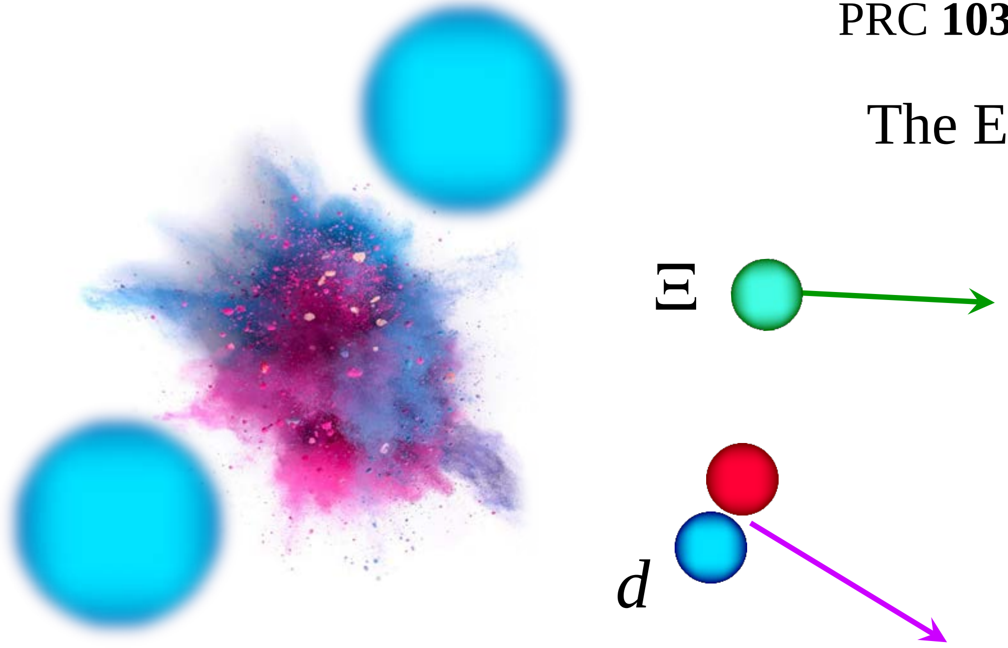
Effect of deuteron breakup on the deuteron-Ξ correlation function

PRC **103**, 065205 (2021) [arXiv:2103.00100]

The EXOTICO workshop @ ECT*



Kazuyuki Ogata[A,B]

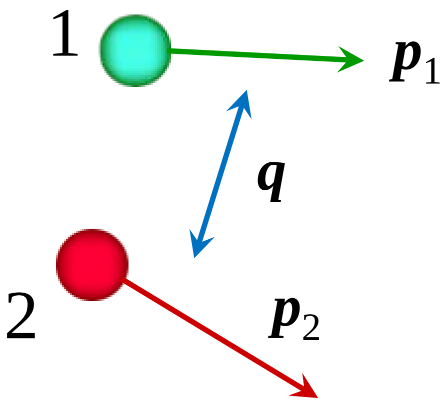
in collaboration with

Tokuro Fukui[C], Yuki Kamiya[D], and Akira Ohnishi[E]

[A]Kyushu Univ., [B]RCNP, Osaka Univ.

[C]RIKEN, [D]Rheinische Friedrich-Wilhelms-Universität Bonn, [E]YITP

Correlation function (CF)



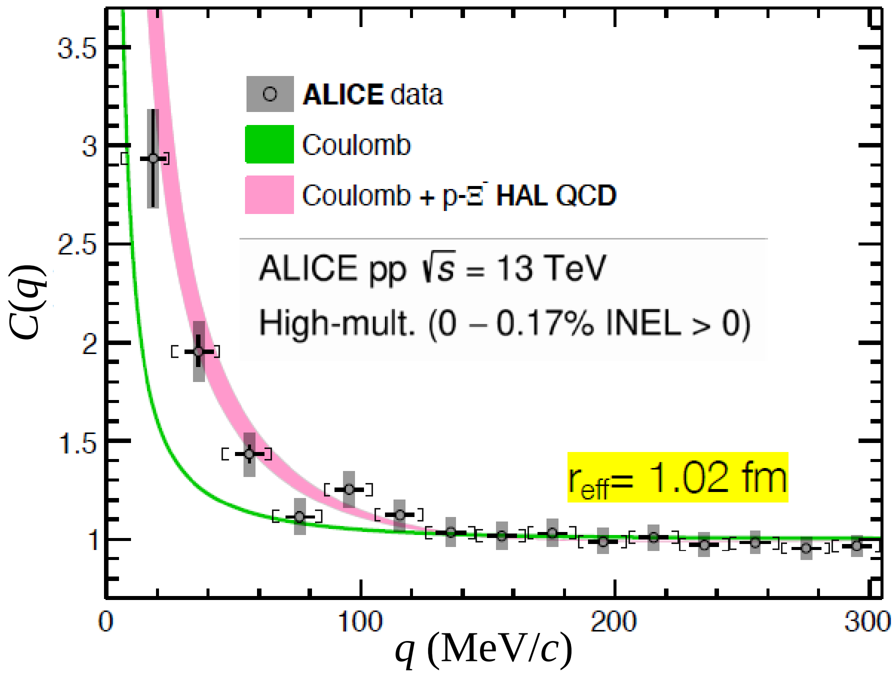
S. E. Koonin, Phys. Lett. B ***70****, 43 (1977); S. Pratt, Phys. Rev. D* ***33****, 1314 (1986).*

source function

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1) N_2(\boldsymbol{p}_2)} \approx \int S_{12}(\boldsymbol{R}) \left| \psi_{12}^{(-)}(\boldsymbol{R}) \right|^2 d\boldsymbol{R}$$

relative wave function

ALICE Coll. Nature 588, 232–238 (2020)

