MICROSCOPIC OPTICAL POTENTIAL FOR ELASTIC PROTON- AND ANTIPROTON-NUCLEUS SCATTERING FROM CHIRAL FORCES

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TNPI2019 Theoretical Nuclear Physics in Italy, Cortona 9-11 October 2019

OPTICAL POTENTIAL

The OP provides a suitable framework to describe elastic nucleon-nucleus scattering

Its use can be extended to inelastic scattering and to calculate the cross section of a wide variety of nuclear reactions

In our models for QE electron and neutrino-nucleus scattering the OP describes FSI between the emitted nucleon and the residual nucleus

OPTICAL POTENTIAL

PHENOMENOLOGICAL: assume a form and a dependence on a number of adjustable parameters for the real and imaginary parts that characterize the shape of the nuclear density distribution and that vary with the nuclear energy and the nucleus mass number.

Parameters obtained through a fit to pA elastic scattering data

OPTICAL POTENTIAL

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Parameters obtained through a fit to pA elastic scattering data

THEORETICAL: microscopic calculations require the solution of the full many-body nuclear problem. Some approximations are needed.

We do not expect better description of experimental data (at least for data in the database used to generate phen. OP) but greater predictive power when applied to situations where exp. data not available

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)

Theoretical optical potential derived from nucleon-nucleon chiral potentials

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)

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PHYSICAL REVIEW VOLUME 89, NUMBER 3 FEBRUARY 1, 1953

Multiple Scattering and the Many-Body Problem—Applications to Photomeson Production in Complex Nuclei*

KENNETH M. WATSON
Physics Department, Indiana University, Bloomington, Indiana
(Received October 1, 1952)

The Scattering of Fast Nucleons from Nuclei

A. K. Kerman
Massachusetts Institute of Technology, Cambridge, Massachusetts

H. McManus
Chalk River Laboratory, Chalk River, Ontario, Canada

and

R. M. Thaler
Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received May 27, 1959

PHYSICAL REVIEW VOLUME 92, NUMBER 2 OCTOBER 15, 1953

The Elastic Scattering of Particles by Atomic Nuclei*

N. C. FRANCIS AND K. M. WATSON†
Department of Physics, Indiana University, Bloomington, Indiana
(Received June 1, 1953)

M. Vorabbi, P. Finelli, C. Giusti,   PRC 93 034619 (2016)

Theoretical optical potential derived from nucleon-nucleon chiral potentials

Purpose: study the domain of applicability of microscopic chiral potentials to the construction of an OP

Theoretical framework for pA elastic scattering

We start from the full (A+1) body LS equation

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

Separation into two coupled integral equations

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

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

T transition op. for elastic scattering,

U OP

Free propagator

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

Projection operators

$$P + Q = 1$$

Free Hamiltonian

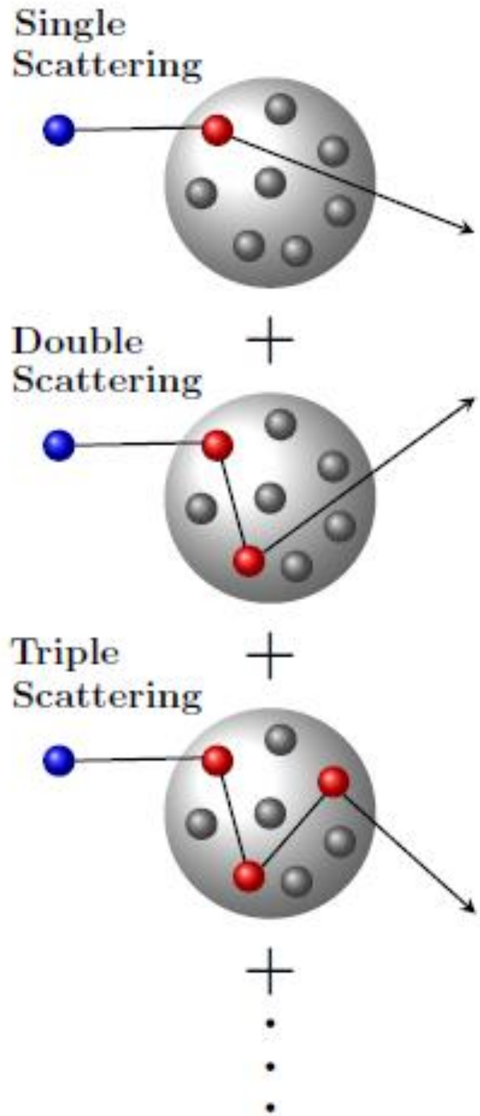
$$H_0 = h_0 + H_A$$

External interaction

$$V = \sum_{i=1}^{A} v_{0i}$$

The spectator expansion

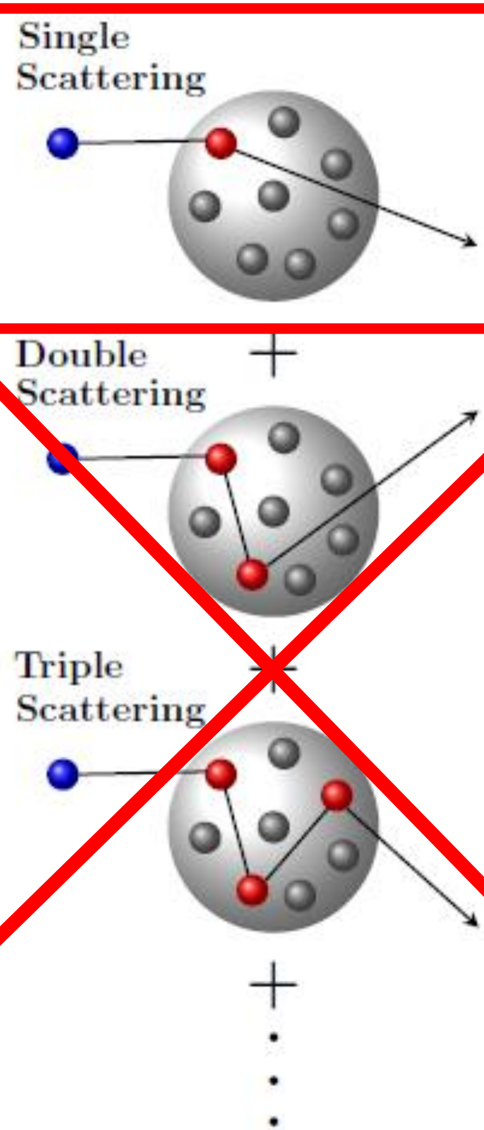
Consistent framework to calculate U and T



$$U = \sum_{i=1}^{A} \tau_i + \sum_{i,j\neq i}^{A} \tau_{ij} + \sum_{i,j\neq i,k\neq i,j}^{A} \tau_{ijk} + \cdots$$

The spectator expansion

Consistent framework to calculate U and T



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The spectator expansion

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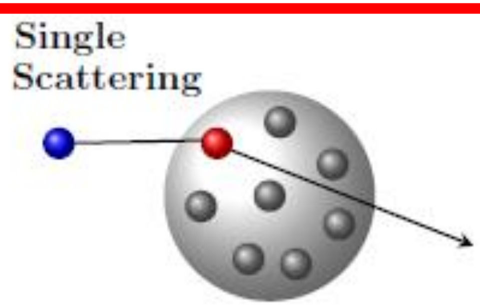

$$U = \sum_{i=1}^{A} \tau_i$$

$$\tau_i = v_{0i} + v_{0i} G_0(E) Q \tau_i$$

Impulse Approximation

$$\tau_i \approx t_{0i}$$

The free NN t matrix

$$t_{0i} = v_{0i} + v_{0i} g_i t_{0i}$$

The free two-body propagator

$$g_i = \frac{1}{E - h_0 - h_i + i\epsilon}$$

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

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The free two-body propagator

$$g_i = \frac{1}{E - h_0 - h_i + i\epsilon}$$

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

We have to solve only 2-body equations

Optimum Factorization Approximation

$$U(\boldsymbol{q},\boldsymbol{K};\omega) = \frac{A-1}{A}\,\eta(\boldsymbol{q},\boldsymbol{K}) \sum_{N=n,p} t_{pN}\left[q, \frac{A+1}{A}\boldsymbol{K};\omega\right] \rho_N(q)$$

NN t-matrix
NN interaction

n, p densities

$$\boldsymbol{q}=\boldsymbol{k}'-\boldsymbol{k} \qquad \boldsymbol{K}=\tfrac{1}{2}(\boldsymbol{k}'+\boldsymbol{k})$$

Optimum Factorization Approximation

$$U(\boldsymbol{q}, \boldsymbol{K}; \omega) = \frac{A-1}{A} \eta(\boldsymbol{q}, \boldsymbol{K}) \sum_{N=n,p} t_{pN} \left[\boldsymbol{q}, \frac{A+1}{A} \boldsymbol{K}; \omega \right] \rho_N(q)$$

Moeller factor
imposes the Lorentz invariance of the flux when passing from the NA to the NN frame in which the t matrices are evaluated

$$U(q,K;\omega) = U^c(q,K;\omega) + \frac{i}{2}\sigma \cdot q \times K\, U^{ls}(q,K;\omega)$$

central spin-orbit

$$U^c(q,K;\omega) = \frac{A-1}{A}\,\eta(q,K) \sum_{N=n,p} t^c_{pN}\left[q, \frac{A+1}{A}K;\omega\right] \rho_N(q)$$

$$U^{ls}(q,K;\omega) = \frac{A-1}{A}\,\eta(q,K)\,\frac{A+1}{2A} \sum_{N=n,p} t^{ls}_{pN}\left[q, \frac{A+1}{A}K;\omega\right] \rho_N(q)$$

$$U(q, K; \omega) = U^c(q, K; \omega) + \frac{i}{2}\sigma \cdot q \times K\, U^{ls}(q, K; \omega)$$

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NN t-matrix
NN interaction

n, p densities

- n,p densities calculated within the RMF description of spherical nuclei using a DDME model
- NN interaction chiral potentials…

NUCLEAR DENSITY DISTRIBUTION

- RMF using a DDME where the couplings between meson and baryon fields are functions of the density

DDME1 T. Nikšić, D. Vretenar, P. Finelli, P. Ring, PRC 66 (2002) 024306

- RMF: nucleus system of Dirac nucleons coupled to the exchange mesons (σ, ω, ρ) and elm fields through an effective Lagrangian, whose parameters adjusted to reproduce NM EOS and global properties of spherical closed-shell nuclei

$$U(q,K;\omega) = U^c(q,K;\omega) + \frac{i}{2}\sigma \cdot q \times K\, U^{ls}(q,K;\omega)$$

central **spin-orbit**

$$U^c(q,K;\omega) = \frac{A-1}{A}\eta(q,K) \sum_{N=n,p} t^c_{pN}\left[q, \frac{A+1}{A}K;\omega\right] \rho_N(q)$$

