Femtoscopy for exotic hadrons and nuclei

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- Introduction — Femtoscopy primer
- Femtoscopy for exotic hadrons
  - K^-p correlations for $\Lambda(1405)$

    Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)
  - DD^* and $D\bar{D}^*$ correlations for T_{cc} and $X(3872)$

    Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)
- Femtoscopy for hypernuclei
  - $\Lambda\alpha$ correlations and Λ in medium

    A. Jinno, Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation
- Summary

In memory of Akira Ohnishi

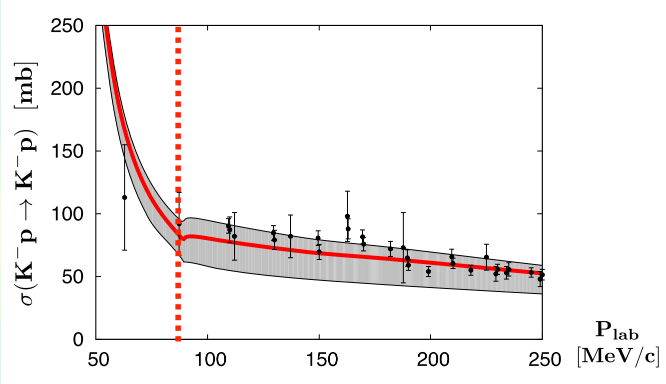
Sep. 13, 2019, after FemTUM19 workshop @ München

Scattering experiments and femtoscopy

Traditional methods: scattering experiments

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)

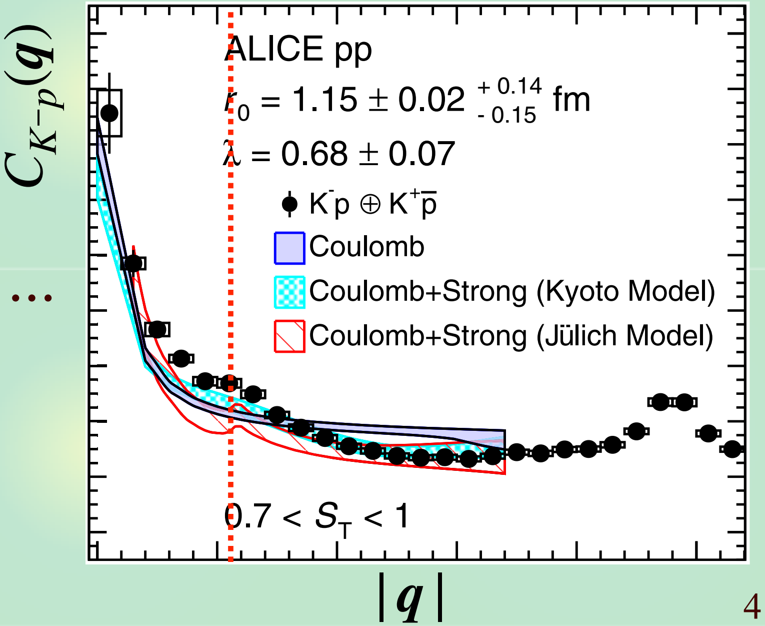
- Limited channels: $NN, YN, \pi N, KN, \bar{K}N, \cdots$
- Limited statistics (low-energy)
- Heavy (c, b) hadrons: impossible



Femtoscopy: correlation function

ALICE collaboration, PRL 124, 092301 (2020)

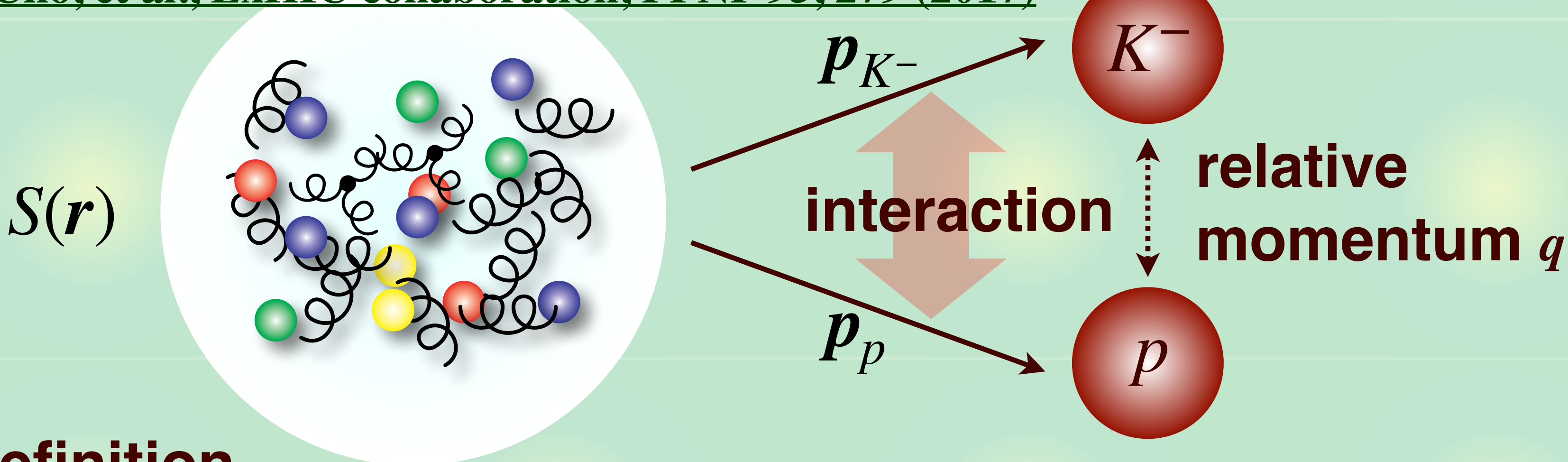
- Various systems: $\Lambda\Lambda, N\Omega, \phi N, \bar{K}\Lambda, DN, \cdots$
- Excellent precision ($\bar{K}^0 n$ cusp)
- Heavy hadrons: possible!



