Hadron-hadron interactions from femtoscopic study

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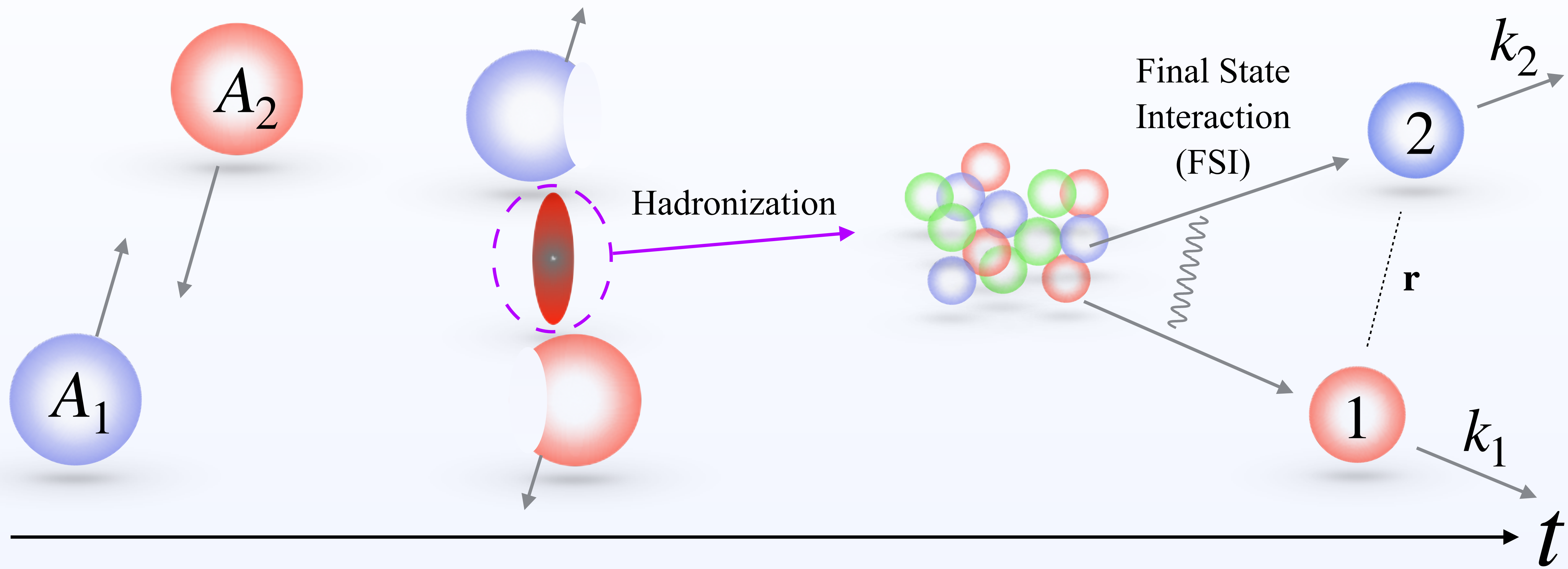
- High energy nuclear collision and FSI

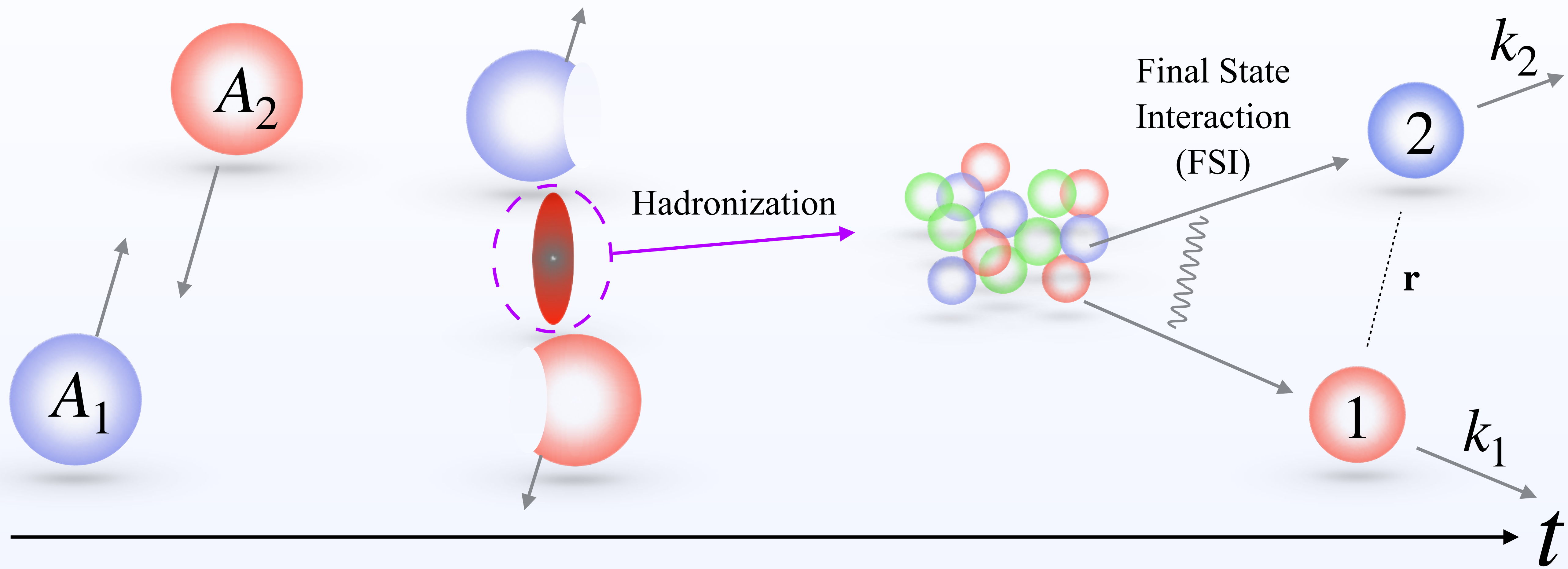


- Hadron-hadron correlation

$$C_{12}(k_1, k_2) = \frac{N_{12}(k_1, k_2)}{N_1(k_1)N_2(k_2)}$$

$$= \begin{cases} 1 & \text{(w/o correlation)} \\ \text{Others} & \text{(w/ correlation)} \end{cases}$$

- High energy nuclear collision and FSI



- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977)
    S. Pratt et. al. PRC 42 (1990)

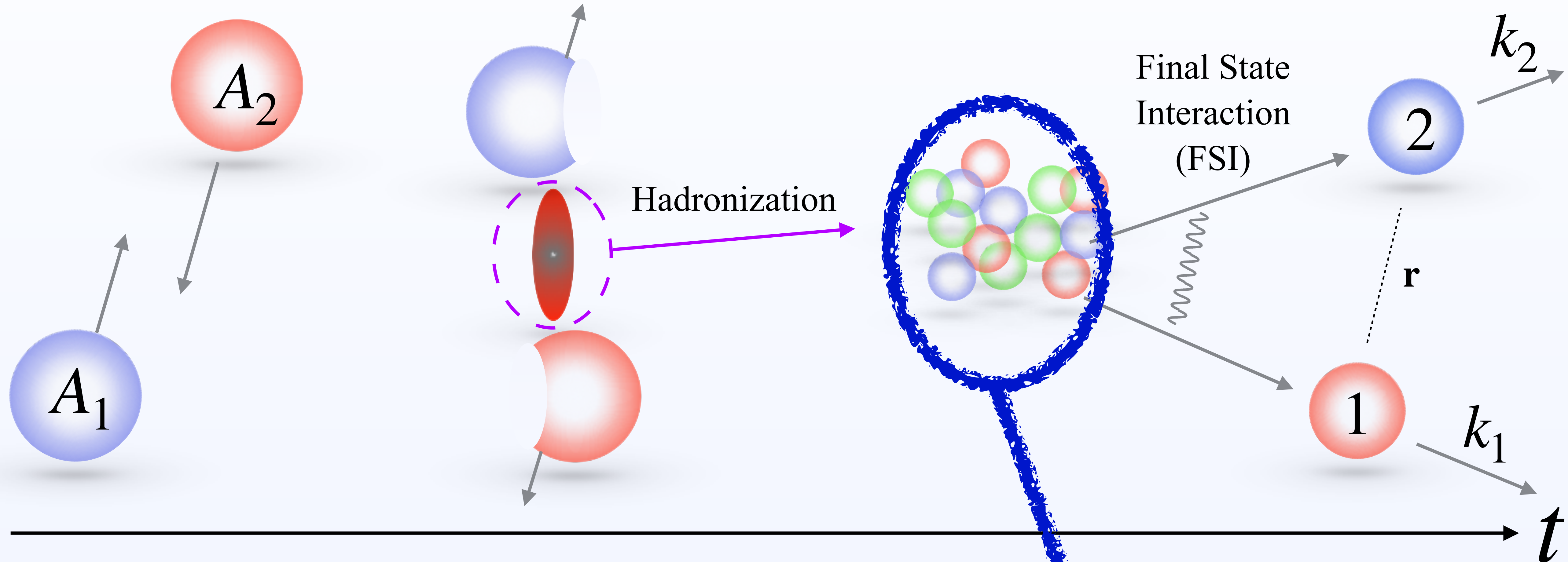
$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2$$

