Comparison of lepton-nucleus scattering models in the QE region

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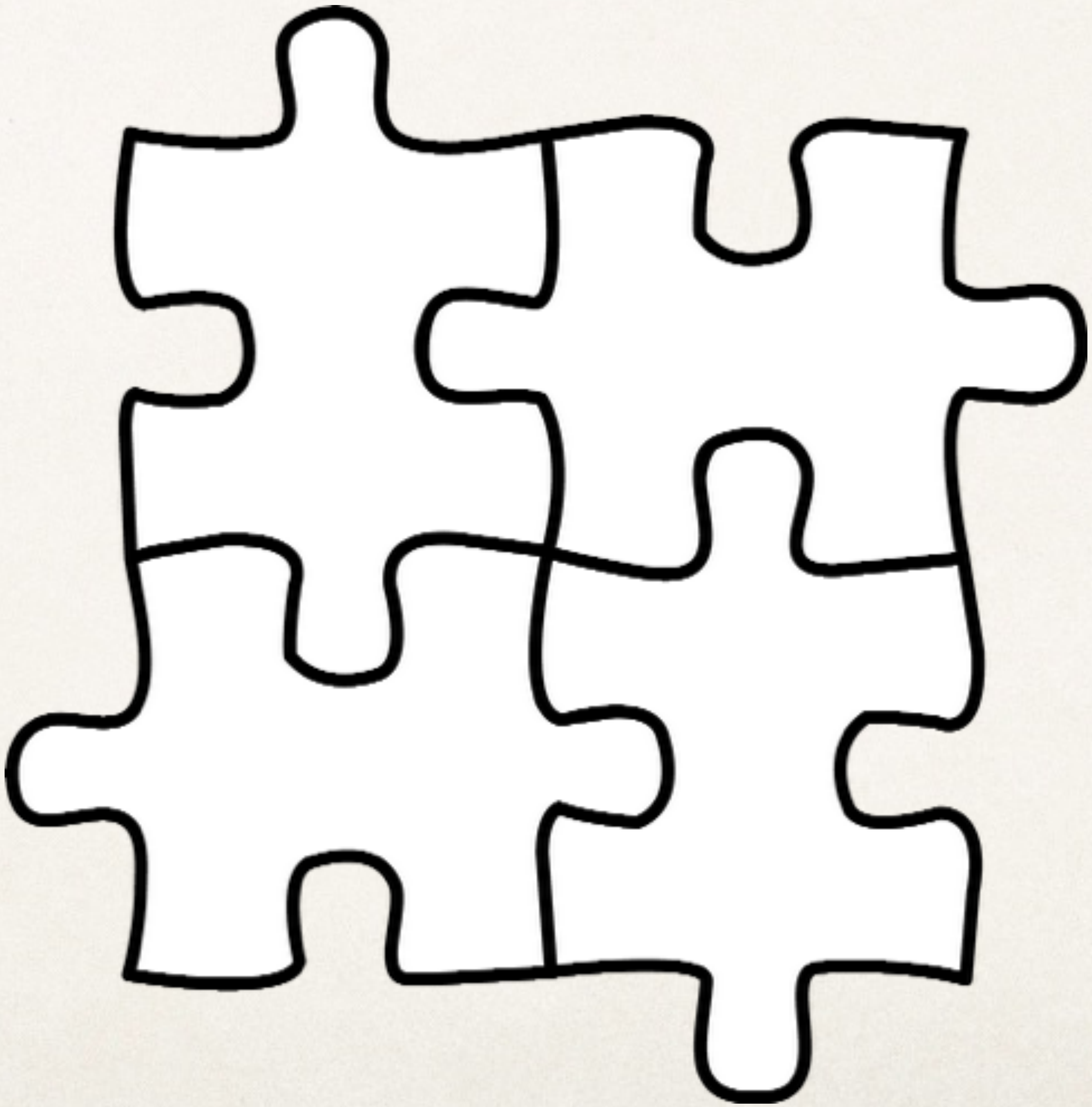
Motivation

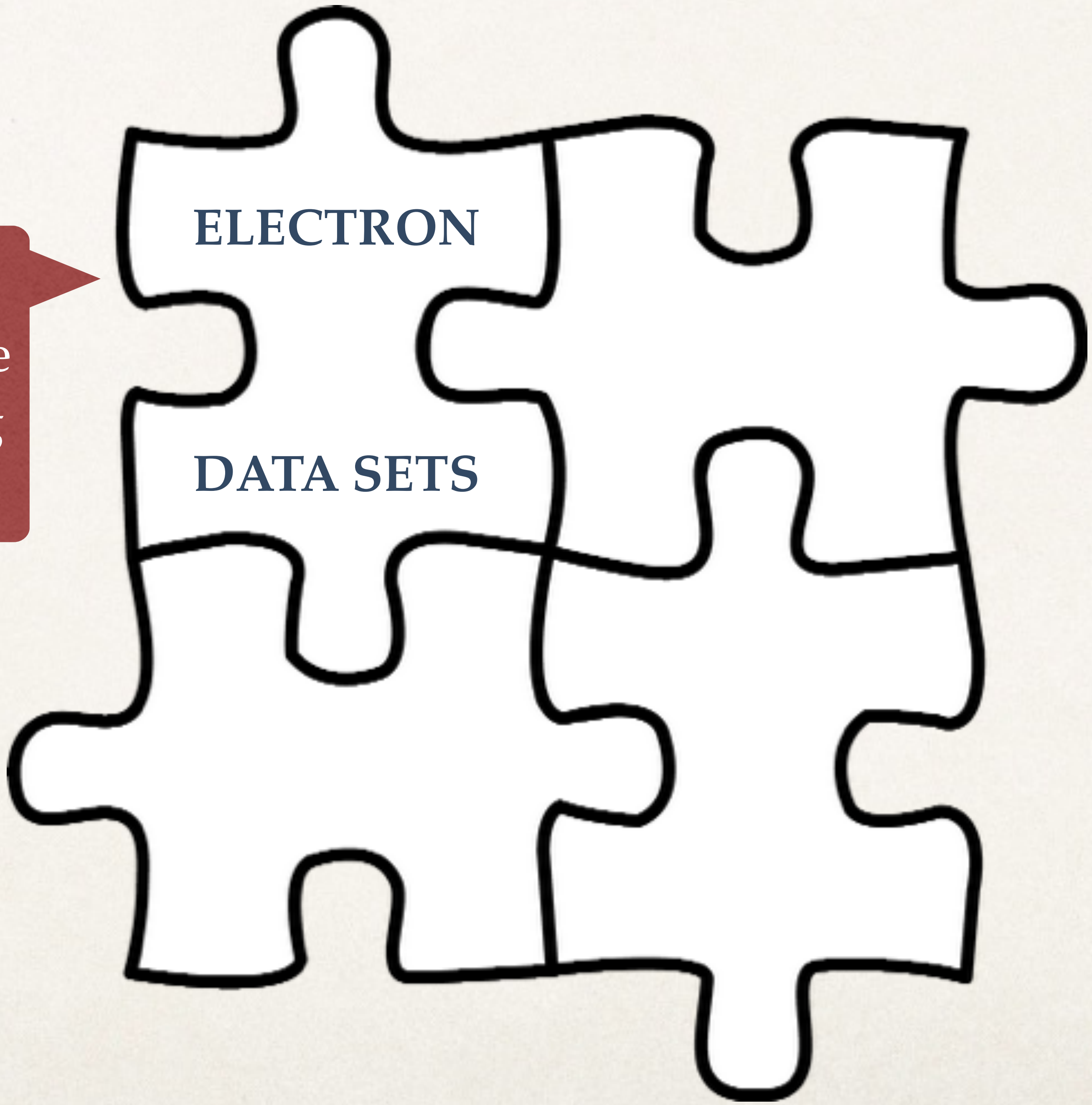
- What is a theoretical uncertainty of the neutrino-nucleus interaction models used in the neutrino studies?
- To what extent can we rely on models that are available now?
- A way to compare neutrino-nucleus scattering models: see how they work for electron-nucleus scattering.
- Let us consider the quasi-elastic mechanism, and the energy region explored in the T2K experiment.

Outline



Outline

with what we can compare (inclusive electron scattering data)



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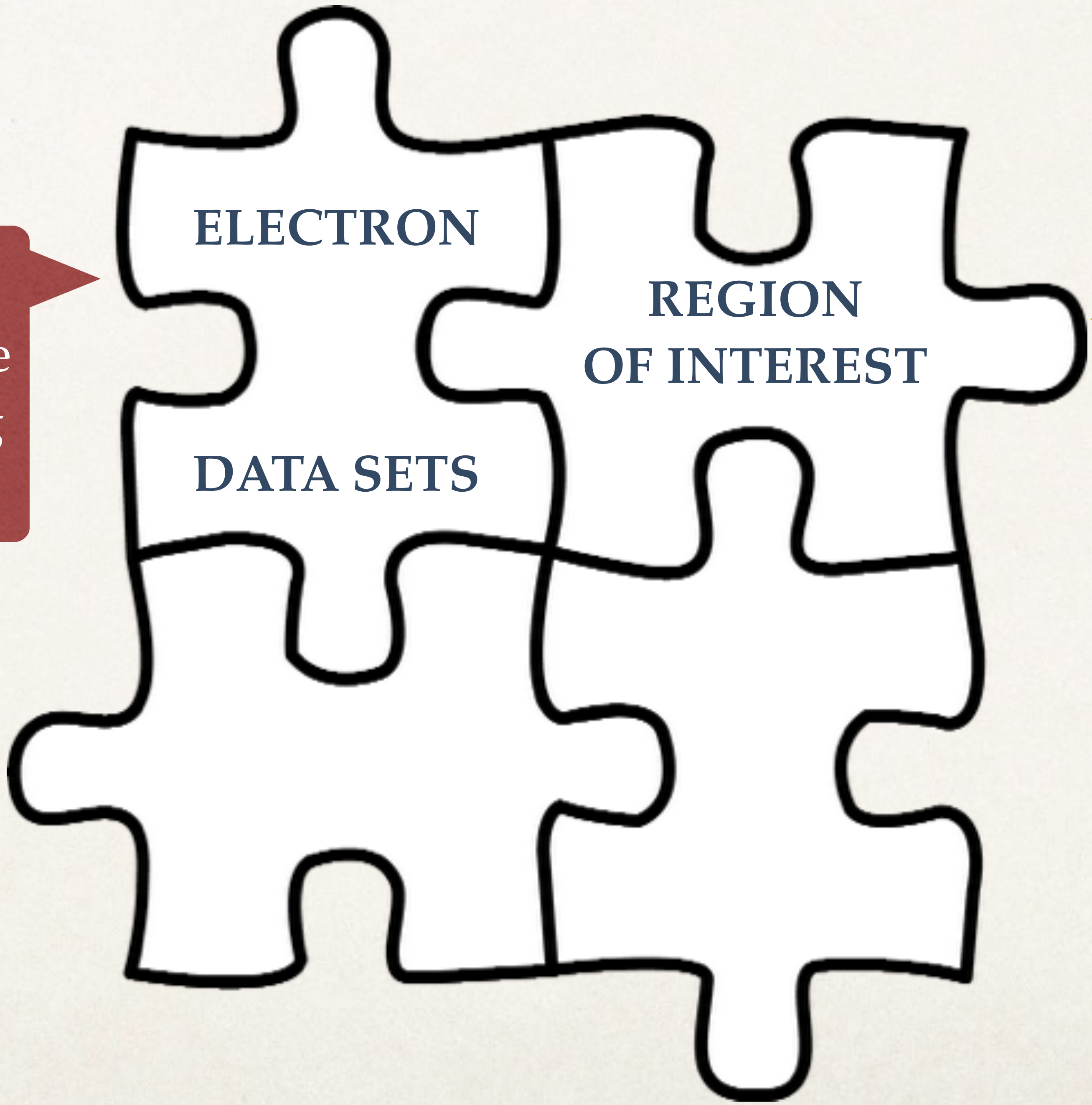
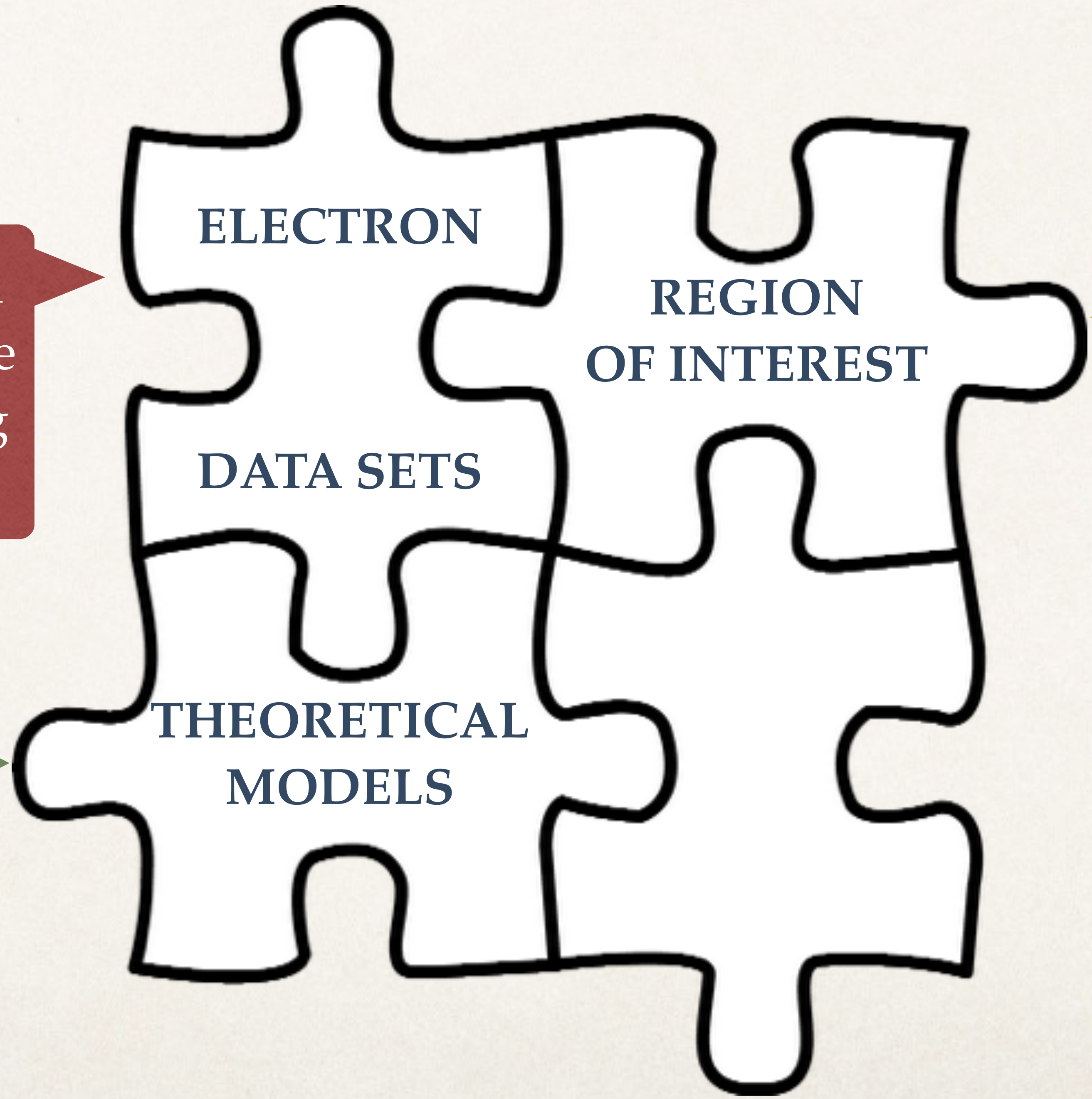


for which energy-momentum transfer QE mechanism is important for the T2K

Outline

with what we can compare (inclusive electron scattering data)



for which energy-momentum transfer QE mechanism is important for the T2K

Fermi gas
Benhar's SF+FSI
GiBUU
Valencia SF
(ONLY FOR THE QE MECHANISM)

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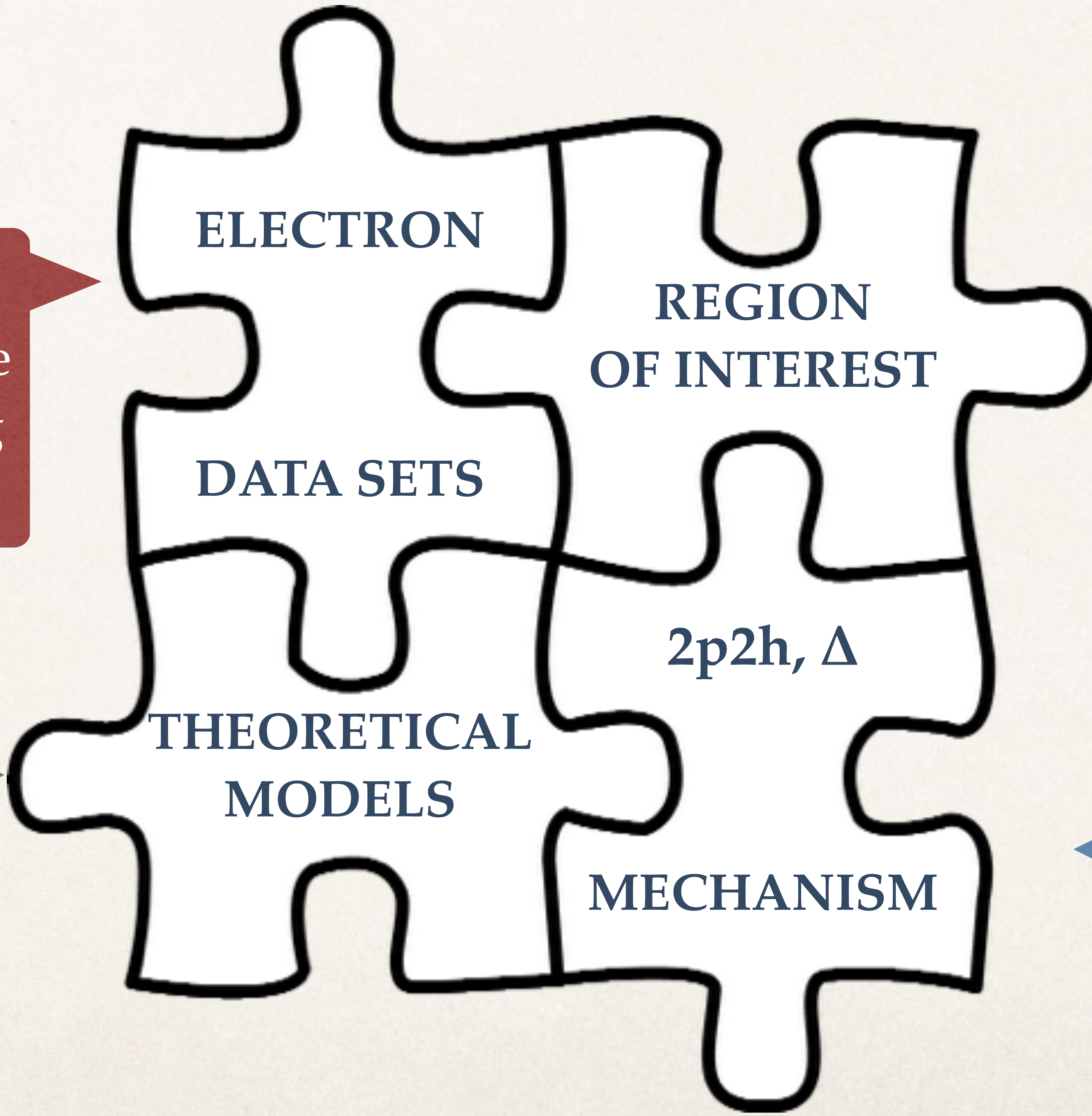