Correlation function and hadron interaction

High-energy collision: chaotic source $S(r)$ of hadron emission

S. Cho, et al., ExHIC collaboration, PPNP 95, 279 (2017)



- Definition

$$C(\boldsymbol{q}) = \frac{N_{K^-p}(\boldsymbol{p}_{K^-}, \boldsymbol{p}_p)}{N_{K^-}(\boldsymbol{p}_{K^-}) N_p(\boldsymbol{p}_p)}$$ **(= 1 in the absence of FSI/QS)**

- Theory (Koonin-Pratt formula)

S.E. Koonin PLB 70, 43 (1977); S. Pratt, PRD 33, 1314 (1986)

$$C(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S(\boldsymbol{r})\, |\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})|^2$$

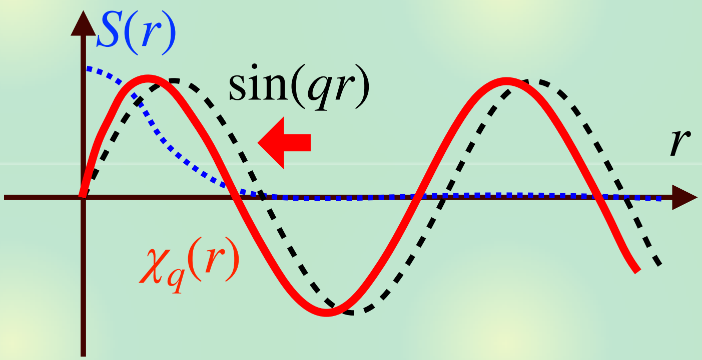
Source function $S(\boldsymbol{r})$ <—> wave function $\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})$ (interaction)

Wave functions and correlations

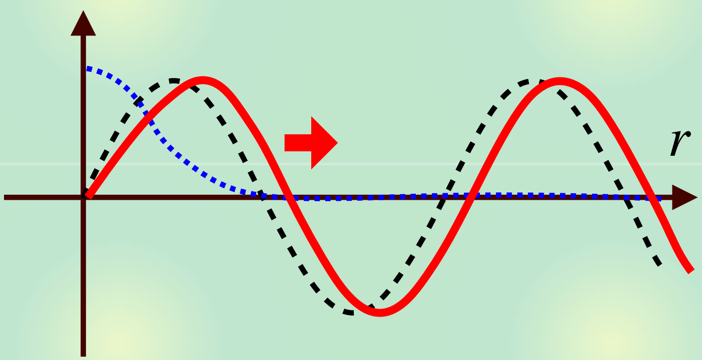
Spherical source with s-wave interaction dominance

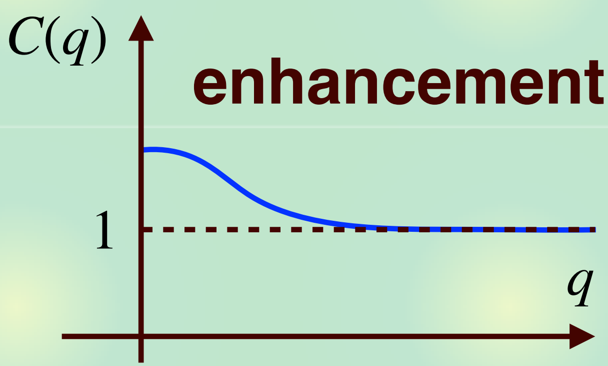
$$C(q) \simeq 1 + \int_0^\infty dr\, S(r)\{\,|\chi_q(r)|^2 - \sin^2(qr)\}$$

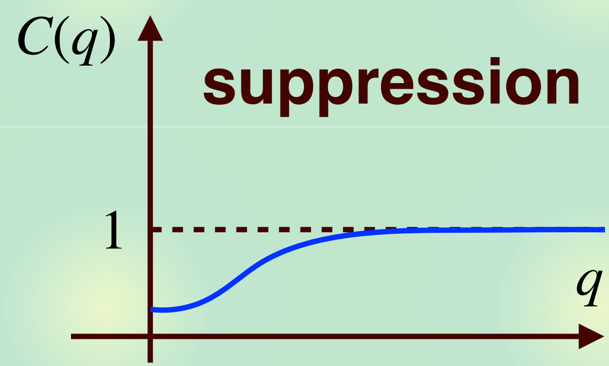
attraction



repulsion







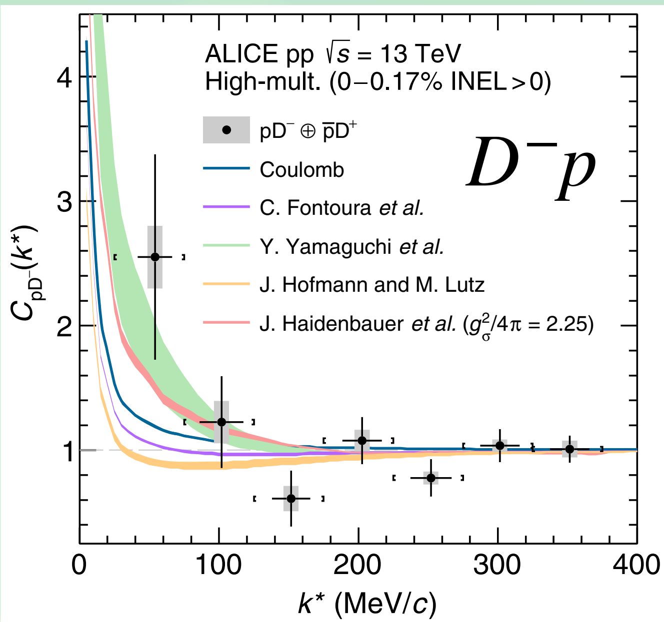
Correlation function <—> nature of interaction

