Summary of low vs. high momentum transfer model consistency discussions

Steven Gardiner

ECT Workshop on Testing and Improving Models of Neutrino Nucleus Interactions in Generators

June 2019

Parallel sessions

- Two talks & some discussion of next steps

LOW/HIGH ENERGY TRANSFER REGIONS IN VALENCIA MODEL

Joanna Sobczyk
4 June 2019

HOW LOW CAN WE GET?

HOW HIGH CAN WE GET?

Consistency between low and high energy models

Alexis Nikolakopoulos
Ghent University

Testing and improving models of neutrino nucleus interactions in generators, ECT, Trento, Italy, 2-7 June, 2019*

I. Description of the Ghent CRPA model

II. The influence of forbidden transitions in charged current scattering on Argon

III. Differences between electron and muon neutrino cross sections

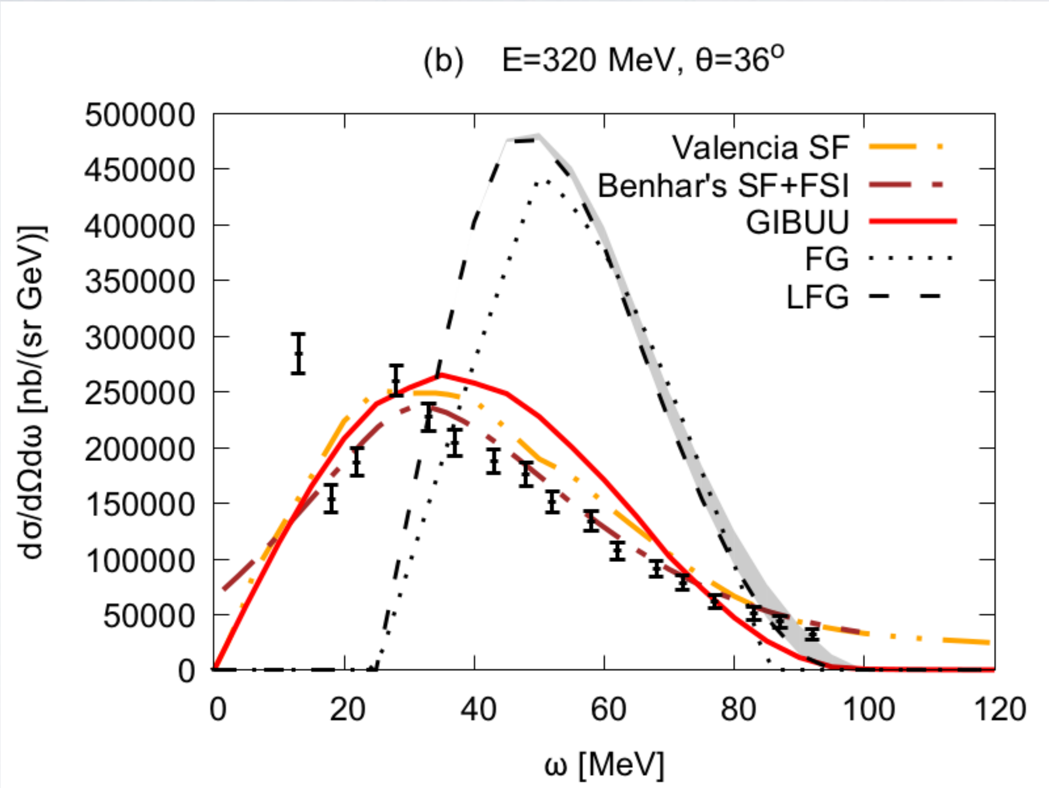
EXISTING DESCRIPTIONS

- LDA + potential (GiBUU)
- SF + Optical potential (Rome)
- Hartree-Fock +CRPA (Ghent)
- LDA + SF (Valencia)
- SuSav2
- ab-initio (GFMC)

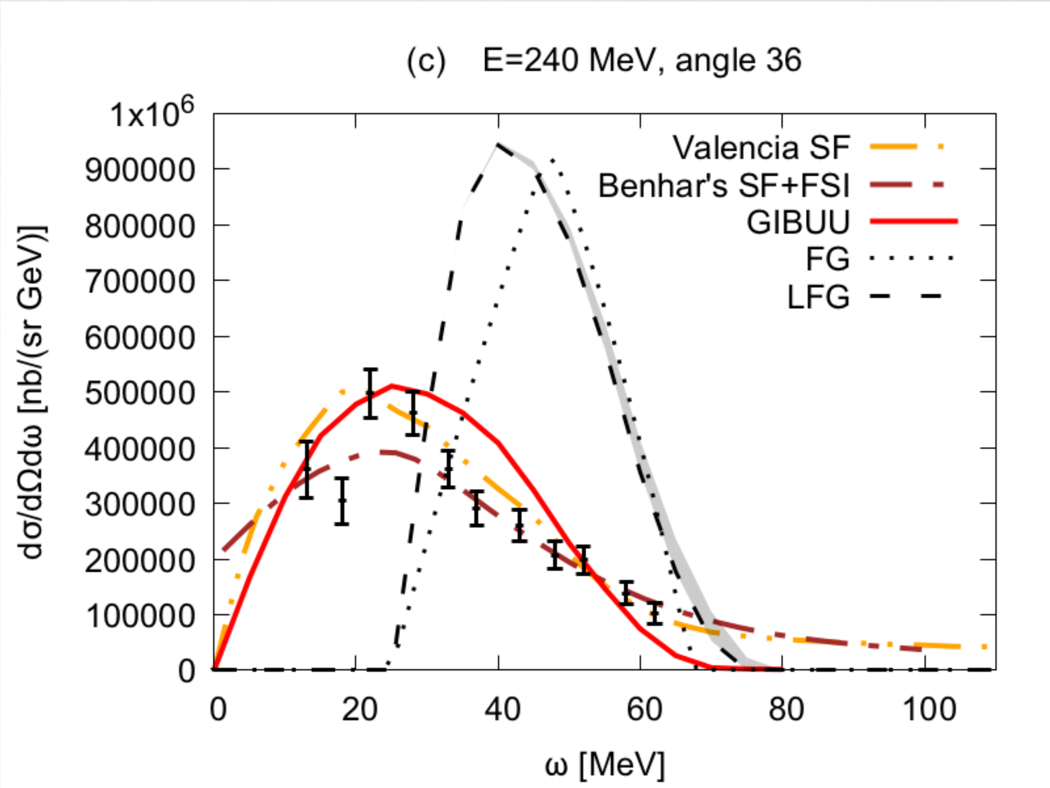
How low/high can we get with these models?

For inclusive QE data they seem to work decently well*

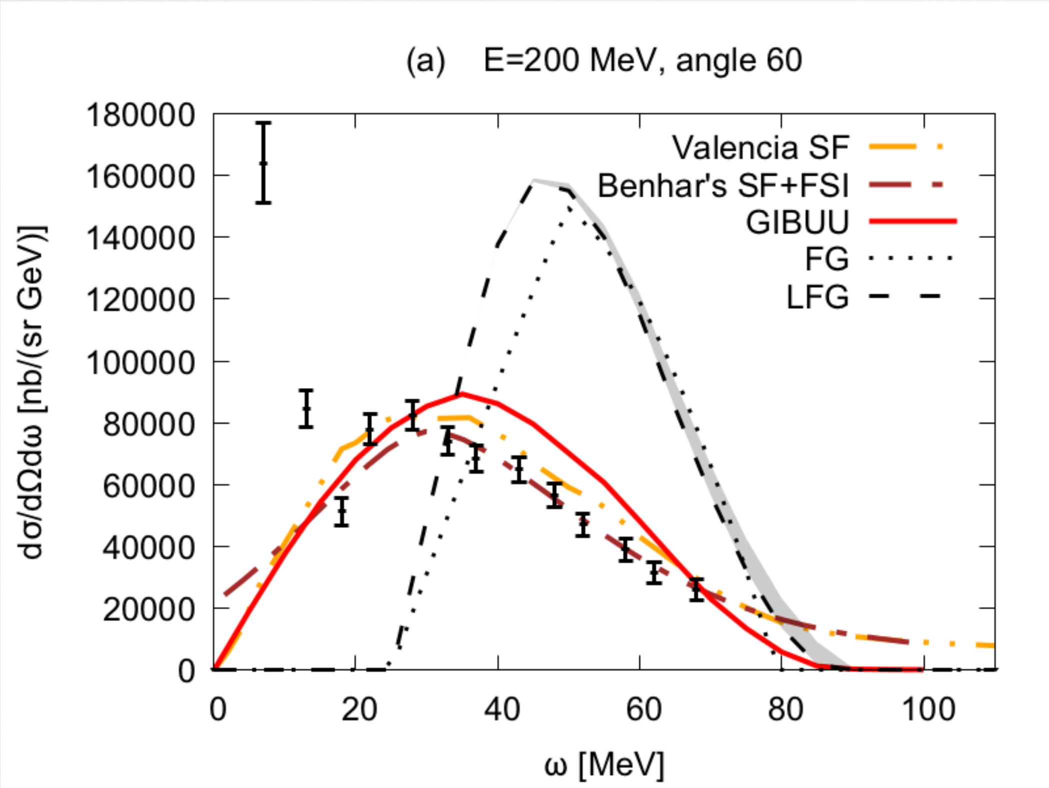
**check when 2p2h and pion production are included*



