Optical potentials and knockout reactions from chiral interactions

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FUSTIPEN Workshop
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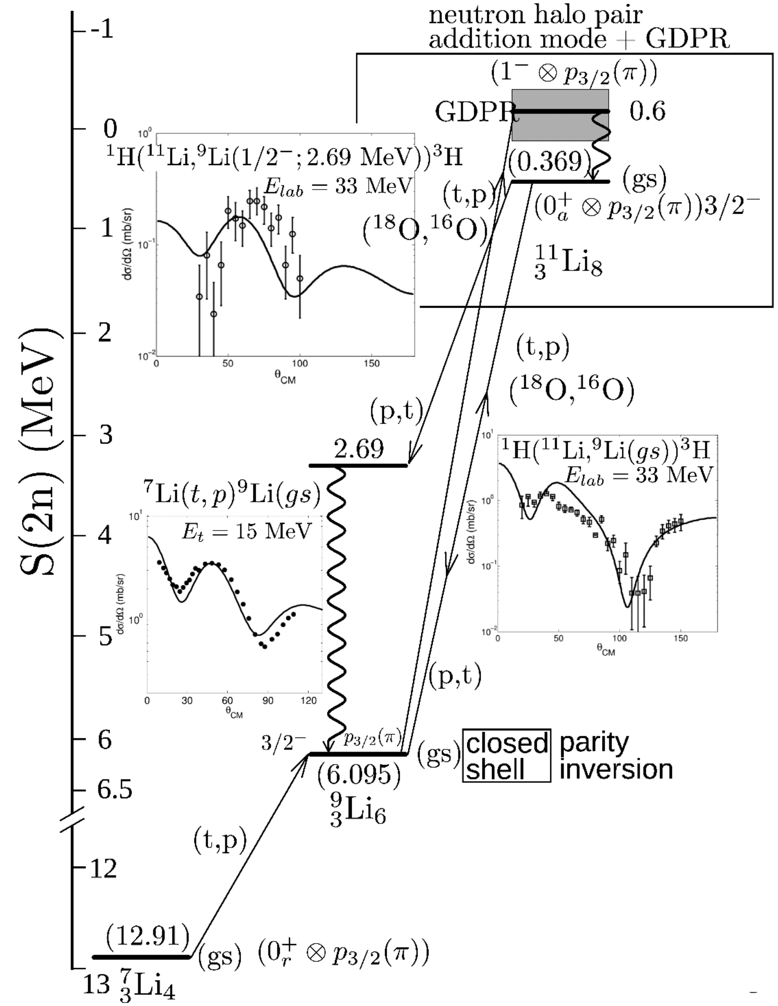
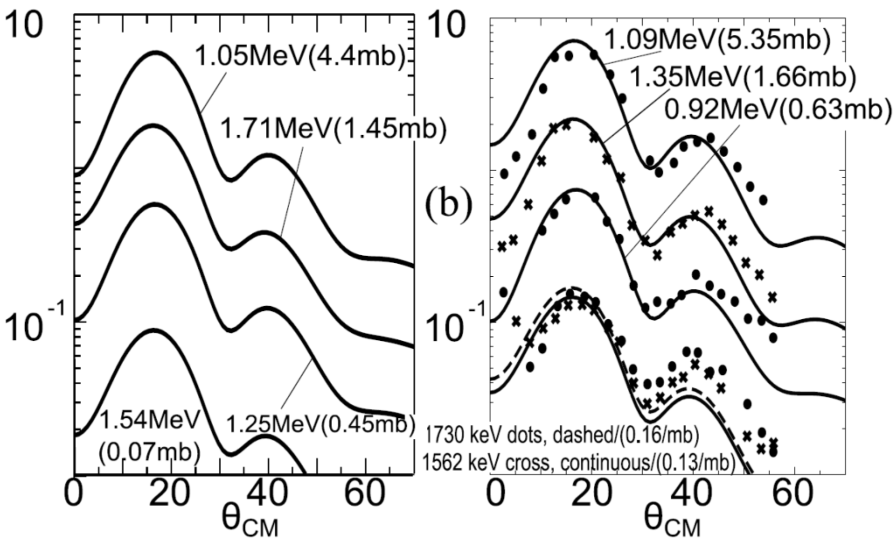
Why optical potentials?

- Optical potentials **reduce many-body complexity** decoupling structure contribution and reactions dynamics.
- Often fitted on elastic scattering data

2 particle transfer



1 particle transfer



A.I. et al. Phys. Rev. C **92**, 031304 (2015)

Broglia et al. *Phys. Scr.* **91** 06301* (2016)

Optical Potentials

Objective: an effective, consistent description of structure and reactions with a single formalism.
(Hopefully) Predictive power of nuclear reactions measurements over a range of exotic isotopes.

Method: Optical potential derived from Self Consistent Green Function and χEFT interactions.

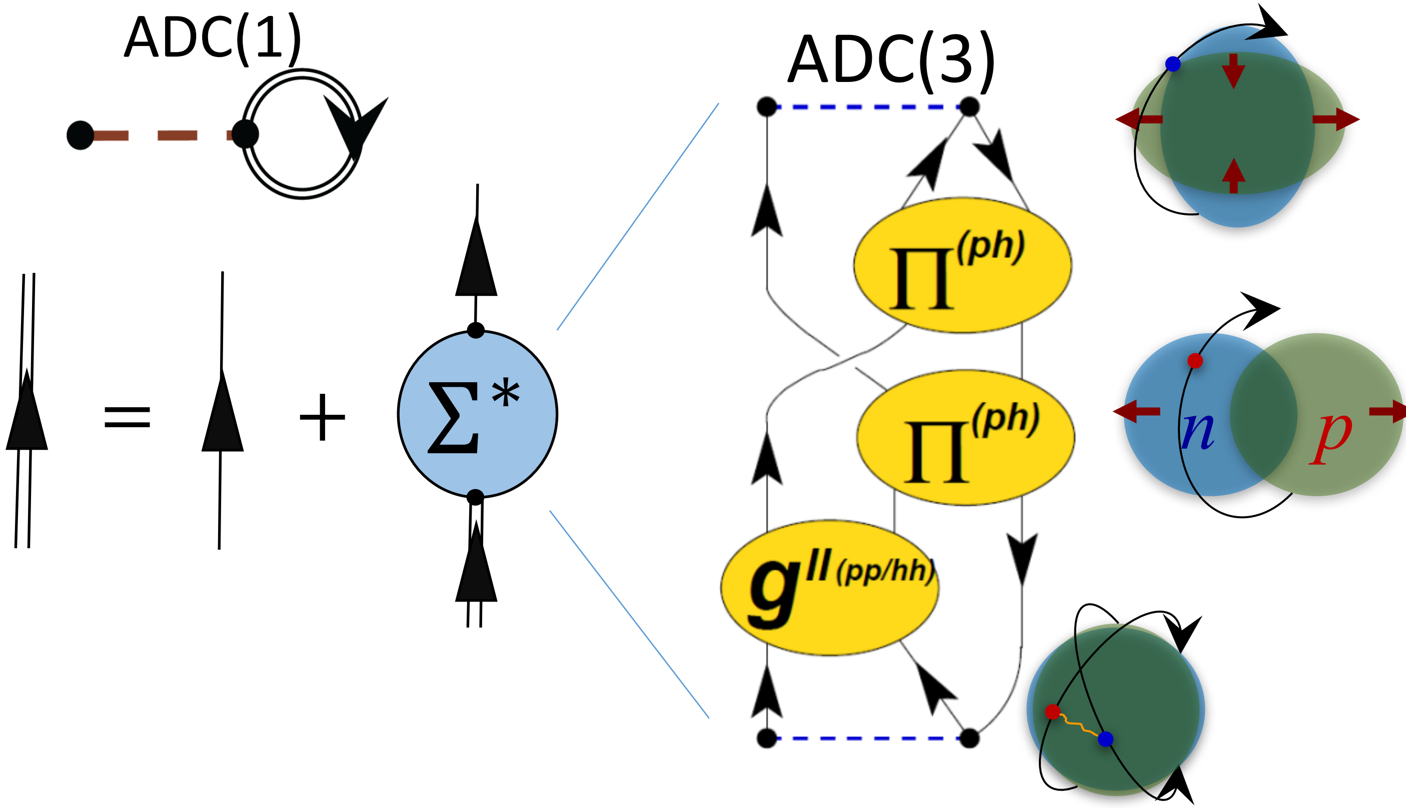
1. reproduce nuclear bulk properties, i.e. binding energy and radii; ***NNLO**$_{sat}$*
2. use the same description to consistently generate an optical potential reproducing elastic scattering data.

Green Functions *(Dyson Equation)*

$$g_{\alpha\beta}(\omega) = g^0_{\alpha\beta}(\omega) + \sum_{\gamma\delta} g^0_{\alpha\gamma}(\omega)\Sigma^\star_{\gamma\delta}(\omega)g_{\delta\beta}(\omega)$$

HF
ADC(1)

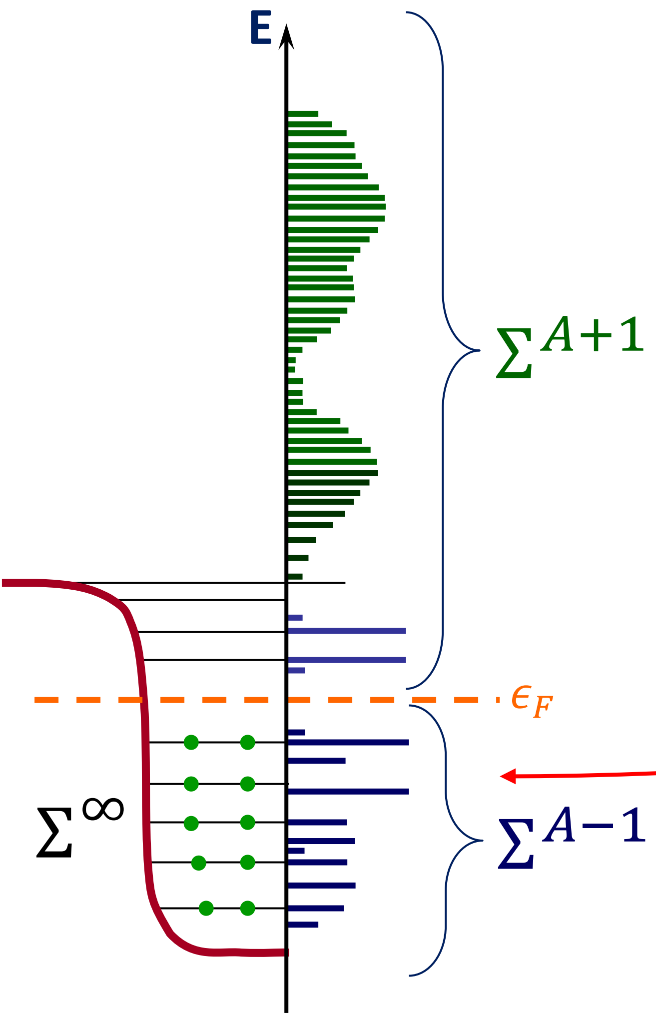
Faddeev RPA
ADC(3)



Particle hole 'polarization' propagator (ph-RPA)

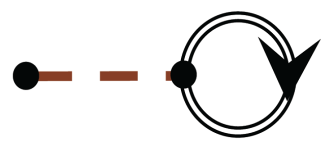
Particle-particle (pp-RPA) two-body correlation 'ladder' propagator