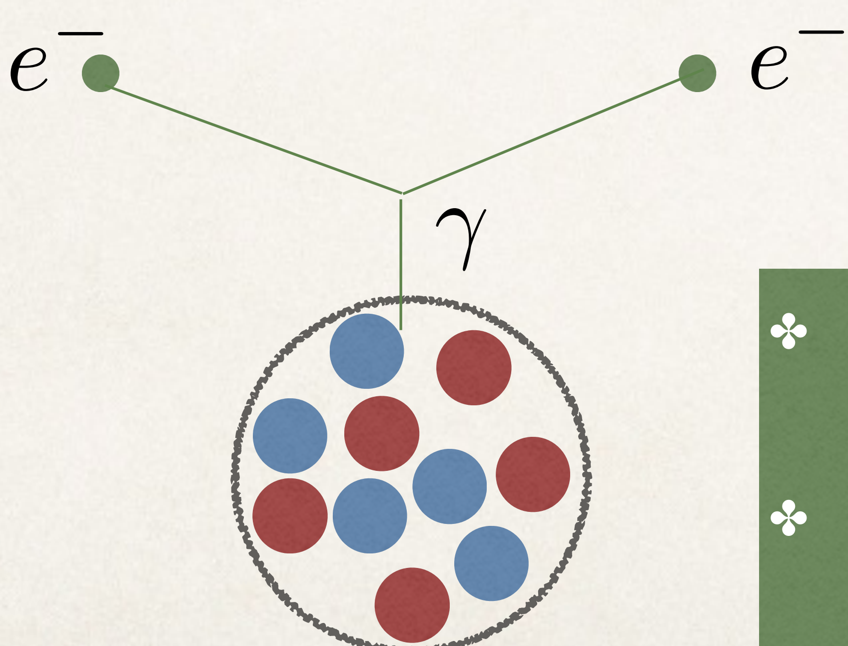
for which energy-momentum transfer QE mechanism is important for the T2K

what is the influence of other mechanisms in the QE region

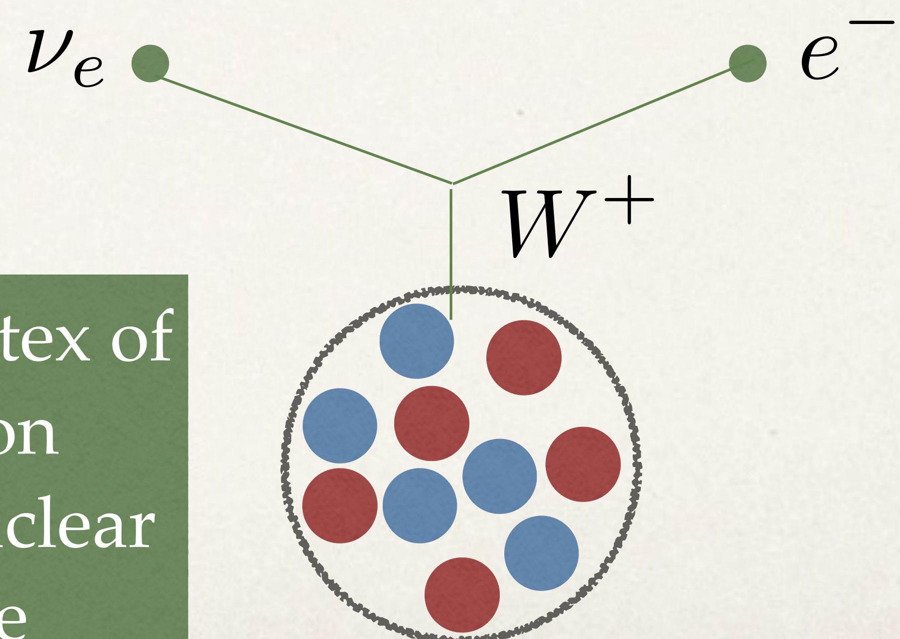
Basic idea

- The general idea: energy-momentum transfer is the input for the **density response of the nuclear system**. And it is **the same** for electron or neutrino scattering (only vertex of interaction is different - there are more structure functions for neutrinos).
- We will therefore analyse $\frac{d\sigma}{dq d\omega}$

q - momentum transfer
ω - energy transfer



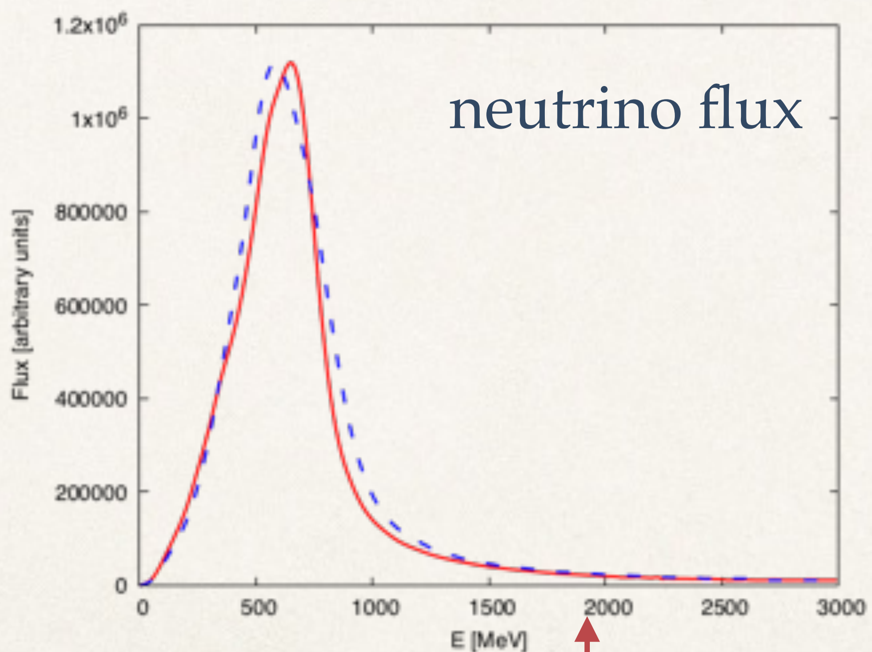
- different vertex of interaction
- the same nuclear response

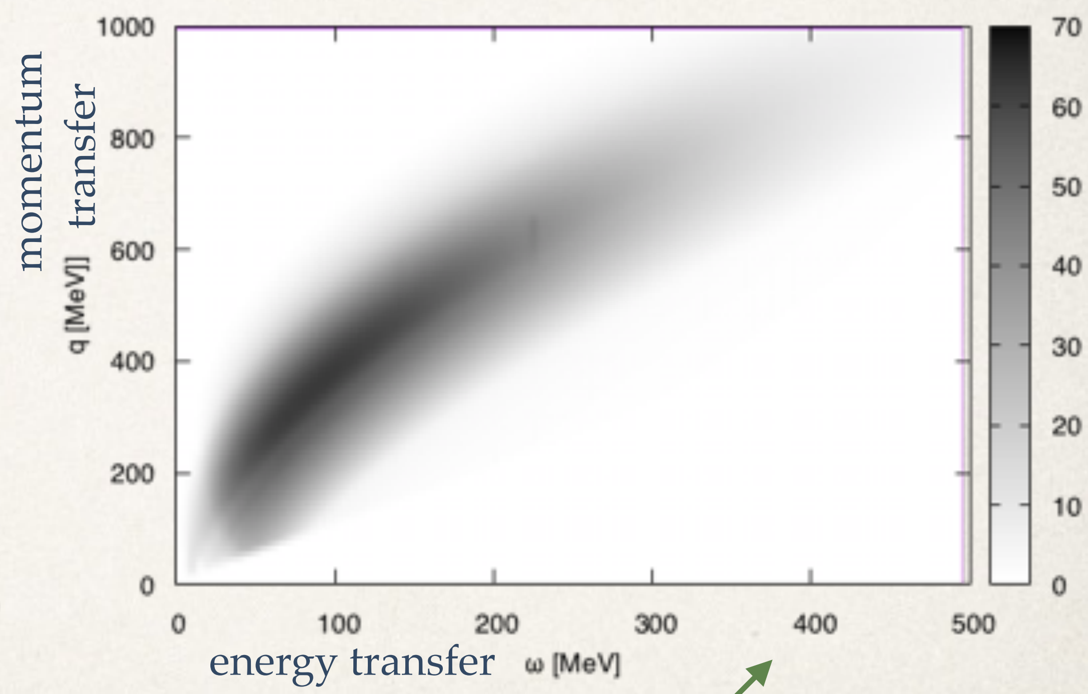


Region of interest for T2K

- There is a lot of data sets for inclusive electron-carbon scattering. Which ones are important from the point of view of the T2K experiment? Let's simulate it…

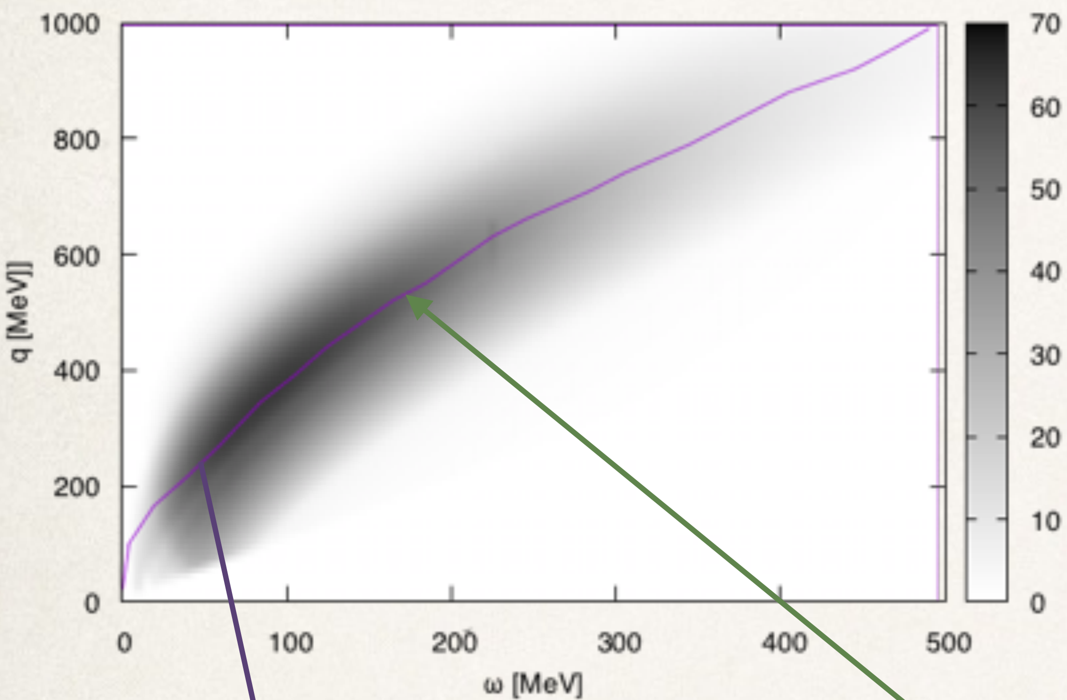
Valencia model prediction

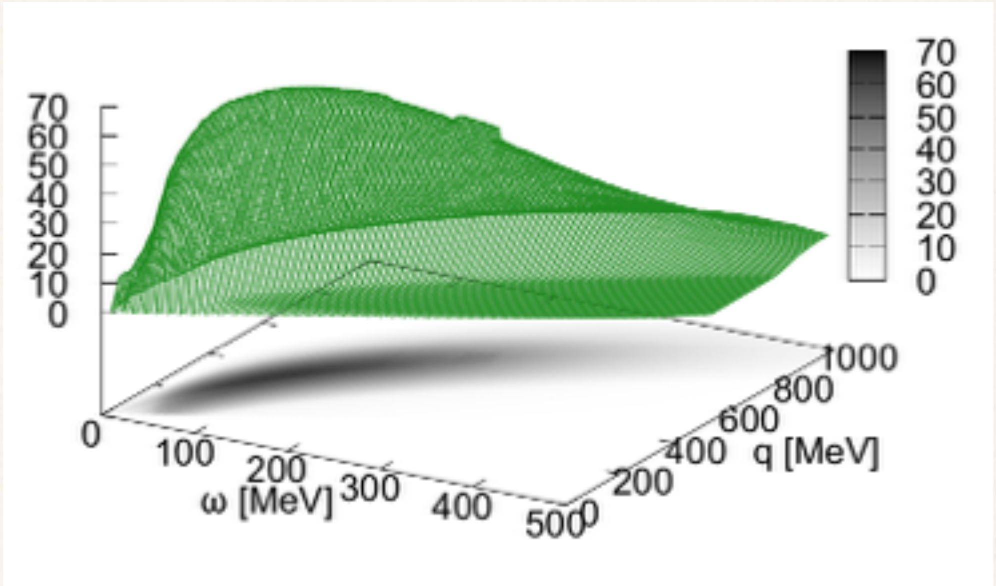




$$\frac{1}{\mathcal{W}}\int dE \left.\frac{d\sigma}{dq\,d\omega}\right|^{CCQE} \mathcal{F}(E)\mathcal{P}_{\nu_\mu\to\nu_e}(E) = \left.\frac{d\sigma}{dq\,d\omega}\right|^{\rm osc}_{T2K}$$

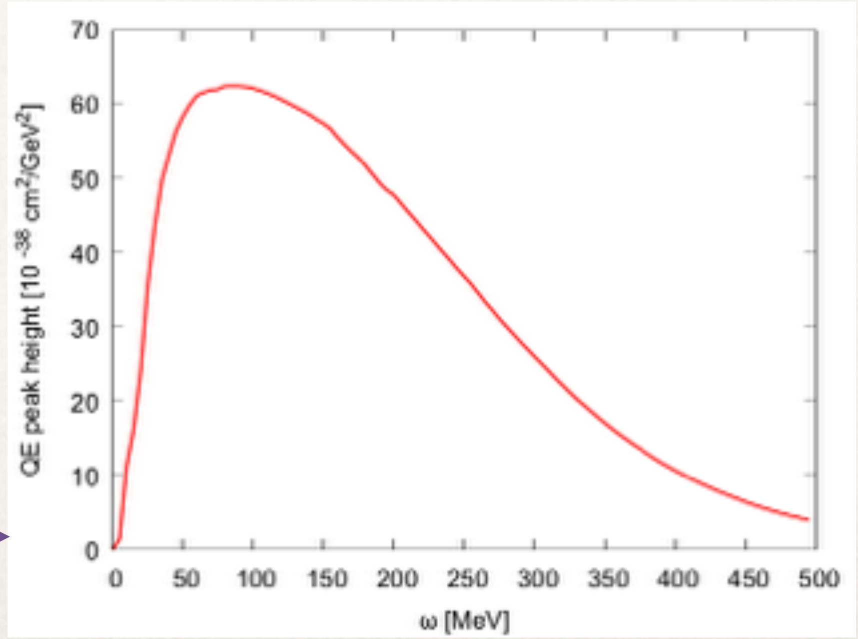
Region of interest



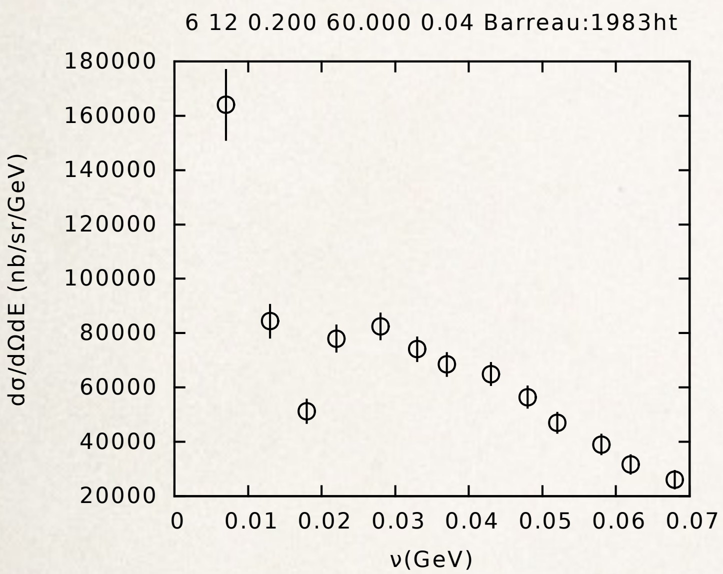


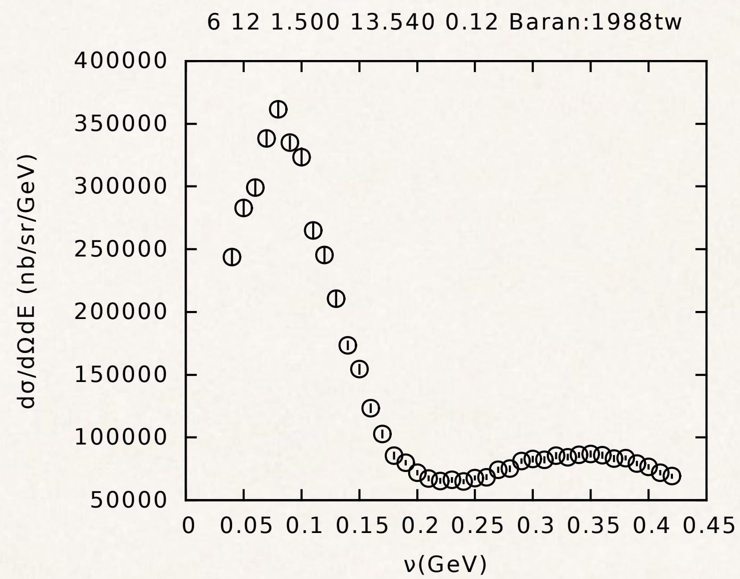
CCQE line
where q is maximal
for a given ω