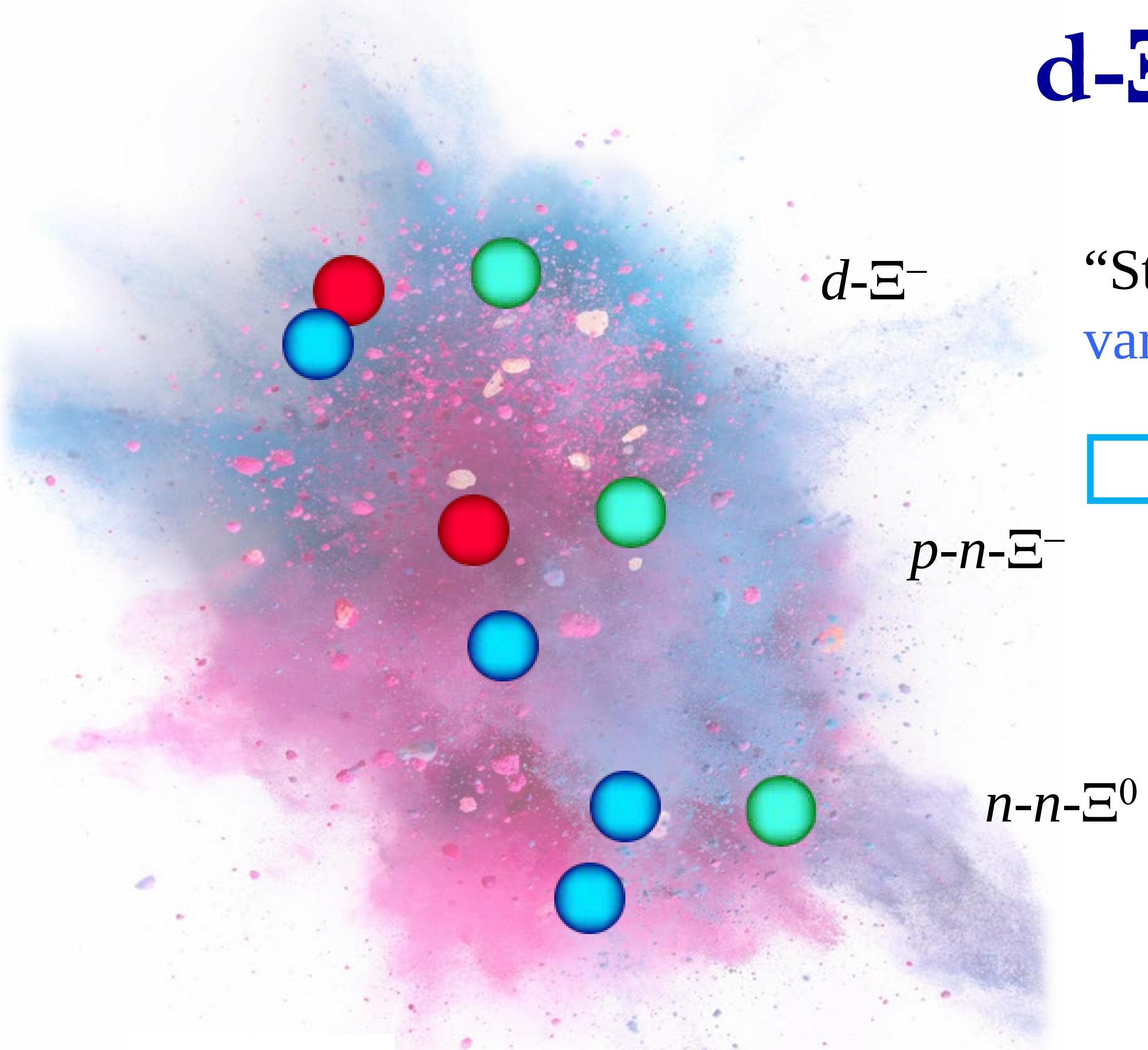


CF contains information on the

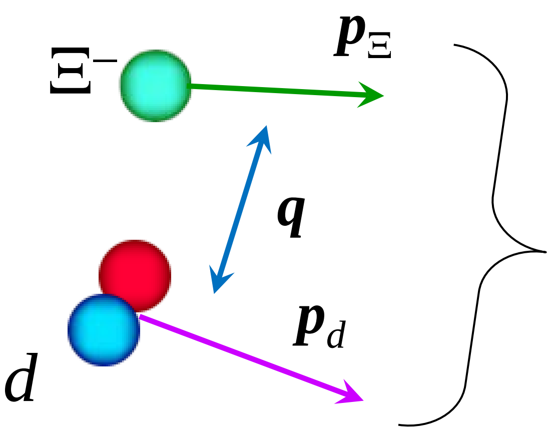
- interaction between 1 and 2
- source function created in collisions.

K. Morita+, PRC ***91****, 024916 (2015); A. Ohnishi+, NPA* ***954****, 294 (2016);*
K. Morita+, PRC ***94****, 031901 (2016); T. Hatsuda+, NPA* ***967****, 856 (2017);*
*D. L. Mihaylov+, EPJ C****78****, 394 (2018); J. Haidenbauer, NPA* ***981****, 1 (2019);*
K. Morita+PRC ***101****, 015201 (2020); Y. Kamiya+, PRL* ***124****, 132501 (2020);*
Y. Kamiya+, PRC ***105****, 014915 (2022).*

d-Ξ 3bCF



"Starts" from
various channels i



i_0 channel detected

$$\Psi_{i_0}^{(-)}(\boldsymbol{r}, \boldsymbol{R}) = \sum_i \phi_i(\boldsymbol{r}) \psi_{i,i_0}^{(-)}(\boldsymbol{R})$$

$$\psi_{i,i_0}^{(-)}(\boldsymbol{R}) \to \delta_{ii_0} e^{i\boldsymbol{K}\cdot\boldsymbol{R}} + \sum_i f_i^*(\Omega) \frac{e^{-iK_c R}}{R}$$

3bCF

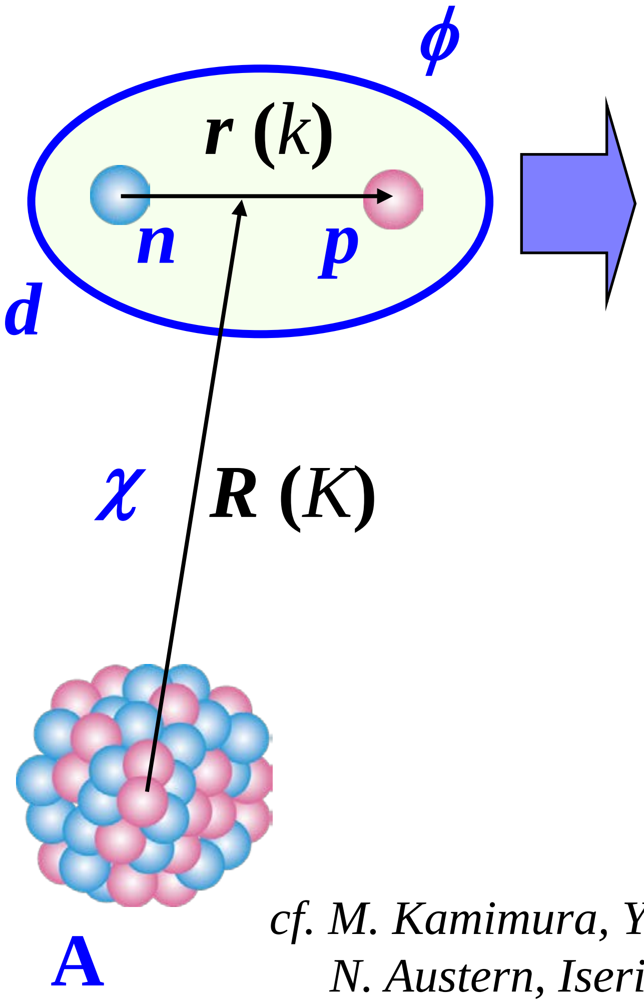
$$C(\boldsymbol{q}) = \sum_i \int \mathcal{S}_i(\boldsymbol{R}) \left| \psi_{i,i_0}^{(-)}(\boldsymbol{R}) \right|^2 d\boldsymbol{R}$$

