I. Hartree-Fock & Continuum RPA calculations of lepton-nucleus interactions

II. Recent Ar(e,e') measurement at Jefferson Lab

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Physics Opportunities in the Near DUNE Detector Hall, Fermilab, Dec 3 - 7, 2018

Prologue

- These are exciting times – at short- and long-baseline neutrino experiments - we are potentially looking at CP violation in leptonic sector, sterile neutrinos, direct detection of dark matter, and many possibilities of finding new physics!

- The success of these programs in achieving discovery level precision rely greatly on how well we understand the basic interaction process in our detector – i.e. how neutrino interacts with the target nucleus.

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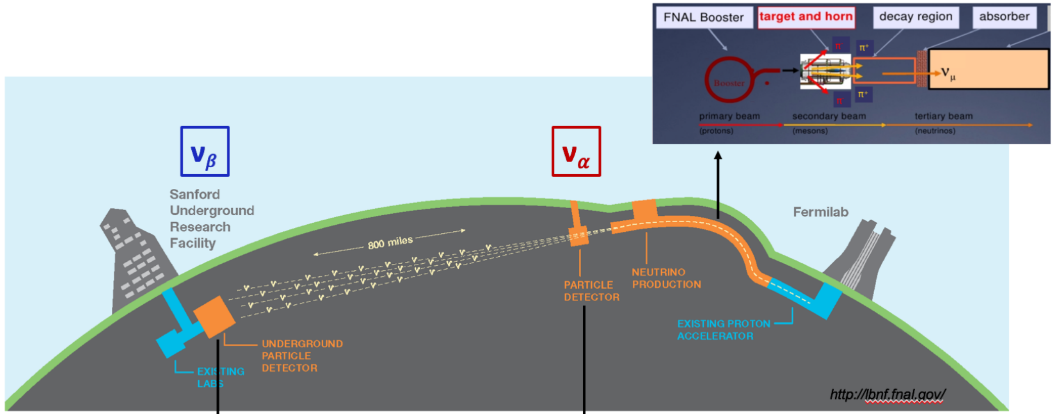
- We know the ratio of far to near detector event rates does not cancel out cross section dependencies.

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



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

*two neutrino flavors, for simplicity

Event Rate at near detector:

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

Event Rate at far detector:

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

Prog. Part. Nucl. Phys. 100, 1 (2018)

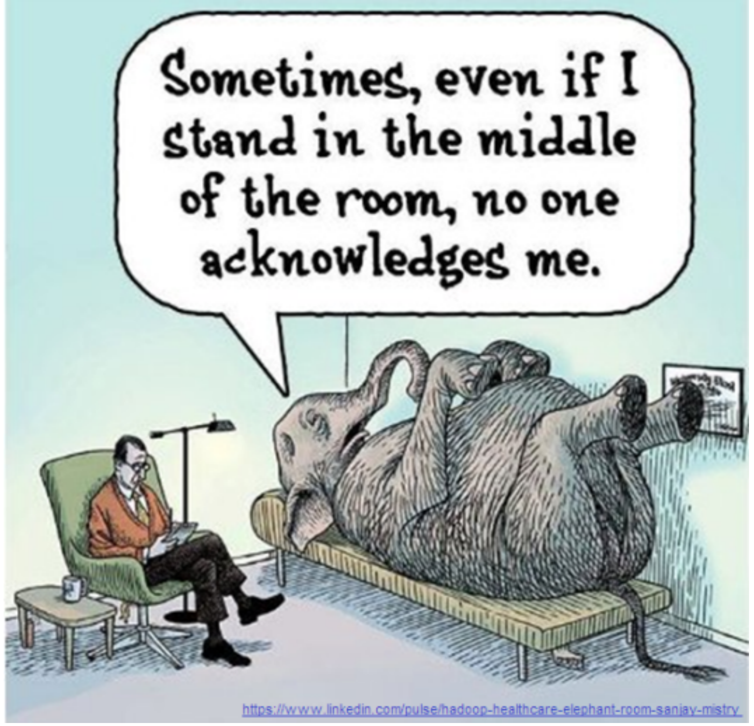
Prologue

- These are exciting times – at short- and long-baseline neutrino experiments - we are potentially looking at CP violation in leptonic sector, sterile neutrinos, direct detection of dark matter, and many possibilities of finding new physics!

- The success of these programs in achieving discovery level precision rely greatly on how well we understand the basic interaction process in our detector – i.e. how neutrino interacts with the target nucleus.

- A precise knowledge of neutrino-nucleus interaction is needed at each step - in evaluating event kinematics, final state particles and their energies, backgrounds, acceptances, and efficiencies to eventually reconstruct the (unknown) neutrino energies and extract the oscillations probabilities and parameters.

- This require cross-community effort - one that entails a detailed understanding of complexity of nuclear physics (theoretical and experimental) as well as an in-depth knowledge of ambiguities pertaining to the questions and needs of experimental neutrino physics.



Outline

I. Hartree-Fock & Continuum RPA calculations of lepton-nucleus interactions

- HF-CRPA approach
- Lepton-nucleus scattering - comparison with data
- ν_{e}, ν_{μ} –nucleus cross section differences

II. Recent Ar(e,e') measurement at Jefferson Lab

- A brief overview of E12-14-012 Experiment
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HF-CRPA Approach

- **Base-model: Hartree-Fock**

  - A reasonable starting point for a microscopic description of the nuclear ground state is to invoke the so-called Mean Field (MF) approximation. One can use the Hartree-Fock (HF) method with a realistic potential and solve the Schrodinger equation to obtain single-particle wave functions filling all the single-particle states up to the Fermi level for all the nucleons in the nucleus.

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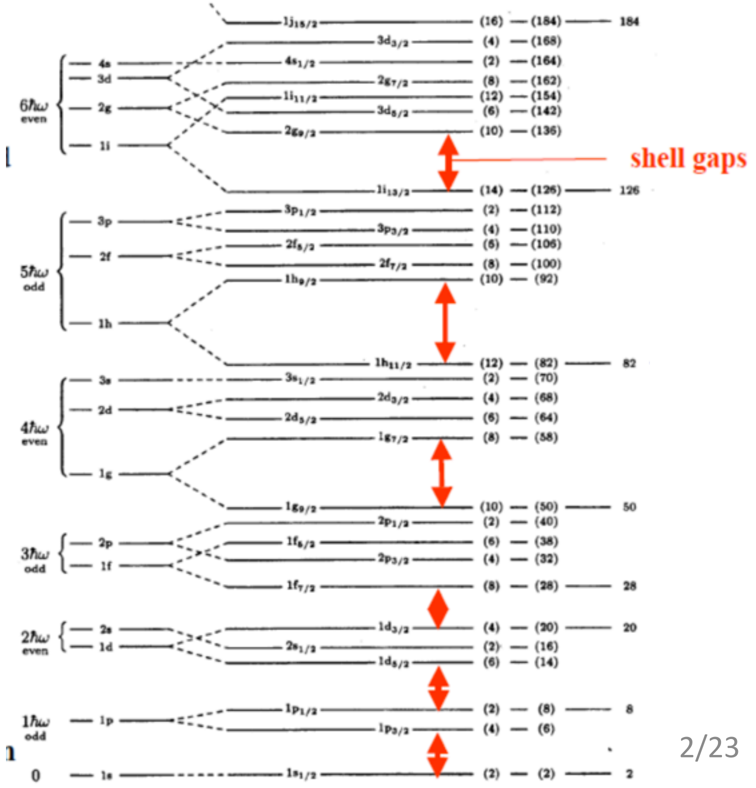
- **Skyrme Potential:** We solve the Schrödinger equation using a Skyrme (SkE2) potential. This parameter set was designed to yield a realistic description of nuclear structure properties over the whole mass table and provide a good reproduction of the experimental single-particle energies.

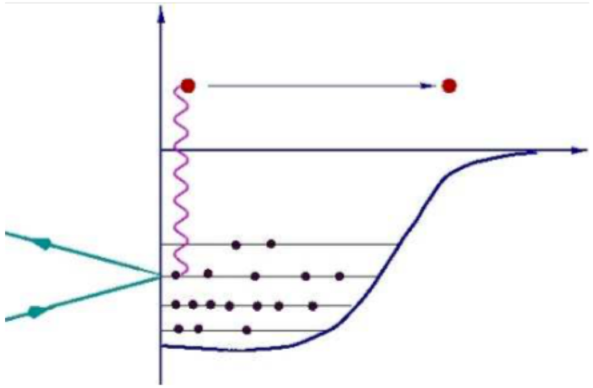
- **Single-particle wave functions:** The solution of Schrödinger equation with SkE2 potential gives us the (radial, orbital, spin-angular momentum, and Isospin dependent) single-particle wave functions written in slater determinant. Single-particle wave functions are antisymmetric under exchange of all quantum numbers (spatial, spin, isospin, ...).

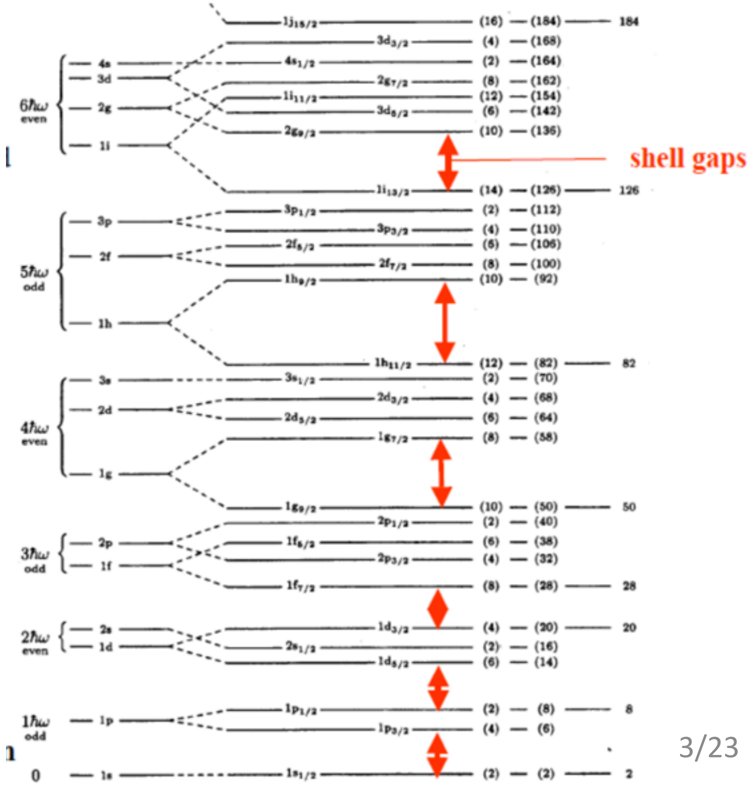


- **Base-model: Hartree-Fock**

  - HF ground state: (single slater determinant) with all single-particle states filled up to the Fermi-level and all higher-lying states being empty.

  - HF excited state: Where a single nucleon, a "particle", occupied the level above the fermi surface, leaving behind a "hole" in the Fermi sea, i.e. – 1p-1h state. We label the excited states by single particle and single hole quantum numbers.