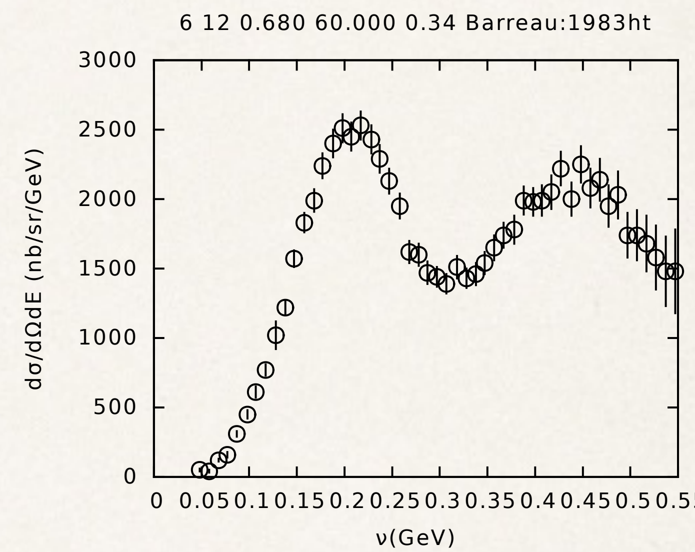
CCQE line
projected on ω axis



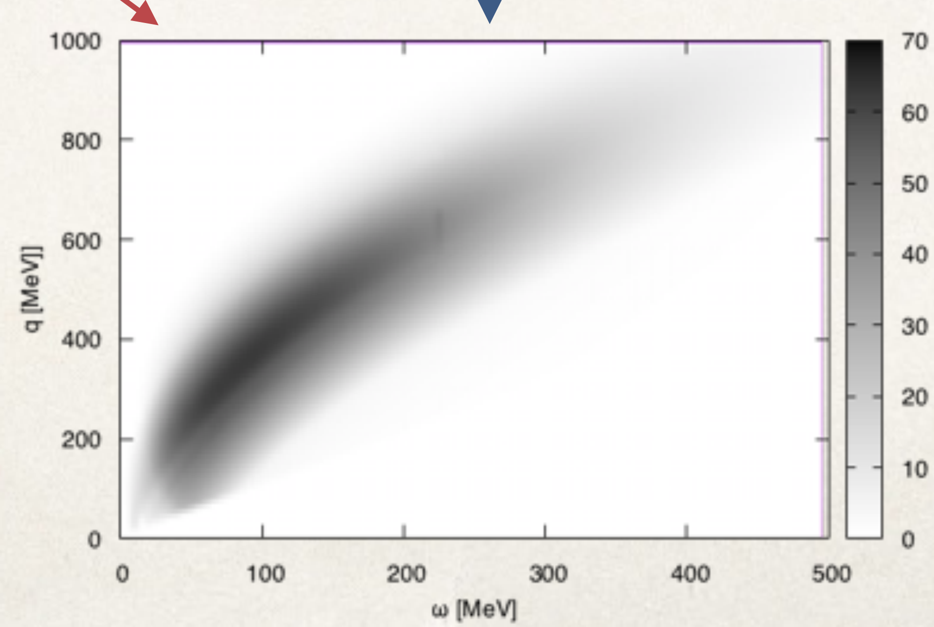
Inclusive electron scattering data



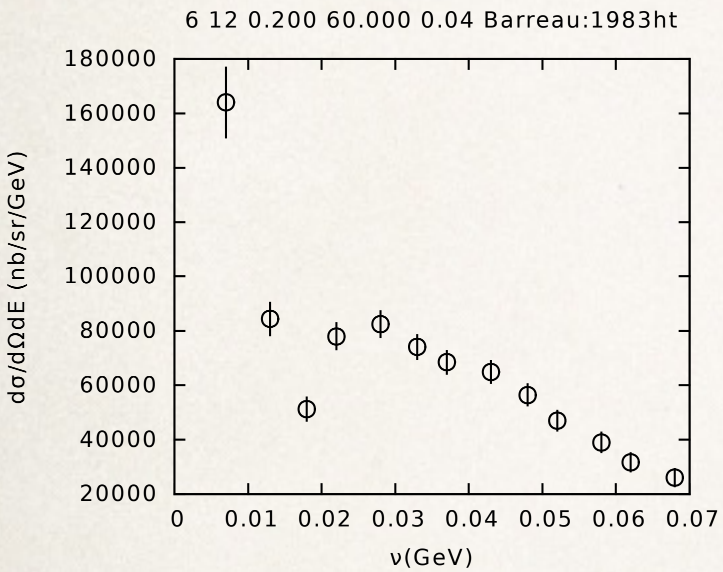


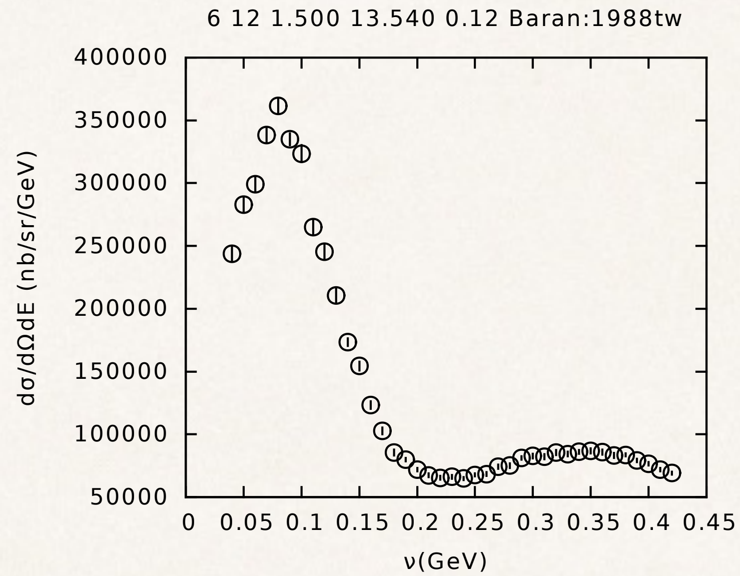


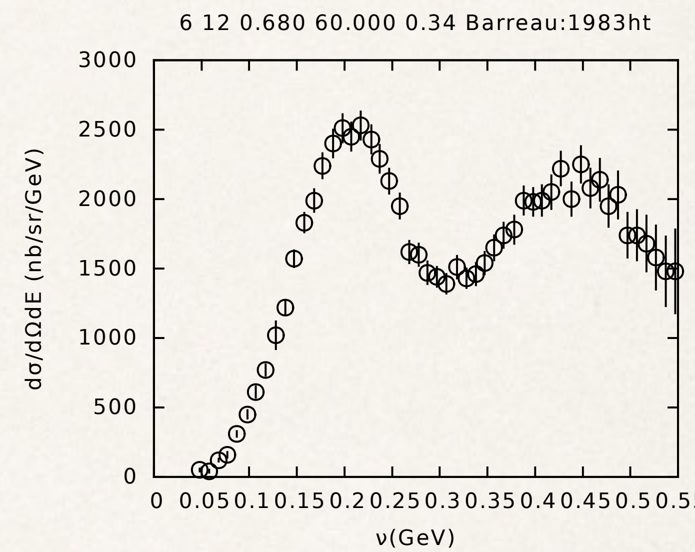
O. Benhar, D. Day, I. Sick
arXiv:nucl-ex/0603032



Inclusive electron scattering data







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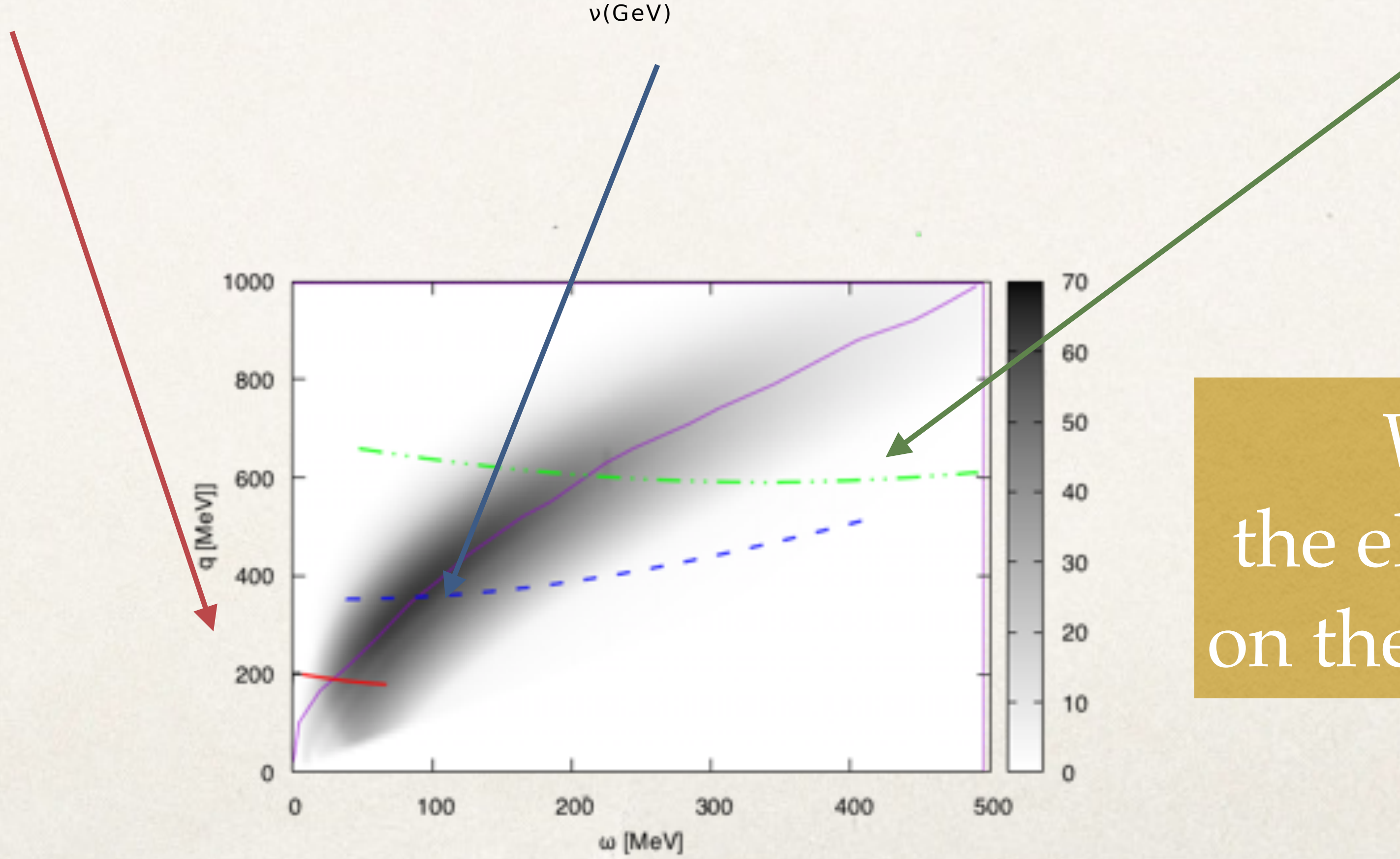
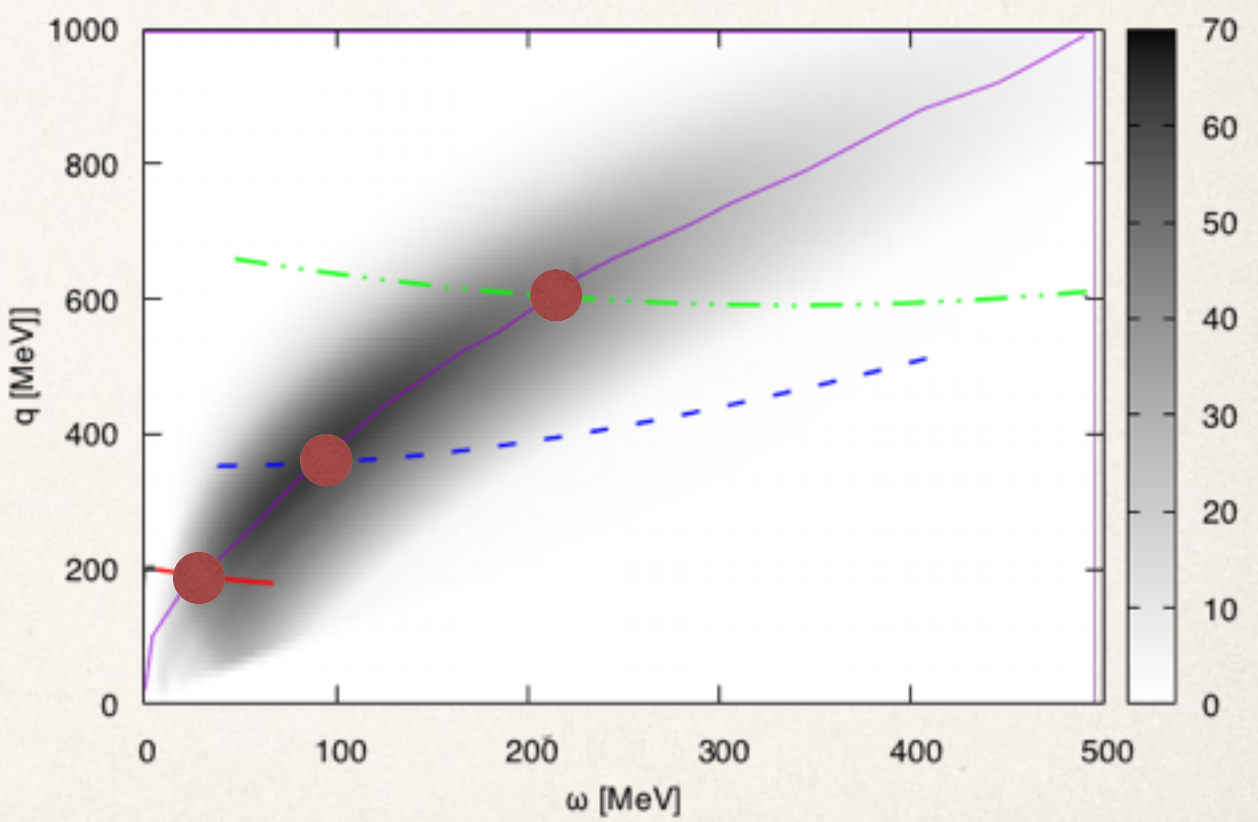


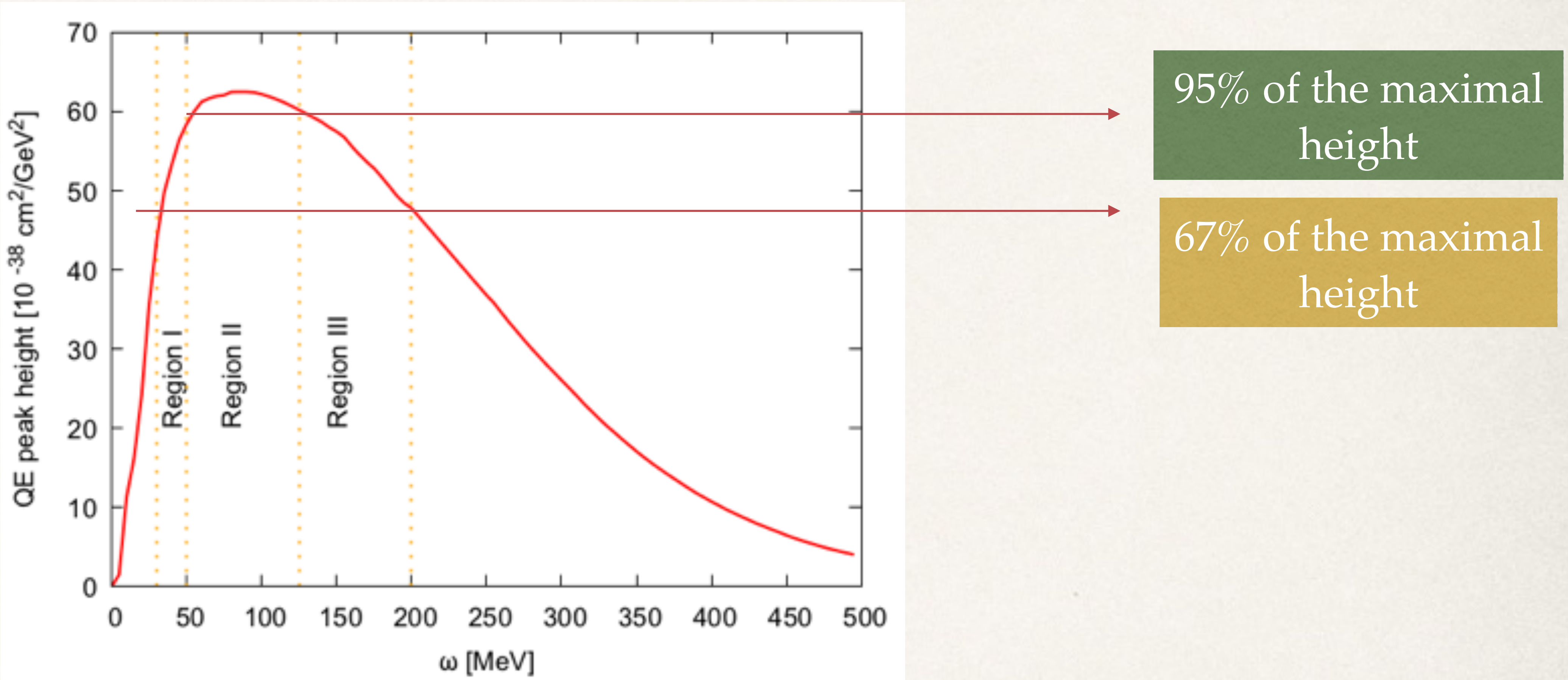
We plot
the electron data
on the same plane

Inclusive electron scattering data

- We should somehow measure the importance of a given data set
- It should depend on the place where it crosses the CCQE line: if $\frac{d\sigma}{dqd\omega}^{\text{osc}}_{T2K}$ in that point is high then the set should be considered more important

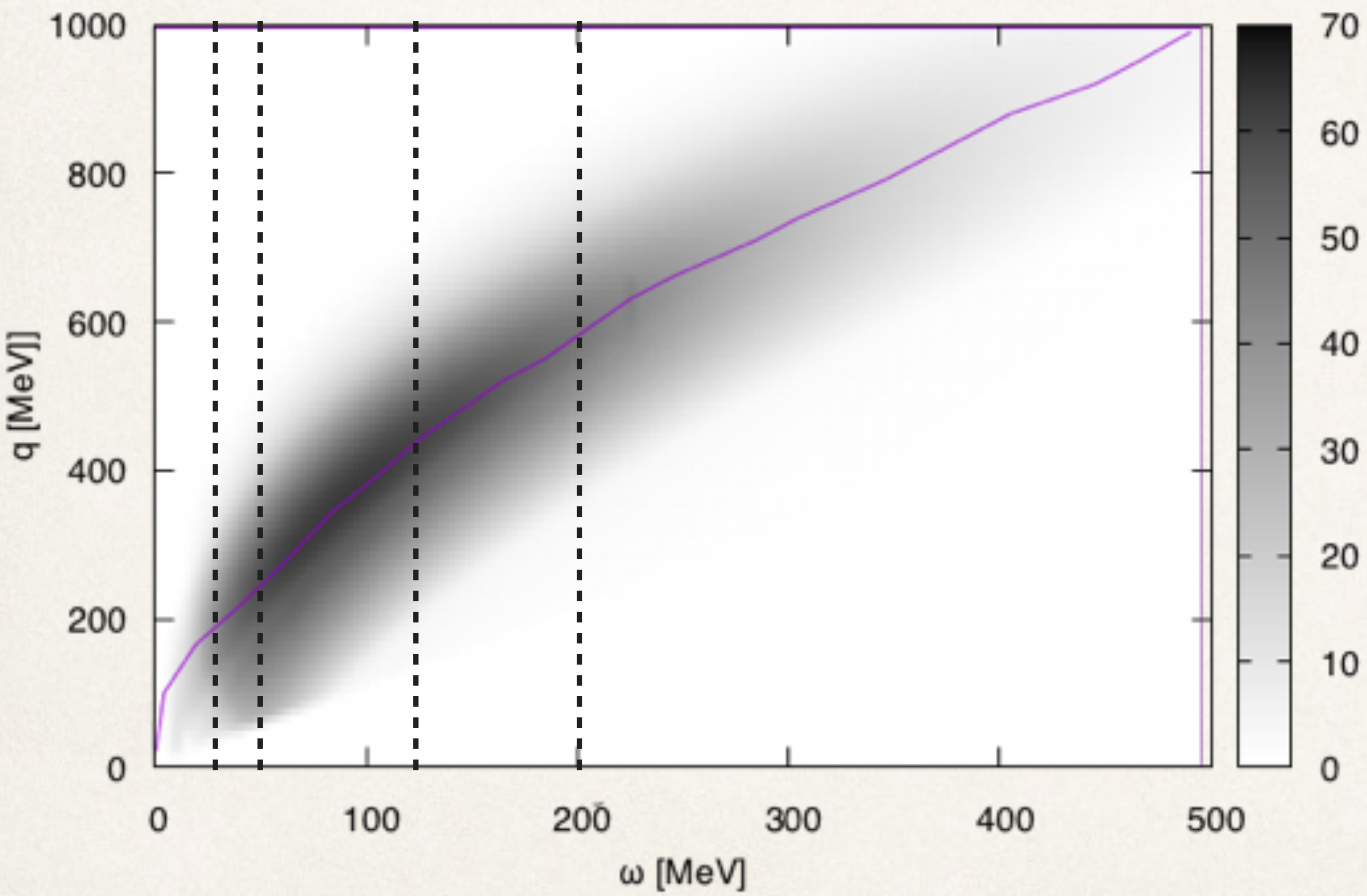


Regions of interest



- We split the available data sets into three regions (low, moderate and high energy transfer): depending on where they cross the CCQE line.
- To simplify analysis, we can compare theoretical models separately in each region.