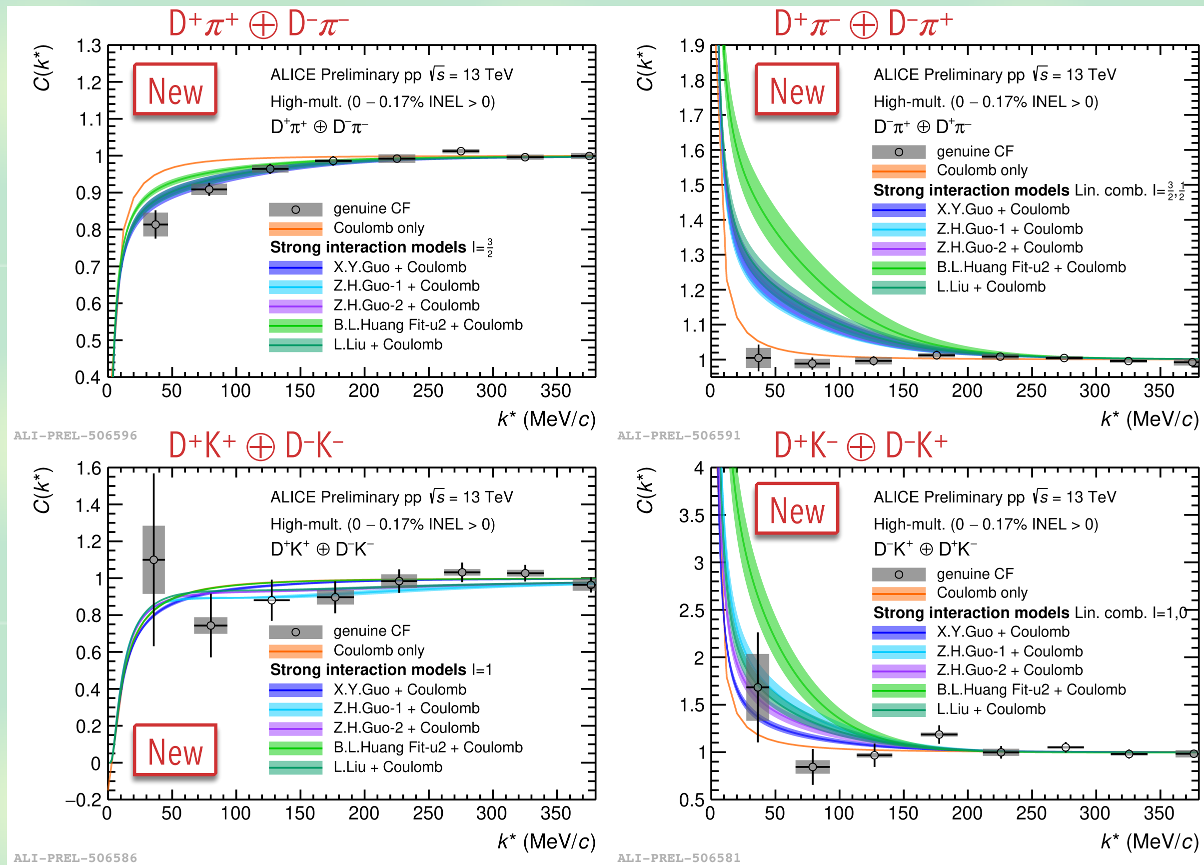
Experimental data in charm sector

Observed correlation functions with charm: $DN, D\pi, DK$

ALICE collaboration, PRD 106, 052010 (2022);

Talk by F. Grosa @ Quark Matter 2022





Unique way to obtain data in charm sector (yet low statistics)

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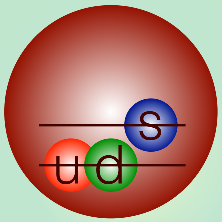
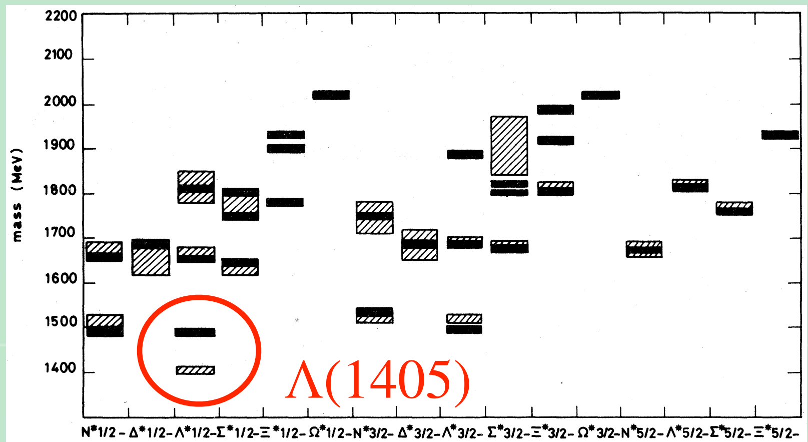
$\Lambda(1405)$ and $\bar{K}N$ scattering

$\Lambda(1405)$ does not fit in standard picture —> exotic candidate

N. Isgur and G. Karl, PRD18, 4187 (1978)



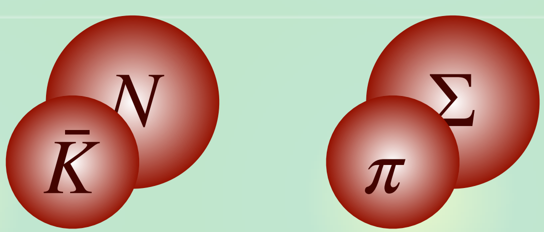


: theory

: experiment

Resonance in coupled-channel scattering

- Coupling to MB: chiral SU(3) dynamics



永江知文、兵藤哲雄「K中間子原子核の物理」（共立出版）

Coupled-channel effects

Schrödinger equation (s-wave)

$$\begin{pmatrix} \frac{-1}{2\mu_1}\frac{d^2}{dr^2} + V_{11}(r) + V_{\rm C}(r) & V_{12}(r) & \cdots \\ V_{21}(r) & \frac{-1}{2\mu_2}\frac{d^2}{dr^2} + V_{22}(r) + \Delta_2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} = E \begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix}$$

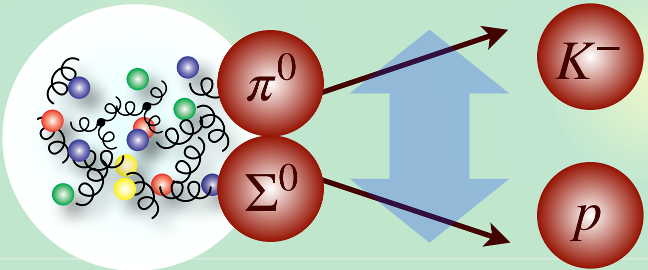
Coulomb threshold energy difference

Asymptotic ($r \to \infty$) wave function

$$\begin{pmatrix} \psi_{K^-p}(r) \\ \psi_{\bar{K}^0 n}(r) \\ \vdots \end{pmatrix} \propto \begin{pmatrix} \# e^{-iqr} + \# e^{iqr} \\ \# e^{-iq_2 r} + \# e^{iq_2 r} \\ \vdots \end{pmatrix}$$

incoming + outgoing

- **Transition** from $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$ is in $\psi_i(r)$ with $i \neq K^-p$