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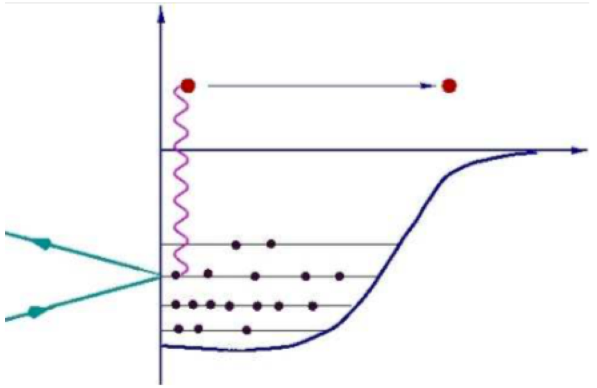
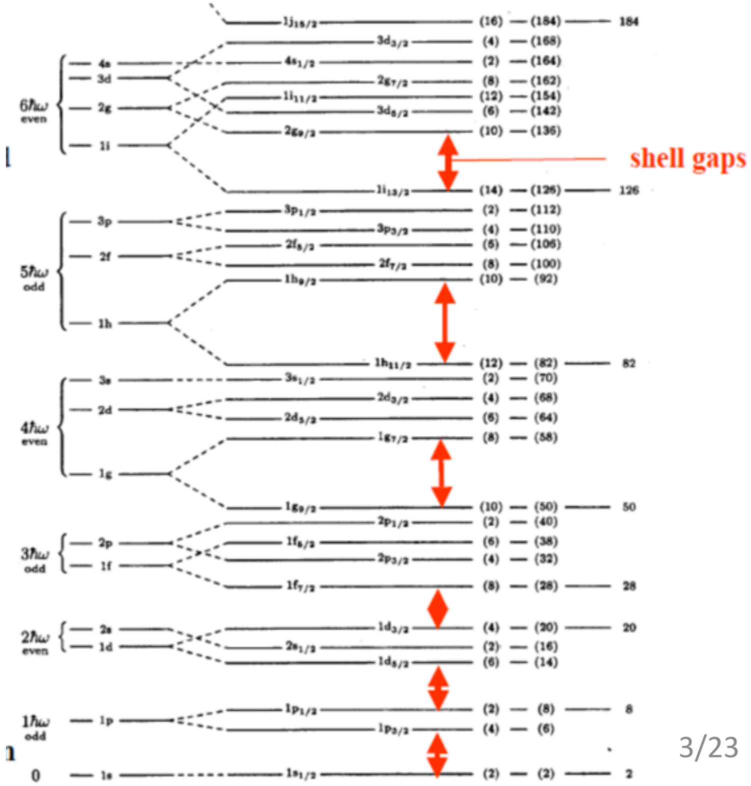


  - When probing the excitation region lying at 10s of MeV in nuclei, some states are found to have much larger strength than predicted on the basis of a transition from the ground state to a 1p-1h state. This is the region of so-called giant resonances (GR).

  - The large strength and location of these excitations point to the fact that GR are collective excitations involving the cooperative participation of several nucleons in contrast to 1p-1h excitations and thus require a more sophisticated treatment => inclusion of long-range correlations between nucleons and a RPA treatment.



HF-CRPA Approach

- **Continuum random phase approximation**

- The CRPA approach describes a nuclear excited state as the linear combination of particle-hole (*ph*$^{-1}$) and hole-particle (*hp*$^{-1}$) excitations out of a correlated nuclear ground state:

$$|\Psi^{C}_{RPA}\rangle = \sum_{C'} \left\{ X_{C,C'} \; |p'h'^{-1}\rangle - Y_{C,C'} \; |h'p'^{-1}\rangle \right\}$$

(C denotes a set of quantum numbers)

- We solve CRPA equations using a Green's function approach which allows one to treat the single-particle energy continuum exactly by solving the RPA equations in coordinate space.

HF-CRPA Approach

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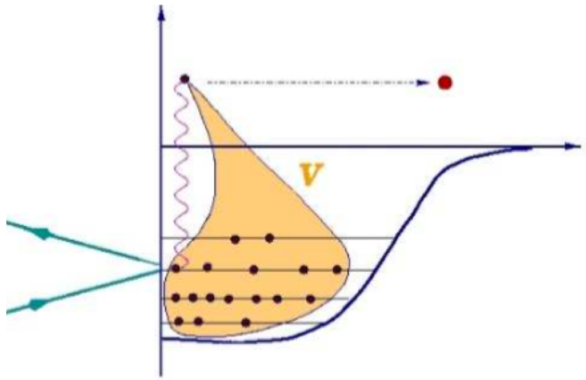
- The propagation of particle-hole pairs in the nuclear medium is described by the polarization propagator. In the Lehmann representation, this particle-hole Green's function is given by

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

The first term represents particle states above fermi level, second term represents hole states below fermi level.

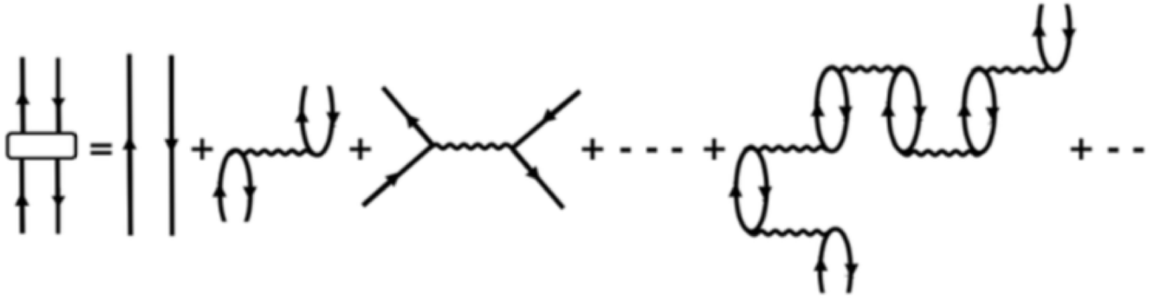
HF-CRPA Approach



- **Continuum random phase approximation**

  - The local RPA-polarization propagator is obtained by an iteration to all orders of the first order contribution to the particle-hole Green's function

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



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

  - CRPA results are generally seen to reflect the q dependence of the data for momentum transfers ranging up to about $\lesssim$ 400 MeV/c (or, $\omega \lesssim$ 50 MeV) and shows the general characteristics of the excitation spectrum.

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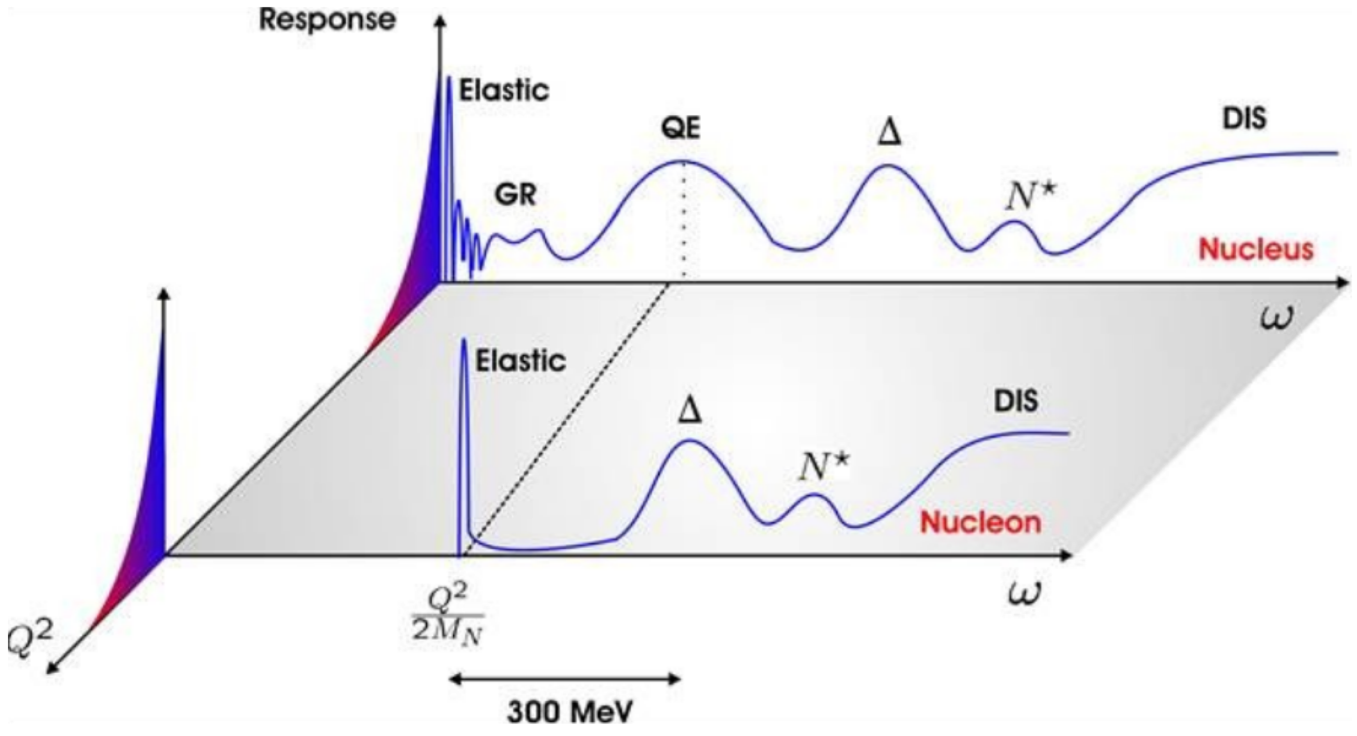
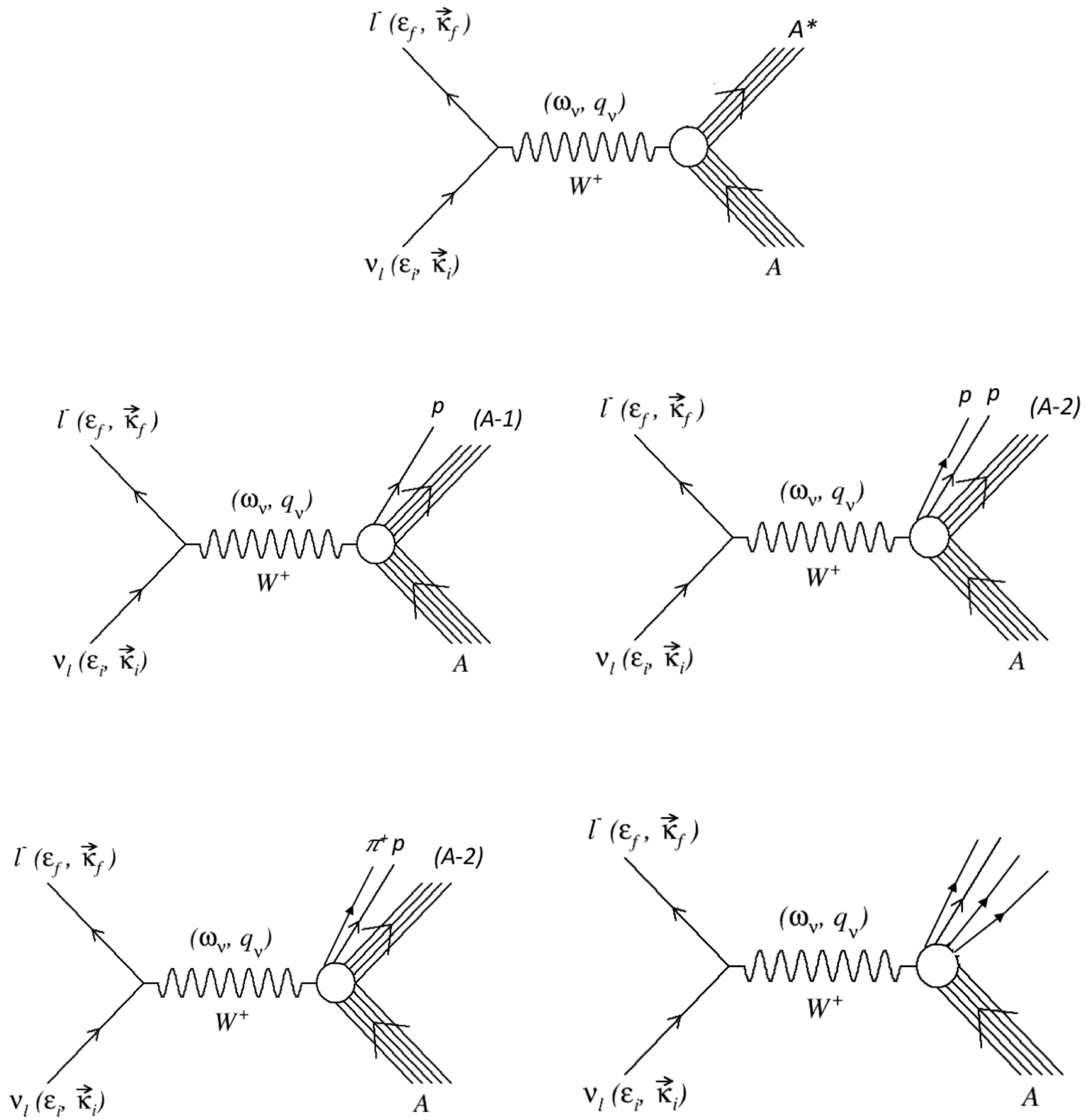
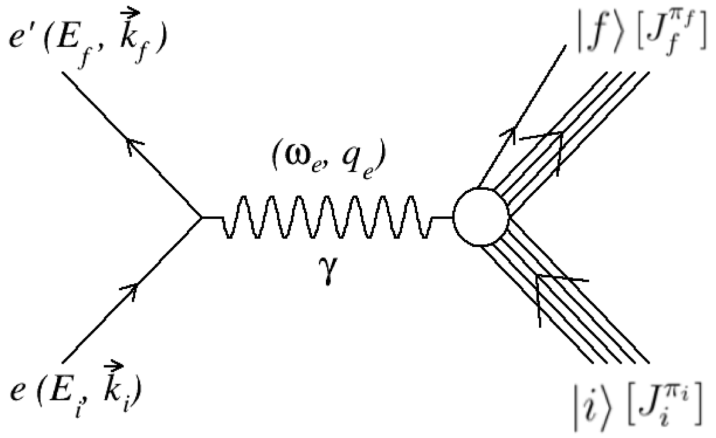
Lepton-nucleus scattering