Regions of interest



- **Region I:**

30-50 MeV energy transfer
(5 sets)

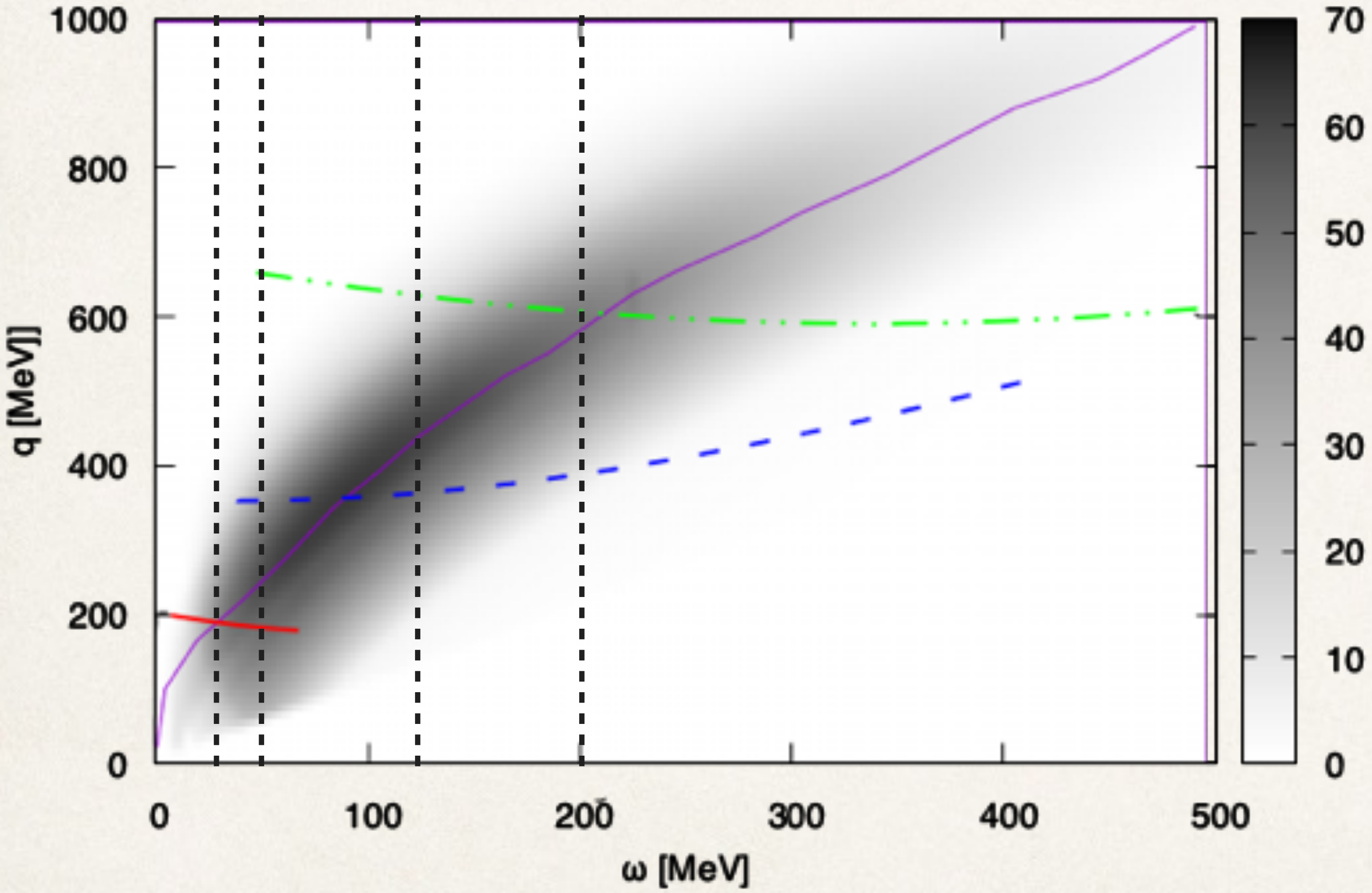
- **Region II**

50-125 MeV energy transfer
(18 data sets)

- **Region III**

125-200 MeV energy transfer
(9 data sets)

Regions of interest



- Region I:

30-50 MeV energy transfer (5 sets)

- Region II

50-125 MeV energy transfer (18 data sets)

- Region III

125-200 MeV energy transfer (9 data sets)

Theoretical models (QE mechanism)

- Fermi gas model as a "starting point" (to see how the statistical correlations & binding energy influence the final result)
- Benhar's spectral function + FSI
- GiBUU
- Valencia spectral function

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{\alpha}{Q^2}\right)^2 \frac{|\vec{k}|}{|\vec{k}'|} L_{\mu\nu} W^{\mu\nu}$$

- We will describe them in terms of the hole and particle spectral functions:

$$W^{\mu\nu}(q) = \int d^3r \rho(r) \int \frac{d^3p}{(2\pi)^3} \frac{3}{4\pi k_F(\rho)^3} \frac{M}{E_p} \frac{M}{E_{p+q}}$$

$$\int dE \, P^h(E, \vec{p}; \rho) \, P^p(\omega - E, \vec{p} + \vec{q}; \rho) \, A^{\mu\nu}(p, q)$$

hole SF — **particle SF = FSI**

they differ in each model

Fermi Gas

- statistical correlation
- constant mean-field (=binding energy)

$$P^h_{FG}(E,p;\rho) = \theta\big(k_F(\rho)-p\big)\,\delta\big(E+\sqrt{M^2+p^2}-M-B\big)$$

GiBUU

- mean field potential (used firstly in heavy ions collisions) for both the hole and the particle state

$$P^h(E,|\vec{p}|;\rho) = \theta\big(k_F(\rho)-p\big)\,\delta\big(E-M^*+\sqrt{M^{*2}+p^2}\big)$$

$$M^*(\vec{p},\vec{r}) = M + U(\vec{p},\vec{r})$$

Valencia model

- the same (semi-phenomenological) spectral function for the particle and the hole state
- nonrelativistic model (but in relativistic regime FSI is switched off)

$$P^h(E,\vec{p};\rho) = -\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(E,\vec{p})}{\big(E-M-\vec{p}^2/2M-\mathrm{Re}\Sigma(E,\vec{p})\big)^2+\mathrm{Im}\Sigma(E,\vec{p})^2}\theta(\mu-E)$$

Benhar's model

- spectral function of the ground state: shell-model (90%) + nucleon-nucleon correlations
- FSI: optical potential

Why these models?

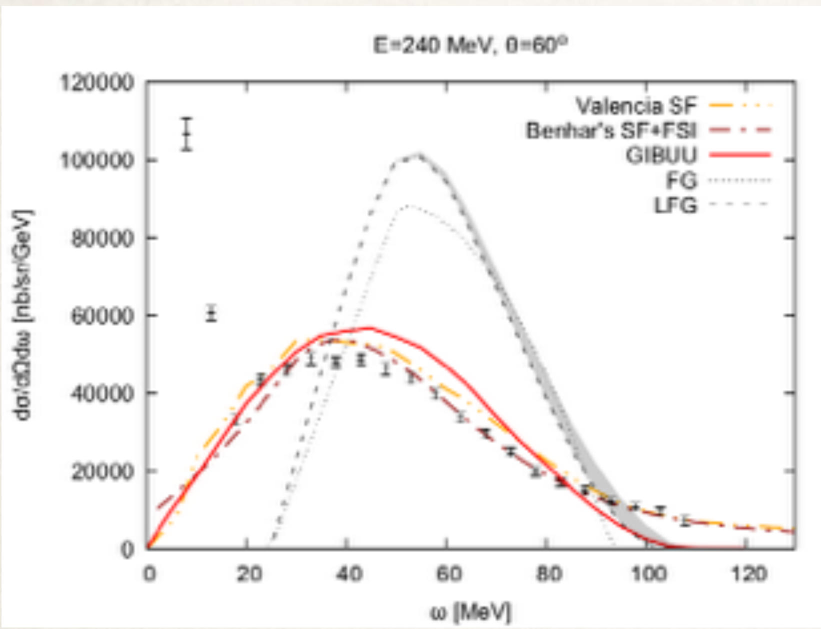
- Each model is derived in a different framework: interesting to see a comparison
- All of them use Impulse Approximation and do not describe collective excitations (that is why e.g. CRPA Ghent model is not included)
- RPA is not included in Valencia model because RPA parameters were fixed for noninteracting LFG.

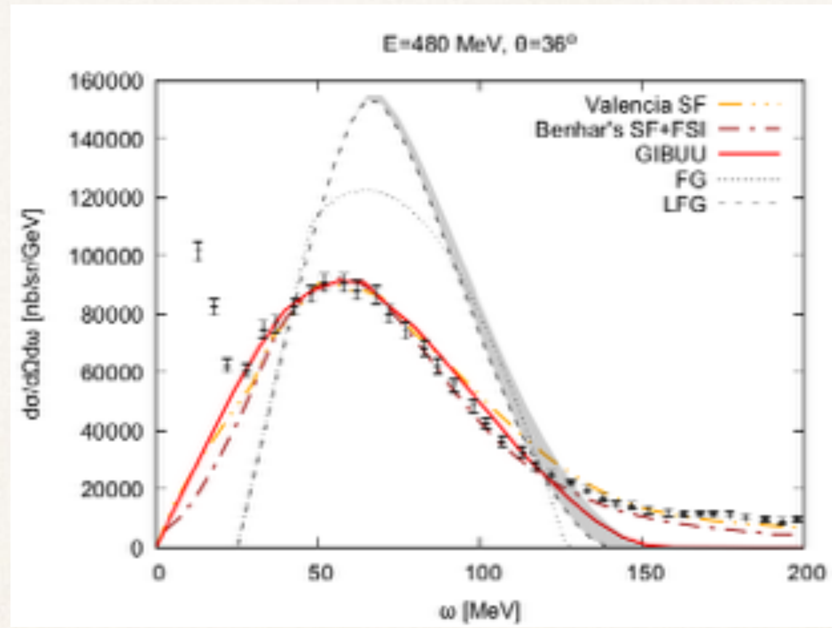
Results (typical data sets)

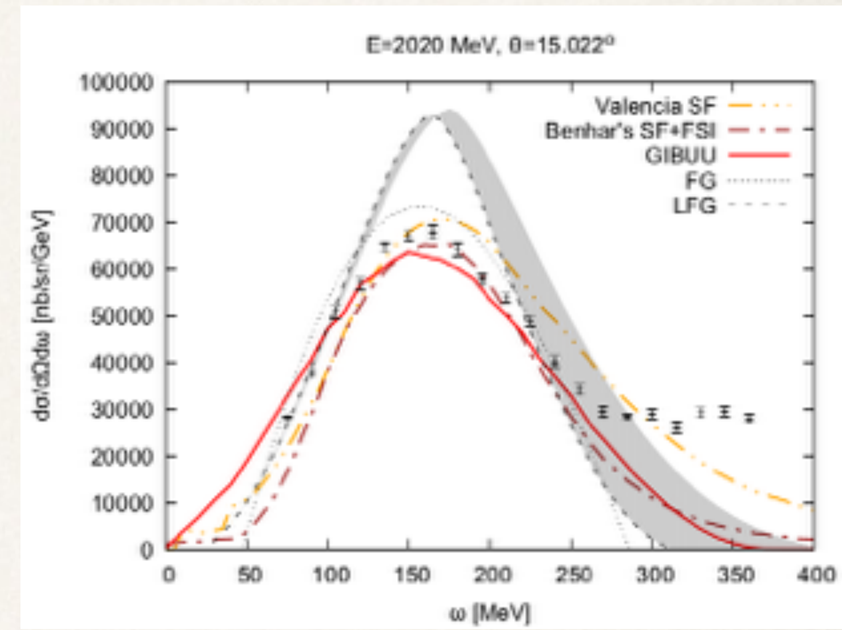
Region I

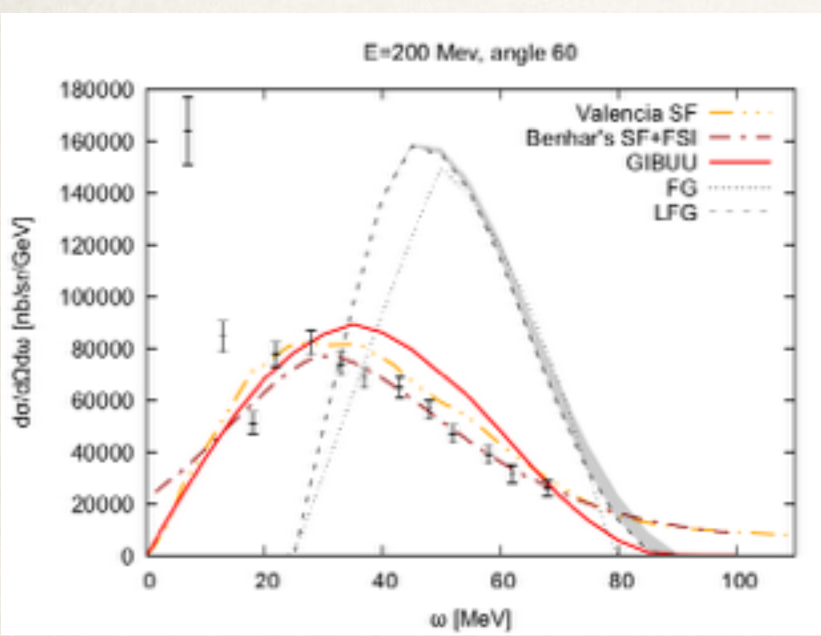
Region II

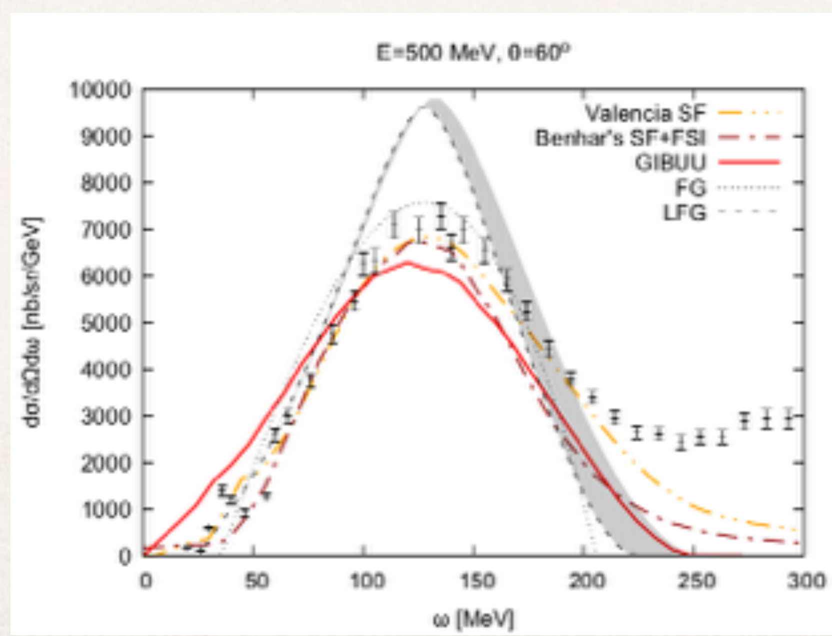
Region III

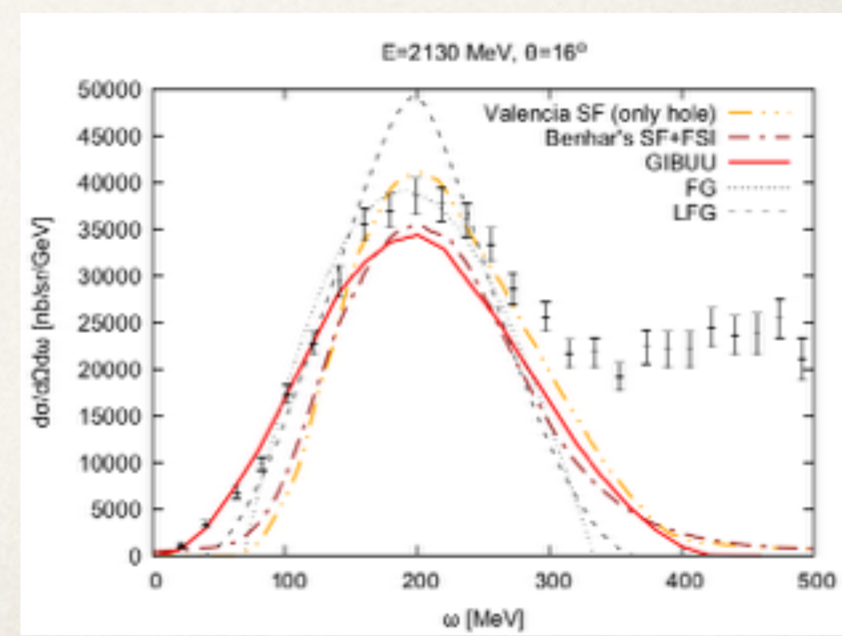








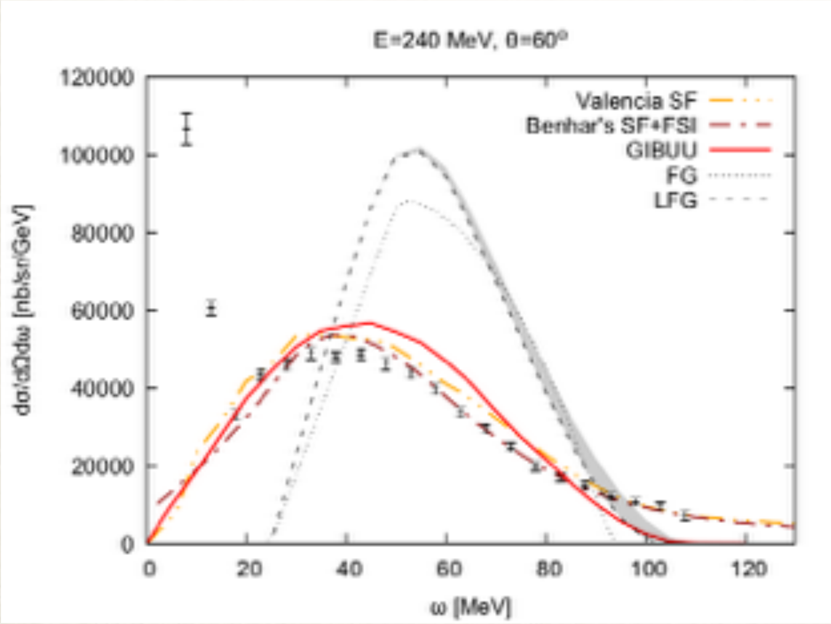


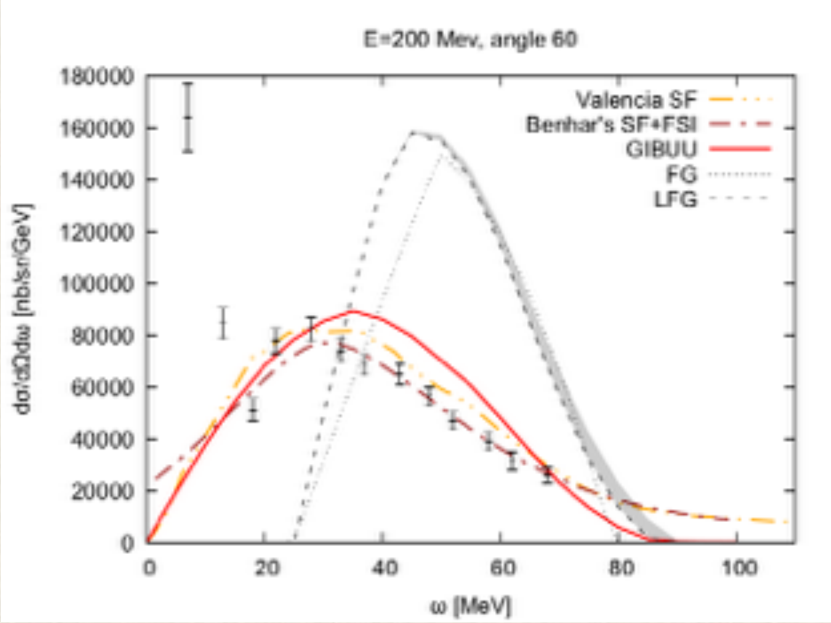


We plot INCLUSIVE electron scattering data and theoretical models for the QE mechanism.

