Femtoscopy for exotic hadrons and nuclei

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- Introduction — Femtoscopy primer
- Correlation functions 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)

- Correlation functions for hypernuclei
  - $\Lambda\alpha, \Xi\alpha$ correlations

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

- Summary

In memory of Akira Ohnishi

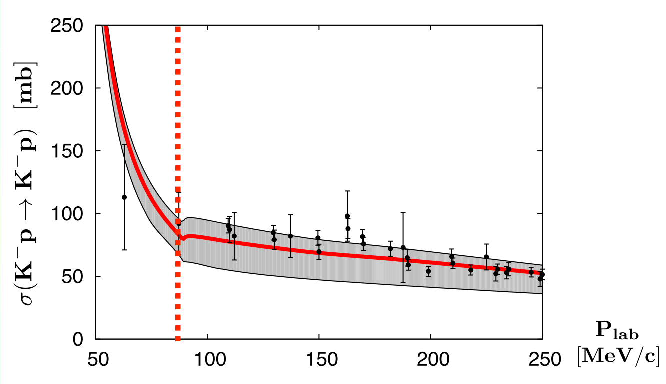
Sep. 13, 2019, after FemTUM19 workshop @ München

Experimental data for hadron interactions

Traditional methods : scattering experiments

- limited channels : $NN, YN, \pi N, KN, \bar{K}N, \cdots$
- limited statistics (low-energy)
- heavy hadron : impossible

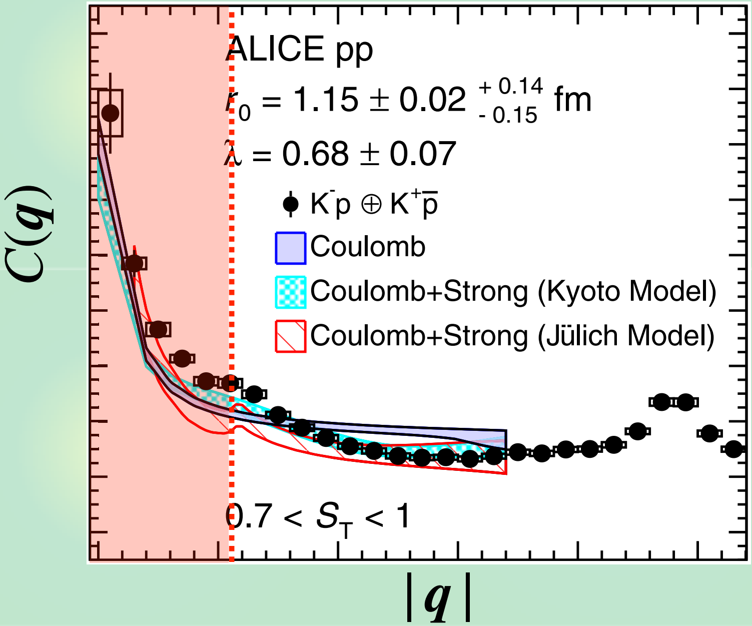
Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011)



Correlation functions

ALICE collaboration, PRL 124, 092301 (2020)

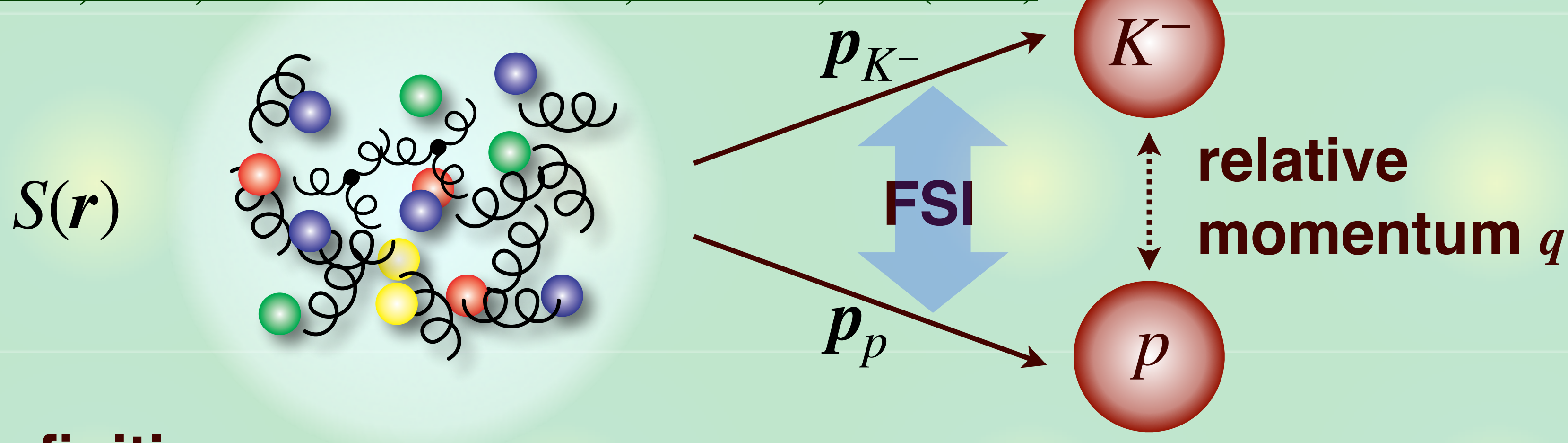
- Excellent **precision** ($\bar{K}^0 n$ cusp)
- Low-energy data **below** $\bar{K}^0 n$
- heavy hadron : **possible!**



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)

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

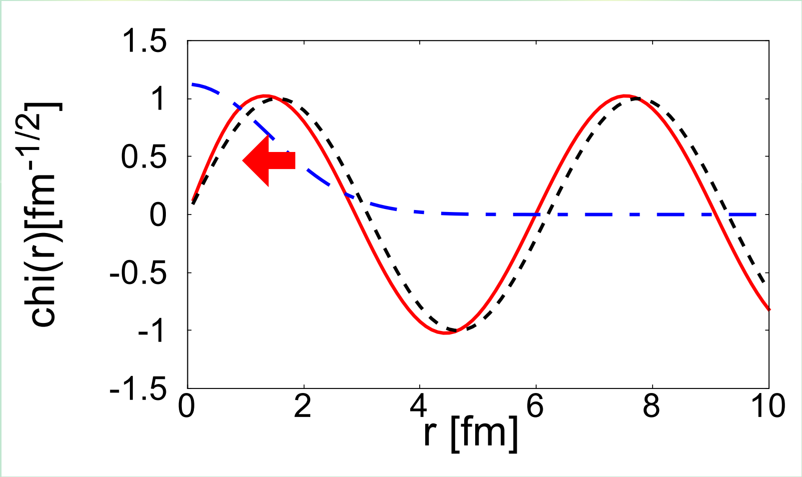
Source function $S(\boldsymbol{r})$ <—> wave function $\Psi_{\boldsymbol{q}}^{(-)}(\boldsymbol{r})$ (FSI)

Wave functions and correlations

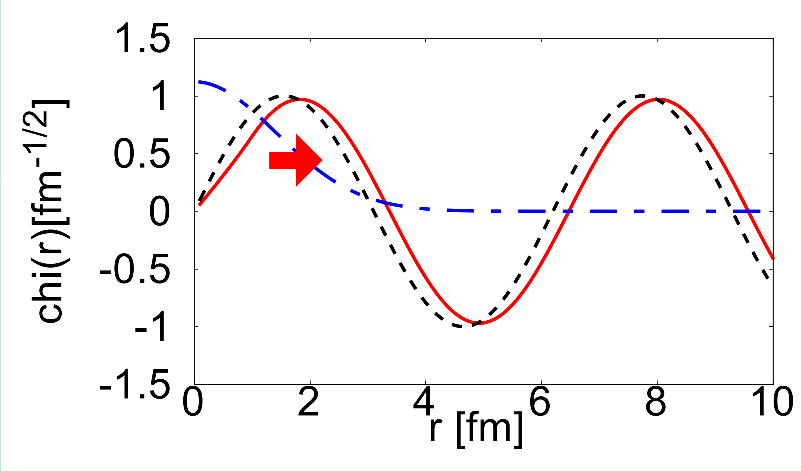
Qualitative behavior

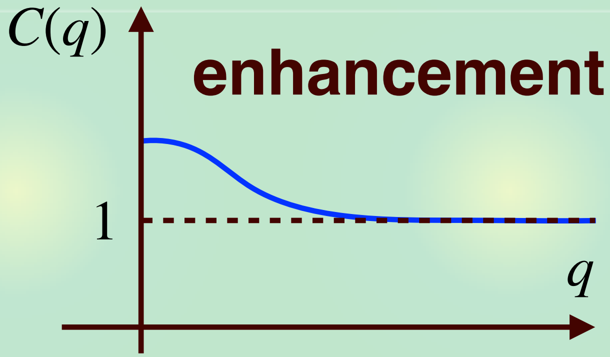
$$C(q) \simeq \int_0^\infty dr\, S(r)\, |\chi_q(r)|^2$$

