Femtoscopic study of hadron interactions including charm

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J-PARC Hadron WS,
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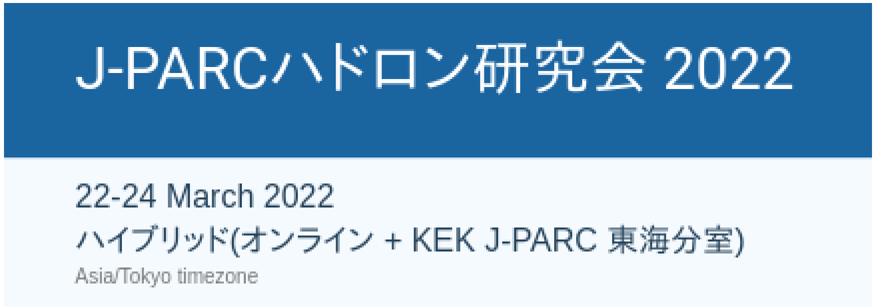

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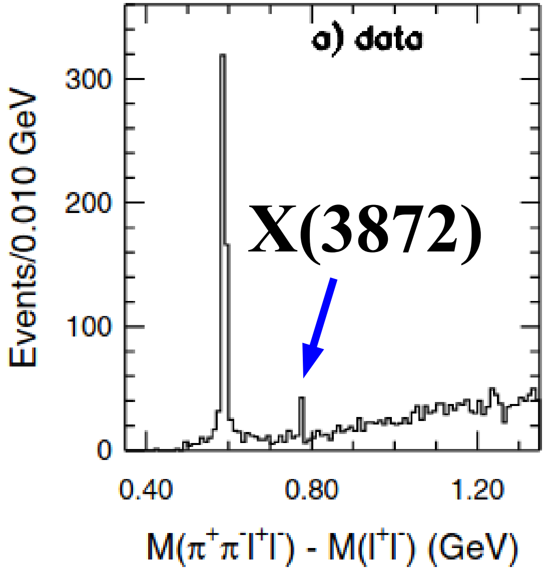
Asia/Tokyo timezone

- Introduction
- Charmed hadron interaction (1) – D^- p
- Charmed hadron interaction (2) – DD^* and $\{D\bar{D}^*\}$
- Summary

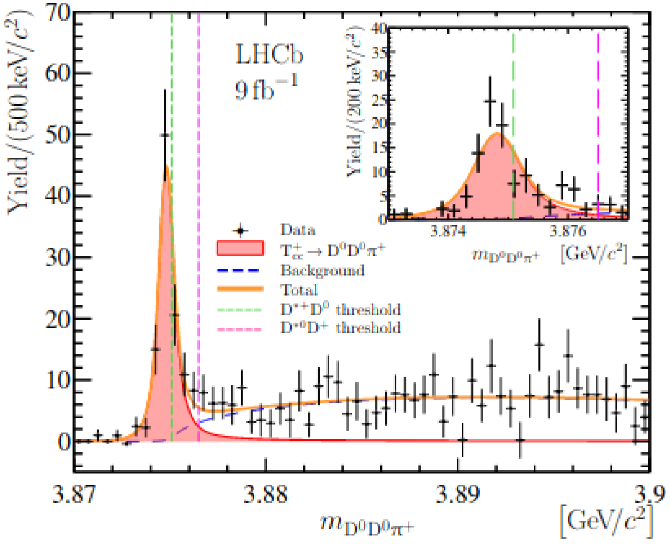
Y. Kamiya, T. Hyodo, A. Ohnishi, in prep;
S. Acharya et al. [ALICE], 2201.05352.

Exotic Hadrons including $c\bar{c}\,/\,cc\,/\,\bar{c}\bar{c}$

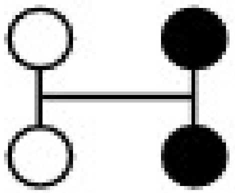
- **Main play ground of exotic hadron physics**
  - **X(3872)** ***Belle ('03)***
  - **Many X,Y,Z states**
    Belle, CDF, BaBar, LHCb, CMS, BESIII, ...
  - **Charmed pentaquark Pc** ***LHCb ('15, '19)***
  - **Doubly charmed tetraquark state Tcc**
    LHCb ('21)
- **Structure of exotic hadrons**
  - **Compact multiquark states**
    → "good" diquark gains energy
  - **Hadronic molecules**
    → Many exotic states around thresholds
  - **Their mixture...**



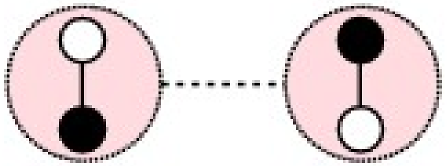
S.K.Choi+[Belle], PRL91, 262001 ('03)



