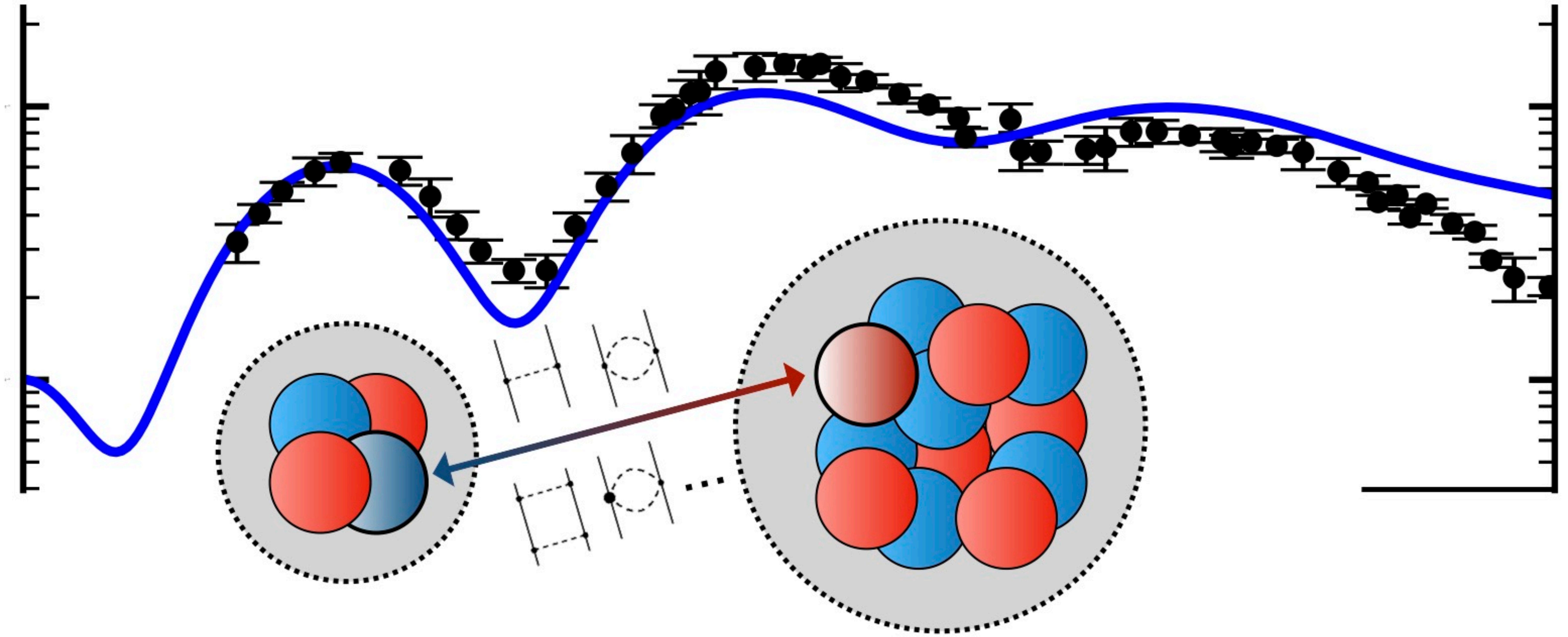
Microscopic Optical Potentials

New developments and achievements

Paolo Finelli, UniBO and INFN

MOdeling Nuclear STructure and REactions



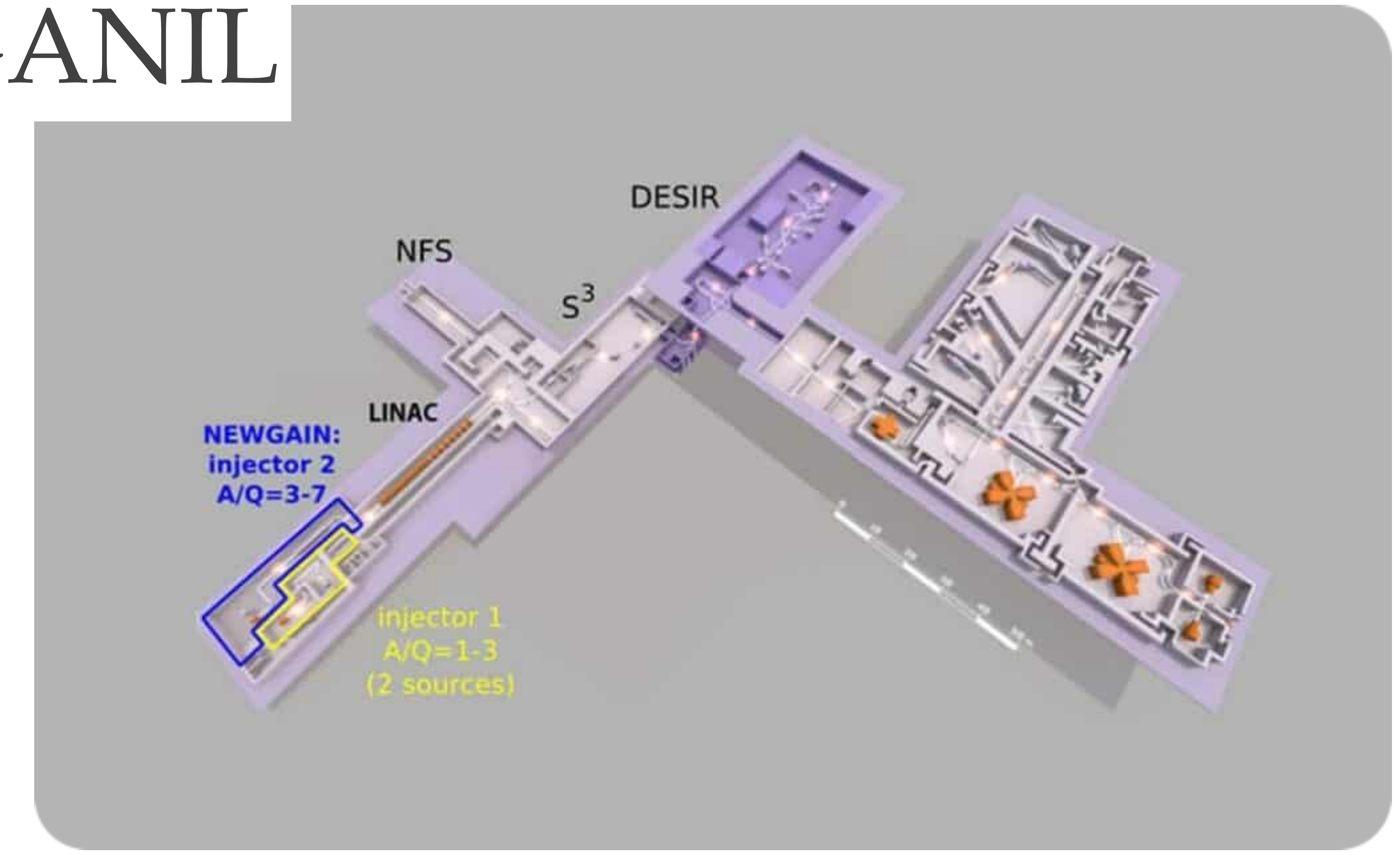
Collaborators

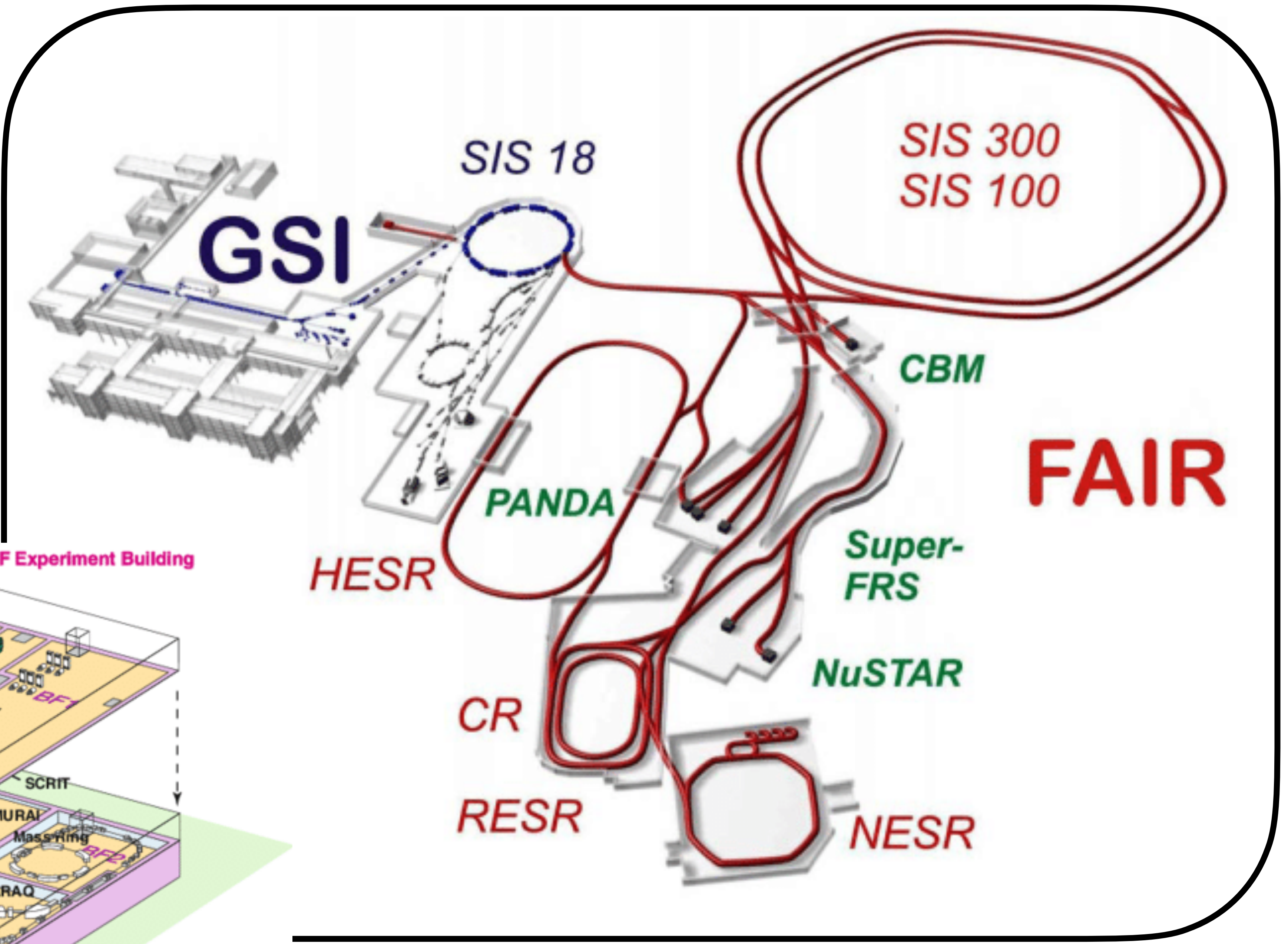
- Matteo Vorabbi
- Carlotta Giusti
- Carlo Barbieri
- Vittorio Somà
- Peter Navratil
- Michael Gennari

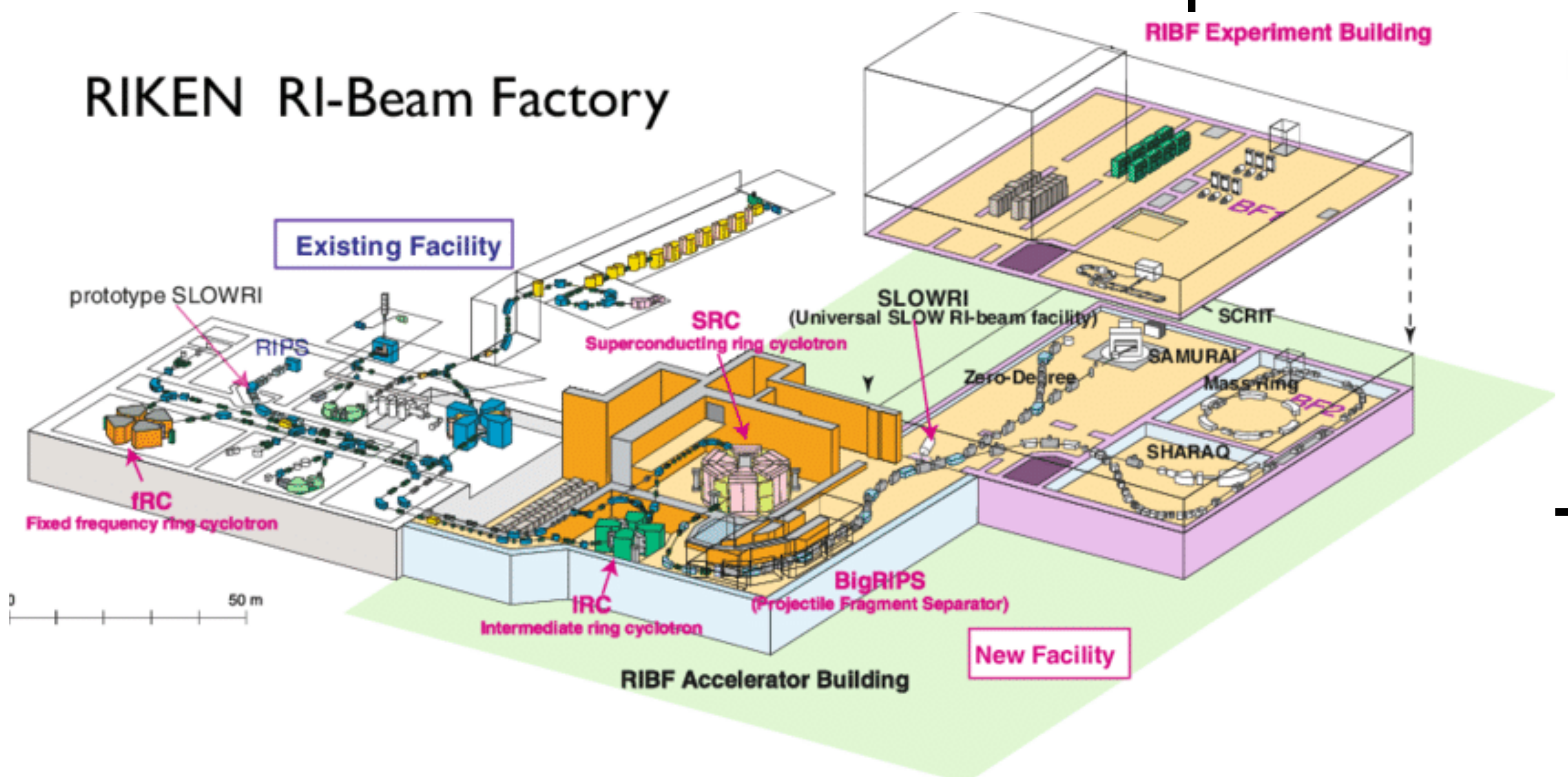
Motivation

Develop a microscopic framework to perform reliable predictions for nuclear reactions (elastic, inelastic, transfer,…) despite the nature of the projectiles (protons, neutrons, antiprotons, ions,…)

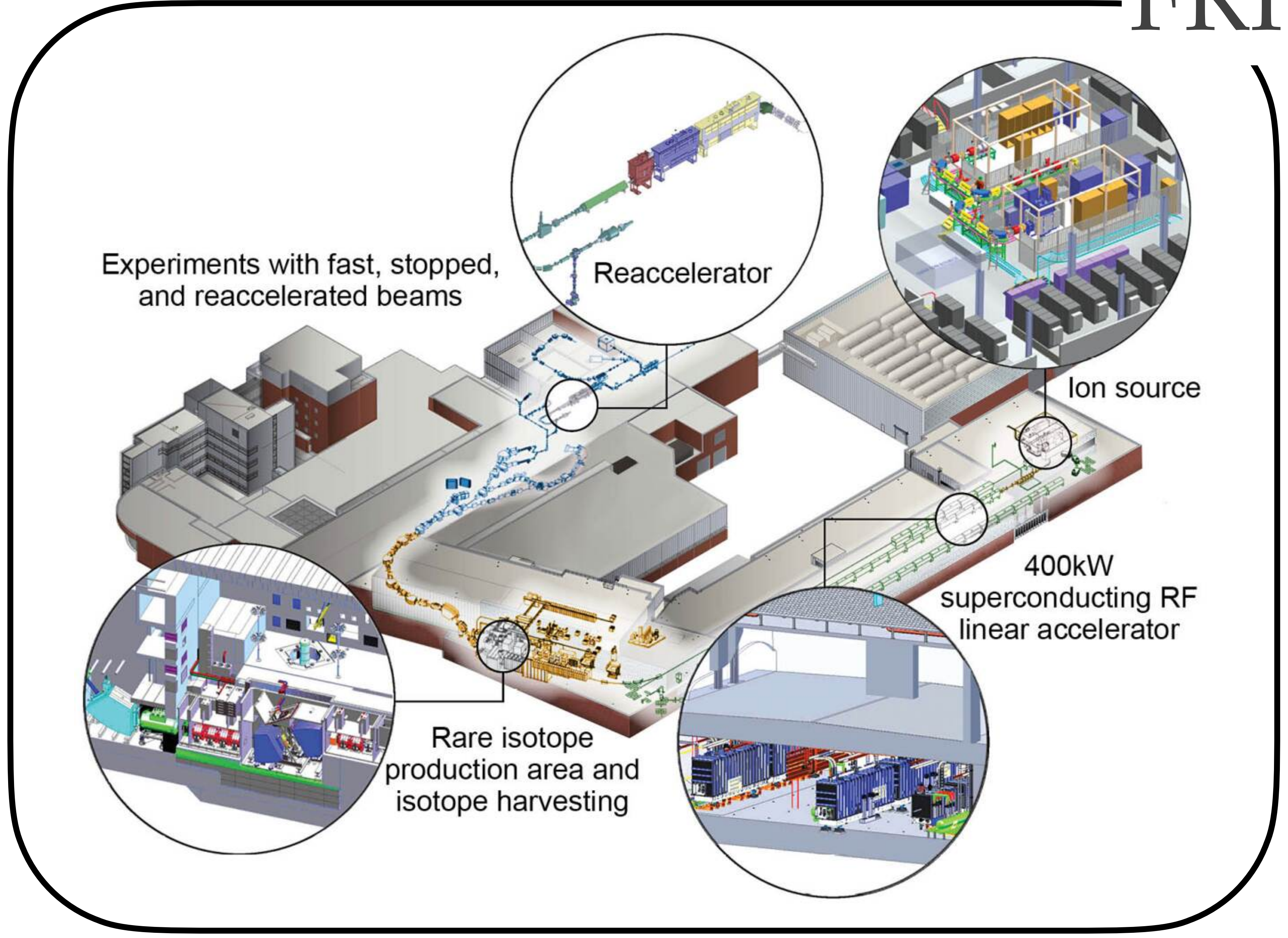
GANIL







FRIB



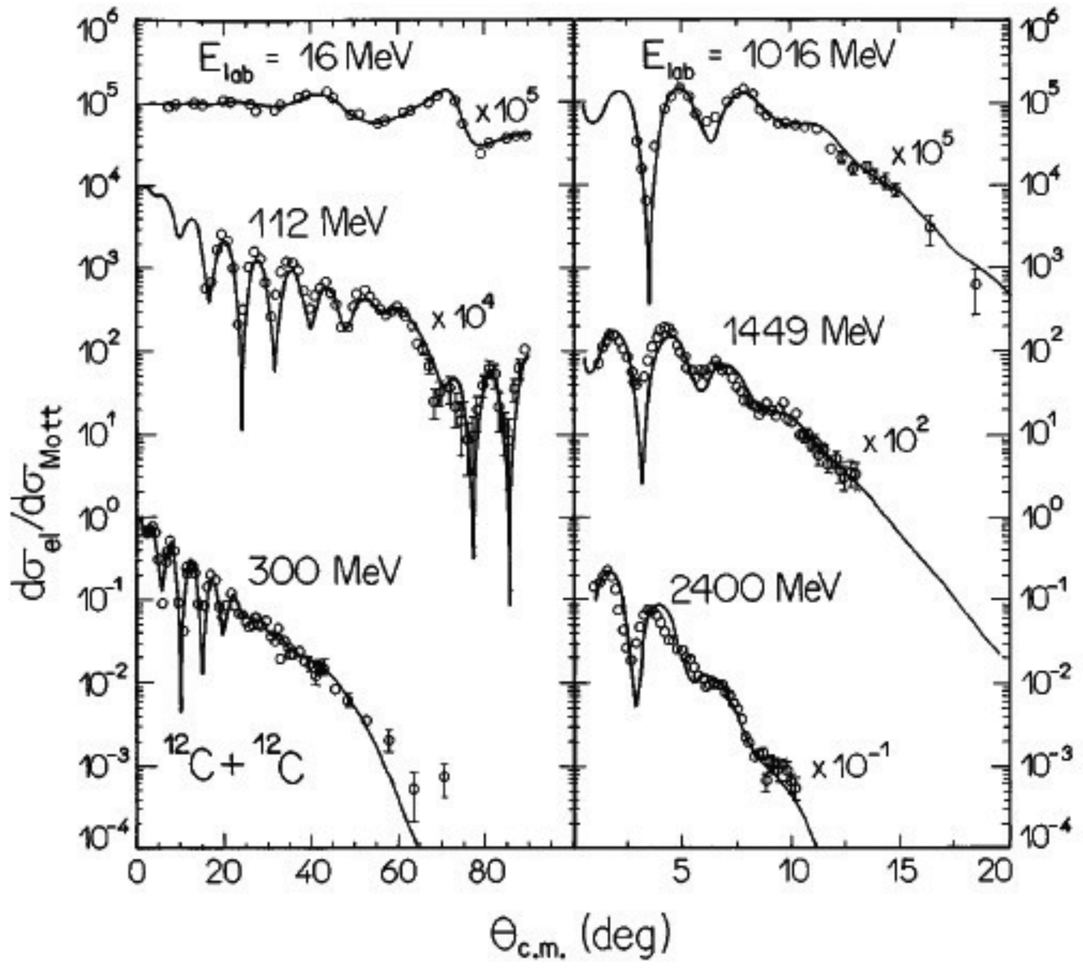
and many more experimental facilities…

Optical potentials

Phenomenological approach

✔ Very successful (large community)
✔ Easy to use (but not always)
✔ Open-access codes (TALYS, FRESCO, EMPIRE, FLUKA,…)

? How to extrapolate to exotic nuclei
? How (and where) to improve the description of data