$$\mathbf{q} = (m_2\mathbf{k}_1 - m_1\mathbf{k}_2)/(m_1+m_2)$$

$S(\mathbf{r})$: Source function

$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

High energy nuclear collision and FSI



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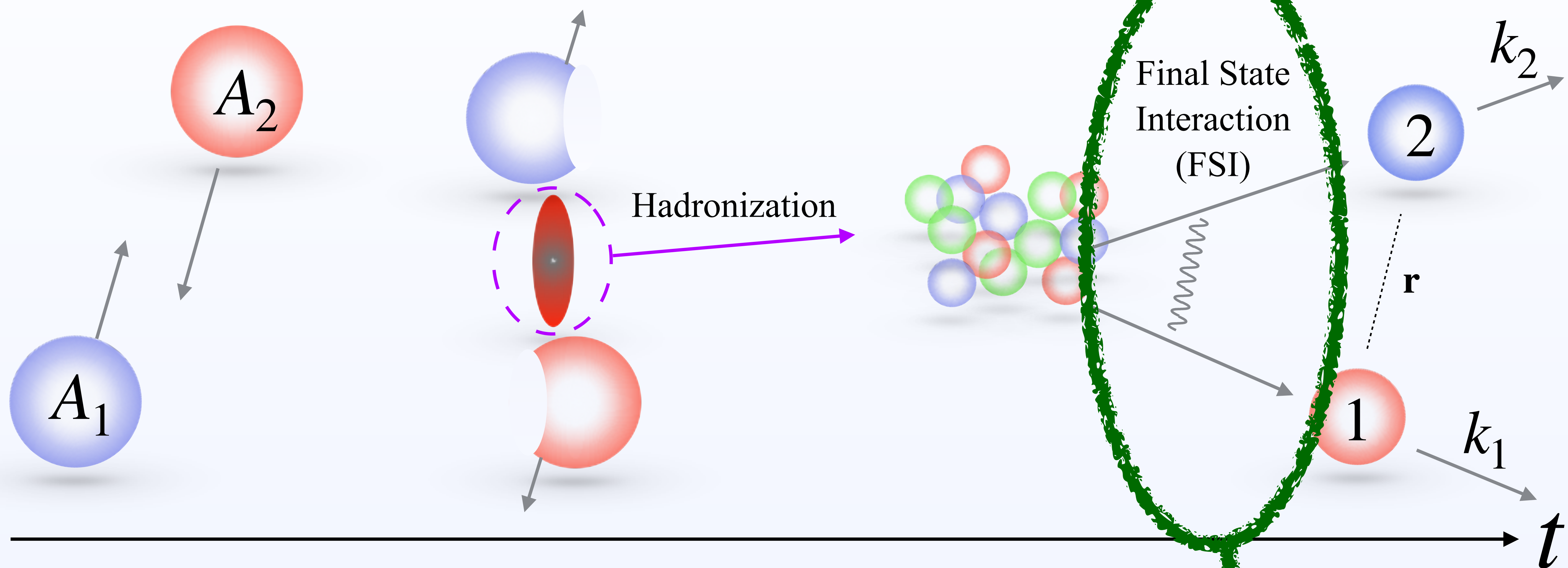
- Depends on …
  Collision detail (A_i, energy, centrality)
- Including information of…
  size of hadron source,
  momentum dependence, weight…

Hadron correlation in high energy nuclear collision

High energy nuclear collision and FSI



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- Depends on …
  Interaction (strong and Coulomb)
  quantum statistics (Fermion, boson)

Hadron correlation in high energy nuclear collision

Analytic model for ideal cases

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

$S(\mathbf{r})$: Source function

$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

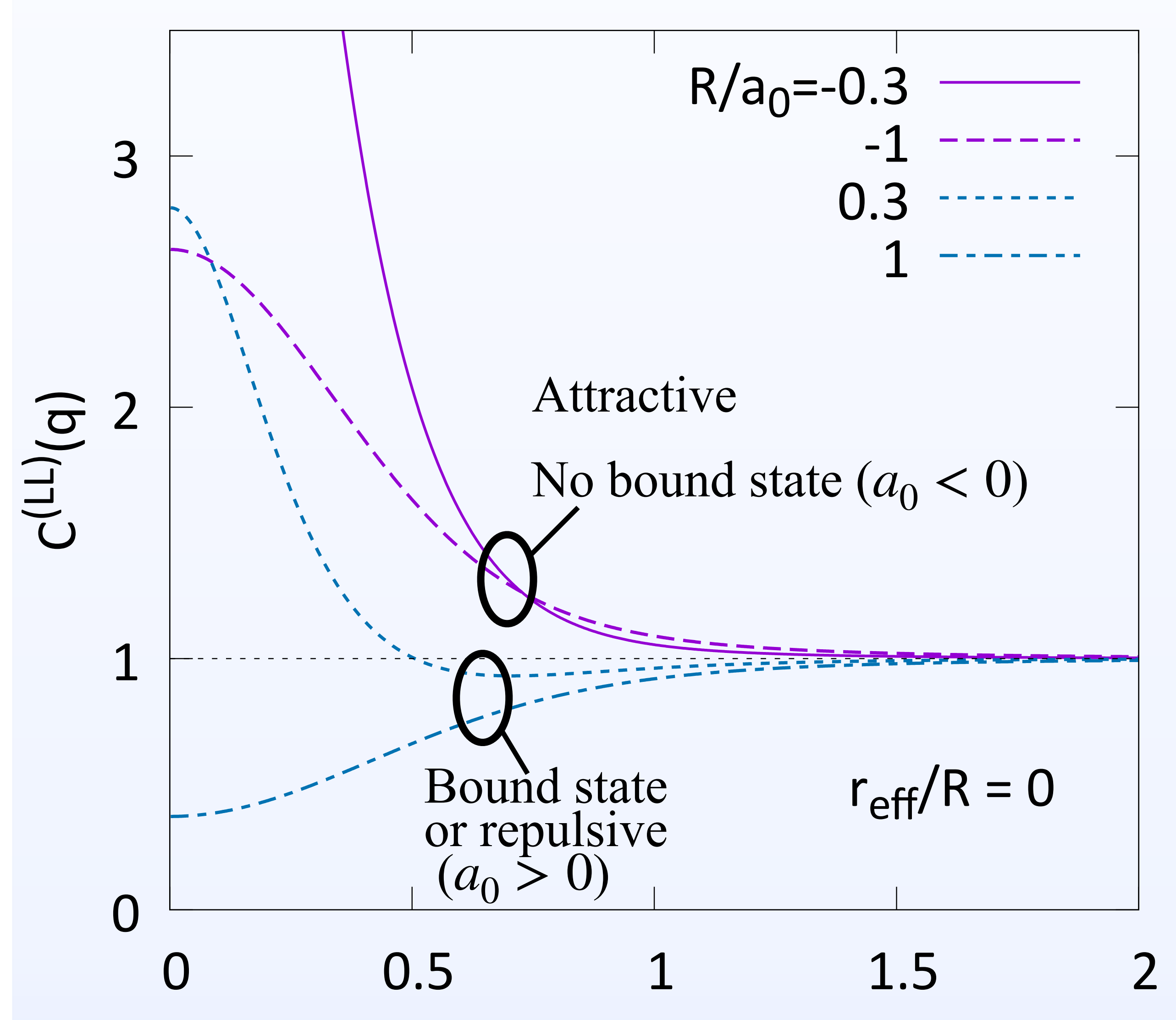
- Gaussian source with radius R
- Approximate φ by asymptotic wave func.
- $\mathscr{F}(q) = [-1/a_0 - iq]^{-1}$ with scat. length a_0

R. Lednicky, et al. Sov. J. Nucl. Phys. 35(1982).

$$\Rightarrow\quad C = C(qR, R/a_0)$$

- $C(q)$ is sensitive to R/a_0 at $qR \lesssim 1$

Sgn(a_0)	Interaction
-	Attraction w/o bound state
+	Attraction w/ bound state or Repulsion



Morita, et al., PRC101 (2020)

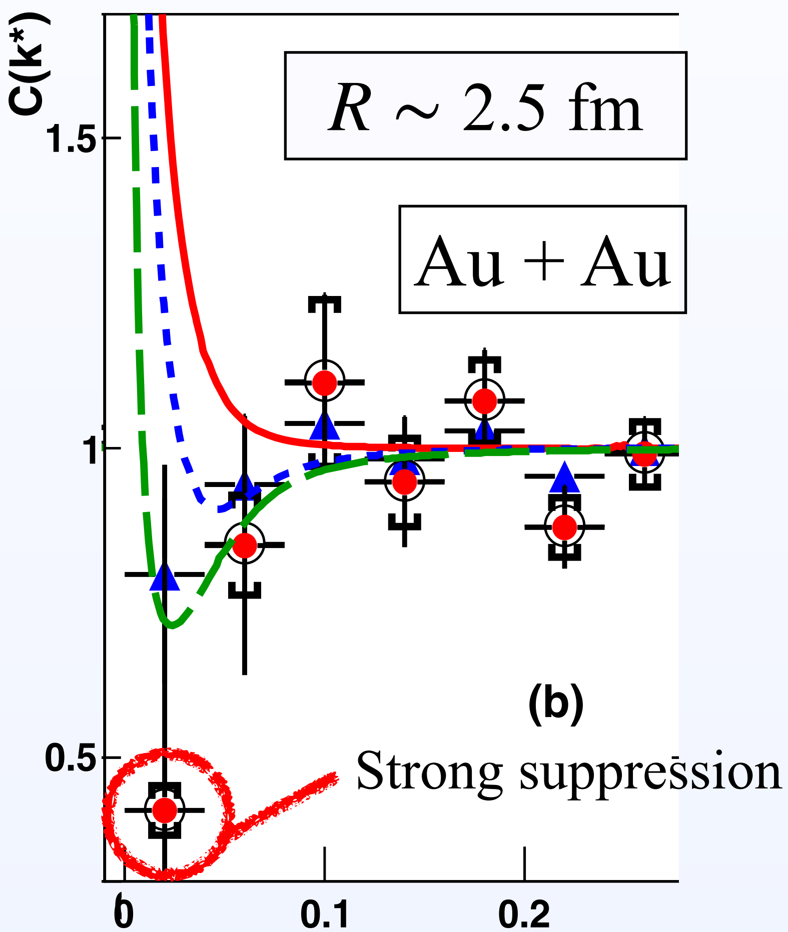
⇒
- Clear relation between $C(q)$ and $\mathscr{F}(q)$
- Sensitive to (non)existence of bound state

