NUCLEAR EFFECTS IN NEUTRINO STUDIES

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June 28, 2017, Trento

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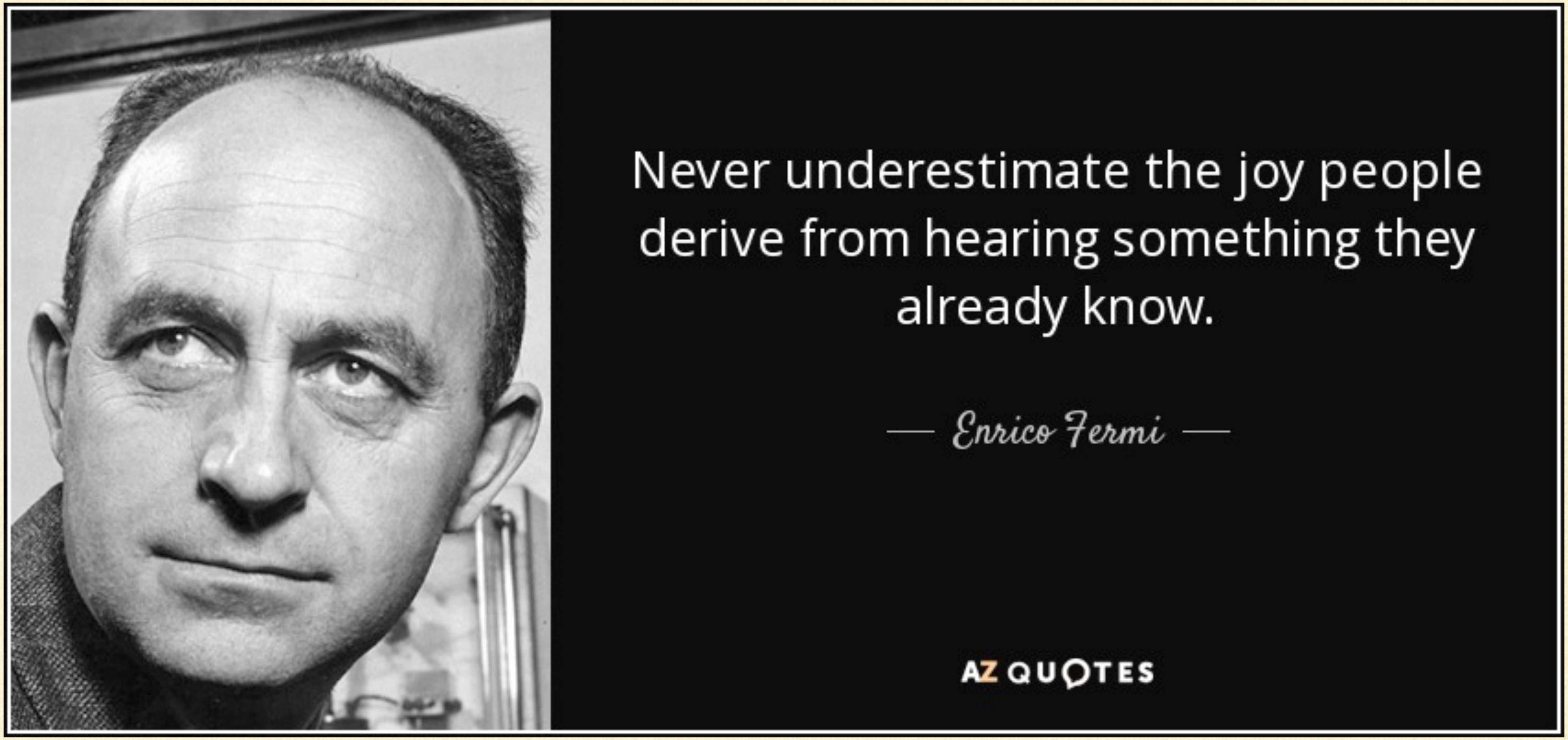

Never underestimate the joy people derive from hearing something they already know.
— Enrico Fermi —
AZ QUOTES


REPETITIO
EST
MATER
STUDIORUM

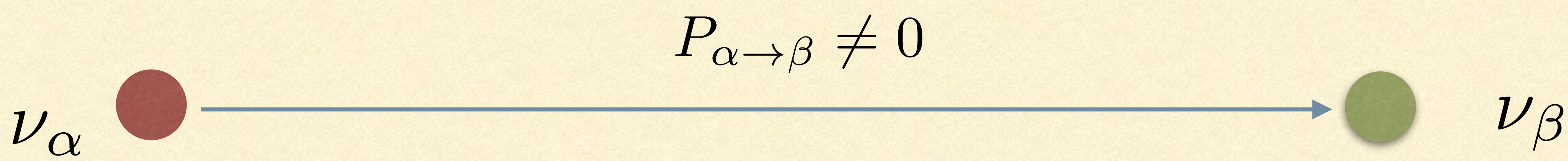
OUTLINE

- Motivation: neutrino physics
- Neutrino oscillation experiments: why nuclear physics is important
- Lepton-nucleus scattering: quasielastic mechanism
  - Fermi Gas model
  - Additional nuclear effects

  → Comparison
- Conclusions

NEUTRINO OSCILLATIONS

- Neutrinos change their "identity" because mass eigenstates are not flavour eigenstates



$\alpha, \beta = e, \mu, \tau$

$i = \text{mass eigenstates}$

$$|\nu_i\rangle = \sum_\alpha U_{i,\alpha} |\nu_\alpha\rangle$$

different basis

$$|\nu_i(t)\rangle = e^{-i(Et - \vec{p}\vec{x})} |\nu_i(0)\rangle$$

mass eigenstates propagate

NEUTRINO OSCILLATIONS

$$P_{\alpha\to\beta} = |\langle\nu_\alpha(t)|\nu_\beta\rangle|^2 = \left|\sum U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

- PMNS matrix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- There are 6 parameters in the SM which influence oscillations.
- Various oscillation experiments are sensitive to different parameters (we can play with L and E)

EXPERIMENTS

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[eV^2][km]}{[GeV]}\right)$$

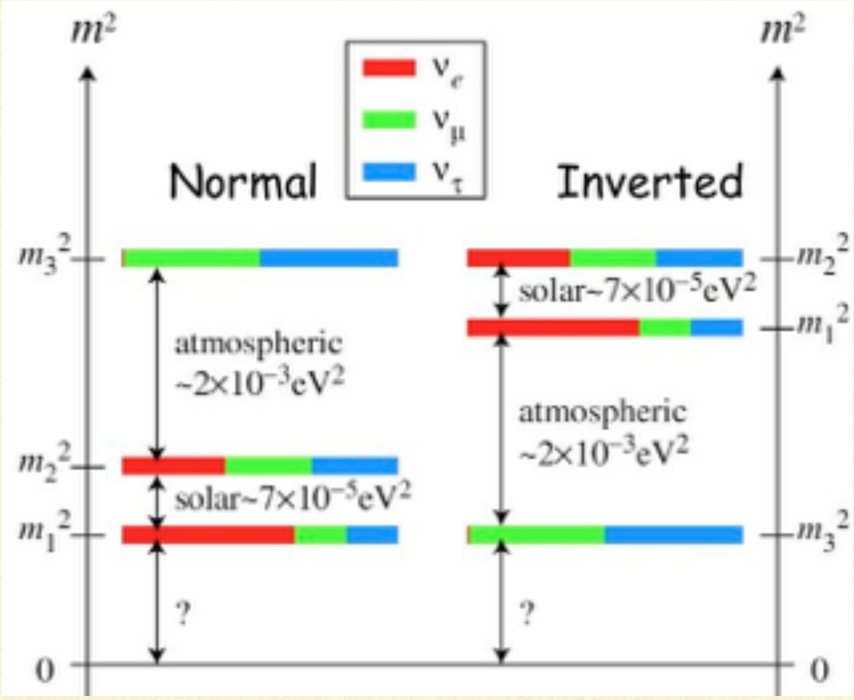
given by the experimental setup

At the experiment one has to:

- distinguish events that are triggered by different neutrino types
- be able to make energy reconstruction to get E (neutrino beams are not monoenergetic!)

NEUTRINO PHYSICS - OPEN QUESTIONS

- STANDARD MODEL
  - $\sin^2(2\theta_{13}) = 0.093 \pm 0.008$
    $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$
    $\sin^2(2\theta_{23}) > 0.92$
  - CP violation phase - still big uncertainty



- BEYOND STANDARD MODEL
  - sterile neutrinos?
  - more flavours?