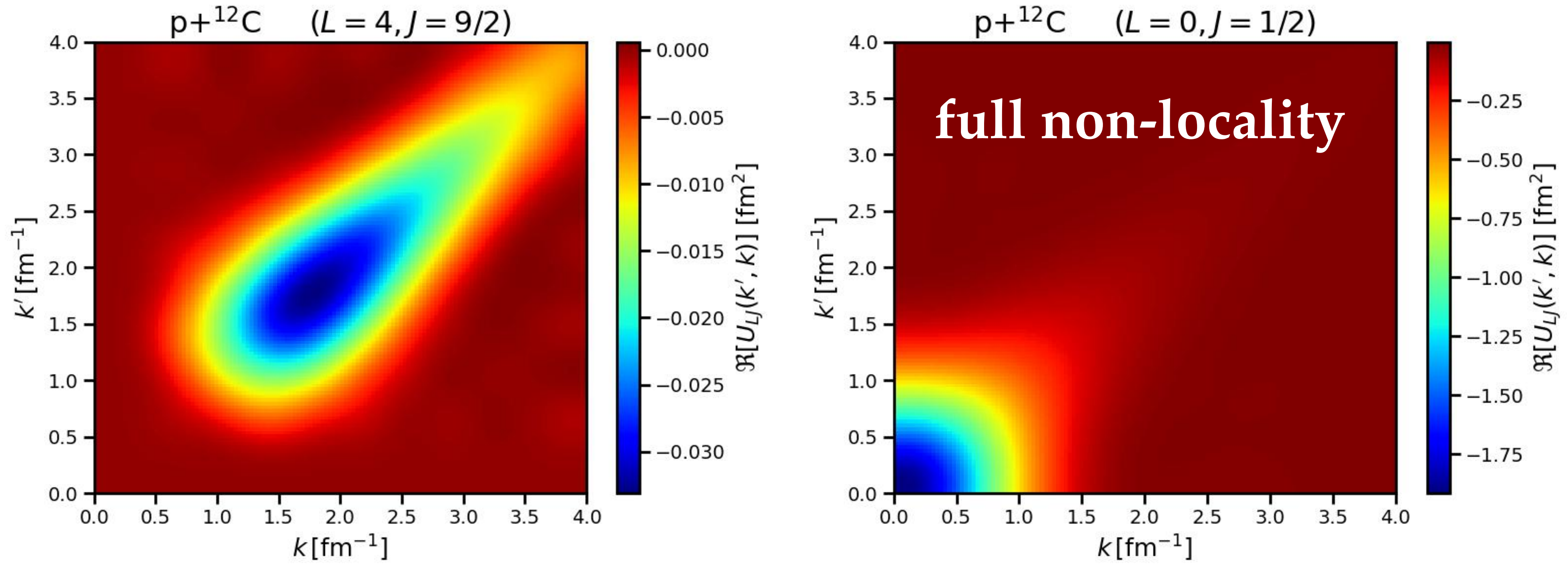
$^{12}C + {}^{12}C$

Di Pietro, Eur. Phys. J. Plus (2018) 133: 404

Microscopic approach

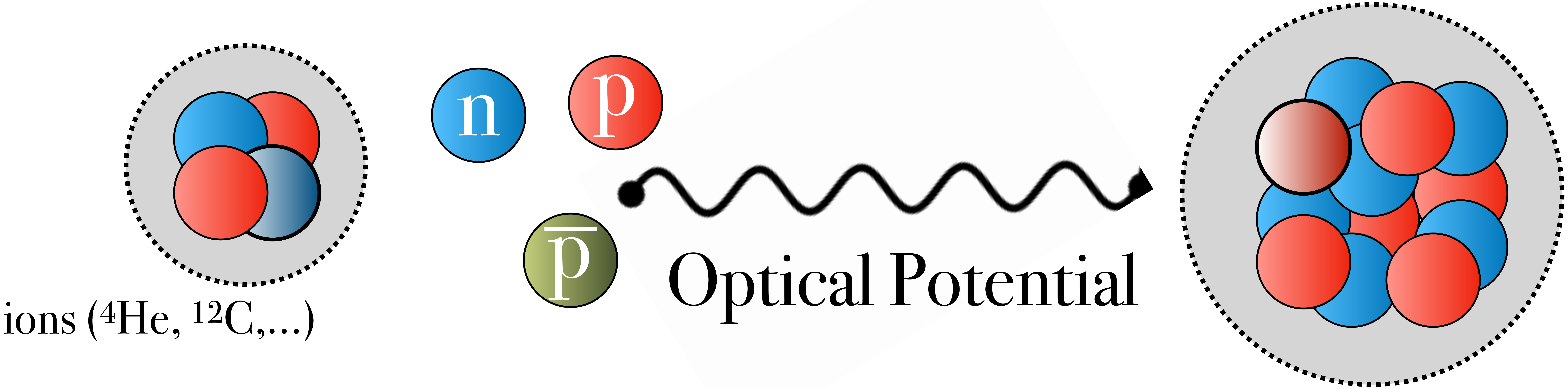
⚠ Difficult to manage
⚠ No open-access codes so far (only to generate NN potentials)
⚠ High-performance computers needed (depends on the reaction)

✔ Parameter free predictions (no fit)
✔ Reliable when extrapolate to exotic nuclei
✔ How (and where) to improve the description of data guided by theory (maybe difficult)

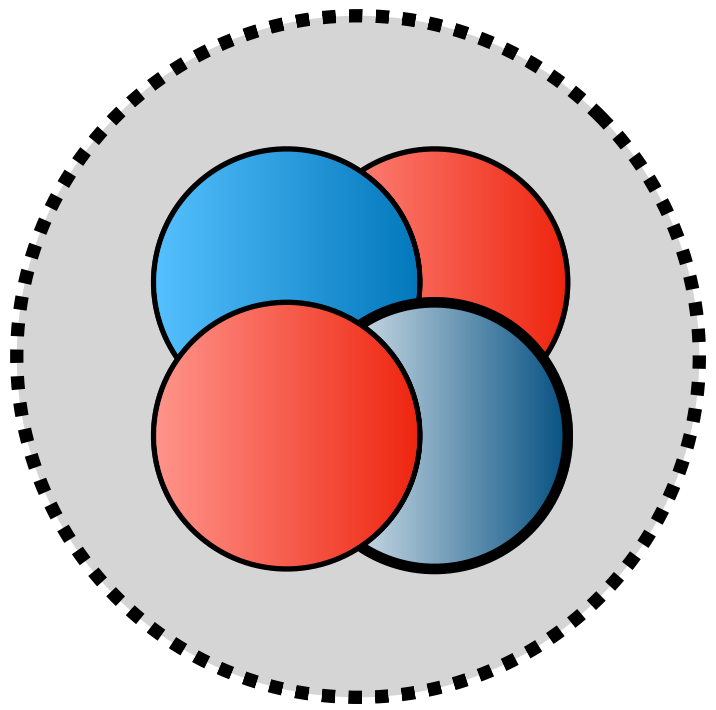


$p + {}^{12}C$

Roadmap towards microscopic optical potentials



Roadmap towards microscopic optical potentials

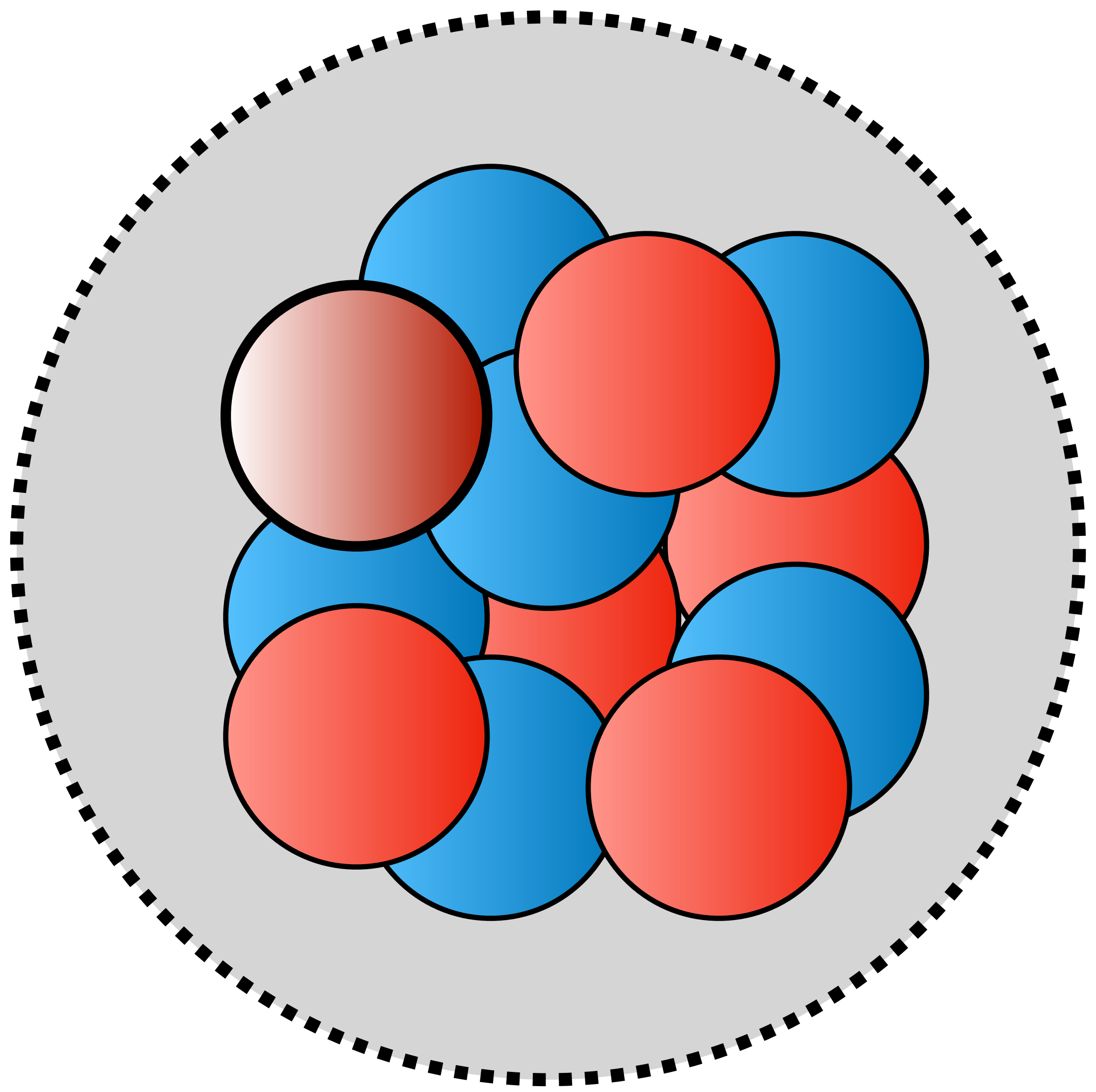


ions (^{4}He, ^{12}C,...)

n p $\bar{\text{p}}$

ChPT

Optical Potential



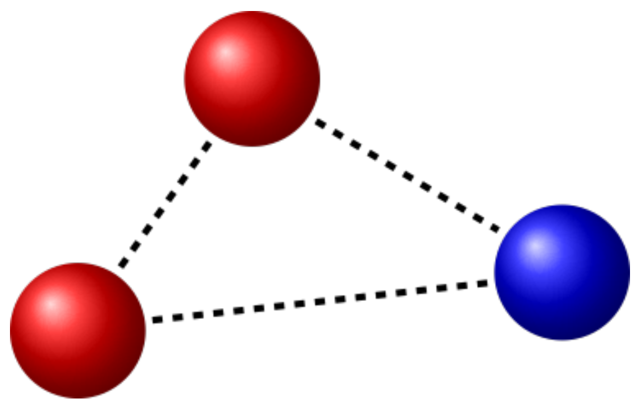
NN data

$$\left(\frac{d\sigma}{d\Omega}\right)_{NN}$$

$$\delta_L(E)$$

NN Body

+



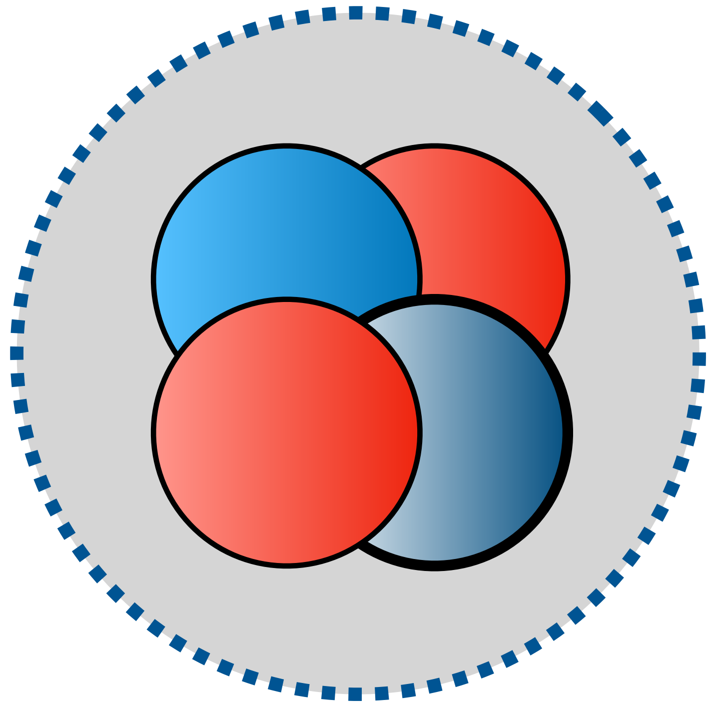
NNN Body

somehow...

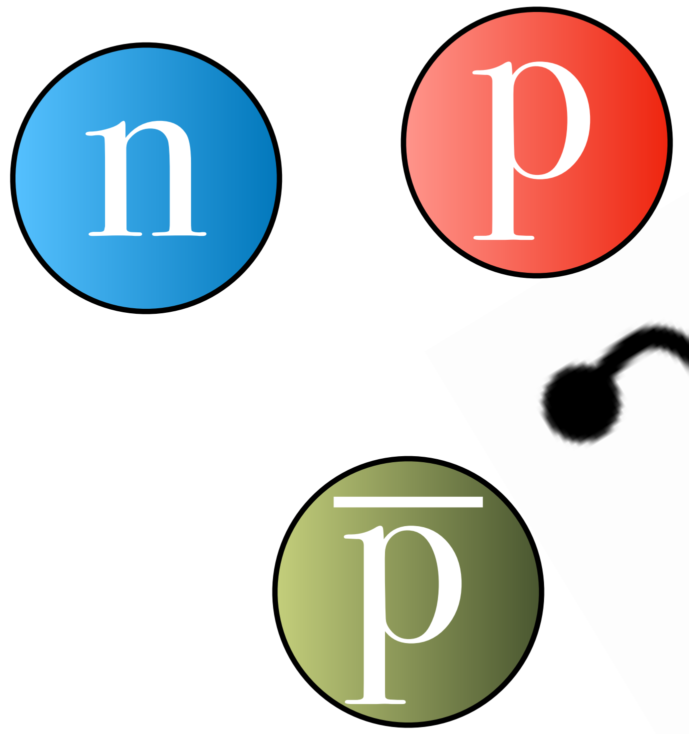
<u>Starting point</u>

in principle everything we need to know

Roadmap towards microscopic optical potentials

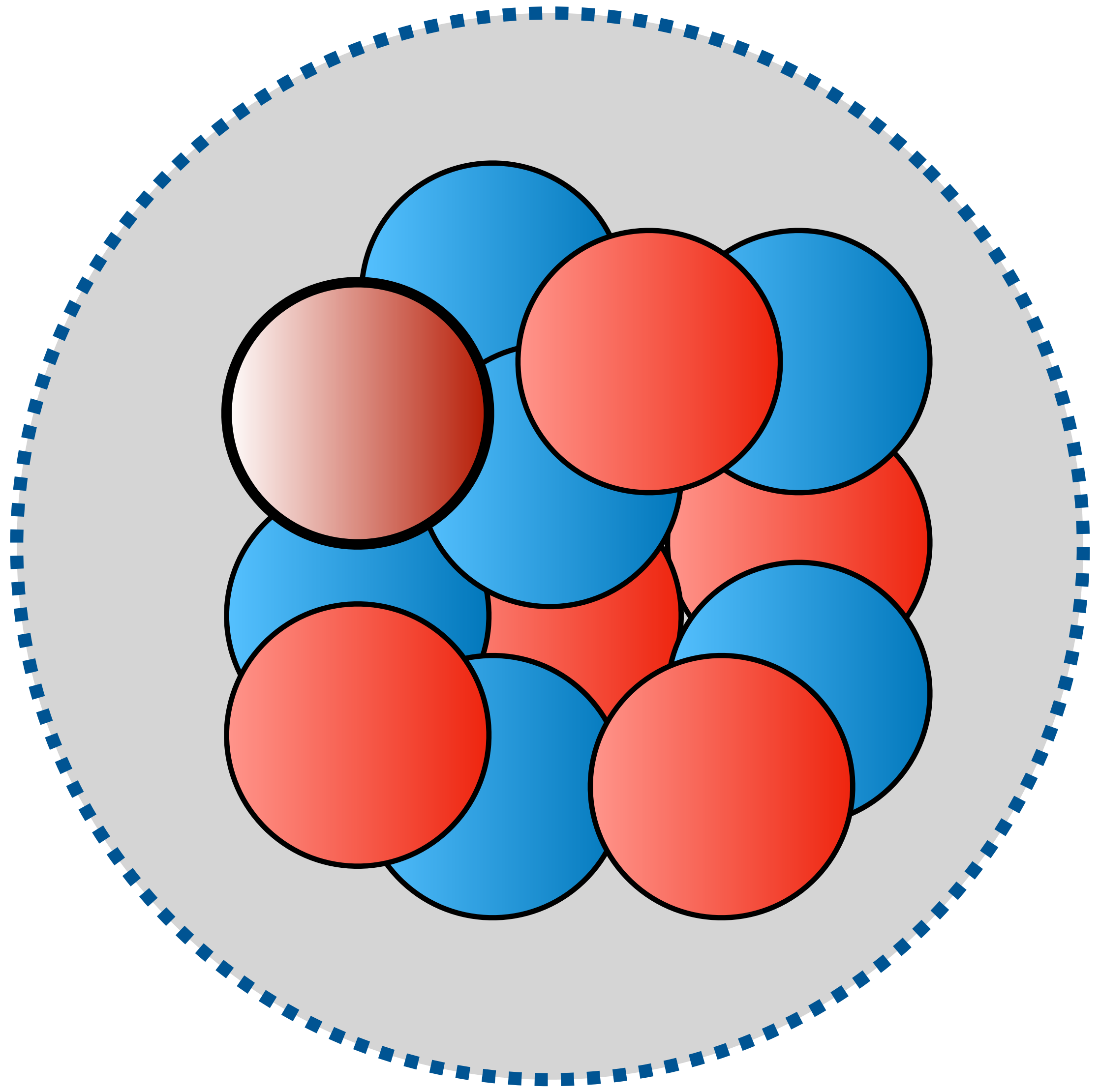


ions (^{4}He, ^{12}C,...)



ChPT

Optical Potential



Effective Interaction

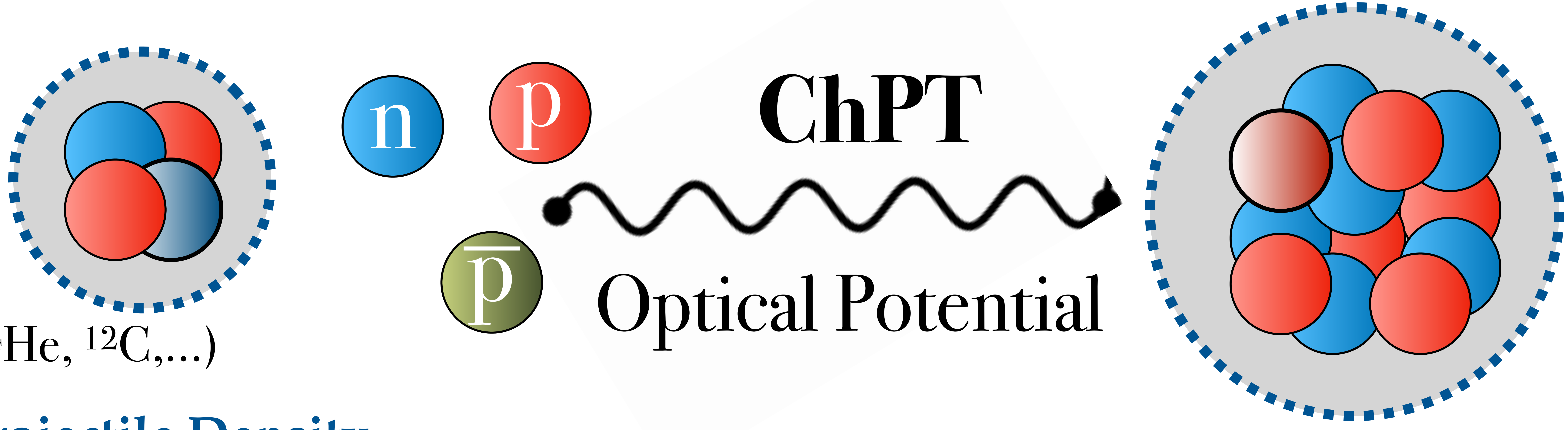
<u>First step</u>

NN Body

$$V_{NN} = \begin{cases} t_{NN} \\ G_{NN} \end{cases}$$

Lippman-Schwinger equation, G-matrix,…

Roadmap towards microscopic optical potentials



Projectile Density

if needed…

A Body

$\rho_P(\boldsymbol{r}', \boldsymbol{r})$

Target Density

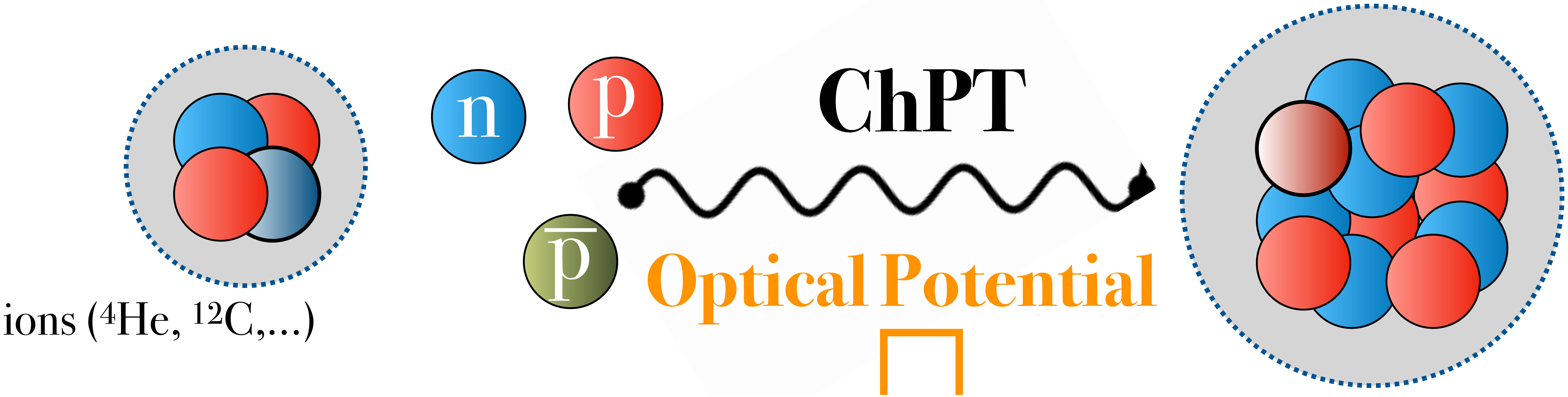
Structure part of the OP

A Body

$\rho_T(\boldsymbol{r}', \boldsymbol{r})$

<u>Second step</u>

Roadmap towards microscopic optical potentials



Multiple scattering theory - spectator expansion

Final step

putting everything together

$$U_{\rm opt}(\boldsymbol{k}', \boldsymbol{k}; E)$$

$$U_{\rm opt} \sim \int V_{NN}\ \rho$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{NA}$$

$$A_y$$

Multiple scattering approximation for NA

Lippmann-Schwinger equation for the nucleon-nucleus transition amplitude

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

elastic case

Projectile-target interaction

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

Full 3N interaction is still missing

Many-body propagator

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

Multiple scattering approximation for NA

Lippmann-Schwinger equation for the nucleon-nucleus transition amplitude

$$T = V + VG_0(E)T$$

elastic case

Let's introduce the **optical potential *U***

$$T = U + UG_0(E)PT$$

$$U = V + VG_0(E)QU$$

Projection operators $P + Q = 1$

P space (elastic)