R. Aaji+ [LHCb], 2109.01038, 2109.01056



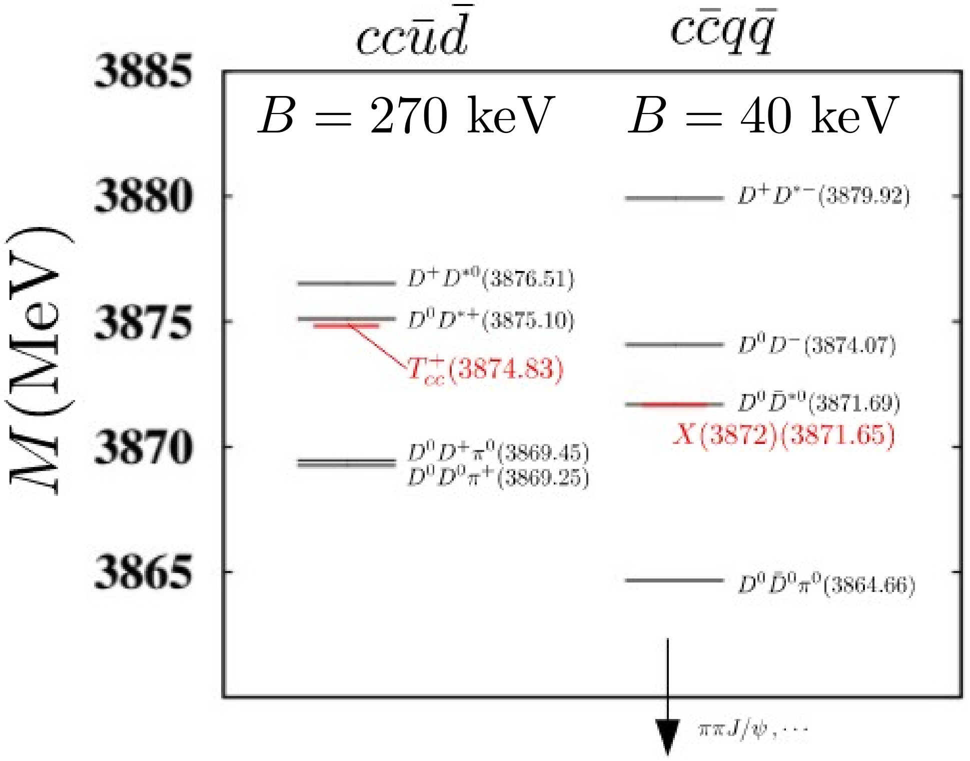
Tetraquarks



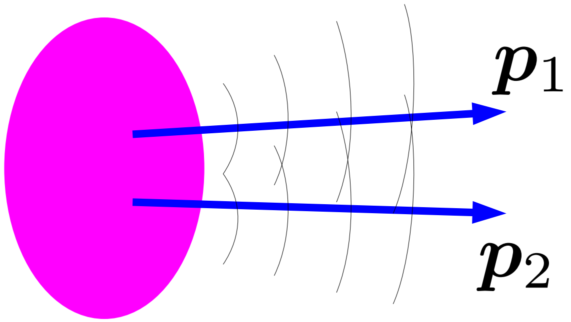
Hadronic Molecules

Hadronic Molecules

- **Deuteron (np), $\Lambda(1405)(\bar{K}N)$, ….**
- **Hadronic Molecule Conditions**
  - **Appears around the threshold (Threshold (Ikeda) rule) → Tcc & X(3872)**
  - **Have large size** $R \simeq 1/\sqrt{2\mu B}$
  - **Described by the *hh* interaction**
- **Tcc**
  - **Compact Tetraquark ?** ***S. Zouzou+('86), ZPC30,457.***
- **X(3872)**
  - **Molecule ? Radiative decay** ***Dong+ (0802.3610)***
  - $c\bar{c}$ **component ? production cross section** ***Bignamini+ (0906.0882)***
  - **Mixture from lattice QCD.** ***Padmanath+ (1503.03257)***
  - **Molecule ! Large yield in Pb+Pb** ***Sirunyan+ [CMS] (2102.13048)*** **c.f. Δr/Δp is similar in HIC and molecule.** ***ExHIC ('11,'11,'17)***



Femtoscopic study of hadron-hadron interaction



- **How can we study interactions between short-lived particles ? → Femtoscopy !**
- **Correlation function (CF)**
  - **Koonin-Pratt formula**

    Koonin('77), Pratt+('86), Lednicky+('82)

source fn. relative w.f.

$$C(\boldsymbol{p}_1,\boldsymbol{p}_2)=\frac{N_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1)N_2(\boldsymbol{p}_2)} \simeq \int d\boldsymbol{r}\,\underline{S_{12}(\boldsymbol{r})}\,\underline{|\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2}$$

- **Source size from quantum stat. + CF (Femtoscopy)**

  Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)
- **Hadron-hadron interaction from source size + CF**
  - **CF of non-identical pair from Gaussian source**

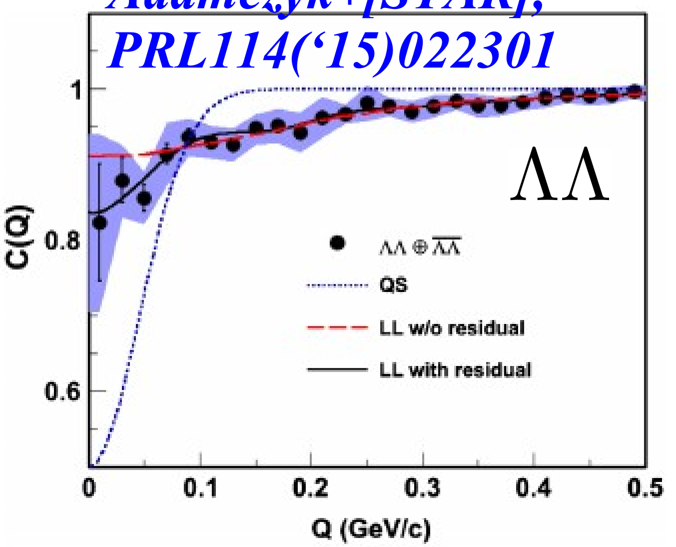
    R. Lednicky, V. L. Lyuboshits ('82); K. Morita, T. Furumoto, AO ('15)

$$C(\boldsymbol{q}) = 1 + \int d\boldsymbol{r}\, S(r)\left\{|\varphi_0(r)|^2 - |j_0(qr)|^2\right\} \quad (\varphi_0 = \text{s-wave w.f.})$$

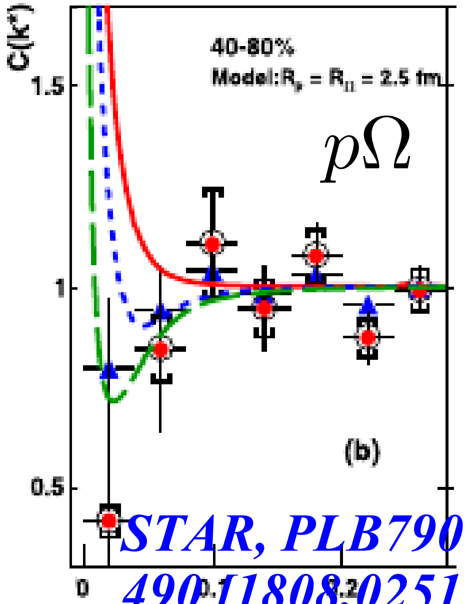
CF shows how much $|\varphi|^2$ is enhanced → V_{hh} effects !

