Application of multiple scattering theory to develop nuclear optical potentials

Matteo Vorabbi

July 10, 2025, IJCLab Seminar

UNIVERSITY OF SURREY

Collaborators:

- Ashley Pitt
- Carlo Barbieri
- Carlotta Giusti
- Michael Gennari
- Paolo Finelli
- Petr Navrátil
- Vittorio Somà

Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

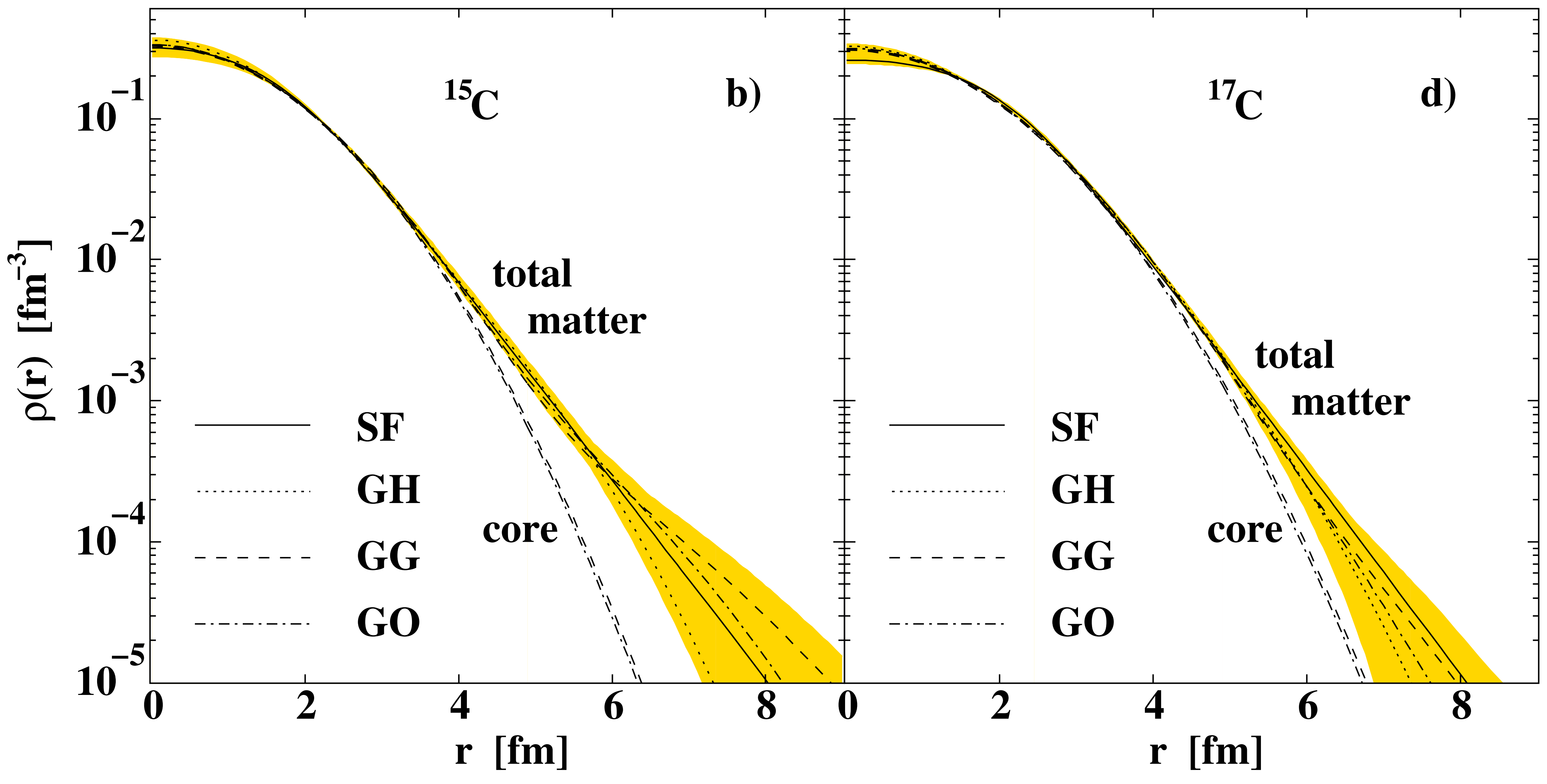
Motivations

- 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

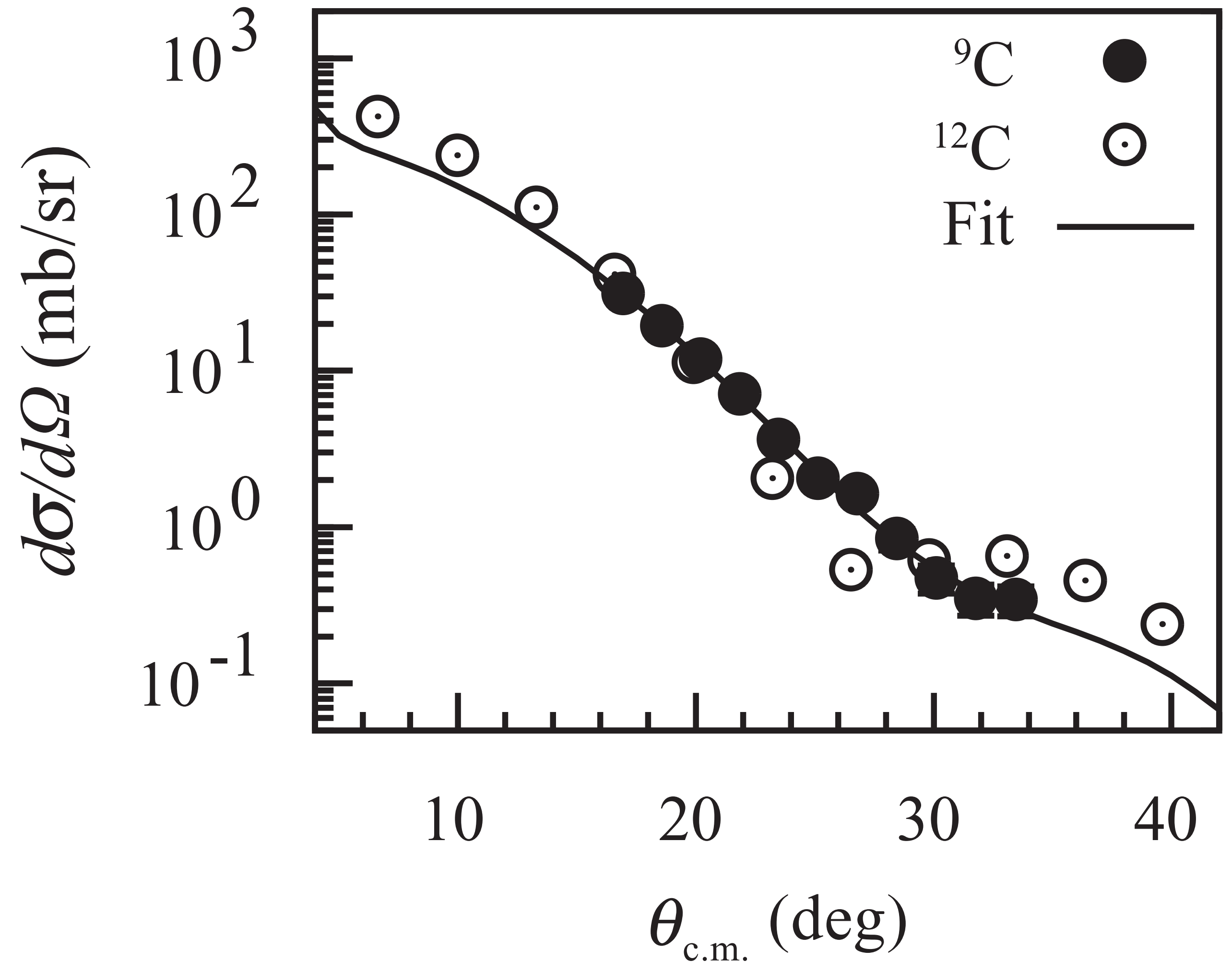
[Sakaguchi, Zenihiro, PPNP 97 (2017) 1–52]

- 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)]

Optical potential

Phenomenological

Unfortunately, current used optical potentials for low-energy reactions are phenomenological and primarily constrained by elastic scattering data.

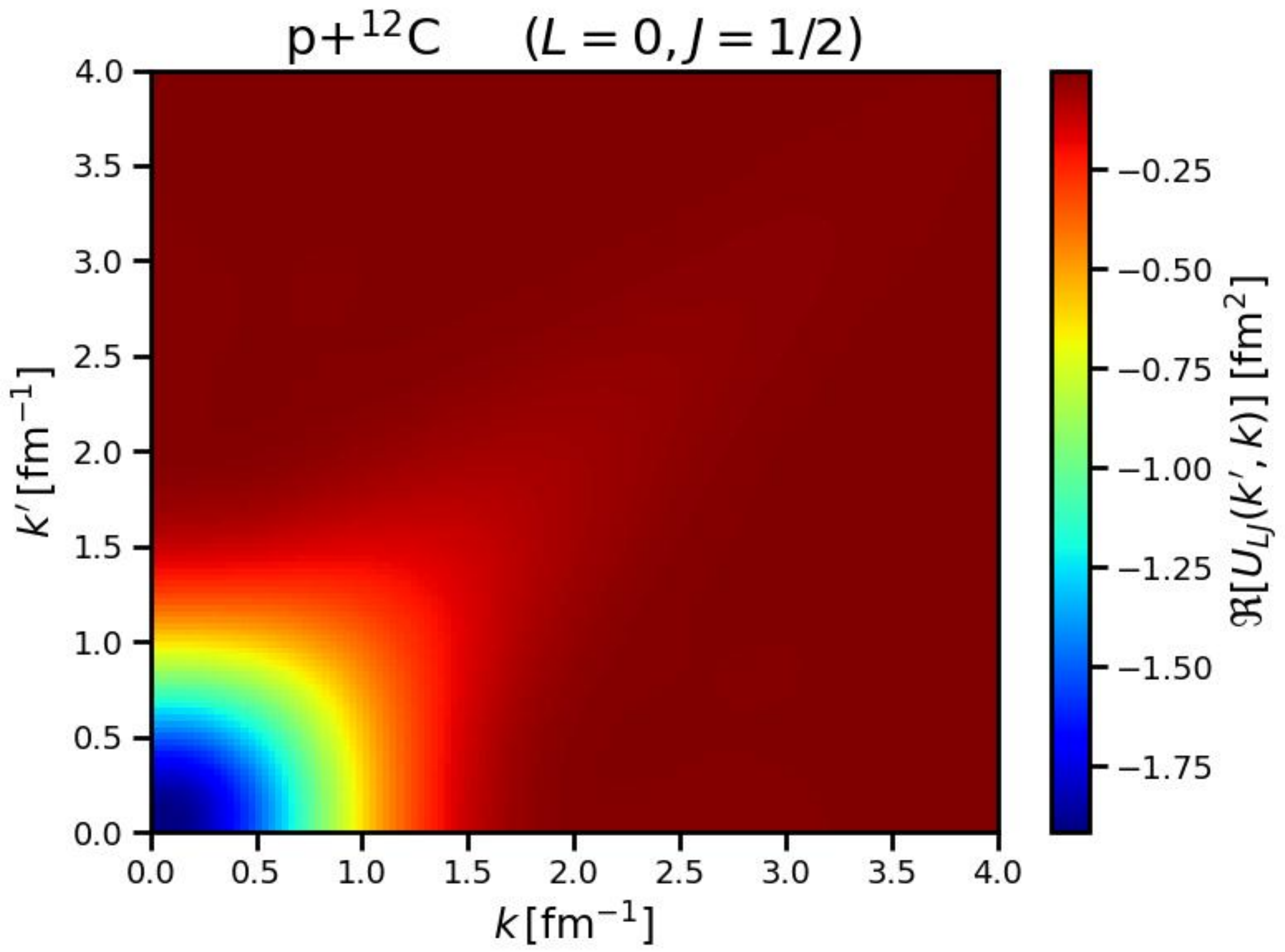
Unreliable when extrapolated beyond their fitted range in energy and nuclei

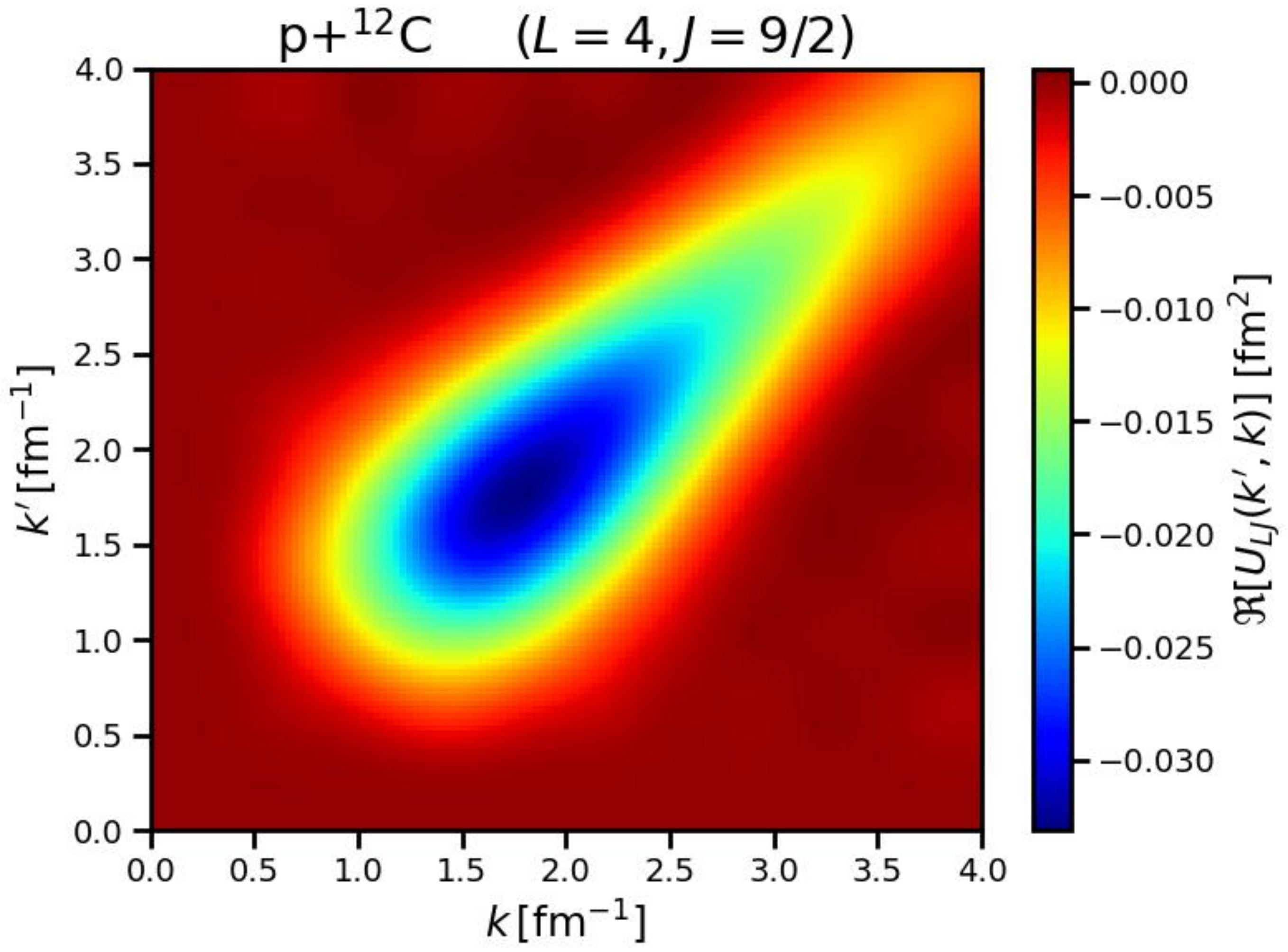
Microscopic

Existing microscopic optical potentials can be developed in a low- (Feshbach theory) or high-energy regime (Watson multiple scattering theory). Calculations are more difficult.

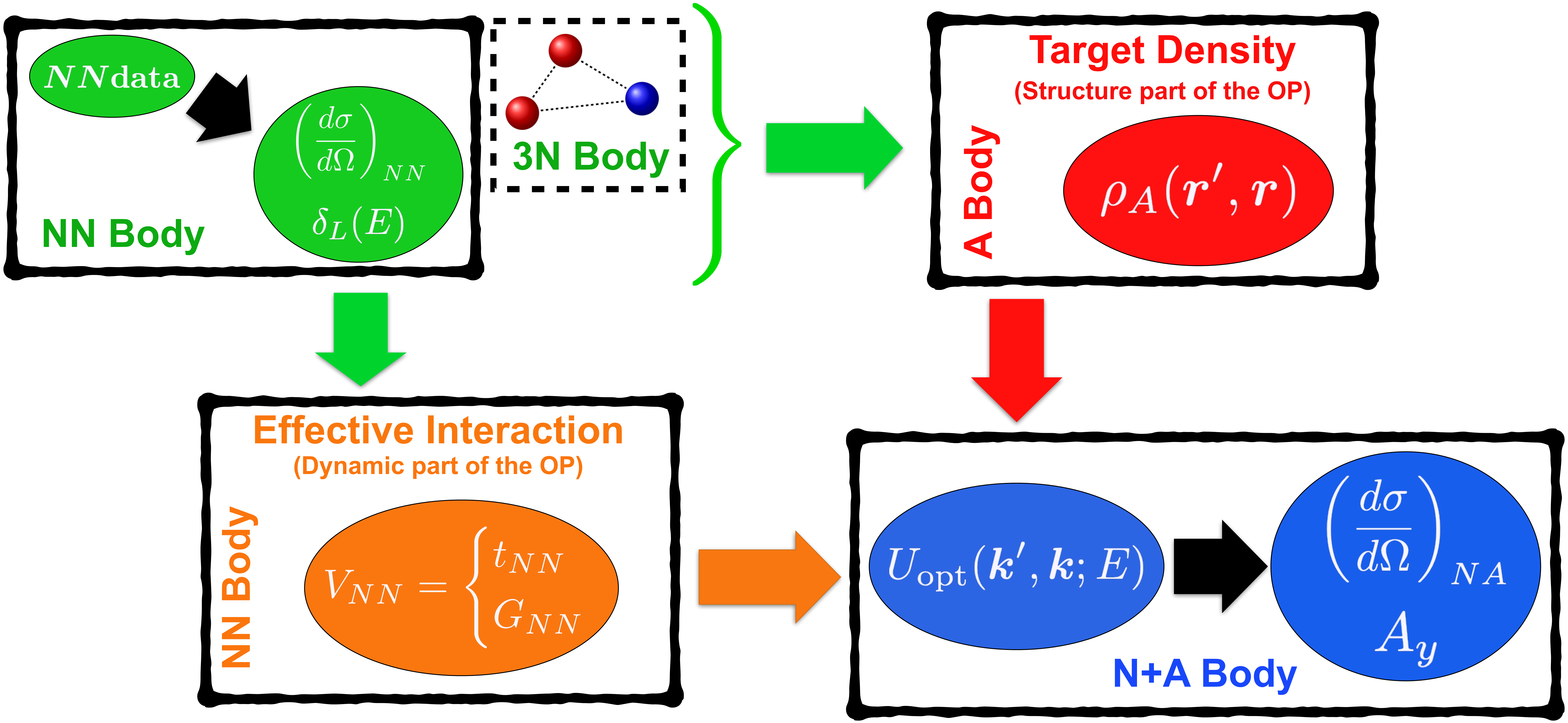
No fit to experimental data

$$
\begin{aligned}
V(r) &= -V_R f_R(r) - iW_V f_V(r) \\
&+ 4a_{VD} V_D \frac{d}{dr} f_{VD}(r) + 4ia_{WD} \frac{d}{dr} f_{WD}(r) \\
&+ \frac{\lambda_\pi^2}{r}\left[V_{SO}\frac{d}{dr} f_{VSO}(r) + iW_{SO}\frac{d}{dr} f_{WSO}(r)\right]\vec{\sigma}\cdot\vec{l}
\end{aligned}
$$





Road map to the optical potential



Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

Theoretical framework

Lippmann-Schwinger equation for the nucleon-nucleus transition amplitude

$$T = V + V G_0(E) T$$

<u>Projectile-target interaction</u>

$$V = \sum_{i=1}^{A} v_{0i} + \sum_{i<j}^{A} w_{0ij}$$

Full 3N interaction is still missing!

