Coulomb effects in few-body reactions

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Outline

- Momentum-space description of few-body scattering: screening and renormalization for Coulomb
  [Taylor, Alt, Sandhas, ...]

- Applications: 3N, 4N, nuclear reactions

Screened Coulomb

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

- standard scattering theory

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- nature: Coulomb is screened at large distances
- large R:
  physical observables insensitive to screening,
  screened and full Coulomb physically indistinguishable

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- standard scattering theory
- nature: Coulomb is screened at large distances
- large R:
  physical observables insensitive to screening,
  screened and full Coulomb physically indistinguishable
- in the $R \to \infty$ limit physical results are recovered

Screened and full Coulomb physically indistinguishable

$$\langle \mathbf{p}' | T_R | \mathbf{p} \rangle \quad \overset{?}{\underset{R\to\infty}{\longrightarrow}} \quad \langle \mathbf{p}' | T_C | \mathbf{p} \rangle$$

Screened and full Coulomb physically indistinguishable

$$e^{2i\phi_R} \langle \mathbf{p}' | T_R | \mathbf{p} \rangle \quad \overset{?}{\underset{R\to\infty}{\longrightarrow}} \quad \langle \mathbf{p}' | T_C | \mathbf{p} \rangle$$

Screened and full Coulomb physically indistinguishable

initial physical state: wave packet $\varphi_{\text{in}}(\mathbf{p})$

outgoing wave packet

$$\varphi_{\text{out}}(\mathbf{p}') = \int d^3\mathbf{p}\, \langle \mathbf{p}'|S|\mathbf{p}\rangle \varphi_{\text{in}}(\mathbf{p})$$

$$\sim \int d^2\hat{\mathbf{p}}\, e^{2i\phi_R} \langle \mathbf{p}'|T_R|\mathbf{p}\rangle \varphi_{\text{in}}(\mathbf{p}) \xrightarrow[R\to\infty]{} \int d^2\hat{\mathbf{p}}\, \langle \mathbf{p}'|T_C|\mathbf{p}\rangle \varphi_{\text{in}}(\mathbf{p})$$

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$p' = p:$ $\quad e^{2i\phi_R} \langle \mathbf{p}'|T_R|\mathbf{p}\rangle \xrightarrow[R\to\infty]{} \langle \mathbf{p}'|T_C|\mathbf{p}\rangle$ as distribution

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$$p' = p: \qquad e^{2i\phi_R} \langle \mathbf{p}'|T_R|\mathbf{p}\rangle \xrightarrow[R\to\infty]{} \langle \mathbf{p}'|T_C|\mathbf{p}\rangle \quad \text{as distribution}$$

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

[*J. R. Taylor, Nuovo Cimento* **B23**, *313 (1974)*]

Screened and full Coulomb wave functions

$$r < R: \qquad w_R(r) \approx w_C(r)$$

$$\Downarrow$$

$$e^{i\phi_{LR}} \langle r | \psi_{LR}^{(+)}(p) \rangle \approx \langle r | \psi_{LC}^{(+)}(p) \rangle$$

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$$e^{i\phi_R} | \psi_R^{(+)}(\mathbf{p}) \rangle \xrightarrow[R\to\infty]{} | \psi_C^{(+)}(\mathbf{p}) \rangle$$

[*V. G. Gorshkov, Sov. Phys.-JETP* **13**, *1037 (1961)*]

Screening and renormalization

Renormalization of the on-shell screened Coulomb transition matrix $T_R = w_R + w_R G_0 T_R$ and wave function in the limit $R \to \infty$ yields Coulomb amplitude and Coulomb wave function

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

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

$$z_R = e^{-2i\phi_R}$$

Two-particle scattering

transition matrix

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

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

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

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

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Renormalized amplitude:

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

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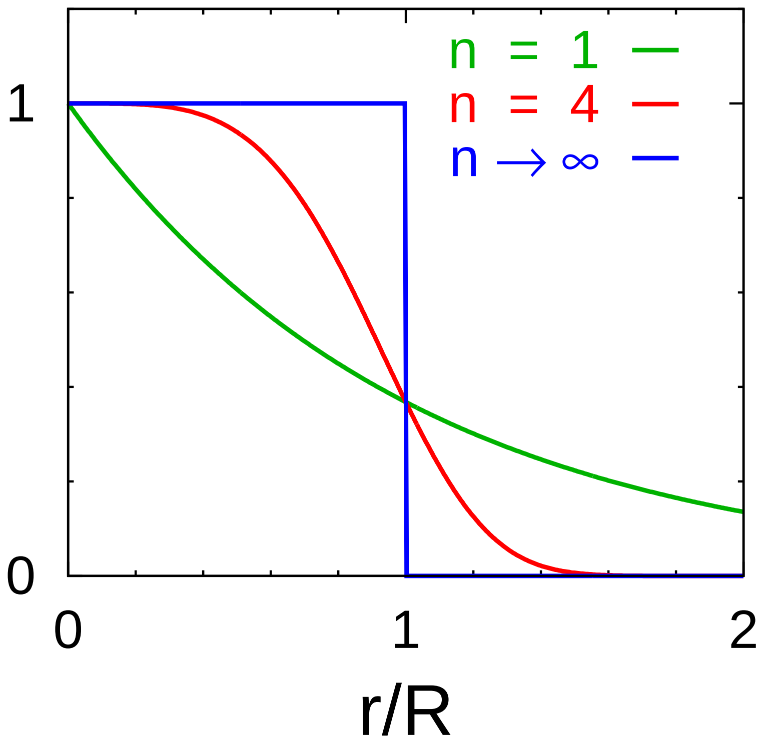
$$= T_C + \lim_{R\to\infty} z_R^{-\frac{1}{2}} [T^{(R)} - T_R] z_R^{-\frac{1}{2}}$$

short-range part: fast convergence with R

Test: convergence with R in pp scattering

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



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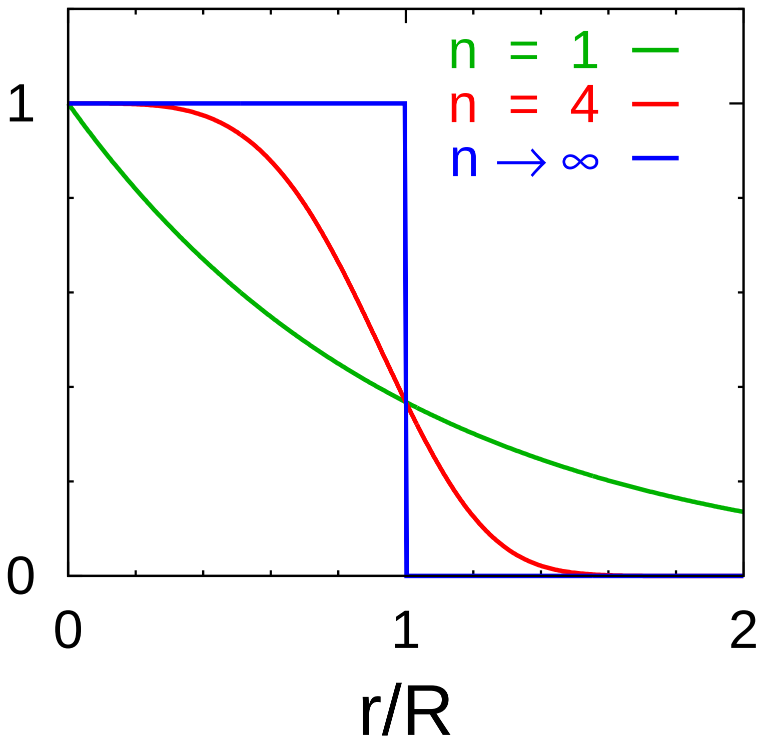

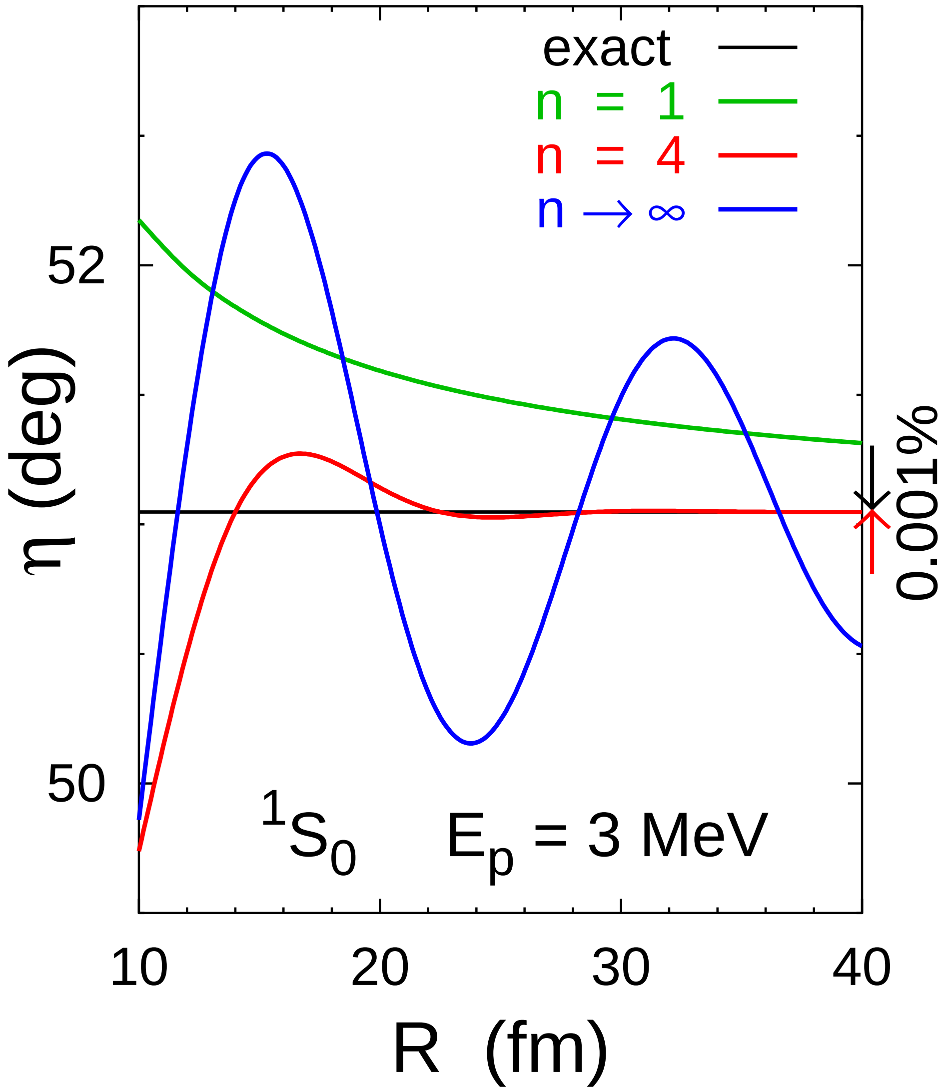

optimal choice: $3 \leq \mathrm{n} \leq 8$

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

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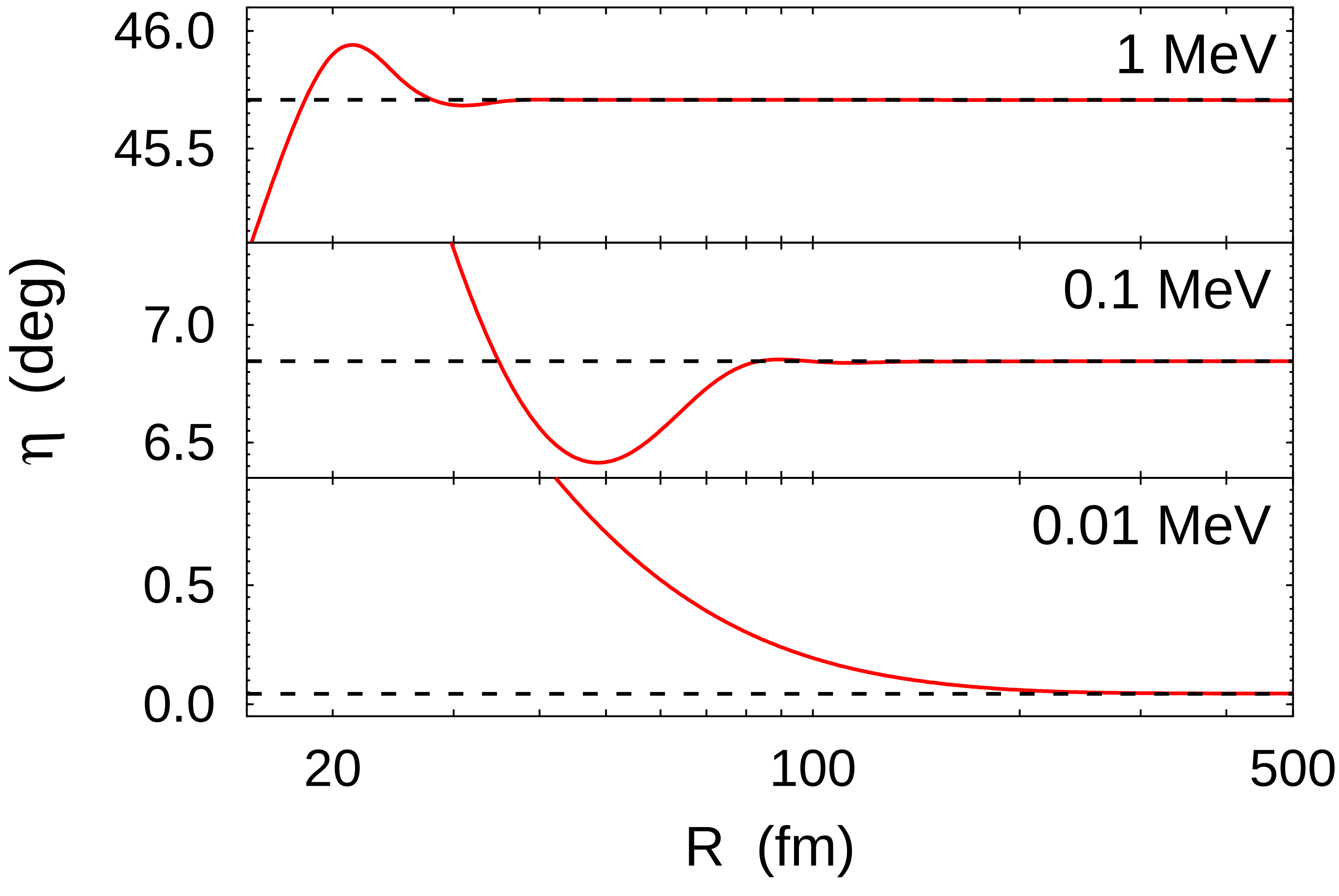
renormalization procedure ill-defined

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



Three-particle scattering: short-range forces

- Faddeev / Alt, Grassberger, and Sandhas equations

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

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

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

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

- momentum-space partial-wave representation

Three-particle scattering: including screened Coulomb

- Faddeev / Alt, Grassberger, and Sandhas equations

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

$$U^{(R)}_{0\alpha} = G_0^{-1} + \sum_{\sigma} T^{(R)}_{\sigma} G_0 U^{(R)}_{\sigma\alpha}$$

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

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

Three-particle scattering: including screened Coulomb

- Faddeev / Alt, Grassberger, and Sandhas equations

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

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

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

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

- momentum-space partial-wave representation
- Additional difficulties:
  quasi-singular nature of screened Coulomb potential
  slow partial-wave convergence
- $R \to \infty$ limit?