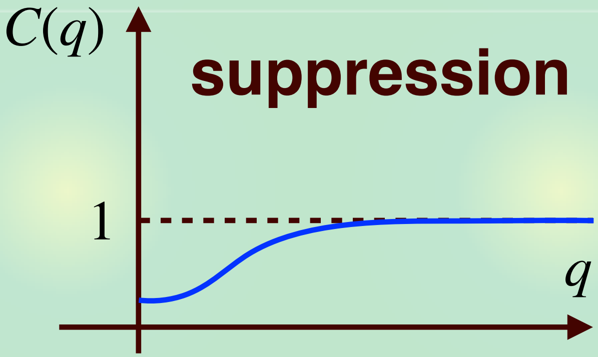
attraction



repulsion





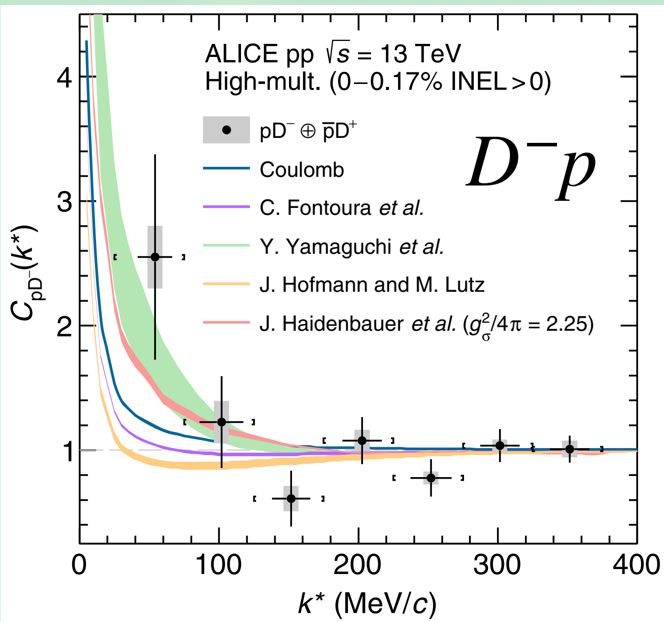


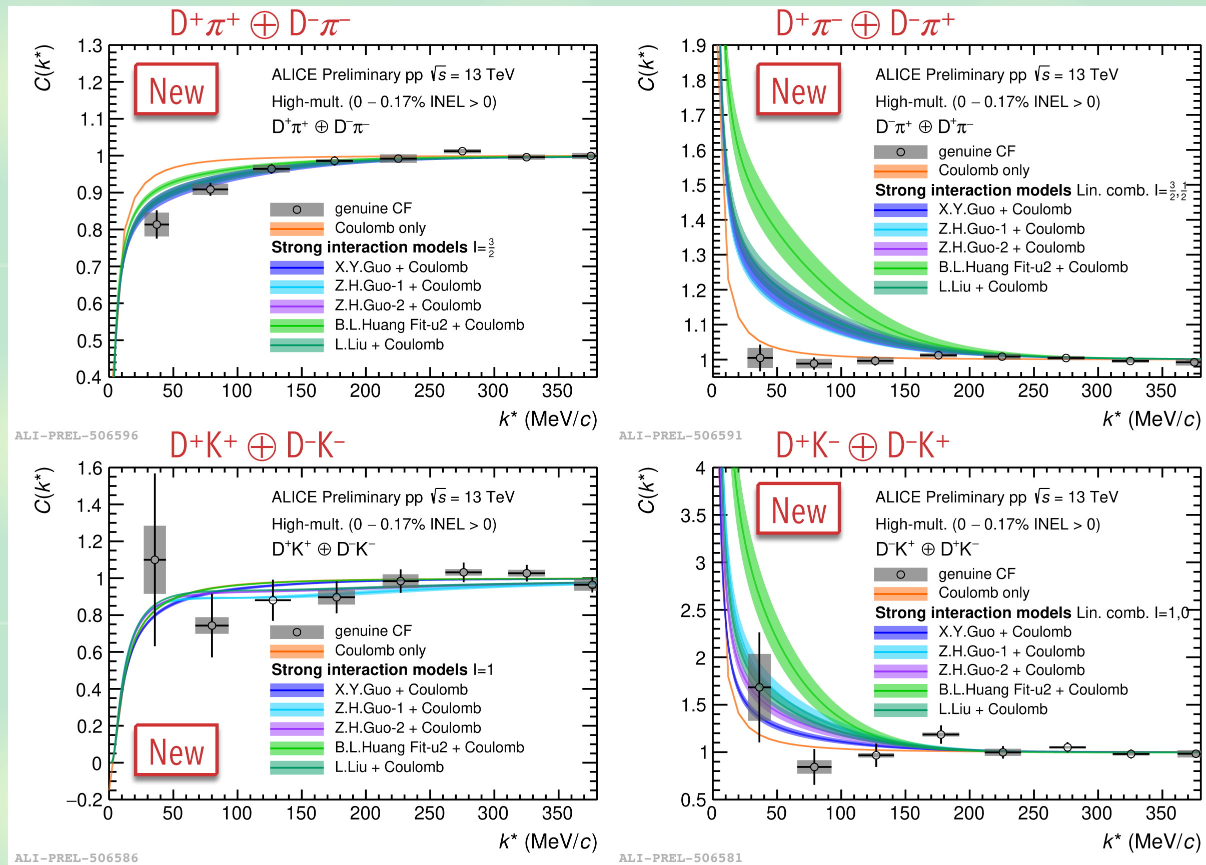
Experimental data in charm sector

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

ALICE collaboration, PRD 106, 052010 (2022);

Talk by F. Grosa @ Quark Matter 2022





One charm meson is possible (still low statistics)

Summary by A. Ohnishi

Scope of Femtoscopic study of HHI

	n	p	K⁻	K⁺	π⁻	π⁺	Λ	Σ	Ξ⁻	Ω⁻	D⁻	D⁺	Ks	φ	+α
n															
p		O	O	O	O	O	O	O	O	O	O	O		O	
K⁻		O	O	O	O	O					O	O	O		
K⁺		O	O	O	O	O					O	O	O		
π⁻		O	O	O	O	O					O	O			
π⁺		O	O	O	O	O					O	O			
Λ		O					O		O						
Σ		O													
Ξ⁻		O					O		O						
Ω⁻		O													
D⁻		O	O	O	O	O									
D⁺		O	O	O	O	O									
Ks			O	O											
φ		O													
+α															

pK^-
Chiral CC pot. (examined)
Bound state (favored)

$p\Xi^-$
Lattice QCD CC pot. (examined)
Bound state (disfavored)

$p\Omega$
Lattice QCD pot. J=2 (examined)
Bound state (favored)

$\Lambda\Lambda$
Scattering pars. (a_0, r_{eff}) (constrained)
Bound state (disfavored)

$p\varphi \to a_0$ (Lattice pot. ?)

$pD^\pm$
Chamed hadron-nucleon interaction
Bound state ?