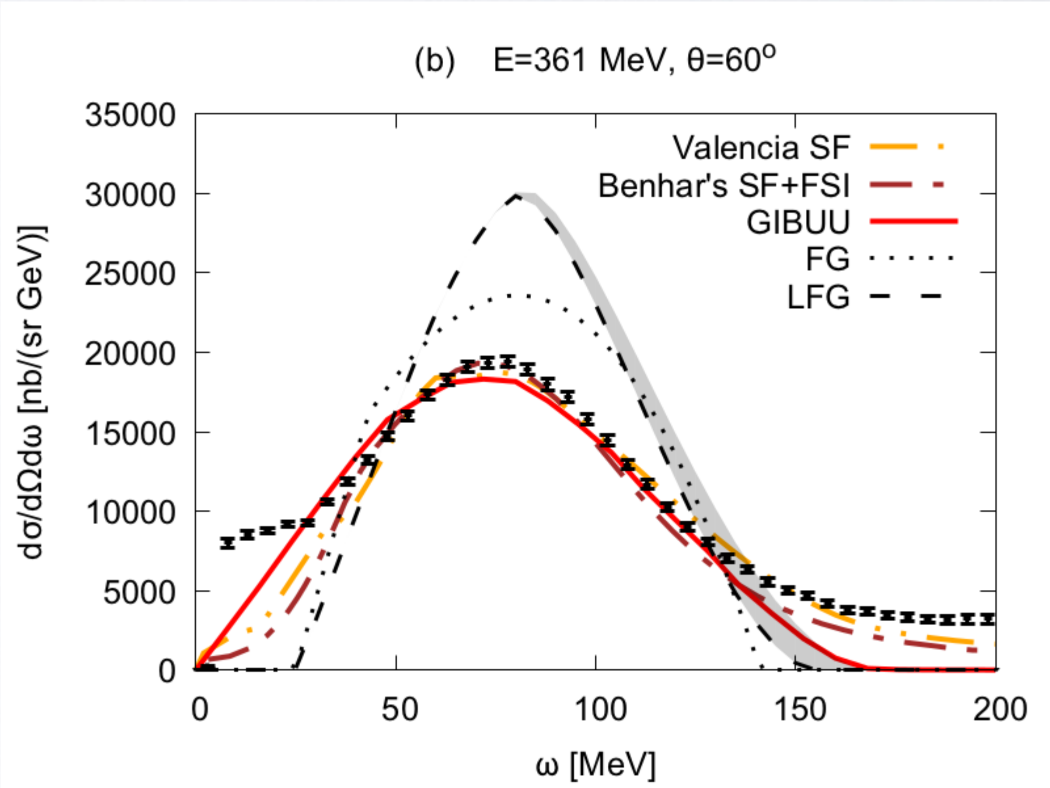
(b) E=320 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/(sr GeV)]
ω [MeV]



(c) E=240 MeV, angle 36
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/(sr GeV)]
ω [MeV]



(a) E=200 MeV, angle 60
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/(sr GeV)]
ω [MeV]



(b) E=361 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/(sr GeV)]
ω [MeV]

GROUND STATE (I)

- Spectral functions:

$$S_{p,h}^{\rm LDA}(\mathbf{p},E) = \mp\frac{1}{\pi}\frac{{\rm Im}\Sigma(\mathbf{p},E)}{\left(E-\mathbf{p}^2/2m-{\rm Re}\Sigma(\mathbf{p},E)\right)^2+{\rm Im}\Sigma(\mathbf{p},E)^2}$$

- Local density approximation (LDA)

$$W^{\mu\nu}_{LDA}(q) = 2\int d^3r\int\frac{d^3p}{(2\pi)^3}\int dE\, S_h^{\rm LDA}(E,\mathbf{p},\rho)\frac{M}{E_p}\frac{M_Y}{E^Y_{p+q}}\delta(E+q^0-E^Y_{p+q}(\rho))A^{\mu\nu}(p,q)$$

$$A^{\mu\nu}(p,q) = \langle\mathbf{p}\,|\,(j^\mu_{cc})^\dagger\,|\,\mathbf{p}+\mathbf{q}\rangle\langle\mathbf{p}+\mathbf{q}\,|\,j^\nu_{cc}\,|\,\mathbf{p}\rangle$$

matrix element for a single nucleon

LOW ENERGY PROCESSES

muons are 300 times heavier than electrons

↓

the wave function overlaps with nucleus

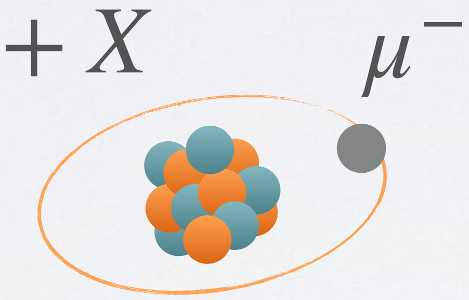
↓

the system is unstable (interaction with nucleus)