Which model is correct?

Further question: are neutrino Majorana particles?
But this cannot be answered by neutrino oscillation experiments.

EXPERIMENT - THEORY

EXPERIMENT

THEORY

- neutrino flux (blured)
- detector (target): carbon, oxygen, argon, iron, etc.

Monte Carlo event generator

Good knowledge of of neutrino-nucleus cross-section is needed!

- SM parameters

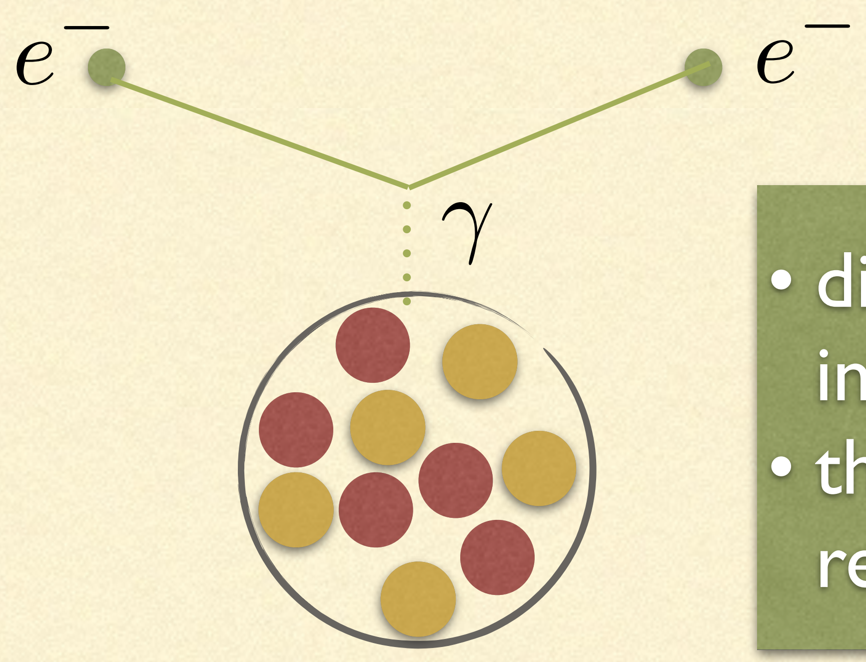
or

- BSM theories

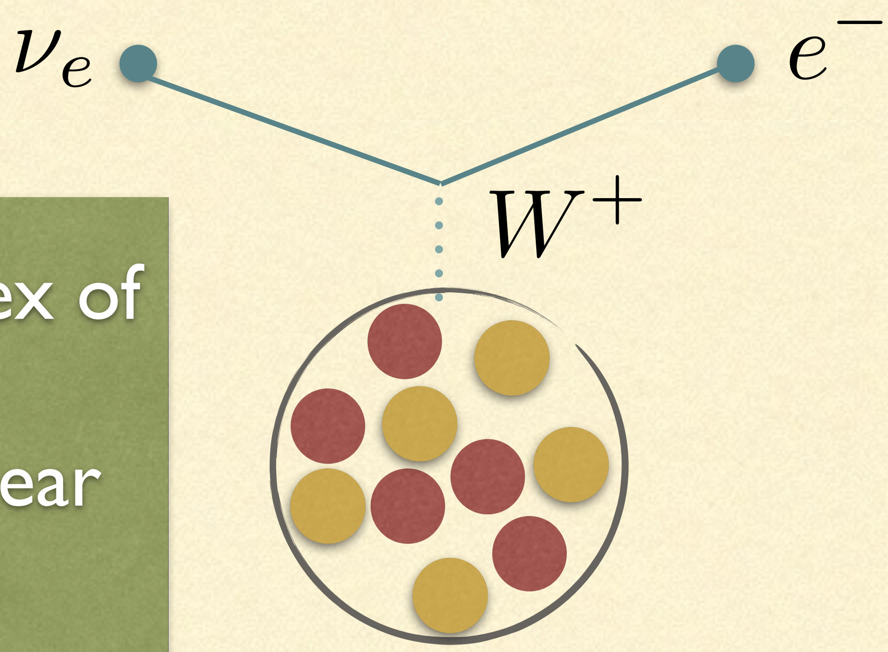
NEUTRINO-NUCLEUS CROSS SECTION

We need a precise model to calculate cross-section for neutrino scattering of various nuclei (carbon, oxygen, argon…)

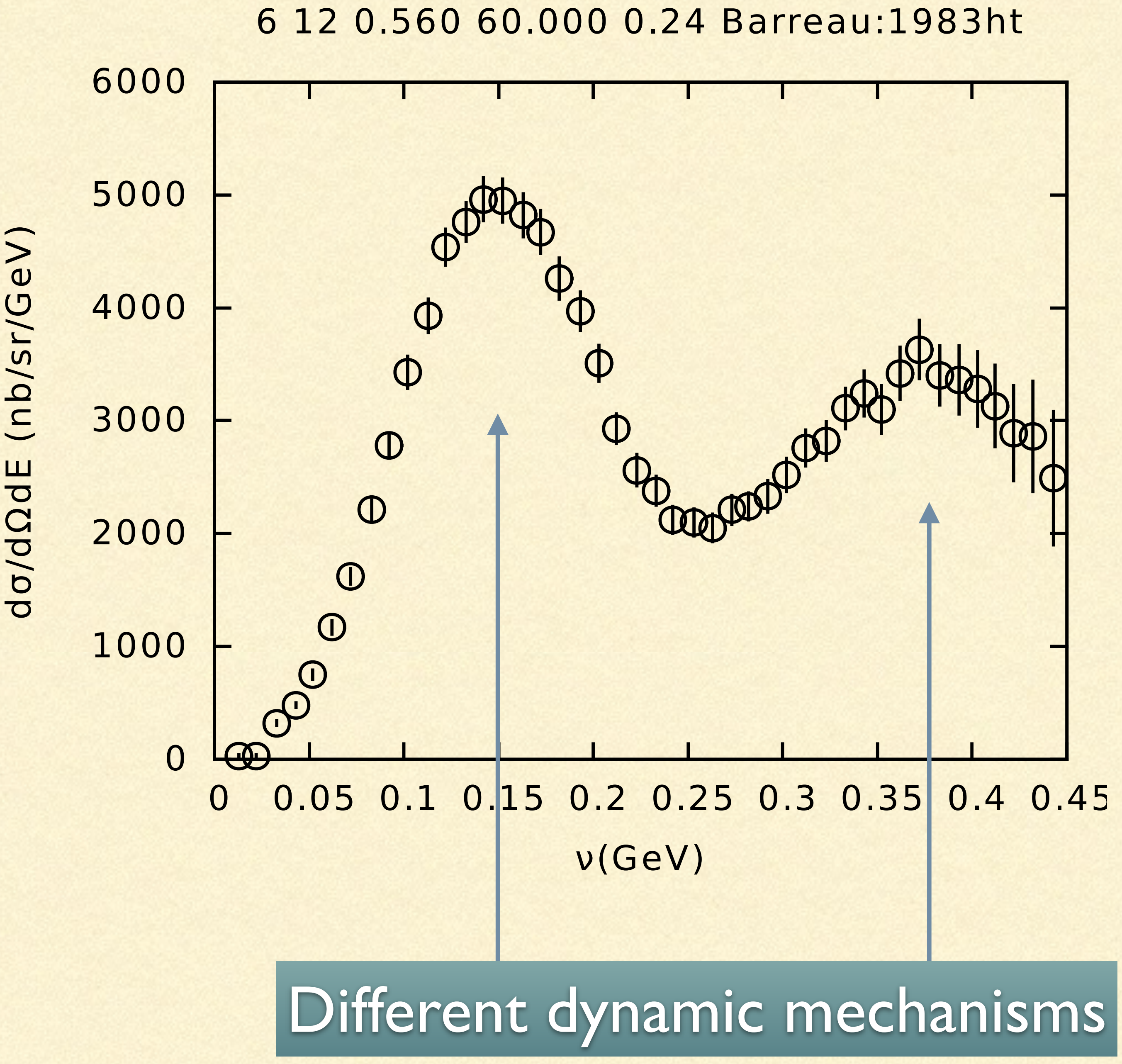
We can check the models for electron scattering instead of neutrino scattering (much more data!)