Coupled-channel correlation function

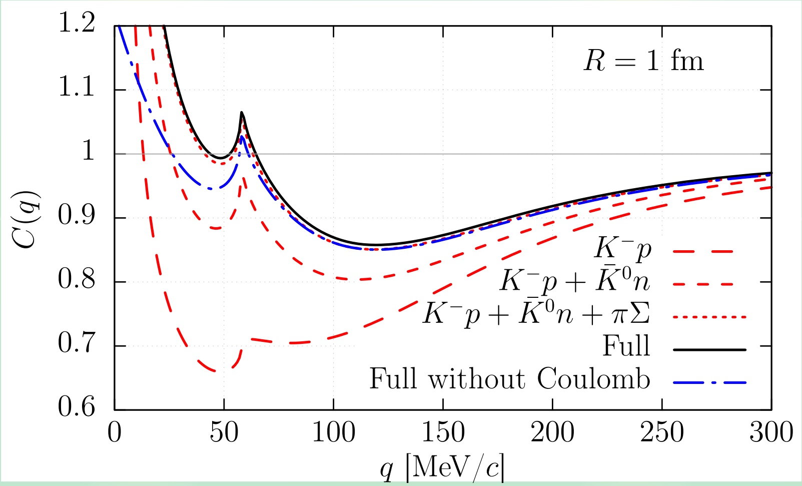
Coupled-channel Koonin-Pratt formula

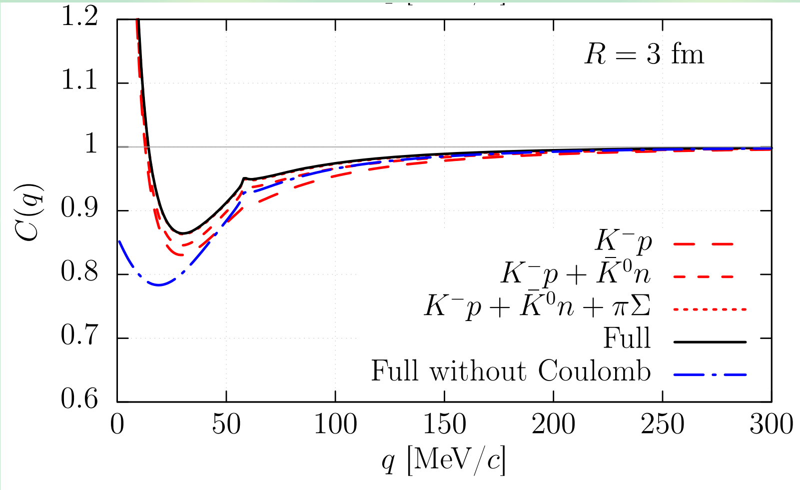
R. Lednicky, V.V. Lyuboshitz, V.L. Lyuboshitz, Phys. Atom. Nucl. 61, 2950 (1998);
J. Haidenbauer, NPA 981, 1 (2019);
Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

$$C_{K^-p}(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S_{K^-p}(\boldsymbol{r})\,|\,\Psi^{(-)}_{K^-p,\boldsymbol{q}}(\boldsymbol{r})\,|^2 + \sum_{i\neq K^-p} \omega_i \int d^3\boldsymbol{r}\, S_i(\boldsymbol{r})\,|\,\Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})\,|^2$$

- Transition from $\bar{K}^0 n, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^-\Sigma^+, \pi^0\Lambda$

- ω_i: weight of channel i source relative to K^-p





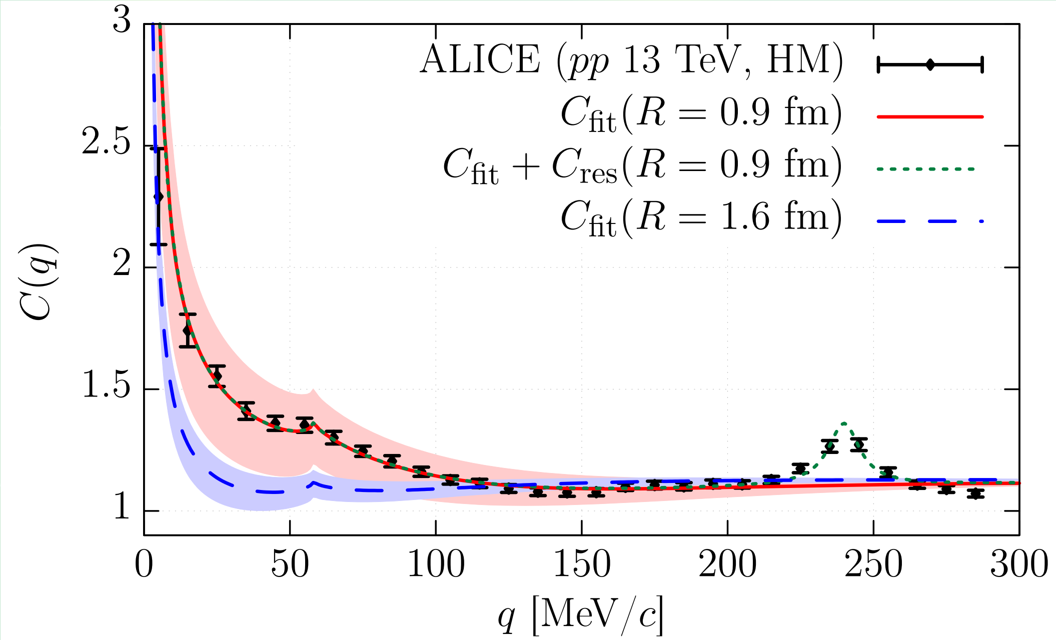
Coupled-channel effect is enhanced for small sources

Correlation from chiral SU(3) dynamics

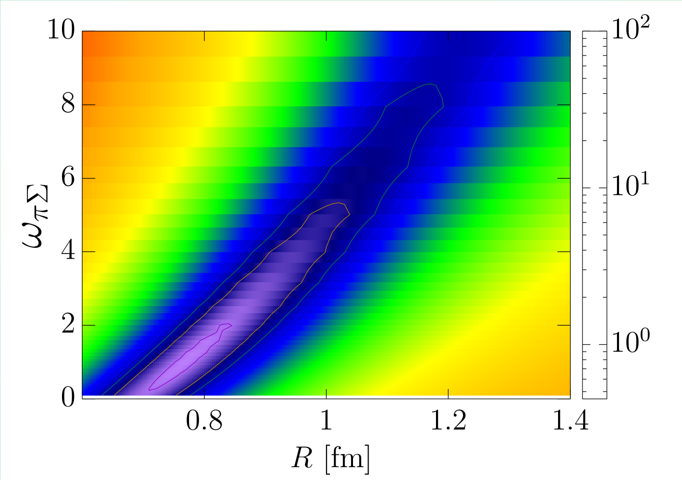
Wave function $\Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})$: Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

K. Miyahara, T. Hyodo, W. Weise, PRC98, 025201 (2018)

- **Source function $S(r)$: gaussian, $R \sim 1$ fm from $K^+ p$ data**
- **Source weight $\omega_{\pi\Sigma} \sim 2$ by simple statistical model estimate**



reduced χ^2



Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise, PRL124, 132501 (2020)