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NN t-matrix
NN interaction

n, p densities

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CHIRAL POTENTIAL

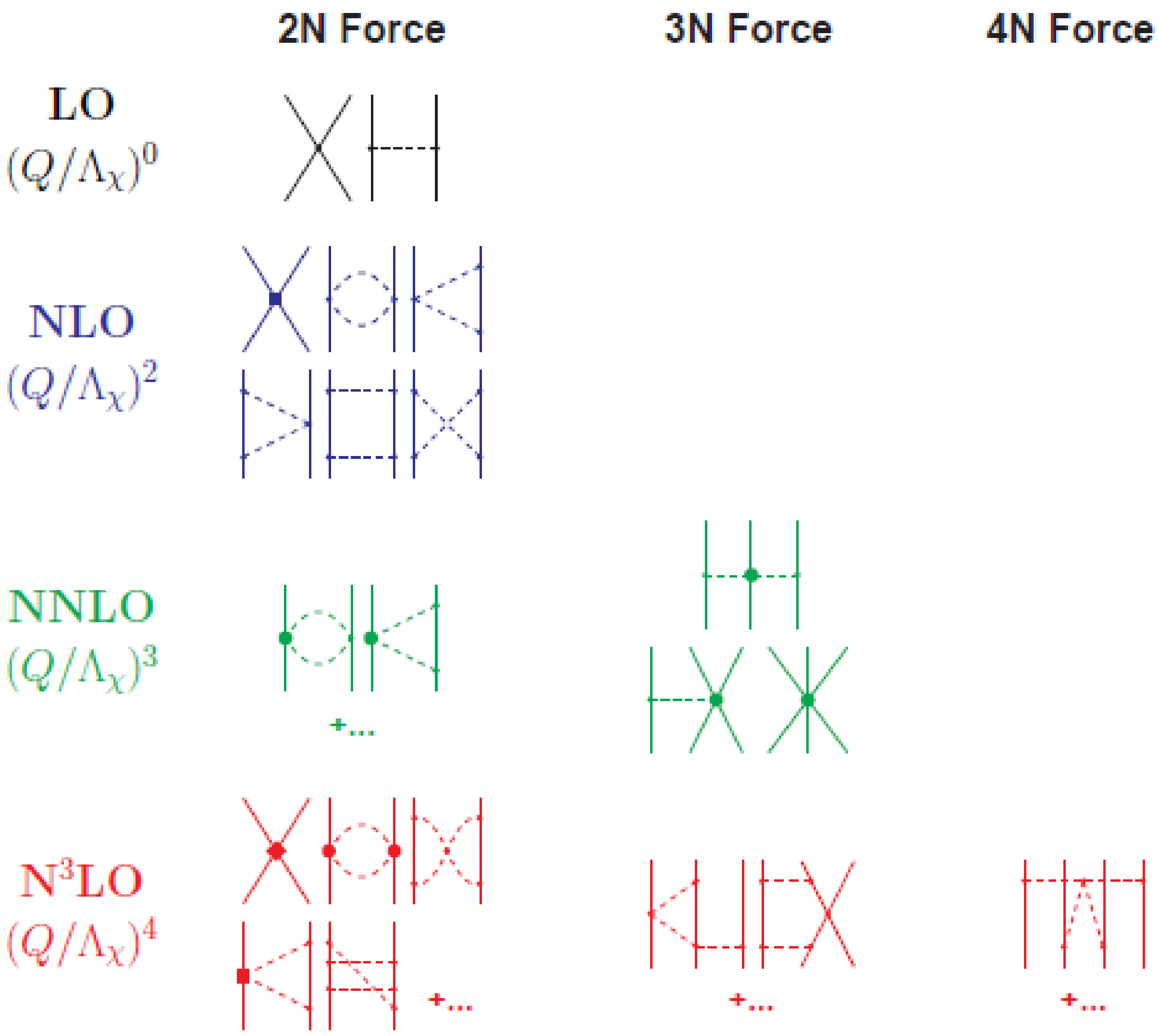
- When the concept of EFT was applied to low-energy QCD, ChPT was developed

- Within ChPT it became possible to implement chiral symmetry consistently in a theory of pionic and nuclear interactions

- The theory is based on a perturbative expansion in powers of $(Q/\Lambda_\chi)^n$ where Q is the magnitude of the three-momentum of the external particles or the pion mass and Λ_χ is the chiral symmetry breaking scale of the chiral EFT

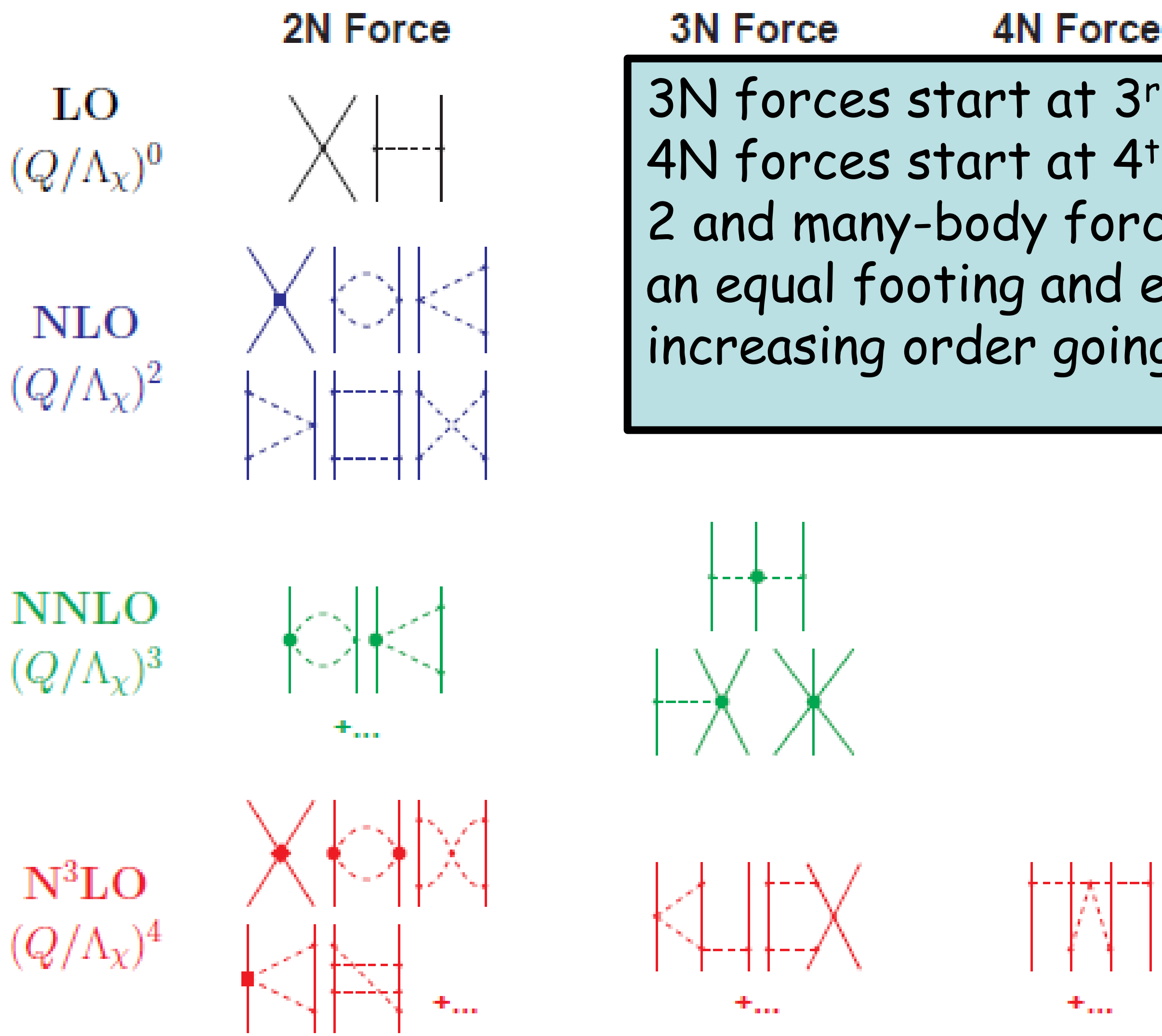
- From the perturbative expansion only a finite number of terms contribute at a given order

CHIRAL POTENTIAL

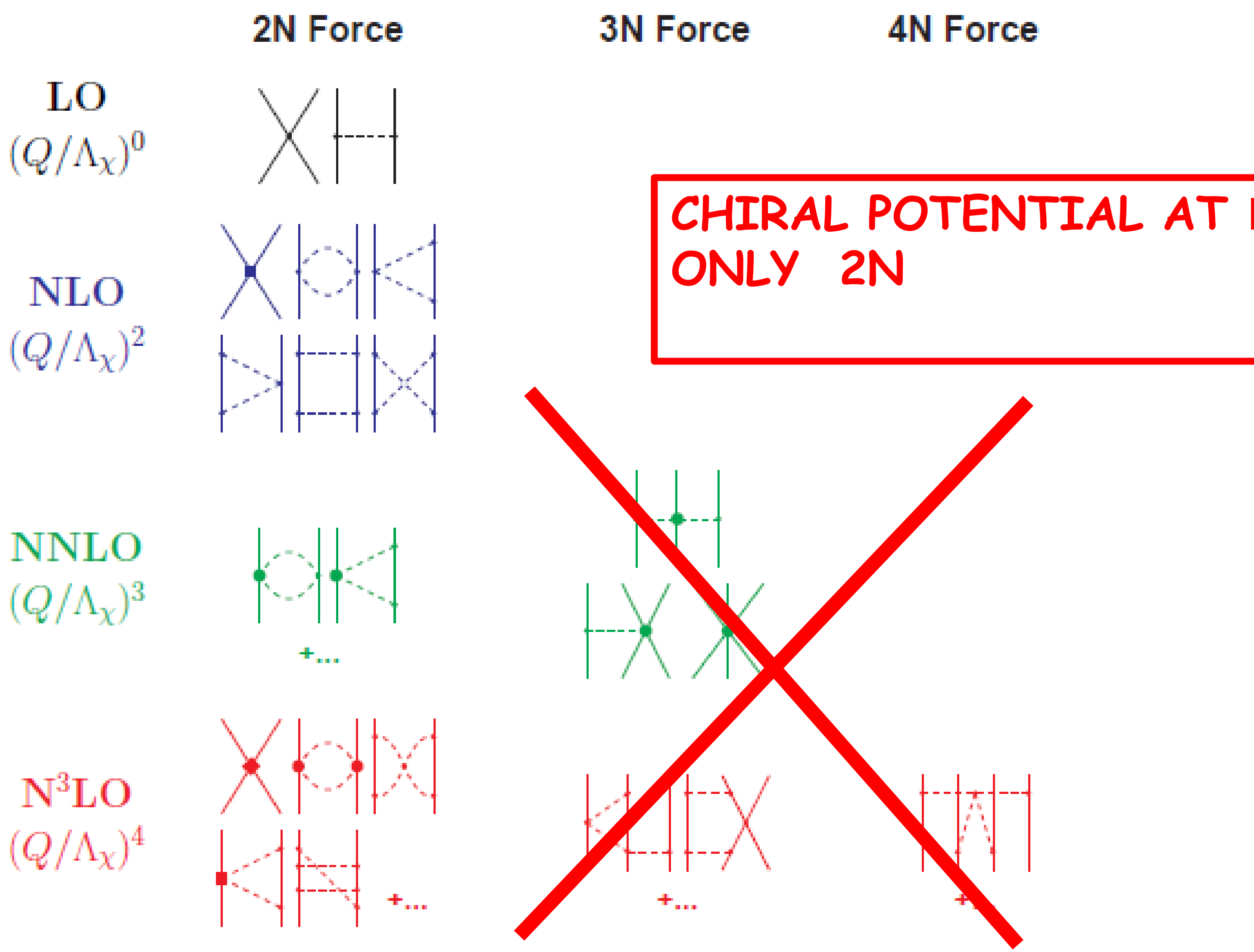


CHIRAL POTENTIAL

3N forces start at 3rd order,
4N forces start at 4th order
2 and many-body forces are created on an equal footing and emerge in increasing order going to higher order