$K^\pm K^0_s$
Tetraquark component in a_0 meson

$\Lambda\Xi, DK, D\bar{K}, D\pi,$
$\Xi\Xi, pd, \Lambda d, \ldots$

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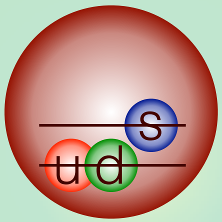
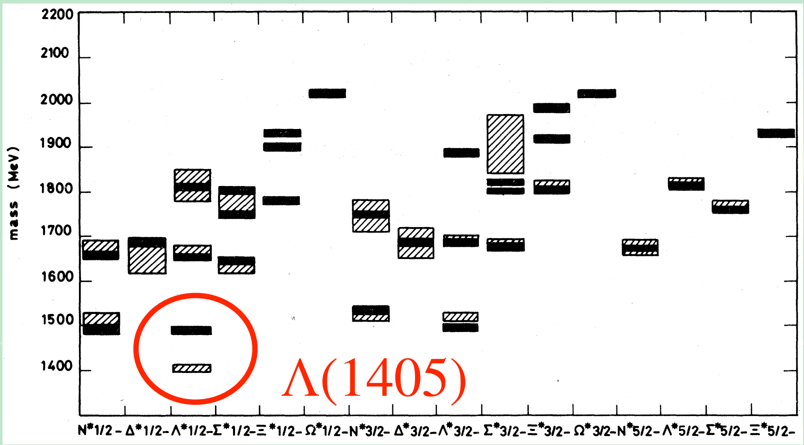
- Summary

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

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

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



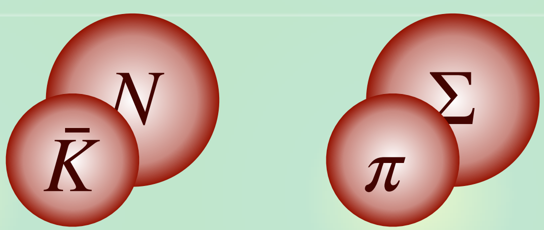


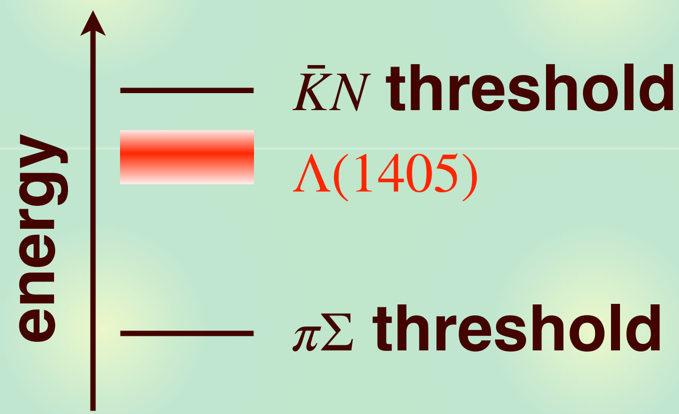
: theory

: experiment

Resonance in coupled-channel scattering

- Coupling to MB states





—> Chiral SU(3) dynamics

Pole positions are determined

2020 update of PDG

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012); ▲
Z.H. Guo, J.A. Oller, PRC87, 035202 (2013); ×
M. Mai, U.G. Meißner, EPJA51, 30 (2015) ■ ○

- Particle Listing section:

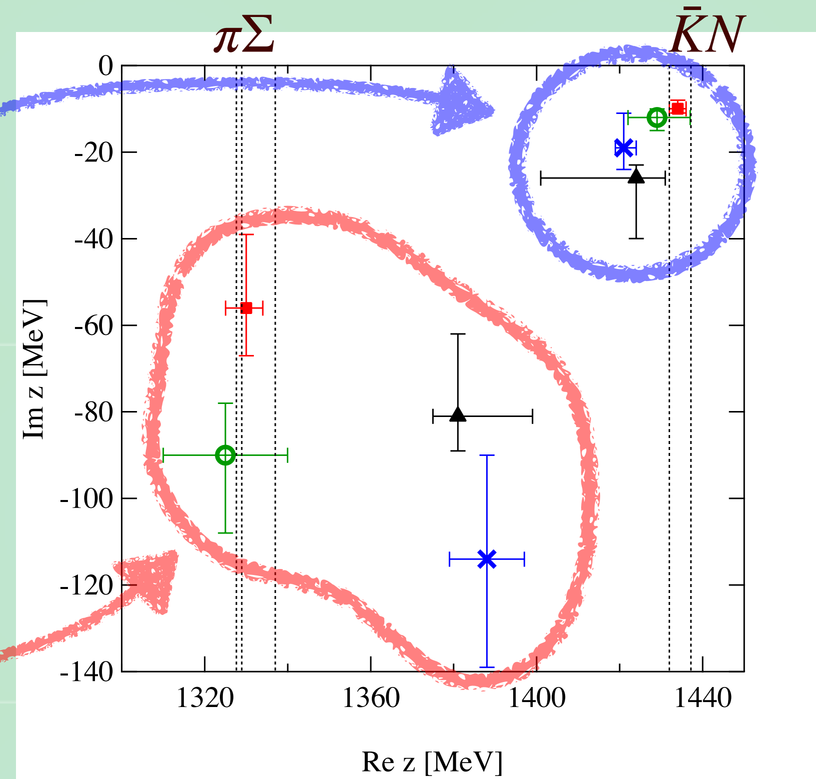
Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1405)\ 1/2^-$ $\quad I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$\Lambda(1380)\ 1/2^-$ $\quad J^P = \frac{1}{2}^-$ Status: ∗∗

new!



T. Hyodo, M. Niiyama, Prog. Part. Nucl. Phys. 120, 103868 (2021)

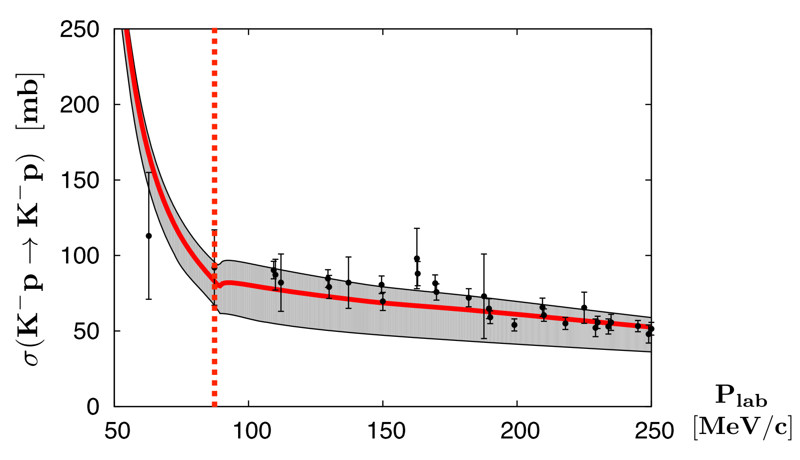
- "$\Lambda(1405)$" is no longer at 1405 MeV but ~ 1420 MeV.
- Lower pole : two-star resonance $\Lambda(1380)$

Experimental data of K^-p correlation

K^-p total cross sections

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

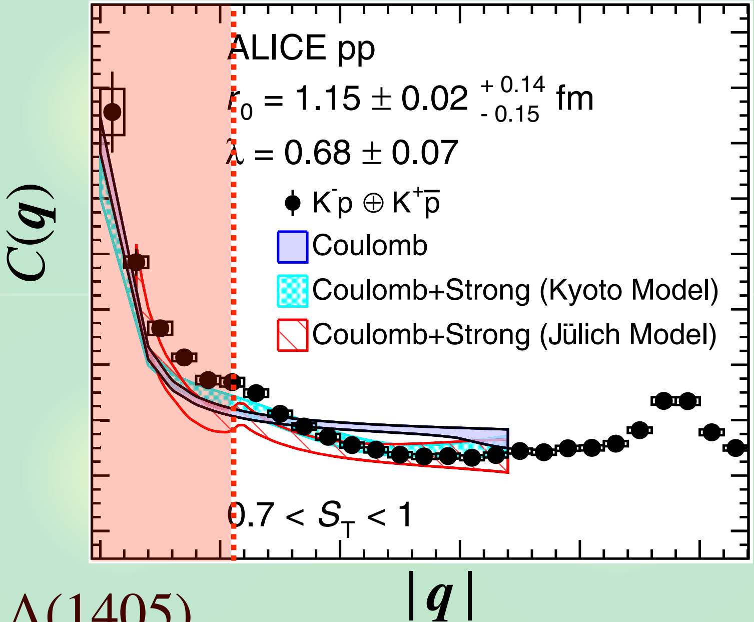
- Old bubble chamber data
- Resolution is not good
- Threshold cusp is not visible



