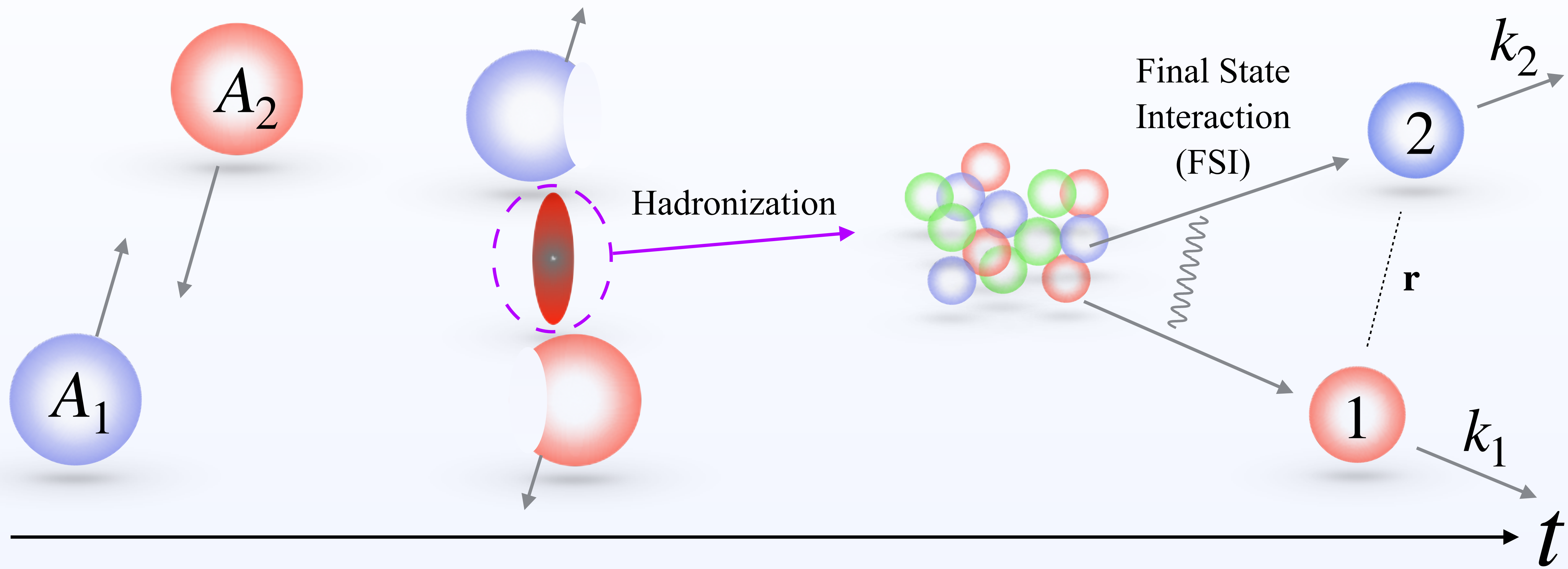
ハドロン運動量相関を用いたチャームハドロン・相互作用の研究

Yuki Kamiya
HISKP, Bonn Univ.

ハドロン分光に迫る反応と構造の物理
@ online 2022/12/6

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



- Hadron-hadron correlation

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

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

Hadron correlation in high energy nuclear collision

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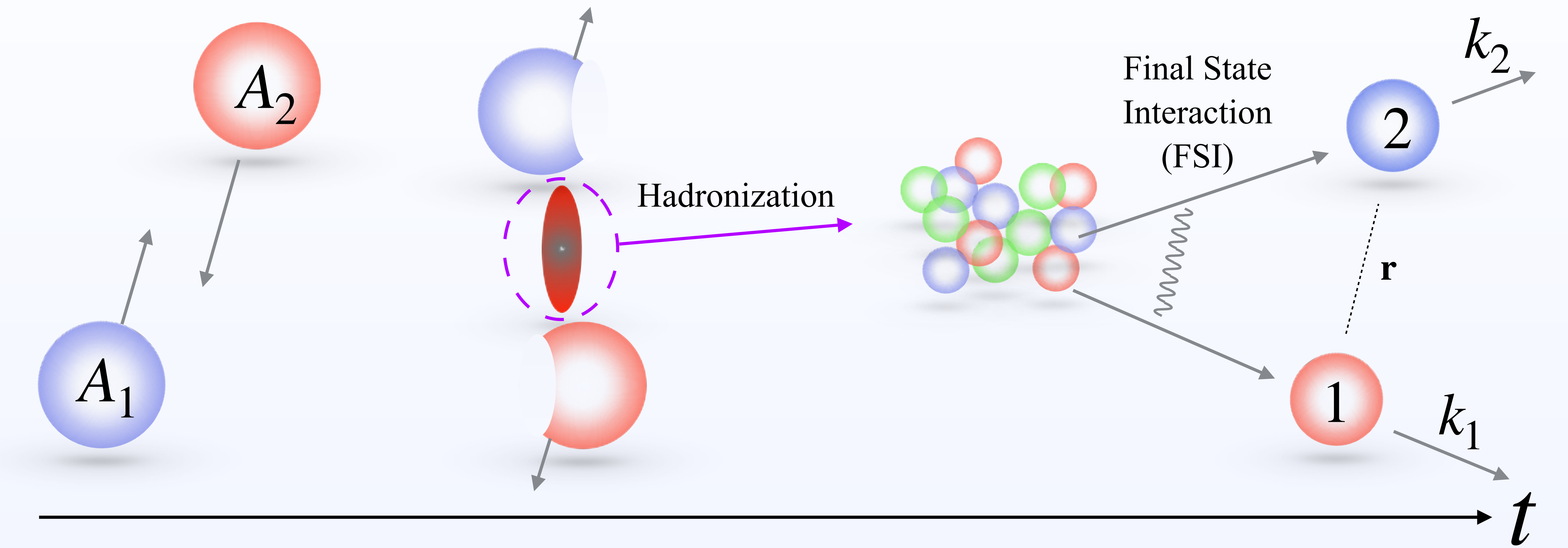

- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977) S. Pratt et. al. PRC 42 (1990)

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

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

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

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

Hadron correlation in high energy nuclear collision

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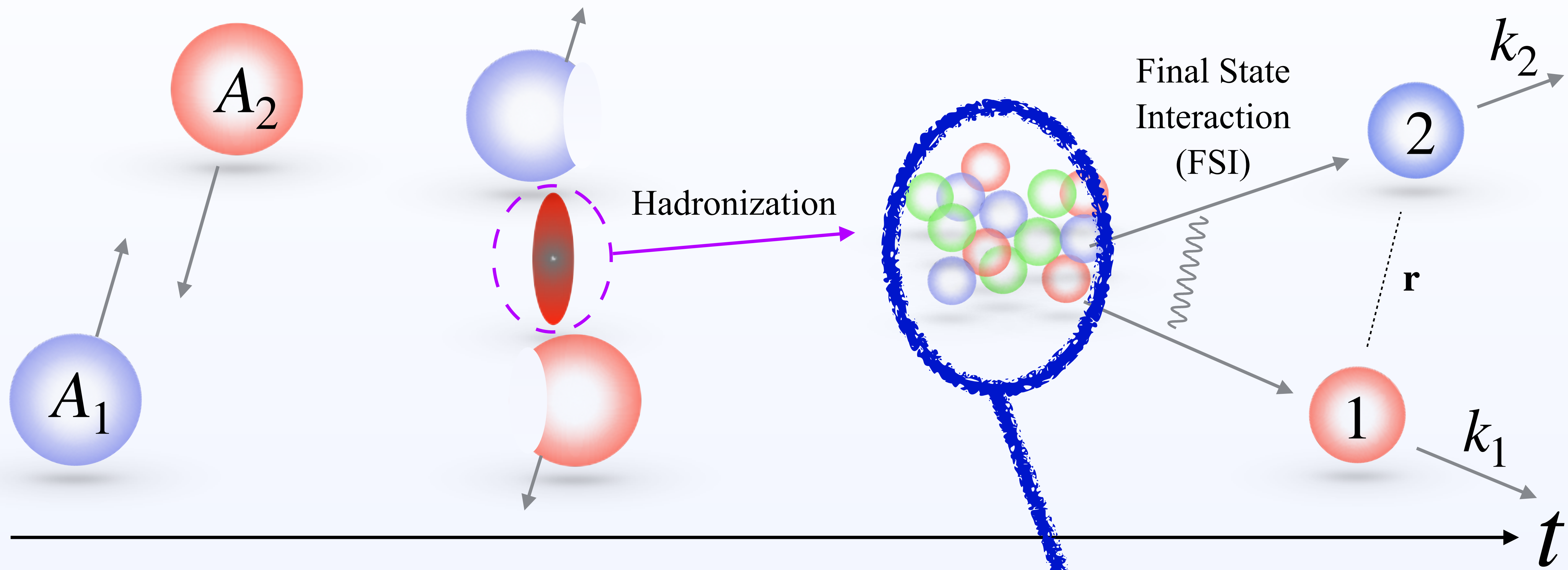

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$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

- Depends on …

  Collision detail (A_i, energy, centrality)

