Microscopic Description of Nuclear Reactions From Two- and Three-Nucleon Interactions

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Outline

1. No-Core Shell Model with Continuum

- Ab initio calculations in nuclear physics
- Application to ^{9}He and $^{7}Be/^{7}Li$

2. Microscopic optical potential at intermediate energies

- Motivations
- Extension of the model

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From QCD to nuclei

Low-energy QCD

↓

NN+3N interactions from chiral EFT

↓

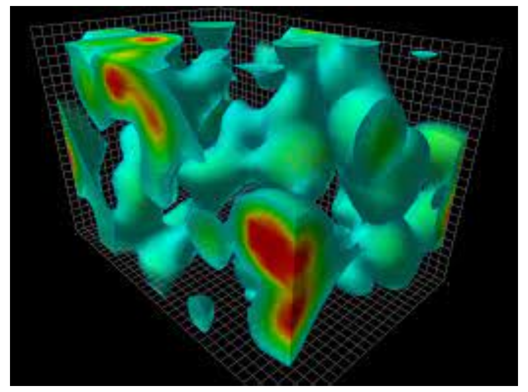
Unitary/similarity transformations

↓

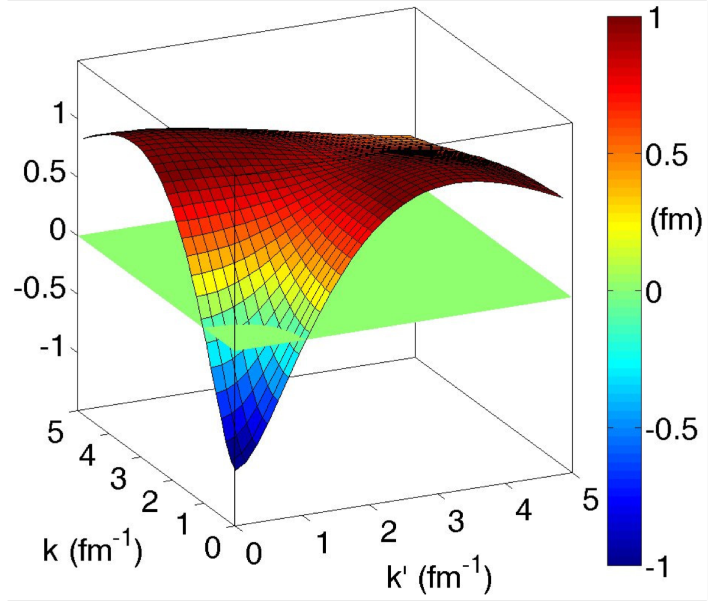
Many-body methods

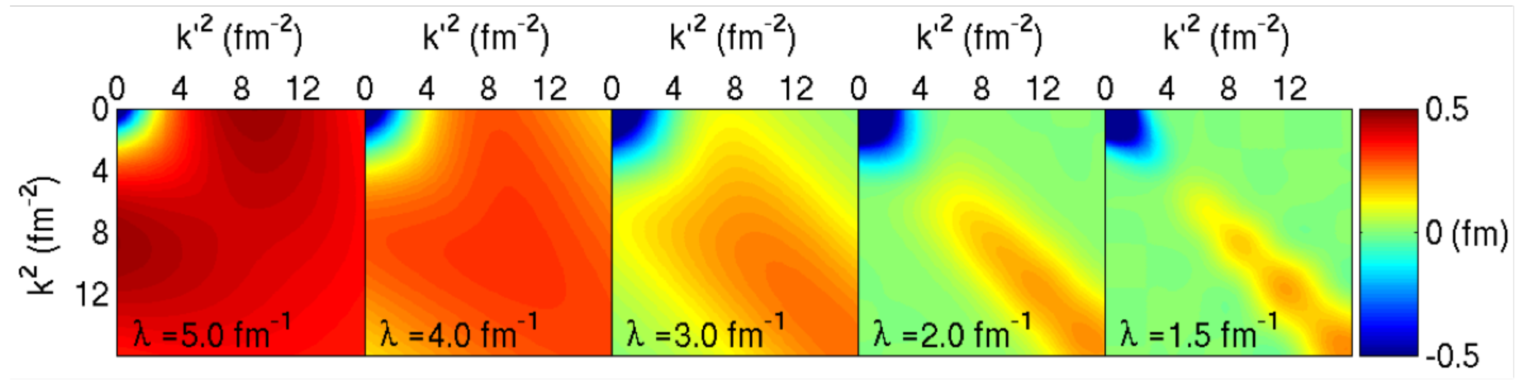
↓

Nuclear structure and reactions



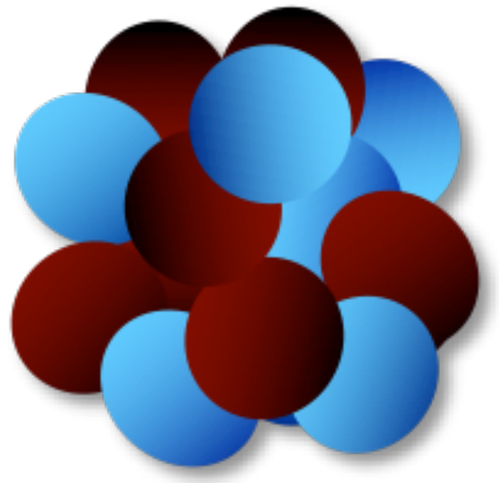
From Derek Leinweber website





From NPB Proceed. Suppl. 00 (2012) 1–37

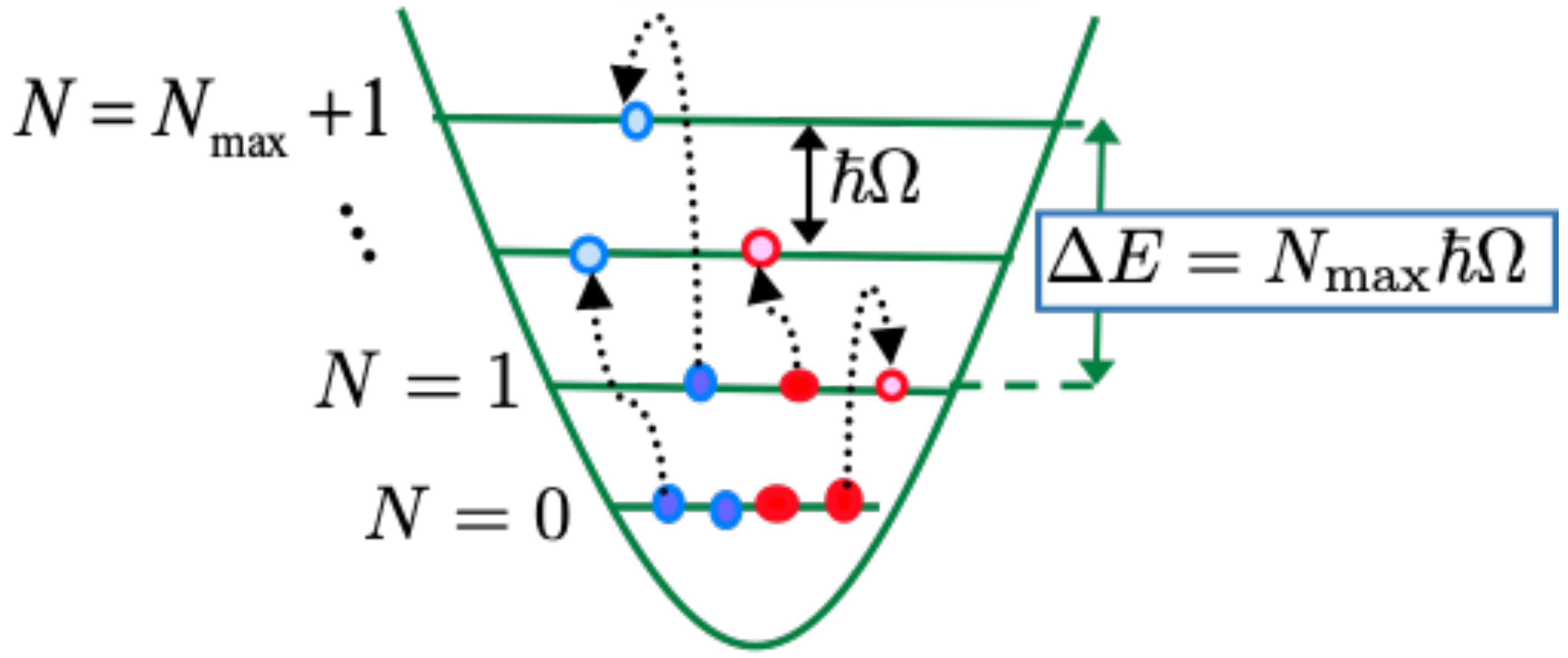
$$H|\Psi\rangle = E|\Psi\rangle$$



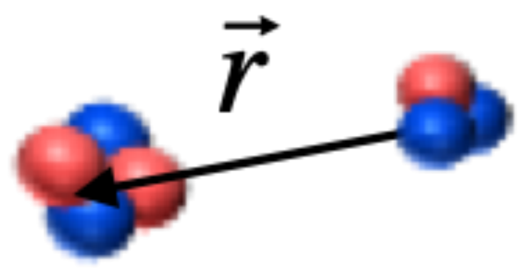
Unified approach to bound & continuum states

- No-Core Shell Model
  - A-nucleon wave function expansion in the harmonic oscillator basis
  - Short- and medium-range correlations
  - Bound states, narrow resonances
- NCSM with Resonating Group Method
  - Cluster expansion, clusters described by NCSM
  - Proper asymptotic behaviour
  - Long-range correlations
- No-Core Shell Model with Continuum