governed by the same CC interaction

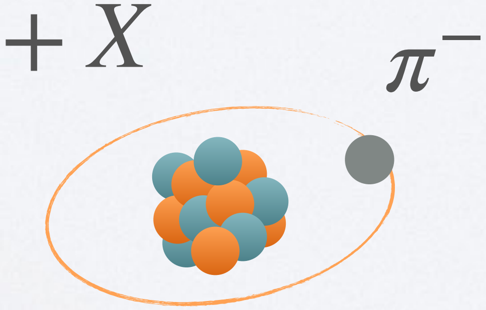
muon capture

$$(A-\mu^-)^{1s}_{\text{bound}} \to \bar{\nu} + X$$



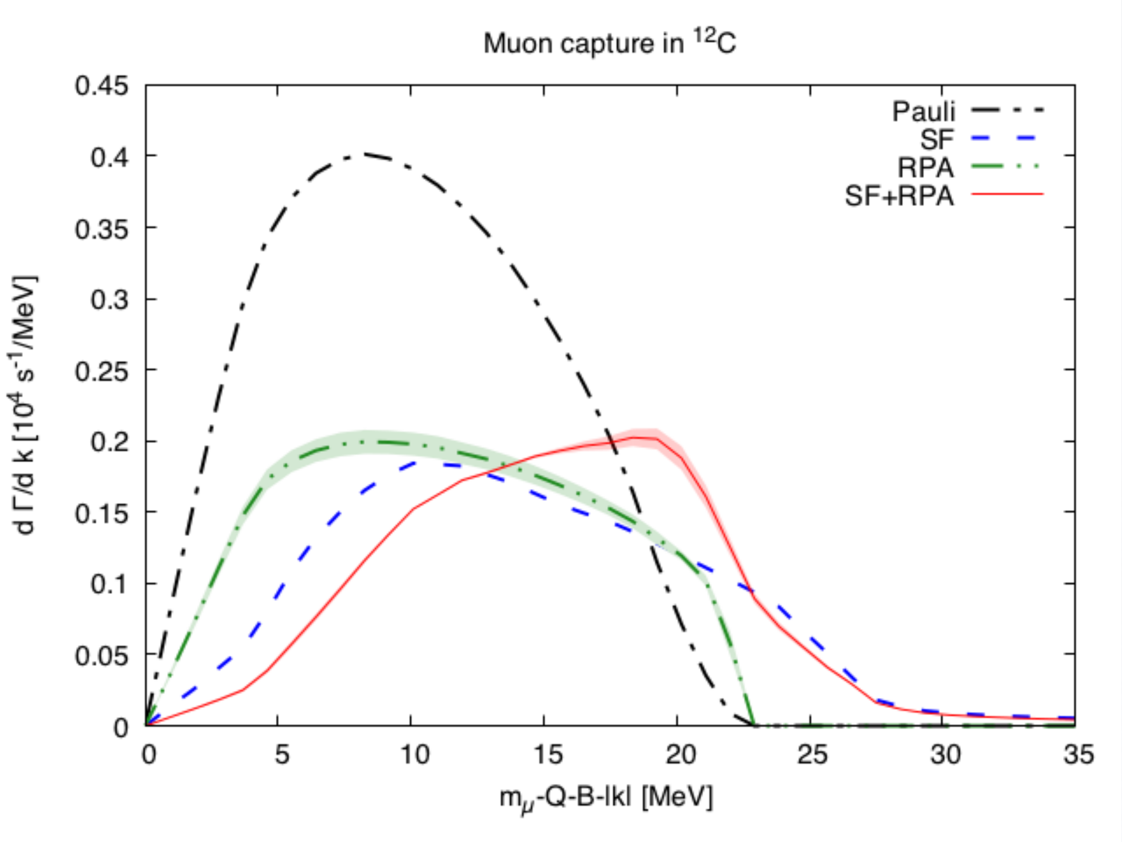
pion radiative capture

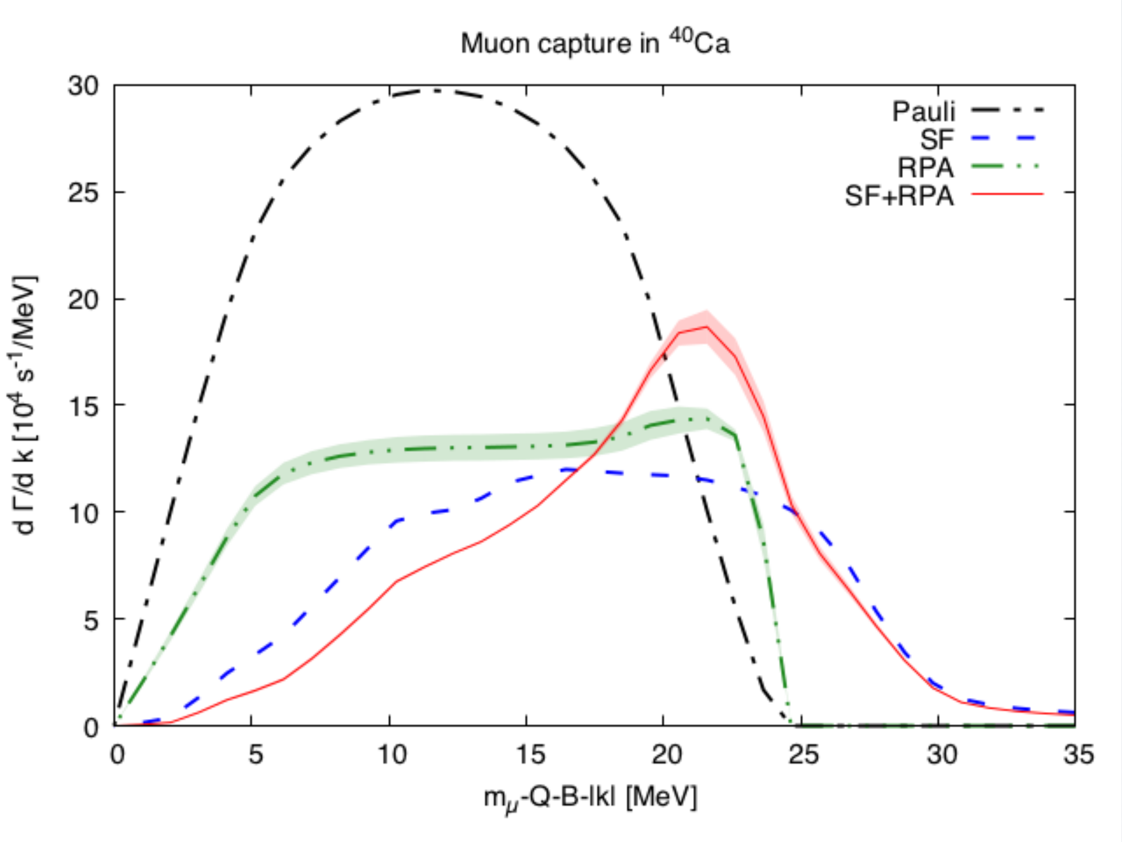
$$(A-\pi^-)_{\text{bound}} \to \gamma + X$$



MUON CAPTURE

(shape shows the general trend)





Nucleus	Pauli (10^4 s^{-1})	RPA (10^4 s^{-1})	SF (10^4 s^{-1})	SF+RPA (10^4 s^{-1})	Exp. (10^4 s^{-1})
^{12}C	5.76	3.37 ± 0.16	3.22	3.19 ± 0.06	3.79 ± 0.03
^{16}O	18.7	10.9 ± 0.4	10.6	10.3 ± 0.2	10.24 ± 0.06
^{18}O	13.8	8.2 ± 0.4	7.0	8.7 ± 0.1	8.80 ± 0.15
^{23}Na	64.5	37.0 ± 1.5	30.9	34.3 ± 0.4	37.73 ± 0.14
^{40}Ca	498	272 ± 11	242	242 ± 6	252.5 ± 0.6

NEUTRINO SCATTERING DATA

Table 5
Experimental and theoretical flux averaged $^{12}C(\nu_\mu, \mu^-)X$ and $^{12}C(\nu_e, e^-)X$ cross sections in 10^{-40} cm^2 units. Theoretical errors in the RPA predictions show MC 68% CL intervals derived from the uncertainties on the $ph(\Delta h)$–$ph(\Delta h)$ effective interaction. We also quote results from other calculations (see text for details).

	Pauli	RPA	SF	SF+RPA	SM	SM	CRPA		Experiment	
					[133]	[44]	[45]	LSND [123]	LSND [124]	LSND [125]
$\bar{\sigma}(\nu_\mu, \mu^-)$	23.1	13.2 ± 0.7	12.2	9.7 ± 0.3	13.2	15.2	19.2	$8.3 \pm 0.7 \pm 1.6$	$11.2 \pm 0.3 \pm 1.8$	$10.6 \pm 0.3 \pm 1.8$
								KARMEN [128]	LSND[126]	LAMPF [127]
$\bar{\sigma}(\nu_e, e^-)$	0.200	0.143 ± 0.006	0.086	0.138 ± 0.004	0.12	0.16	0.15	$0.15 \pm 0.01 \pm 0.01$	0.15 ± 0.01	0.141 ± 0.023

What are the CRPA Ghent results?

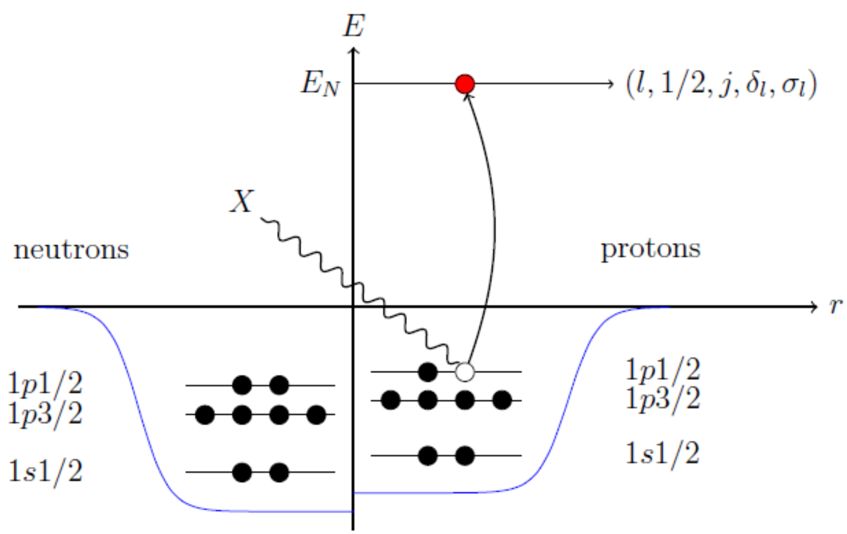
POSITIVE SIDES OF THIS APPROACH

- It is based on the LDA: direct possibility to generate the primary vertex
- Possibility to use of various targets
- Simplicity
- Contains both RPA and SF
- works decently well for electrons
- for low energy transfers description of the hole and particle states within the same formalism

DEFICIENCIES OF THIS APPROACH

- For low energies describes the total strength of RPA but not the spectrum
- Simplicity: no insight into details of the nuclear structure
- For high momentum transfer we can use only plane wave (now we do not use any model for FSI)

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.

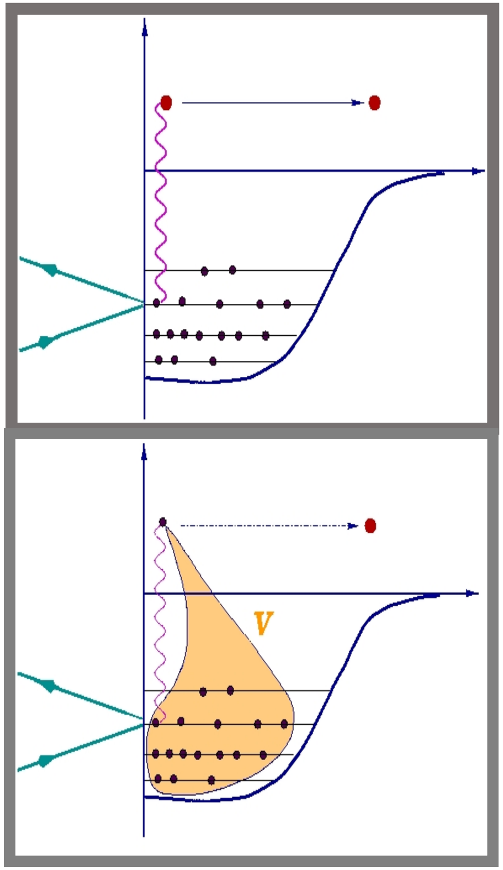
Naturally includes:

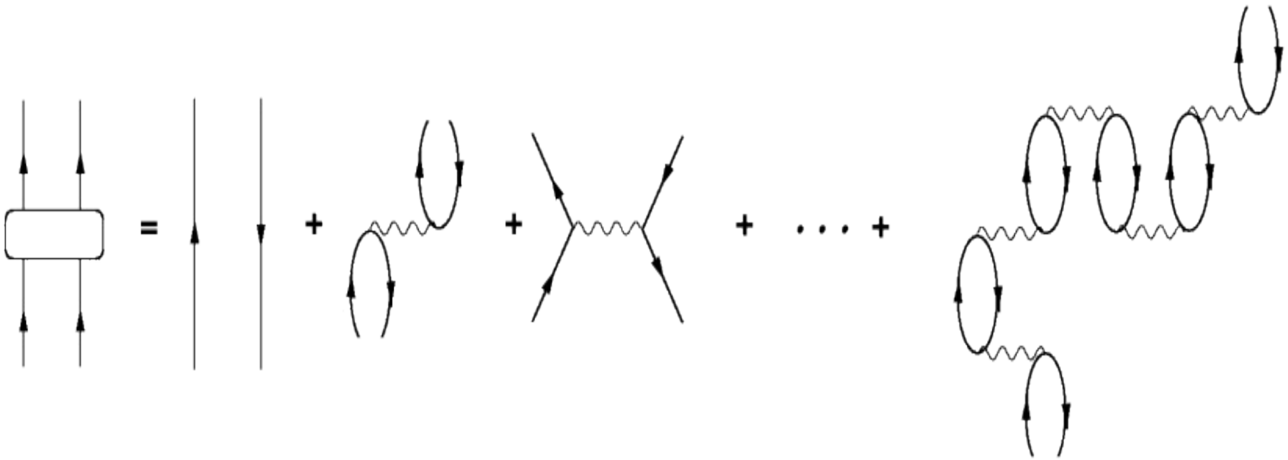
Binding
Fermi motion
Elastic Final state interactions
Pauli blocking
orthogonality