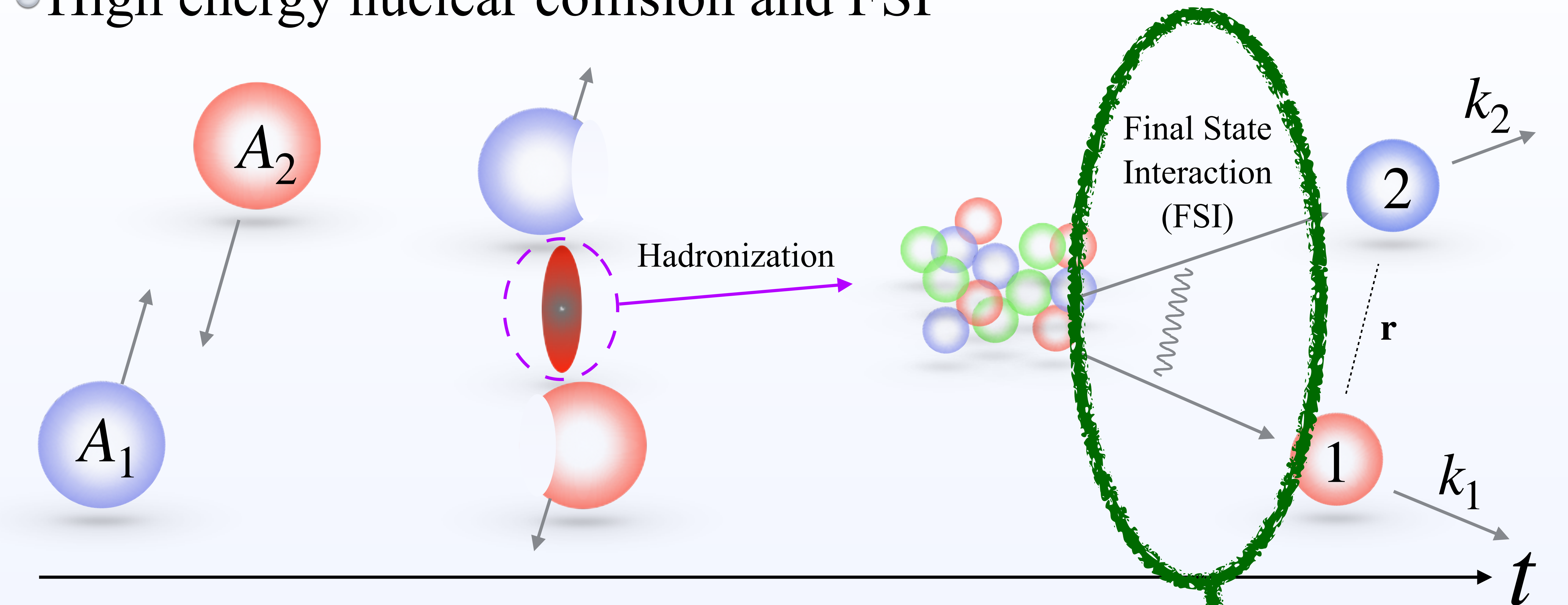
- Including information of…

  size of hadron source,

  momentum dependence, weight…

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



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

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

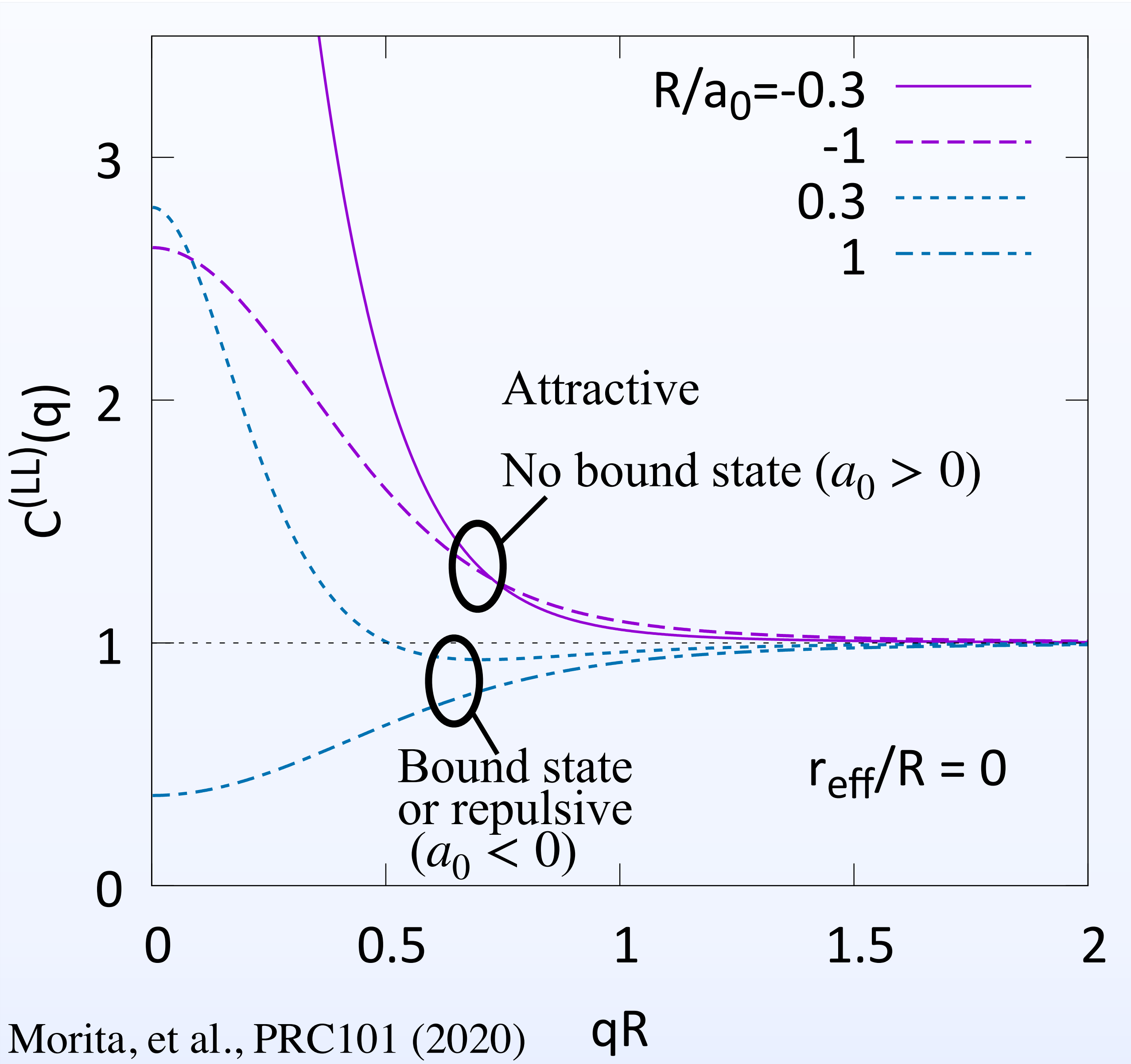
- Depends on …

  Interaction (strong and Coulomb)

  quantum statistics (Fermion, boson)