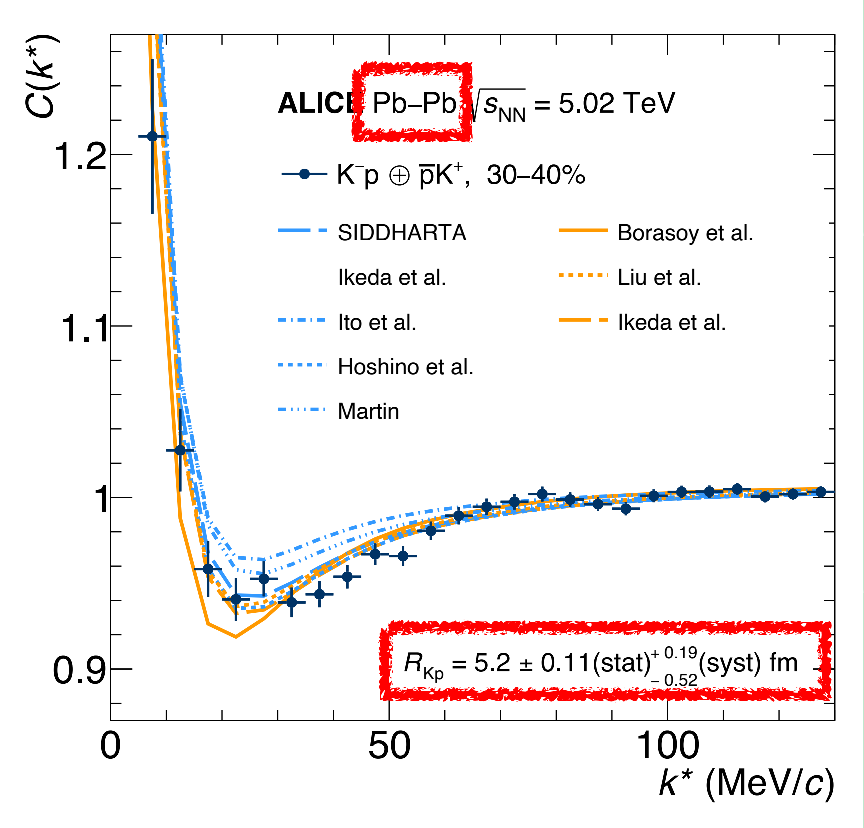
Correlation function by ALICE is well reproduced

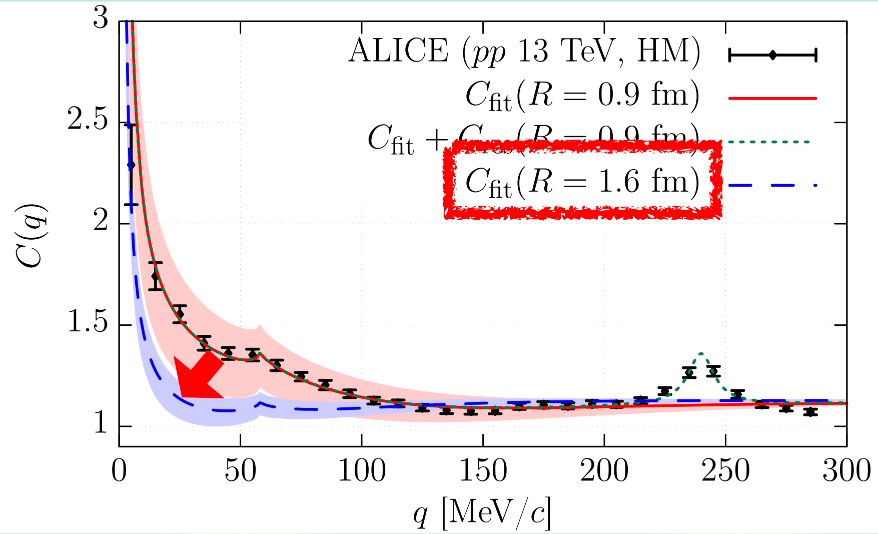
Large source case

New data with Pb-Pb collisions at 5.02 TeV

ALICE collaboration, PLB 822, 136708 (2021)

- Scattering length $a_{K^-p} = -0.91 + 0.92i$ fm





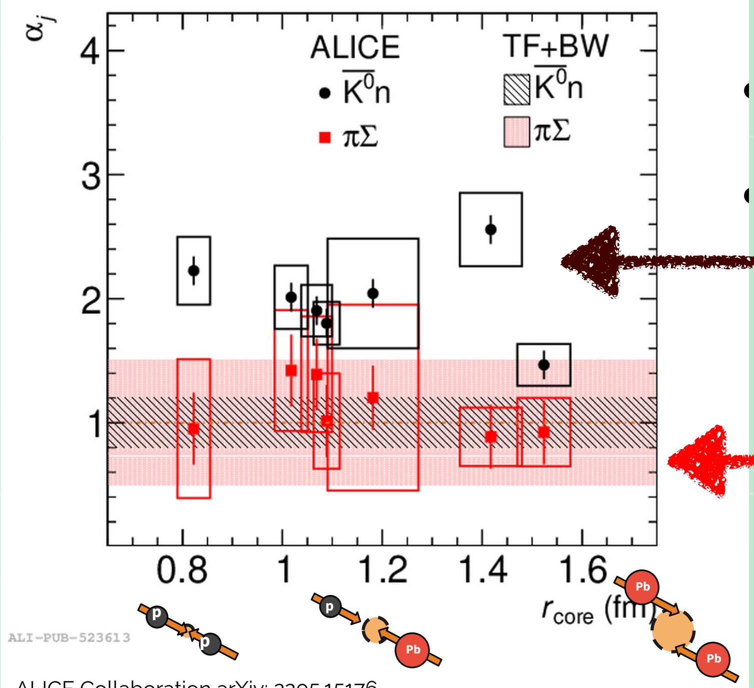
Correlation is suppressed at larger R, as predicted

Systematic study of source size dependence

Correlations in pp, p-Pb, Pb-Pb by Kyoto $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

ALICE collaboration, EPJC 83, 340 (2023)

$$C_{K^-p}(\boldsymbol{q}) \simeq \int d^3\boldsymbol{r}\, S_{K^-p}(\boldsymbol{r})\, |\Psi^{(-)}_{K^-p,\boldsymbol{q}}(\boldsymbol{r})|^2 + \sum_{i \neq K^-p} \omega_i \int d^3\boldsymbol{r}\, S_i(\boldsymbol{r})\, |\Psi^{(-)}_{i,\boldsymbol{q}}(\boldsymbol{r})|^2$$