K^-p correlation function

ALICE collaboration, PRL 124, 092301 (2020)

- Excellent precision ($\bar{K}^0 n$ cusp)
- Low-energy data below $\bar{K}^0 n$



—> Important constraint on $\bar{K}N$ and $\Lambda(1405)$

Coupled-channel effects

Schrödinger equation (s-wave)

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

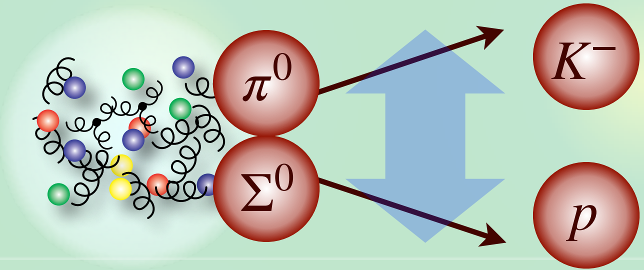
Coulomb threshold energy difference

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 $i \neq K^-p$



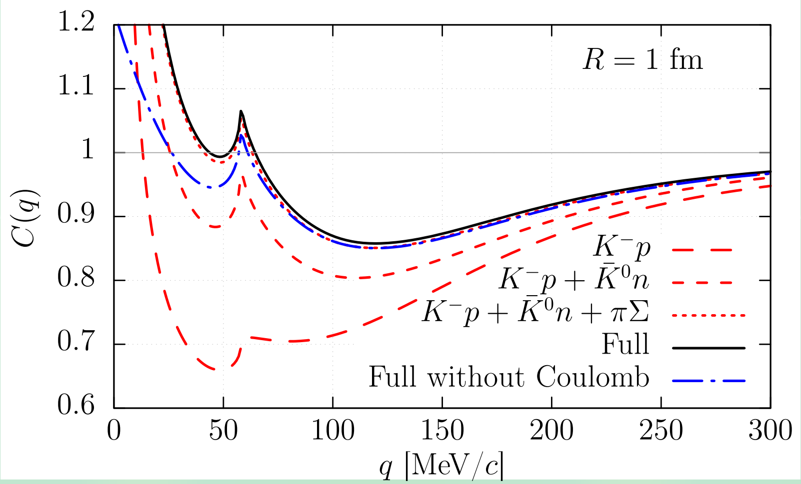
Coupled-channel correlation function

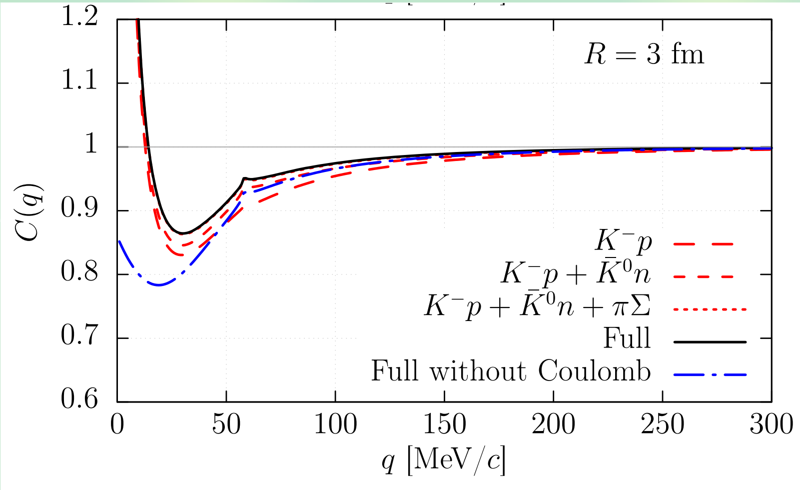
Coupled-channel Koonin-Pratt formula

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 source channel** i **relative to** K^-p





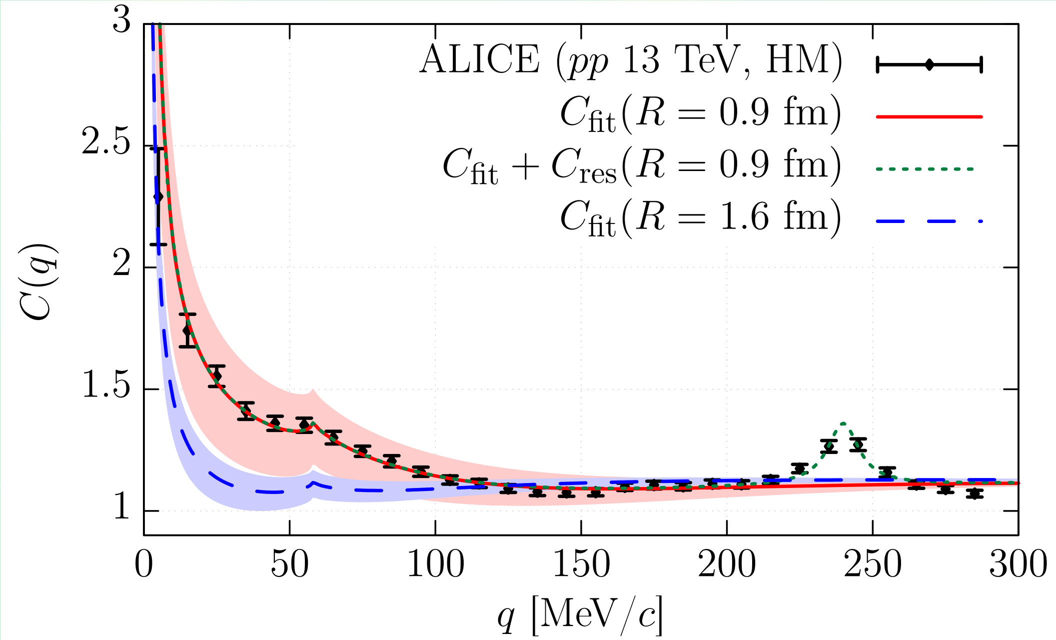
Coupled-channel effect is enhanced for small sources

Correlation from chiral SU(3) dynamics

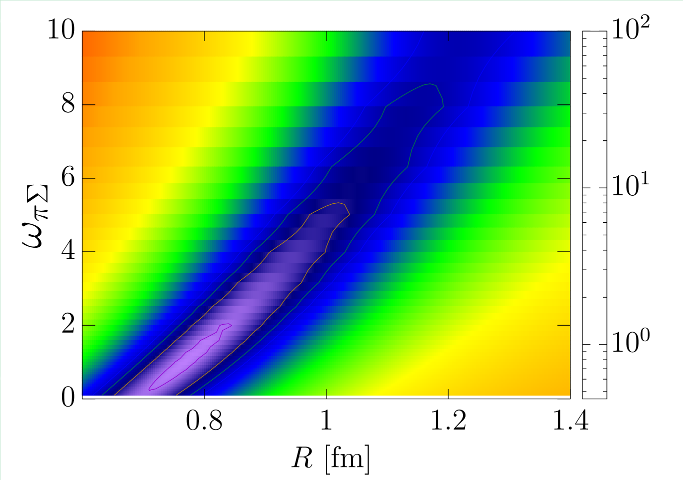
Wave function $\Psi^{(-)}_{i,q}(r)$: coupled-channel $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

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

- Source function $S(r)$: Gaussian, $R \sim 1$ fm in 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)