Lepton-nucleus scattering



Kinematics: $\omega = E_i - E_f, \quad q = |\vec{k_i} - \vec{k_f}|, \quad Q^2 = q^2 - \omega^2$

Cross section: $d\sigma \sim |M_{fi}|^2 \sim |j_\mu \frac{1}{Q^2} J^\mu_{fi}|^2 \sim \frac{1}{Q^4}\; j^*_\mu j_\nu\; J^{\mu *}_{fi} J^{\nu *}_{fi} \sim \frac{1}{Q^4}\; L_{\mu\nu}\; W^{\mu\nu}$

Contracting the leptonic and hadronic tensor, we obtain a sum involving projections of the current matrix elements. It is convenient to choose these to be transverse and longitudinal with respect to the virtual photon direction. Thus we obtain structure of the form: $v_L\, R_L + v_T\, R_T$, where responses are functions of ω and q.

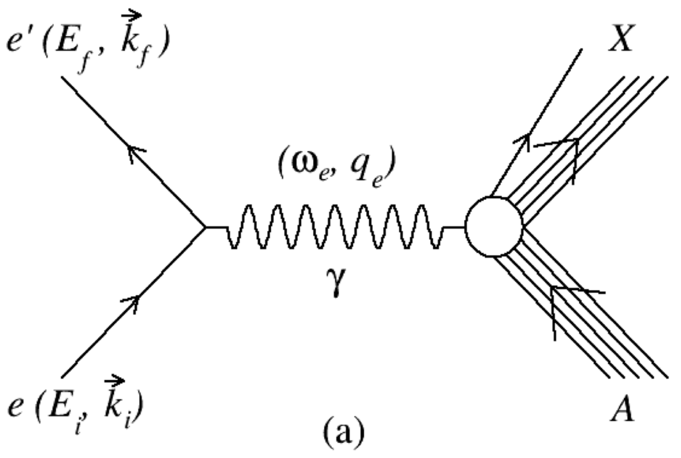
$$\boxed{\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i}\quad \zeta^2\left(Z', E_f, q_e\right)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]}$$

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

- Factor *(2/2J_i+1)* comes from averaging over initial and sum over final states.
- $\zeta^2\,(Z', E_f, q_e)$ takes care of the influence of the Coulomb field of nucleus on the outgoing charged lepton.
- σ_L and σ_T are summed over multipoles corresponds to discrete and continuum states of a nucleus having angular momentum and parity *(J^π)* as good quantum numbers.

Lepton-nucleus scattering

e-A scattering

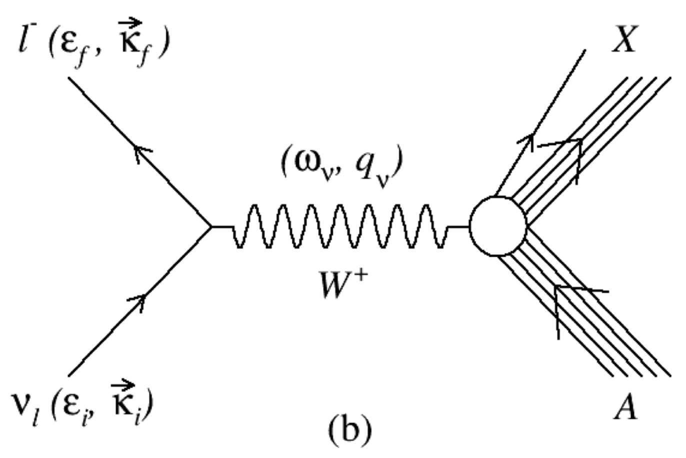


$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma^J_{L,e} + \sum_{J=1}^{\infty}\sigma^J_{T,e}\right]$$

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

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

ν-A scattering



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

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

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

Lepton-nucleus scattering

e-A scattering

$$v_e^L = \frac{Q^4}{|\vec{q}|^4} \qquad v_e^T = \left[\frac{Q^2}{2|\vec{q}|^2} \; + \; \tan^2(\theta/2)\right]$$

$$R_e^L = |\langle J_f||\widehat{\mathcal{M}}_J^e(|\vec{q}|)||J_i\rangle|^2$$

$$R_e^T = \left[|\langle J_f||\widehat{\mathcal{T}}_J^{mag,e}(|\vec{q}|)||J_i\rangle|^2 + |\langle J_f||\widehat{\mathcal{T}}_J^{el,e}(|\vec{q}|)||J_i\rangle|^2\right]$$

v-A scattering

$$v_\nu^{\mathcal{M}} = \left[1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta\right] \qquad v_\nu^{\mathcal{L}} = \left[1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta - \frac{2\varepsilon_i\varepsilon_f}{|\vec{q}|^2}\left(\frac{\kappa_f}{\varepsilon_f}\right)^2 \sin^2\theta\right]$$

$$v_\nu^{\mathcal{ML}} = \left[\frac{\omega}{|\vec{q}|}\left(1 + \frac{\kappa_f}{\varepsilon_f}\cos\theta\right) + \frac{m_l^2}{\varepsilon_f|\vec{q}|}\right] \quad v_\nu^T = \left[1 - \frac{\kappa_f}{\varepsilon_f}\cos\theta + \frac{\varepsilon_i\varepsilon_f}{|\vec{q}|^2}\left(\frac{\kappa_f}{\varepsilon_f}\right)^2 \sin^2\theta\right]$$

$$v_\nu^{TT} = \left[\frac{\varepsilon_i + \varepsilon_f}{|\vec{q}|}\left(1 - \frac{\kappa_f}{\varepsilon_f}\cos\theta\right) - \frac{m_l^2}{\varepsilon_f|\vec{q}|}\right],$$

$$R_\nu^{\mathcal{M}} = |\langle J_f||\widehat{\mathcal{M}}_J^\nu(|\vec{q}|)||J_i\rangle|^2 \qquad R_\nu^{\mathcal{L}} = |\langle J_f||\widehat{\mathcal{L}}_J^\nu(|\vec{q}|)||J_i\rangle|^2$$

$$R_\nu^{\mathcal{ML}} = \mathcal{R}\left[\langle J_f||\widehat{\mathcal{L}}_J^\nu(|\vec{q}|)||J_i\rangle\langle J_f||\widehat{\mathcal{M}}_J^\nu(|\vec{q}|)||J_i\rangle^*\right]$$

$$R_\nu^T = \left[|\langle J_f||\widehat{\mathcal{T}}_J^{mag,\nu}(|\vec{q}|)||J_i\rangle|^2 + |\langle J_f||\widehat{\mathcal{T}}_J^{el,\nu}(|\vec{q}|)||J_i\rangle|^2\right]$$

$$R_\nu^{TT} = \mathcal{R}\left[\langle J_f||\widehat{\mathcal{T}}_J^{mag,\nu}(|\vec{q}|)||J_i\rangle\langle J_f||\widehat{\mathcal{T}}_J^{el,\nu}(|\vec{q}|)||J_i\rangle^*\right]$$

Multipole operators: Coulomb, longitudinal, transverse electric, and transverse magnetic are:

$$\widehat{\mathcal{M}}_{JM}(\kappa) = \int d\vec{x}\; \left[j_J\,(\kappa r)\; Y_J^M\;(\Omega_x)\right]\; \hat{J}_0(\vec{x})$$

$$\widehat{\mathcal{L}}_{JM}(\kappa) = \frac{i}{\kappa}\int d\vec{x}\; \left[\vec{\nabla}\left(j_J\,(\kappa r)\; Y_J^M\;(\Omega_x)\right)\right]\cdot\widehat{\vec{J}}(\vec{x})$$

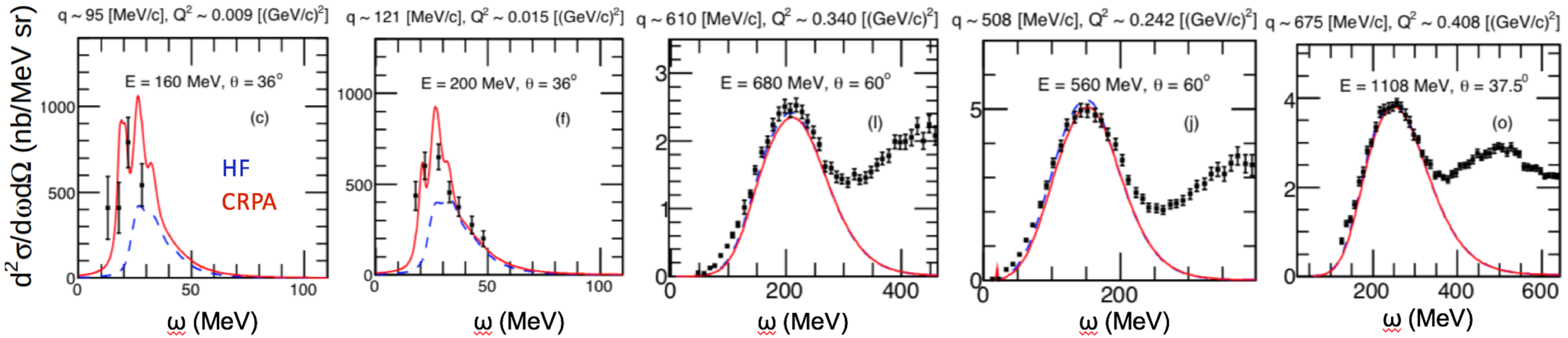
$$\widehat{\mathcal{T}}_{JM}^{el}(\kappa) = \frac{1}{\kappa}\int d\vec{x}\; \left[\vec{\nabla}\times\left(j_J\,(\kappa r)\;\vec{\mathcal{Y}}_{J,J}^M\;(\Omega_x)\right)\right]\cdot\widehat{\vec{J}}(\vec{x})$$

$$\widehat{\mathcal{T}}_{JM}^{mag}(\kappa) = \int d\vec{x}\; \left[j_J\,(\kappa r)\;\vec{\mathcal{Y}}_{J,J}^M\;(\Omega_x)\right]\cdot\widehat{\vec{J}}(\vec{x})$$