Measured Correlation Functions (examples)

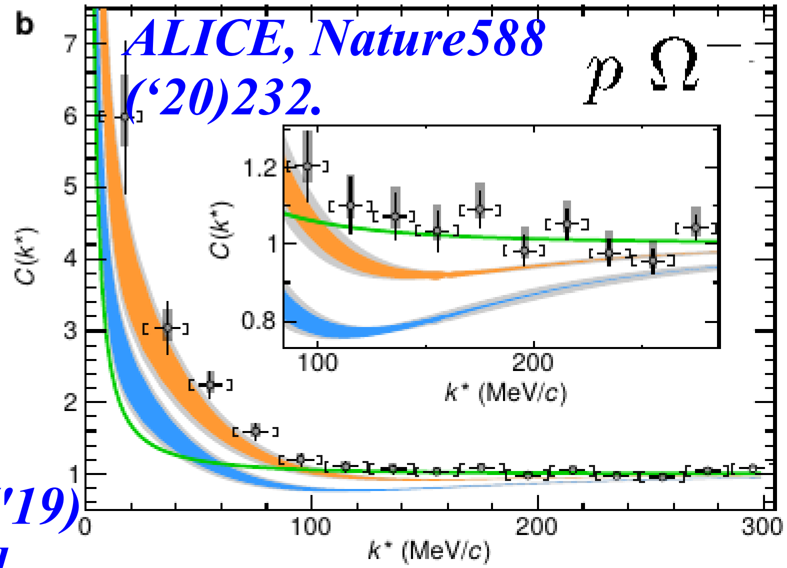
Adamczyk+[STAR], PRL114('15)022301



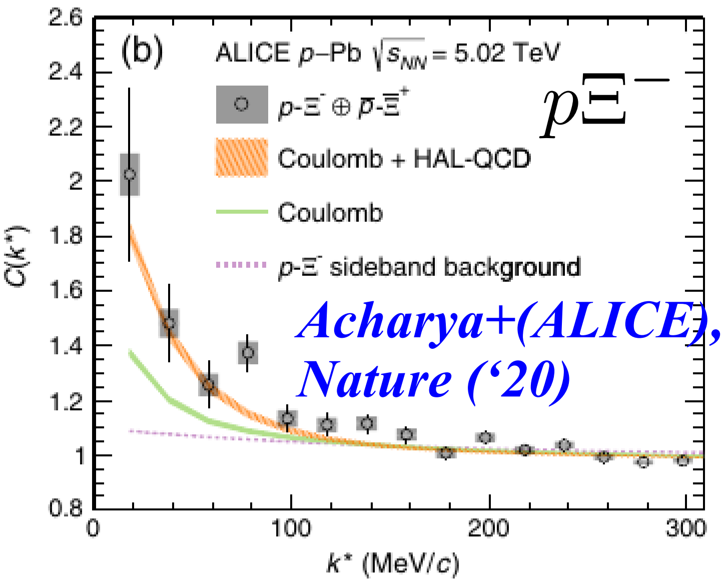
STAR, PLB790 ('19) 490 [1808.02511].



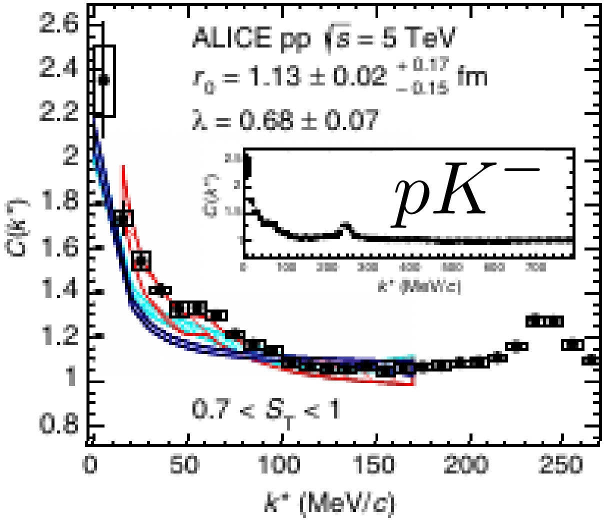
ALICE, Nature588 ('20)232.



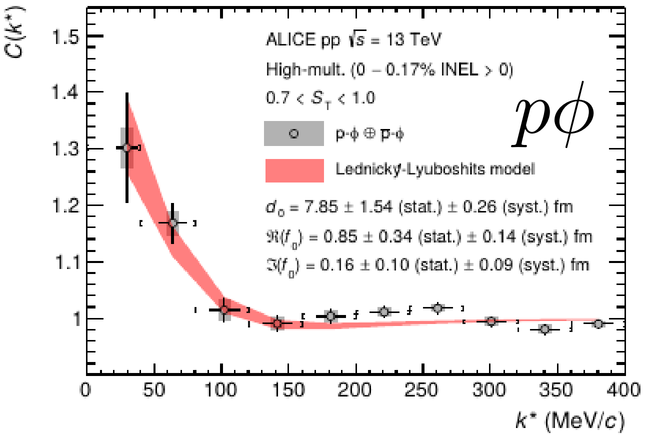
Acharya+(ALICE), Nature ('20)



S. Acharya+[ALICE], PRL124('20)092301



ALICE, 2105.05578



So far, so good.

Strange hadron (s-wave) interactions seem to be constrained from femtoscopy.