- different vertex of interaction
- the same nuclear response



INCLUSIVE CROSS SECTION

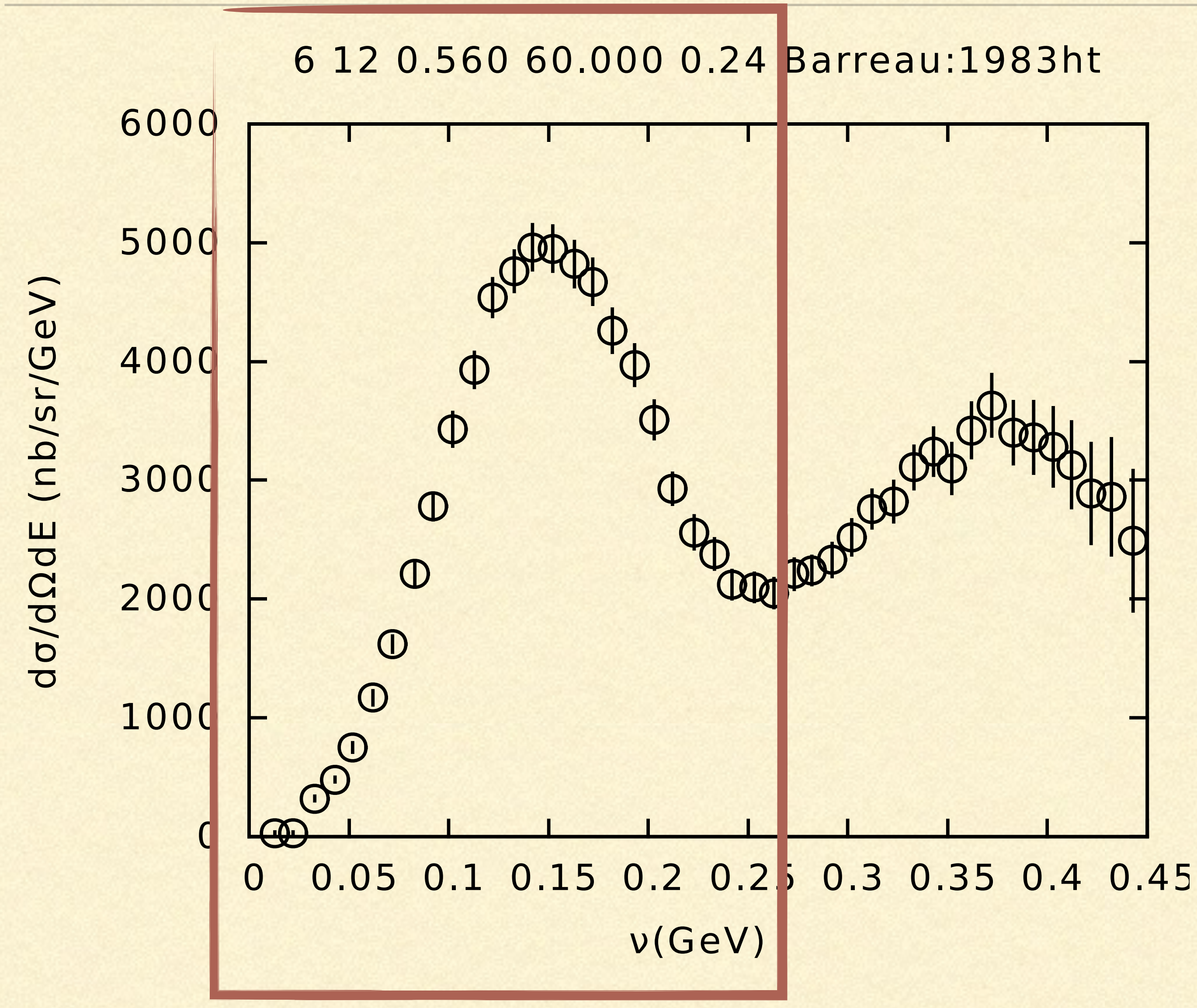


We have precise data for the electron scattering

$$e +^{12} C \to e + X$$

E=560 MeV, θ=60°

CROSS SECTION



QUASIELASTIC MECHANISM

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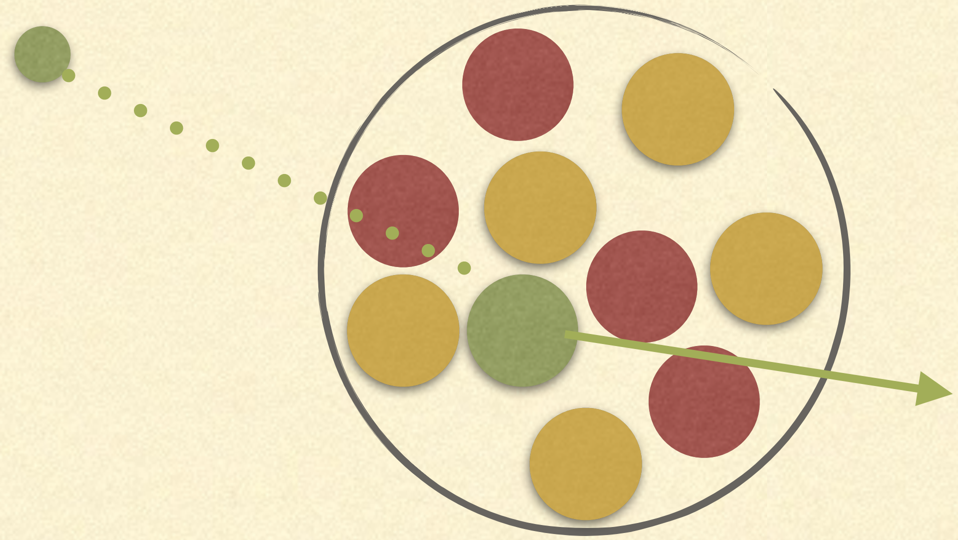
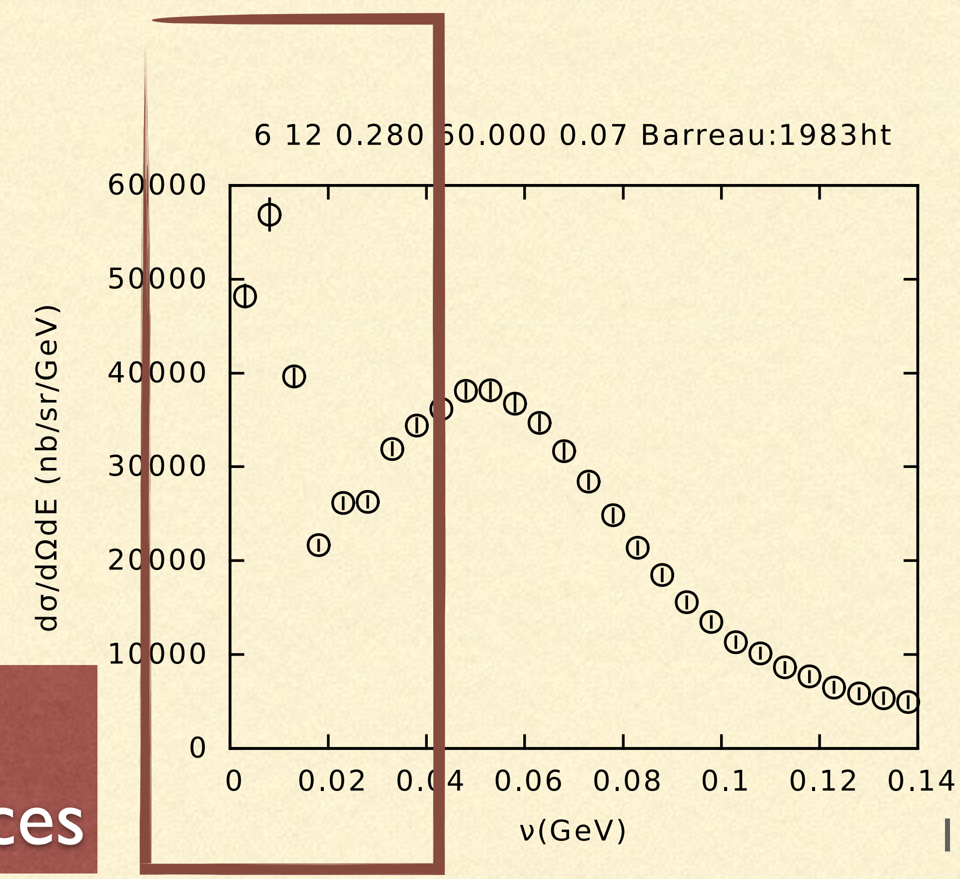