CHIRAL POTENTIAL



CHIRAL POTENTIAL AT N³LO
ONLY 2N

CHIRAL POTENTIAL

Two different versions of chiral potentials at N^3LO
Entem and Machleidt (EM) , Epelbaum et al. (EGM)

In general the integral in the LS eq . is divergent and needs to be regularized

Usual procedure: $$V(k',k) \longmapsto V(k',k)\, e^{-(k'/\Lambda)^{2n}}\, e^{-(k/\Lambda)^{2n}}$$

EM present results with Λ = 450, 500, 600 MeV
EGM present results with Λ = 450, 550, 600 MeV
and treat differently the short-range part of the 2PE contribution, that has an unphysically strong attraction.
EM dimensional regularization
EGM spectral function regularization introduces an additional cutoff $\tilde{\Lambda}$ and give cut-off combinations: (Λ, $\tilde{\Lambda}$) = (450,500), (450,700), (550,600), (600,600), (600,700)

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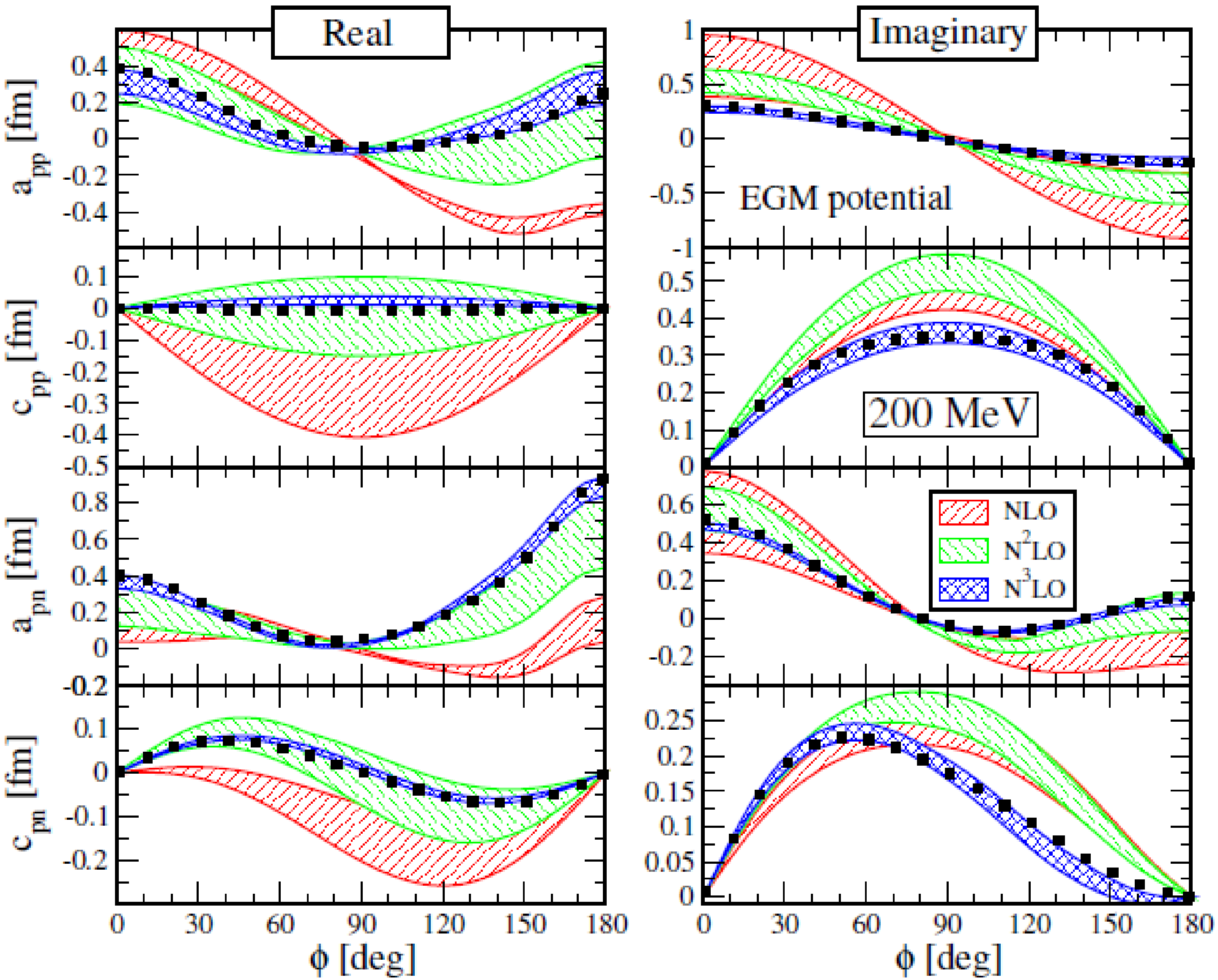
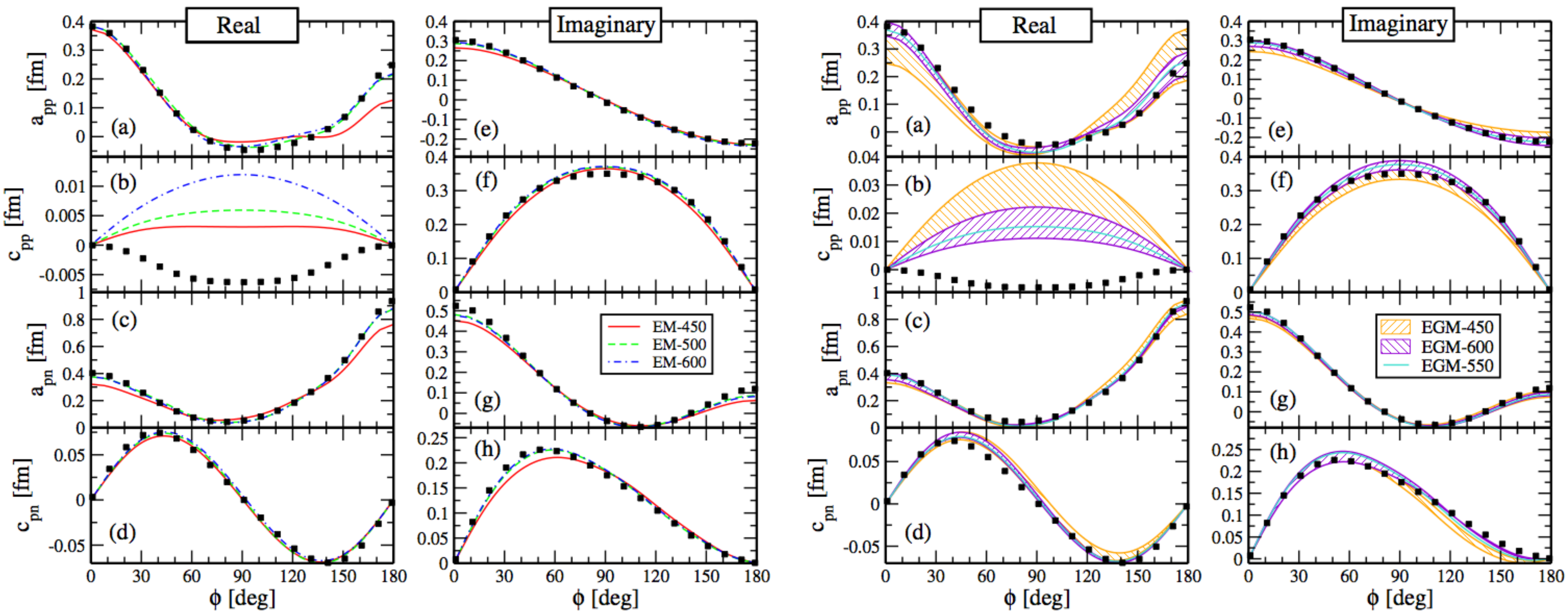
sensitivity to the cutoff parameters
order by order convergence

THE NUCLEON-NUCLEON AMPLITUDES



M. Vorabbi, P. Finelli, and C. Giusti, Phys. Rev. C **93**, 034619 (2016)

NN AMPLITUDES 200 MeV



M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2016)

OP and scattering observables

The most general form of the amplitude for elastic p scattering from a spin 0 nucleus

$$M(k_0, \theta) = A(k_0, \theta) + \boldsymbol{\sigma} \cdot \hat{\mathbf{N}}\, C(k_0, \theta)$$

Scattering observables

$$\frac{d\sigma}{d\Omega}(\theta) = |A(\theta)|^2 + |C(\theta)|^2$$

unpolarized differential cross section

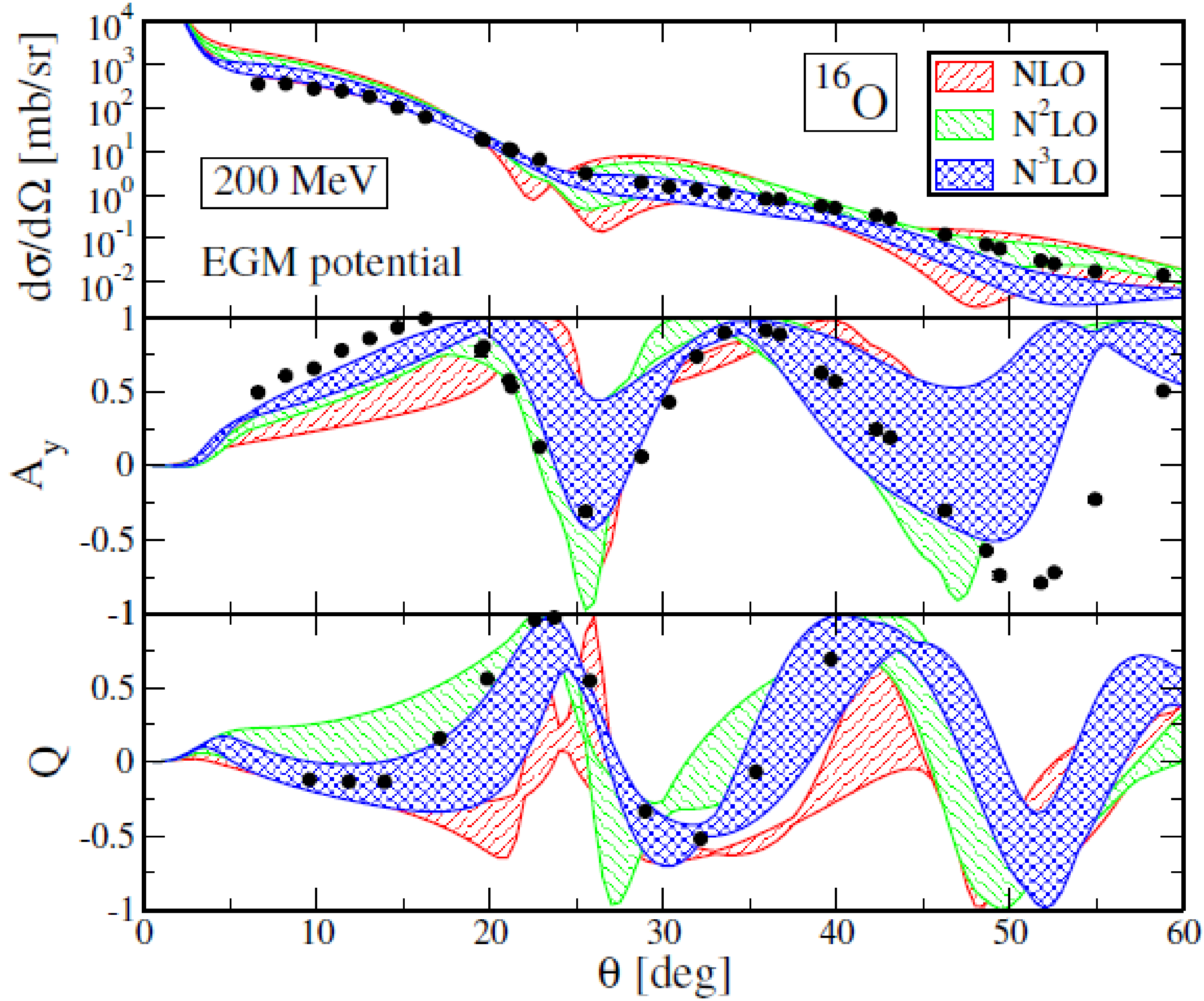
$$A_y(\theta) = \frac{2\mathrm{Re}[A^*(\theta)\, C(\theta)]}{|A(\theta)|^2 + |C(\theta)|^2}$$