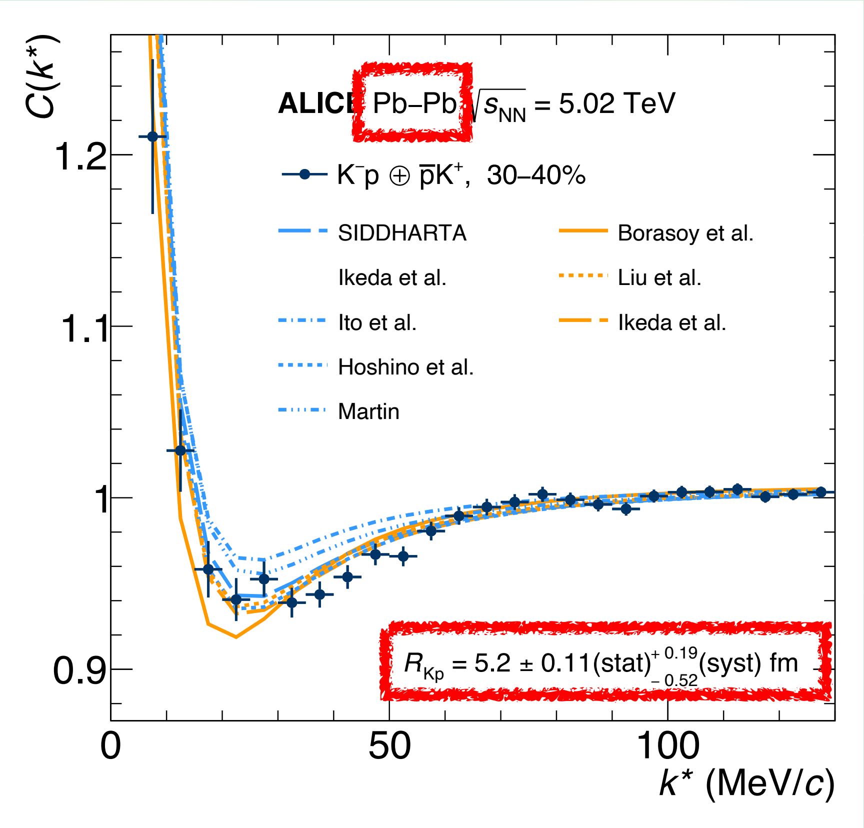
Correlation function by ALICE is well reproduced

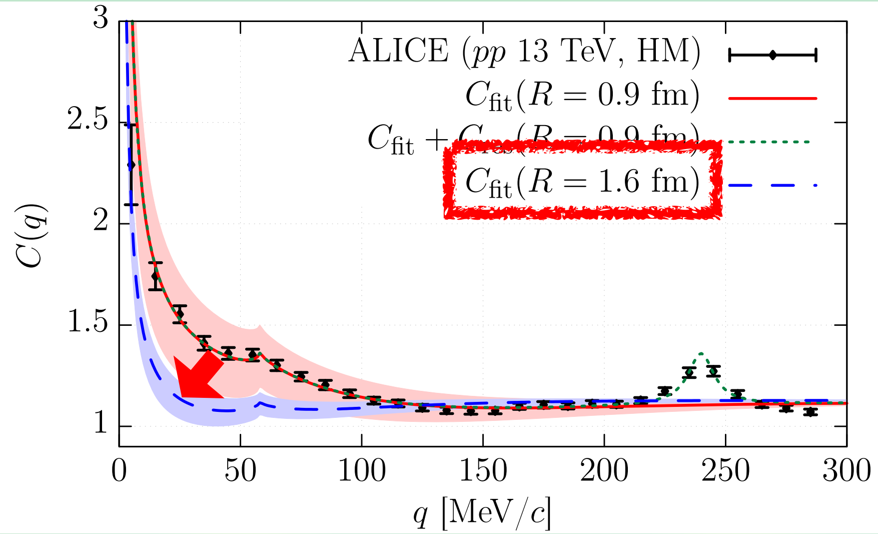
Source size dependence

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





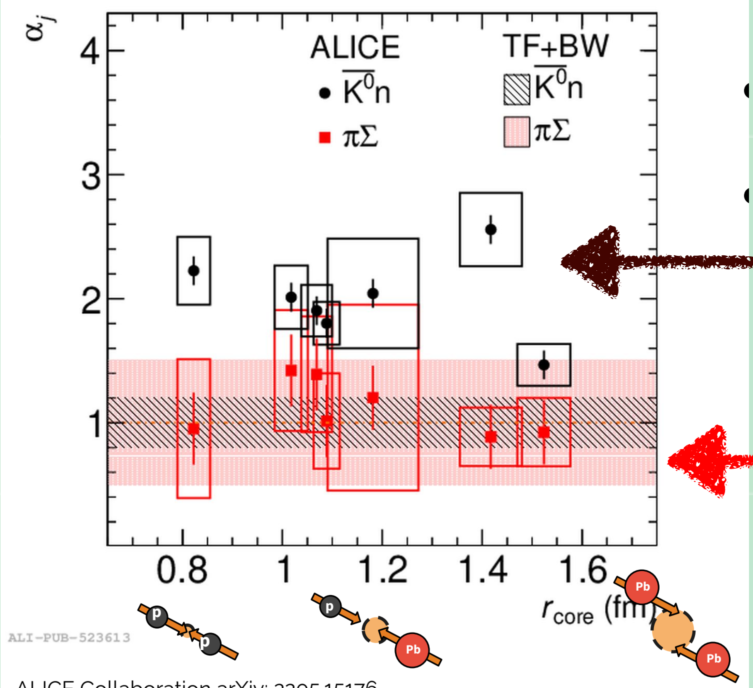
Correlation is suppressed at larger R, as predicted

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

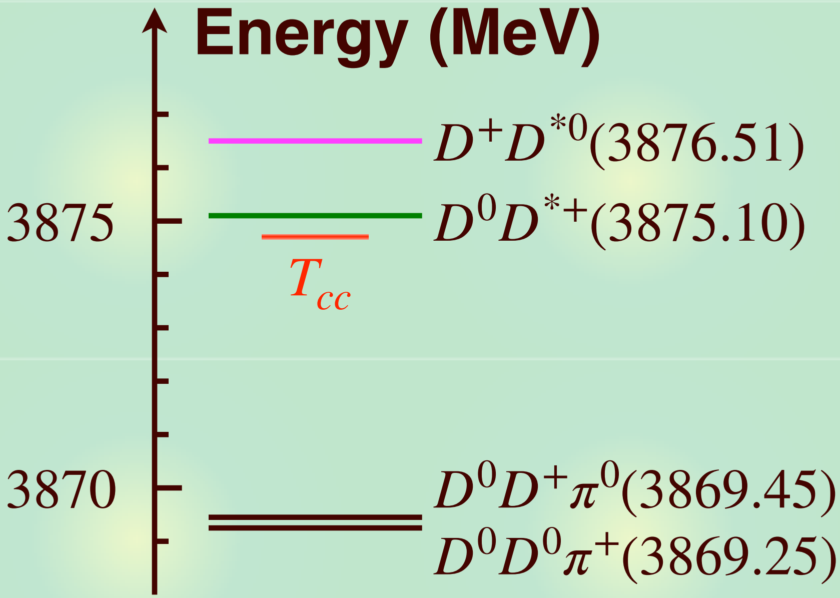
Contents

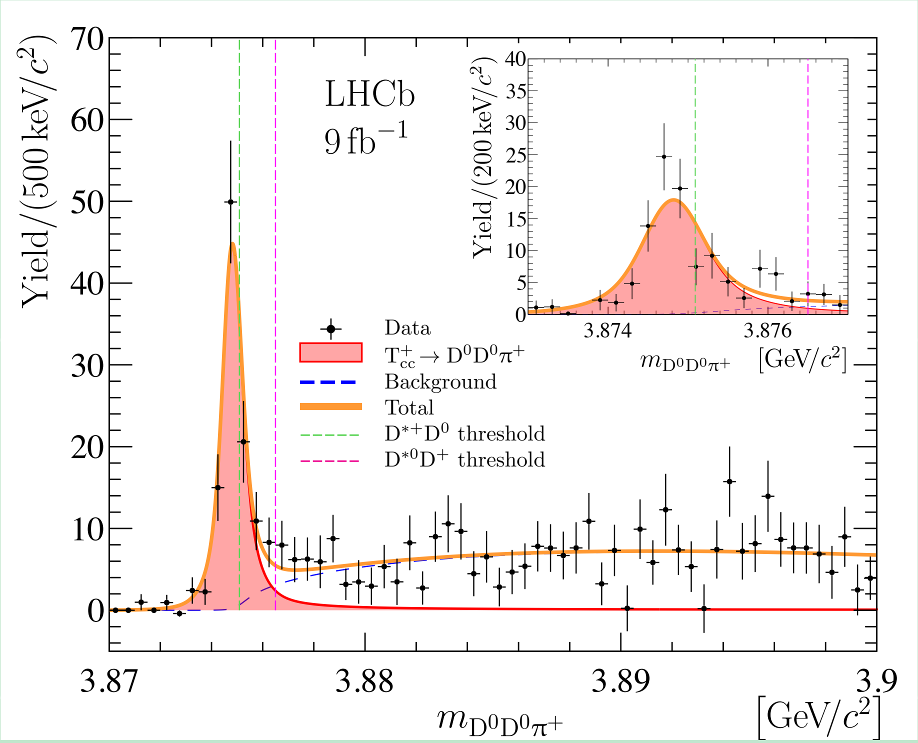
Observation of T_{cc}

T_{cc} observed in $D^0D^0\pi^+$ spectrum

LHCb collaboration, Nature Phys., 18, 751 (2022); Nature Comm., 13, 3351 (2022)