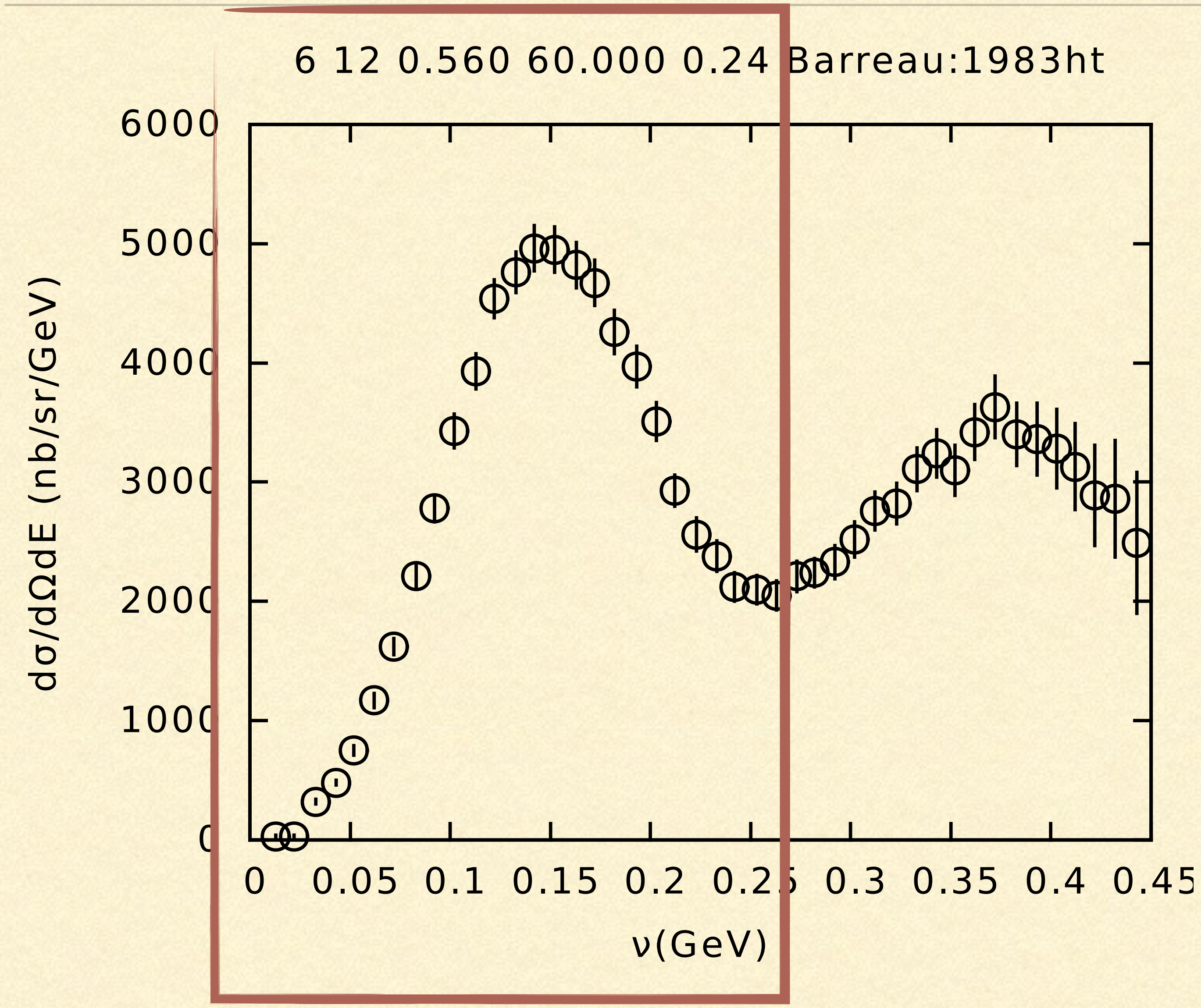
Impulse Approximation:
only one interacting nucleon

It is correct
if momentum transfer
~ inter-nucleons distance
in nuclei
1 fm = 200 MeV/c



giant resonances

QE PEAK'S POSITION



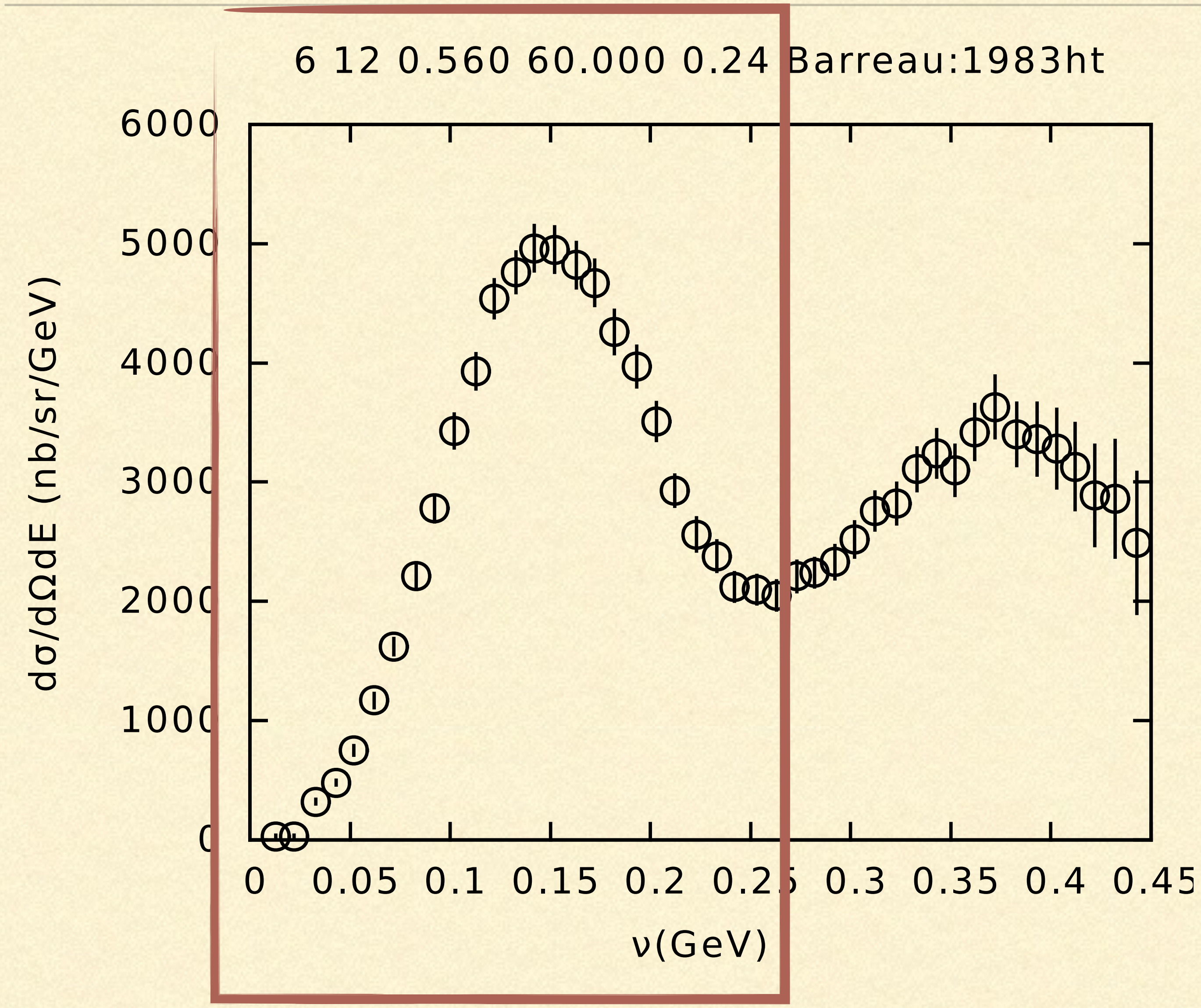
QUASIELASTIC MECHANISM

Suppose the elementary process is eN → eN.