analyzing power

$$Q(\theta) = \frac{2\mathrm{Im}[A(\theta)\, C^*(\theta)]}{|A(\theta)|^2 + |C(\theta)|^2}$$

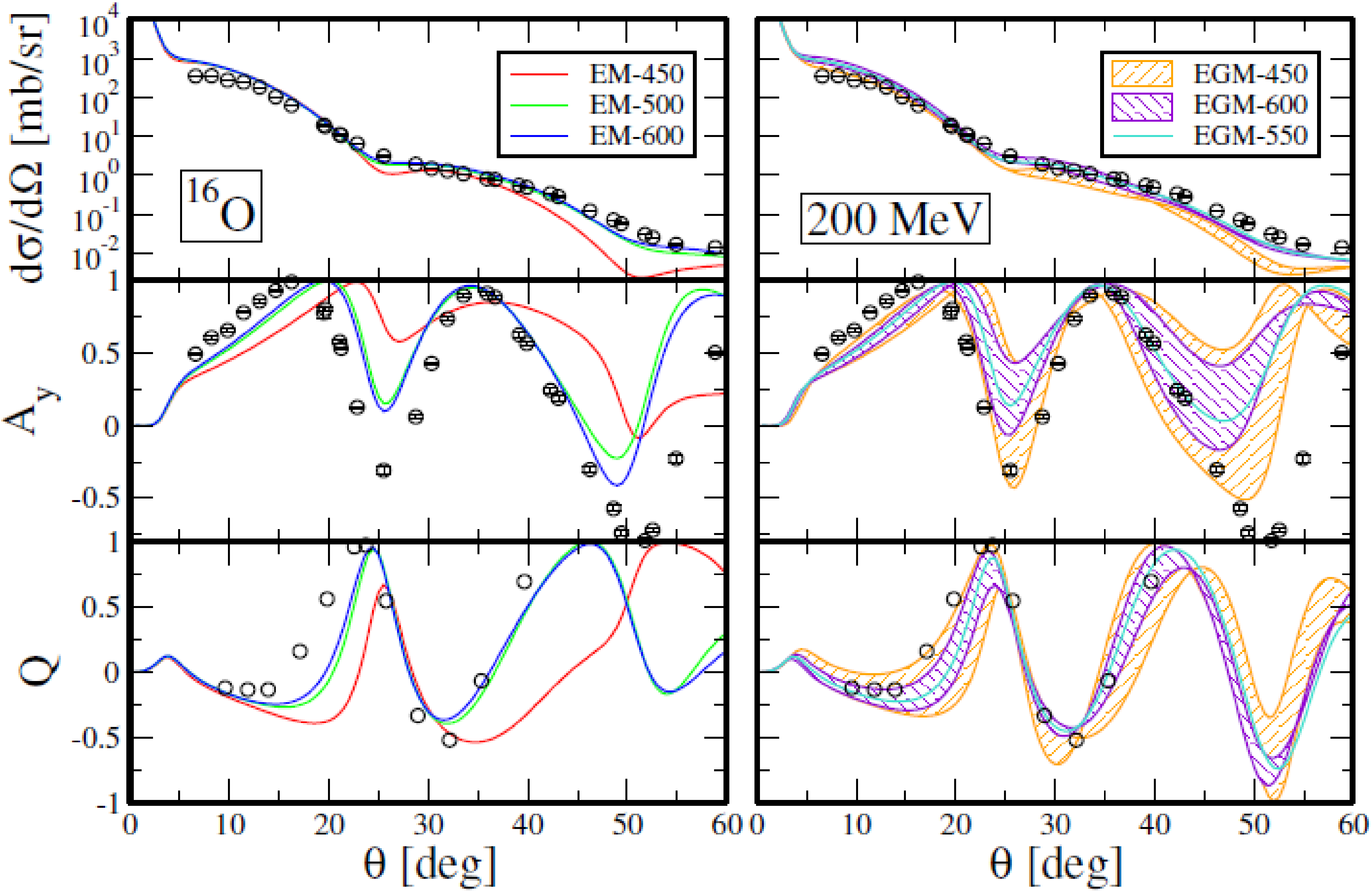
spin rotation

ELASTIC PROTON SCATTERING



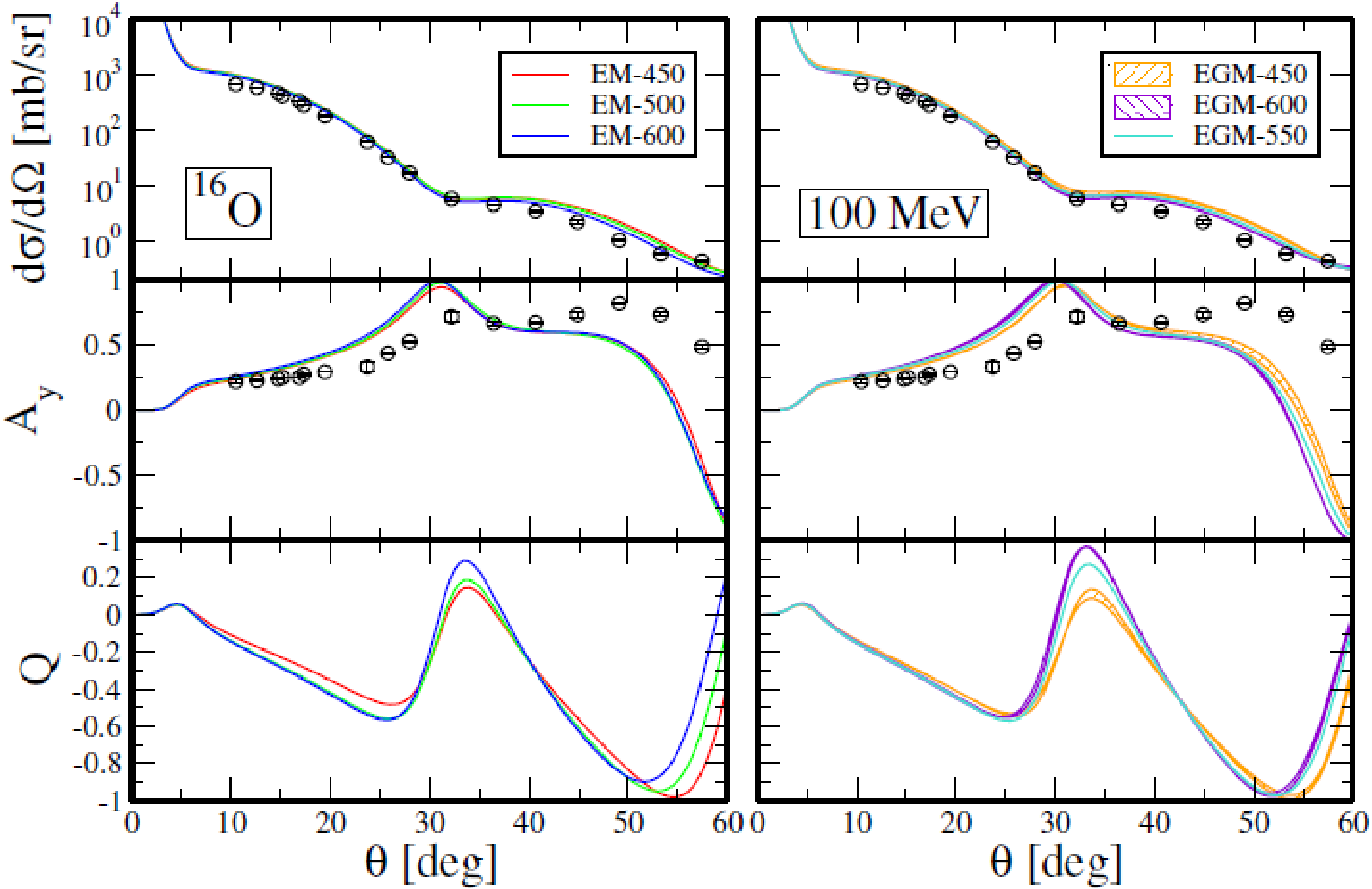
M. Vorabbi, P. Finelli, and C. Giusti, Phys. Rev. C **93**, 034619 (2016)