- Line shapes of $C(q)$: relation to interaction

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



Morita, et al., PRC101 (2020)

- Scattering length a_0 and source size R determines the suppression/enhancement of line shape   * $a_0 = \mathscr{F}(q=0)$

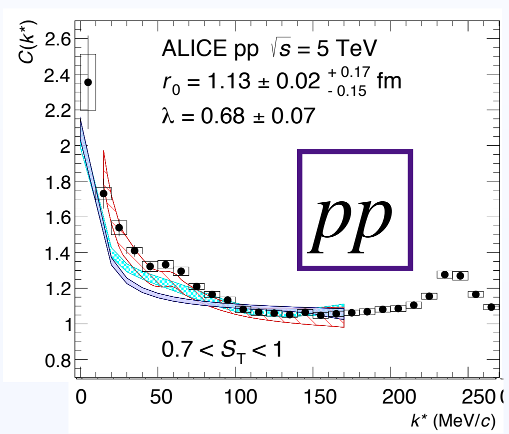
- Repulsive int. ($a_0 < 0$, small $|a_0|$)
  - ➡ Suppressed $C(q)$

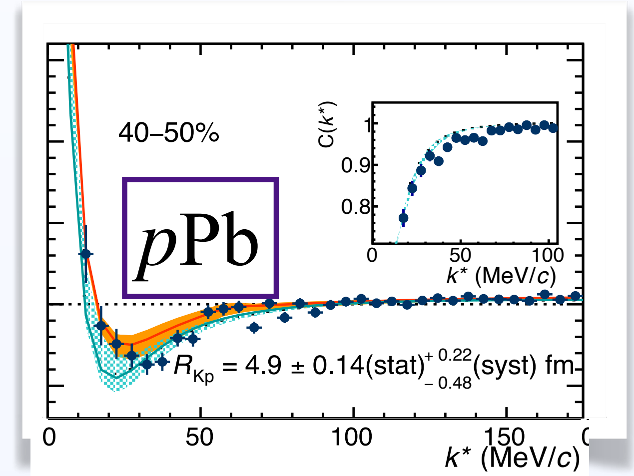
- Attractive int. w/ bound state ($a_0 < 0$, large $|a_0|$)
  - ➡ Suppressed $C(q)$ for Large R
    Enhanced $C(q)$ for small R

- Attractive int. w/o bound state ($a_0 > 0$)
  - ➡ Enhanced $C(q)$

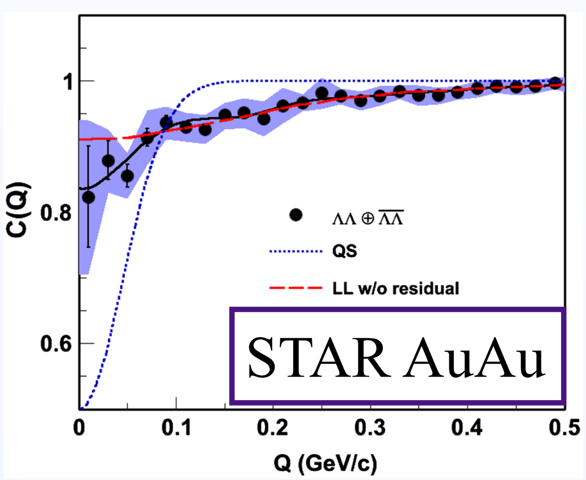
Experimental data in various sectors

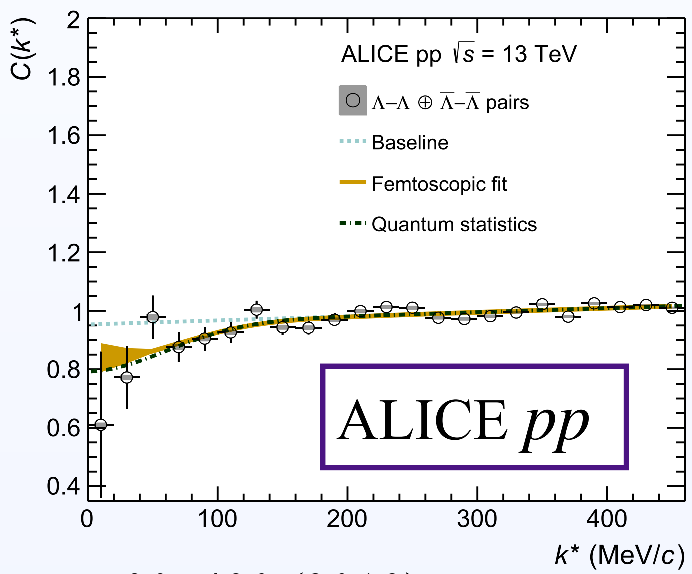
- $K^{\pm}p$ ALICE *pp*: PRL 124 (2020) 9, 092301
  PbPb: PLB 822 (2021) 136708
  STAR AuAu: NPA 982 (2019) 359