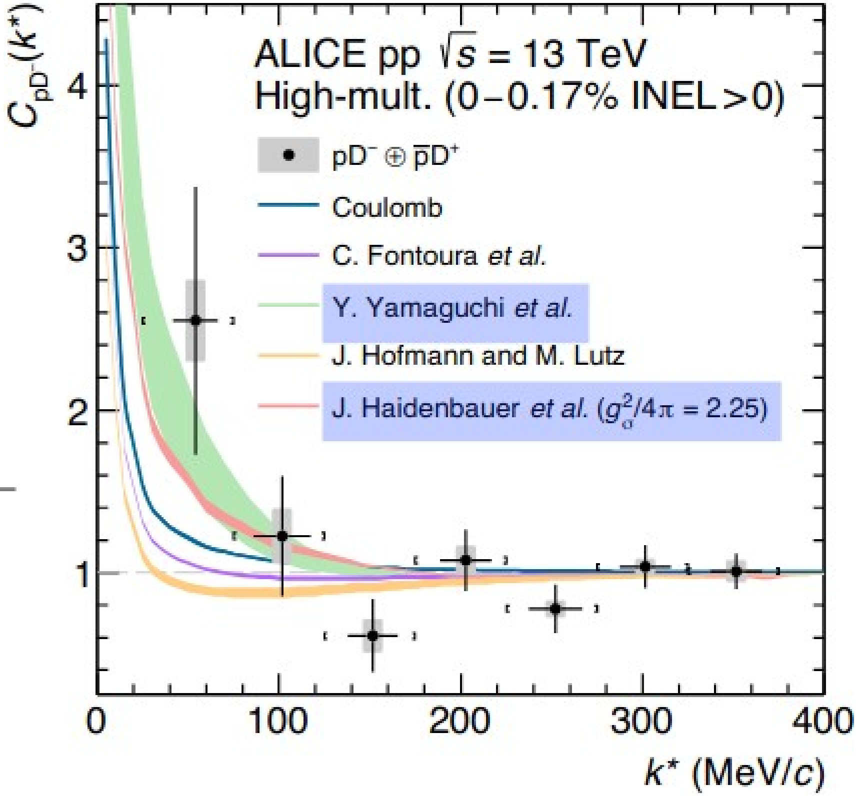
Next, we should proceed to charm hadron interactions !

Femtoscopic study of charm hadron interactions (1)

- D^- p correlation function -

Femtoscopic study of charmed hadron int. (1)

- **“First ~~study~~ measurement of the two-body scattering involving charm hadrons”, *Acharya+[ALICE] (2201.05352)***
  - **D^- p corr. func. is measured.**
  - **Enhanced CF from Coulomb.**
  - **One range gaussian potential with strength fitted to the I=0 scattering length of the model → attractive potentials are favored**



Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
Coulomb			(1.1–1.5)
Haidenbauer et al. [21]			
$-\ g^2_\sigma/4\pi = 1$	0.14	−0.28	(1.2–1.5)
$-\ g^2_\sigma/4\pi = 2.25$	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [22]	−0.16	−0.26	(1.3–1.6)
Yamaguchi et al. [24]	−4.38	−0.07	(0.6–1.1)
Fontoura et al. [23]	0.16	−0.25	(1.1–1.5)

[21] Haidenbauer+(0704.3668) (weakly / mildly attractive (I=0))
[22] Hofmann, Lutz (hep-ph/0507071) (repulsive (I=0))
[23] Fontoura+(1208.4058) (weakly attractive (I=0))
[24] Yamaguchi, Ohkoda, Yasui, Hosaka (1105.0734) (att., w/ bound state (I=0))

To be bound or not to be bound

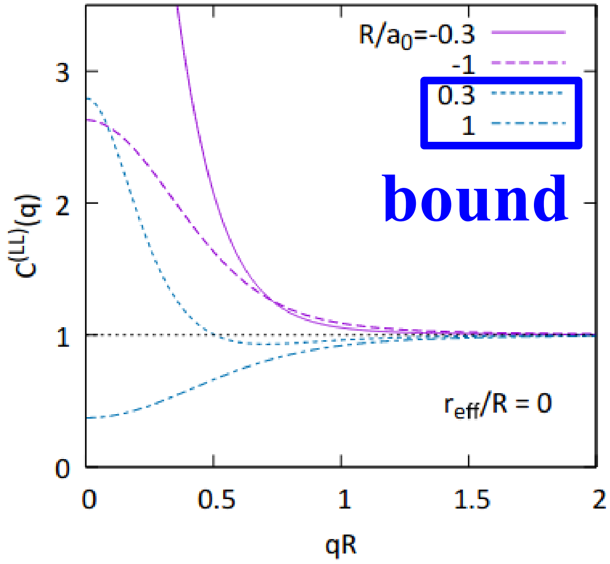
- **When there is a bound state, CF shows interesting dependence on the source size and relative momentum.**
- **D^-p corr. func. shows the behavior with a bound state, and the best fit parameter set (R, a_0) is in the bound region. (If bound, it is the first weakly decaying pentaquark state.)**

$$k\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_\mathrm{eff}k^2 + \mathcal{O}(k^3)$$

(Nuclear and atomic phys. convention.)

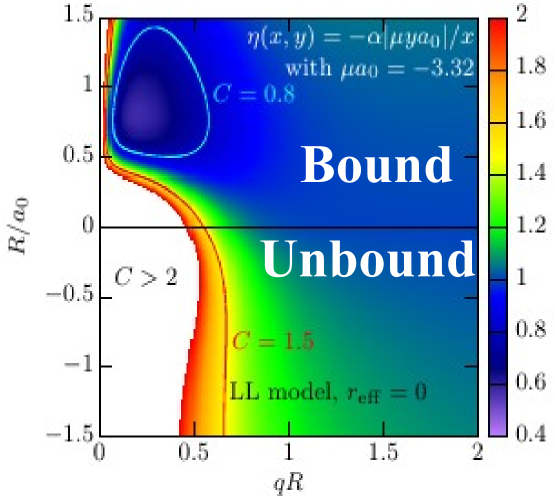
$$k\cot\delta = +\frac{1}{f_0} + \frac{1}{2}r_\mathrm{eff}k^2 + \mathcal{O}(k^3)$$

(High-E. phys. convention.)