$P = |\Psi_0\rangle\langle\Psi_0|$

Q Space

$Q = 1 - P$

Works by Thaler, Watson, Satchler,…

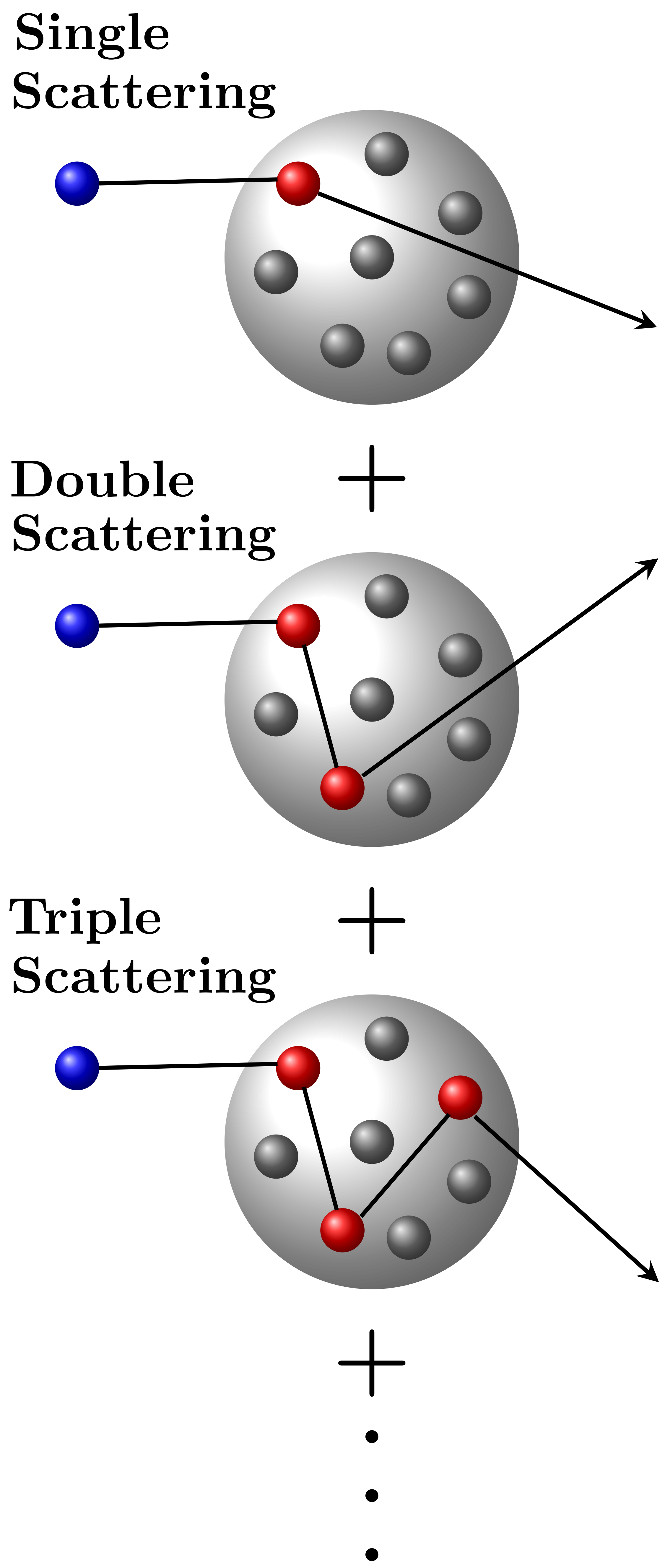
The spectator expansion

Transition amplitude for elastic scattering

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

The spectator expansion

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



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

The **first-order** spectator expansion

Transition amplitude for elastic scattering

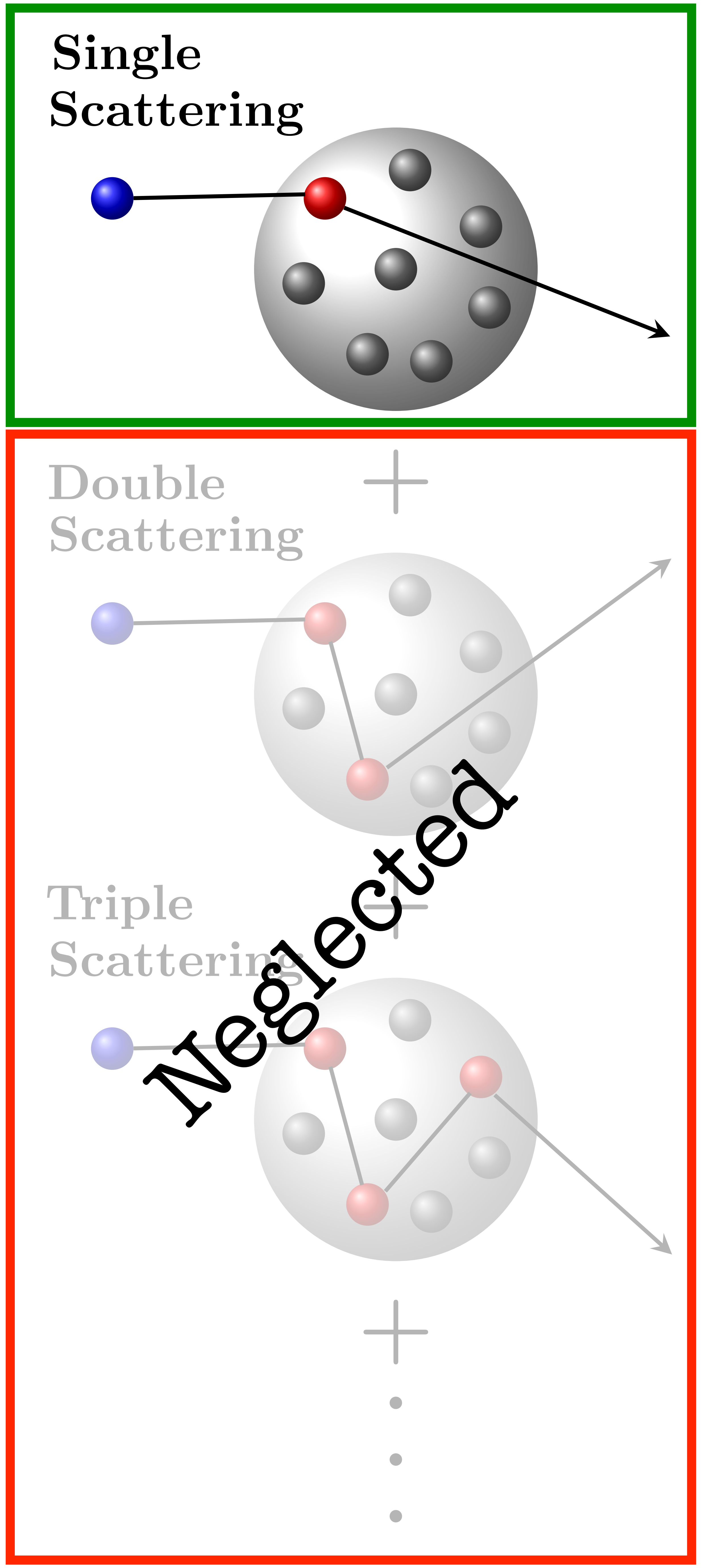
$$T_{\rm el} \equiv PTP = PUP + PUPG_0(E)T_{\rm el}$$

The spectator expansion

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

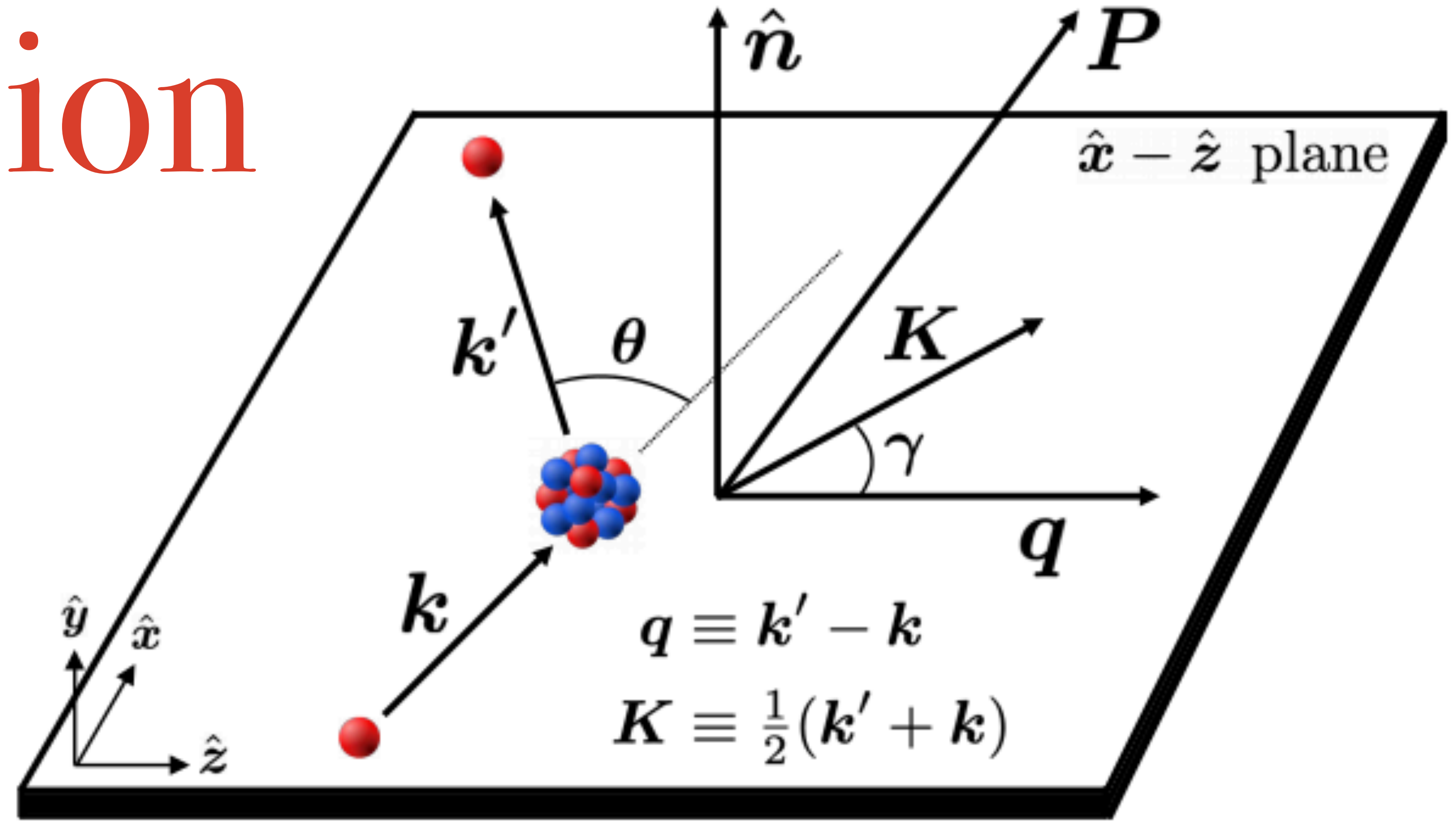
$$U \simeq \sum_{i=1}^{A} \tau_{0i} \longrightarrow \tau_{0i} \approx t_{0i} = v_{0i} + v_{0i}\, g_0(E)\, t_{0i}$$

Impulse approximation Two-body propagator



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

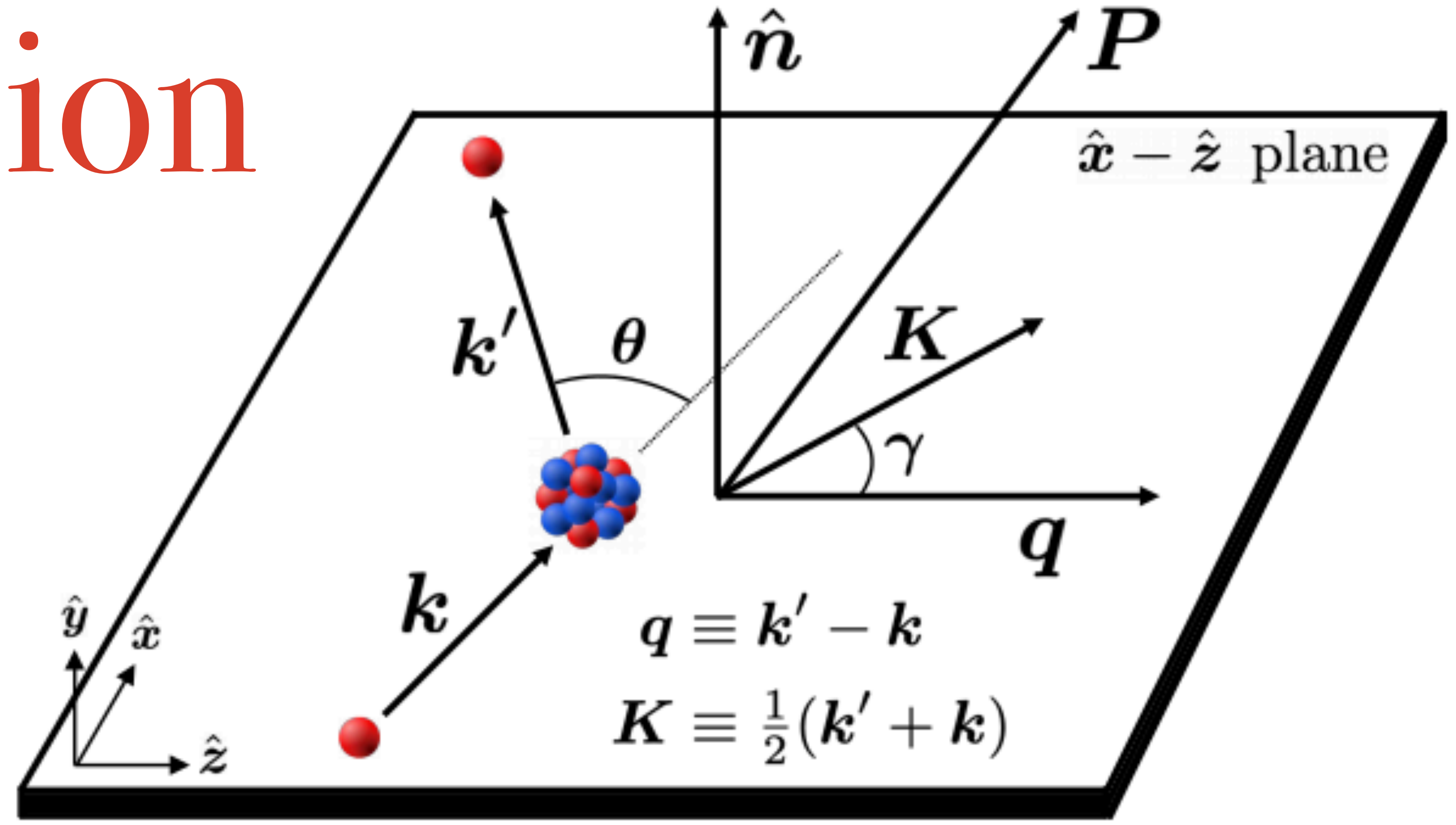
The first-order spectator expansion



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

1. Folding procedure with full non-locality
2. Many-body complexity has been strongly reduced
3. Well suited for intermediate energies (70 - 350 MeV), we need improvements (work is in progress) for lower and higher energies
4. It does not require any correction/fit, approximations should be considered

The first-order spectator expansion



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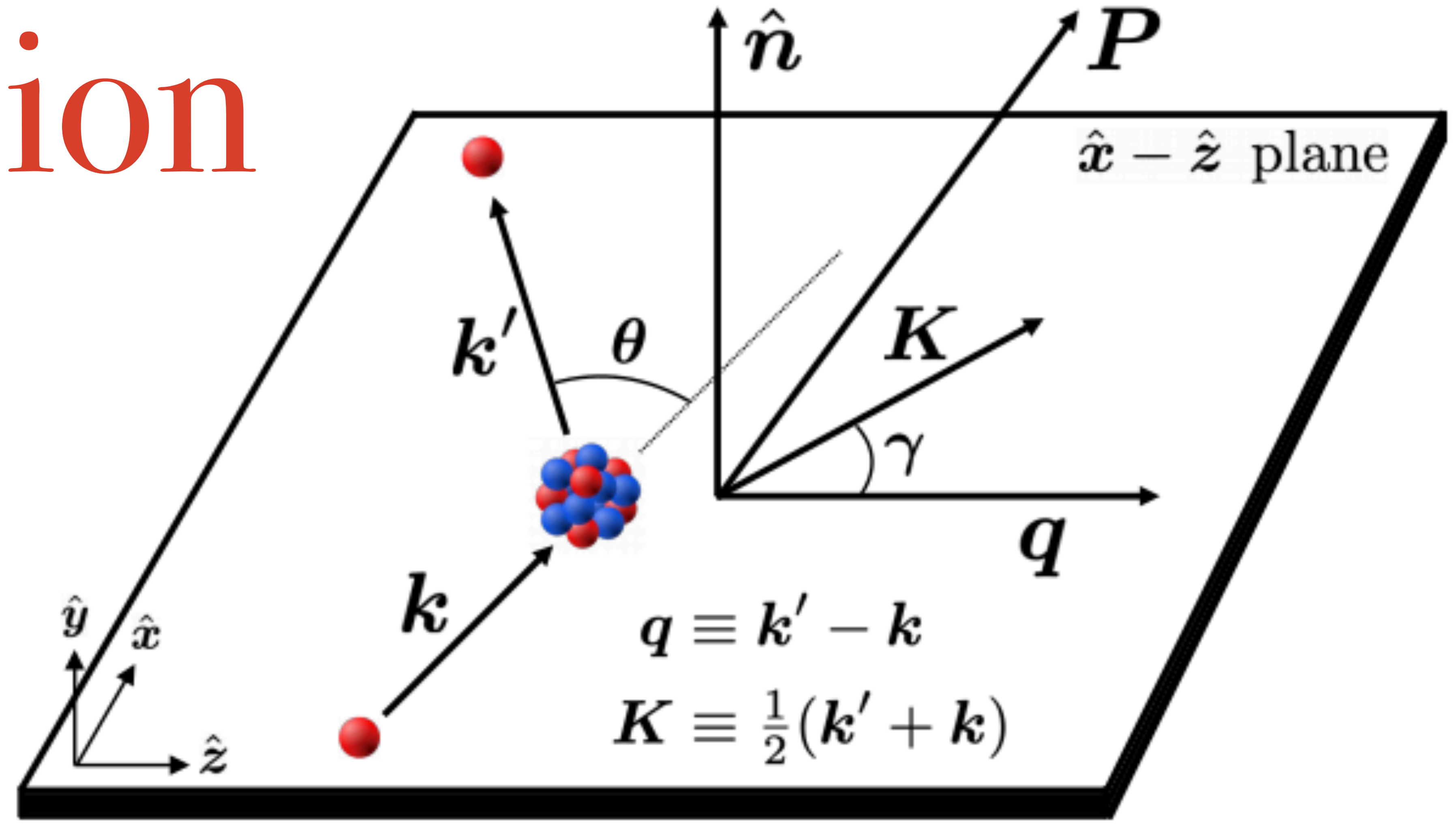
Free two-body scattering matrix

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

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

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

The first-order spectator expansion



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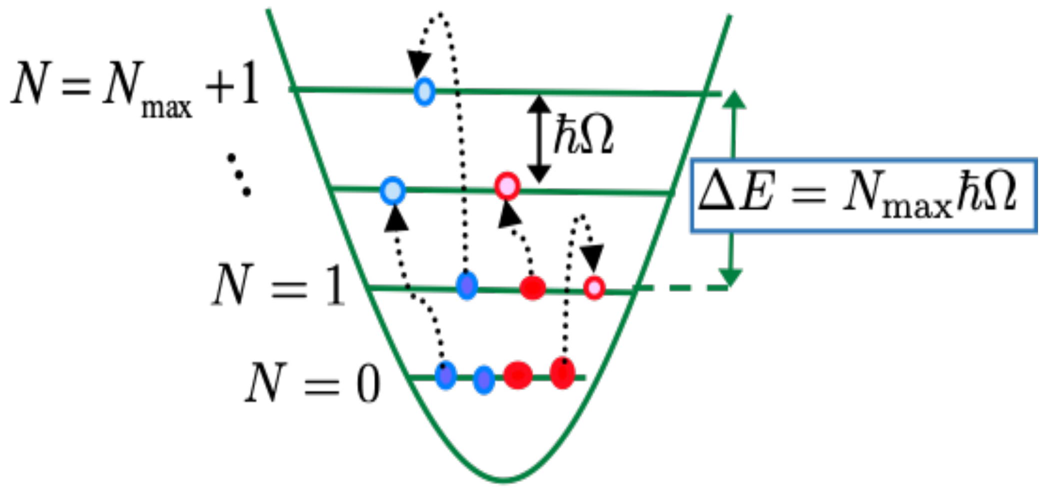
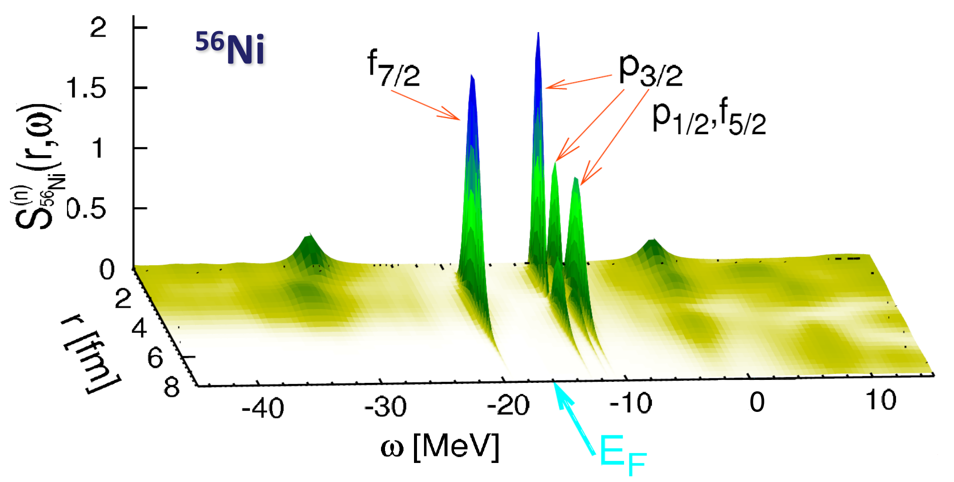
- Only **NN** interaction