Results

Region I (energy transfer in the QE peak: 30-50 MeV)



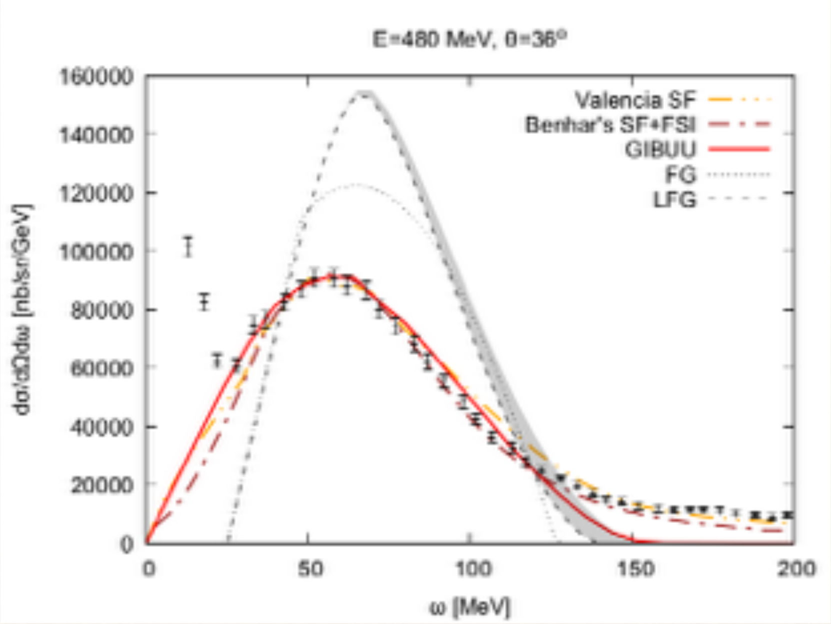


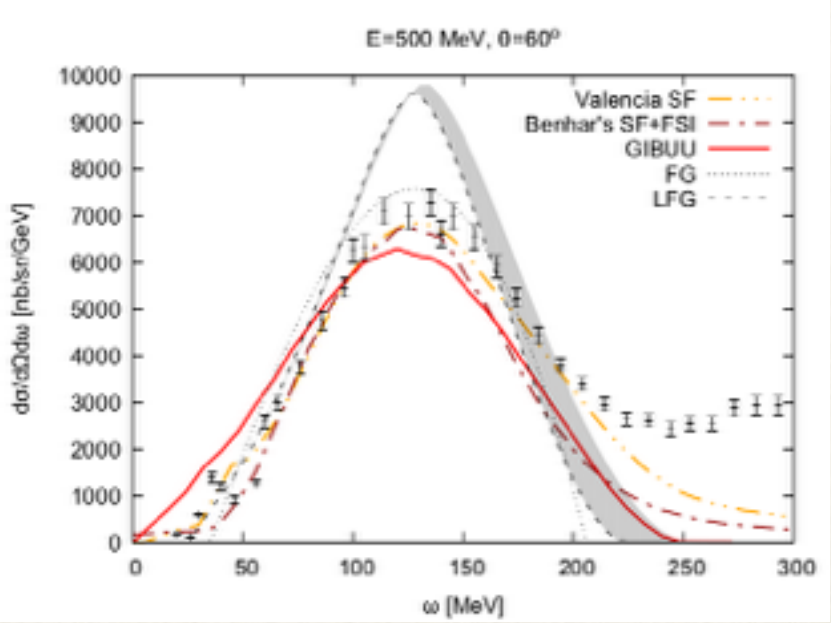
- There are giant resonances in the data not recovered
- No relativistic effects (yet)
- Fermi Gas works quite bad…
- Long tail in the case of Benhar and Valencia (correlations)
- GiBUU slightly overestimates the QE peak

Results

Region II (energy transfer in the QE peak: 50-125 MeV)

- In some case there are still giant resonances in the data not recovered (depends on the momentum transfer)
- Relativistic effects are getting higher
- 2p2h & Δ in some cases contribute to the QE peak



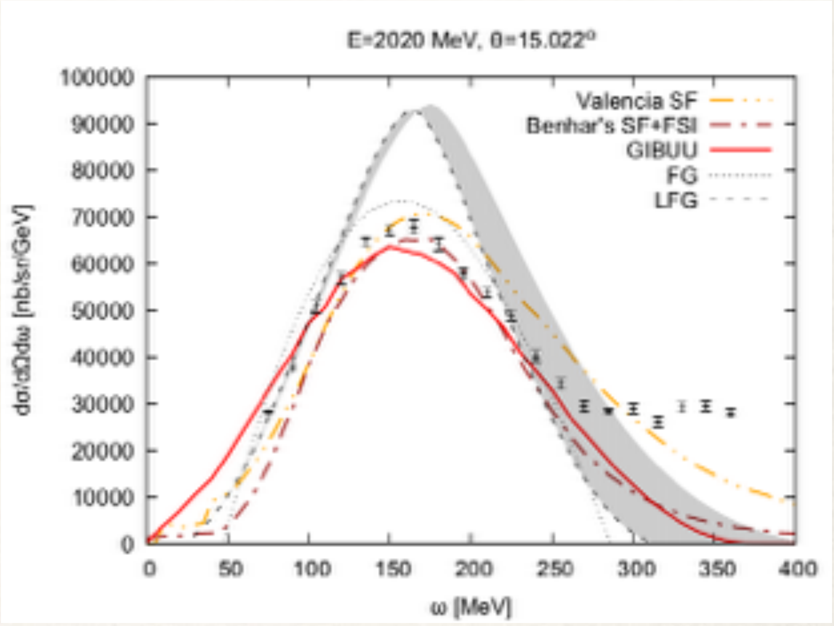


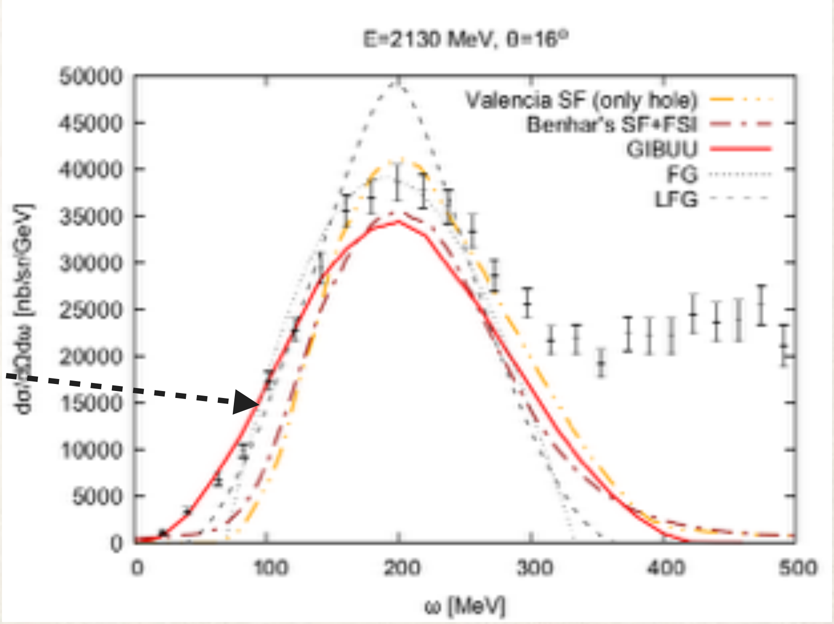
- Fermi Gas still does not work well
- Valencia: too broad peak because of the relativistic effects
- GiBUU predictions for low energy transfer are higher than Benhar and Valencia

Results

Region III (energy transfer in the QE peak: 125-200 MeV)

- Relativistic effects are already pronounced
- Other mechanisms overlap with the QE peak
- Global Fermi Gas works much better than for lower energy transfer
- Valencia model: in this region it is better to switch off FSI (but then the peak is higher than Benhar's and GiBUU)
- GiBUU is broader for low energy transfer





2p2h & Δ inclusion

- How do we know they are sizeable?

$$\frac{d^2\sigma}{d\Omega d\omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\frac{Q^4}{\vec{q}^4} R_L(q) + \left(\frac{1}{2}\frac{Q^2}{\vec{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(q)\right]$$

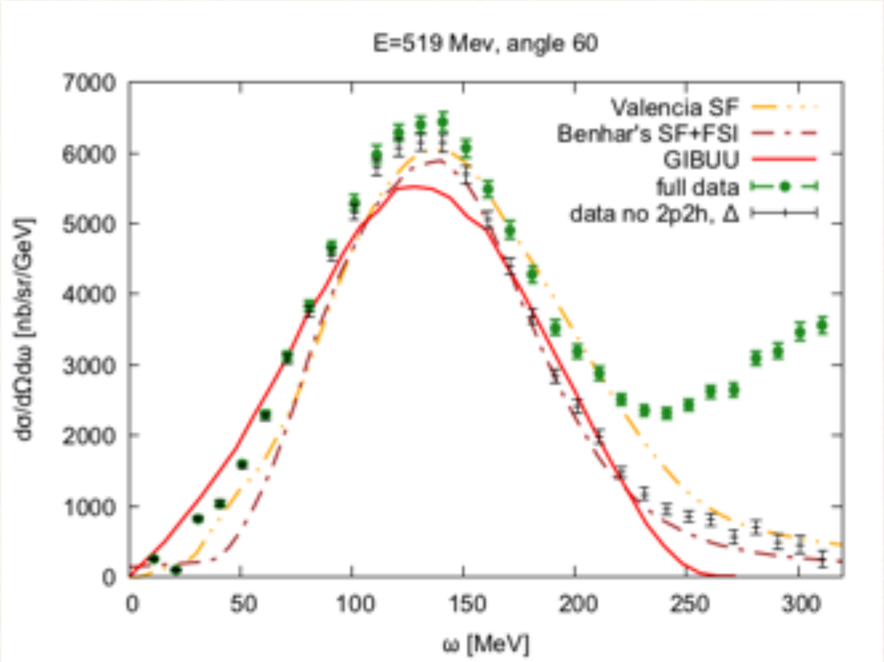
$$= \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\sigma_L + \sigma_T\right]$$

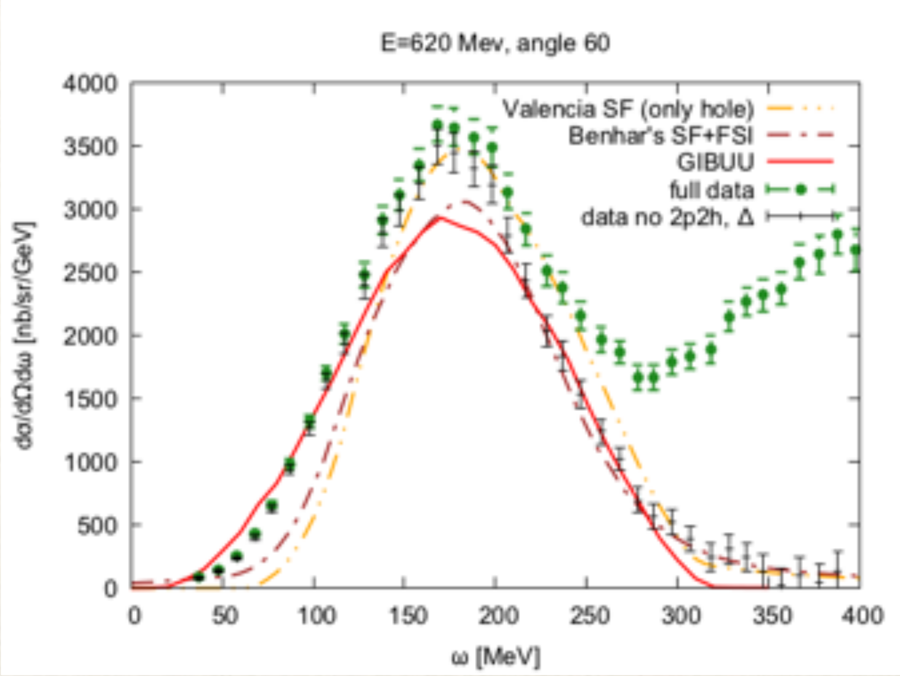
Kinematics is important: it might "kill" R_T

- We split the cross section into longitudinal and transverse part
- 2p2h and Δ give contribution to the transverse channel… so if it is large in comparison to the longitudinal one, then we expect sizeable 2p2h and Δ effect

2p2h & Δ inclusion

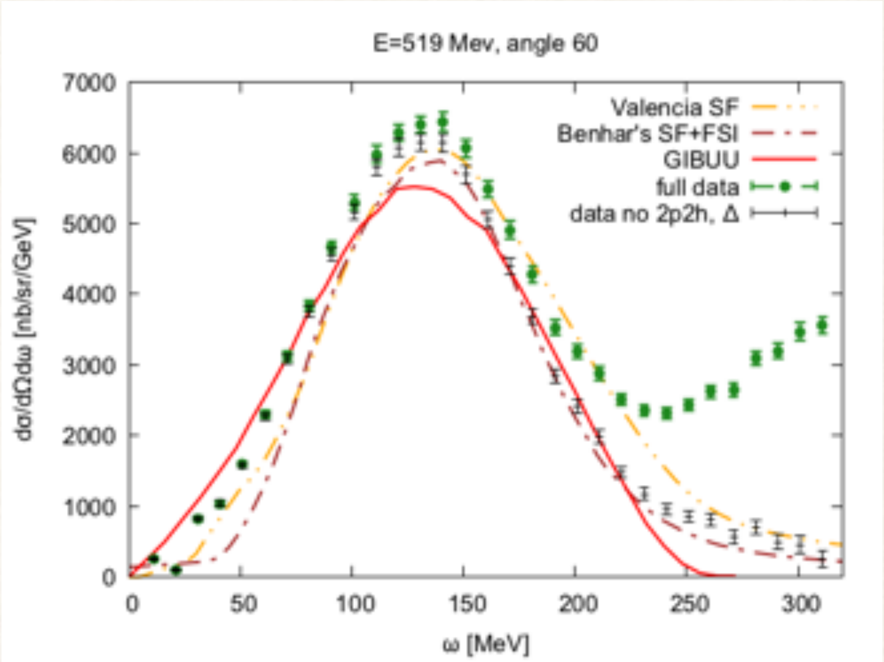
For the sake of better legibility data points have been moved by subtracting theoretical predictions for 2p2h and Δ! Sorry for that!