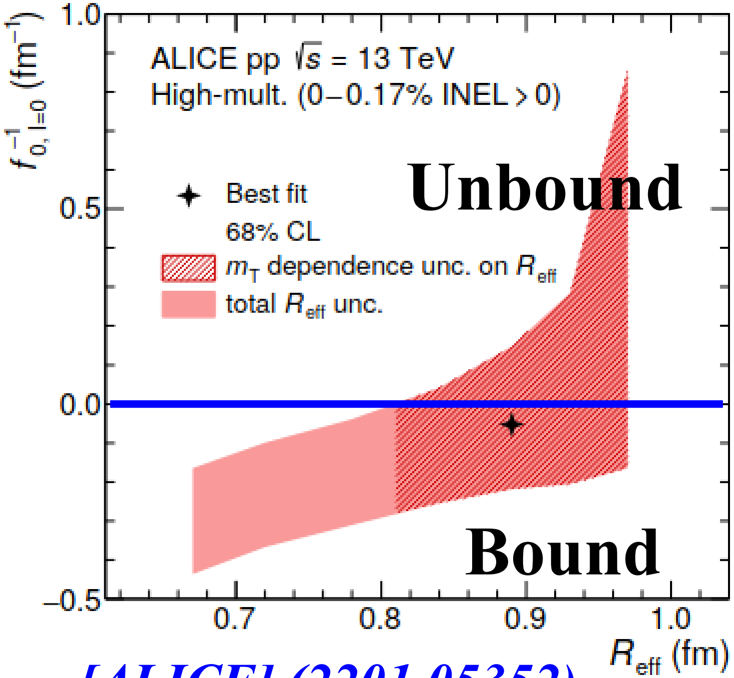


Morita+(1908.05414)

With Coulomb



Kamiya+(2108.09644)



[ALICE] (2201.05352)

Femtoscopic study of charm hadron interactions (2)

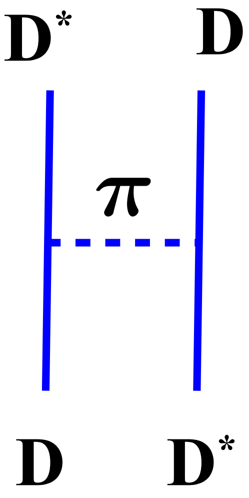
- DD^* and $D\bar{D}^*$ correlation func. -

Femtoscopic study of charmed hadron int. (2)

- DD^* and $D\bar{D}^*$ correlation functions. *Kamiya, Hyodo, AO, in prep.*
  - Related with Tcc and X(3872)
  - DD^* and $D\bar{D}^*$ interactions

$$V = \frac{1}{2}\begin{pmatrix} V_{I=0}+V_{I=1} & V_{I=0}-V_{I=1} \\ V_{I=0}-V_{I=1} & V_{I=0}+V_{I=1} \end{pmatrix}$$

  - I=0: One range gaussian, strength fitted to the mass
  - I=1: ignored
  - Range = one pion exchange *Yasui, Sudoh (0906.1452)*
  - Strength is fitted to the pole mass.



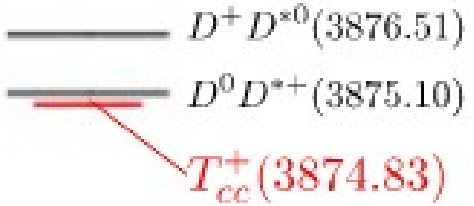
$\{D^0\bar{D}^{*0}\} = (D^0\bar{D}^{*0} + \bar{D}^0 D^{*0})/\sqrt{2}\ (C=+1)$

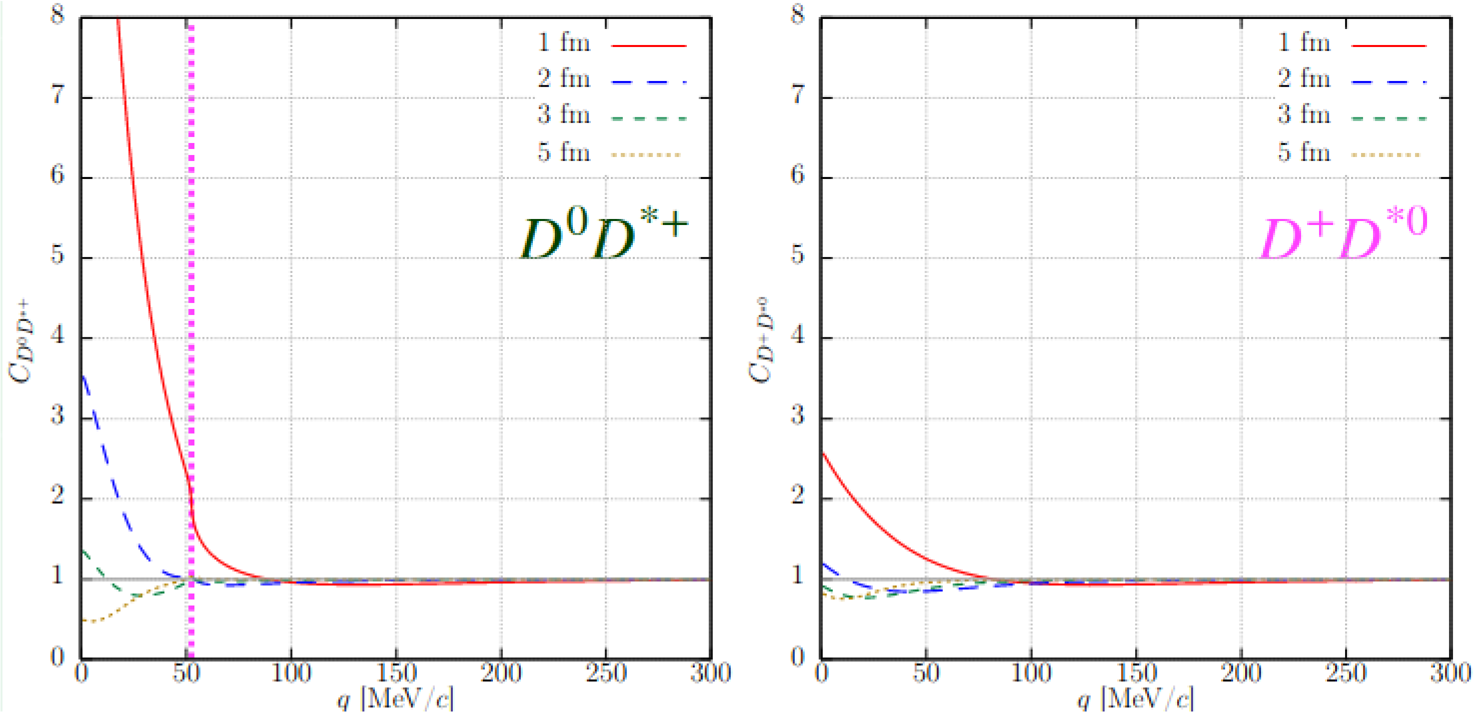
$\{D^+D^{*-}\} = (D^+D^{*-} + D^-D^{*+})/\sqrt{2}\ (C=+1)$