Three-particle scattering: $R \longrightarrow \infty$ limit

long-range part

$$T_{\alpha R}^{\text{c.m.}} = W_{\alpha R}^{\text{c.m.}} + W_{\alpha R}^{\text{c.m.}} G_{\alpha}^{(R)} T_{\alpha R}^{\text{c.m.}}$$

Three-particle scattering: $R \to \infty$ limit

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

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

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

Three-particle scattering: $R \to \infty$ limit

Split into long-range part

$$T_{\alpha R}^{\text{c.m.}} = W_{\alpha R}^{\text{c.m.}} + W_{\alpha R}^{\text{c.m.}} G_{\alpha}^{(R)} T_{\alpha R}^{\text{c.m.}}$$

and Coulomb-distorted short-range part

$$U_{\beta\alpha}^{(R)} = \delta_{\beta\alpha} T_{\alpha R}^{\text{c.m.}} + [1 + T_{\beta R}^{\text{c.m.}} G_{\beta}^{(R)}] \tilde{U}_{\beta\alpha}^{(R)} [1 + G_{\alpha}^{(R)} T_{\alpha R}^{\text{c.m.}}]$$

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

Renormalized amplitudes:

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

$$U_{0\alpha} = \lim_{R \to \infty} z_{R}^{-\frac{1}{2}} U_{0\alpha}^{(R)} Z_{R\,i}^{-\frac{1}{2}}$$

Three-particle scattering: $R \to \infty$ limit

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

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

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

Renormalized amplitudes:

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

$$U_{0\alpha} = \lim_{R\to\infty} z_R^{-\frac{1}{2}} U^{(R)}_{0\alpha} Z_{Ri}^{-\frac{1}{2}}$$

short-range part: fast convergence with R

Proton-deuteron scattering

- Symmetrized Faddeev / AGS equations

$$U^{(R)} = PG_0^{-1} + PT^{(R)}G_0U^{(R)}$$

$$U_0^{(R)} = (1+P)G_0^{-1} + (1+P)T^{(R)}G_0U^{(R)}$$

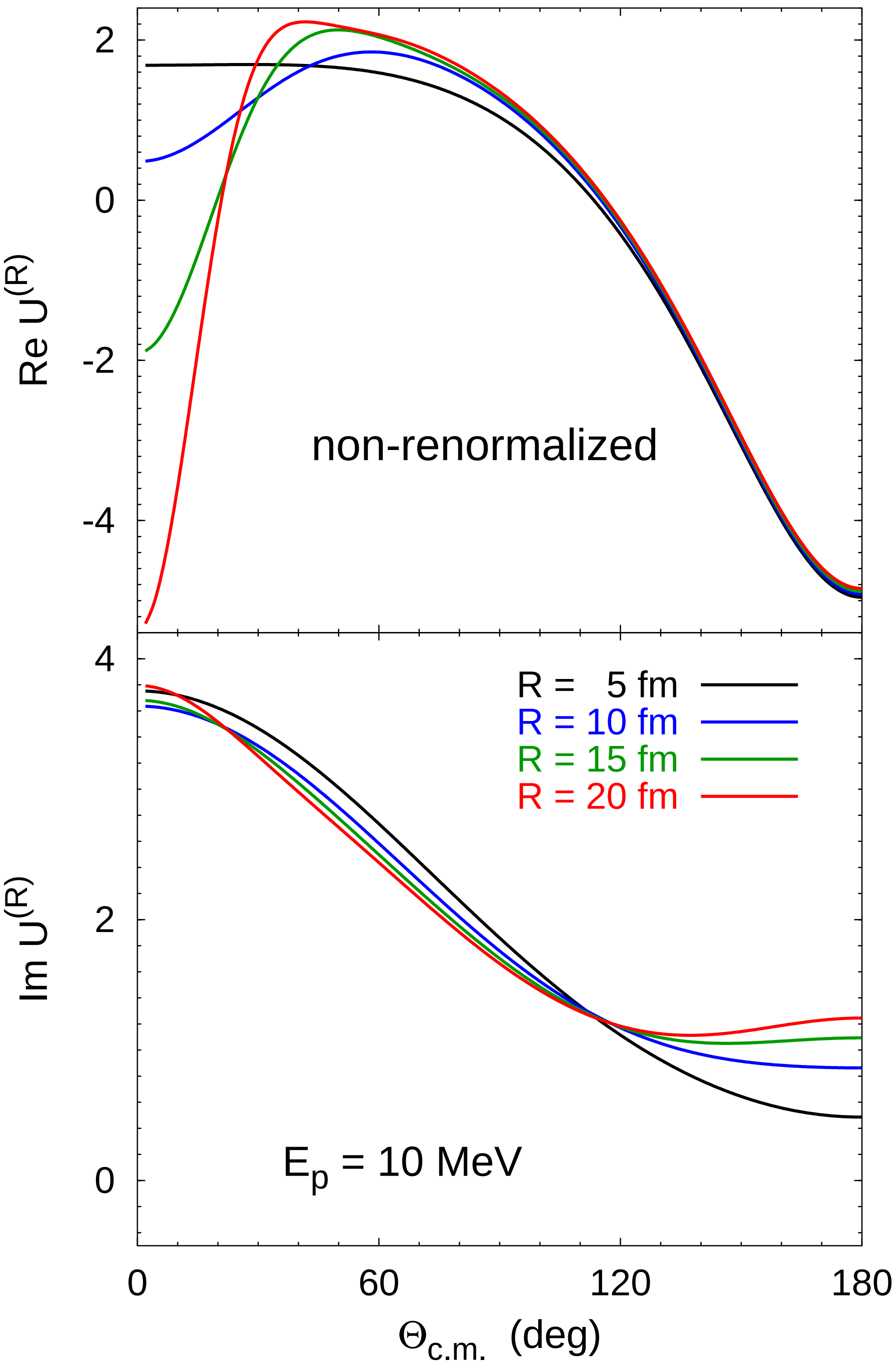
$$P = P_{12}P_{23} + P_{13}P_{23}$$

- Screening function with $n = 4$
- Renormalized amplitudes:

$$U = T_C^{\text{c.m.}} + \lim_{R\to\infty} Z_R^{-1}[U^{(R)} - T_R^{\text{c.m.}}]$$

$$U_0 = \lim_{R\to\infty} z_R^{-\frac{1}{2}} U_0^{(R)} Z_R^{-\frac{1}{2}}$$

pd elastic amplitude (spin-diagonal)



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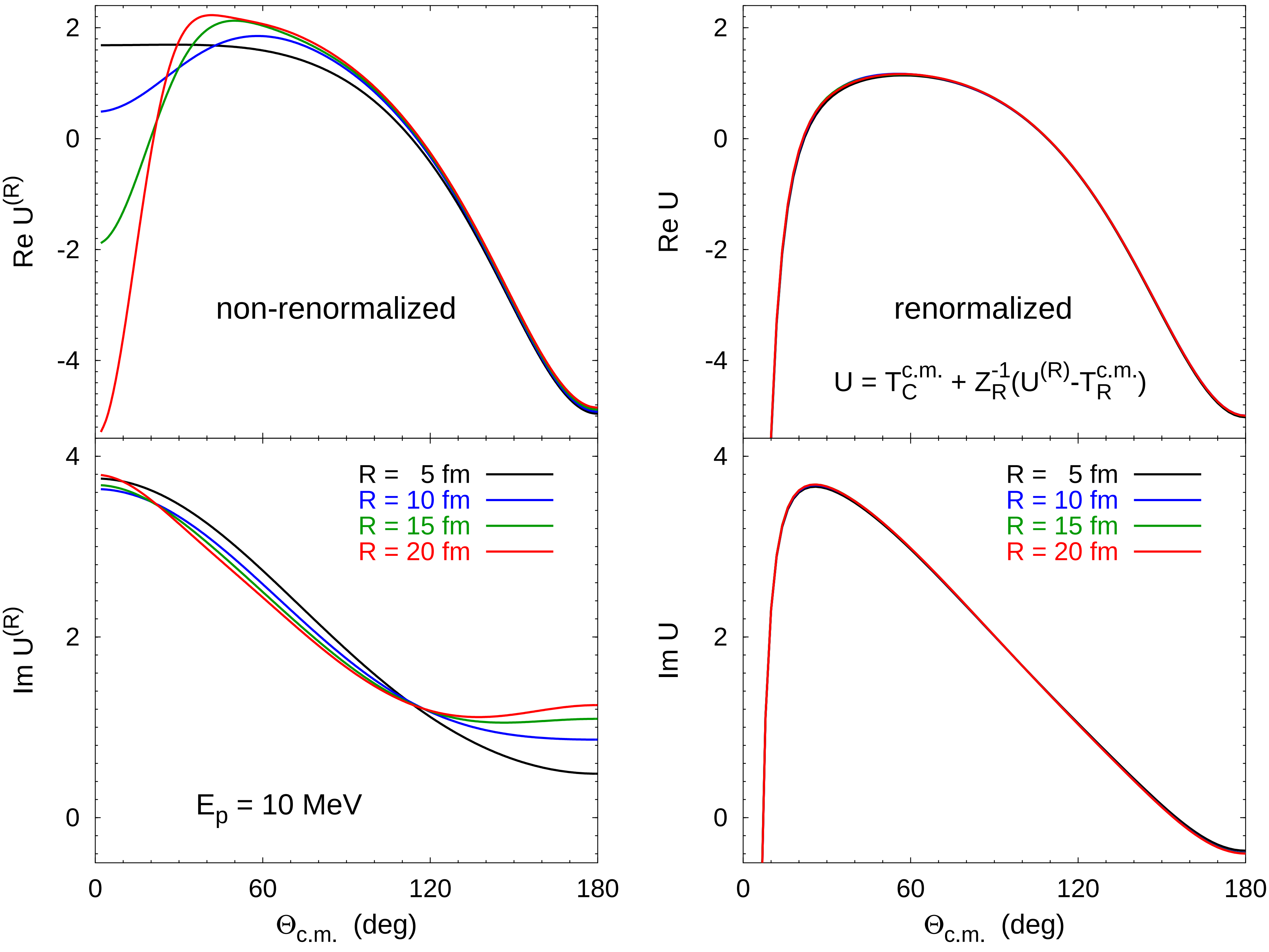
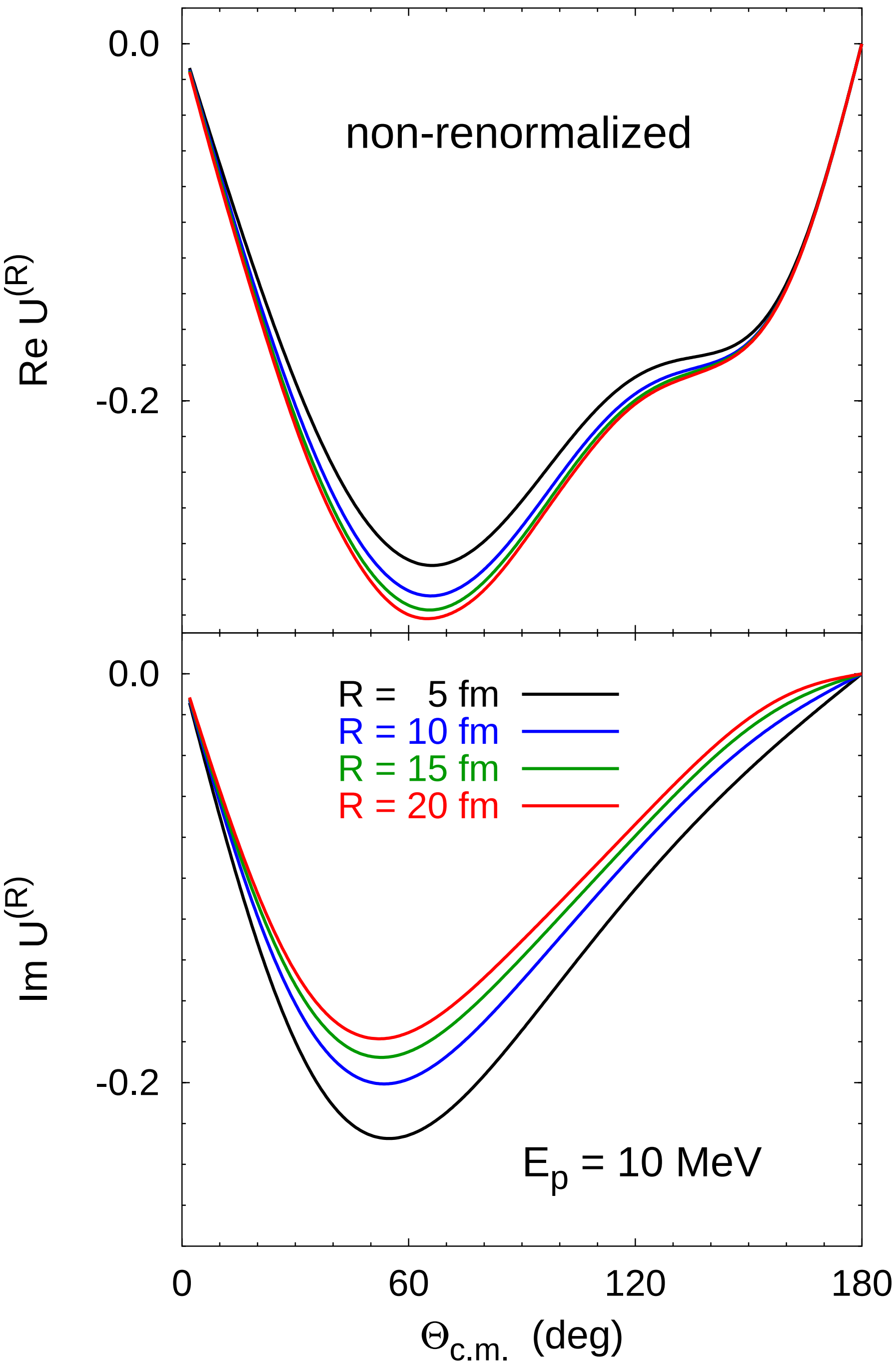
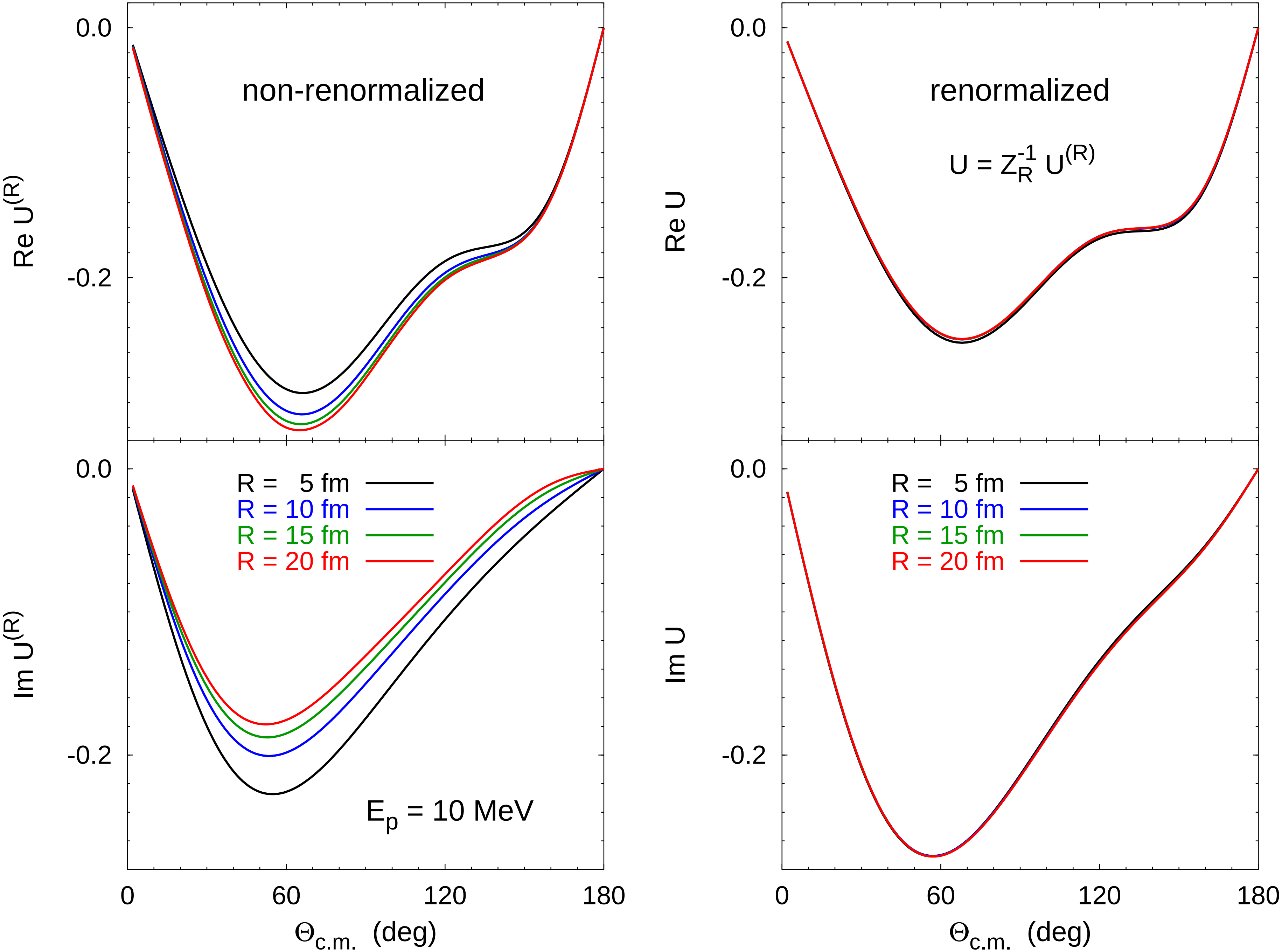


