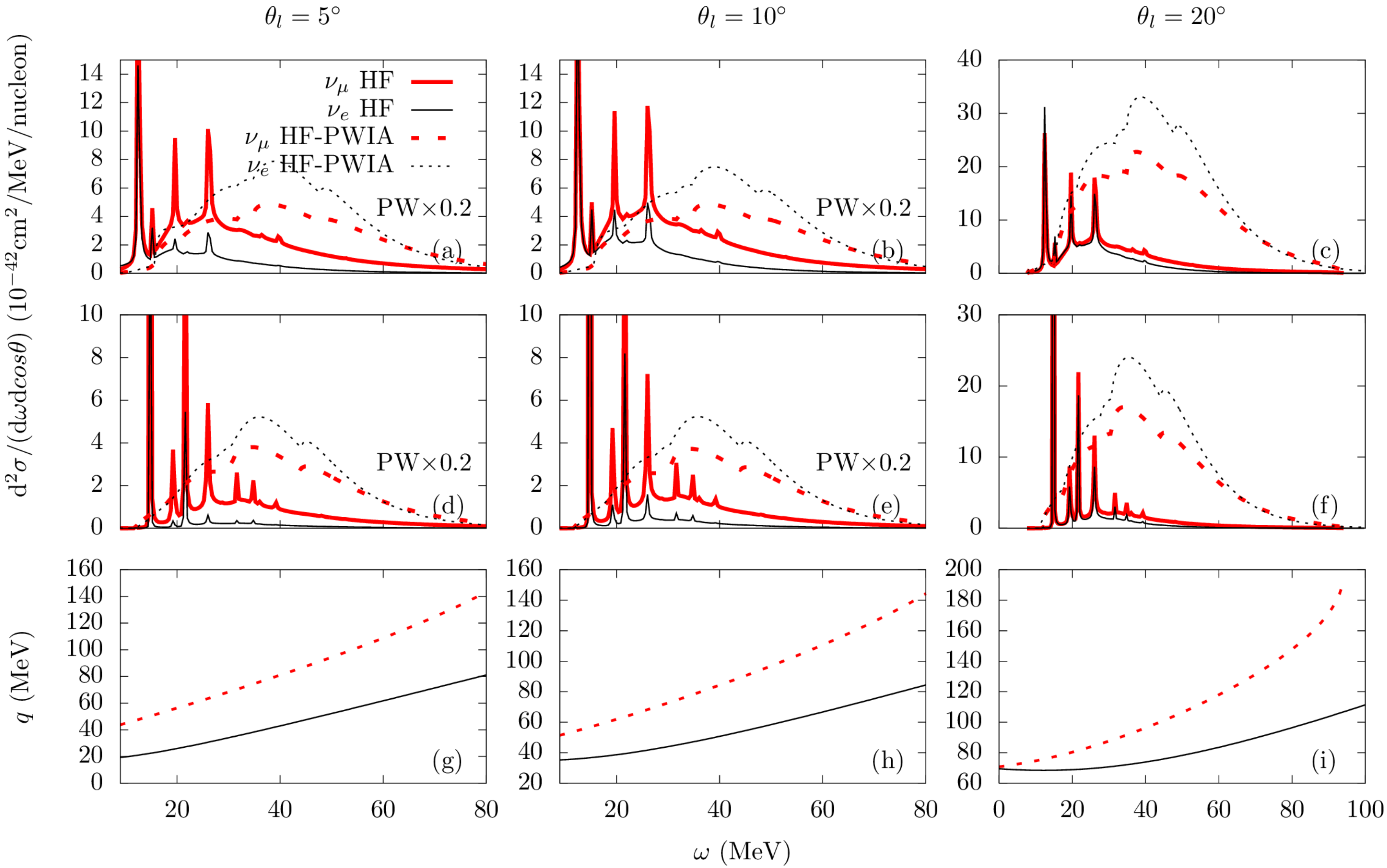


N. Jachowicz et al.
J. Phys. G 46, number 8

R. Gonzalez-Jimenez et al.
ArXiv:1904.10696

Comparison to PWIA

Large reduction at low ω and q with distorted waves



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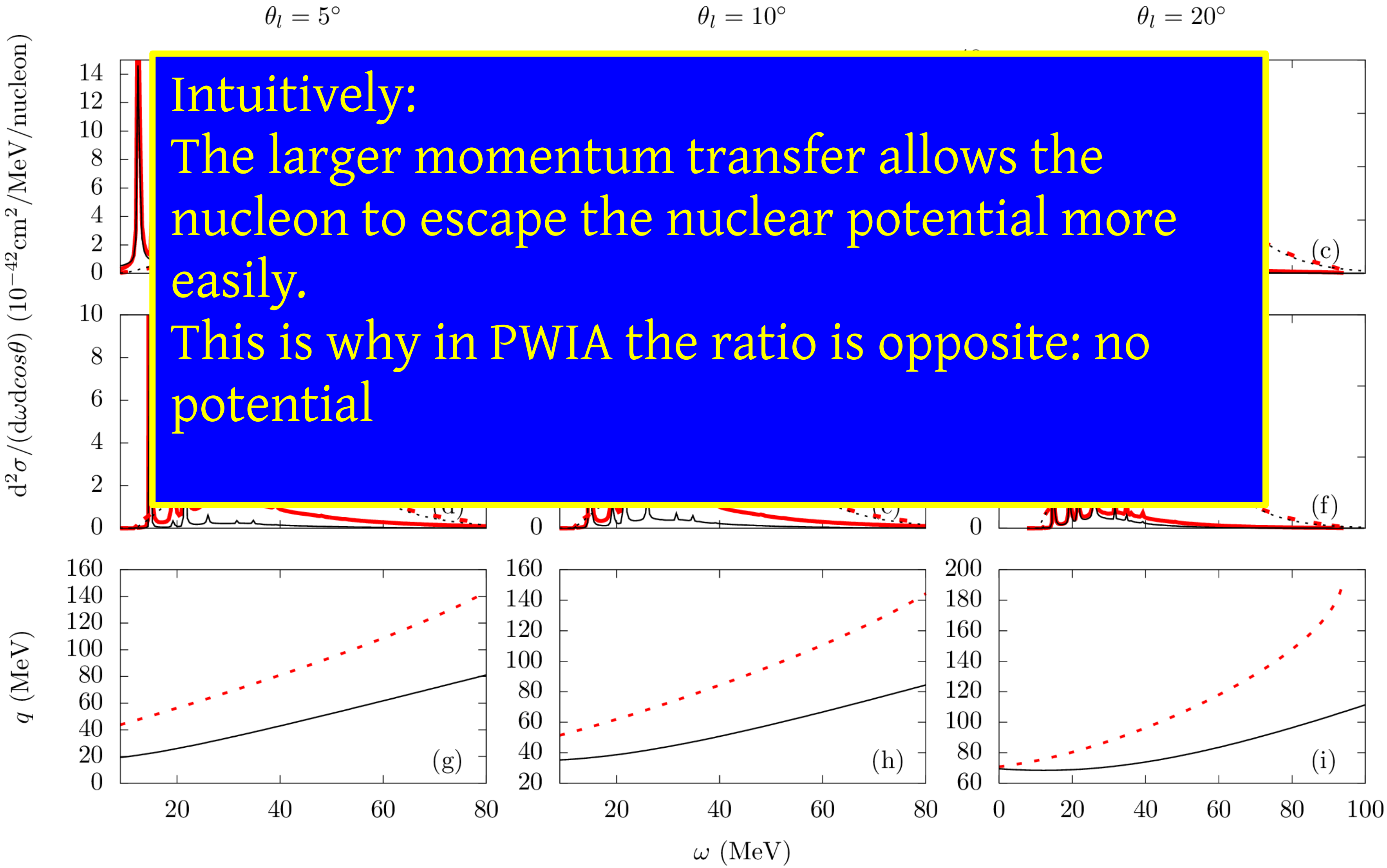
Comparison to PWIA

Large reduction at low ω and q with distorted waves



Intuitively:
The larger momentum transfer allows the nucleon to escape the nuclear potential more easily.
This is why in PWIA the ratio is opposite: no potential

Orthogonality and Pauli-blocking

Pauli blocked RPWIA (PB-RPWIA) (arXiv:1904.10696, R. Gonzalez-Jimenez et al.)