<u>Many-body propagator</u>

$$G_0(E) = (E - H_0 + i\epsilon)^{-1}$$

$$H_0 = h_0 + H_A$$

h_0 = kinetic term of the projectile

Target Hamiltonian

$$H_A |\Psi_0\rangle = E_0 |\Psi_0\rangle$$

Theoretical framework

Lippmann-Schwinger equation for the nucleon-nucleus transition amplitude

$$T = V + V G_0(E) T$$

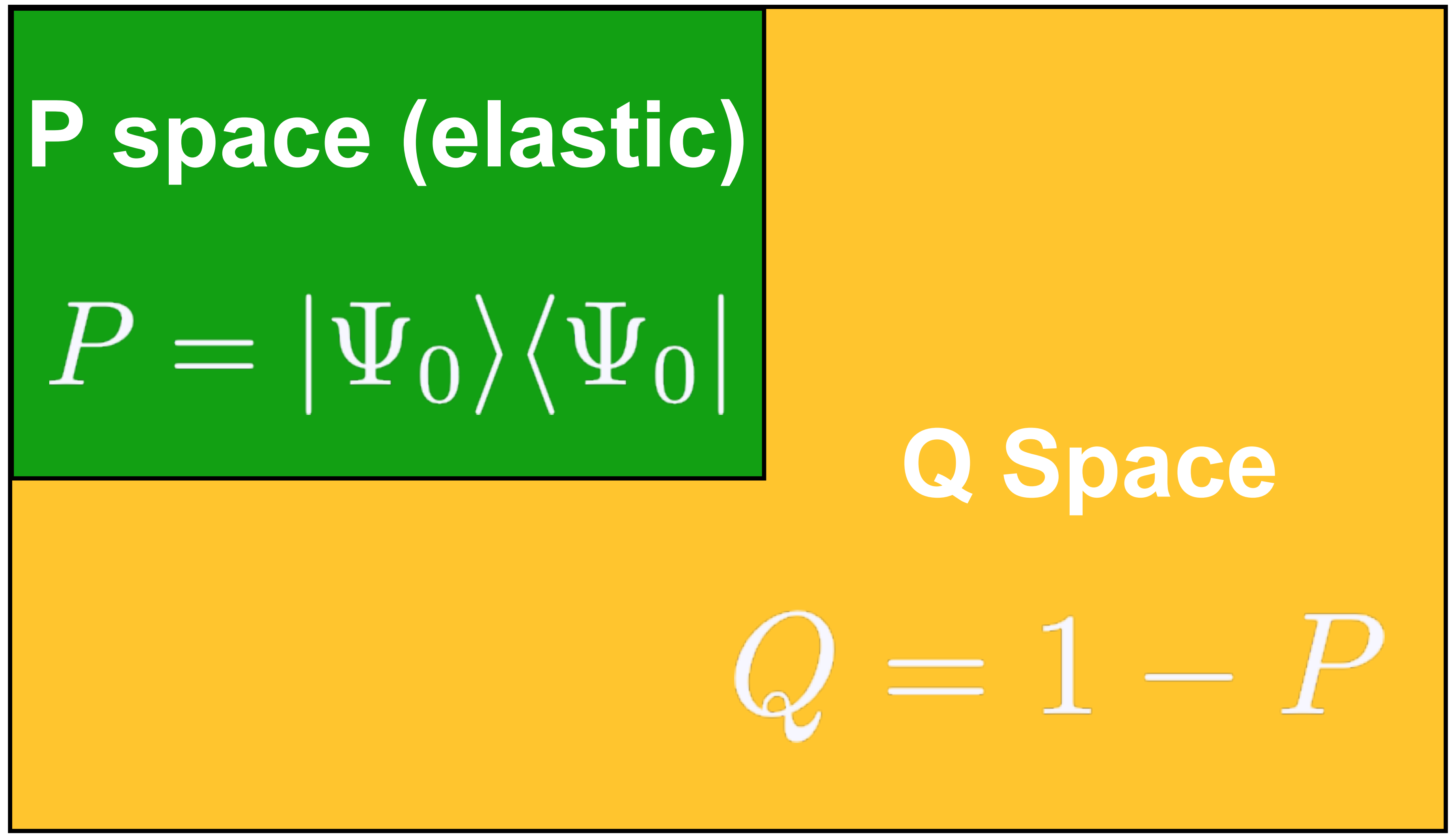
Let's introduce the optical potential *U*

$$T = U + U G_0(E) P T$$

$$U = V + V G_0(E) Q U$$

Projection operators

$$P + Q = 1$$



Theoretical framework

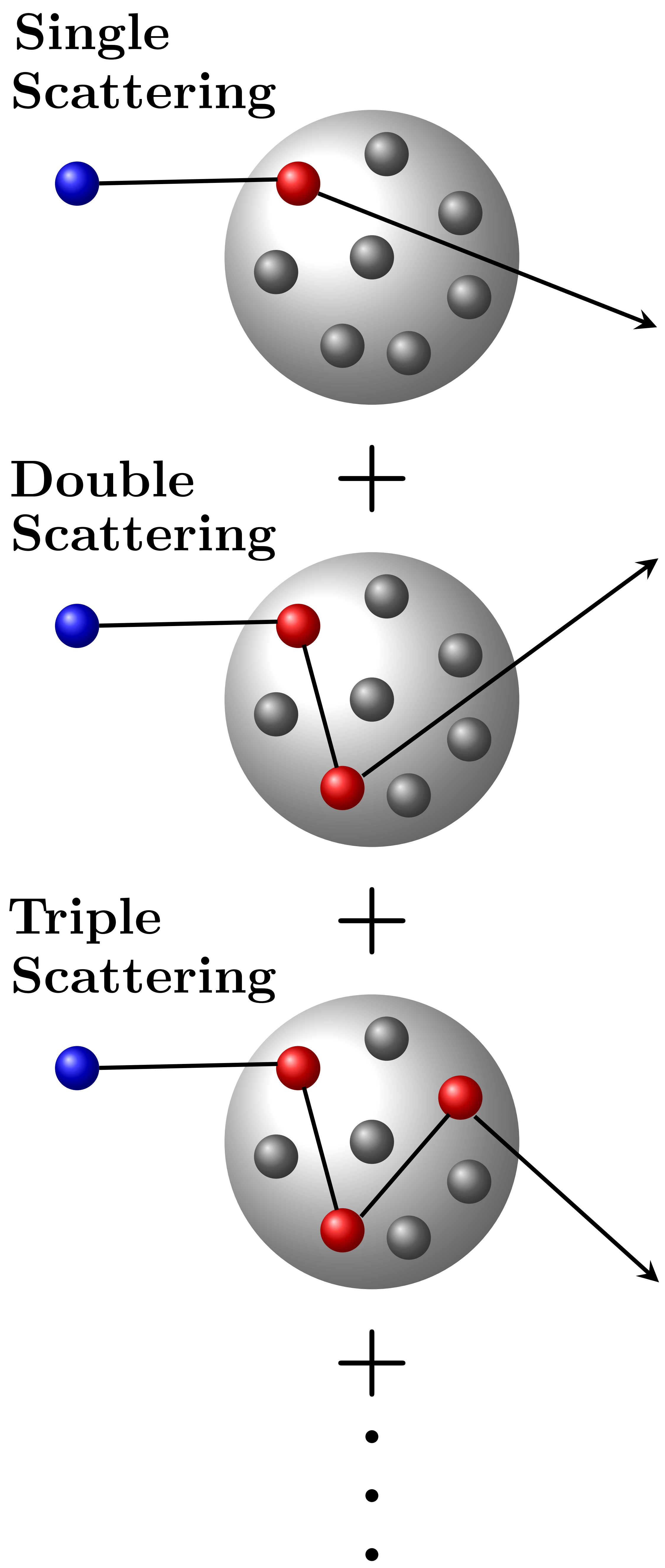
Transition amplitude for elastic scattering

$$T_{\text{el}} \equiv PTP = PUP + PUPG_0(E)T_{\text{el}}$$

The spectator expansion

[Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)]

$$U = \underbrace{\sum_{i=1}^{A} \tau_{0i} + \sum_{i,j\neq i}^{A} \tau_{0ij} + \sum_{i,j\neq i,k\neq i,j}^{A} \tau_{0ijk} + \ldots}_{\textbf{A terms}}$$



Theoretical framework

Transition amplitude for elastic scattering

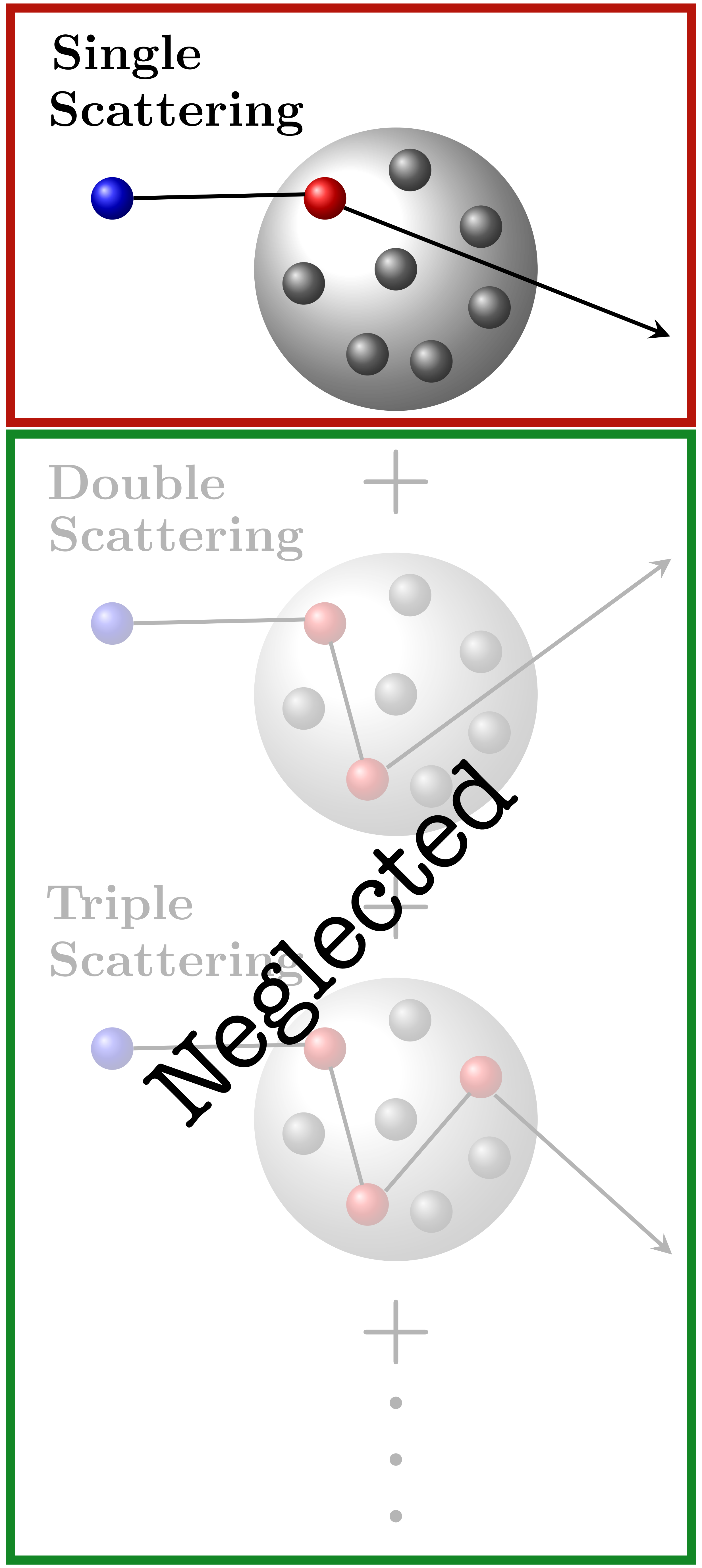
$$T_{\rm el} \equiv PTP = PUP + PUPG_0(E)T_{\rm el}$$

The spectator expansion

[Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)]

$$U \simeq \sum_{i=1}^{A} \tau_{0i} \qquad \tau_{0i} = v_{0i} + v_{0i}G_0(E)\tau_{0i}$$

(A+1)-body propagator



Theoretical framework

Transition amplitude for elastic scattering

$$T_{\rm el} \equiv PTP = PUP + PUPG_0(E)T_{\rm el}$$

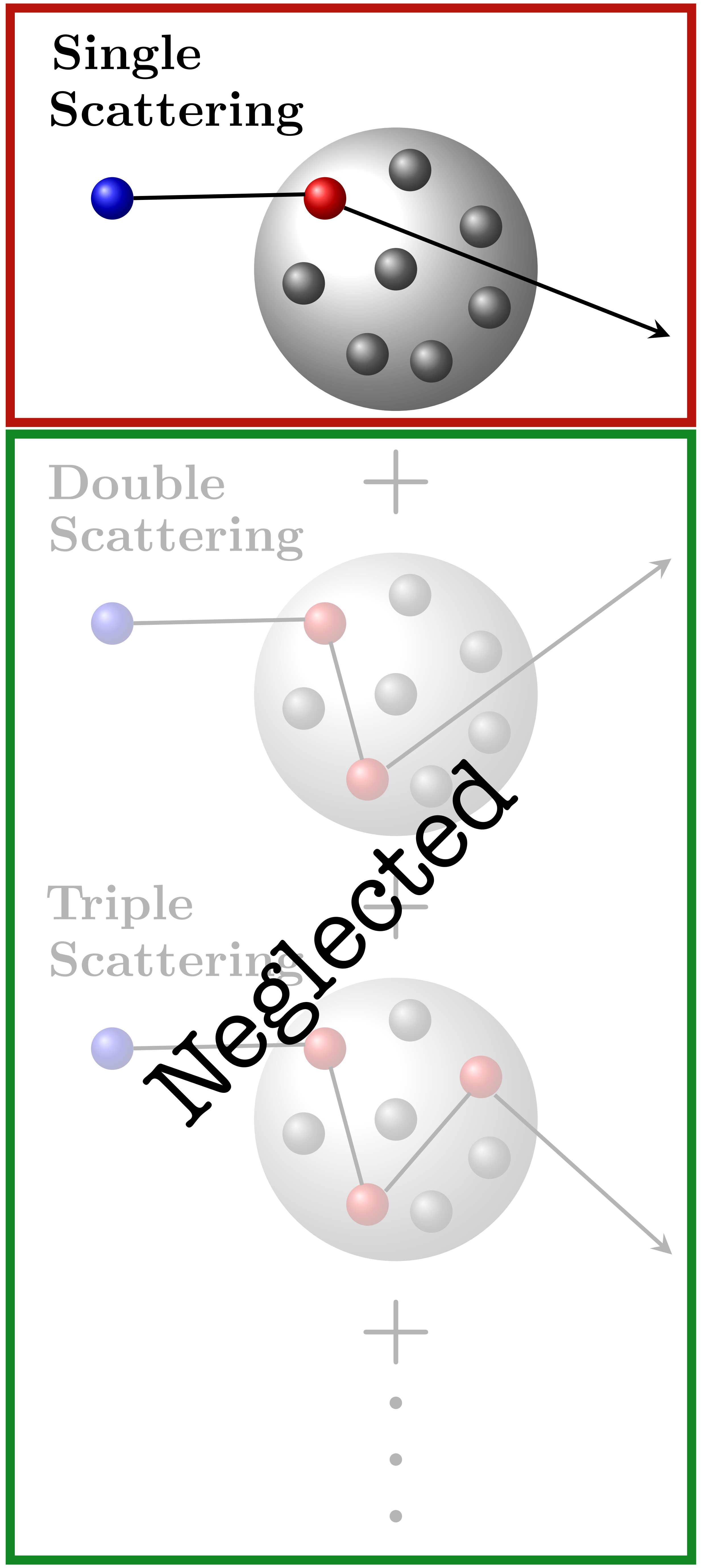
The spectator expansion

[Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)]

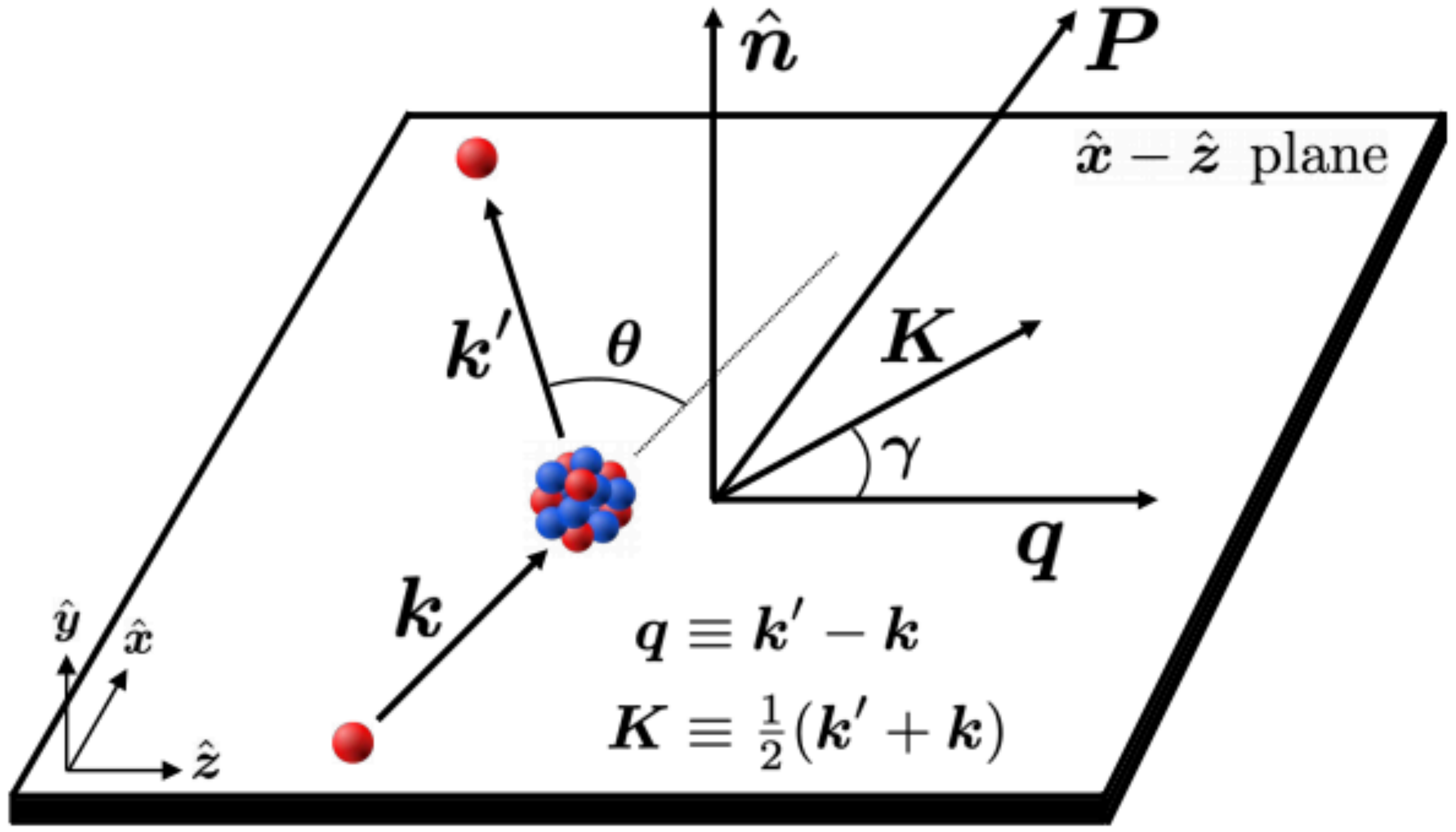
$$U \simeq \sum_{i=1}^{A} \tau_{0i} \quad \rightarrow \quad \tau_{0i} \approx t_{0i} = v_{0i} + v_{0i}\, g_0(E)\, t_{0i}$$