NCSM



NCSM/RGM



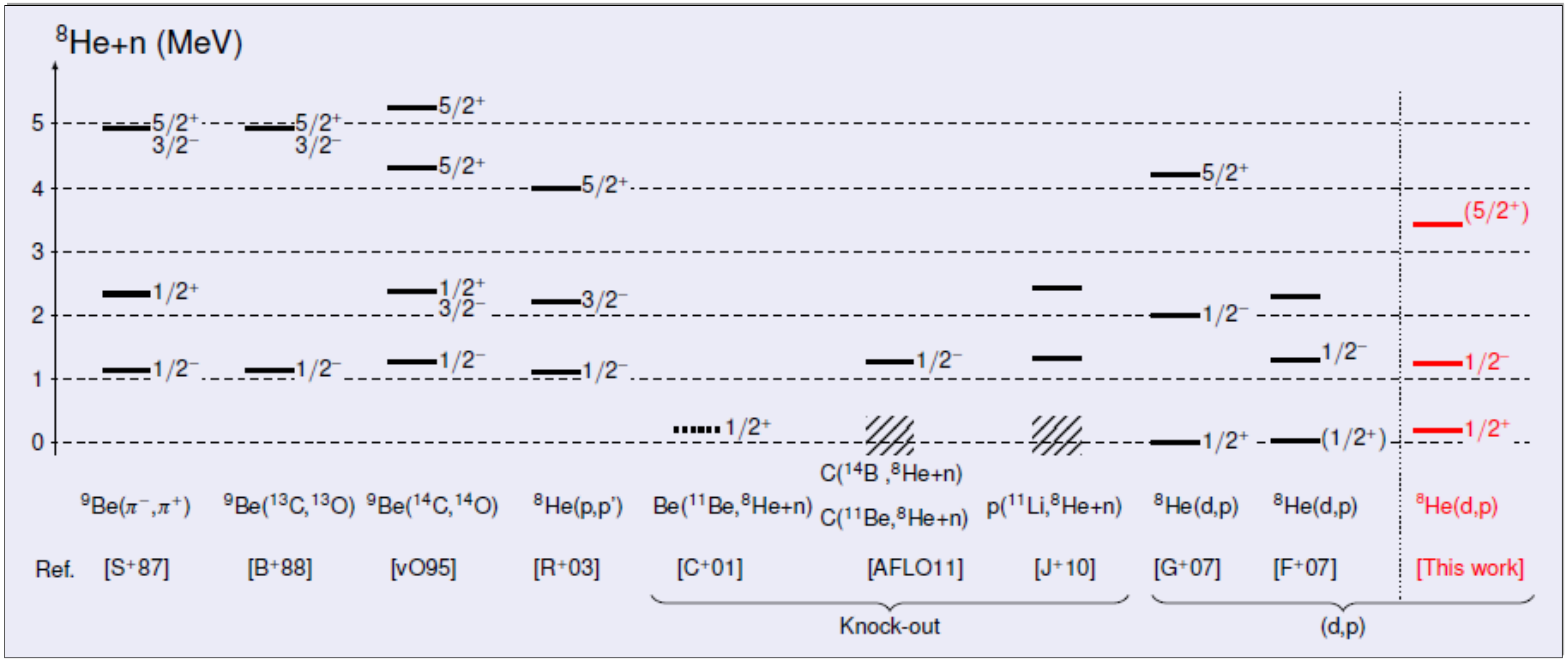
NCSMC

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| {}^{(A)} , \lambda \right\rangle + \sum_{\nu} \int d\vec{r}\; \gamma_{\nu}(\vec{r}\,)\; \hat{A}_{\nu} \left| {}_{(A-a)} \;\; \vec{r} \;\; {}_{(a)} , \nu \right\rangle$$

Unknowns

Structure of the ^{9}He system

From talk by Nigel Orr at ECT* (2013)

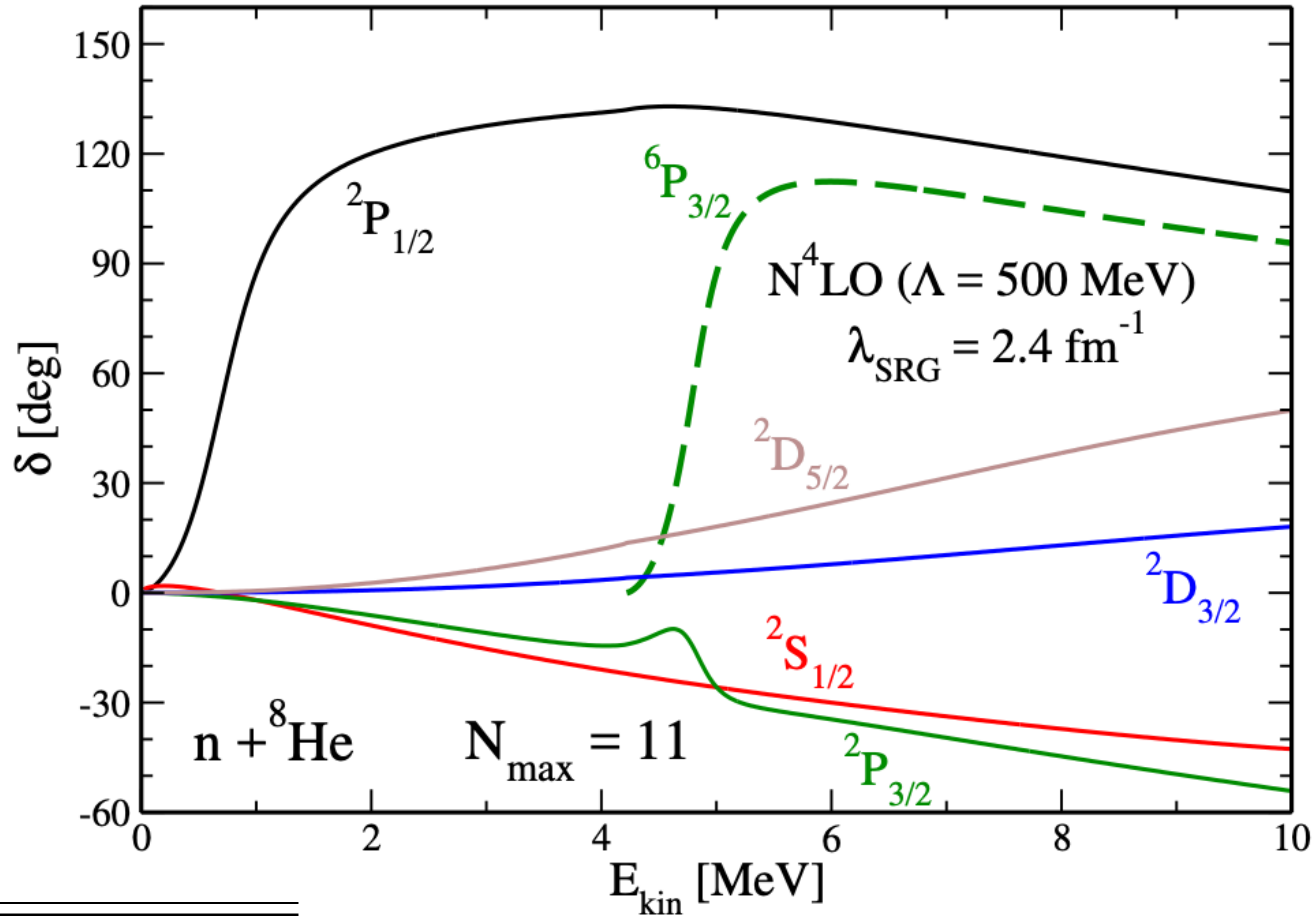


Two longstanding problems affect the physics of the ^{9}He system

1. The existence of the $1/2^+$ resonance
2. The width of the $1/2^-$ resonance
   - Experimentally ~ 0.1 MeV
   - Theoretically ~ 1 MeV

Structure of the ^{9}He system

- Two resonances found corresponding to $1/2^-$ and $3/2^-$ states
- No $1/2^+$ resonance has been found
- To reproduce the correct width of the $1/2^-$ resonance is extremely important to reproduce the excitation energy of the 2^+ state of ^{8}He



[Vorabbi et al., PRC **97**, 034314 (2018)]

J^π	NCSMC		NCSMC-pheno	
$1/2^-$	$E_R = 0.69$	$\Gamma = 0.83$	$E_R = 0.68$	$\Gamma = 0.37$
$3/2^-$	$E_R = 4.70$	$\Gamma = 0.74$	$E_R = 3.72$	$\Gamma = 0.95$

^{7}Be and ^{7}Li systems

Nuclear Astrophysics

- Determination of the ^{7}Li abundance in the early universe

$$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be} \qquad ^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$$

- Prediction of the production rate of ^{8}B and ^{7}Be neutrinos in the sun

$$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$$

Tritium Breeding

- Fusion energy generation with deuteron-tritium fuel such ITER https://www.iter.org

$$^6\mathrm{Li}(n,{}^3\mathrm{H})^4\mathrm{He}$$

$^6\mathbf{Li}(\mathbf{p},\gamma)^7\mathbf{Be}$

- **Lanzhou experiment:** possible resonant enhancement near the threshold
  [He et al., Phys. Lett. B **725**, 287 (2013)]

- **New LUNA experiment:** ruled out the existence of low-energy resonances
  [Piatti et al., Phys. Rev. C **102**, 052802(R) (2020)]

Theoretical Calculations

- Analyzed mass partitions for ^{7}Be
  - ^{3}He + ^{4}He
  - ^{6}Li + p

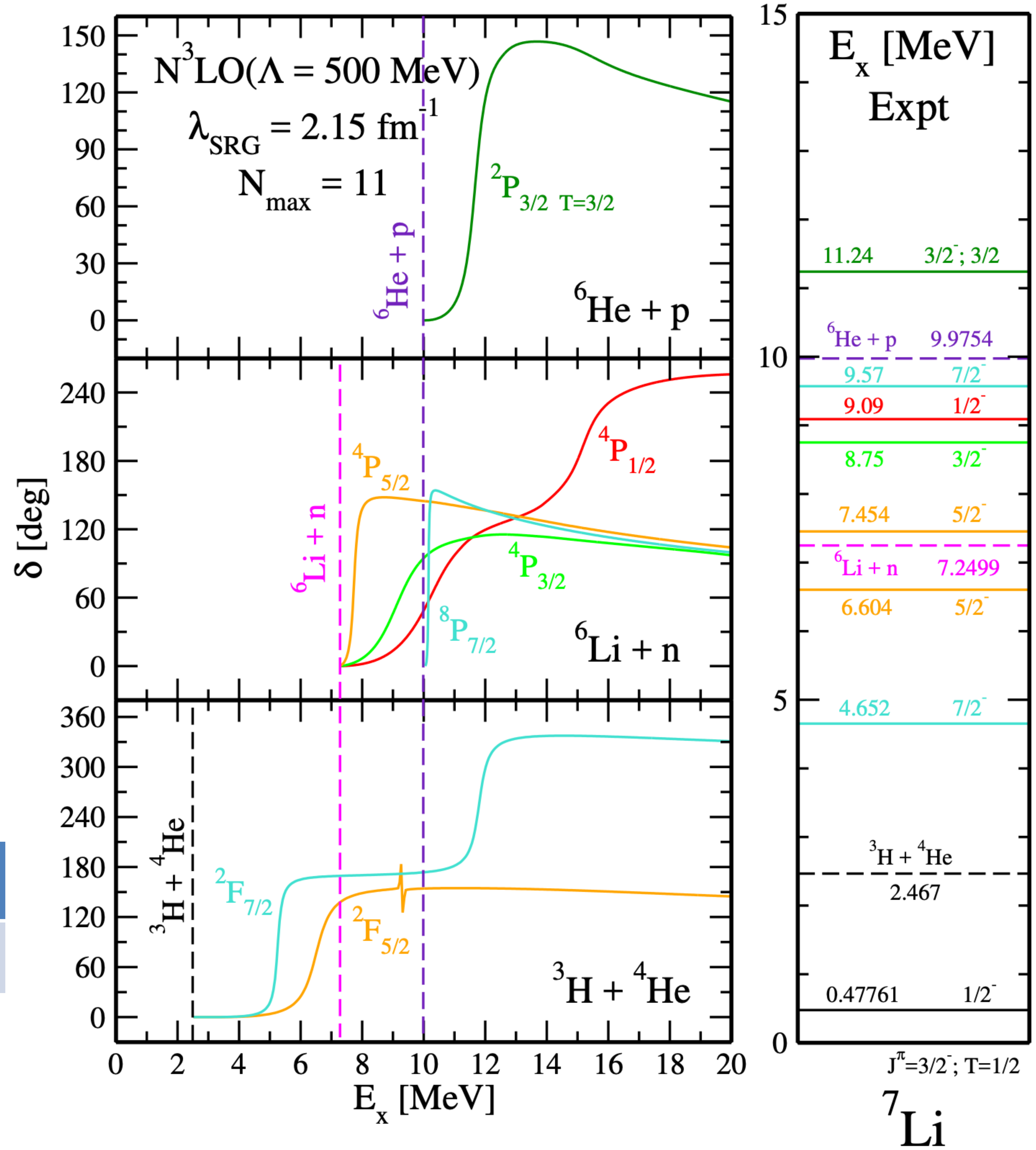
- Analyzed mass partitions for ^{7}Li
  - ^{3}H + ^{4}He
  - ^{6}Li + n
  - ^{6}He + p