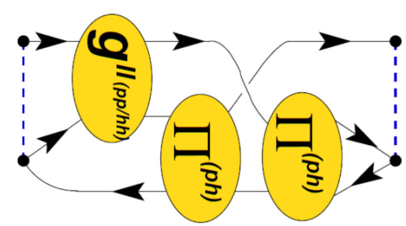
Nucleon elastic scattering



The irreducible self-energy is a nucleon-nucleus optical potential*

$$\Sigma^{*}_{\alpha\beta}(r,r';\omega) = \underbrace{\Sigma^{\infty}_{\alpha\beta}}_{\text{correlated mean-field}} + \underbrace{\sum_i \frac{m^i_\alpha\, m^{i*}_\beta}{\omega - \epsilon_i \pm i\eta}}_{\text{resonances beyond mean-field}}$$





Correlations

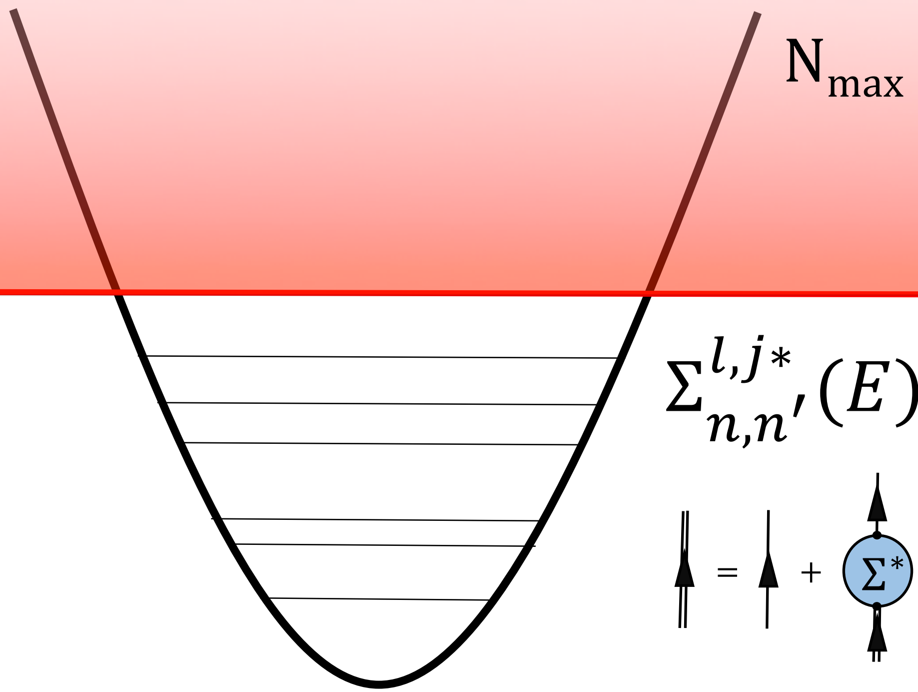
➔ This provides *consistent* many-body and scattering wave functions

*Mahaux & Sartor, Adv. Nucl. Phys. 20 (1991), Escher & Jennings PRC66:034313 (2002)

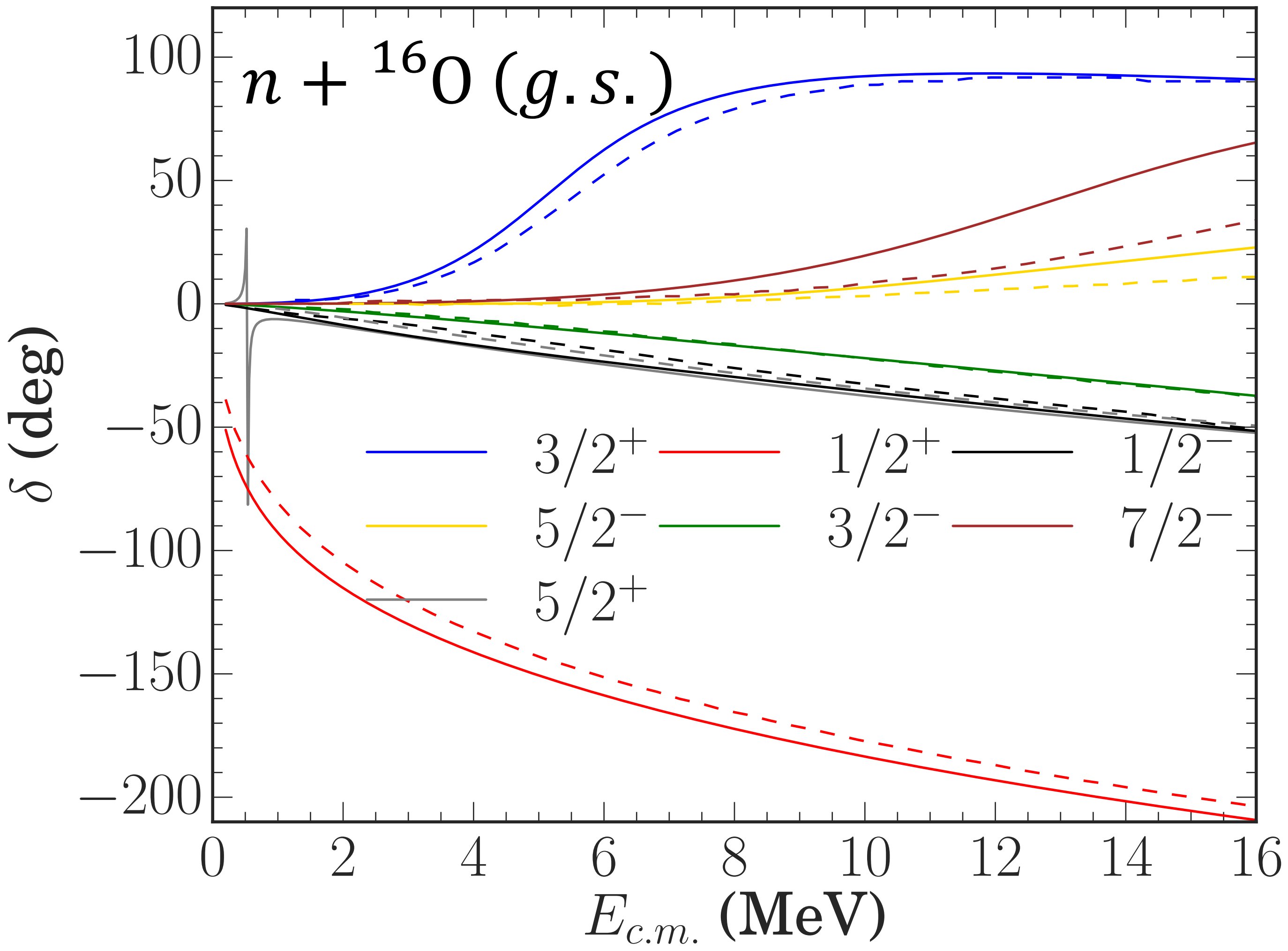
- Solve Dyson equation in HO Space, find $\Sigma^{l,j*}_{n,n'}(E)$

- diagonalize in full continuum momentum space $\Sigma^{l,j*}(k,k',E)$

$$\frac{k^2}{2m}\psi_{l,j}(k) + \int dk' k'^2 \left(\Sigma^{l,j*}(k,k',E)\right)\psi_{l,j}(k') = \mathrm{E}\,\psi_{l,j}(k)$$

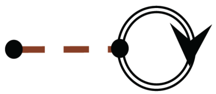


SRG-N^{3}LO, $\Lambda = 2.66\ \mathrm{fm}^{-1}$



Navràtil, Roth, Quaglioni, PRC82, 034609 (2010)

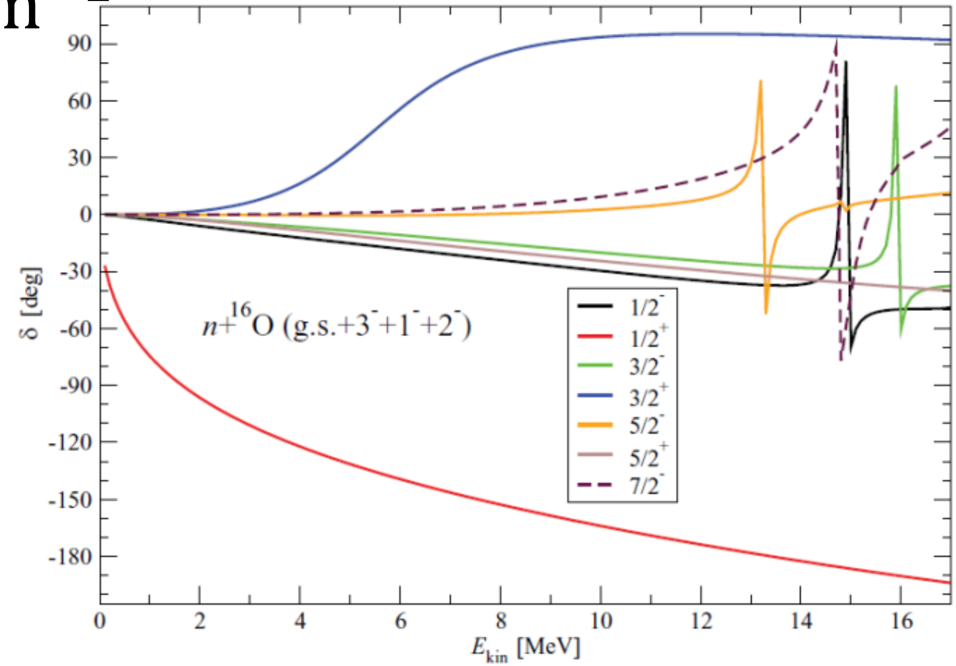
Σ^{∞}



SRG-N^{3}LO, $\quad \Lambda = 2.66\ \mathrm{fm}^{-1}$

Navràtil, Roth, Quaglioni,
PRC82, 034609 (2010)