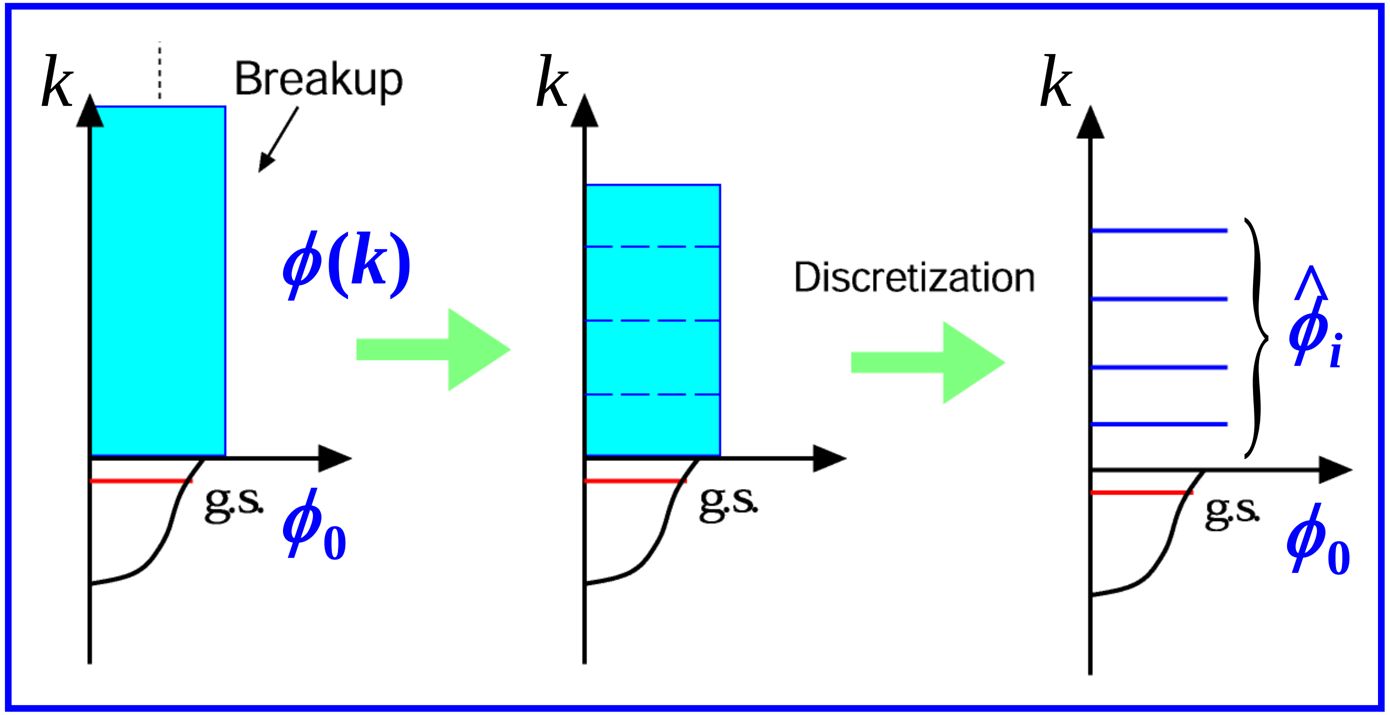
Purpose

Clarification of the CC (deuteron breakup) effect on the d-Ξ 3bCF

In this work, $\mathcal{S}_i(\boldsymbol{R}) \to \mathcal{S}(\boldsymbol{R})$.

The Continuum-Discretized Coupled-Channels method: CDCC (after *l*-truncation)



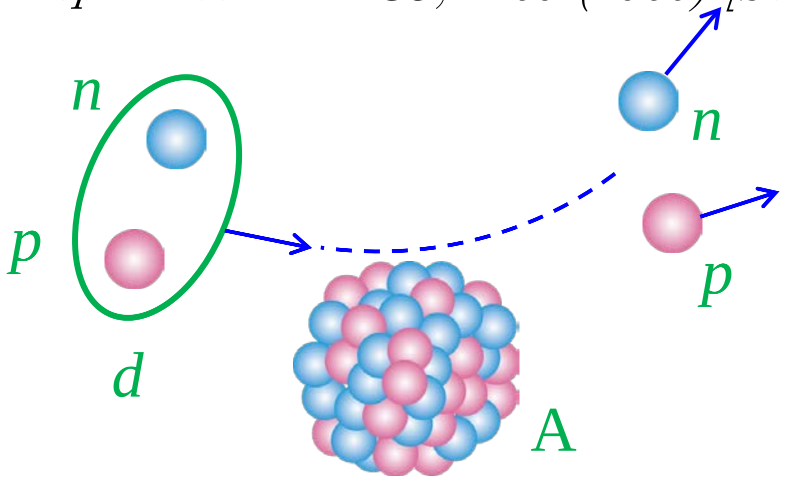


$$\psi = \phi_0 \chi_0 + \int_0^\infty \phi_k \chi_k dk \Rightarrow \psi^{\mathrm{CDCC}} = \sum_i^{i_{\max}} \hat{\phi}_i \hat{\chi}_i$$

cf. *M. Kamimura, Yahiro, Iseri, Sakuragi, Kameyama, and Kawai, PTP Suppl.* ***89****, 1 (1986);*
N. Austern, Iseri, Kamimura, Kawai, Rawitscher, and Yahiro, Phys. Rep. ***154*** *(1987) 126;*
M. Yahiro, Ogata, Matsumoto, and Minomo, PTEP ***2012****, 01A206 (2012).*

The Faddeev theory

L. D. Faddeev, Zh. Eksp. Theor. Fiz. ***39****, 1459 (1960) [Sov. Phys. JETP* ***12****, 1014 (1961)].*



$$[E - K - V_{pn} - V_{pA} - V_{nA}]\,\Psi = 0, \quad \Psi = \Psi_d + \Psi_p + \Psi_n.$$

Faddeev Eqs.

$$[E - K - V_{pn}]\,\Psi_d = V_{pn}\left(\Psi_p + \Psi_n\right),$$

$$[E - K - V_{nA}]\,\Psi_n = V_{nA}\Psi_d + V_{nA}\Psi_p,$$

$$[E - K - V_{pA}]\,\Psi_p = V_{pA}\Psi_d + V_{pA}\Psi_n.$$

Three-body theory in a model space

N. Austern, M. Yahiro, and M. Kawai, Phys. Rev. Lett. ***63****, 2649 (1989);*
N. Austern, M. Kawai, and M. Yahiro, Phys. Rev. C ***53****, 314 (1996).*

$$[E - K - V_{pn} - V_{pA} - V_{nA}]\,\Psi = 0, \quad \Psi = \Psi_d + \Psi_p + \Psi_n.$$

Distorted Faddeev Eqs.

not pair int. but 3-body int.

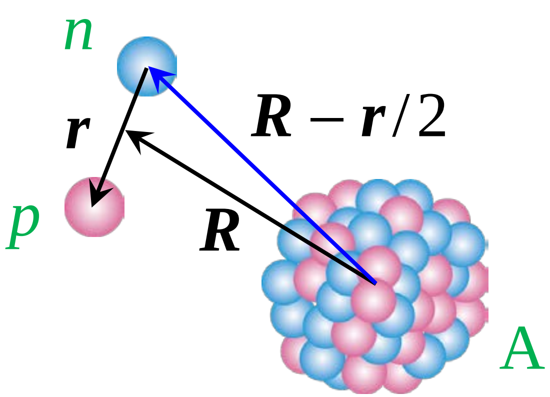
$$[E - K - V_{pn} - \mathcal{P}_{l_{\max}}(V_{nA} + V_{pA})\,\mathcal{P}_{l_{\max}}]\,\Psi_d = V_{pn}\,(\Psi_p + \Psi_n)\,,$$

$$[E - K - V_{nA}]\,\Psi_n = (V_{nA} - \mathcal{P}_{l_{\max}} V_{nA} \mathcal{P}_{l_{\max}})\,\Psi_d + V_{nA}\Psi_p,$$

$$[E - K - V_{pA}]\,\Psi_p = (V_{pA} - \mathcal{P}_{l_{\max}} V_{pA} \mathcal{P}_{l_{\max}})\,\Psi_d + V_{pA}\Psi_n.$$

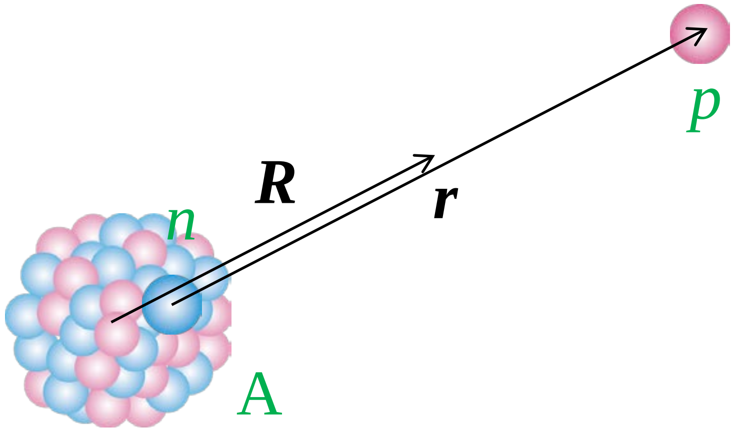
$$\mathcal{P}_{l_{\max}} = \int d\hat{\boldsymbol{r}}' \sum_{l \le l_{\max}} \sum_{m} Y_{lm}(\hat{\boldsymbol{r}})\, Y^*_{lm}(\hat{\boldsymbol{r}}')$$

$$\mathcal{P}_0 e^{-\mu(\boldsymbol{R} - \boldsymbol{r}/2)^2} \to e^{-\mu R^2} e^{-\mu r^2/4}$$



l-truncation, the center of CDCC

N. Austern, M. Yahiro, and M. Kawai, Phys. Rev. Lett. ***63****, 2649 (1989);*
N. Austern, M. Kawai, and M. Yahiro, Phys. Rev. C ***53****, 314 (1996).*



$$\mathcal{P}_{l_{\max}} = \int d\hat{\boldsymbol{r}}' \sum_{l \le l_{\max}} \sum_{m} Y_{lm}(\hat{\boldsymbol{r}})\, Y_{lm}^{*}(\hat{\boldsymbol{r}}')$$

$\mathcal{P}_{l_{\max}}$ smears out $\hat{\boldsymbol{r}}$ w/ the resolution of $1/l_{\max}$.

