Few-body reactions in neutron-rich systems

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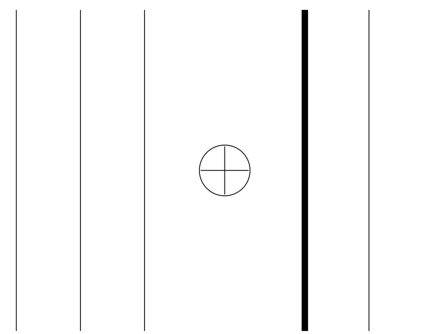
Supported by Alexander von Humboldt-Stiftung

Outline

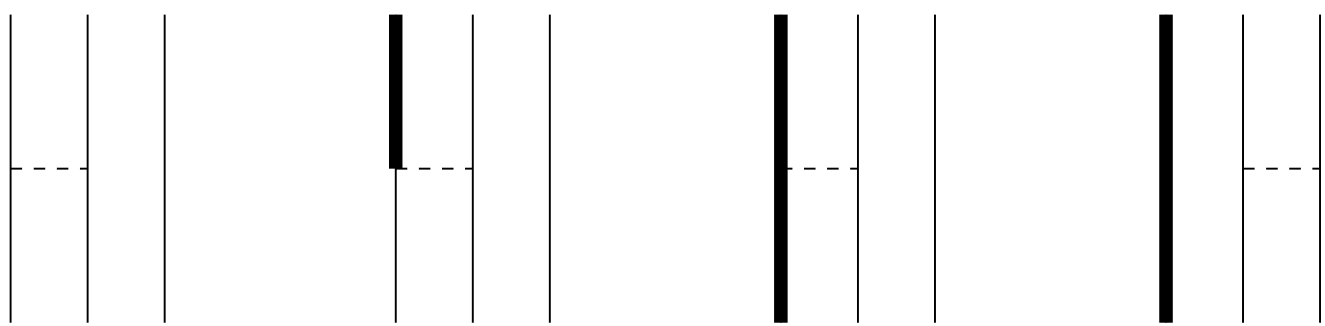
- core excitation in 3-body nuclear reactions:
  — extended Faddeev/AGS formalism
  — $^{20}\mathrm{O}(d,p)$
- trineutron resonances
- tetraneutron resonances
- four-fermion universality

Core excitation (CX): extended Hilbert space

$$\mathcal{H} = \mathcal{H}_g \oplus \mathcal{H}_x$$



sector coupling by interaction



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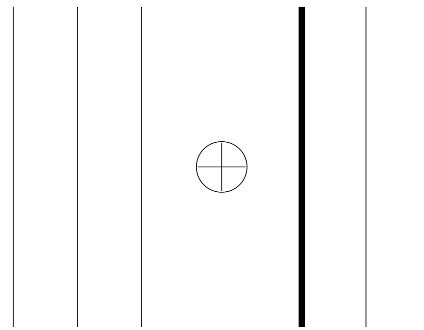

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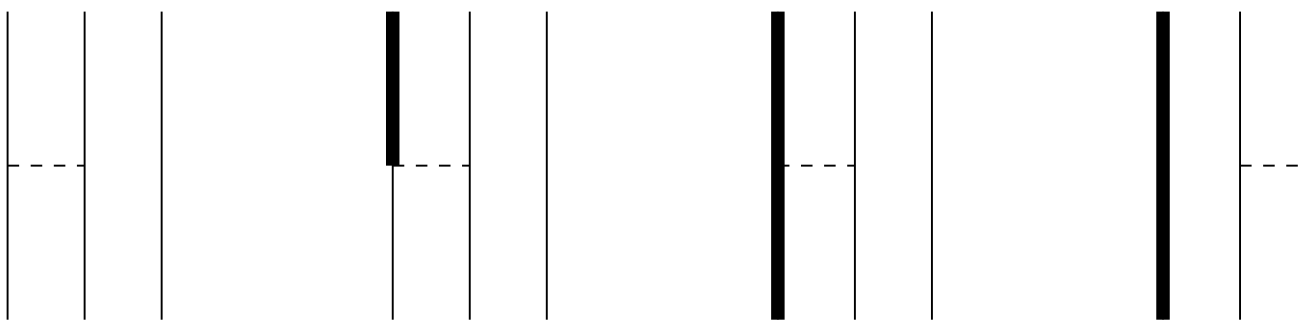


standard operator form of 3-body AGS equations

with $H_0 \to H_0 + h_A^{\text{int}}$

$$h_A^{\text{int}} |\mathcal{H}_a\rangle = (m_{A^*} - m_A)\delta_{ax} |\mathcal{H}_a\rangle$$

3-body AGS equations with core excitation

$$U_{\beta\alpha}^{ba} = \bar{\delta}_{\beta\alpha}\delta_{ba}G_0^{-1} + \sum_{\sigma}\sum_{j}\bar{\delta}_{\beta\sigma}T_{\sigma}^{bj}G_0U_{\sigma\alpha}^{ja}$$

$$U_{0\alpha}^{ba} = \delta_{ba}G_0^{-1} + \sum_{\sigma}\sum_{j}T_{\sigma}^{bj}G_0U_{\sigma\alpha}^{ja}$$

$$T_{\sigma}^{ba} = v_{\sigma}^{ba} + \sum_{j}v_{\sigma}^{bj}G_0T_{\sigma}^{ja}$$

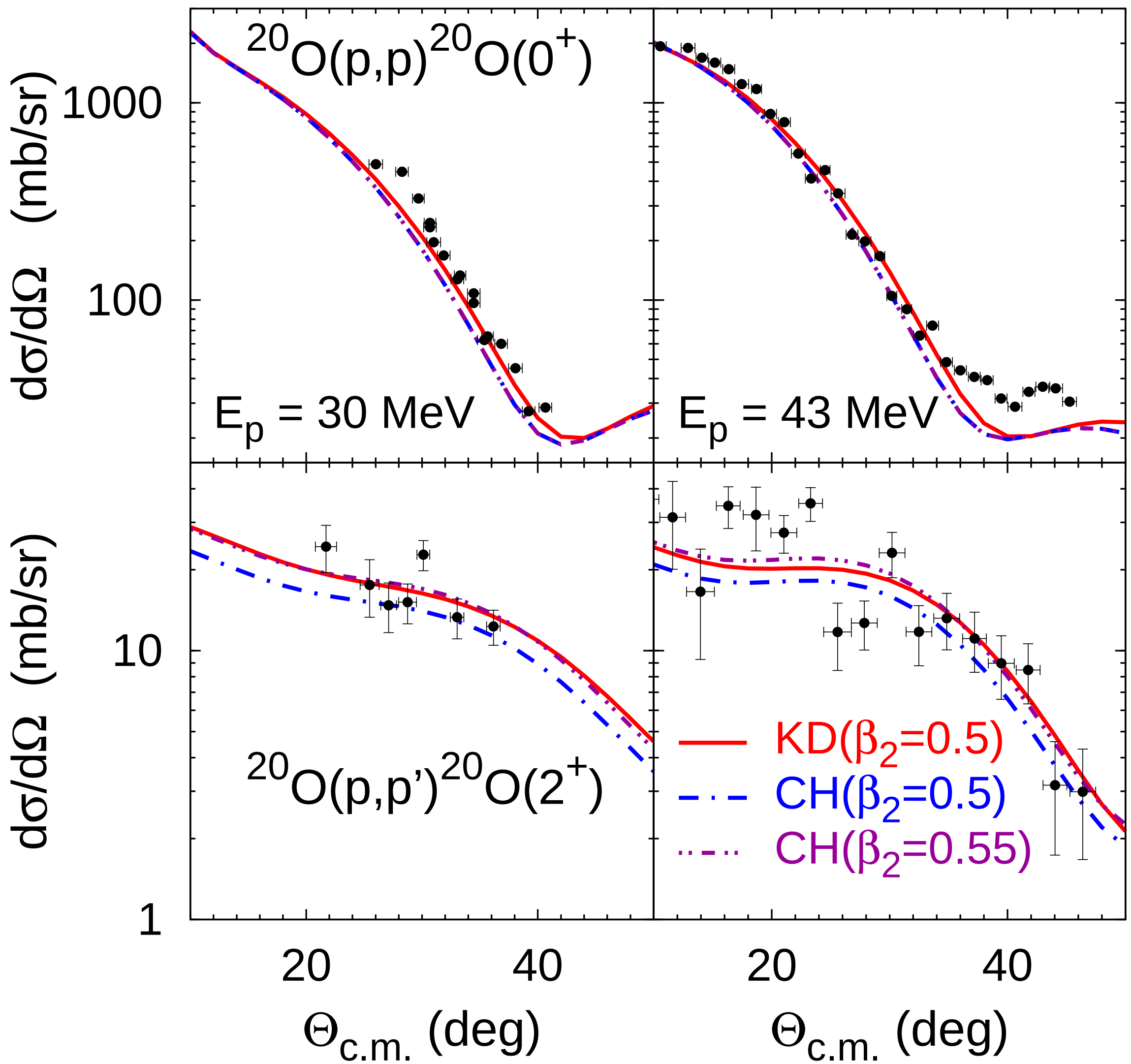
$$G_0 = (E + i0 - H_0)^{-1}$$

channel states $(E - H_0)|\phi_{\alpha}^{a}\rangle = \sum_{j} v_{\alpha}^{aj}|\phi_{\alpha}^{j}\rangle$

$$H_0|\mathbf{p}_{\alpha}\mathbf{q}_{\alpha}\rangle^{a} = [p_{\alpha}^{2}/2\mu_{\alpha} + q_{\alpha}^{2}/2M_{\alpha} + (m_{A^*} - m_A)\delta_{ax}]|\mathbf{p}_{\alpha}\mathbf{q}_{\alpha}\rangle^{a}$$