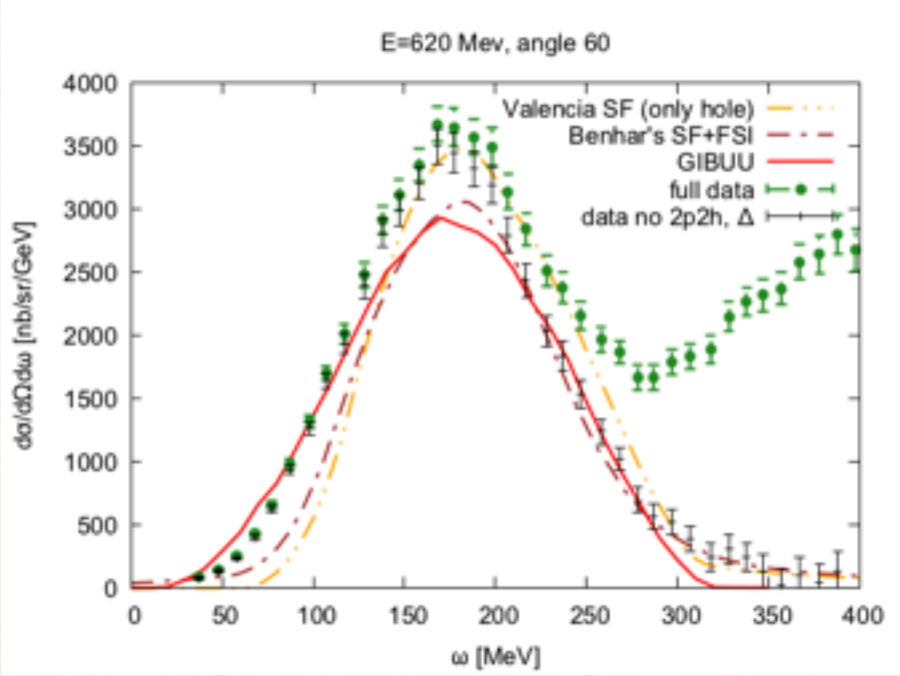




2p2h & Δ inclusion

- For higher energy transfer these effects have to be taken into account
- In principle we need to compare models which comprise all the effects
- Difficult to handle because model-dependant… (here we use SUSA results: PhysRevD. 94.013012)





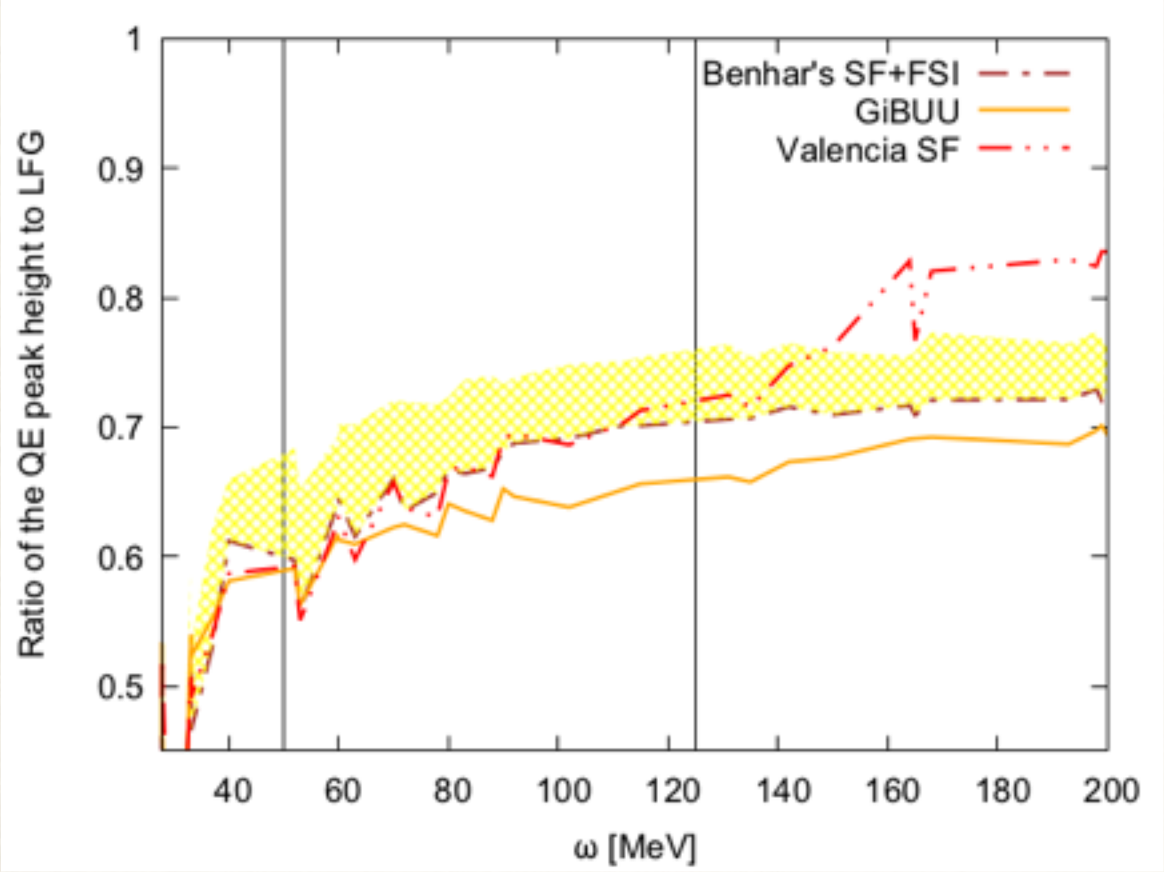
Conclusions and Outlook

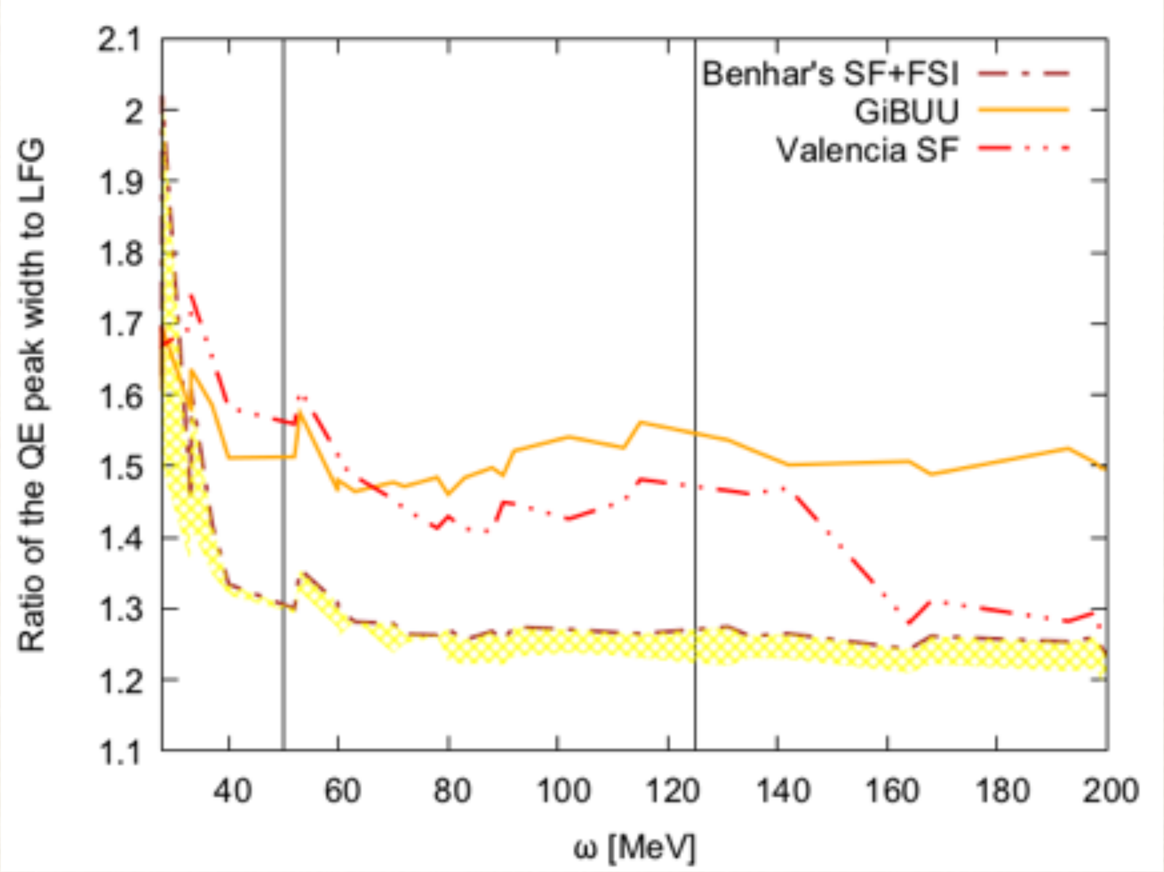
- Fermi Gas is not enough - we need to include further nuclear corrections. Especially for lower energy transfer. Global FG works better than Local FG.
- The three other models are working quite well.
- One can think of a better way to choose the data for comparison and measure the goodness of the model.
- 2p2h & Δ should be also taken into account (use full computation for each model).

THANK YOU!

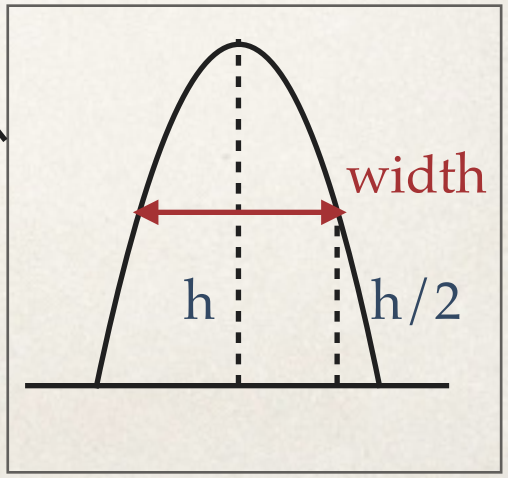
BACKUP

Comparison to the LFG

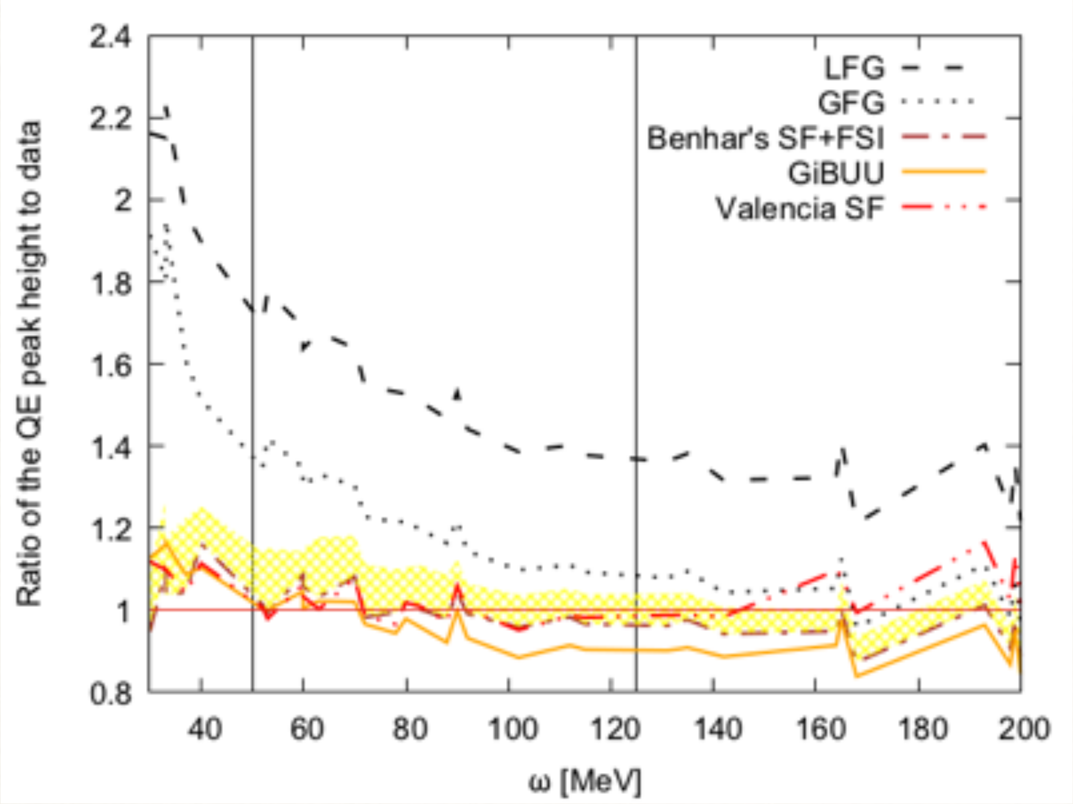




- low energy transfer: nuclear effects are more important
- Valencia model: remember about the relativistic effects which broaden the peak
- Benhar's FSI effect: quenching of the peak and slightly redistribution of the peak
- GiBUU model: in general peak is lower and broader



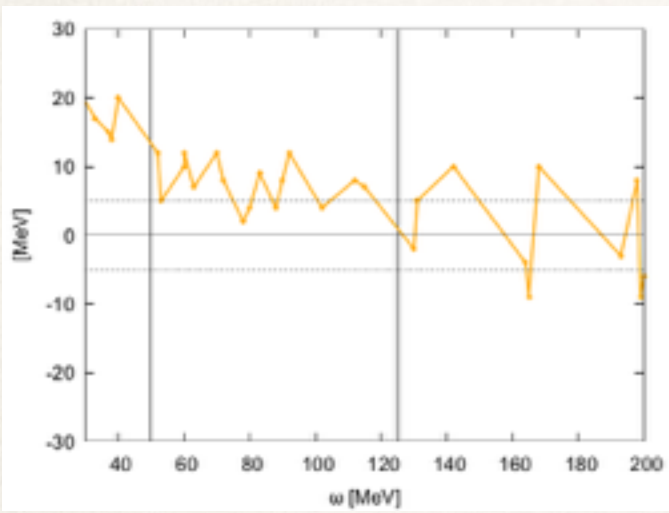
Comparison to the data - height of the peak



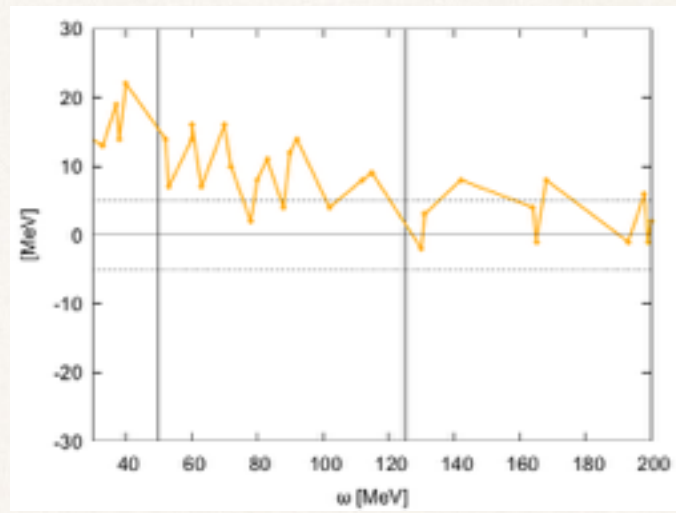
- Fermi Gas models: overestimate the peak
- GiBUU predicts the lowest height
- Valencia model gets higher for Region III because there we neglect FSI

- We cannot compare the width of the peak because:
  - for low energy transfer there are giant resonances
  - for high energy transfer 2p2h broadens the peak

Comparison to the data - position of the peak



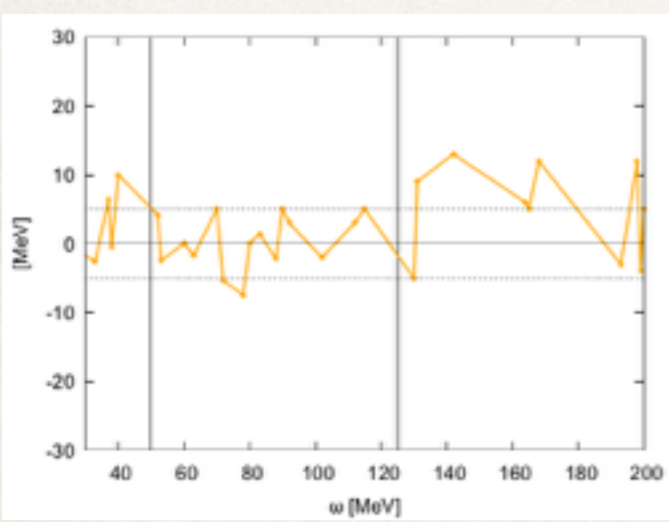
GFG



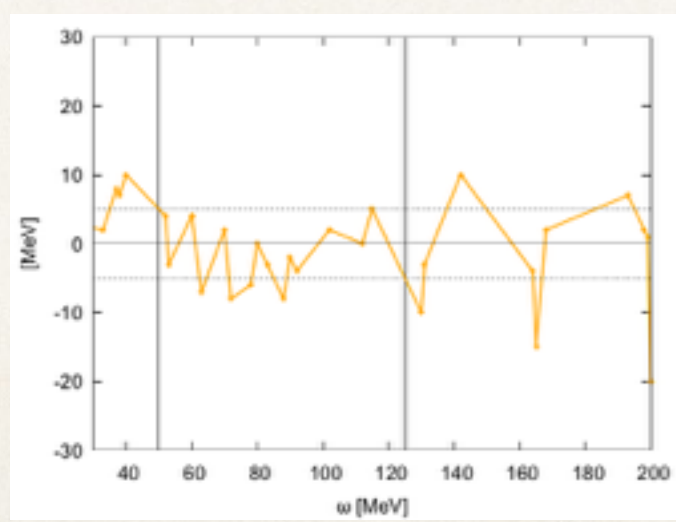
LFG

Clear tendency: peak is shifted for Region I (and partially II)

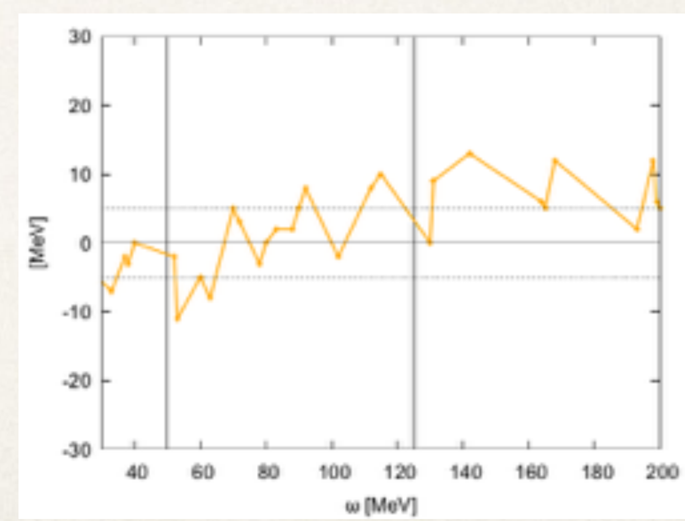
In general within 5-10 MeV



Benhar



GiBUU



Valencia

GiBUU

used potential:

$$U(\vec{p},\vec{r}) = A\frac{\rho(\vec{r})}{\rho_0} + B\left(\frac{\rho(\vec{r})}{\rho_0}\right)^{\tau} + \frac{2C}{\rho_0} g \int \frac{d^3p'}{(2\pi)^3} \frac{\Theta(k_F - |\vec{p}|)}{1 + (\frac{\vec{p}-\vec{p}'}{\Lambda})^2},$$

- it uses LDA (local density approximation): first we make calculation for the nuclear matter and then integrate over nucleus density profile
- In principle one could use also the collisional broadening, but it is not taken into account for the standard GiBUU simulations.