[If $l_{\max} \rightarrow \infty$, it means $\delta(\boldsymbol{r}' - \boldsymbol{r})$.]

- We have no rearrangement-like channel in the asymptotic region because of $\mathcal{P}_{l_{\max}}$.
- As $l_{\max}$ increases, the coupling between the 1st Eq. and the other two becomes weaker.

Three-body theory in a model space

N. Austern, M. Yahiro, and M. Kawai, Phys. Rev. Lett. **63**, 2649 (1989);
N. Austern, M. Kawai, and M. Yahiro, Phys. Rev. C **53**, 314 (1996).

$$[E - K - V_{pn} - V_{pA} - V_{nA}]\,\Psi = 0, \quad \Psi = \Psi_d + \Psi_p + \Psi_n.$$

Distorted Faddeev Eqs.

not pair int. but 3-body int. $\rightarrow 0$

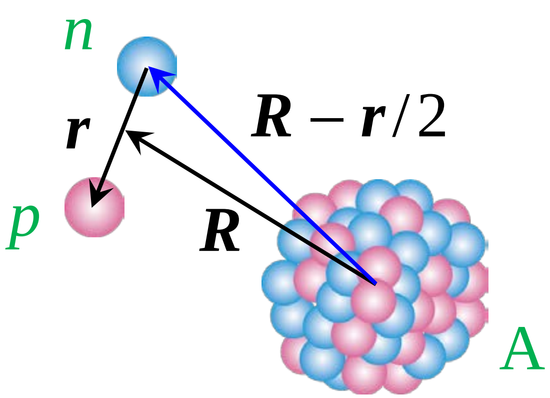
$$[E - K - V_{pn} - \mathcal{P}_{l_{\max}}(V_{nA} + V_{pA})\,\mathcal{P}_{l_{\max}}]\,\Psi_d = V_{pn}(\Psi_p + \Psi_n),$$

$$[E - K - V_{nA}]\,\Psi_n = (V_{nA} - \mathcal{P}_{l_{\max}} V_{nA} \mathcal{P}_{l_{\max}})\,\Psi_d + V_{nA}\Psi_p,$$

$$[E - K - V_{pA}]\,\Psi_p = (V_{pA} - \mathcal{P}_{l_{\max}} V_{pA} \mathcal{P}_{l_{\max}})\,\Psi_d + V_{pA}\Psi_n.$$

$$\mathcal{P}_{l_{\max}} = \int d\hat{\boldsymbol{r}}' \sum_{l \le l_{\max}} \sum_m Y_{lm}(\hat{\boldsymbol{r}})\, Y^*_{lm}(\hat{\boldsymbol{r}}')$$

$$\mathcal{P}_0 e^{-\mu(\boldsymbol{R}-\boldsymbol{r}/2)^2} \rightarrow e^{-\mu R^2} e^{-\mu r^2/4}$$



CDCC, as an alternative to the Faddeev theory

N. Austern, M. Yahiro, and M. Kawai, Phys. Rev. Lett. ***63****, 2649 (1989);*
N. Austern, M. Kawai, and M. Yahiro, Phys. Rev. C ***53****, 314 (1996).*

CDCC solves the following LS eq.:

$$\Psi^{\mathrm{CDCC}} = e^{i\boldsymbol{K}\cdot\boldsymbol{R}}\phi_d + \frac{1}{E - H_d + i\varepsilon}\mathcal{P}_{l_{\max}}\left(V_{nA} + V_{pA}\right)\mathcal{P}_{l_{\max}}\Psi^{\mathrm{CDCC}}.$$

CDCC gives a proper solution to a three-body scattering problem

if the solution converges w/ respect to *l*.

- Continuum-Discretization has nothing to do w/ the justification of CDCC.
- *l*-truncation allows one to truncate also *r* and *k*.
- Convergence for other quantities ($r_{\max}$, $k_{\max}$, and Δk, etc.) must be confirmed to obtain a proper solution to the LS Eq.

Faddeev-AGS vs. CDCC

N. J. Upadhyay, A. Deltuva, F. M. Nunes, PRC ***85****, 054621 (2012).*

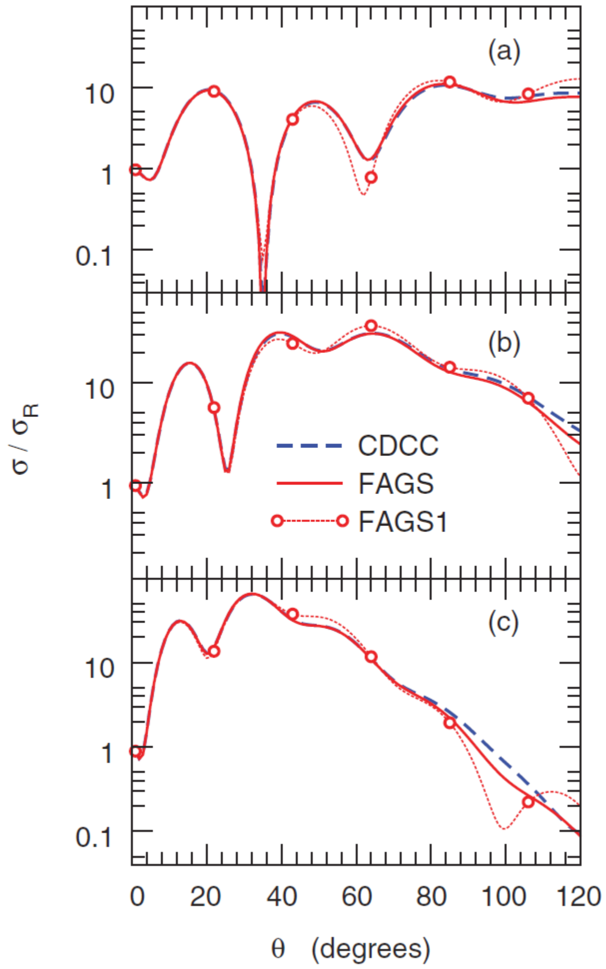


FIG. 2. (Color online) Elastic cross section for $d+^{10}$Be: (a) $E_d = 21.4$ MeV, (b) $E_d = 40.9$ MeV, and (c) $E_d = 71$ MeV.

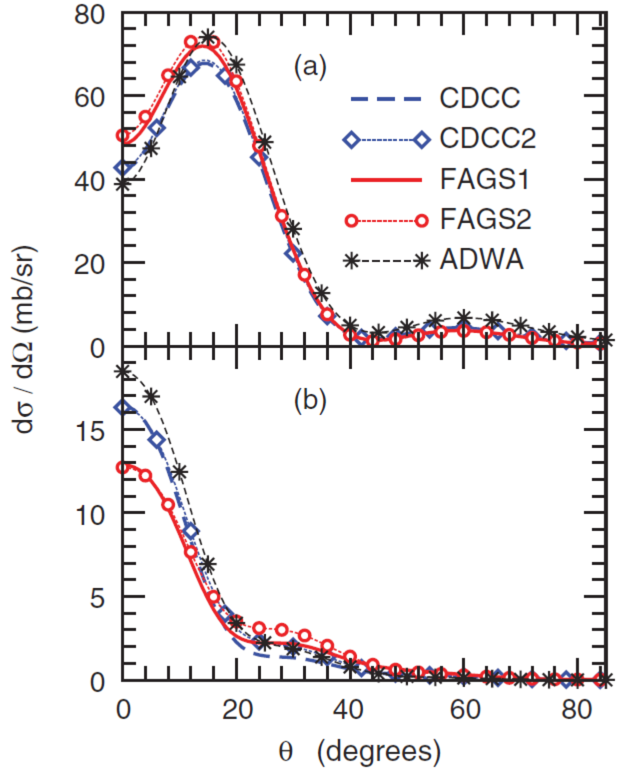


FIG. 6. (Color online) Angular distribution for ^{12}C$(d,p)^{13}$C: (a) $E_d = 12$ MeV and (b) $E_d = 56$ MeV.

