Faddeev-type calculations of three- and four-body nuclear reactions

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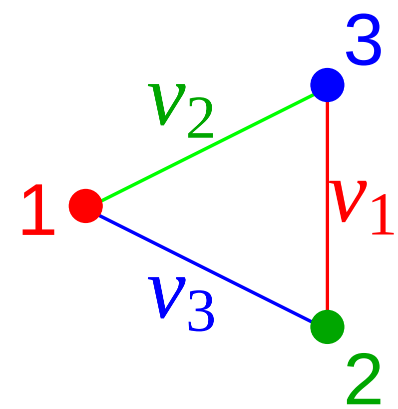
Few-body scattering

- Three-body scattering equations
- Inclusion of the Coulomb interaction

- Three-nucleon system
- Three-body direct nuclear reactions

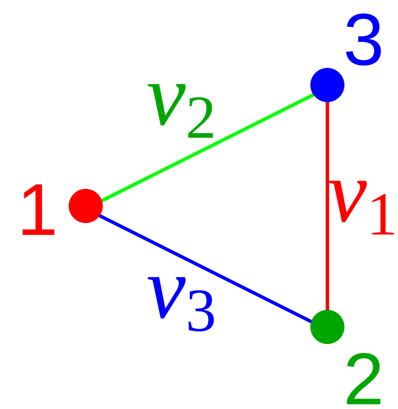
- Four-nucleon scattering

Three-body system



Hamiltonian $H_0 + \sum_{\alpha} v_\alpha$

Three-body system



Hamiltonian $H_0 + \sum_{\alpha} v_{\alpha}$

- Faddeev equations

$$(E - H_0 - v_{\alpha})|\psi_{\alpha}\rangle = v_{\alpha} \sum_{\sigma} \bar{\delta}_{\alpha\sigma} |\psi_{\sigma}\rangle$$

$$|\Psi\rangle = \sum_{\alpha} |\psi_{\alpha}\rangle$$

Alt-Grassberger-Sandhas equations

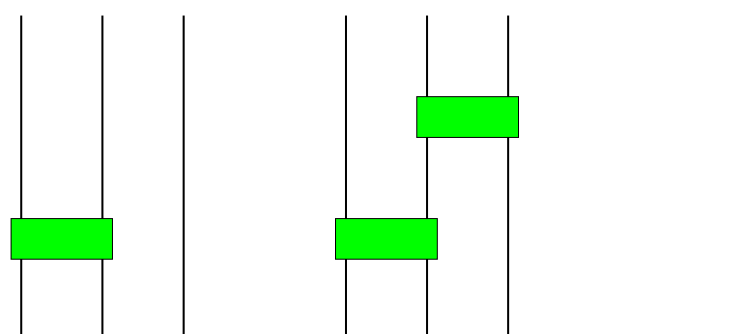
$$U_{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_{\sigma} \bar{\delta}_{\beta\sigma} T_{\sigma} G_0 U_{\sigma\alpha}$$

$$U_{0\alpha} = G_0^{-1} + \sum_{\sigma} T_{\sigma} G_0 U_{\sigma\alpha}$$

$$T_{\sigma} = v_{\sigma} + v_{\sigma} G_0 T_{\sigma}$$

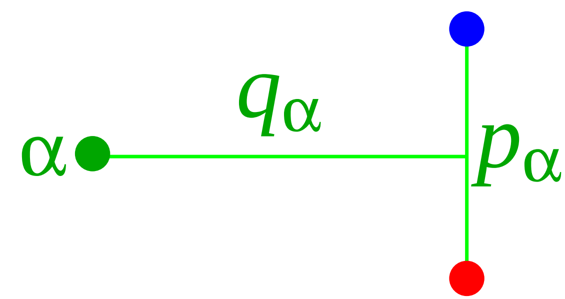
$$G_0 = (E + i0 - H_0)^{-1}$$

channel states $(E - H_0 - v_{\alpha})|\phi_{\alpha}\rangle = 0$



AGS equations: numerical solution

$$U_{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_{\sigma} \bar{\delta}_{\beta\sigma} T_{\sigma} G_0 U_{\sigma\alpha}$$



- 3 sets of Jacobi momenta
- momentum-space partial wave basis
- set of coupled 2-variable integral equations
- integrable singularities in kernel
- Gaussian integration, spline interpolation, Padé summation

Inclusion of Coulomb: screening

$$w_R(r) = \frac{\alpha_e}{r}\, e^{-\left(\frac{r}{R}\right)^n}$$

- standard scattering theory

$$v_\sigma \longrightarrow v_\sigma + w_{\sigma R} : \quad T_\sigma,\, U_{\beta\alpha} \longrightarrow T_\sigma^{(R)},\, U_{\beta\alpha}^{(R)}$$

Inclusion of Coulomb: screening

$$w_R(r) = \frac{\alpha_e}{r}\, e^{-\left(\frac{r}{R}\right)^n}$$

- standard scattering theory

  $v_\sigma \longrightarrow v_\sigma + w_{\sigma R}: \quad T_\sigma,\, U_{\beta\alpha} \longrightarrow T_\sigma^{(R)},\, U_{\beta\alpha}^{(R)}$
- nature: Coulomb is screened at large distances
- large R:
  physical observables insensitive to screening,
  screened and full Coulomb physically indistinguishable
- calculations: $R \to \infty$

Screening and renormalization

J. R. Taylor, Nuovo Cimento **B23**, *313 (1974),*
V. G. Gorshkov, Sov. Phys.-JETP **13**, *1037 (1961)*:

Renormalization of the on-shell screened Coulomb transition matrix $T_R = w_R + w_R G_0 T_R$ and wave function

$$T_R z_R^{-1} \xrightarrow[R\to\infty]{} T_C \quad \text{as distribution}$$

$$(1 + G_0 T_R)|\mathbf{p}\rangle z_R^{-\frac{1}{2}} \xrightarrow[R\to\infty]{} |\psi_C^{(+)}(\mathbf{p})\rangle$$

in the limit $R \to \infty$ yields Coulomb amplitude and Coulomb wave function

$$z_R \xrightarrow[R\to\infty]{} \exp(-2i(\sigma_L - \eta_{LR})) \xrightarrow[R\to\infty]{} \exp(-2i\alpha_e M/p\, [\ln(2pR) - C/n])$$

Two-particle scattering

transition matrix

$$T^{(R)} = v + w_R + (v + w_R) G_0 T^{(R)}$$

with long-range and Coulomb-distorted short-range parts

$$T^{(R)} = T_R + (1 + T_R G_0) \tilde{T}^{(R)} (1 + G_0 T_R)$$

$$\tilde{T}^{(R)} = v + v G_R \tilde{T}^{(R)}$$

Two-particle scattering

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$$T^{(R)} = T_R + (1 + T_R G_0) \tilde{T}^{(R)} (1 + G_0 T_R)$$
$$\tilde{T}^{(R)} = v + v G_R \tilde{T}^{(R)}$$

Renormalized amplitude:

$$T^{(R)} z_R^{-1} \xrightarrow[R \to \infty]{} T = T_C + \langle \psi_C^{(-)} | \tilde{T}^{(C)} | \psi_C^{(+)} \rangle$$
$$= T_C + \lim_{R \to \infty} z_R^{-\frac{1}{2}} [T^{(R)} - T_R] z_R^{-\frac{1}{2}}$$

short-range part: fast convergence with R

Three-particle scattering

Split into long-range part

$$T^{\text{c.m.}}_{\alpha R} = W^{\text{c.m.}}_{\alpha R} + W^{\text{c.m.}}_{\alpha R} G^{(R)}_{\alpha} T^{\text{c.m.}}_{\alpha R}$$

and Coulomb-distorted short-range part

$$U^{(R)}_{\beta\alpha} = \delta_{\beta\alpha} T^{\text{c.m.}}_{\alpha R} + [U^{(R)}_{\beta\alpha} - \delta_{\beta\alpha} T^{\text{c.m.}}_{\alpha R}]$$

$$[U^{(R)}_{\beta\alpha} - \delta_{\beta\alpha} T^{\text{c.m.}}_{\alpha R}] = [1 + T^{\text{c.m.}}_{\beta R} G^{(R)}_{\beta}] \tilde{U}^{(R)}_{\beta\alpha} [1 + G^{(R)}_{\alpha} T^{\text{c.m.}}_{\alpha R}]$$

$$U^{(R)}_{0\alpha} = [1 + T_{\rho R} G_0] \tilde{U}^{(R)}_{0\alpha} [1 + G^{(R)}_{\alpha} T^{\text{c.m.}}_{\alpha R}] \quad [\rho \text{ is neutral}]$$

Three-particle scattering

Split into long-range part

$$T^{c.m.}_{\alpha R} = W^{c.m.}_{\alpha R} + W^{c.m.}_{\alpha R} G^{(R)}_{\alpha} T^{c.m.}_{\alpha R}$$

and Coulomb-distorted short-range part

$$U^{(R)}_{\beta\alpha} = \delta_{\beta\alpha} T^{c.m.}_{\alpha R} + [U^{(R)}_{\beta\alpha} - \delta_{\beta\alpha} T^{c.m.}_{\alpha R}]$$

$$[U^{(R)}_{\beta\alpha} - \delta_{\beta\alpha} T^{c.m.}_{\alpha R}] = [1 + T^{c.m.}_{\beta R} G^{(R)}_{\beta}] \tilde{U}^{(R)}_{\beta\alpha} [1 + G^{(R)}_{\alpha} T^{c.m.}_{\alpha R}]$$

$$U^{(R)}_{0\alpha} = [1 + T_{\rho R} G_0] \tilde{U}^{(R)}_{0\alpha} [1 + G^{(R)}_{\alpha} T^{c.m.}_{\alpha R}]$$ [ρ is neutral]

Renormalized amplitudes:

$$U_{\beta\alpha} = \delta_{\beta\alpha} T^{c.m.}_{\alpha C} + \lim_{R\to\infty} Z_{R\,f}^{-\frac{1}{2}} [U^{(R)}_{\beta\alpha} - \delta_{\beta\alpha} T^{c.m.}_{\alpha R}] Z_{R\,i}^{-\frac{1}{2}}$$

$$U_{0\alpha} = \lim_{R\to\infty} z_R^{-\frac{1}{2}} U^{(R)}_{0\alpha} Z_{R\,i}^{-\frac{1}{2}}$$ fast convergence with R