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

- **^{12}C (e,e') cross sections**

Phys. Rev. C92, 024606 (2015)



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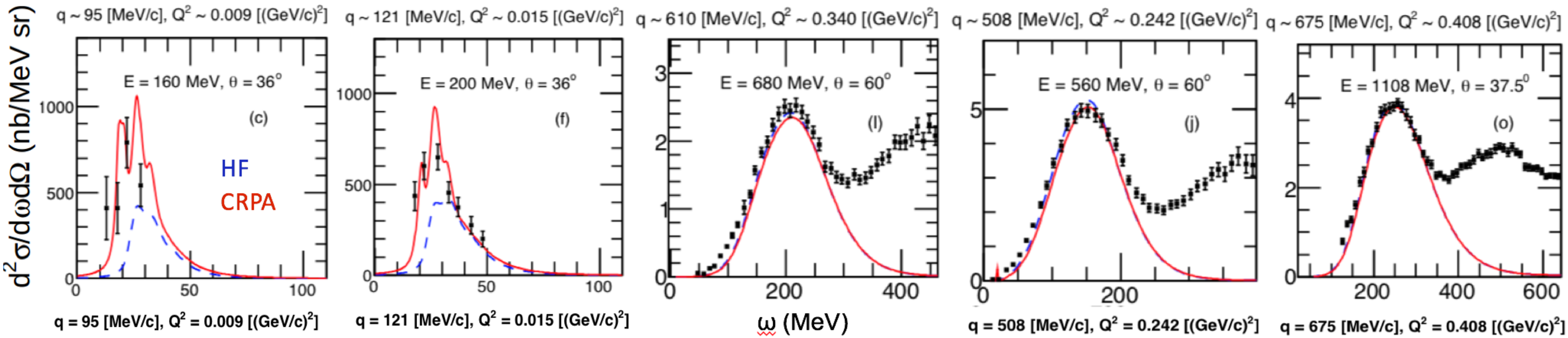
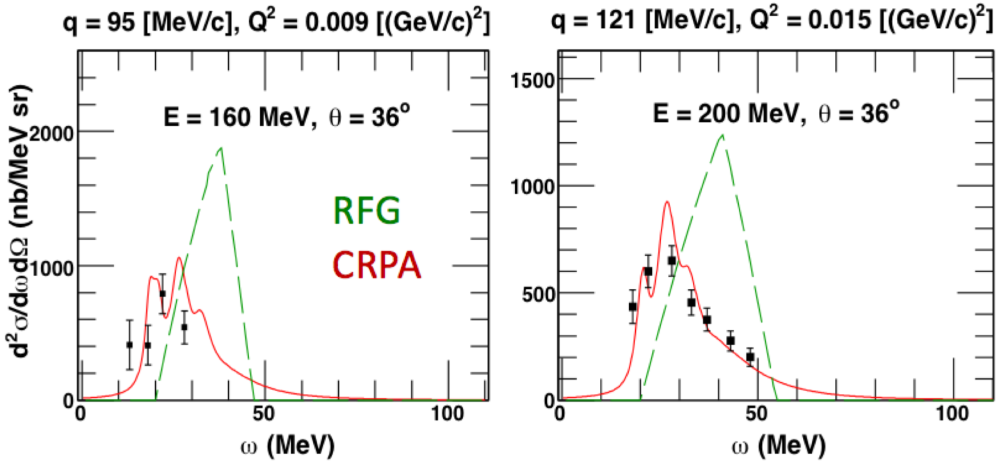
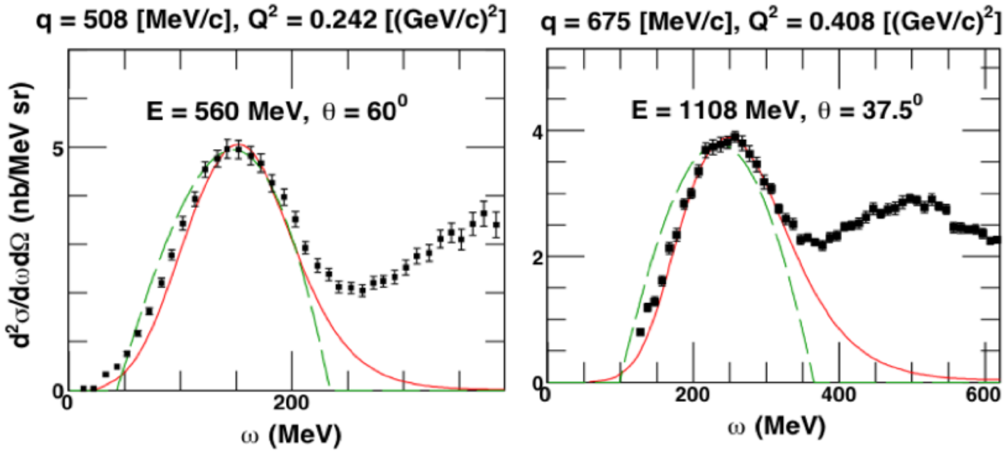




In comparison to RFG

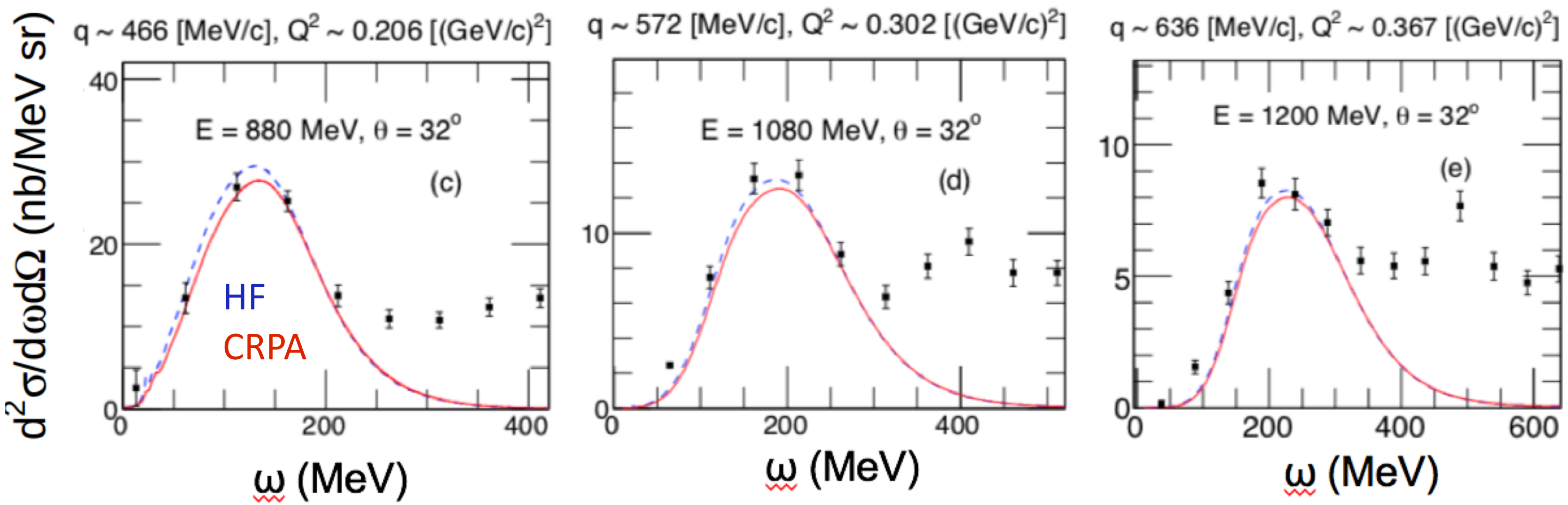


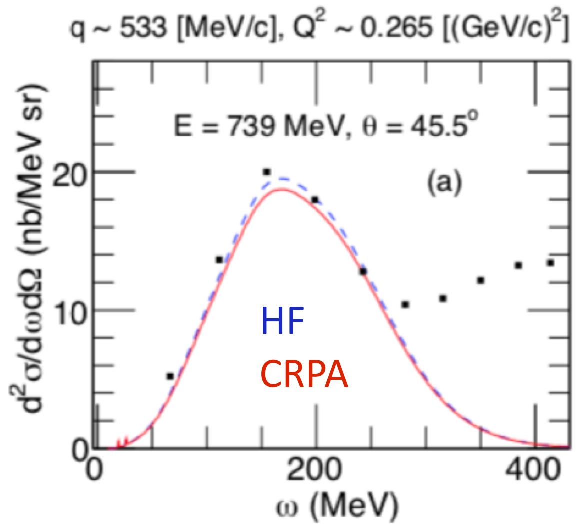
- **^{16}O (e,e') and ^{40}Ca (e,e') cross sections**

Phys. Rev. C92, 024606 (2015)

^{16}O (e,e')