Impulse approximation

Two-body propagator



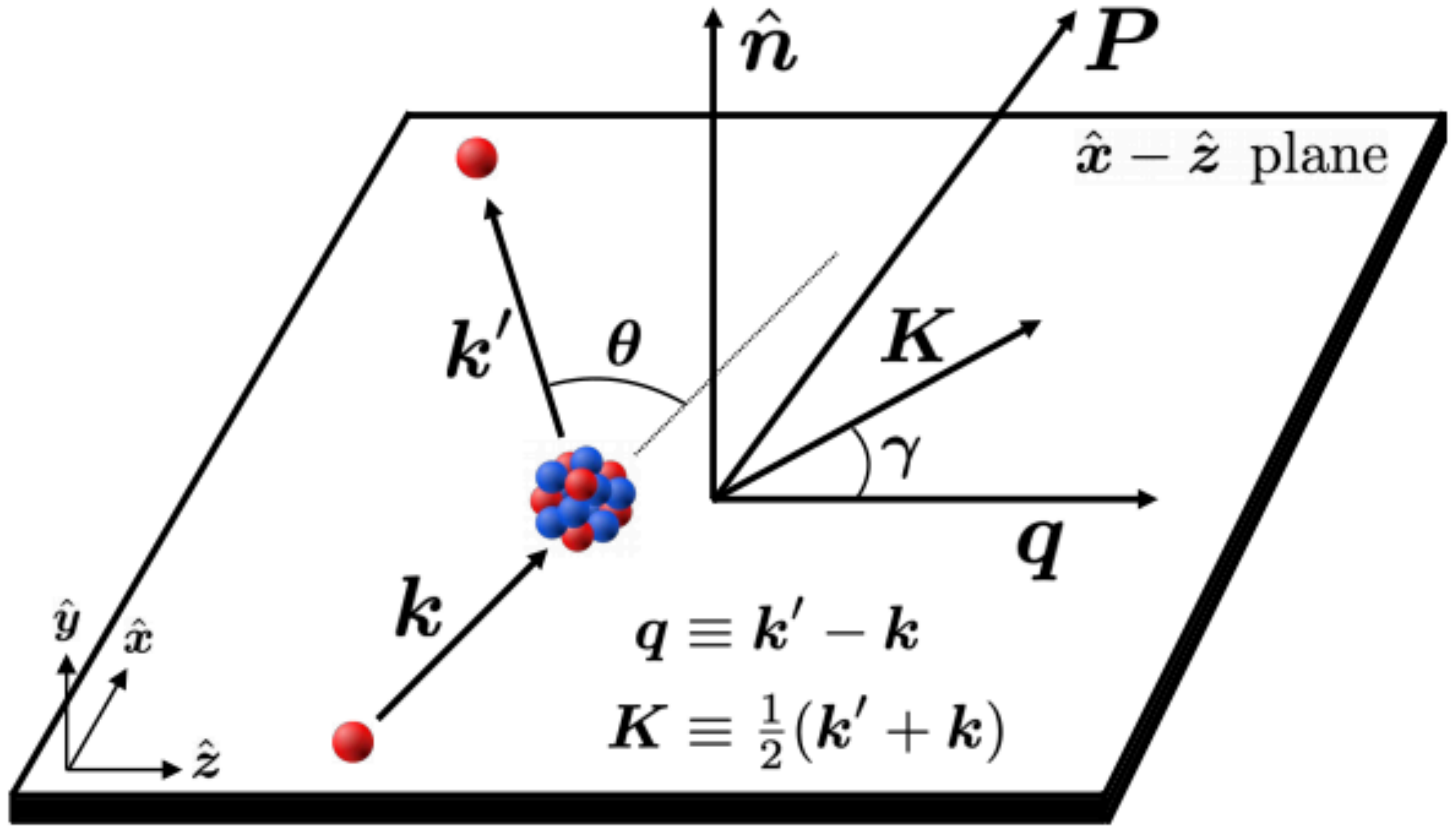
The first-order optical potential



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

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

The first-order optical potential



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

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

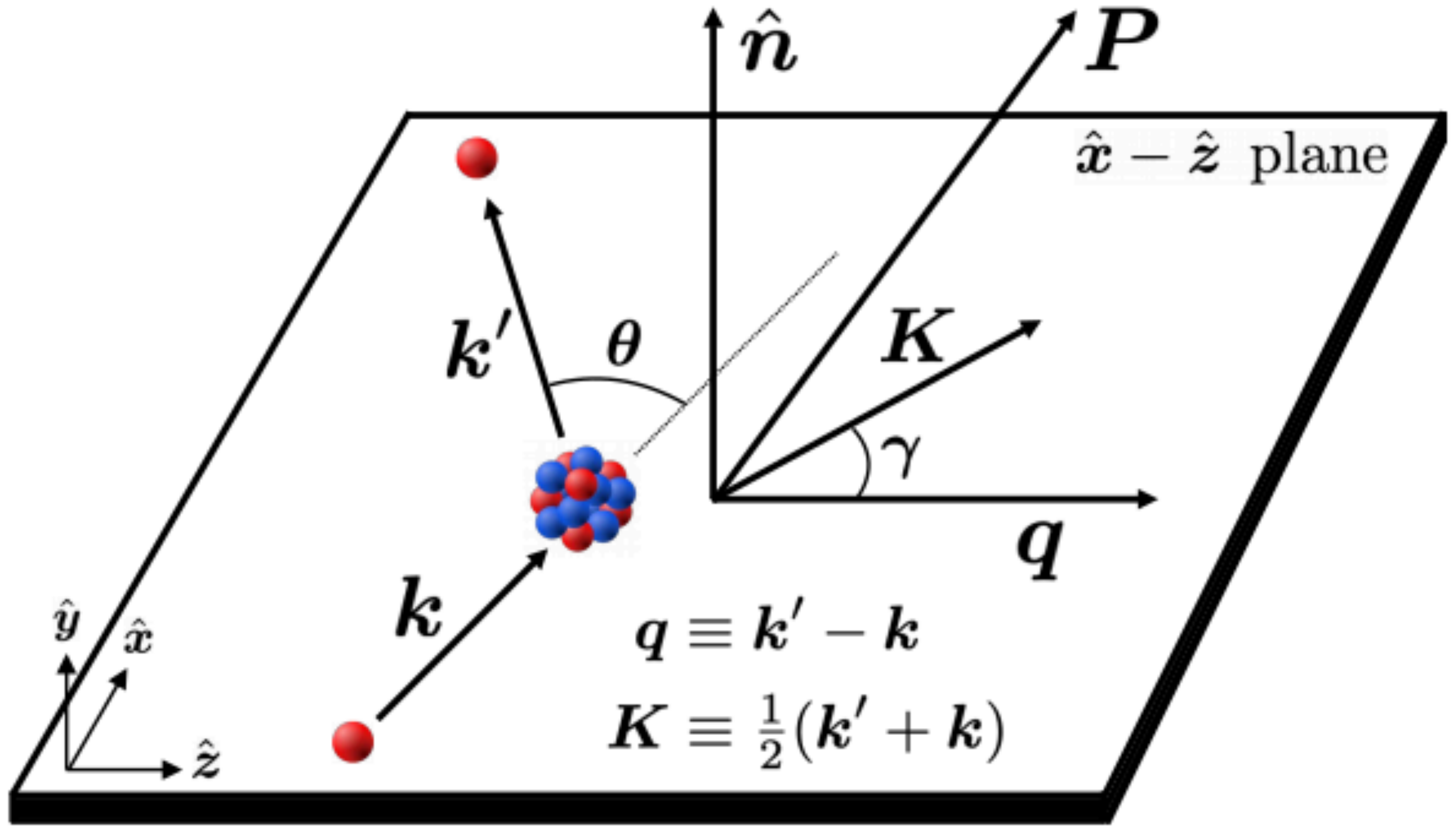
<u>Free two-body scattering matrix</u>

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

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

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

The first-order optical potential



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

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

Free two-body scattering matrix

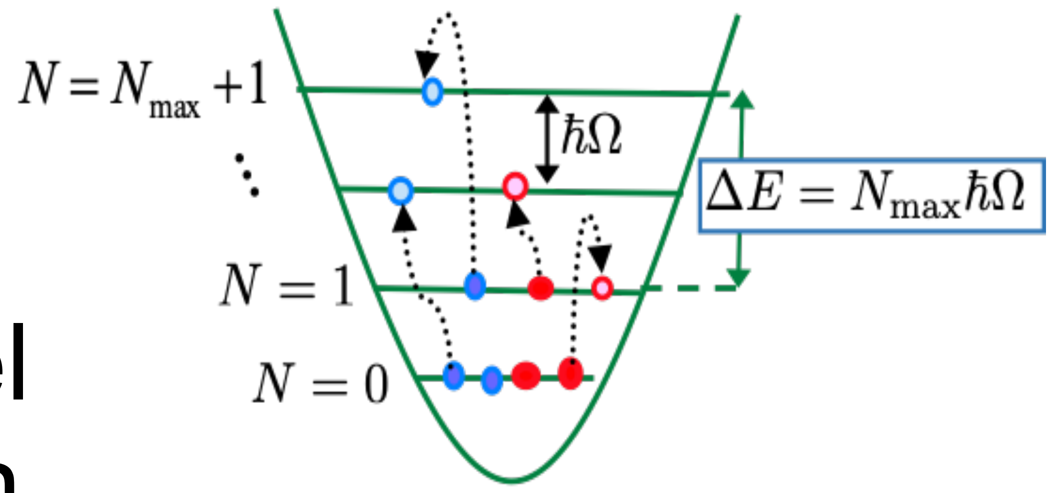
$$t_{0i} = v_{0i} + v_{0i}\, g_{0i}\, t_{0i}$$

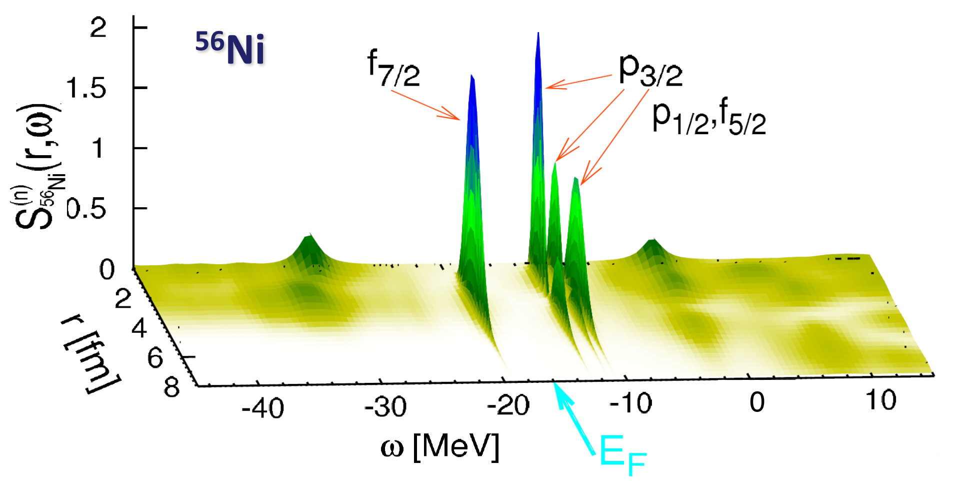
$$g_{0i} = (E - h_0 - h_i + i\epsilon)^{-1}$$

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

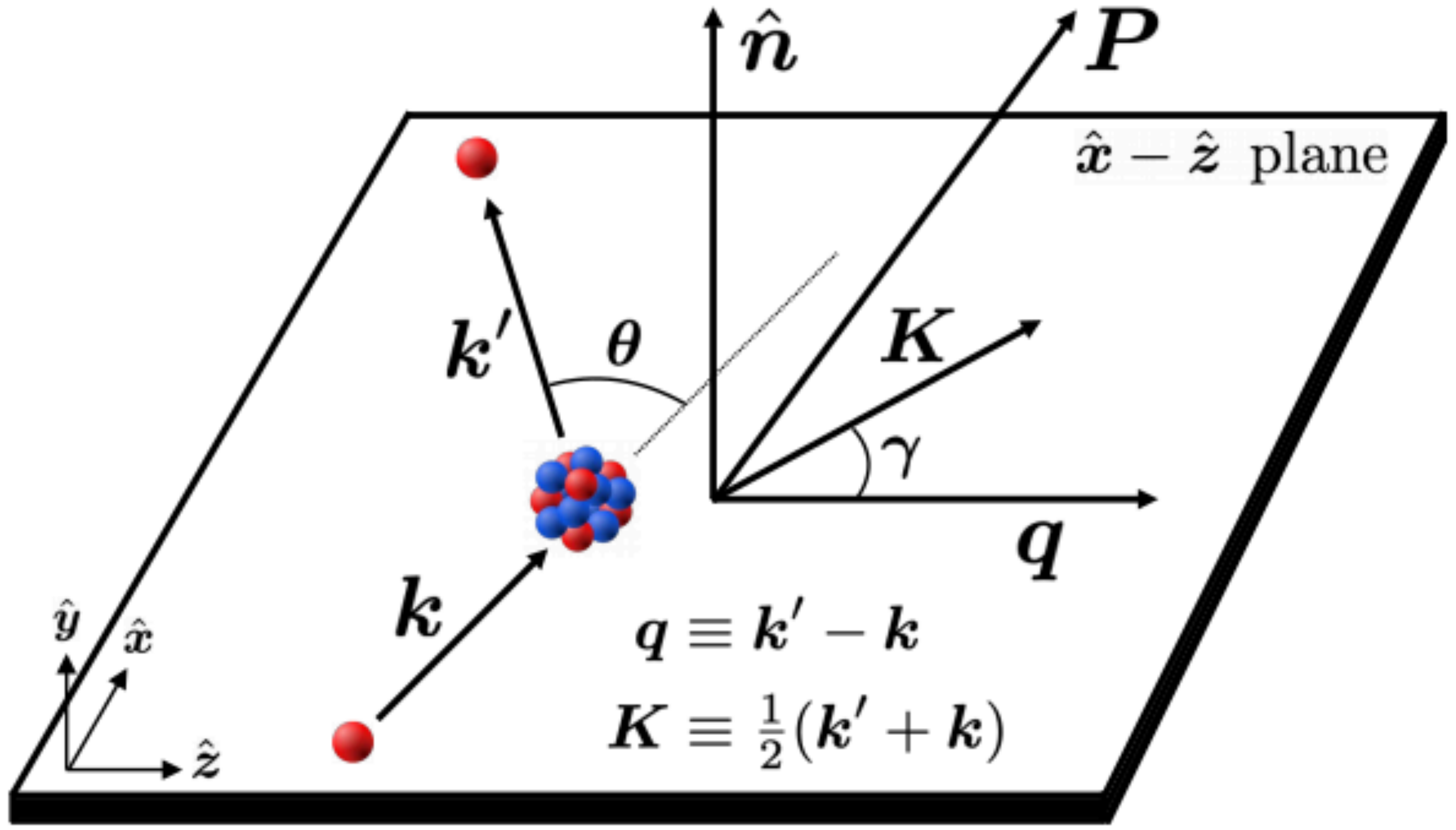
Nonlocal one-body density

- Computationally expensive
- Obtained from the No-Core Shell Model or the Self-Consistent Green's Function
- Calculation performed with **NN** and **3N** interaction





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

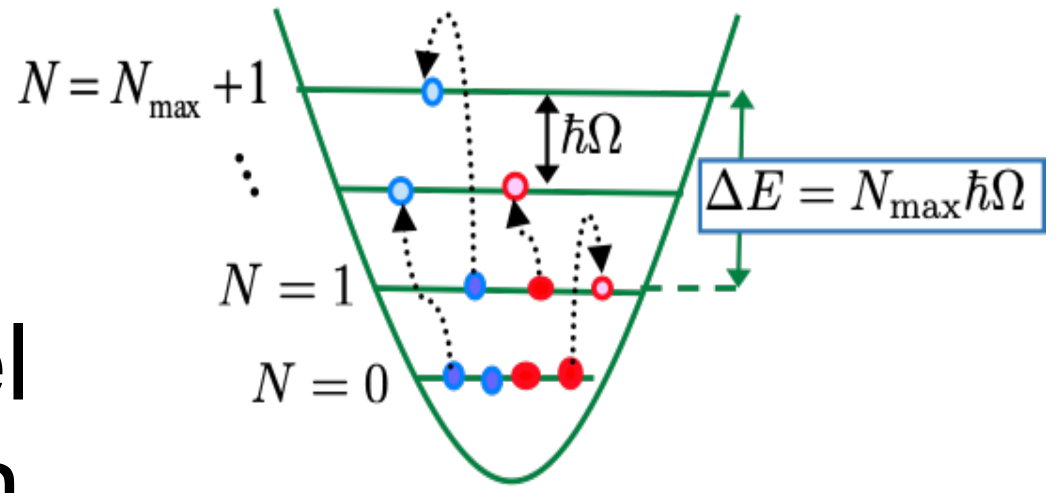
$$t_{0i} = v_{0i} + v_{0i}\, g_{0i}\, t_{0i}$$

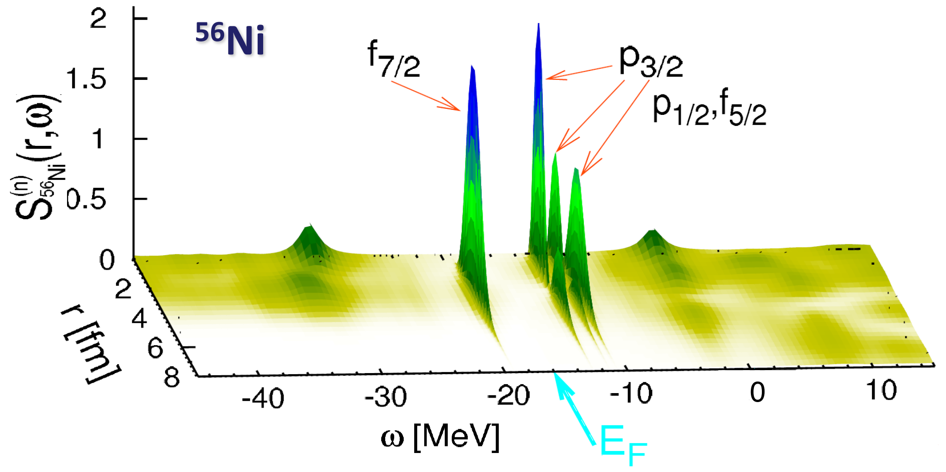
$$g_{0i} = (E - h_0 - h_i + i\epsilon)^{-1}$$

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

Nonlocal one-body density

- Computationally expensive
- Obtained from the No-Core Shell Model or the Self-Consistent Green's Function
- Calculation performed with **NN** and **3N** interaction





Outline

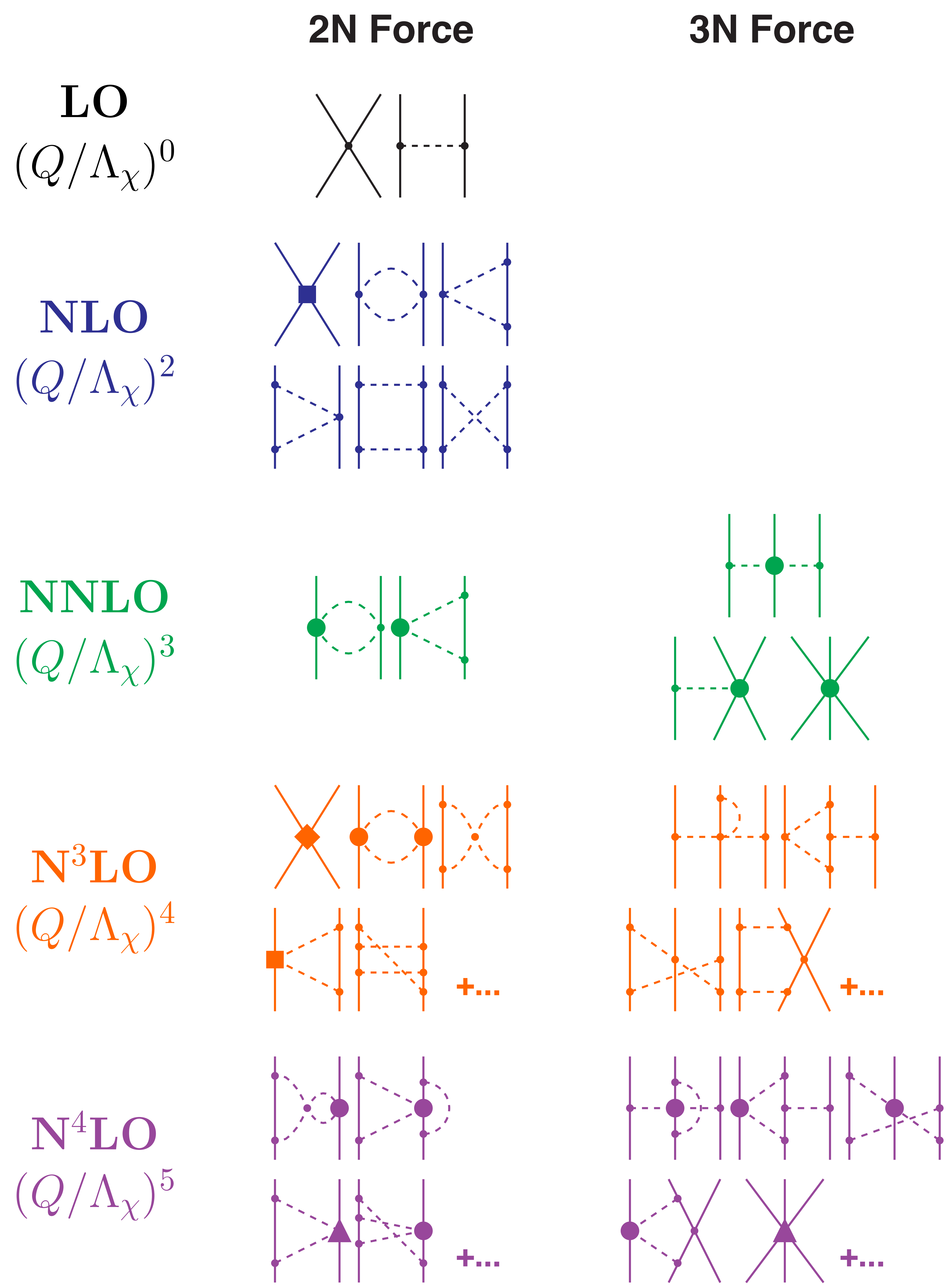
- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

Chiral interactions

Advantages

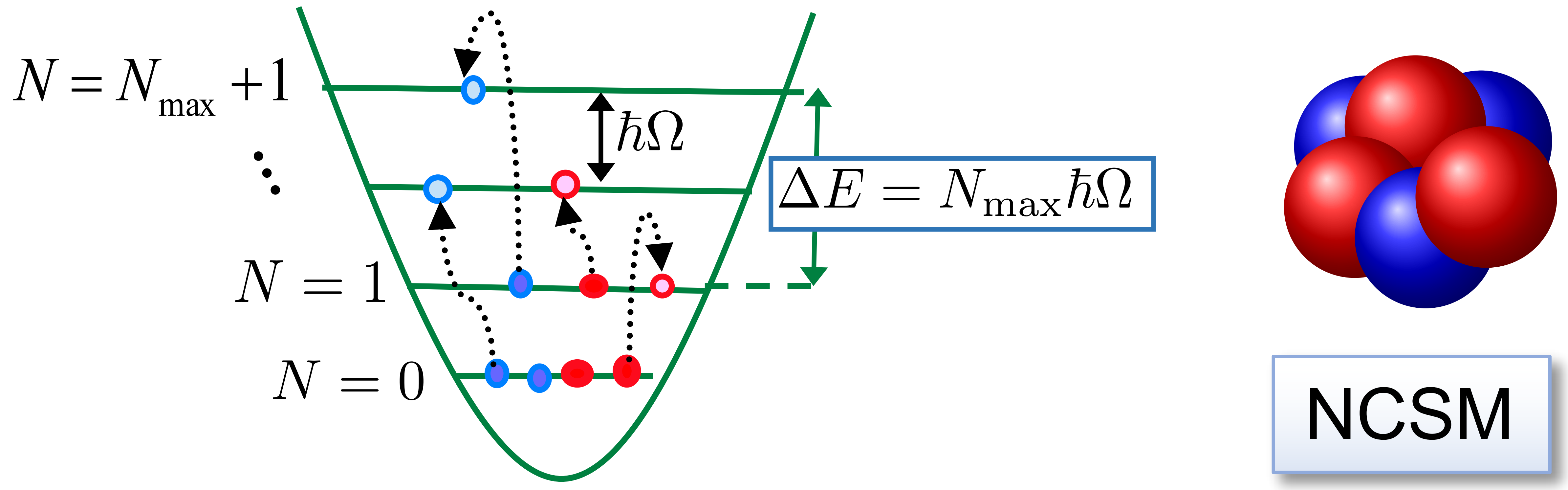
- QCD symmetries are consistently respected
- Systematic expansion (order by order we know exactly the terms to be included)
- Theoretical errors
- Two- and three-nucleon forces belong to the same framework

We use these interactions as the **only** input to calculate the **effective interaction** between projectile and target and the **target density**