[PRC 88, 011601(R)]

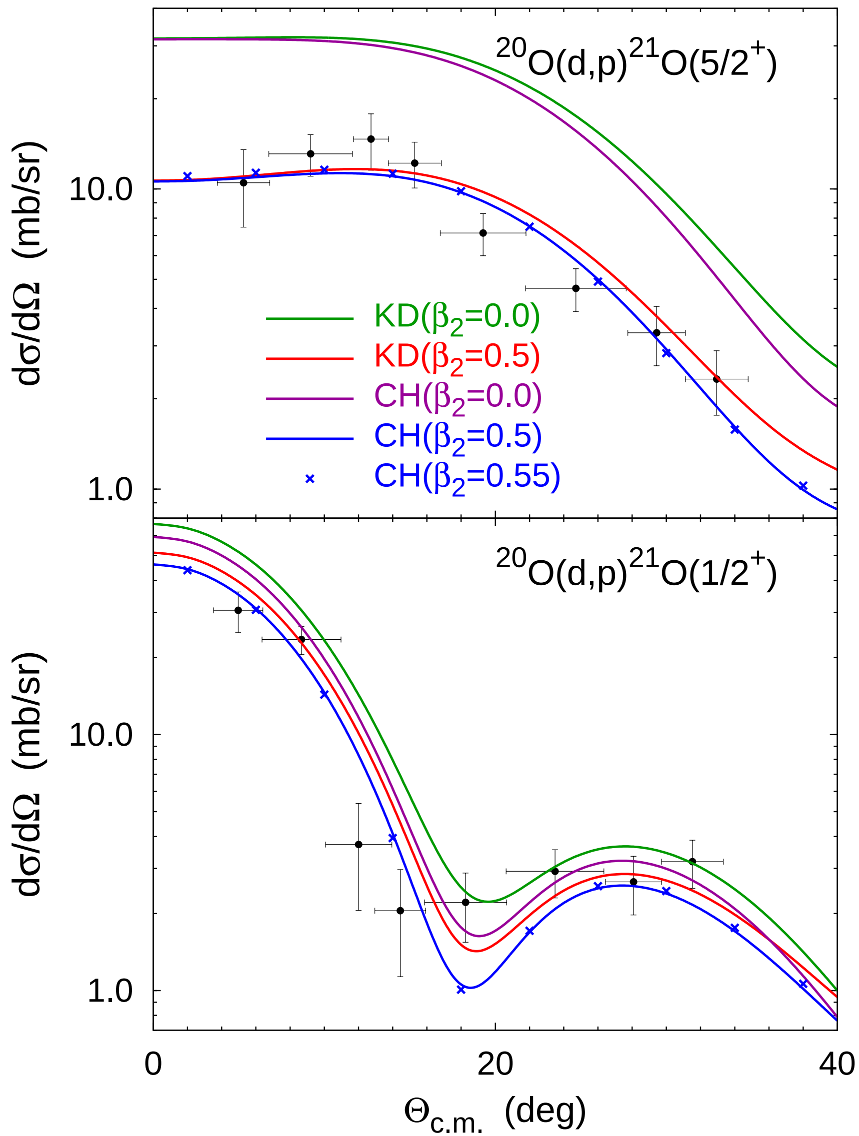
Potential test: N + ^{20}O



Vibrational model for V_{NA}

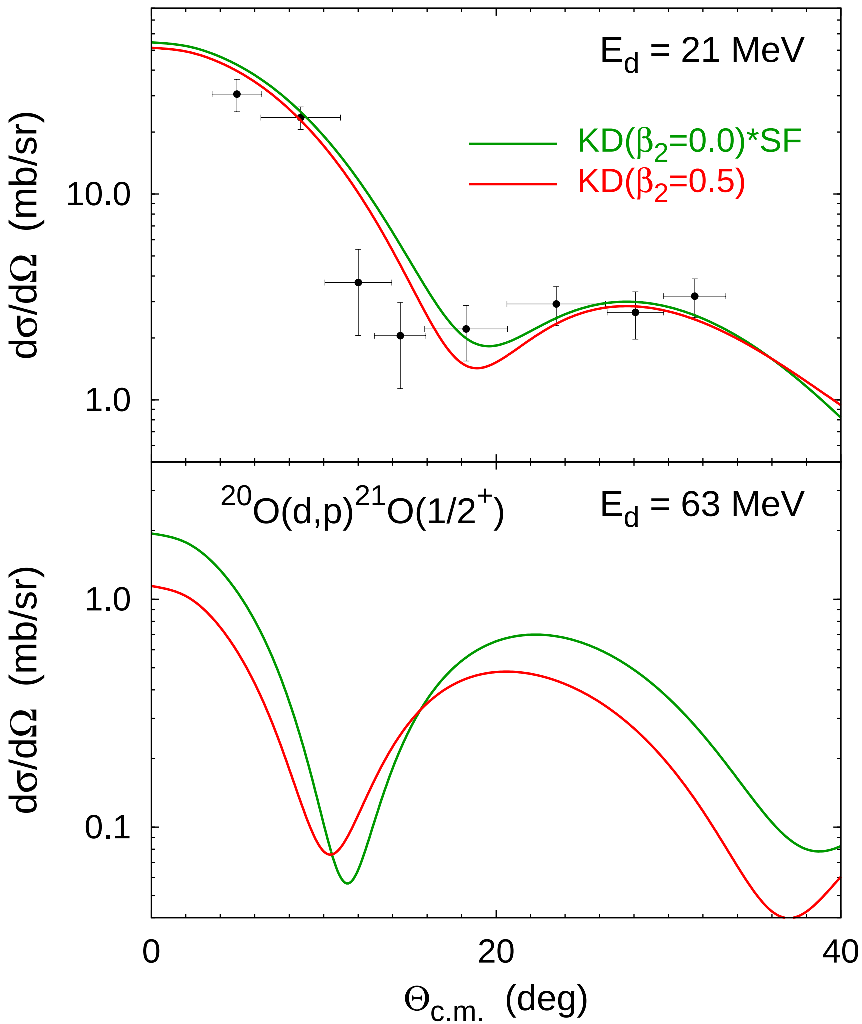
Shell-model SF for ^{21}O: $0.34(\frac{5}{2}^+)$, $0.82(\frac{1}{2}^+)$

$^{20}O(d,p)^{21}O$ at 21 MeV



[PLB 769, 202; exp. data PRC 84, 011301]

$^{20}O(d,p)^{21}O$: extracting SF?



