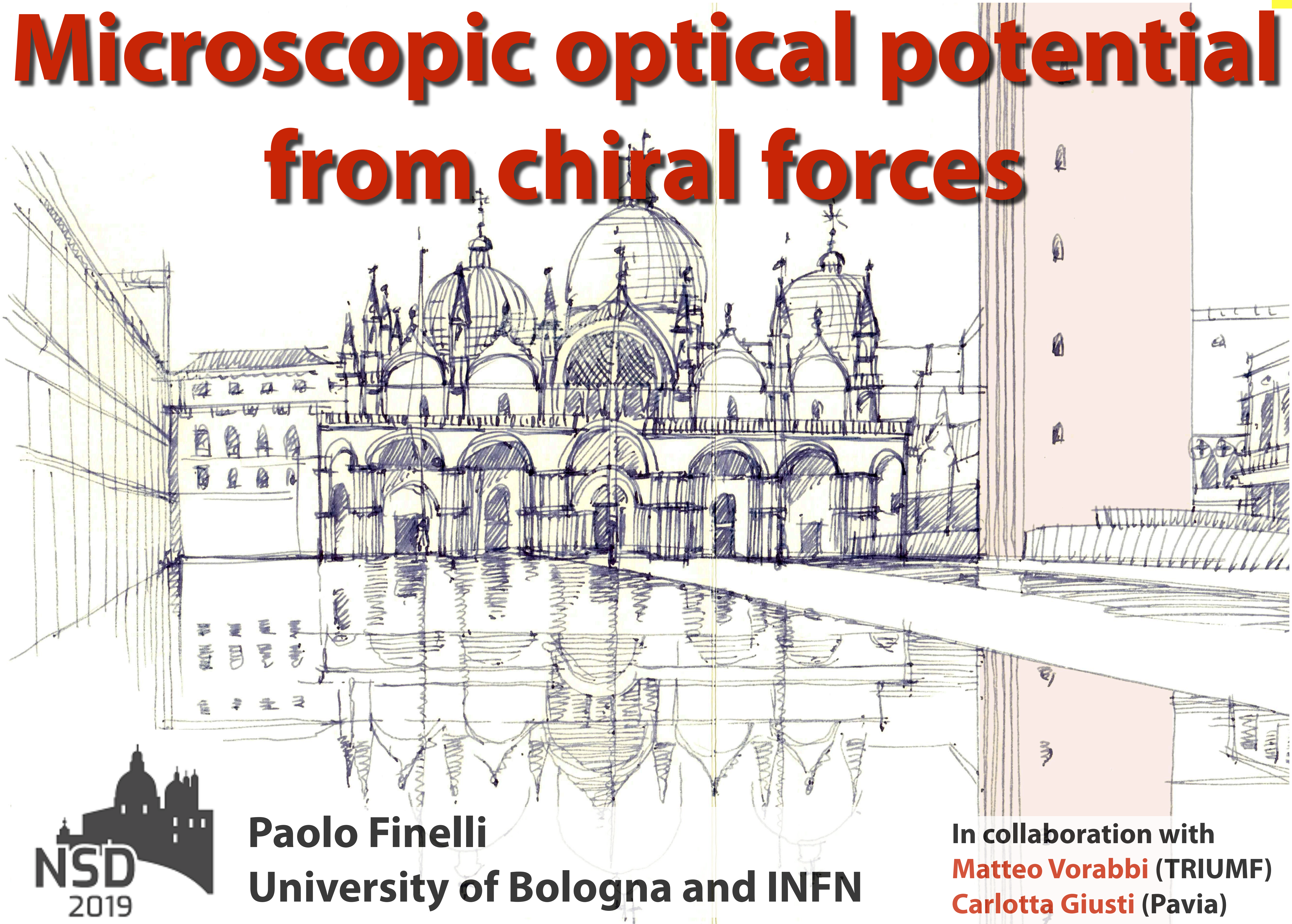
Microscopic optical potential from chiral forces



Paolo Finelli
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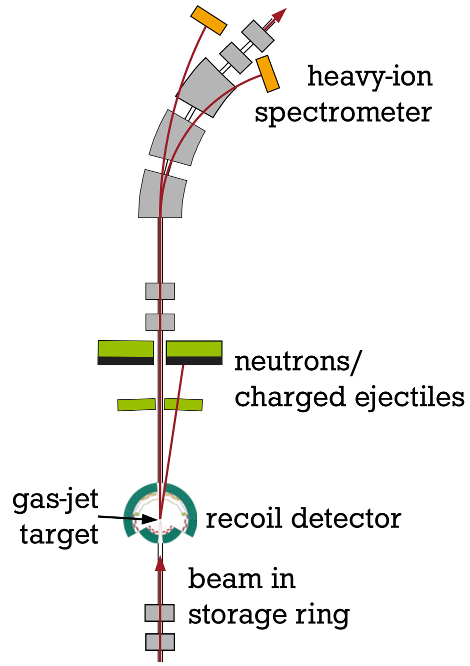
In collaboration with
Matteo Vorabbi (TRIUMF)
Carlotta Giusti (Pavia)

NSD 2019

Motivation

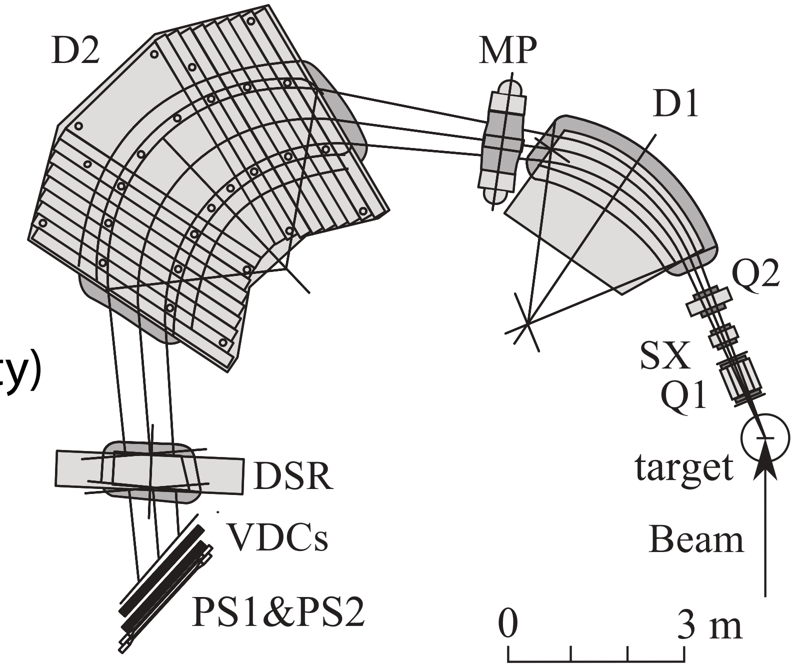
Experimental matter densities

The aim of the **EXL experiment** is to study the structure of unstable exotic nuclei in light-ion scattering experiments at intermediate energies



see *Nuclear matter distribution of Ni56 measured with EXL*, M. Von Schmid (2015)

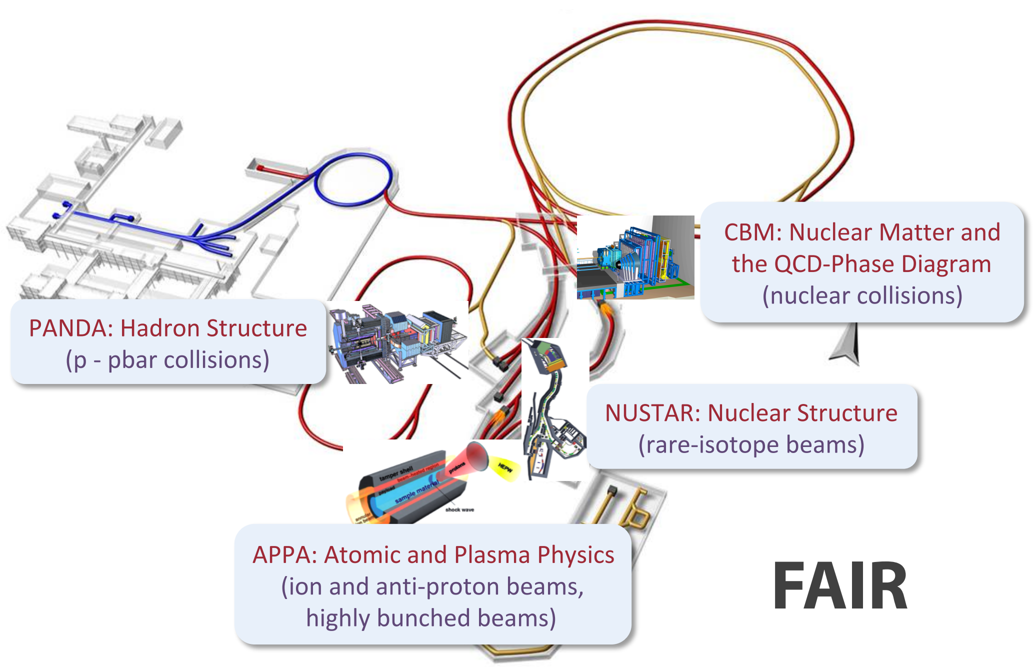
RCNP (Osaka University)



Proton elastic scattering from tin isotopes at 295 MeV and systematic change of neutron density distributions, **PRC77 (2008) 024317**

Neutron density distributions of ^{204,206,208}Pb deduced via proton elastic scattering at $E_p = 295$ MeV, **PRC82 (2010) 044611**

Antiproton physics



Theoretical point of view

It is important to constrain and to test the most recent chiral potentials

- convergence
- accuracy
- predictive power

Method

Nuclear reaction theory relies on reducing the many-body problem to a problem with few degrees of freedom: **optical potentials**.

2 body

… and 3 body?

NN data
(but also $\bar{N}$N data)

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

$$\delta_L(E)$$

Effective interaction

No fitting to empirical data

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

N + A

More predictive power where no exp. data are available

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

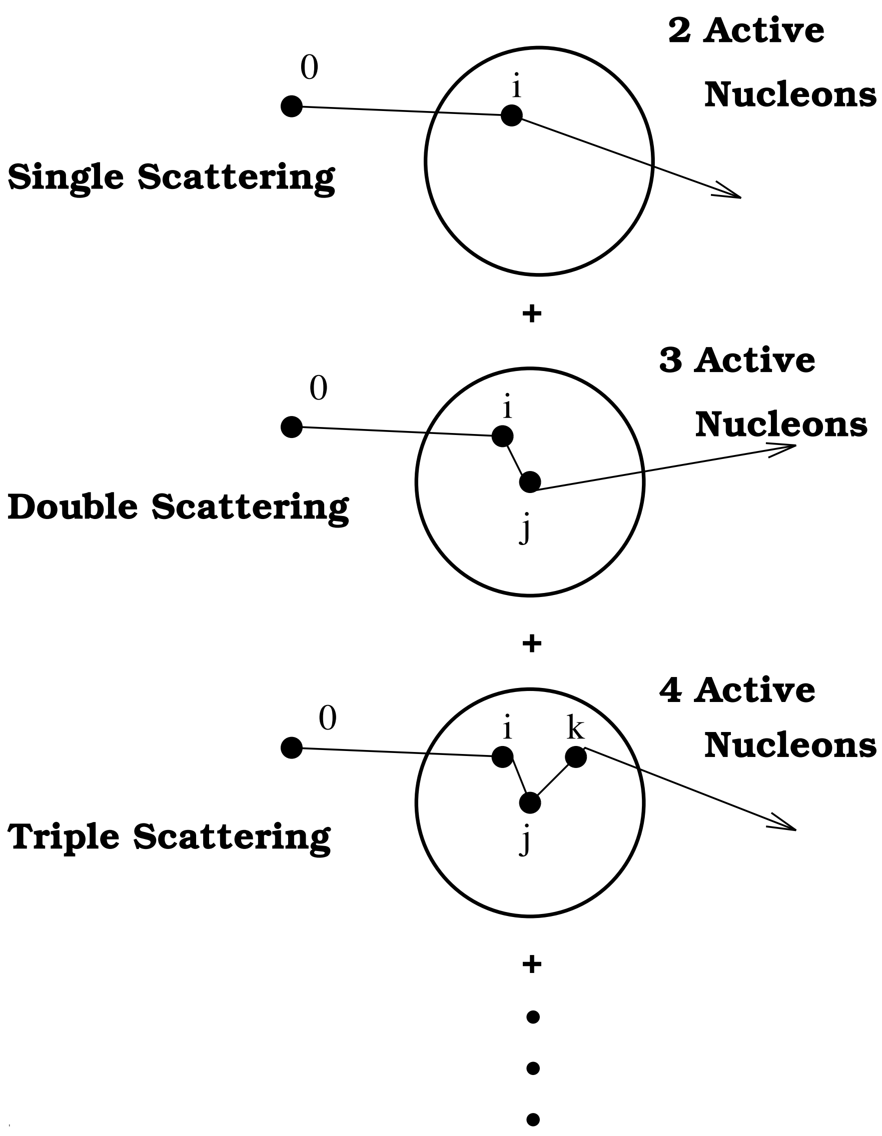
$$\left(\frac{d\sigma}{d\Omega}\right)_{NA}$$

$$A_y$$

Model

The general goal when solving the scattering problem of a nucleon from a nucleus is to solve the corresponding **Lippmann-Schwinger equation** for the many-body transition amplitude T

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



Phys. Rev. C 93, 034619 (2016)

The general goal when solving the scattering problem of a nucleon from a nucleus is to solve the corresponding **Lippmann-Schwinger equation** for the many-body transition amplitude T

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

Spectator expansion

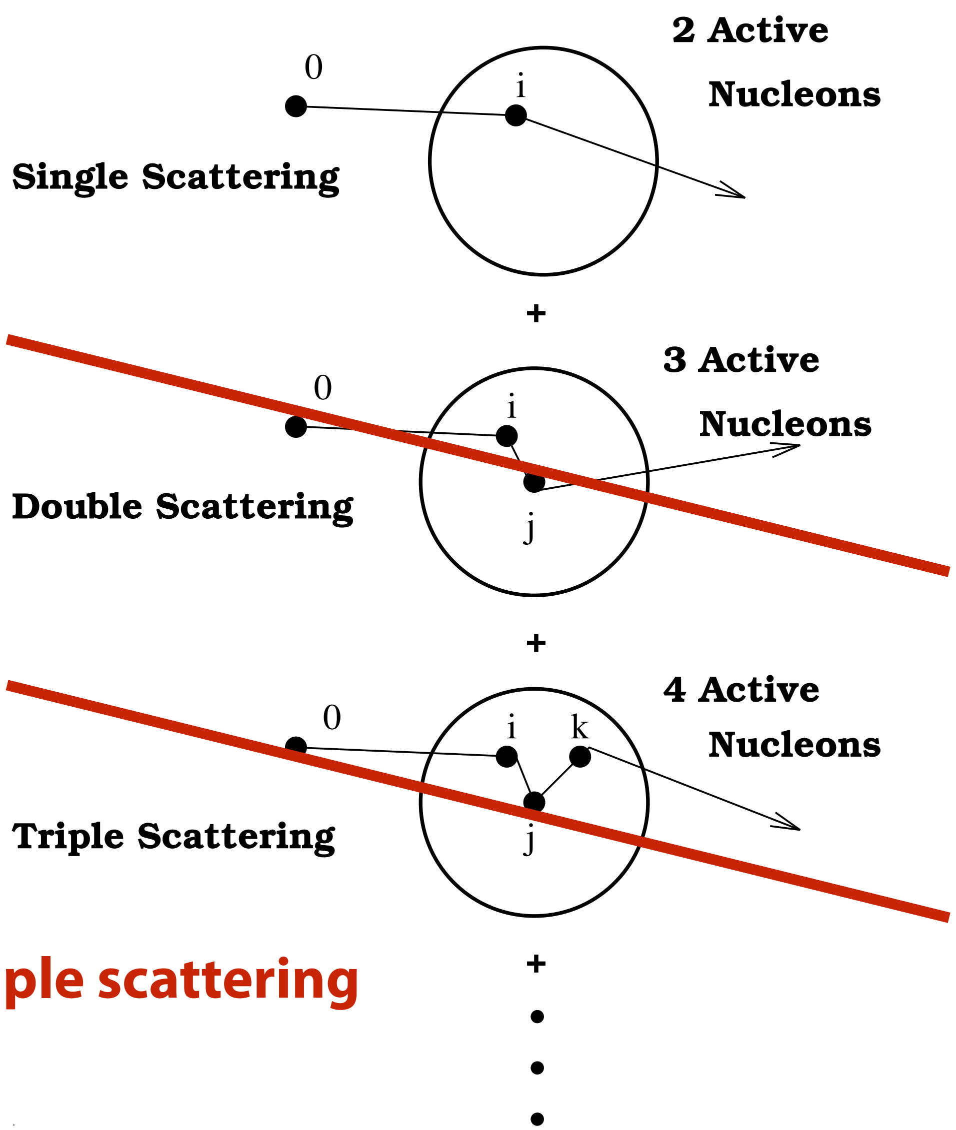
two nucleon interaction dominates the scattering process