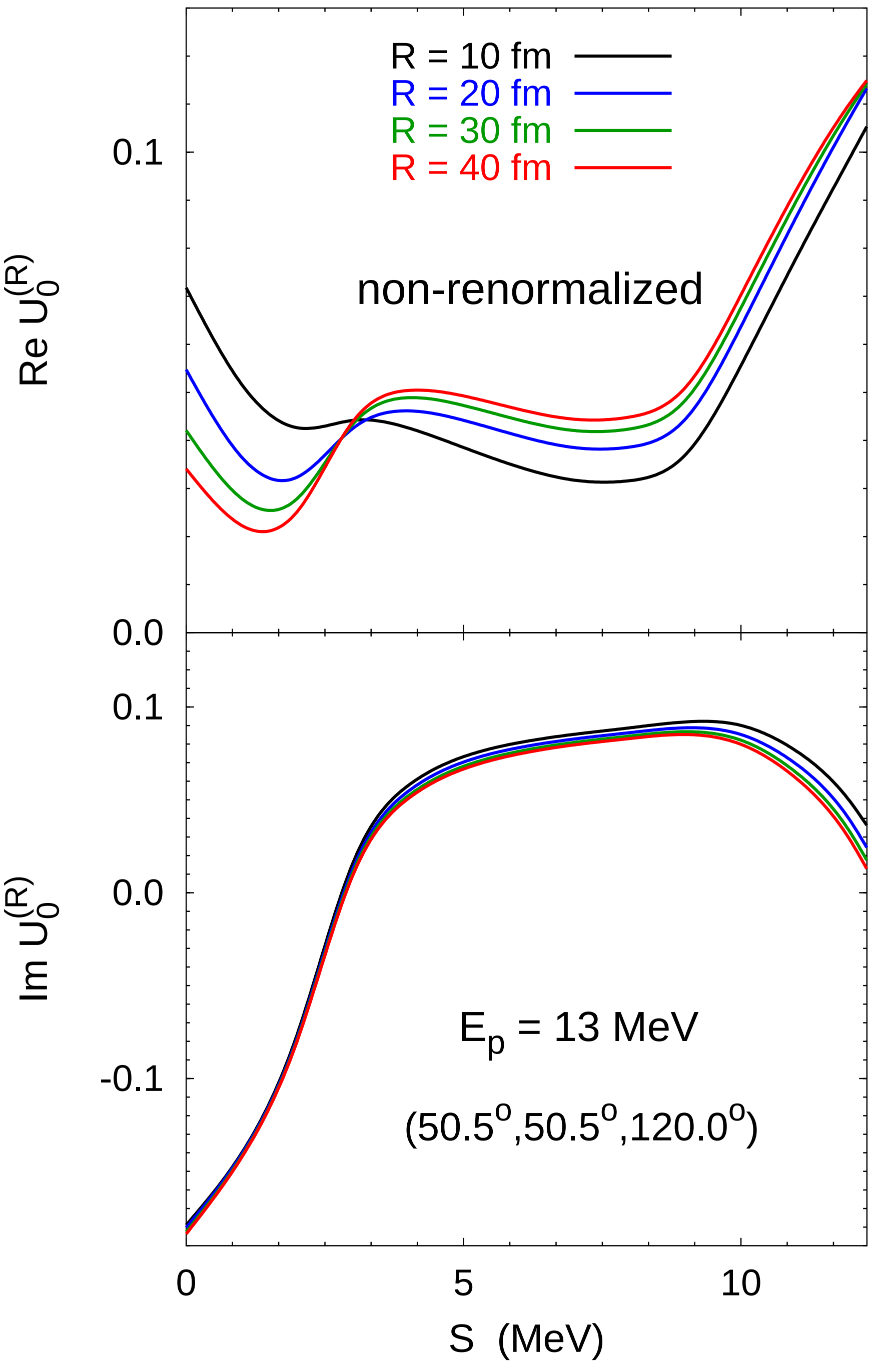
pd elastic amplitude (spin-nondiagonal)



pd elastic amplitude (spin-nondiagonal)



pd breakup amplitude



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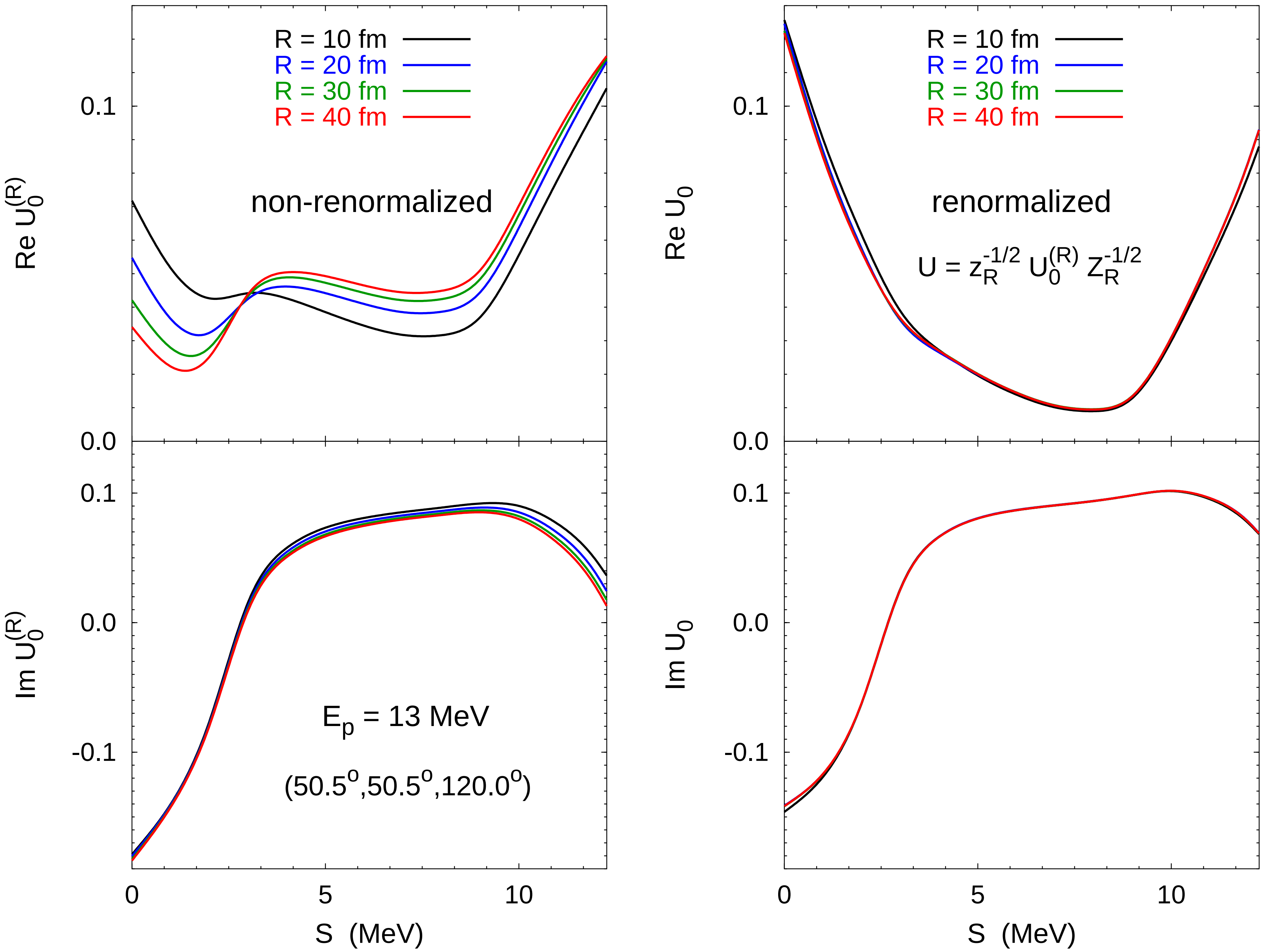
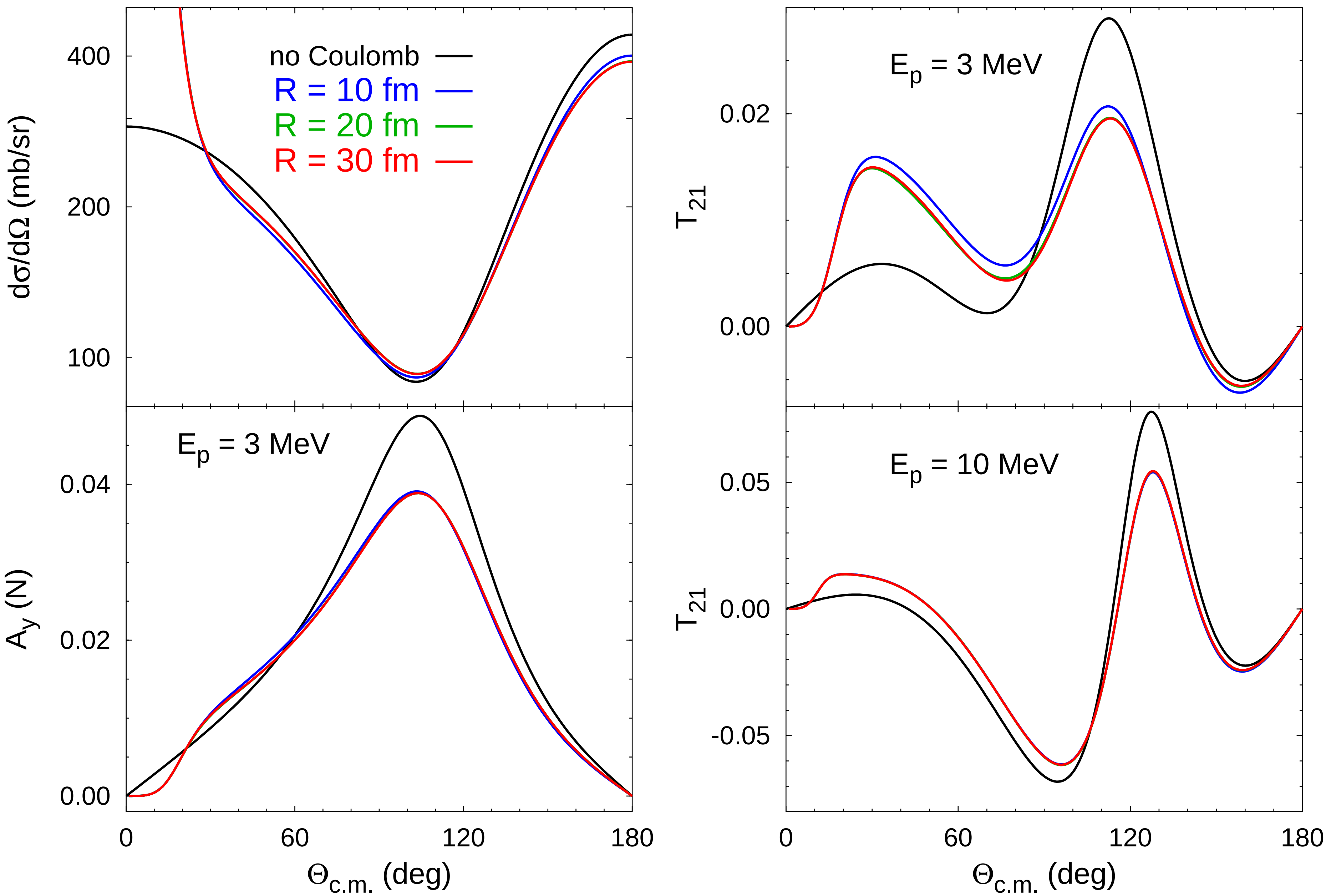
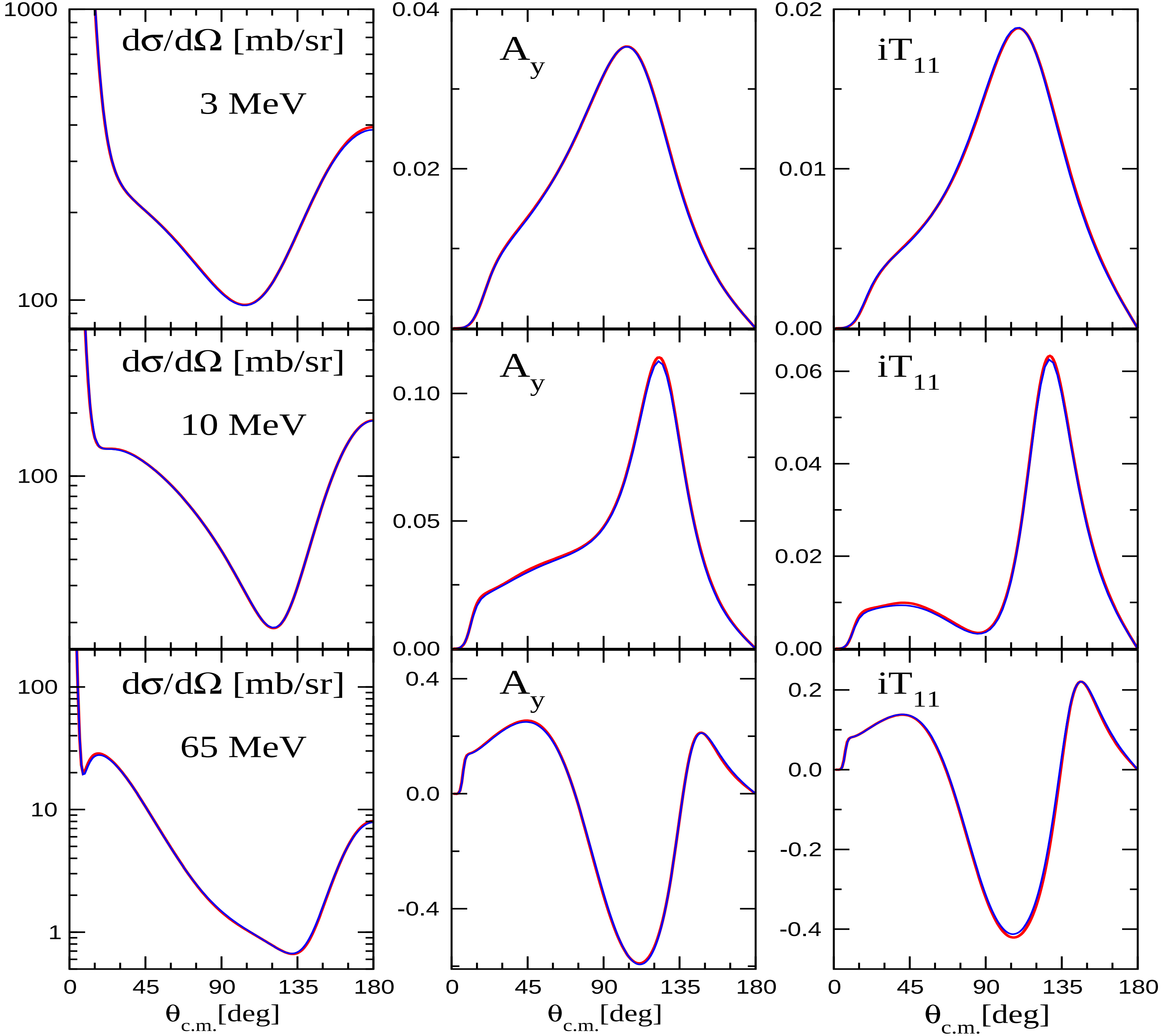