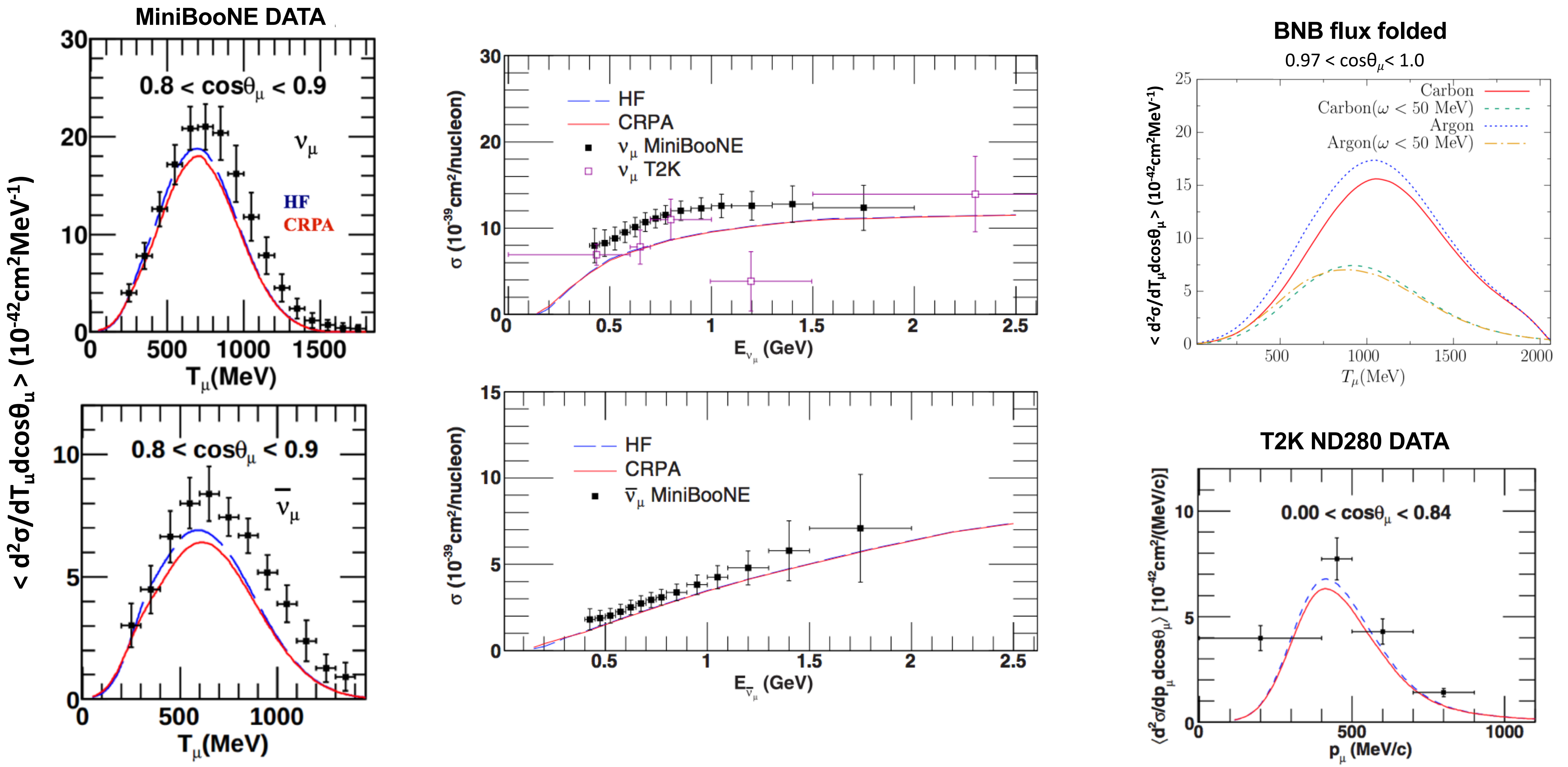
^{40}Ca (e,e')





Comparison with neutrino data

Phys. Rev. C94, 054609 (2016), Phys. Rev. C97, 044616 (2018)



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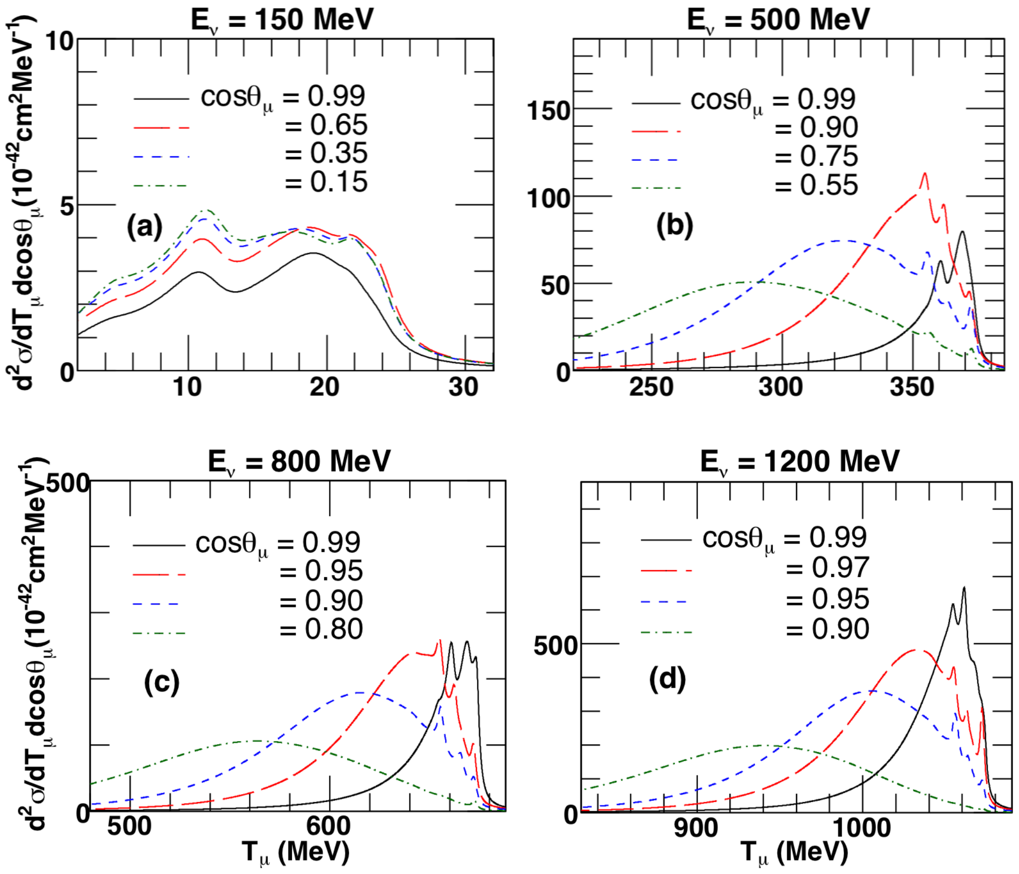
Phys. Rev. C94, 054609 (2016)

▪ Low-energy effects in neutrino scattering

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

- E_ν $\sim$ 1 GeV : Forward scatterings receive contribution from low-energy excitations.

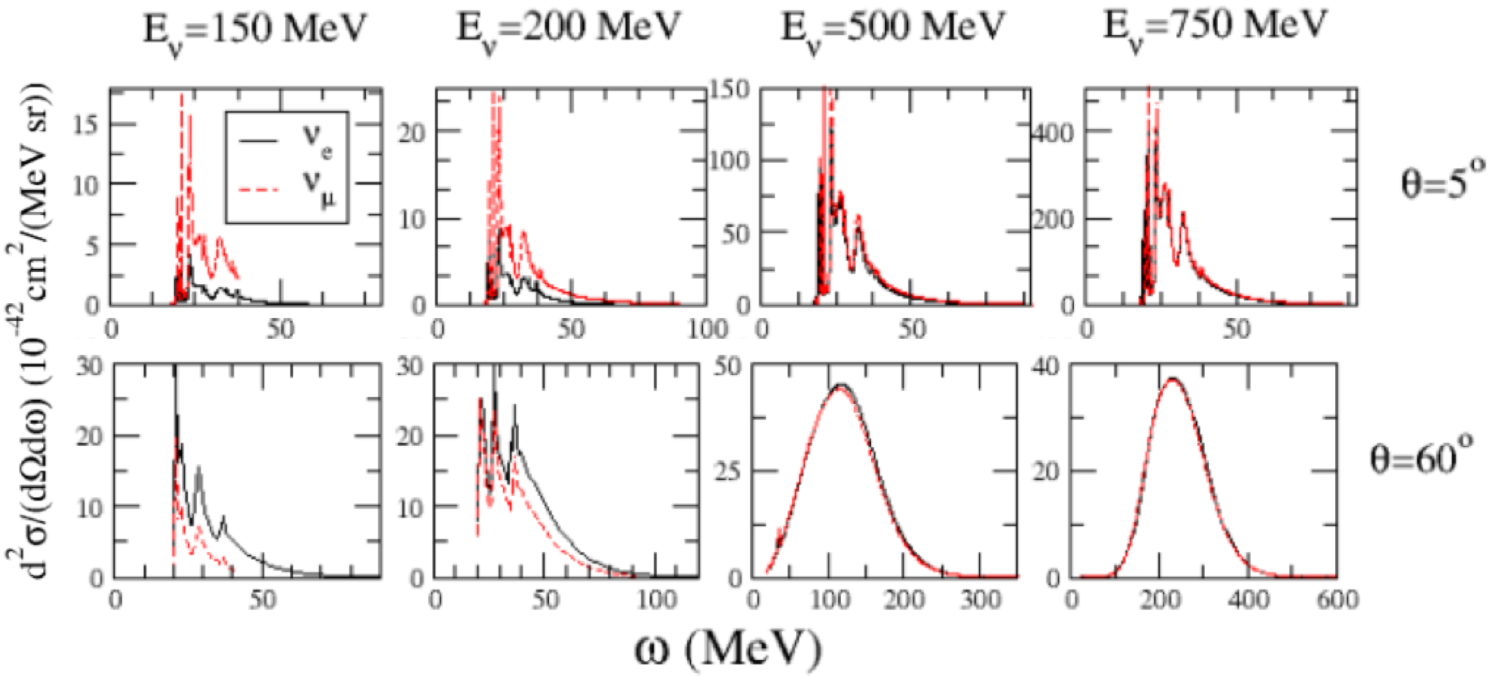


ν_e, ν_μ–nucleus cross section

Phys. Rev. C94, 015501 (2016)

- At lower energies:
  - For small scattering angles, ν_μ cross sections are higher than the ν_e ones.
  - For larger scattering angles, this behavior is opposite.

- At higher energies:
  - ν_e and ν_μ cross sections roughly coincide.



ν_e, ν_μ–nucleus cross section

Phys. Rev. C94, 015501 (2016)

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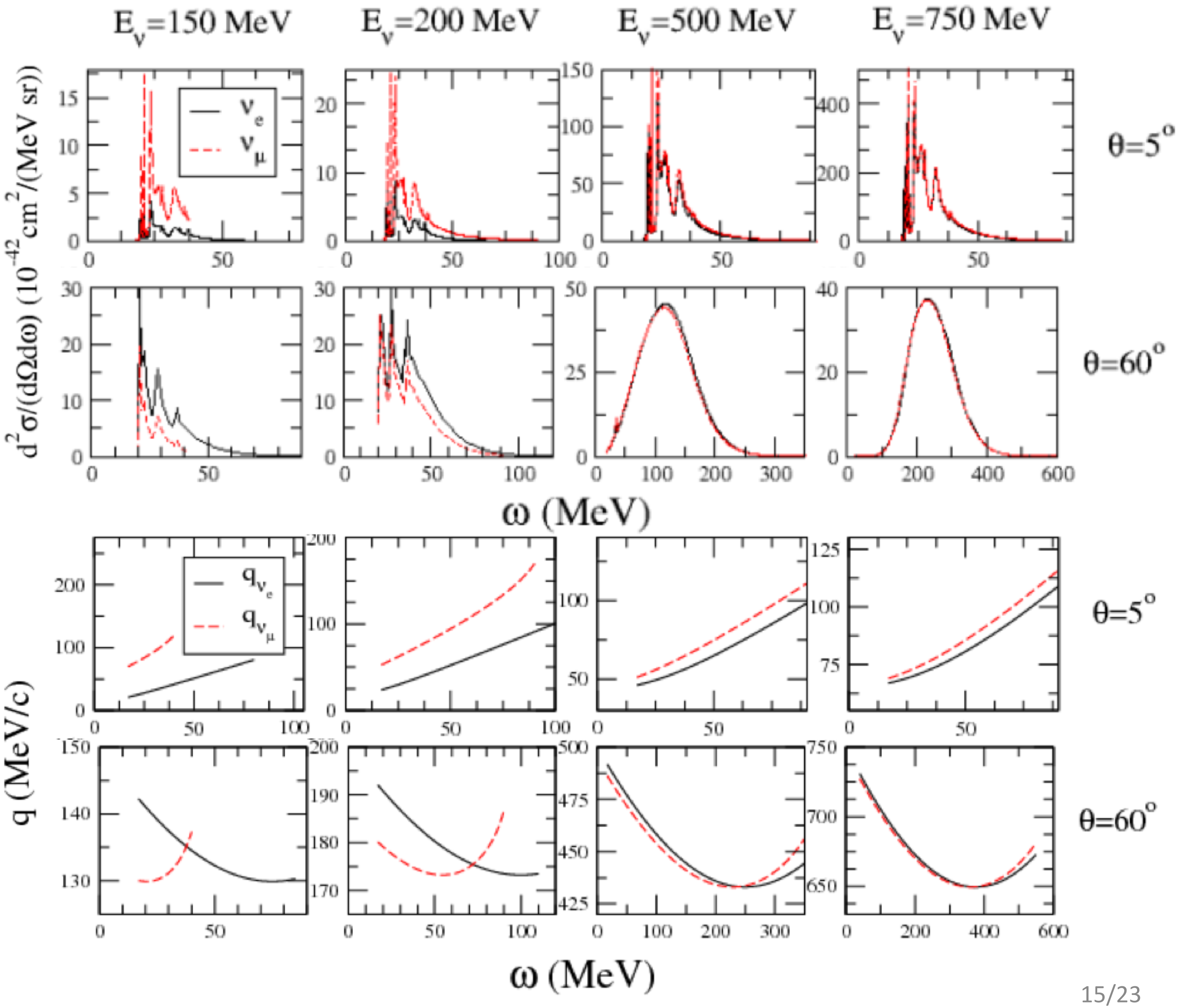
  - For larger scattering angles, such as 60^0, this behavior is opposite.
- At higher energies:
  - ν_e and ν_μ cross sections roughly coincide.
- Looking at q vs ω:
  - At lower energies, there are significant differences in the behavior.