$N\Omega$ dibaryon and $p\Omega$ correlation

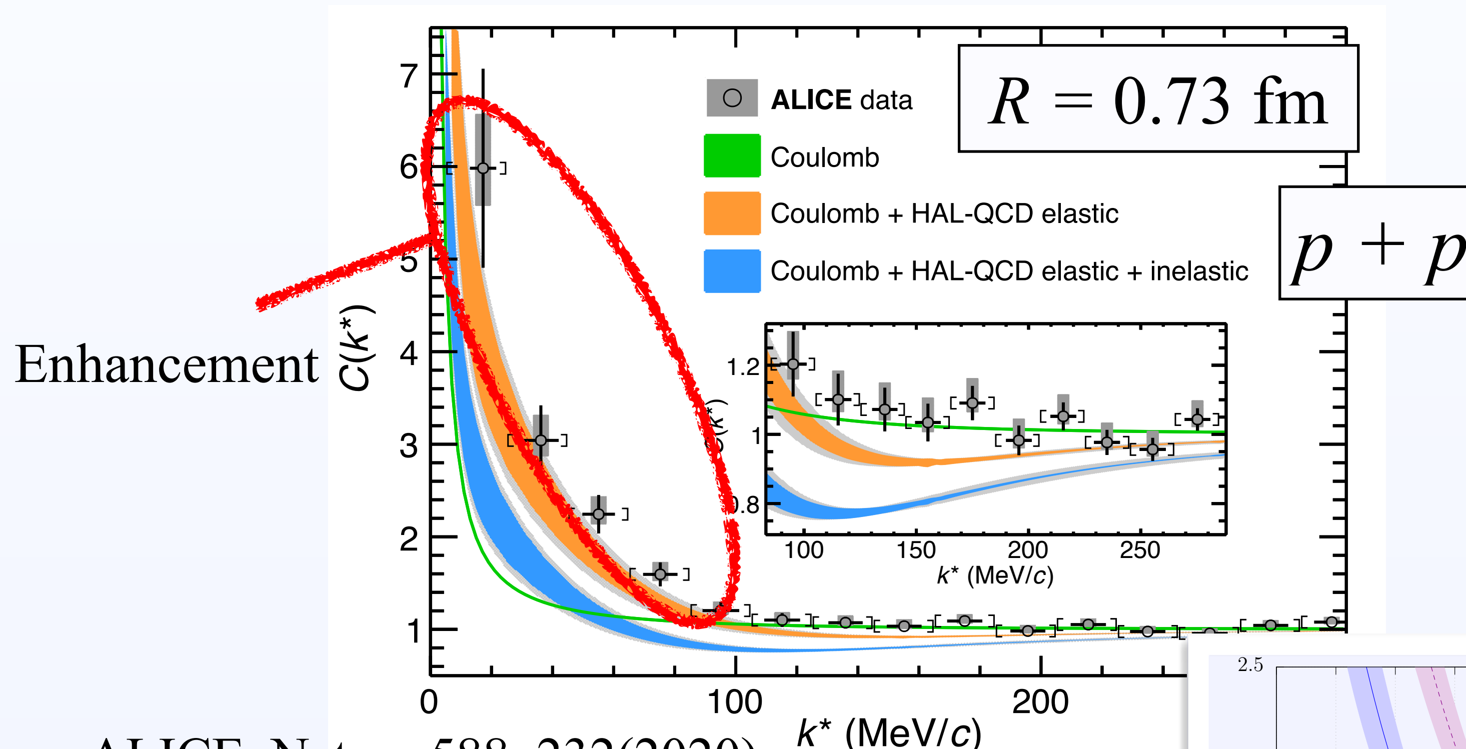
- $N\Omega$ dibaryon state ($J = 2$) is predicted by the Lattice HAL QCD potential

T. Iritani et al. PLB 792 (2019) 284–289

- Large source (STAR AuAu)
- Small source (ALICE pp)

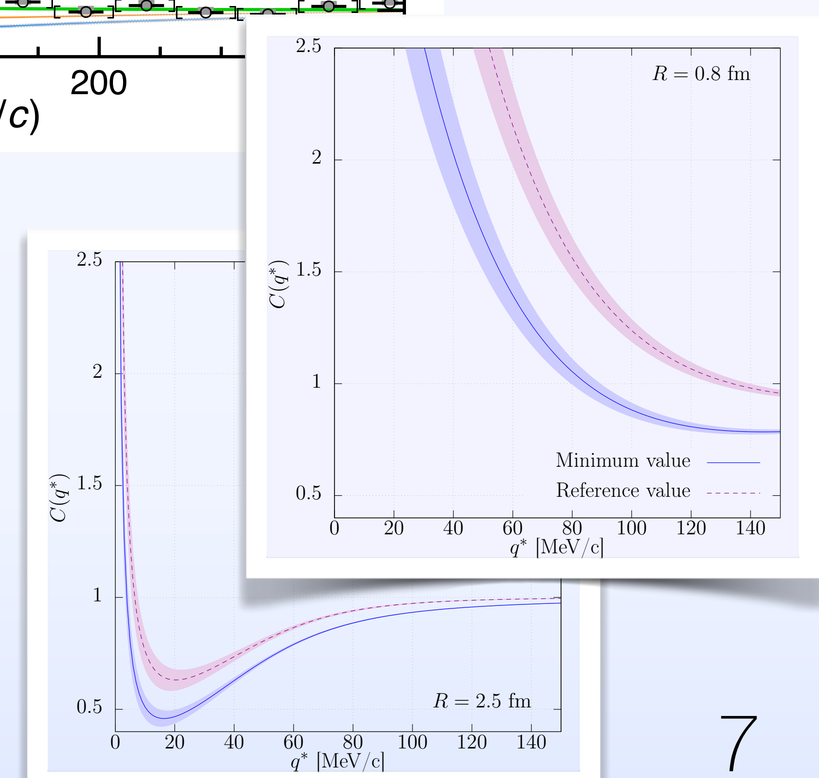


Adam et. al.PLB 790 (2019)



ALICE, Nature 588, 232(2020)

Fabbietti, et.al. [2012.09806]



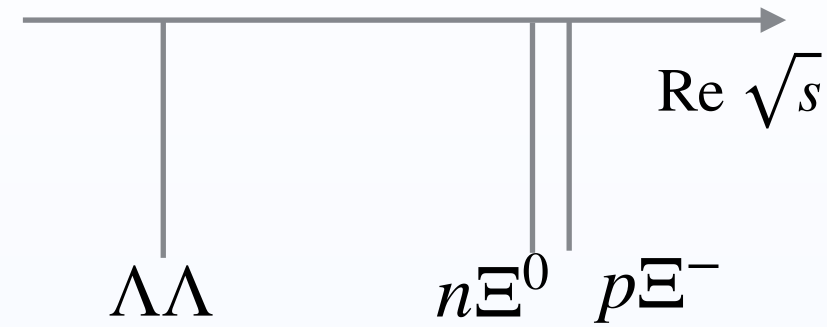
- Dip structure only in the large source data
  ==> $p\Omega$ dibaryon state?
- Consistent with HALQCD potential CF model

Morita, et al., PRC101 (2020)

$\Lambda\Lambda$-$N\Xi$ correlation function and H dibaryon

- Long history of discussion on $(J, I) = (0,0)$ sector related to $H(uuddss)$-dibaryon.

  R. L. Jaffe, PRL 38 (1977), 195.



- Lattice HAL QCD $\Lambda\Lambda$-$N\Xi$ coupled-channel potential

  K. Sasaki et al. [HAL QCD], NPA 998 (2020), 121737.

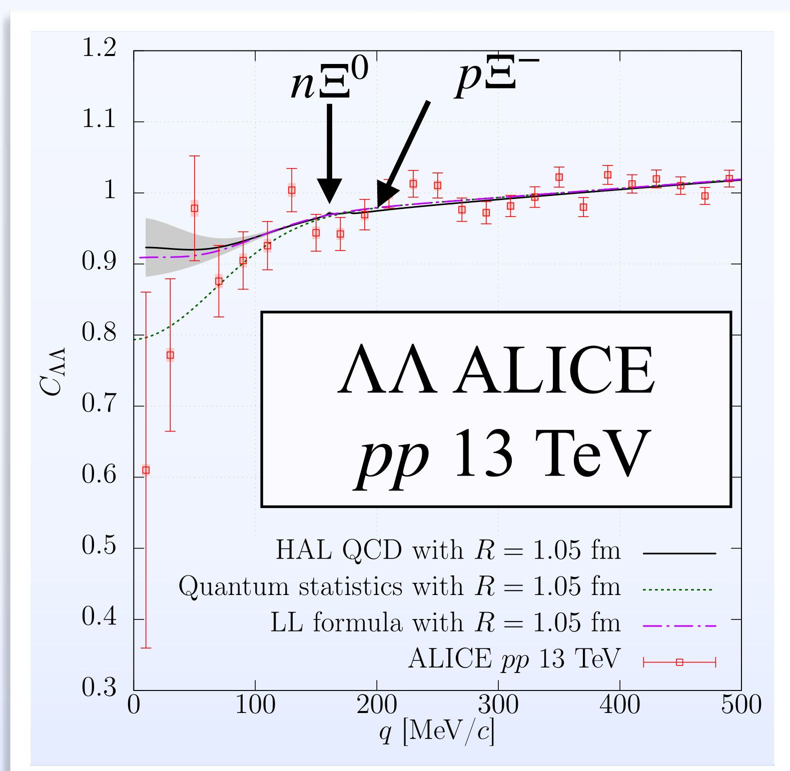
  - Strong attraction in $J = 0$, $I = 0$ $N\Xi$ channel