Practical realization

- Calculation of short-range part using
  standard scattering theory (Faddeev/AGS)
  for nuclear + screened Coulomb interaction

$$U_{\beta\alpha}^{(R)} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_\sigma \bar{\delta}_{\beta\sigma} T_\sigma^{(R)} G_0 U_{\sigma\alpha}^{(R)}$$

$$T_\sigma^{(R)} = v + w_{\sigma R} + (v + w_{\sigma R}) G_0 T_\sigma^{(R)}$$

+ renormalization

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- Calculation of short-range part using
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$$U^{(R)}_{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_\sigma \bar{\delta}_{\beta\sigma} T^{(R)}_\sigma G_0 U^{(R)}_{\sigma\alpha}$$

$$T^{(R)}_\sigma = v + w_{\sigma R} + (v + w_{\sigma R}) G_0 T^{(R)}_\sigma$$

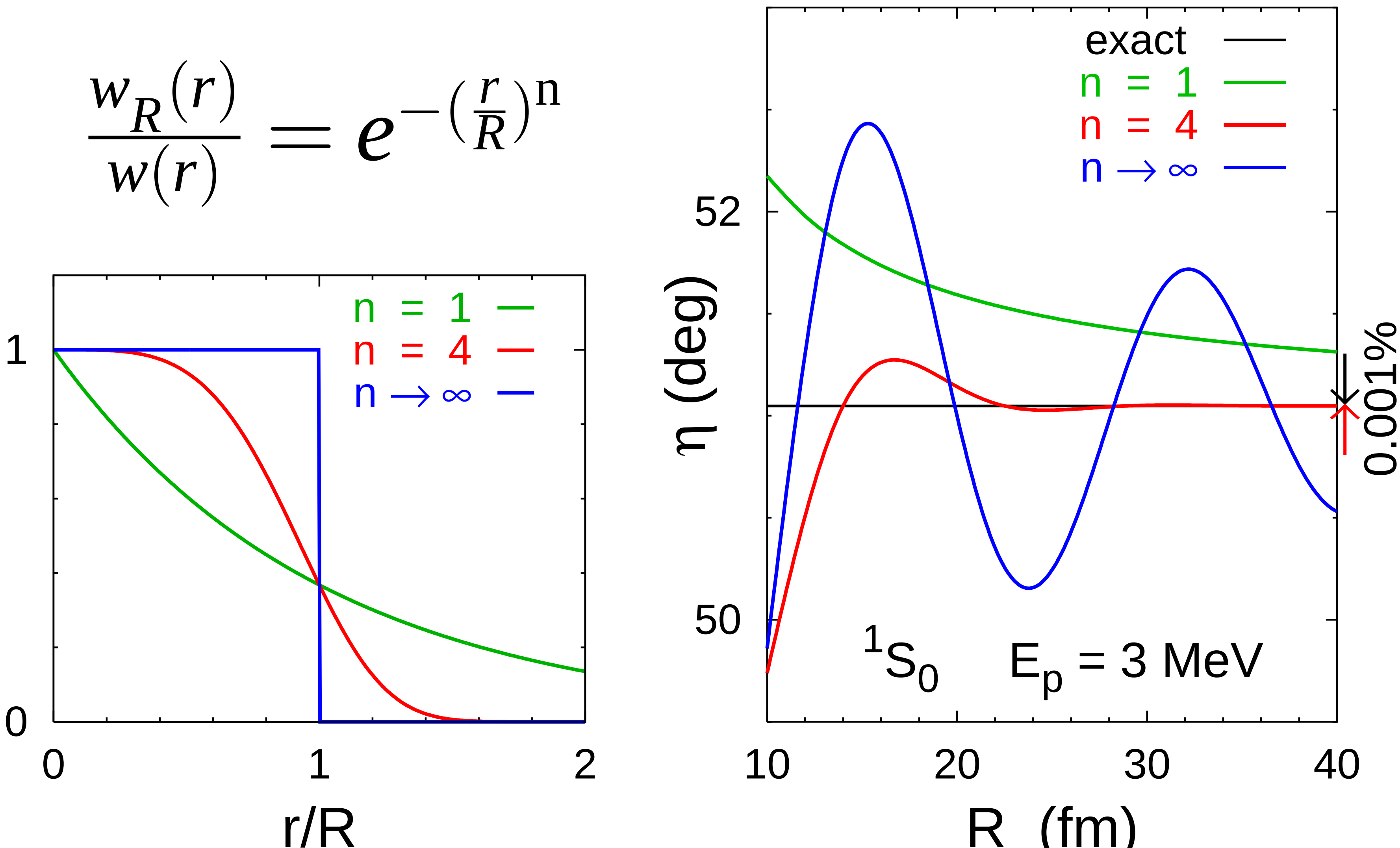
+ renormalization

- Additional difficulties:
quasi-singular nature of screened Coulomb potential
slow partial-wave convergence

- Success of the method depends strongly on the choice of screening function

Screened Coulomb potential

$$\frac{w_R(r)}{w(r)} = e^{-\left(\frac{r}{R}\right)^{\mathrm{n}}}$$



optimal choice: $3 \leq \mathrm{n} \leq 8$

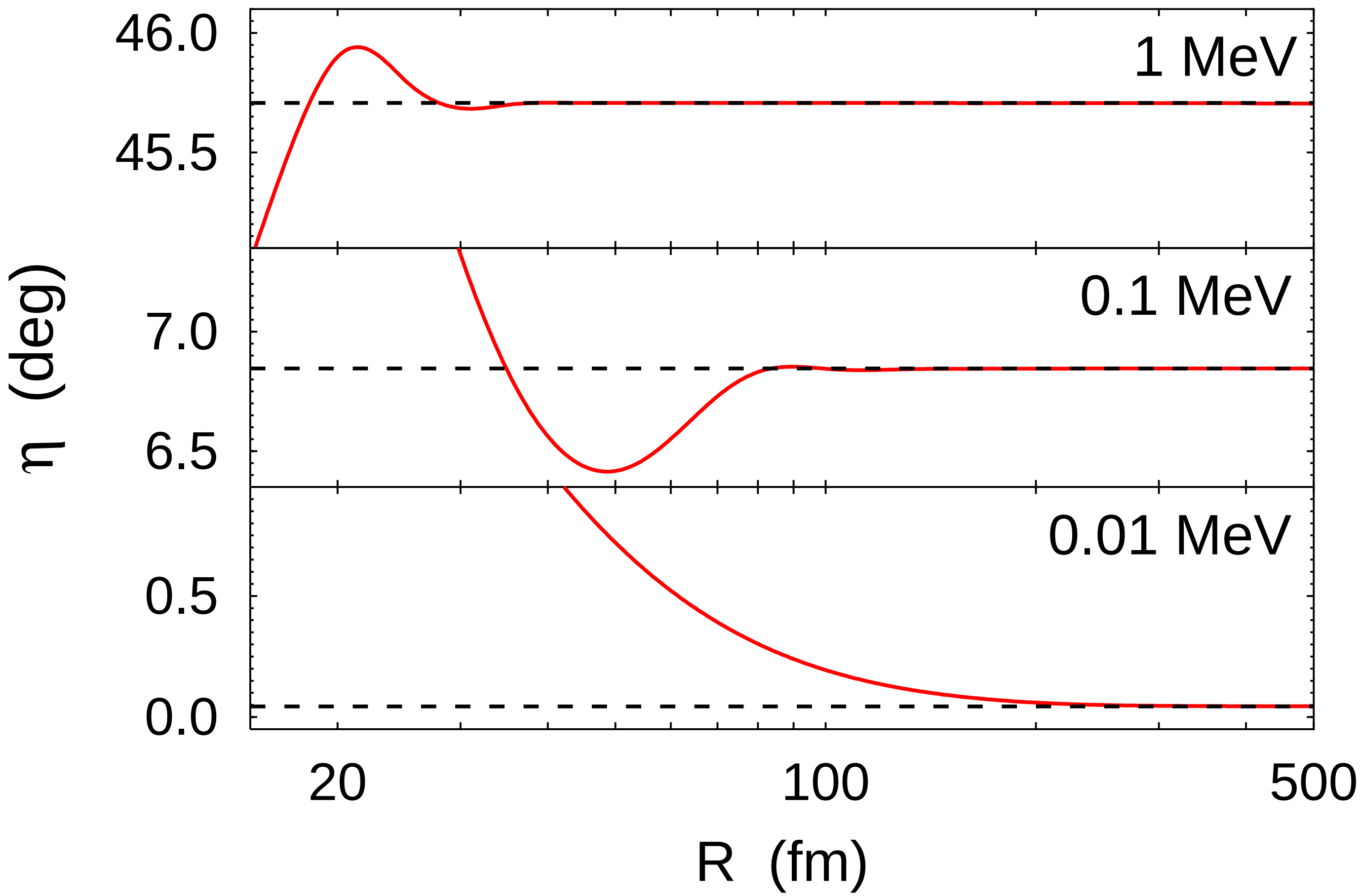
Limits of practical applicability

$p \longrightarrow 0$:

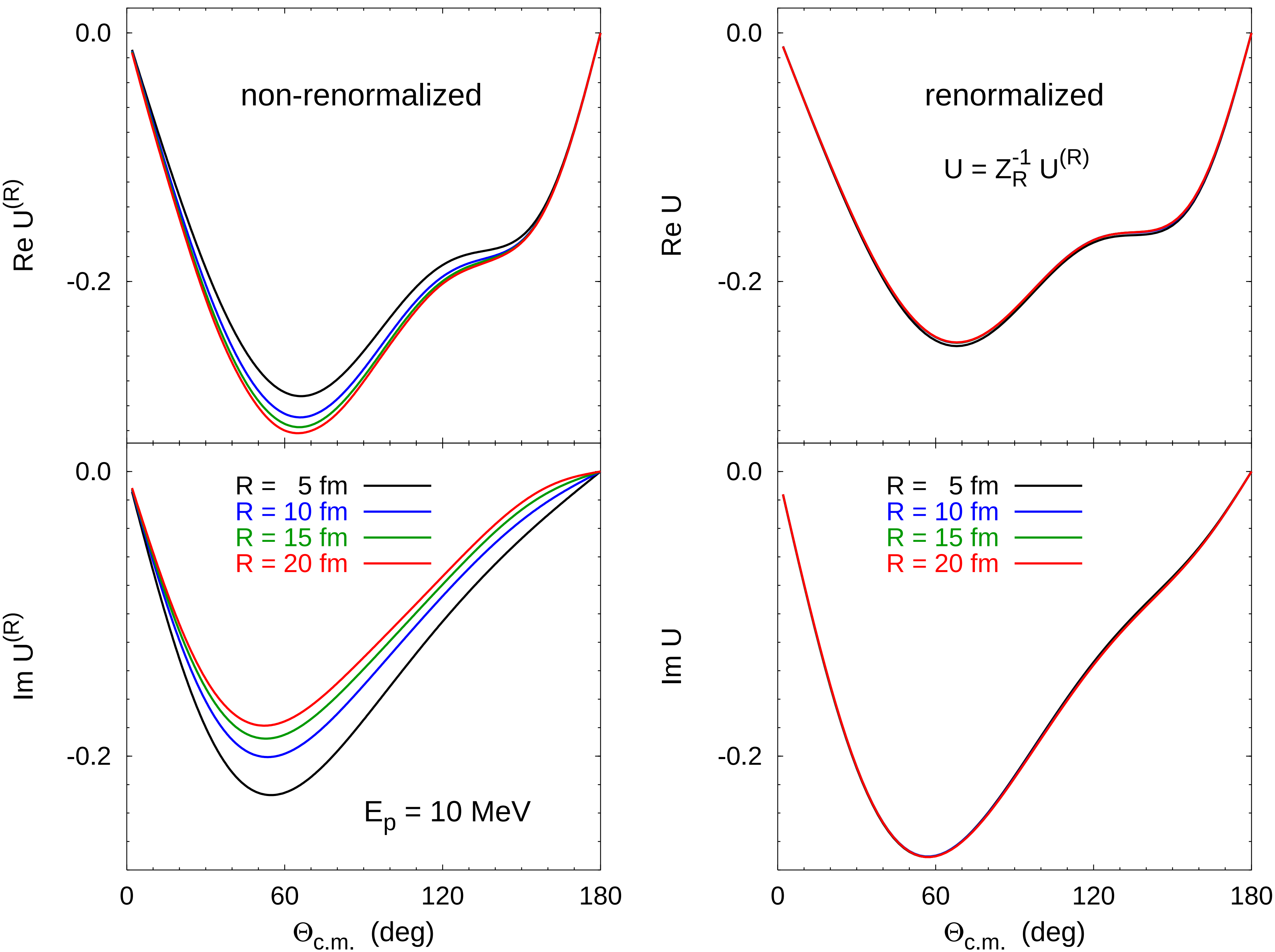
$\kappa = \alpha M/p$, $\sigma_L = \arg\Gamma(1+L+i\kappa)$, and z_R diverge,