$$T = \sum_{i=1} T_{0i}$$

$$T_{0i} = v_{0i} + v_{0i}G_0(E)T,$$

$$\begin{aligned} T_{0i} &= v_{0i} + v_{0i}G_0(E)\sum_j T_{0j} \\ &= v_{0i} + v_{0i}G_0(E)T_{0i} + v_{0i}G_0(E)\sum_{j\neq i} T_{0j} \\ (1 - v_{0i}G_0(E))T_{0i} &= v_{0i} + v_{0i}G_0(E)\sum_{j\neq i} T_{0j} \end{aligned}$$

$$\boxed{T_{0i} = t_{0i} + t_{0i}G_0(E)\sum_{j\neq i} T_{0j}.}$$



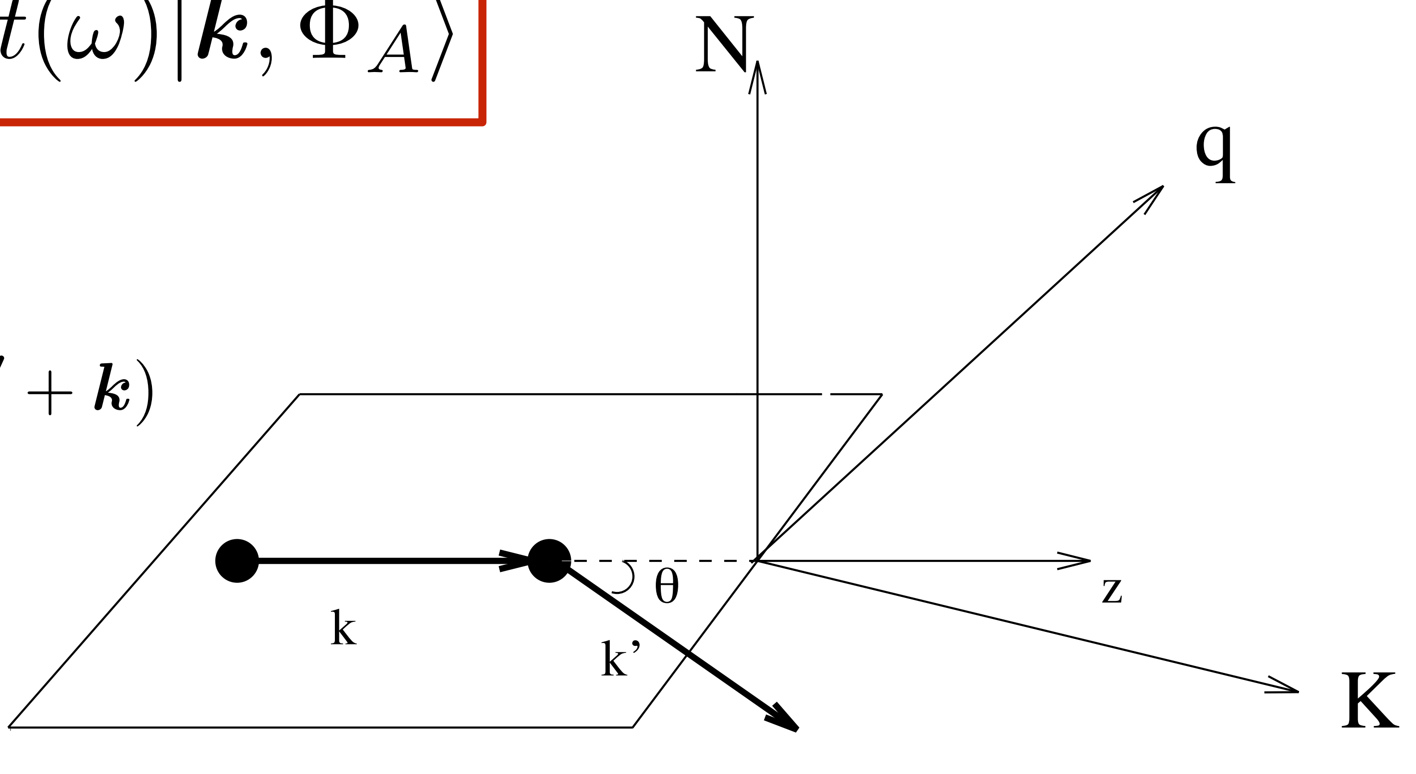
Watson multiple scattering

Phys. Rev. C 93, 034619 (2016)

First-order optical potential

Kerman, McManus and Thaler, Ann. Phys. **8** (1959) 551 and many others

$$\boxed{\hat{U}(\boldsymbol{k}', \boldsymbol{k}; \omega) = (A-1)\,\langle \boldsymbol{k}', \Phi_A | t(\omega) | \boldsymbol{k}, \Phi_A \rangle}$$



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

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

Optimum factorization factor

Møller factor

$$\eta(\boldsymbol{q}, \boldsymbol{K}) = \left[\frac{E_{\mathrm{proj}}(\boldsymbol{\kappa}')\,E_{\mathrm{proj}}(-\boldsymbol{\kappa}')\,E_{\mathrm{proj}}(\boldsymbol{\kappa})\,E_{\mathrm{proj}}(-\boldsymbol{\kappa})}{E_{\mathrm{proj}}(\boldsymbol{k}')\,E_{\mathrm{proj}}\left(-\frac{\boldsymbol{q}}{2} - \frac{\boldsymbol{K}}{A}\right)\,E_{\mathrm{proj}}(\boldsymbol{k})\,E_{\mathrm{proj}}\left(\frac{\boldsymbol{q}}{2} - \frac{\boldsymbol{K}}{A}\right)}\right]^{\frac{1}{2}}$$

Phys. Rev. C 93, 034619 (2016)

First-order optical potential

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

Central component

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

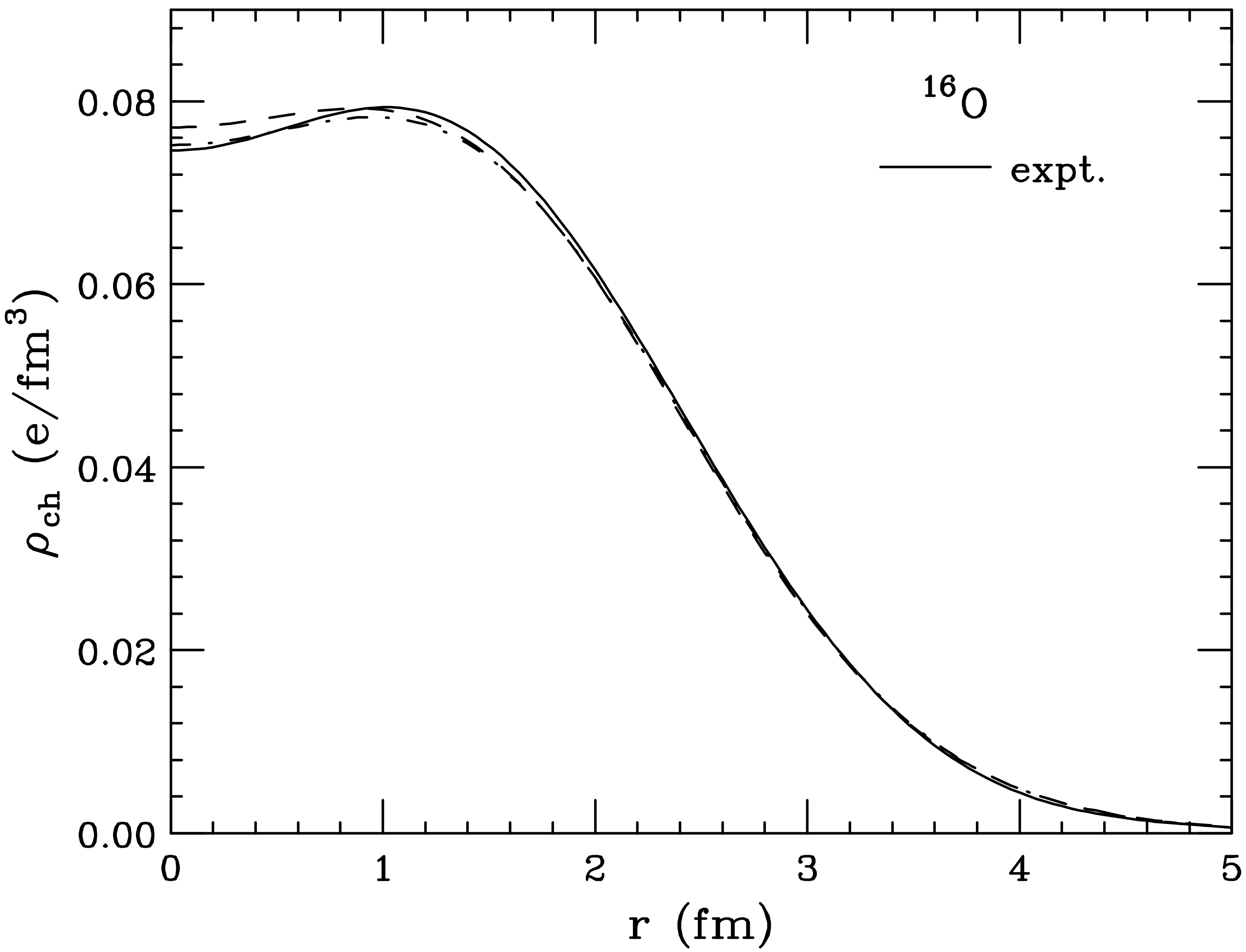
Spin-orbit component

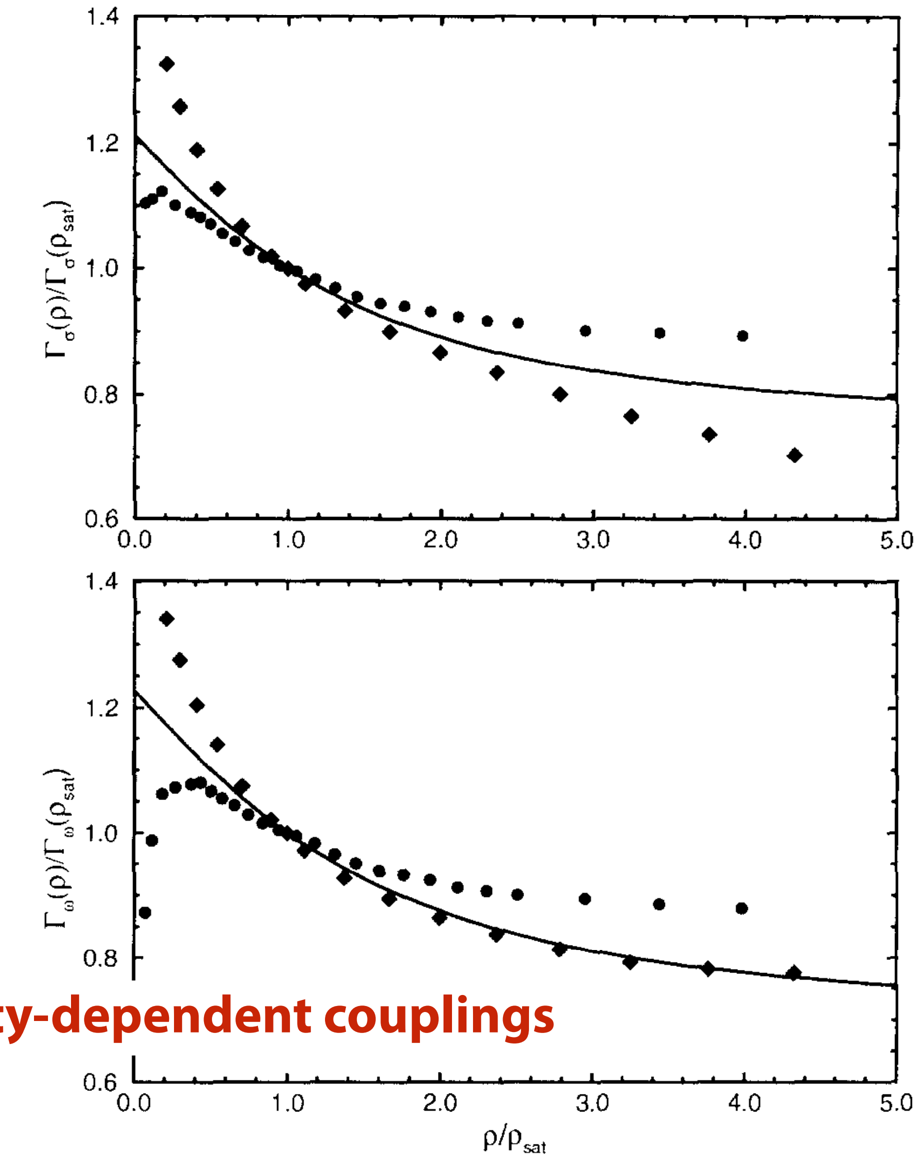
$$\hat{U}^{ls}(\boldsymbol{q},\boldsymbol{K};\omega) = \frac{A-1}{A}\eta(\boldsymbol{q},\boldsymbol{K})\left(\frac{A+1}{2A}\right) \times \sum_{N=n,p} t^{ls}_{pN}\left[\boldsymbol{q},\frac{A+1}{A}\boldsymbol{K};\omega\right]\rho_N(q)$$

Phys. Rev. C 93, 034619 (2016)

Matter densities

Typel and Wolter , Nuc. Phys. A **656** (1999) 331





Density-dependent couplings

$$\mathcal{L} = \bar{\Psi}\left[\gamma^\mu\left(i\partial_\mu - \Gamma_\omega A^{(\omega)}_\mu - \Gamma_\varrho \frac{\boldsymbol{\tau}}{2}\cdot \boldsymbol{A}^{(\varrho)}_\mu - e\frac{1+\tau_3}{2}A^{(\gamma)}_\mu\right) - (m - \Gamma_\sigma \phi)\right]\Psi$$
$$+\frac{1}{2}\left[\partial_\mu\phi\partial^\mu\phi - m_\sigma^2\phi^2 - \frac{1}{2}F^{(\omega)}_{\mu\nu}F^{(\omega)\mu\nu} + m_\omega^2 A^{(\omega)}_\mu A^{(\omega)\mu}\right.$$
$$\left.-\frac{1}{2}\boldsymbol{F}^{(\varrho)}_{\mu\nu}\cdot\boldsymbol{F}^{(\varrho)\mu\nu} + m_\varrho^2\boldsymbol{A}^{(\varrho)}_\mu\cdot\boldsymbol{A}^{(\varrho)\mu} - \frac{1}{2}F^{(\gamma)}_{\mu\nu}F^{(\gamma)\mu\nu}\right]$$

DDME1 parametrization

T. Nikšić, D. Vretenar, P. Finelli and P. Ring
Phys. Rev. C **66** (2002) 024306

Scattering observables

Spin-flip amplitude

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

$$A(\theta) = \frac{1}{2\pi^2}\sum_{L=0}^{\infty}\left[(L+1)F_L^{+}(k_0) + LF_L^{-}(k_0)\right]P_L(\cos\theta)$$

$$F_{LJ}(k_0) = -\frac{A}{A-1}4\pi^2\mu(k_0)\hat{T}_{LJ}(k_0,k_0;E)$$

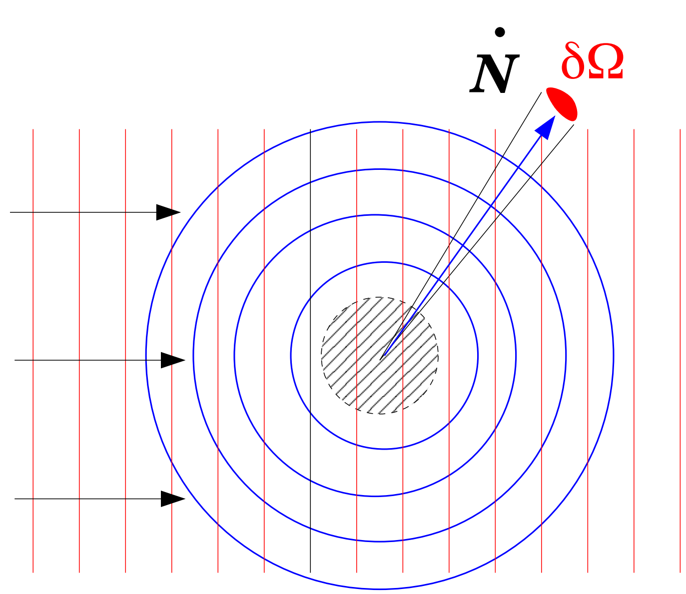
$$C(\theta) = \frac{i}{2\pi^2}\sum_{L=1}^{\infty}\left[F_L^{+}(k_0) - F_L^{-}(k_0)\right]P_L^{1}(\cos\theta)$$