^{7}Li system

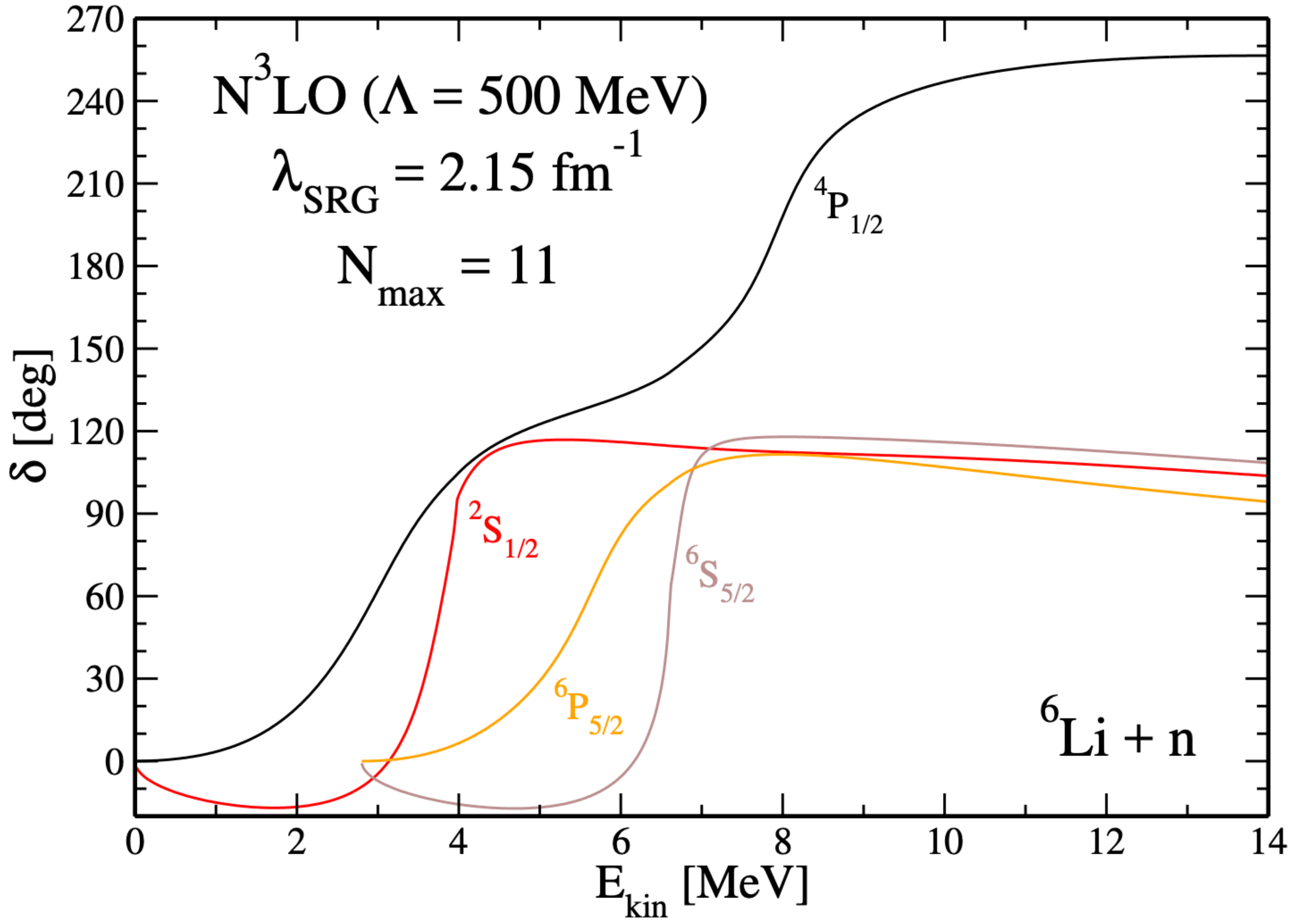
- Analysed mass partitions
    1. ^{3}H + ^{4}He
    2. ^{6}Li + n
    3. ^{6}He + p
- The experimental energy spectrum is reproduced in the correct order
- No coupling between the different mass partitions
- Ground state and first excited state are obtained as *bound states*

$J^p = 3/2^-$	^{3}H + ^{4}He	^{6}Li + n	^{6}He + p	Exp.
E [MeV]	-38.65	-38.13	-38.06	-39.245

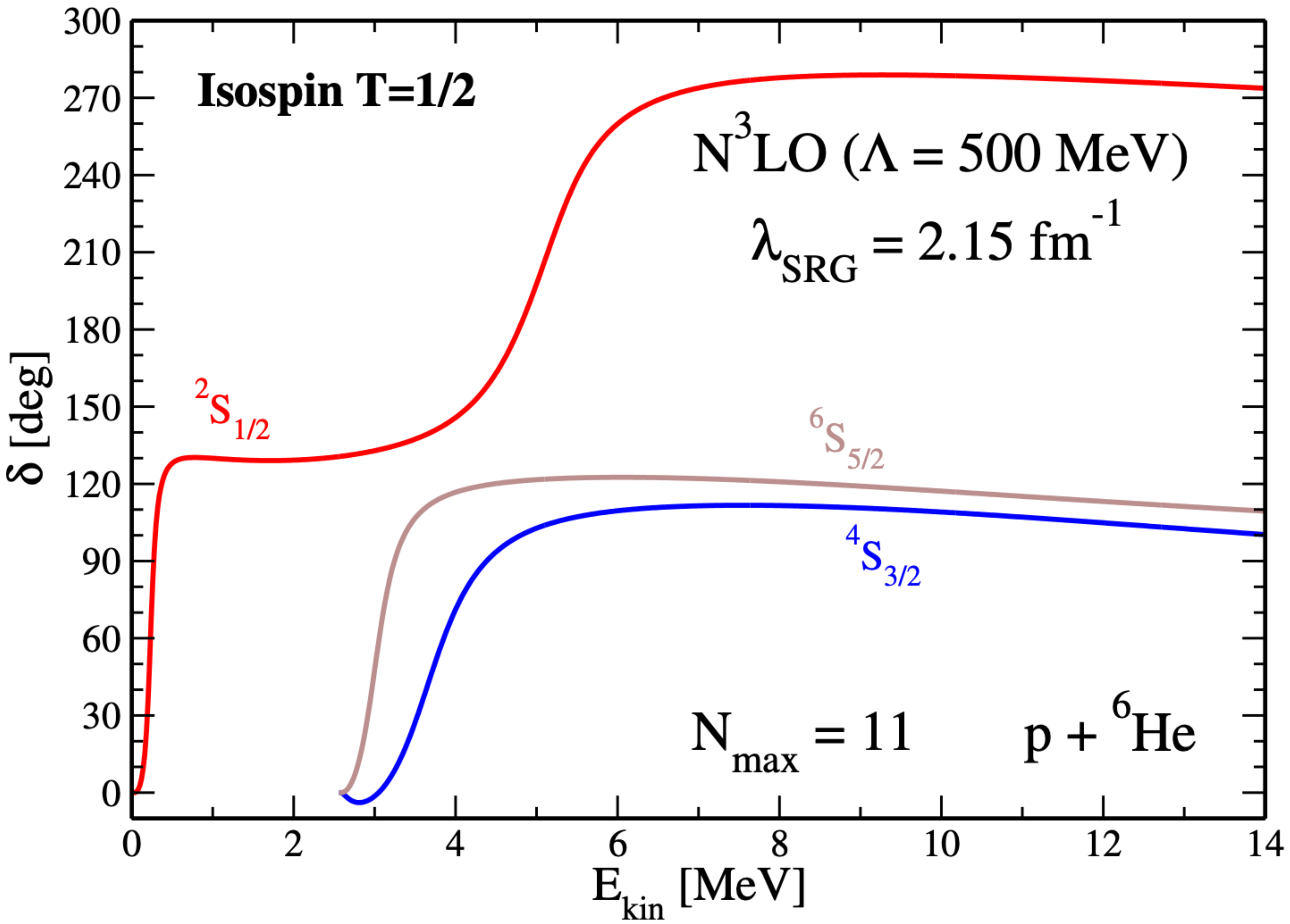
[Vorabbi, Navrátil, Quaglioni, Hupin, PRC **100**, 024304 (2019)]



^{7}Li system – New predicted states



- Prediction of **new states** also with **positive** parity
- Interesting prediction of a $1/2^+$ resonance just above the threshold of p+^{6}He
- We still have to keep in mind that this state is in the 3B continuum (^{4}He+d+n)



Future experiment at TRIUMF!!!
Status: approved
Study of low-lying states in ^{7}Li via ^{6}He+p resonant elastic scattering in inverse kinematics