- Signal near DD^* threshold
- Charm $C = +2 : \sim cc\bar{u}\bar{d}$
- Level structure



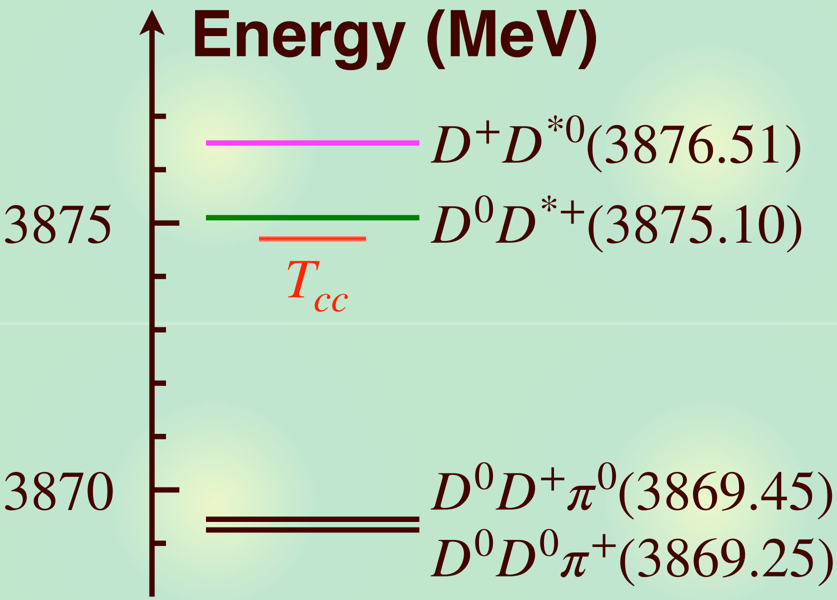


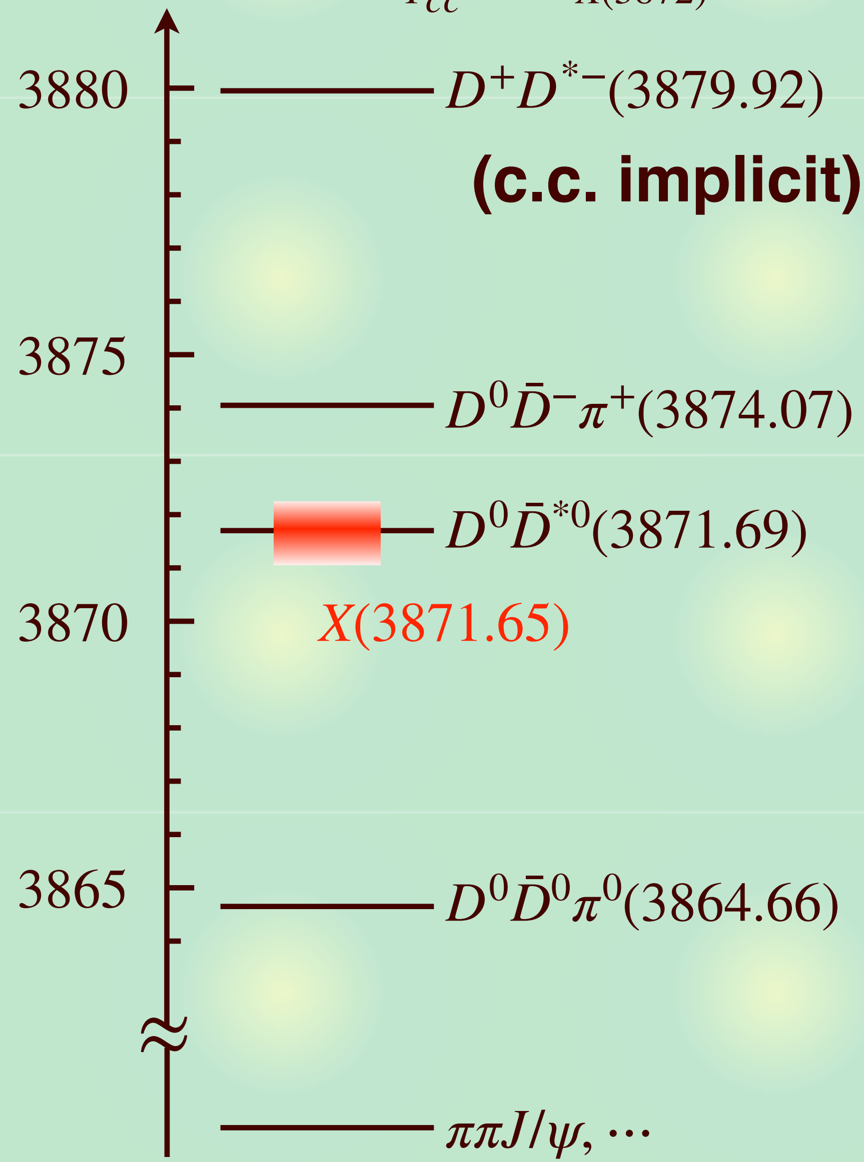
- Very small (**few MeV ~ keV**) energy scale involved

T_{cc} and $X(3872)$

$X(3872)$ **: another near-threshold state with** $M_{T_{cc}} \sim M_{X(3872)}$

- **Masses from PDG Live**





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

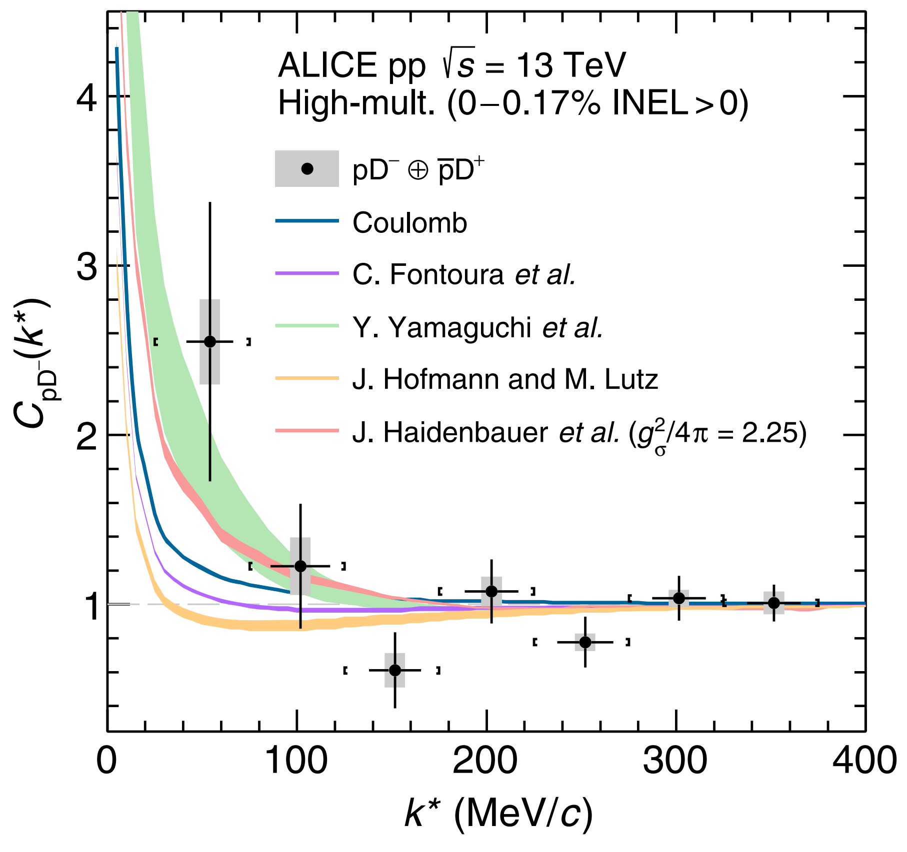
—> Molecule nature?