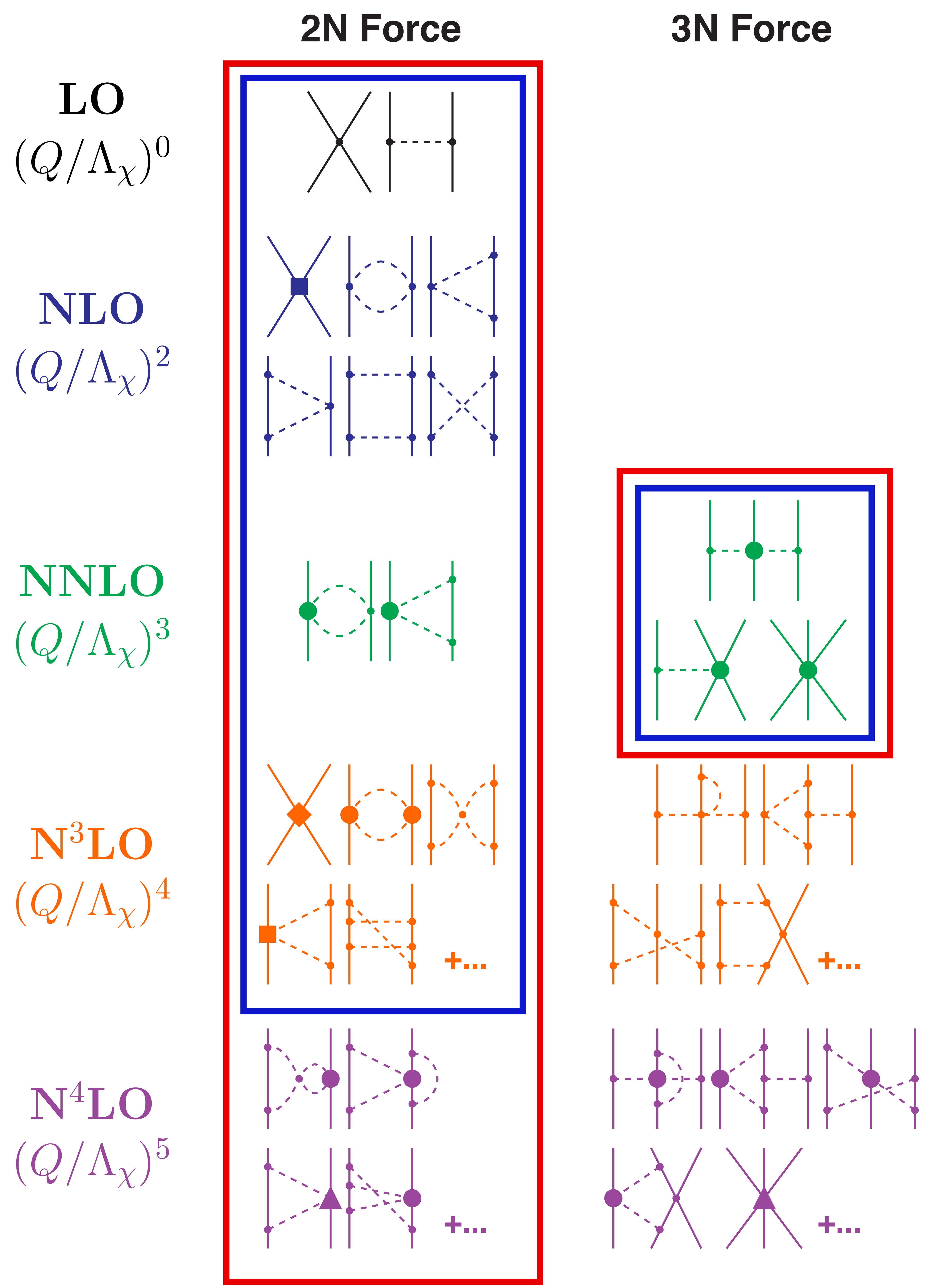
Target description

No-Core Shell Model



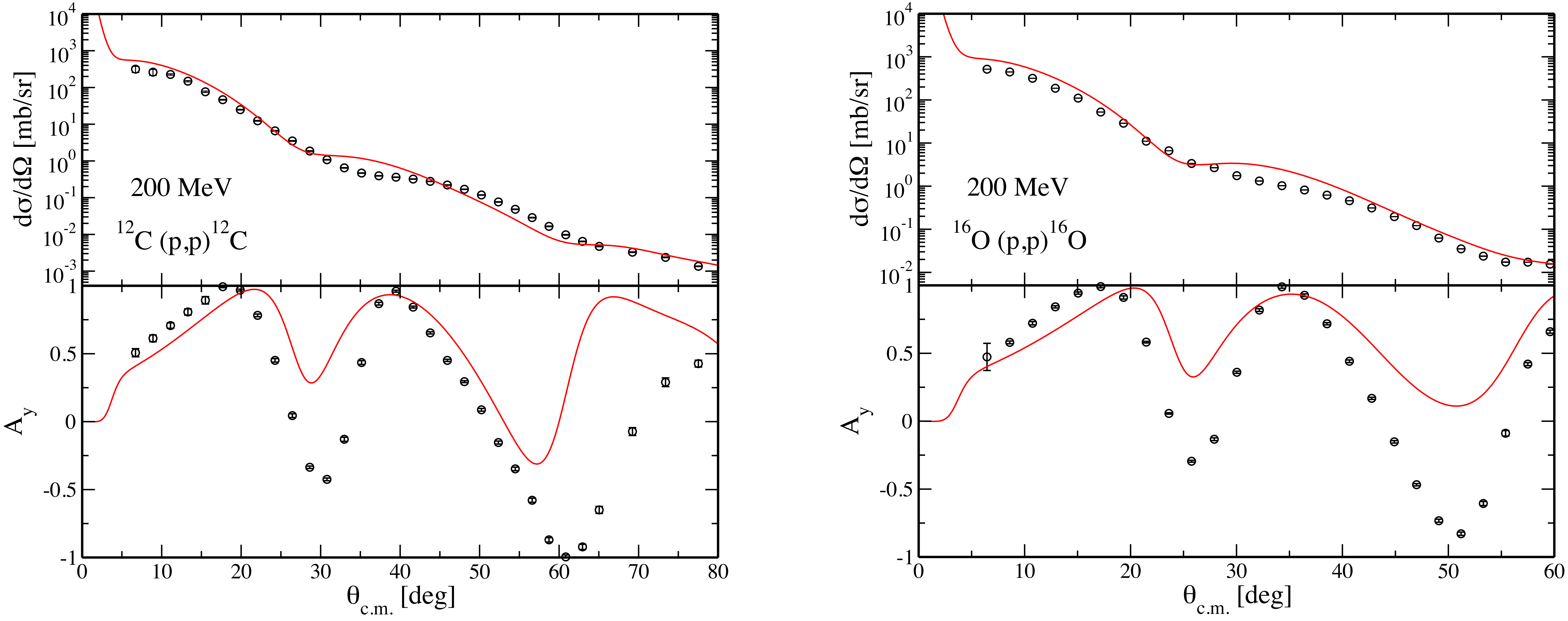
In collaboration with P. Navrátil and M. Gennari (TRIUMF)

- **NN-N^{4}LO + 3NlnI (^{12}C, ^{16}O)**
  - N^{4}LO: Entem et al., Phys. Rev. C **96**, 024004 (2017)
  - 3NlnI: Navrátil, Few-Body Syst. **41**, 117 (2007)
  - c_D & c_E: Kravvaris et al., Phys. Rev. C **102**, 024616 (2020)
- **NN-N^{3}LO + 3NlnI (^{9,13}C, ^{6,7}Li, ^{10}B)**
  - N^{3}LO: E&M, Phys. Rev. C **68**, 041001(R) (2003)
  - 3NlnI: Navrátil, Few-Body Syst. **41**, 117 (2007)
  - c_D & c_E: Somà et al., Phys. Rev. C **101**, 014318 (2020)



Results for p+^{12}C and p+^{16}O with the basic model

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



- The t matrix is computed with the N^{4}LO interaction
- The density is computed with the N^{4}LO + 3NlnI interaction

Assessing the impact of the 3N interaction

General equation for the optical potential

$$U = (V_{NN} + V_{3N}) + (V_{NN} + V_{3N})G_0(E)QU$$

Treatment of the 3N force

[Holt et al., Phys. Rev. C **81**, 024002 (2010)]

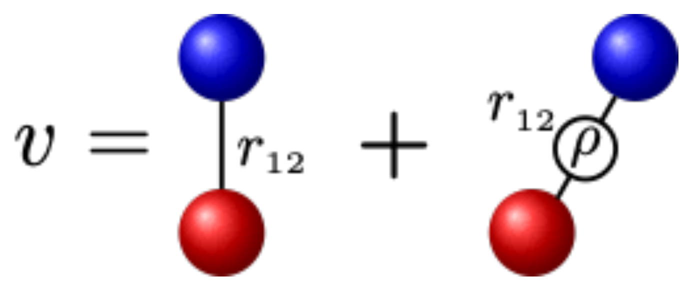
$$V_{3N} = \frac{1}{2}\sum_{i=1}^{A}\sum_{\substack{j=1\\ j\neq i}}^{A} w_{0ij} \approx \sum_{i=1}^{A}\langle w_{0i}\rangle$$

Density dependent

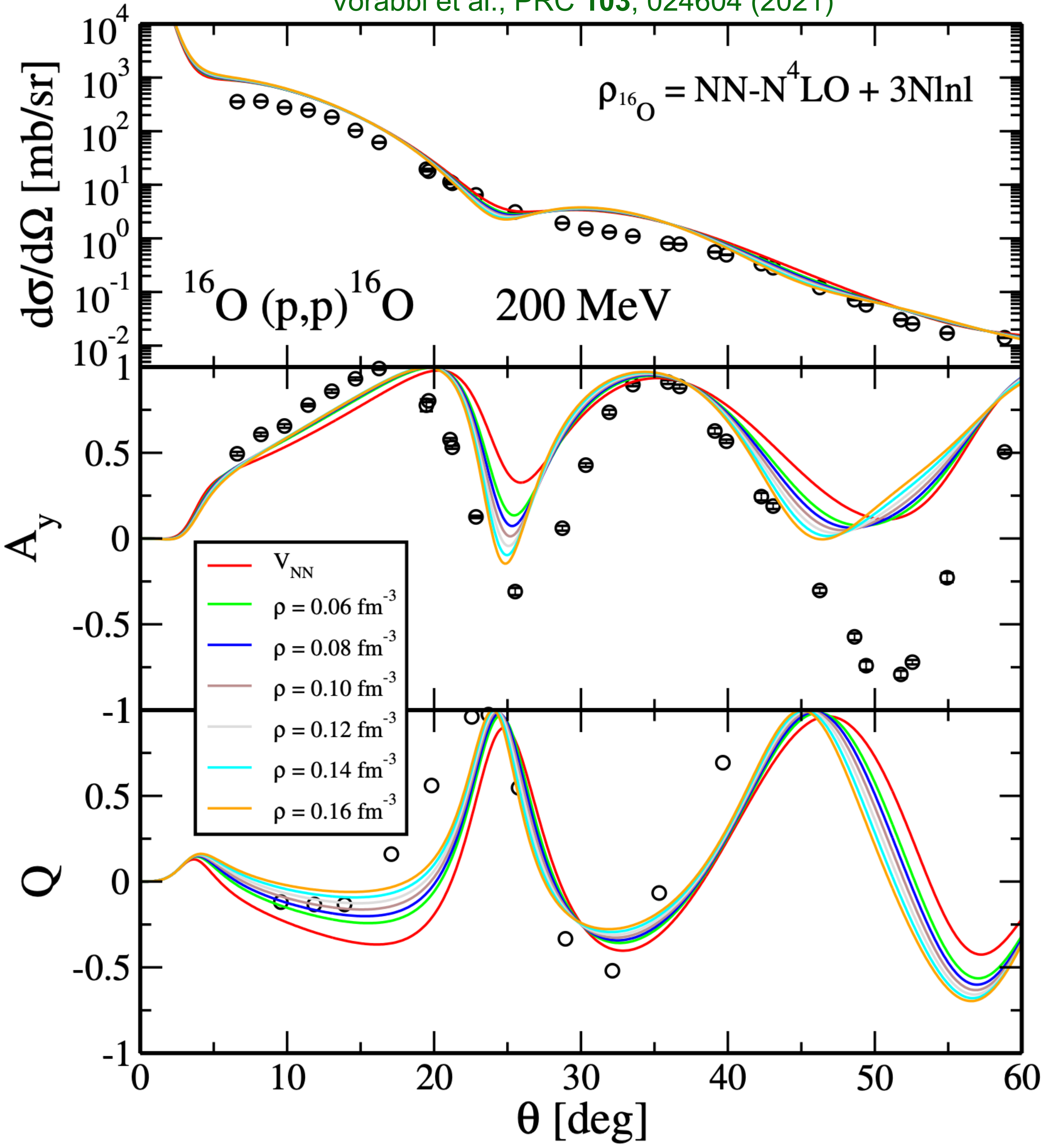
Modification of the *t* matrix

$$t_{0i} = v_{0i}^{(1)} + v_{0i}^{(2)} g_{0i}\, t_{0i}$$

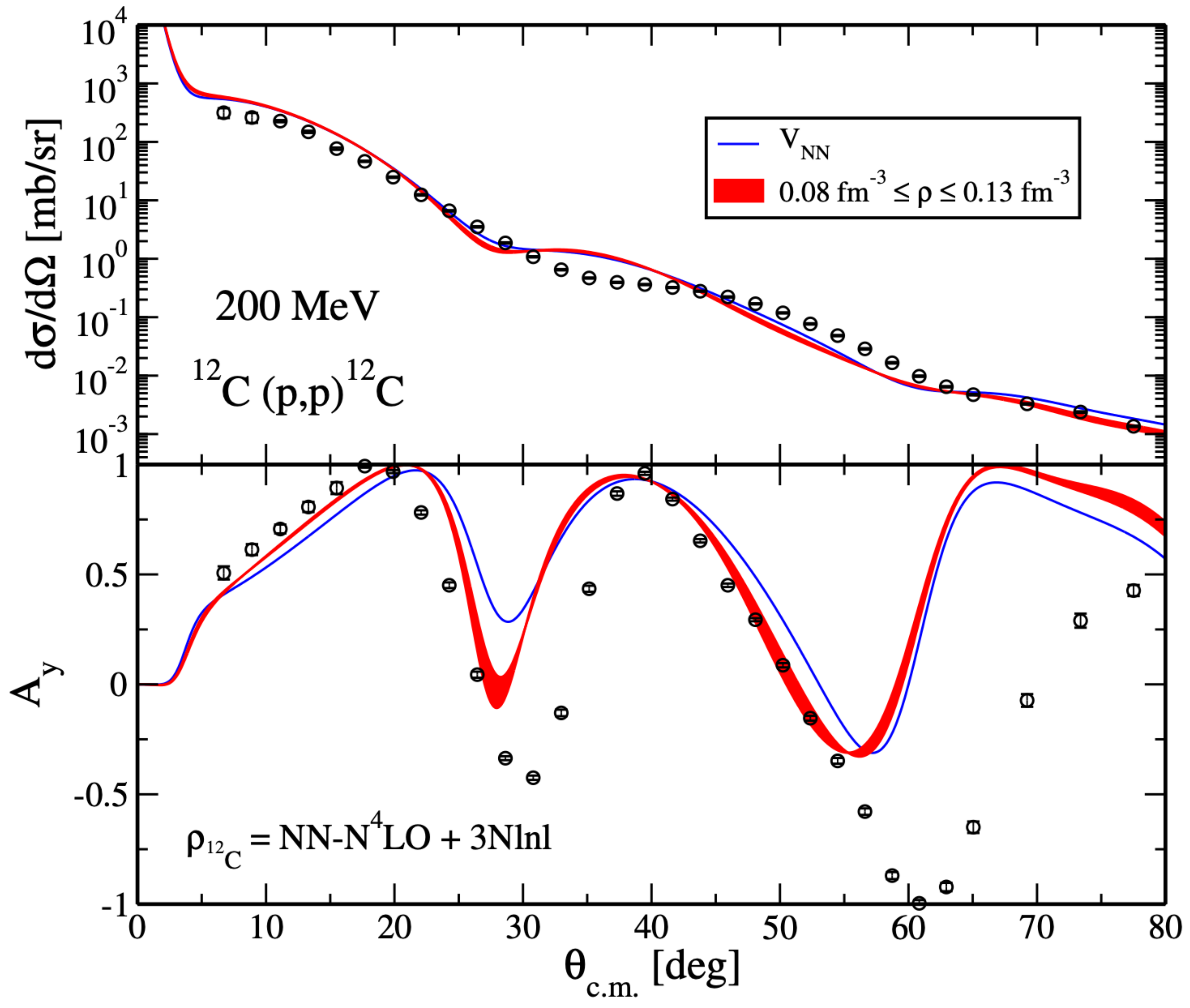
$$v_{0i}^{(1)} = v_{0i} + \tfrac{1}{2}\langle w_{0i}\rangle$$
$$v_{0i}^{(2)} = v_{0i} + \langle w_{0i}\rangle$$



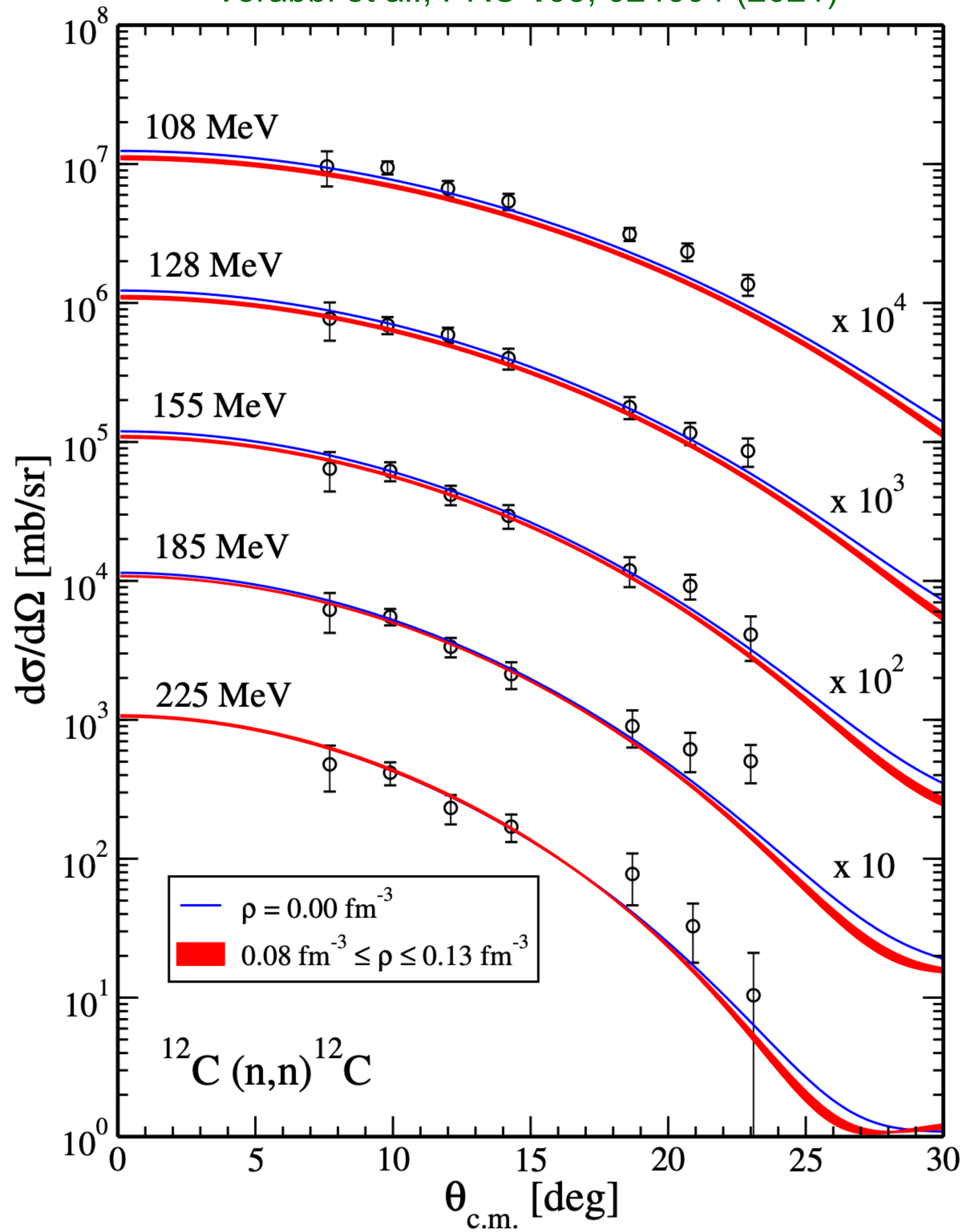
Vorabbi et al., PRC **103**, 024604 (2021)



Assessing the impact of the 3N interaction



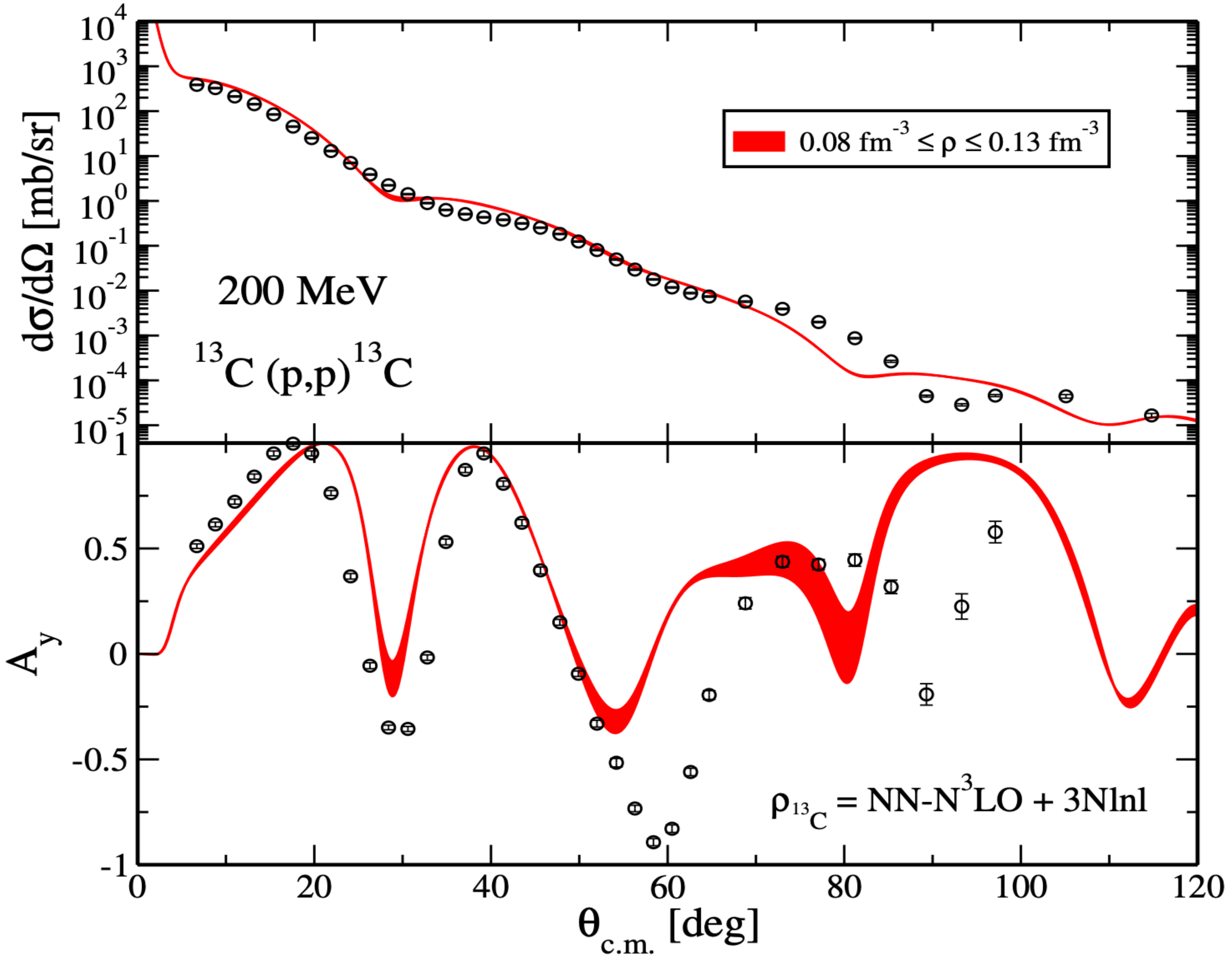
Vorabbi et al., PRC **103**, 024604 (2021)