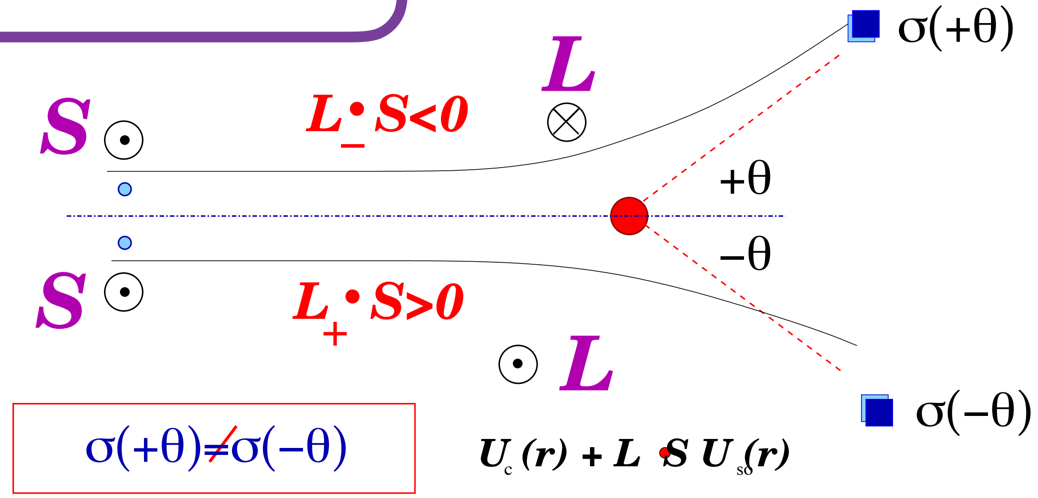
Differential cross section

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

Analyzing power

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





NN potential

Chiral potentials: why?

Chiral potentials

1. *QCD symmetries are consistently respected*
2. *Systematic expansion (order by order you know exactly the terms to be included)*
3. *Theoretical errors*
4. *Two- and three- body forces belong to the same framework*

Phenomen. potentials

1. *QCD symmetries are not respected*
2. *Expansion determined by phenomenology (add whatever you need). A lot of freedom*
3. *Errors can’t be estimated*
4. *Two- and three- body forces are not related one to each other*

Nucleon-Nucleon Chiral potentials

Entem, Machleidt, Nosyk (N4LO)

Phys. Rev. C91, 014002 (2015), Phys.Rev. C96 (2017)

Long-range

$$V(\boldsymbol{k},\boldsymbol{k}') \to V(\boldsymbol{k},\boldsymbol{k}')f^{\Lambda}(k,k')$$

$$f^{\Lambda} = \exp\left(-(k'/\Lambda)^{2n} - (k/\Lambda)^{2n}\right)$$

Short-range

spectral function subtraction

Epelbaum, Krebs, Meissner (N4LO)

Phys. Rev. Lett. 115, 122301 (2015), Eur. Phys. J. A51, 53 (2015)

Long-range

$$V^{\mathrm{reg}}_{\mathrm{long-range}}(\boldsymbol{r}) = V_{\mathrm{long-range}}(\boldsymbol{r}) f\left(\frac{r}{R}\right)$$

$$f\left(\frac{r}{R}\right) = \left(1 - \exp\left(-\frac{r^2}{R^2}\right)\right)^n$$

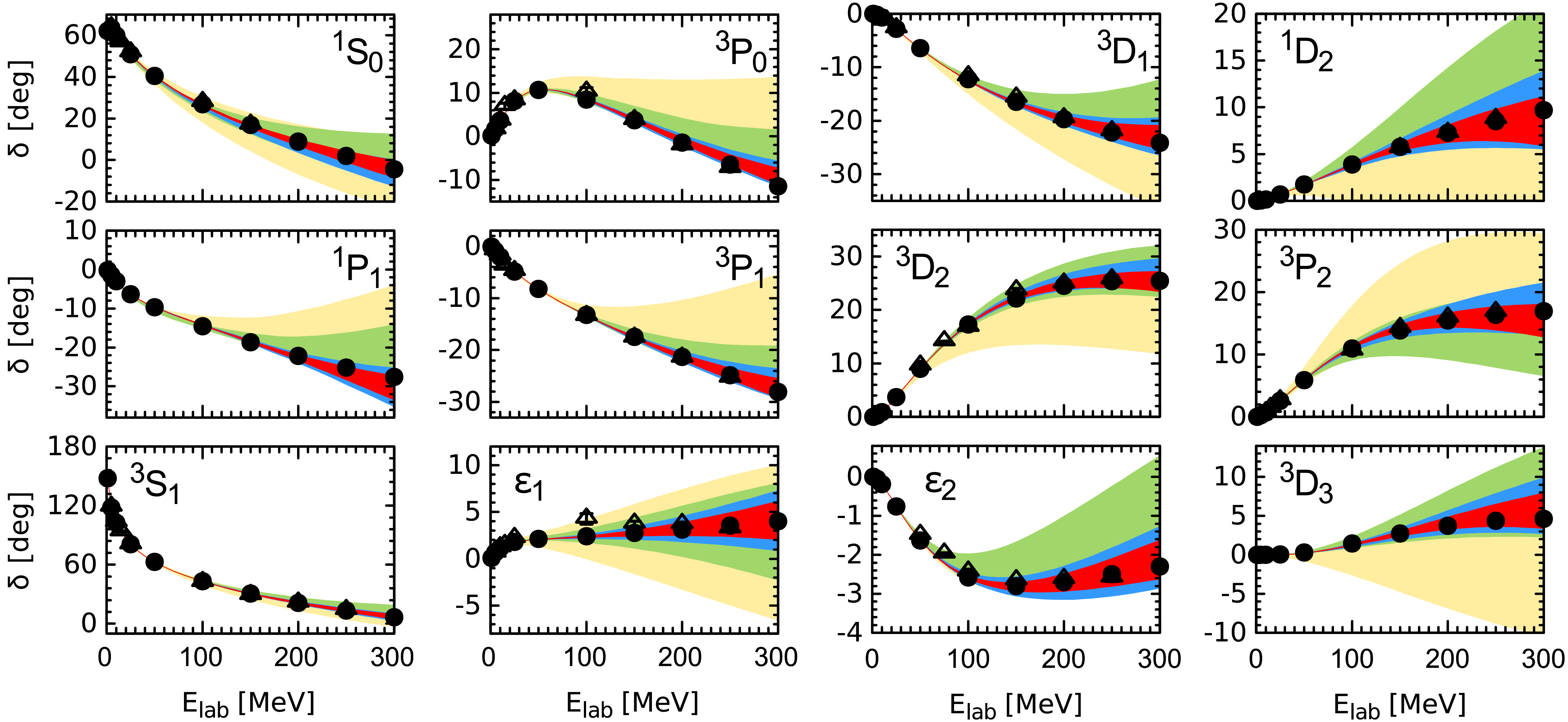
Short-range

$$V(\boldsymbol{k},\boldsymbol{k}') \to V(\boldsymbol{k},\boldsymbol{k}')f^{\Lambda}(k,k')$$

$$f^{\Lambda} = \exp\left(-(k'/\Lambda)^{2n} - (k/\Lambda)^{2n}\right)$$

Chiral potentials- Phase shifts

Phys. Rev. Lett. 115, 122301 (2015), Eur. Phys. J. A51, 53 (2015)



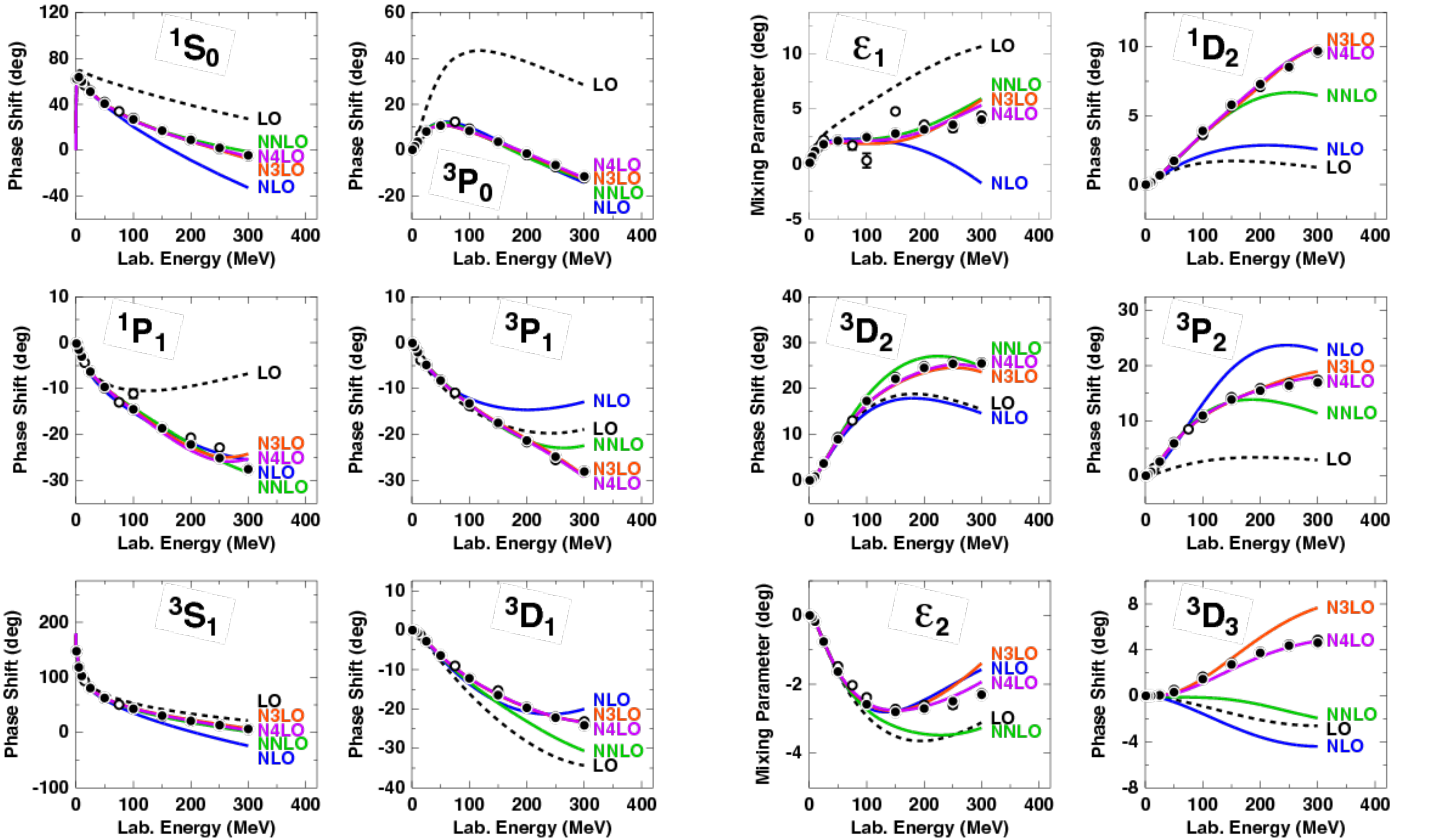
R = 0.9 fm — NLO — N²LO — N³LO — N⁴LO

New renormalisation technique in the coordinate space with the cutoff *R* being chosen in the range of *R = 0.8 . . . 1.2 fm.* For contact interactions, they use a non- local Gaussian regulator in momentum space with the cutoff $\Lambda = 2R^{-1}$

$$f\left(\frac{r}{R}\right) = \left[1 - \exp\left(-\frac{r^2}{R^2}\right)\right]^6$$

Chiral potentials- Phase shifts

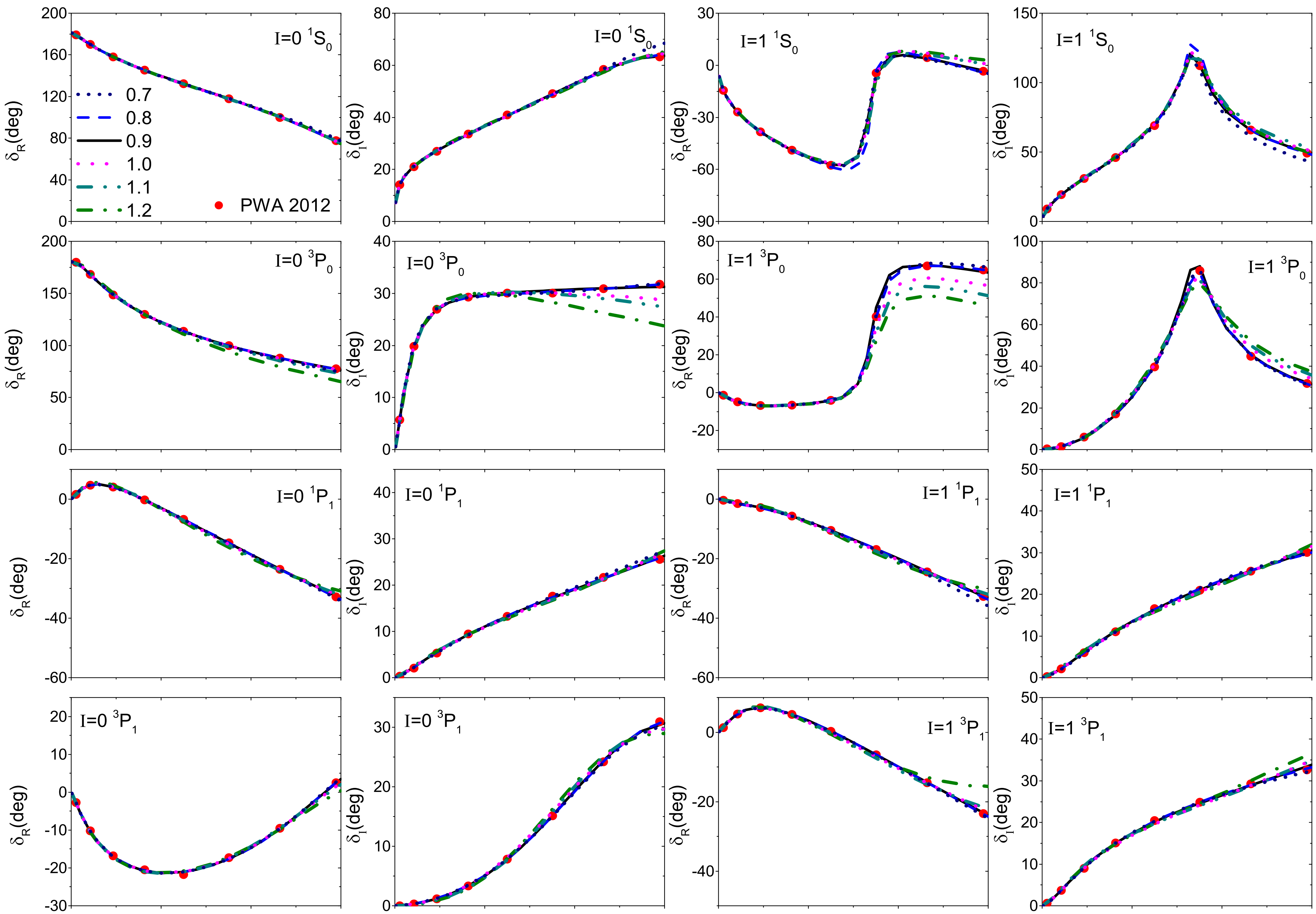
Phys. Rev. C91, 014002 (2015), Phys.Rev. C96 (2017)