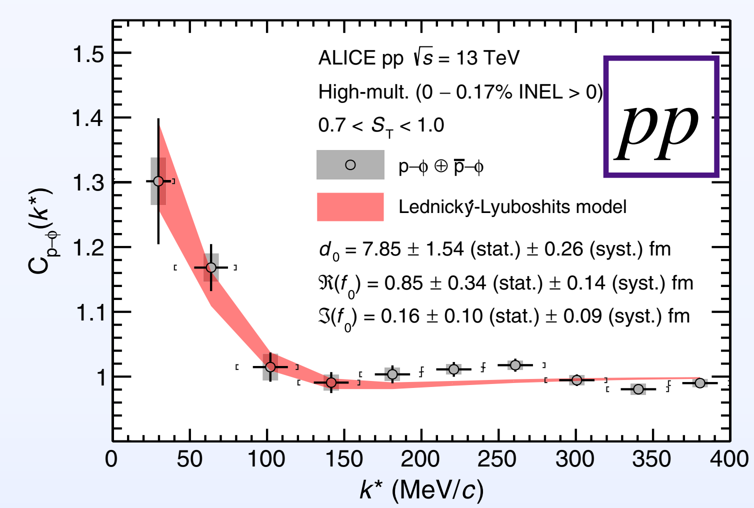


- $\Lambda\Lambda$ STAR AuAu: PRL 114,022301(2015)
  ALICE *pp*: PLB 797 (2019) 134822
  PbPb: PRC99, 024001 (2019)

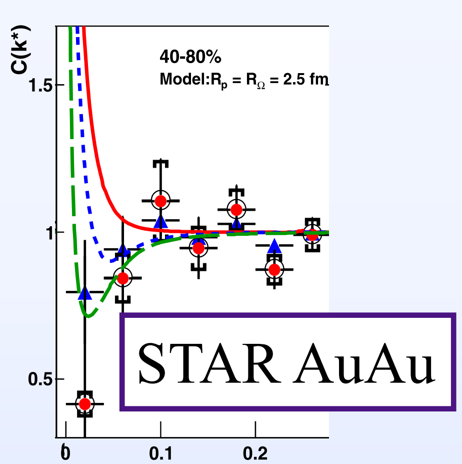


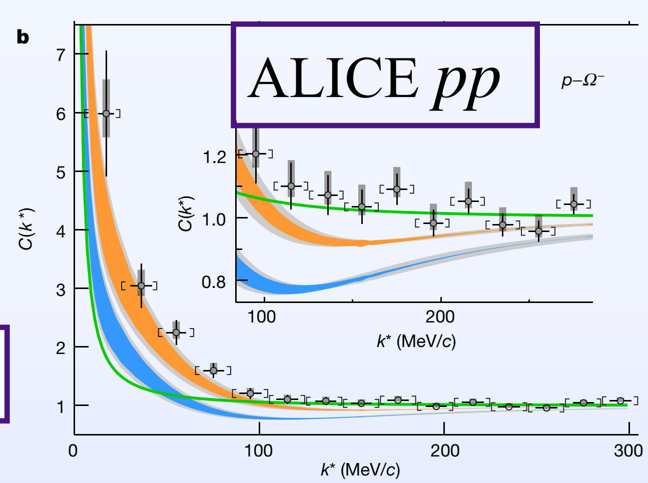


- $p\phi$ ALICE *pp*: PRL 127 (2021) 17, 172301



- $p\Omega$ STAR AuAu: PLB 790, 490 (2019)
  ALICE *pp*: Nature 588 (2020) 232





How to construct correlation model from theory; $\mathscr{F}(q) \to C(q)$

- Using effective potential
  - Construct the eff. potential by reproducing the amplitude $\mathscr{F}$ (or threshold parameters (a_0, r_e))
  - Solving the Schrödinger eq. $\longrightarrow \varphi$
- Using half offshell T-matrix $T_l(q, k; E)$ Haidenbauer, Nuclear Physics A 981 (2019) 1–16
  - $T_l(q, k; E) \longrightarrow \varphi$

$$\tilde{\psi}(k, r) = j_l(kr) + \frac{1}{\pi}\int j_l(qr)\, dq q^2 \frac{1}{E - E_1(q) - E_2(q) + i\epsilon} T_l(q, k; E)$$

- Using Lednicky-Lyuboshitz formula
  - Direrct relation between $C(q)$ and $\mathscr{F}(q)$
  - Detaill —> Next slide

➡ Comparison of model predictions and correlation data

How to extract interaction from Correlation data; $C(q) \to \mathscr{F}(q)$

- Lednicky-Lyuboshitz (LL) formula R. Lednicky, et al. Sov. J. Nucl. Phys. 35(1982).
  - Approximate φ by asymptotic wave func.(s-wave only)

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

$$\varphi^{(-)}(\mathbf{q},\mathbf{r}) \xrightarrow{r\to\infty} \exp(-i\mathbf{q}\cdot\mathbf{r}) + \frac{\mathscr{F}(-q)}{r}\exp(-iqr)$$