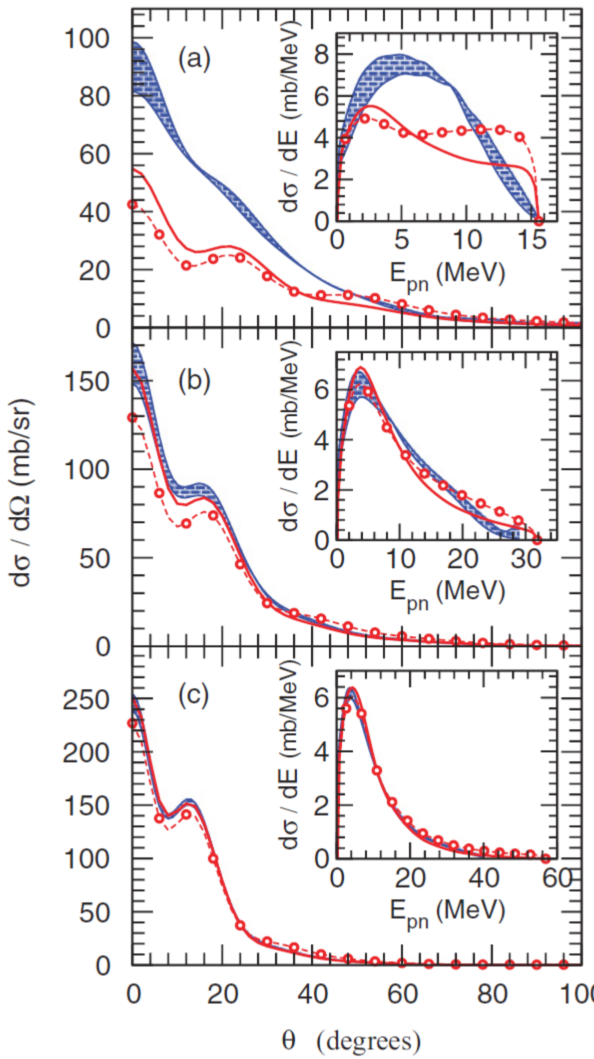


FIG. 8. (Color online) Breakup distributions for the ^{10}Be$(d,pn)^{10}$Be reaction at (a) $E_d = 21$ MeV, (b) $E_d = 40.9$ MeV, and (c) $E_d = 71$ MeV. Results for CDCC (hatched band), FAGS (solid), and FAGS1 (circles).

Faddeev-AGS vs. CDCC

N. J. Upadhyay, A. Deltuva, F. M. Nunes, PRC ***85****, 054621*

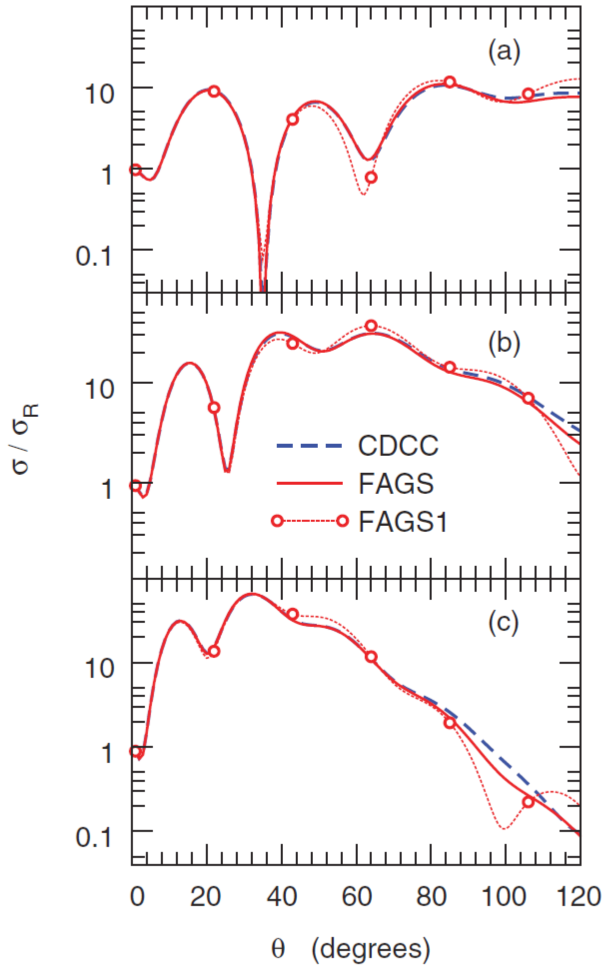


FIG. 2. (Color online) Elastic cross section for $d+^{10}$Be: (a) $E_d = 21.4$ MeV, (b) $E_d = 40.9$ MeV, and (c) $E_d = 71$ MeV.

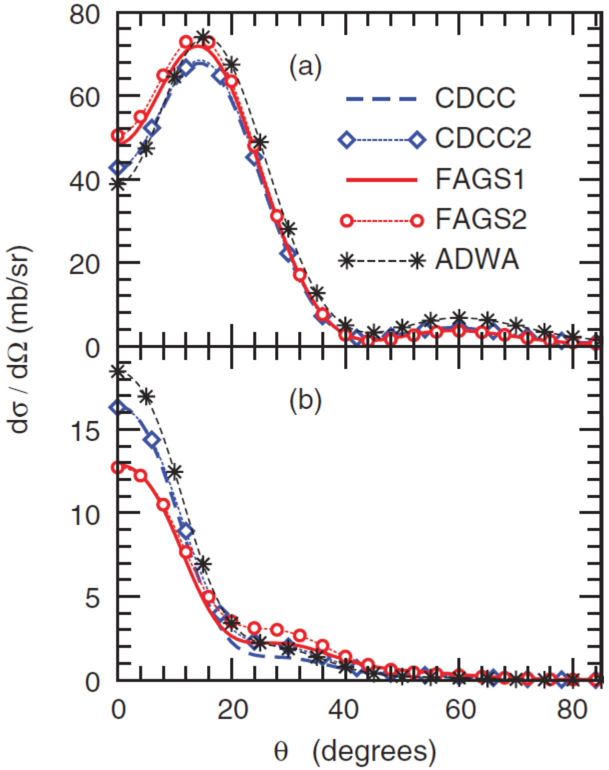
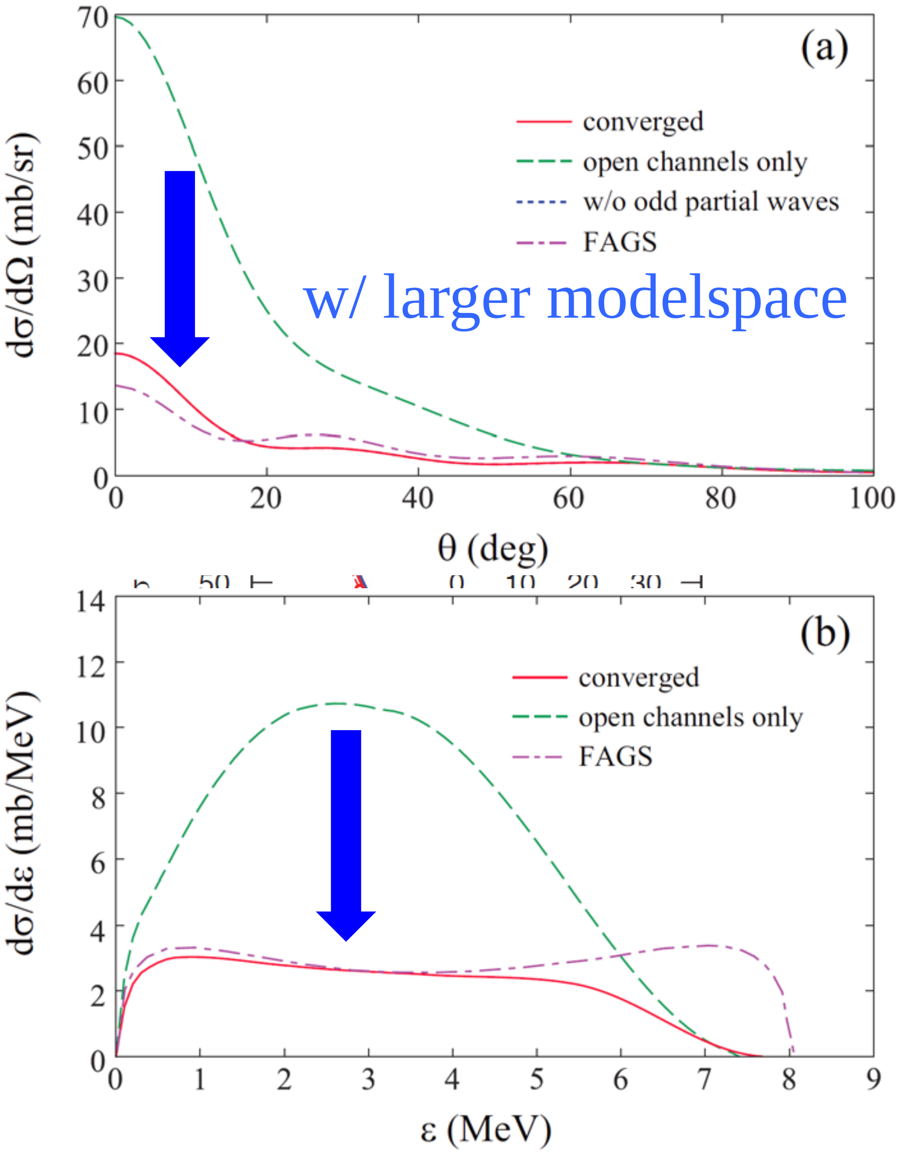