ALICE Collaboration arXiv: 2205.15176

enhancement needed to explain data

expected weight ω_i by Thermal Fist + Blast Wave

More strength is needed in the $\bar{K}^0 n$ channel

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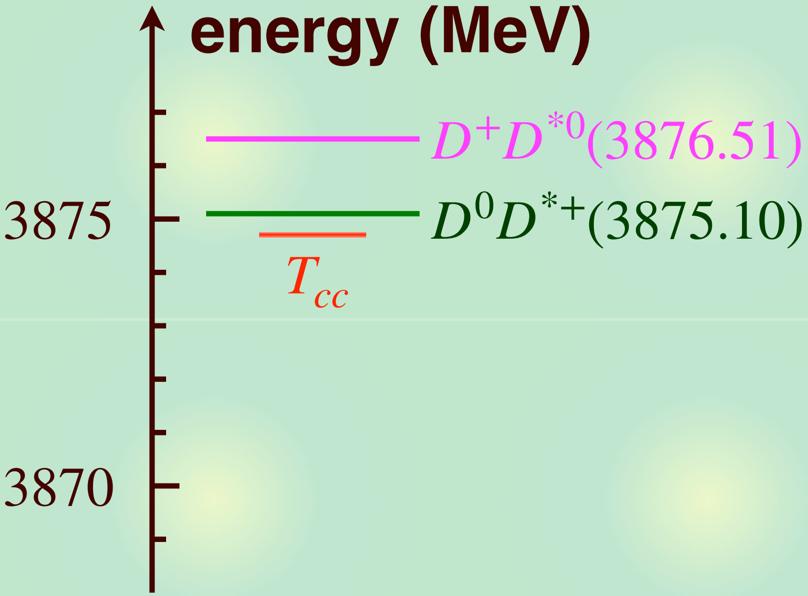
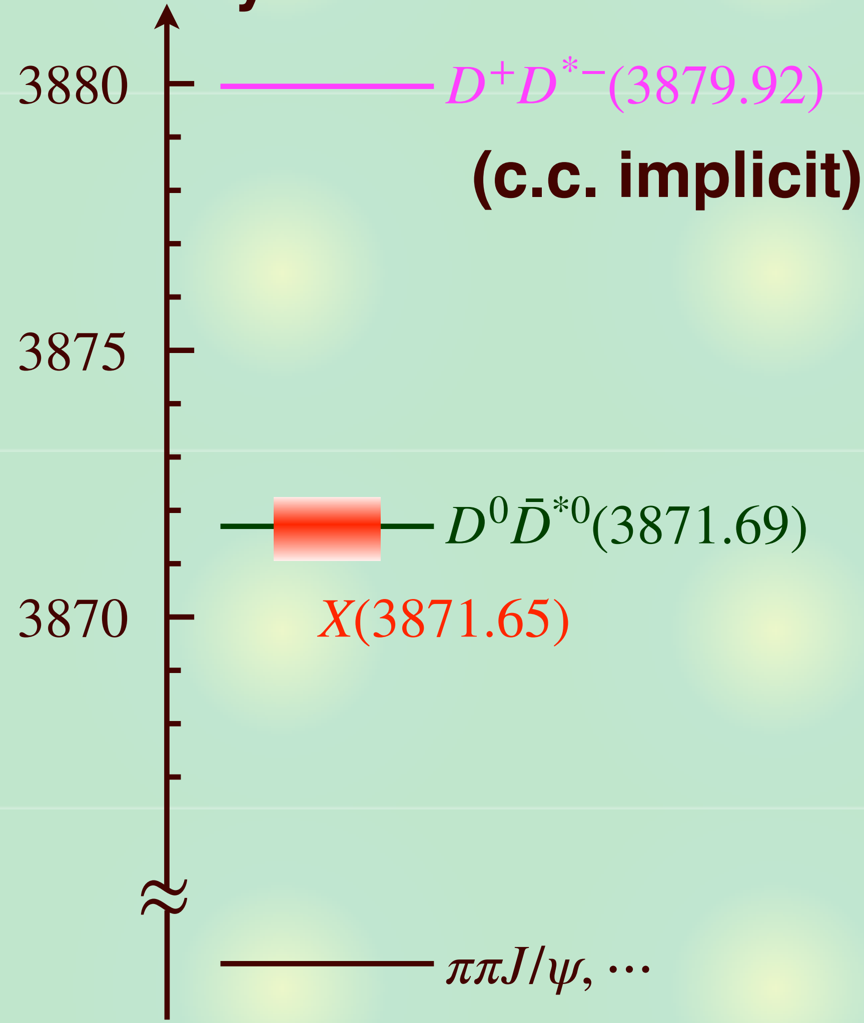
T_{cc} and $X(3872)$

T_{cc} near DD^* / $X(3872)$ near $D\bar{D}^*$: similarity





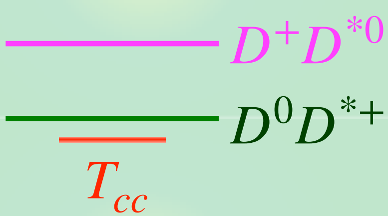
- isospin symmetry breaking
- $X(3872)$ has decay channel

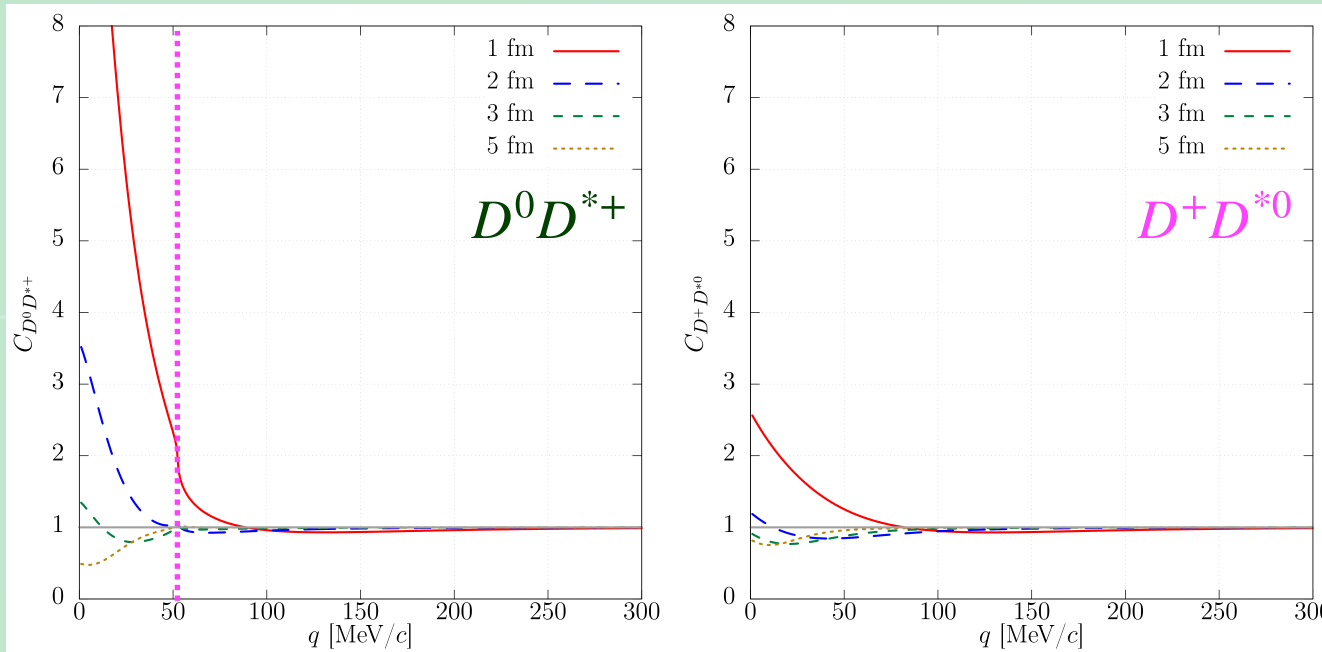
DD^* and $D\bar{D}^*$ correlation functions —> nature of T_{cc} and $X(3872)$