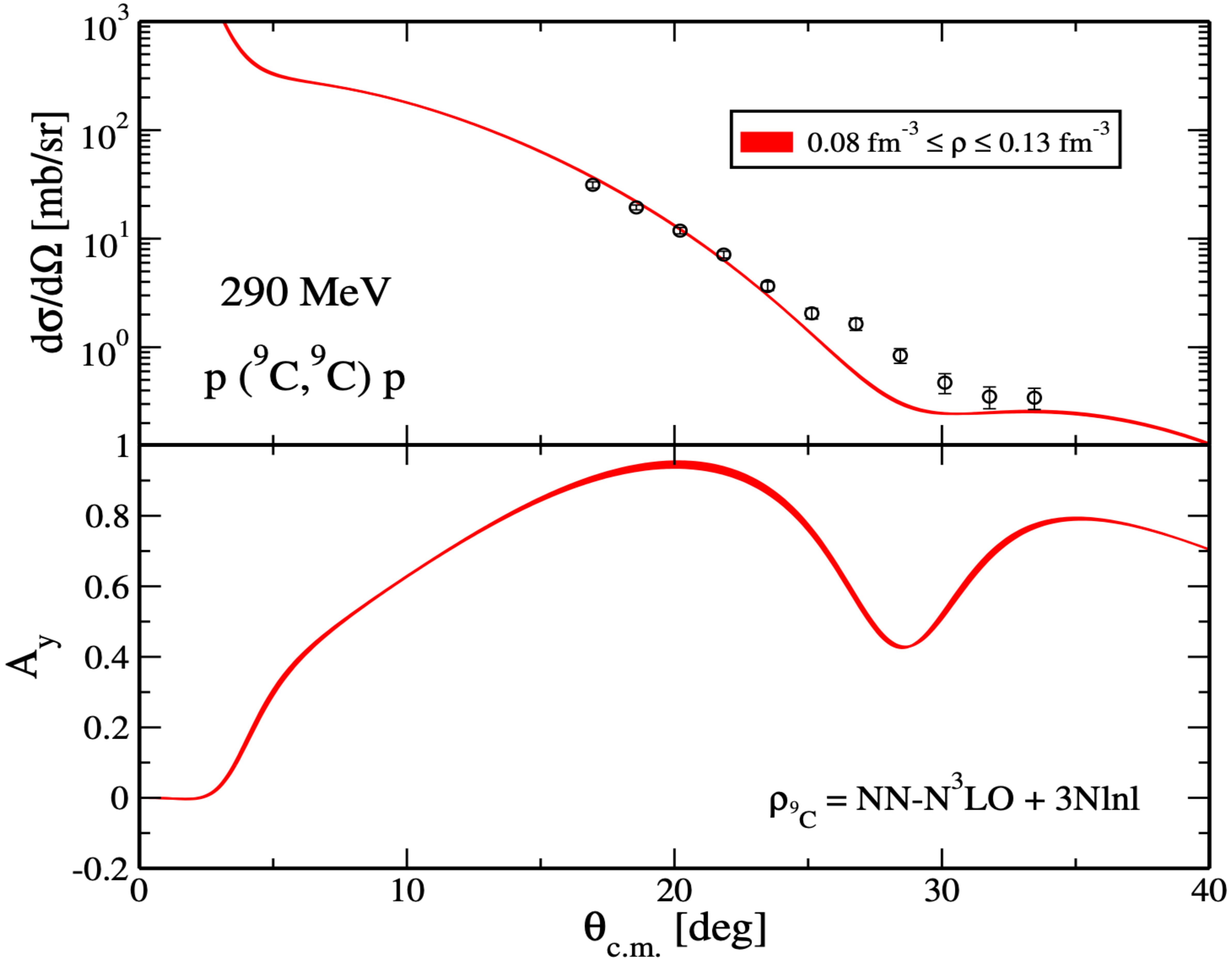
- For all nuclei we found very small contributions to the differential cross section
- The contributions to the spin observable are larger and they seem to improve the agreement with the data

Extension to non-zero spin targets

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



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



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

Convergence in the chiral expansion

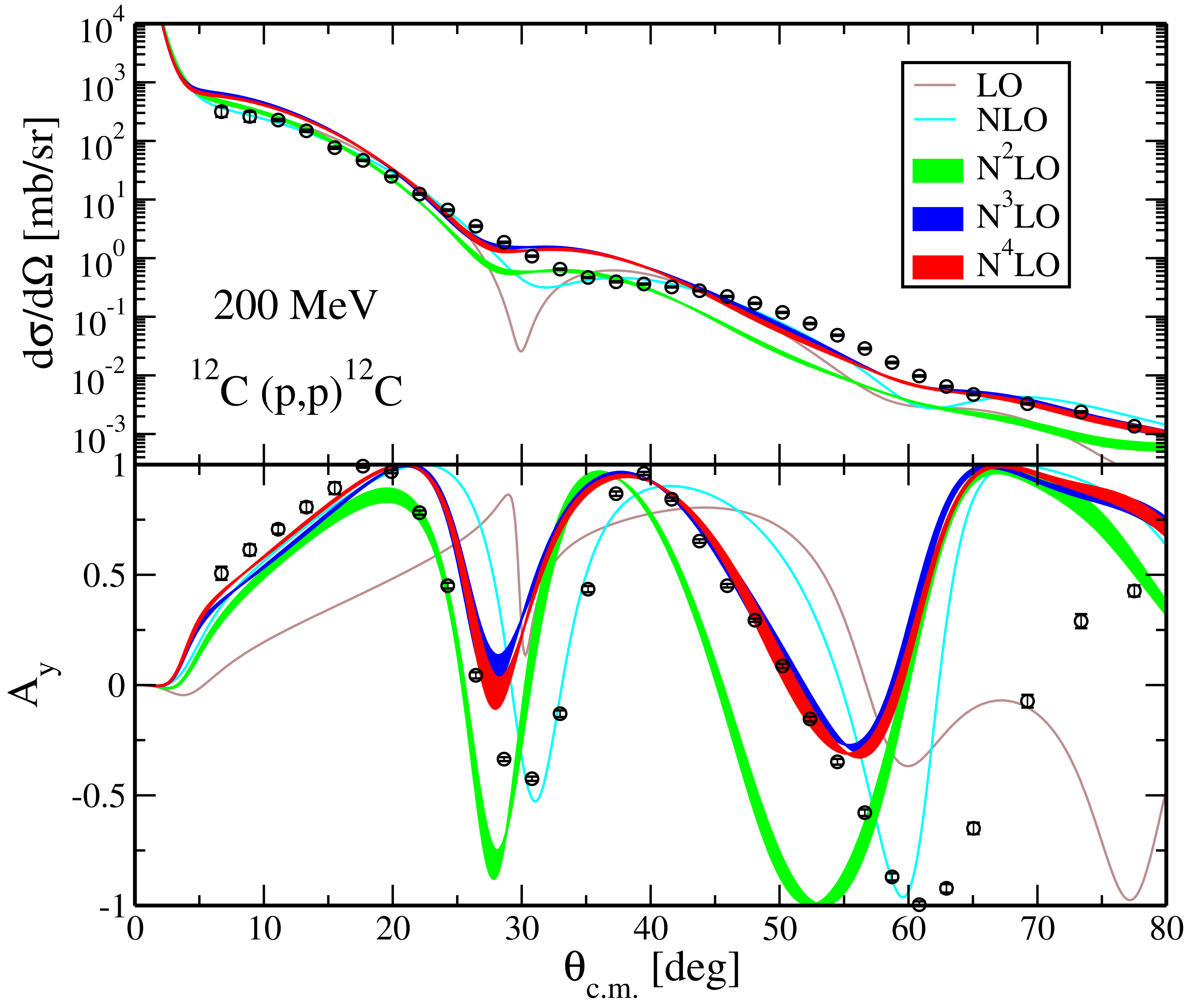
- Density computed with NN+3N interaction

  -NN interactions at all orders taken from
  Entem et al., PRC **96**, 024004 (2017)

  -3N only at N²LO with c_D and c_E refitted at each order
  Kravvaris et al., PRC **102**, 024616 (2020)

- Bands are obtained starting from N²LO when the matter density ρ is allowed to vary between 0.08 and 0.13 fm^{-3}

- At N³LO the results seem to achieve a good degree of convergence



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

Extension to antiproton-nucleus elastic scattering

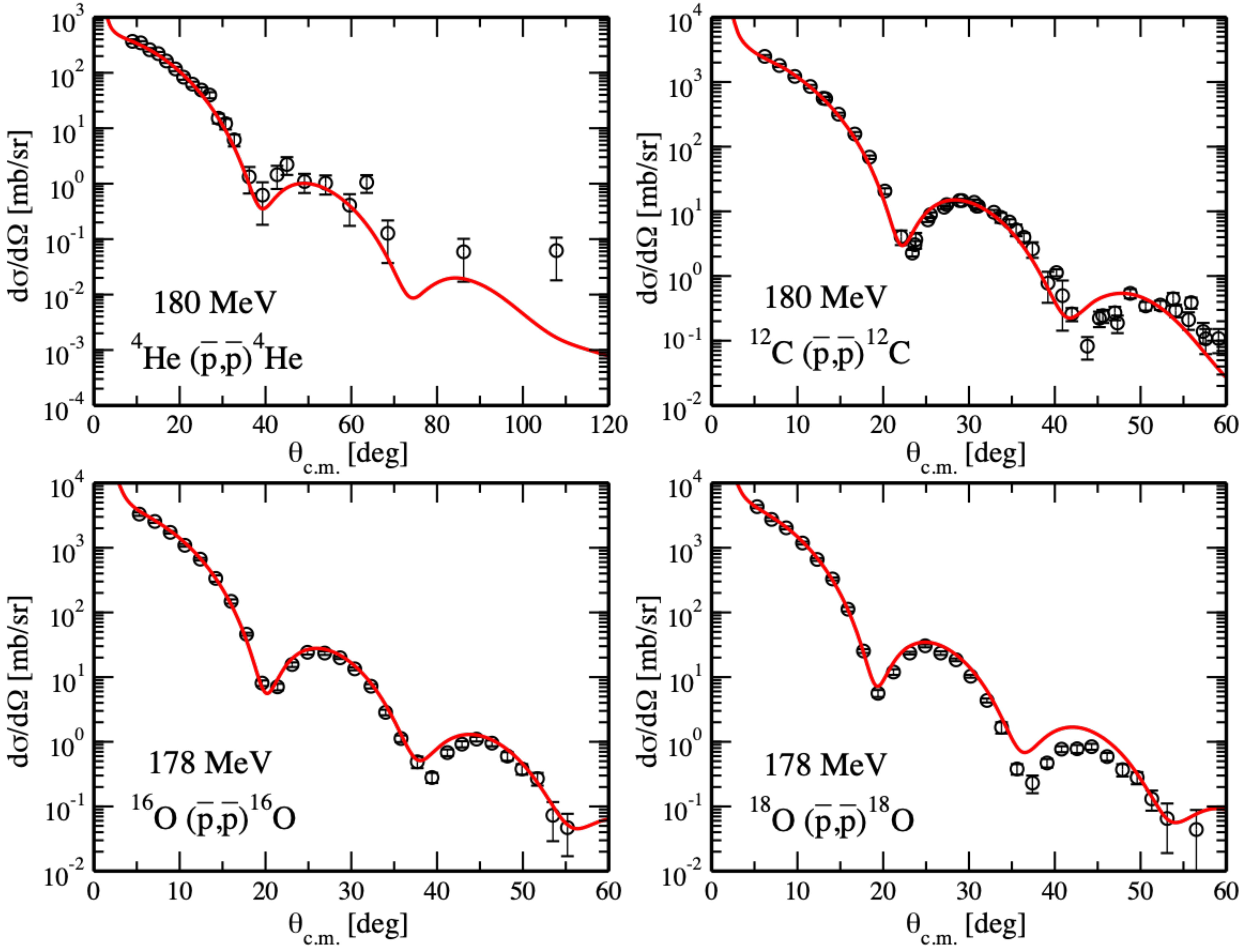
$$U_p(\boldsymbol{q},\boldsymbol{K}) = \sum_{N=p,n} \int d\boldsymbol{P}\, \eta(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P})\, t_{pN}(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P})\, \rho_N(\boldsymbol{q},\boldsymbol{P})$$

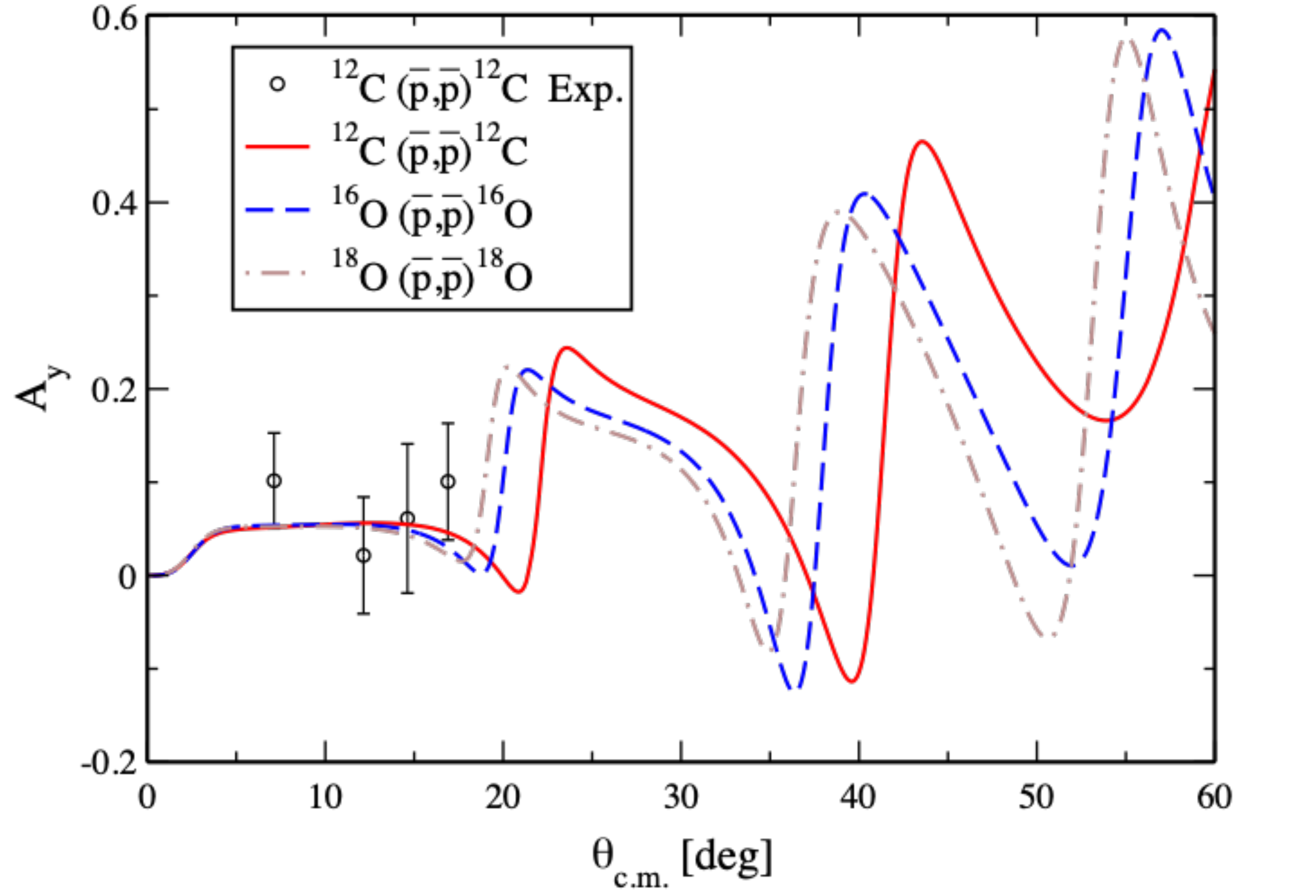
$$t_{pN} \Rightarrow t_{\bar{p}N}$$

- The projectile information only enters the t_{pN} matrix. For antiprotons we make the following replacement
- An antiproton-nucleon interaction is needed! $\bar{p}N$ chiral interaction derived up to N[3]LO

  [Dai, Haidenbauer, Meißner, JHEP 07 (2017) 78]
- No projectile-target anti-symmetrisation!
- Antiprotons are mostly absorbed at the surface of the nucleus so the first-order expansion should work better in this case!

Extension to antiproton-nucleus elastic scattering





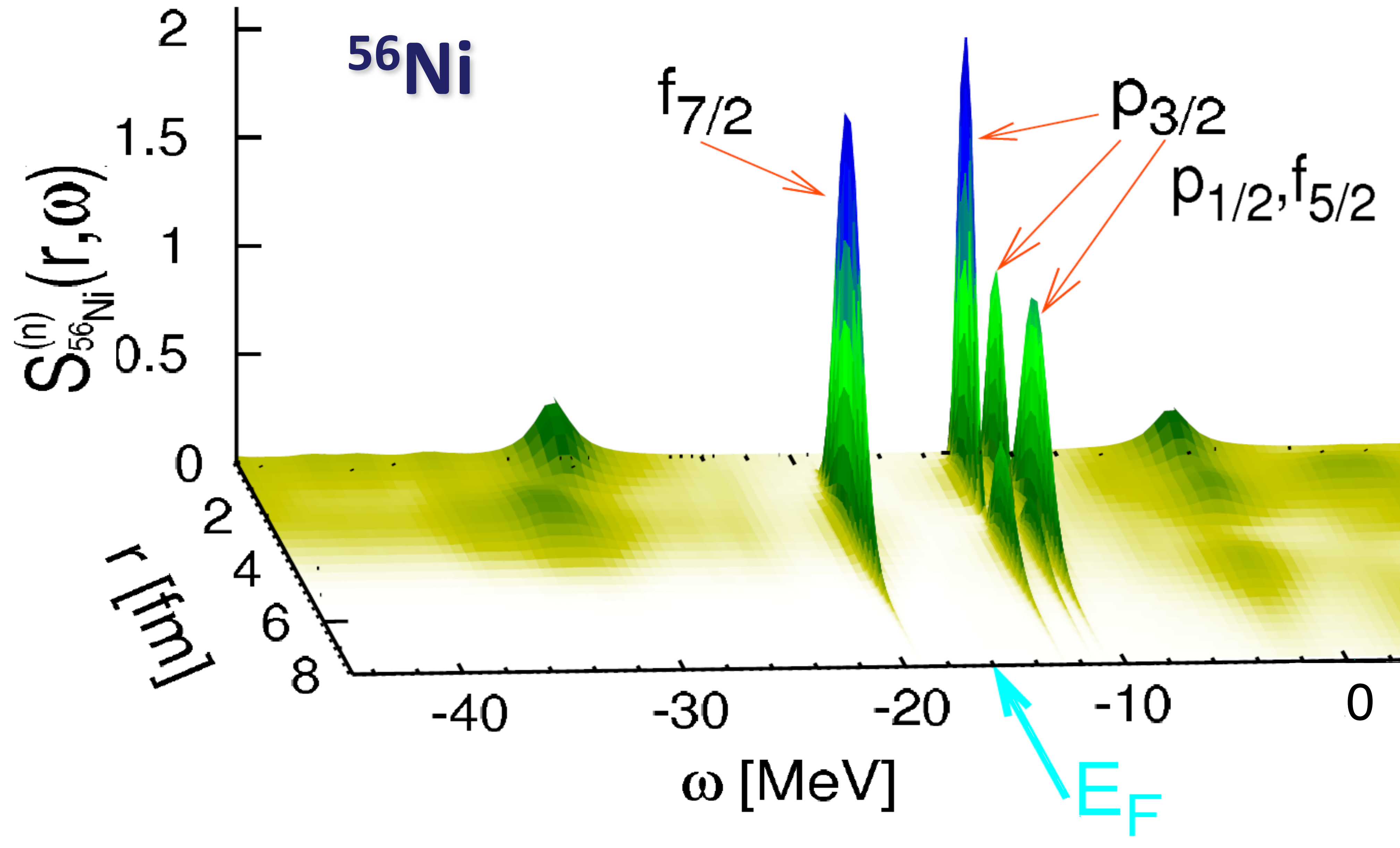
Elastic Antiproton-Nucleus Scattering from Chiral Forces

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

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

Extension to heavier nuclei

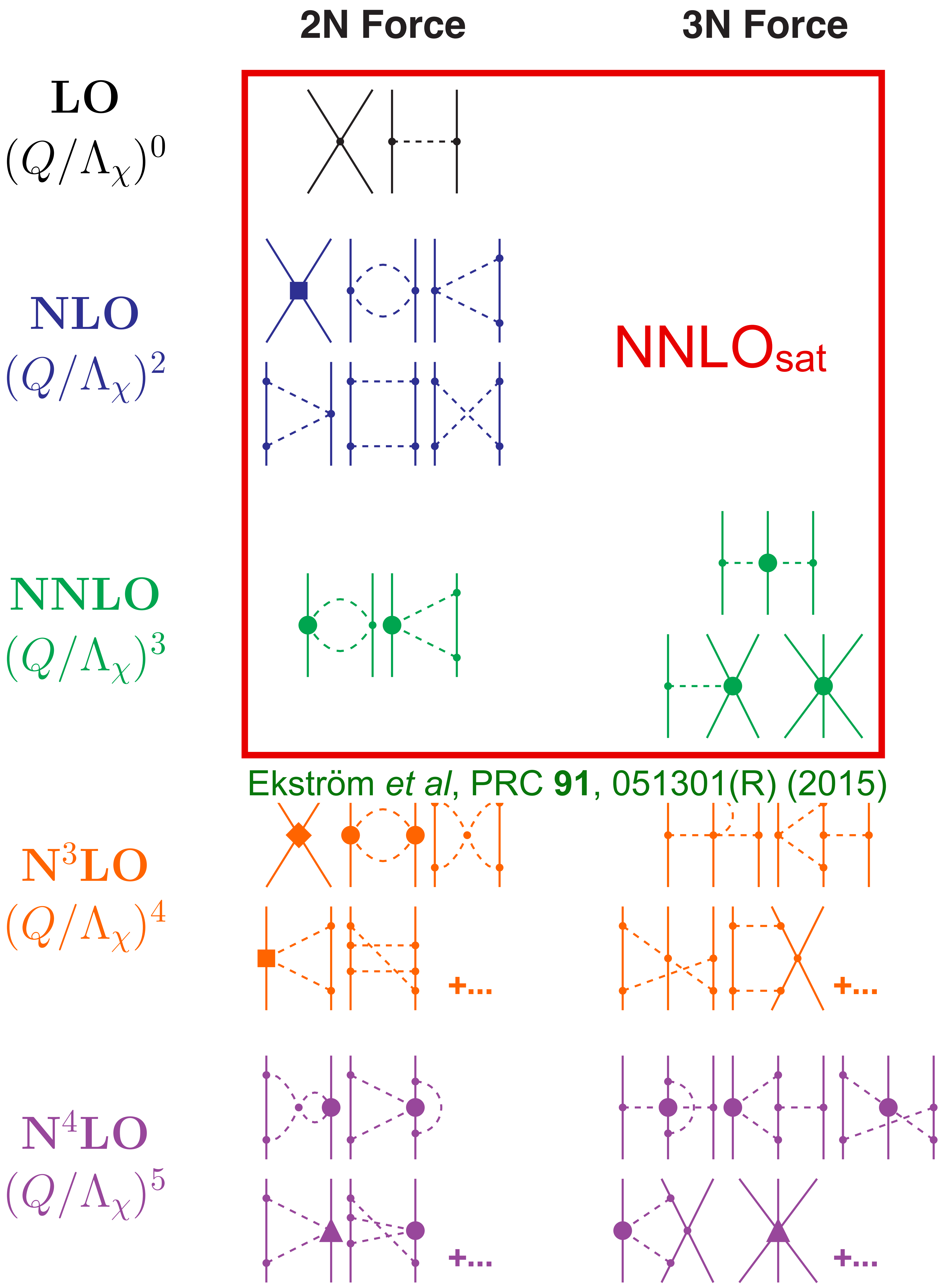
Self Consistent Green's Function (SCGF)