renormalization procedure ill-defined

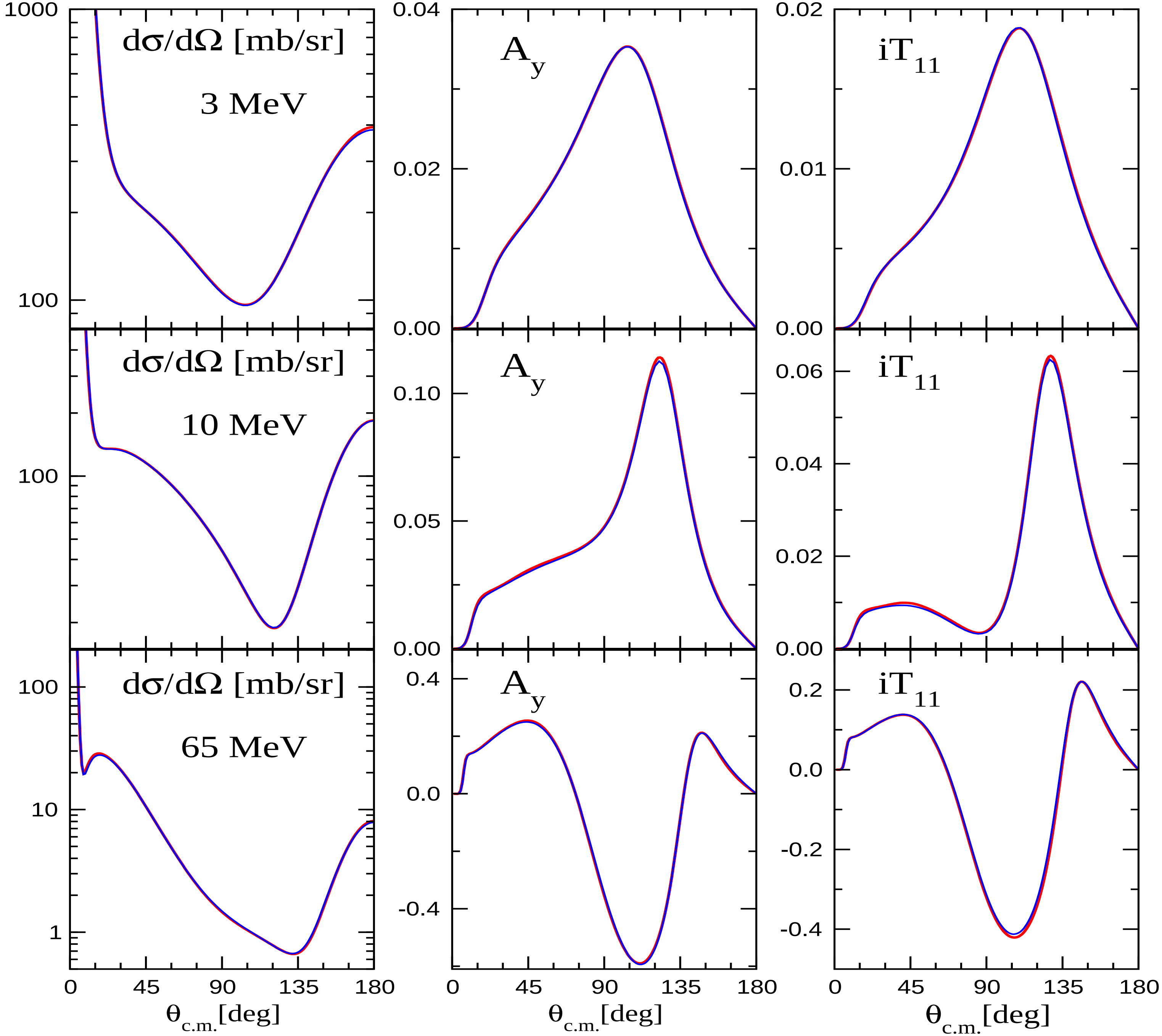
$\Rightarrow$ slow convergence with R at low relative energies



pd elastic amplitude: convergence with R



Comparison with configuration-space results

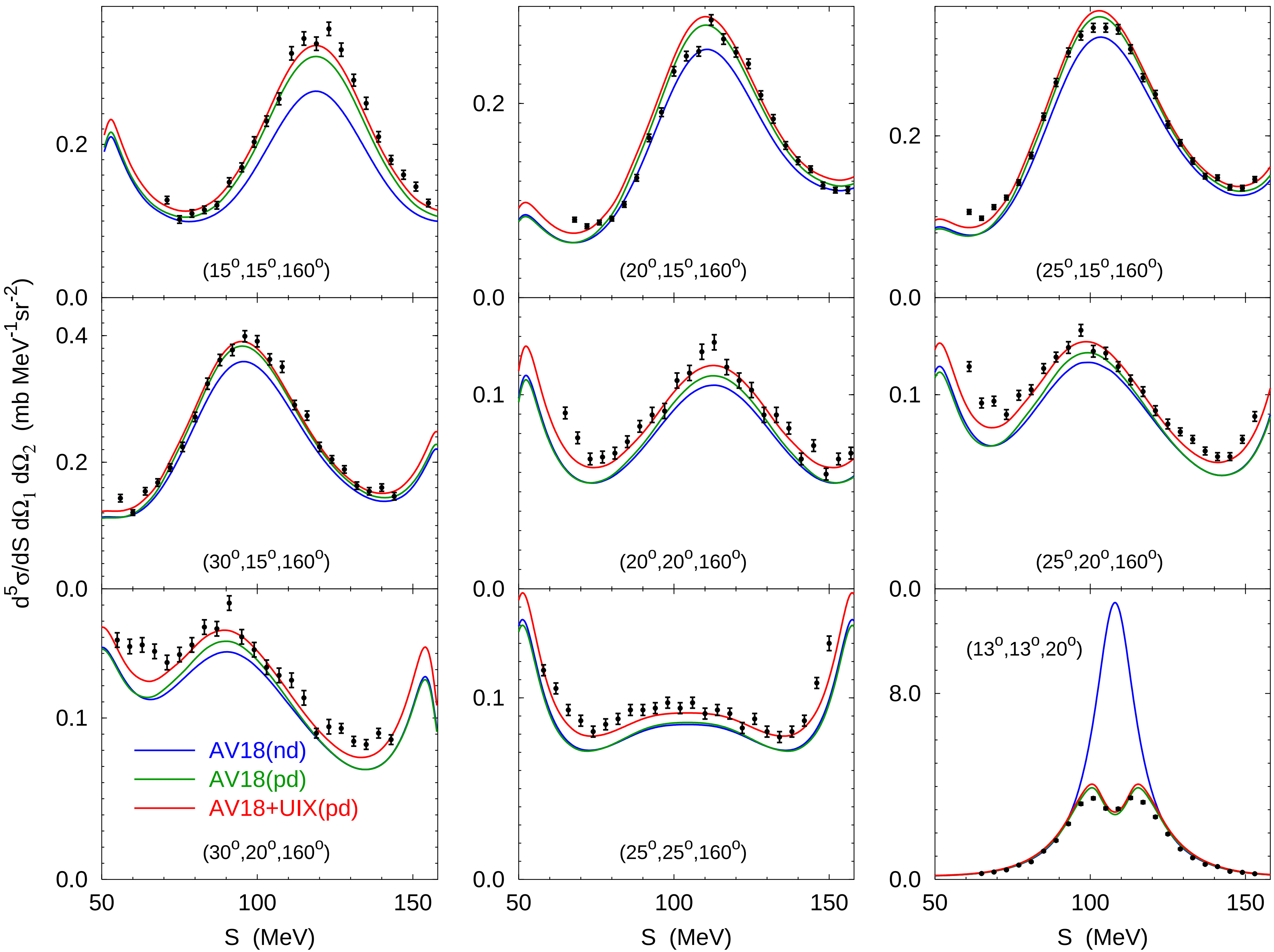


p-*d* elastic scattering:

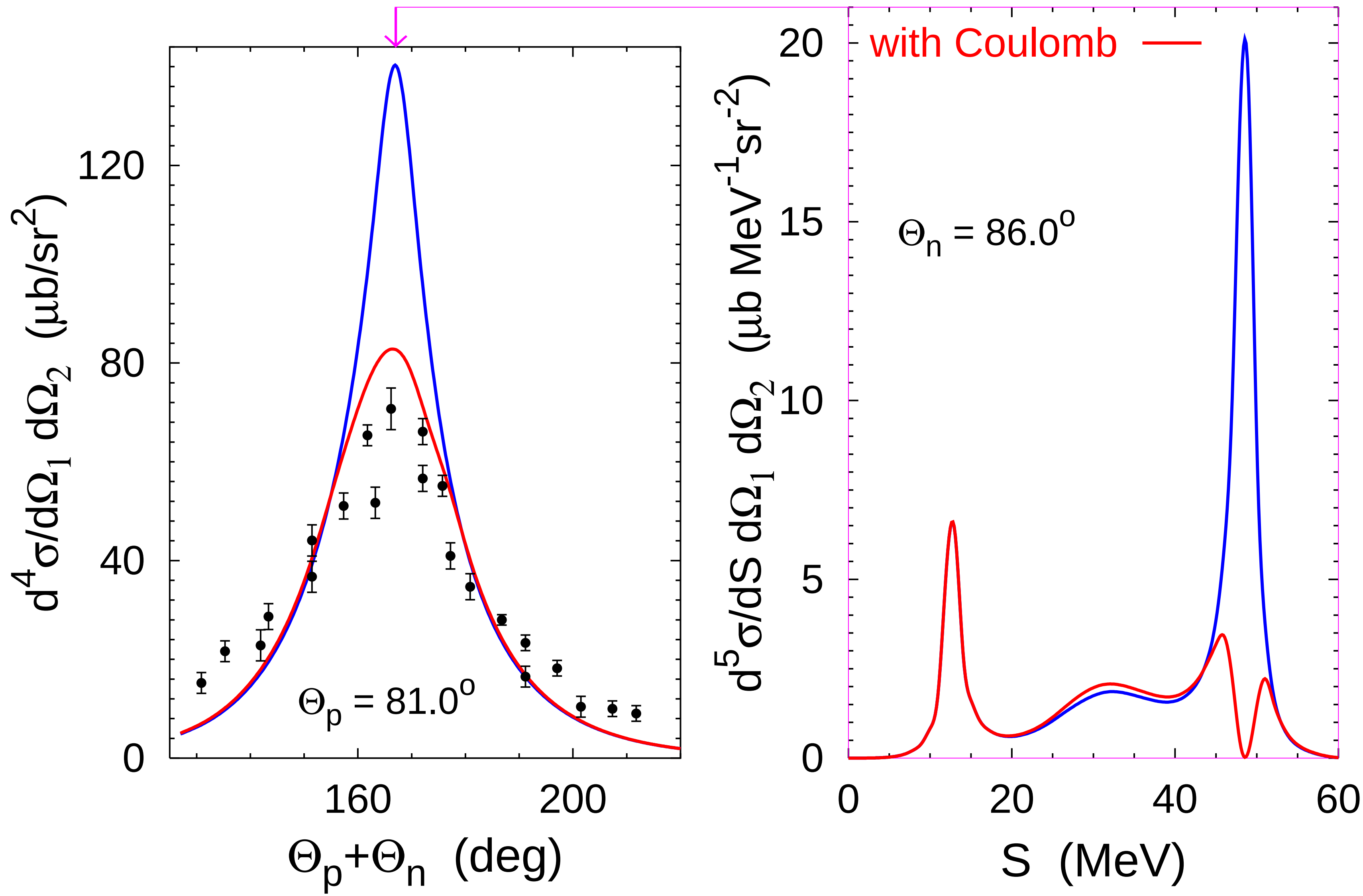
Kohn variational principle (Pisa)