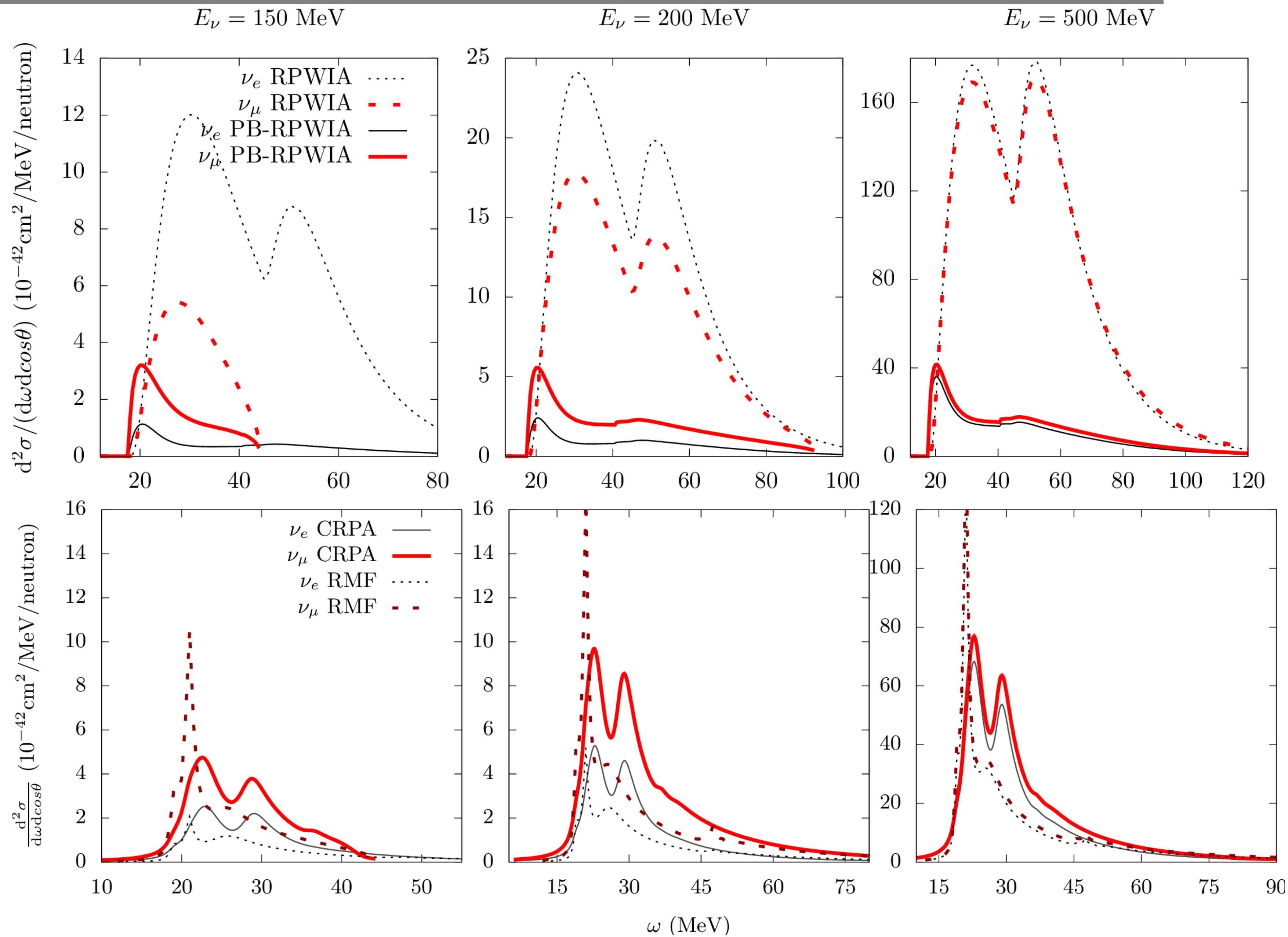
$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = |\psi^{s_N}_{pw}(\mathbf{p}_N)\rangle - \sum_{\kappa,m_j} [C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)]^{\dagger} |\psi^{m_j}_{\kappa}\rangle$$

$$C^{m_j,s_N}_{\kappa}(\mathbf{p}_N) = (2\pi)^{3/2}\sqrt{\frac{M}{VE_N}} \times u(\mathbf{p}_N, s_N)^{\dagger}\psi^{m_j}_{\kappa}(\mathbf{p}_N) \,.$$

Orthogonalize the relativistic plane wave with respect to the bound states of the nucleus.