$n + {}^{16}\mathrm{O}$



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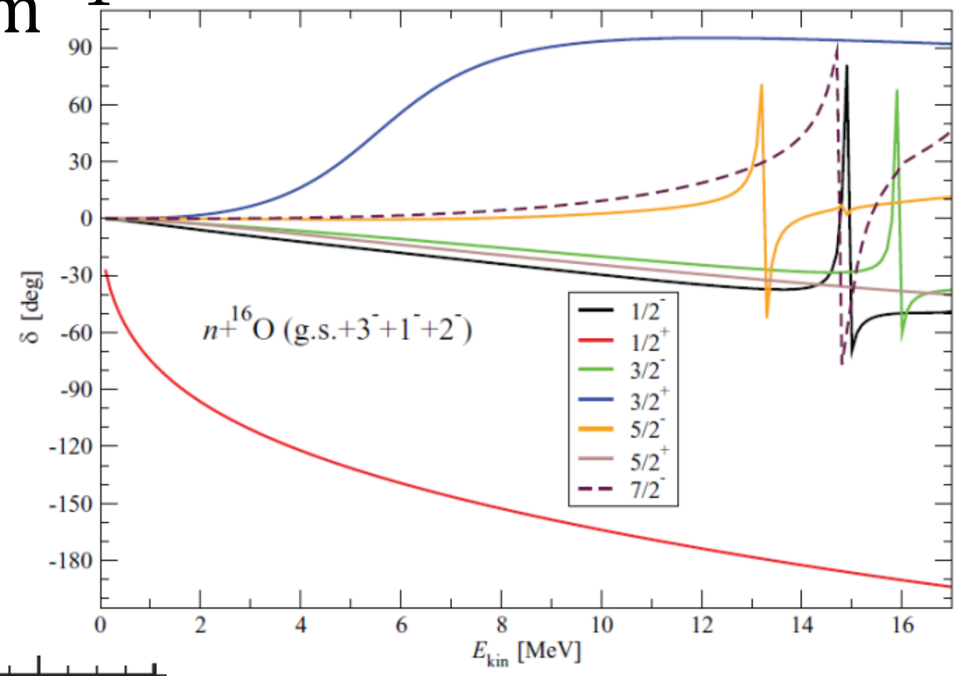
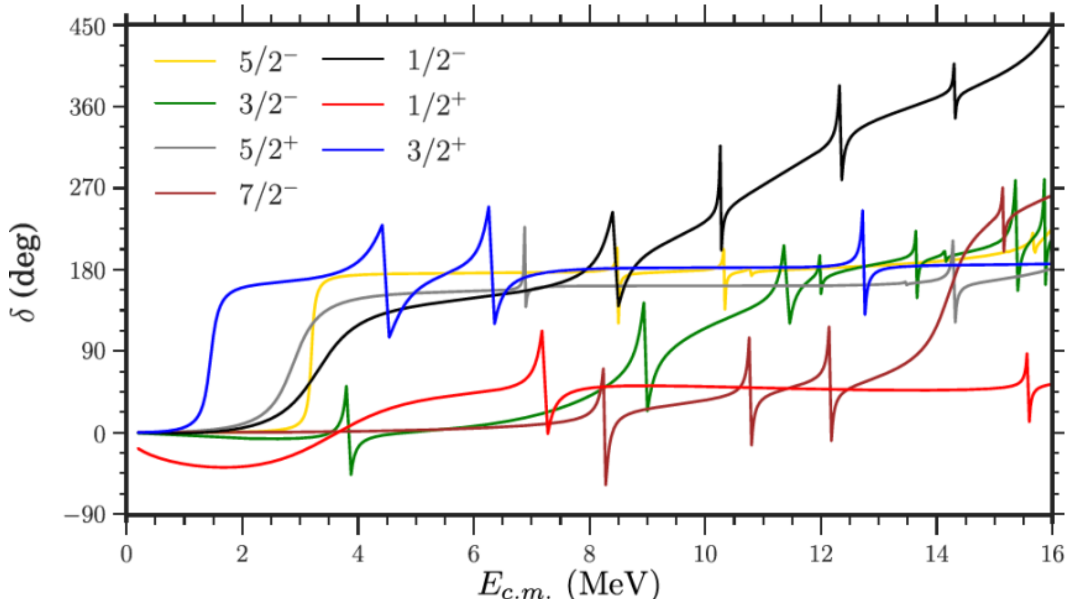
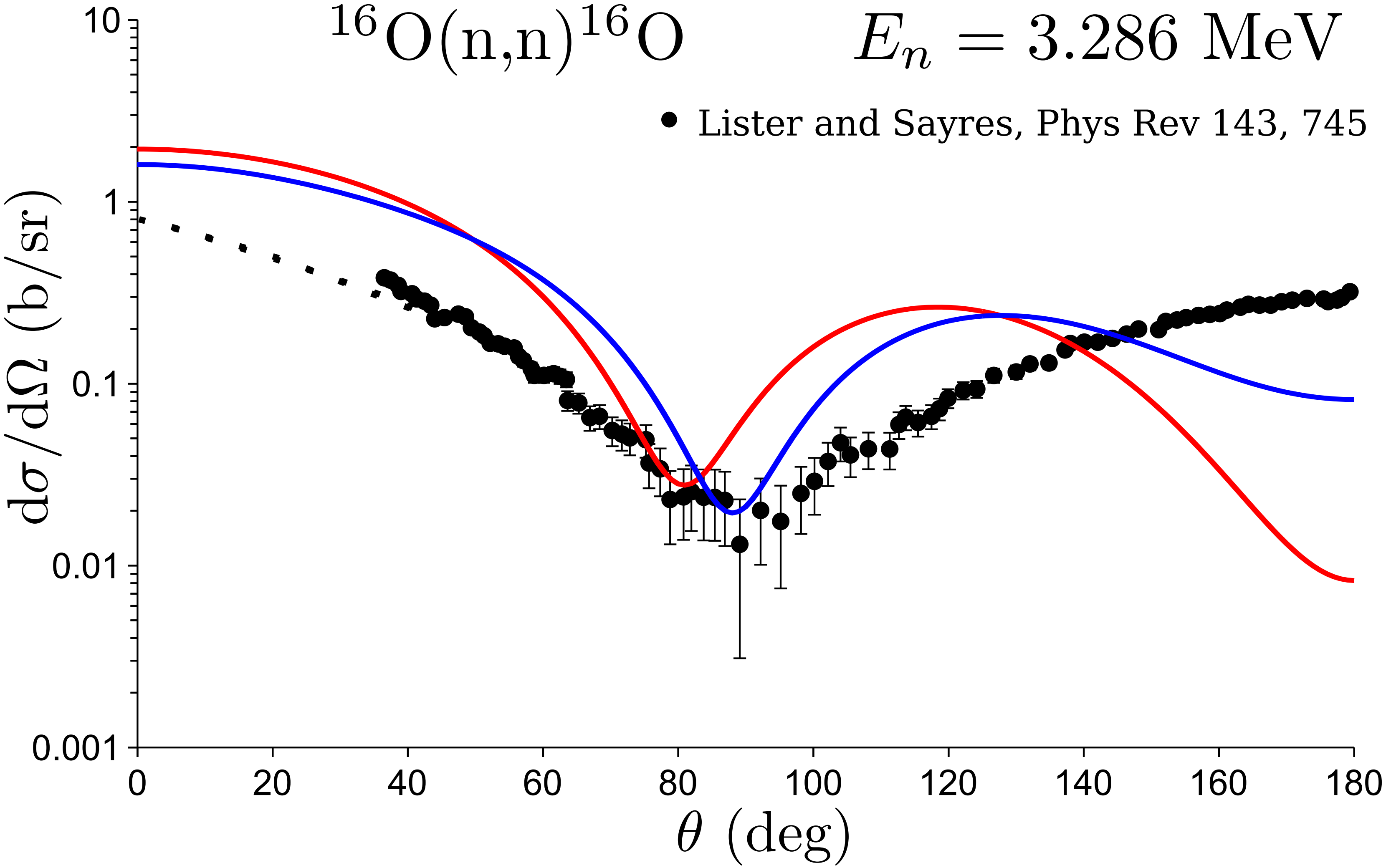