In collaboration with C. Barbieri (Milan) and V. Somà (Paris)

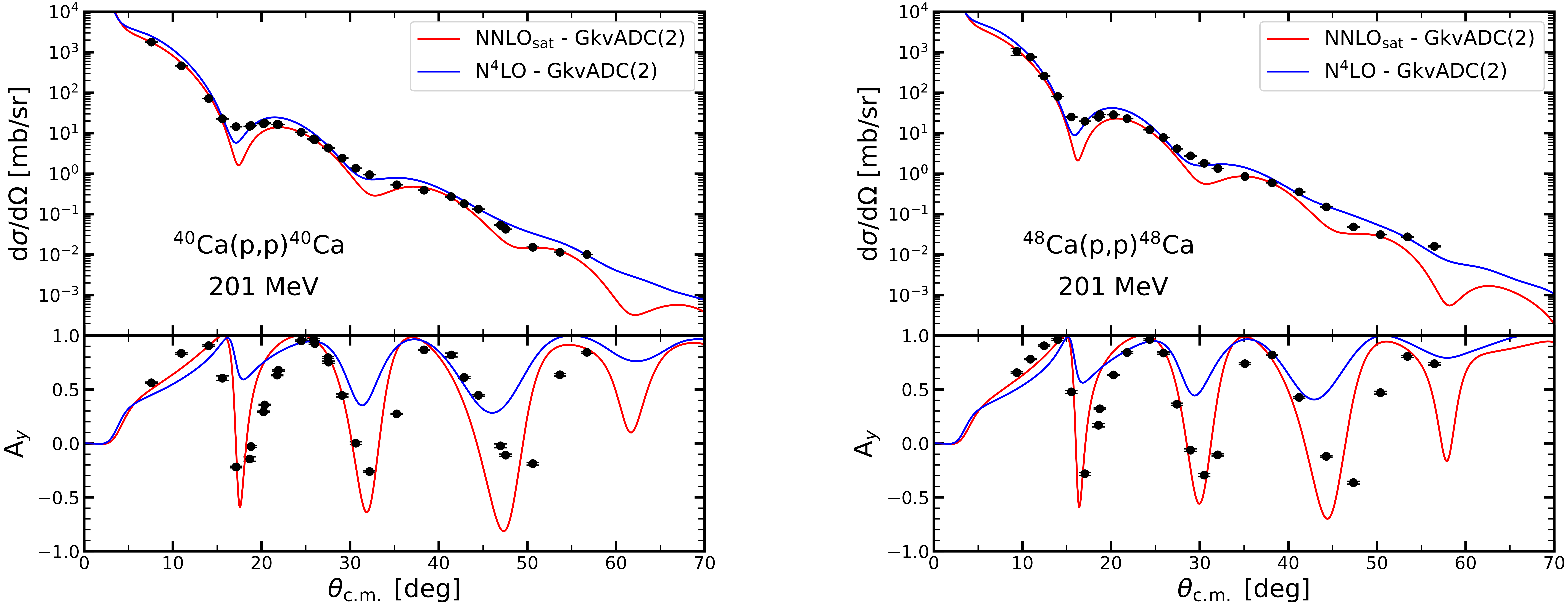
Somà, *SCGF Theory for Atomic Nuclei*, Frontiers **8** (2020) 340

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



Results for proton scattering off ^{40,48}Ca

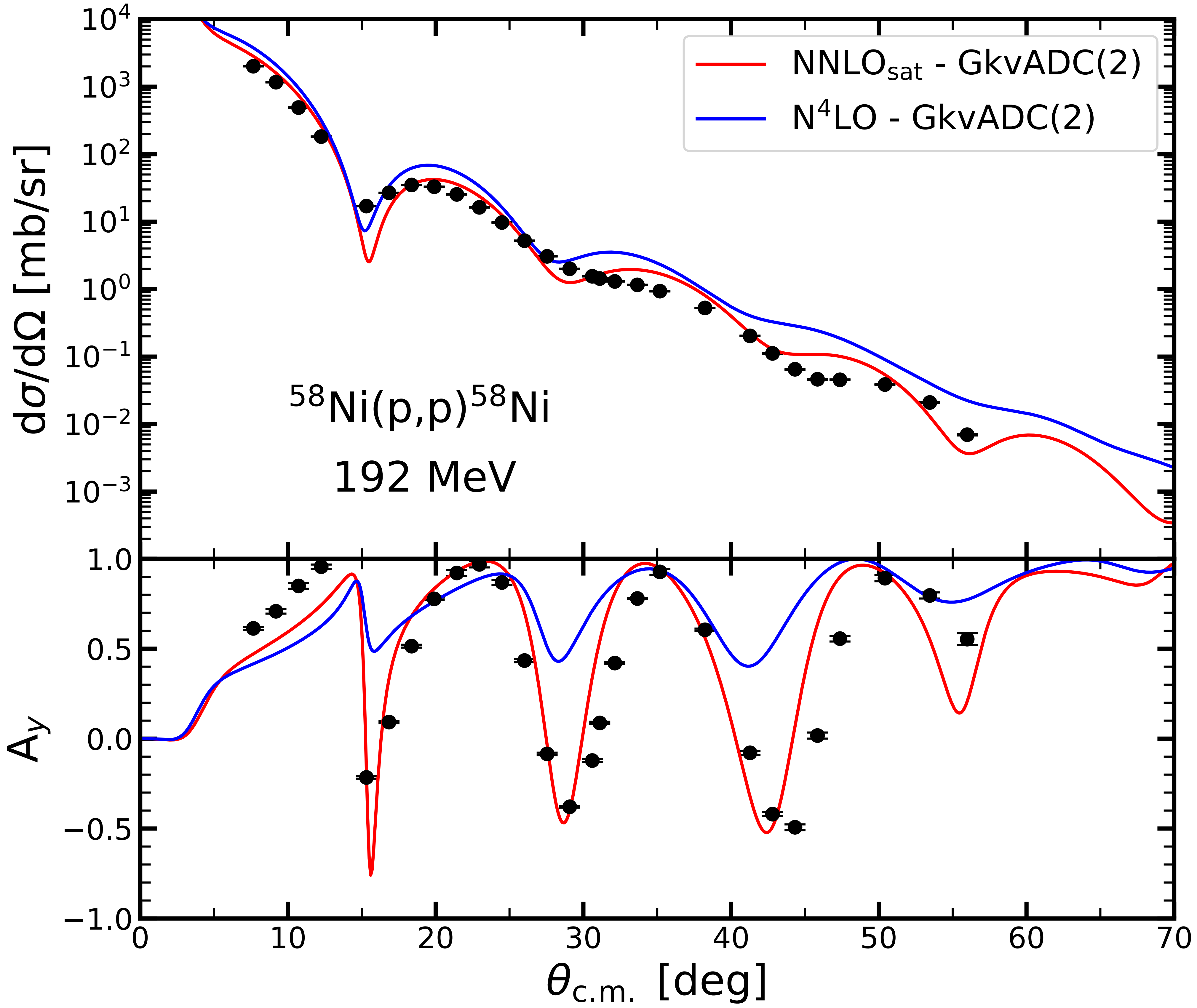
[Vorabbi et al., PRC **109**, 034613 (2024)]

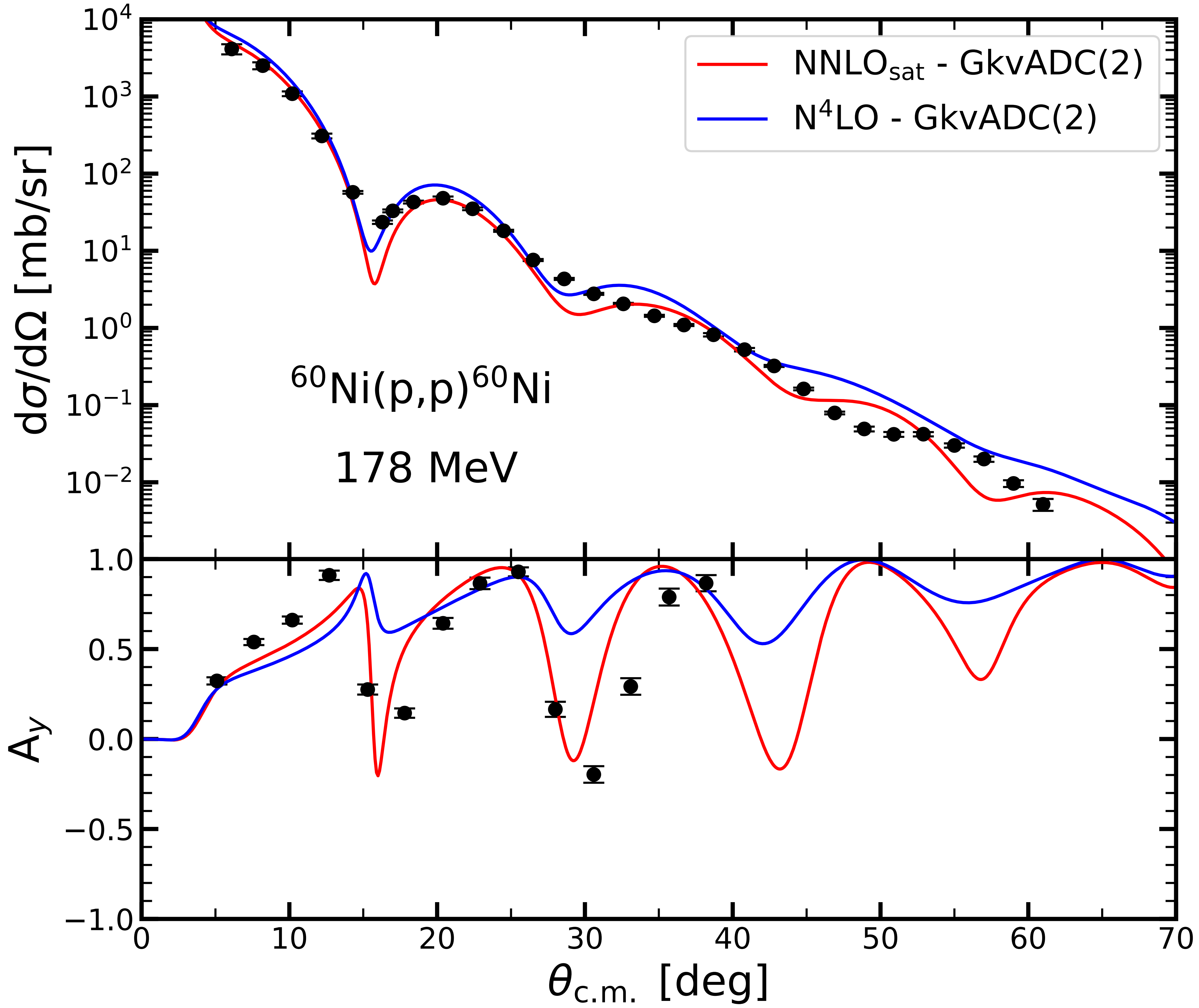


- First microscopic optical potential for calcium and nickel from *ab initio* densities
- For this comparison the densities are always computed with the NNLO$_{sat}$

Results for proton scattering off $^{58,60}Ni$

[Vorabbi et al., PRC **109**, 034613 (2024)]

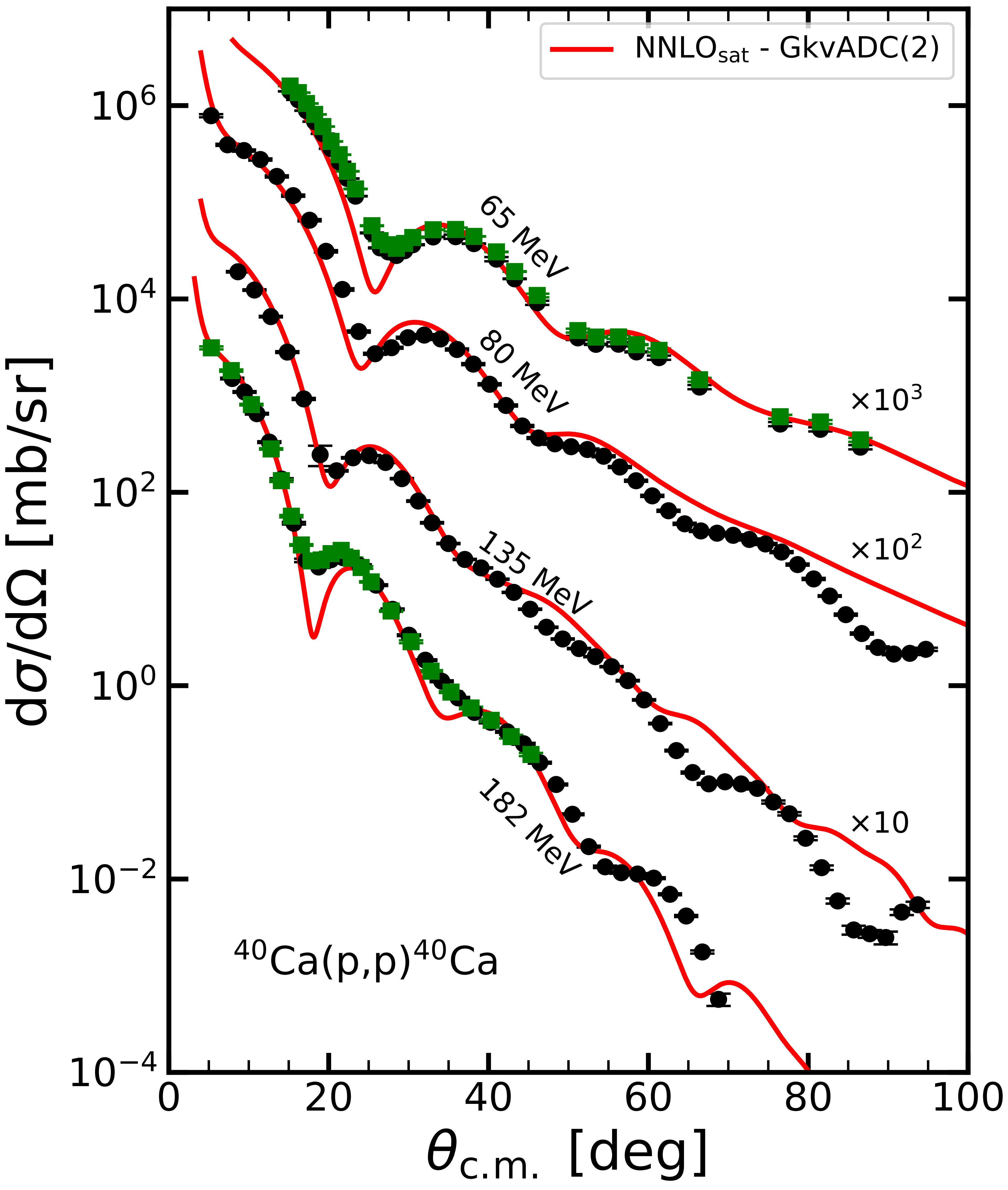




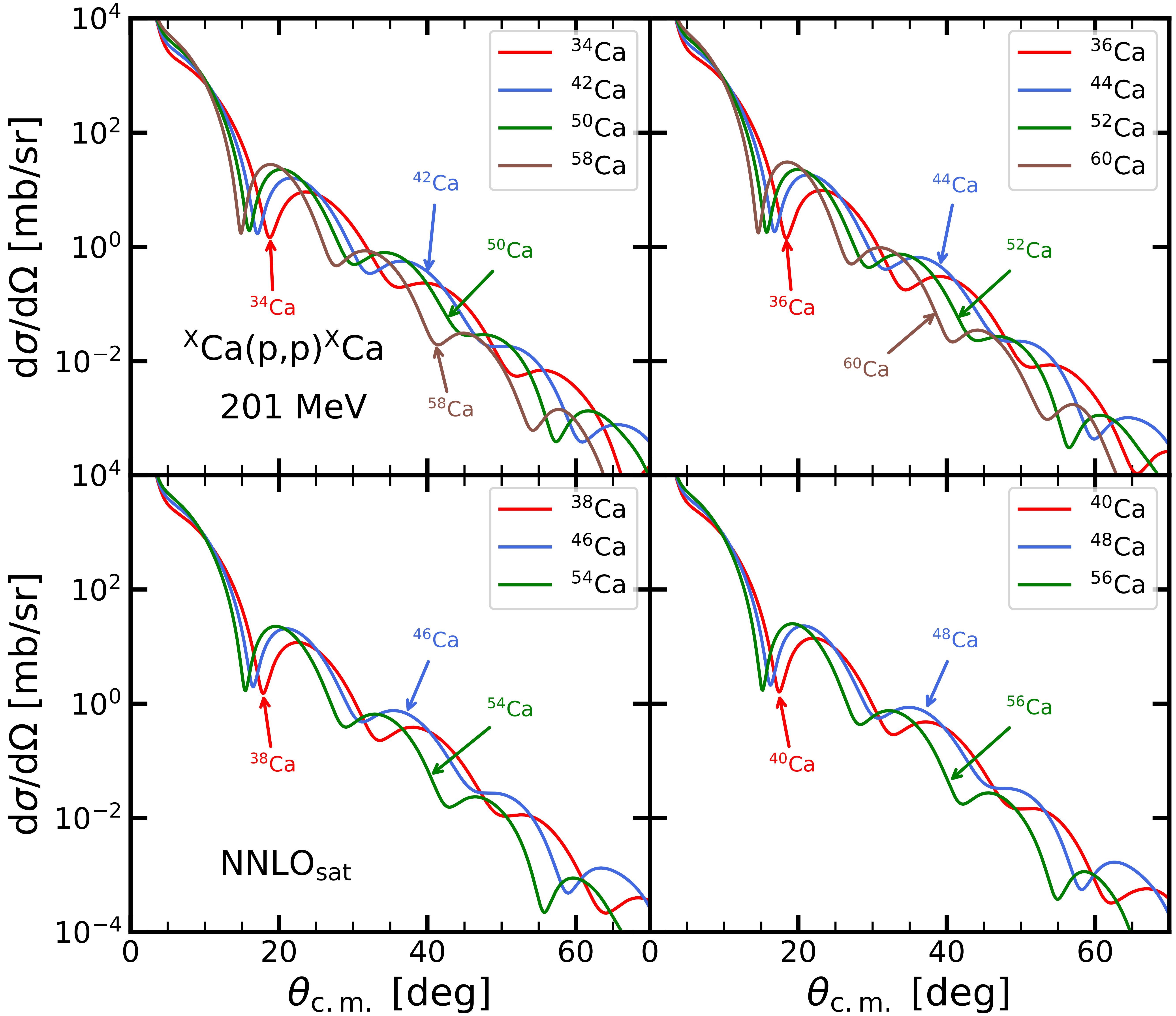
The data for the analysing power is remarkably well described!

(but remember that the NN potential does not reproduce the NN amplitudes)

Results for Calcium isotopic chain



[Vorabbi et al., PRC **109**, 034613 (2024)]



Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

Distorted wave theory of inelastic scattering

The inelastic transition amplitude

$$T_{fi}^{\mathrm{inel}} = \left\langle \psi_f^{(-)} \middle| U_{\mathrm{tr}} \middle| \psi_i^{(+)} \right\rangle$$

Distorted waves

$$\left| \psi_i^{(+)} \right\rangle = \left| \Phi_i \boldsymbol{k} \right\rangle + G_0 U_{\mathrm{el}} \left| \psi_i^{(+)} \right\rangle \qquad \left\langle \psi_f^{(-)} \right| = \left\langle \boldsymbol{k}' \Phi_f \right| + \left\langle \psi_f^{(-)} \right| U_{\mathrm{ex}} G_0$$

General expression of the potential

$$U = \sum_{k=1}^{A} t_{0k}$$

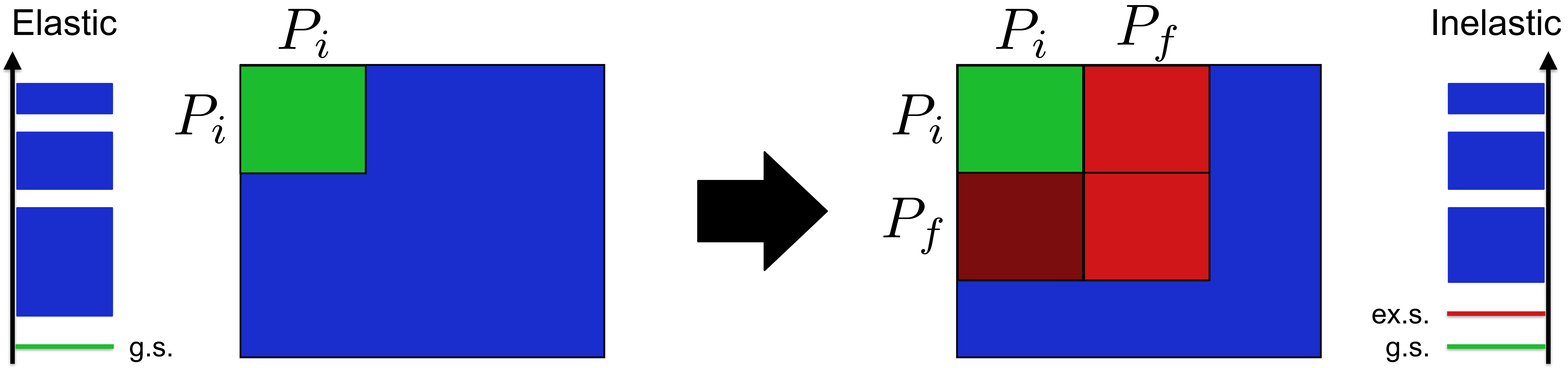
- This is obtained in the impulse approximation
- We need to introduce the projection operators to obtain the 3 potentials that we need for the calculations: U_{tr}, U_{el}, and U_{ex}

Distorted wave theory of inelastic scattering

Projection operators

$$P_i = |\Phi_i\rangle\langle\Phi_i| \qquad P_f = |\Phi_f\rangle\langle\Phi_f|$$

Eigenstates of the target



Potentials

$$U_{\mathrm{el}} = \sum_{k=1}^{A} P_i t_{0k} P_i \qquad U_{\mathrm{ex}} = \sum_{k=1}^{A} P_f t_{0k} P_f \qquad U_{\mathrm{tr}} = \sum_{k=1}^{A} P_f t_{0k} P_i$$

Distorted wave theory of inelastic scattering

[Picklesimer, Tandy, Thaler, Phys. Rev. C **25**, 1215 (1982)]
[Picklesimer, Tandy, Thaler, Phys. Rev. C **25**, 1233 (1982)]