- $X(3872)$ **has decay channels**

Measurement of $D^- p$ correlation

First measurement of correlation involving charm

ALICE collaboration, PRD 106, 052010 (2022)



Favors bound state with exotic quantum number $D^- p \sim \bar{c}duud$

Correlation function with charm can be measured

$DD^*, D\bar{D}^*$ potentials

Coupled-channel potentials

$$V_{DD^*/D\bar{D}^*} = \frac{1}{2}\begin{pmatrix} V_{I=1} + V_{I=0} & V_{I=1} - V_{I=0} \\ V_{I=1} - V_{I=0} & V_{I=1} + V_{I=0} + V_c \end{pmatrix} \begin{matrix} D^0D^{*+}/\{D^0\bar{D}^{*0}\} \\ D^+D^{*0}/\{D^+D^{*-}\} \end{matrix}$$

↑ **Coulomb for** $\{D^+D^{*-}\}$

- $I = 0$ **: one-range gaussian potentials,** $I = 1$ **neglected**

$$V_{I=0} = V_0 \exp\{-m_\pi^2 r^2\}, \quad V_{I=1} = 0$$

↑ **range by** π **exchange**

$V_0 \in \mathbb{C}$ **<— scattering lengths (molecule picture)**

- T_{cc} **:** $a_0^{D^0D^{*+}} = -7.16 + i1.85$ fm **(LHCb analysis)**

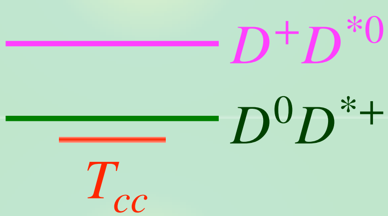
  LHCb collaboration, Nature Comm., 13, 3351 (2022)

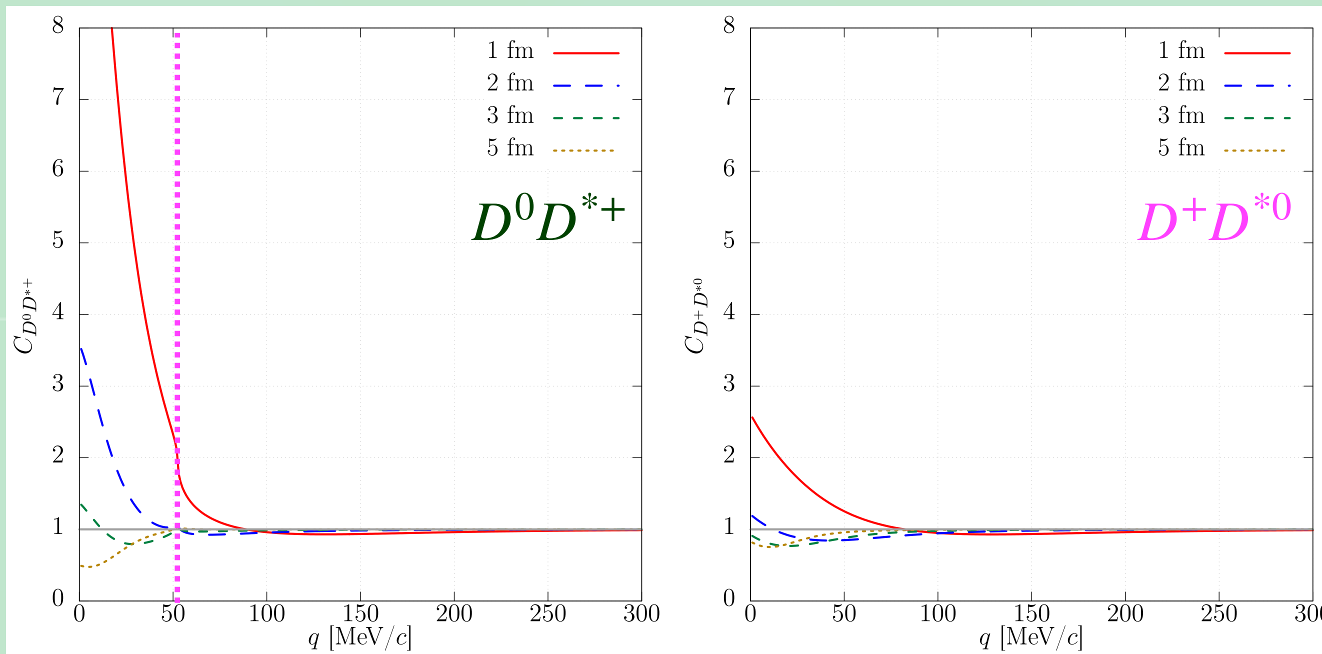
- $X(3872)$ **:** $a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95$ fm **(**$a_0 = -i/\sqrt{2\mu E_h}$ **with PDG** E_h**)**

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

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

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



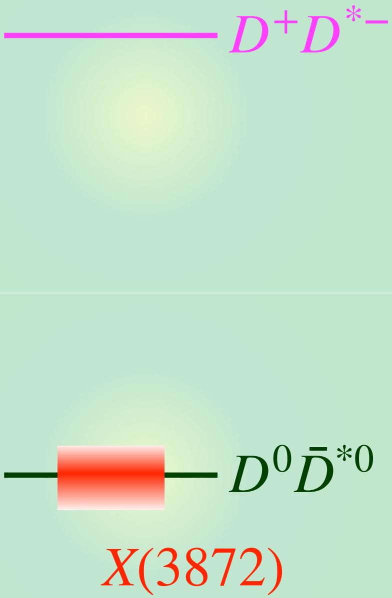


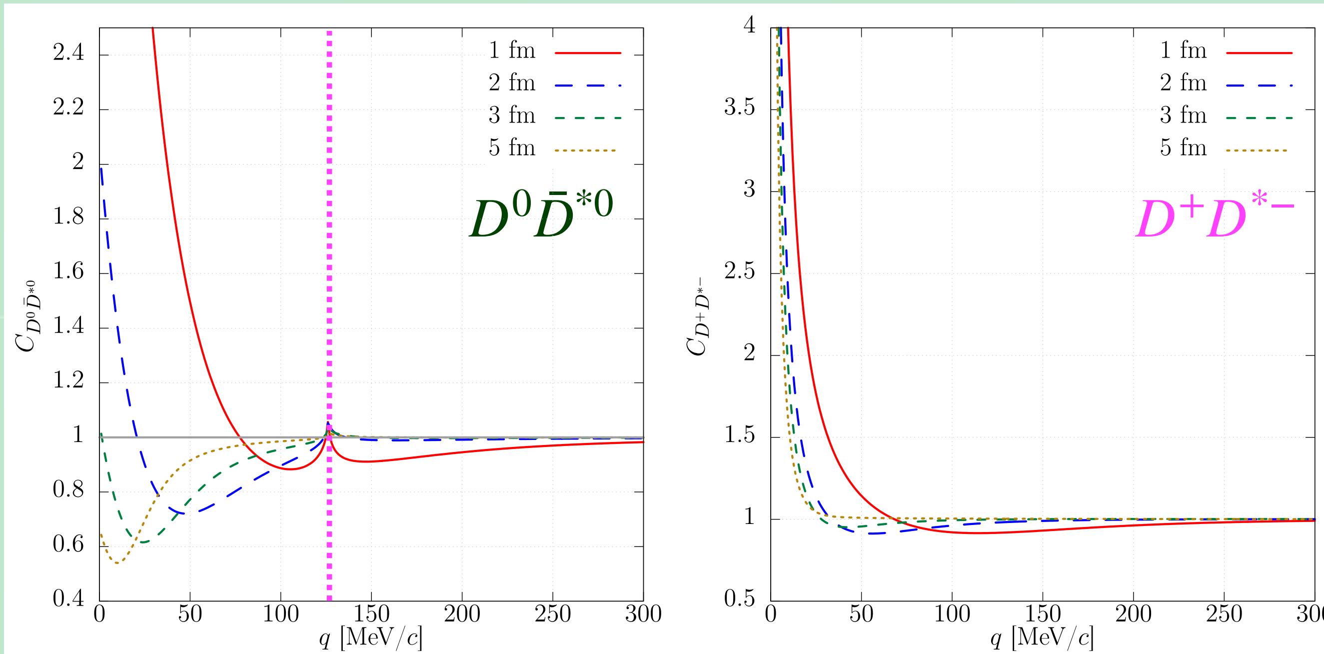
- Bound state feature (source size dep.) in both channels
- Strong signal in D^0D^{*+}, weaker one in D^+D^{*0}
- D^+D^{*0} cusp in D^0D^{*+} ($q \sim 52$ MeV) is not very prominent