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

Long-range correlations : Continuum RPA

- Green's function approach
- Skyrme SkE2 residual interaction
- self-consistent calculations





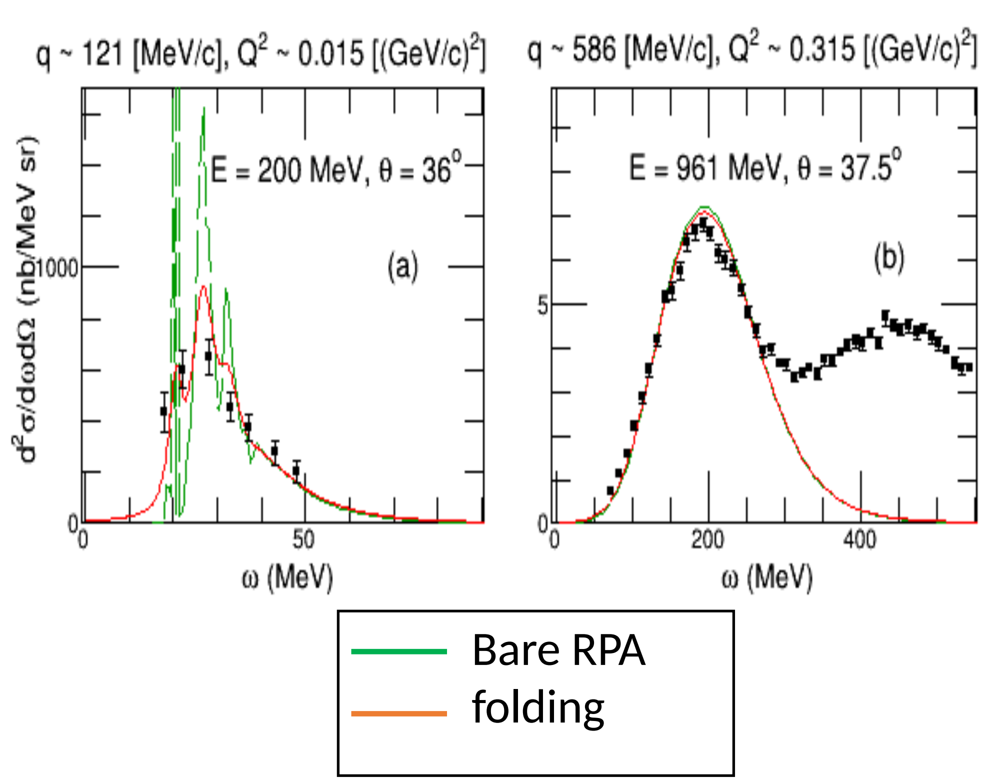
$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\}$$

$+ \quad \ldots$

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

Final state interactions

-Calculations of the wave function of the outgoing nucleon in the same (real) nuclear potential used for the initial state
-influence of the spreading width of the particle states is implemented through a folding procedure