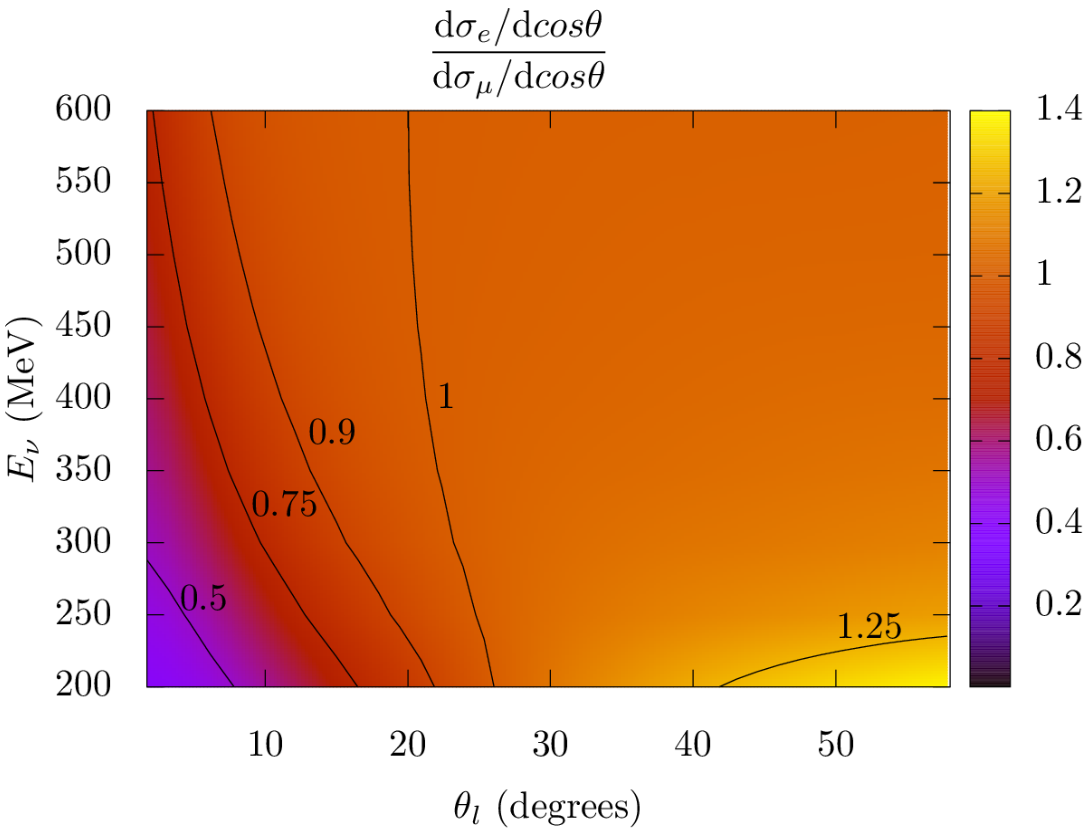
In a consistent model all nucleon states are orthogonal to each other
This implies Pauli-blocking as the nucleon wave function does not overlap with a bound state

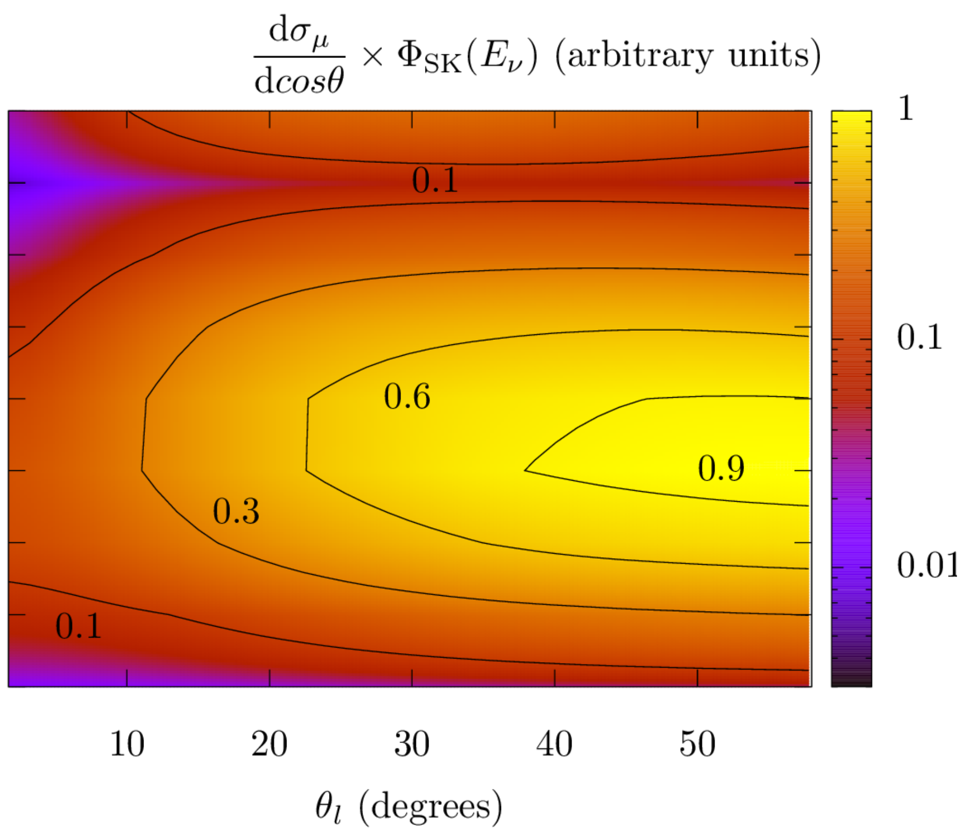
Orthogonality and Pauli-blocking



Difference between ν_μ and ν_e

Non-trivial ratio of electron versus muon neutrino cross sections have a significant overlap with the T2K oscillated flux weighted cross section





Conclusions

I. When the initial and final state wave functions are treated consistently the muon neutrino induced cross section is larger than the electron neutrino one for small scattering angles notwithstanding the larger mass in the final state

II. By orthogonalization of the final state PW to the bound states of the nucleus we remove spurious non-orthogonal contributions and obtain qualitatively the same behavior as in the full calculation