Antinucleon-Nucleon Chiral potentials

Antinucleon-nucleon interaction at next-to-next-to-next-to-leading order in chiral effective field theory

Ling-Yun Dai, Johann Haidenbauer and Ulf-G. Meißner JHEP07(2017)078



Real and imaginary parts of various $\overline{N}N$ phase shifts at N^3LO for cutoffs $R = 0.7$–1.2 fm

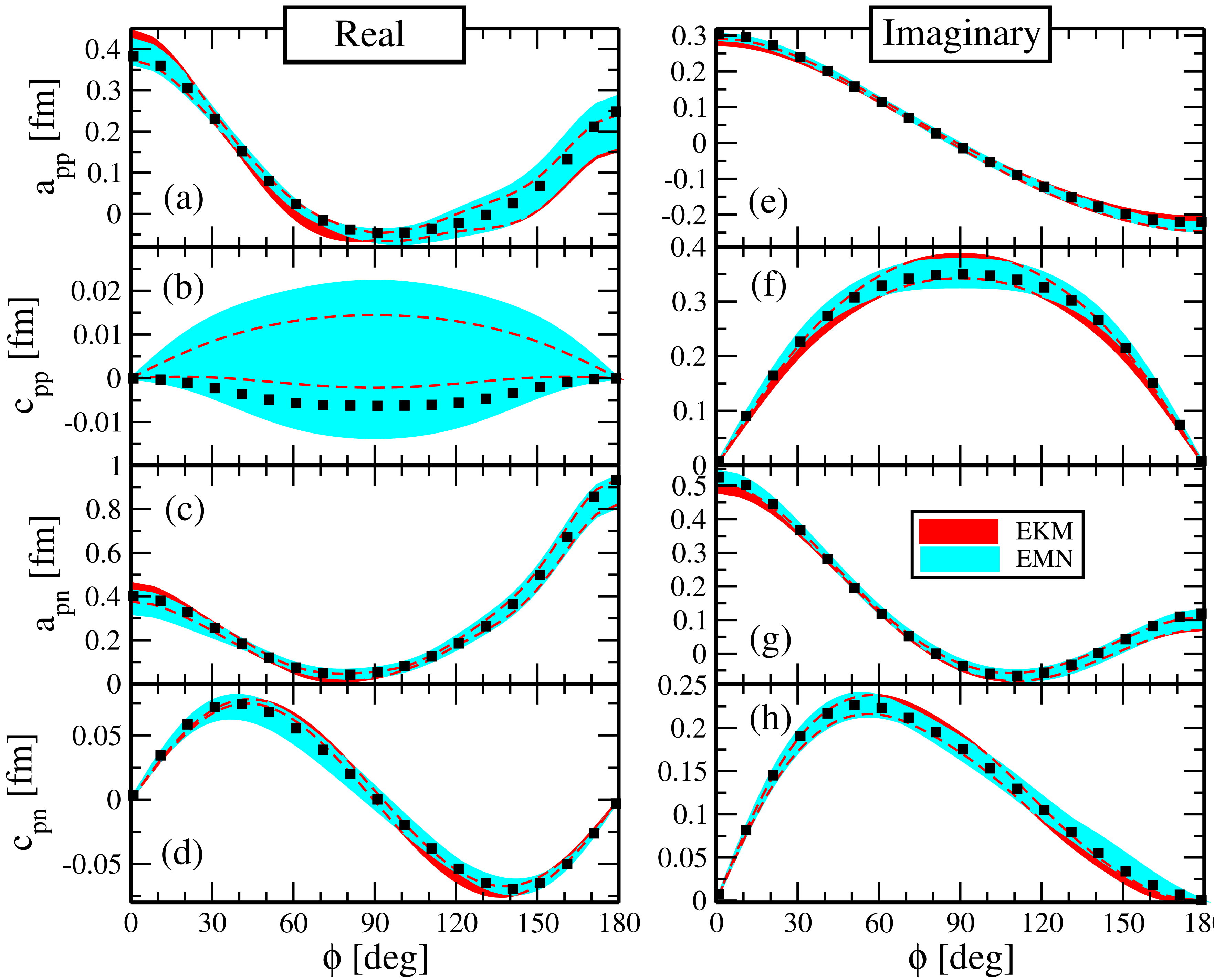
Results

NN amplitudes - 200 MeV

$$M(\boldsymbol{\kappa}', \boldsymbol{\kappa}, \omega) = \langle \boldsymbol{\kappa}' | M(\omega) | \boldsymbol{\kappa} \rangle = -4\pi^2 \mu \, \langle \boldsymbol{\kappa}' | t(\omega) | \boldsymbol{\kappa} \rangle$$

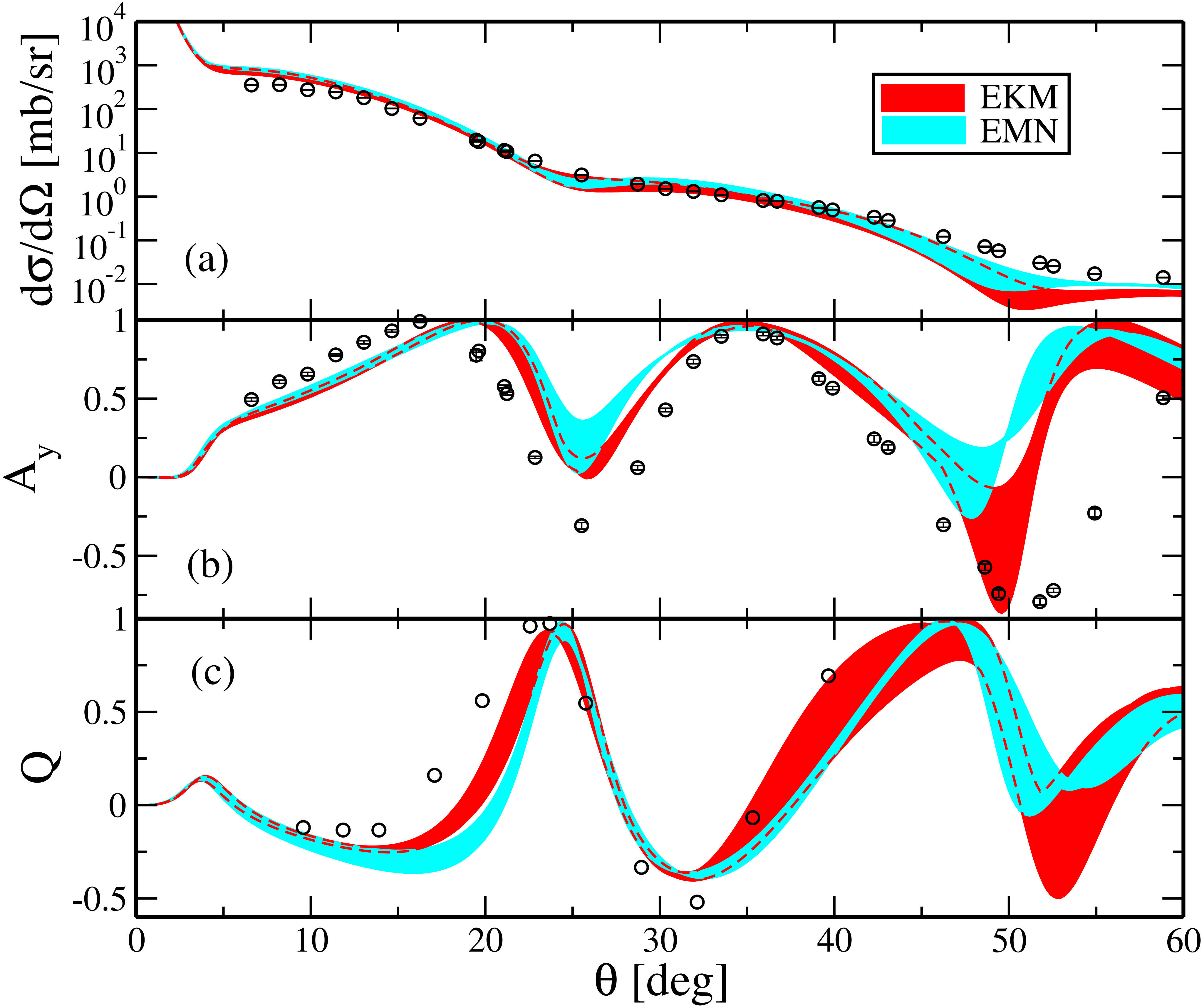
$$a_{pN} = \frac{1}{f_{pN}\pi^2} \sum_{L=0}^{\infty} P_L(\cos\phi) \Big[(2L+1)\, M_{LL}^{L,S=0} + (2L+1)\, M_{LL}^{L,S=1} + (2L+3)\, M_{LL}^{L+1,S=1} + (2L-1)\, M_{LL}^{L-1,S=1} \Big]$$

$$c_{pN} = \frac{i}{f_{pN}\pi^2} \sum_{L=1}^{\infty} P_L^1(\cos\phi) \left[\left(\frac{2L+3}{L+1}\right) M_{LL}^{L+1,S=1} - \left(\frac{2L+1}{L(L+1)}\right) M_{LL}^{L,S=1} - \left(\frac{2L-1}{L}\right) M_{LL}^{L-1,S=1} \right]$$



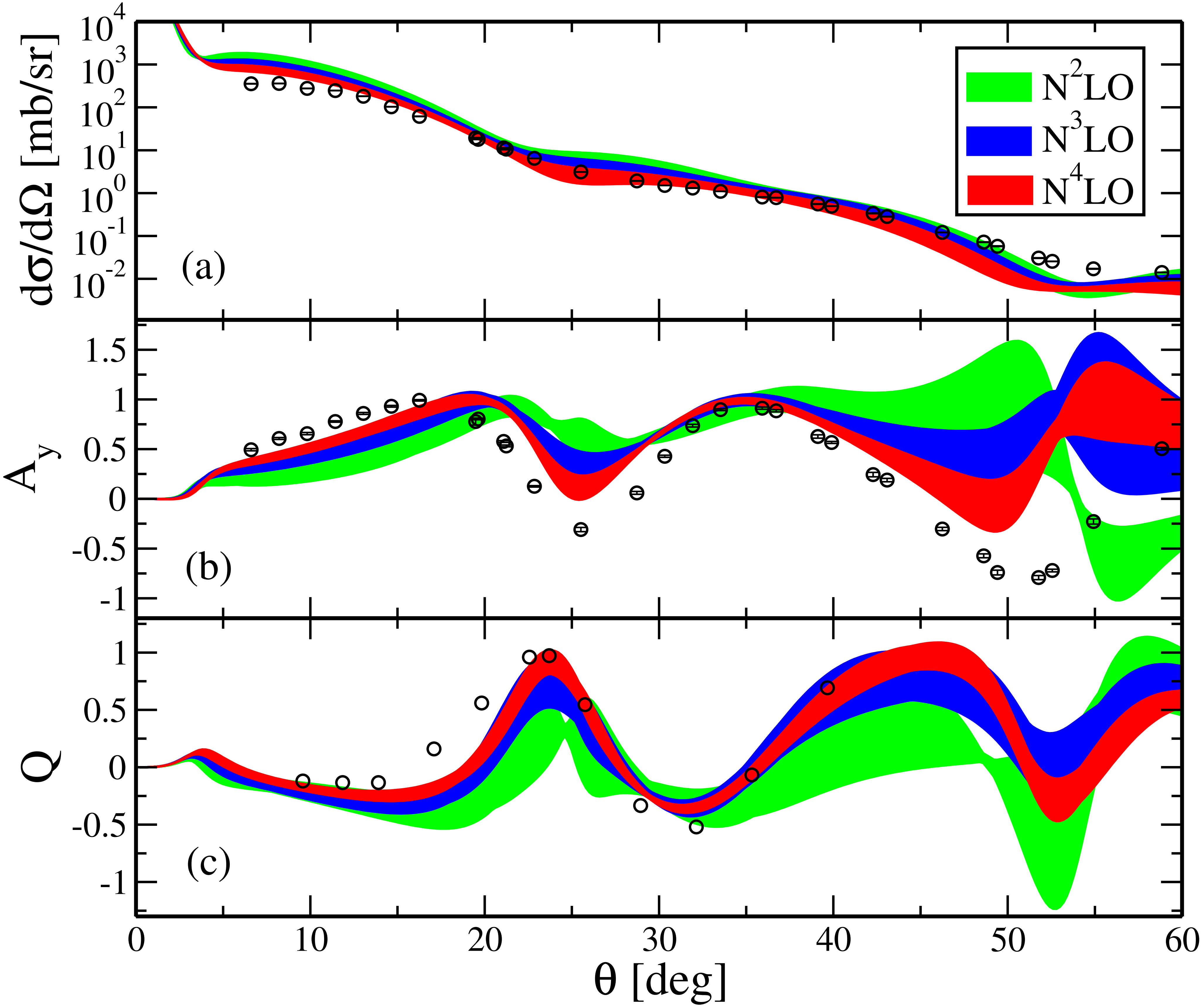
Phys. Rev. C 96 (2017) 044001

Oxygen 16



Phys. Rev. C 96 (2017) 044001

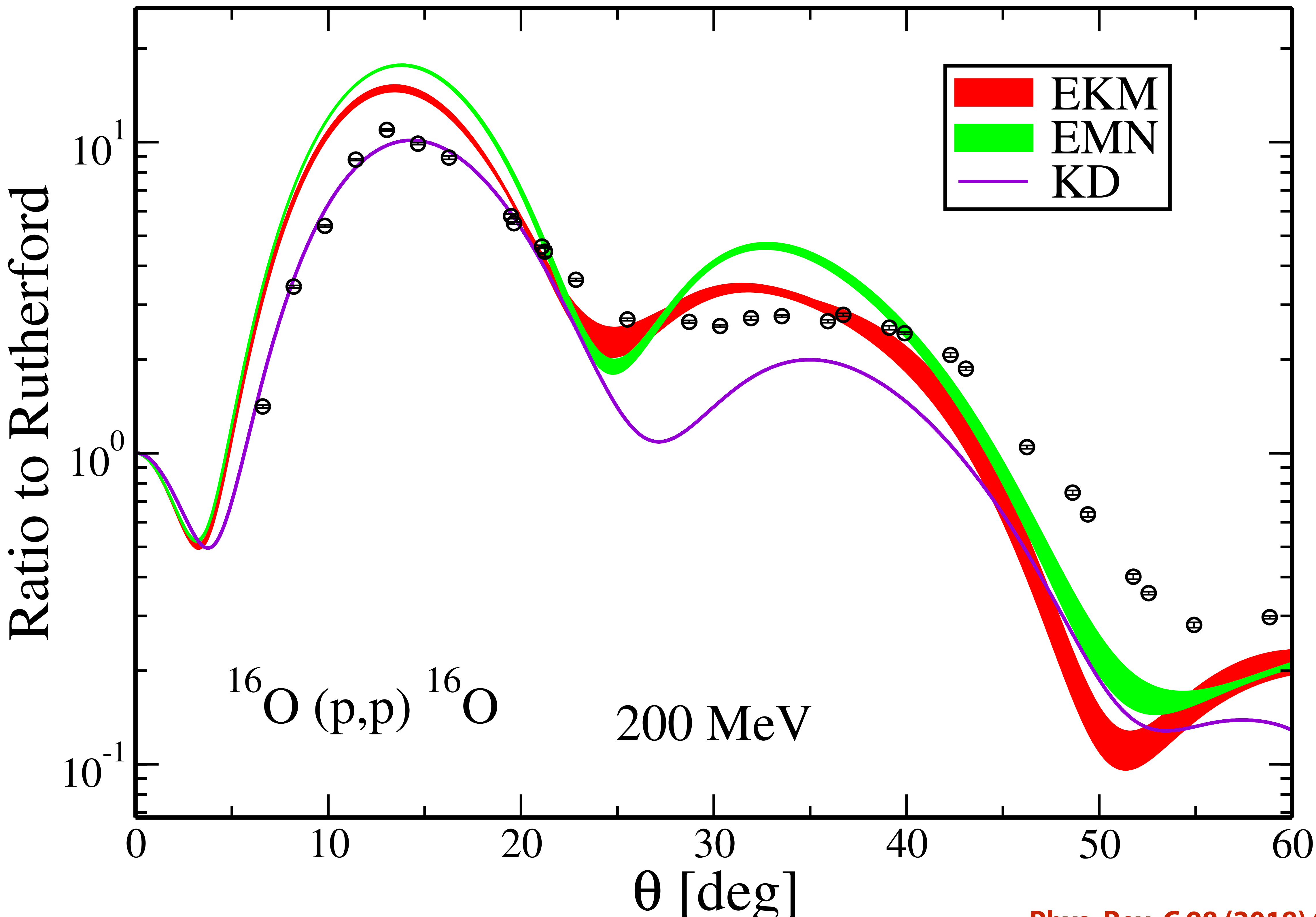
Oxygen 16



Phys. Rev. C 96 (2017) 044001

Microscopic vs. Phenomenological

KD: A. J. Koning and J. P. Delaroche, Nucl. Phys. A713, 231 (2003)