ELASTIC P-A SCATTERING



M. Vorabbi, P. Finelli, and C. Giusti, Phys. Rev. C **93**, 034619 (2016)

ELASTIC P-A SCATTERING

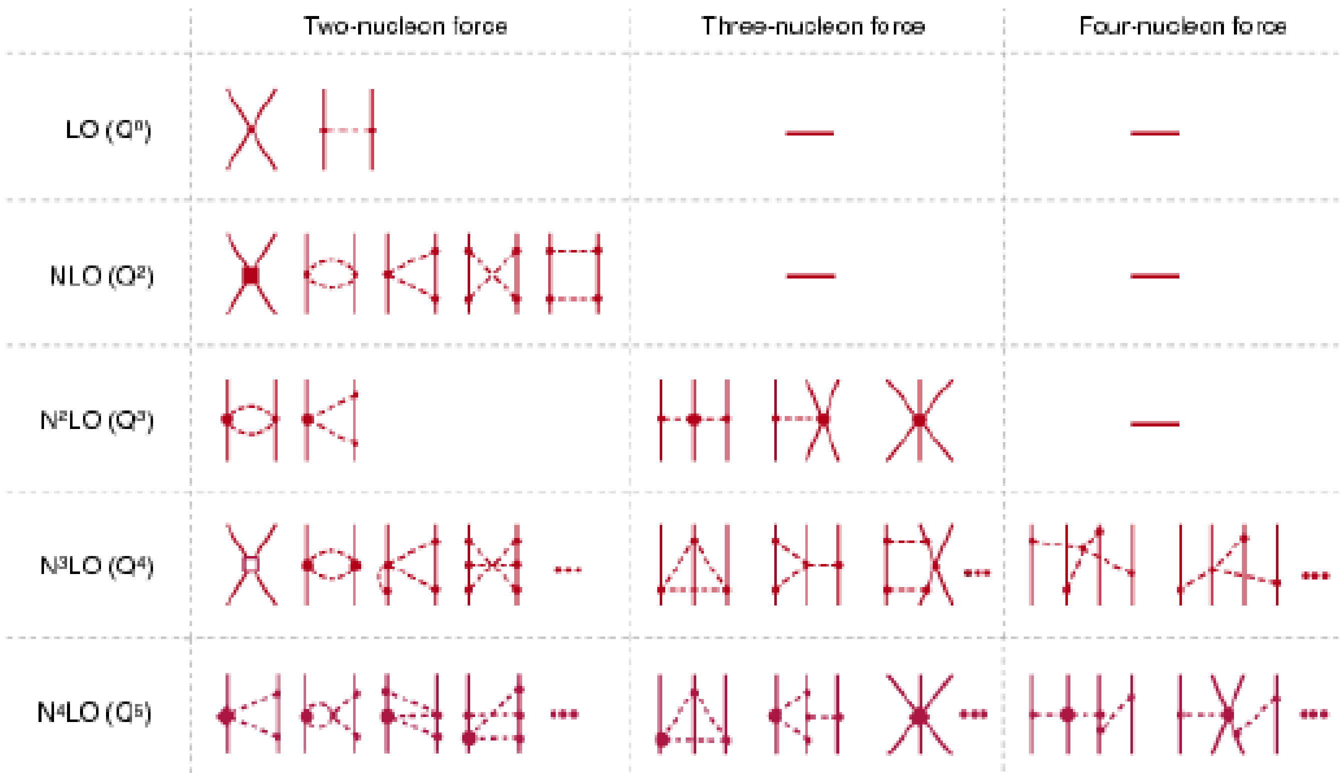


M. Vorabbi, P. Finelli, and C. Giusti, Phys. Rev. C **93**, 034619 (2016)

M. Vorabbi, P. Finelli, C. Giusti, PRC 96 044001 (2017)

Optical potential derived from nucleon-nucleon chiral potentials at N^4LO

CHIRAL POTENTIAL AT N^{4}LO

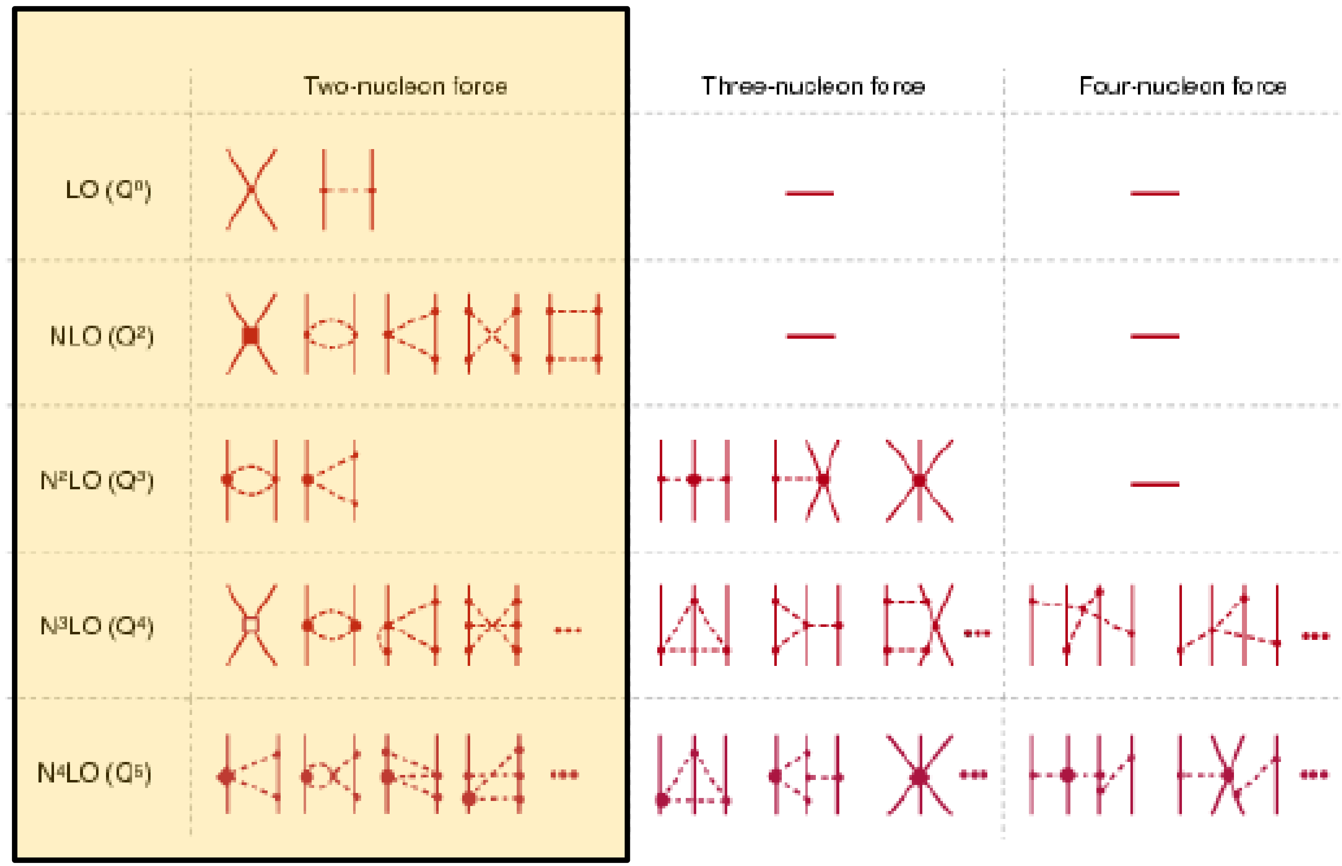


E. Epelbaum et al. . PRL 115 122391 (2015), EPJA 51 53 (2015) EKM

D.R. Entem et al. PRC 91 014002 (2015), PRC 96 024004 (2017) EMN

CHIRAL POTENTIAL AT N^4LO

NN



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M. Vorabbi, P. Finelli, C. Giusti,   PRC 93 034619 (2017)

Theoretical optical potential derived from nucleon-nucleon chiral potentials at N^4LO

Purpose: check the convergence and assess the theoretical errors associated with the truncation of the chiral expansion in the construction of an OP

M. Vorabbi, P. Finelli, C. Giusti, PRC 93 034619 (2017)

Theoretical optical potential derived from nucleon-nucleon chiral potentials at N^4LO

Purpose: check the convergence and assess the theoretical errors associated with the truncation of the chiral expansion in the construction of an OP

Results: robust convergence has been reached at N^4LO, agreement with data neither better nor worse than with chiral NN potentials at N^3LO

Comparison with phenomenological OP

- investigate and compare predictive power of our microscopic OP and of phenomenological OP in comparison with exp. data in a wider range of nuclei, including isotopic chains

M. Vorabbi, P. Finelli, C. Giusti, PRC 98 064602 (2019)
Proton-Nucleus Elastic Scattering: Comparison between Phenomenological and Microscopic Optical Potentials

Comparison with phenomenological OP

- investigate and compare predictive power of our microscopic OP and of phenomenological OP in comparison with exp. data in a wider range of nuclei, including isotopic chains

PHENOMENOLOGICAL OP
parameters fitted to data,
data very well described in particular situations.
Investigate capability to describe data in different situations

MICROSCOPIC OP
obtained from a model and approximations
may be less able to describe specific data
should have a greater predictive power for situations for which data not yet available

Comparison phenomenological and microscopic NROP

PHENOMENOLOGICAL OP

GLOBAL given in a wide range of nuclei and energies

NROP up to ~200 MeV, for higher energies it is generally believed that the Schroedinger picture should be taken over by a Dirac approach. Global ROP available up to ~1 GeV

NROP Koning at al. NPA 713 231 (2003) (KD) for nuclei $24 \leqslant A \leqslant 209$ and energies from 1 keV to 200 MeV, recently extended to 1 GeV, to test at which energy the predictions of a phen. NROP fail

Calculations with TALYS (ECIS-06)

MICROSCOPIC OP
chiral potentials at N^4LO describe NN scattering data up to 300 MeV and our OP can be used up to ~ 300 MeV