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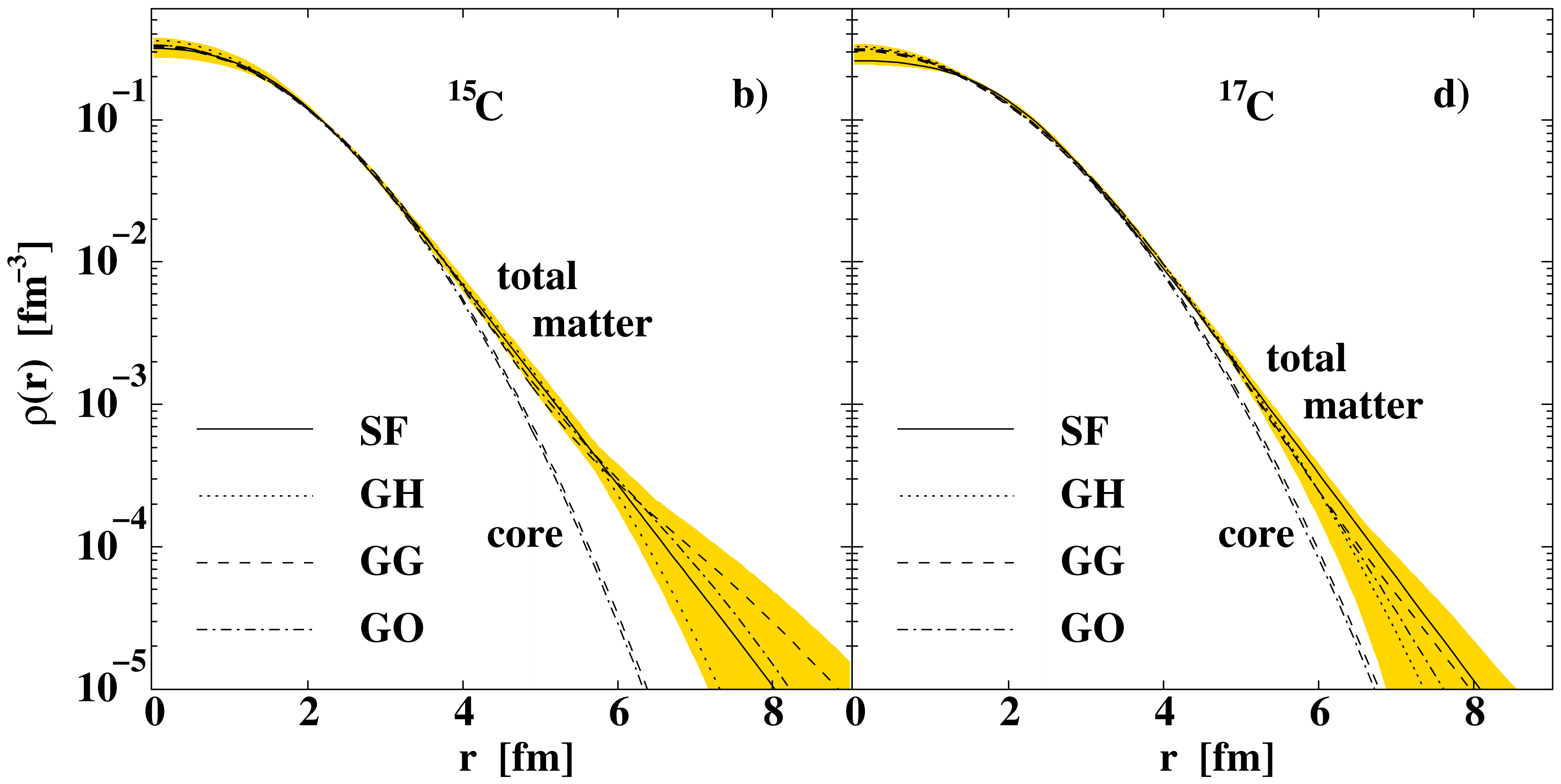
Motivations

- Increasing experimental efforts to develop the technologies necessary to study the elastic proton scattering in inverse kinematics
- Attempts to use such experiments to determine the matter distribution of nuclear systems at intermediate energies

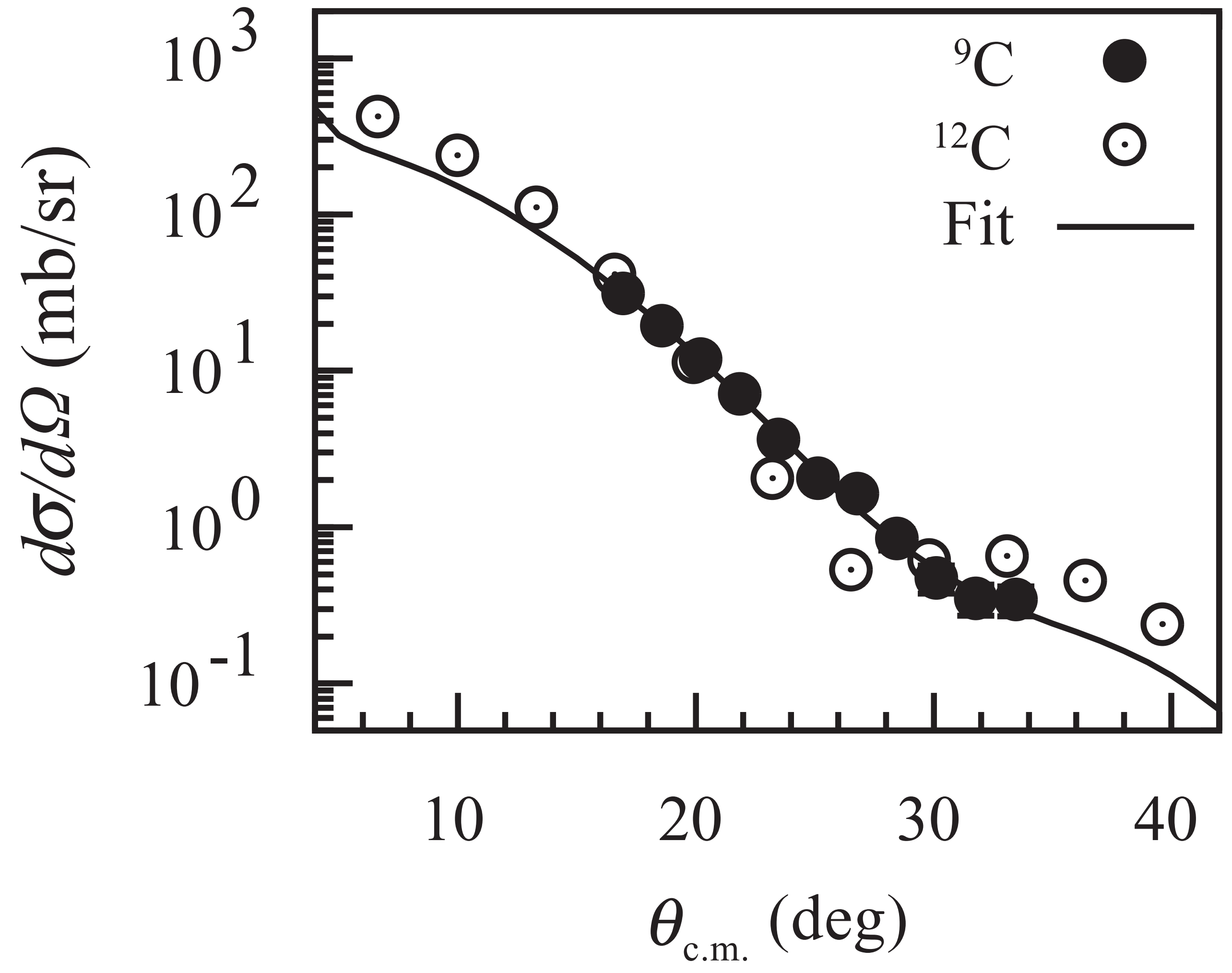
[Sakaguchi, Zenihiro, PPNP 97 (2017) 1–52]

- Measurements are not free from sizeable uncertainties
- The Glauber model is used to analyse the data
- An essential step in the data analysis is the subtraction of contributions from the inelastic scattering

Develop a microscopic approach to make reliable predictions for elastic and inelastic scattering

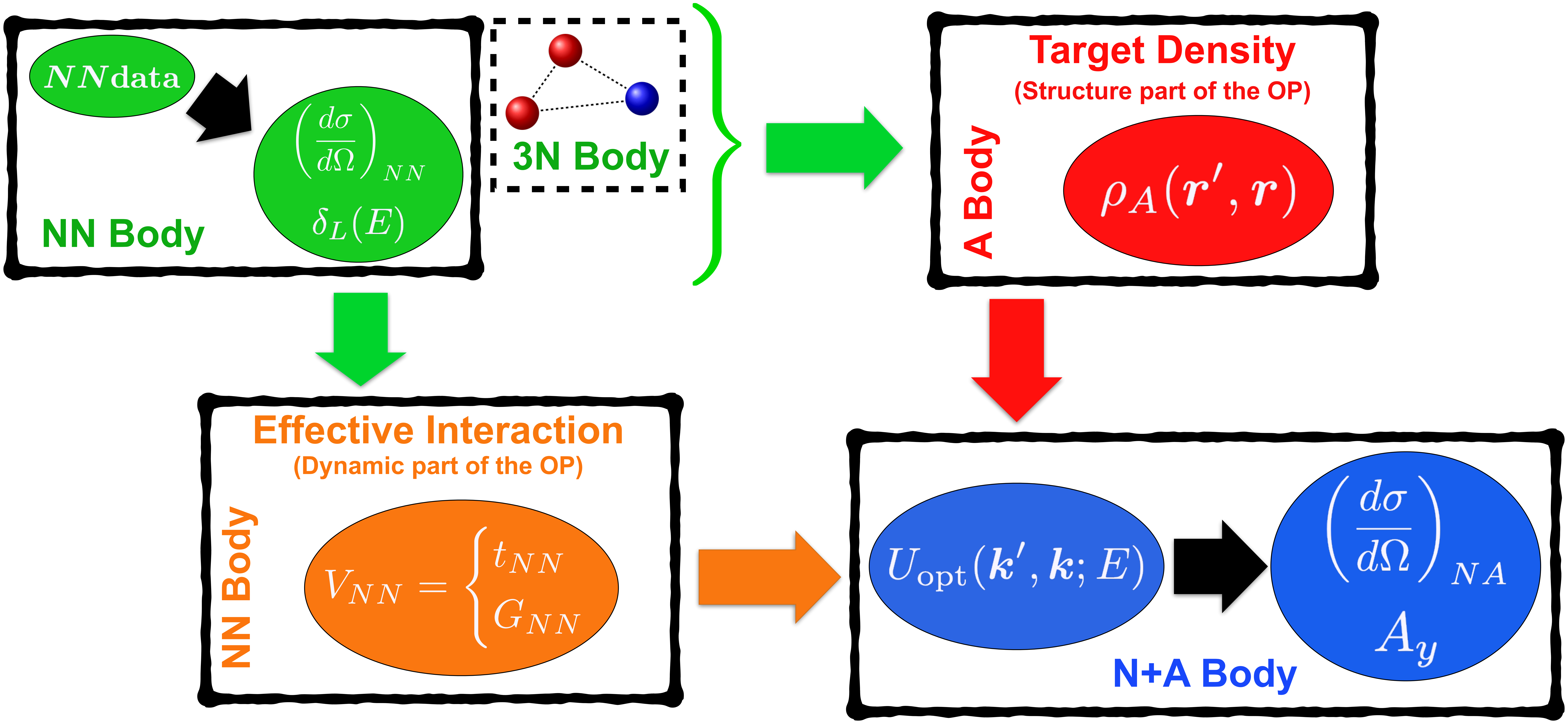


[Dobrovolsky et al., NPA 1008 (2021) 122154]