$DD^* \sim T_{cc}$ sector

D^0D^{*+} and D^+D^{*0} correlation functions ($cc\bar{u}\bar{d}$)

Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)



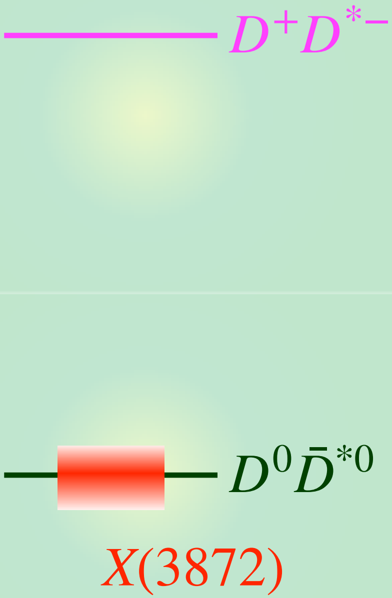


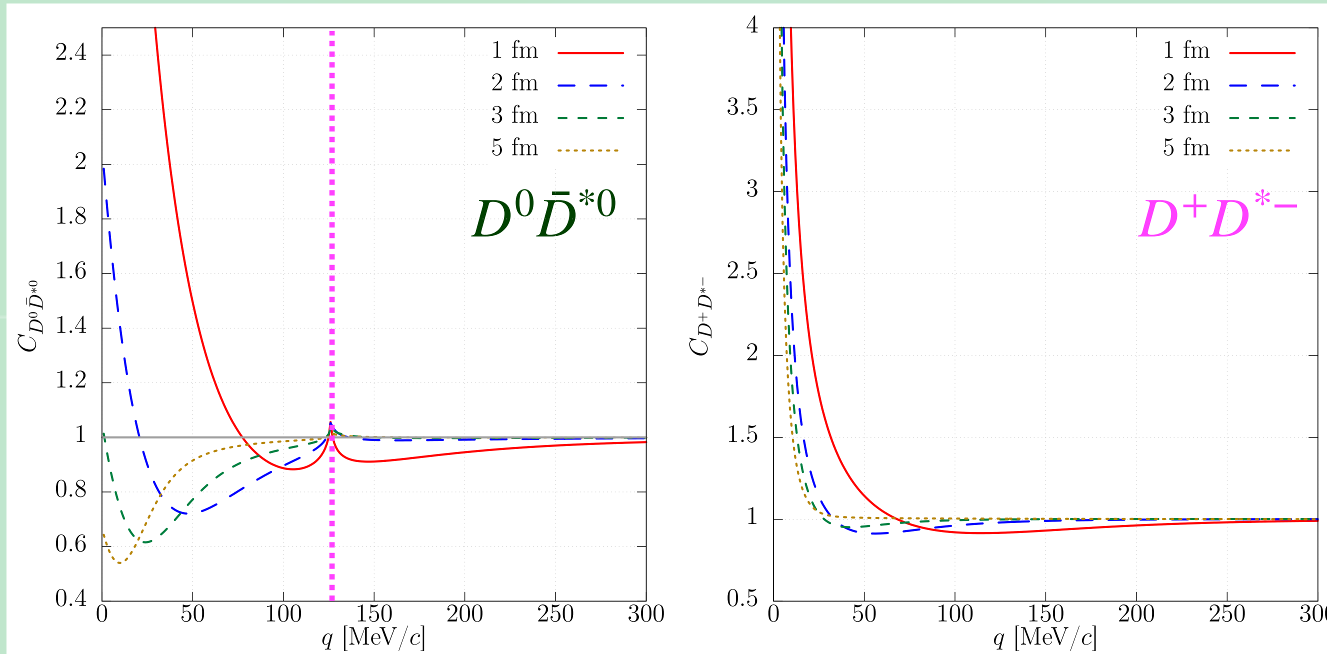
- Bound state feature (source size dep.) in both channels
- Strong signal in D^0D^{*+}, weaker one in D^+D^{*0}
- D^+D^{*0} cusp in D^0D^{*+} ($q \sim 52$ MeV) is not very prominent

$D\bar{D}^* \sim X(3872)$ sector

$D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$ correlation functions ($c\bar{c}q\bar{q}$)

Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)





- Bound state feature in $D^0\bar{D}^{*0}$ correlation
- Sizable D^+D^{*-} cusp in $D^0\bar{D}^{*0}$ ($q \sim 126$ MeV)
- D^+D^{*-} correlation: Coulomb attraction dominance

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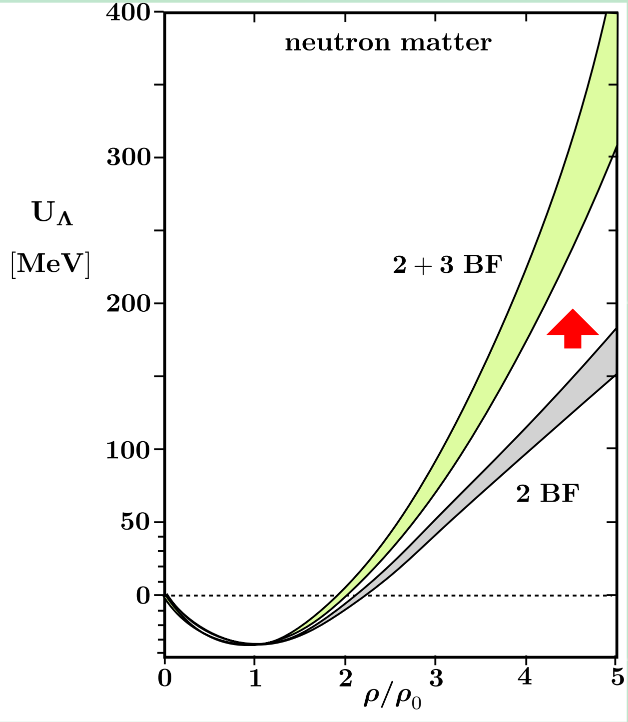
Motivation

A solution to hyperon puzzle in neutron stars

- ΛNN three-body force for repulsion at high density

D. Gerstung, N. Kaiser, W. Weise, EPJA 55, 175 (2020)



How to verify this in experiments?