Valencia model

$$P^h(E,\vec{p};\rho) = -\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(E,\vec{p})}{\left(E - M - \vec{p}^2/2M - \mathrm{Re}\Sigma(E,\vec{p})\right)^2 + \mathrm{Im}\Sigma(E,\vec{p})^2}\theta\left(\mu - E\right)$$

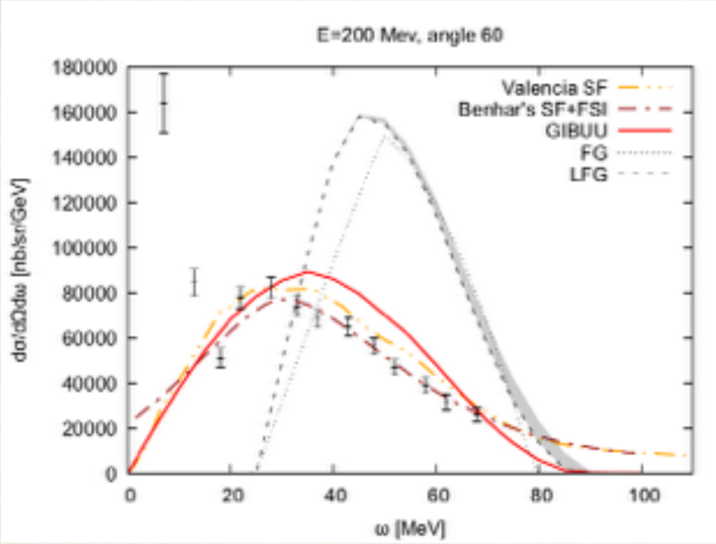
- it uses LDA (local density approximation): first we make calculation for the nuclear matter and then integrate over nucleus density profile
- Σ - nucleon self-energy obtained within a model by P. Fernandez de Cordoba and E. Oset (PRC 46
- it uses nucleon-nucleon scattering data as an input + adds in-medium effects
- For higher energy-momentum transfer we neglect FSI

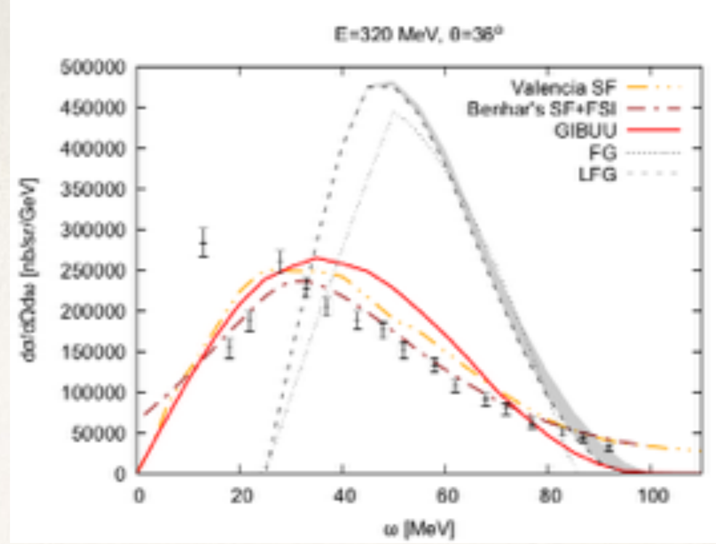
Data sets from Region I

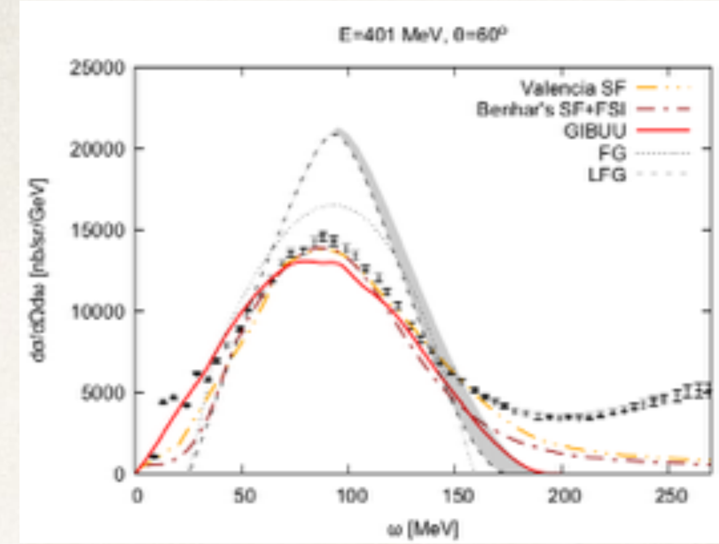
Energy [MeV]	Angle [Degrees]	ω^{QE} [MeV]	$\|\vec{q}\|^{QE}$ [MeV]	$\frac{d\sigma}{dqd\omega}{}^{\text{osc}}_{T2K}(\omega^{QE}, \|\vec{q}\|^{QE})$ $[10^{-38}\ \text{cm}^2/\text{GeV}^2]$	$\frac{\text{height}}{\text{max height}}$ [%]	$\frac{\sigma_T}{\sigma_L}(\omega^{QE}, \|\vec{q}\|^{QE})$
280	60	53	258	60.1	96.1	0.4
1300	11.95	60	271	61.2	98.0	0.2
480	36	62	284	61.5	98.3	0.3
320	60	63	294	61.3	98.1	0.5
1500	11.95	70	313	61.7	98.8	0.3
1300	13.54	70	306	61.9	99.1	0.3
560	36	72	331	62.2	99.4	0.4
361	60	73	331	62.2	99.5	0.6
1650	11.95	80	345	62.1	99.4	0.4
1500	13.54	80	353	62.4	99.9	0.4
401	60	88	365	62.3	99.7	0.7
620	36	92	365	62.3	99.7	0.5
440	60	98	400	61.7	98.7	0.8
1650	13.54	100	390	62.0	99.2	0.4
680	36	102	401	61.5	98.5	0.6
480	60	112	435	60.5	96.9	0.9
730	37.1	115	442	60.2	96.3	0.7
500	60	125	451	59.9	95.8	1.0

Data sets from Region II and III

Energy [MeV]	Angle [Degrees]	ω^{QE} [MeV]	$\lvert\vec{q}\rvert^{QE}$ [MeV]	$\frac{d\sigma}{dqd\omega}{}^{\text{osc}}_{T2K}(\omega^{QE}, \lvert\vec{q}\rvert^{QE})$ $[10^{-38}\ \text{cm}^2/\text{GeV}^2]$	$\frac{\text{height}}{\text{max height}}$ [%]	$\frac{\sigma_T}{\sigma_L}(\omega^{QE}, \lvert\vec{q}\rvert^{QE})$
200	60	43	182	50.3	80.5	0.2
320	36	43	189	51.9	83.0	0.2
240	36	48	141	44.7	71.5	0.1
240	60	48	220	56.8	90.9	0.3
400	36	52	236	58.3	93.3	0.2
519	60	131	468	59.0	94.3	1.0
560	60	142	504	57.0	91.2	1.2
2020	15.022	150	530	54.2	86.7	0.7
2000	15	150	524	55.0	88.0	0.7
1930	16	164	539	53.2	85.1	0.8
620	60	168	555	51.6	82.6	1.3
2130	16	179	595	47.2	75.5	0.9
1930	18	182	603	46.0	73.7	0.9
961	37.5	183	585	48.7	78.0	1.0
680	60	188	608	46.0	73.7	1.5


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


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


E=401 MeV, θ=60°
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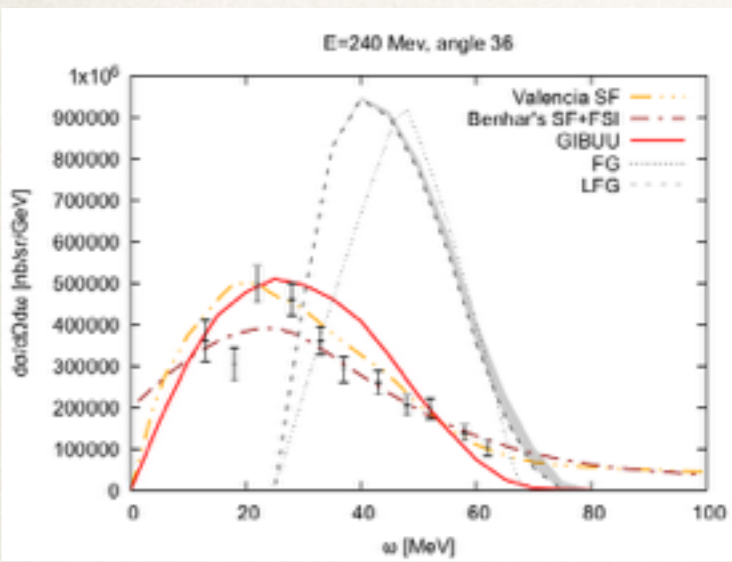
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


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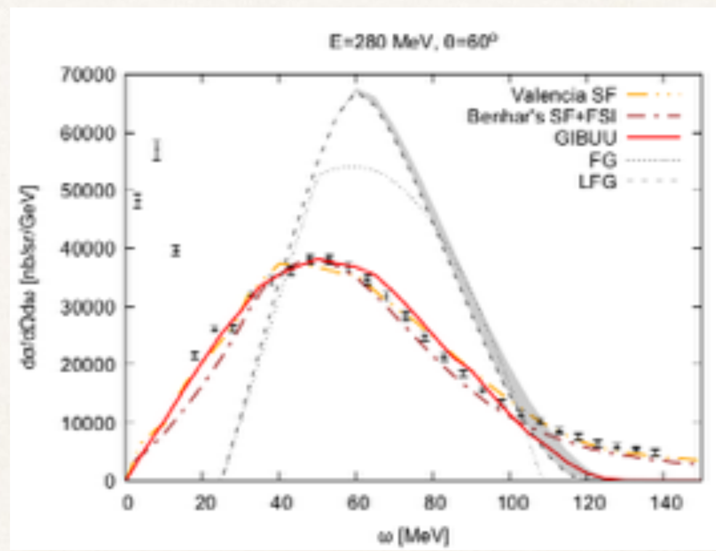
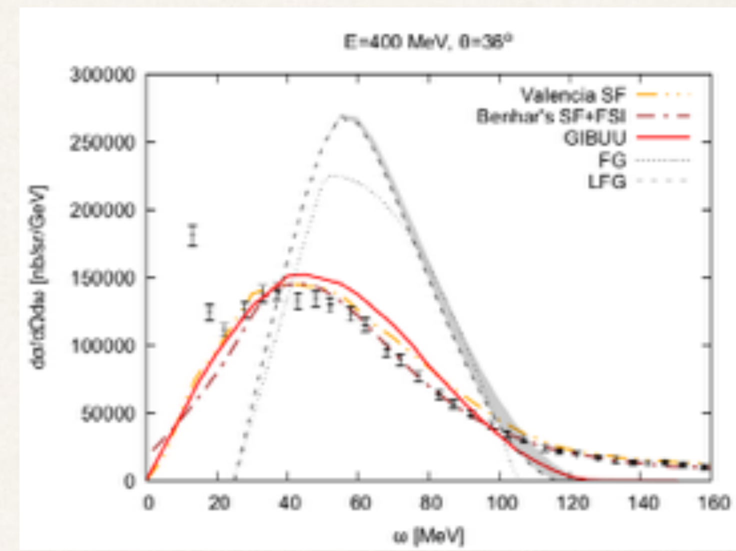
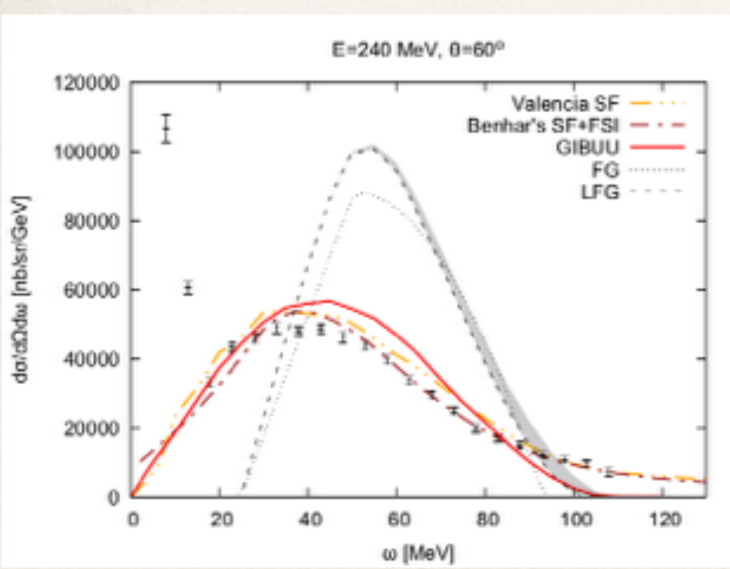
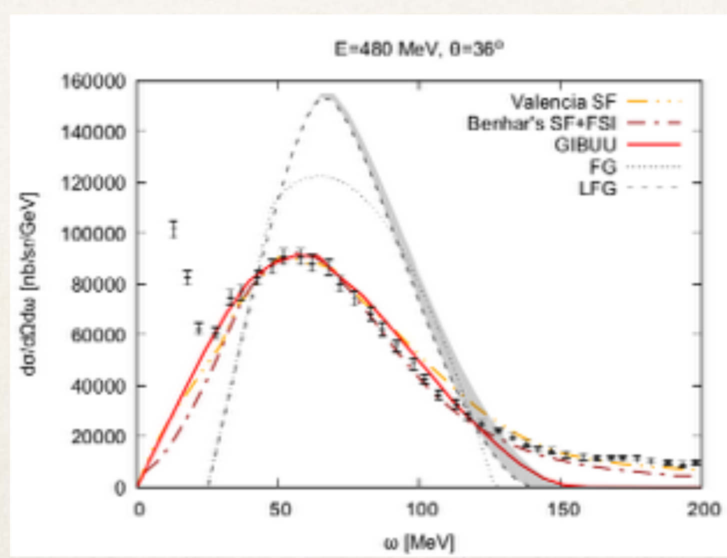
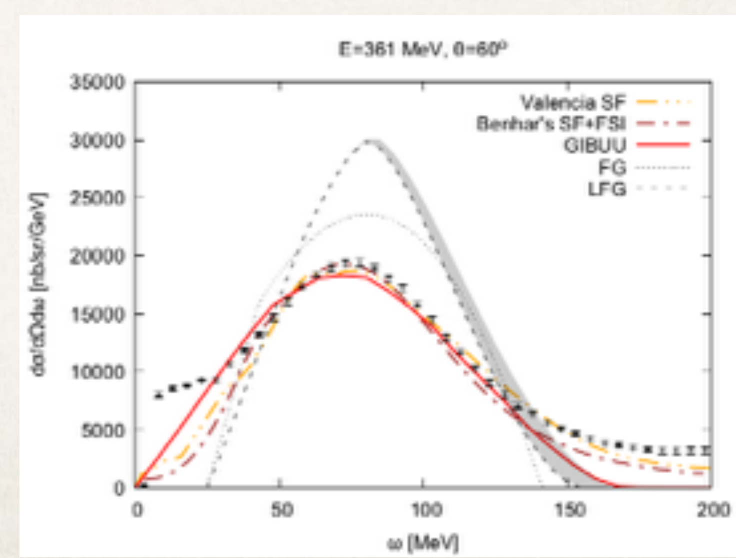
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