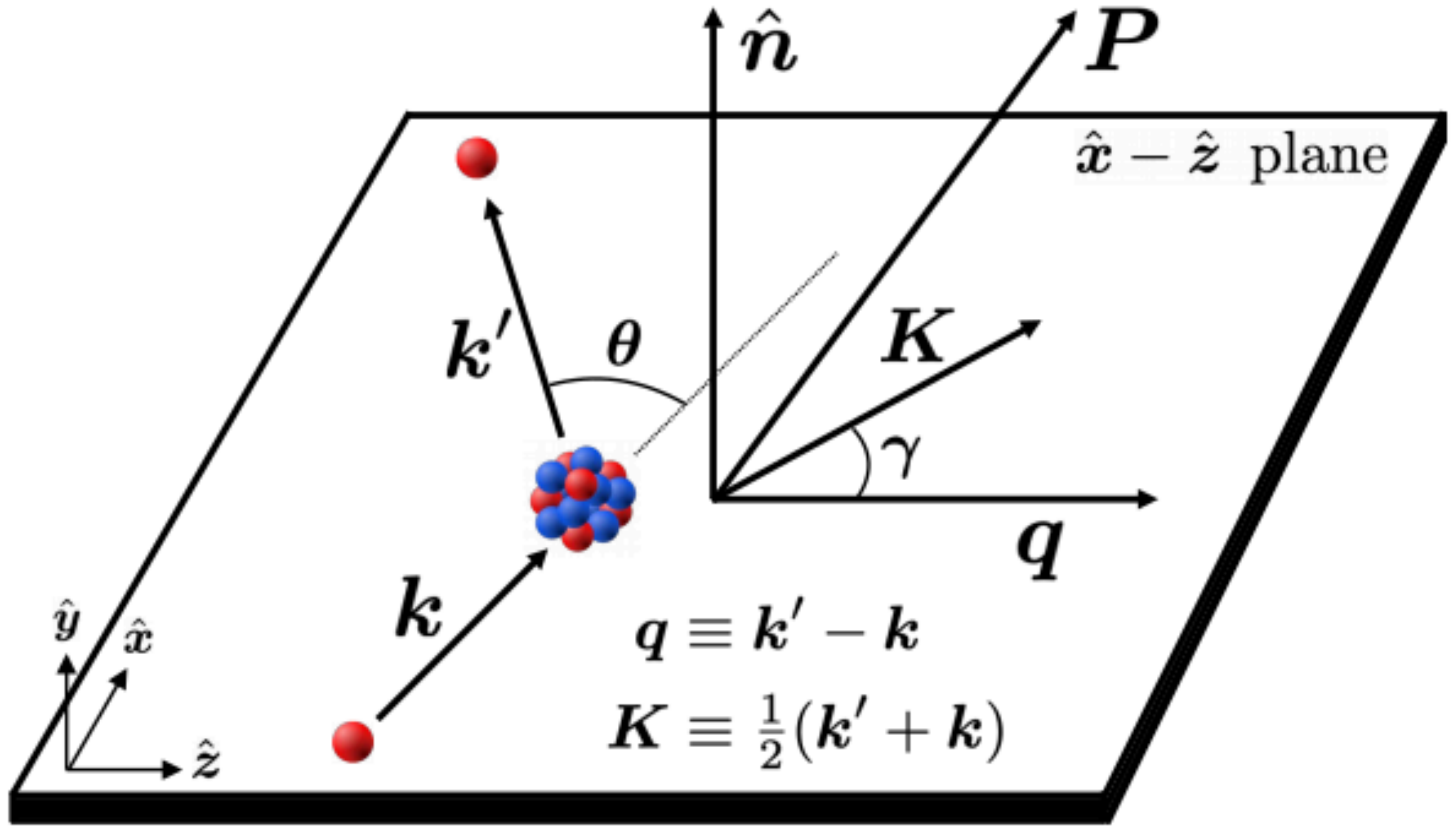


[Matsuda et al., PRC **87**, 034614 (2013)]

Motivations



The first-order optical potential



Møller factor

$$t^{(NA)}_{\mathbf{p}N}=\eta\, t^{(NN)}_{\mathbf{p}N}$$

It imposes the Lorentz invariance of flux when we pass from the NA to the NN frame where the t matrices are evaluated

$$U_{\mathbf{p}}(\boldsymbol{q},\boldsymbol{K})=\sum_{N=p,n}\int d\boldsymbol{P}\,\eta(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P})\,t_{\mathbf{p}N}(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P})\,\rho_N(\boldsymbol{q},\boldsymbol{P})$$

$\mathbf{p}=(p,n,\bar{p})$

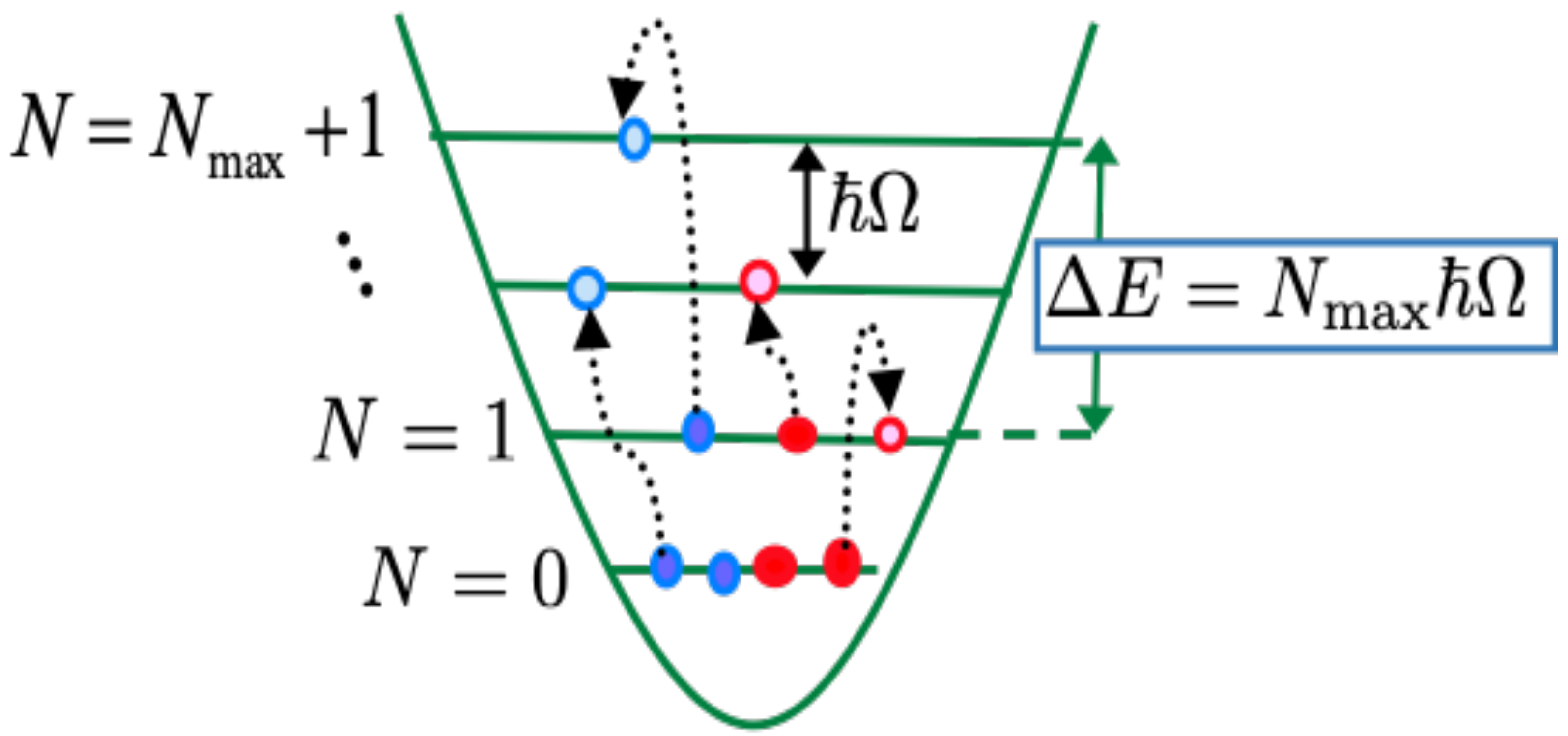
Free two-body scattering matrix

$$t_{0i}=v_{0i}+v_{0i}\,g_{0i}\,t_{0i}$$

$$g_{0i}=(E-h_0-h_i+i\epsilon)^{-1}$$

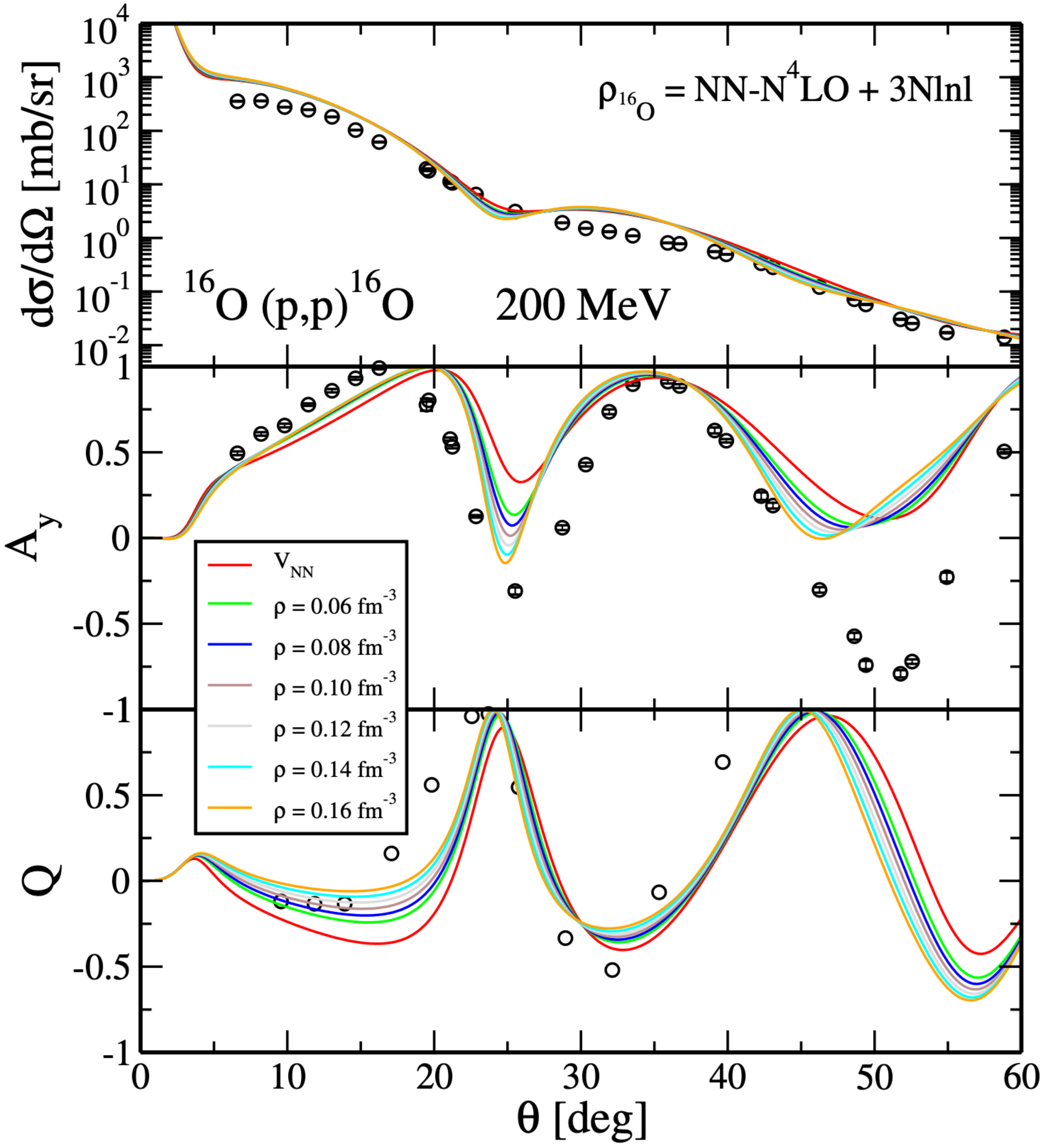
- Simple one-body equation
- Can be solved easily
- Only **NN** interaction