DD^*	V_0 [MeV]	$a_0^{D^0D^{*+}}$ [fm]	$a_0^{D^+D^{*0}}$ [fm]
	$-36.569 - i1.243$	$-7.16 + i1.85$	$-1.75 + i1.82$
$\{D\bar{D}^*\}$	V_0 [MeV]	$a_0^{\{D^0\bar{D}^{*0}\}}$ [fm]	$a_0^{\{D^+D^{*-}\}}$ [fm]
	$-43.265 - i6.091$	$-4.23 + i3.95$	$-0.41 + i1.47$

D^0D^{*+} and D^+D^{*0} Correlation Functions

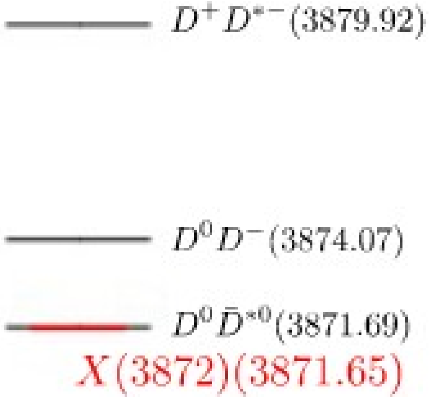
- For small source (R= 1 fm)
  C(q) > 8 for the lower channel (D^0D^{*+}) (Very strong)
  C(q) ~ 2.5 for upper channel (D^+D^{*0}) (strong)
- For large source (R=5 fm), CF show a dip
- Strong enhancement for small source, dip for large source
  → Characteristic dependence with a bound state (Tcc)
- Cusp is not significant