screening and renormalization

Coulomb vs 3NF: ^{1}H(d,pp)n at $E_d = 130$ MeV



^{3}He$(\gamma, pn)p$ at $E_\gamma = 55$ MeV



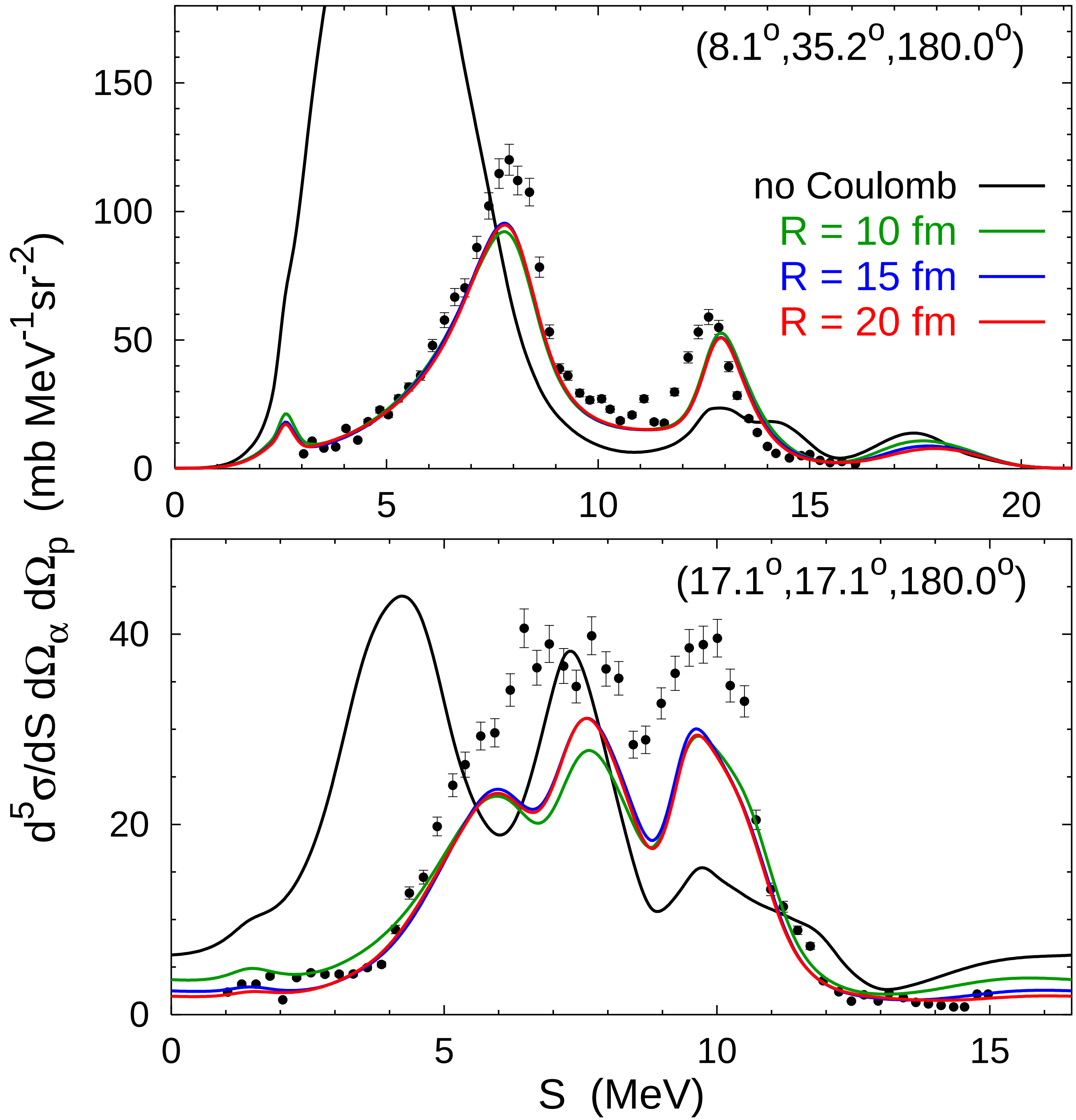
Application to 3-body nuclear reactions

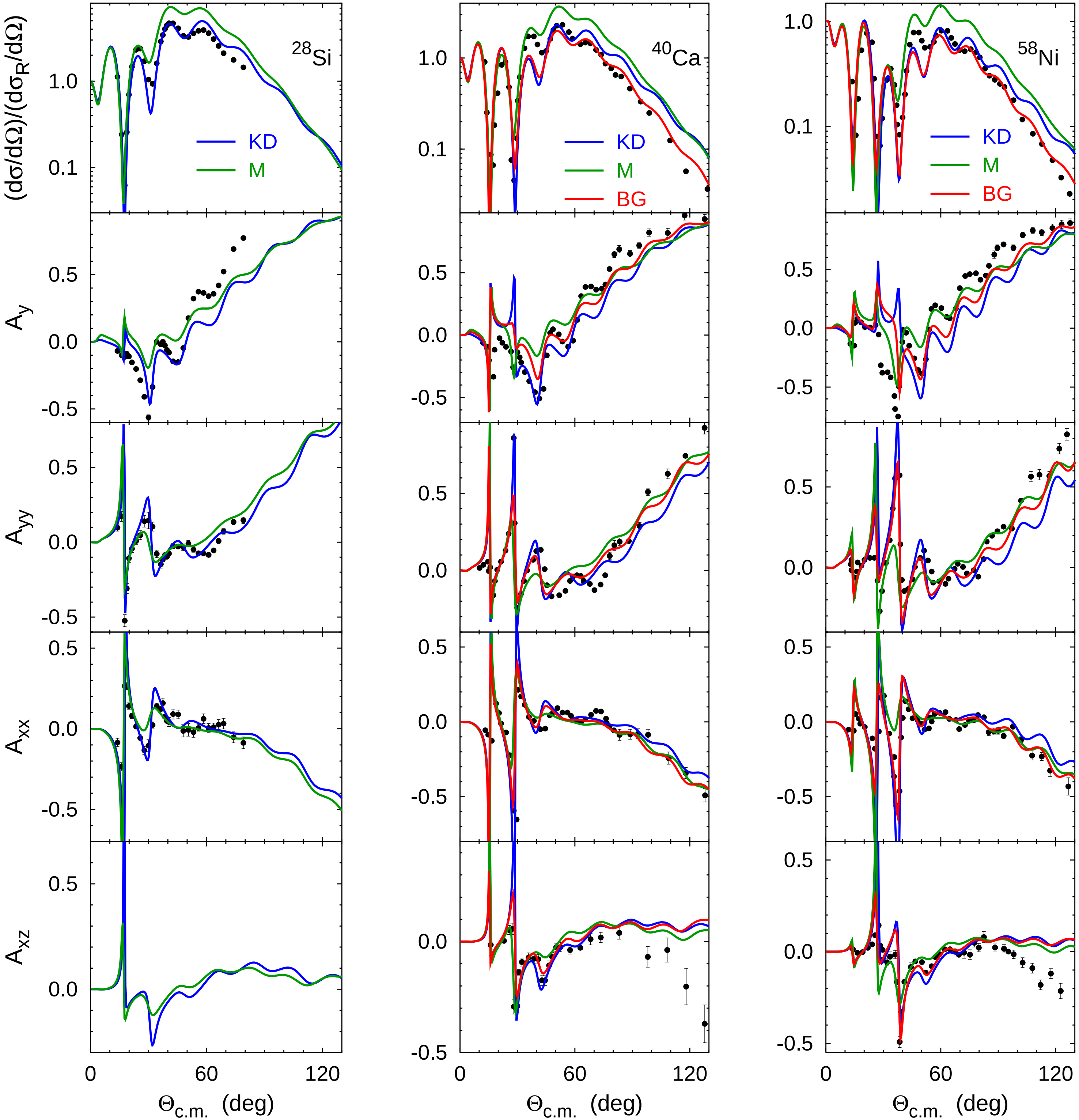
$$\left.\begin{array}{l} p+(nA) \\ d+A \end{array}\right\} \longrightarrow \left\{\begin{array}{l} n+(pA) \\ p+(nA) \\ d+A \\ p+n+A \end{array}\right.$$

with $A = {}^{4}\mathrm{He},\ {}^{10}\mathrm{Be},\ {}^{12}\mathrm{C},\ {}^{14}\mathrm{C},\ {}^{16}\mathrm{O},\ {}^{28}\mathrm{Si},\ {}^{40}\mathrm{Ca},\ {}^{58}\mathrm{Ni},\ \ldots$

- Validity test of approximate nuclear reaction methods: CDCC, DWBA, Glauber, . . .
- Novel dynamic input: nonlocal potentials, . . .