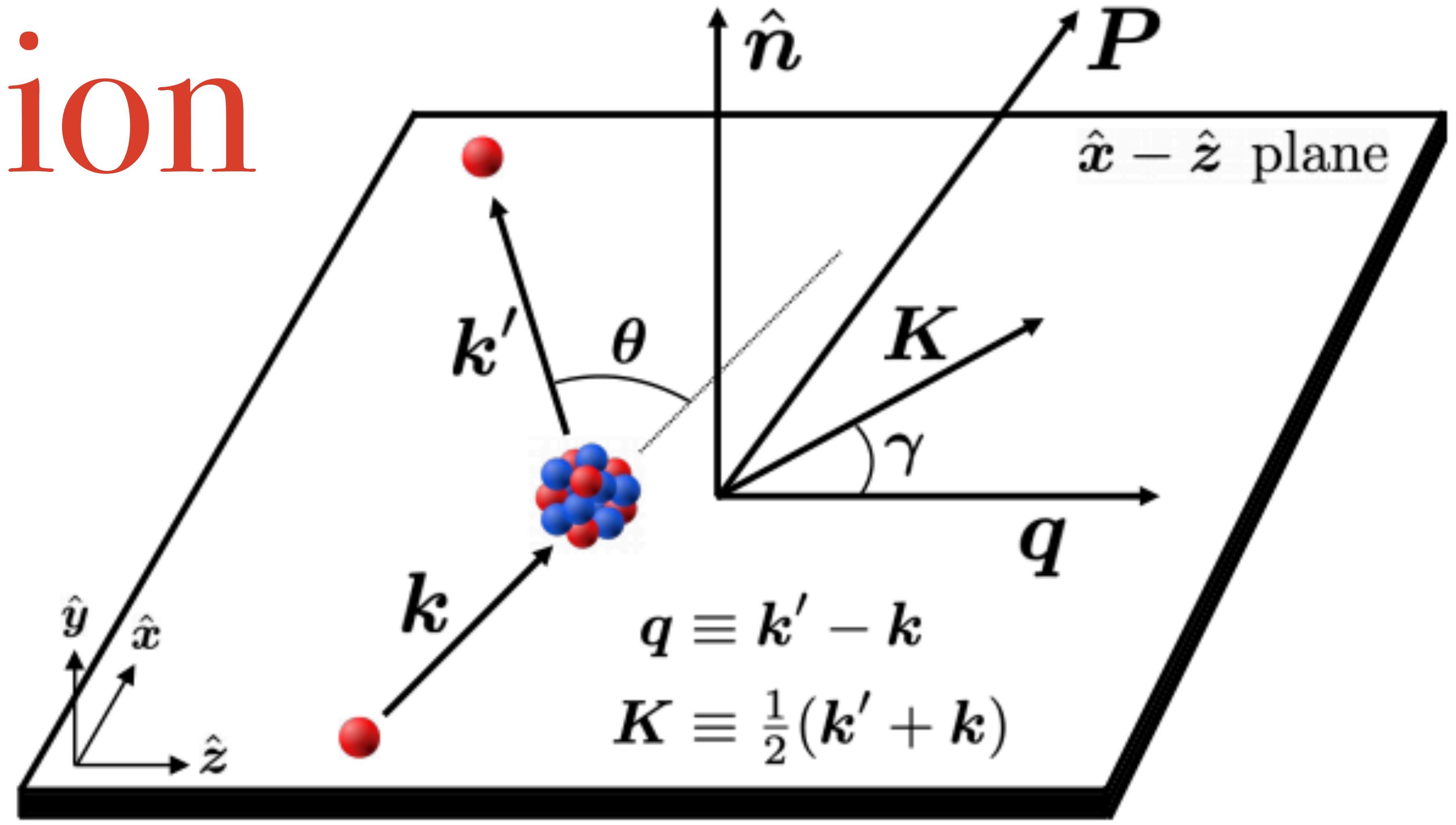
Nonlocal one-body density

- 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 spectator expansion



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

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

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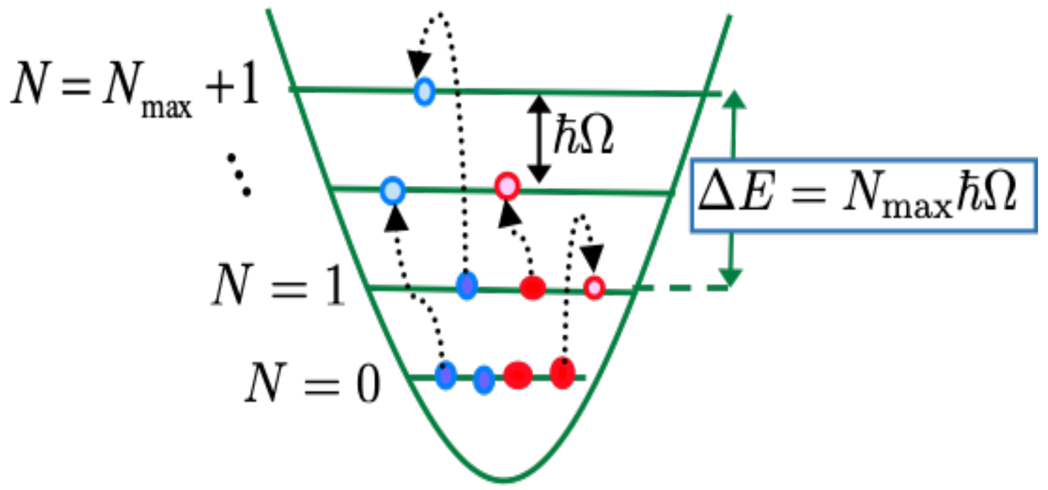
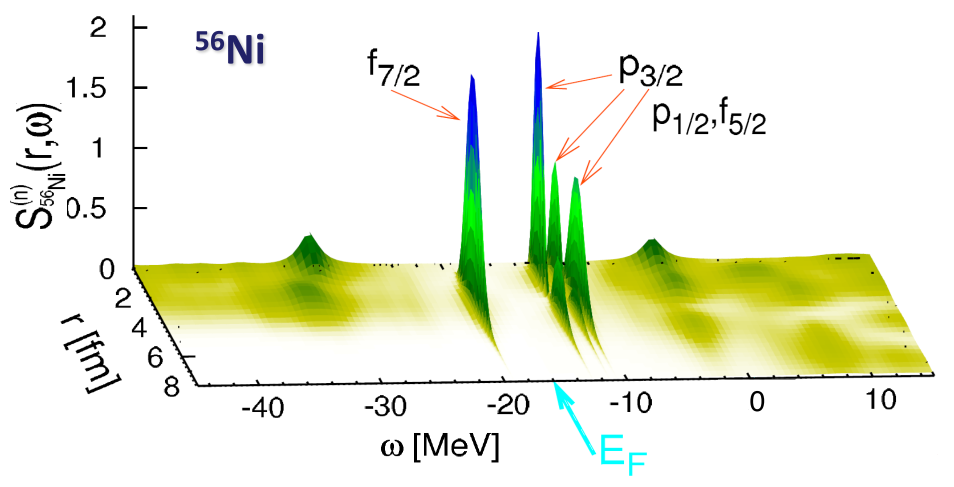


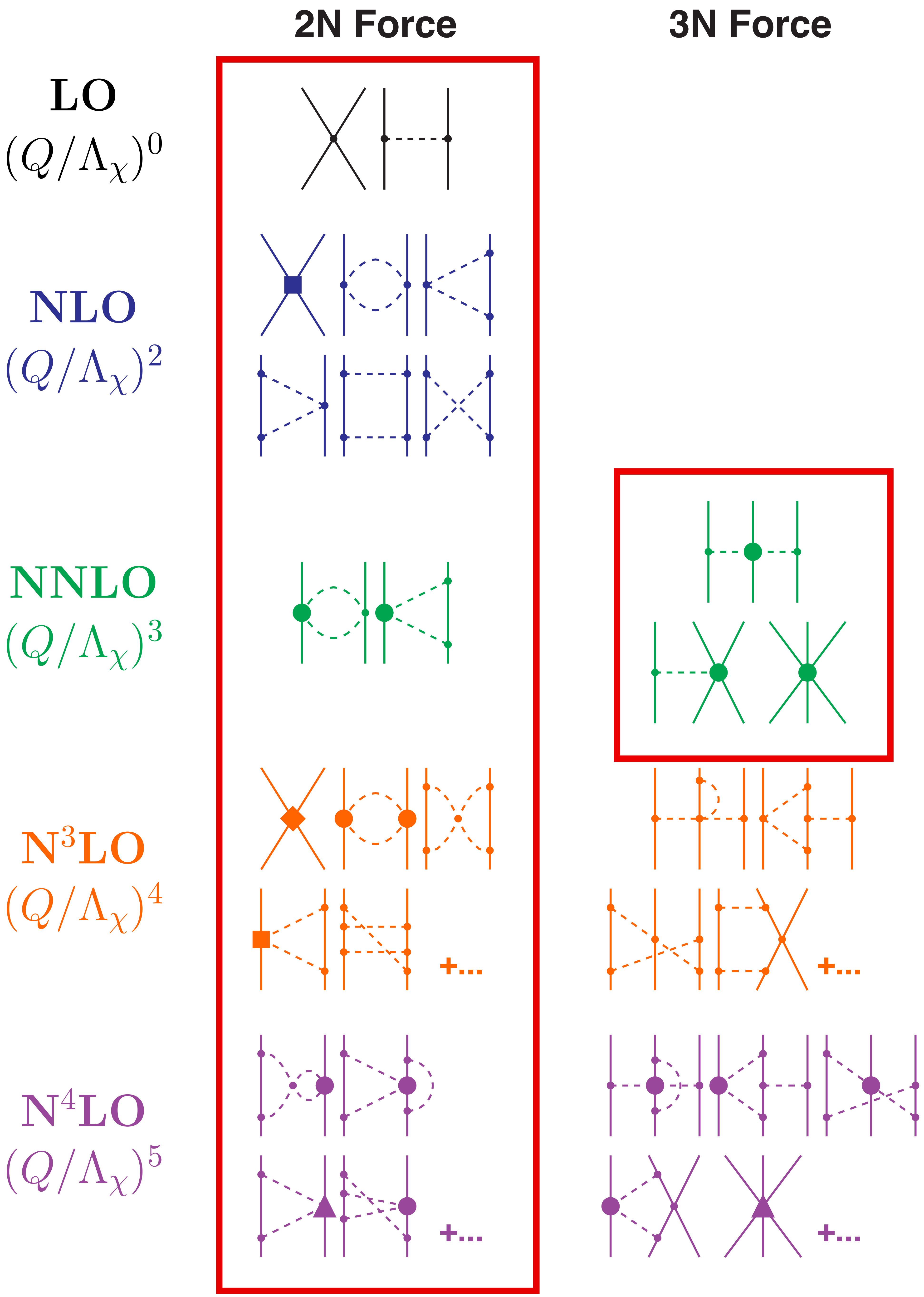


Chiral interactions

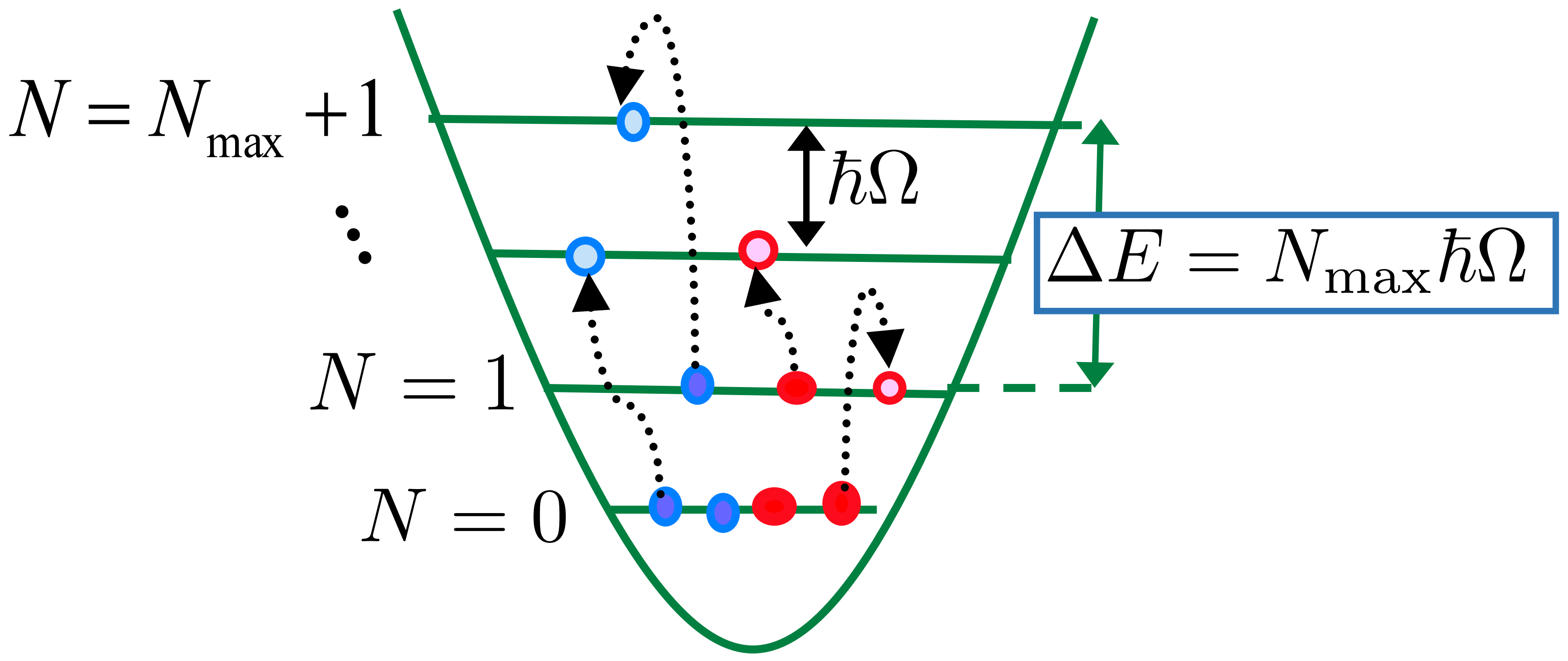
Advantages

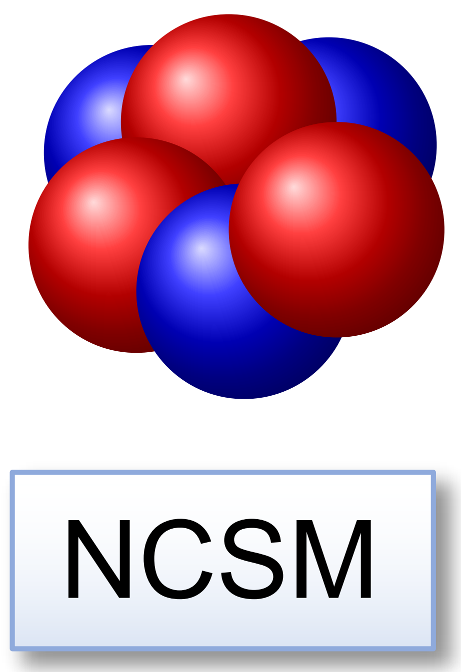
- ☑ QCD symmetries are consistently respected
- ☑ Systematic expansion (order by order we know exactly the terms to be included)
- ☑ Theoretical errors
- ☑ Two- and three-nucleon forces belong to the same framework

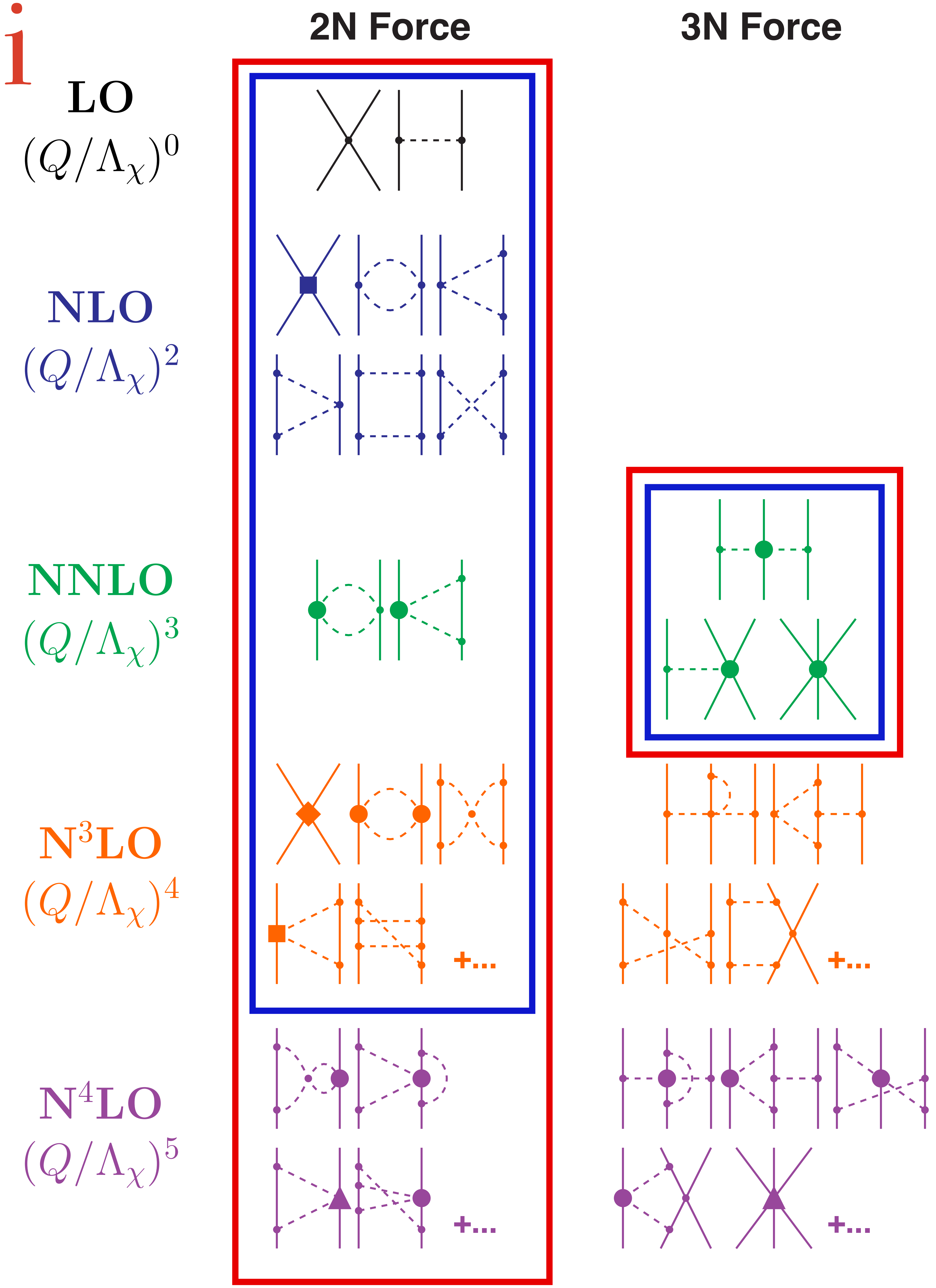
We use these interactions as **the only input** to calculate the effective interaction between projectile and the target and into the description of the target density



Target description - light nuclei



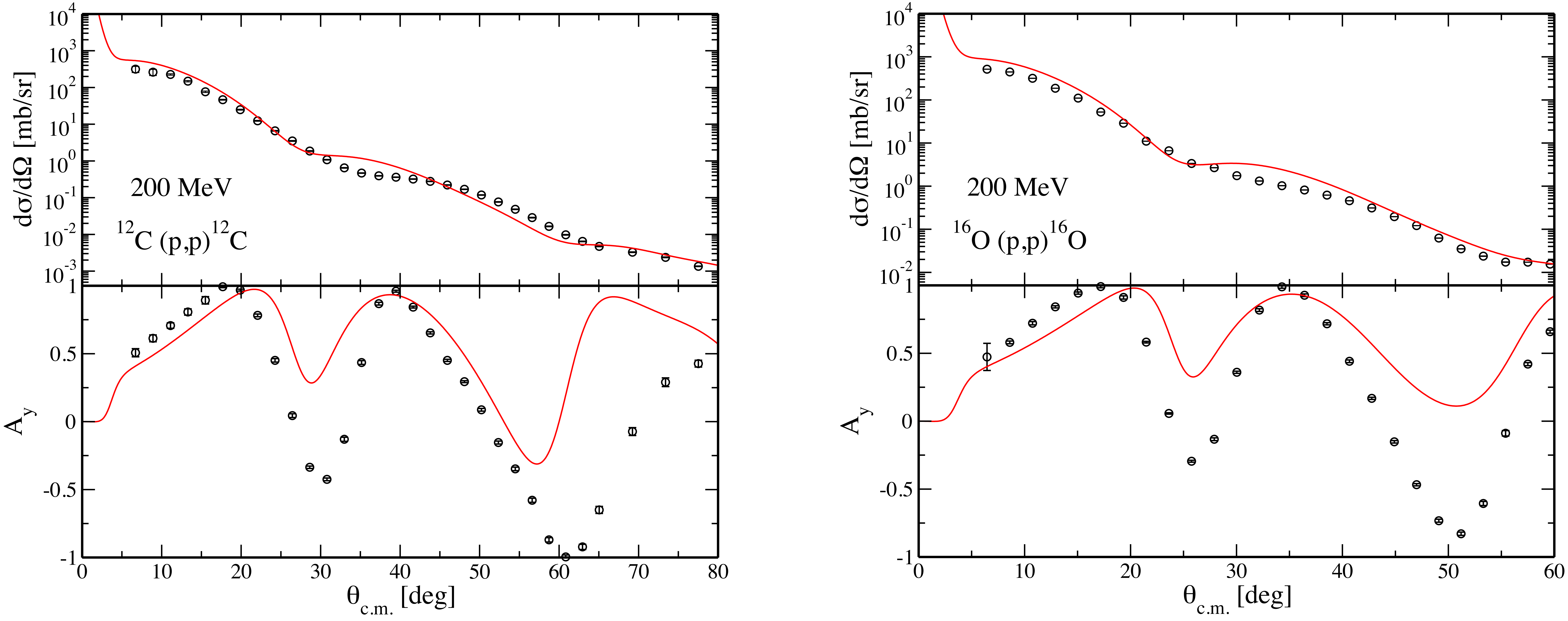




- **NN-N^{4}LO + 3Nlnl (^{12}C, ^{16}O)**
  - N^{4}LO: Entem et al., Phys. Rev. C **96**, 024004 (2017)
  - 3Nlnl: Navrátil, Few-Body Syst. **41**, 117 (2007)
  - c_D & c_E: Kravvaris et al., Phys. Rev. C **102**, 024616 (2020)
- **NN-N^{3}LO + 3Nlnl (^{9,13}C, ^{6,7}Li, ^{10}B)**
  - N^{3}LO: E&M, Phys.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