Phys. Rev. C 98 (2018) 064602

Microscopic vs. Phenomenological

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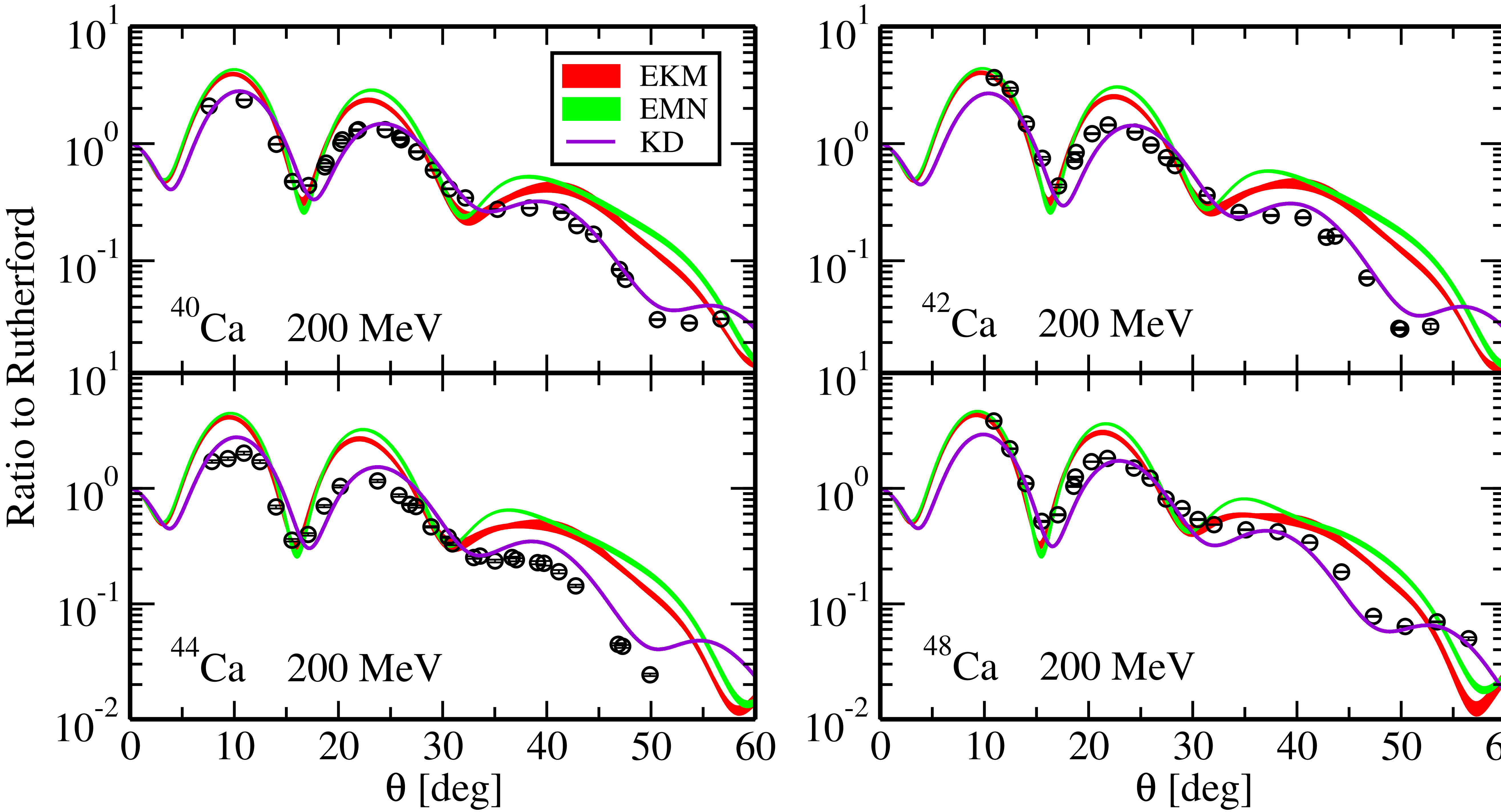

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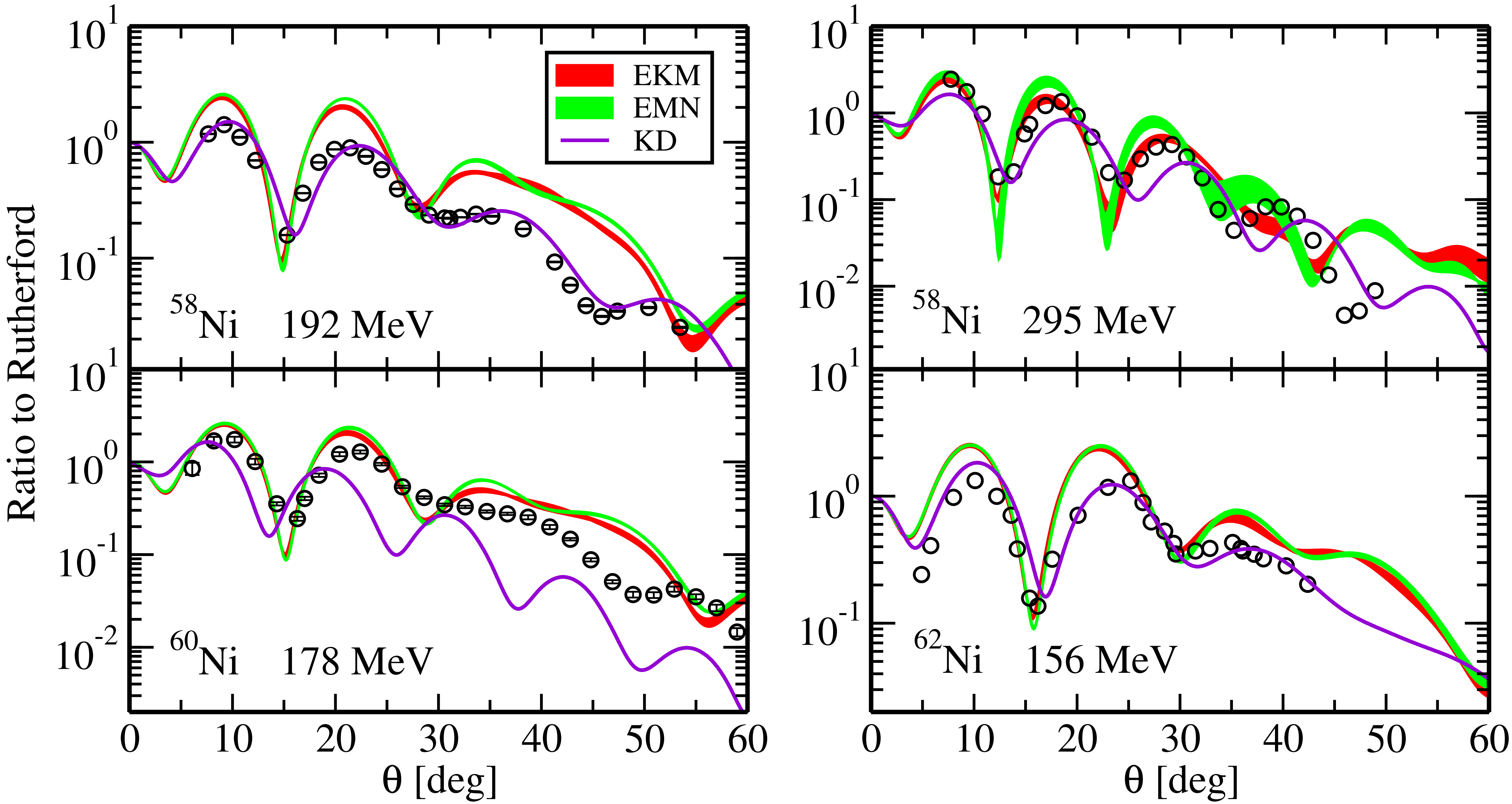
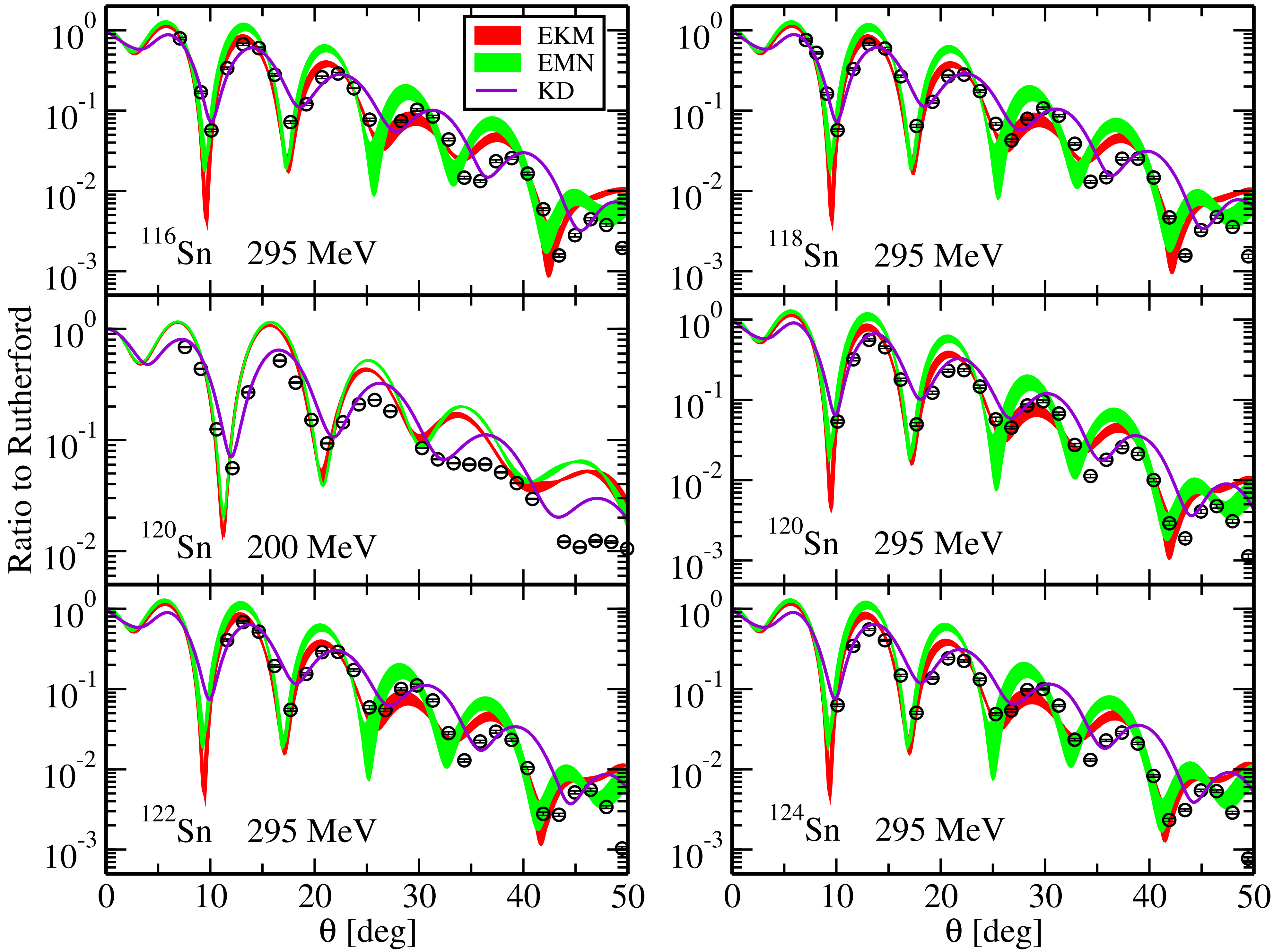


Phys. Rev. C 98 (2018) 064602

Microscopic vs. Phenomenological

KD: A. J. Koning and J. P. Delaroche, Nucl. Phys. A713, 231 (2003) and extension to 1GeV



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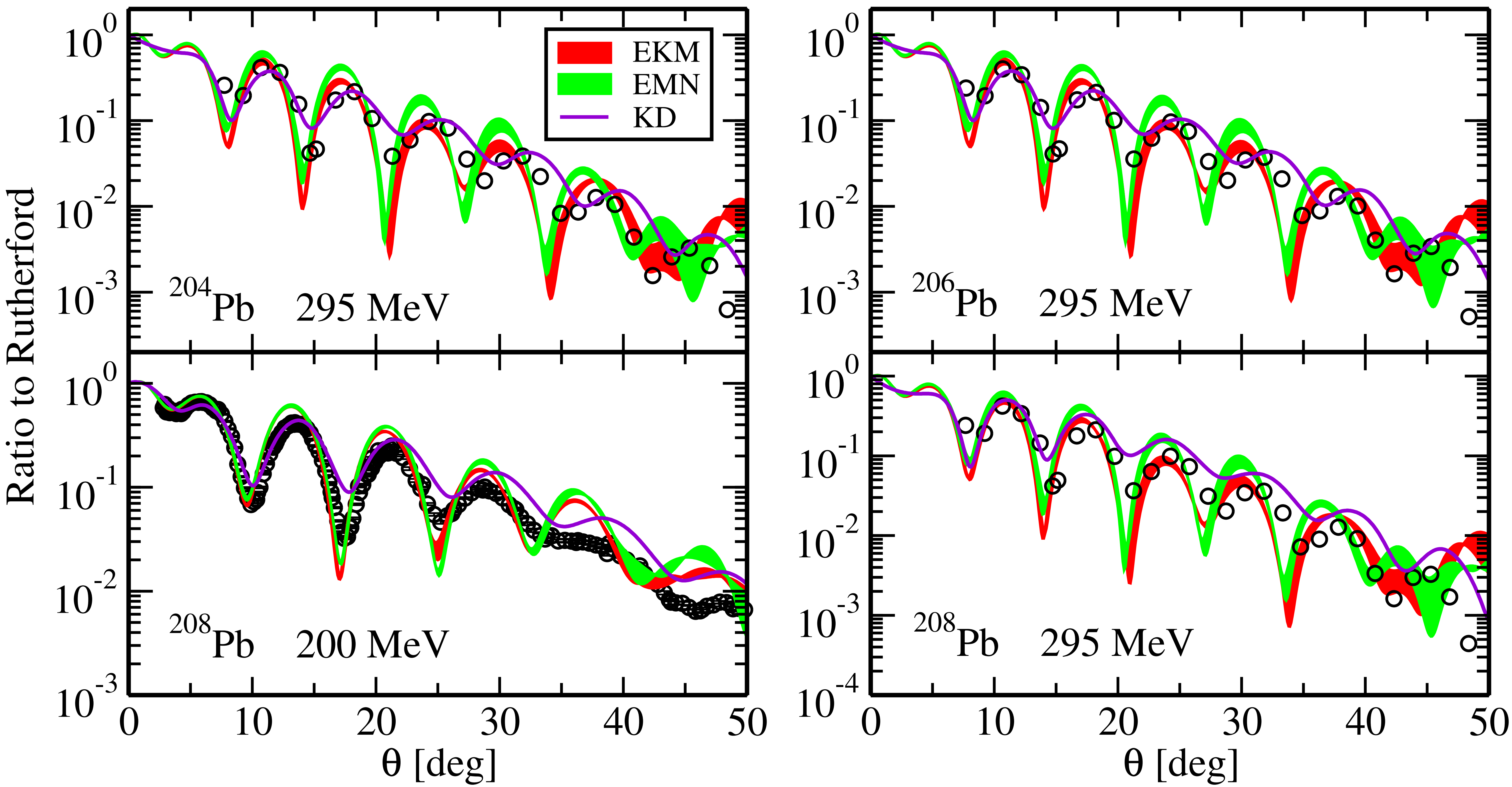