Comparison phenomenological and microscopic NROP

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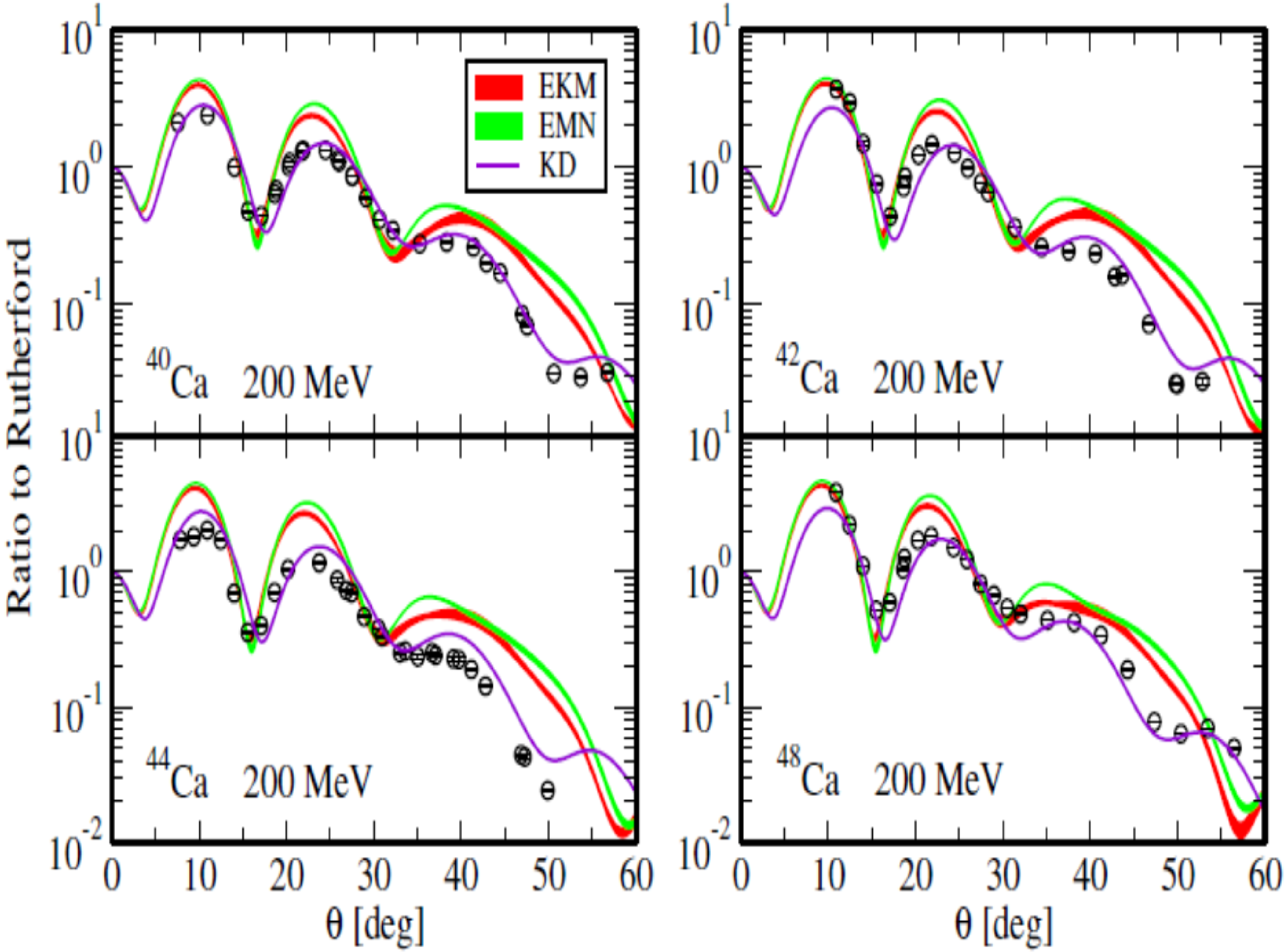
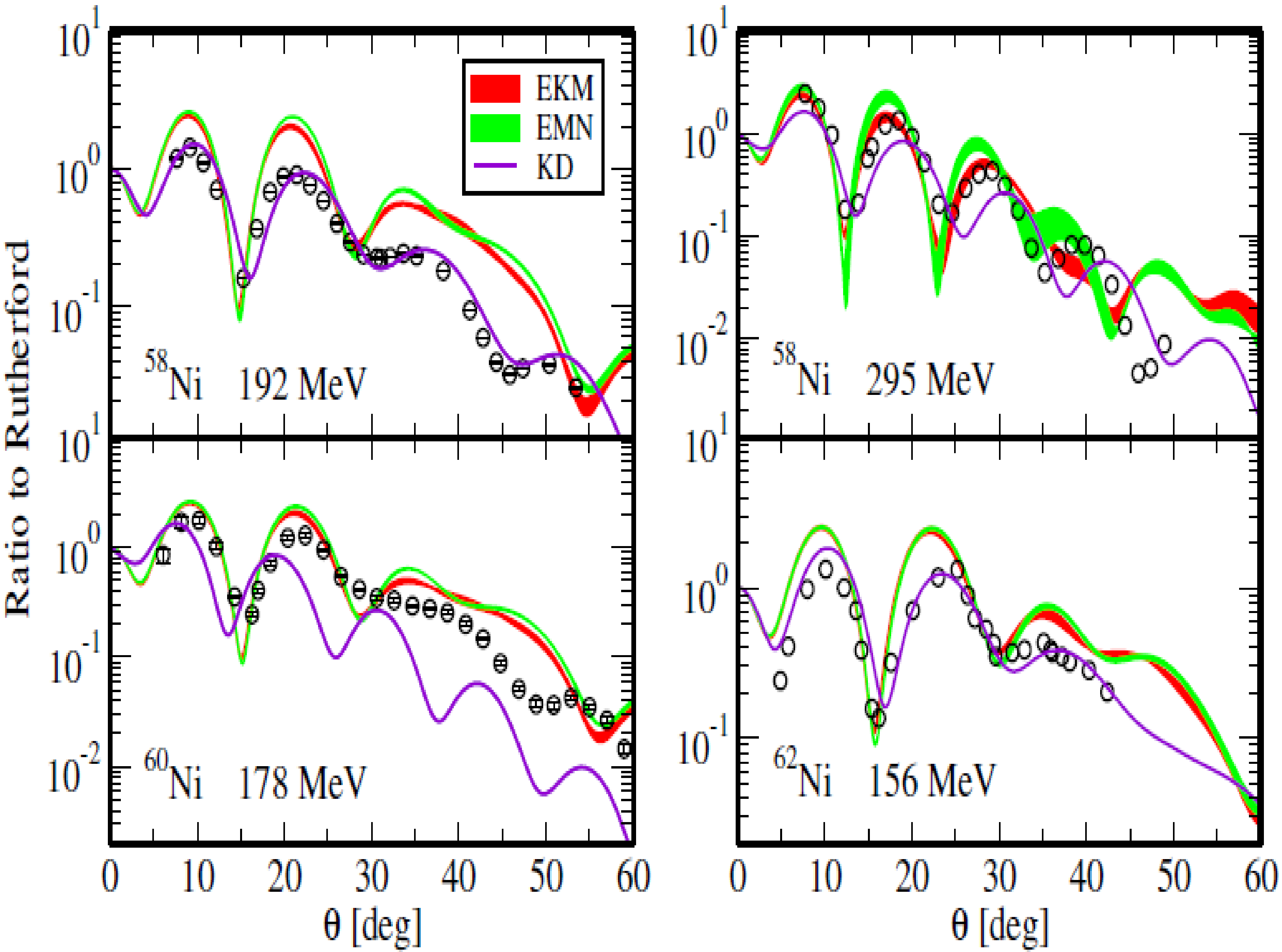
Results of the comparison in the energy range 150-330 MeV

Comparison with phenomenological OP



Comparison with phenomenological OP



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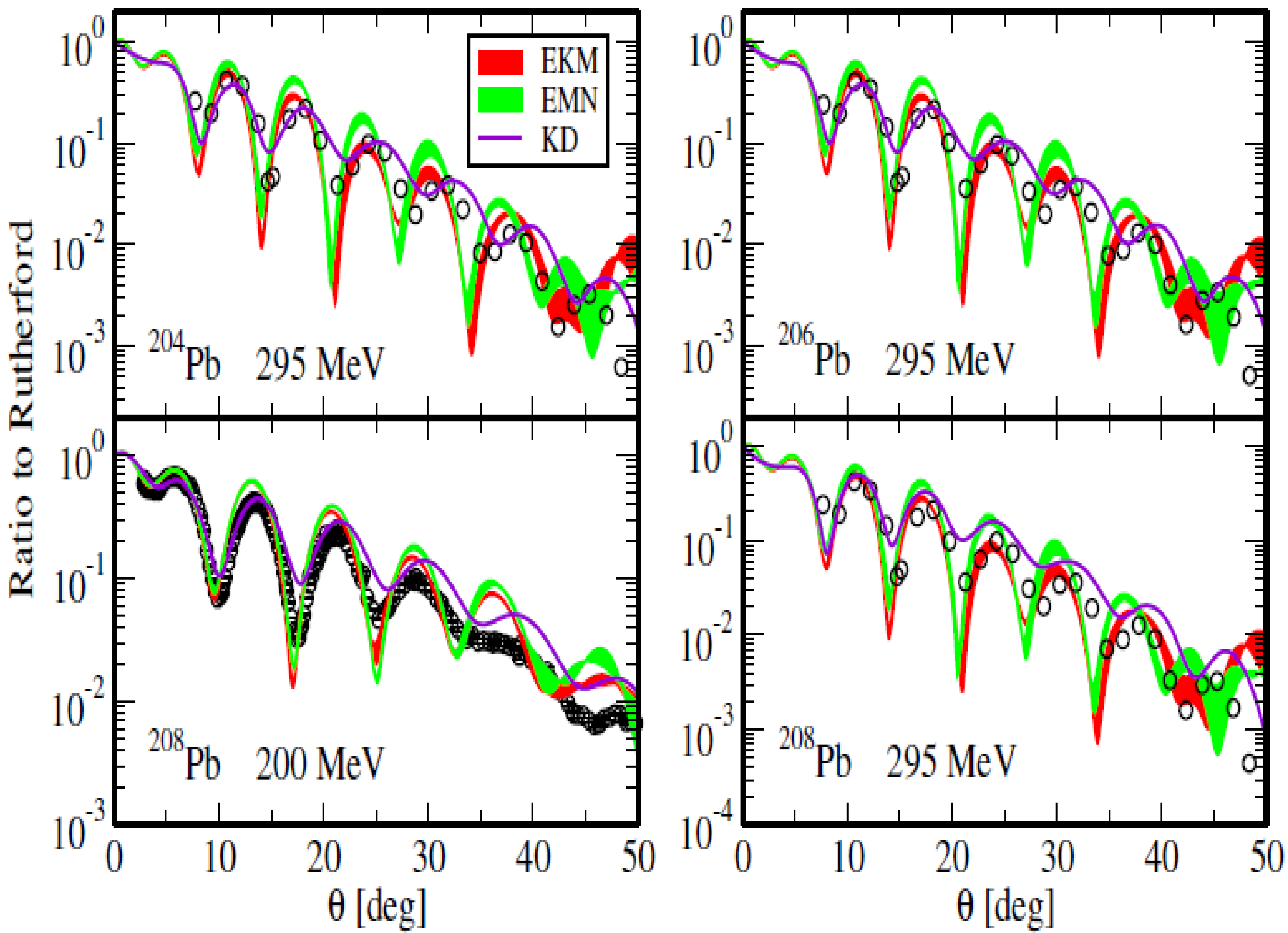

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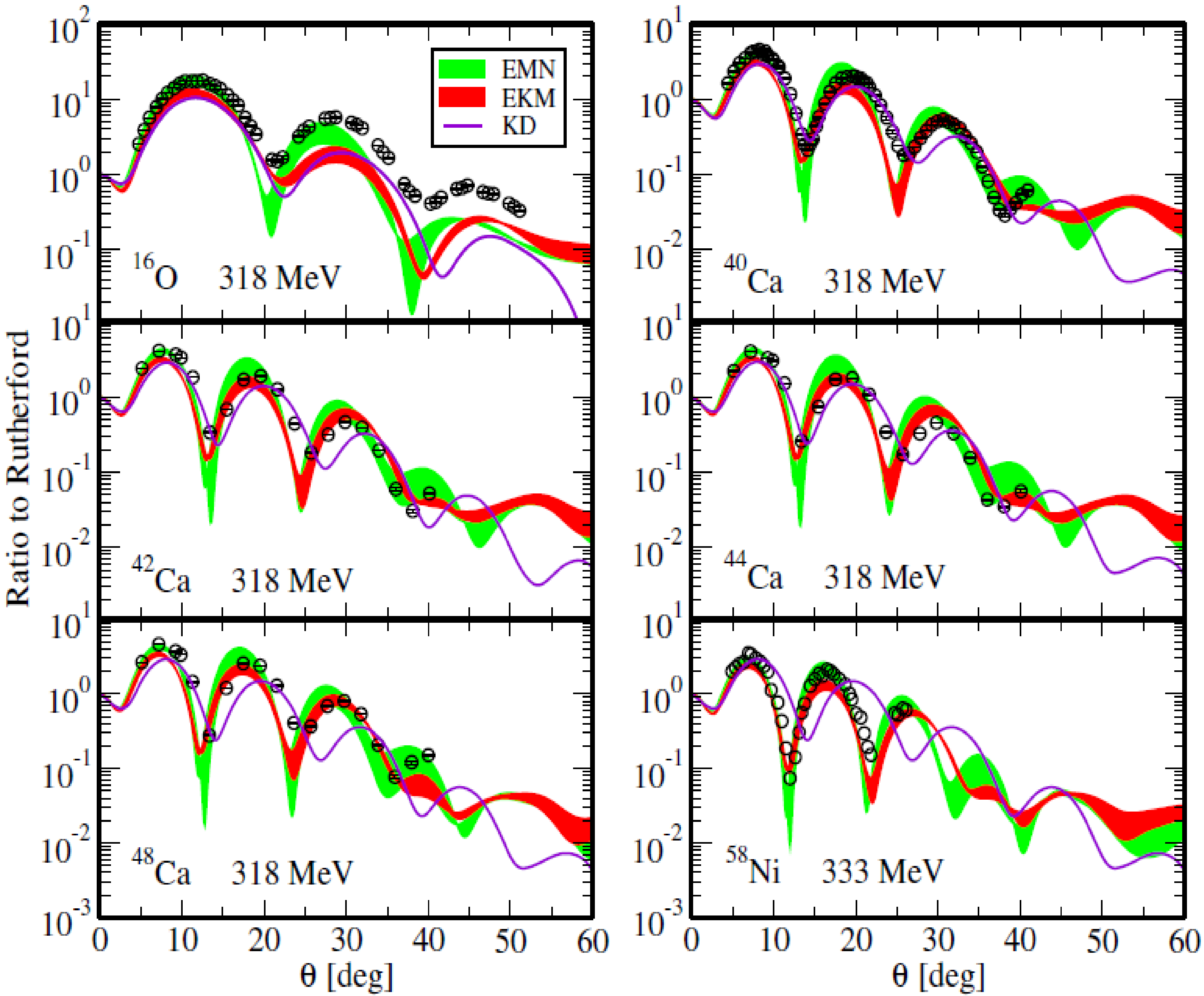