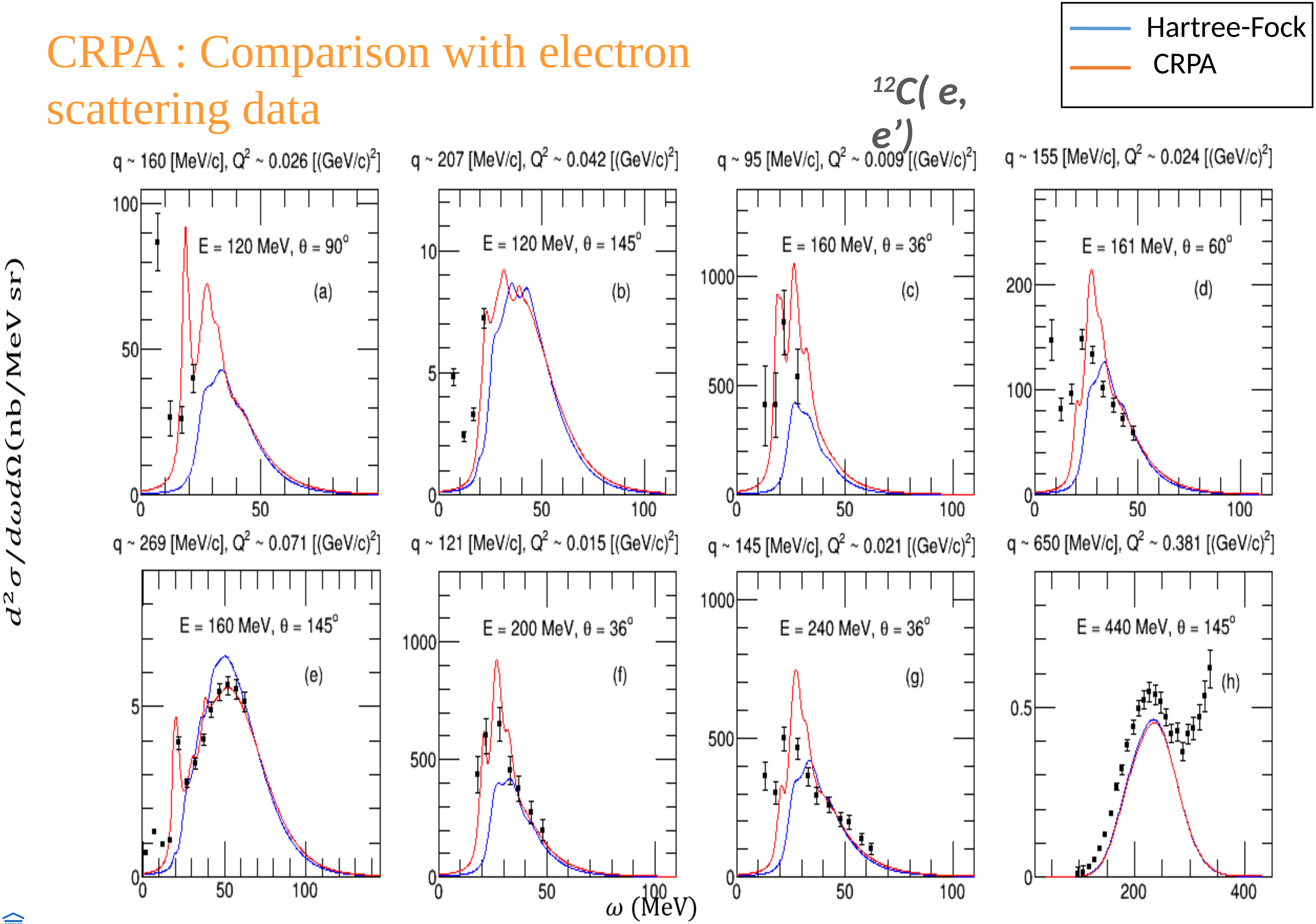


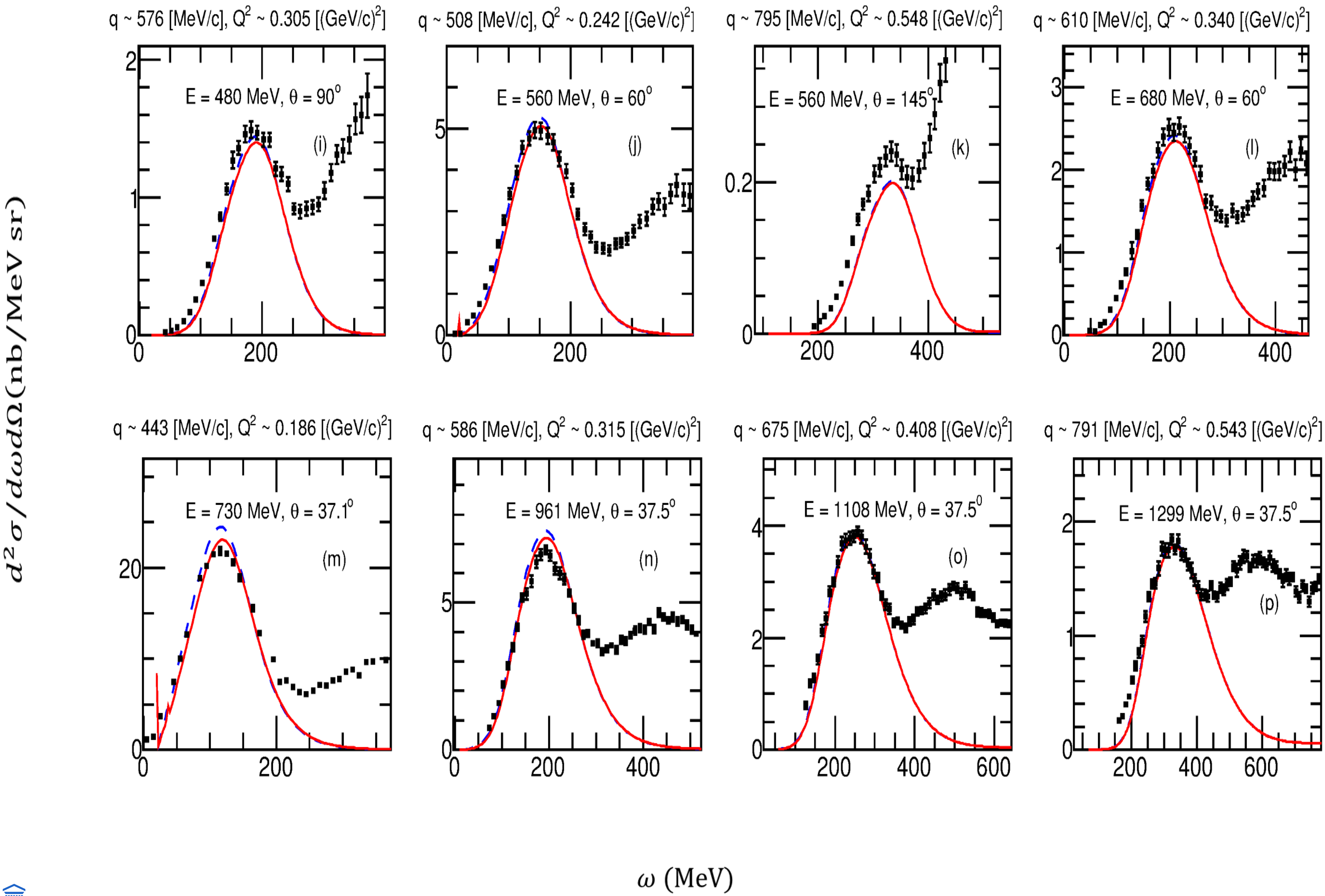
$$R'(q,\omega') = \int_{-\infty}^{\infty} d\omega\ R(q,\omega)\ L(\omega,\omega'),$$

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

CRPA : Comparison with electron scattering data

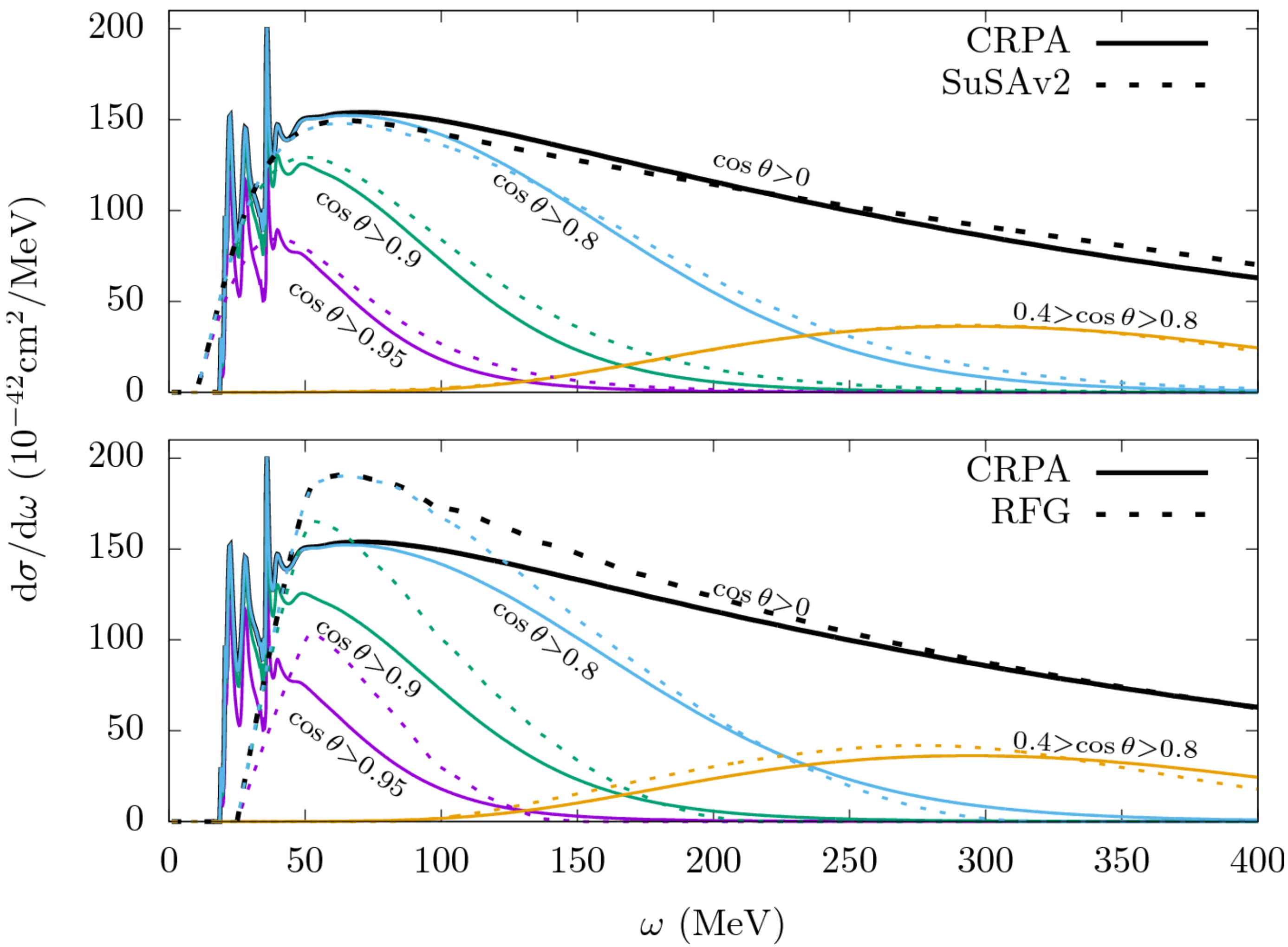
$^{12}C(e, e')$





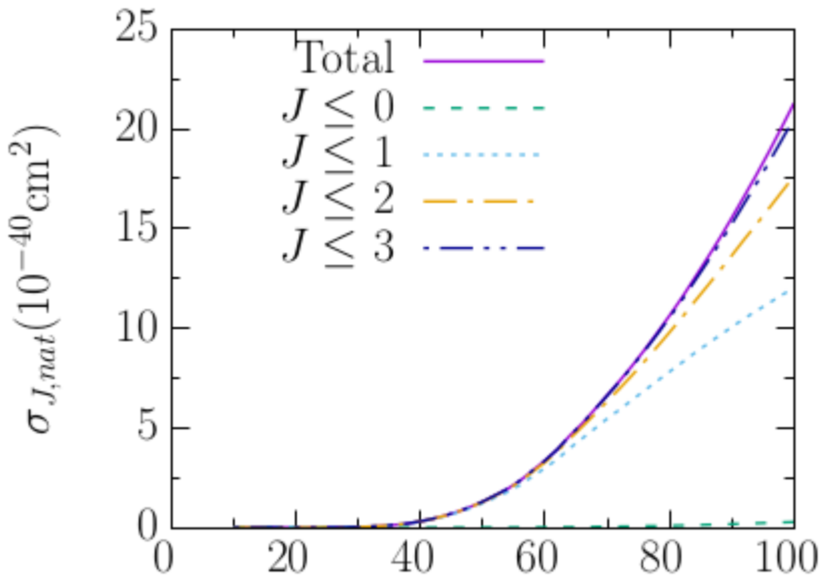
q ~ 576 [MeV/c], Q² ~ 0.305 [(GeV/c)²]
E = 480 MeV, θ = 90°
(i)
q ~ 508 [MeV/c], Q² ~ 0.242 [(GeV/c)²]
E = 560 MeV, θ = 60°
(j)
q ~ 795 [MeV/c], Q² ~ 0.548 [(GeV/c)²]
E = 560 MeV, θ = 145°
(k)
q ~ 610 [MeV/c], Q² ~ 0.340 [(GeV/c)²]
E = 680 MeV, θ = 60°
(l)
q ~ 443 [MeV/c], Q² ~ 0.186 [(GeV/c)²]
E = 730 MeV, θ = 37.1°
(m)
q ~ 586 [MeV/c], Q² ~ 0.315 [(GeV/c)²]
E = 961 MeV, θ = 37.5°
(n)
q ~ 675 [MeV/c], Q² ~ 0.408 [(GeV/c)²]
E = 1108 MeV, θ = 37.5°
(o)
q ~ 791 [MeV/c], Q² ~ 0.543 [(GeV/c)²]
E = 1299 MeV, θ = 37.5°
(p)
d²σ/dωdΩ(nb/MeV sr)
ω (MeV)