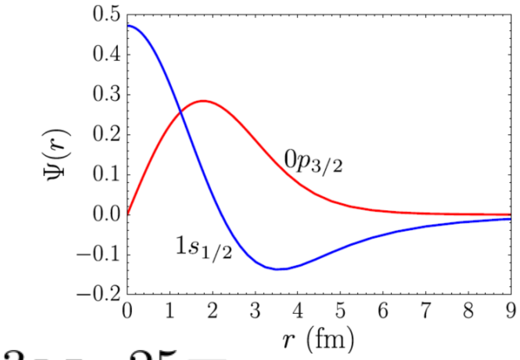


Using the ab initio optical potential for neutron elastic scattering on Oxygen

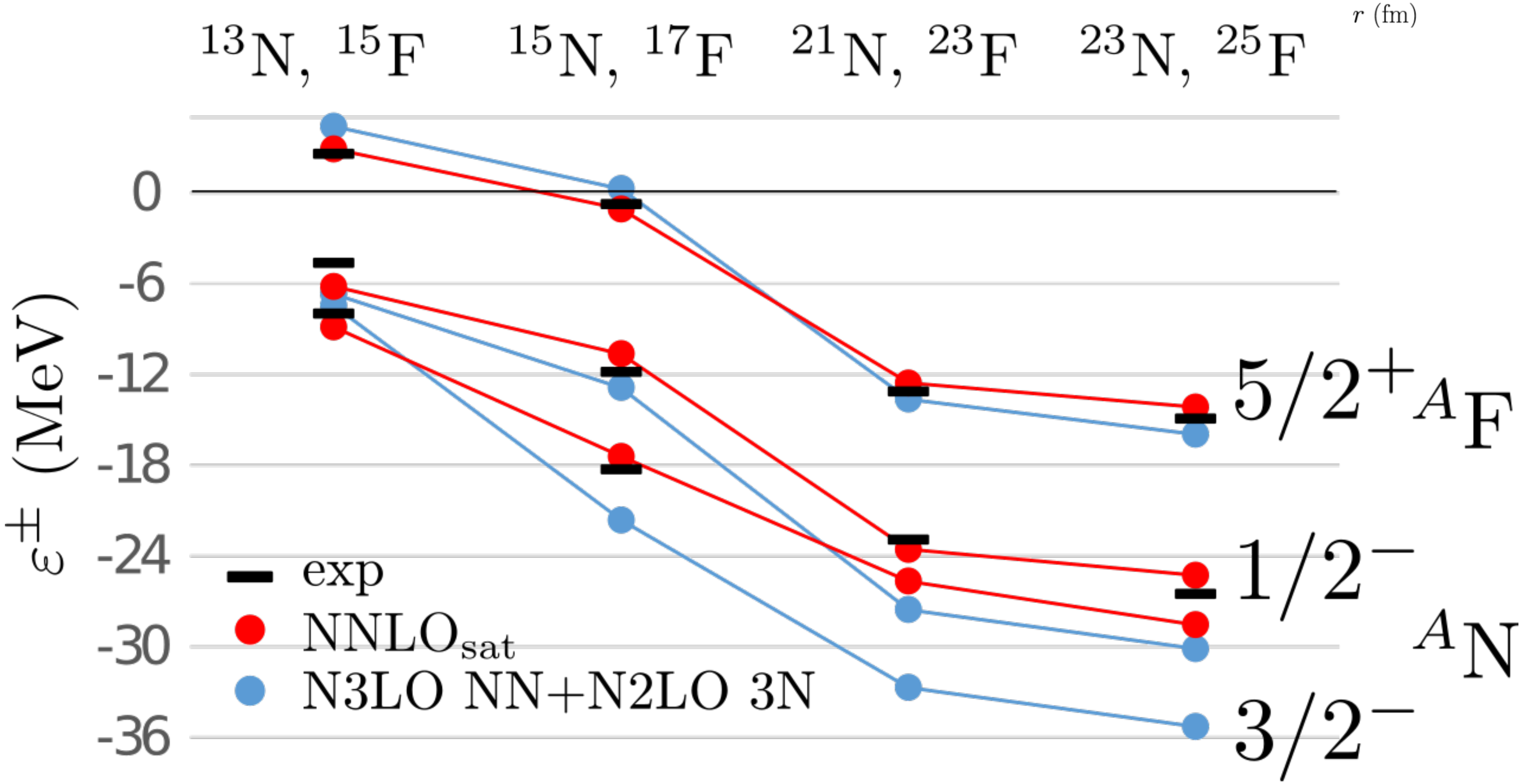


Overlap function

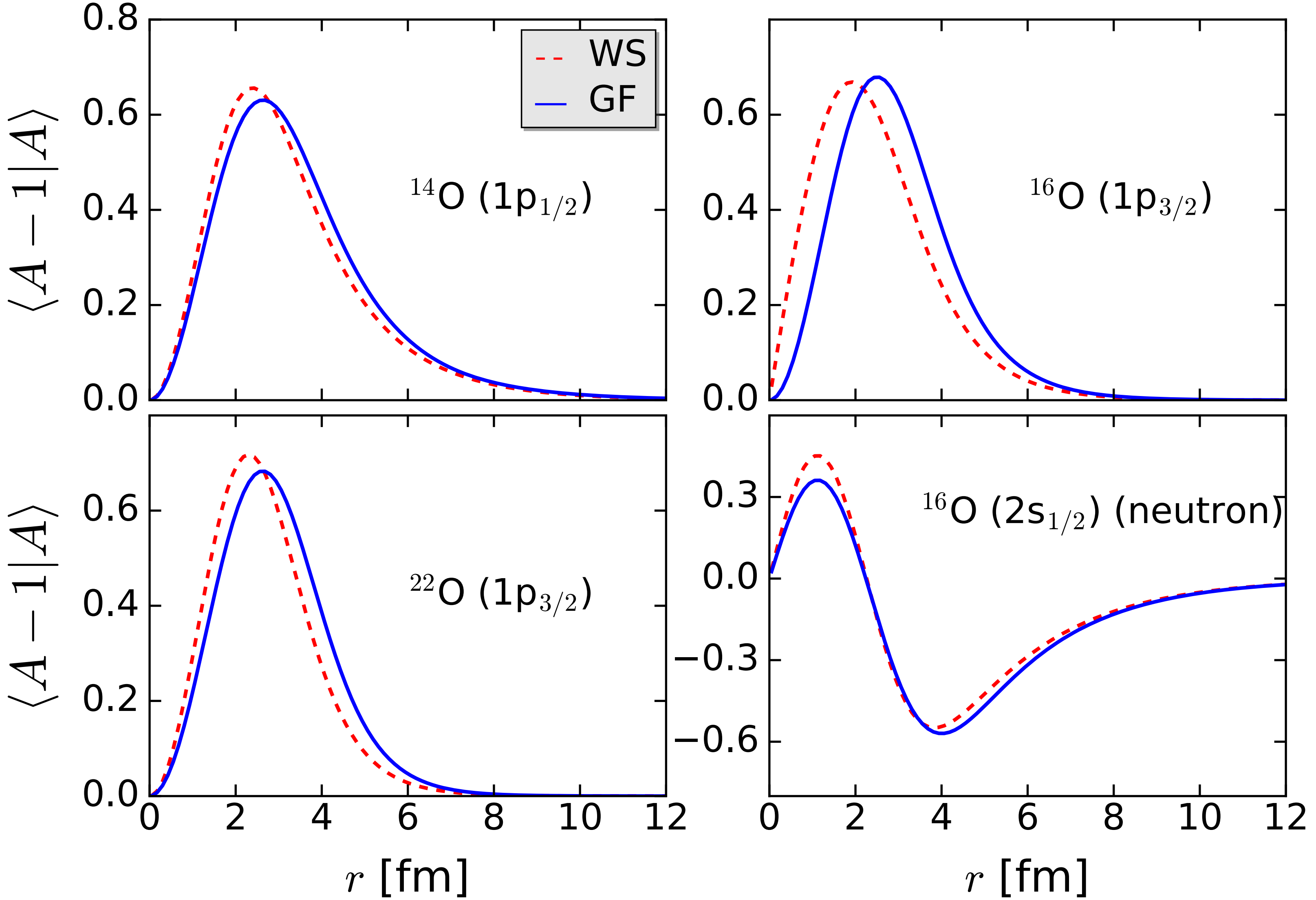
$$\Psi_i(r) = \sqrt{A}\int dr_1 \underset{r_i}{\cancel{\ldots}} dr_A \Phi^+_{(A-1)}(r_1, \underset{r_i}{\cancel{\ldots}}, r_{A-1})\Phi^+_{(A)}(r_1, \underset{r_i}{\cancel{\ldots}}, r_A)$$



Proton particle-hole gap



EM results from A. Cipollone PRC**92**, 014306 (2015)

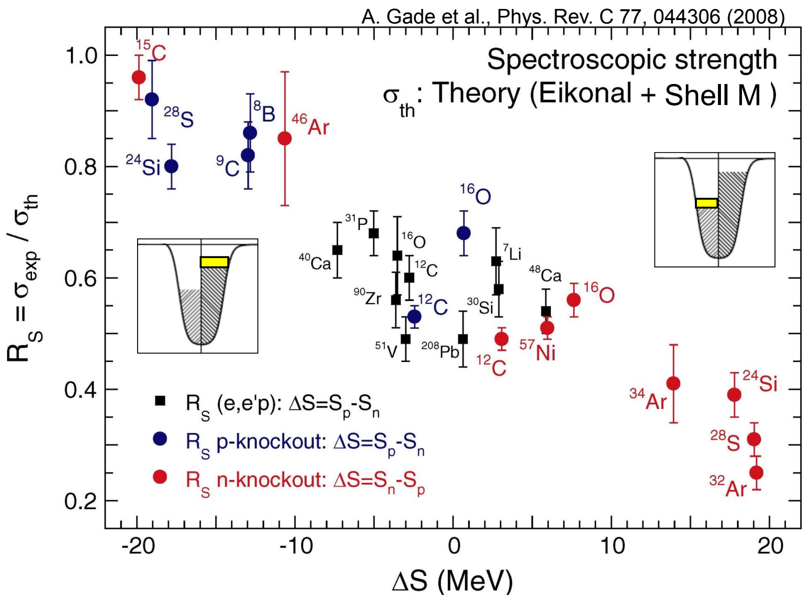


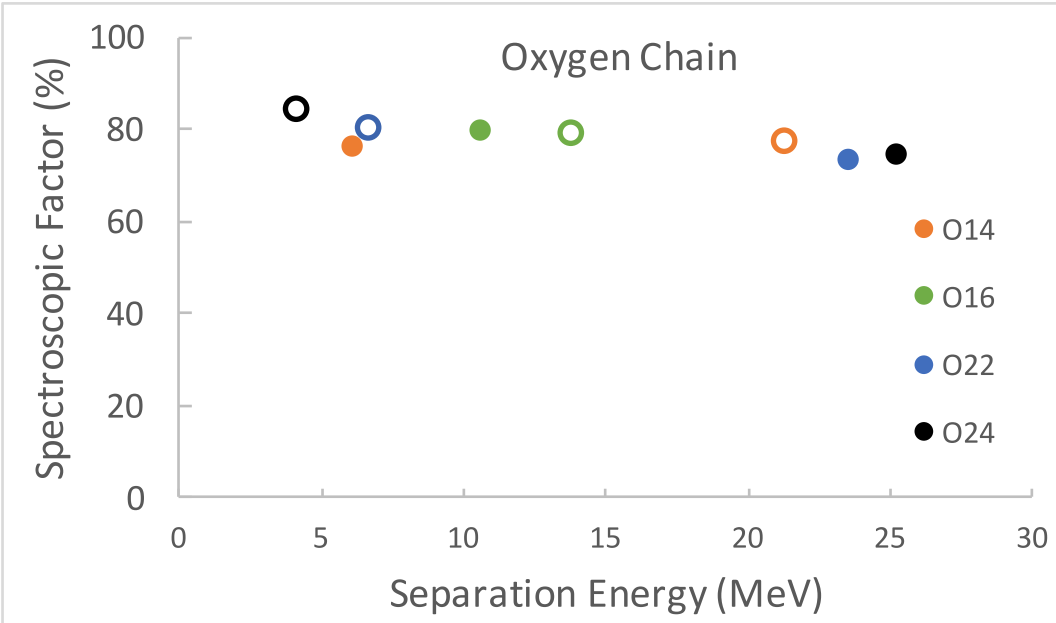
Collaboration with C. Bertulani

Knockout Spectroscopic Factors

$$\frac{k^2}{2m}\psi_{l,j}(k) + \int dk' k'^2 \left(\Sigma^{l,j*}(k,k',E)\right)\psi_{l,j}(k') = \mathrm{E}\,\psi_{l,j}(k)$$

$$SF = \left|\left\langle \Phi_n^{(A-1)} \middle| \Phi_{g.s.}^A \right\rangle\right|^2$$





open circles neutrons, closed protons

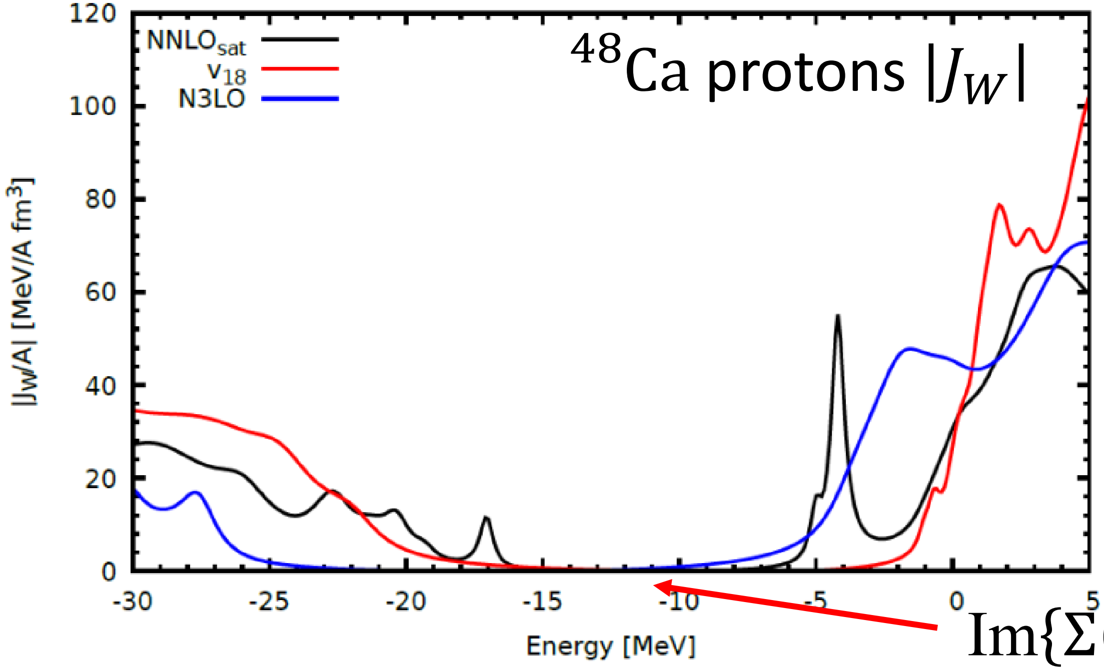
Volume integrals

$$J_W^\ell(E) = 4\pi \int drr^2 \int dr' r'^2 \mathrm{Im}\ \Sigma_0^\ell(r, r', E)$$

Non local potential

$$J_V^\ell(E) = 4\pi \int drr^2 \int dr' r'^2 \mathrm{Re}\ \Sigma_0^\ell(r, r'; E).$$

$$\tilde{\Sigma}^{\ell j}_{n_a,n_b}(E) = \sum_r \frac{m^r_{n_a} m^r_{n_b}}{E - \varepsilon_r \pm i\eta}$$