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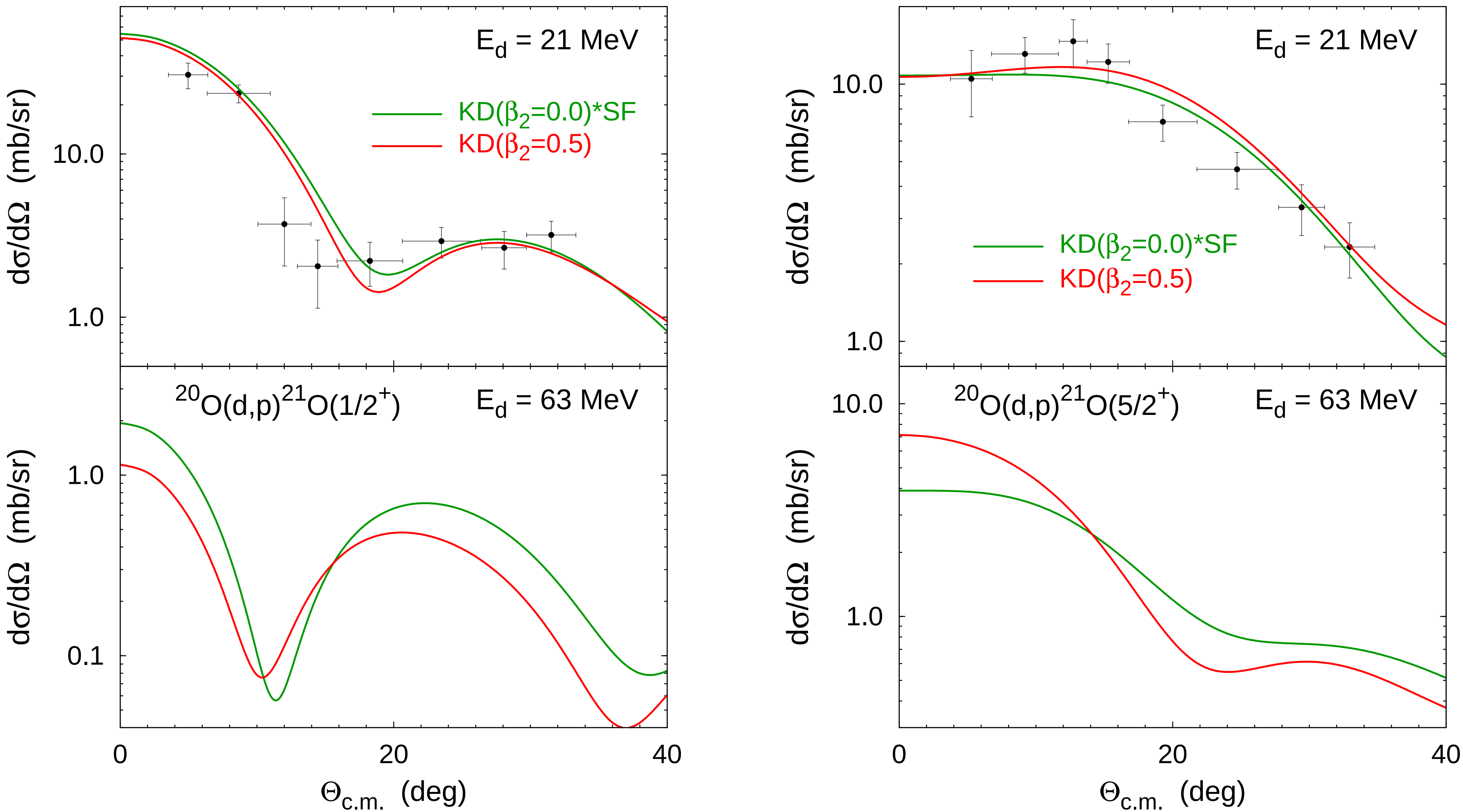

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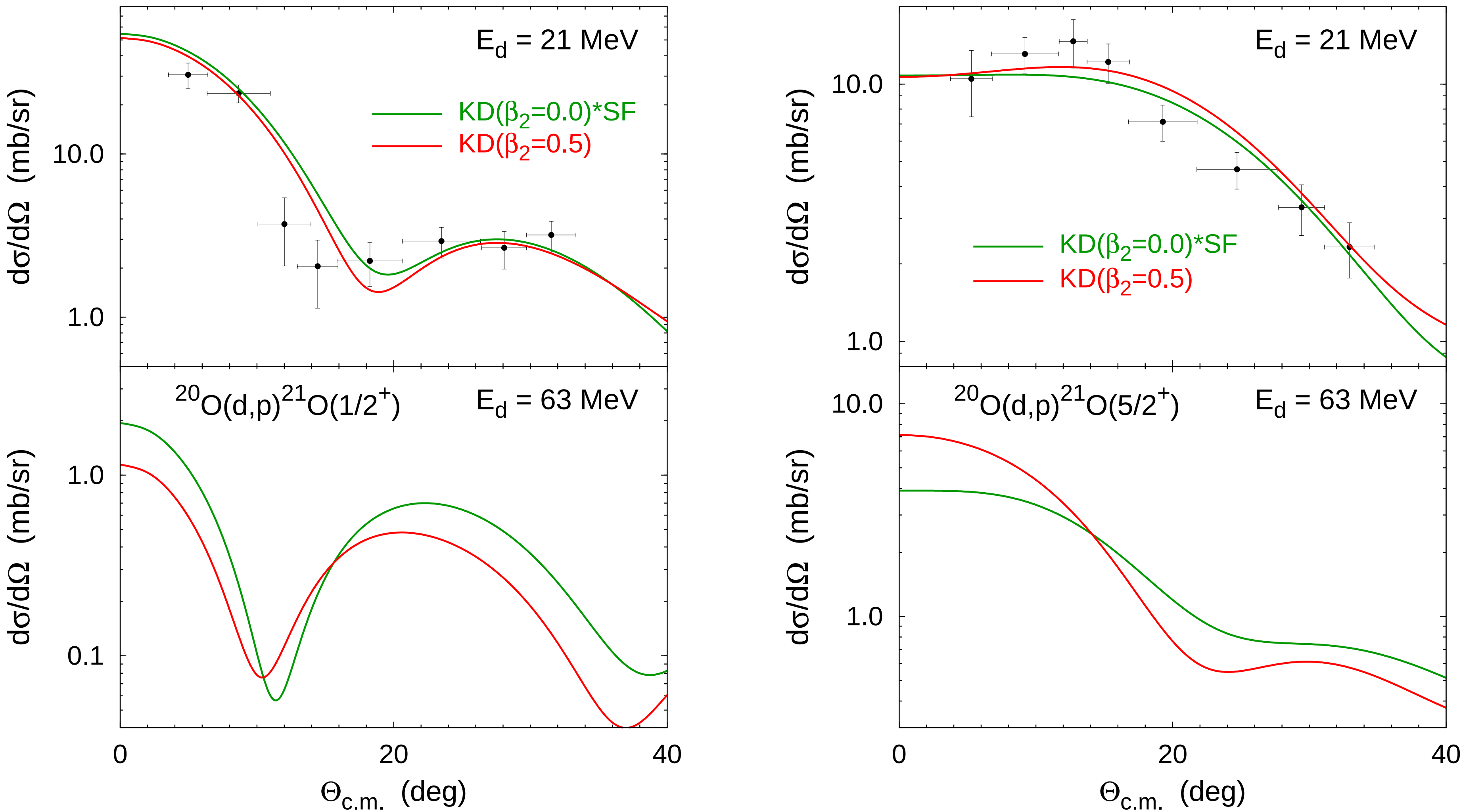


SF= σ_{exp}/σ_{SP} in general unreliable !

Faddeev/AGS: (V_{NA} - SF - data) compatibility check

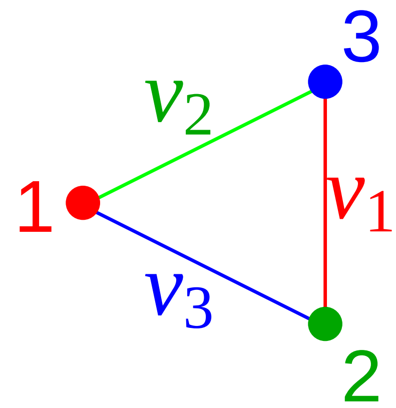
Experiment and theory: 3n

- no experimental evidence for 3n resonance
- Hemmdan, Kamada, Glöckle, PRC 66, 054001,
  Lazauskas, Carbonell, Hiyama, Kamimura,
  PRC 71, 044004, PRC 93, 044004:
  no observable 3n resonance
- Gandolfi, Hammer, Klos, Lynn, Schwenk,
  PRL 118, 232501:
  3n resonance $E_r = 1.1$ MeV

Experiment and theory: 4n

- Kisamori et al, PRL 116, 052501:
  few events in ^{4}He(^{8}He,^{8}Be) $\rightarrow$ 4n state at
  $E_r = 0.83 \pm 0.65 \pm 1.25$ MeV, $\Gamma < 2.6$ MeV
- Lazauskas, Carbonell, Hiyama, Kamimura,
  PRC 72, 034003, PRC 93, 044004:
  no observable 4n resonance
- Shirokov, Papadimitriou, Mazur, Mazur, Roth, Vary,
  PRL 117, 182502:
  4n resonance $(E_r, \Gamma) = (0.8, 1.4)$ MeV
- Gandolfi, Hammer, Klos, Lynn, Schwenk, PRL 118,
  232501: 4n resonance $E_r = 2.1$ MeV
- Fossez, Rotureau, Michel, Ploszajczak, PRL 119,
  032501: 4n resonance $(E_r, \Gamma) = (7.3, 3.8)$ MeV