Elastic scattering: p+^{12}C and p+^{16}O

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



$$U \sim \sum \int \eta \; t_{pN} \; \rho_N$$

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

Assessing the impact of the 3N interaction

General equation for the optical potential

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

Treatment of the 3N force

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

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

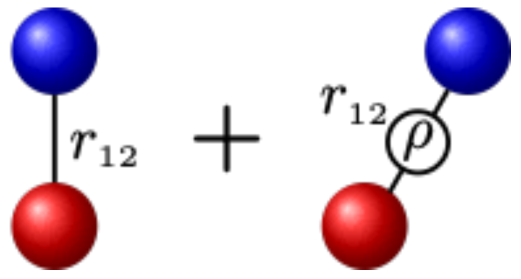
Density dependent

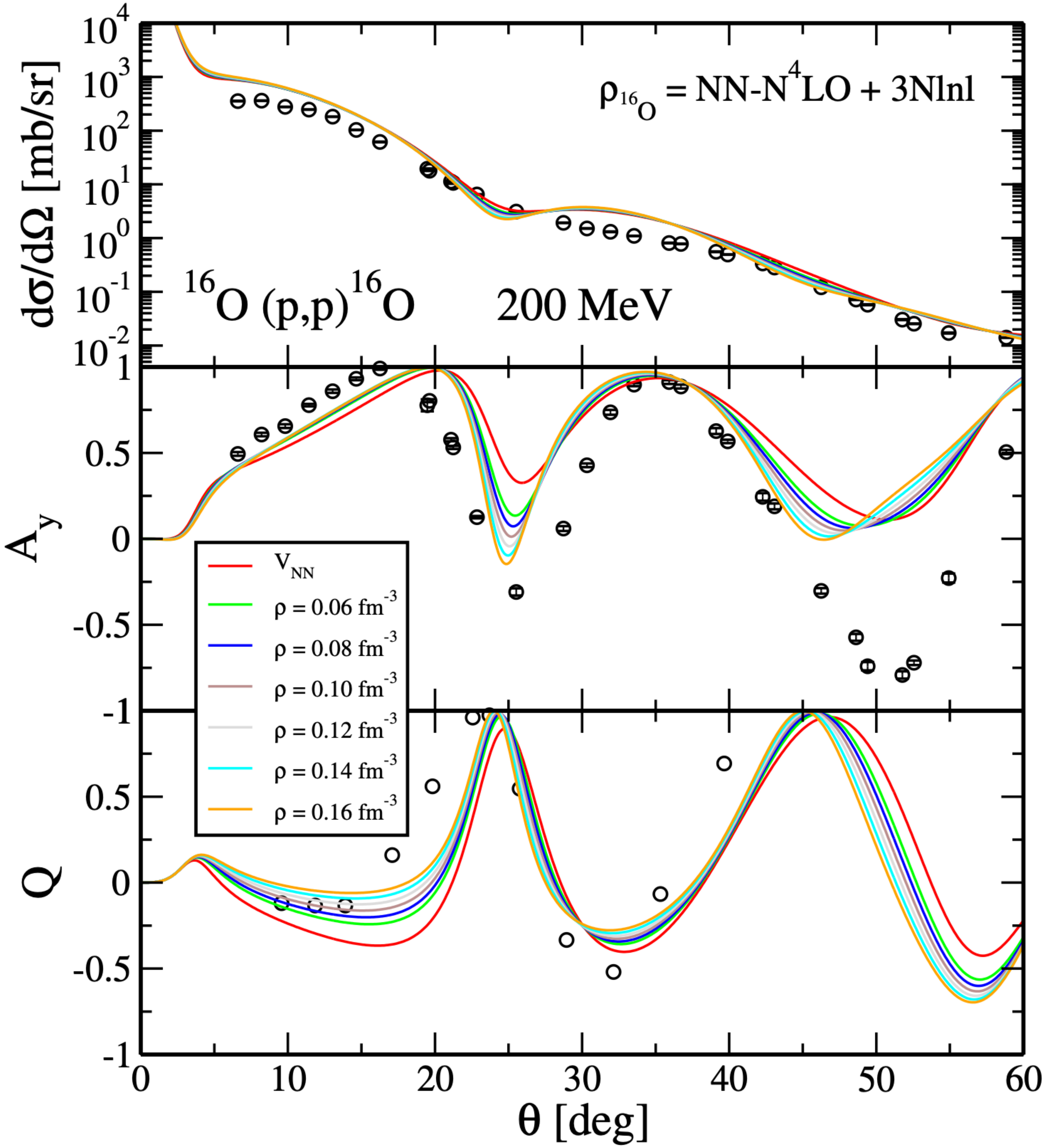
Modification of the *t* matrix

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

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

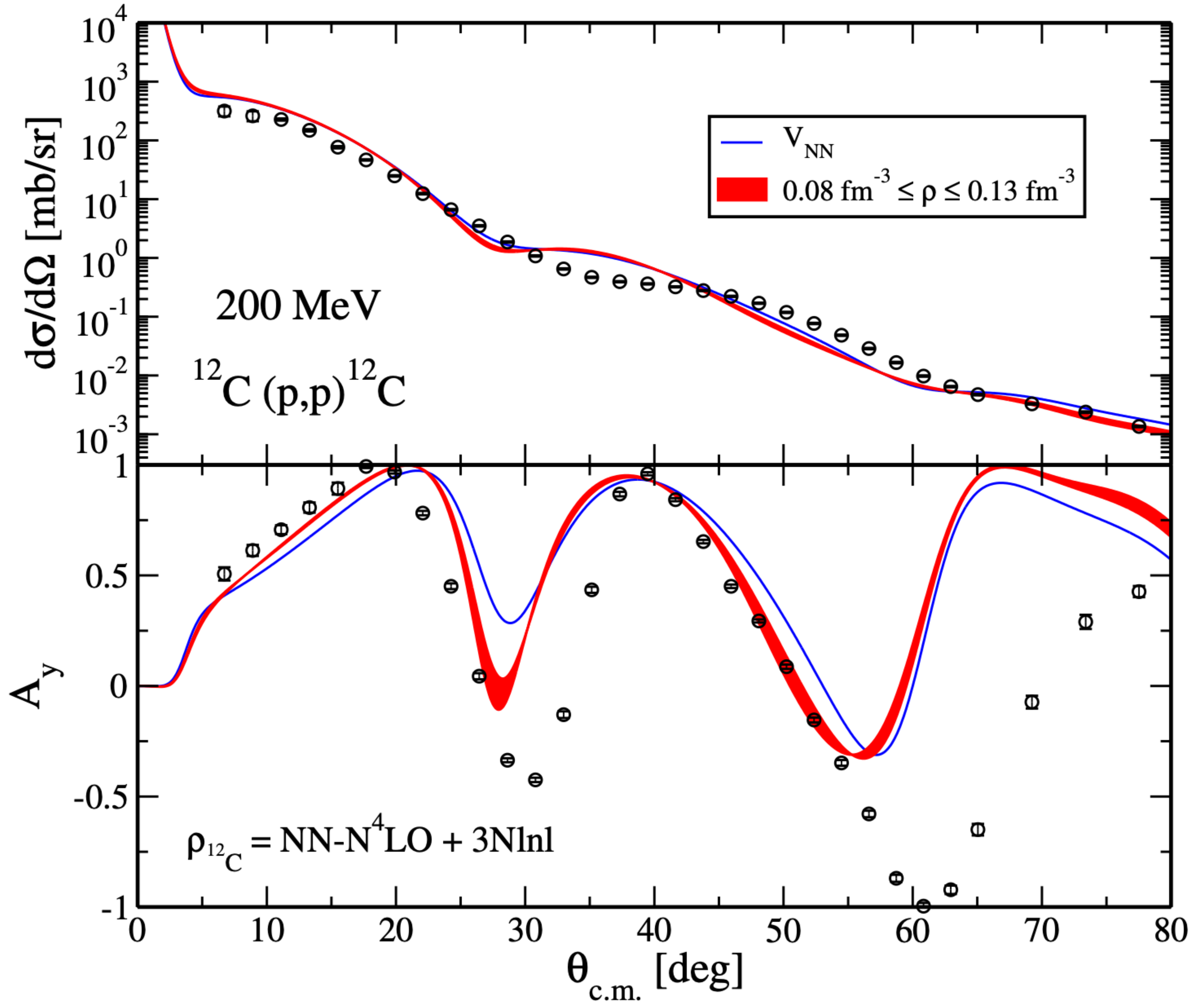
$$v_{0i}^{(2)} = v_{0i} + \langle w_{0i}\rangle$$

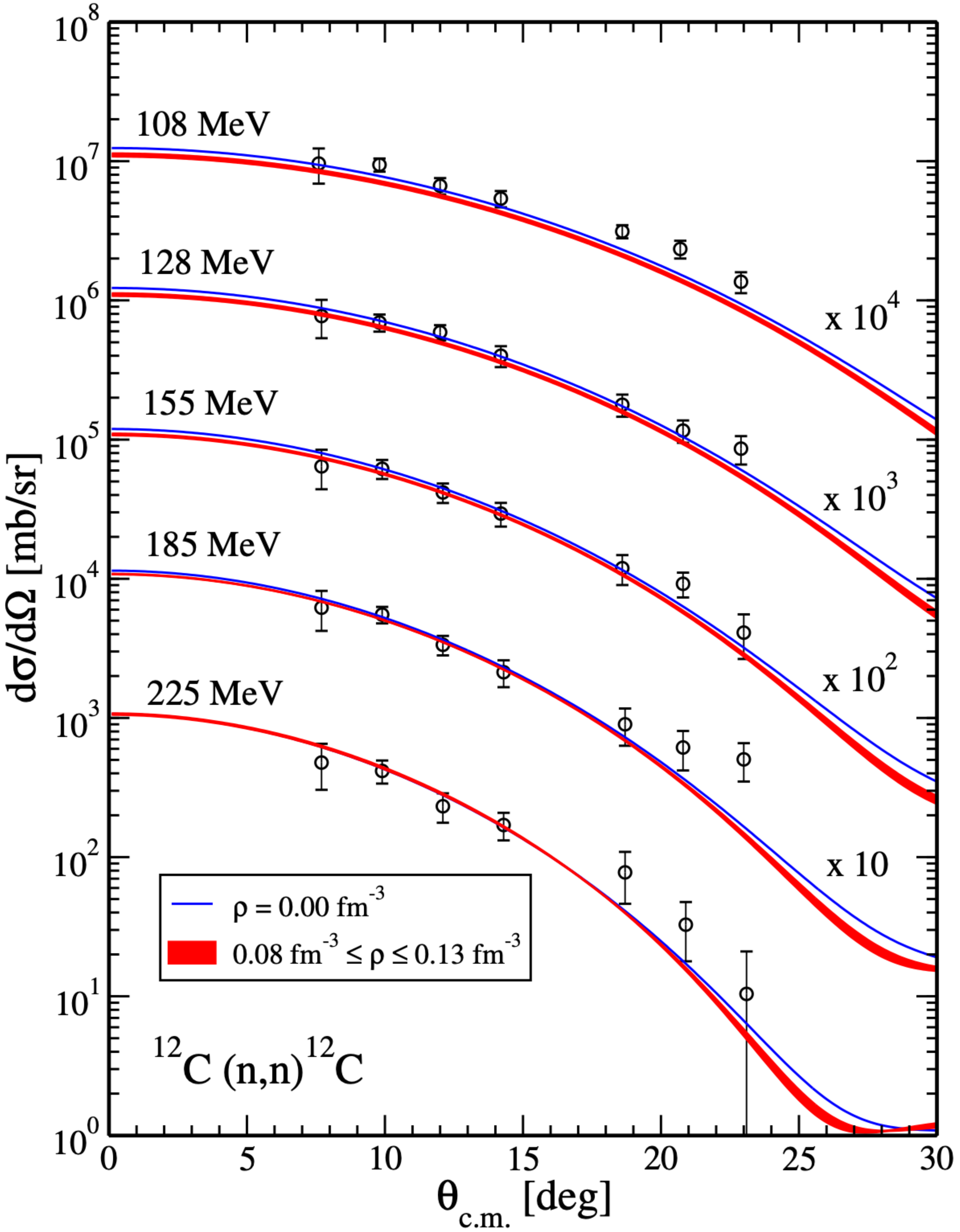
$v =$ 



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

Assessing the impact of the 3N interaction



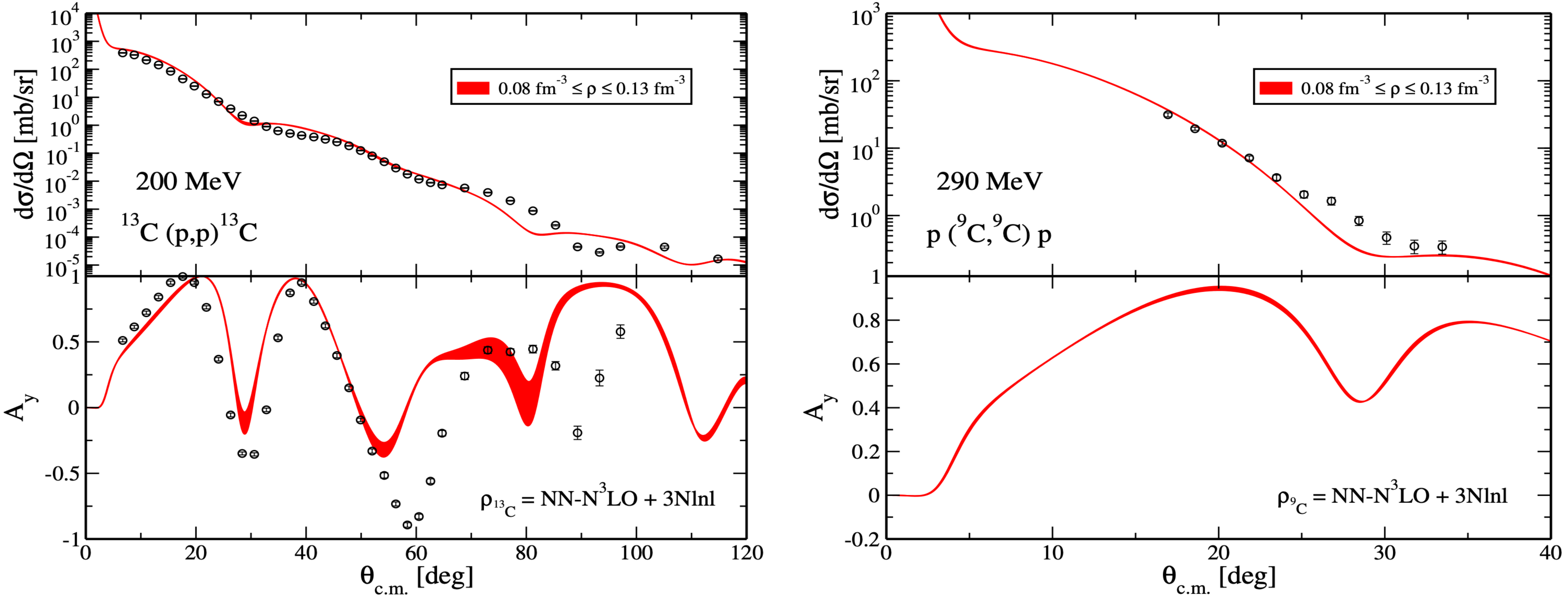


- For all nuclei we found very small contributions to the differential cross section
- The contributions to the spin observable are larger and they seem to improve the agreement with the data

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

Extension to non-zero spin targets

$J^\pi = 1/2^-$ $\quad$ $J^\pi = 3/2^-$



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

Convergence (where to stop the chiral expansion)

- Density computed with NN+3N interaction

  -NN interactions at all orders

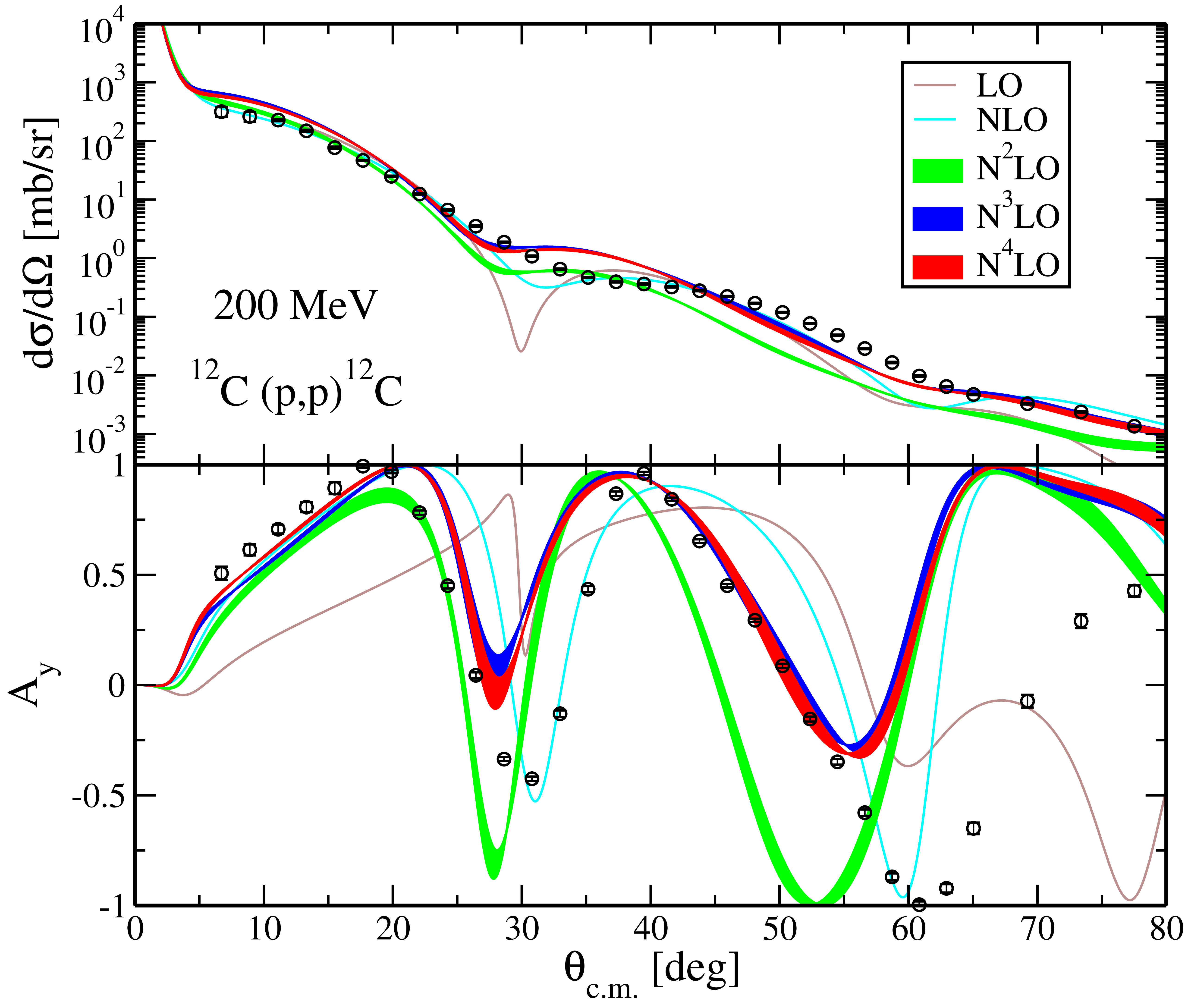
  Entem et al., PRC **96**, 024004 (2017)

  -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

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

- The projectile information only enters the t_{pN} matrix. For antiprotons we make the following replacement

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

- An antiproton-nucleon interaction is needed. $\bar{p}N$ chiral interaction derived up to N^{3}LO

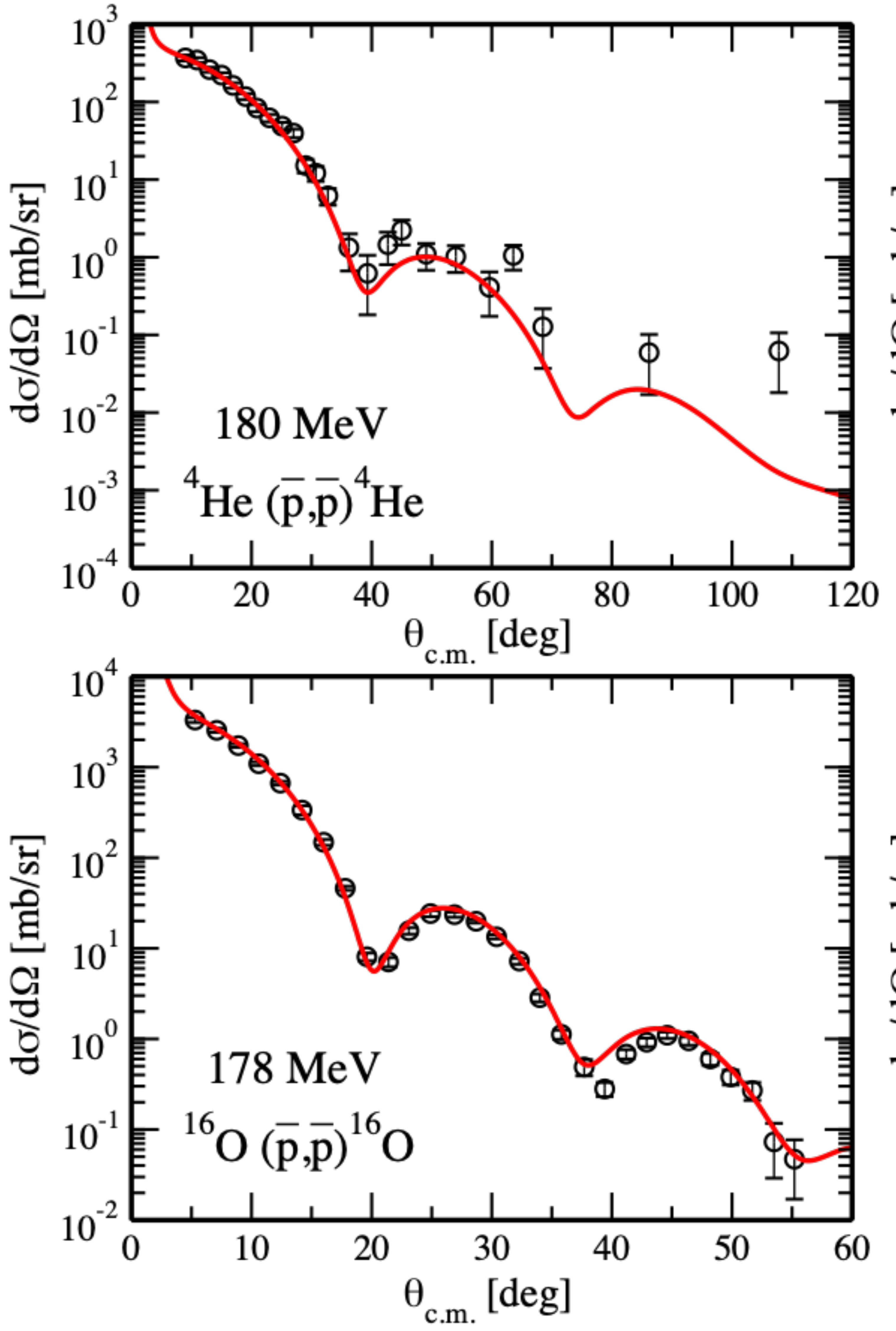
[Dai, Haidenbauer, Meißner, JHEP 07 (2017) 78]

- No projectile-target anti-symmetrisation

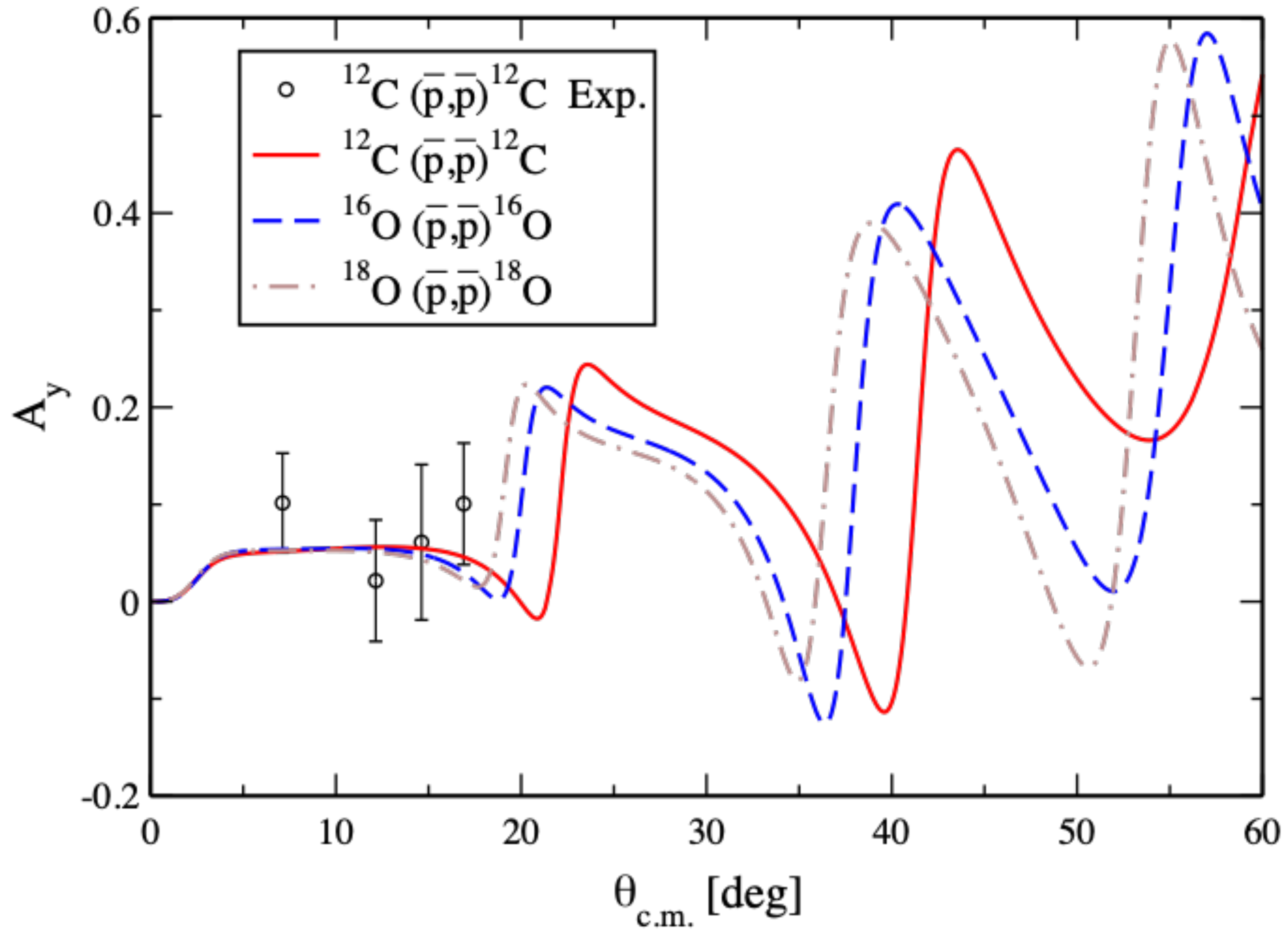
- Antiprotons are mostly absorbed at the surface of the nucleus so the first-order expansion should work better in this case!