Nonlocal one-body density

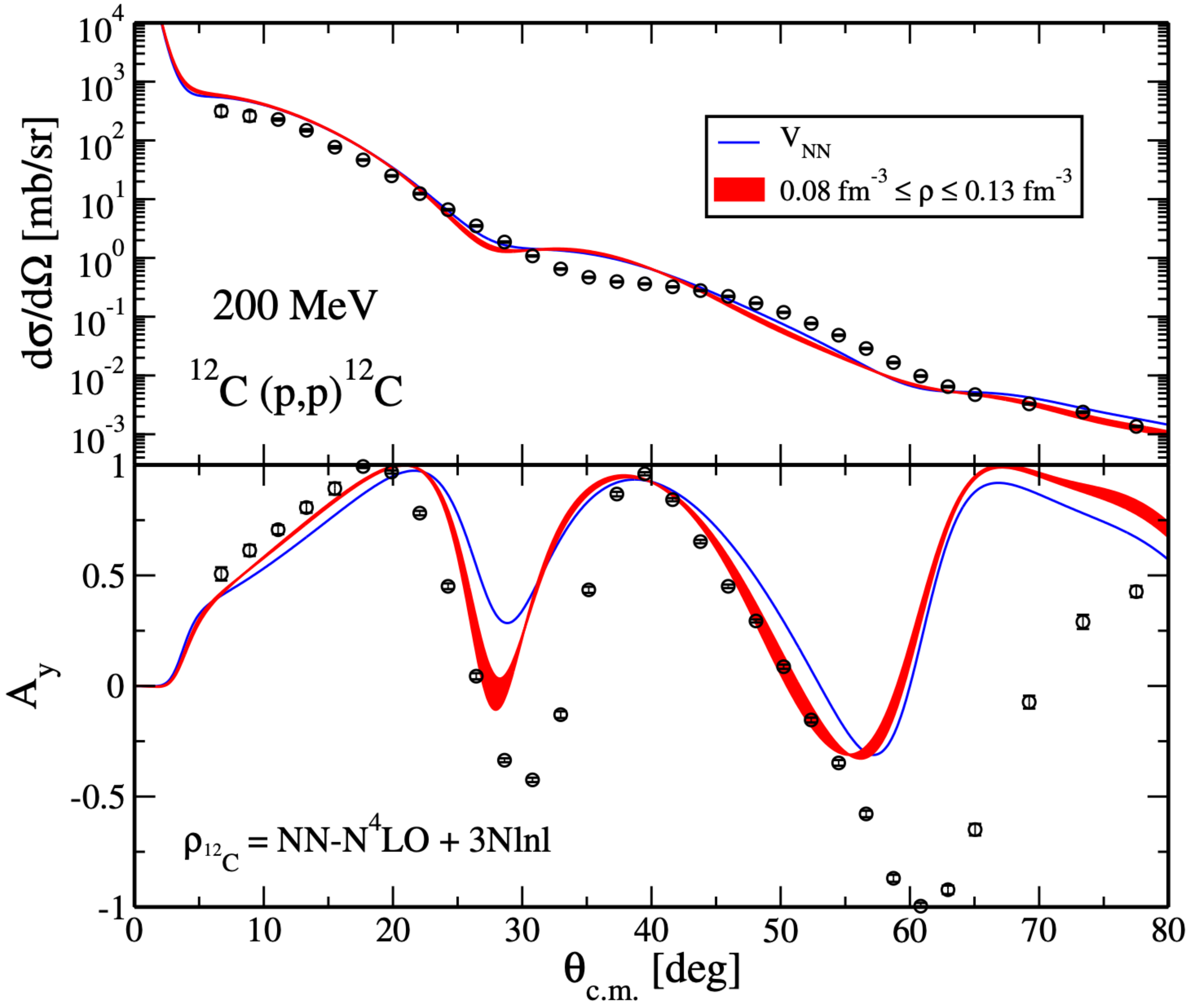


- Computationally expensive
- Obtained from the No-Core Shell Model
- Calculation performed with **NN** and **3N** interaction

Assessing the impact of the 3N interaction



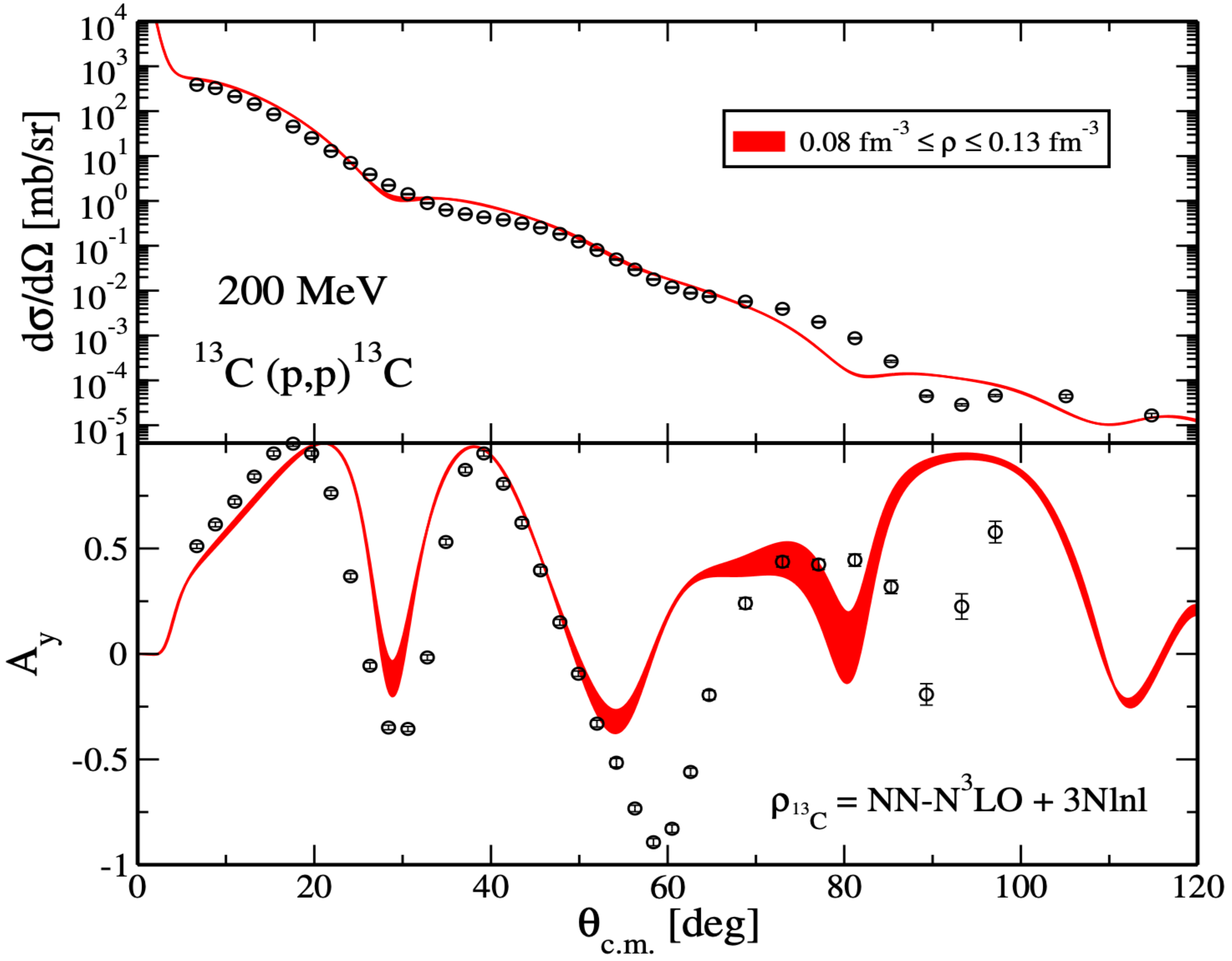
Vorabbi et al., PRC **103**, 024604 (2021)



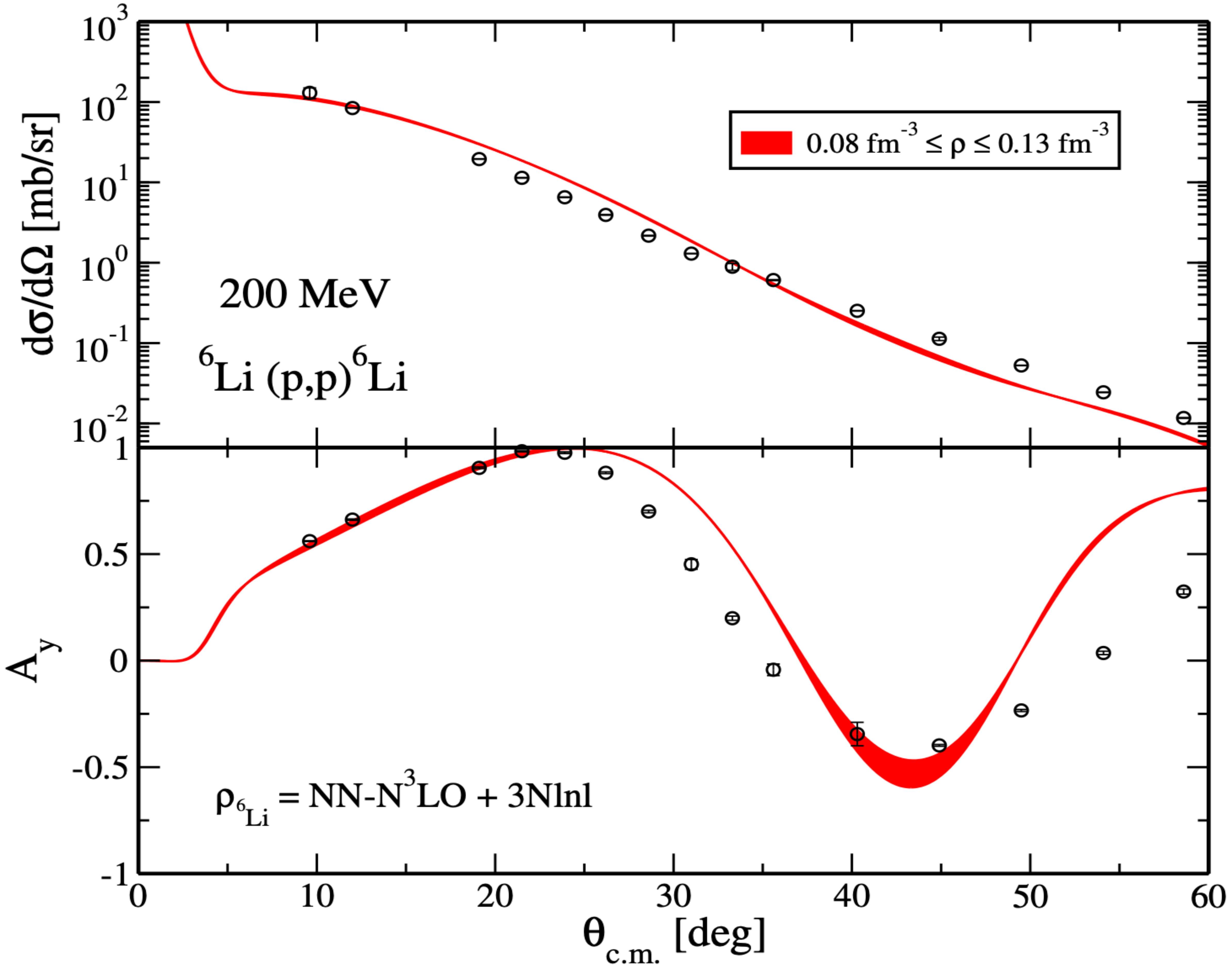
- For all nuclei we found very small contributions to the differential cross section
- The contributions to the spin observable are larger and they seem to improve the agreement with the data