  - Use effective range expansion for amplitude $\mathscr{F}$

$$\mathscr{F}(q) = \left[\frac{1}{a_0} + \frac{r_e}{2}q^2 - iq\right]^{-1}$$

$$C(q) = 1 + \left[\frac{|\mathscr{F}(q)|^2}{2R^2}F_3\left(\frac{r_{\mathrm{eff}}}{R}\right) + \frac{2\mathrm{Re}\ \mathscr{F}(q)}{\sqrt{\pi}R}F_1(2qR) - \frac{\mathrm{Im}\ \mathscr{F}(q)}{R}F_2(2qR)\right]$$

  - Fit the data with formula

- Direct relation between $C(q)$ and $\mathscr{F}(q)$
- Difficult to introduce the detailed interaction e.g. coupled-channel
- Coulomb int. can be only introduced with Gamow factor (too crude for $C(q)$)

How to extract interaction from Correlation data; $C(q) \to \mathscr{F}(q)$

- Potential method

$$C(q) \to V(r) \to \mathscr{F}(q)$$

- Parametrize the potential

e.g. $V(r) = V_0 \exp(-(mr)^2) \xrightarrow{H\varphi = E\varphi} \varphi \xrightarrow{C(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r}) |\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2} C(q)$

- Determine the parameters by fitting the data

- Calculate the amplitude or threshold parameters (a_0, r_e) from $V(r)$

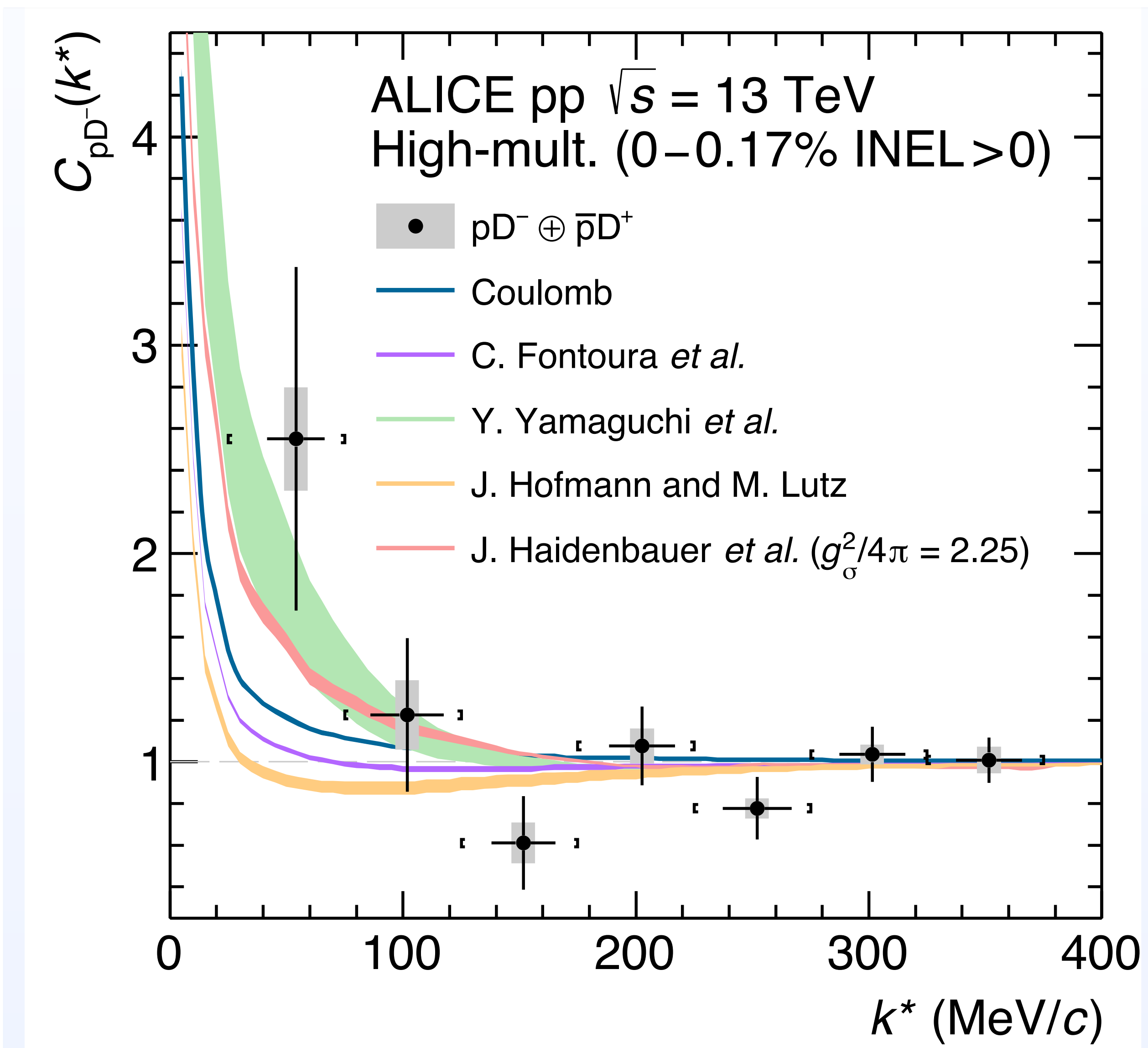
  - More fitting costs (needs to solve Schrödinger eq. for every change of parameters.)
  - Easy to introduce coupled-channel effect
  - Coulomb effect can be precisely calculated by adding Coulomb pot. in H.