ν_e , ν_μ –nucleus cross section

Phys. Rev. C94, 015501 (2016)

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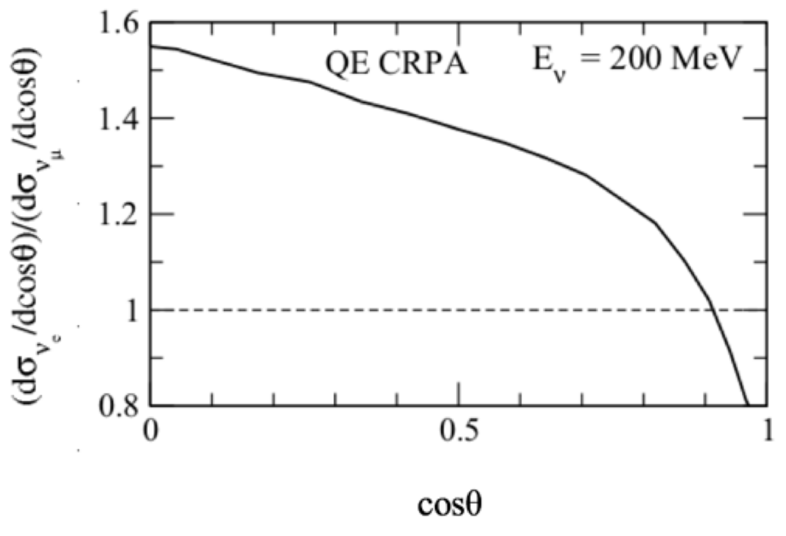
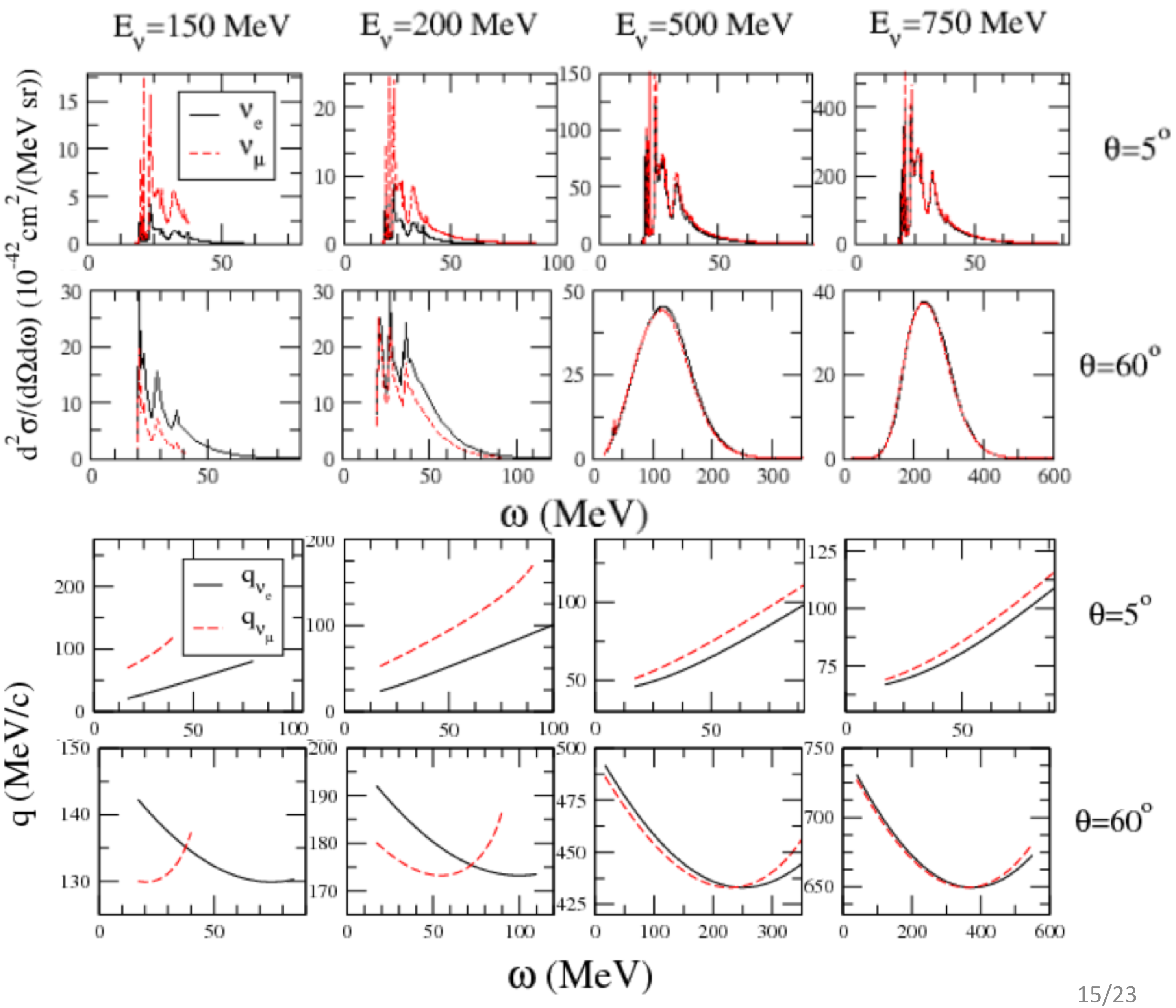
- At higher energies:
  - ν_e and ν_μ cross sections roughly coincide.
- Looking at q vs ω:
  - At lower energies, there are significant differences in the behavior.





Summary-I

- We presented a microscopic nuclear many-body calculations, HF-CRPA, for lepton-nucleus scattering covering processes from threshold to quasielastic.
- The model successfully describes (e,e') data on different nuclei covering a broad range of kinematics.
- The model is extended for neutrino-nucleus scattering, no tuning of any sort is involved.
- We found some non-trivial differences between electron-neutrinos and muon-neutrinos cross sections at lower energies.
- The key feature of the model is the description of low-energy excitations physics, which makes it suitable for the description of supernova neutrino cross sections.

Outline

I. Hartree-Fock & Continuum RPA calculations of lepton-nucleus interactions

- HF-CRPA approach
- Lepton-nucleus scattering - comparison with data
- ν_e, ν_μ –nucleus cross section differences

II. Recent Ar(e,e') measurement at Jefferson Lab

- A brief overview of E12-14-012 Experiment
- C(e,e’), Ti(e,e’) and Ar(e,e’) cross section results

Electron-argon experiment at Jefferson Lab [E12-14-012]

Goals:

- Measuring spectral functions of Ar nucleus.
- Measuring (e,e') and (e,e'p) cross sections on Ar, Ti (and C, Al) nuclei.

PR12-14-012

Scientific Rating: A-

Recommendation: Approve

Title: **Measurement of the Spectral Function of ^{40}Ar through the (e,e'p) reaction**

Spokespersons: O. Benhar, C. Mariani, C.-M. Jen, D.B. Day, D. Higinbotham

Motivation: This experiment is motivated by the need to model the response of liquid Argon detectors to neutrino beams. This information is important for the LBNF program (and other oscillation experiments) that use liquid Ar. The critical issue is that reconstruction of the neutrino energy depends on the spectral functions of neutrons and protons in ^{40}Ar. The neutrino beam has an energy spread and hence the neutrino flux as a function of energy has to be extracted by simulations that include the correct nuclear physics. A challenge is that the next generation of neutrino oscillation experiments aim at a precision of 1% and hence ensuring that the nuclear corrections are properly addressed is critical. This data will provide experimental input to construct the argon spectral function, thus allowing the most reliable estimate of the neutrino cross sections. In addition, the analysis of the (e,e'p) data will help a number of theoretical developments, such as the description of final-state interactions needed to isolate the initial-state contributions to the observed single-particle peaks, that is also needed for the interpretation of the signal detected in neutrino experiments.

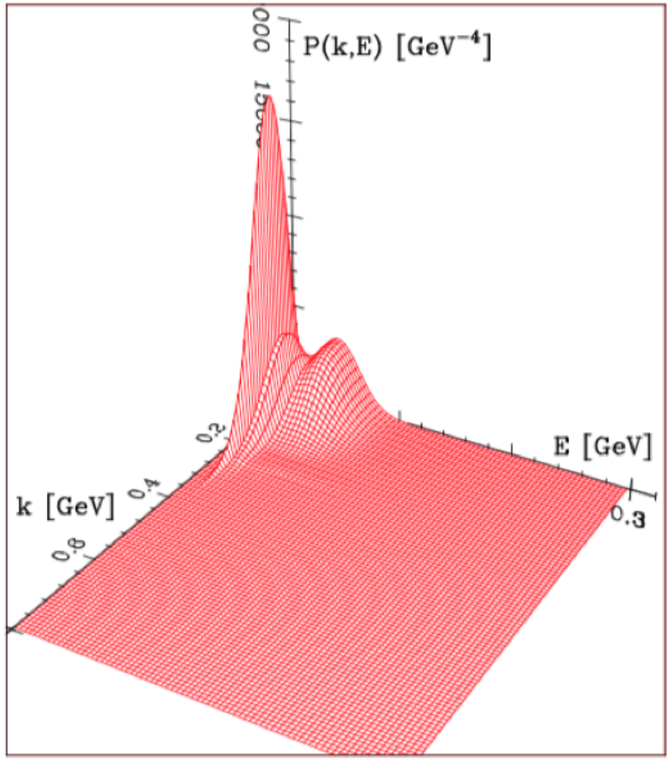
Electron-argon experiment at Jefferson Lab [E12-14-012]

Goals:

- Measuring spectral functions of Ar nucleus.
- Measuring (e,e') and (e,e'p) cross sections on Ar, Ti (and C, Al) nuclei.