Vorabbi et al., PRL **124**, 162501 (2020)

Extension to antiproton-nucleus elastic scattering



Antiprotons mostly interact at the surface of the nucleus so the first-order expansion should work better in this case.



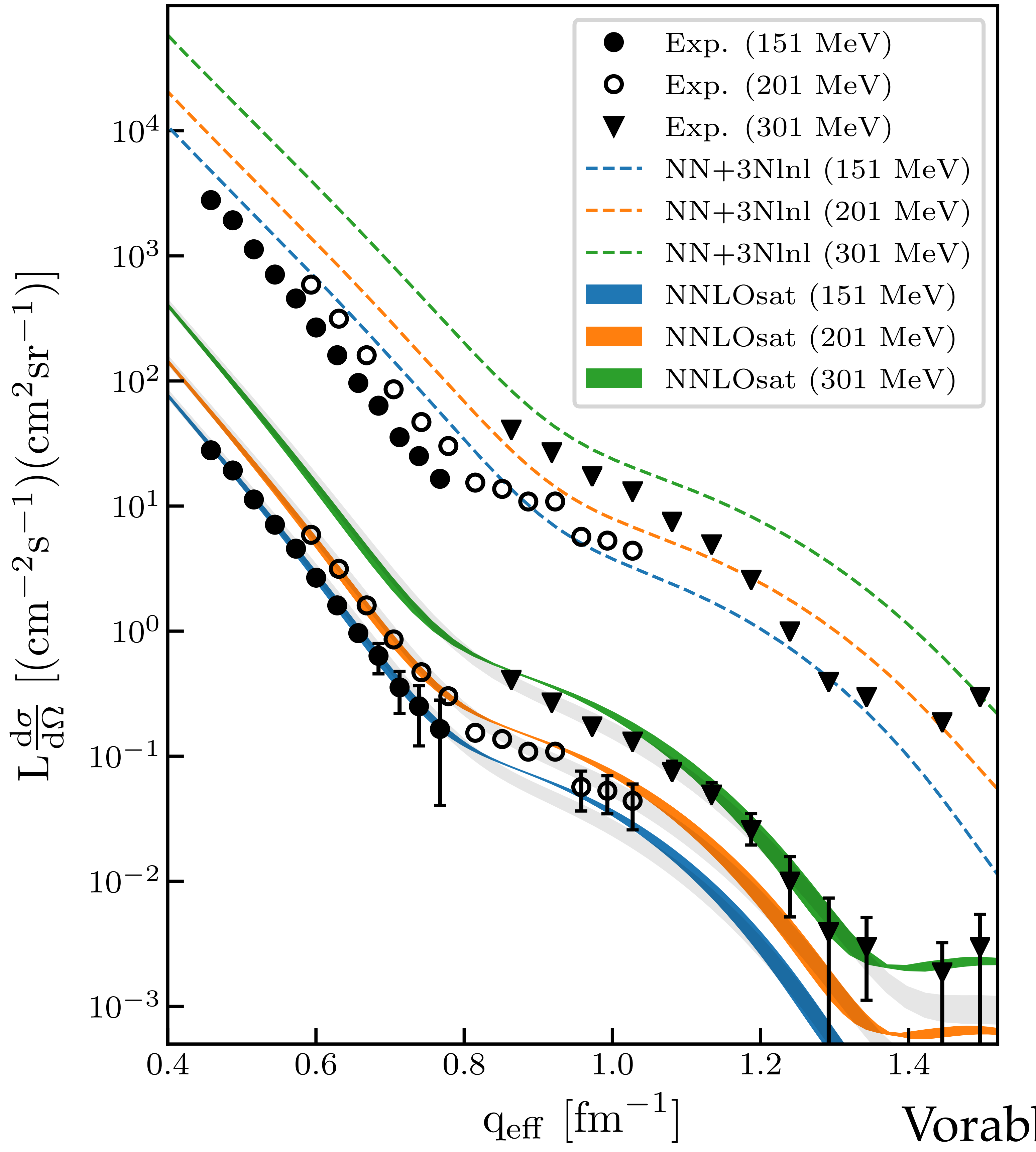
Vorabbi et al., PRL **124**, 162501 (2020)

Extension to heavier nuclei - SCGF

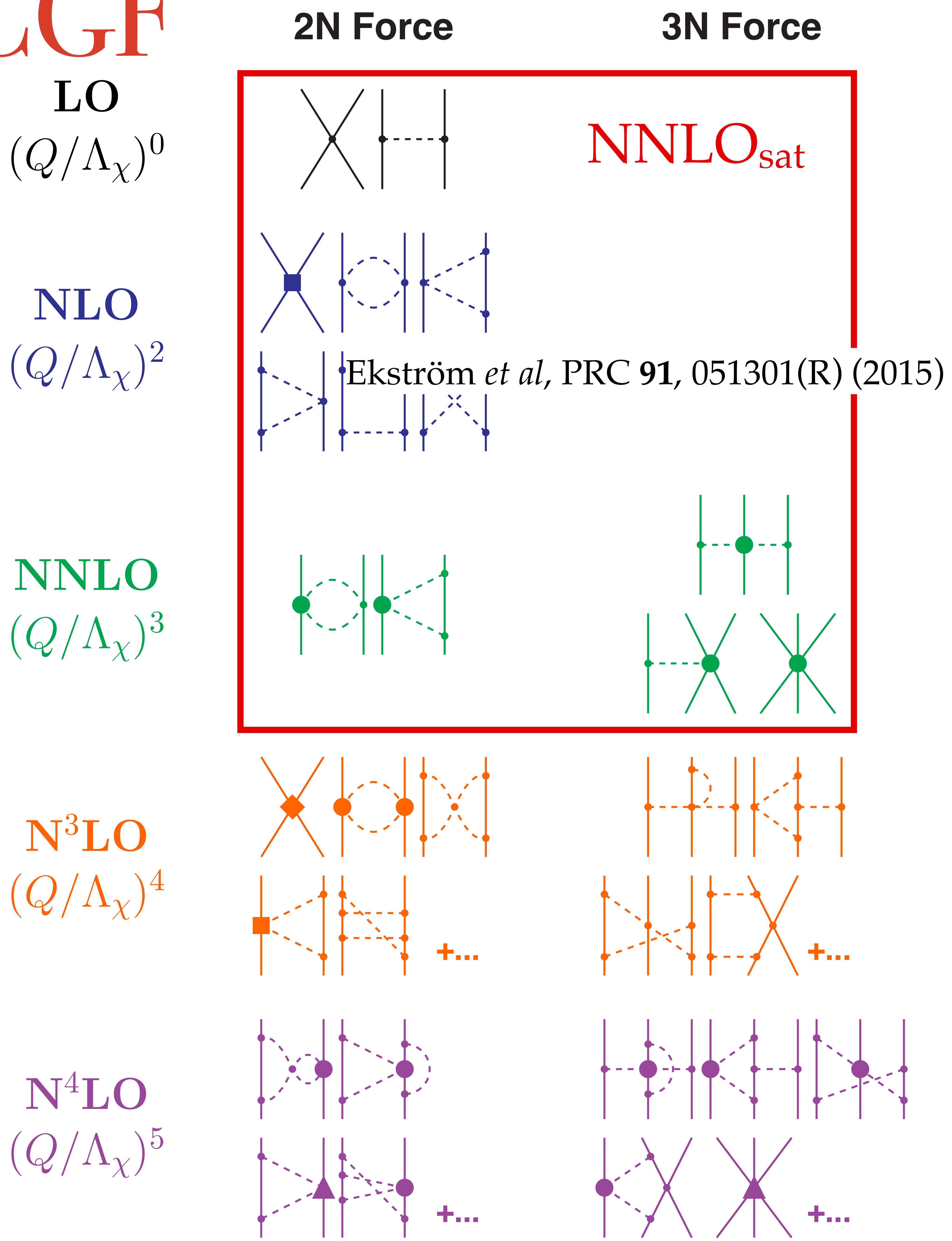
Self Consistent Green's Function (**SCGF**)

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

Somà, Frontiers **8** (2020) 340



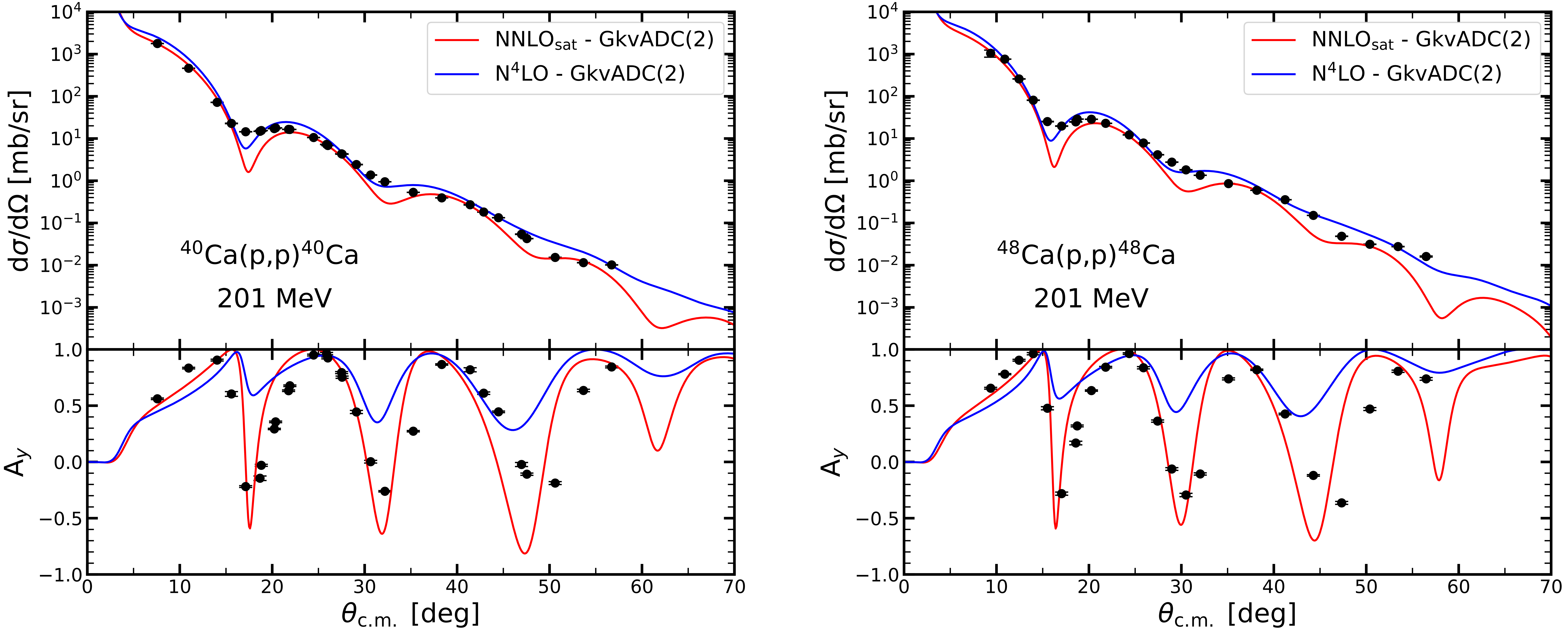
Vorabbi et al., PRL **125**, 182501 (2020)



Ekström *et al*, PRC **91**, 051301(R) (2015)

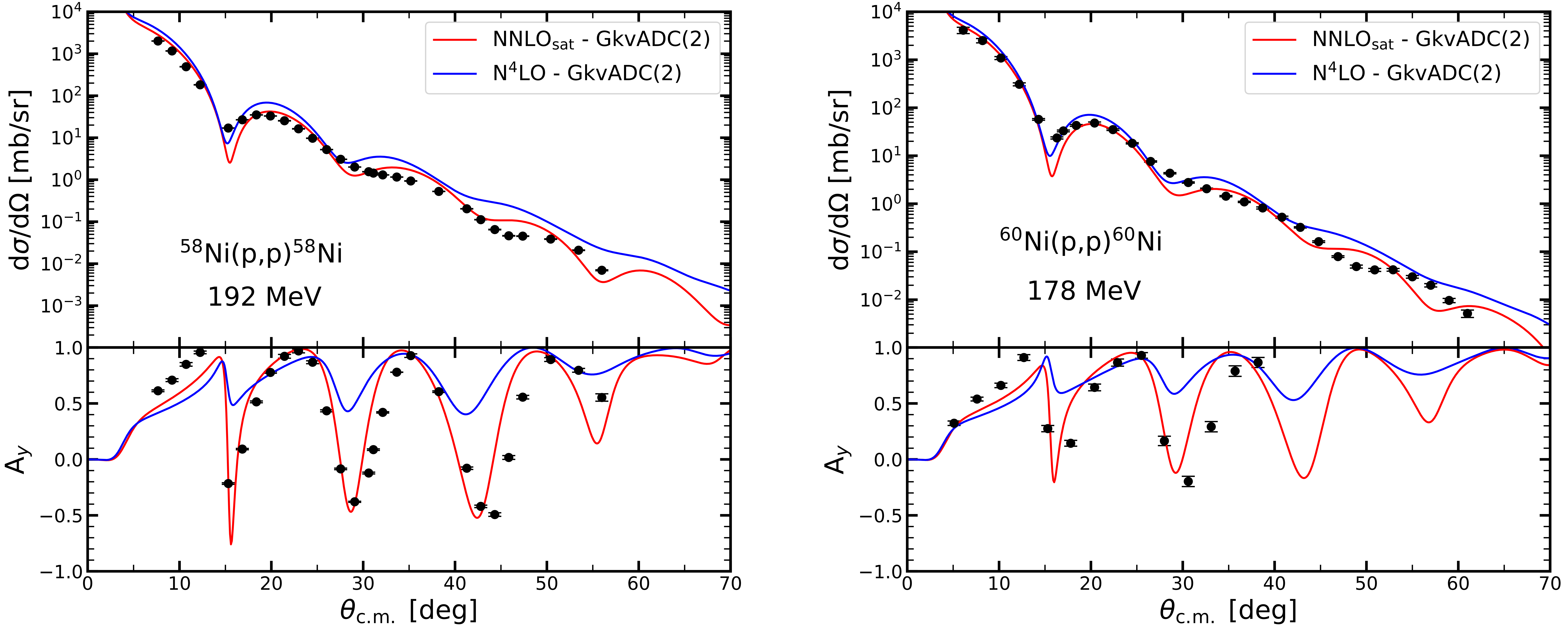
Results for proton scattering off ^{40,48}Ca

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



- First microscopic OP calculations for calcium and nickel from *ab initio* densities
- Densities are always computed with the NNLO$_{sat}$

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

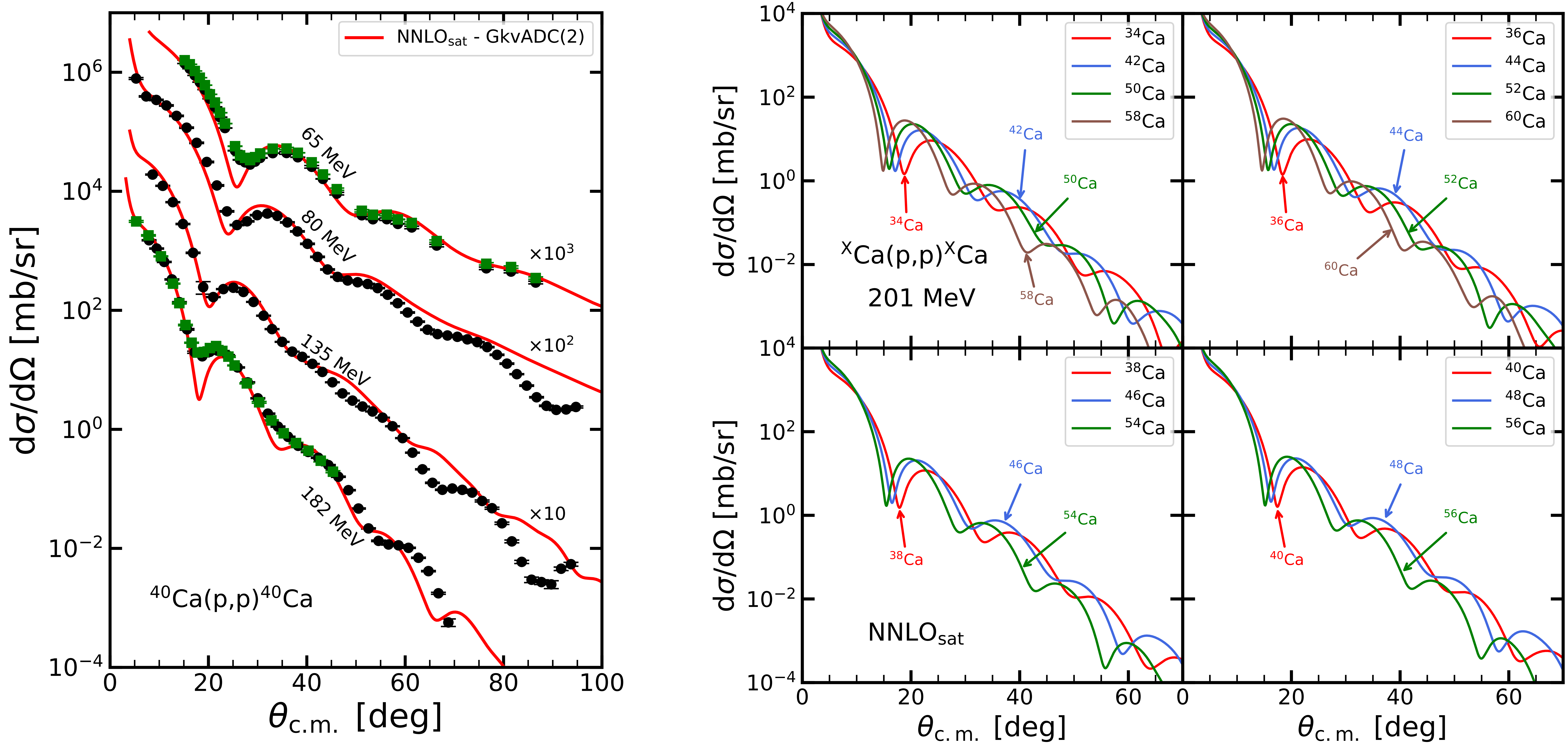


The data for the analysing power are remarkably well described

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

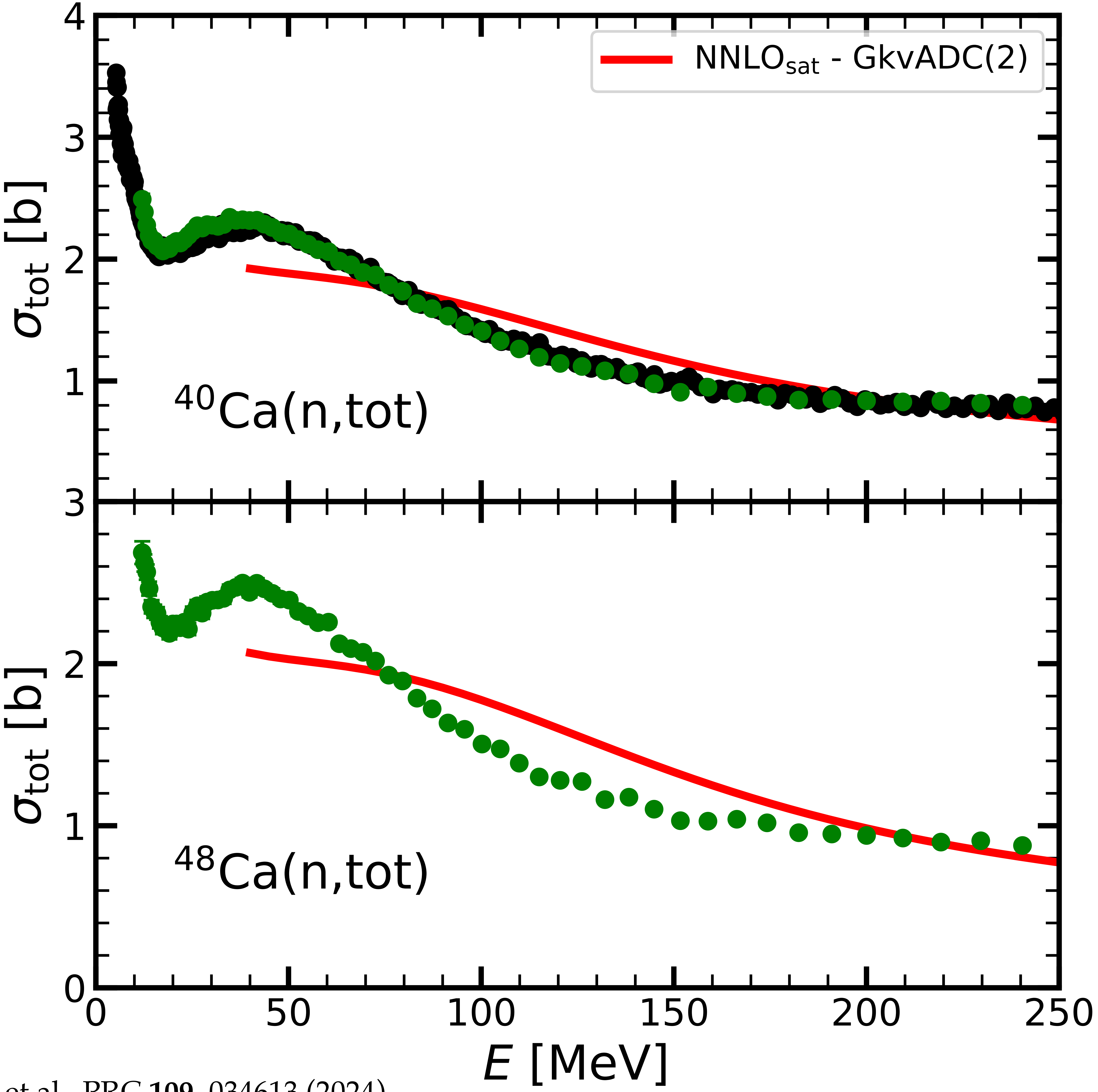
Results for Calcium isotopic chain

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



Total cross sections

- At high energies, 180-250 MeV, our approach is able to describe the data
- The adopted impulse approximation gradually worsens as the energy decreases, without any abrupt divergence
- In the range 70-180 MeV, data are overestimated
- Below 70 MeV, the impulse approximation is questionable