FIG. 6. (Color online) Angular distribution for ^{12}C(d
(a) $E_d = 12$ MeV and (b) $E_d = 56$ MeV.

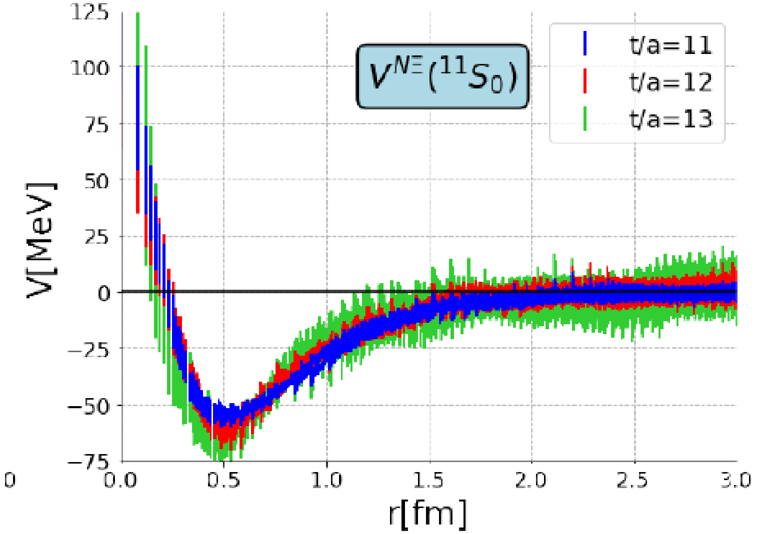
KO and K. Yoshida, PRC ***94****, 051603(R) (2016).*



and (c) $E_d = 71$ MeV. Results for CDCC (hatched band), FAGS (solid), and FAGS1 (circles).

CDCC + LQCD for the d-Ξ 3bCF

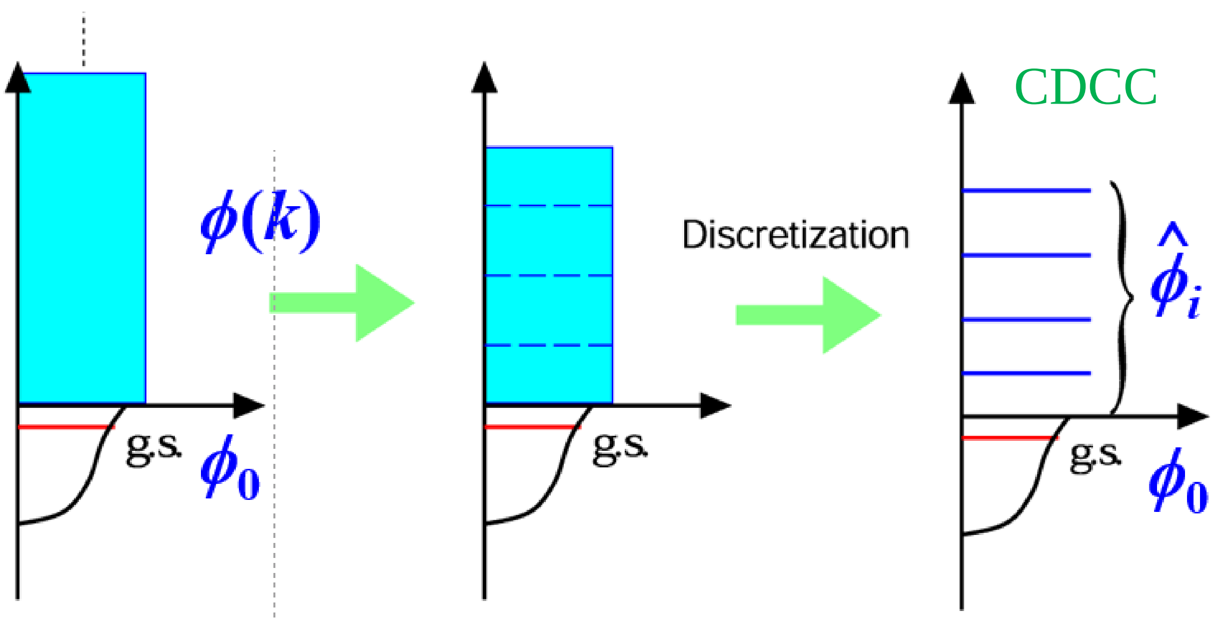
K. Sasaki+ (HAL-QCD), Nucl. Phys. A **998**, 121737 (2020).



s-wave N-Ξ pot.

by LQCD

KO, T. Fukui, Y. Kamiya, and A. Ohnishi, PRC ***103****, 065205 (2021).*



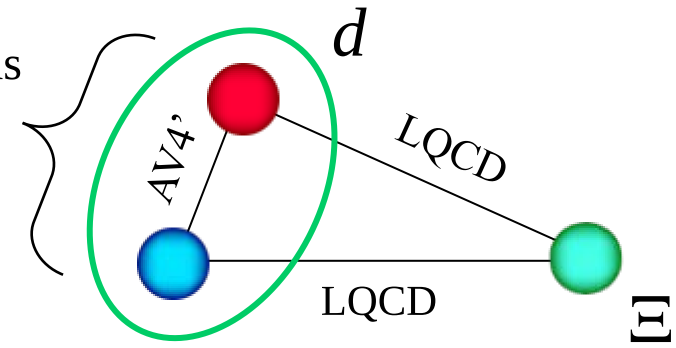
$^{13}S_1$ (*pn*): g.s. + 10 bins

$^{31}S_1$ (*nn*): 400 bins

(up to 166 MeV)