Convergence with *R*: *pd* elastic scattering



Comparison with configuration-space results

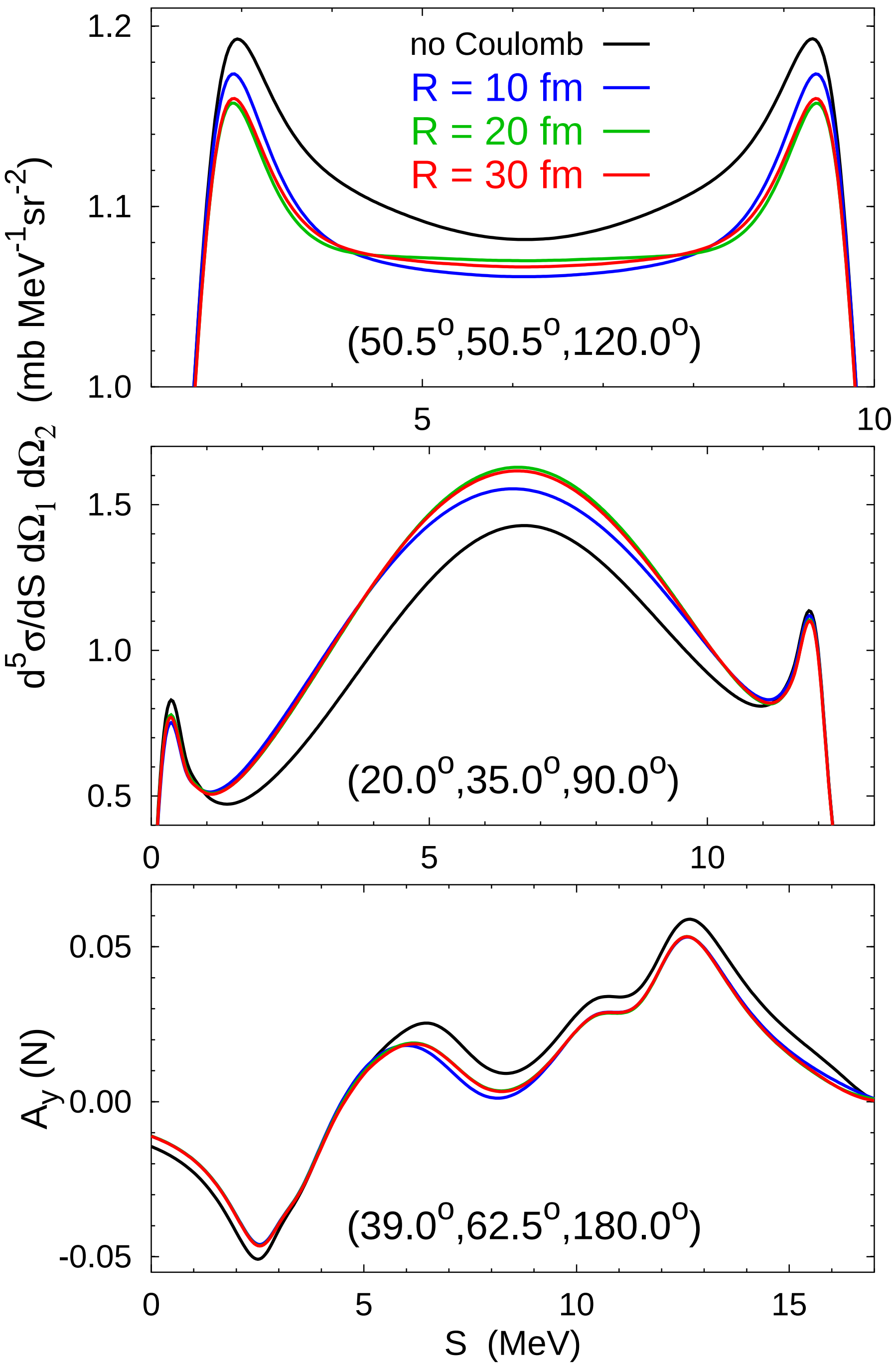


pd elastic scattering:

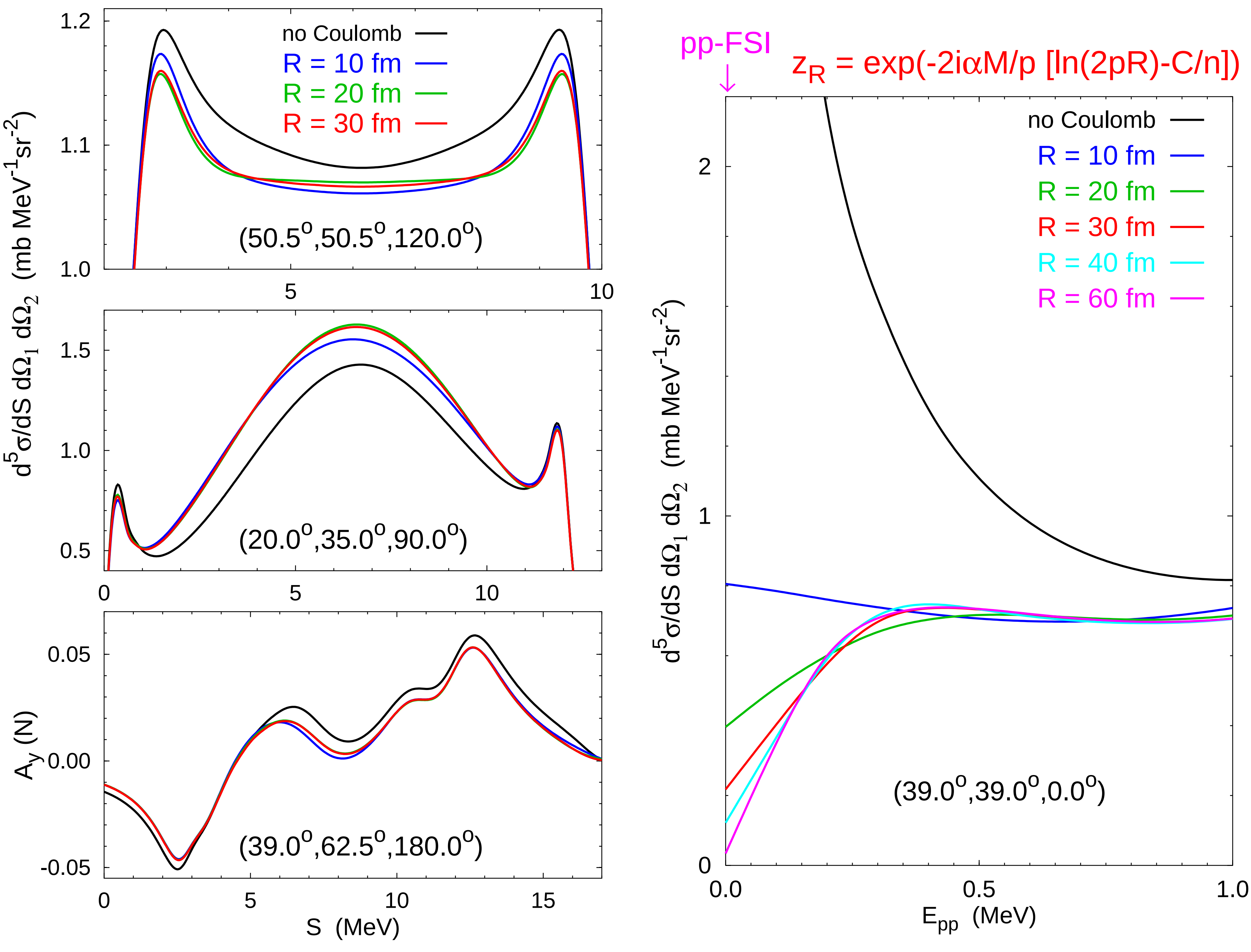
Kohn variational principle (Pisa)

screening and renormalization

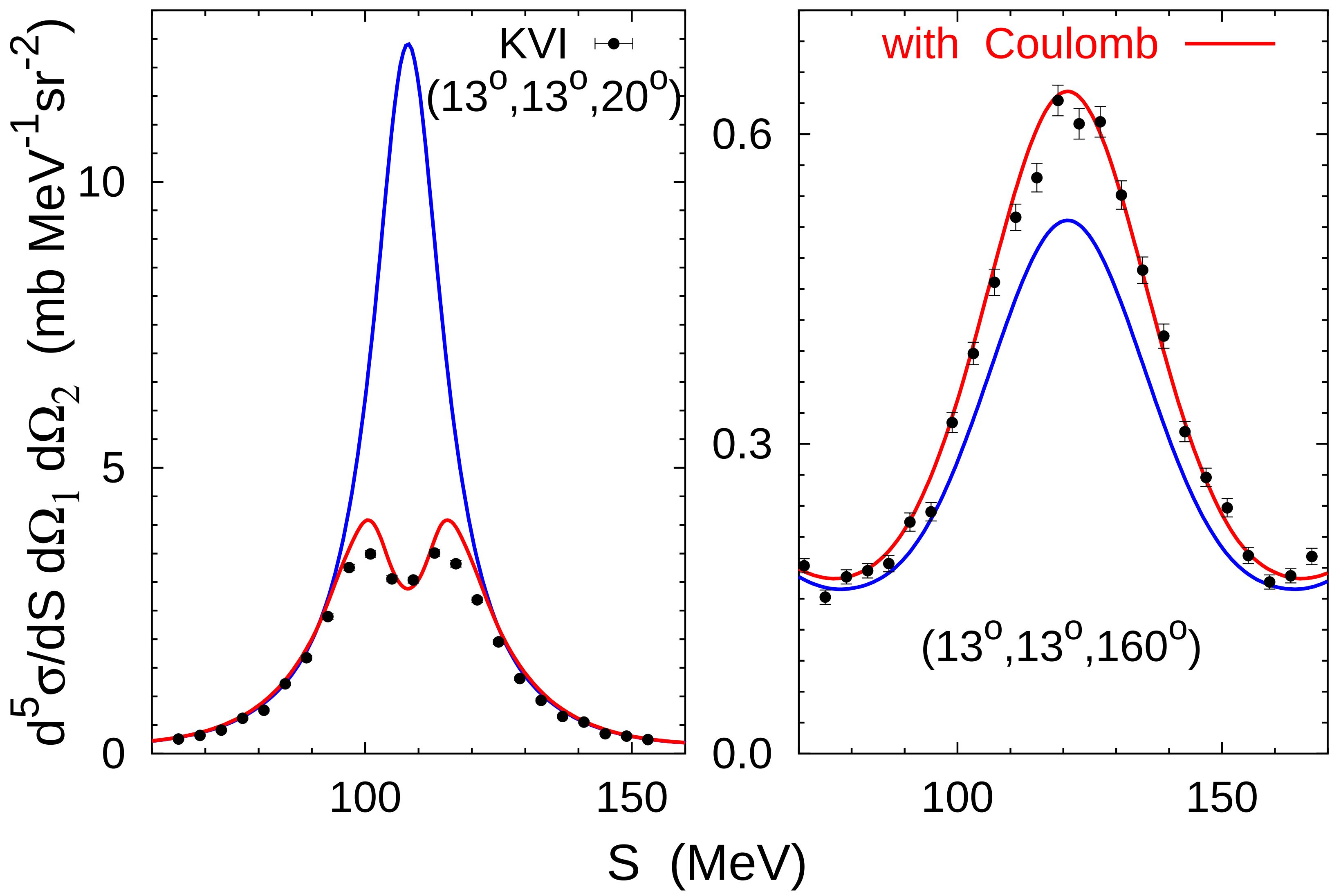
Convergence with R: pd breakup at $E_p = 13$ MeV



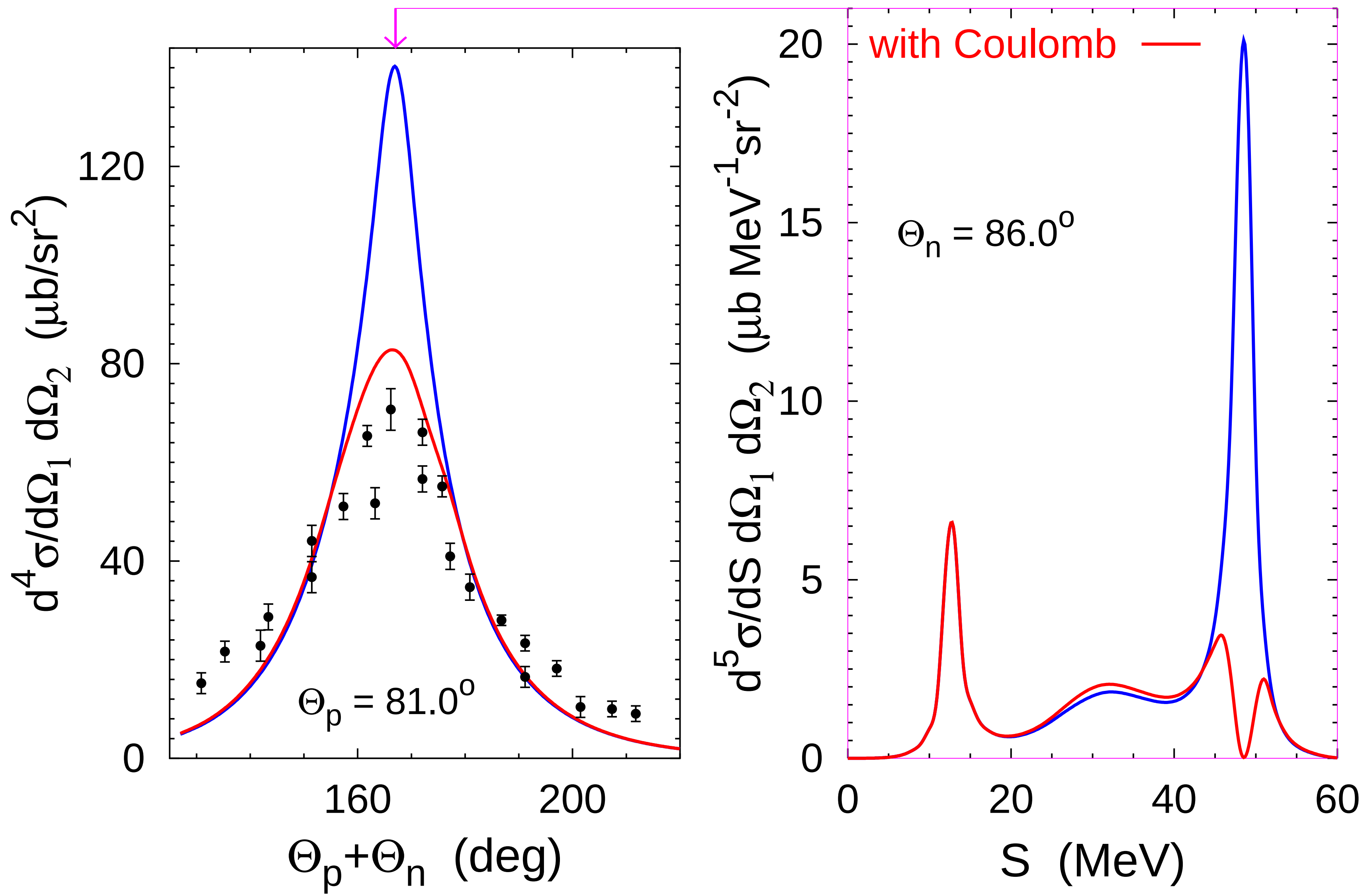
Convergence with R: pd breakup at $E_p = 13$ MeV