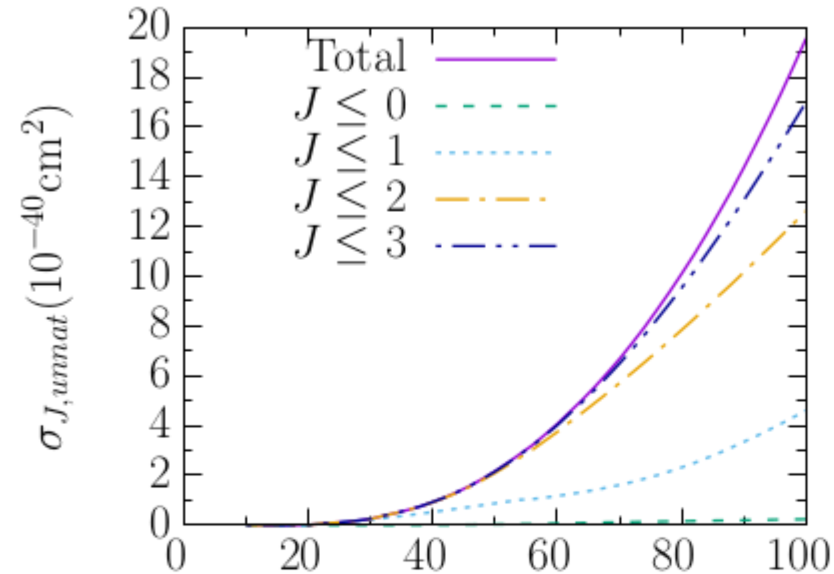
Low energy excitations at higher E_ν



CRPA takes into account in a satisfactory way the nuclear response for QE starting from low to intermediate ω and q

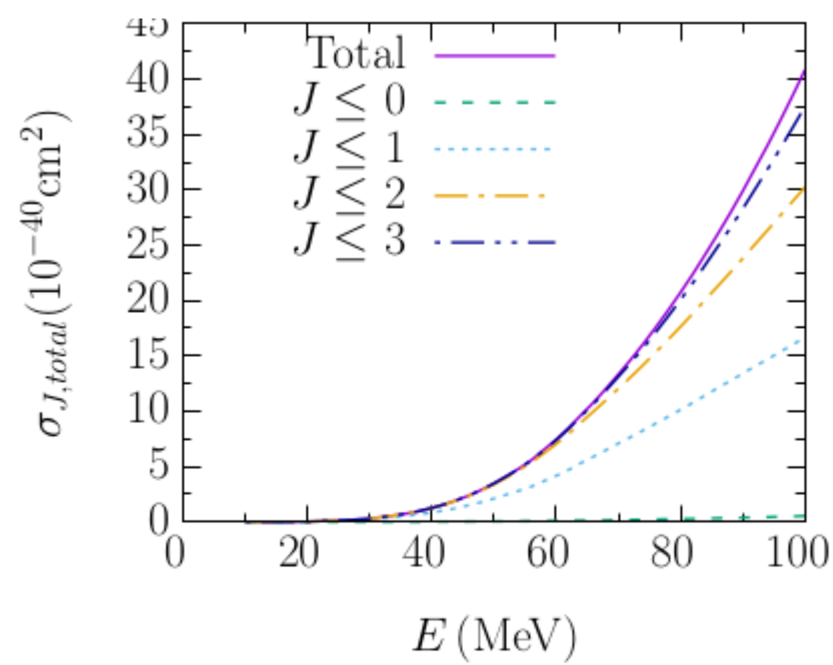
Multipole contributions to total CS

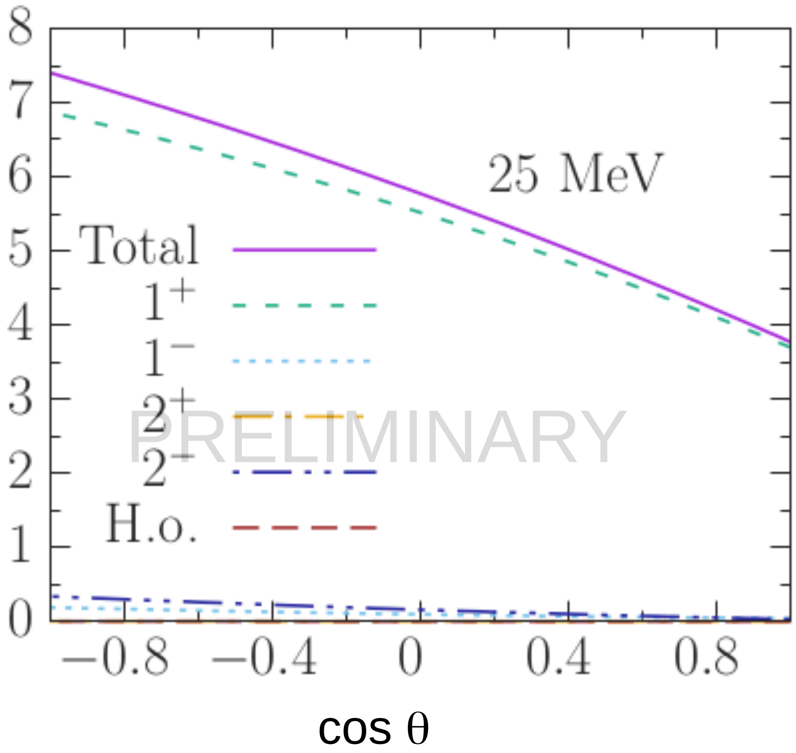


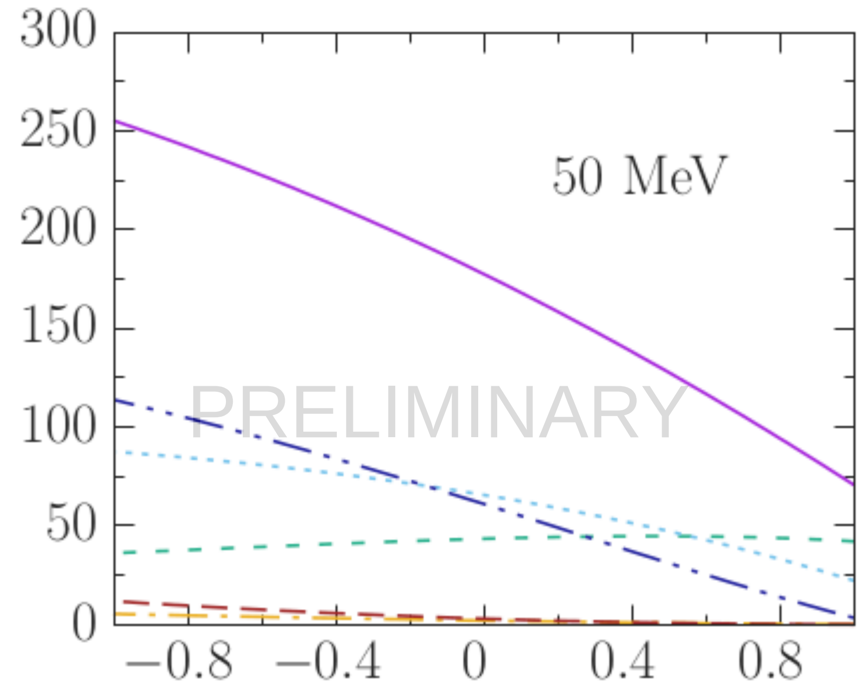


CC scattering of electron neutrinos neutrinos scattering on Argon.
Different multipoles shown cumulatively.

Forbidden transitions carry significant strength for continuum excitations!