↓

411 channels

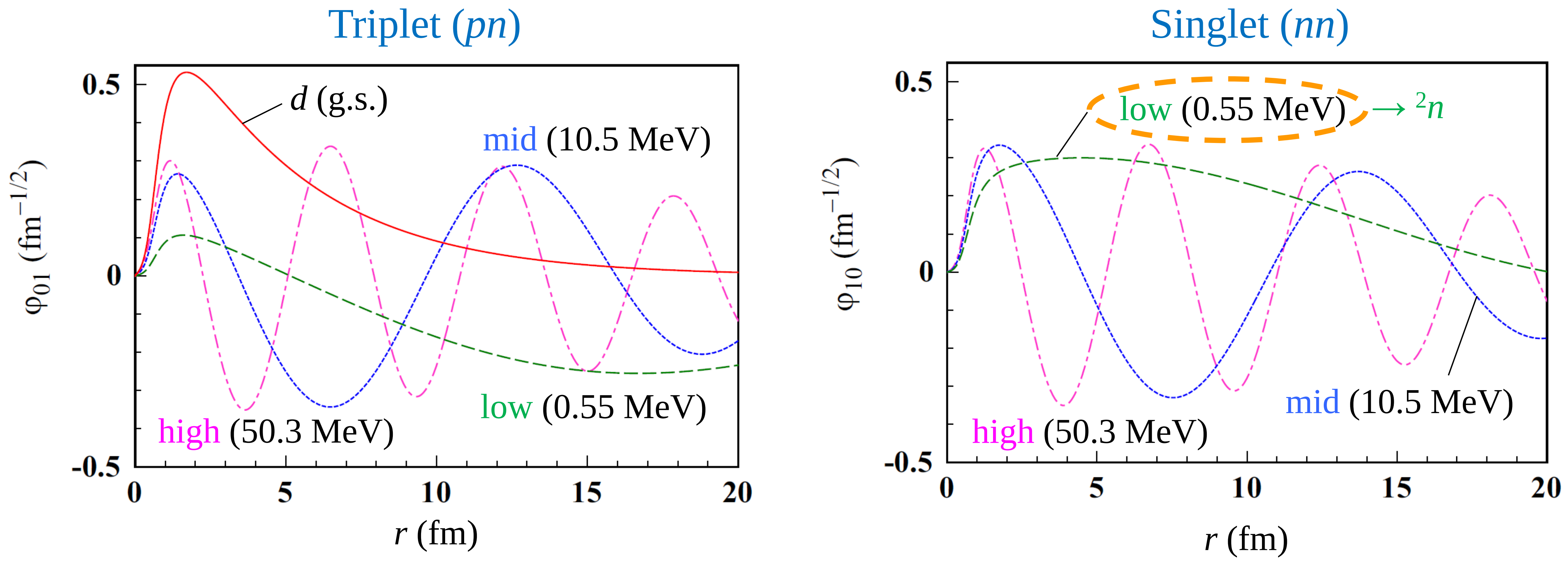


All interactions are isospin-spin dep.

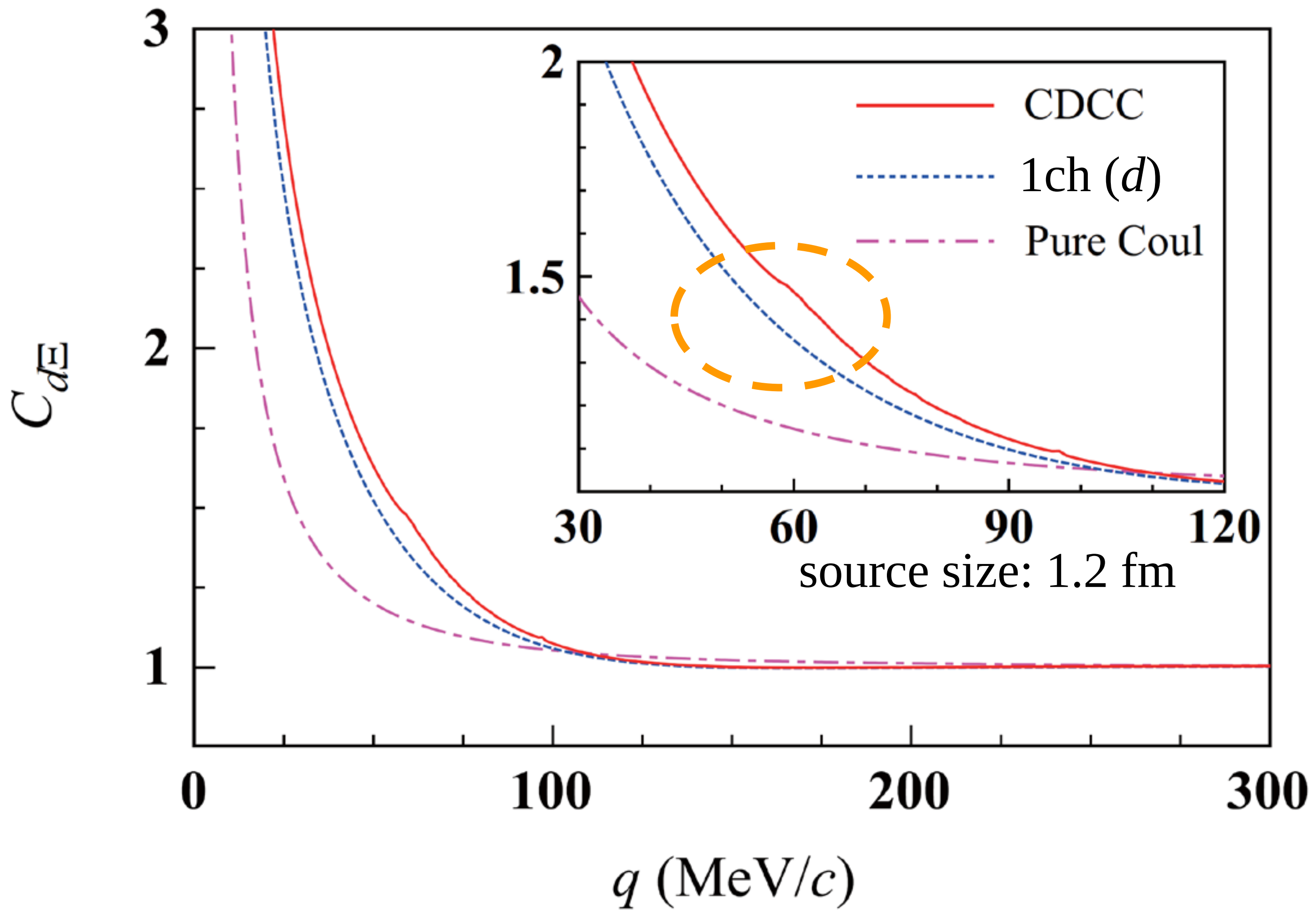
<u>Limitations</u>

- Coulomb int. presents in all channels.
- Isospin dep. of masses of *N* and Ξ is ignored.
- Orbital ang. moms. are restricted to 0.
- Rearrangement channels are disregarded.