dp breakup at $E_d = 130$ MeV



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



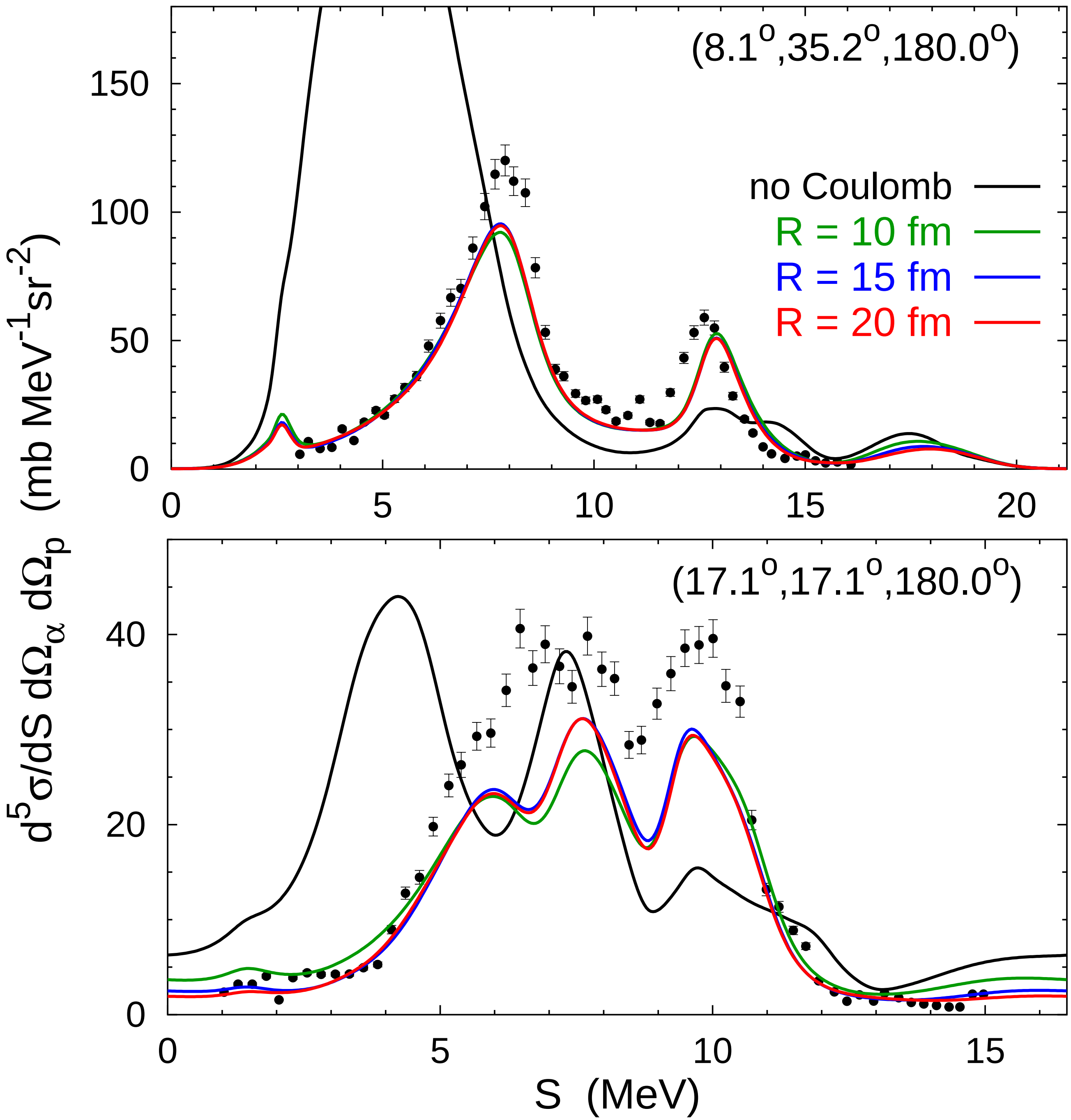
Application to 3-body nuclear reactions

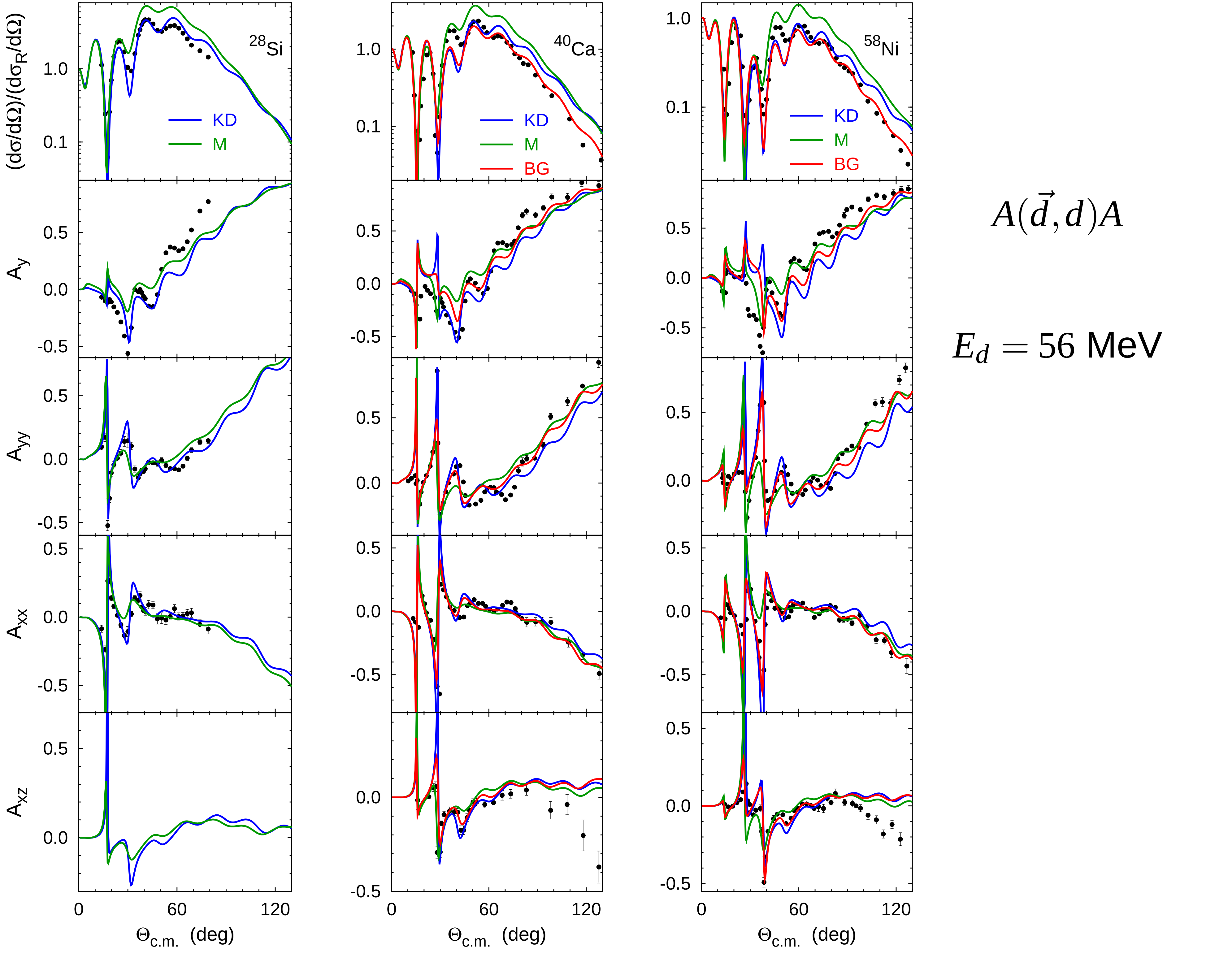
$$\left.\begin{array}{l} p+(nA) \\ d+A \end{array}\right\} \rightarrow \left\{\begin{array}{l} n+(pA) \\ p+(nA) \\ d+A \\ p+n+A \end{array}\right.$$

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, ...

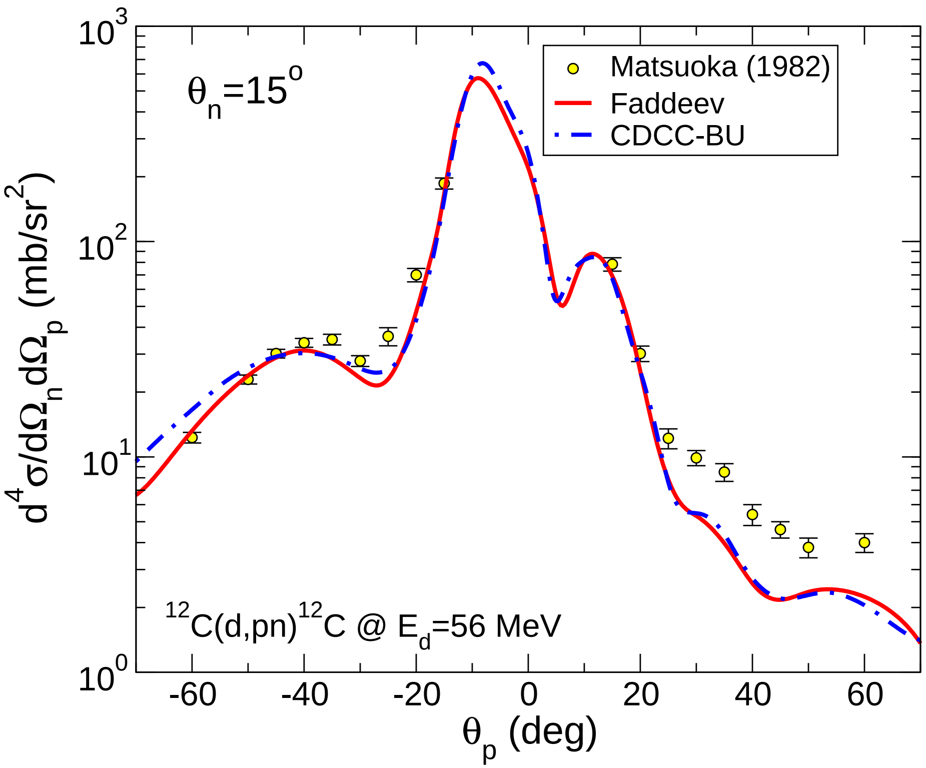
Convergence with *R*: α-*d* breakup at $E_\alpha = 15$ MeV

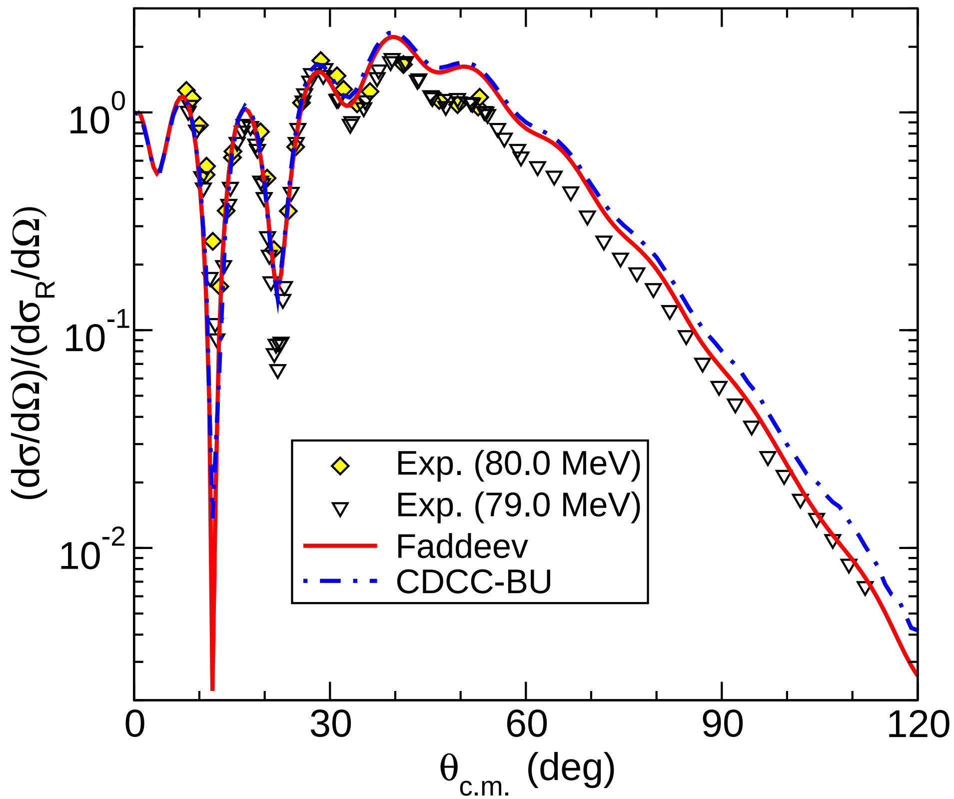




^{28}Si
^{40}Ca
^{58}Ni
KD
M
BG
(dσ/dΩ)/(dσ$_R$/dΩ)
A_y
A_{yy}
A_{xx}
A_{xz}
$\Theta_{c.m.}$ (deg)
$A(\vec{d},d)A$
$E_d = 56$ MeV

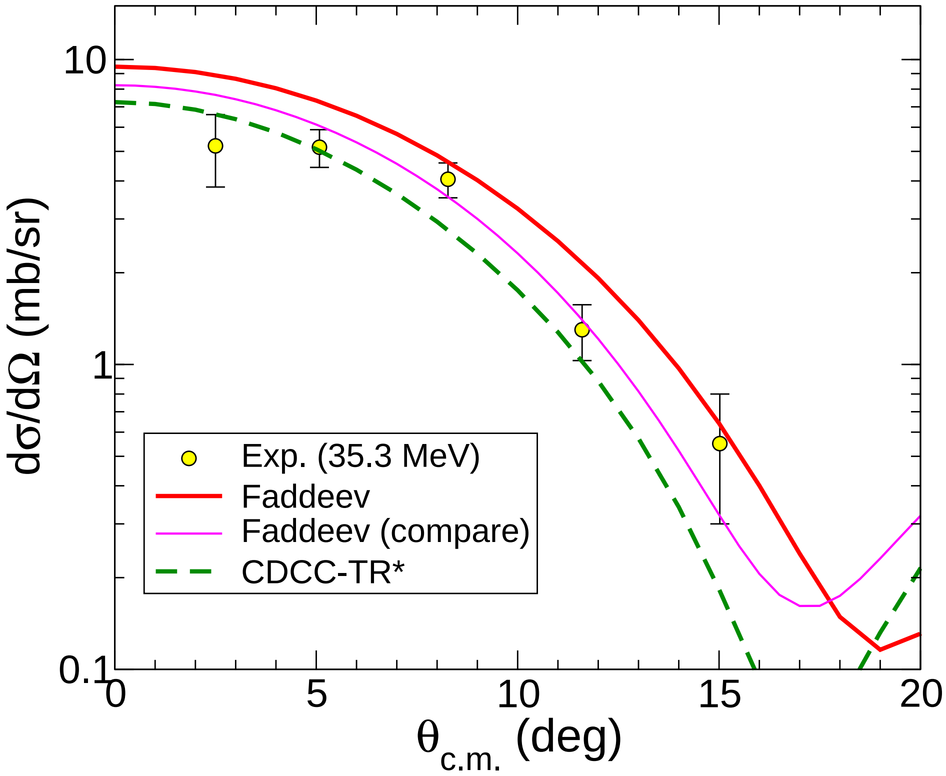
CDCC test: $^{12}\mathrm{C}(d,pn)^{12}\mathrm{C}$ and $^{58}\mathrm{Ni}(d,d)^{58}\mathrm{Ni}$

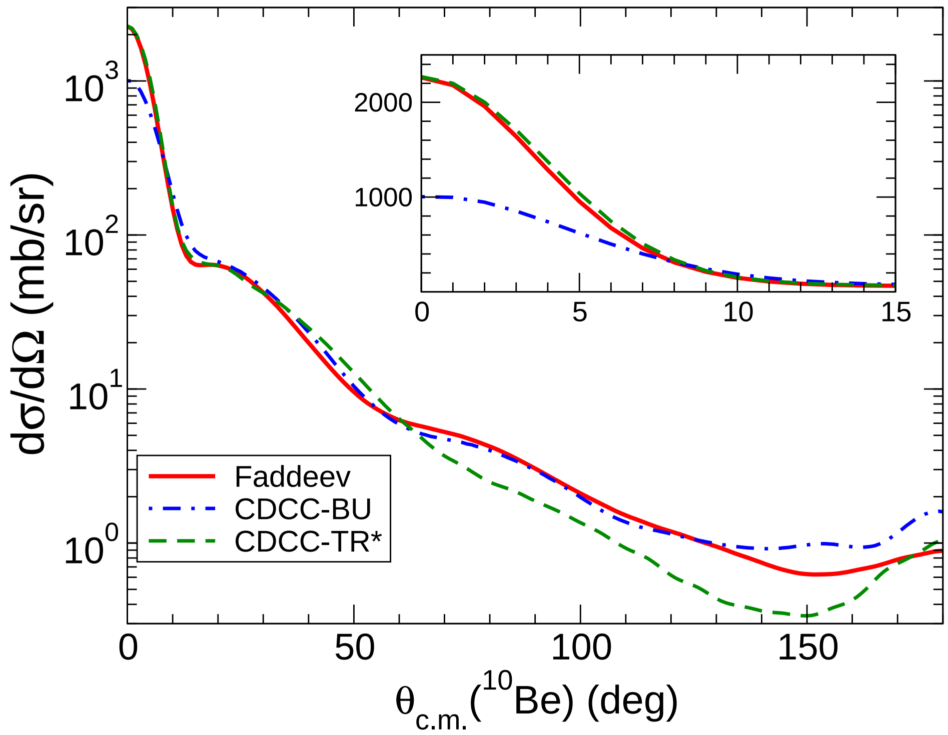




CDCC: A. M. Moro and F. M. Nunes

CDCC test: $p(^{11}\text{Be},{}^{10}\text{Be})d$ and $p(^{11}\text{Be},{}^{10}\text{Be})np$