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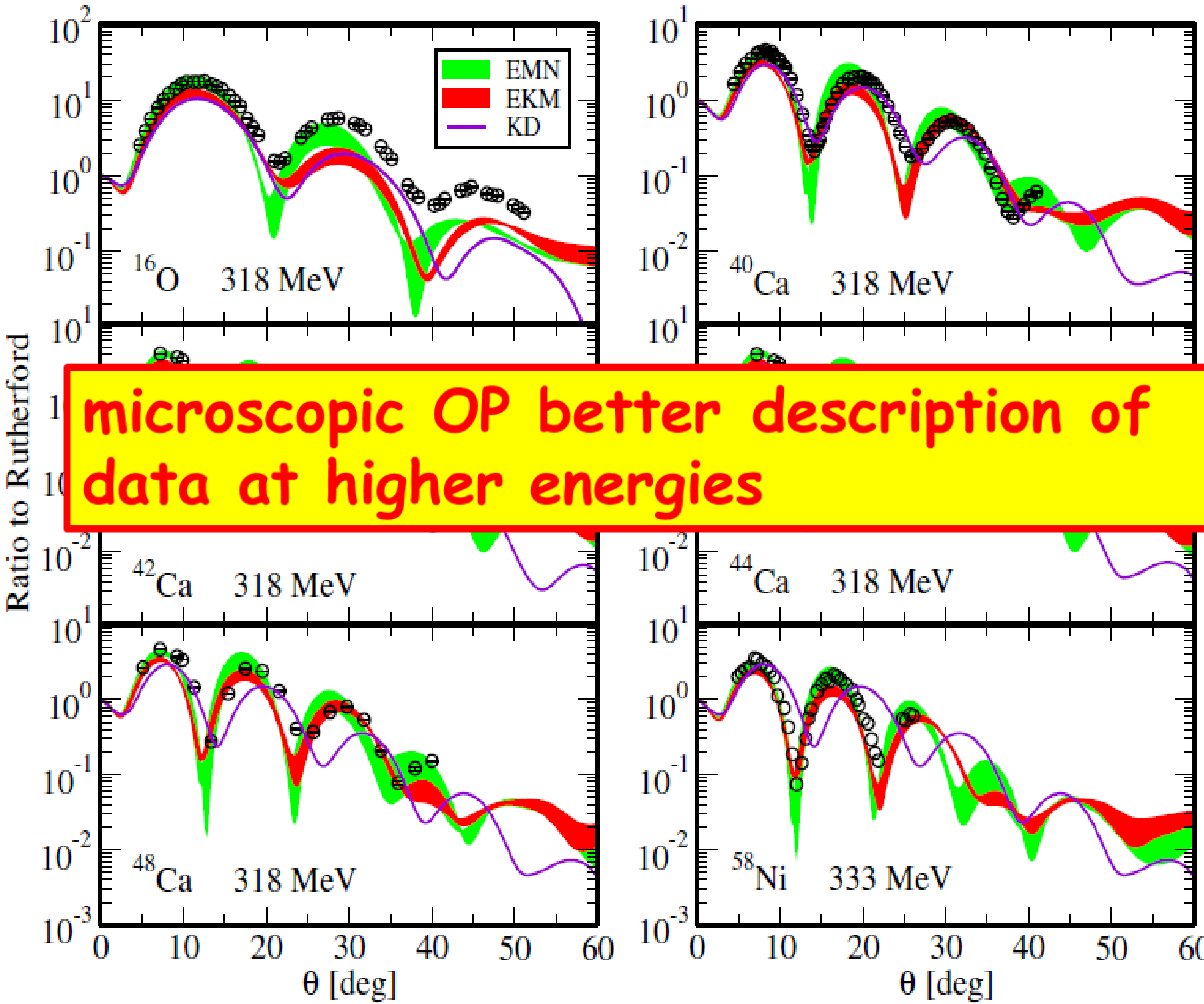

microscopic OP better description of data at higher energies

PROSPECTS...

- model can be improved

Microscopic optical potentials derived from *ab initio* translationally invariant nonlocal one-body densities

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Matteo Vorabbi,† Angelo Calci, and Petr Navrátil‡
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada
(Dated: December 11, 2017)

Background: The nuclear optical potential is a successful tool for the study of nucleon-nucleus elastic scattering and its use has been further extended to inelastic scattering and other nuclear reactions. The nuclear density of the target nucleus is a fundamental ingredient in the construction of the optical potential and thus plays an important role in the description of the scattering process.
Purpose: In this work we derive a microscopic optical potential for intermediate energies using *ab initio* translationally invariant nonlocal one-body nuclear densities computed within the no-core shell model (NCSM) approach utilizing two- and three-nucleon chiral interactions as the only input.
Methods: The optical potential is derived at first-order within the spectator expansion of the non-relativistic multiple scattering theory by adopting the impulse approximation. Nonlocal nuclear densities are derived from the NCSM one-body densities calculated in the second quantization. The translational invariance is generated by exactly removing the spurious center-of-mass (COM) component from the NCSM eigenstates.
Results: The ground state local and nonlocal densities of ^{4,6,8}He, ^{12}C, and ^{16}O are calculated and applied to optical potential construction. The differential cross sections and the analyzing powers for the elastic proton scattering off of these nuclei are then calculated for different values of the incident proton energy. The impact of nonlocality and the COM removal is discussed.
Conclusions: The use of nonlocal densities has a substantial impact on the differential cross sections and improves agreement with experiment in comparison to results generated with the local densities especially for light nuclei. For the halo nuclei ^{6}He and ^{8}He, the results for the differential cross section are in a reasonable agreement with the data although a more sophisticated model for the optical potential is required to properly describe the analyzing powers.

PACS numbers: 24.10.-i; 24.10.Ht; 24.70.+s; 25.40.Cm;21.60.De;27.10.+h;27.20.+n

M. Gennari, M. Vorabbi, A. Calci, P. Navratil, PRC 97 034619 (2018)

PROSPECTS...

- the model can be improved
- 3N forces, medium effects

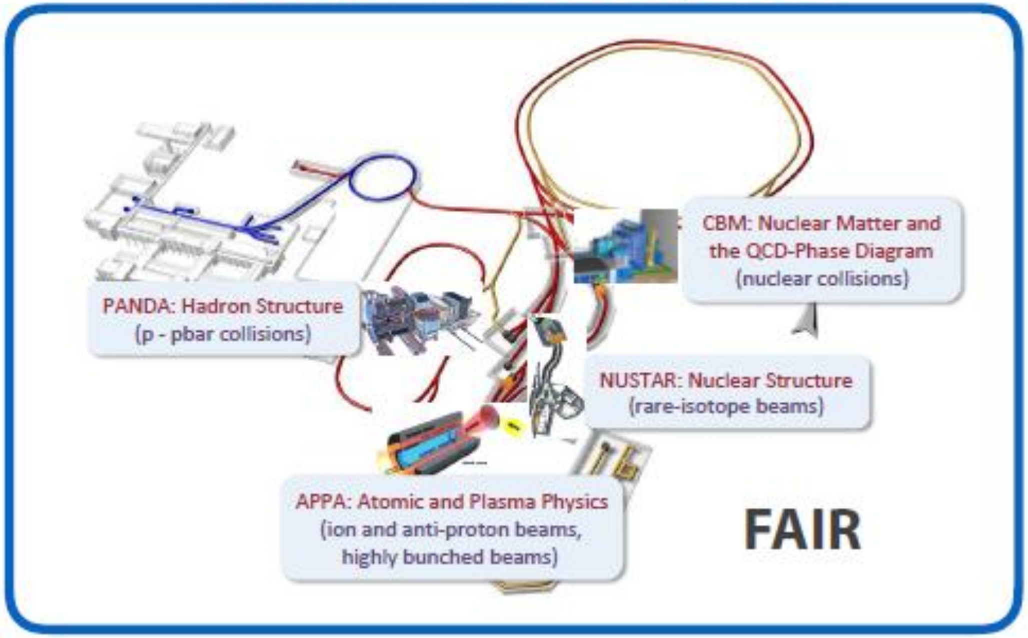
PROSPECTS...