→ Amplitude can be directly determined from correlation data

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

$f_0 \equiv \mathscr{F}(E = E_{\mathrm{th}})$
+ : 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]			
– $g_\sigma^2/4\pi = 1$	0.14	−0.28	(1.2–1.5)
– $g_\sigma^2/4\pi = 2.25$	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

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

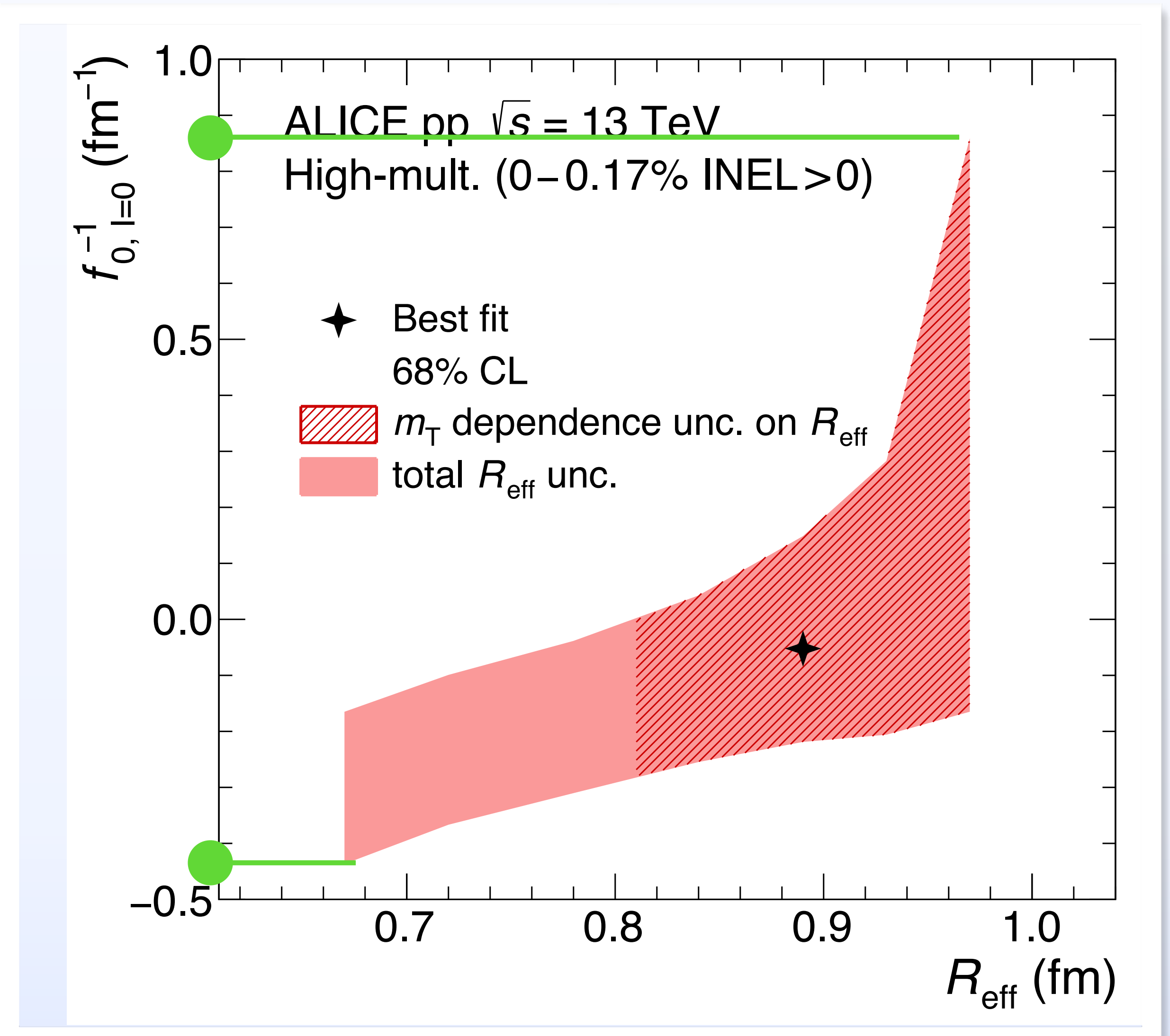
ALICE PRD 106 (2022) 5, 052010

- 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.