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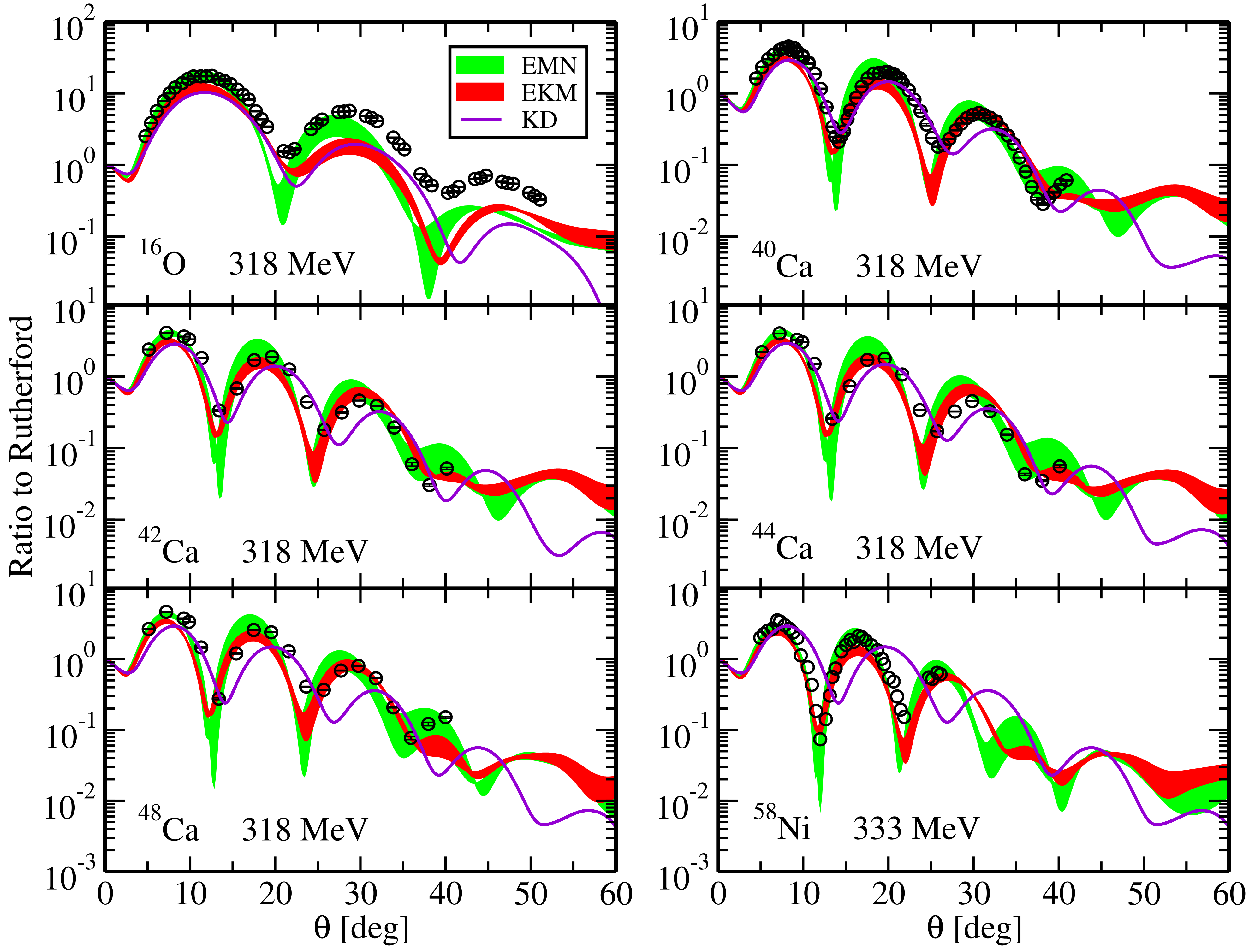

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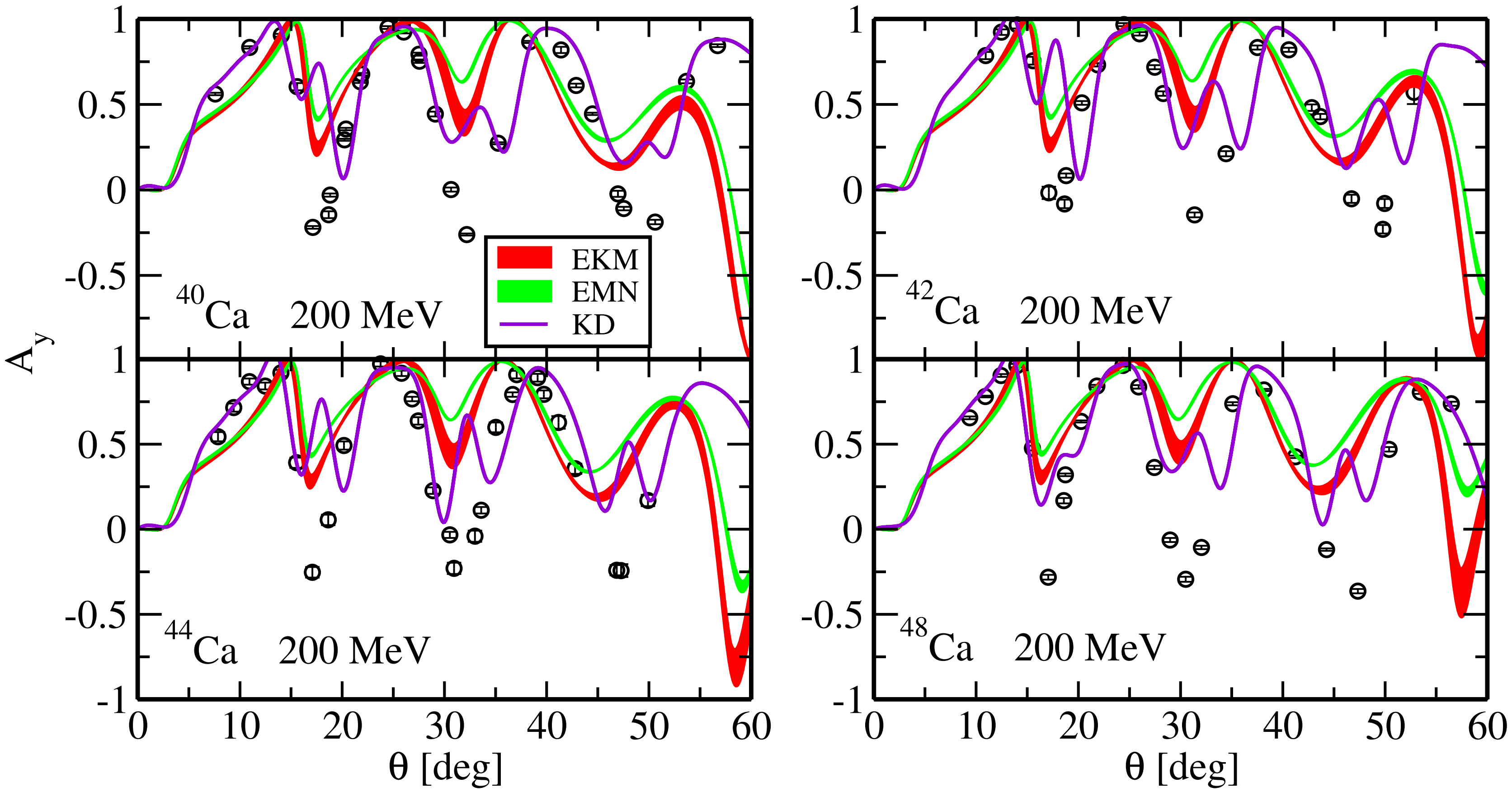

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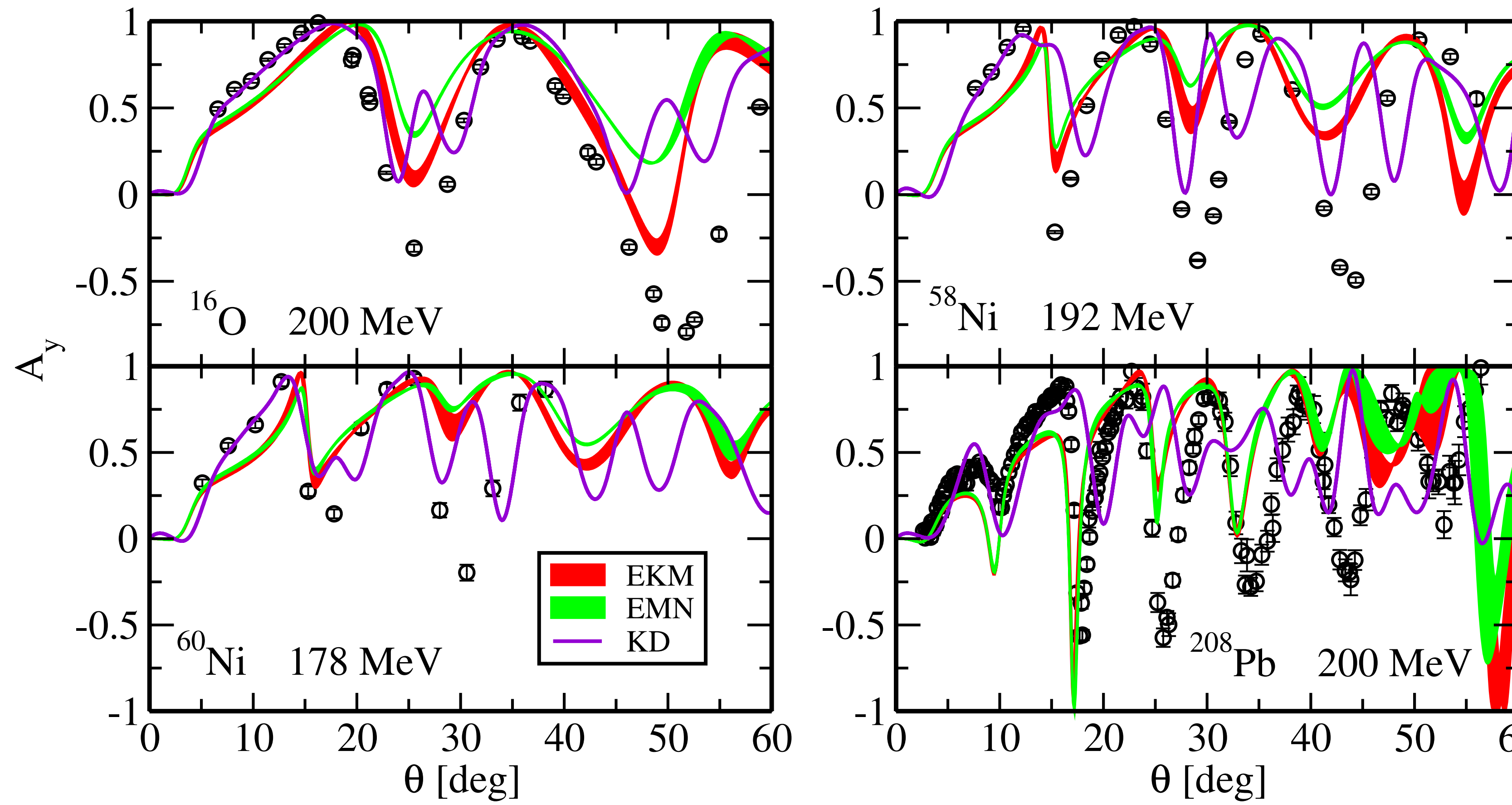

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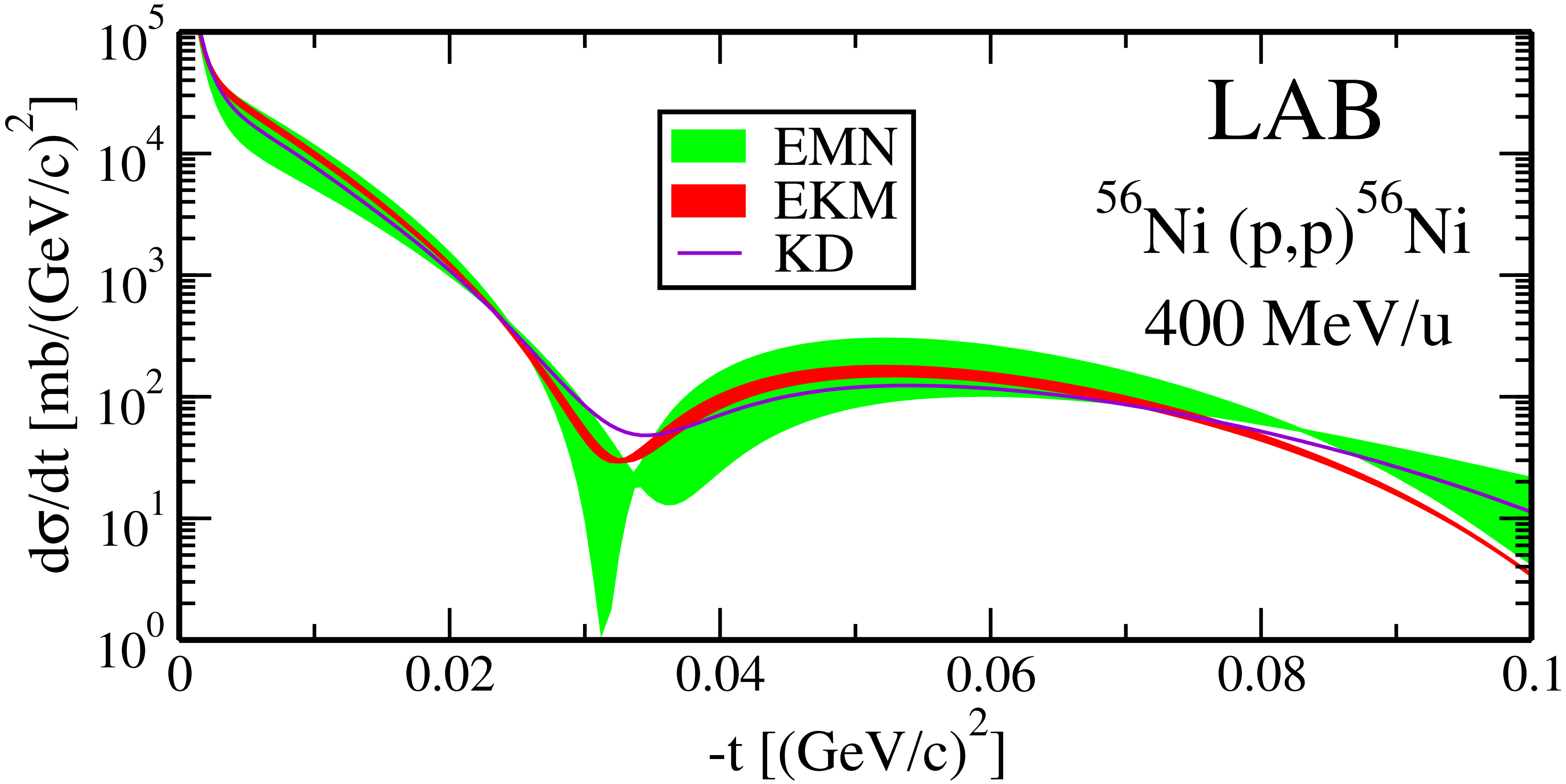