α-d breakup at $E_\alpha = 15$ MeV: convergence with R

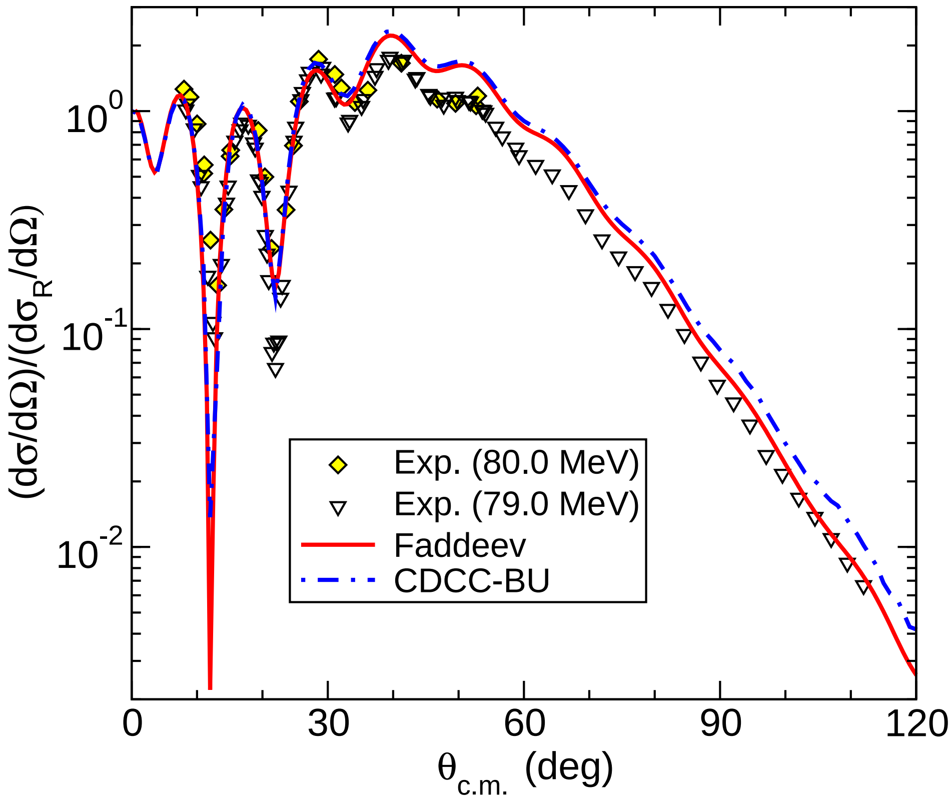


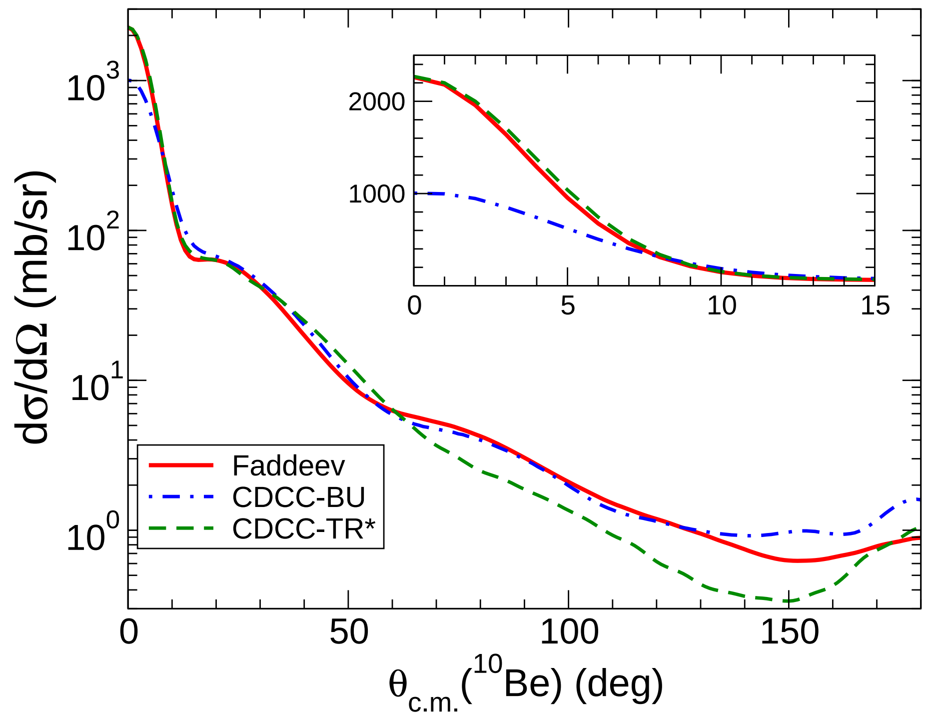


$A(\vec{d},d)A$

$E_d = 56$ MeV

CDCC test: ^{58}Ni$(d,d)^{58}$Ni and ^{1}H$(^{11}$Be$,^{10}$Be$)np$



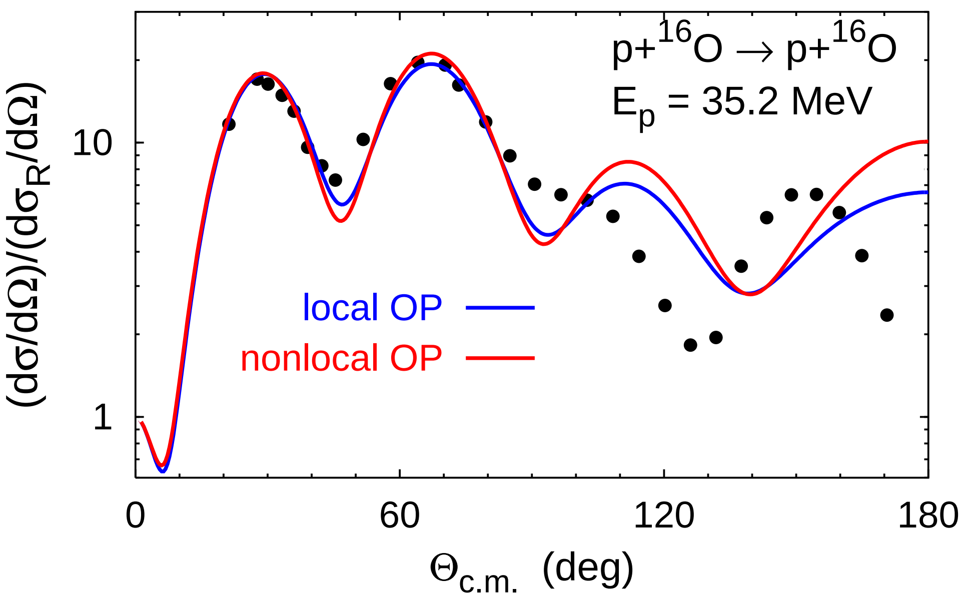


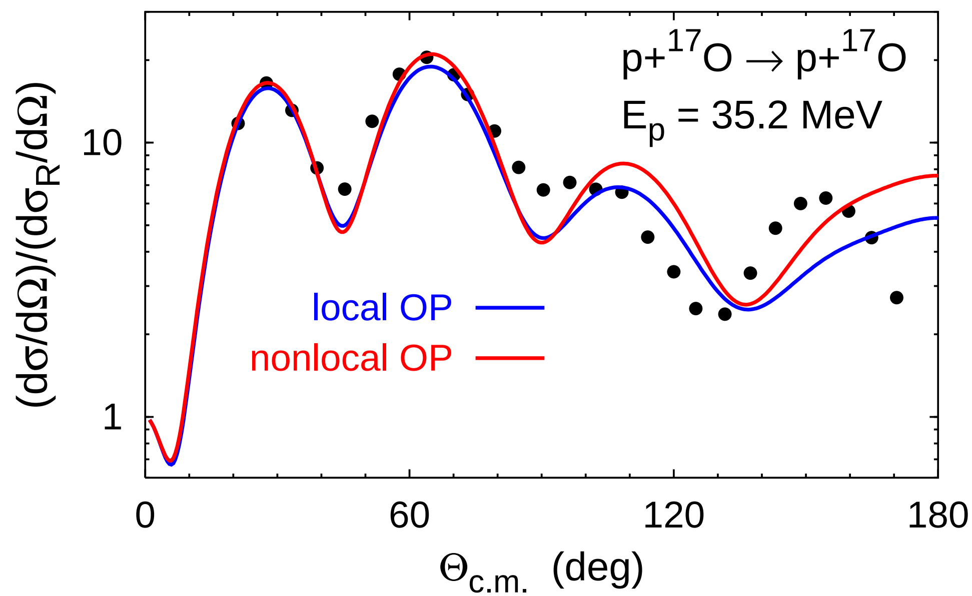
CDCC: A. M. Moro and F. M. Nunes

Nonlocal optical potential: proton elastic scattering

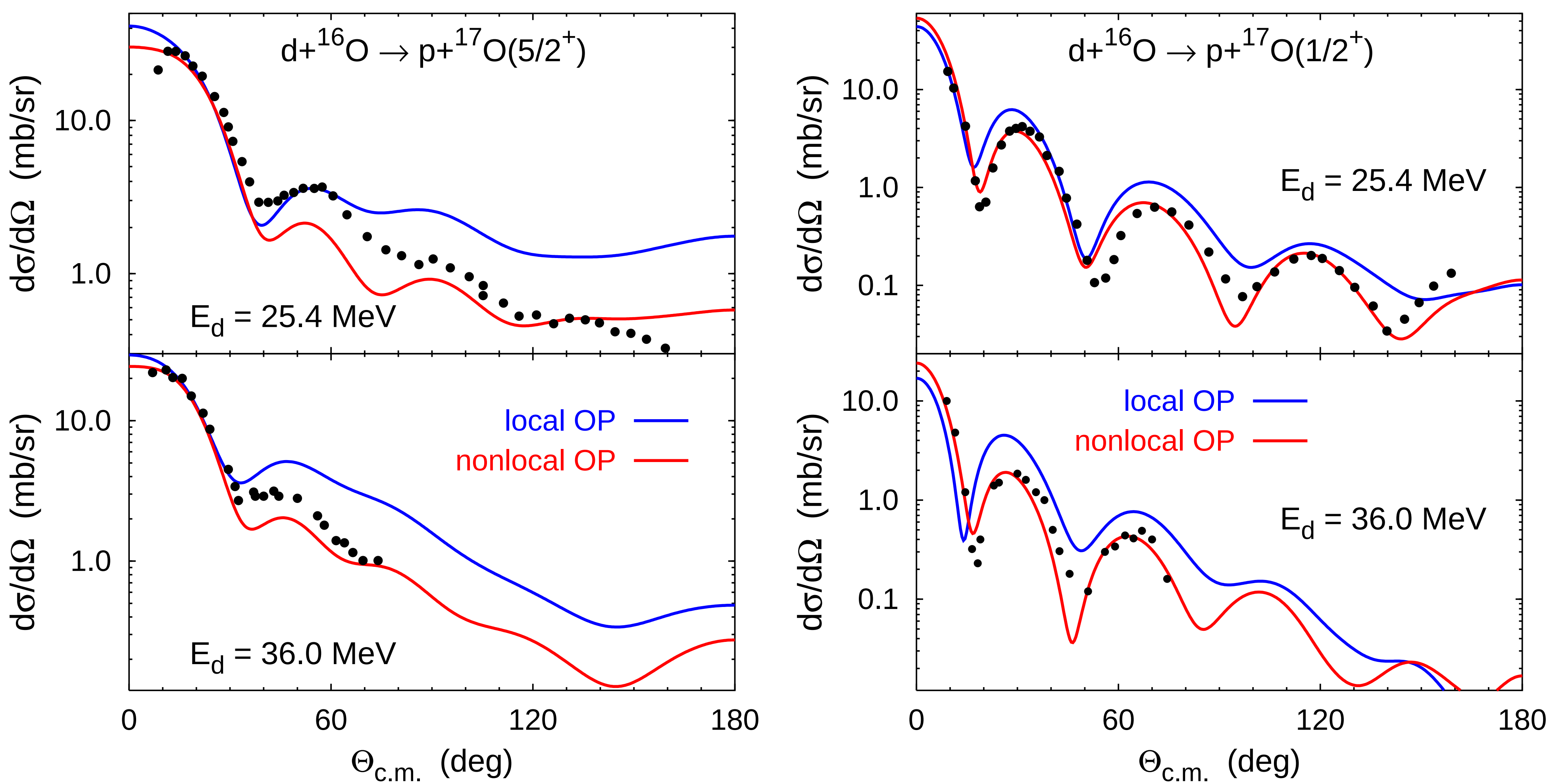
$$V_N(\mathbf{r}',\mathbf{r}) \sim e^{-(\mathbf{r}'-\mathbf{r})^2/\beta^2} V((\mathbf{r}'+\mathbf{r})/2)$$

[M. M. Giannini *et al.*,
Ann. Phys. (NY) 102, 458 (1976) & 124, 208 (1980)]