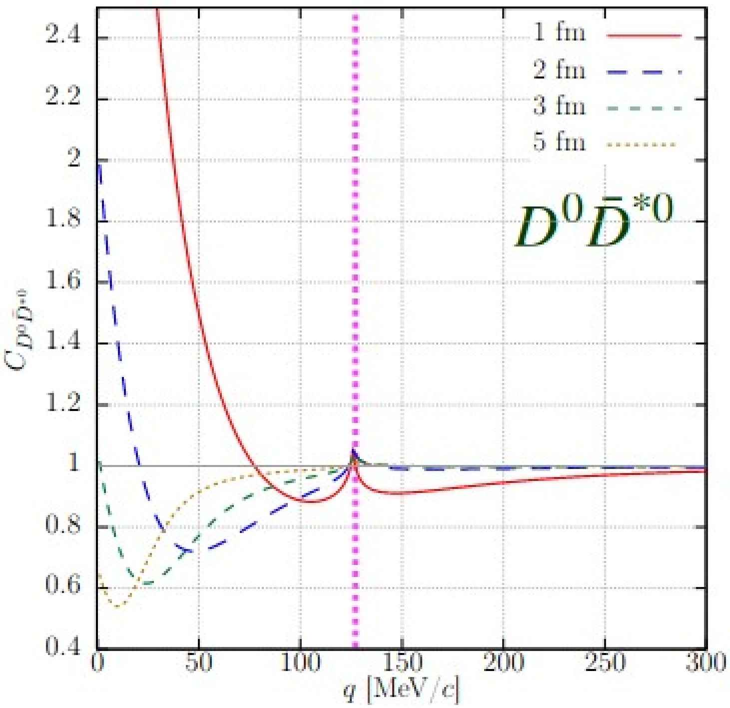


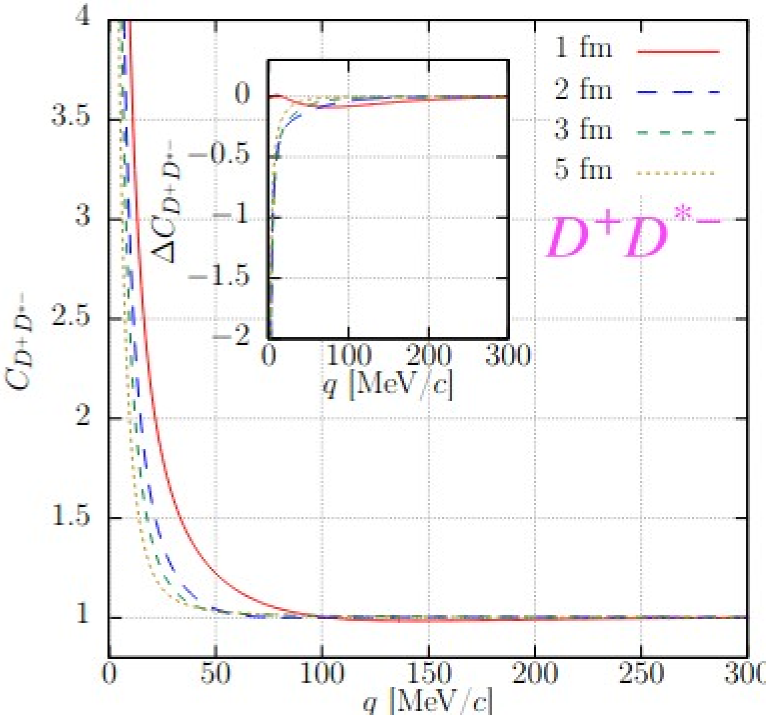


$D^0\bar{D}^{*0}$ and $D^+\bar{D}^{*-}$ Correlation Functions

- $C(D^0\bar{D}^{*0})$: **Strong enh. for small source, dip for large source**
  → Characteristic dependence with a bound state (X(3872))
- $C(D^+\bar{D}^{*-})$: **Coulomb dominant**
- **Cusp may be observed for small size**







Tcc and X(3872) structure

- **Hadronic molecule structure is assumed**
  → Eigenmomentum $k \simeq -i/a_0\,,\ a_0 \simeq 1/\sqrt{2\mu B}$
- **What happens when multiquark state mixes ?**
  → Deviation from weak binding relation

Weinberg, Phys. Rev. 137, B672 (1965), Hyodo, Jido, Hosaka (1108.5524)

$$a_0 = R\left[\frac{2X}{1+X}\right] + \mathcal{O}(m_\pi^{-1})$$

- **Smaller scattering length in DD* may signal the tetraquark nature of Tcc.**

Summary

- **Two-particle correlation functions are useful to deduce**
  - **Scattering length**
  - **Existence of a bound state**
  - **and hopefully the compositeness**
- **Charm hadron interactions are within the reach.**
  - **D^- p correlation function data favor attractive interaction. (c.f. Yasui's talk)**
  - DD^* and $D\bar{D}^*$ **correlation functions are predicted to reflect the existence of bound states (Tcc and X(3872)) by using simple potentials fitting to the mass and width.**
- **Strange hadron corr. funcs. from pA and K^-A reactions can be measured (KP formula or Migdal-Watson approach).**

Thank you for attention !

Y. Kamiya

T. Hyodo

AO

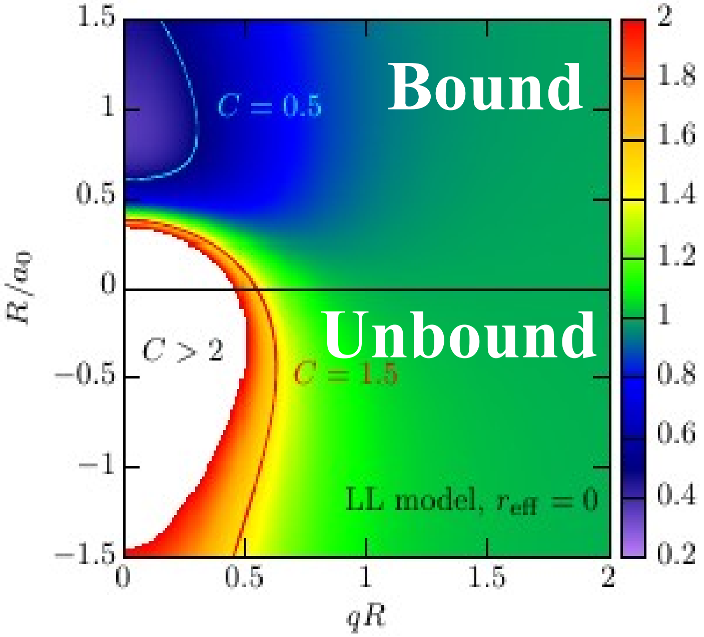
R Dependence of Correlation Function

- **Source size (R) dependence of C(q) is helpful to deduce the existence of a bound state.**

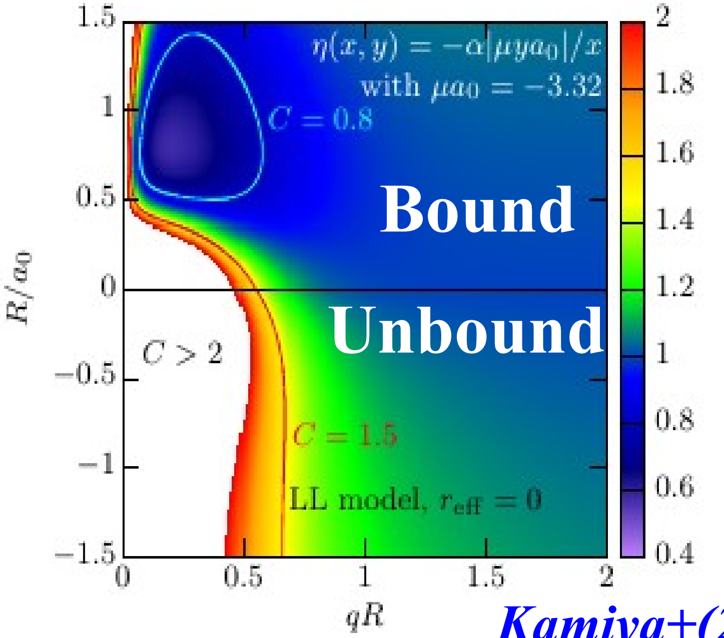
  Morita+('16, '20), Kamiya+('20), Kamiya+(2108.09644)