Extension to non-zero spin targets

$J^{\pi} = 1/2^{-}$



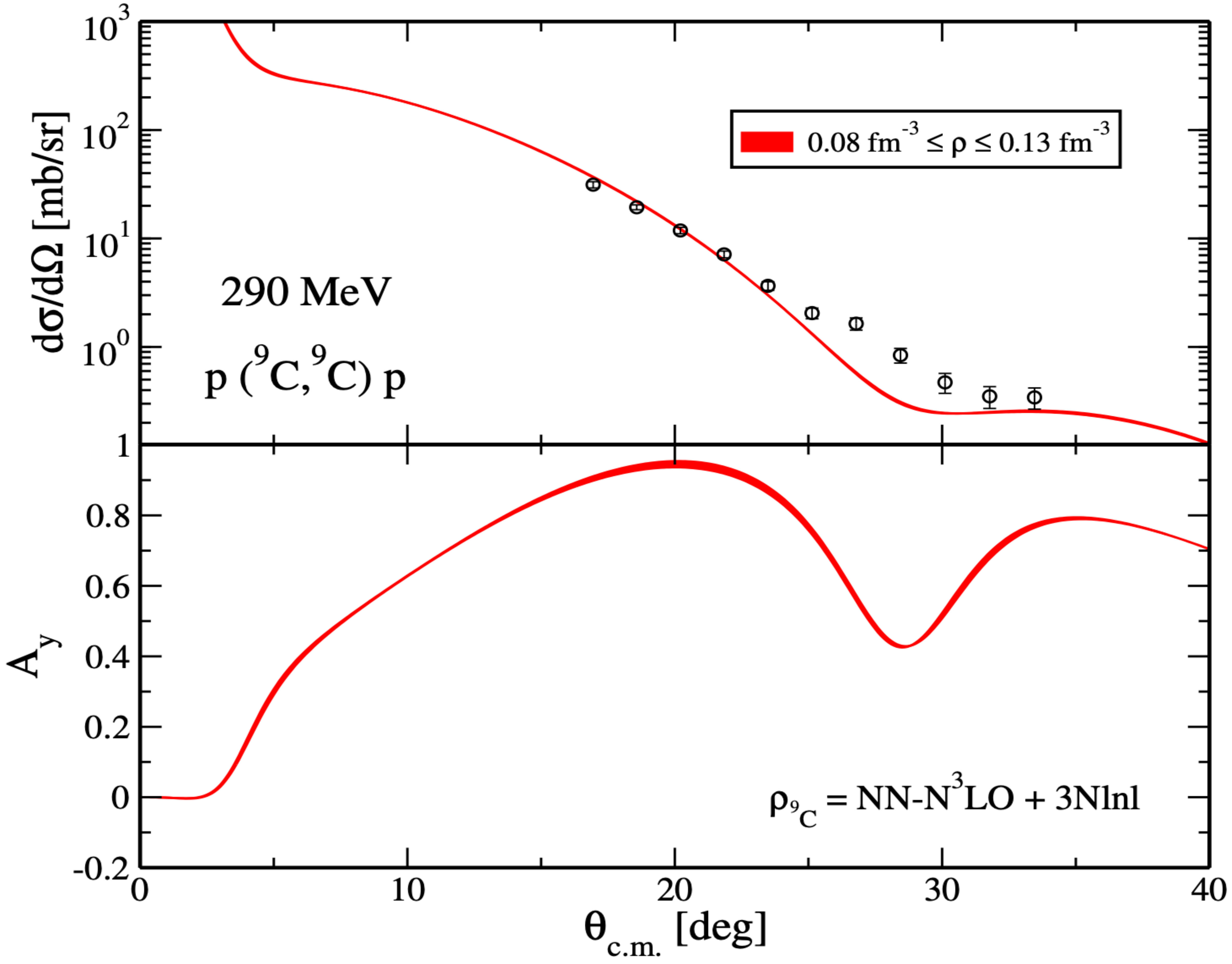
$J^{\pi} = 1^{+}$



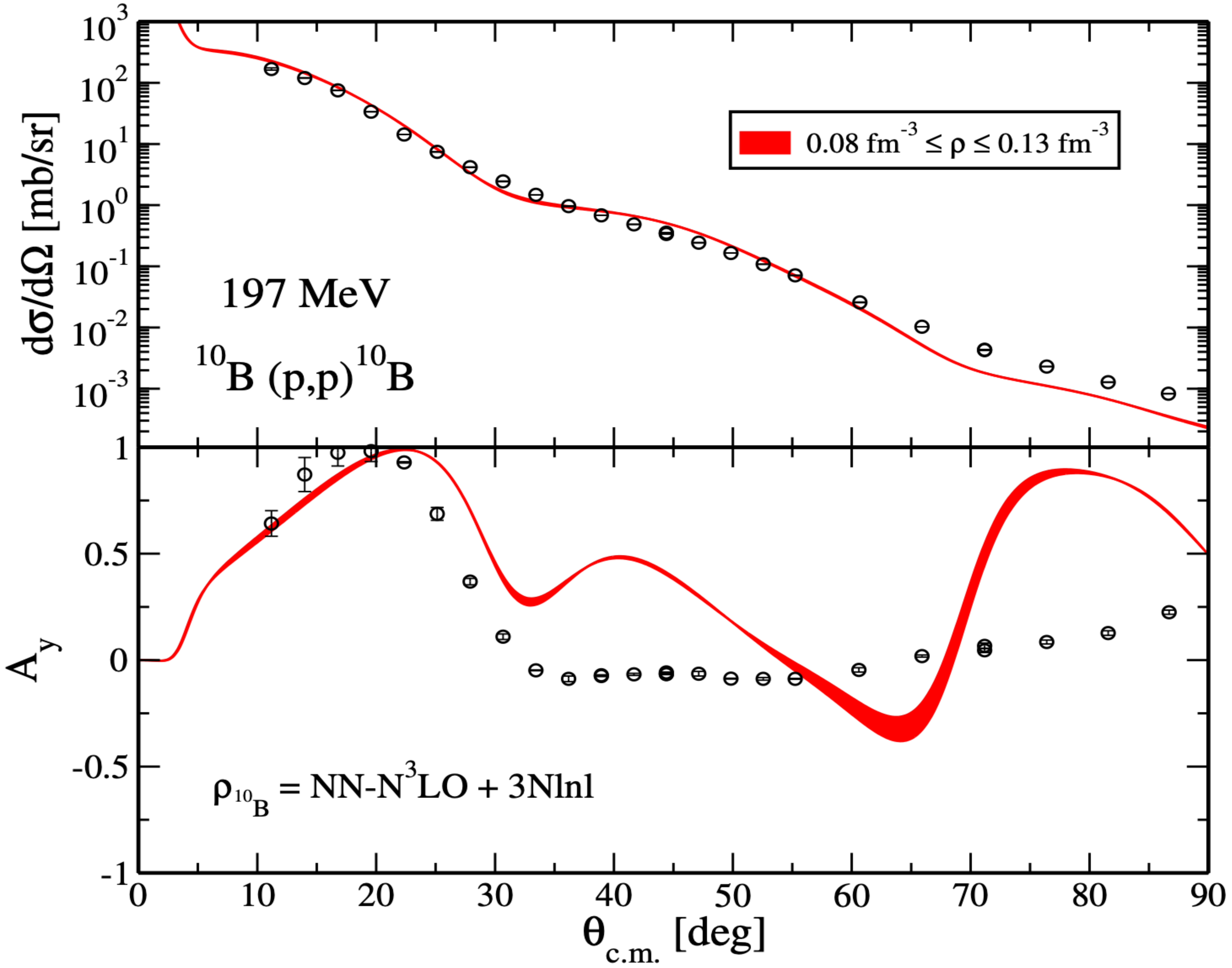
[Vorabbi et al., Phys. Rev. C **105**, 014621 (2022)]