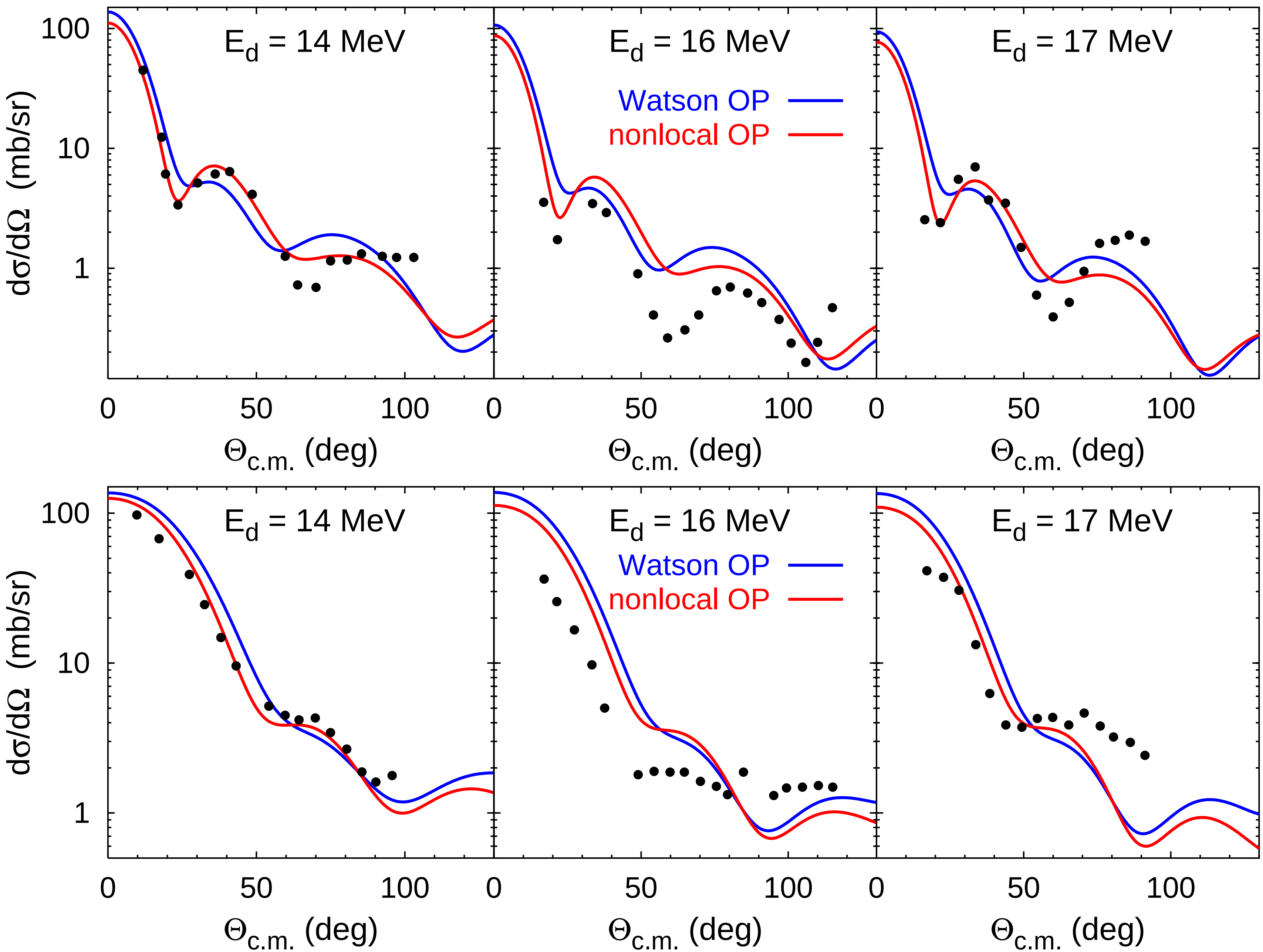




Nonlocal OP: transfer reactions $^{16}O(d,p)^{17}O$



Nonlocal OP: transfer reactions $^{14}\mathrm{C}(d,p)^{15}\mathrm{C}$



4N system

- "theoretical laboratory" to test models of nuclear interaction

$$n + {}^3\mathrm{H} \quad \longrightarrow \quad n + {}^3\mathrm{H}$$

$$p + {}^3\mathrm{He} \quad \longrightarrow \quad p + {}^3\mathrm{He}$$

$$\left. \begin{array}{l} p + {}^3\mathrm{H} \\ n + {}^3\mathrm{He} \\ d + d \end{array} \right\} \longrightarrow \left\{ \begin{array}{l} p + {}^3\mathrm{H} \\ n + {}^3\mathrm{He} \\ d + d \end{array} \right.$$

4N scattering: symmetrized AGS equations

two-cluster 1+3 and 2+2 transition operators

$$\mathcal{U}_{11} = -(G_0 T G_0)^{-1} P_{34} - P_{34} U_1 G_0 T G_0 \, \mathcal{U}_{11} + U_2 G_0 T G_0 \, \mathcal{U}_{21}$$

$$\mathcal{U}_{21} = (G_0 T G_0)^{-1} (1 - P_{34}) + (1 - P_{34}) U_1 G_0 T G_0 \, \mathcal{U}_{11}$$

$$\mathcal{U}_{12} = (G_0 T G_0)^{-1} - P_{34} U_1 G_0 T G_0 \, \mathcal{U}_{12} + U_2 G_0 T G_0 \, \mathcal{U}_{22}$$

$$\mathcal{U}_{22} = (1 - P_{34}) U_1 G_0 T G_0 \, \mathcal{U}_{12}$$

$$U_j = P_j G_0^{-1} + P_j T G_0 U_j$$

$$P_1 = P = P_{12} P_{23} + P_{13} P_{23}$$

$$P_2 = \tilde{P} = P_{13} P_{24}$$

$$T = v + v G_0 T$$

scattering amplitude $\quad \mathcal{T}_{fi} = S_{fi} \langle \mathbf{p}_f \phi_f | \mathcal{U}_{fi} | \mathbf{p}_i \phi_i \rangle$

$$|\phi_j\rangle = G_0 T P_j |\phi_j\rangle$$

Screening and renormalization in 4N scattering

$$v \longrightarrow v + w_R$$

$$T,\ U_j,\ \mathcal{U}_{fi},\ \mathcal{T}_{fi} \longrightarrow T^{(R)},\ U_j^{(R)},\ \mathcal{U}_{fi}^{(R)},\ \mathcal{T}_{fi}^{(R)}$$

isolate long-range interaction
and Coulomb distortion between c.m. of two clusters

Screening and renormalization in 4N scattering

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$$T,\ U_j,\ \mathcal{U}_{fi},\ \mathcal{T}_{fi} \longrightarrow T^{(R)},\ U_j^{(R)},\ \mathcal{U}_{fi}^{(R)},\ \mathcal{T}_{fi}^{(R)}$$

isolate long-range interaction
and Coulomb distortion between c.m. of two clusters

Renormalization:

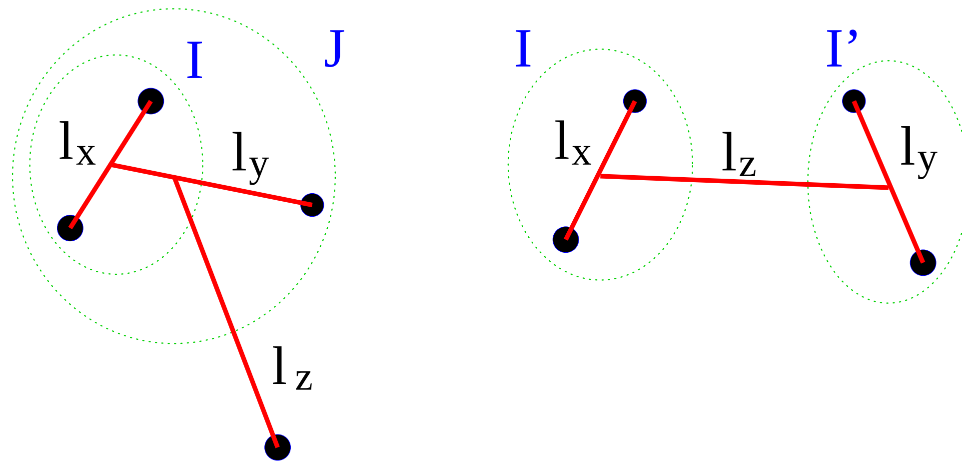
$$\mathcal{T}_{fi} = \lim_{R\to\infty} Z_{Rf}^{-\frac{1}{2}} \mathcal{T}_{fi}^{(R)} Z_{Ri}^{-\frac{1}{2}}$$

$$= \delta_{fi} T_{Ci}^{\mathrm{c.m.}} + \lim_{R\to\infty} Z_{Rf}^{-\frac{1}{2}} [\mathcal{T}_{fi}^{(R)} - \delta_{fi} T_{Ri}^{\mathrm{c.m.}}] Z_{Ri}^{-\frac{1}{2}}$$

Coulomb-distorted short-range part: fast convergence with R

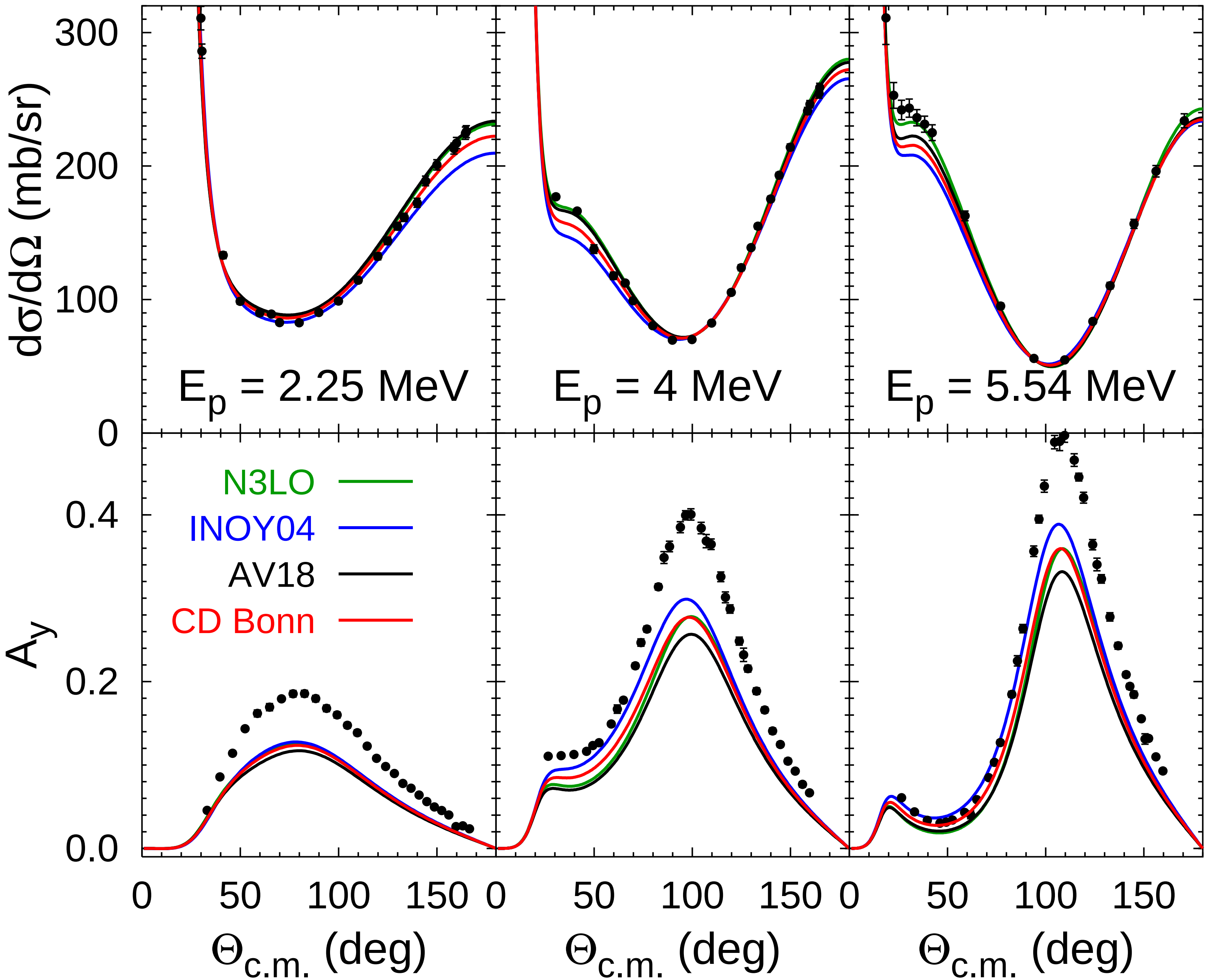
Practical realization

$$\mathcal{U}_{12} = (G_0 T G_0)^{-1} - P_{34} U_1 G_0 T G_0 \, \mathcal{U}_{12} + U_2 G_0 T G_0 \, \mathcal{U}_{22}$$