Three-particle system



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

Alt, Grassberger, and Sandhas equations

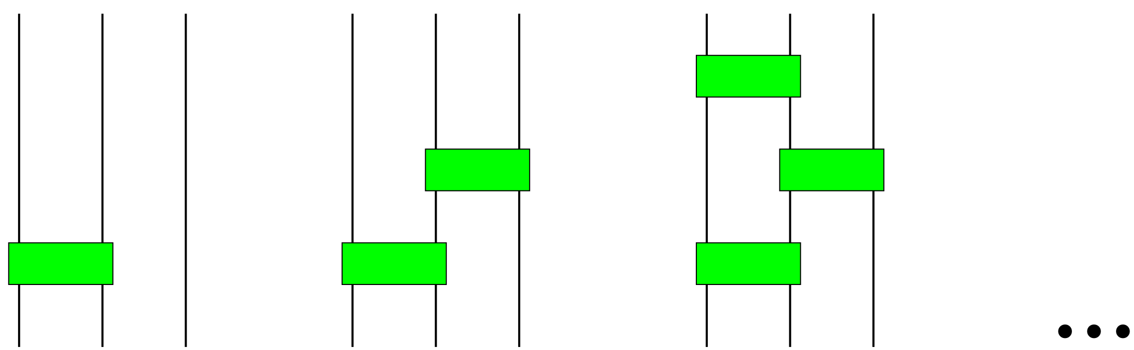
$$U_{\beta\alpha} = \bar{\delta}_{\beta\alpha} G_0^{-1} + \sum_{\sigma} \bar{\delta}_{\beta\sigma} t_{\sigma} G_0 U_{\sigma\alpha}$$

$$U_{00} = \sum_{\alpha} t_{\alpha} + \sum_{\beta\alpha} t_{\beta} G_0 U_{\beta\alpha} G_0 t_{\alpha}$$

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

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

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



Symmetrized AGS equations

$$U = PG_0^{-1} + PtG_0U$$

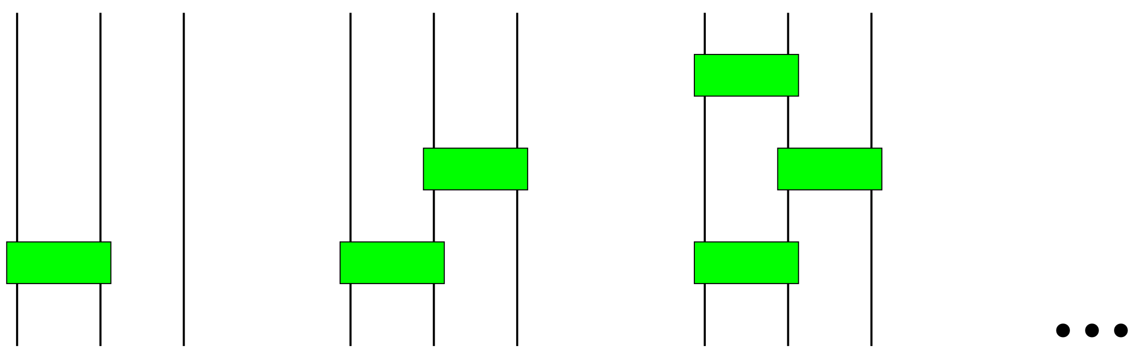
$$T = tG_0UG_0t$$

$$T = tG_0Pt + tG_0PT$$

$$U_{00} = (1+P)t(1+P) + (1+P)T(1+P)$$

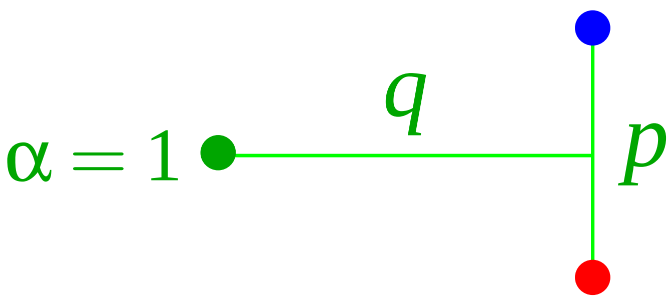
$$t = v + vG_0t$$

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



Resonance: pole of T

$$T_{J^\Pi} = \sum_{n=-1}^{\infty} \tilde{T}_{J^\Pi}^{(n)} (E - E_r + i\Gamma/2)^n$$



Basis states $|pq(l\{[L(s_2 s_3)s]j\, s_1\}S)\, JM\rangle$

Trial states:

- p-state ${}^{2s+1}L_j^p$: $p = \sqrt{mE}$, $q = 0$
- q-state ${}^1S_0^q$: $p = 0$, $q = \sqrt{4mE/3}$
- off-shell state ${}^1S_0^{\text{off}}$: Gaussian for p, $q = \sqrt{4m(E + \varepsilon_{\text{off}})/3}$

Force models

- CD Bonn
- Reid93
- NLO [Epelbaum et al, PRL 115, 122301]
- SRG of AV18 with $\lambda = 1.8\,\mathrm{fm}^{-1}$

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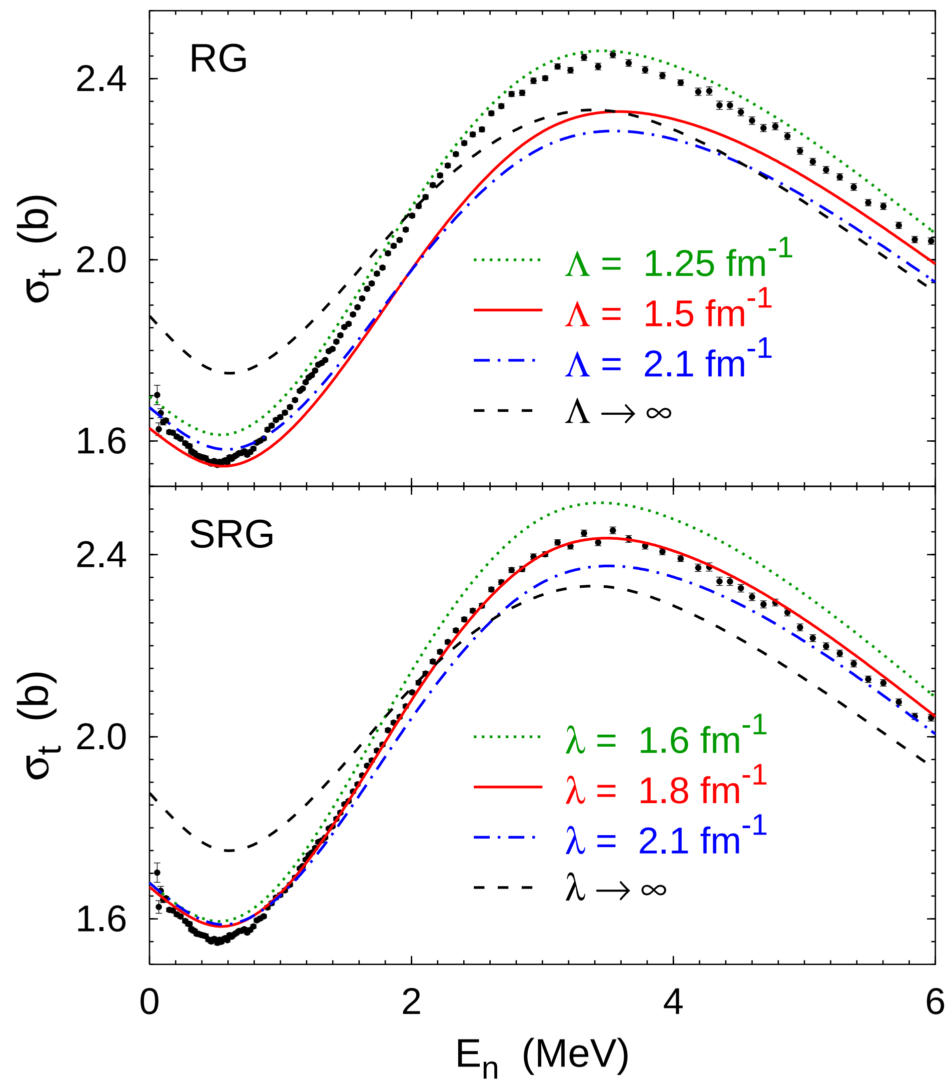
$n + {}^3$H total cross section



Enhancing nn interaction

$v = v_{nn}$ for $^1S_0$ (bound if enhanced by ~ 1.1)
$v = f\, v_{nn}$ for higher waves $L > 0$

Bound dineutron
at threshold:

$^{2s+1}L_j$	f
	SRG
$^3P_2$ - $^3F_2$	7.24
$^3P_0$	7.97
	Reid93
$^3P_2$ - $^3F_2$	4.00
$^3P_0$	5.95