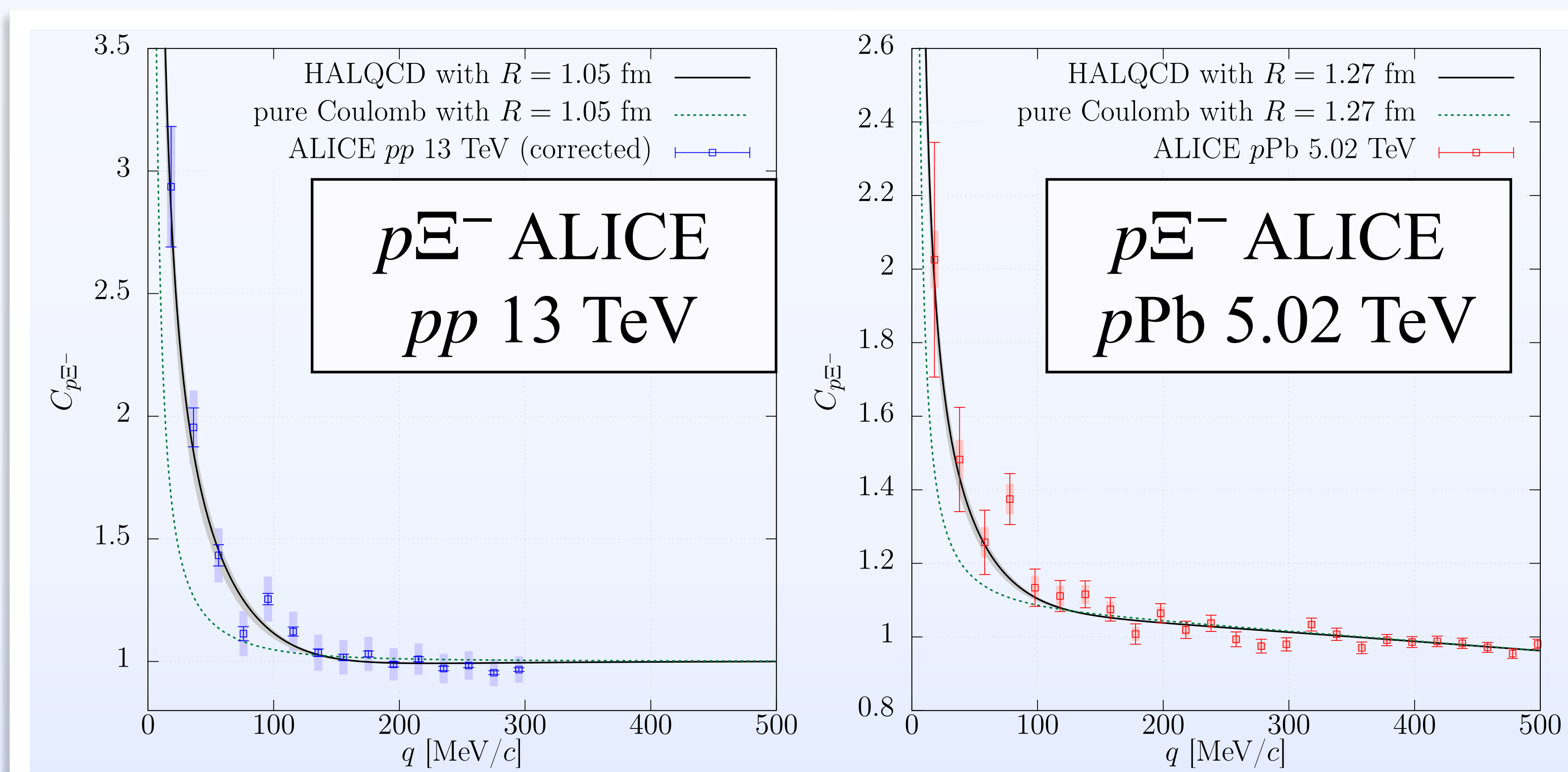
    $a_0^{p\Xi^-(J=0)} = -1.21 - i1.52$

    H dibaryon state is just barely unbound.

- Full coupled-channel analysis with HAL QCD potential is consistent with $\Lambda\Lambda$ and $p\Xi^-$ correlation data

Y. Kamiya, K. Sasaki, T. Fukui, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda, Phys.Rev.C 105 (2022) 1, 014915



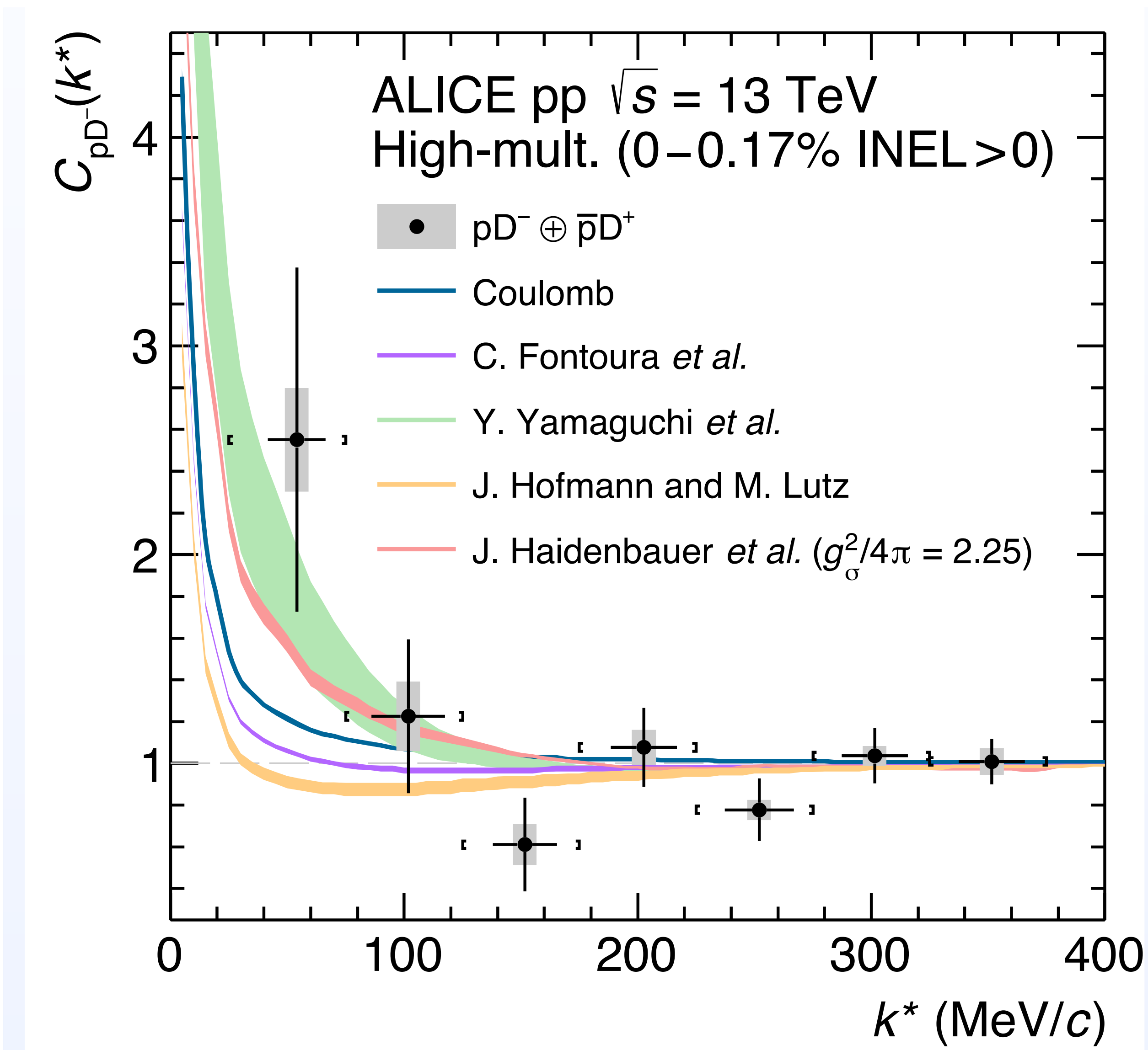


$\bar{D}N$ interaction and $D^{-}p$ correlation function

$\bar{D}(\bar{c}l)N$ interaction $(C = -1)$

$f_0 \equiv \mathscr{F}(E = E_{\text{th}})$
+ : attractive w/o bound
- : repulsive
or attractive w/ bound

- $D^{-}p$ correlation function ALICE PRD 106 (2022) 5, 052010



* Background including miss PID is subtracted

- Model scattering lengths f_0

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)

- pure Coulomb case is compatible with data
- Better agreement with strongly attractive interaction models for $I = 0$.
- pion exchange model of Yamaguchi et al. predicting 2 MeV bound state gives the lowest n_σ

$\bar{D}N$ interaction and D^-p correlation function

Constraint on $I = 0$ scattering length f_0

ALICE PRD 106 (2022) 5, 052010

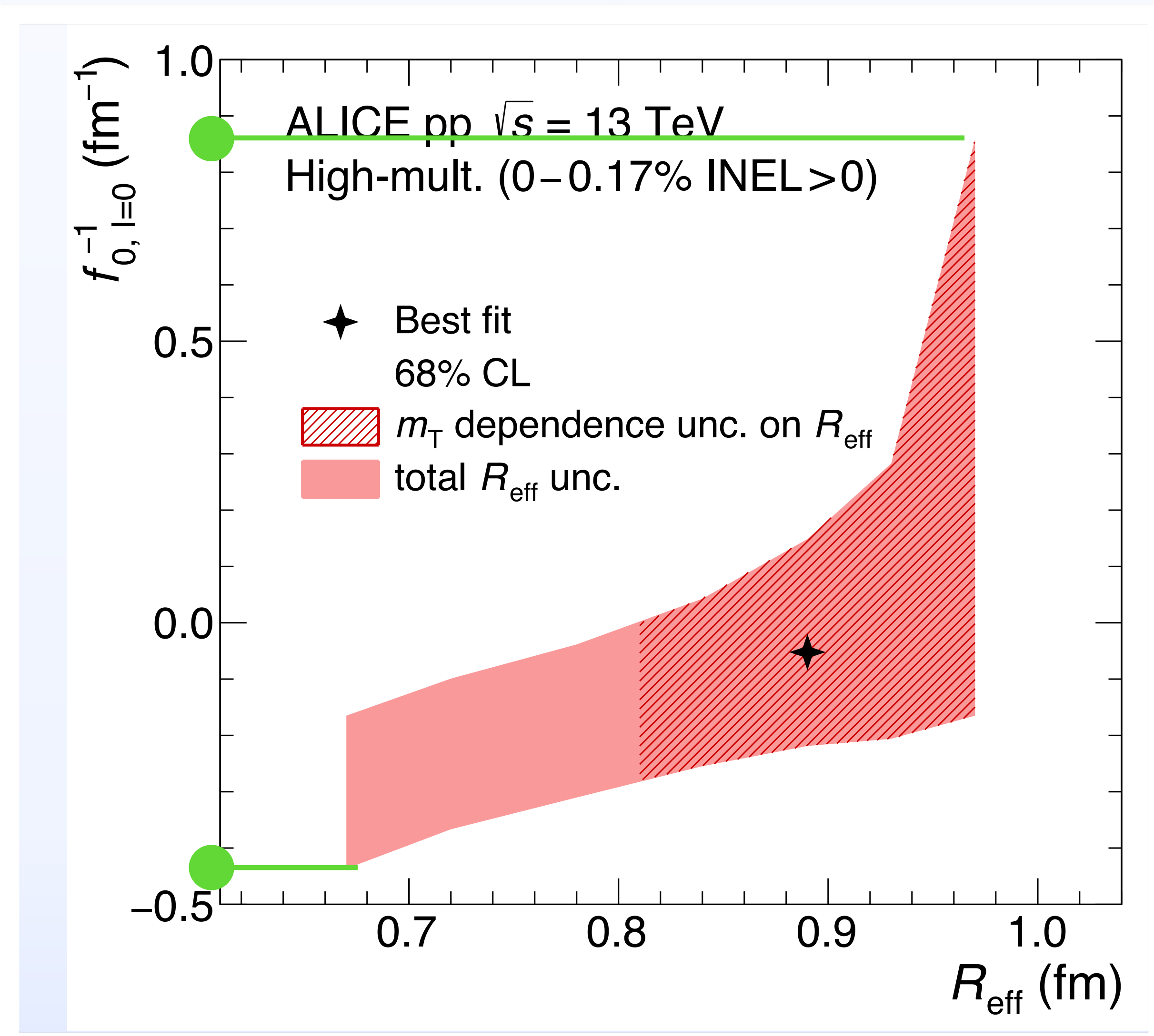
$f_0 \equiv \mathscr{F}(E = E_{\mathrm{th}})$
+ : attractive w/o bound
- : repulsive
  or attractive w/ bound

- Analysis with one range Gaussian potential

$$V(r) = V_0 \exp(-m^2 r^2)$$

- m <— ρ exchange ($m = m_\rho$)
- Assume negligible $I = 1$ int.