NN states

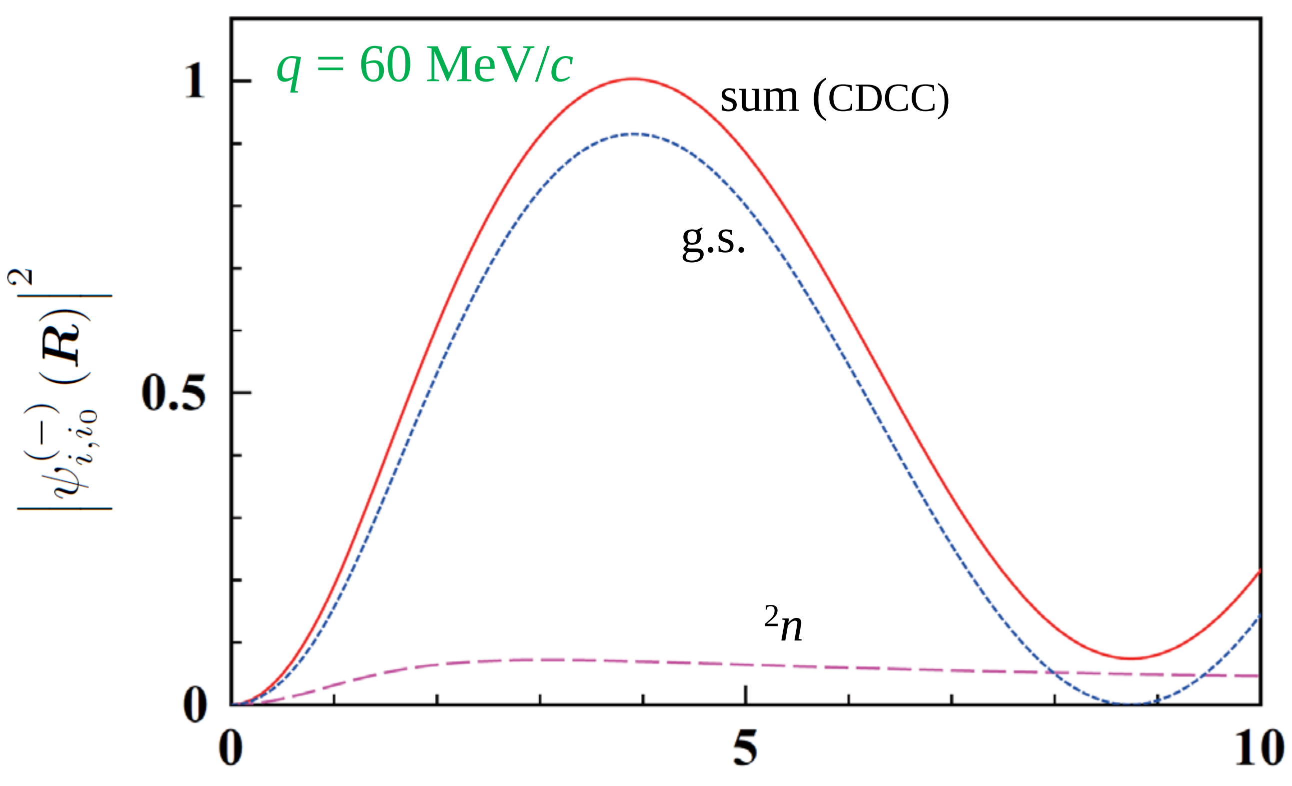

Triplet (pn)
d (g.s.)
mid (10.5 MeV)
low (0.55 MeV)
high (50.3 MeV)
φ01 (fm−1/2)
0.5
0
-0.5
0
5
10
15
20
r (fm)
Singlet (nn)
low (0.55 MeV) → 2n
mid (10.5 MeV)
high (50.3 MeV)
φ10 (fm−1/2)
0.5
0
-0.5
0
5
10
15
20
r (fm)

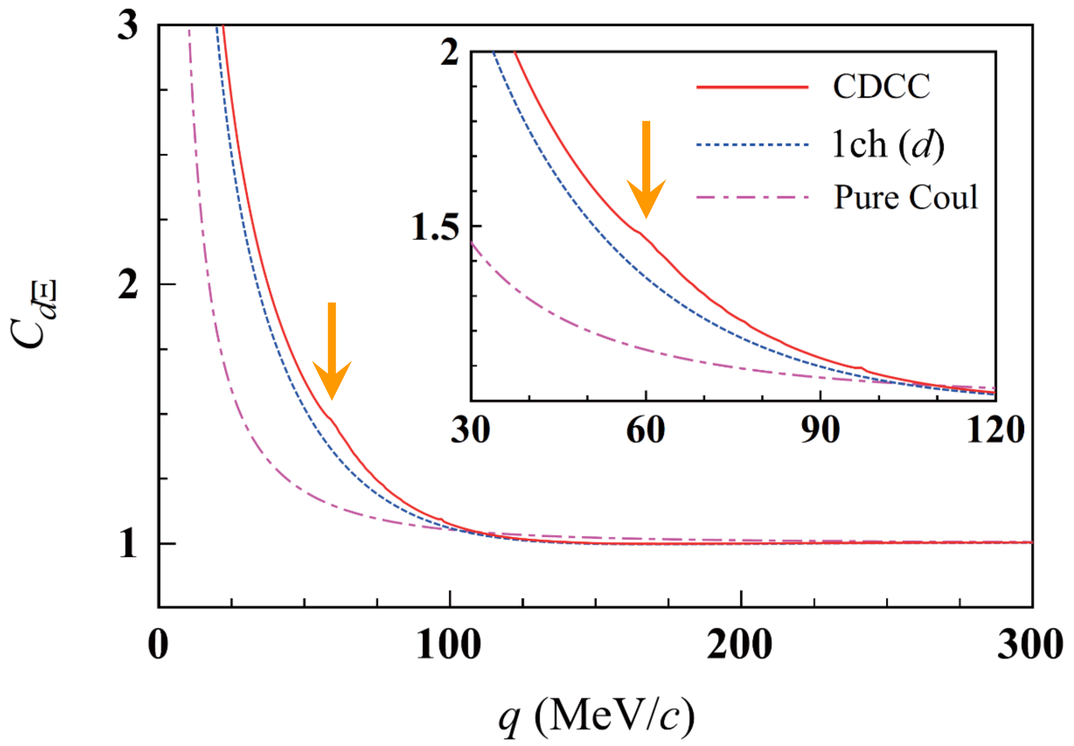
d-Ξ correlation function



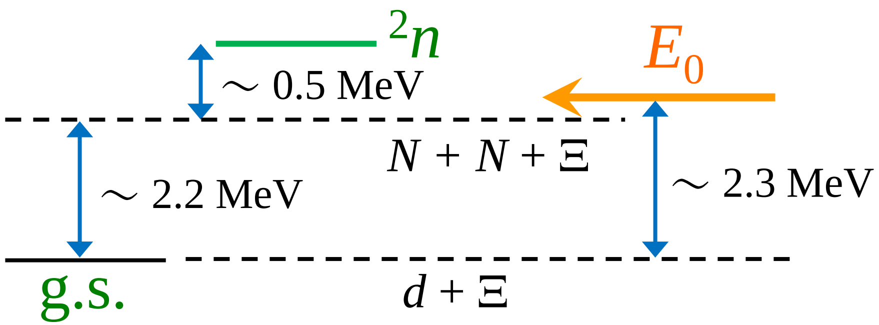
- Increase due to strong int. showing an attractive nature of the d-Ξ int. (no bound state, though)
- Slight enhancement due to the breakup effect.

NN-Ξ relative W.Fn.: around the NN-Ξ threshold





- The contribution from the ^2n channel is important.
- This is because the ^2n-Ξ channel is located just above the incident energy (kind of Feshbach resonance).



Summary

- We have investigated the deuteron BU effect on the d-Ξ CF with CDCC adopting LQCD $N\Xi$ interactions.
  - ✓ The deuteron BU effect is found to be not very significant, giving an enhancement of the CF by about 7 %.
  - ✓ The coupling with the ${}^{2}n$-Ξ channels is strong and dictates the BU effect on the CF.
  - ✓ Our result may justify a simple $d + \Xi$ two-body model calculation for the CF.

*KO, T. Fukui, Y. Kamiya, and A. Ohnishi, PRC **103**, 065205 (2021) [arXiv:2103.00100].*

- The result of the present calculation may change if the isospin dependence of the particle masses, a proper treatment of Coulomb, and channel dep. of the source Fn. are considered.

*cf. Y. Kamiya+, PRC **105**, 014915 (2022) for $p\Xi^{-}$-$\Lambda\Lambda$ CF calculation.*

- The framework proposed in this study will be applicable to N+N+X 3bCF (X $\neq$ nucleon), if rearrangement channels can be disregarded.