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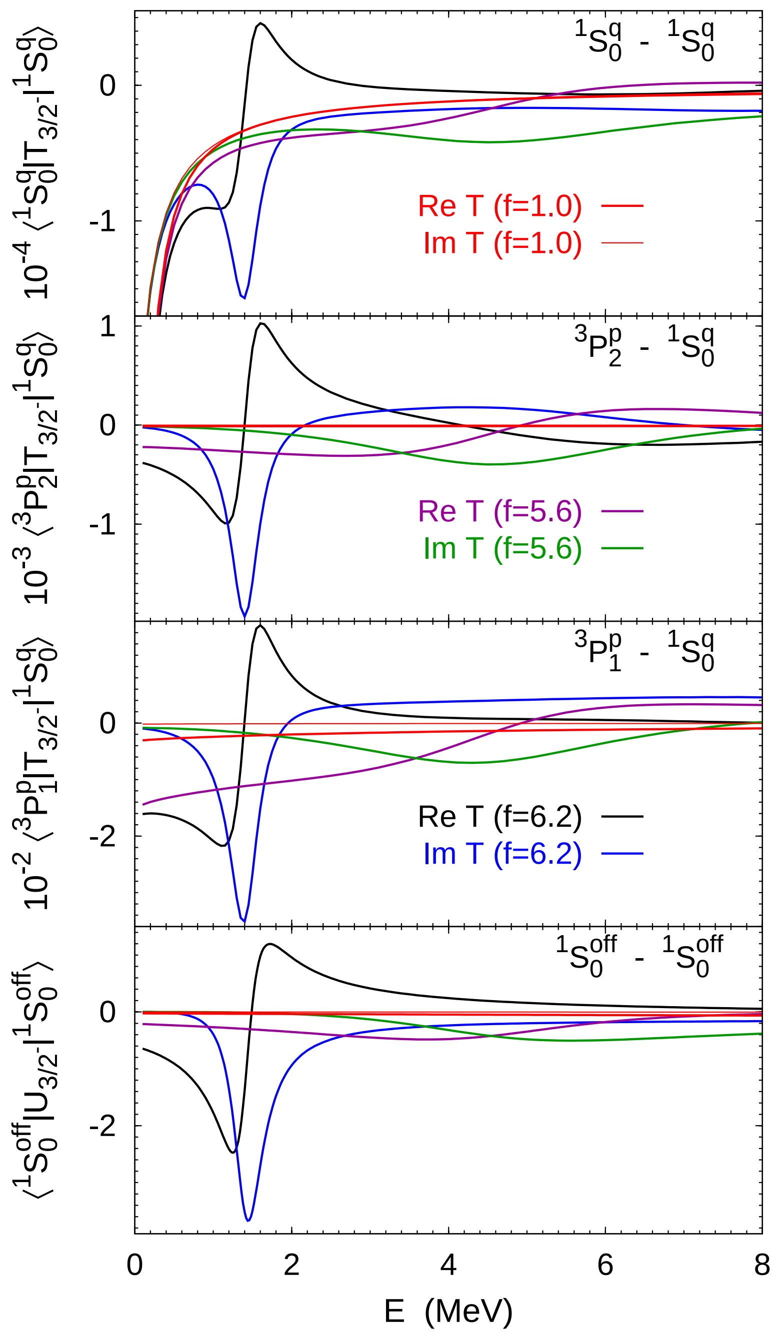
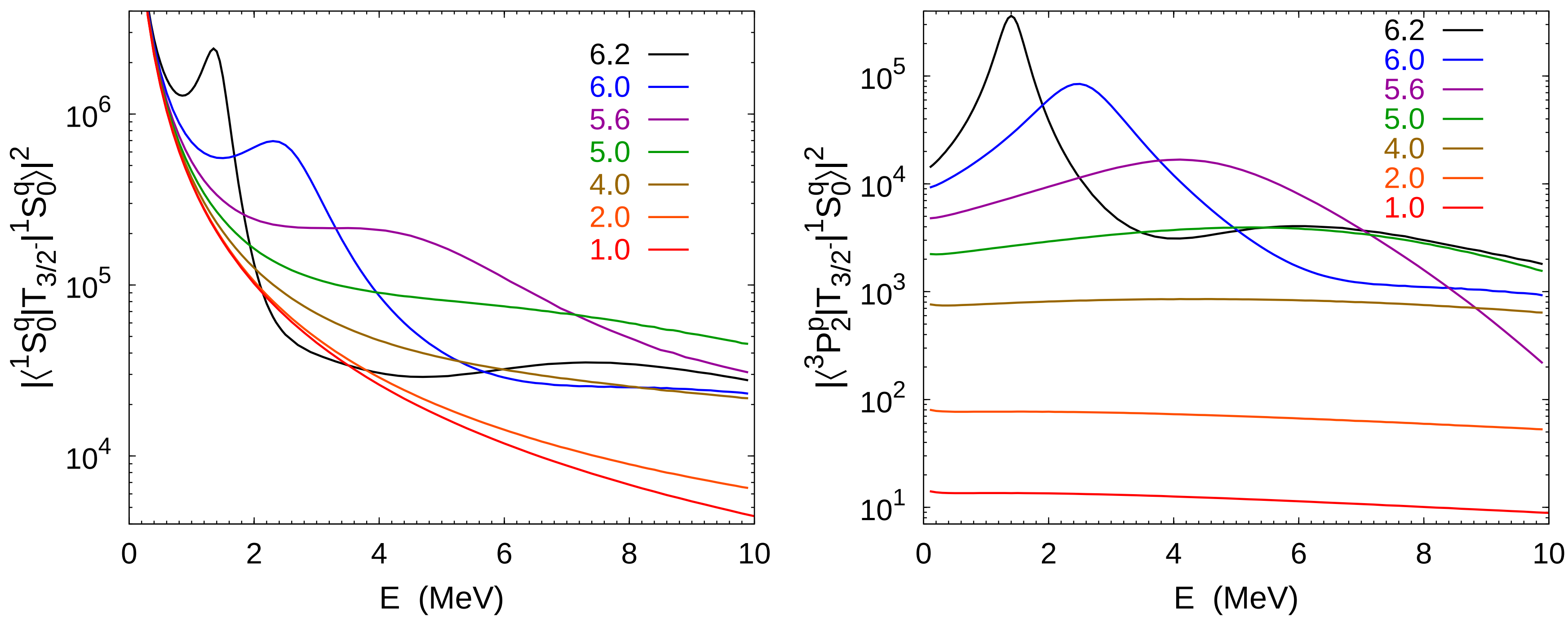
Bound trineutron
at threshold:

J^Π	f(SRG)
$1/2^+$	> 7.24
$1/2^-$	> 7.24
$3/2^+$	6.71
$3/2^-$	6.42
$5/2^+$	6.02
$5/2^-$	6.94

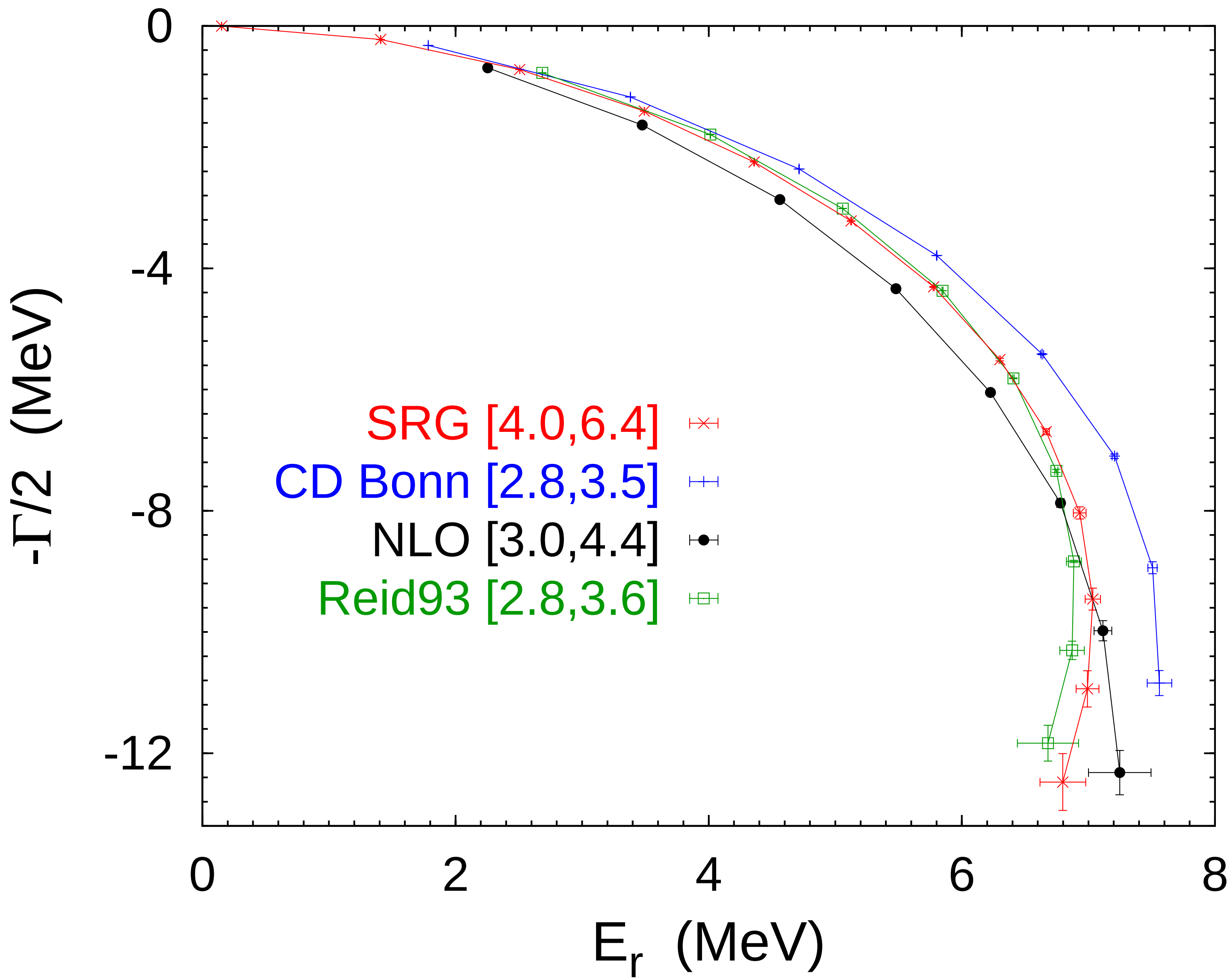
Resonance in all $J^{\Pi} = 3/2^{-}$ channels