$D\bar{D}^* \sim X(3872)$ 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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  - DD^* and $D\bar{D}^*$ correlations for T_{cc} and $X(3872)$

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

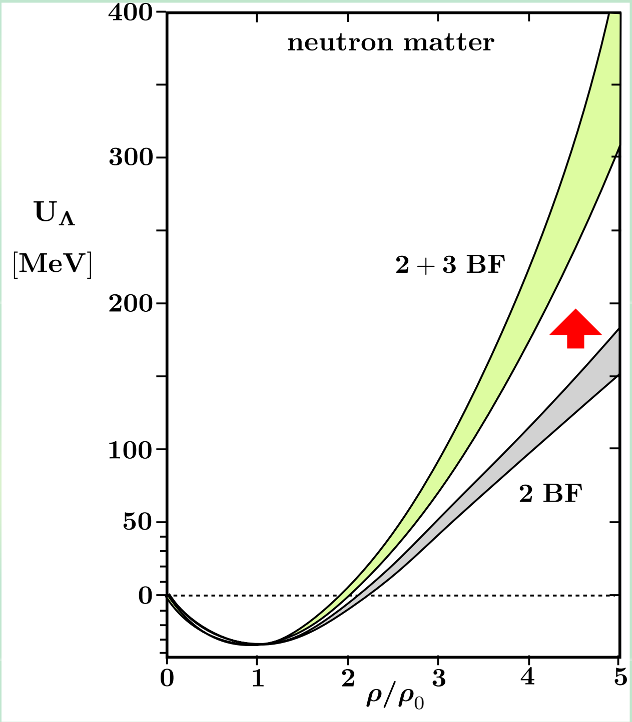
- Summary

Motivation

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 —> high central density $\gtrsim 2\rho_0$

Possible three-body force in $\Lambda\alpha$ correlation function

$\Lambda\alpha$ potentials

Skyrme-Hartree Fock potentials for Λ hypernuclei

- LY4 : empirical potential

  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 reproduce hypernuclear data from C to Pb

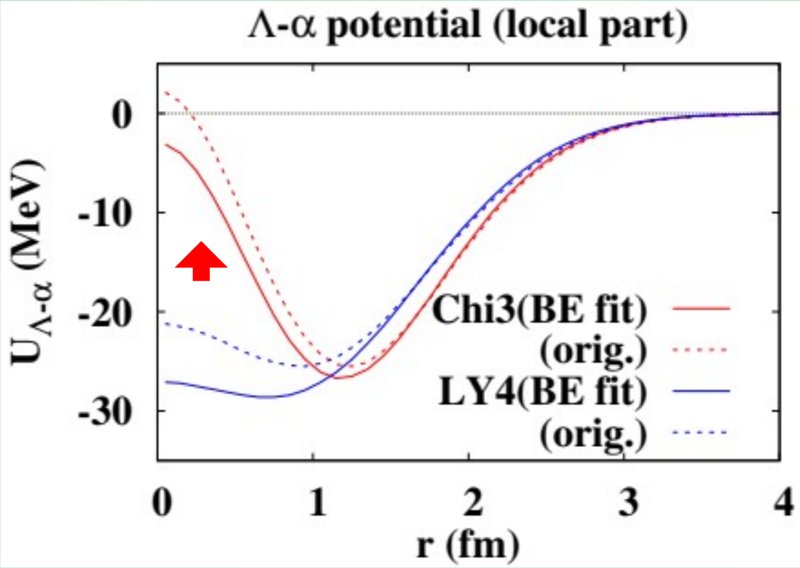
$\Lambda\alpha$ potentials

- overestimate ${}^{5}_{\Lambda}$He binding energy

  —> adjustment of parameters

- LY4 : Woods-Saxon like

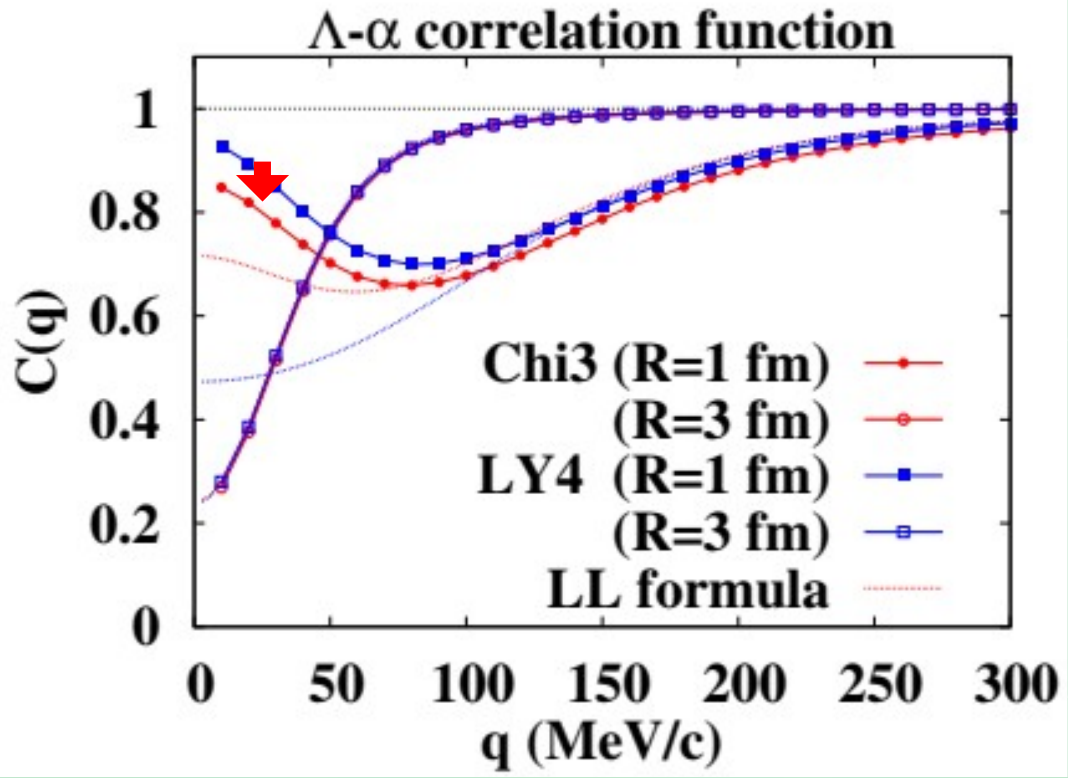
- Chi3 : central repulsion



$\Lambda\alpha$ correlation functions

Results of correlation function

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



- Bound state signature (dip at small q)
- Effect of ΛNN force is not visible for $R = 3\ \mathrm{fm}$, but gives **slightly stronger** correlation for $R = 1\ \mathrm{fm}$

Summary

- Correlation functions are useful 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)
- $\Lambda\alpha, \Xi\alpha$ correlations
  - opportunity for hypernuclear physics

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