Extension to non-zero spin targets

$J^\pi = 3/2^-$

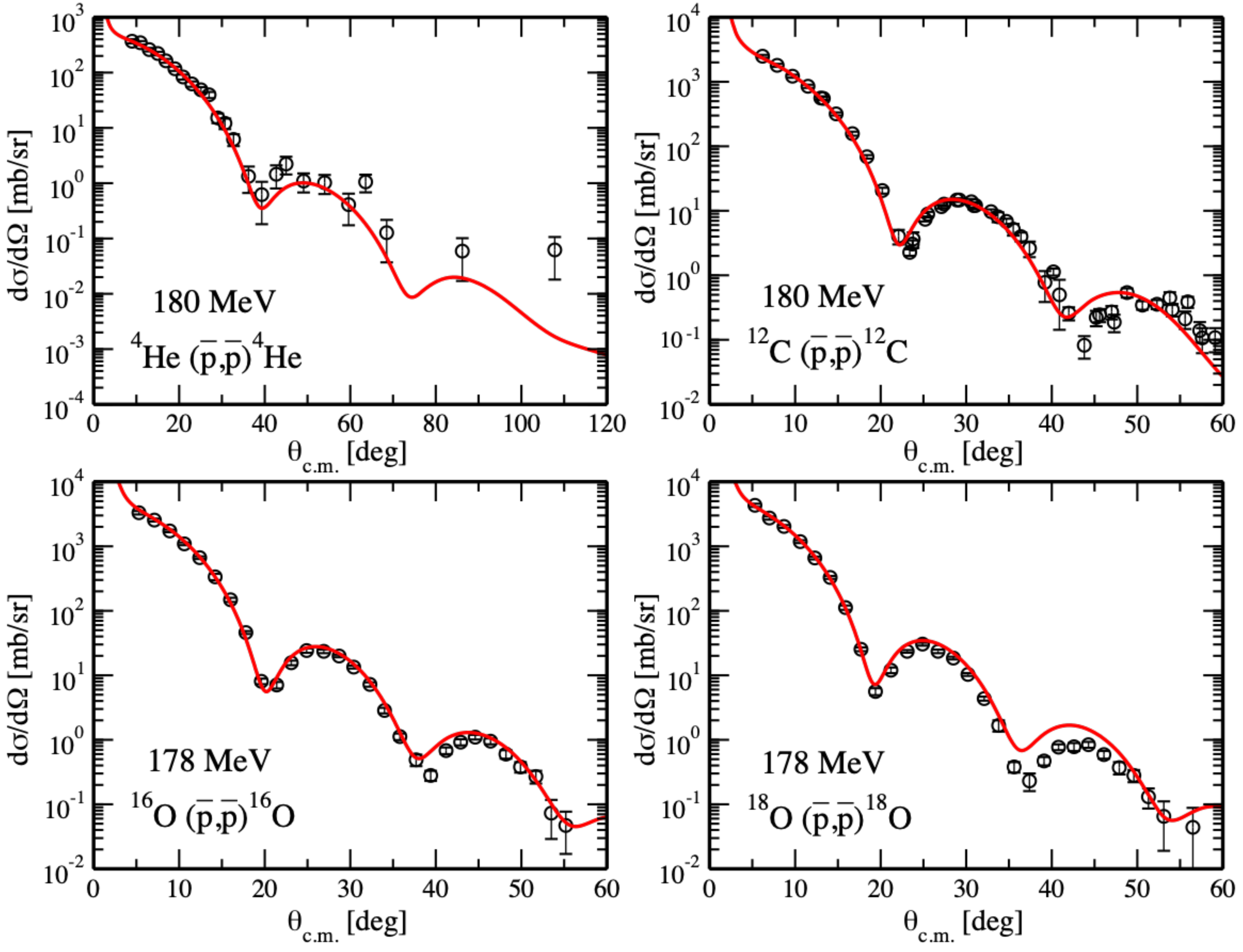


$J^\pi = 3^+$

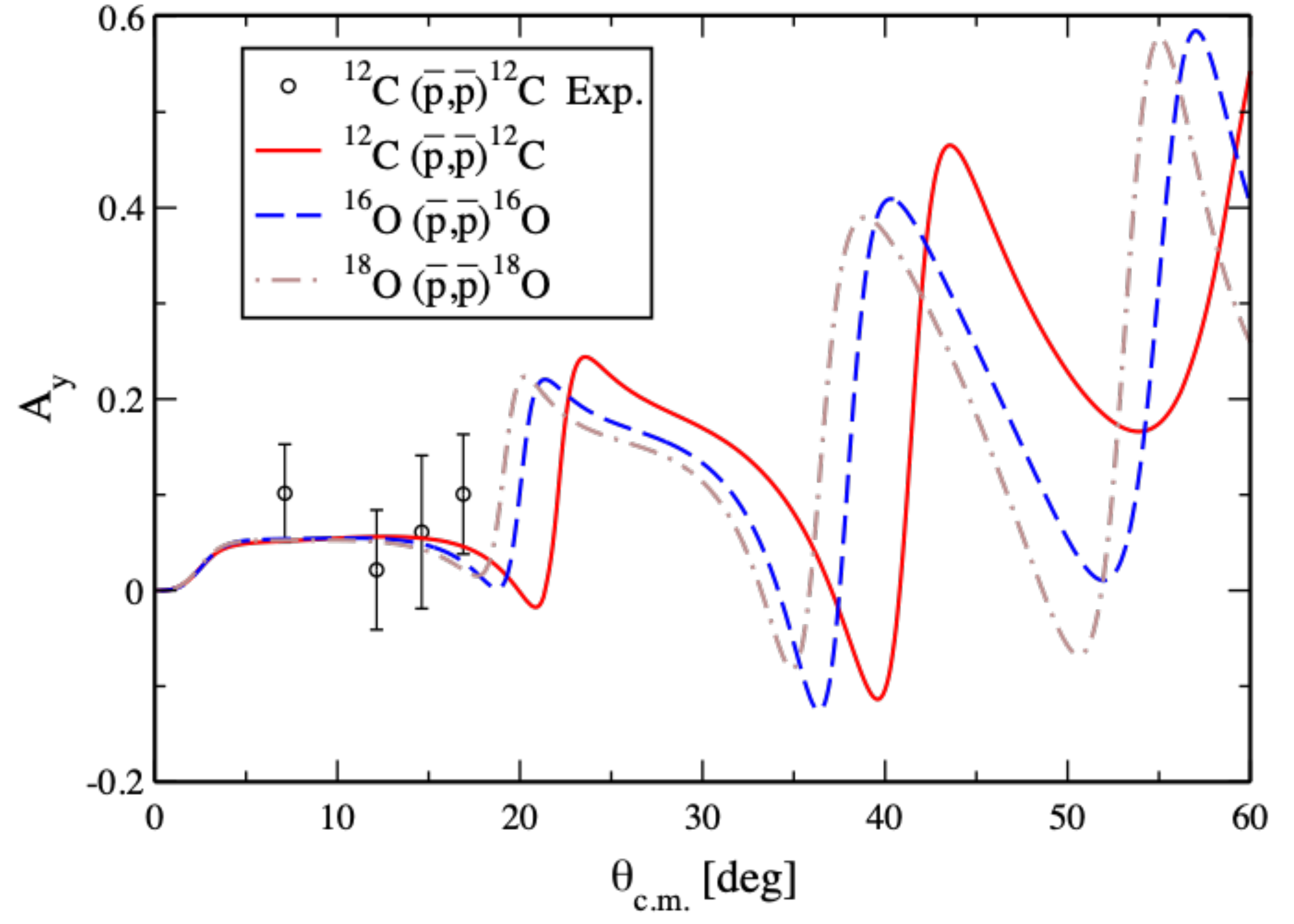


[Vorabbi et al., Phys. Rev. C **105**, 014621 (2022)]

Extension to antiproton-nucleus elastic scattering



$$t_{pN} \Rightarrow t_{\bar{p}N}$$



Elastic Antiproton-Nucleus Scattering from Chiral Forces

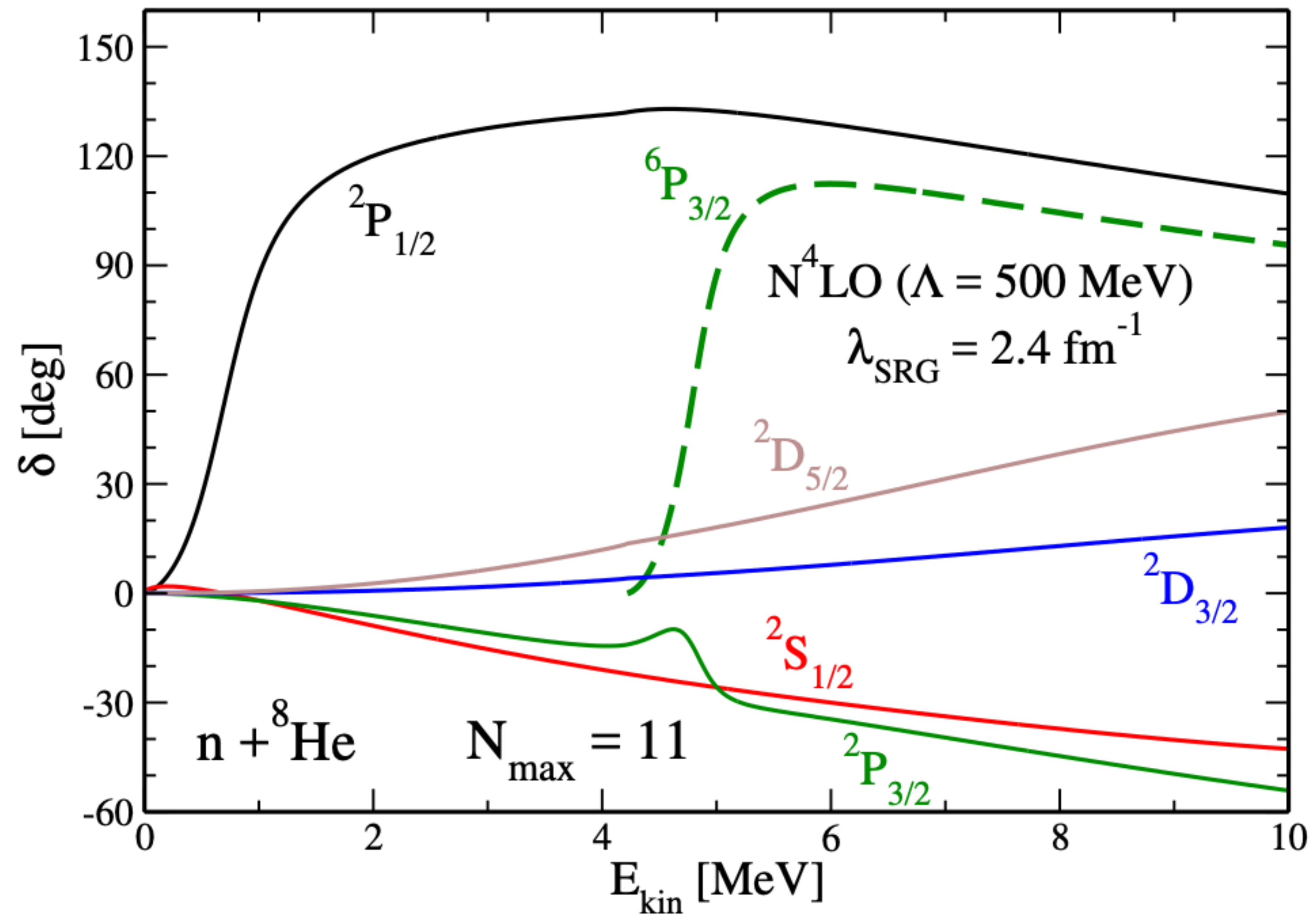
Matteo Vorabbi,[1,2] Michael Gennari,[2,3] Paolo Finelli,[4] Carlotta Giusti,[5] and Petr Navrátil[2]

PHYSICAL REVIEW LETTERS **124,** 162501 (2020)

Summary

No-Core Shell Model with Continuum

- Inclusion of short- and long-range correlations
- Proper asymptotic behaviour
- Unified description of bound and scattering states
- Future *ab initio* description of alpha clusters in light nuclei



Microscopic Optical Potential

- Simplification of the full many-body problem
- Derivation of an effective nucleon-nucleus complex interaction
- Good description of the elastic scattering observables
- Future extension to inelastic scattering and other processes