Spectral Function

- The spectral function, P(k,E), yields the probability of removing a nucleon of momentum k from the nuclear ground state leaving the residual system with excitation energy E.



- We study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

Coincidence *(e,e'p)* process:

- Both the outgoing electron and the proton are detected in coincidence, and the recoiling nucleus can be left in any bound state.

- Within the Plane Wave Impulse Approximation (PWIA) scheme:

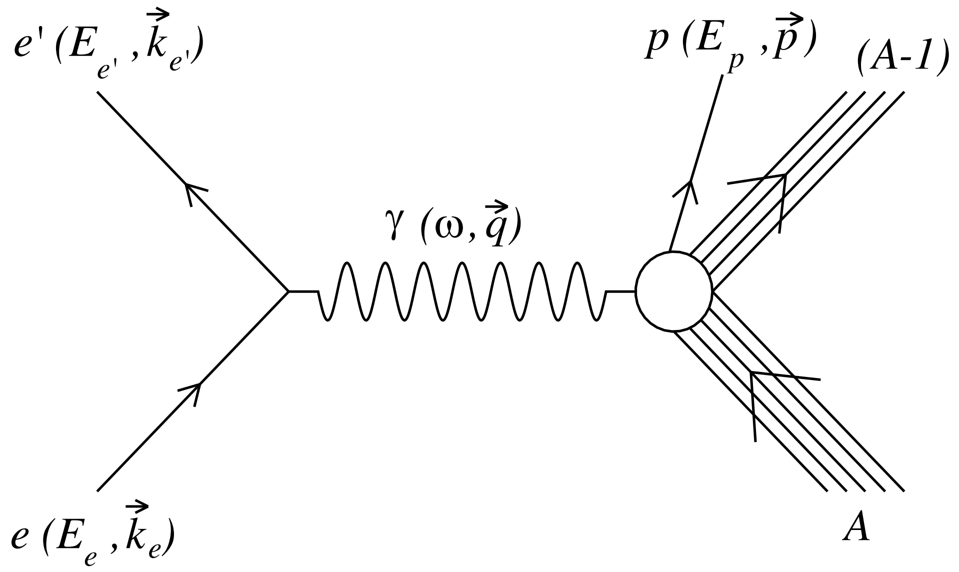
$$\frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

- The initial energy and momentum of the knocked out nucleon can be identified with the measured missing momentum and energy, respectively as

$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$

$$E_m = \omega - T_p - T_{A-1} \sim \omega - T_p$$

Where $T_p = E_p - m$, is the kinetic energy of the outgoing proton.



- We study the **coincidence (e,e'p) processes** in the **kinematical region** in which single nucleon knock out of a nucleon occupying a shell model orbit is the dominant reaction mechanism.

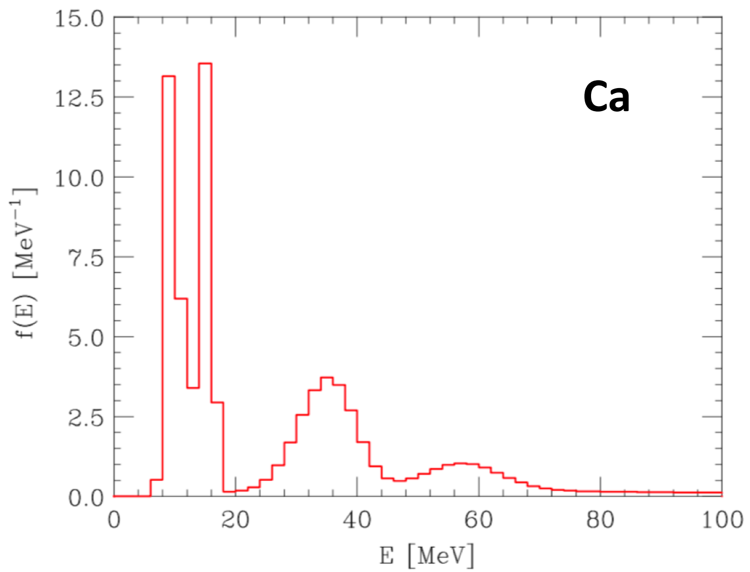
Kinematic region:

- Separation energies of the proton and neutron shell model states for Ca and Ar ground states

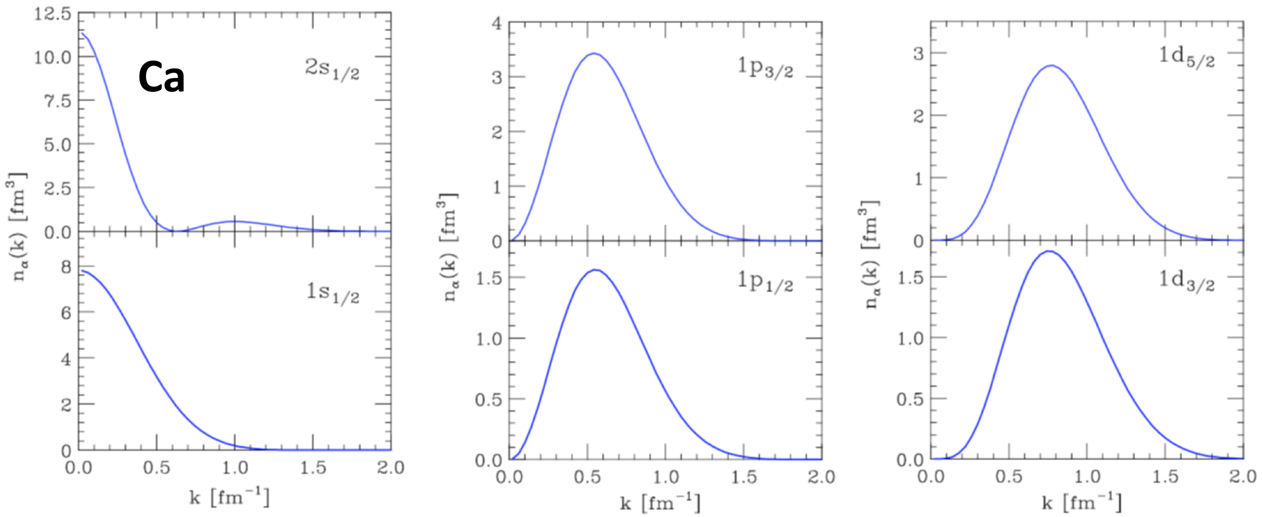
	protons		neutrons	
	$^{40}_{20}$Ca	$^{40}_{18}$Ar	$^{40}_{20}$Ca	$^{40}_{18}$Ar
$1s_{1/2}$	57.38	52	66.12	62
$1p_{3/2}$	36.52	32	43.80	40
$1p_{1/2}$	31.62	28	39.12	35
$1d_{5/2}$	14.95	11	22.48	18
$2s_{1/2}$	10.67	8	17.53	13.15
$1d_{3/2}$	8.88	6	15.79	11.45
$1f_{7/2}$				5.56

- The energy distribution

$$f(E) = 4\pi \int dk\ k^2 P(k,E)$$



- The momentum distribution

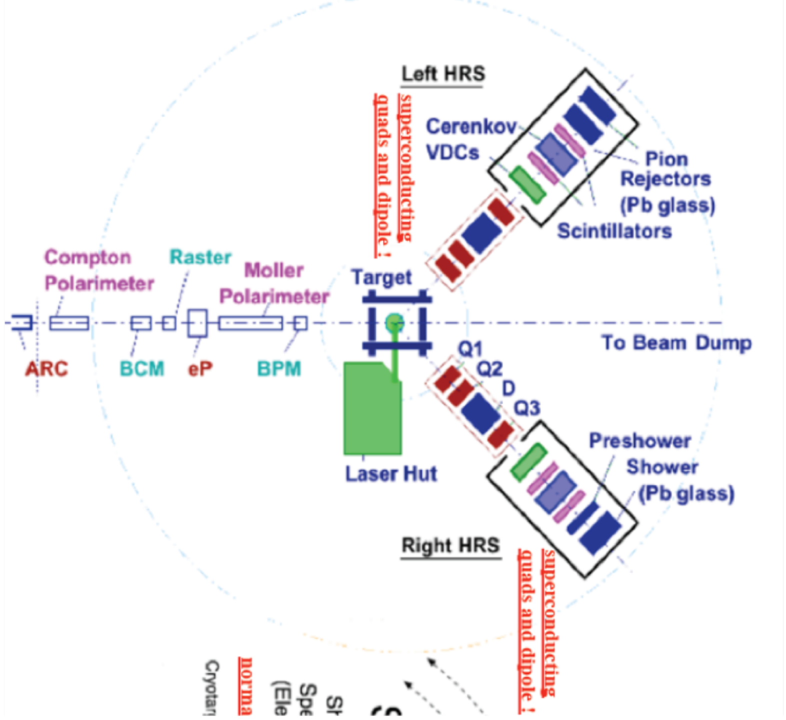


> ➢ Kinematic region for argon
> 6 MeV $\lesssim$ E_m $\lesssim$ 60 MeV
> $\mathbf{p}_m \lesssim$ 350 MeV

A. M. Ankowski and J. T. Sobczyk, Phys. Rev. C77, 044311 (2008)

Kinematic setups

	E_e MeV	$E_{e'}$ MeV	θ_e deg	P_p MeV/c	θ_p deg	$\lvert\mathbf{q}\rvert$ MeV/c	p_m MeV/c
kin1	2222	1799	21.5	915	−50.0	857.5	57.7
kin3	2222	1799	17.5	915	−47.0	740.9	174.1
kin4	2222	1799	15.5	915	−44.5	658.5	229.7
kin5	2222	1716	15.5	1030	−39.0	730.3	299.7
kin2	2222	1716	20.0	1030	−44.0	846.1	183.9
Inc-kin5	2222	-	15.5	-	-	730.3	299.7