  - **With a bound state, C(q) is suppressed at small q when R ~ $|a_0|$.** **(w.f. has a node at r ~ $|a_0|$ with a bound state.)**
  - **Qualitative understanding by the analytic model (LL formula)** *[Lednickey, Lyuboshits ('82)]* **with the zero range approx. ($r_{\rm eff}$=0)**

w/o Coulomb



With Coulomb



Kamiya+(2108.09644)

Coupled-Channel Correlation Function

- **Correlation function with CC effects (KPLLL formula)**
  → sum of j-th channel contributions leading to j=1 with outgoing momentum *q*

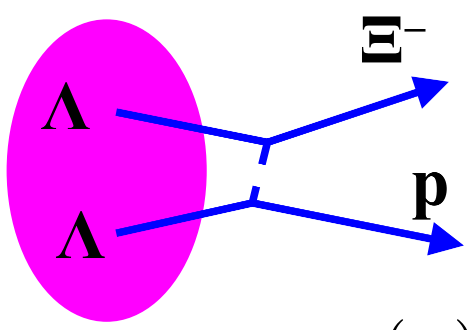
  Lednicky, Lyuboshits, Lyuboshits ('98); Haudenbauer ('19)

$$C(\boldsymbol{q}) = \sum_j \omega_j \int d\boldsymbol{r} S_j(\boldsymbol{r}) |\Psi_j^{(-)}(\boldsymbol{r})|^2$$

$$\Psi_j^{(-)}(\boldsymbol{r}) = [e^{i\boldsymbol{q}\cdot\boldsymbol{r}} - j_0(qr)]\delta_{1j} + \psi_j^{(-)}(r)$$

$$\psi_j^{(-)}(q) \propto e^{-iqr}/r \text{ or } e^{-\kappa r}/r \ (r \to \infty)$$

(No Coulomb case)



Outgoing Mom. *q* in channel j=1

$$\underline{\omega_j}\,\underline{S_j(\boldsymbol{r})}|\Psi_j^{(-)}(\boldsymbol{r})|^2$$

Source weight

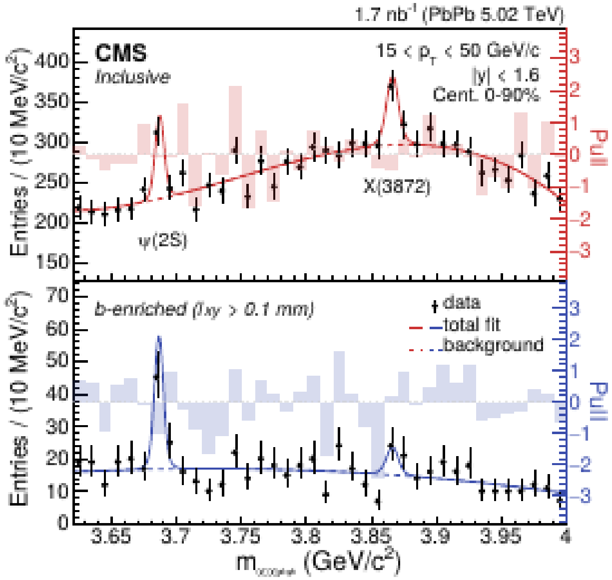
Normalized Source fn.

- **Effects of coupled-channel, strong & Coulomb pot., and threshold difference are taken into account in the charge base, pΞ⁻, nΞ⁰, ΛΛ.**
  Y. Kamiya+, PRL('20, K⁻ p)
- **Source size (R) and source weight (ω_j) need to be determined.**

A New Insight from CMS: Exotic/Normal Ratio

- **ExHIC index = Coalescence / Statistical Ratio**

$$R_h^{\mathrm{CS}} = \frac{\text{Yields in Coalescence}}{\text{Yields in Statistical model}}$$



- **CMS index = Exotic / Normal Ratio**

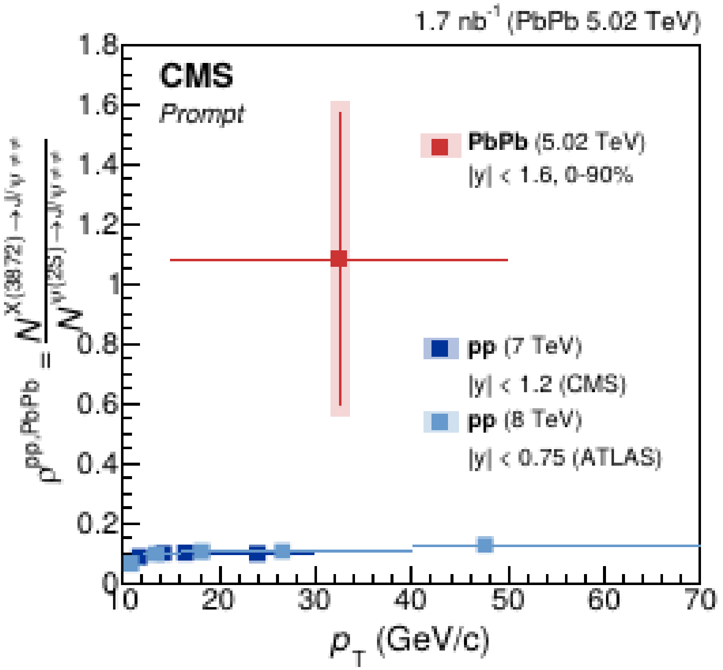
Sirunyan+ [CMS], arXiv:2102.13048

$$\rho_{\mathrm{exo/nor}} = \frac{N(\text{Exotic hadron candidate})}{N(\text{Normal hadron})}$$

- **X(3872) / ψ(2S) ratio in pp and PbPb collisions.**

$$\rho_{X/\psi}(\mathrm{PbPb}) = 1.08 \pm 0.49(\mathrm{stat.}) \pm 0.52(\mathrm{syst.})$$

$$\rho_{X/\psi}(pp) \simeq 0.1$$



ExHIC prediction is found to be (qualitatively) true !