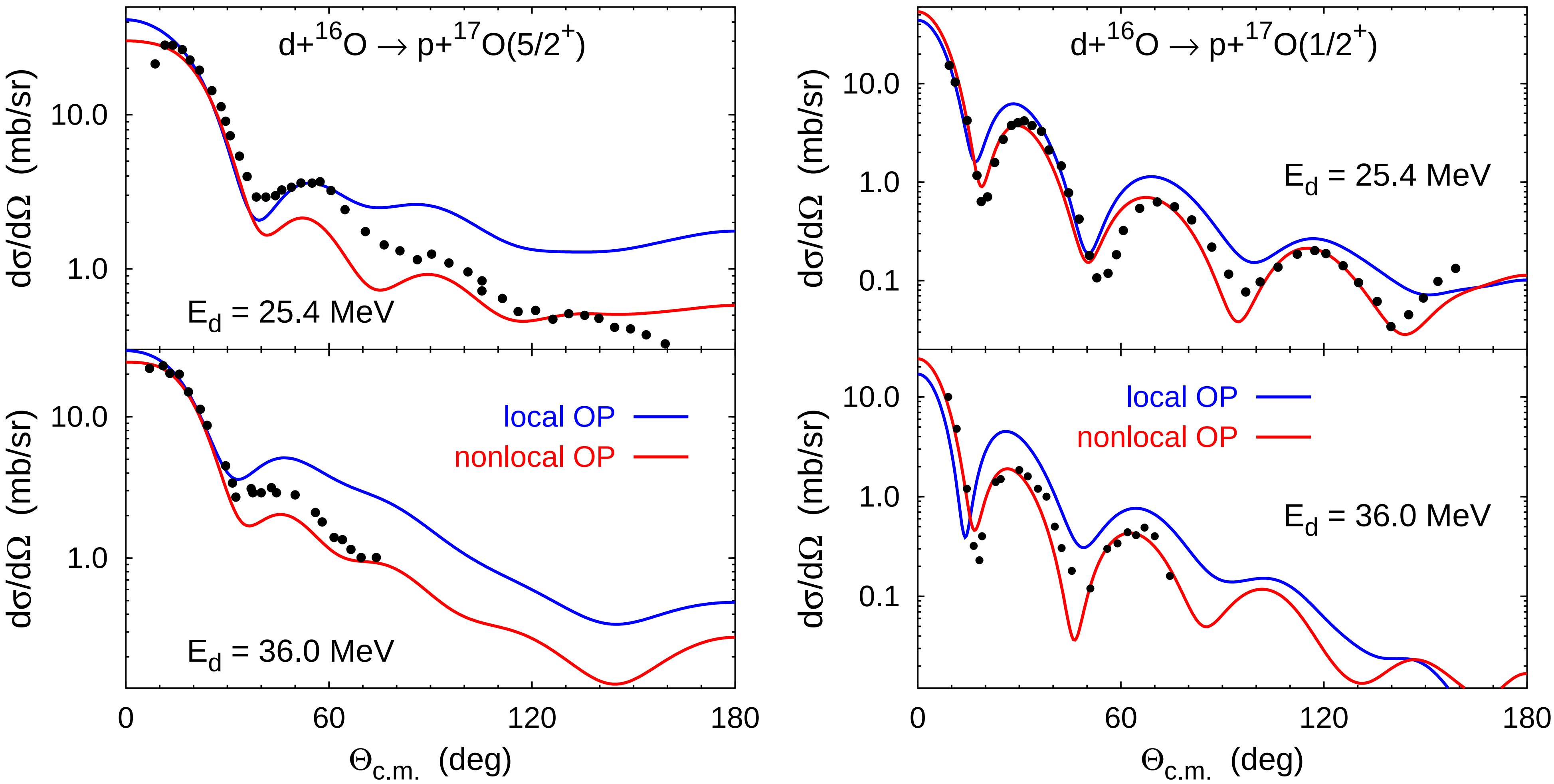




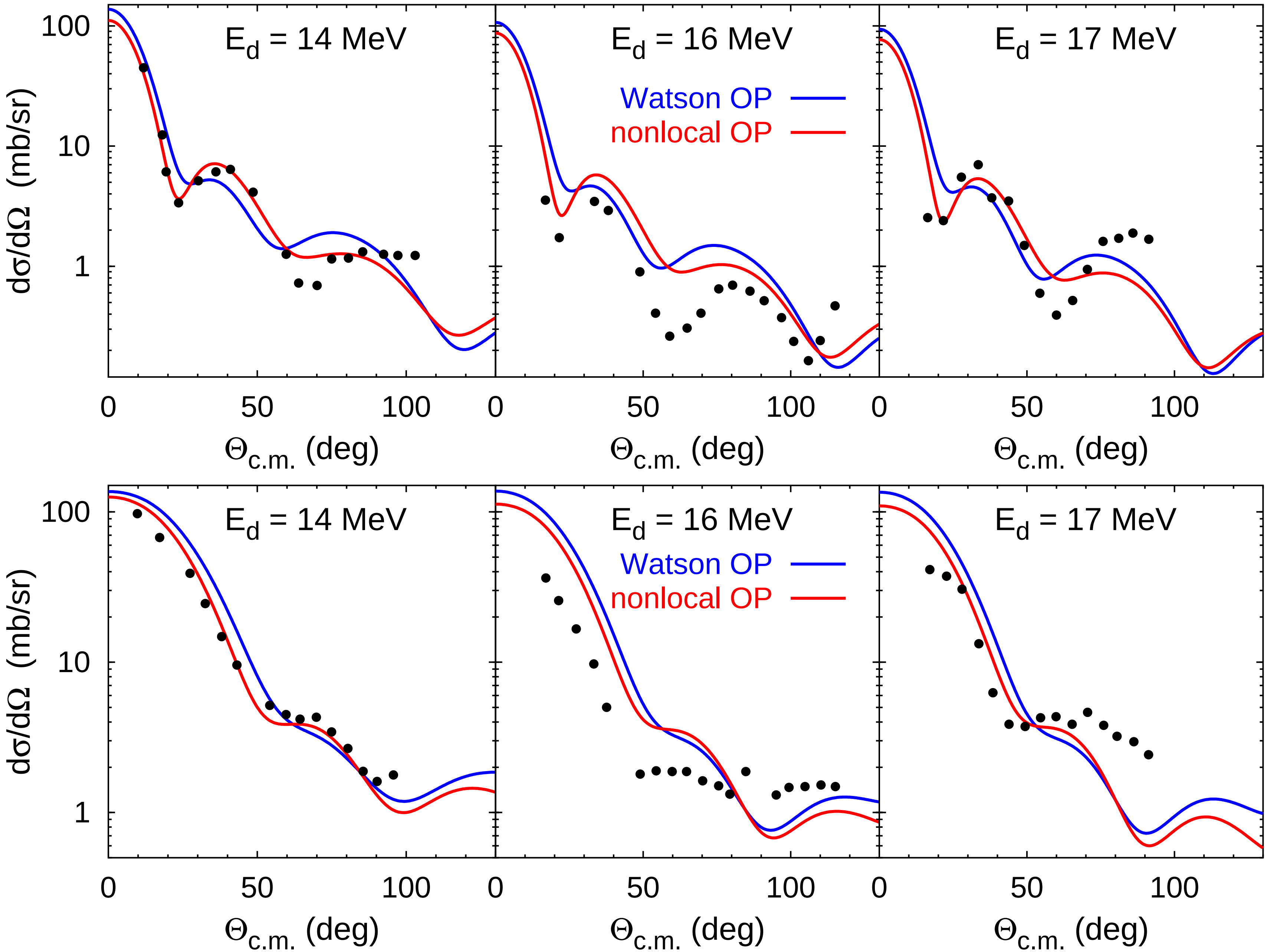
$$E/A = 38 \text{ MeV}$$

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

Nonlocal optical potential: transfer reactions $^{16}\mathrm{O}(d,p)^{17}\mathrm{O}$



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



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

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

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

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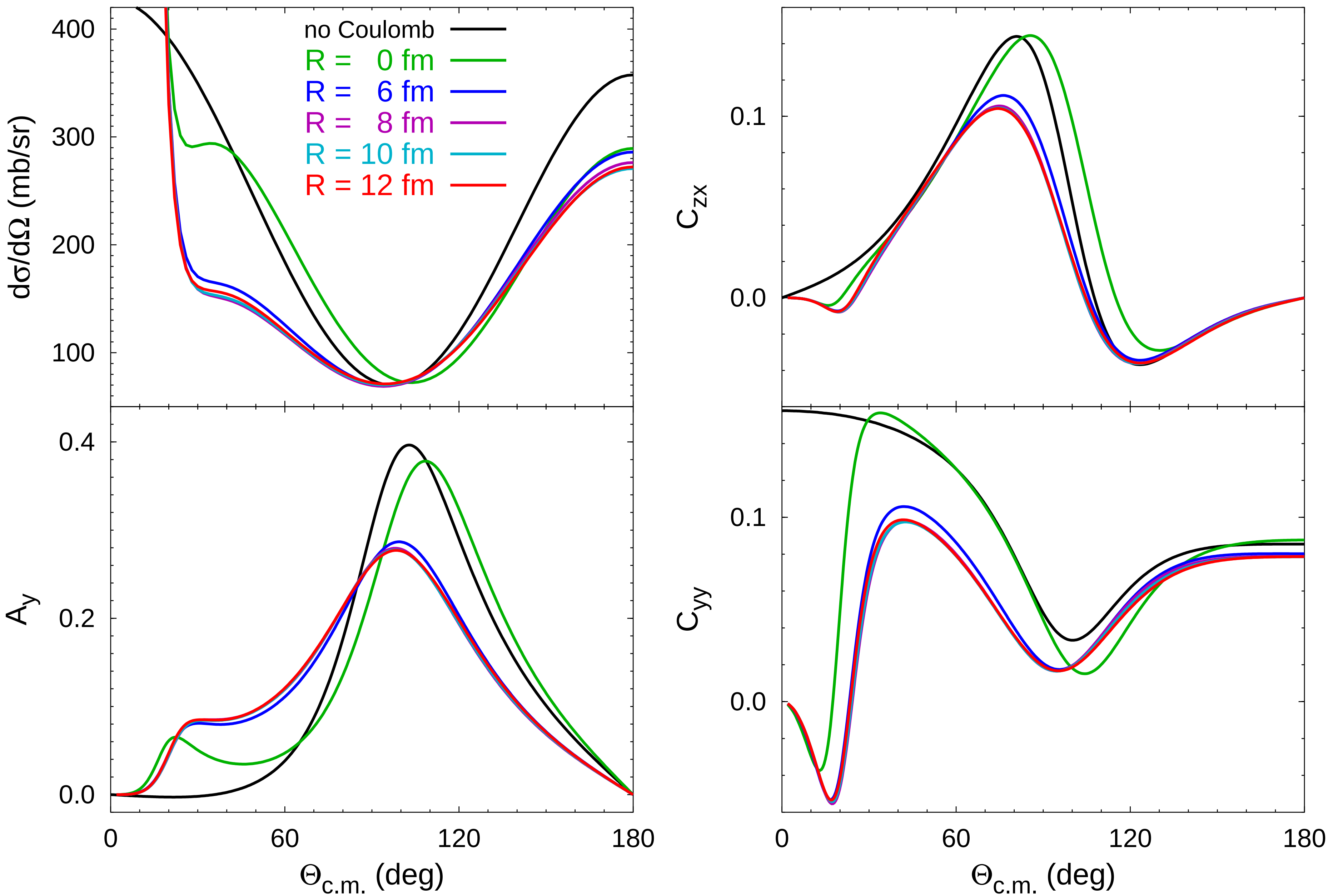
Renormalization:

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

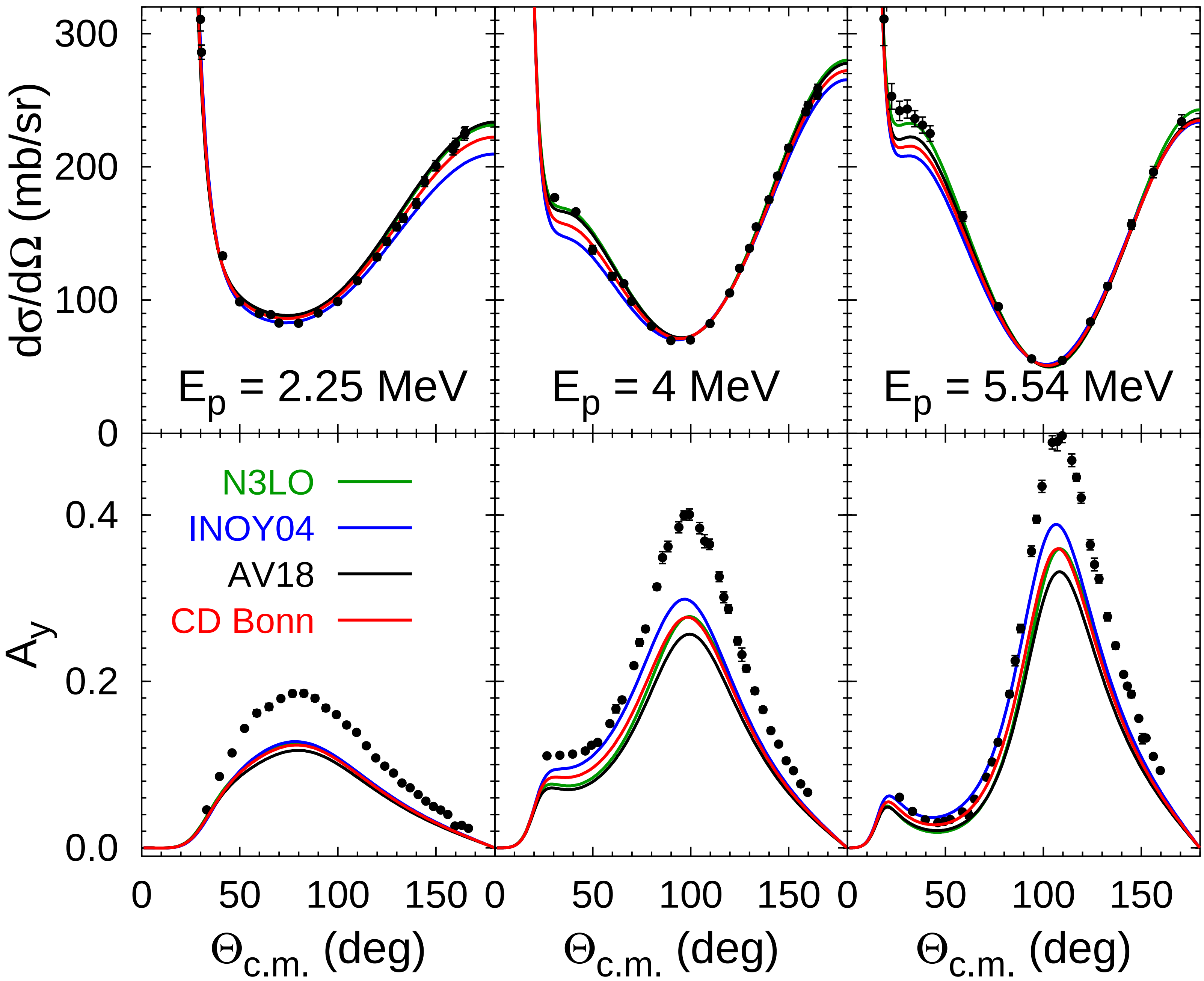
$$= \delta_{fi} T_{Ci}^{\mathrm{c.m.}} + \lim_{R\to\infty} Z_{Rf}^{-\frac{1}{2}} [\mathcal{T}_{fi}^{(R)} - \delta_{fi} T_{Ri}^{\mathrm{c.m.}}] Z_{Ri}^{-\frac{1}{2}}$$