Run Period: Feb-March 2017

kin1

Collected Data	Hours	Events (k)
Ar	29.6	43955
Ti	12.5	12755
Dummy	0.75	955

kin3

Collected Data	Hours	Events (k)
Ar	13.5	73176
Ti	8.6	28423
Dummy	0.6	2948

kin2

Collected Data	Hours	Events (k)
Ar	32.1	62981
Ti	18.7	21486
Dummy	4.3	5075
Optics	1.15	1245
C	2.0	2318

kin4

Collected Data	Hours	Events (k)
Ar	30.9	158682
Ti	23.8	113130
Dummy	7.1	38591
Optics	0.9	4883
C	3.6	21922

kin5

Collected Data	Hours	Events (k)
Ar	12.6	45338
Ti	1.5	61
Dummy	5.9	16286
Optics	2.9	160

kin5 - Inclusive

Collected Data	Minutes	Events (k)
Ar	57	2928
Ti	50	2993
Dummy	56	3235
C	115	3957

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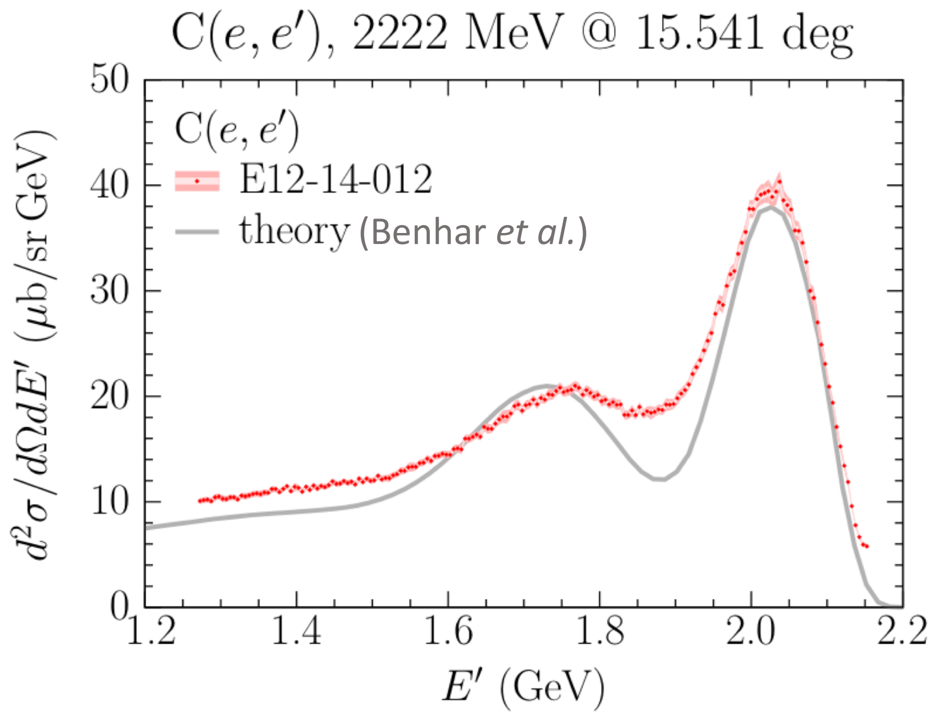
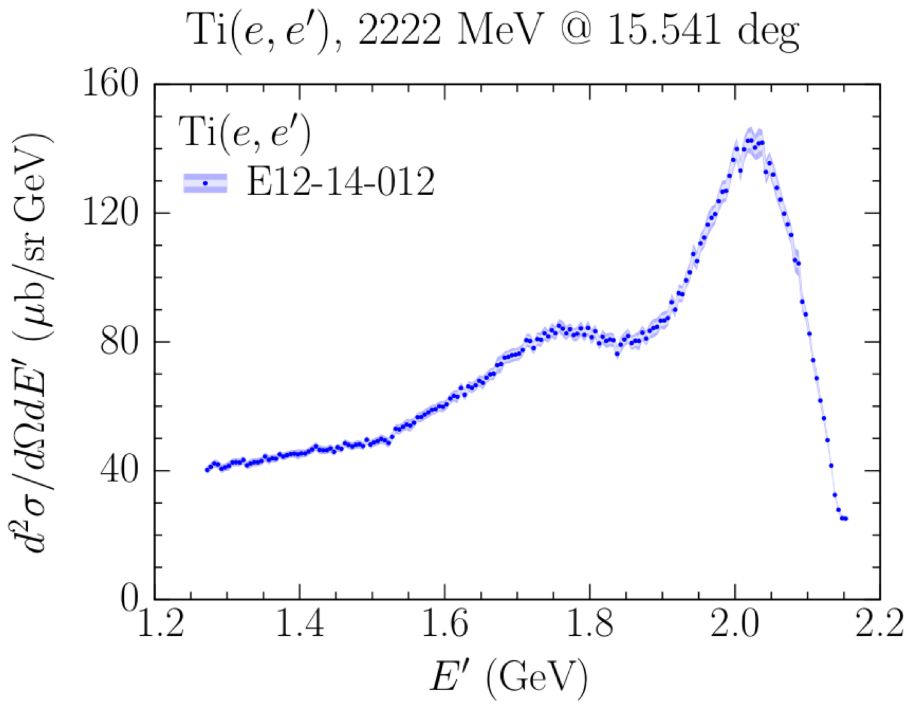
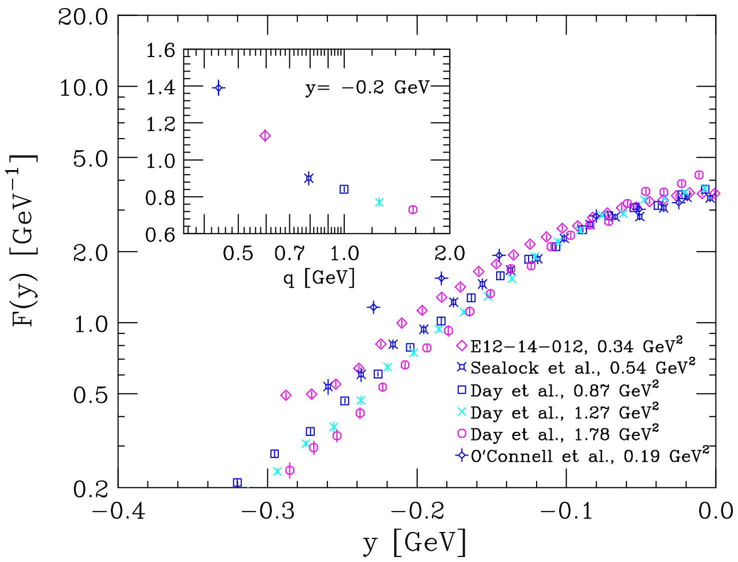
Inclusive Cross Section Results

Phys. Rev. C98, 014617 (2018)







The y-scaling function: F(y)

Previous datasets:

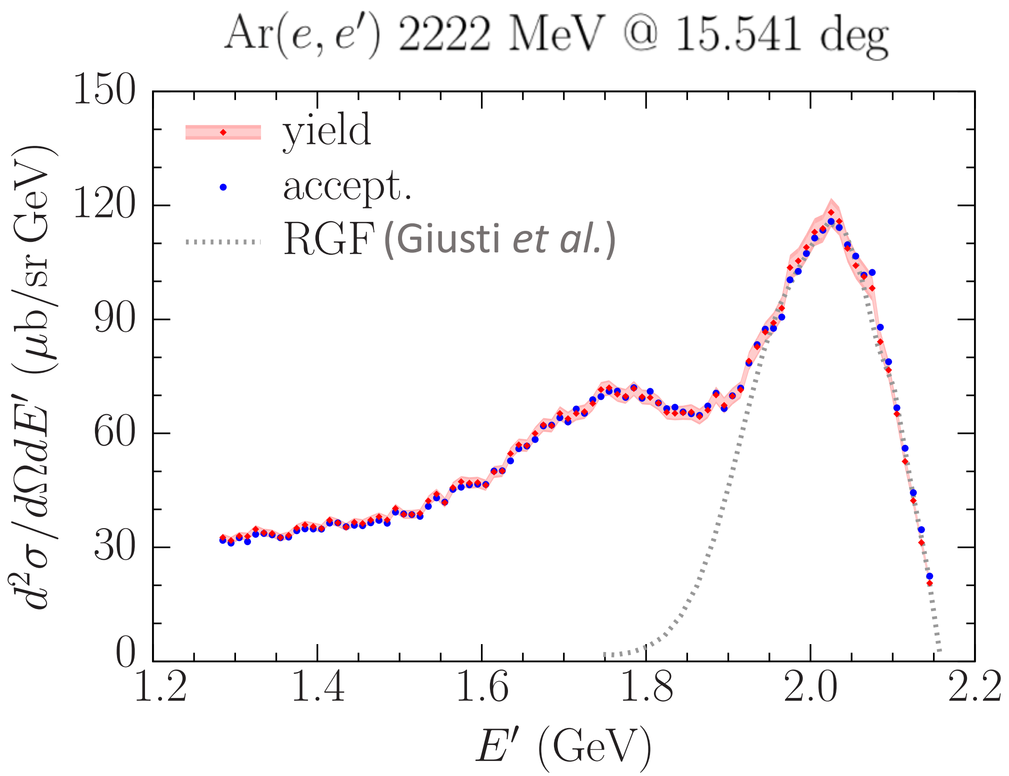
R. M. Sealock et al, Phys. Rev. Lett. 62, 1350 (1989).

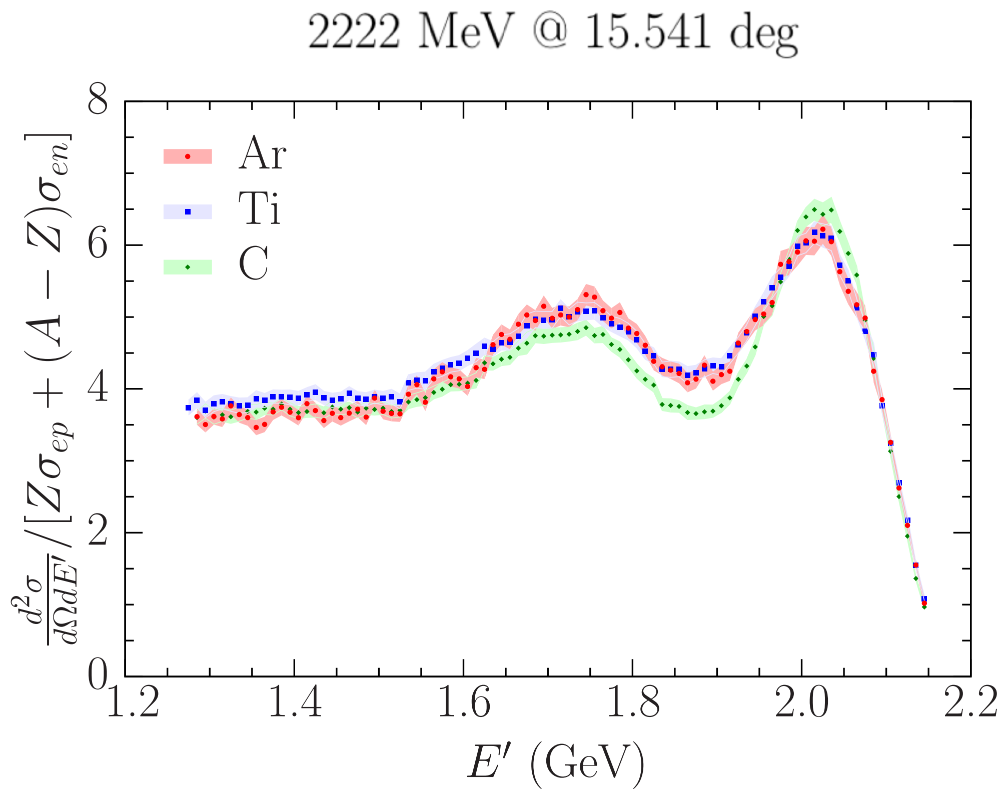
D. B. Day et al, Phys. Rev. C 48, 1849 (1993).

J. S. O'Connell et al., Phys. Rev. C 35, 1063 (1987).

Inclusive Cross Section Results

arXiv:1810.10575 [nucl-ex]





Summary - II

- In E12-14-012 experiment at Jefferson Lab Hall A, we study the properties of argon and titanium nucleus by the scattering of precise (continuous) electron beam on nuclei.

- We presented measured C(e,e’), Ti(e,e’), and Ar(e,e’) cross sections at beam energy E = 2.222 GeV and scattering angle θ =15.541 deg. The measured cross section covers a broad range of energy transfer where quasielastic scattering and delta production are the dominant reaction mechanisms.

- The new precise measurement on argon nucleus will be of great value for the development of realistic models of the electroweak response of neutron-rich nuclei, vital for the success of the current and next generation of neutrino experiments employing liquid-argon based detectors.

- More results including (e,e’p) cross sections will follow soon - stay tuned!