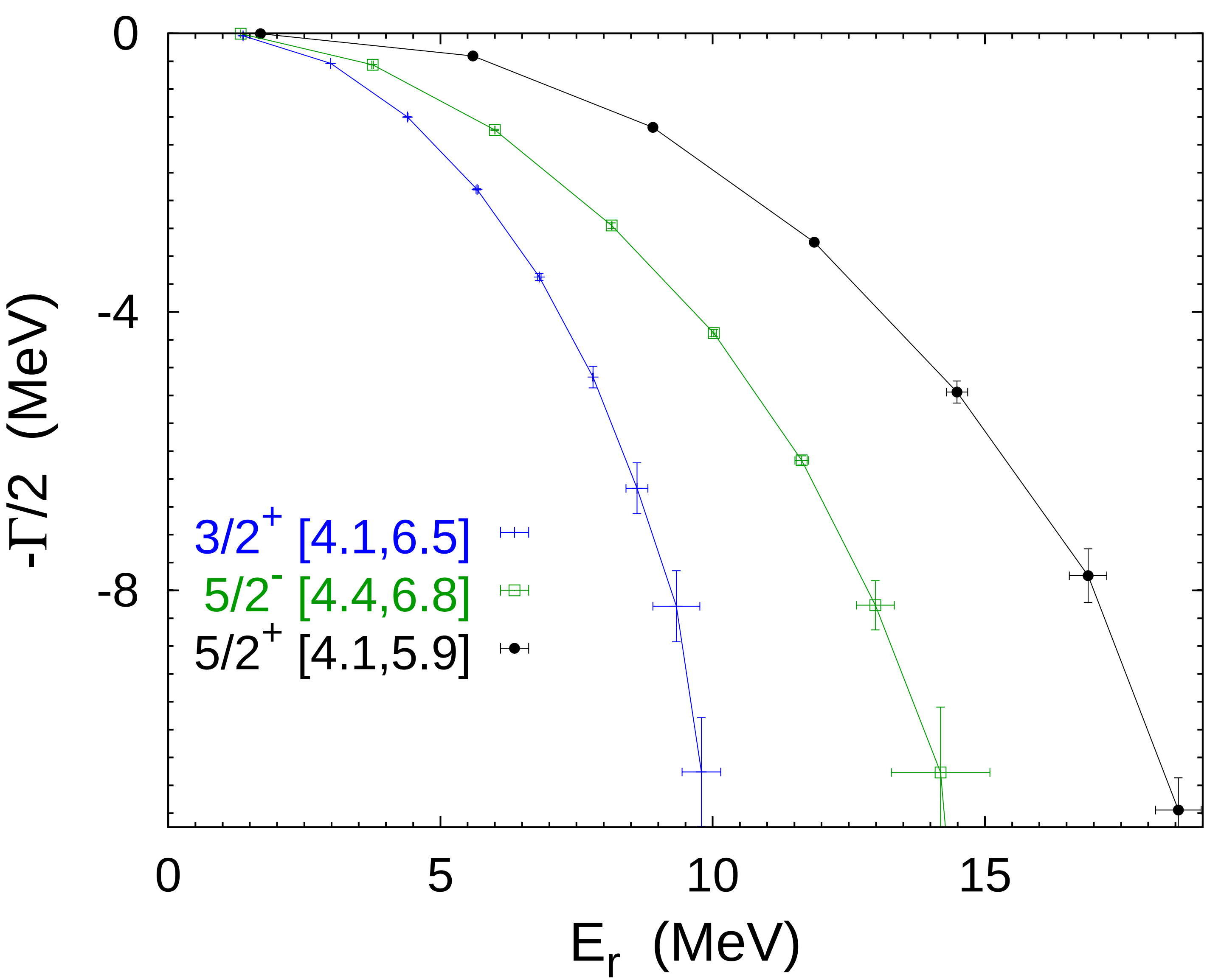
No $3/2^{-}$ resonance at physical strength



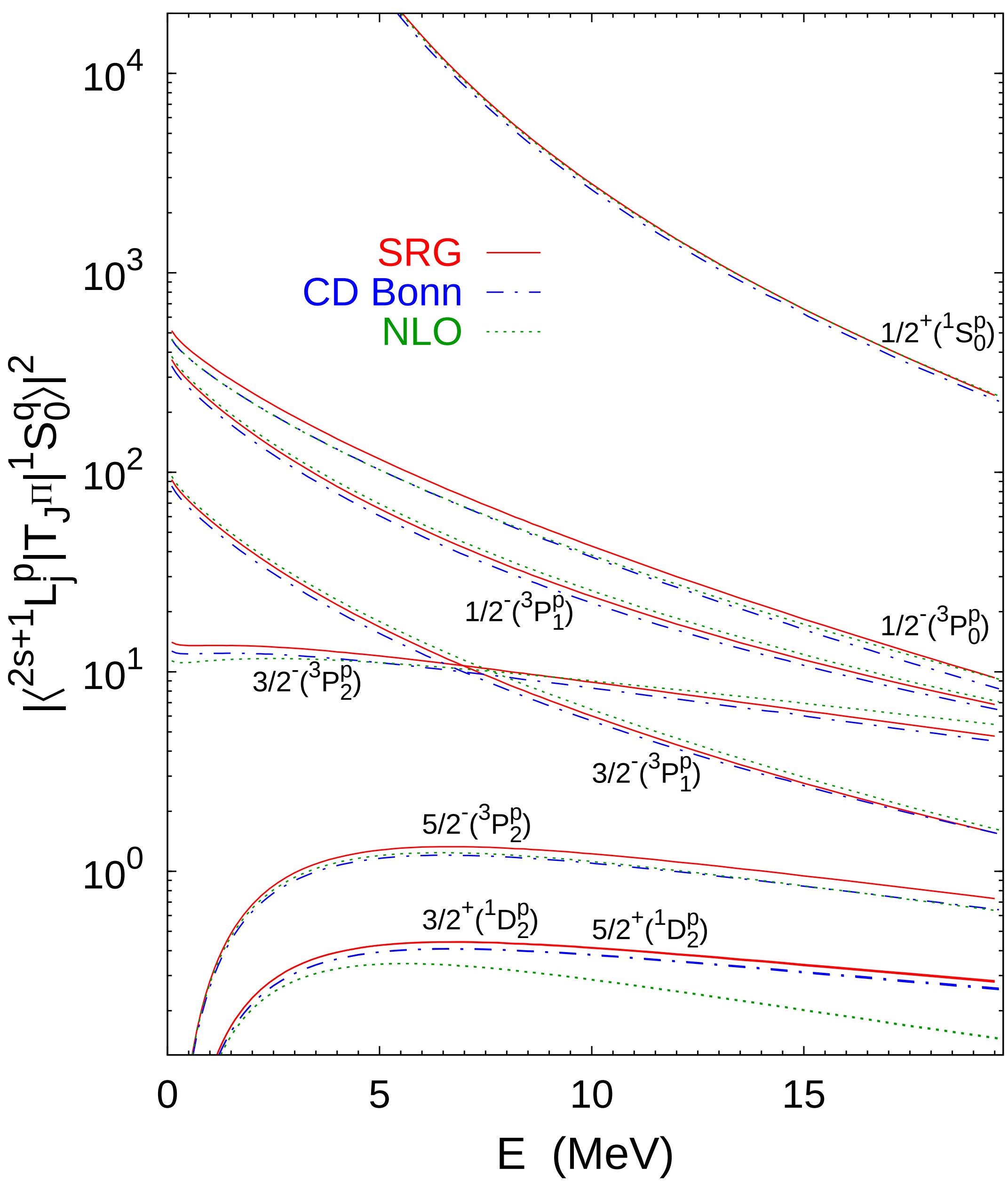
$3/2^-$ resonance trajectory



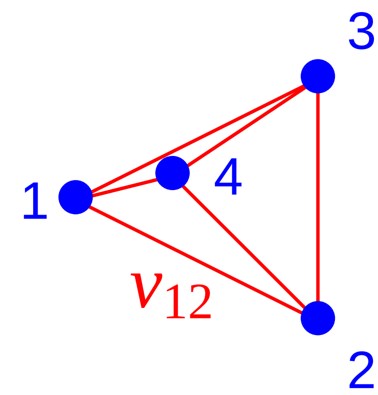
Resonance trajectories



3n → 3n transition strengths: resonance?