- Constraint on $f_{0,\,I=0}$



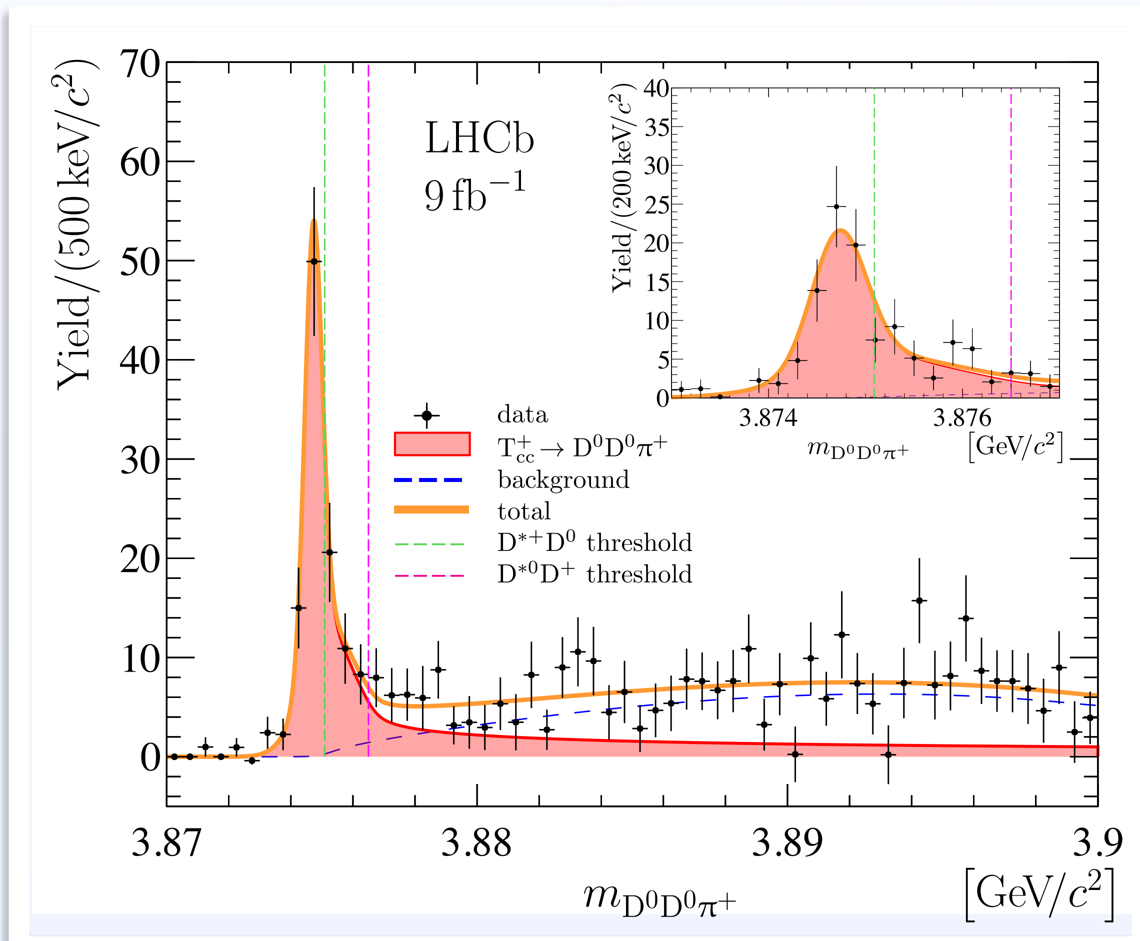
- 1σ constraint —> $f^{-1}_{0,\,I=0} \in [-0.4, 0.9]$ fm^{-1}:
- strongly attractive with or without bound state

* Most models predicts repulsive int. for $I = 1$
—> $I = 0$ may have more attraction in reality.

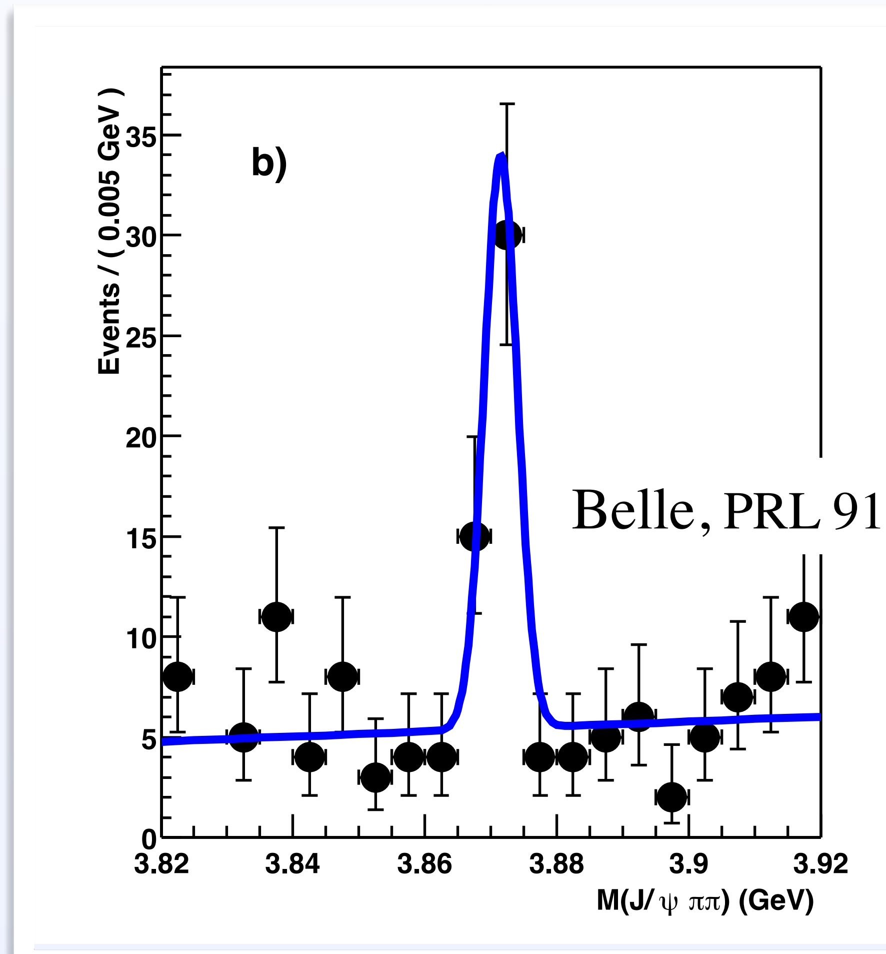
DD^* and $D\bar{D}^*$ int. from femtoscopy

- T_{cc}
  - Observed in $D^0D^0\pi$ spectrum

LHCb, Nature Com. 13 (2022) 1



- $X(3872)$ or χ_{c1}
  - Firstly observed in $\pi\pi J/\Psi$ spectrum
    Belle, PRL 91, 262001 (2003)
  - Confirmed by Babar: PRD71, 071003 (2003)
    CDF: PRL 93 072001 (2004)
    D0: PRL 93 162002 (2004)



Belle, PRL 91, 262001 (2003)

DD^* and $D\bar{D}^*$ int. from femtoscopy

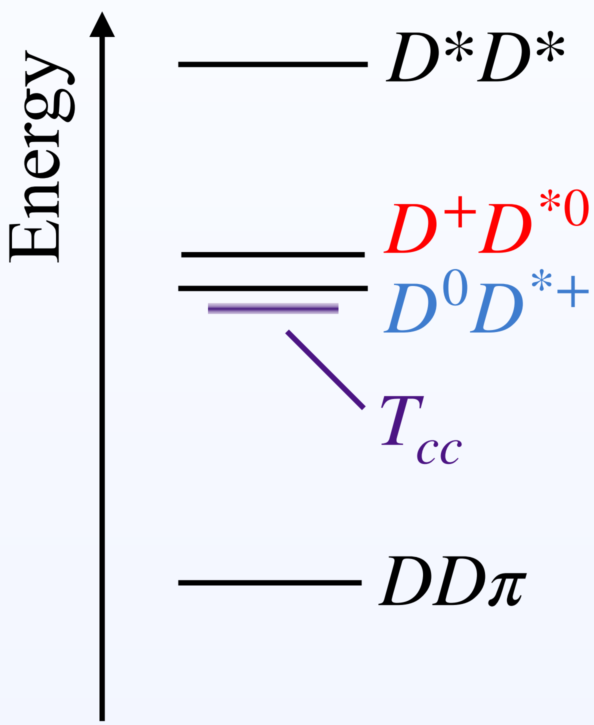
DD^* and $D\bar{D}^*$ sector

$a_0 \equiv \mathcal{F}(E = E_{\rm th})$

+ : attractive w/o bound

- : repulsive
  or attractive w/ bound

$C = 2$



LHCb, Nature Com. 13 (2022) 1

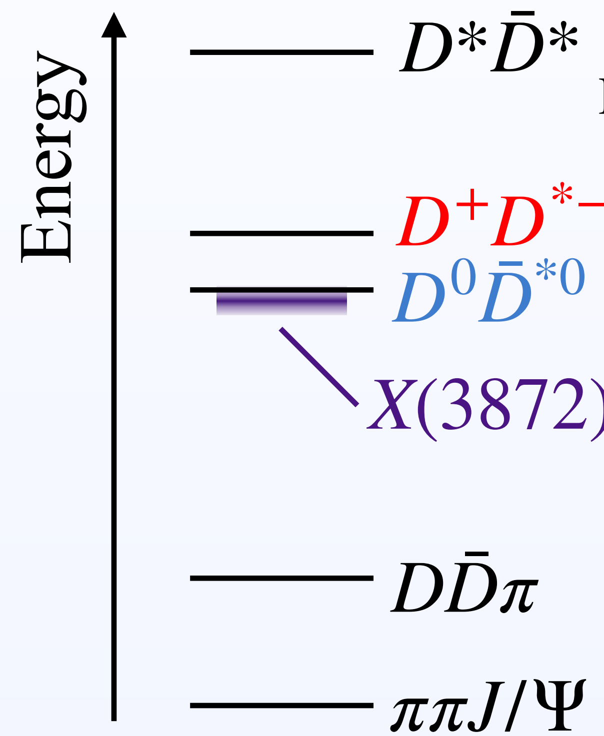
$$E_{T_{cc}} = \delta_m - \frac{i}{2}\Gamma$$

$$\delta m = -0.36 \text{ MeV}$$

$$\Gamma = 0.048 \text{ MeV}$$

$$a_0 = -7.16 + i1.85 \text{ fm}$$

$C = 0$



PDG, PTEP 2020, 083C01 (2020).

$$E_{X(3872)} = \delta_m - \frac{i}{2}\Gamma$$

$$\delta m = -0.04 \text{ MeV}$$

$$\Gamma = 1.19 \text{ MeV}$$

$$a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95\text{fm}$$

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

  ==> meson-meson molecule?