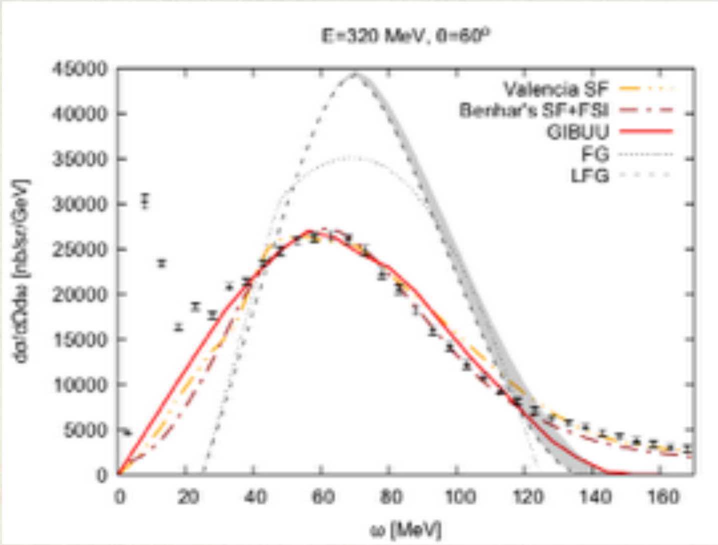

E=280 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

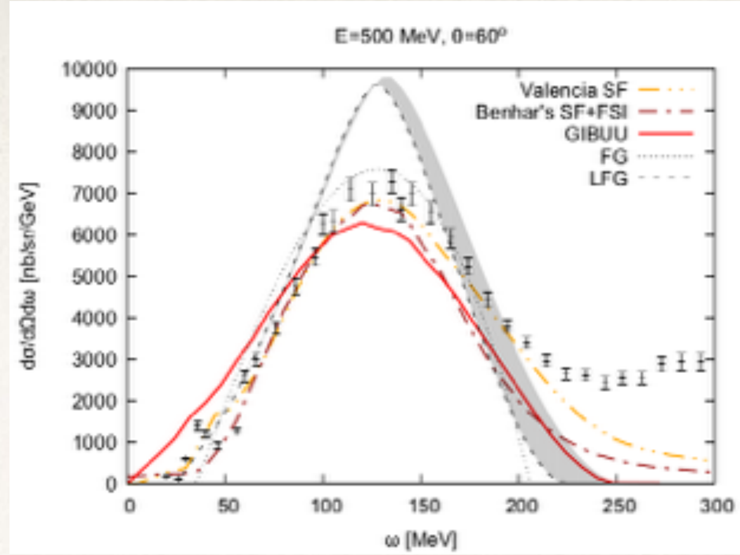

E=400 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

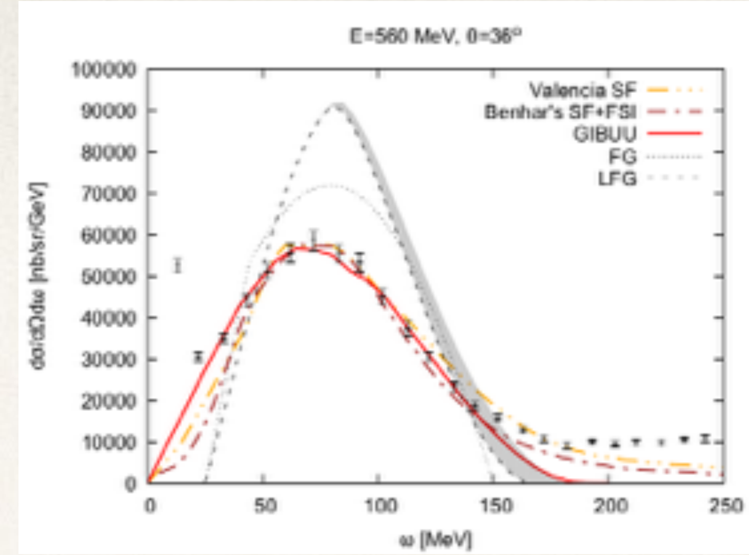

E=240 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

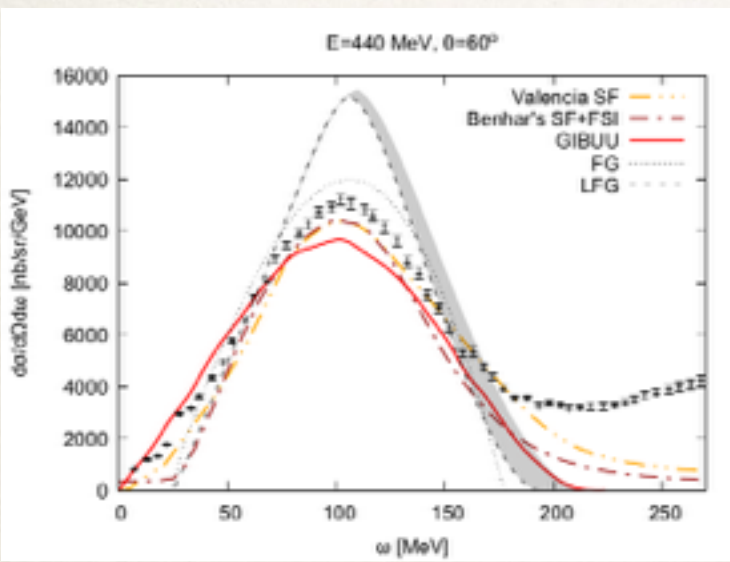

E=480 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

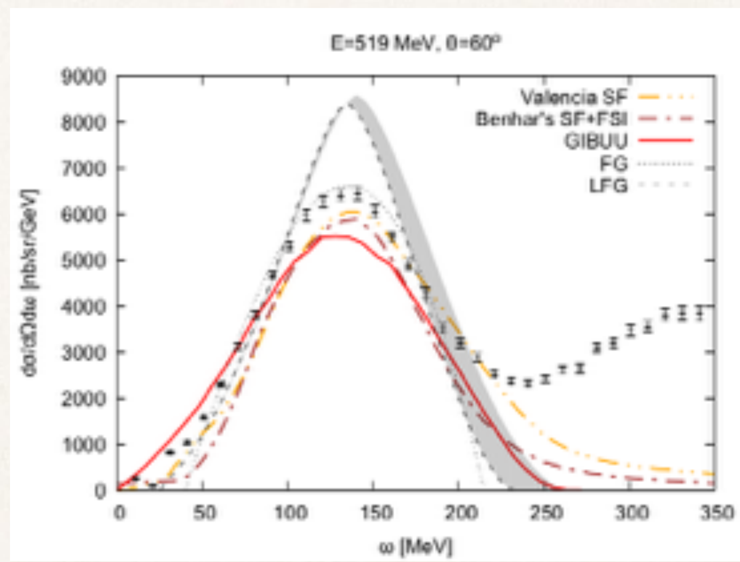

E=361 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

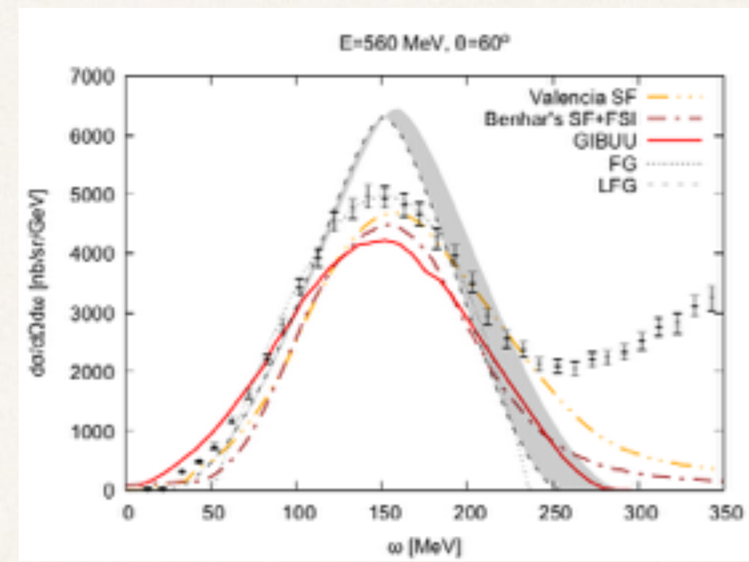

E=320 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

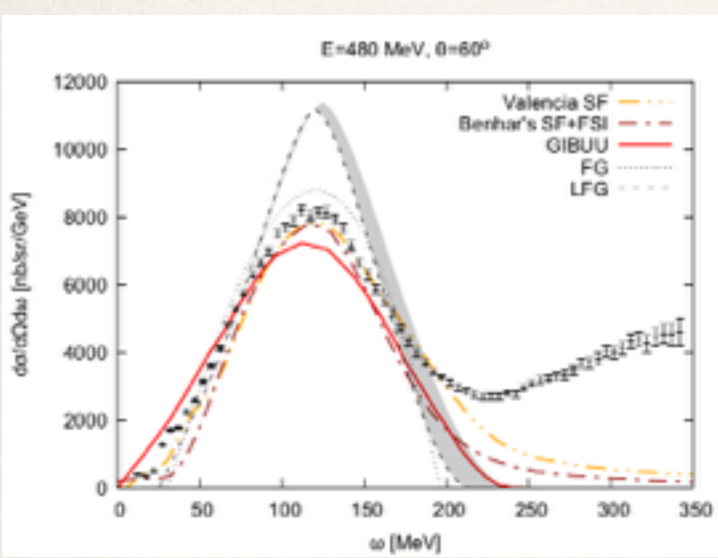

E=500 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

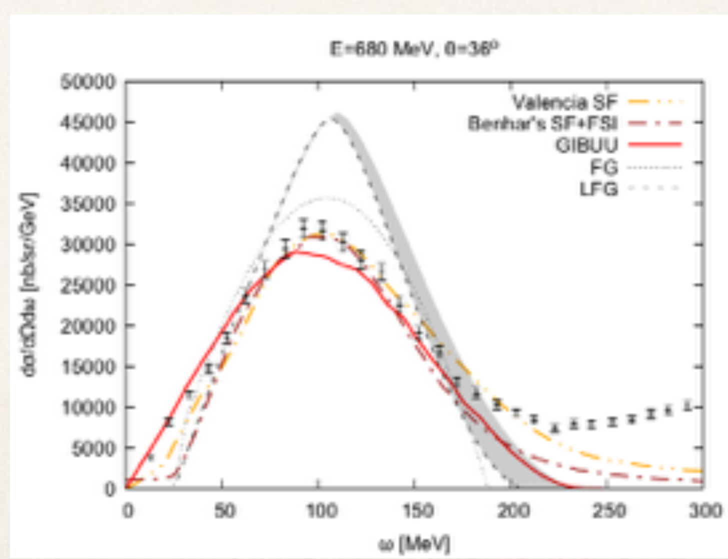

E=560 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

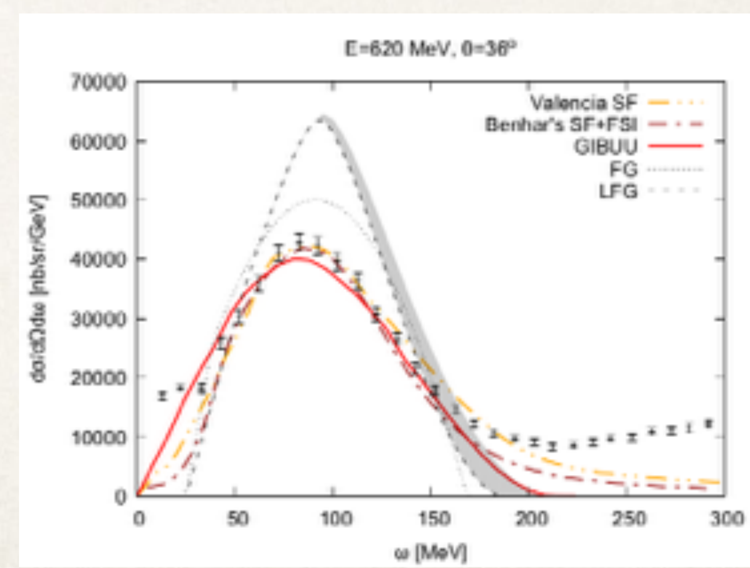

E=440 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

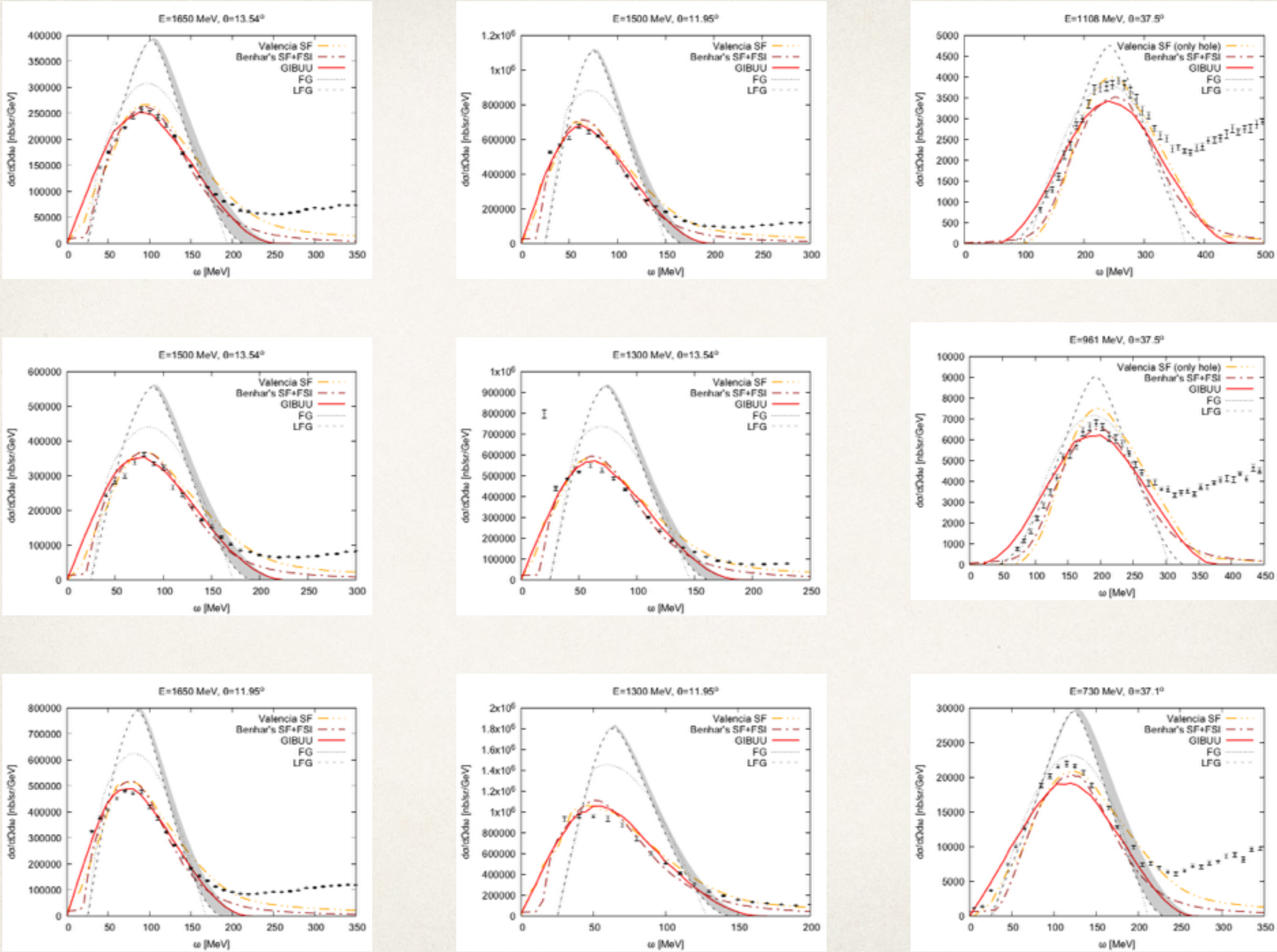

E=519 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

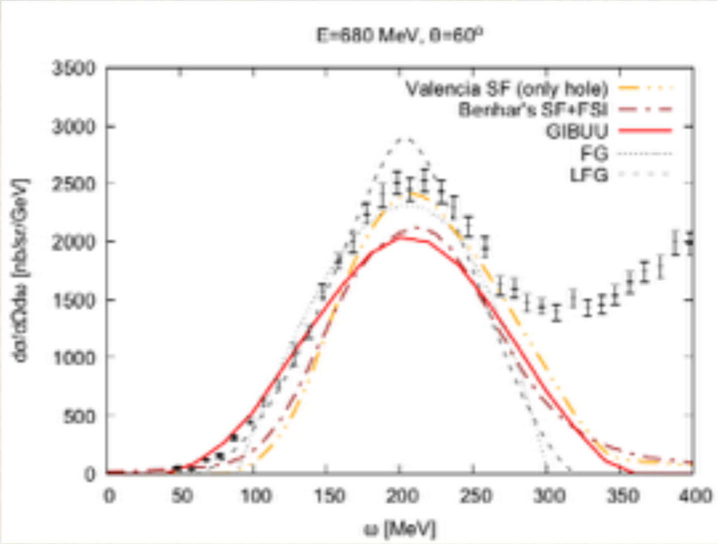

E=560 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

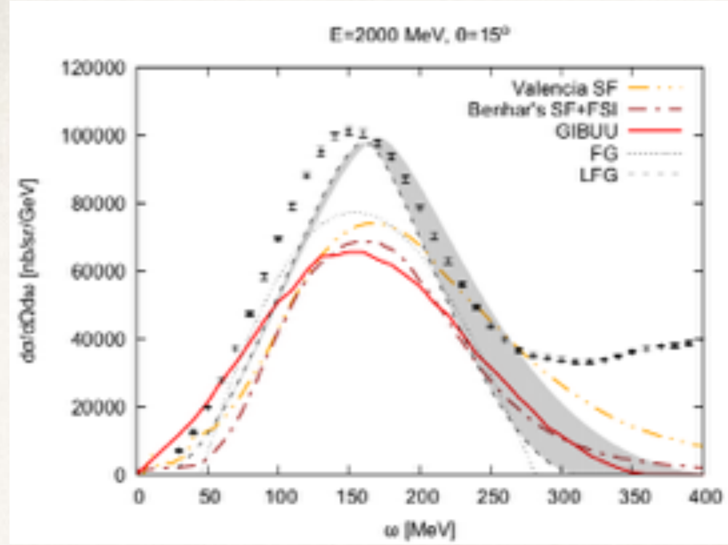

E=480 MeV, θ=60°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

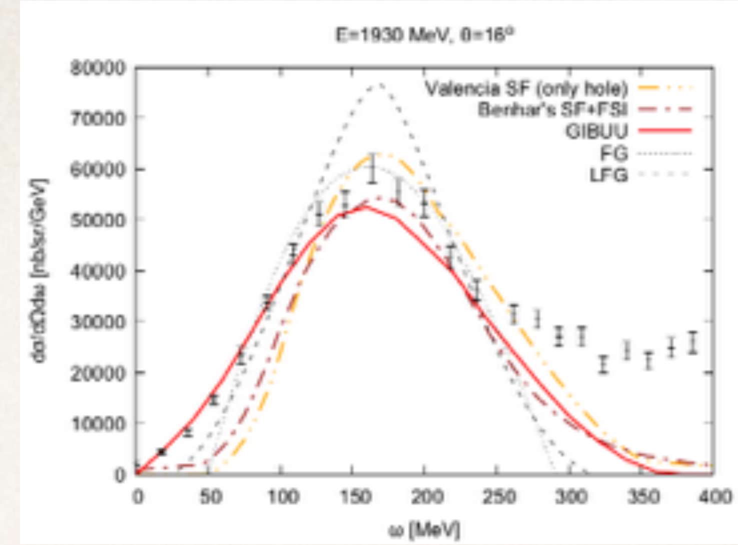

E=680 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

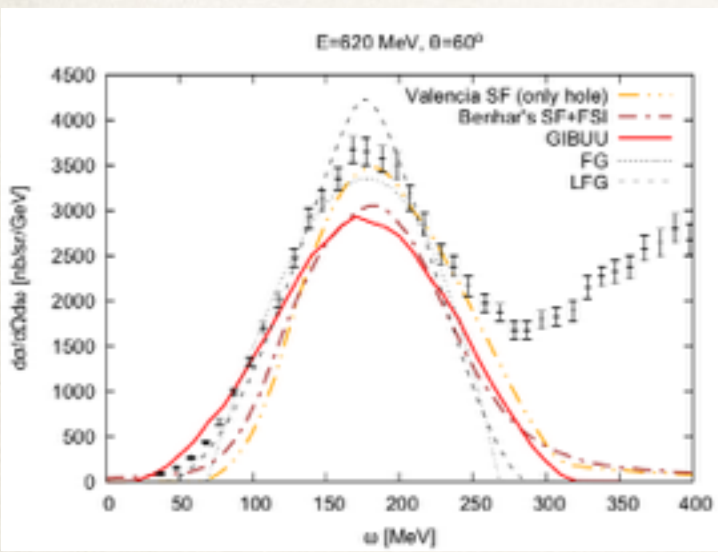

E=620 MeV, θ=36°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

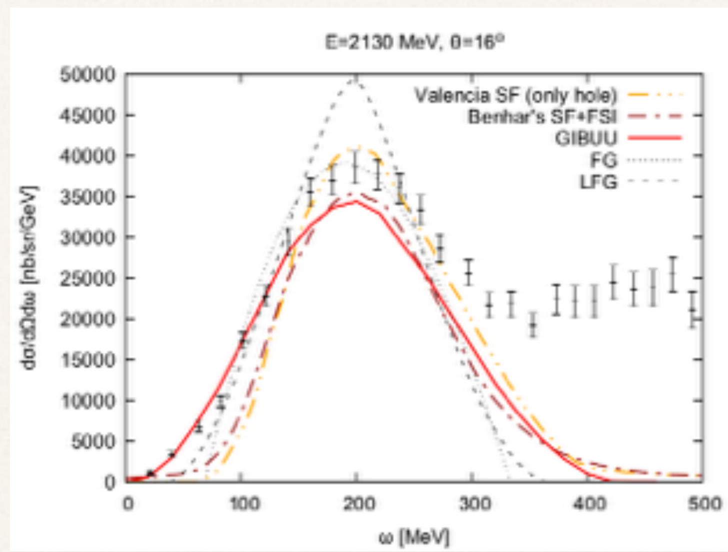

E=1650 MeV, θ=13.54°
E=1500 MeV, θ=11.95°
E=1108 MeV, θ=37.5°
E=1500 MeV, θ=13.54°
E=1300 MeV, θ=13.54°
E=961 MeV, θ=37.5°
E=1650 MeV, θ=11.95°
E=1300 MeV, θ=11.95°
E=730 MeV, θ=37.1°
Valencia SF
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

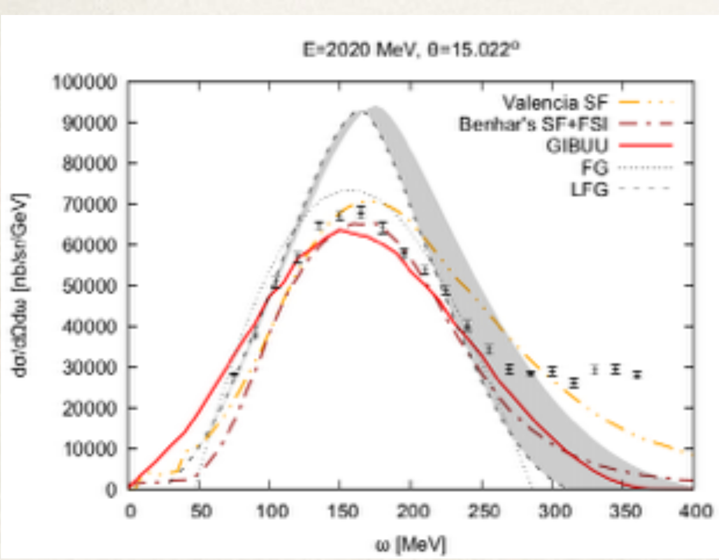

E=680 MeV, θ=60°
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]

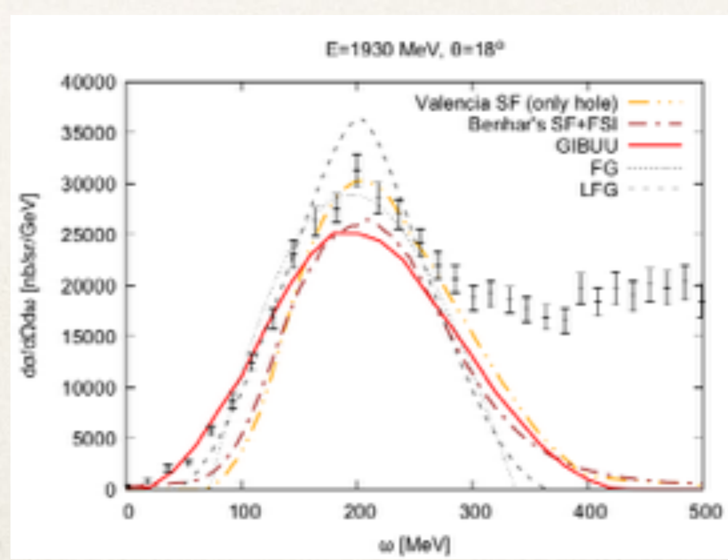

E=2000 MeV, θ=15°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


E=1930 MeV, θ=16°
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


E=620 MeV, θ=60°
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


E=2130 MeV, θ=16°
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


E=2020 MeV, θ=15.022°
Valencia SF
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]


E=1930 MeV, θ=18°
Valencia SF (only hole)
Benhar's SF+FSI
GIBUU
FG
LFG
dσ/dΩdω [nb/sr/GeV]
ω [MeV]