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

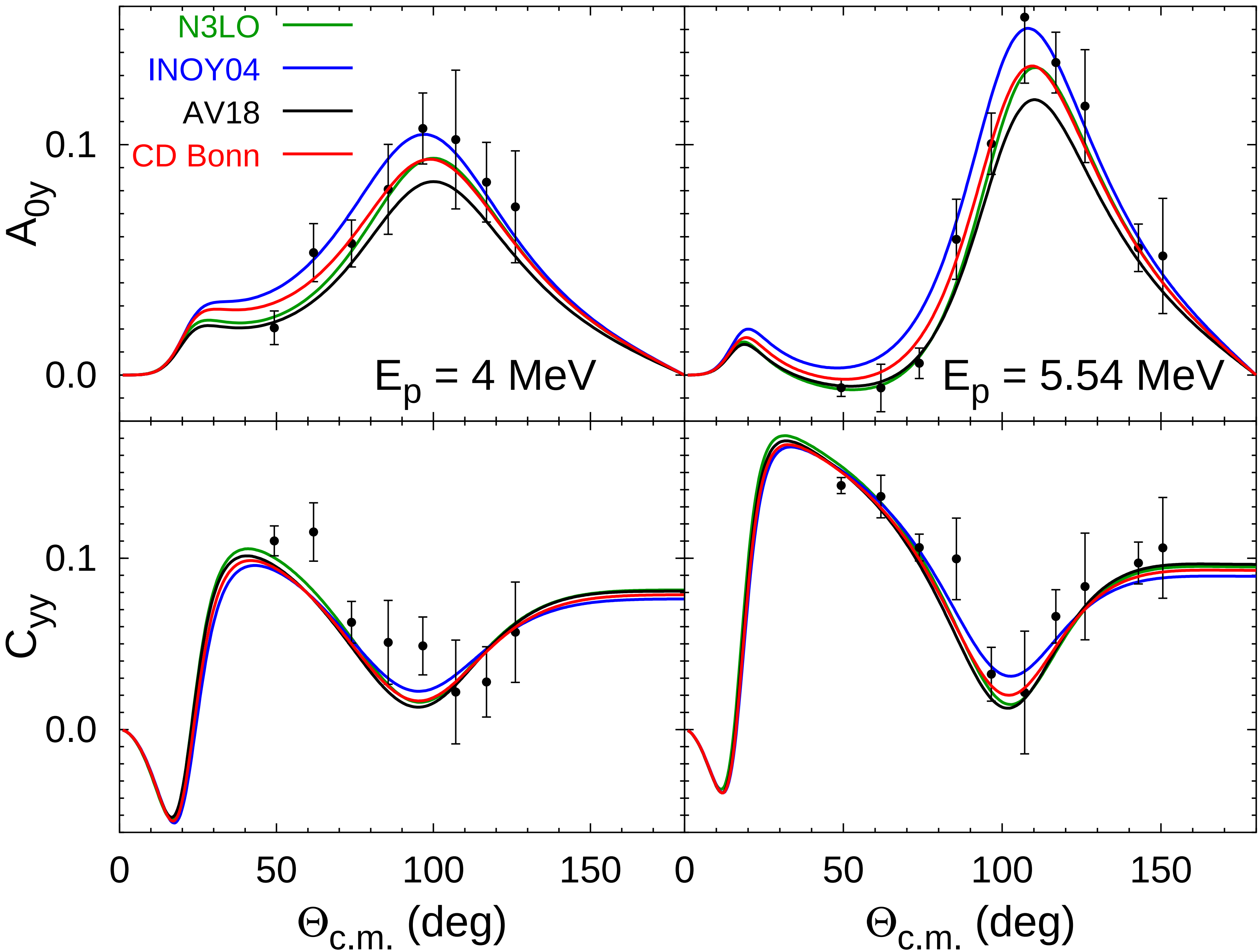
Convergence with R: p-^{3}He scattering at $E_p = 4$ MeV