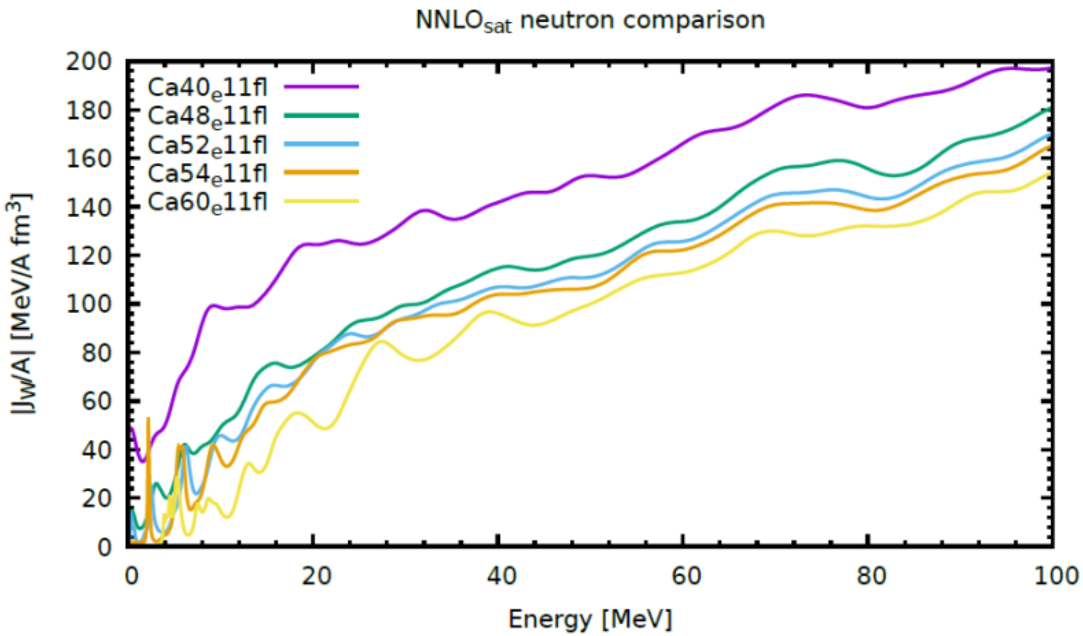
$\mathrm{Im}\{\Sigma(\epsilon_F)\} = 0$

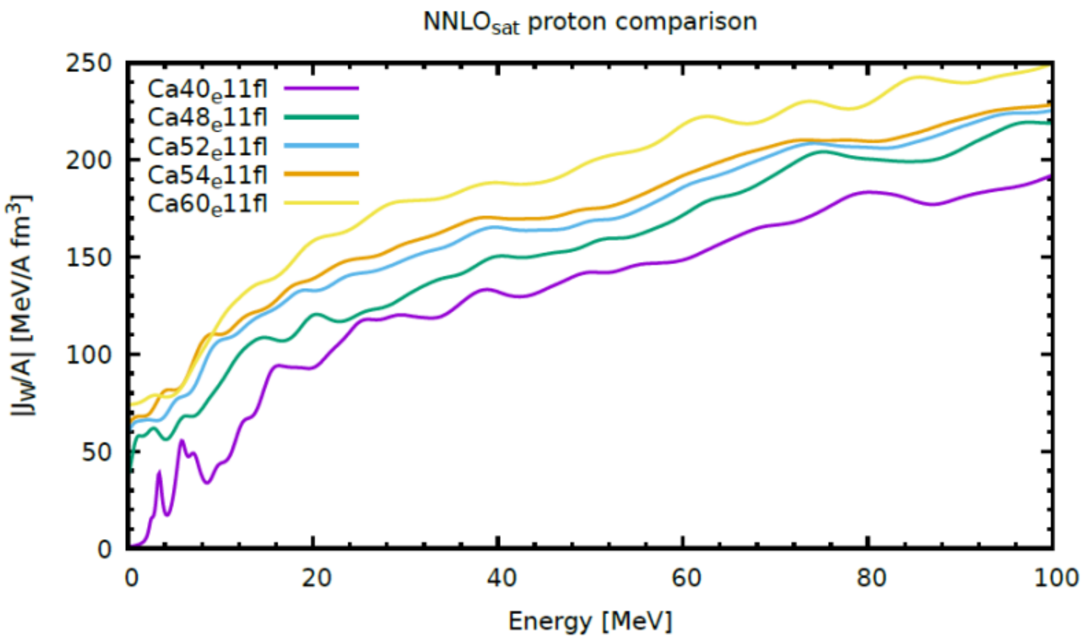
different Fermi energies and particle-hole gap for different interactions

S. Waldecker et al. PRC**84**, 034616(2011)

Ca isotopes

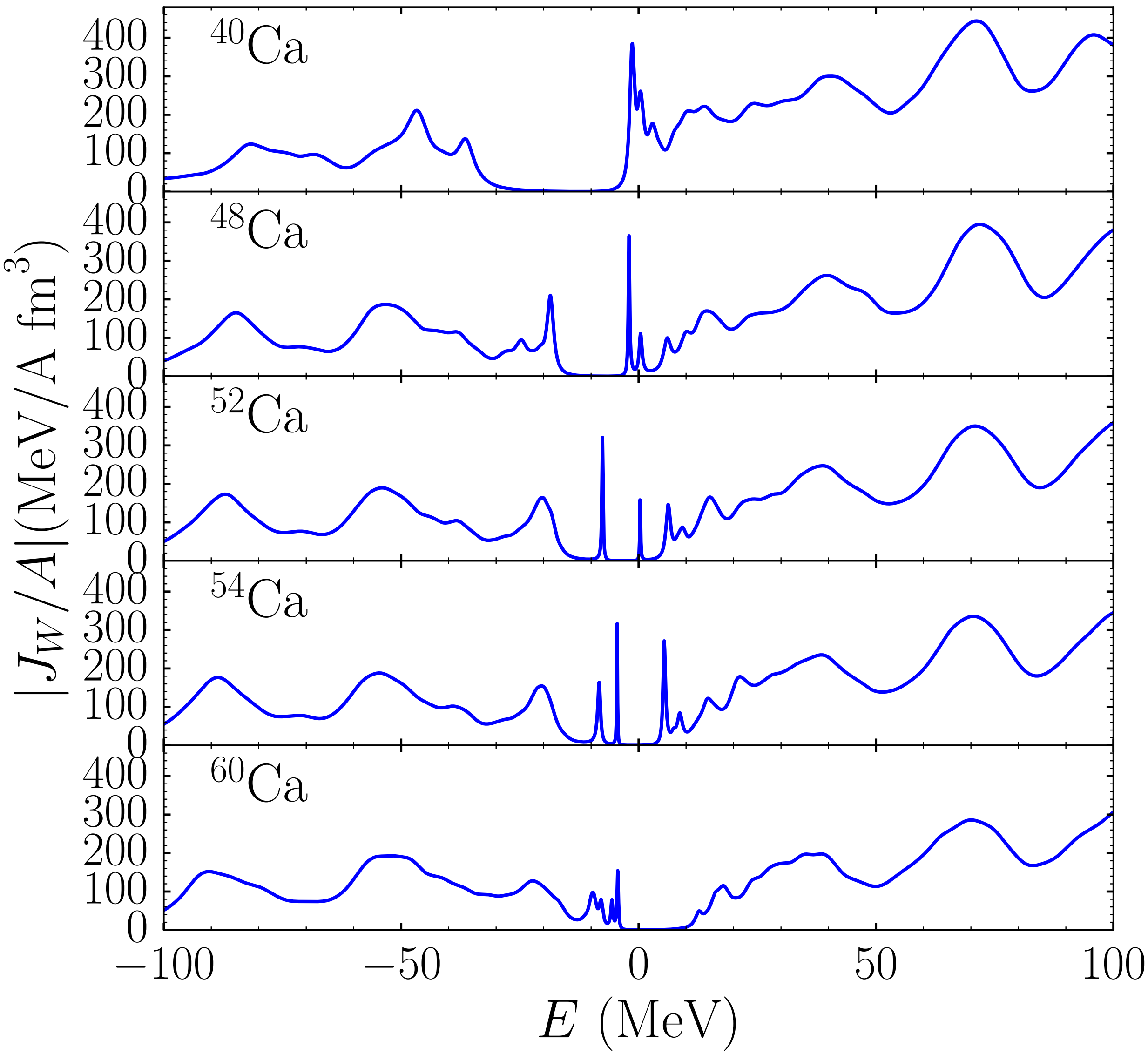
neutron and proton volume integrals of self energies.





Ca isotopes

neutron volume integrals of self energies.



Derivation of model density functionals

Lagrange multiplier

$$\delta E' = \delta\langle\Psi|\hat{H} - \sum_{j=1}^{m} \lambda^j \hat{V}_j|\Psi\rangle = 0,$$

Ab initio solution used for variational problem

Model (ab initio) one body densities

$$V_i[\rho_{\lambda_j}] = \langle\Psi(\lambda_j)|\hat{V}_i|\Psi(\lambda_j)\rangle$$

Model (Ab initio) Energies

$$E(\lambda^j) = \sum_{i=1}^{m} C^i V_i\left[\rho_{\lambda^j}\right]$$

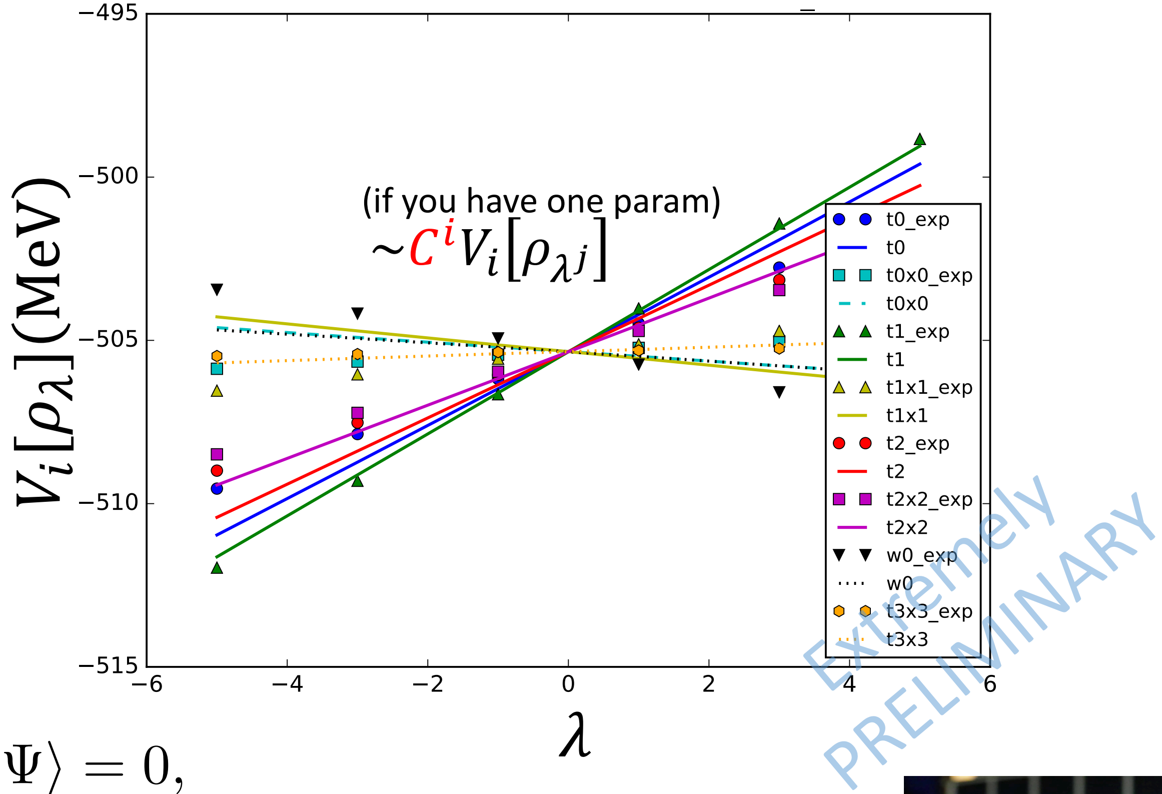
Coupling constants extracted with **linear regression**

Dobaczewski JPG43, 04LT01 (2016)