Energy-momentum conservation

$$\nu = \frac{4E^2 \sin^2 \frac{\theta}{2}}{2M + 4E \sin^2 \frac{\theta}{2}} \Rightarrow \nu = 129\mathrm{MeV}$$

QE PEAK'S POSITION



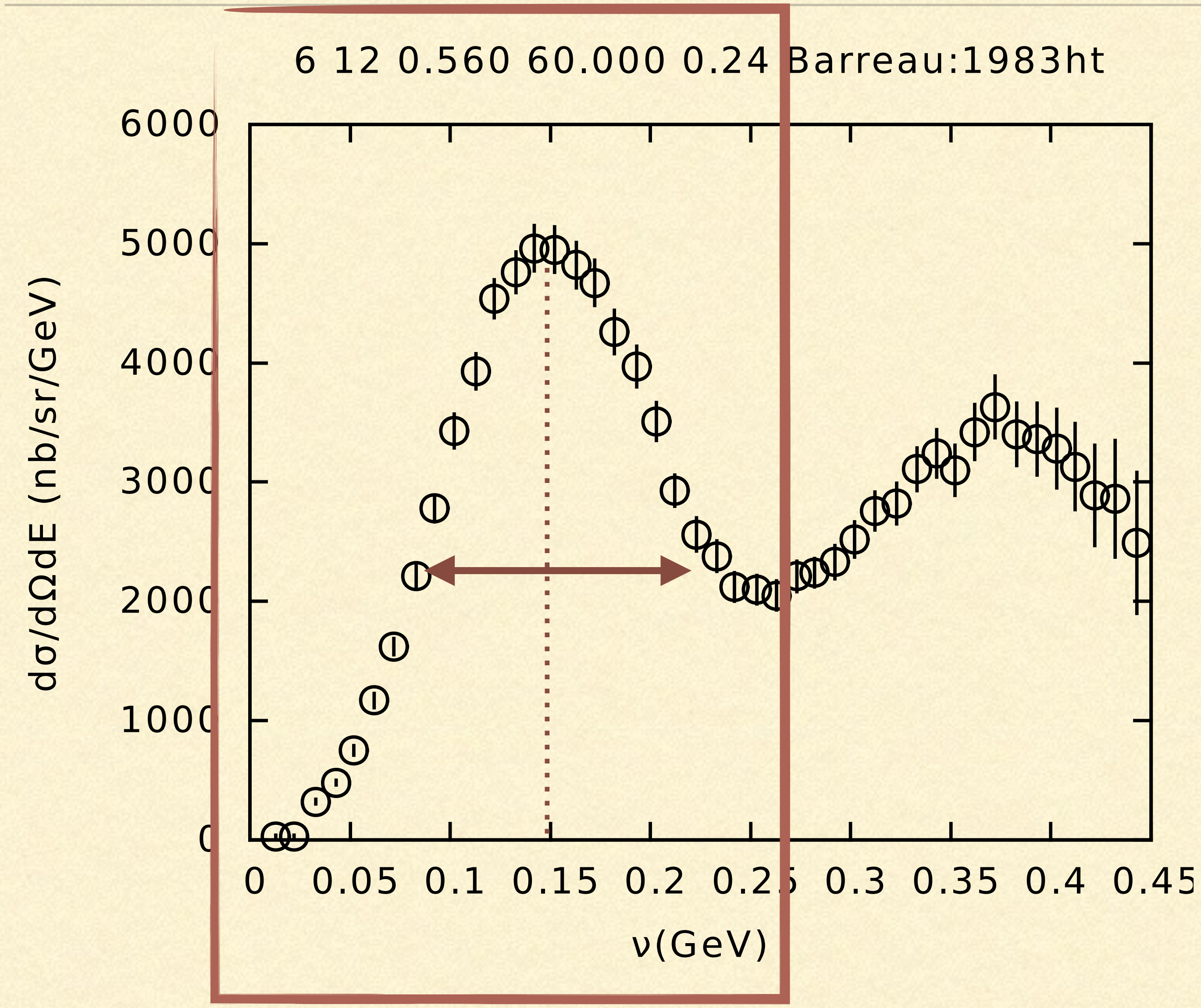
Suppose the elementary process is eN → eN.

Energy-momentum conservation

$$\nu = \frac{4E^2 \sin^2 \frac{\theta}{2} + 2MB - B^2}{2M - 2B + 4E \sin^2 \frac{\theta}{2}}, \quad B = 25\mathrm{MeV} \to \nu = 150\mathrm{MeV}$$

binding energy

QE PEAK'S WIDTH



- Peak's width arises due to Fermi motion
- Peak's width tells us about the Fermi momentum

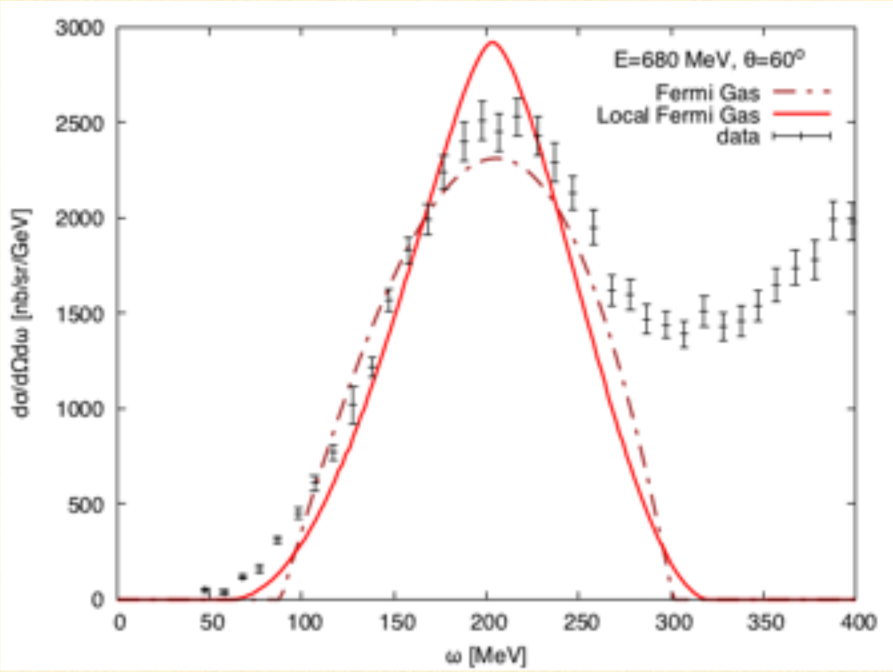
FERMI GAS

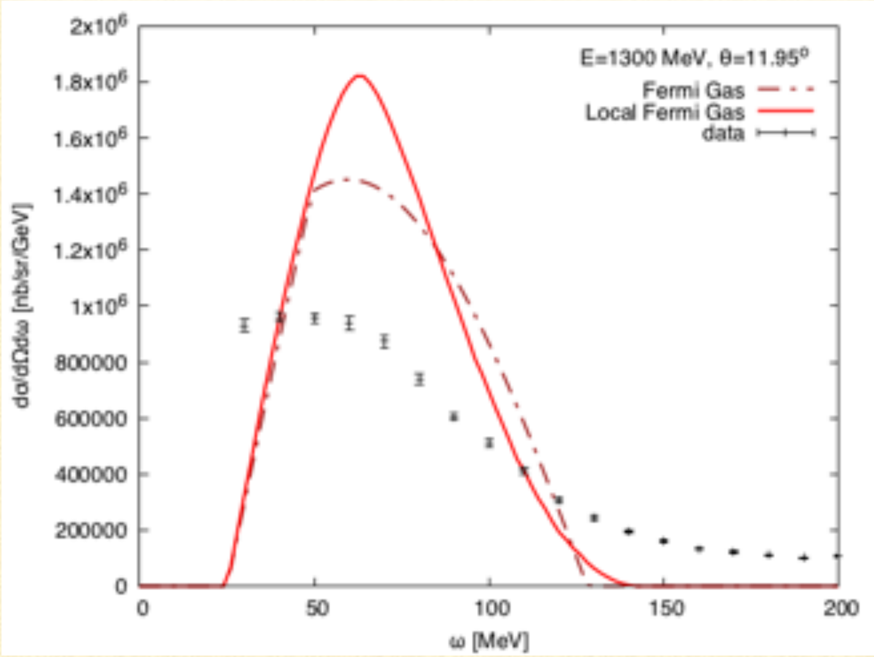
- The most basic approach:
  statistical correlations + constant binding energy