  ==>Strong attractive interaction

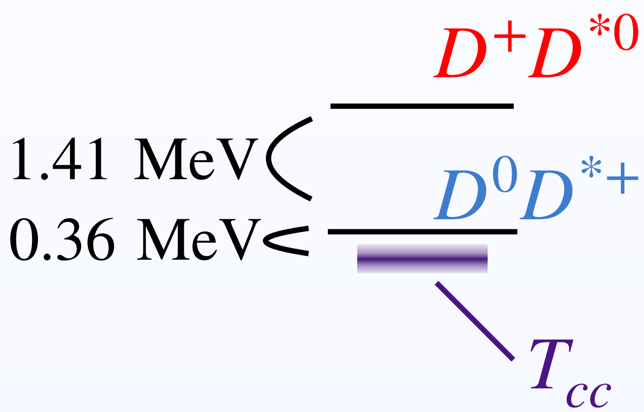
- Gaussian potential

  $$V(r) = V_0 \exp(-m^2r^2)$$

  - m <— π exchange ($m = m_\pi$)
  - V_0<— scattering lengths
  - Assume dominant contribution from exotic channel ($I = 0$)
  - Coupled-channel of two isospin channels

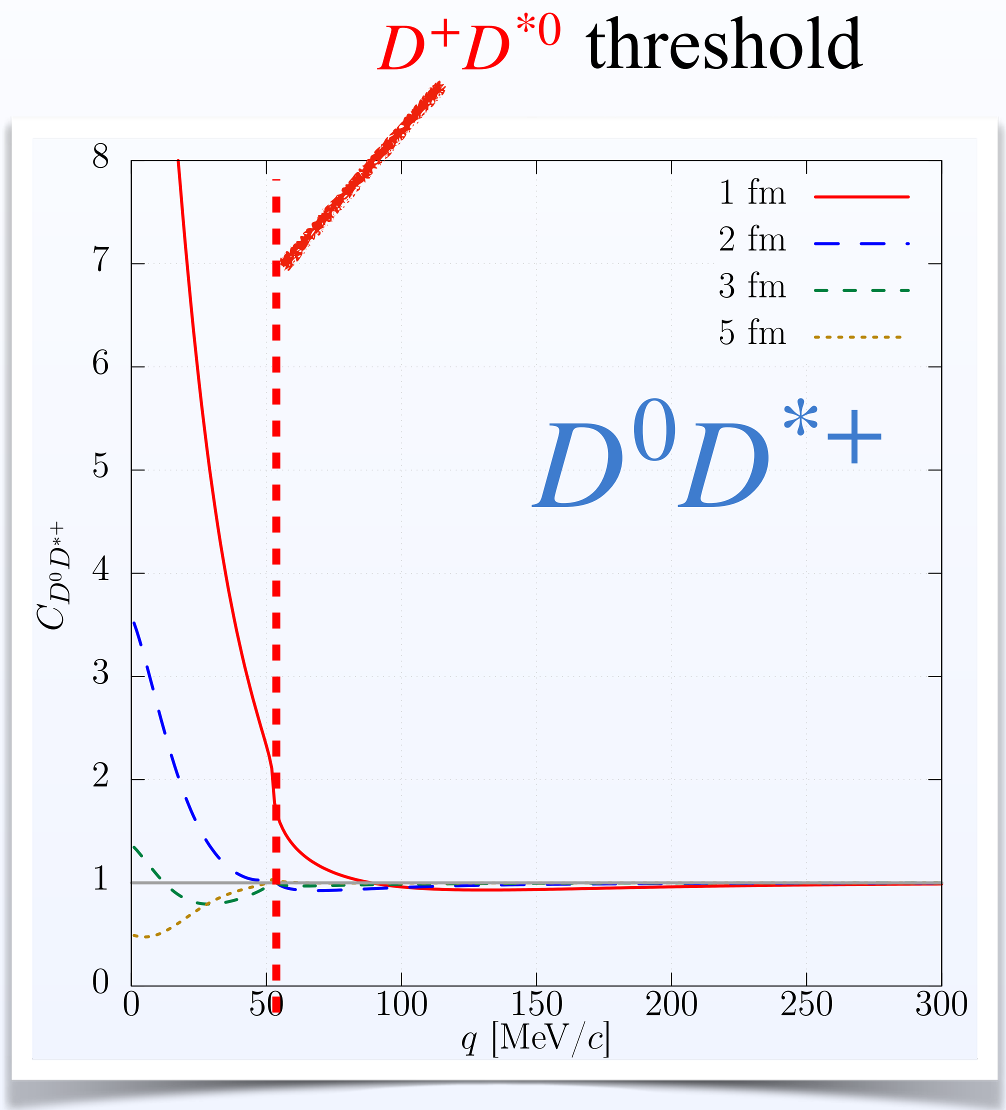
DD^* and $D\bar{D}^*$ int. from femtoscopy

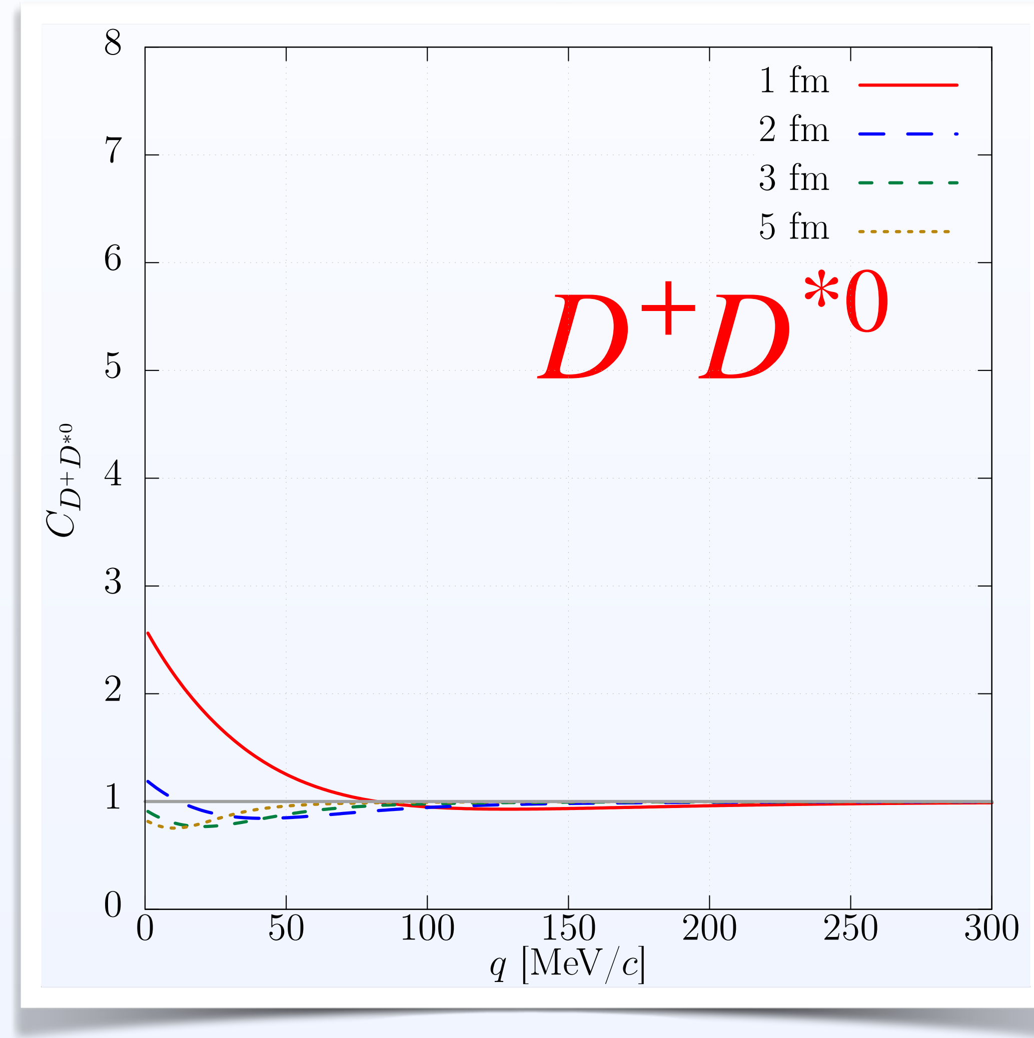
- DD^* correlation and T_{cc} state



$$E_{T_{cc}} = \delta m - \frac{i}{2}\Gamma,$$
$$\delta m = -360 \ \text{keV},$$
$$\Gamma = 48 \ \text{keV}$$
$$a_0 = -7.16 + i1.85 \ \text{fm}$$