^{16}O

CD-Bonn Interaction without Coulomb 2nd order on Skyrme SV

Model energy

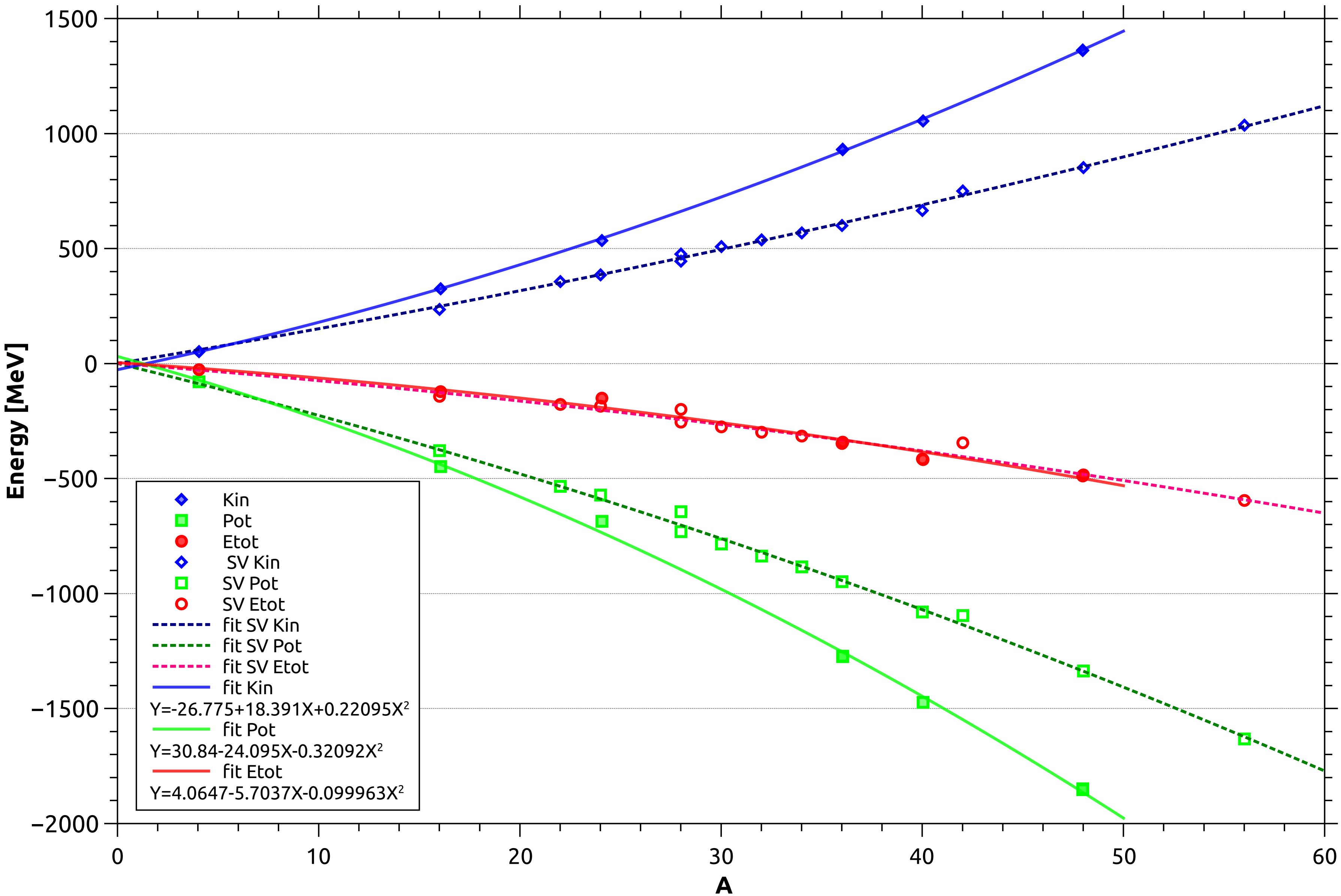


$$\delta E' = \delta\langle\Psi|\hat{H} - \sum_{j=1}^{m} \lambda^j \hat{V}_j|\Psi\rangle = 0,$$

$$E(\lambda^j) = \sum_{i=1}^{m} C^i V_i[\rho_{\lambda^j}]$$

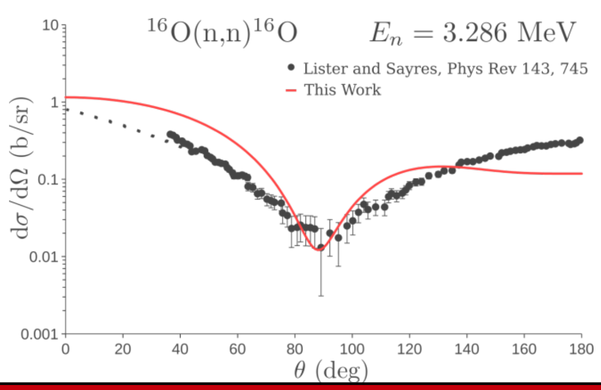
Gianluca Salvioni, PhD Jyvaskyla

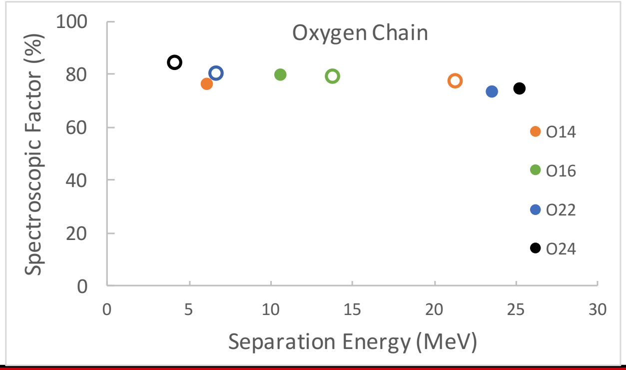
CD_Bonn-V_Coul (case λ=0) vs SV

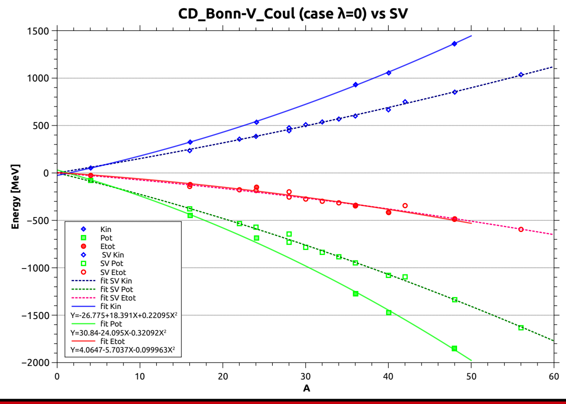


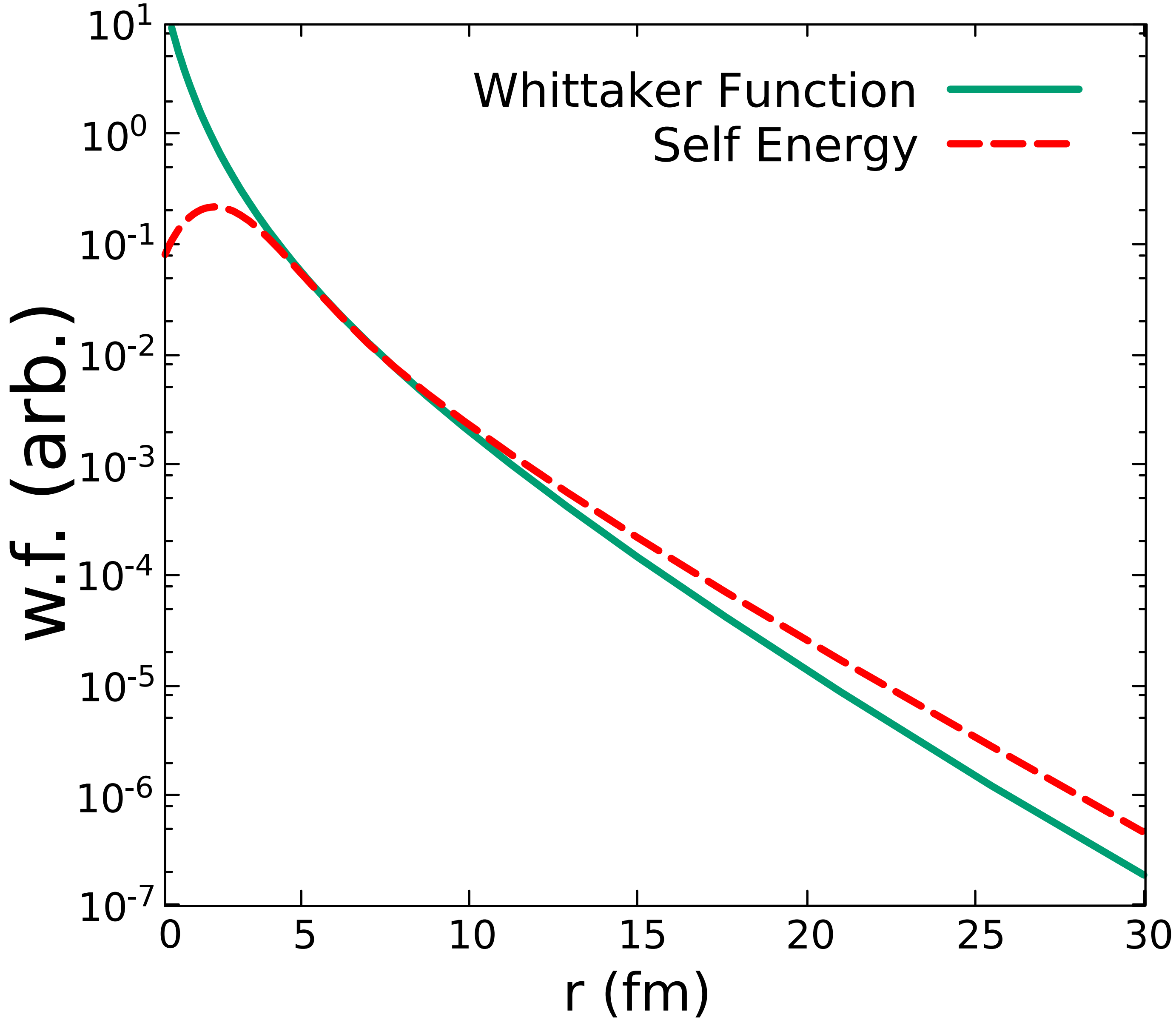
Conclusions and Perspectives

- We are developing an interesting tool to study nuclear reactions effectively.
  We have defined a non-local generalized optical potential corresponding to nuclear self energy.
- This tool is useful to probe properties of nuclear interactions.
- Spectroscopic Factors from ab-initio overlap wavefunctions do not seem to depend much on proton-neutron asymmetry







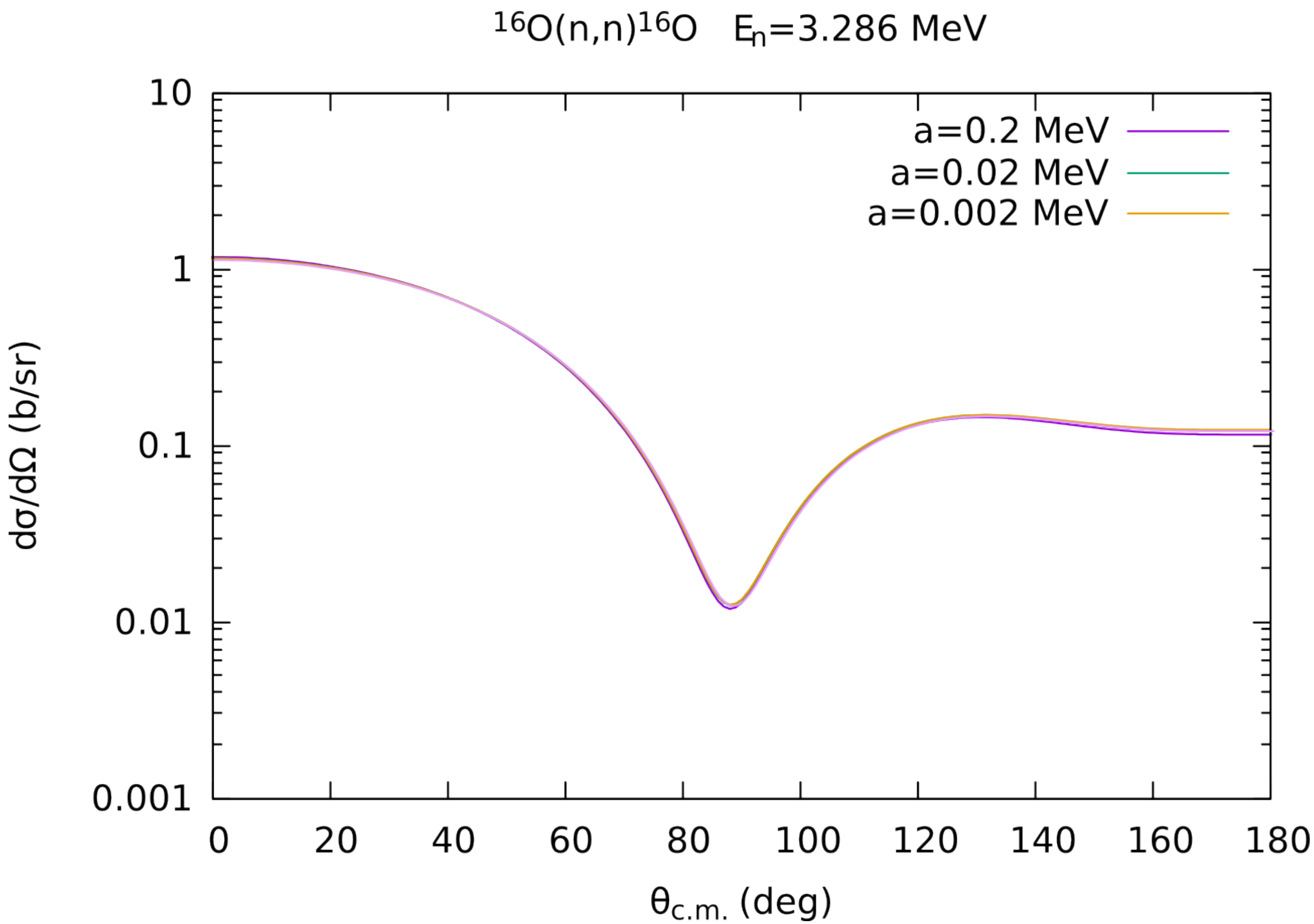


Whittaker Function
Self Energy
w.f. (arb.)
r (fm)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
5
10
15
20
25
30