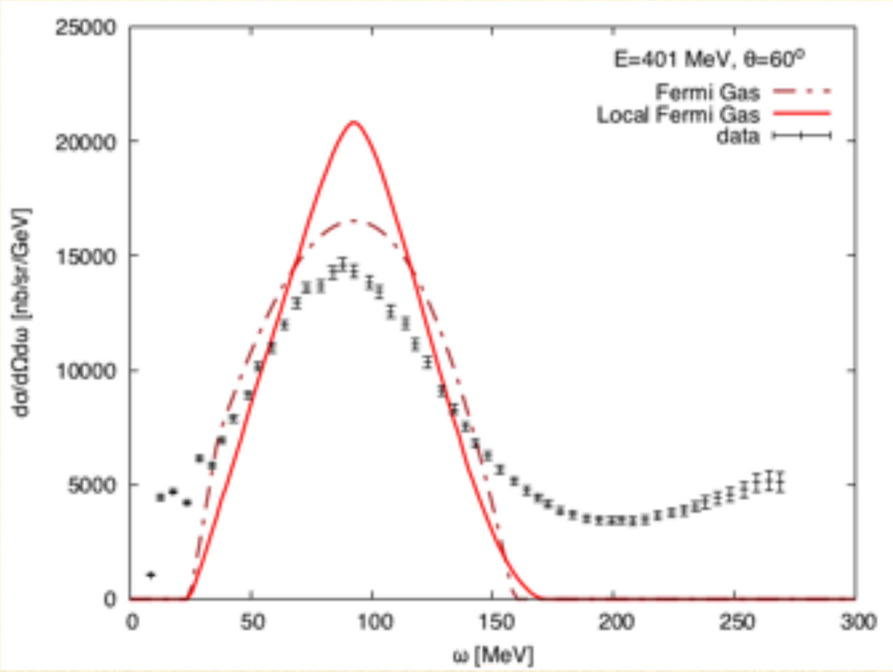
$$\mathcal{H} = \sum_{i \in \text{nucleons}} \frac{p_i^2}{2M}$$

- We know with a very good precision how describe the interaction $e^- + N \to e^- + N$
- For neutrinos there is a room for improvement (axial form-factor)

FERMI GAS







Clearly, it is not possible
to find a good parametrisation
(binding energy and Fermi
momentum)
in terms of (L)FG

TURN-ON INTERACTION

- We need to employ a more sophisticated model for nucleons in the nuclei.

non-relativistic propagator:

$$\mathcal{G}(E,p,\rho) = \frac{1}{E - \frac{p^2}{2M} - \Sigma(E,p,\rho)}$$

we include the SELF-ENERGY which is complex

ImΣ(E,p) - particle width

SPECTRAL FUNCTION

This is described by means of a spectral function:

$$E < \mu \qquad S_h(E,p) = \frac{1}{\pi}\mathrm{Im}G(E,p)$$

$$E > \mu \qquad S_p(E,p) = -\frac{1}{\pi}\mathrm{Im}G(E,p)$$

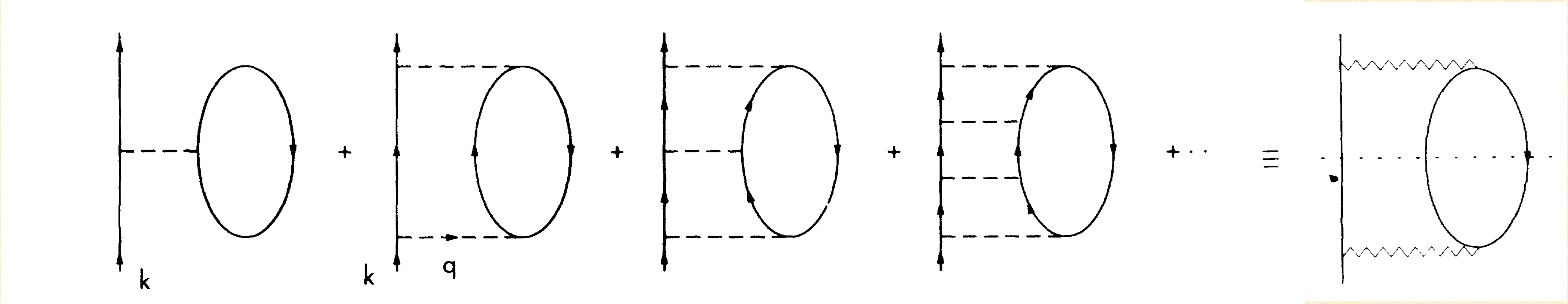
$$S_{h/p}(E,p) = \pm\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(E,p)}{[E - p^2/2M - \mathrm{Re}\Sigma(E,p)]^2 + [\mathrm{Im}\Sigma(E,p)]^2}$$

It can be shown that hole spectral function is the probability density for removing a particle with momentum k, with the removal energy E from the ground state.

E. OSET AND F. DE CORDOBA SEMIPHENOMENOLOGICAL MODEL

- A simple, semi-phenomenological approach to calculate nucleon self-energy in nuclear matter
- We calculate the SF for the infinite nuclear matter at constant density. Then we use LDA (local density approximation), meaning we integrate SF with a density profile function to model the nucleus.
- The calculation is non-relativistic which is OK for the hole SF but might be poor for the particle SF.

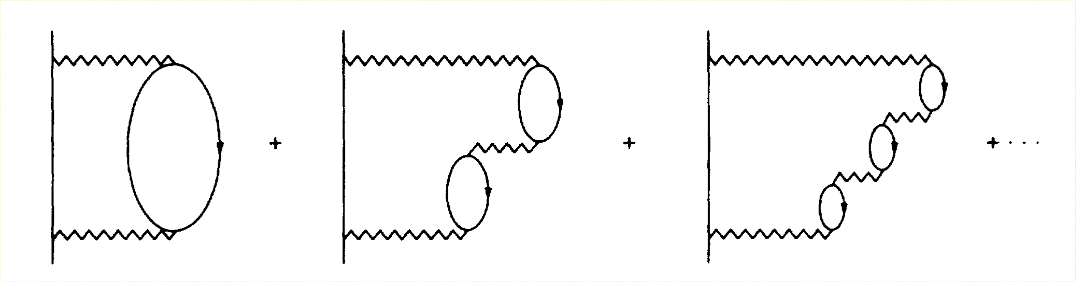
E. OSET AND F. DE CORDOBA SEMIPHENOMENOLOGICAL MODEL



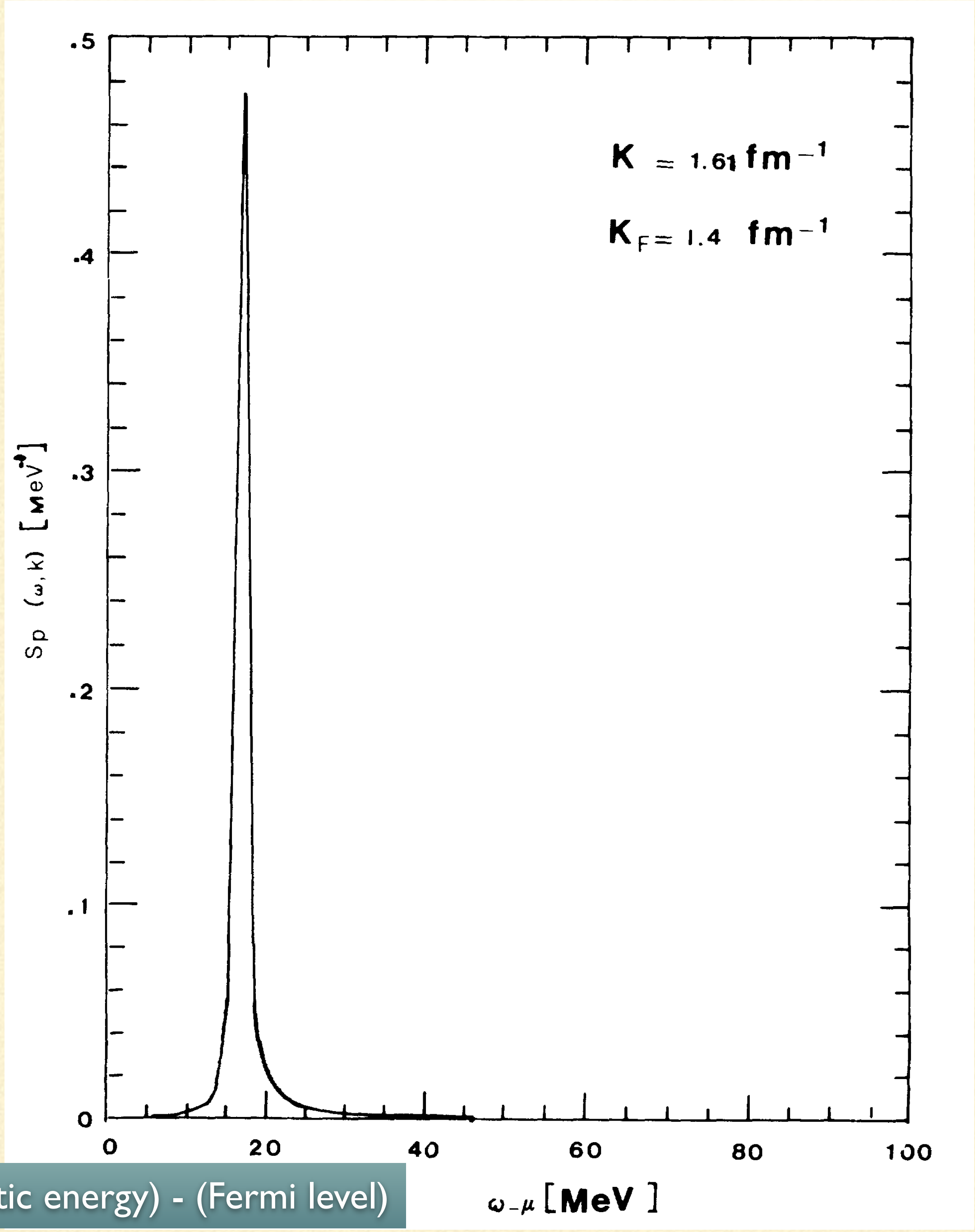
(F. de Cordoba, E. Oset, PRC 46, 5)