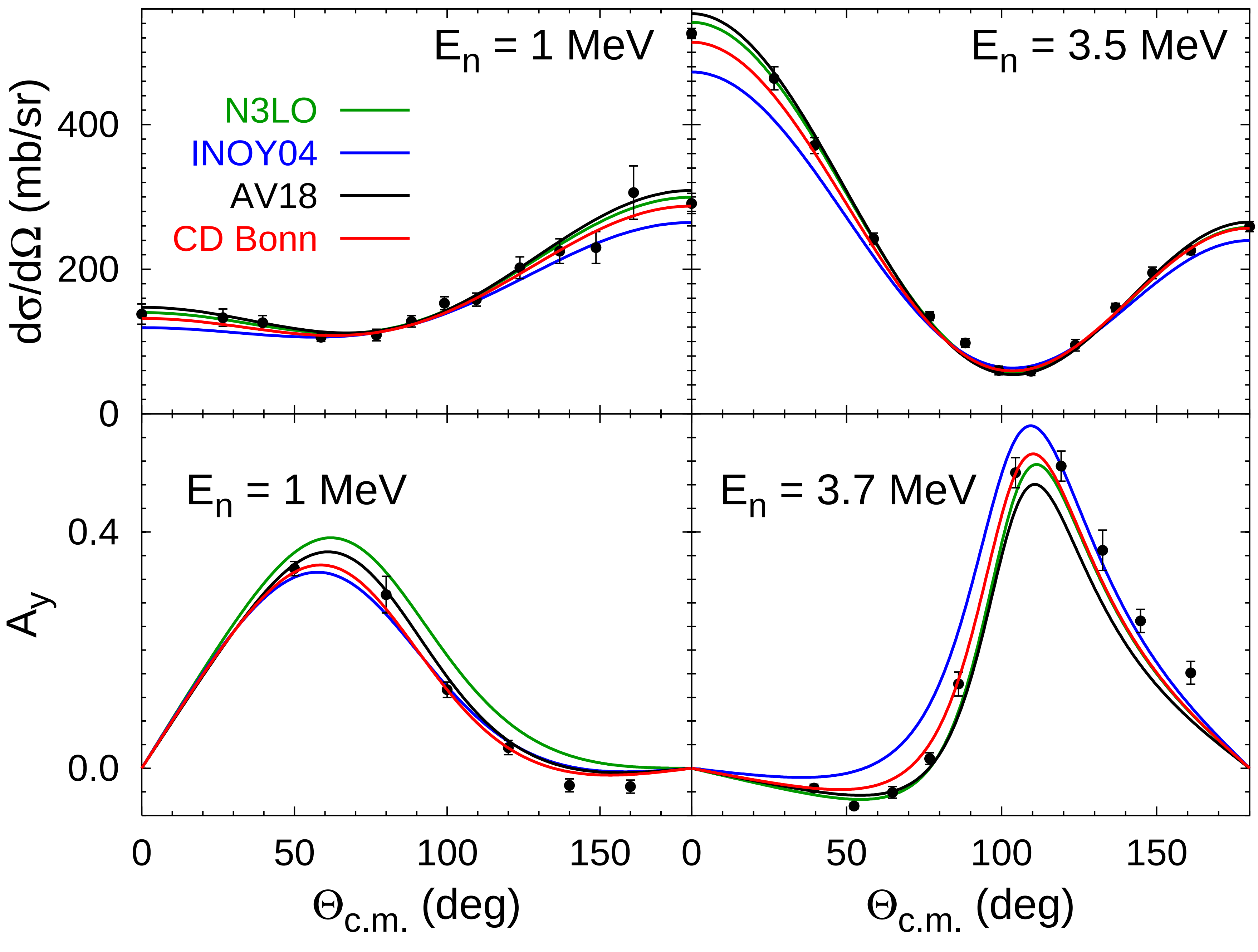


- momentum-space partial-wave basis
  (up to 30000 partial waves)
- set of coupled integral equations in 3 variables
- integrable singularities in the kernel
- Gaussian integration, spline interpolation,
  double Padé summation