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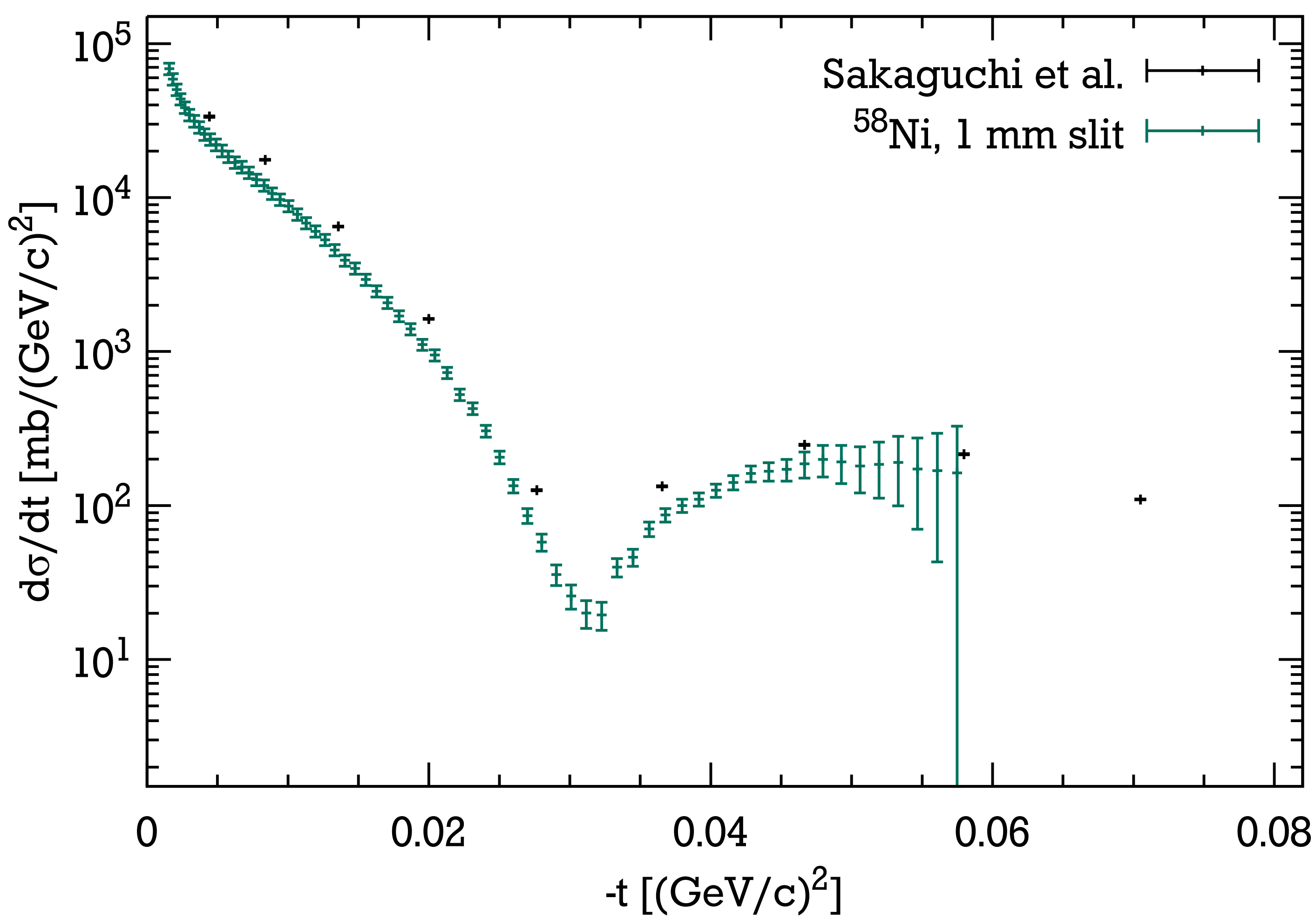



Nuclear matter distribution of ^{56}Ni measured with EXL

Kerndichteverteilung von ^{56}Ni gemessen mit EXL
Vom Fachbereich Physik der Technischen Universität Darmstadt zur Erlangung des Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.)
genehmigte Dissertation von Mirko von Schmid M.Sc. aus Fulda
2015 — Darmstadt — D 17

TECHNISCHE UNIVERSITÄT DARMSTADT

Fachbereich Physik
Institut für Kernphysik
AG Kröll

Antiproton

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

$$\times\, \rho_N\left(\boldsymbol{P} - \frac{A-1}{2A}\boldsymbol{q}, \boldsymbol{P} + \frac{A-1}{2A}\boldsymbol{q}\right)$$

Projectiles

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

$$\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$$

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

Basic ingredients

- (Anti)nucleon-nucleon scattering matrix $t_{\alpha N}$
- Non-local nuclear densities

$$\rho_{\mathrm{op}} = \sum_{i=1}^{A} \delta(\boldsymbol{r} - \boldsymbol{r}_i)\delta(\boldsymbol{r}' - \boldsymbol{r}'_i)$$

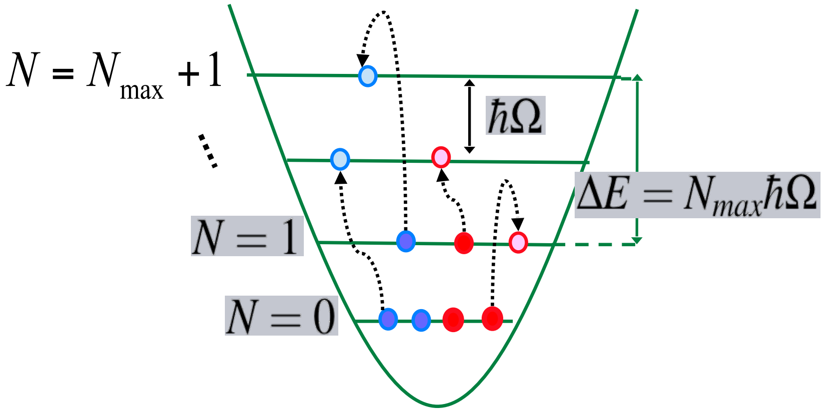
The matrix elements between a general initial and final state are obtained from the NCSM PRC **97**, 034619 (2018)

- **Target density**
  NN - N^{4}LO500 Entem, Machleidt, Nosyk, PRC **96** 024004 (2017)
  + 3N - N^{2}LO Navratil, Few-Body Syst. **41** 117 (2007)

- **Scattering matrix**
  – N^{3}LO Dai, Haidenbauer, Meißner, JHEP **2017**, 78 (2017)
  - ➢ Local regulator for the long range part: $R = 0.9$ fm
  - ➢ Non-local regulator for the contact terms: $\Lambda = 2\, R^{-1}$
  - ➢ The interaction is connected to the NN one through the G-parity in an unambiguous way

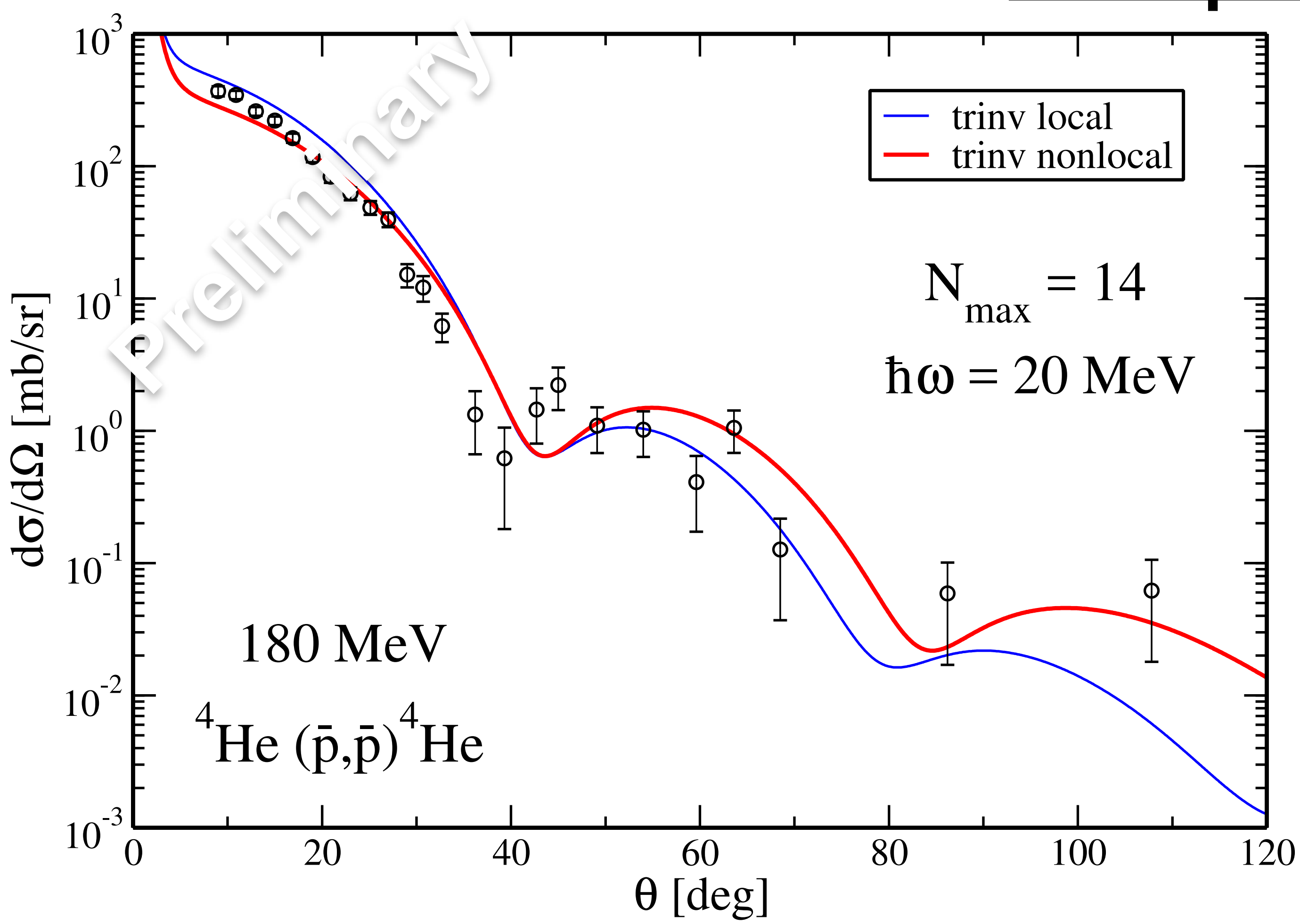
NCSM

$$|\Psi_A^{J^\pi T}\rangle = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni}^{J^\pi T} |ANiJ^\pi T\rangle$$



In collaboration with P. Navratil (TRIUMF), to appear soon

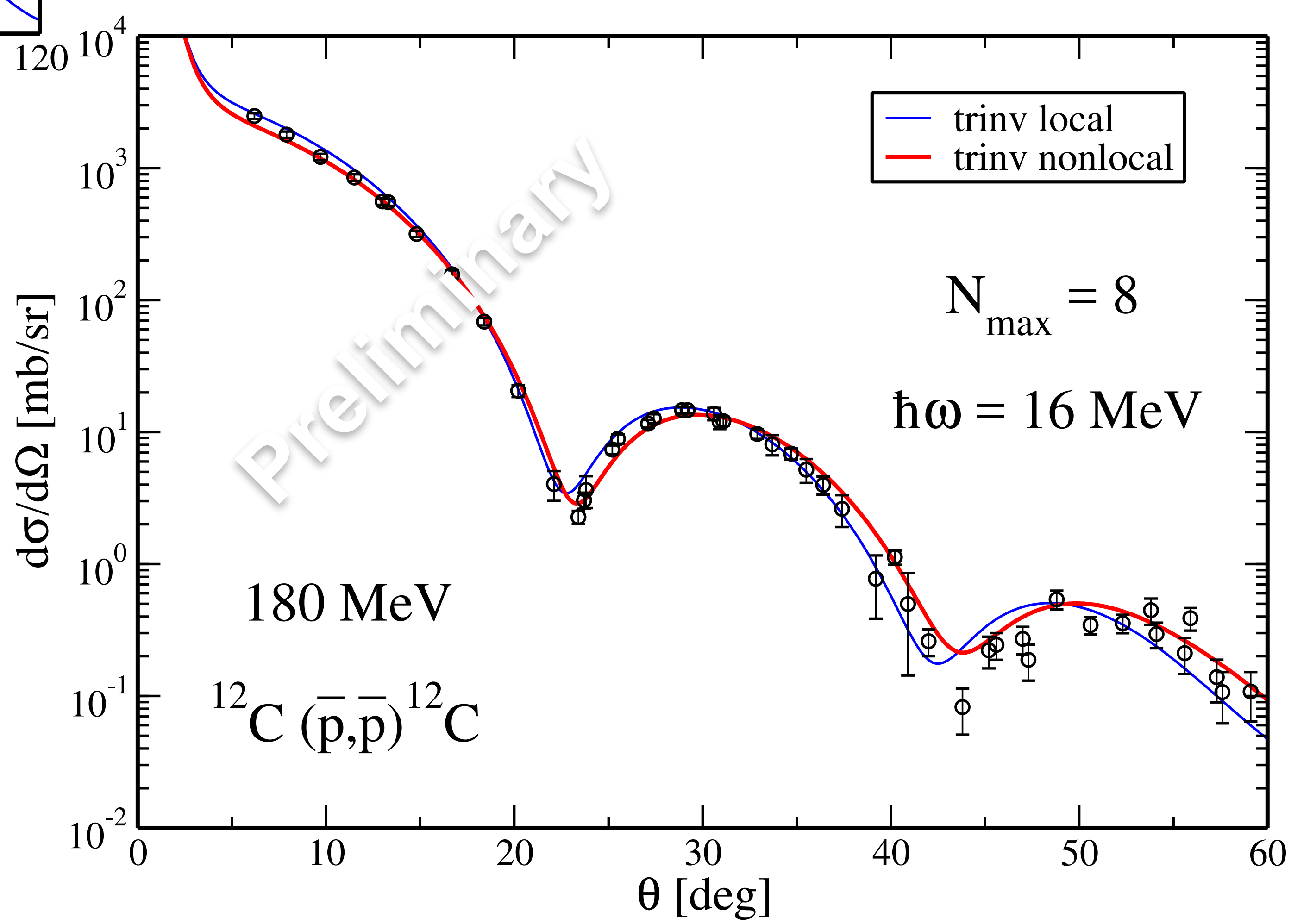
Antiproton



Experimental data are from the LEAR collaboration at CERN

Local: factorized optical potential

$$U(\boldsymbol{q}, \boldsymbol{K}; E) \sim \sum_{\alpha=n,p} t_{p\alpha}\left[\boldsymbol{q}, \frac{A+1}{2A}\boldsymbol{K}; E\right]\rho_\alpha(q)$$



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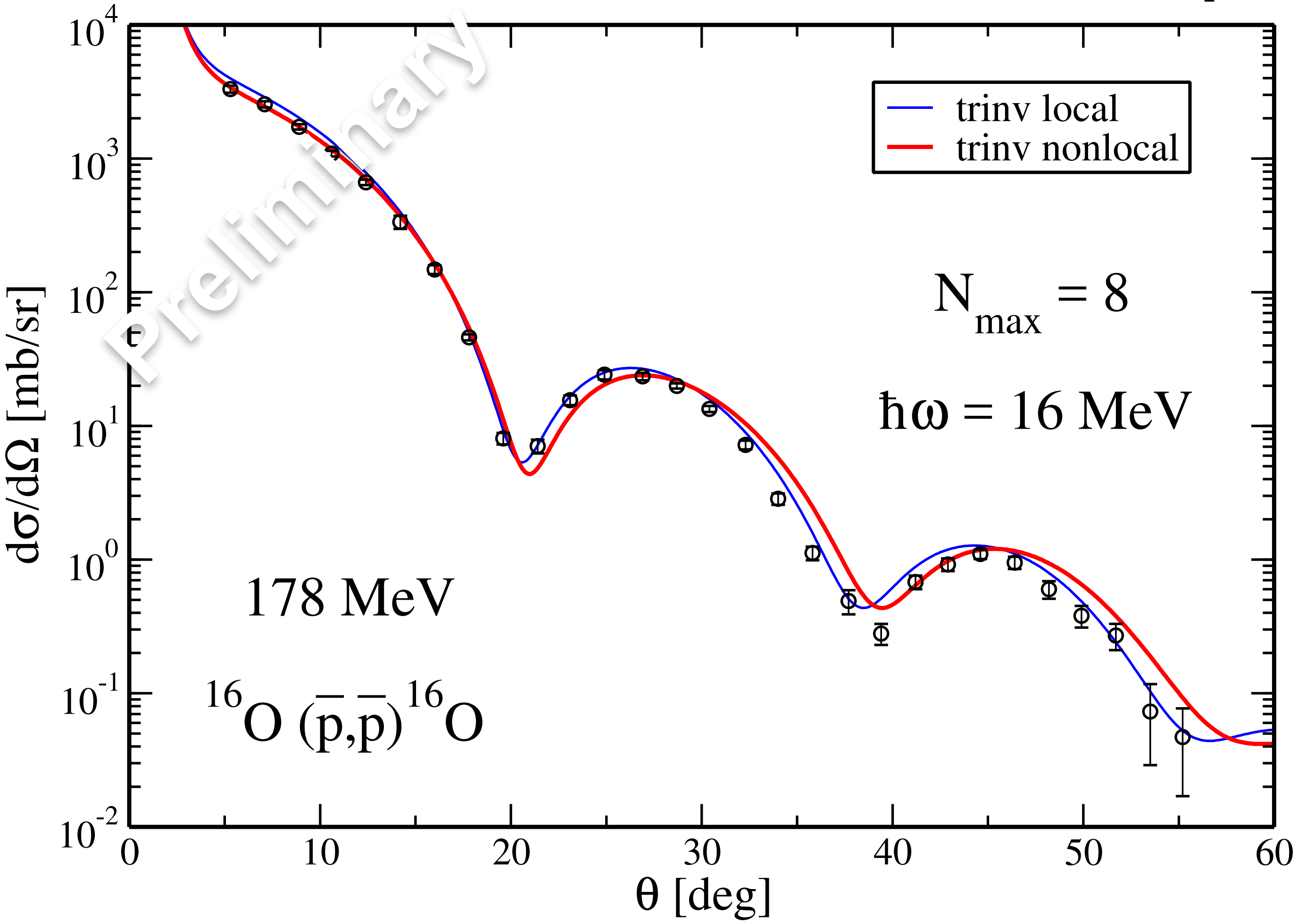
Antiproton