4N scattering



Hamiltonian $$H_0 + \sum_{i>j} v_{ij}$$

- Wave function:
  Schrödinger equation (HH + Kohn VP, r-space)
  [M. Viviani, A. Kievsky, L. E. Marcucci, S. Rosati, L. Girlanda]
- Wave function components:
  Faddeev-Yakubovsky equations (r-space)
  [R. Lazauskas, J. Carbonell]
- Transition operators:
  Alt-Grassberger-Sandhas equations (p-space)
  [AD, A. C. Fonseca]

4-body scattering: AGS equations

4-body transition operators

$$t_i = v_i + v_i G_0 t_i$$

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

$$U_\gamma^{jk} = G_0^{-1} \bar{\delta}_{jk} + \sum_i \bar{\delta}_{ji} t_i G_0 U_\gamma^{ik}$$

$$\mathcal{U}_{\beta\alpha}^{ji} = (G_0 t_i G_0)^{-1} \bar{\delta}_{\beta\alpha} \delta_{ji} + \sum_{\gamma k} \bar{\delta}_{\beta\gamma} U_\gamma^{jk} G_0 t_k G_0 \mathcal{U}_{\gamma\alpha}^{ki}$$

i, j, k: pairs ($\equiv$ three-cluster (2+1+1) partitions)
α, β, γ: two-cluster (1+3 or 2+2) partitions

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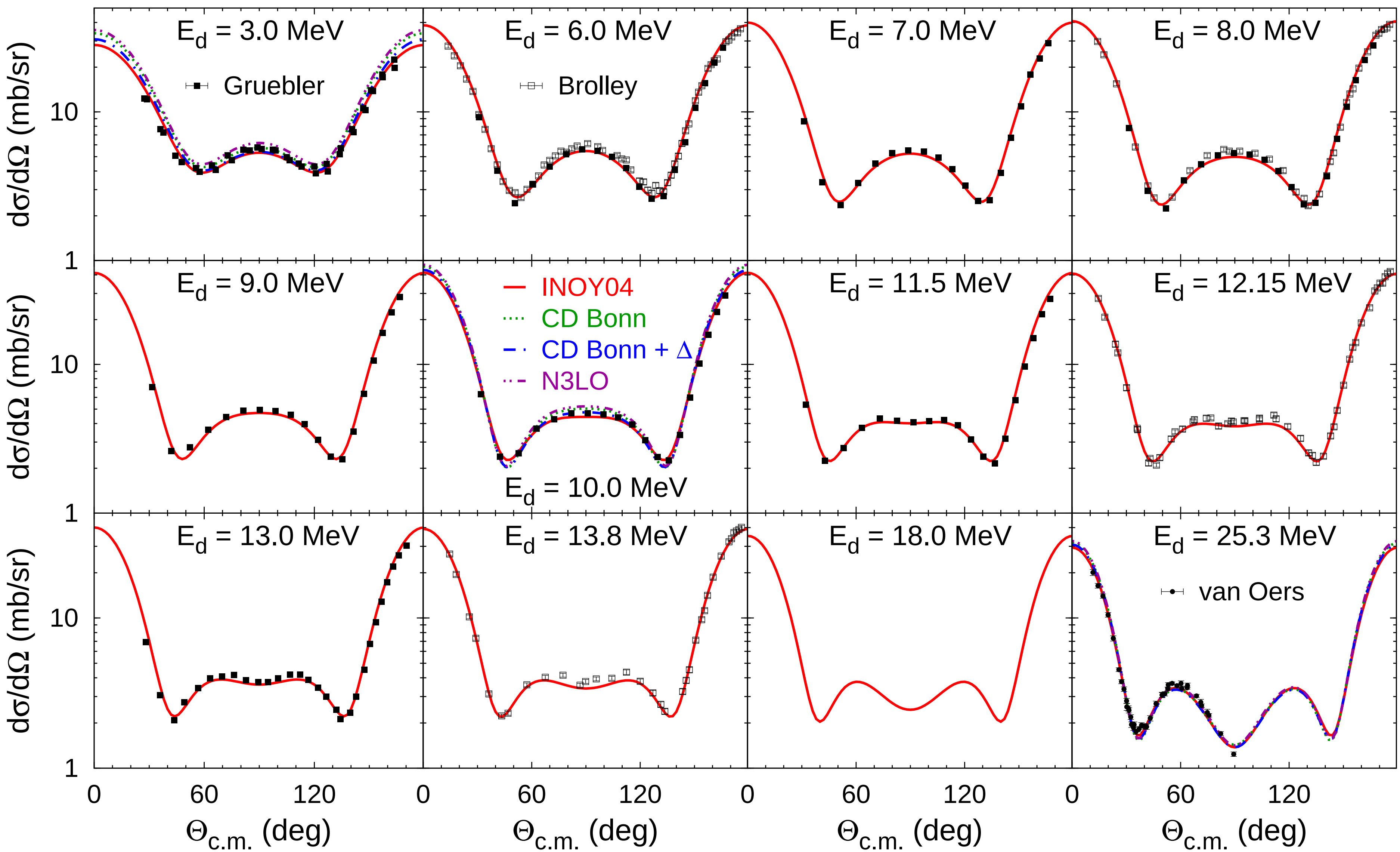
wave function

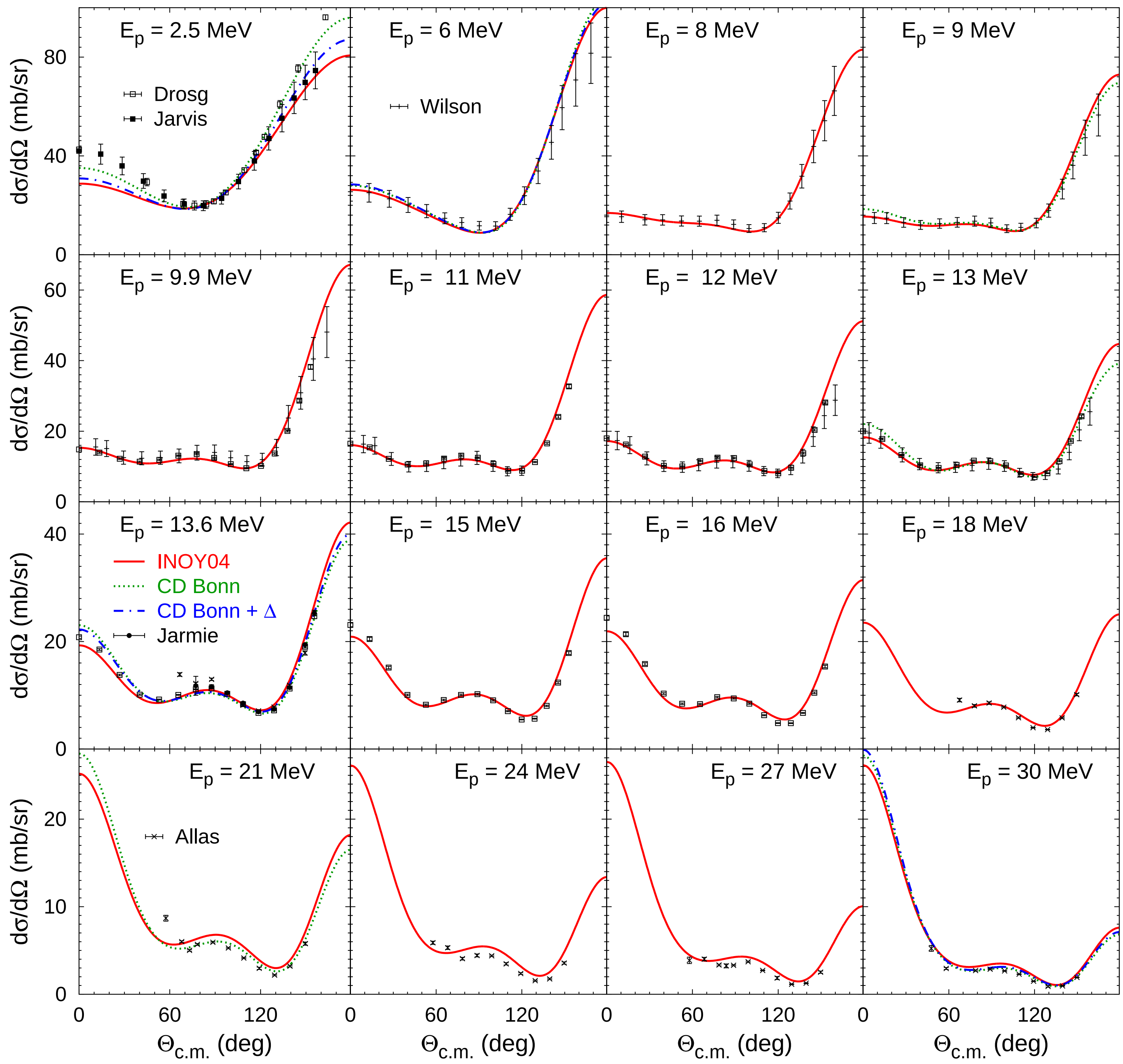
$$|\Psi_\alpha\rangle = |\Phi_\alpha\rangle + \sum_{\gamma jki} G_0 t_j G_0 U_\gamma^{jk} G_0 t_k G_0 \mathcal{U}_{\gamma\alpha}^{ki} |\phi_\alpha^i\rangle$$

$$|\Phi_\alpha\rangle = \sum_i |\phi_\alpha^i\rangle, \qquad |\phi_\alpha^i\rangle = G_0 \sum_j \bar{\delta}_{ij} t_j |\phi_\alpha^j\rangle$$