LHCb, Nature Com. 13 (2022) 1

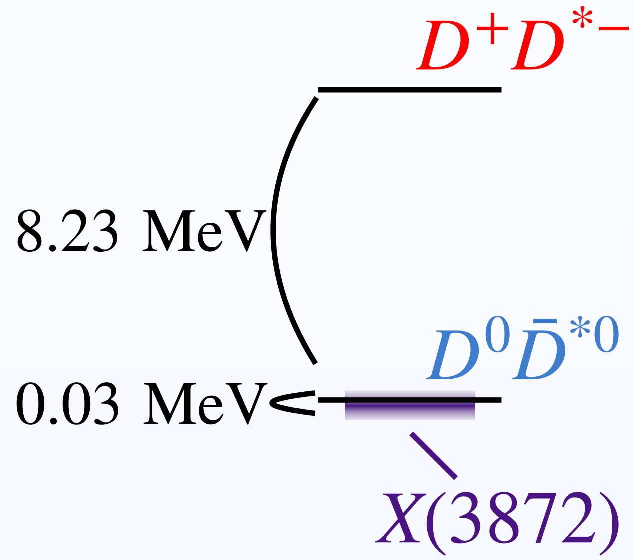




- Bound state like behavior for both pairs
- Stronger source size dep. for D^0D^{*+}
- D^+D^{*0} cusp is not prominent

DD^* and $D\bar{D}^*$ int. from femtoscopy

- $D\bar{D}^*$ correlation and $X(3872)$ state



PDG, PTEP 2020, 083C01 (2020)

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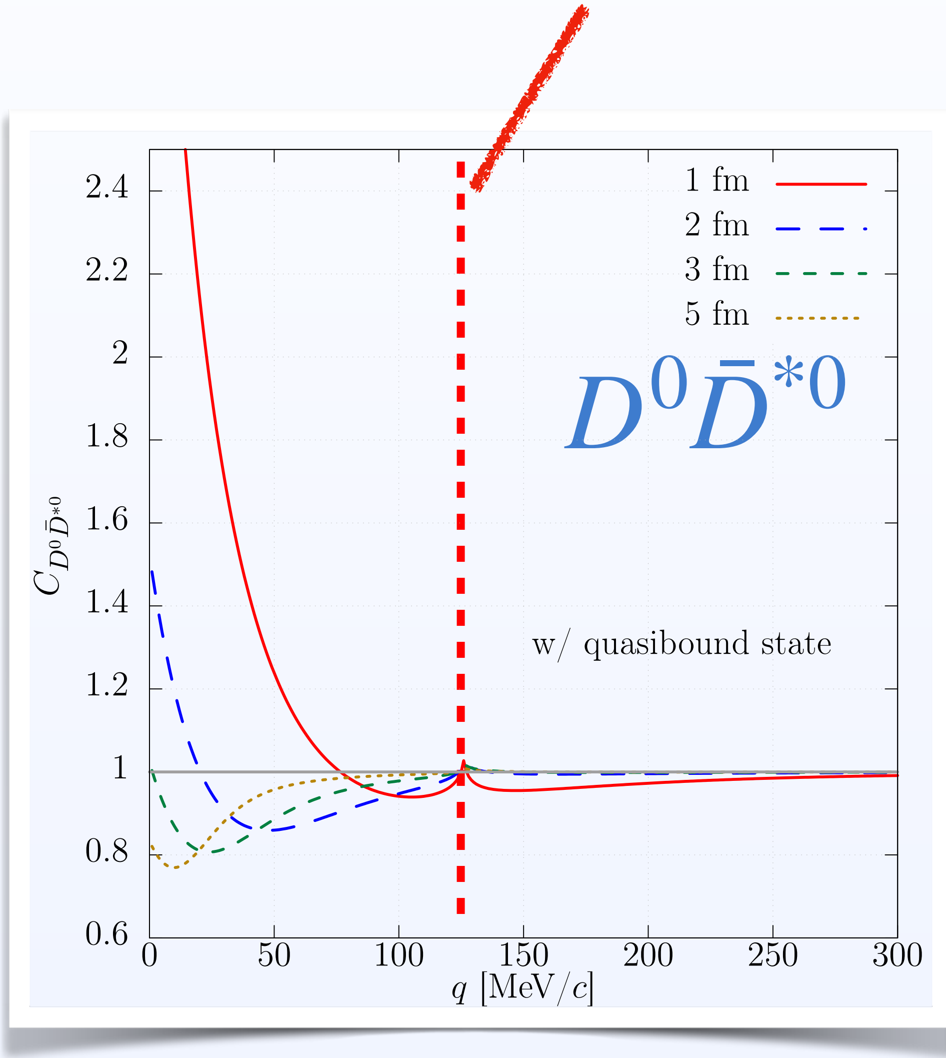
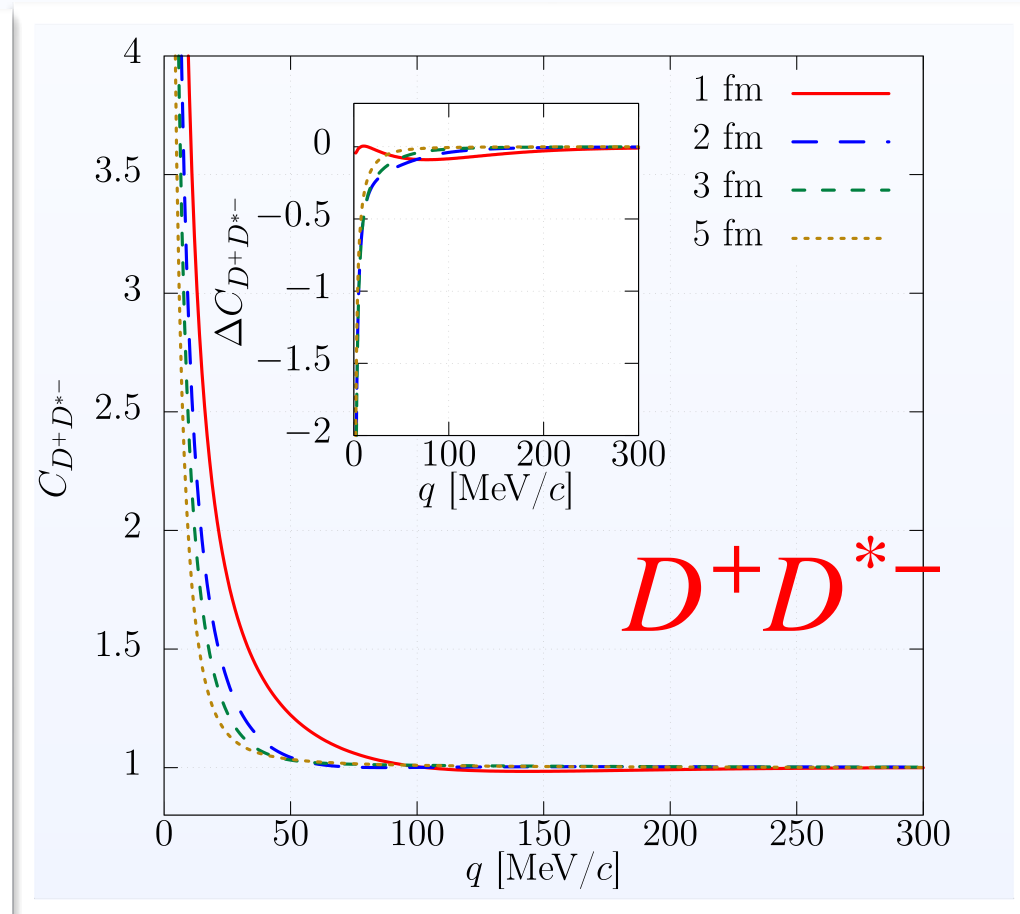
D^+D^{*-} threshold

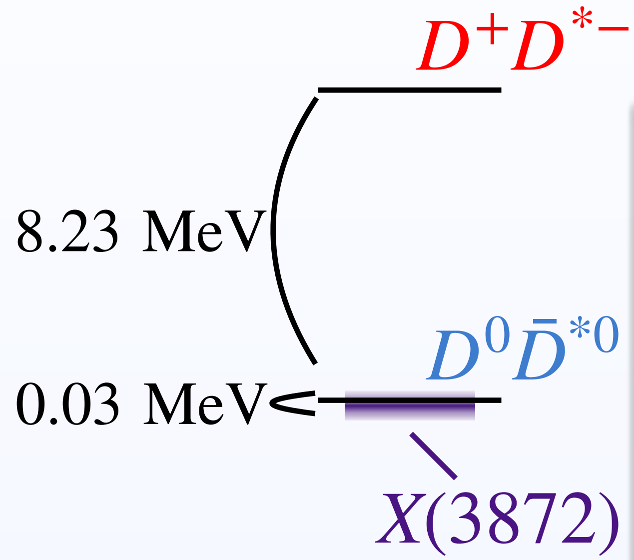




- D^0D^{*+} : Strong source size dep.
- D^+D^{*-} : Small effect of the strong int. (Coulomb int dominance)
- Moderate D^+D^{*+} cusp

DD^* and $D\bar{D}^*$ int. from femtoscopy

- $D\bar{D}^*$ correlation and $X(3872)$ state



PDG, PTEP 2020, 083C01 (2020)