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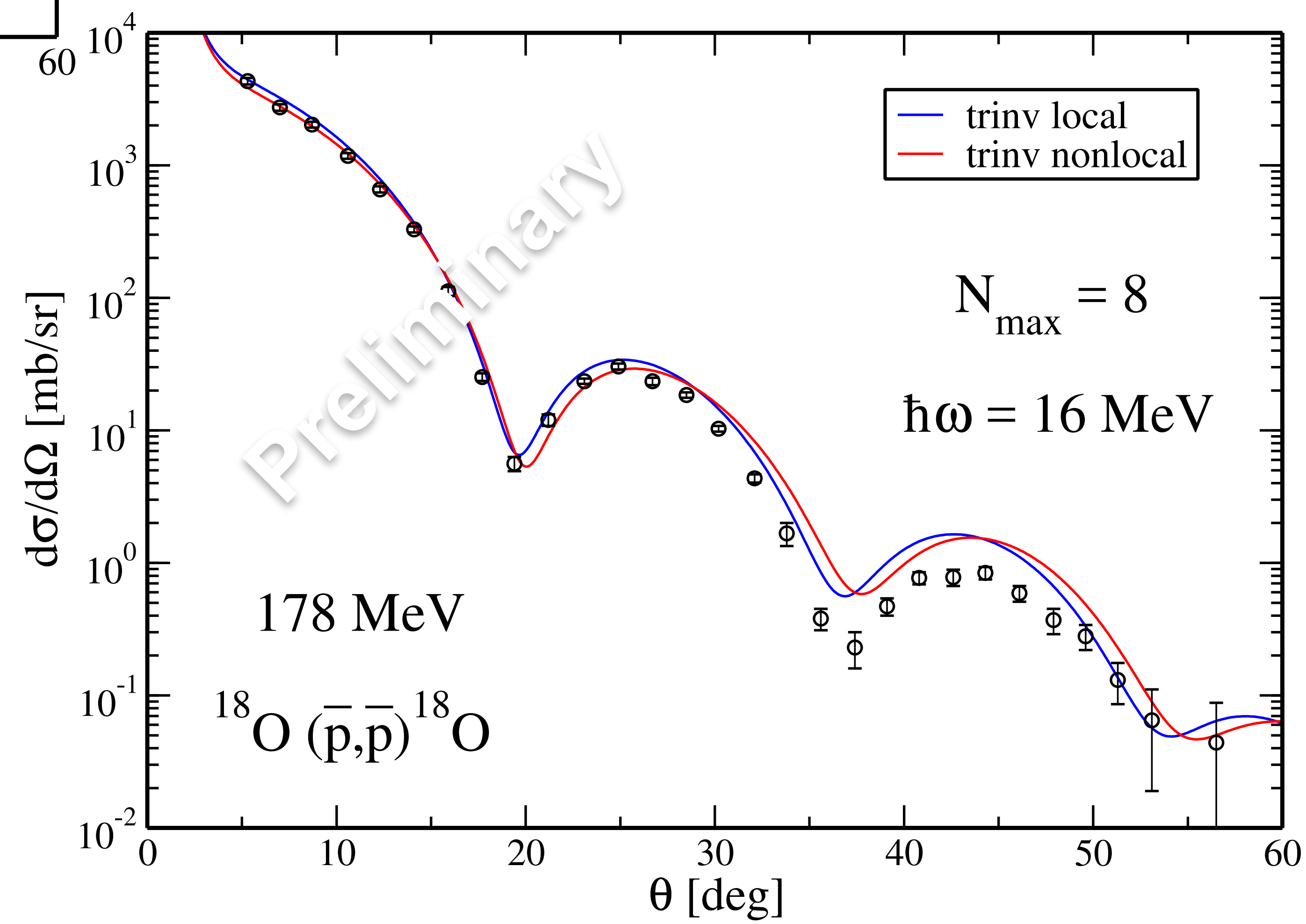
Factorized optical potential

$$U(\boldsymbol{q},\boldsymbol{K};E) \sim \sum_{\alpha=n,p} t_{p\alpha}\left[\boldsymbol{q},\frac{A+1}{2A}\boldsymbol{K};E\right]\rho_\alpha(q)$$



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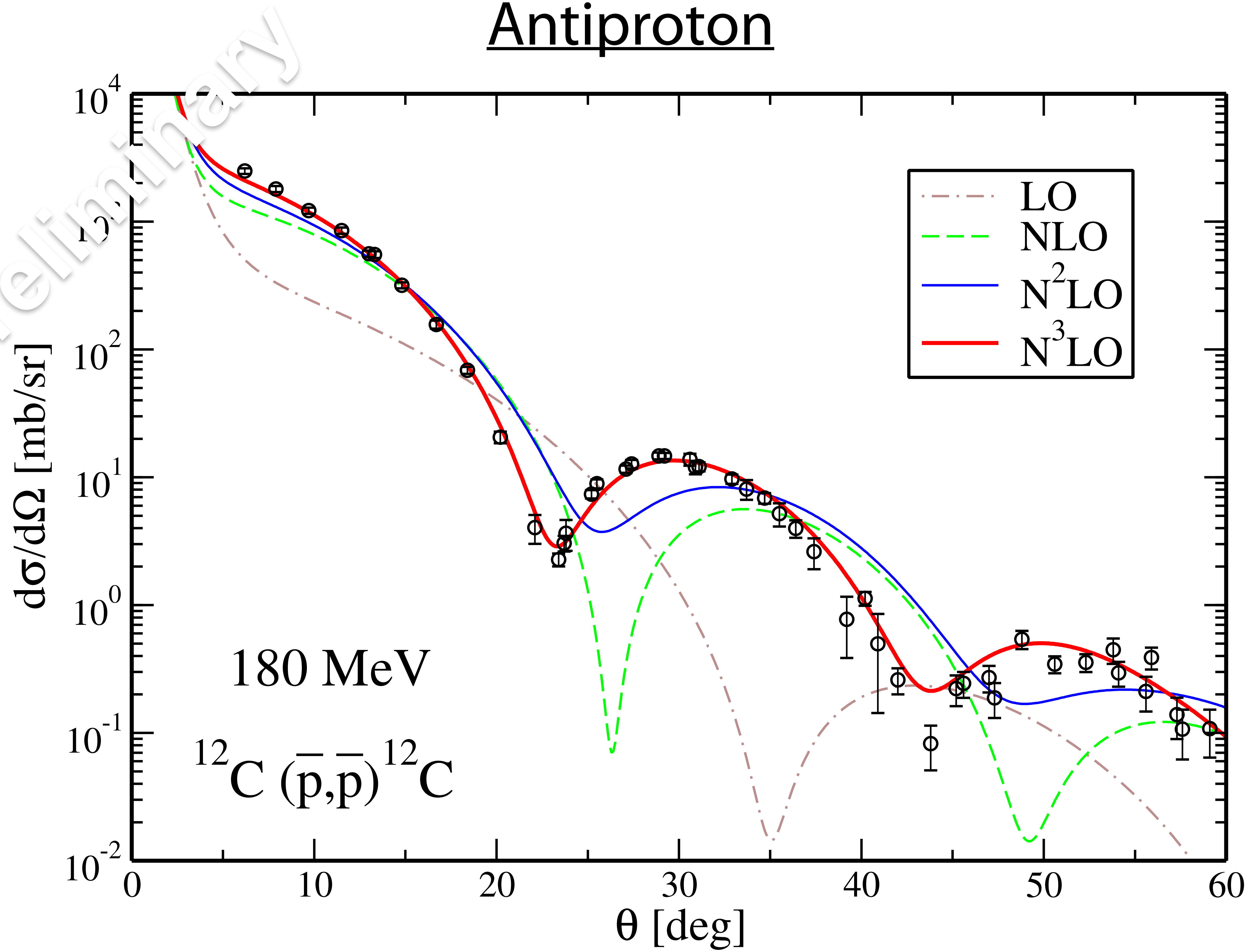

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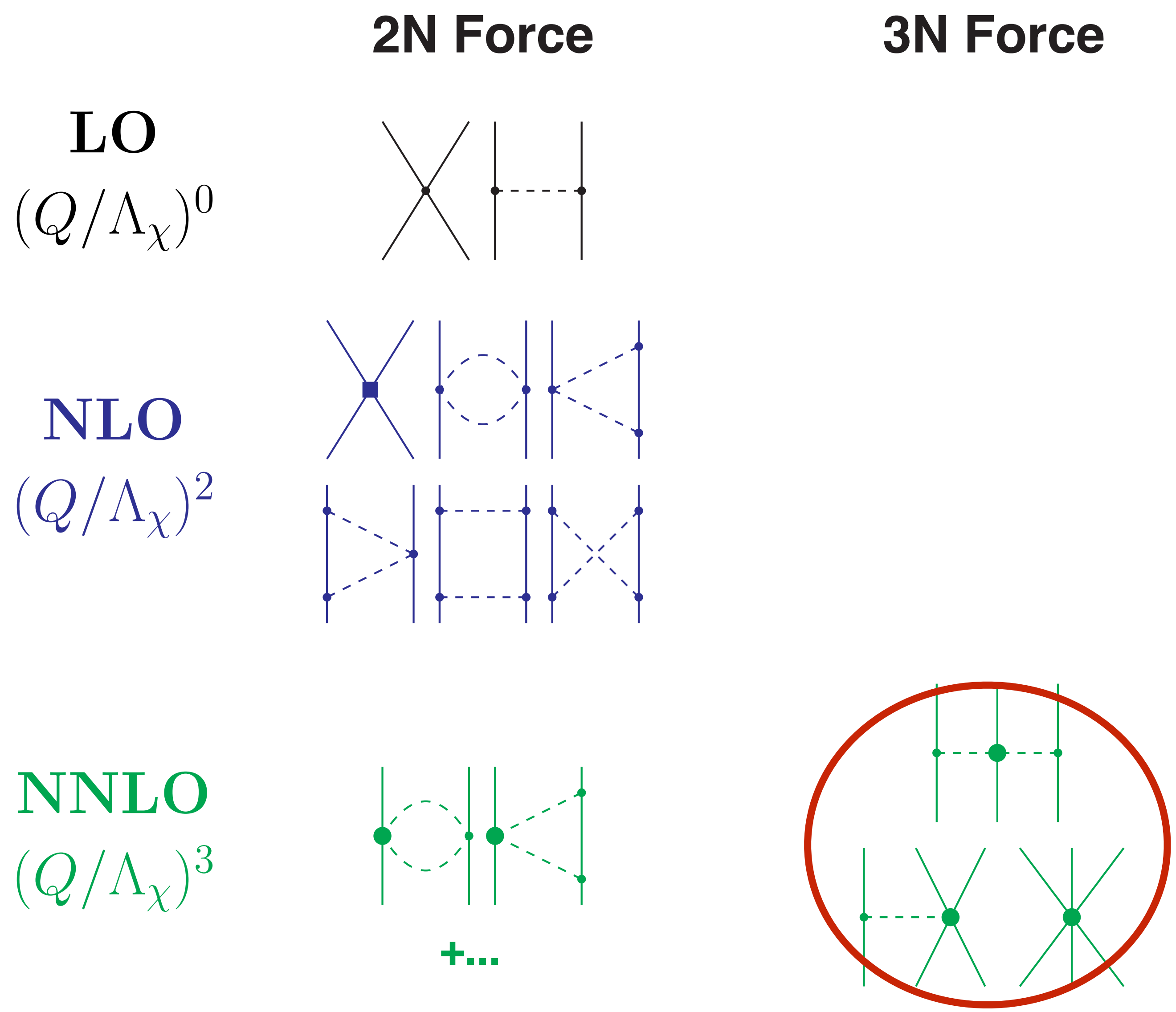
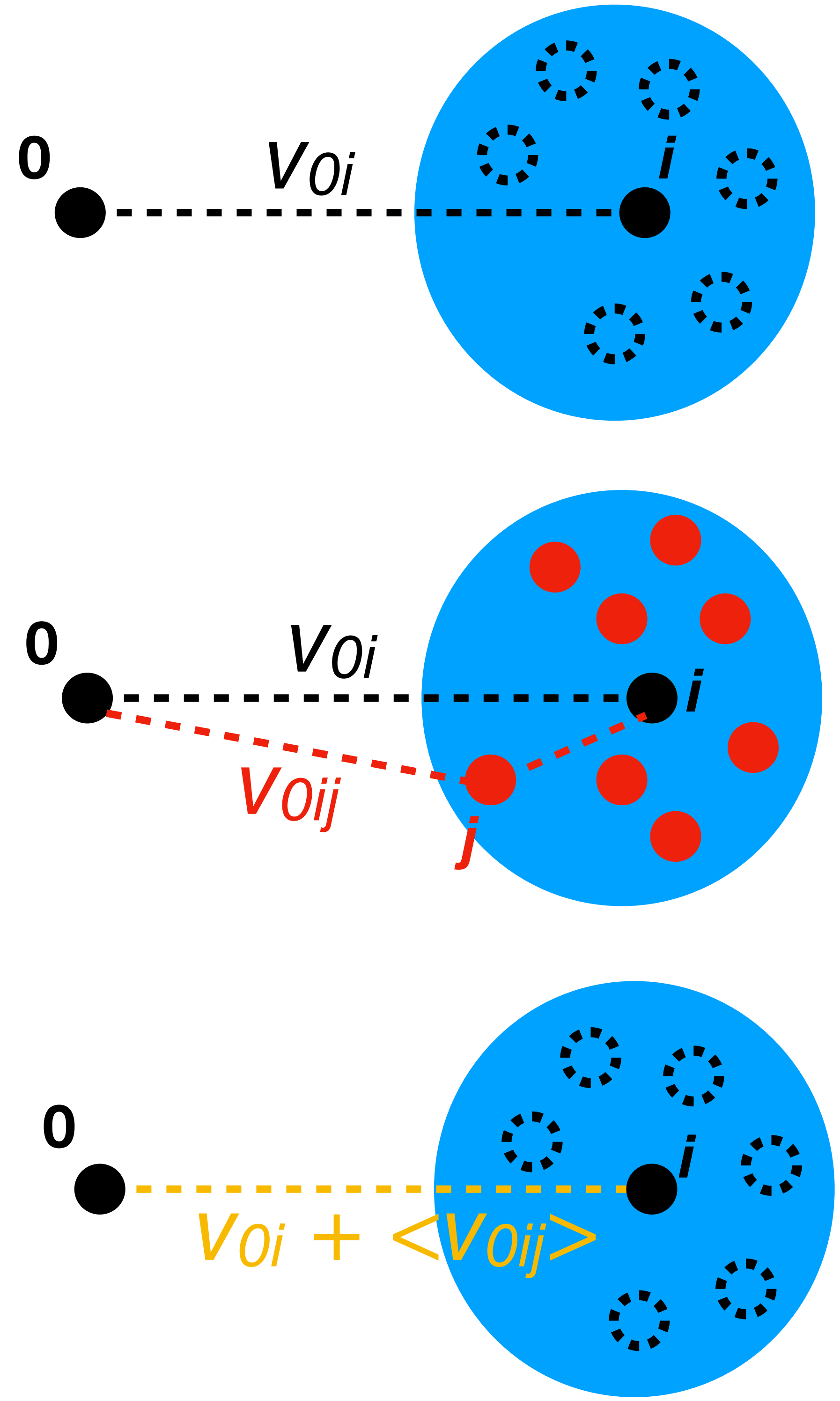
Future

Include three-body forces and medium effects





- Contribution to the potential through a density-dependent two body forces
- To be consistent, also medium corrections to the propagator should be included
- Not consistent with the perturbative order of the two-body sector (N4LO)

In collaboration with R. Machleidt (Idaho), work in progress

Thank you very much