The inelastic transition amplitude

$$T_{\rm inel}(\boldsymbol{k}_*, \boldsymbol{k}_0) = \int d\boldsymbol{r}' \int d\boldsymbol{r}\, \psi^\dagger(\boldsymbol{k}_*, \boldsymbol{r}')\, U_{\rm tr}(\boldsymbol{r}', \boldsymbol{r})\, \psi(\boldsymbol{k}_0, \boldsymbol{r})$$

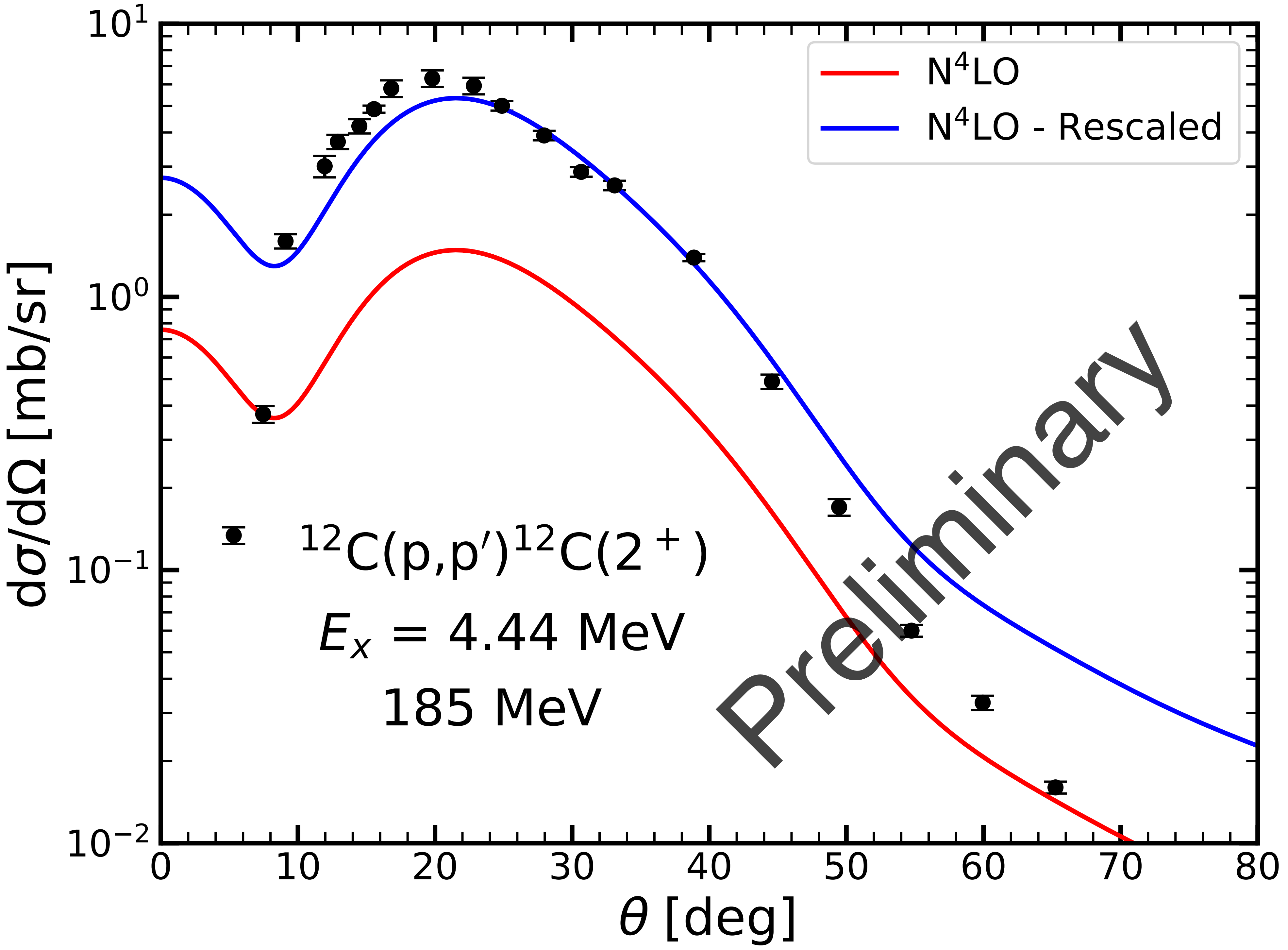
Required potentials

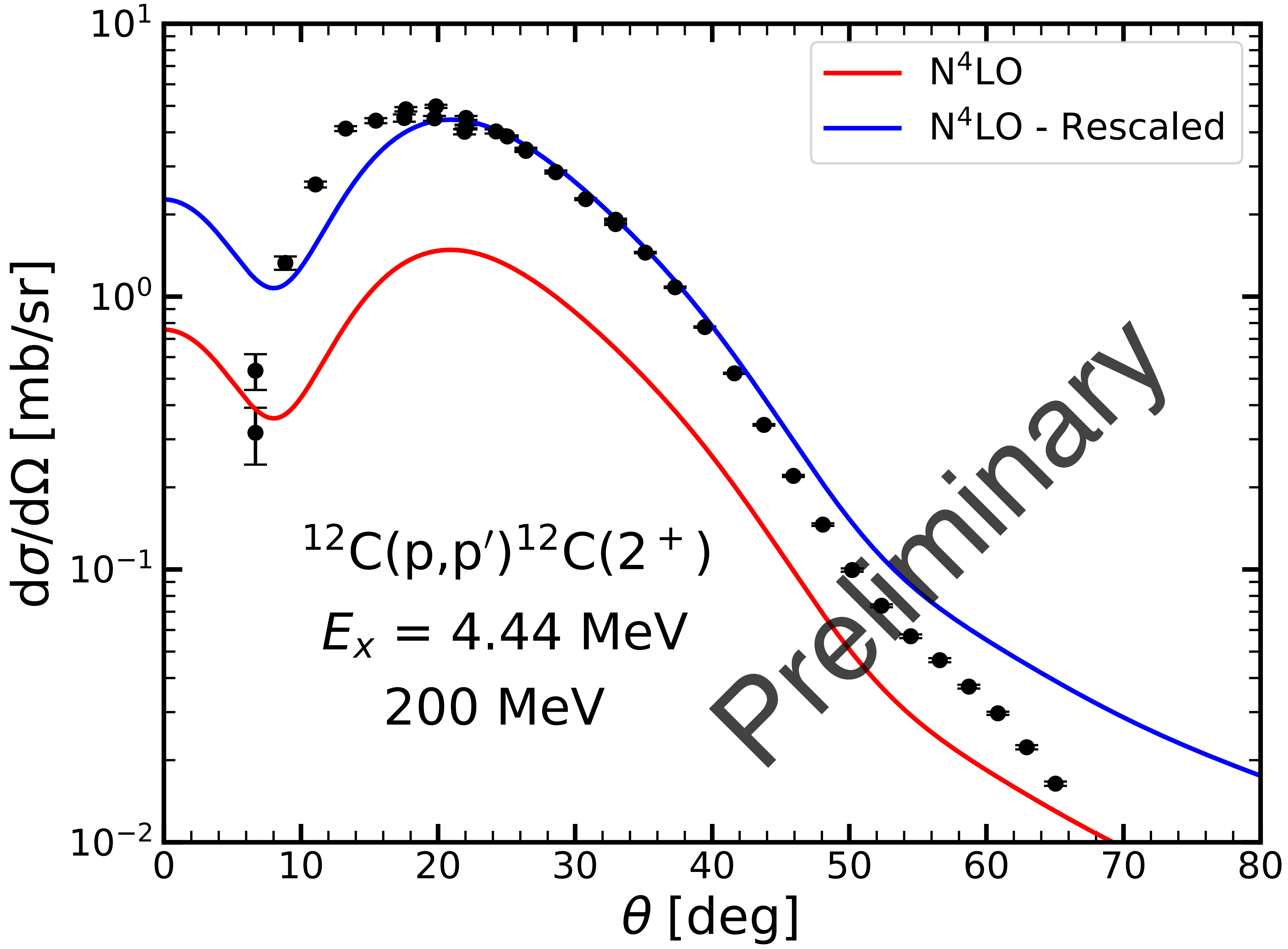
$$U_{\rm ex}(\boldsymbol{q}, \boldsymbol{K}) = \sum_{N=p,n} \int d\boldsymbol{P}\, \eta(\boldsymbol{q}, \boldsymbol{K}, \boldsymbol{P})\, t_{pN}(\boldsymbol{q}, \boldsymbol{K}, \boldsymbol{P})\, \rho_N^{(\rm ex)}(\boldsymbol{q}, \boldsymbol{P})$$

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

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

Distorted wave theory of inelastic scattering





- The general shape of the data is reproduced, however the data is underestimated
- We applied a scaling factor to the transition potential to shift the differential cross section and compare it to the data
- The NN *t* matrix adopted for the calculation of the 3 potentials only contains two terms

$$A + i(\boldsymbol{\sigma} \cdot \hat{\boldsymbol{n}})C$$

Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

Inclusion of medium effects in elastic scattering

First-order term of the spectator expansion

$$\tau_{0i} = t_{0i} + t_{0i} g_{0i} W_i G_i(E) \tau_{0i}$$

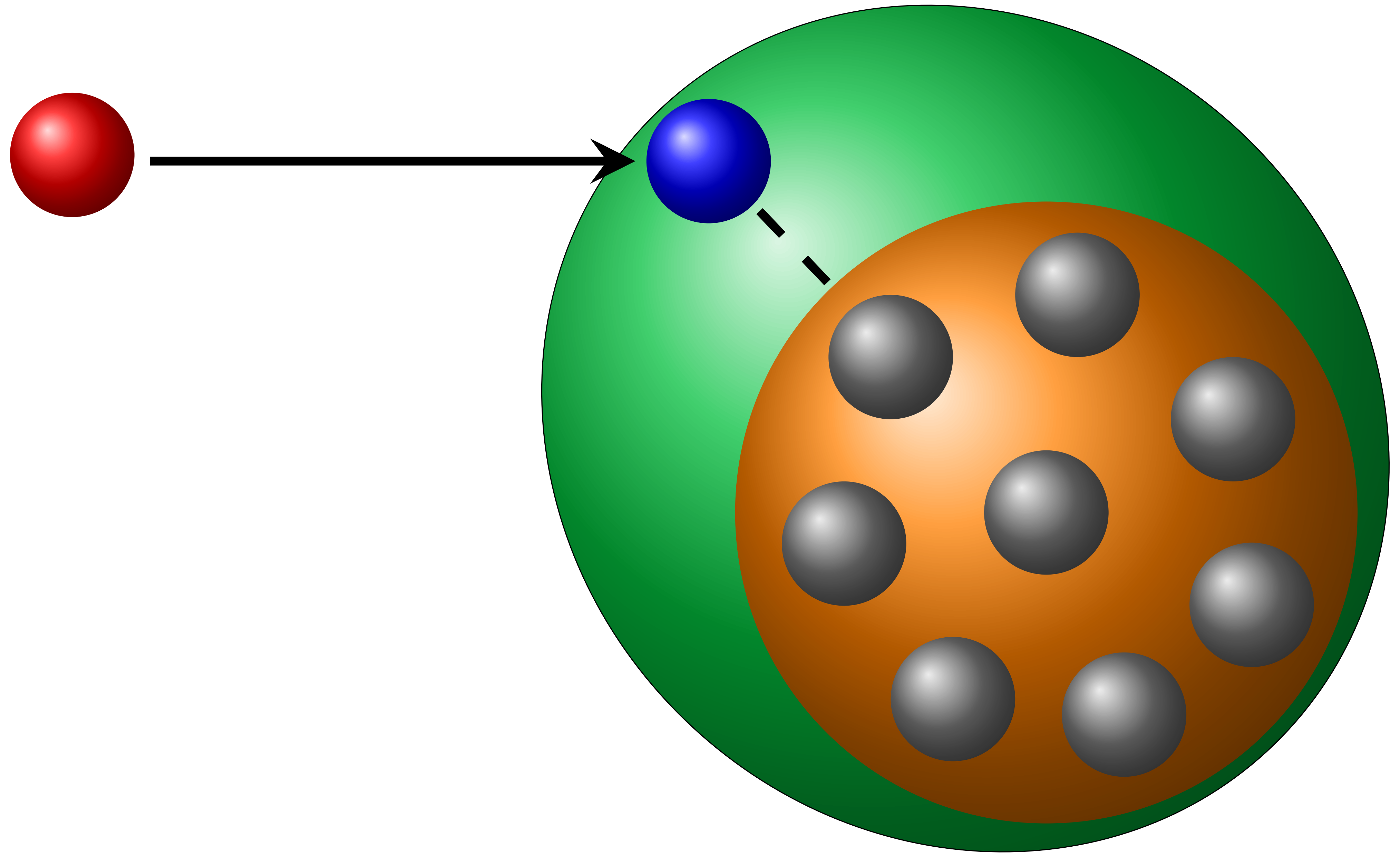
Coupling between the target nucleon and the residual nucleus

In-medium propagator

Inclusion of medium effects

- Work has been done to include these effects at a mean-field level [Chinn *et al.*, PRC **52**, 1992 (1995)]
- However, with an ab initio description of the target it is not clear how to extract the coupling potential consistently

The first-order term is a 3-body problem



Inclusion of medium effects in elastic scattering

<u>Ansatz:</u> approximate the medium effects with a scaling factor that suppresses the strength of the free propagator

$$g_{0i} W_i G_i(E) \approx -\lambda(E) g_{0i}$$

<u>In-medium two-nucleon scattering matrix</u>

$$\tau_{0i} \approx \sum_{n=0}^{N} (-1)^n \lambda^n(E) \left[t_{0i} g_{0i}\right]^n t_{0i}$$

$$\approx t_{0i} - \lambda(E) t_{0i} g_{0i} t_{0i} + \lambda^2(E) t_{0i} g_{0i} t_{0i} g_{0i} t_{0i} + \dots$$

Effectively equivalent to using

$t_{0i},\ t_{0i} g_{0i} t_{0i},\ t_{0i} g_{0i} t_{0i} g_{0i} t_{0i},\ \dots$

to expand the matrix τ_{0i}

Inclusion of medium effects in elastic scattering

Calculation of λ: we interpret λ as the effective scattering probability of the projectile nucleon inside the target nucleus

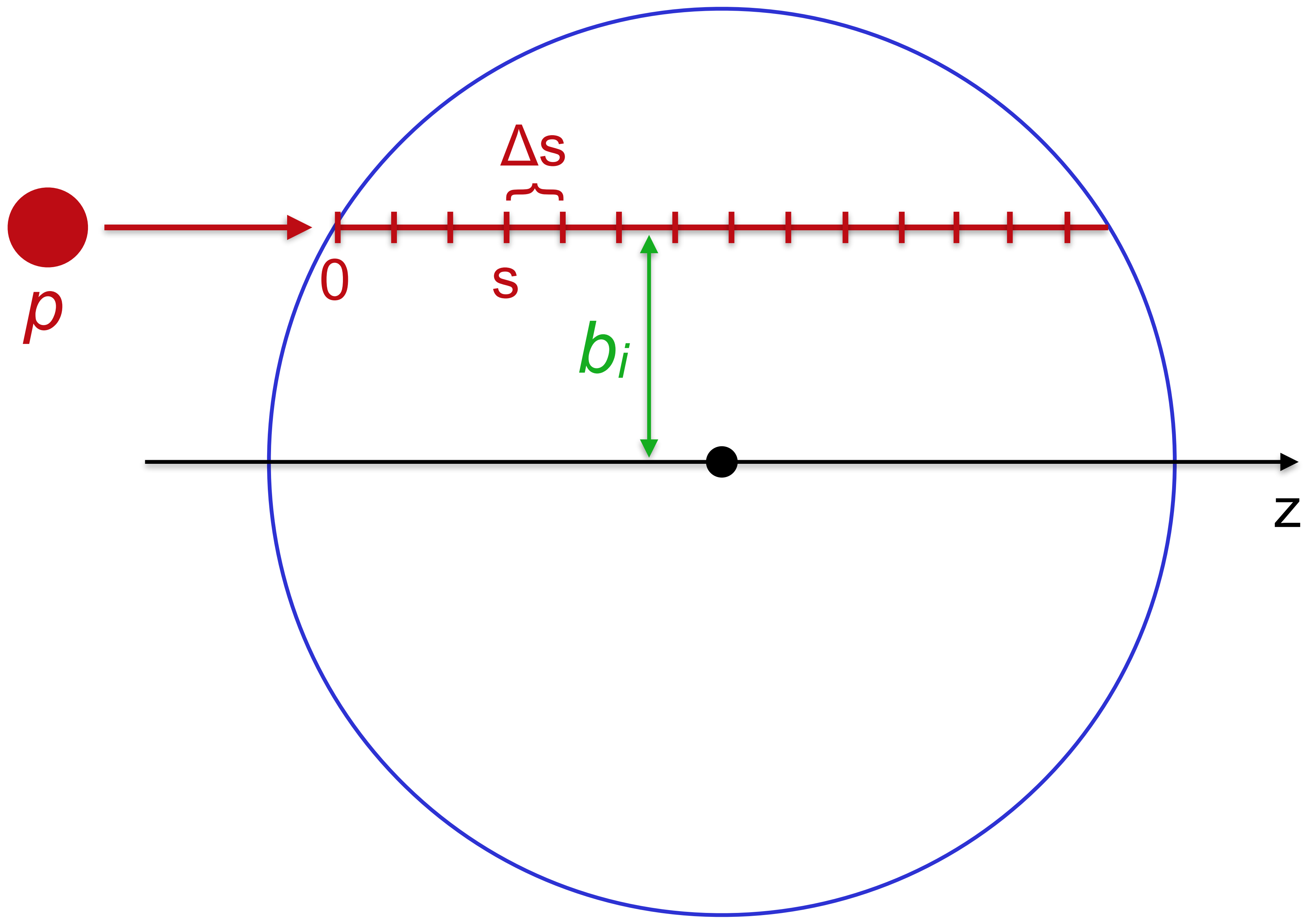
Algorithm

- For each segment Δs we compute the probability P_{pN} of the projectile to interact with a nucleon as

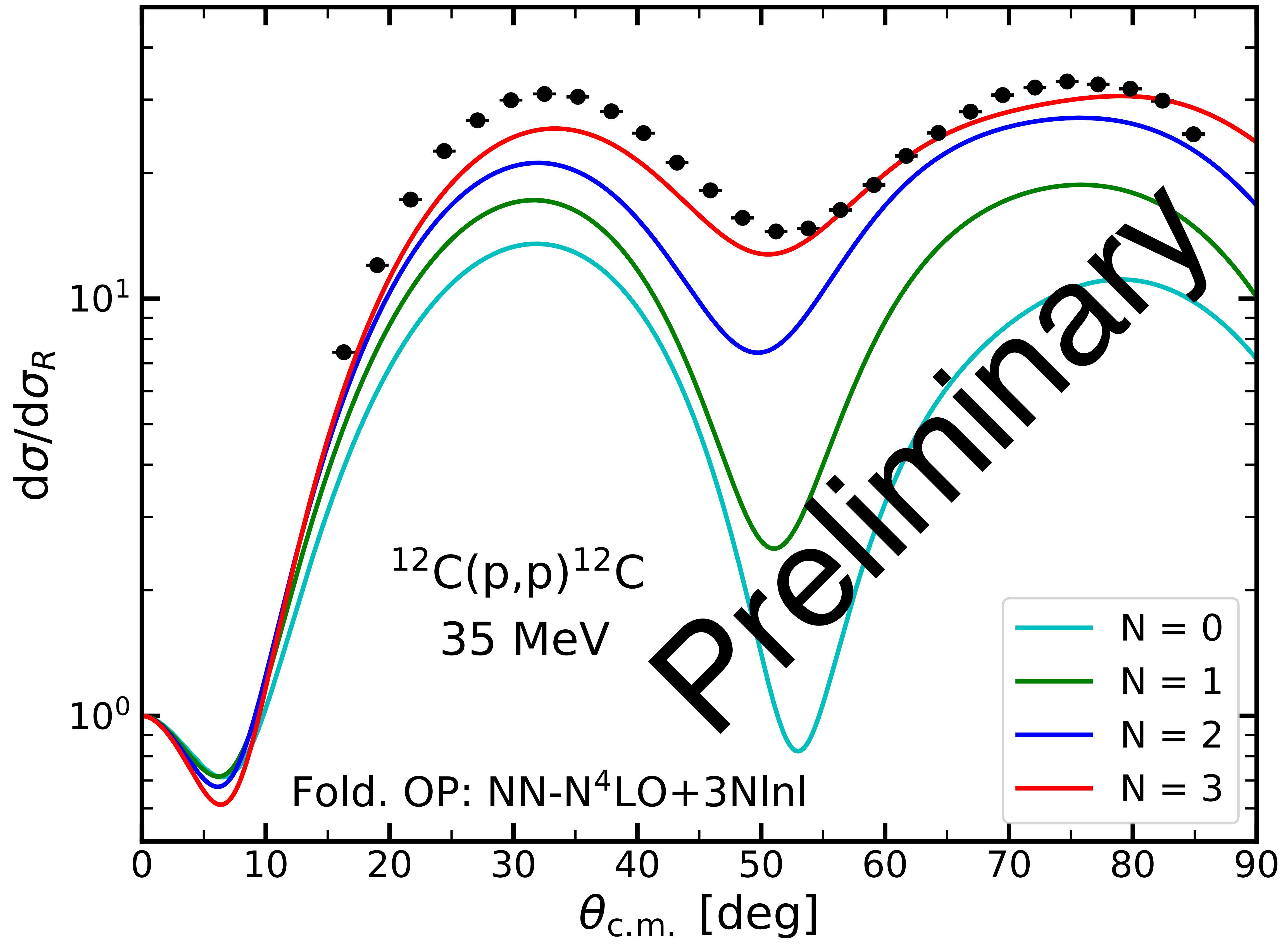
$$P_{pN} = \sigma_{pN}(E)\rho_N(s)\Delta s$$