- calculate the nucleon self-energy by summing Lippmann-Schwinger series
- approximate t matrix with the free NN scattering matrix (average over angles -> use NN cross section)
- the density modifications will come

  from medium polarization



SPECTRAL FUNCTION



(kinetic energy) - (Fermi level)

Particle spectral function at a density such that Fermi momentum k_F=1.4 fm^{-1}=280 MeV

For a particle of momentum k=1.61 fm^{-1}=320 MeV the largest probability is for kinetic energy ~17 MeV higher then the Fermi level

(F. de Cordoba, E. Oset, PRC 46, 5)

SPECTRAL FUNCTIONS IN THE CROSS-SECTION

$$\frac{d\sigma}{d\omega d\Omega} = \int \frac{d^3p}{(2\pi)^3} \int dE\, S_h(E,\vec{p}) S_p(w - E, \vec{p}+\vec{q}) L_{\mu\nu} W^{\mu\nu}$$

nucleon's momentum

removal energy

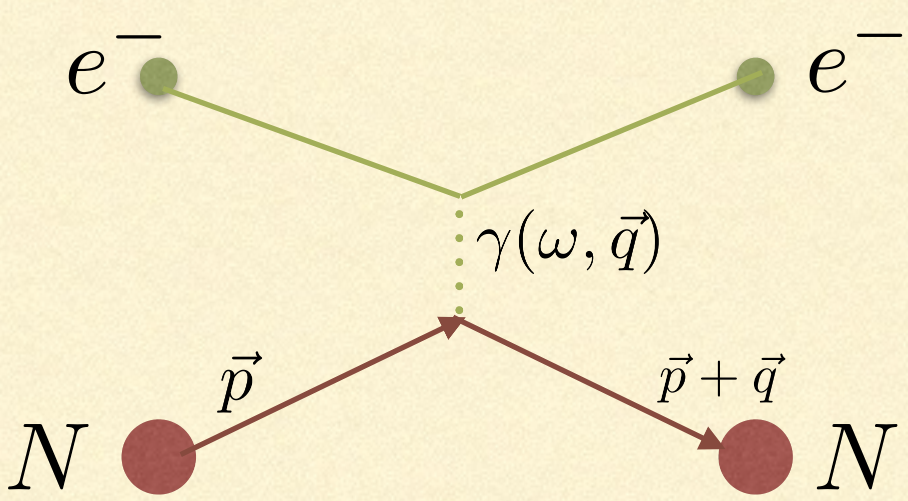
energy transfer

scattering angle

lepton tensor

hadron tensor

For large energy-momentum transfer this nucleon becomes relativistic…



SPECTRAL FUNCTIONS IN THE CROSS-SECTION

$$\frac{d\sigma}{d\omega d\Omega} = \int \frac{d^3p}{(2\pi)^3} \int dE S_h(E, \vec{p}) S_p(w - E, \vec{p} + \vec{q}) L_{\mu\nu} W^{\mu\nu}$$

This is difficult to calculate numerically so some approximations can be done, e.g.

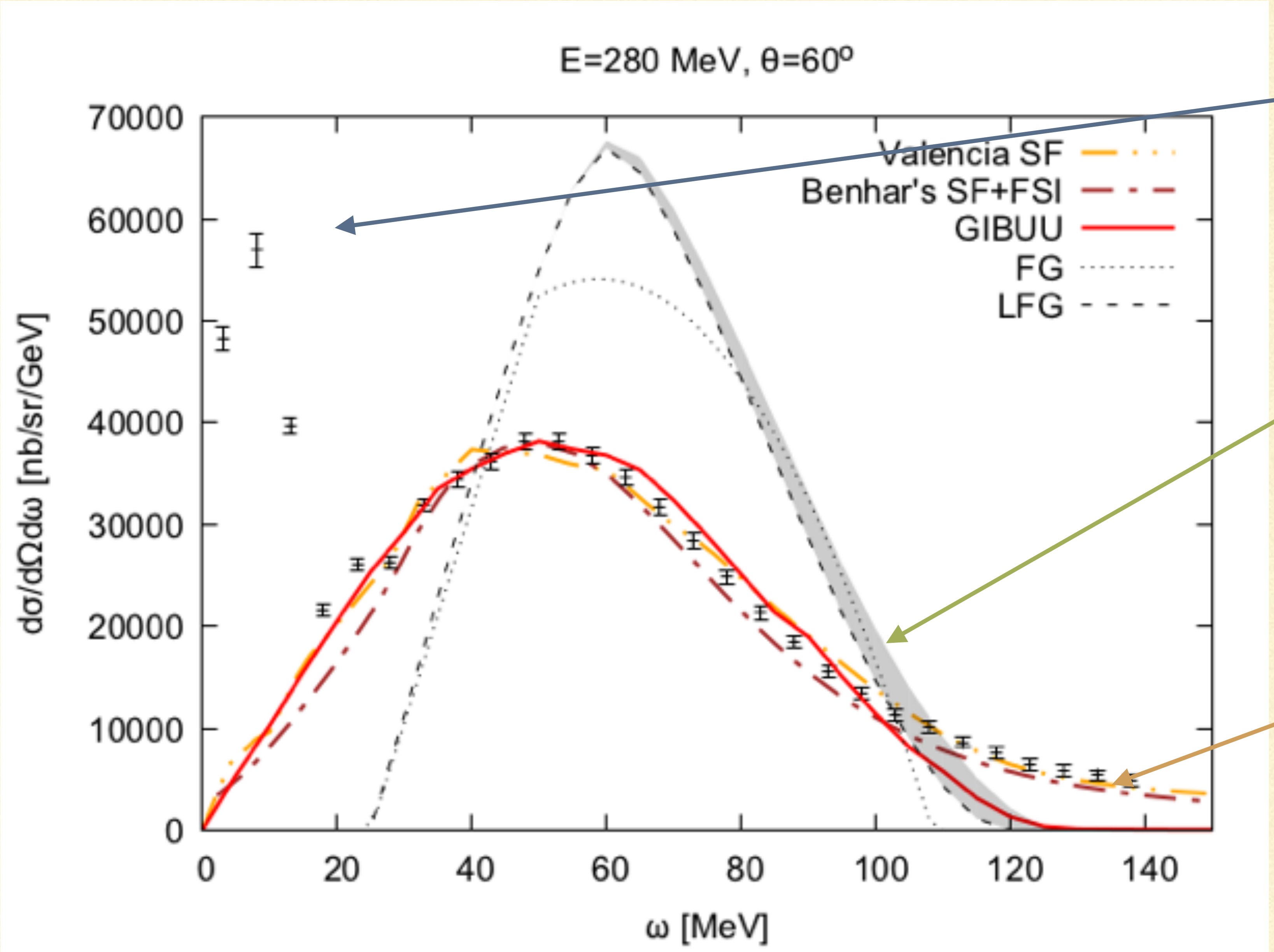
$$S_{h/p}(E, p) = \pm \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(E, p)}{[E - p^2/2M - \mathrm{Re}\Sigma(E, p)]^2 + [\mathrm{Im}\Sigma(E, p)]^2}$$