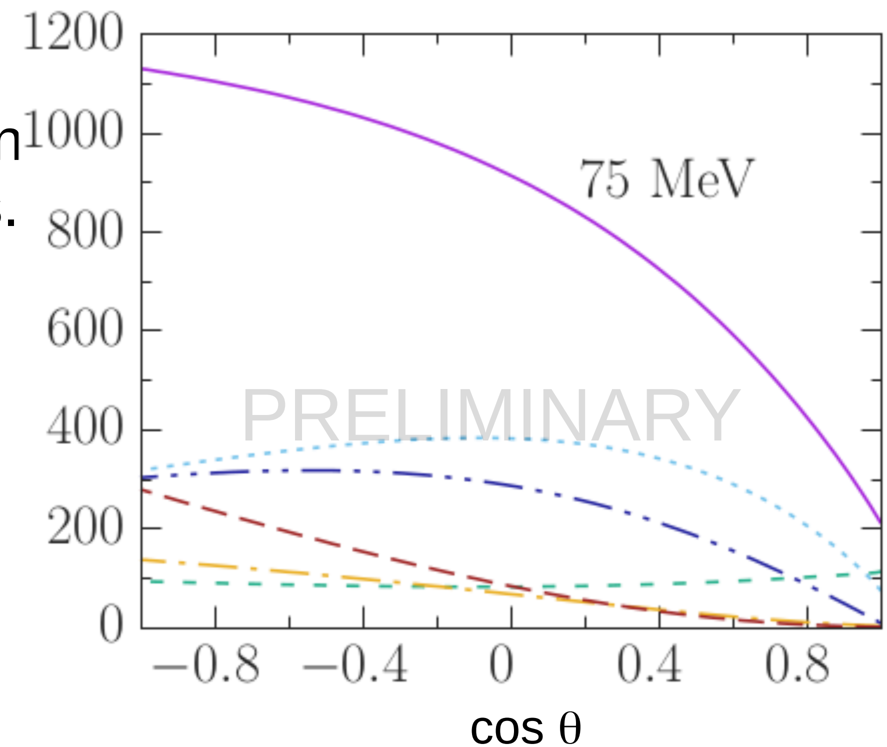


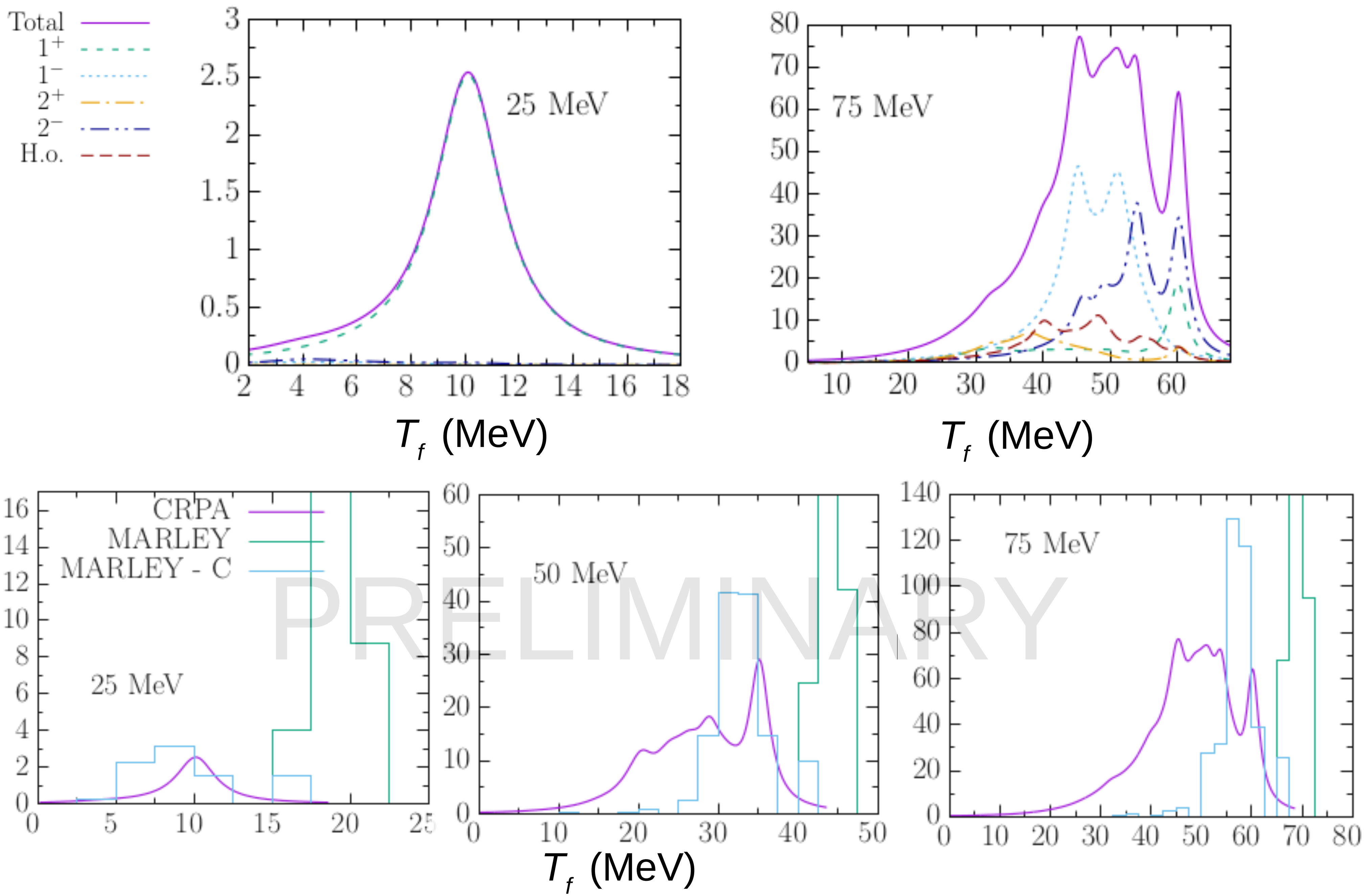


CC scattering of electron neutrino on argon at different incoming energies.

The angular distribution of the outgoing charged lepton for the allowed (1+) transition is flat.

Higher order multipoles heavily affect the shape of the differential cross section





The higher order multipoles give significant strength for low outgoing lepton energies

Electron versus muon neutrino induced cross sections in charged current quasi-elastic processes

A. Nikolakopoulos,[1,*] N. Jachowicz,[1,†] N. Van Dessel,[1]
K. Niewczas,[1,2] R. González-Jiménez,[3] J. M. Udías,[3] and V. Pandey[4]

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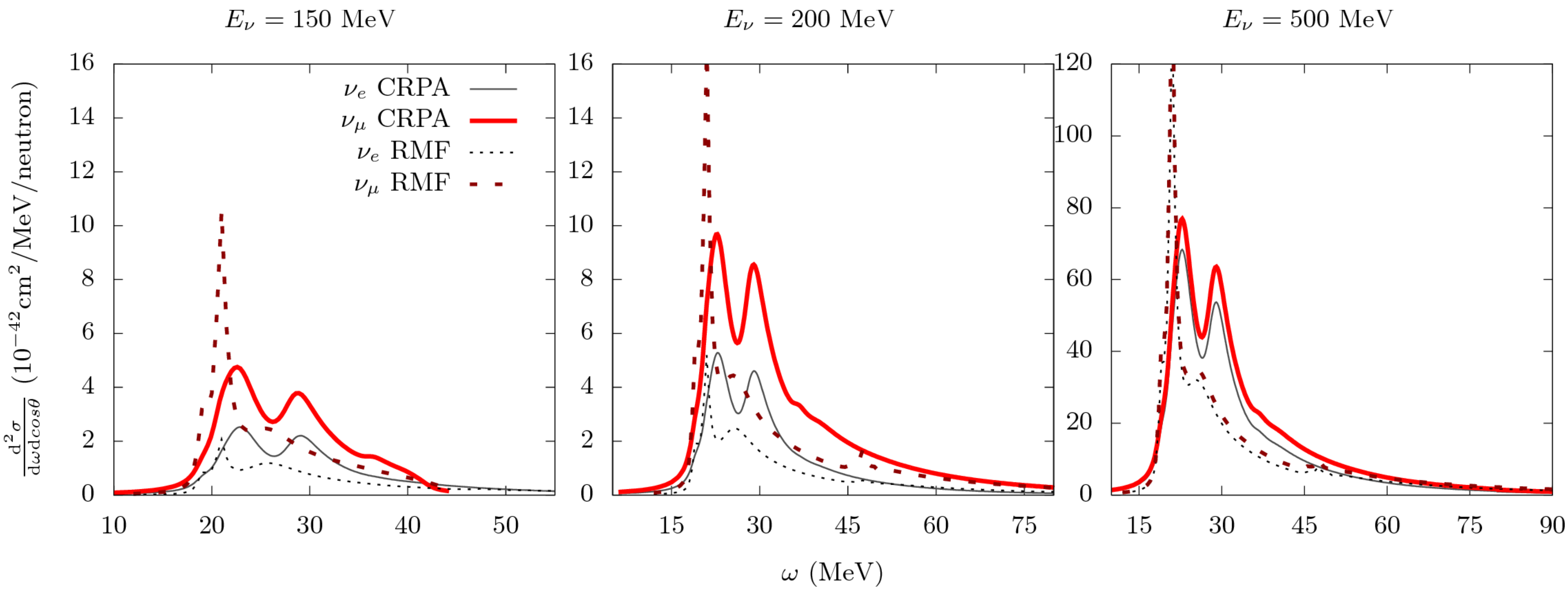
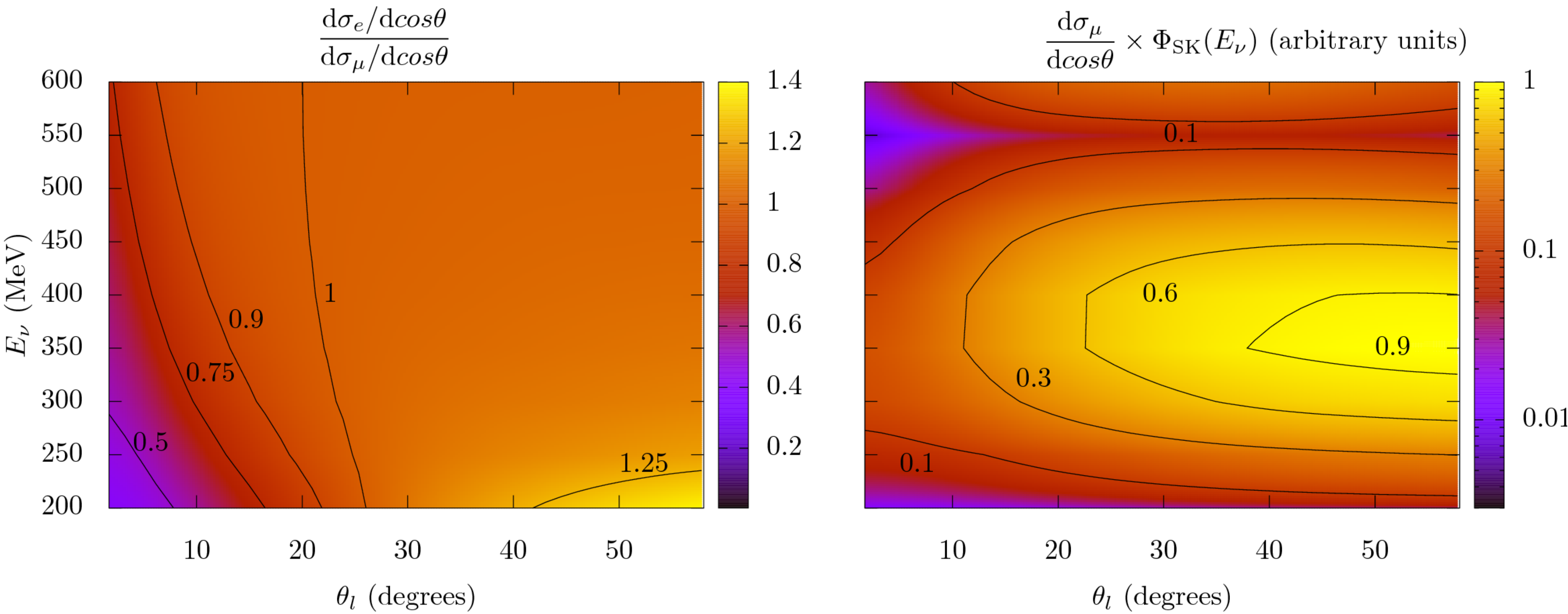