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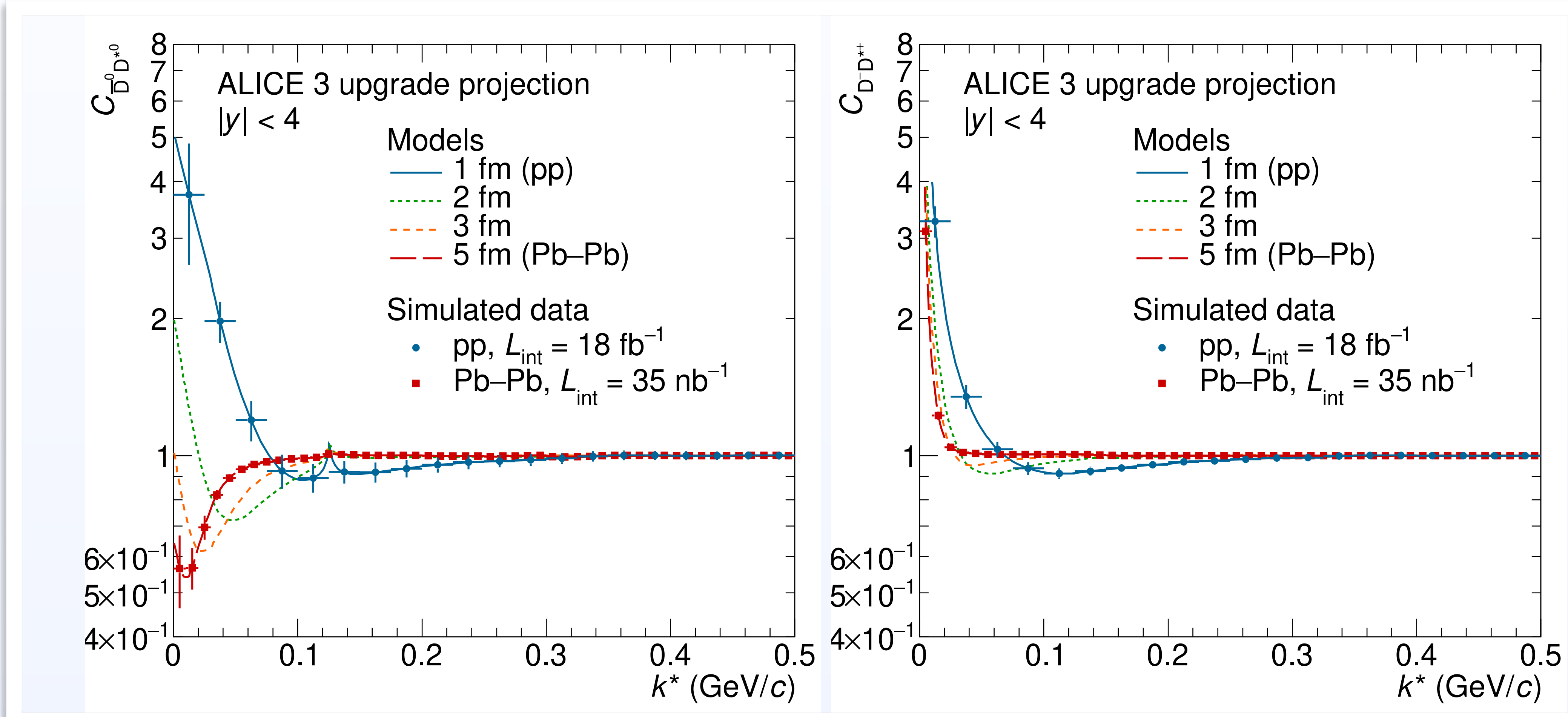


ALICE collab., CERN-LHCC-2022-009 (2022).

- D^0D^{*+} : Strong source size dep.
- D^+D^{*-} : Small effect of the strong int. (Coulomb int dominance)
- Moderate D^+D^{*+} cusp

$X(3872)$ with various assumptions

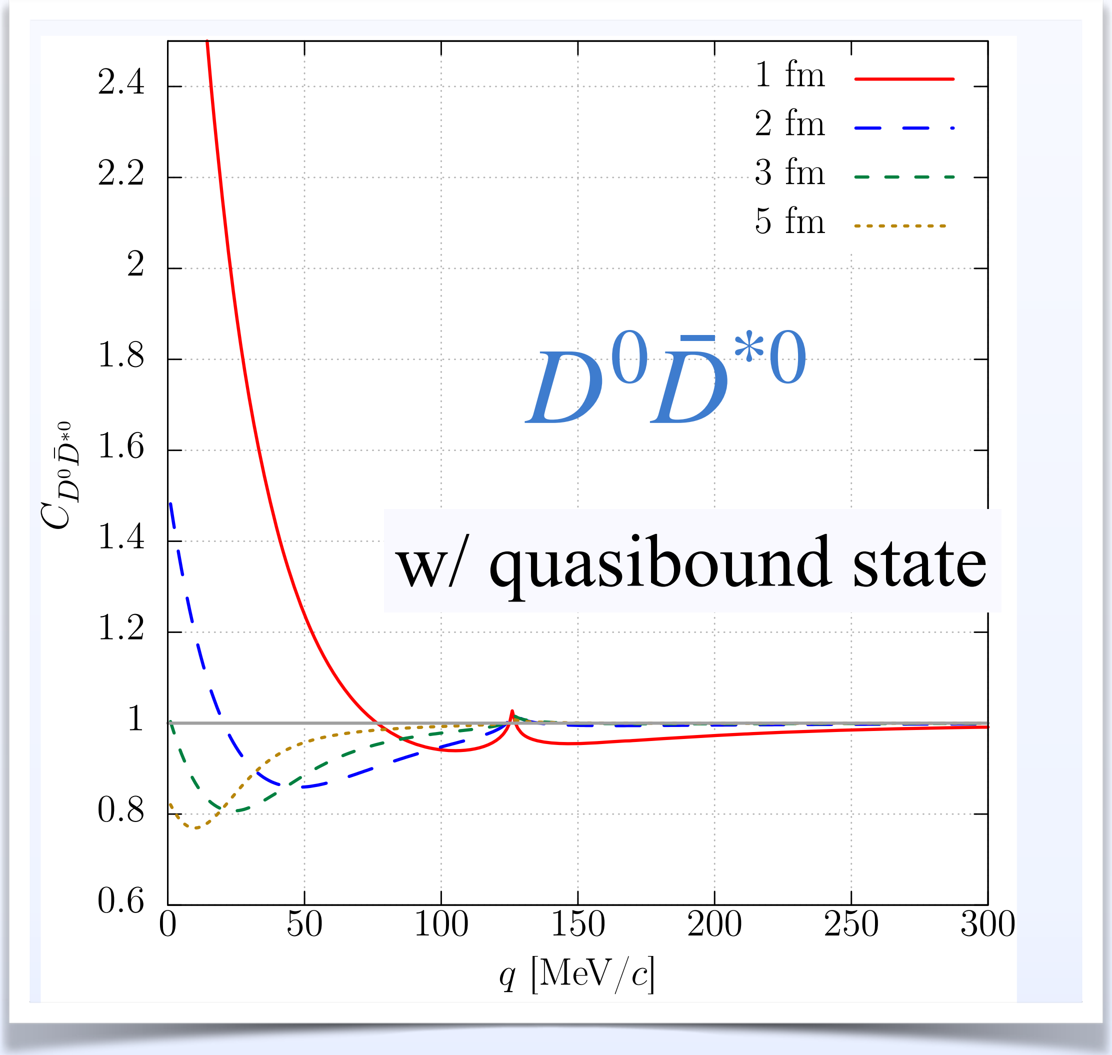
$a_0 \equiv \mathscr{F}(E = E_{\text{th}})$
+ : attractive w/o bound
- : repulsive
or attractive w/ bound

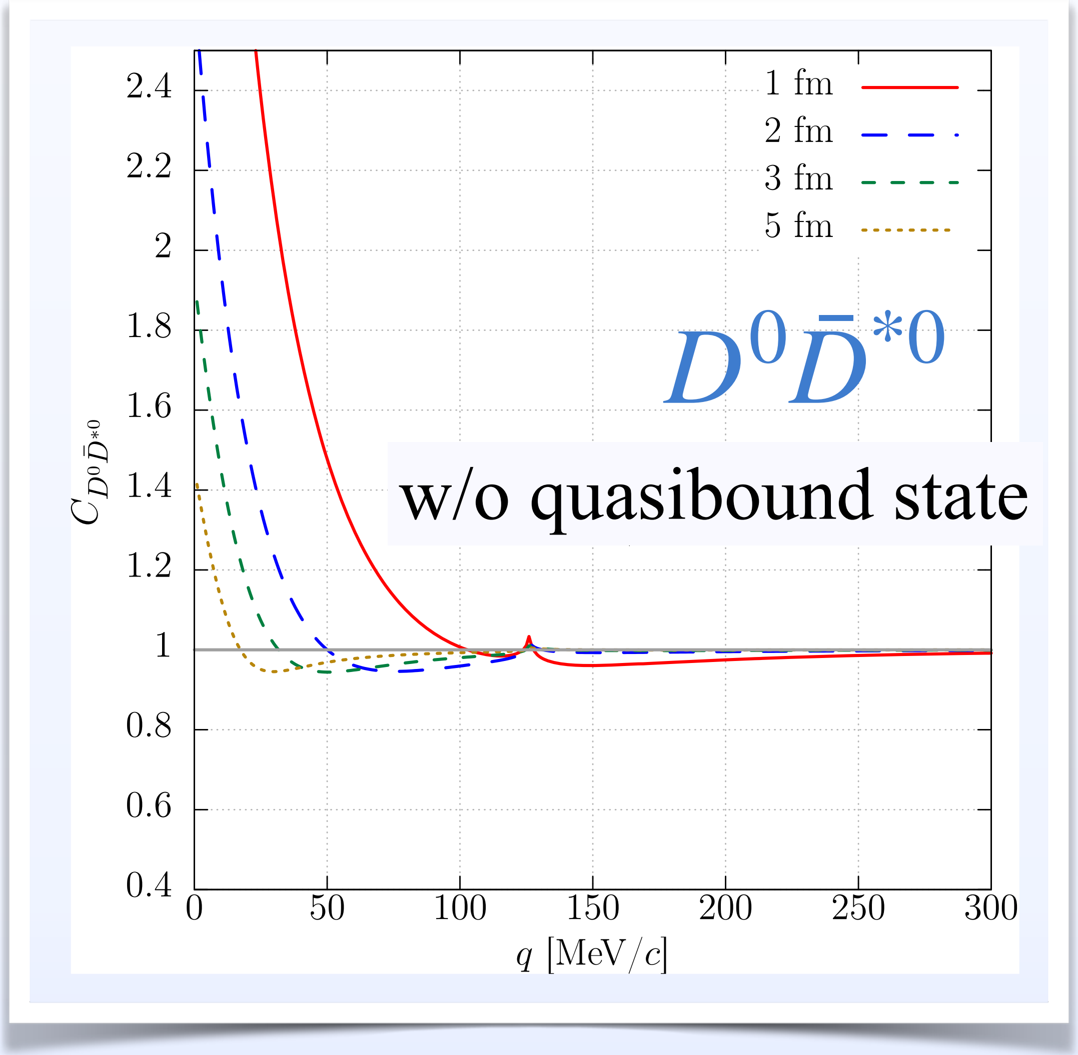
- $X(3872)$ as cusp
  - Empirical scattering length

$a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95\text{fm}$

weaken interaction

$a_0^{D^0\bar{D}^{*0}} = 2.30 + i4.00 \text{ fm}$





Summary

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the nature of bound state.

- $D^{-}p$
  Non-interacting model can explain data but strong attractive interaction reduce the standard deviation.

- $DD^{*}/D\bar{D}^{*}$
  The lower isospin partner channels are expected to show the strong source size dependence due to the near threshold $T_{cc}/X(3872)$ states.

Thank you for your attention!