neglect the width: $\mathrm{Im}\Sigma(E, p) \to 0$

$$S_h \propto \delta(E - \bar{E}(p))\theta(\mu - E)$$

$$\bar{E}(p) = \frac{p^2}{2M} - \mathrm{Re}\Sigma(\bar{E}(p), p)$$

RESULTS



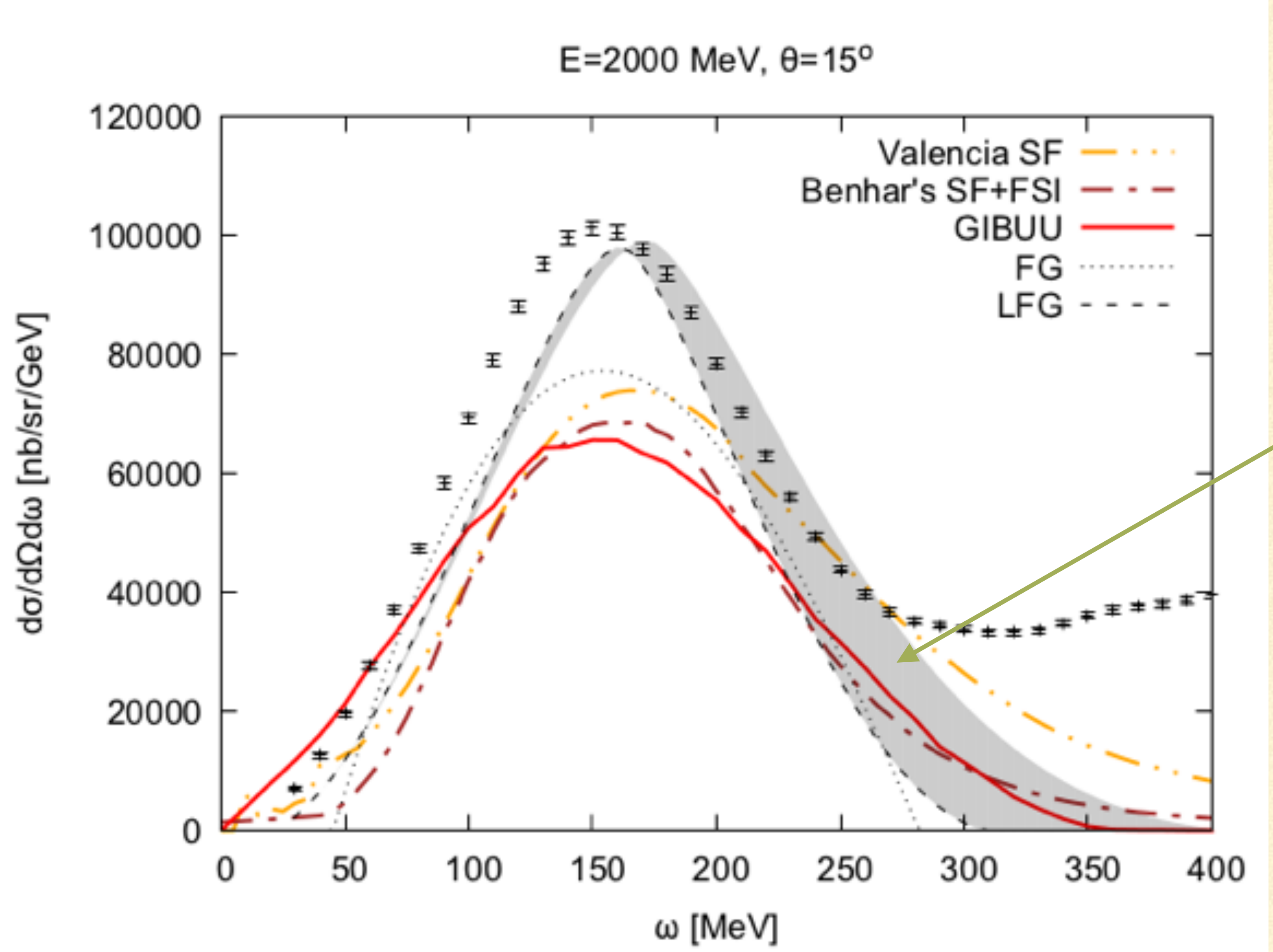
giant resonances not reproduced

relativistic effects are small

the long tail comes from imaginary part of spectral functions

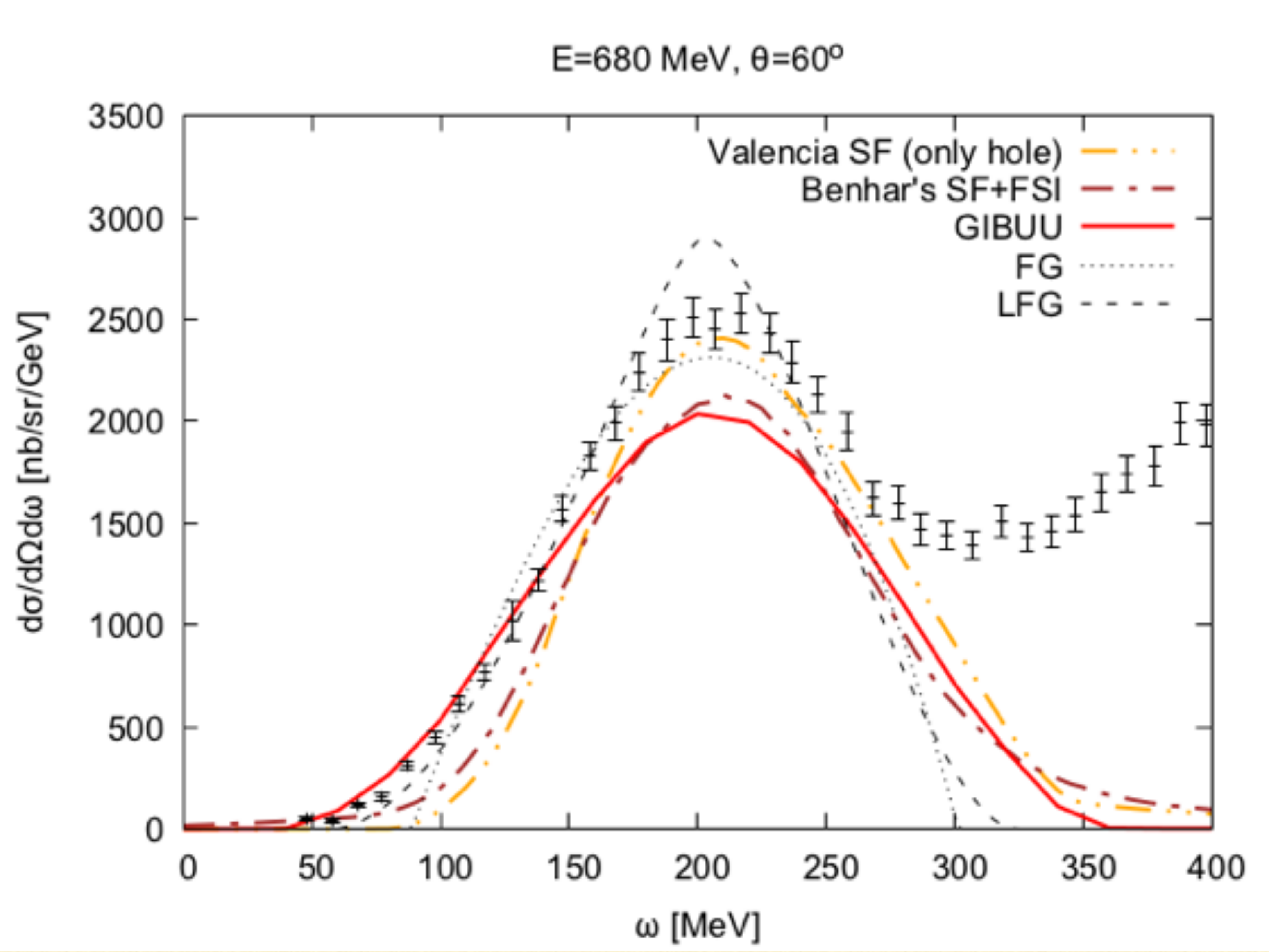
(J.E.S. arXiv: 1706.06739)

RESULTS



relativistic effects are huge

RESULTS



(**J.E.S**. arXiv: 1706.06739)

giant resonances not visible (large momentum transfer)

relativistic effects are huge

other mechanism overlap with the QE peak:
2p2h + delta prod.

IDEAS TO TAKE HOME

- We need a precise knowledge of neutrino-nucleus interaction. Nuclear effects are crucial for the analysis of neutrino experimental data

- First we should see how the models work for electron scattering.

- One has to account for different mechanisms: quasielastic, 2p2h, delta excitation…

- The fact that we are dealing with high energy transfer is a challenge

THANK YOU!