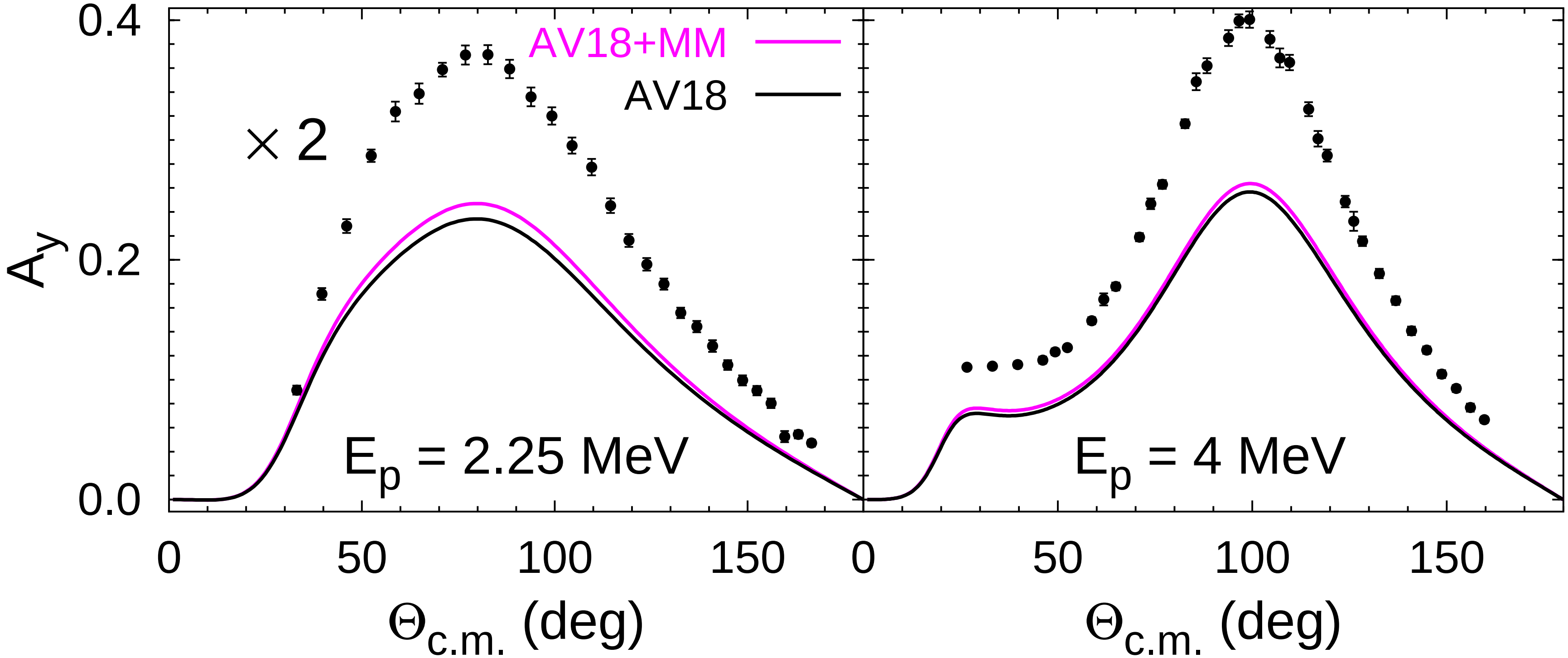
p-^{3}He scattering



p-^{3}He scattering

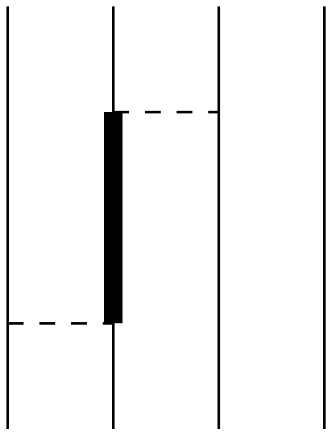


p-^{3}He A_y puzzle: NN magnetic moment interaction

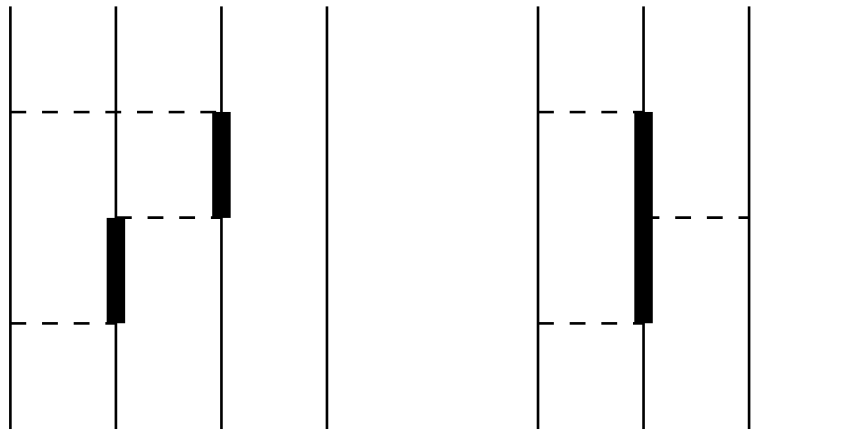


Δ-isobar excitation: effective 3N and 4N forces

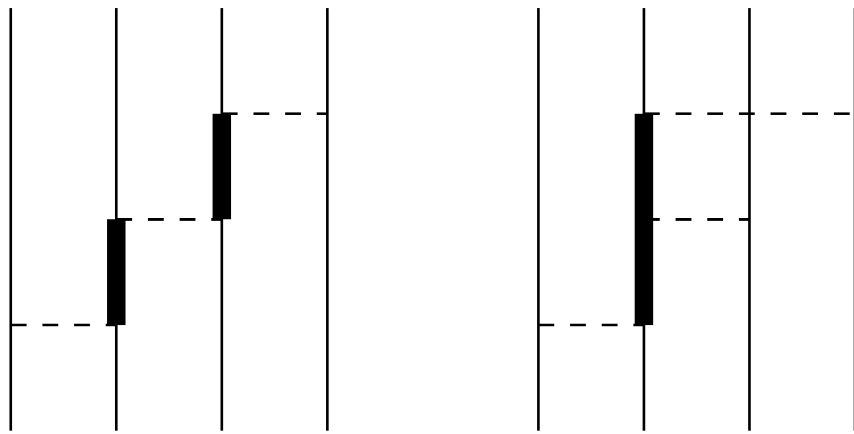
Fujita-Miyazawa



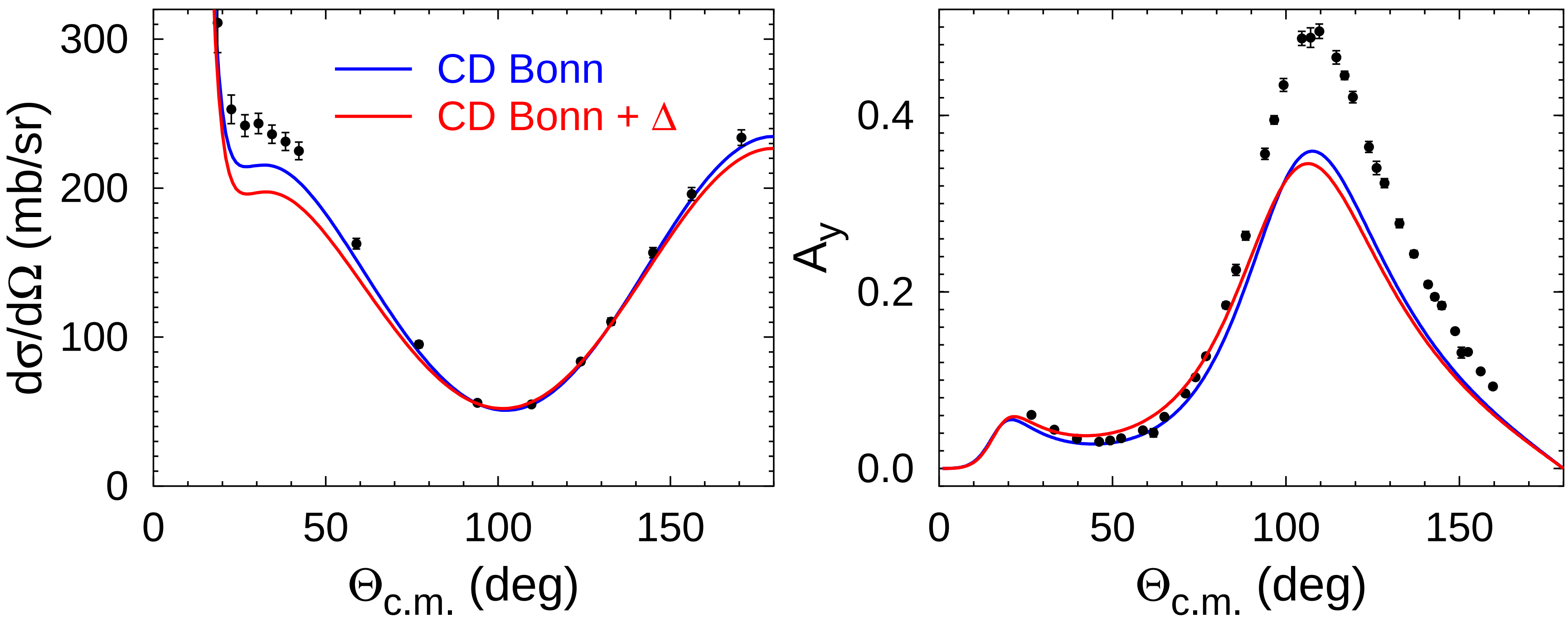
higher order 3N force



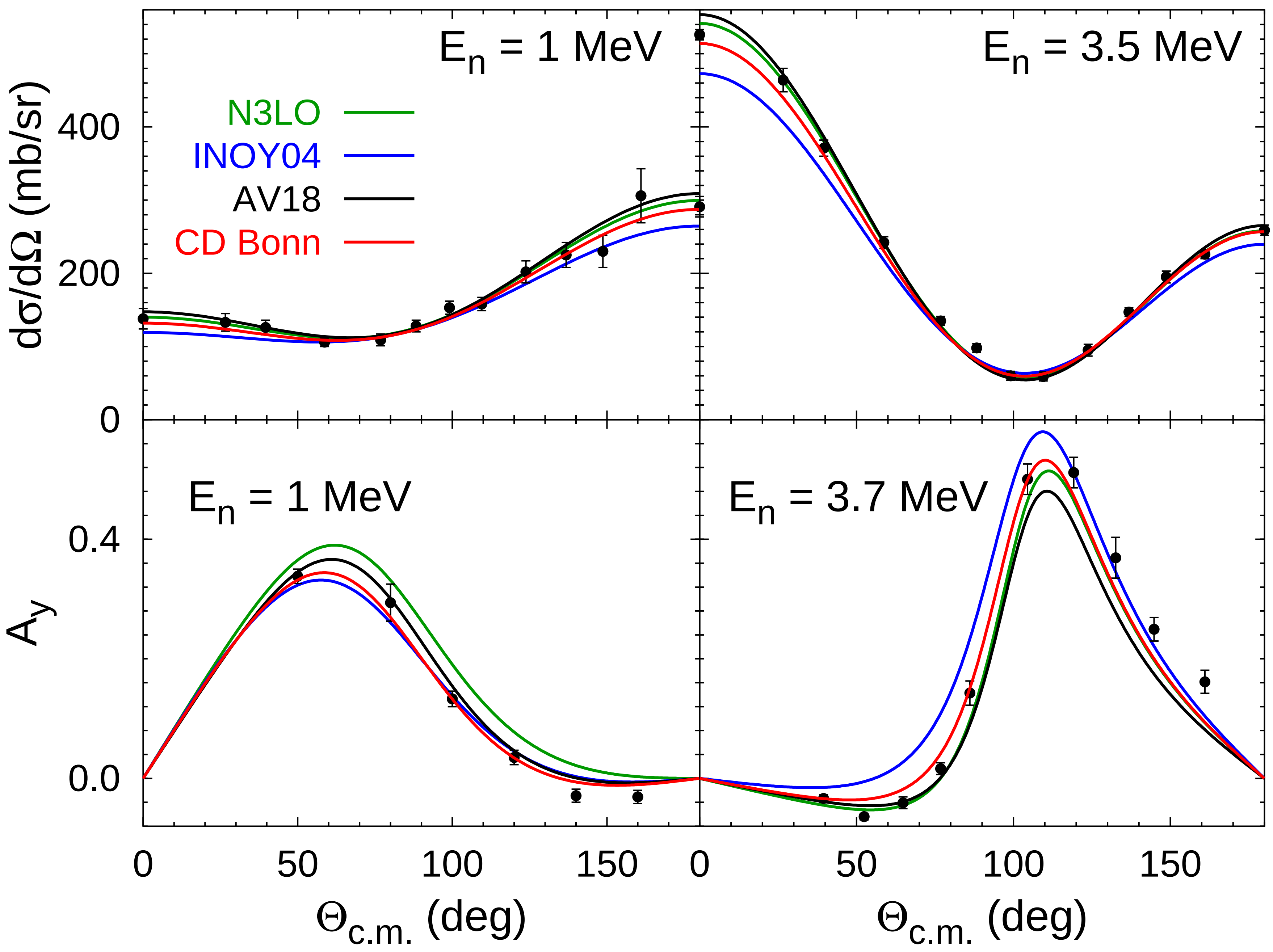
4N force



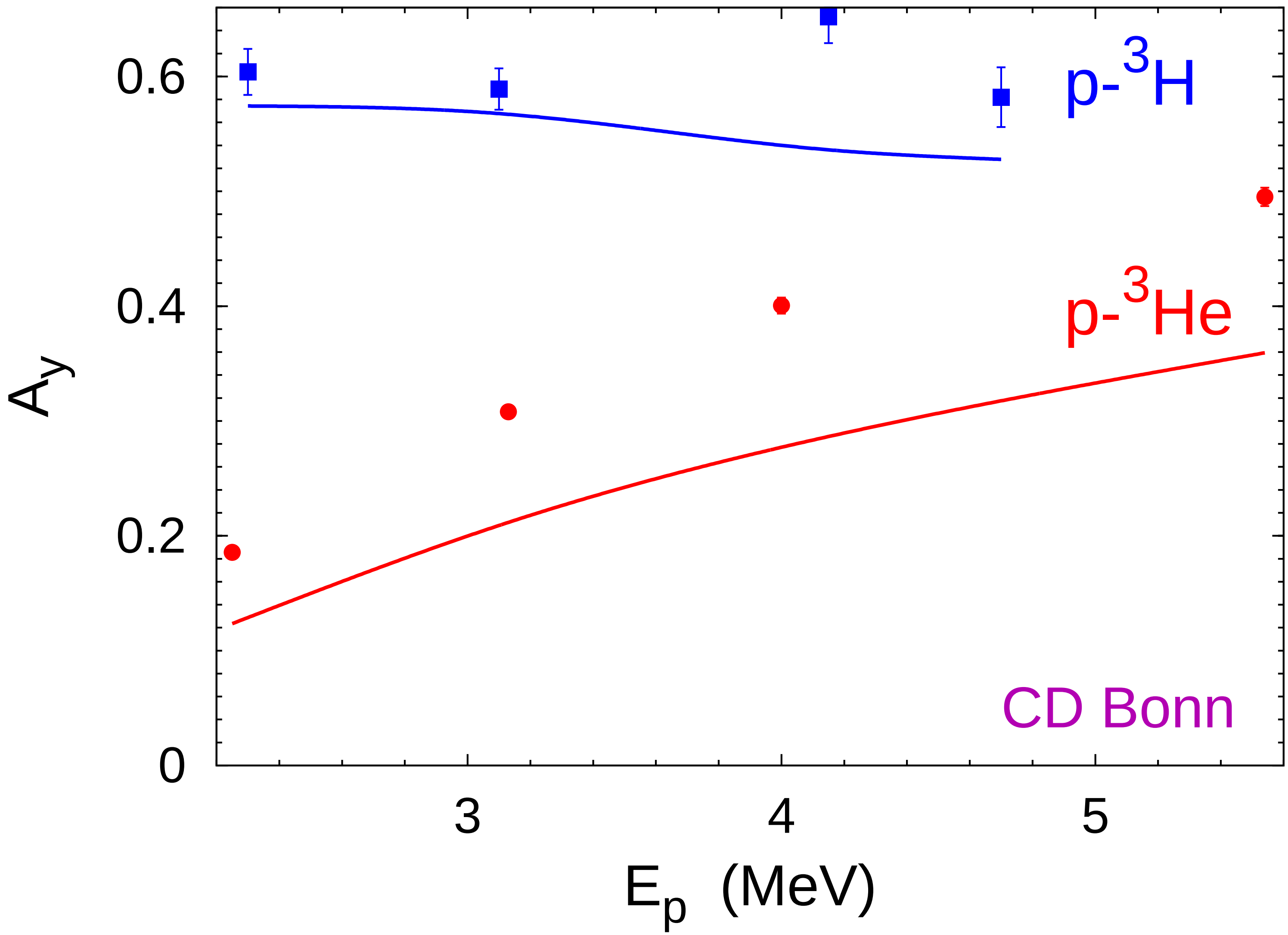
Δ isobar in p-^{3}He



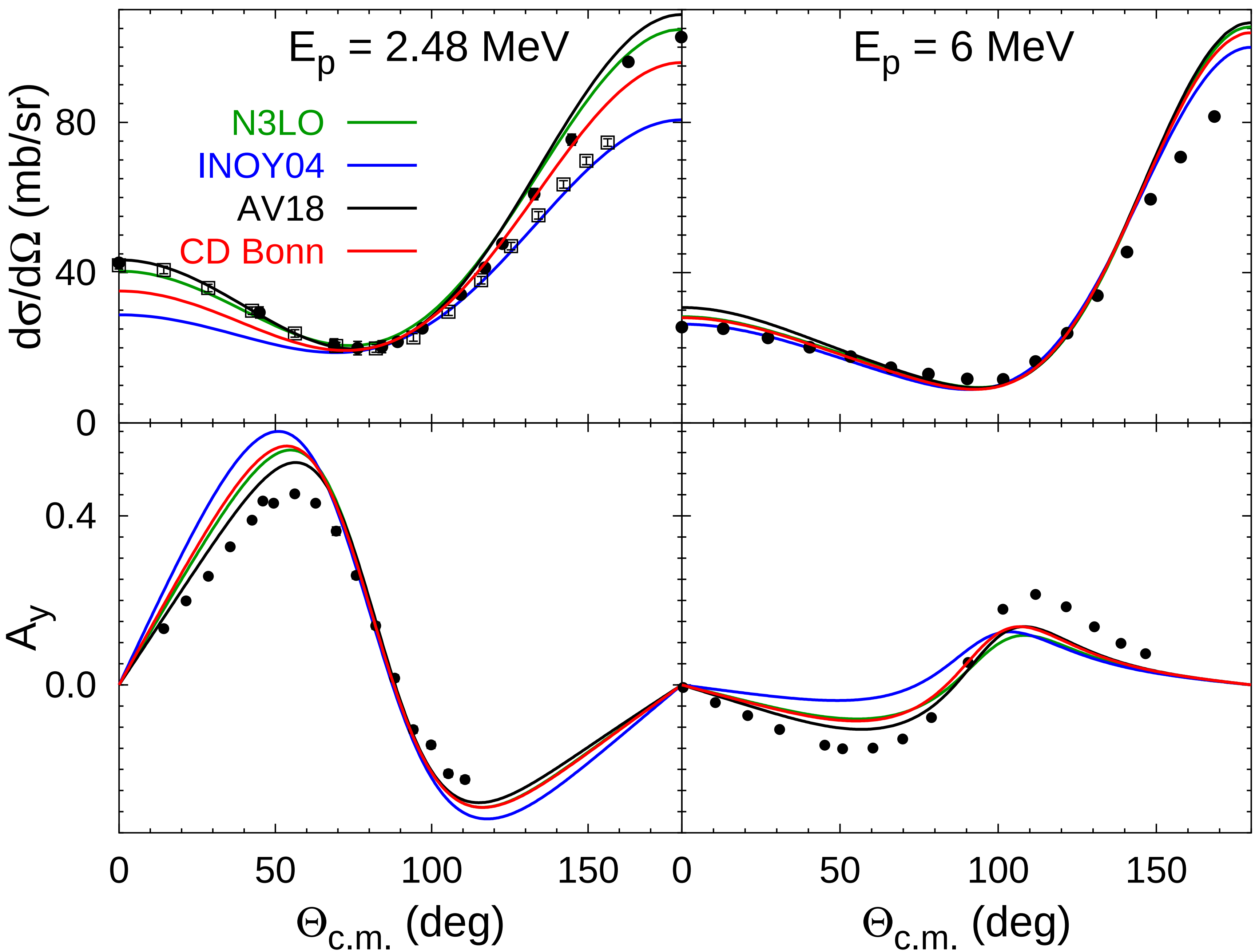
n-^{3}He **elastic scattering**



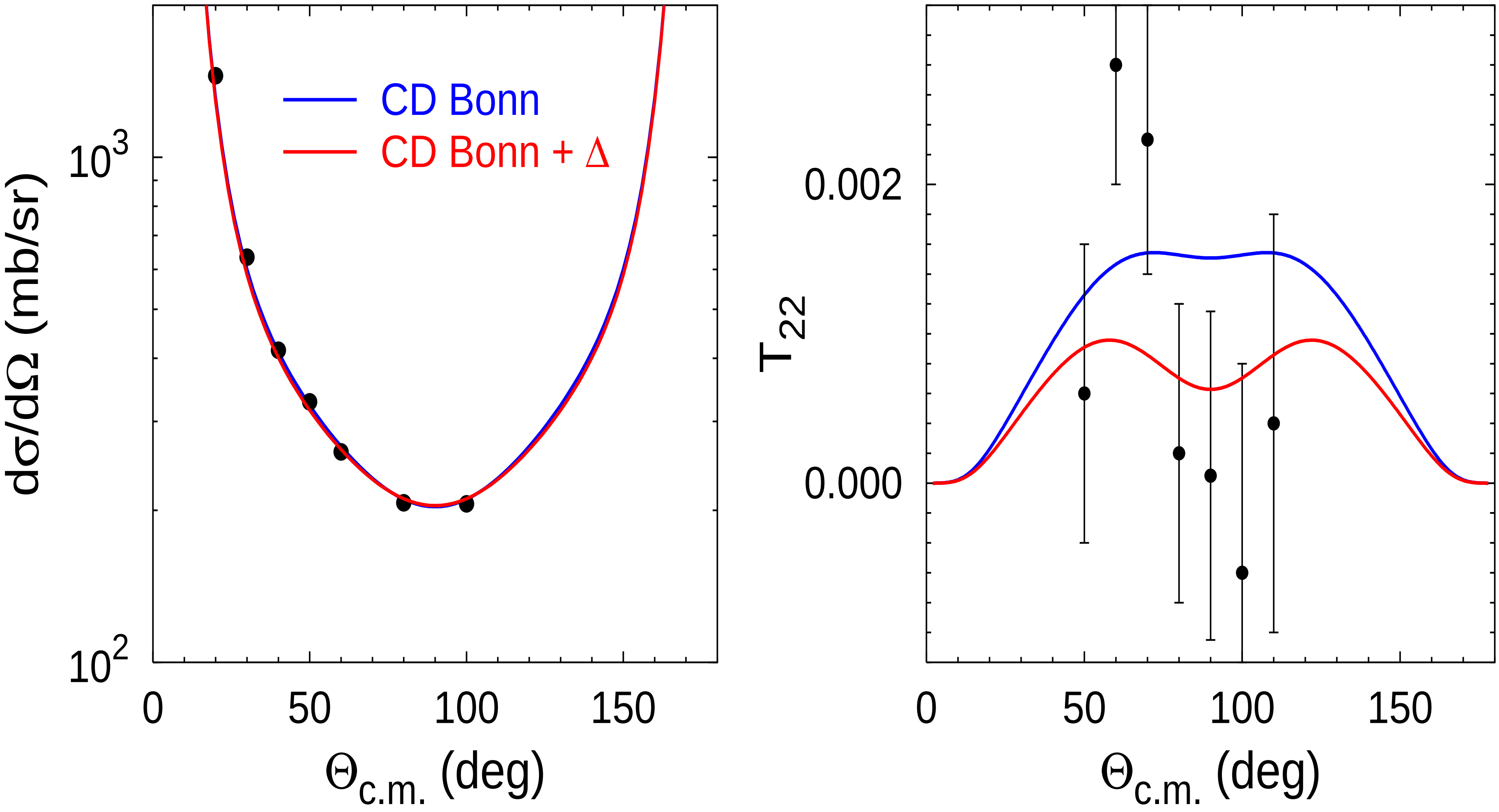
A_y maximum in p-^{3}He and p-^{3}H elastic scattering



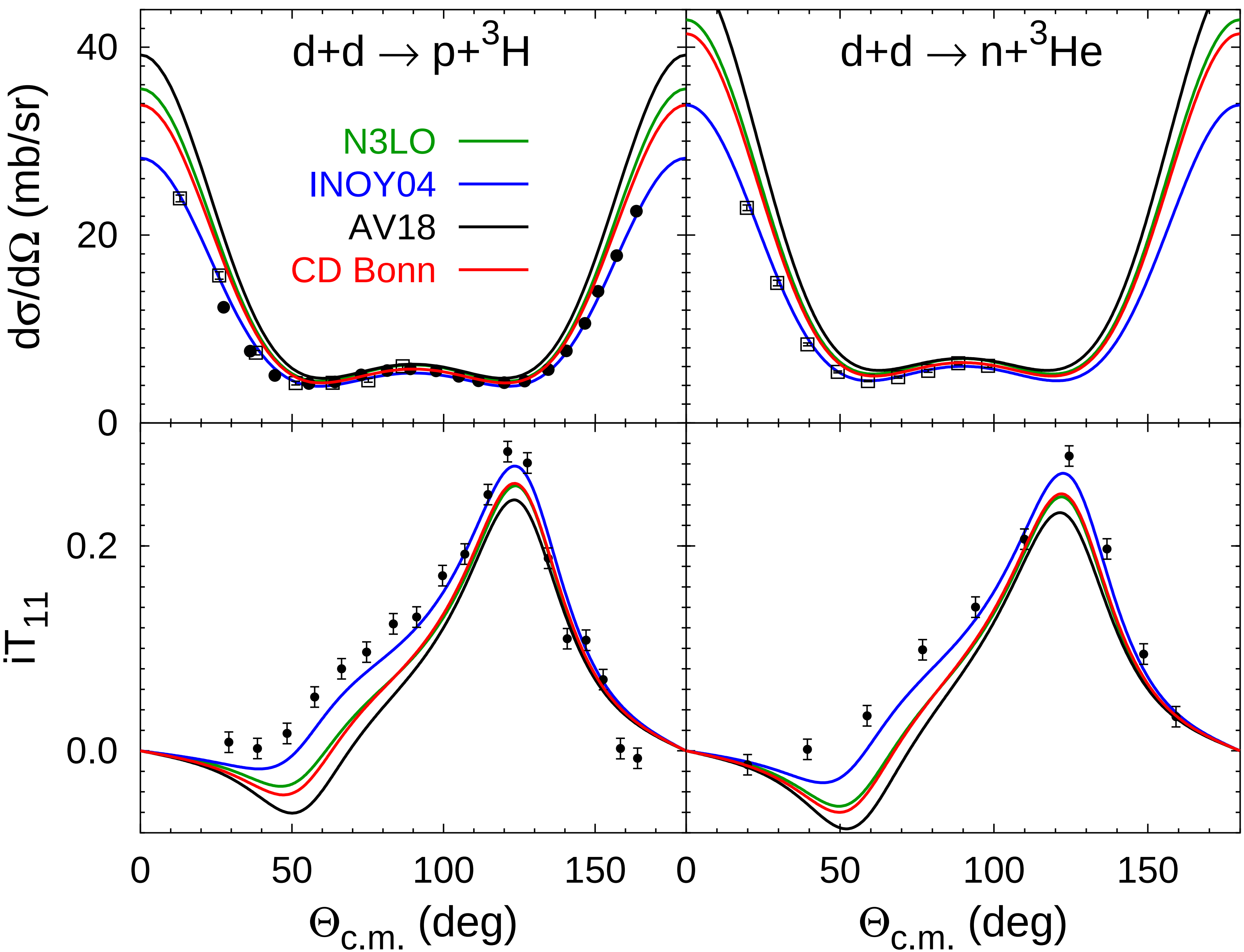
Transfer reaction $p + {}^3\mathrm{H} \rightarrow n + {}^3\mathrm{He}$



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



$d + d \to N + [3N]$ transfer at $E_d = 3$ MeV



Summary

- Faddev/AGS equations
- Coulomb interaction: screening and renormalization

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- Coulomb interaction: screening and renormalization

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