- the model can be improved
- folding integral
- 3N forces, medium effects
- optical potential for elastic antiproton-nucleus scattering

M. Vorabbi, M. Gennari, P. Finelli, C. Giusti, P. Navratil, arXiv:1906.11984

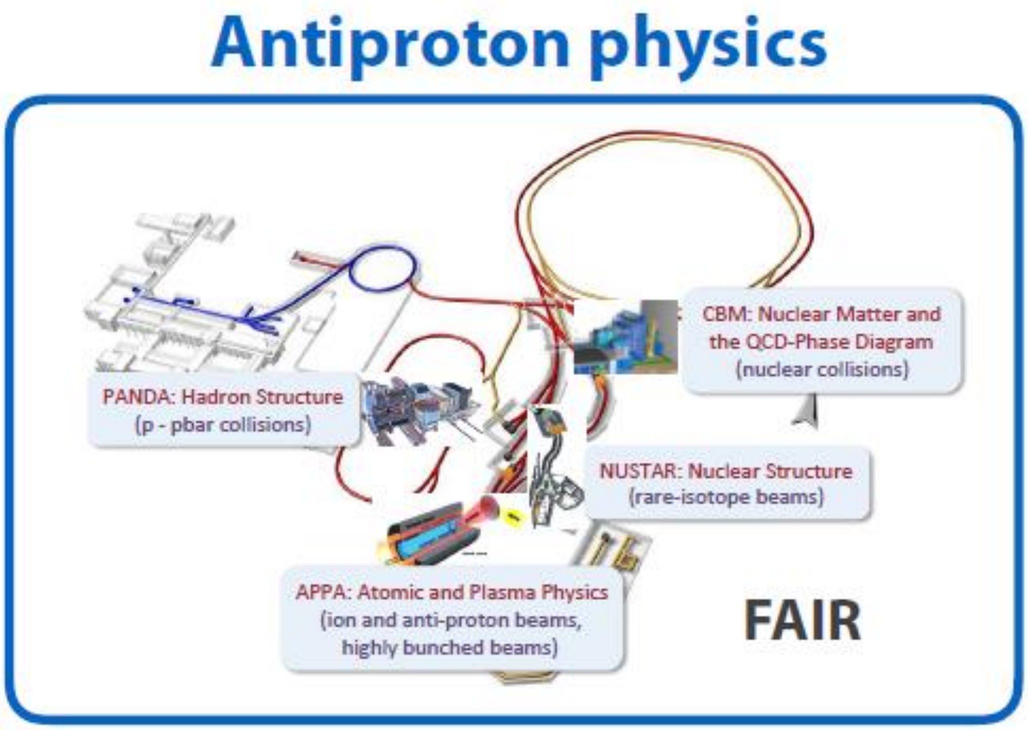
OP for $\bar{p}$ A scattering

Antiproton physics



Facilities ELENA (CERN) and FAIR (Darmstadt) under construction, experiments on $\bar{p}A$ scattering will experience a new renaissance

OP for $\bar{p}$ A scattering



Facilities ELENA (CERN) and FAIR (Darmstadt) under construction, experiments on $\bar{p}A$ scattering will experience a new renaissance

- new chiral $\bar{N}$N interaction recently derived up to N^3LO
  Dai, Haidenbauer, Meißner, JHEP 78 (2017)

OP for $\bar{p}$ A scattering

$$U(\boldsymbol{q},\boldsymbol{K};\omega) = \sum_{N=n,p} \int d^3\boldsymbol{P}\, \eta(\boldsymbol{P},\boldsymbol{q},\boldsymbol{K})$$
$$\times\, t_{\bar{p}N}\left[\boldsymbol{q}, \frac{1}{2}\left(\frac{A+1}{A}\boldsymbol{K} + \sqrt{\frac{A-1}{A}}\boldsymbol{P}\right);\omega\right]$$
$$\times\, \rho_N\left(\boldsymbol{P} + \frac{1}{2}\sqrt{\frac{A-1}{A}}\boldsymbol{q}, \boldsymbol{P} - \frac{1}{2}\sqrt{\frac{A-1}{A}}\boldsymbol{q}\right)$$

Moeller factor

$\bar{N}$N t-matrix
$\bar{N}$N chiral interaction

non local n, p densities

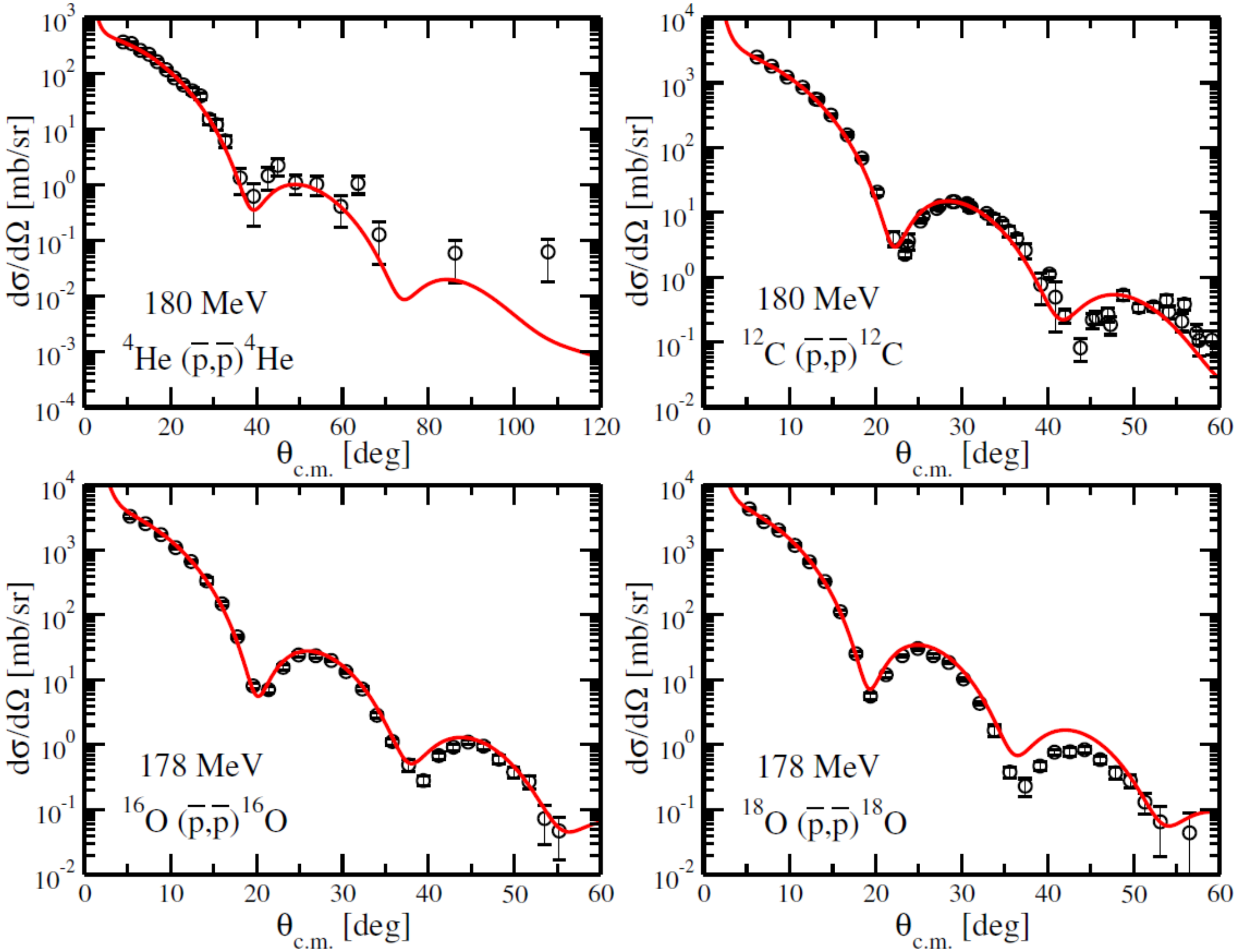
$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k} \qquad \boldsymbol{K} = \frac{1}{2}(\boldsymbol{k}' + \boldsymbol{k})$$

folding integral

CHIRAL FORCES

- Target density: one-body translationally invariant densities computed within the *ab initio* NCSM approach using NN - N^4LO500, Entem et al. PRC 96 024004(2017) and 3N-N^2LO, Navratil, Few-Body Syst. 41 117 (2007)
- Scattering matrix: $\bar{N}$N -N^3LO Dai, Haidenbauer, Meißner, JHEP 78 (2017)

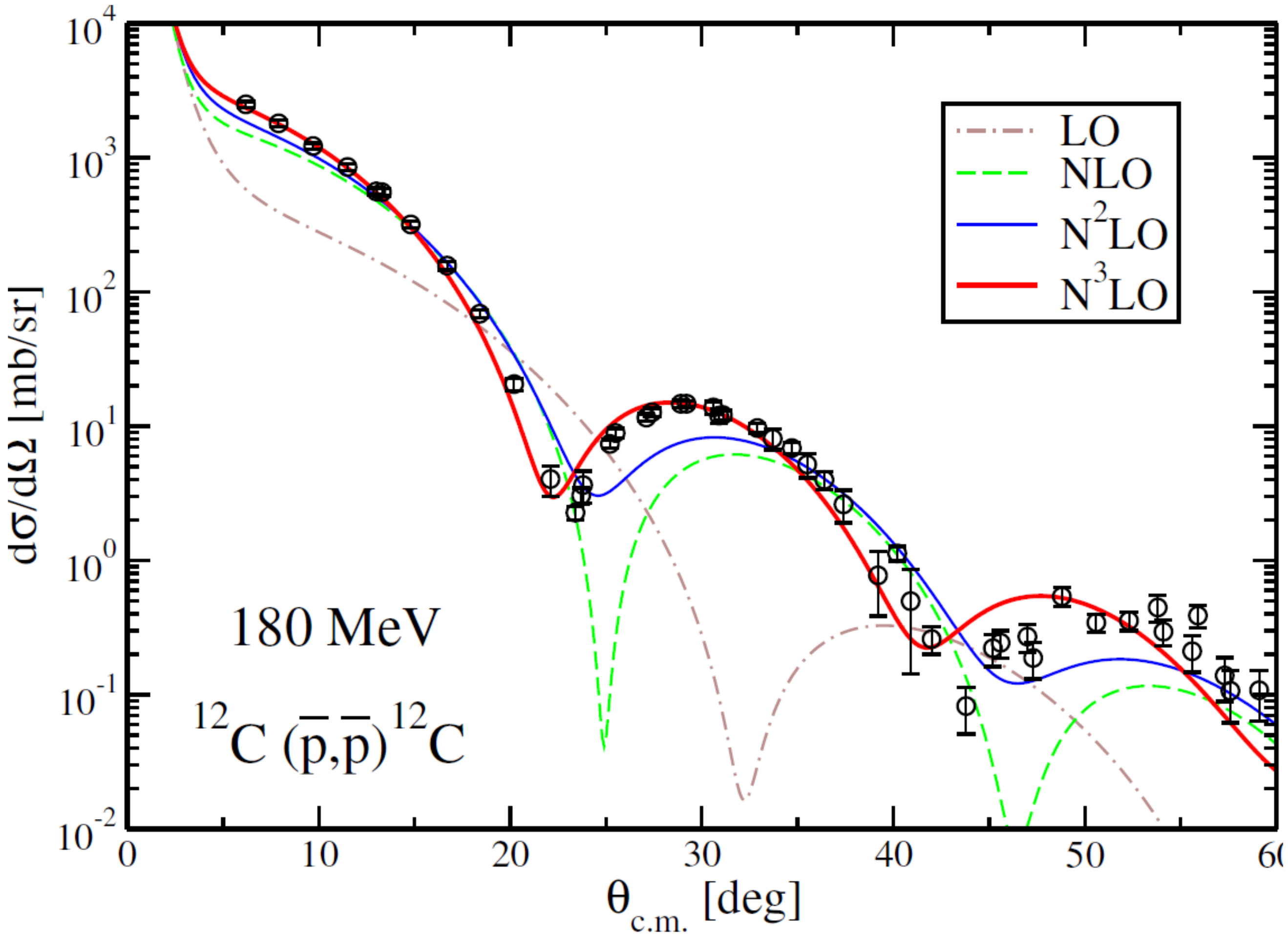
$\bar{p}$ A scattering



data from LEAR

M. Vorabbi, M. Gennari, P. Finelli, C. Giusti, P. Navratil, arXiv:1906.11984

$\bar{p}$ A scattering



data from LEAR

M. Vorabbi, M. Gennari, P. Finelli, C. Giusti, P. Navratil, arXiv:1906.11984