«Imaginary» Parameter

$$\Gamma(E) = \frac{1}{\pi} \frac{a\,(E - E_F)^2}{(E - E_F)^2 - b^2}$$

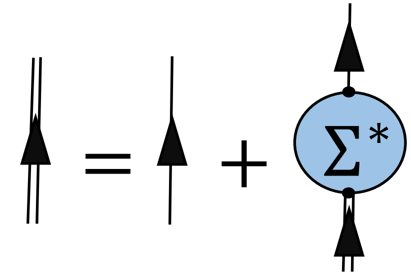
$b = 22.36$ MeV



Why Green's Functions?

Dyson Equation

$$g_{\alpha\beta}(\omega) = g^0_{\alpha\beta}(\omega) + \sum_{\gamma\delta} g^0_{\alpha\gamma}(\omega)\Sigma^\star_{\gamma\delta}(\omega)g_{\delta\beta}(\omega)$$



Equation of motion

$$\left(E + \frac{\hbar^2}{2m}\nabla^2_r\right)G(\mathbf{r},\mathbf{r}';E) - \int d\mathbf{r}''\Sigma(\mathbf{r},\mathbf{r}'';E)G(\mathbf{r}'',\mathbf{r}';E) = \delta(\mathbf{r}-\mathbf{r}')$$

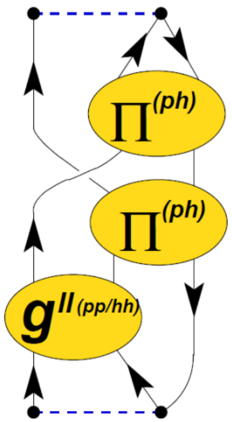
Corresponding Hamiltonian

$$\mathcal{H}_{\mathcal{M}}(\mathbf{r},\mathbf{r}') = -\frac{\hbar^2}{2m}\nabla^2_r\delta(\mathbf{r}-\mathbf{r}') + \Sigma(\mathbf{r},\mathbf{r}';E+i\epsilon)$$

Σ corresponds to the Feshbach's generalized optical potential

Escher & Jennings PRC66 034313 (2002)

$$\Sigma^{\star}_{\alpha\beta}(\omega) = \Sigma^{(\infty)}_{\alpha\beta} + \sum_{i,j} \mathbf{M}^{\dagger}_{\alpha,i} \left[\frac{1}{\omega - (\mathbf{K}^{>} + \mathbf{C}) + i\eta} \right]_{i,j} \mathbf{M}_{j,\beta} + \sum_{r,s} \mathbf{N}_{\alpha,r} \left[\frac{1}{\omega - (\mathbf{K}^{<} + \mathbf{D}) - i\eta} \right]_{r,s} \mathbf{N}^{\dagger}_{s,\beta}$$

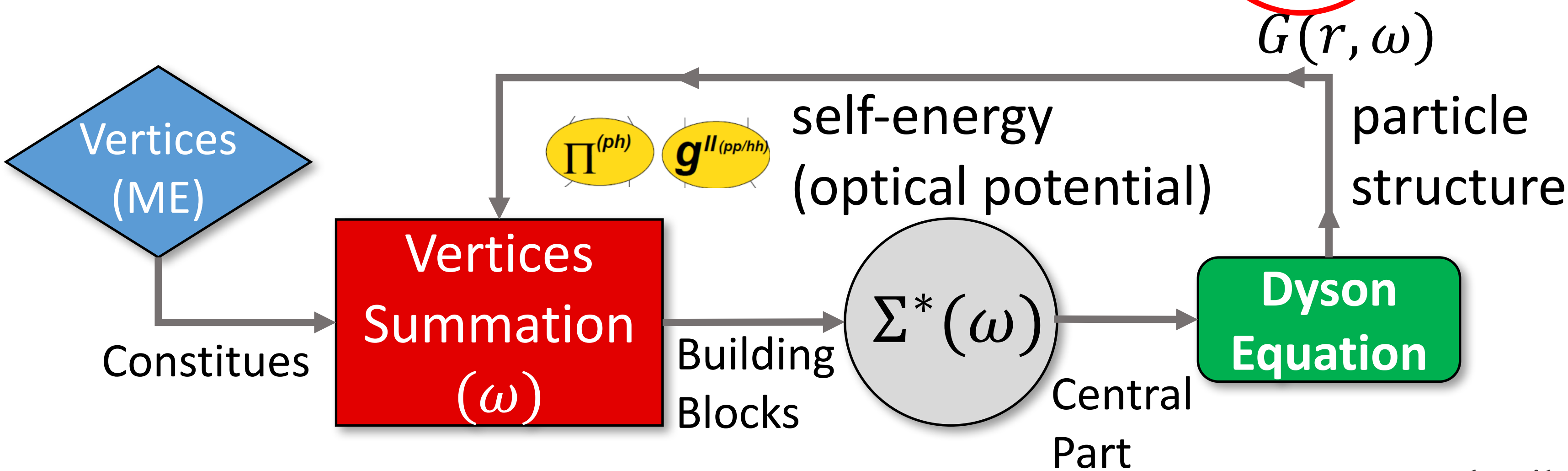


2p1h

2p2h

Unknown

$$\begin{pmatrix} \widehat{T} + \Sigma^{(\infty)} & M^{\dagger} & N \\ M & E^{>} + C & \\ N^{\dagger} & & E^{<} + D \end{pmatrix} \begin{pmatrix} \mathcal{Z}^{i} \\ \mathcal{W}^{i} \\ \mathcal{V}^{i} \end{pmatrix} = \begin{pmatrix} \mathcal{Z}^{i} \\ \mathcal{W}^{i} \\ \mathcal{V}^{i} \end{pmatrix} \varepsilon_{i}$$



More details in C. Barbieri, A. Carbone Lect. Notes Phys. arXiv:1611.03923 [nucl-th]

Dipole Response and Polarizability

With
<u>Francesco Raimondi</u>

$$R(E) = \sum_i \left| \langle \psi_i^A | \hat{D} | \psi_0^A \rangle \right|^2 \delta(E_i - E)$$

$$\sum_{\alpha\beta} \langle \alpha | \hat{D} | \beta \rangle \langle \psi_i^A | c_\alpha^\dagger c_\beta | \psi_0^A \rangle$$

HO ME

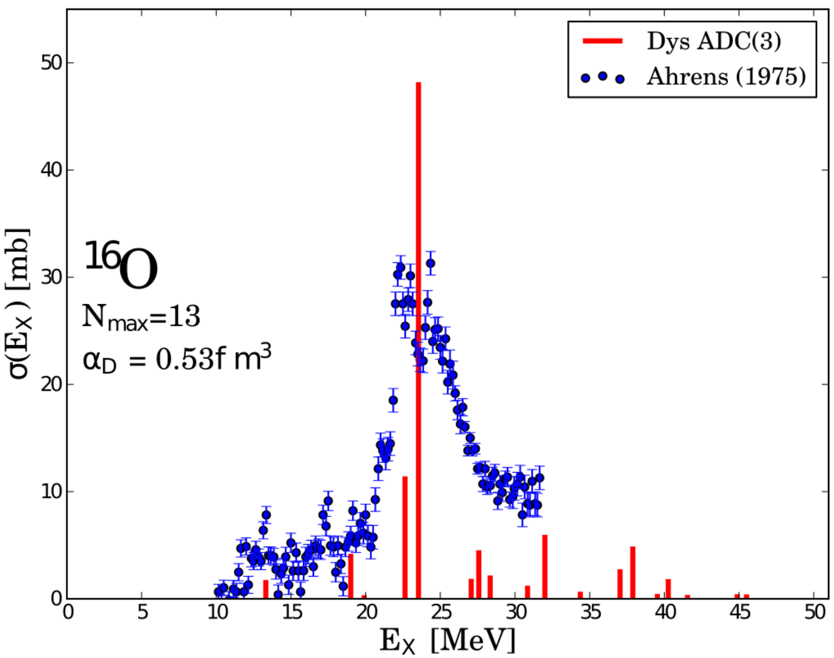
RPA

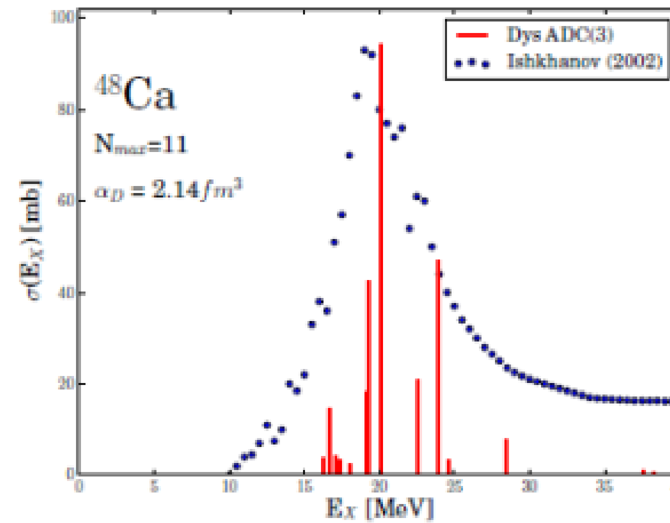
$$\sigma_\gamma(E) = 4\pi^2 \alpha E R(E)$$

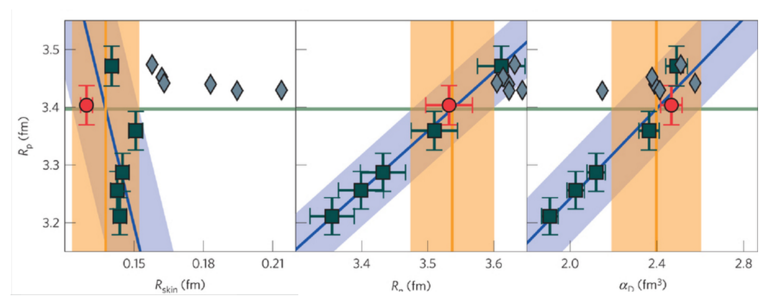
$$\alpha_D = 2\alpha \int dE \, R_Z(E)/E$$

Dipole polarizability α_D (fm^3)

Nucleus	SCGF	CC/LIT	Exp
^{40}Ca	1.89	1.47 $(1.87)_{thresh}$	1.87(3)
^{48}Ca	2.14	2.45	2.07(22)