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

Application of MST to inelastic scattering

The inelastic transition amplitude

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

Distorted waves

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

General expression of the potential

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

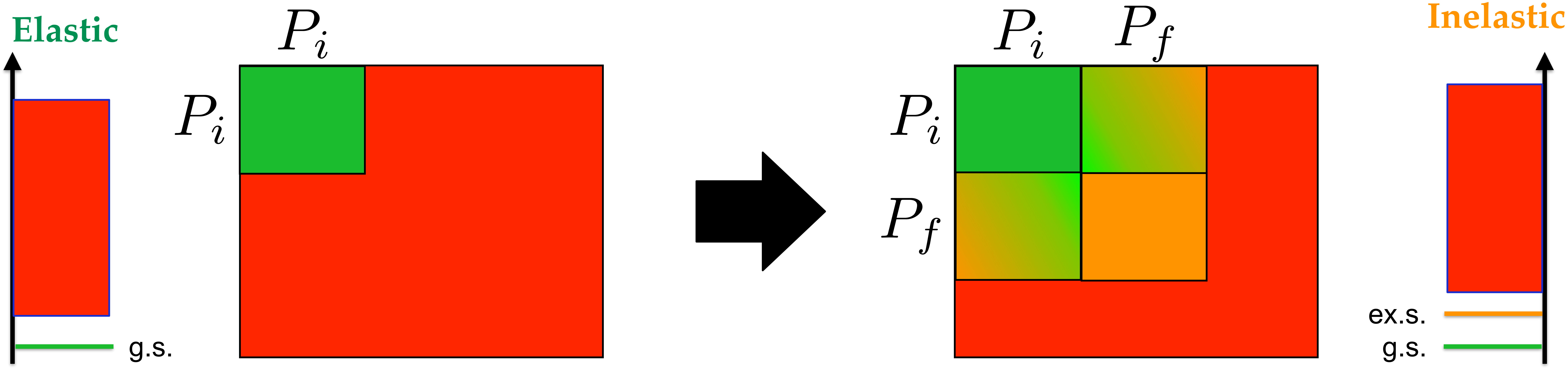
- U still defined within multiple scattering theory
- Impulse approximation
- New projection operators to obtain **OP** components

Application of MST to 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

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

for the initial distorted wave

for the final distorted wave

Application of MST to inelastic scattering

The inelastic transition amplitude

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

Required potentials

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

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

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

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

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

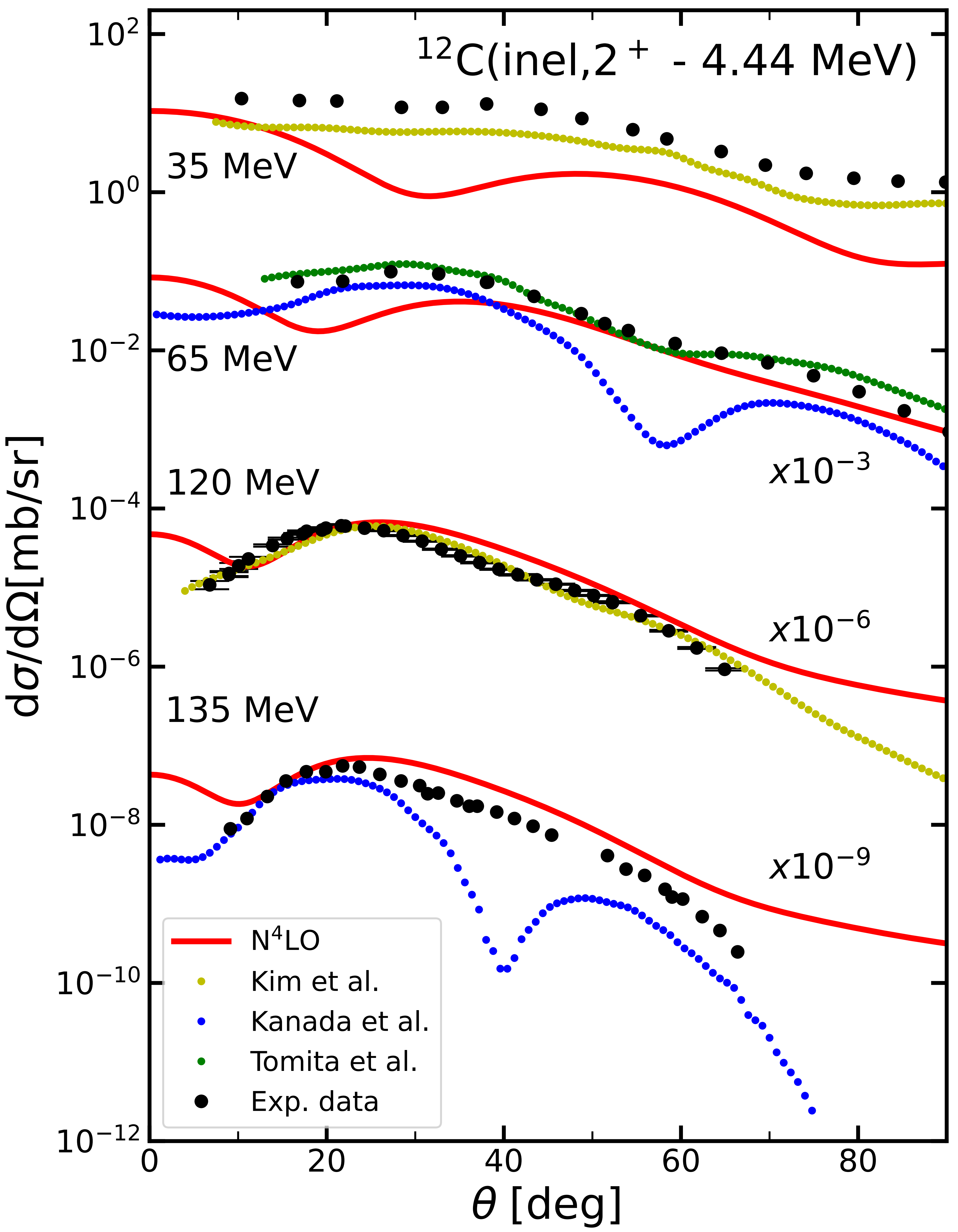
Inelastic scattering: first results

Vorabbi et al., submission to PRC (2025)

- The general shape of the data is reproduced
- The NN t matrix adopted for the calculation of the 3 potentials contains only two terms so far

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

- No adjustments, no free parameters
- Large angles behaviour needs improvement



Theoretical B(E2; $0^+ \to 2^+$) = 35.2987 e^2 fm^4
Experimental B(E2; $0^+ \to 2^+$) = 39.7(33) e^2 fm^4

Inelastic scattering: first results

Vorabbi et al., submission to PRC (2025)

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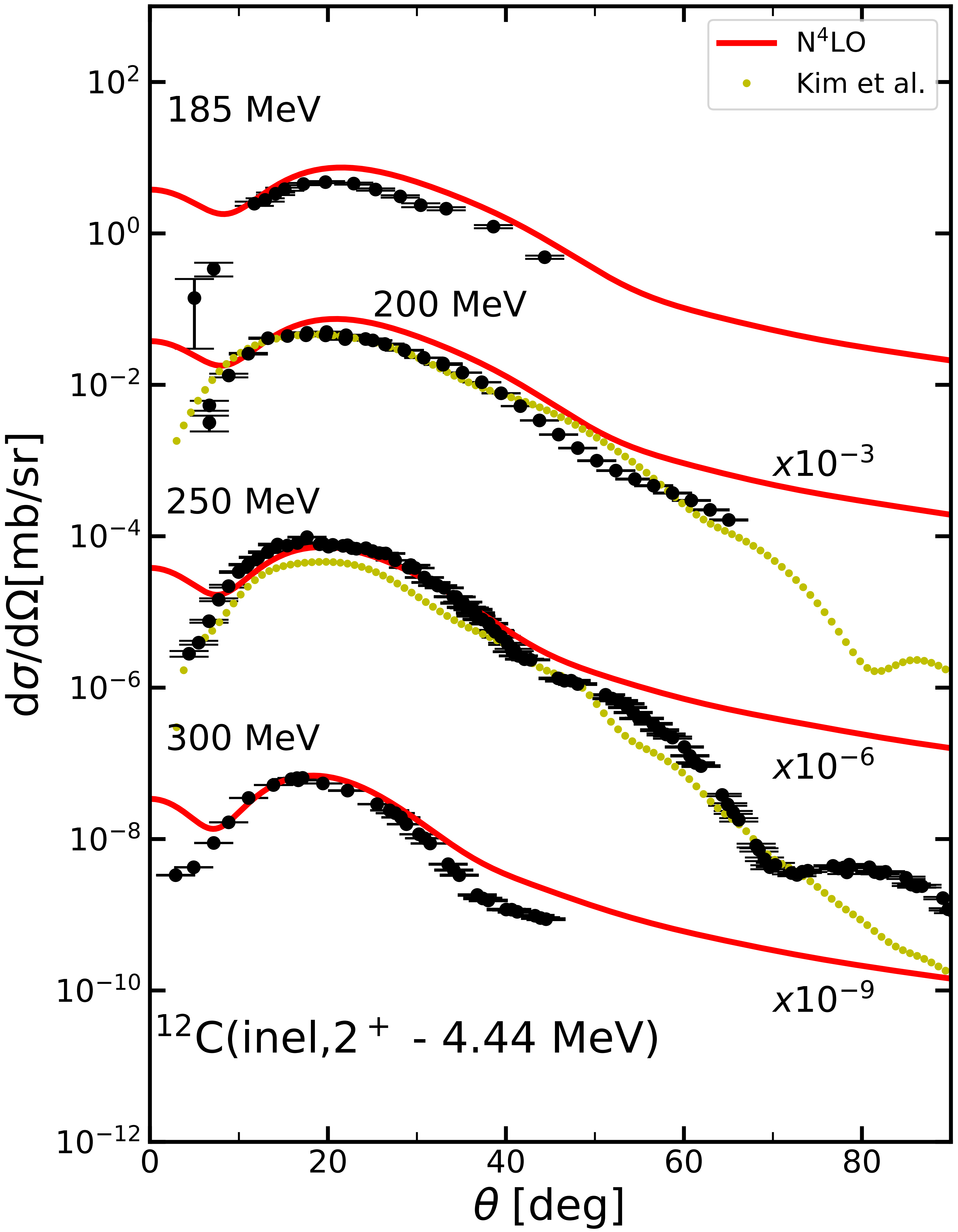


Theoretical B(E2; 0^+ -> 2^+) = 35.2987 e^2 fm^4

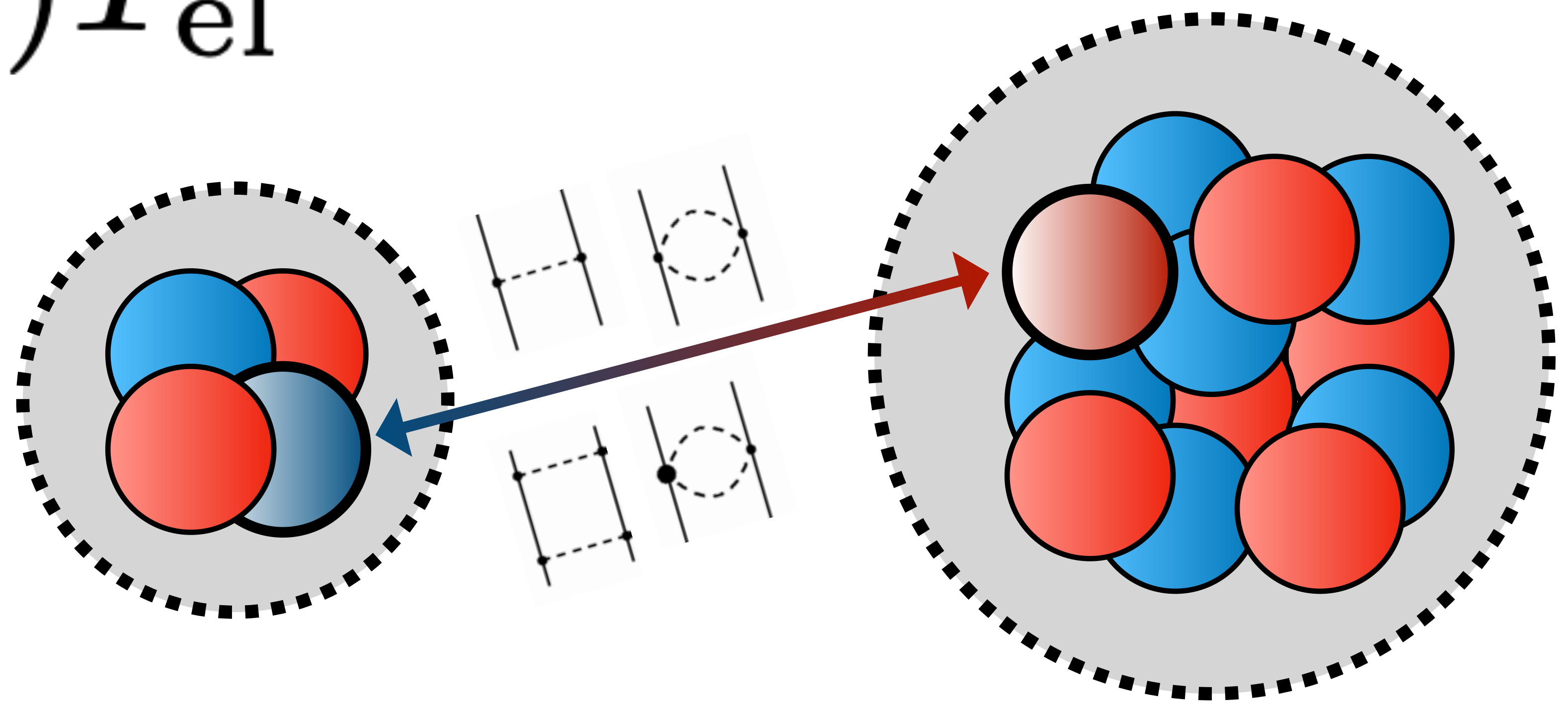
Experimental B(E2; 0^+ -> 2^+) = 39.7(33) e^2 fm^4

OP for nucleus-nucleus elastic scattering

Transition amplitude for elastic scattering

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

The spectator expansion



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

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

$$\tau_{ij} \approx t_{ij} = v_{ij} + v_{ij}\, g_0(E)\, t_{ij}$$

Impulse approximation

Two-body propagator

Vorabbi et al., accepted in PRL (2025)

First-order OP for nucleus-nucleus elastic scattering

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

Projectile density

Target density

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

Free two-body scattering matrix

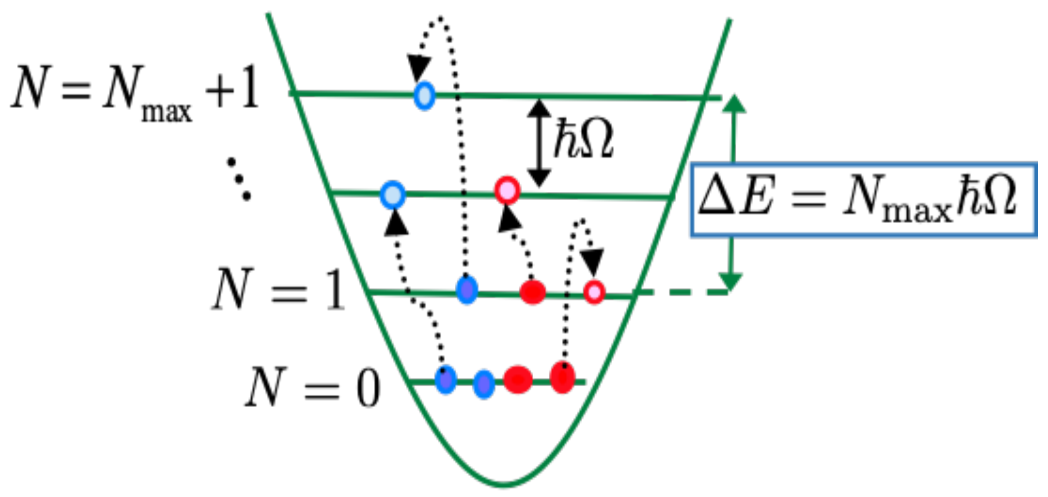
$$t_{0i} = v_{0i} + v_{0i}\, g_{0i}\, t_{0i}$$

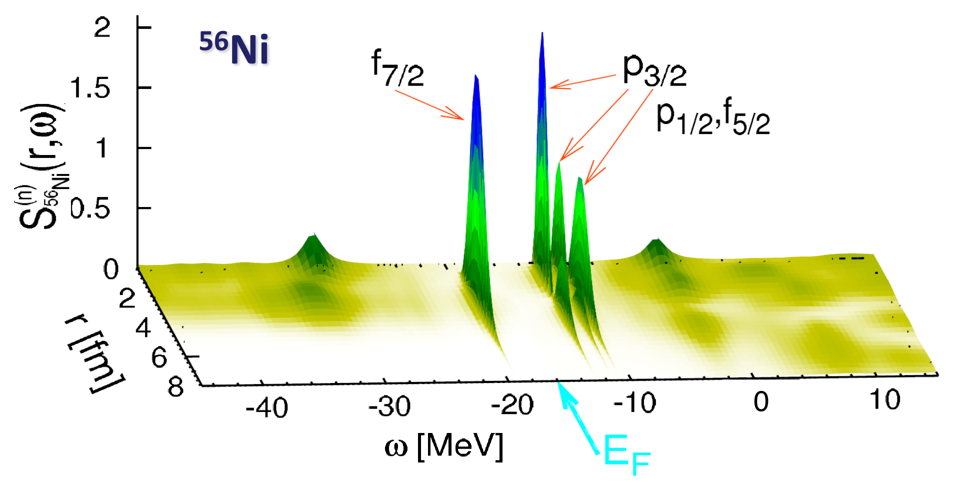
$$g_{0i} = (E - h_0 - h_i + i\epsilon)^{-1}$$

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

Nonlocal one-body density

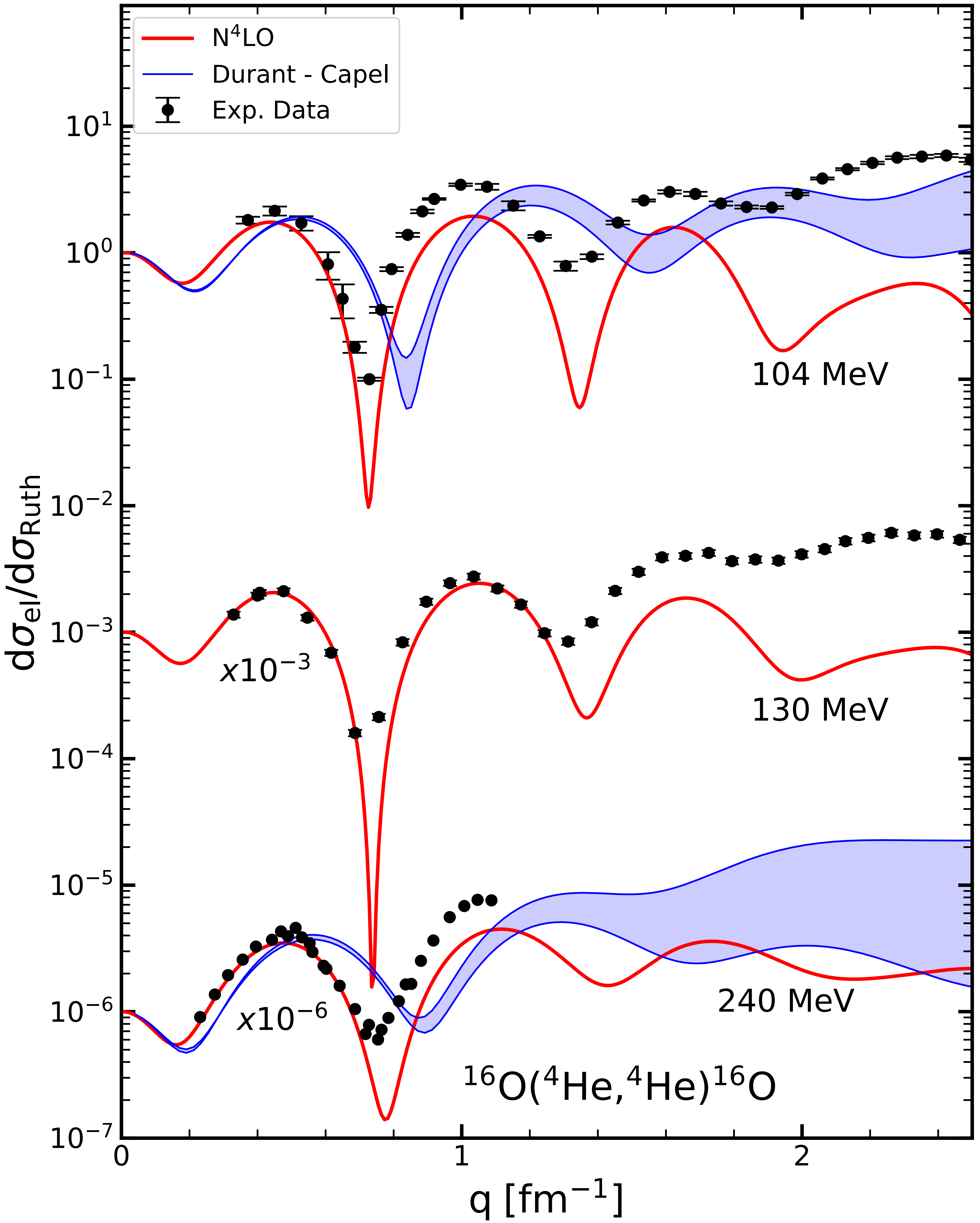
- Computationally expensive
- Obtained from the No-Core Shell Model or the Self-Consistent Green's Function
- Calculation performed with **NN** and **3N** interaction





Elastic ^{4}He-^{16}O scattering

- Parameter-free predictions
- Nice reproduction of experimental data at low-momentum transfer ($q \lesssim 1\ fm^{-1}$)
- Underestimates the high q behaviour, too much absorption?
- Competitive with a chiral microscopic *inspired* model by Durant and Capel