- Mean field models give larger ν_μ than ν_e cross sections for low ω and q
- Collective excitations add significant strength

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



MARLEY + Ghent CRPA

- Comparing generator predictions based on low & high energy pictures of the nucleus useful, but we need to get MARLEY up beyond few 10s of MeV

- Forbidden transitions have important impact on observables of interest for DUNE supernova program, potentially for other experiments looking at ν_e

  - Currently neglected in MARLEY (0+ and 1+ multipoles only)

  - Clearly necessary before we can have a fair comparison to high-E generators in the low 100s of MeV

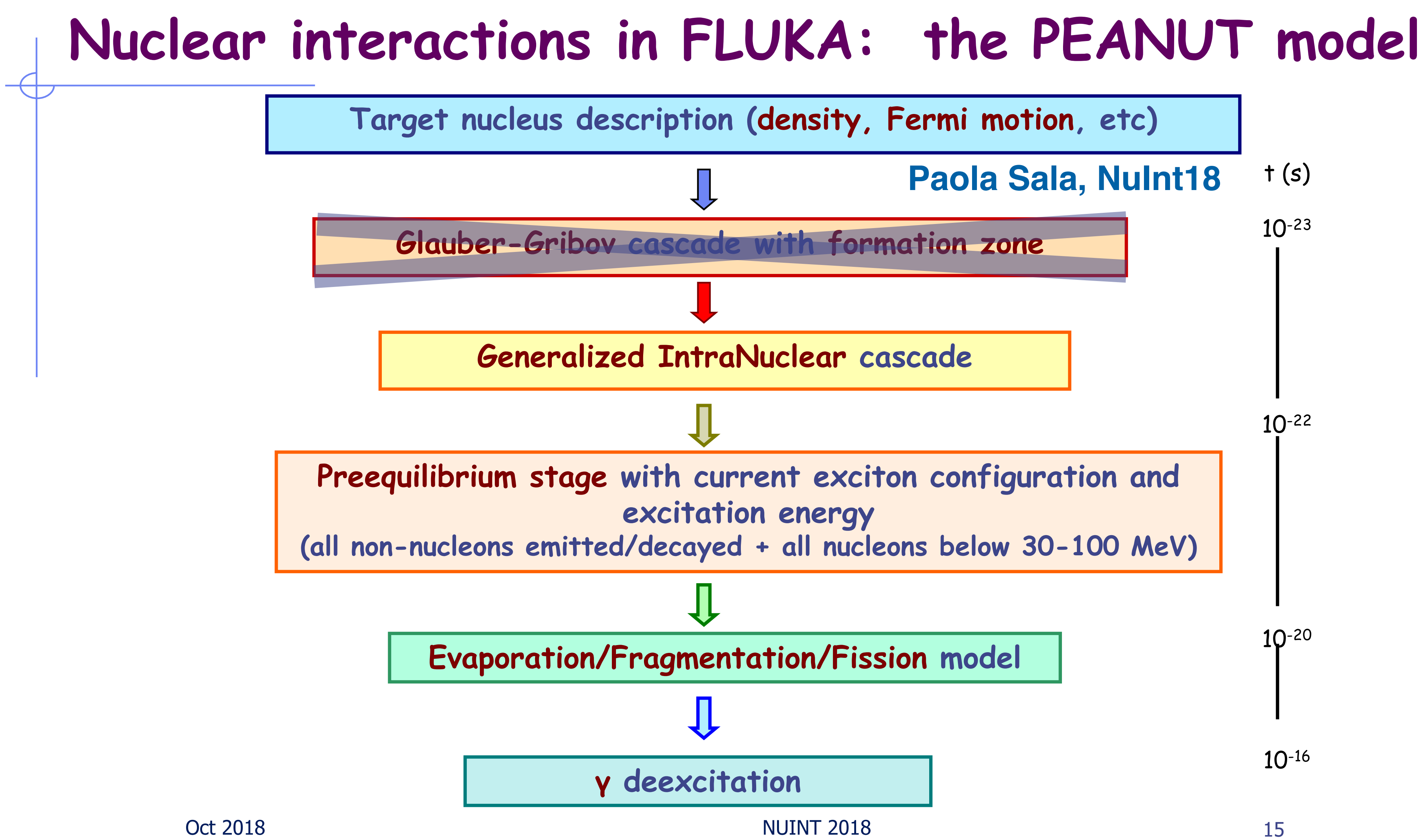
- Plan to replace existing MARLEY treatment of continuum contribution with Ghent CRPA
  - Could provide matrix elements, but tables of $d\sigma(E_\nu, \omega, J^\pi) / d\cos\theta$ likely good enough for now
  - Comparisons to data for cross sections & muon capture (rates, isotopic yields)
  - **Still needs discrete level contribution**
    - Data-driven for 40Ar
    - Would need another approach (e.g, shell model) for other targets

MARLEY comparisons

- In my opening talk, I mentioned that I was working on some MARLEY / GENIE comparisons
  - Started down that path this week, but I found that doing a "fair" comparison is subtle
    - At very low energies, GENIE makes CC QE & MEC events
    - MARLEY, on the other hand, makes plenty of events with e- + gammas only, nucleon emission isn't QE-like at all
    - Predictions are quite different as a result
- I'll continue to pursue this, but it shouldn't be rushed

Connection to high-energy generator FSI models

- Adding a MARLEY-like de-excitation model post-cascade provides a way to realistically simulate neutrino-induced low-energy activity
  - FLUKA's PEANUT model already does this, but it's not open source



De-excitation models well-validated against non-neutrino nuclear data

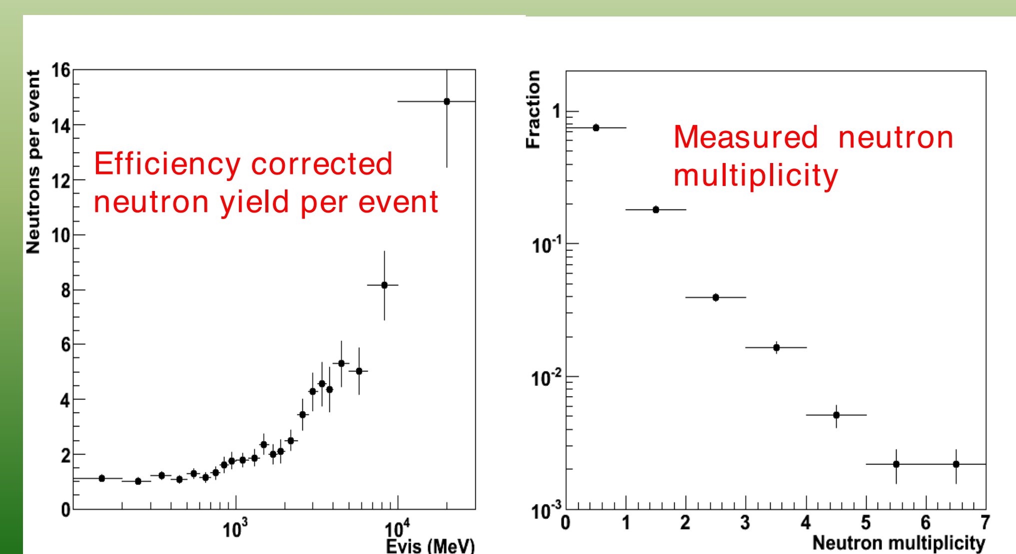
Connection to high-energy generator FSI models

- Adding a MARLEY-like de-excitation model post-cascade provides a way to realistically simulate neutrino-induced low-energy activity
  - FLUKA's PEANUT model already does this, but it's not open source
- GENIE actively pursuing INCL++ & Geant4 interfaces, both have a similar treatment
  - Unlike PEANUT, both INCL++ and Geant4 use strength function models for gamma emission (no discrete lines)
  - INCL++ calls an external code (ABLA07) for evaporation step, could likely replace with MARLEY, which does include discrete gammas
- Competition between direct reaction picture (scatter on a nucleon or pair) and a compound reaction picture (collective excitations) of the cross section
  - Low-energy nucleon scattering calculations may serve as a useful guide

Do we really care about the low-energy de-excitations?

- We've been able to safely ignore them for a long time, but experiments are pushing toward ever-greater sensitivity
  - De-excitation gammas in Super-K, ArgoNeuT
  - Neutron yields in Super-K, MINERvA, ANNIE
- Neutron tagging in water-based detectors relies on capture gamma cascade
  - Low-energy "boil-off" neutrons and higher-energy "knock-out" neutrons look the same
  - To interpret such measurements, having a model that accounts for both will be valuable

Neutron yield & multiplicity in ν interactions at SK-IV



TAUP2011, 5th ~9th Sept.'11, Munich