- Λ directed flow in heavy ion collisions

Y. Nara, A. Jinno, K. Murase, A. Ohnishi, PRC 106, 044902 (2022)

Λ-nucleus correlation function?

- Heavy nuclei are difficult to produce
- Strong binding of α: two-body treatment justified

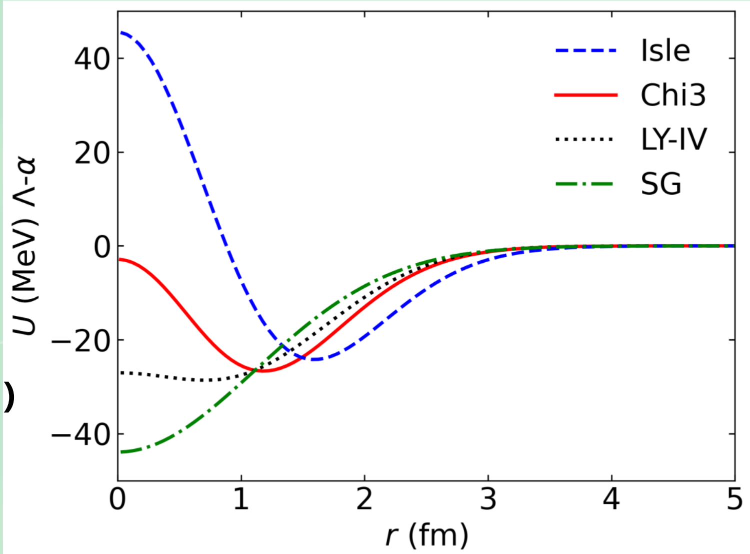
$\Lambda\alpha$ correlation function —> nature of $\Lambda\alpha$ potential?

$\Lambda\alpha$ potentials

Phenomenological $\Lambda\alpha$ potentials ($^{5}_{\Lambda}\mathrm{He}$ binding energy)

I. Kumagai-Fuse, S. Okabe, Y. Akaishi, PLB 345, 386 (1997)

- **SG**: single gaussian
- **Isle**: two gaussians (with core)



Skyrme-Hartree Fock methods

- **LY4**: phenomenorogical

D.E. Lanskoy, Y. Yamamoto, PRC 55, 2330 (1997)

- **Chi3**: based on chiral EFT with ΛNN force

A. Jinno, K. Murase, Y. Nara, A. Ohnishi, arXiv:2306.17452 [nucl-th]

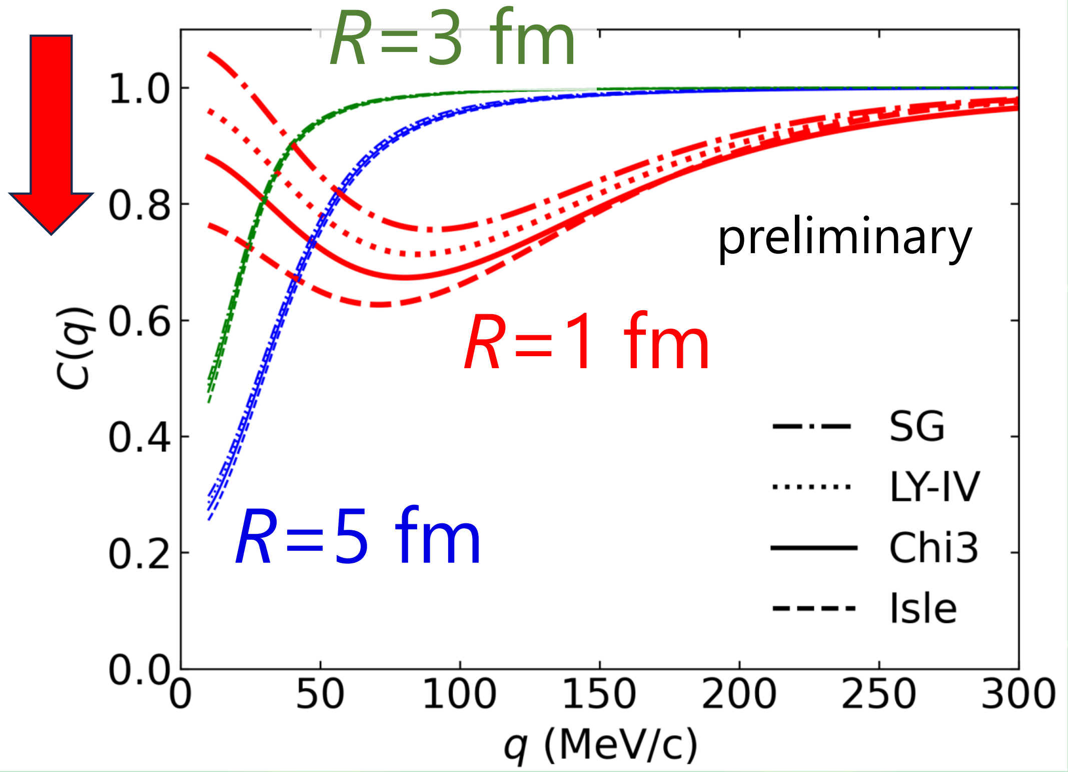
- Both potentials reproduce hypernuclear data from C to Pb
- α density distribution —> $\Lambda\alpha$ potentials

Effect of repulsive core —> correlation function?

$\Lambda\alpha$ correlation functions

Results of correlation functions

A. Jinno, Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation



- Bound state signature (dip at small q)
- Central repulsion **suppresses** correlation for $R = 1$ fm

Summary

- Femtoscopy: novel and useful method to study interactions of exotic hadrons and nuclei
- $K^- p$ correlations
  - precise test for $\Lambda(1405)$ and $\bar{K}N$ interactions

  Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, W. Weise. PRL124, 132501 (2020)
- DD^* and $D\bar{D}^*$ correlations
  - (quasi-)bound nature of T_{cc} and $X(3872)$

  Y. Kamiya, T. Hyodo, A. Ohnishi, EPJA58, 131 (2022)
- $\Lambda\alpha$ correlations
  - hint for repulsive core in $\Lambda\alpha$ interaction

  A. Jinno, Y. Kamiya, T. Hyodo, A. Ohnishi, in preparation