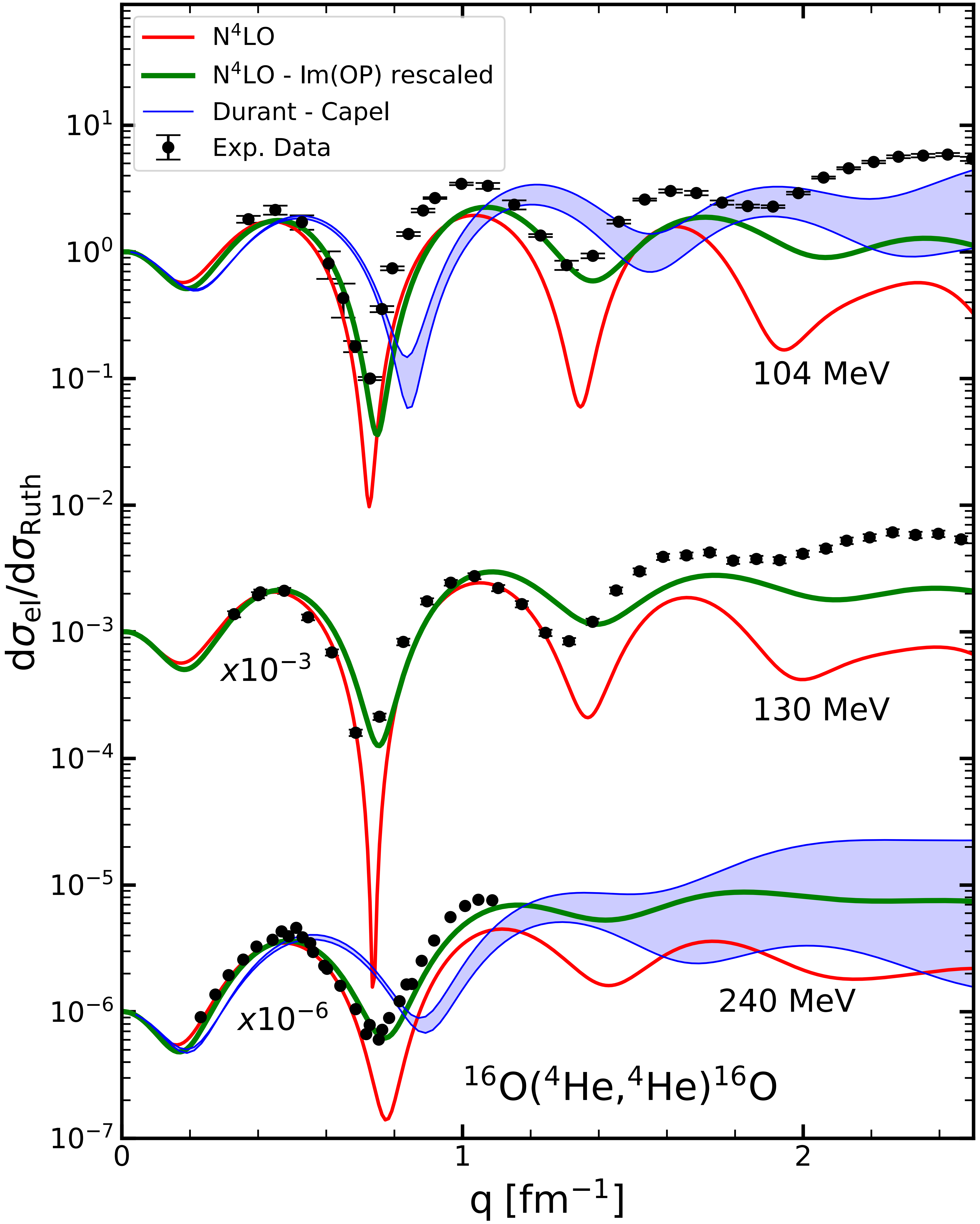
Vorabbi et al., accepted in PRL (2025)

Elastic ^{4}He-^{16}O scattering

How to solve the high-*q* behaviour? Very likely the introduction of higher-order effects would help

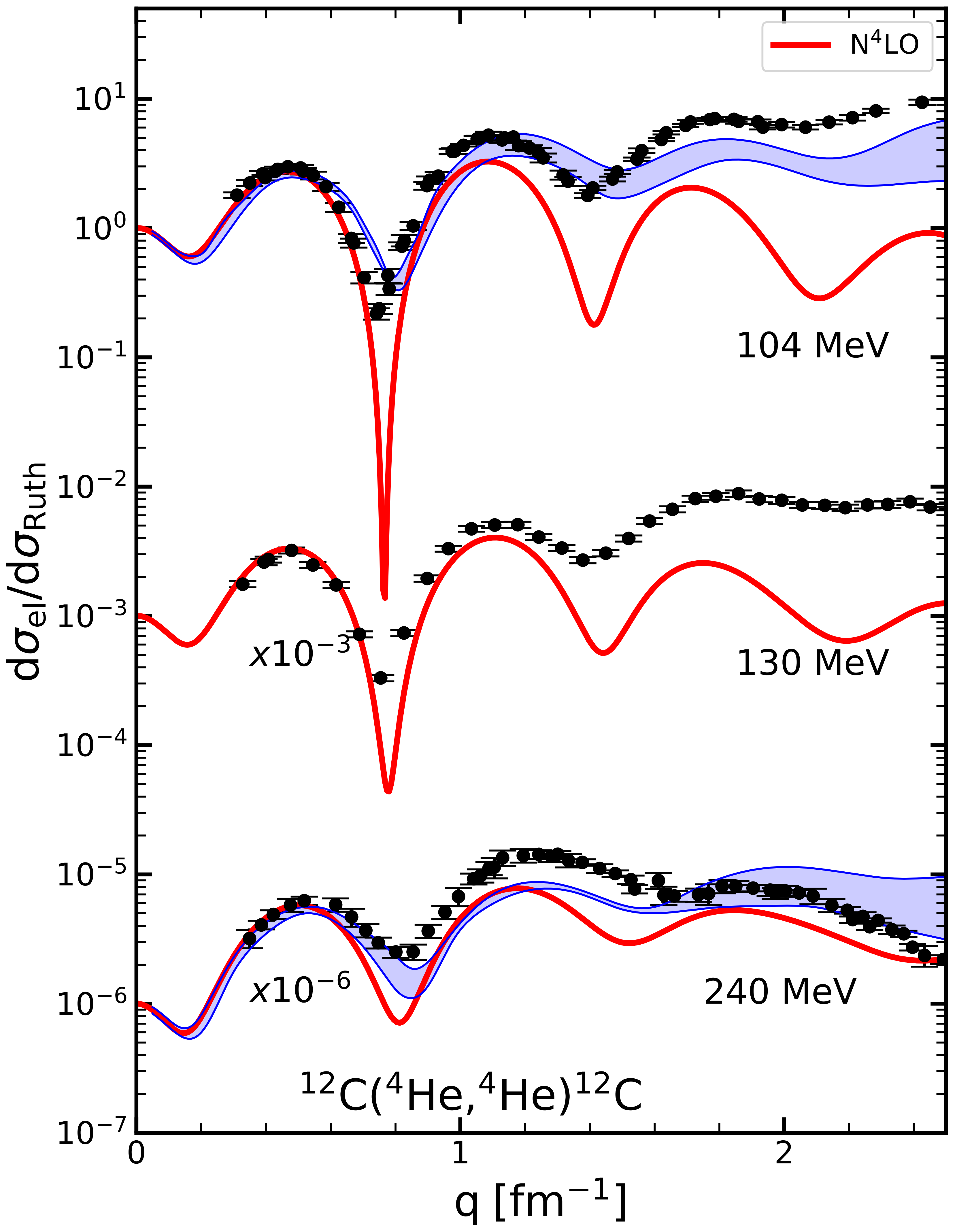
In the meantime, inspired by phenomenological optical potentials, we can reduce by hand the imaginary part

A guess in the range of 0.5/0.6 could be tested. We have chosen 0.5 (**green line**). The agreement is nicely improved.

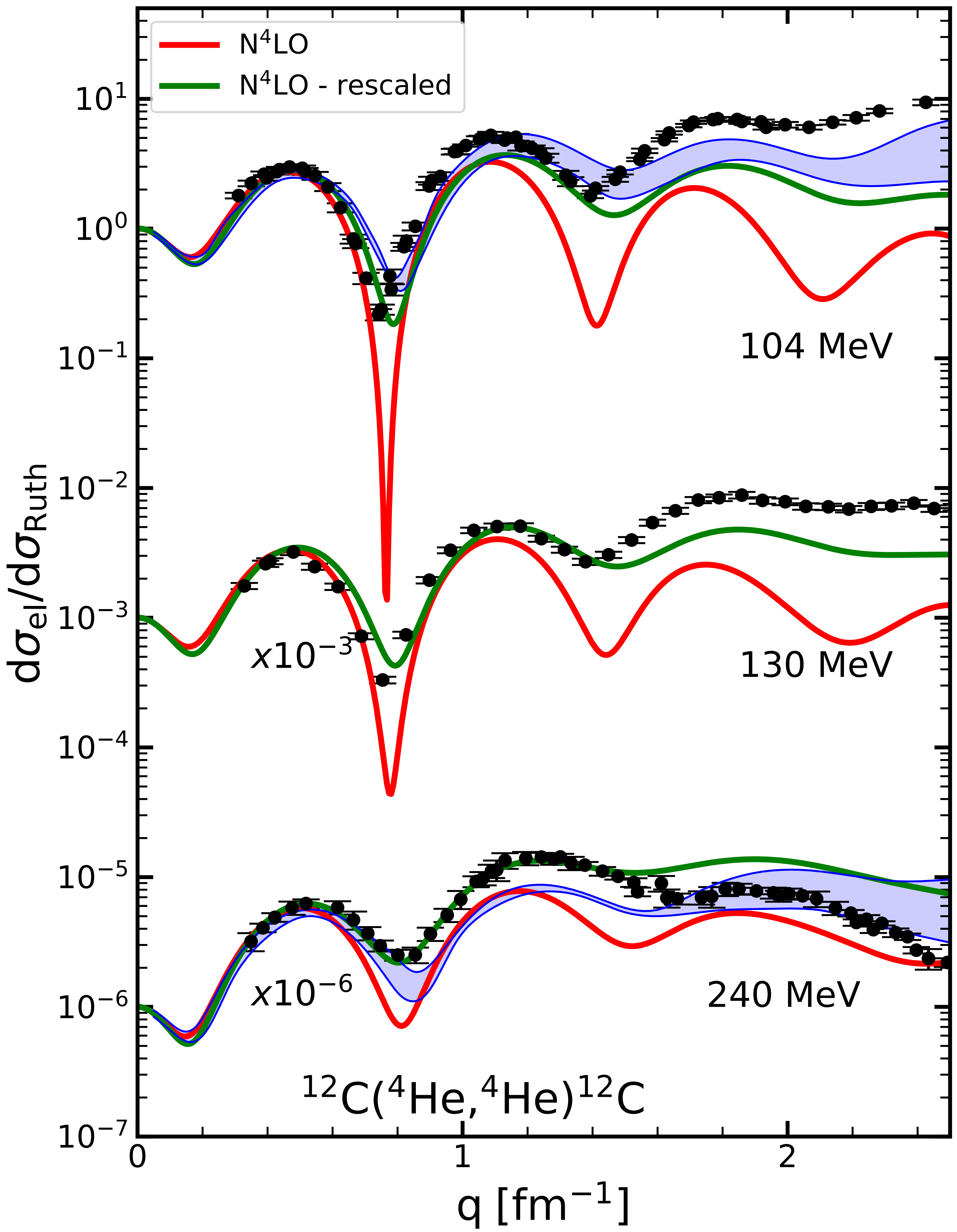


Vorabbi et al., accepted in PRL (2025)

Elastic ^{4}He-^{12}C scattering



- Same behaviour as in the oxygen case.
- A highly non-trivial fact is the quality of agreement along different energies without any other corrections aside the absoprtion reduction.



Vorabbi et al., accepted in PRL (2025)

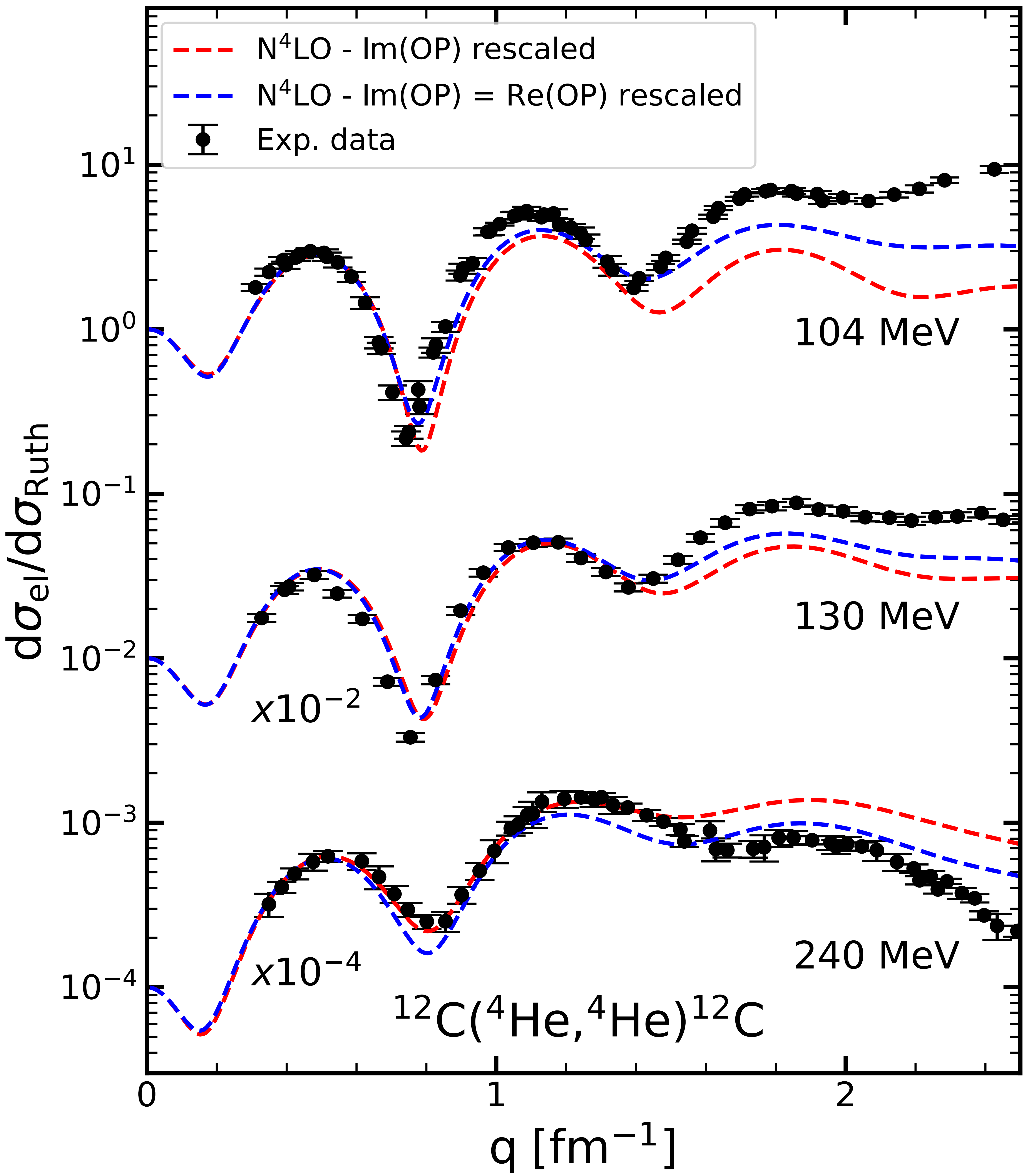
Elastic ^{4}He-^{12}C scattering

It is interesting to study a connection between phenomenology and theoretically inspired approaches.

We tested the usual adopted convention that the imaginary component of the optical potential could be taken as follows

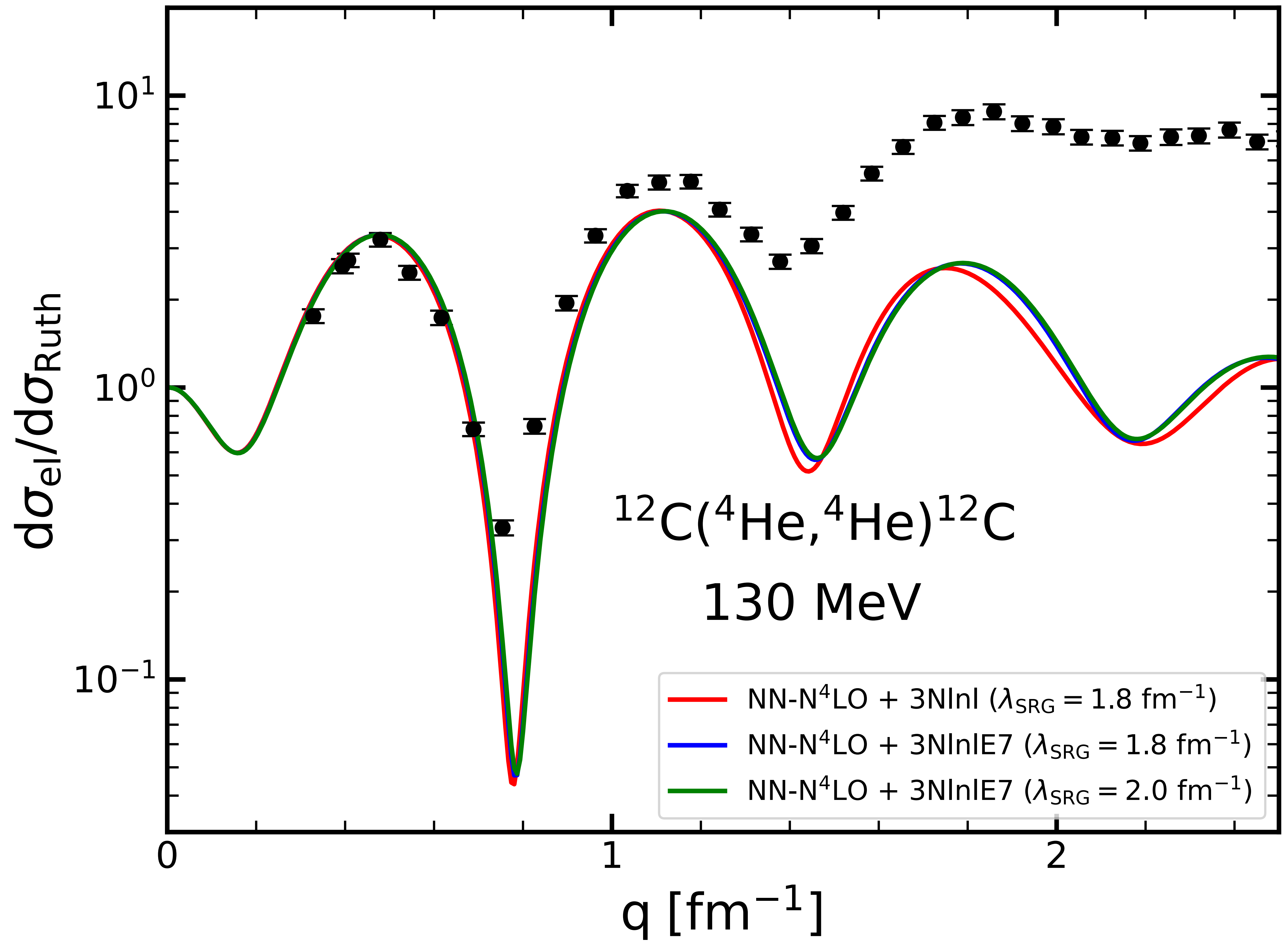
$$Im\, \mathrm{U}_{\mathrm{opt}} = 1/2\, Re\, \mathrm{U}_{\mathrm{opt}}$$

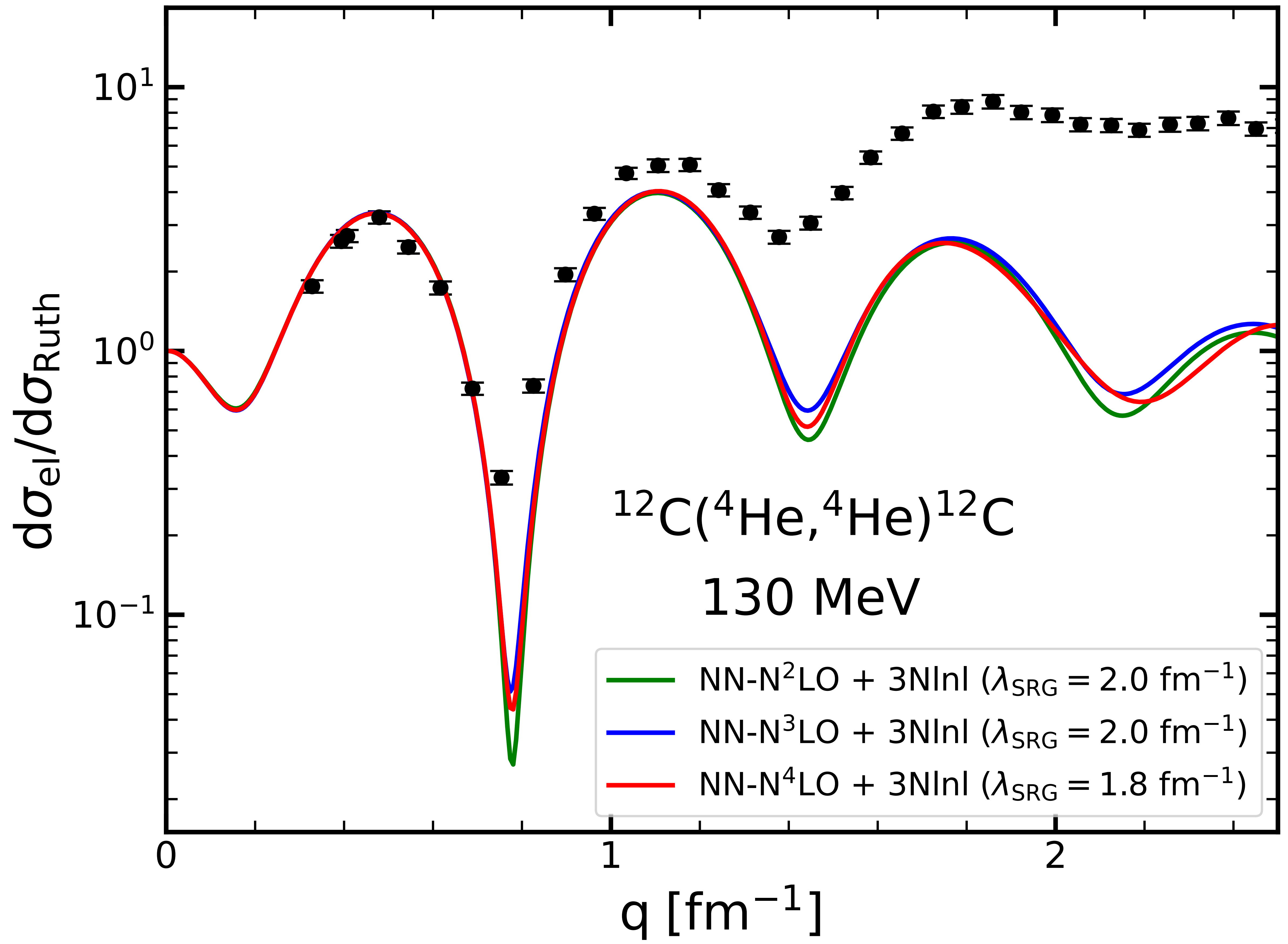
meaning that from a phenomenogical point of view they have the same functional dependence. <u>We conferm the prescription from a microscopic approach</u>.



Vorabbi et al., accepted in PRL (2025)

Nucleus-nucleus scattering: NN sensitivity





Vorabbi et al., accepted in PRL (2025)

Conclusions

- ☑ Achieved a satisfactory description of nucleon **elastic** scattering of light and medium-mass nuclei at the first order of the spectator expansion
- ☑ Extension of the model to nucleon-nucleus **inelastic** scattering
- ☑ Achieved a first step in the derivation of a **nucleus-nucleus** optical potential

- ☐ Inclusion of medium effects/higher order effects (soon, end of 2025)
- ☐ 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
- ☐ **Extend the formalism to transfer/charge-exchange** (long term goal)