Example: $^2\mathrm{H}(d,p)^3\mathrm{H}$

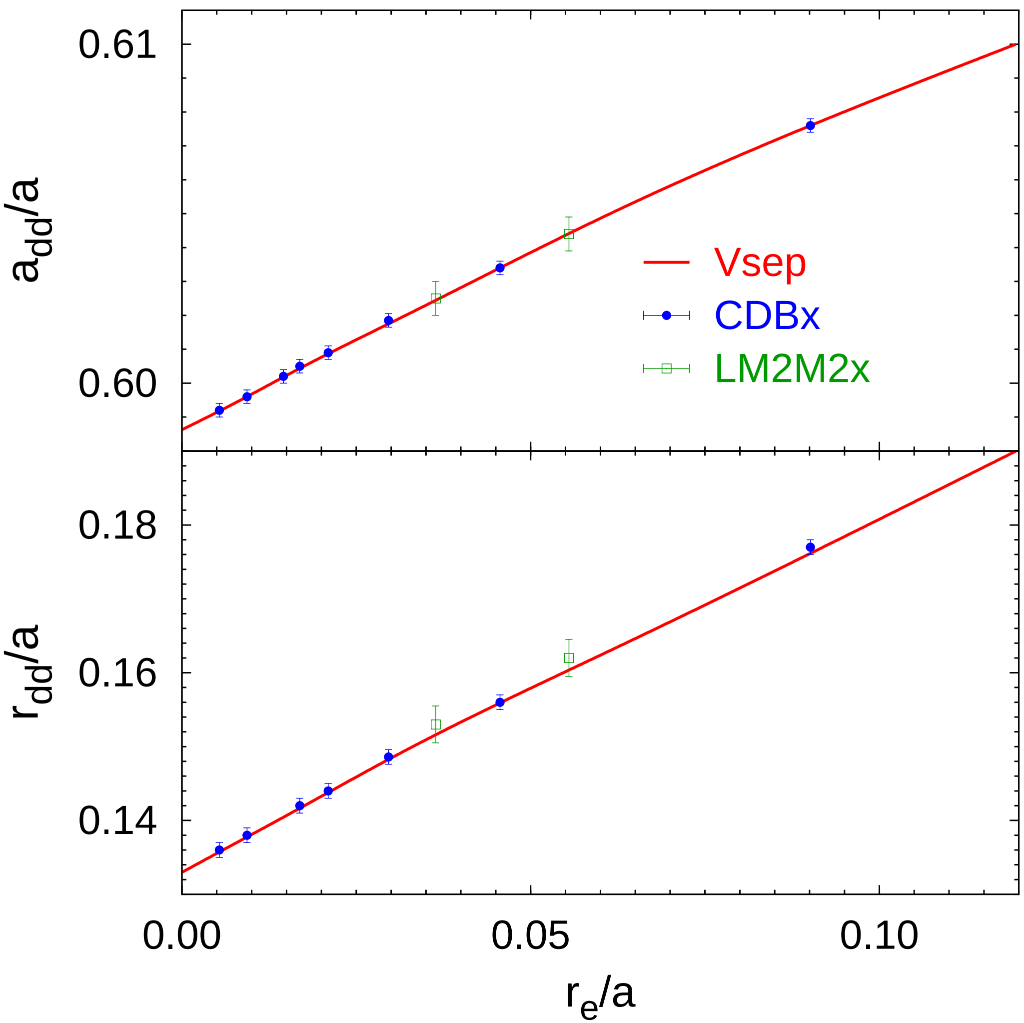


Example: $^{3}H(p,n)^{3}He$



Fermionic dimer-dimer scattering: range effects

$$\text{ERE}: \quad ap_{dd}\cot\delta_0 \approx -\frac{a}{a_{dd}} + \frac{1}{2}\frac{r_{dd}}{a}(ap_{dd})^2 - \frac{1}{4}c_{dd}(ap_{dd})^4$$



[PRA 96, 022701]

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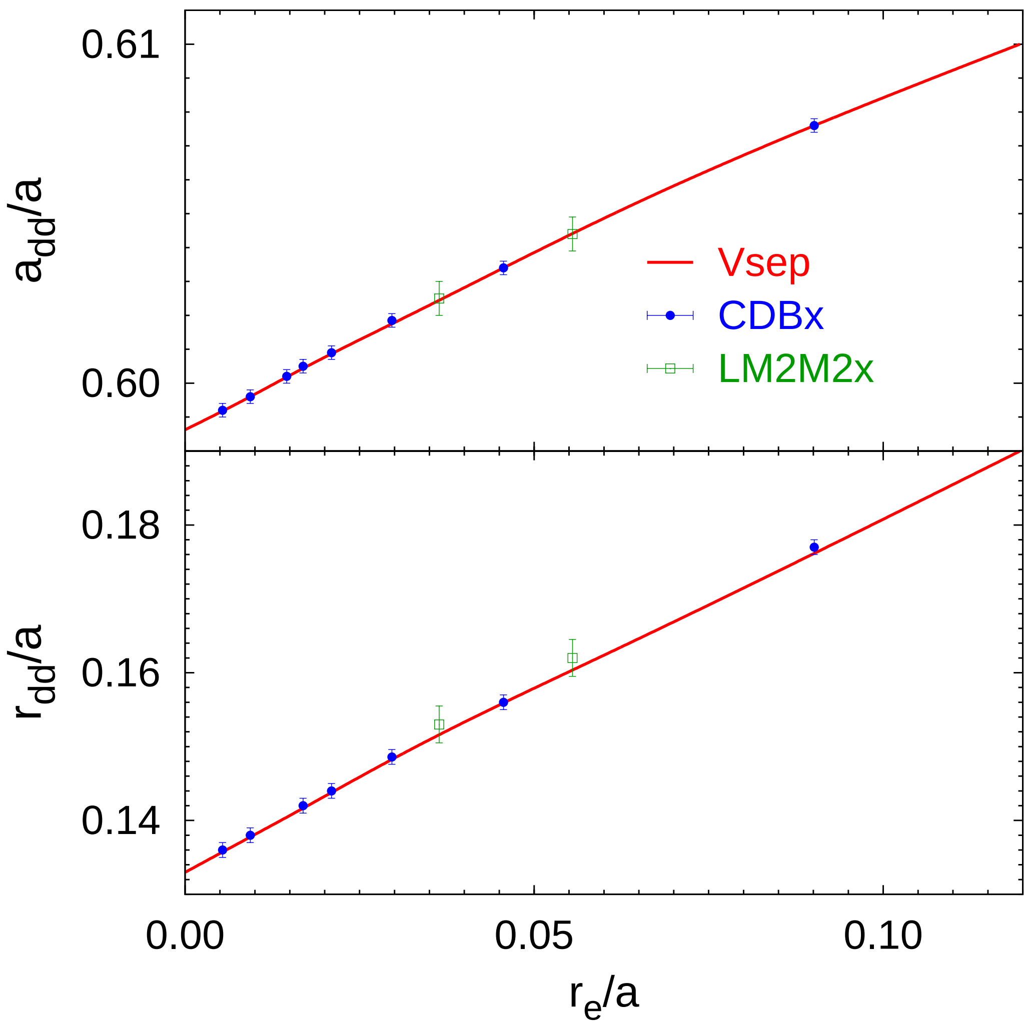

$$\frac{a_{dd}}{a} = 0.5986 + 0.105\frac{r_e}{a}$$

$$\frac{r_{dd}}{a} = 0.133 + 0.51\frac{r_e}{a}$$

$$c_{dd} = 0.026 - 0.1\frac{r_e}{a}$$

Greene et al - OK

Elhatisari et al - wrong

[PRA 96, 022701]

Conclusion

- L- and energy-dependent CX effects in transfer reactions, no simple relation to SF