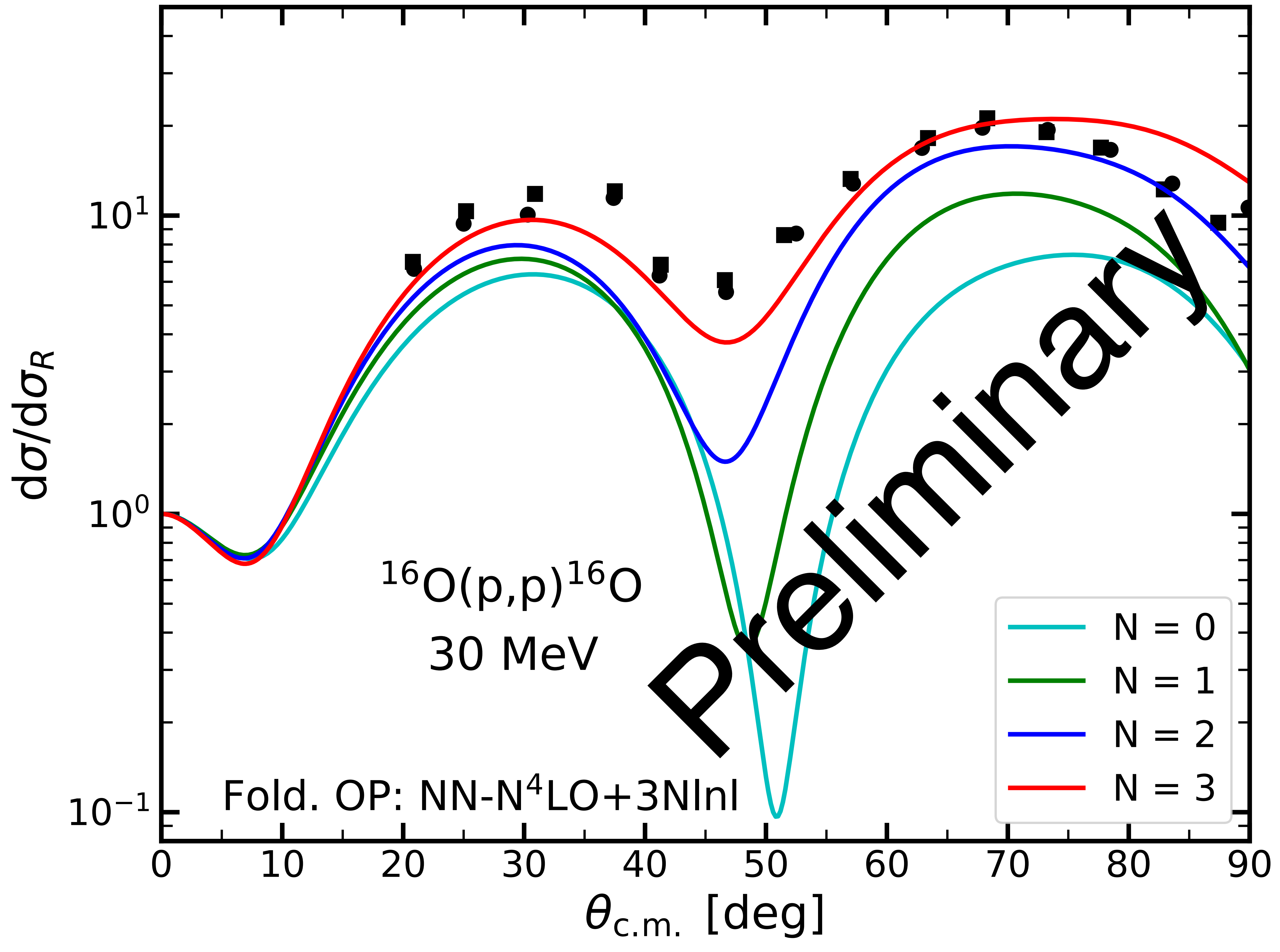
- We generate a random number *n* between 0 and 1 and we compare it to P_{pN}.
  - If $n > P_{pN}$ no interaction occurred.
    We continue this process for the next step along the trajectory
  - If $n < P_{pN}$ an interaction occurred! We record the interaction in the variable I_i. We stop the algorithm and we restart it again considering a different impact parameter b_i.
- We repeat the procedure N_{trials} times sampling a different impact parameter b_i.
- The value of λ is obtained as

$$\lambda = \frac{\sum_{i=1}^{N_{\text{trials}}} b_i I_i}{\sum_{i=1}^{N_{\text{trials}}} b_i}$$



Inclusion of medium effects in elastic scattering





- Despite the simplicity of the model, calculations performed at different orders converge toward the experimental data
- Calculations performed so far indicate N=3 gives the best agreement with data

Outline

- Motivations
- The nucleon-nucleus optical potential within the multiple scattering theory
- Application to light and medium-mass nuclei
- Extension to inelastic scattering
- Inclusion of medium effects
- Extension to nucleus-nucleus optical potential
- Summary & outlook

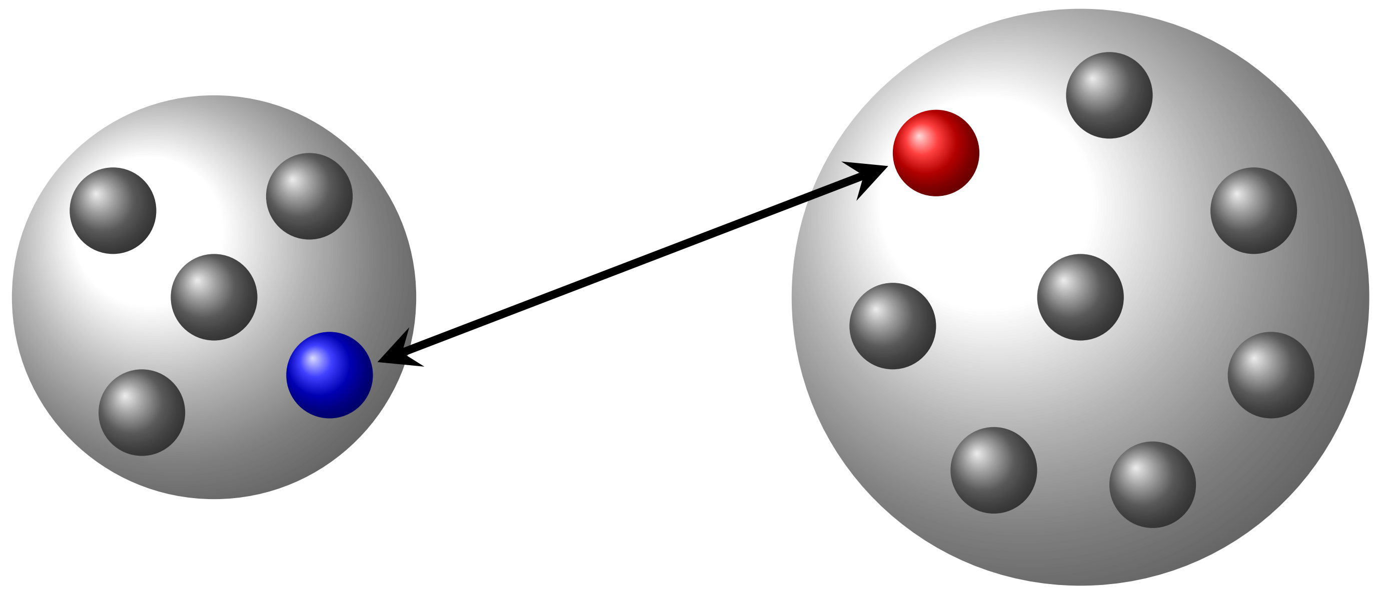
Optical potential for nucleus-nucleus elastic scattering

Transition amplitude for elastic scattering

$$T_{\mathrm{el}} \equiv PTP = PUP + PUPG_0(E)T_{\mathrm{el}}$$

The spectator expansion

[Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)]



$$U \simeq \sum_{i=1}^{A} \sum_{j=A+1}^{A+B} \tau_{ij}$$

$$\tau_{ij} = v_{ij} + v_{ij}G_0(E)\tau_{ij}$$

(A+B)-body propagator
More complicated than
the NA case

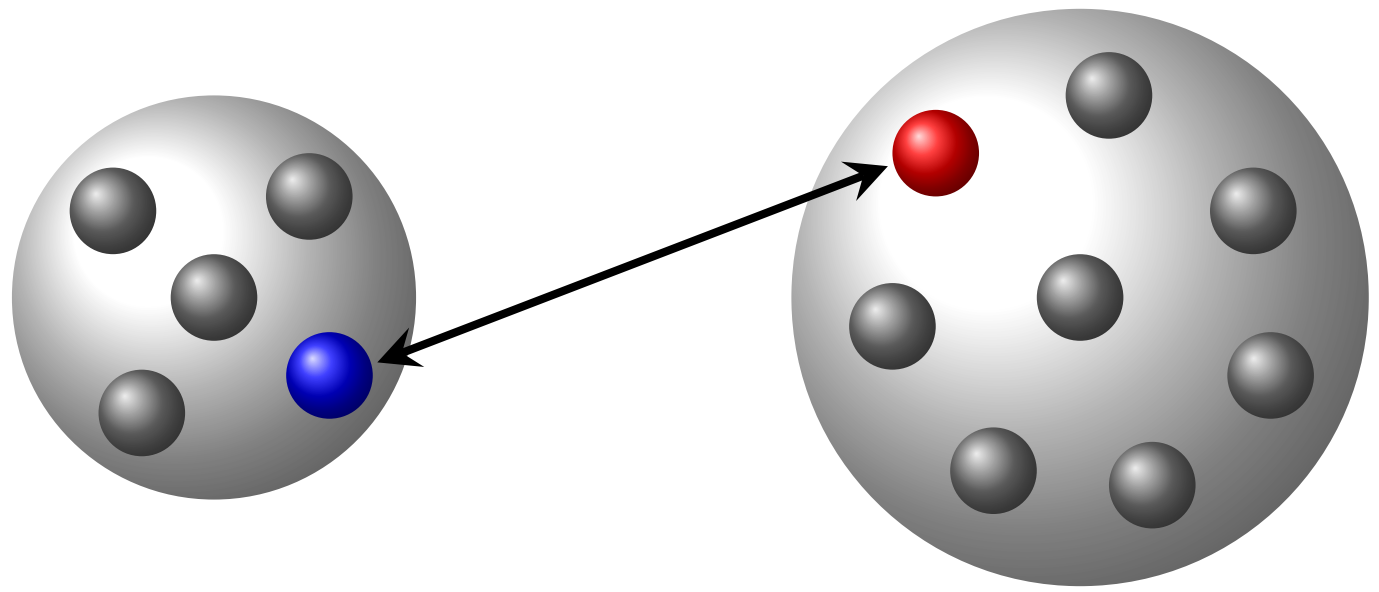
Optical potential for nucleus-nucleus elastic scattering

Transition amplitude for elastic scattering

$$T_{\text{el}} \equiv PTP = PUP + PUPG_0(E)T_{\text{el}}$$

The spectator expansion

[Chinn, Elster, Thaler, Weppner, PRC **52,** 1992 (1995)]



$$U \simeq \sum_{i=1}^{A} \sum_{j=A+1}^{A+B} \tau_{ij} \qquad \tau_{ij} \approx t_{ij} = v_{ij} + v_{ij}\, g_0(E)\, t_{ij}$$

Not the best approximation, but the simplest!

Two-body propagator

The first-order optical potential

Møller factor

$$t_{NN}^{(AB)} = \eta\, t_{NN}^{(NN)}$$

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

Projectile density

Target density

$$U(\boldsymbol{q},\boldsymbol{K}) = \sum_{\alpha=n,p}\sum_{\beta=n,p}\int d\boldsymbol{P}\int d\boldsymbol{Q}\,\eta(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P},\boldsymbol{Q})\,t_{\alpha\beta}(\boldsymbol{q},\boldsymbol{K},\boldsymbol{P},\boldsymbol{Q};\mathcal{E})\,\rho_\alpha^{(\mathbb{P})}(\boldsymbol{q},\boldsymbol{P})\,\rho_\beta^{(\mathbb{T})}(\boldsymbol{q},\boldsymbol{Q})$$

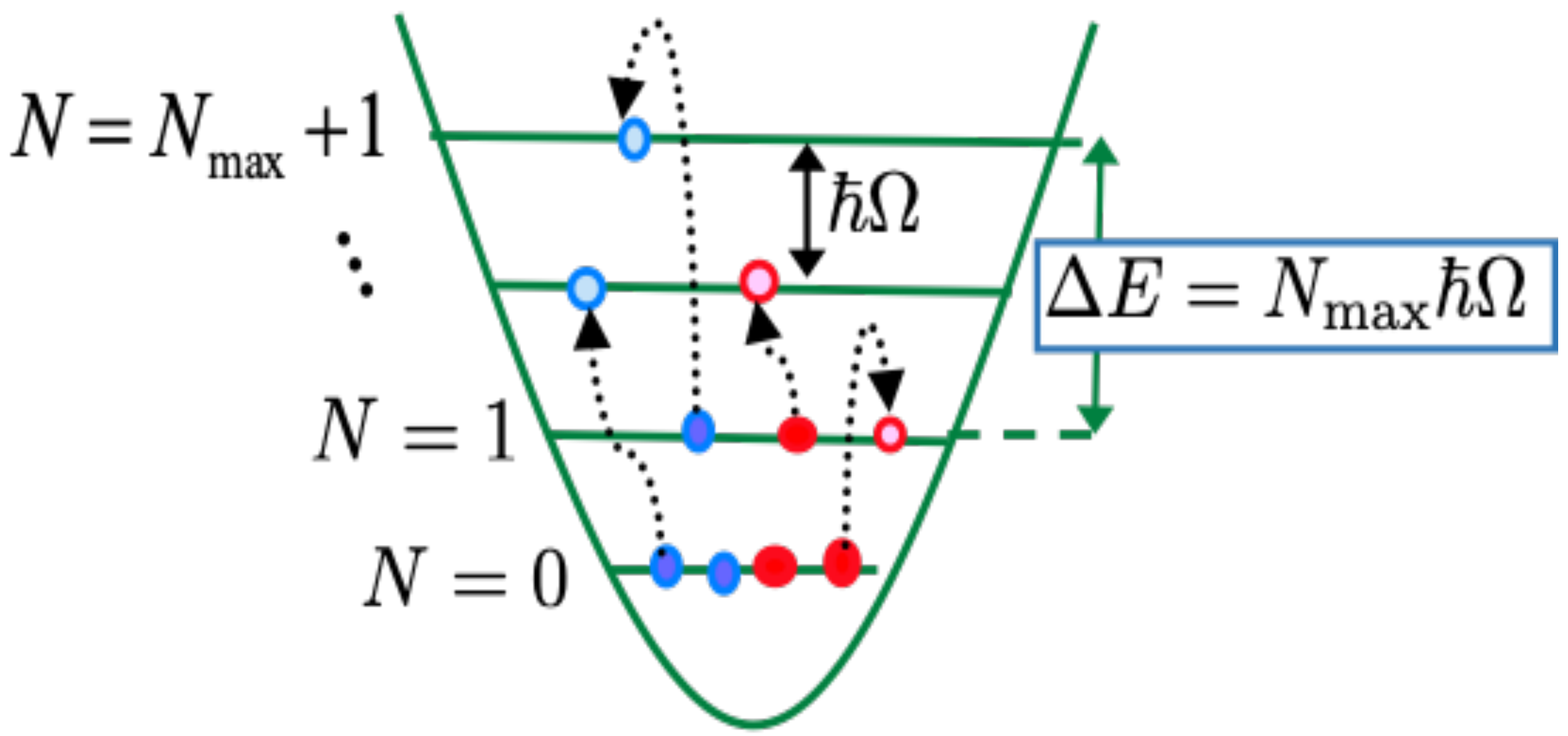
Free two-body scattering matrix

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

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

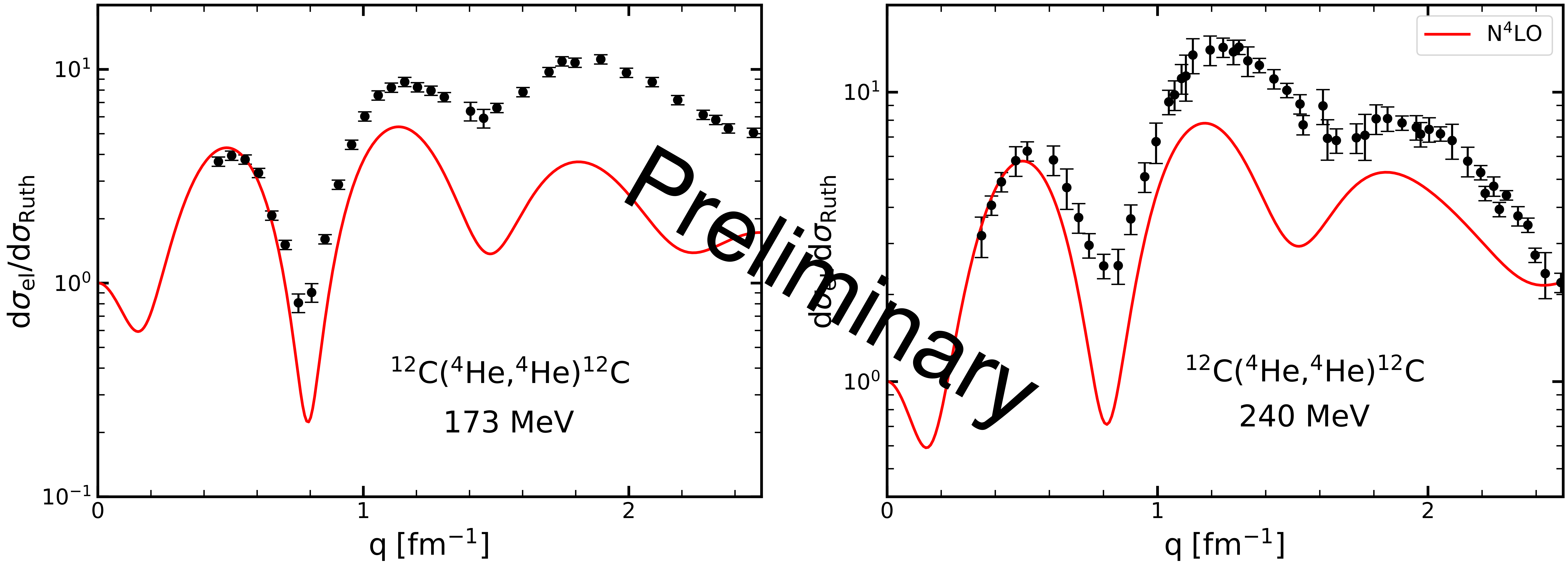
- Simple one-body equation
- Can be solved easily
- Only **NN** interaction

Nonlocal one-body density



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

Results for elastic α-^{12}C scattering



- Interesting results despite the approximations!
- The potential seems to be too absorptive

How to reduce the absorption

A simple rescaling of the imaginary part seems to confirm that!

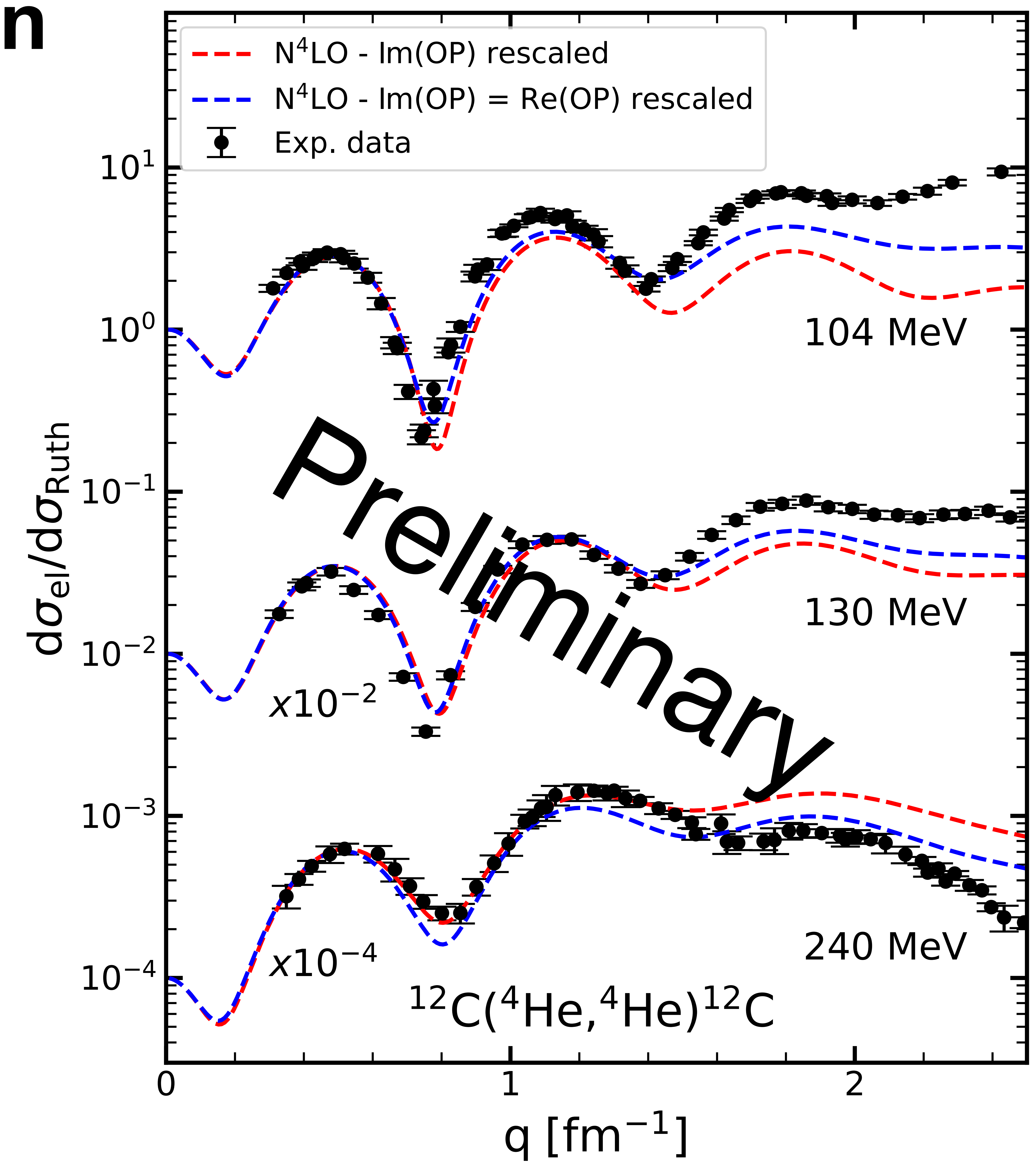
How can we decrease the absorption?

- Inclusion of medium effects
- Introducing the energy dependence of the t matrix in the double-folding integral

$$t_{NN}(\boldsymbol{q}, \boldsymbol{K}, \boldsymbol{P}, \boldsymbol{Q}, \mathcal{E})$$

- Adding the double scattering term

[Crespo *et al.*, PRC **46**, 279 (1992)]



Summary & outlook

- ☑ Achieved a description of nucleon elastic scattering of light and medium-mass nuclei at the first order of the spectator expansion
- ☑ The choice of the NN interaction is crucial to define the energy limits of applicability of the optical potential
- ☑ Extension of the model to nucleon-nucleus inelastic scattering
- ☑ Inclusion of medium effects in nucleon-nucleus elastic scattering
- ☑ Achieved a first step in the derivation of a nucleus-nucleus optical potential

- ☐ Extend the high-energy limits of applicability of the optical potential
- ☐ Inclusion of the second-order term of the spectator expansion
- ☐ Consistent treatment of the full 3N interaction
- ☐ Inclusion of medium effects in the nucleus-nucleus optical potential