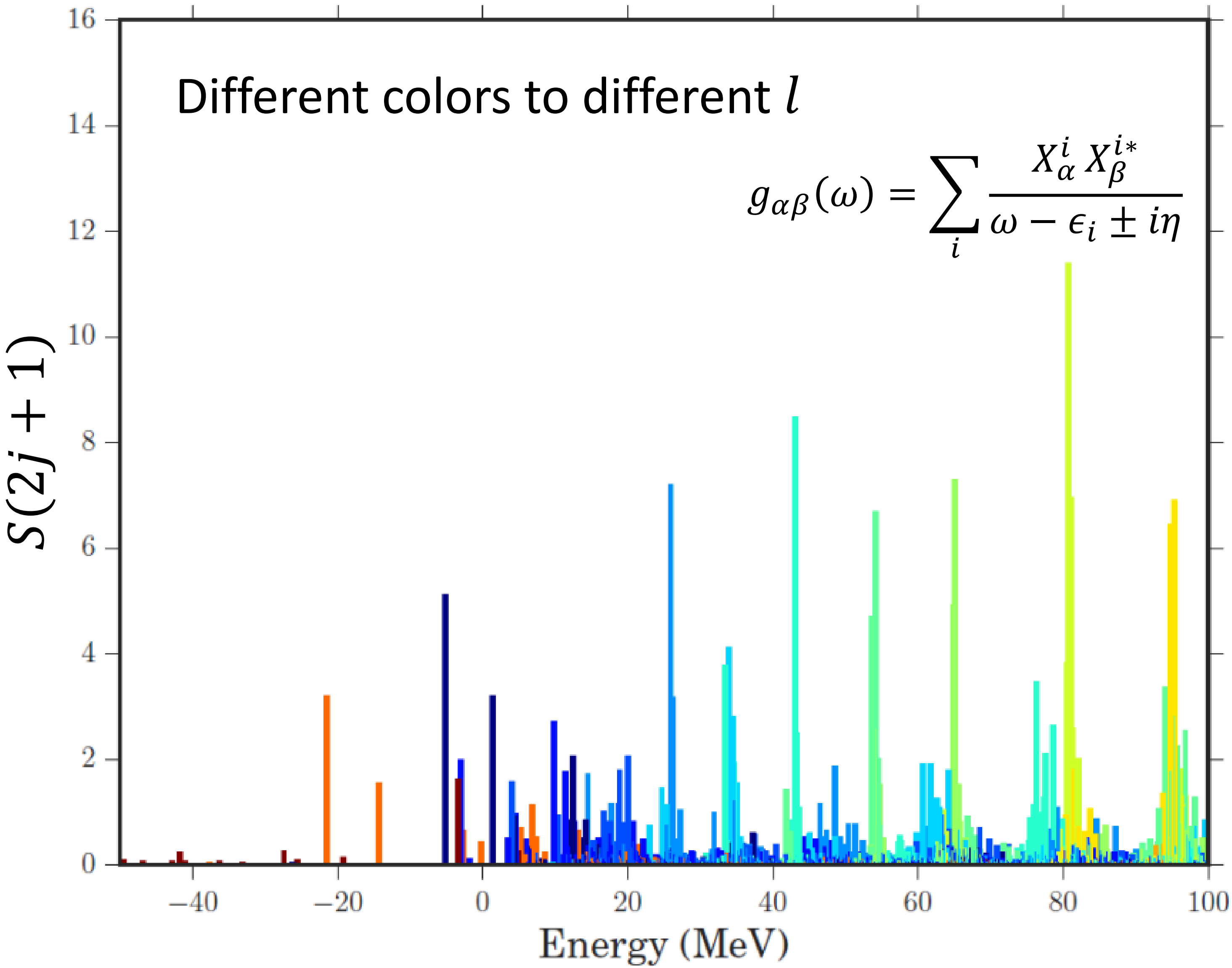


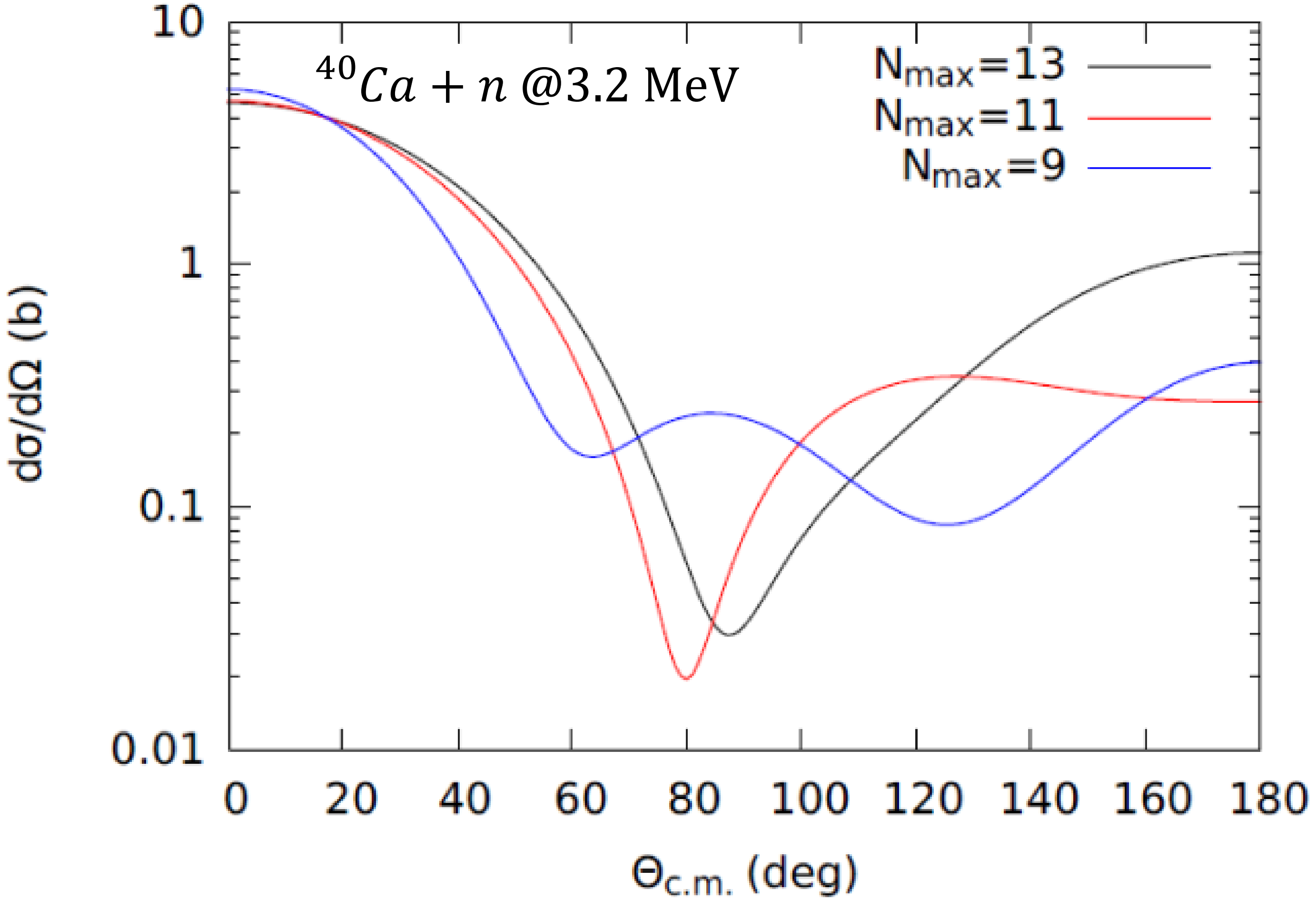




Hagen *et al.*, *Nature Physics* **12**, 186

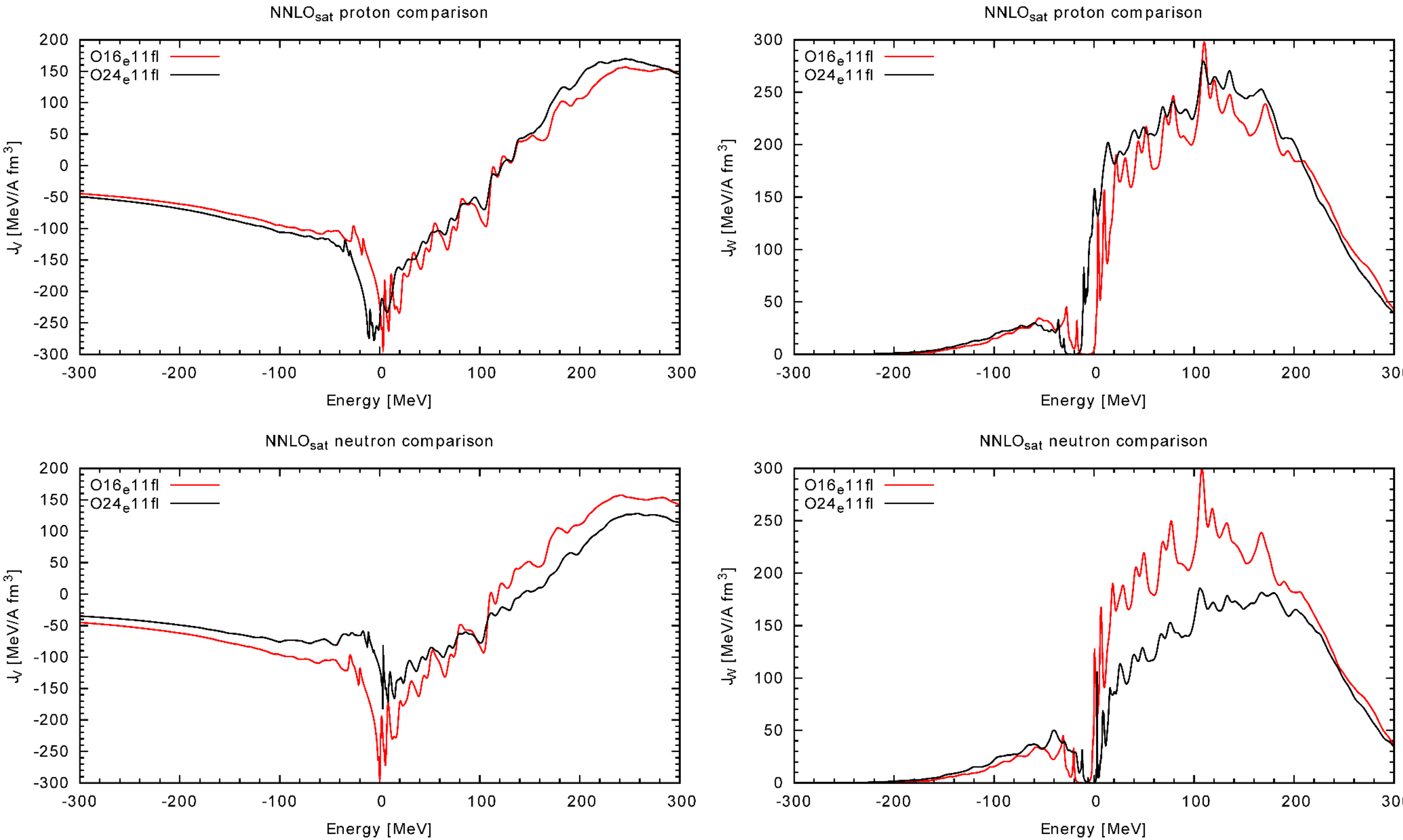
^{16}O neutron propagator





$^{40}Ca + n$ @3.2 MeV
N_{max}=13
N_{max}=11
N_{max}=9
10
1
0.1
0.01
dσ/dΩ (b)
0
20
40
60
80
100
120
140
160
180
$\Theta_{c.m.}$ (deg)

^{16}O and ^{24}O



NNLOsat proton comparison
NNLOsat proton comparison
NNLOsat neutron comparison
NNLOsat neutron comparison
O16e11fl
O24e11fl
JV [MeV/A fm3]
JW [MeV/A fm3]
Energy [MeV]