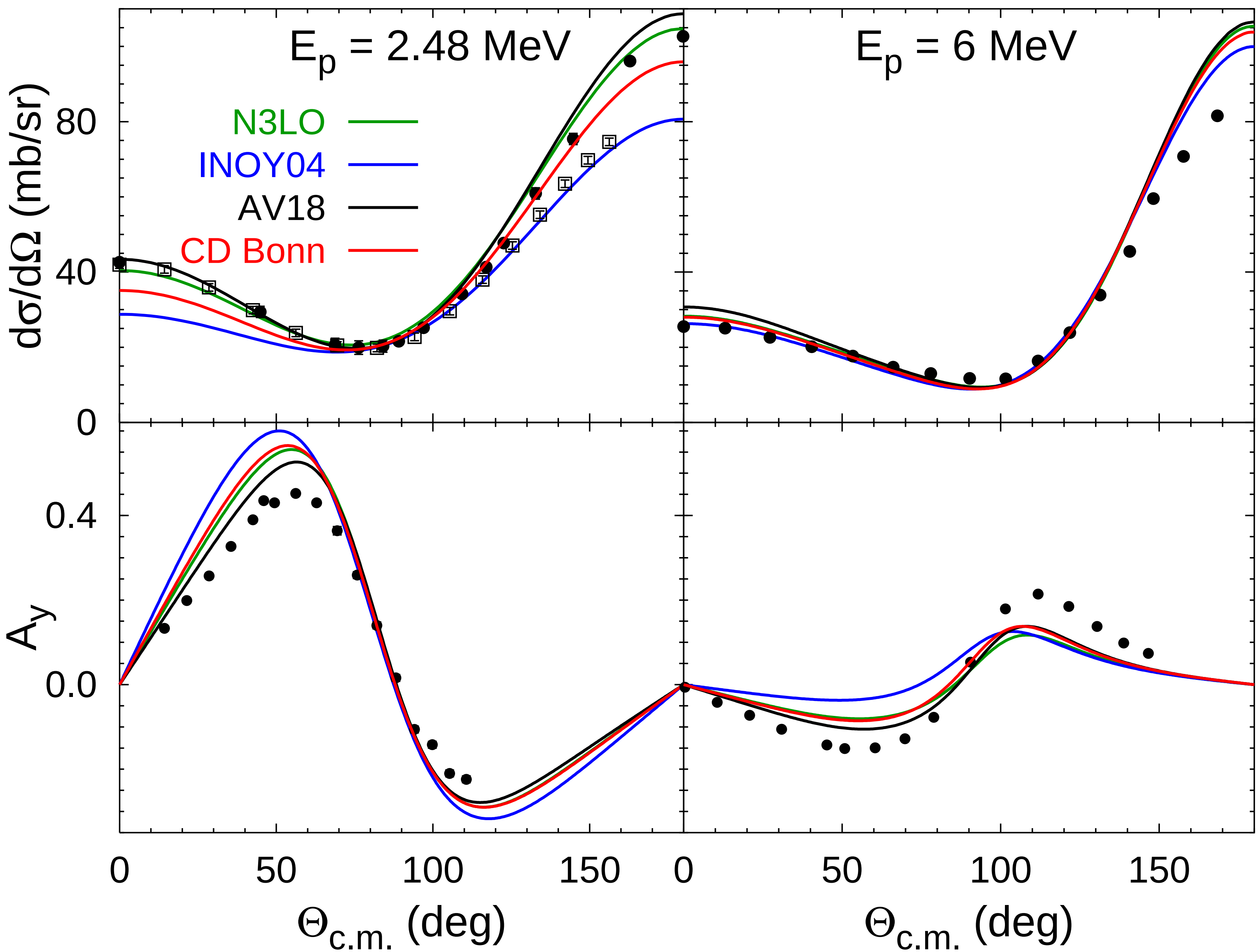
p-^{3}He scattering



n-^{3}He elastic scattering

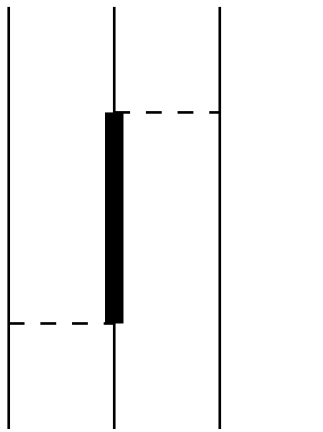


Charge exchange reaction $p + {}^3\mathrm{H} \rightarrow n + {}^3\mathrm{He}$

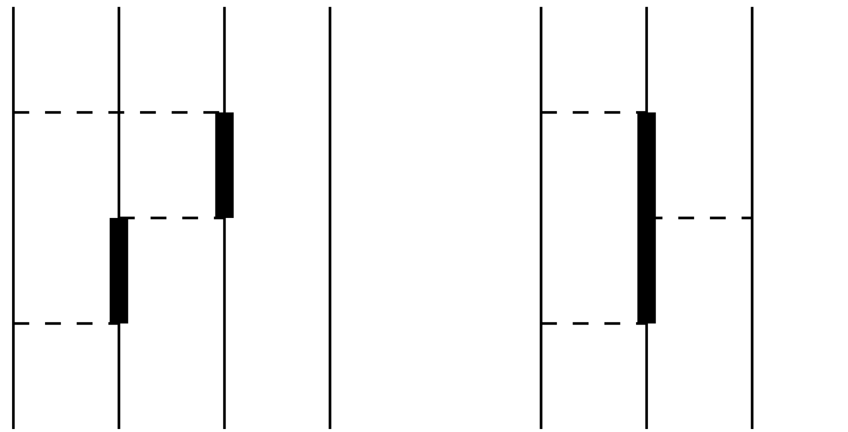


Δ-isobar excitation: effective 3N and 4N forces

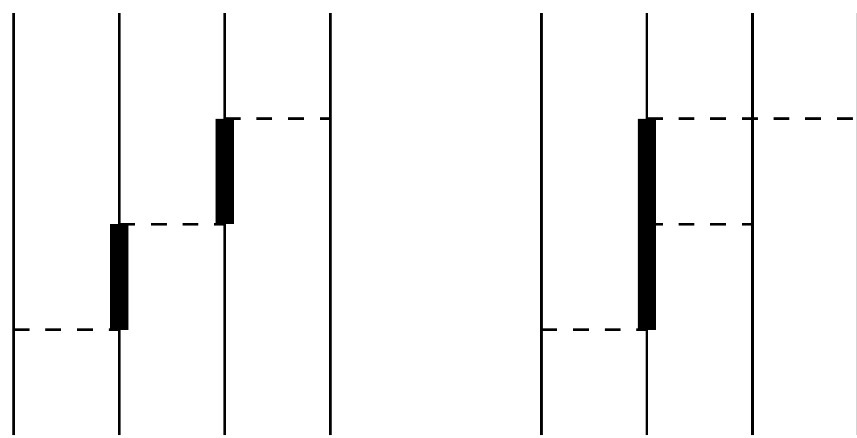
Fujita-Miyazawa



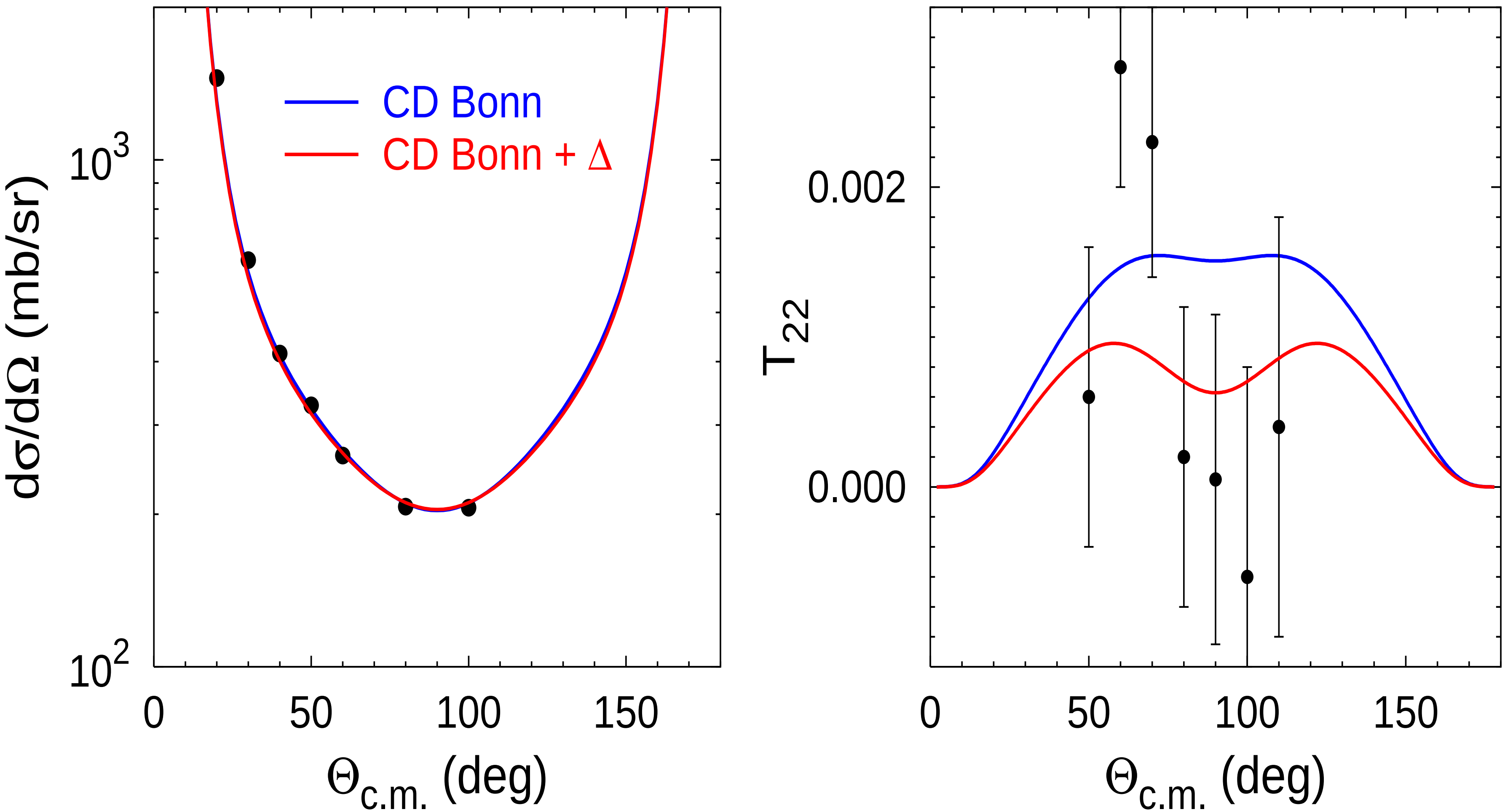
higher order 3N force



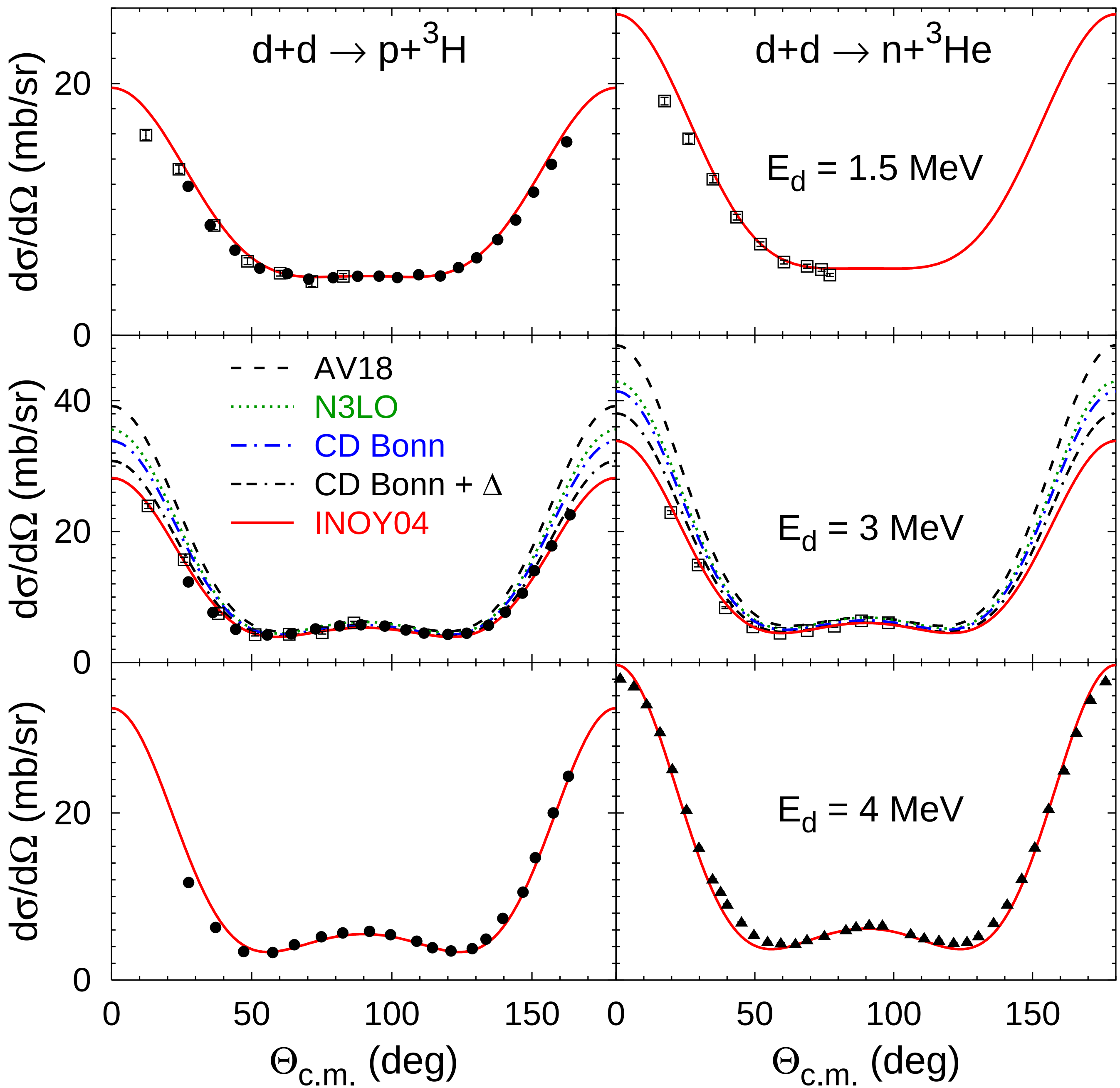
4N force



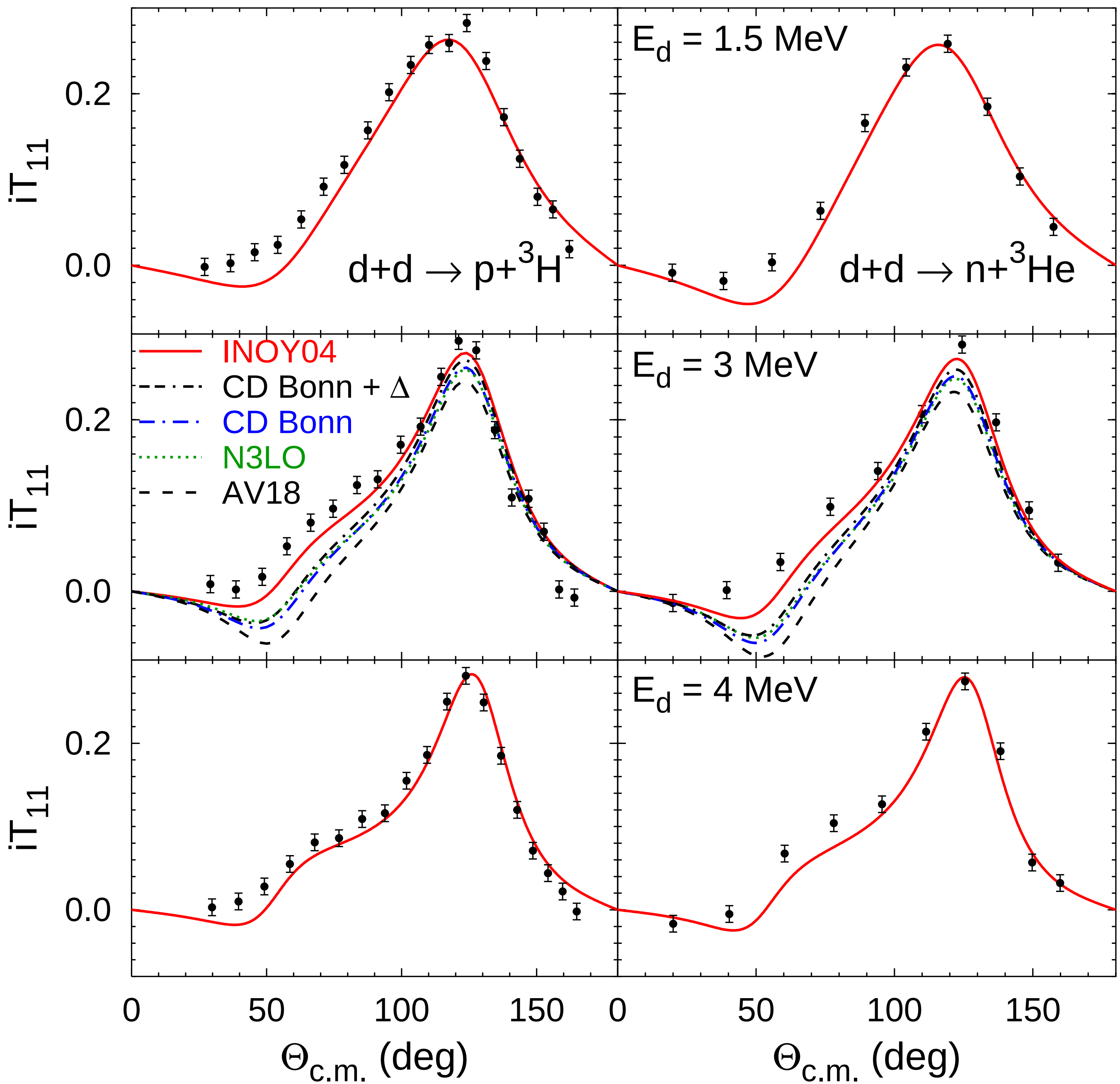
d-d elastic scattering at $E_d = 3$ MeV



$d + d \to N + [3N]$ transfer



$d + d \rightarrow N + [3N]$ transfer



Summary

- Faddev/AGS equations in momentum space
- Coulomb interaction: screening and renormalization

Summary

- Faddev/AGS equations in momentum space
- Coulomb interaction: screening and renormalization

- hadronic and electromagnetic 3N reactions
- 3-body nuclear reactions
- low energy 4N scattering