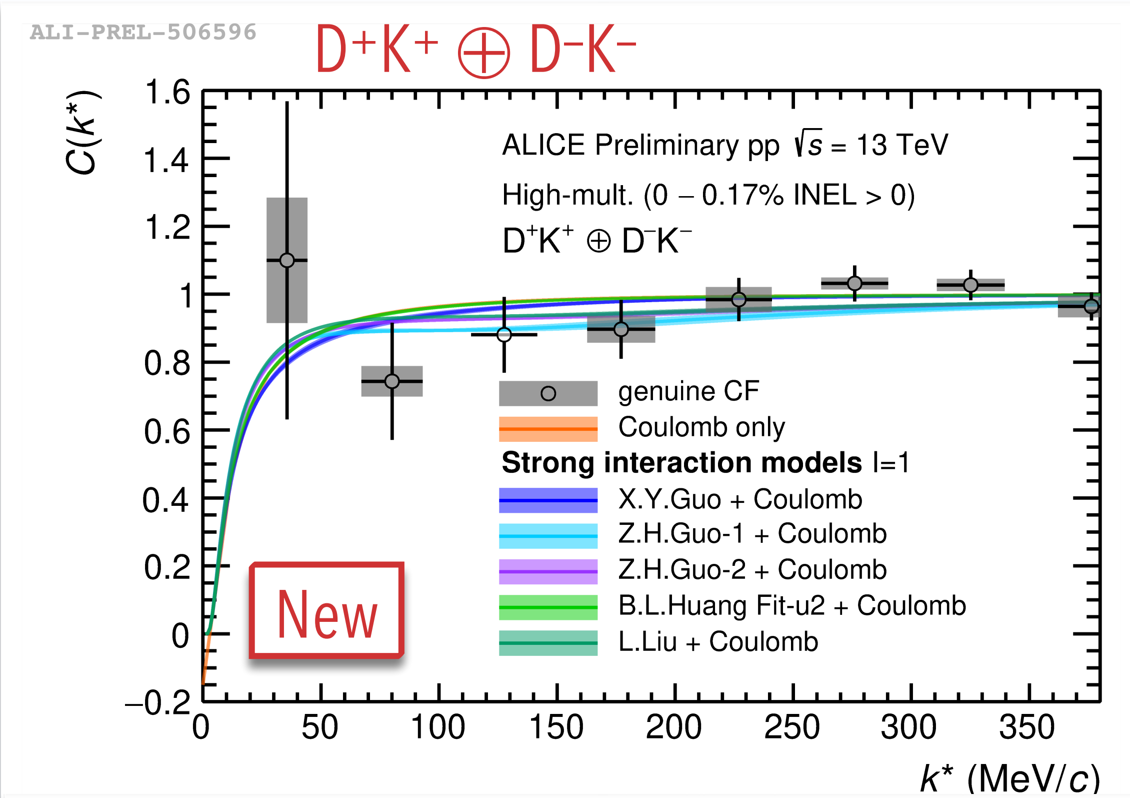
- Constraint on $f_{0,\, I=0}$

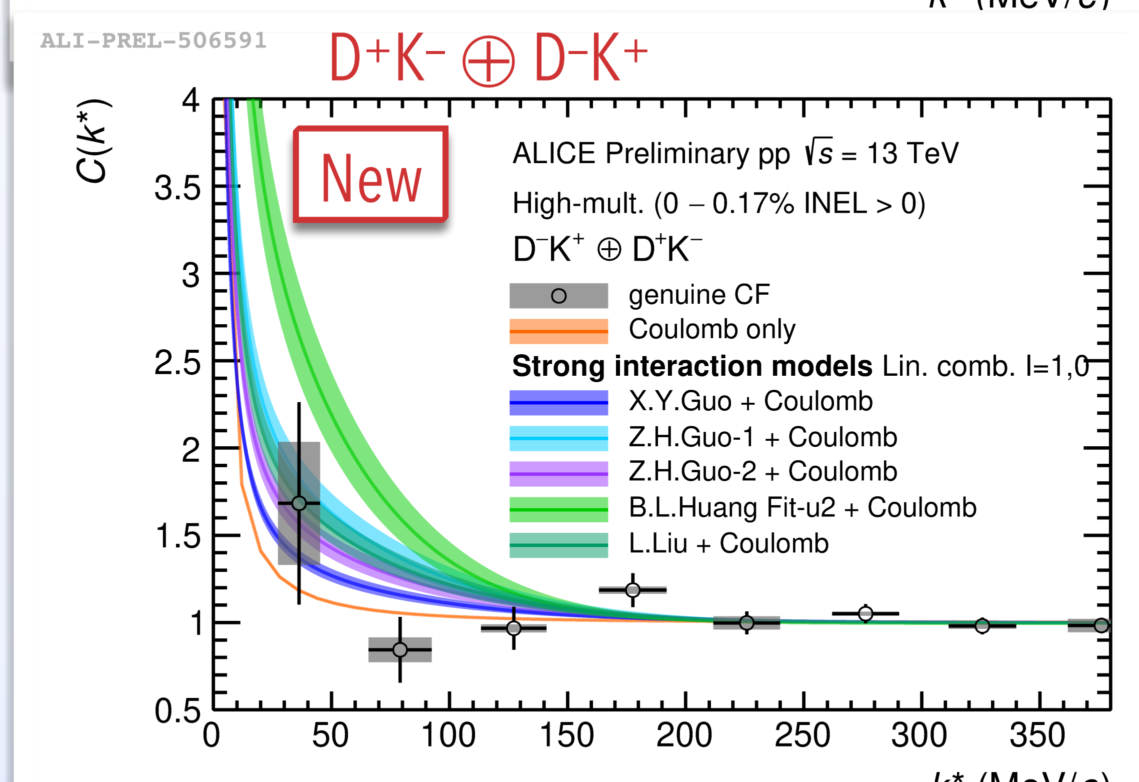


- 1σ constraint —> $f^{-1}_{0,\, I=0} \in [-0.4, 0.9]$ fm^{-1}:
- strongly attractive with or without bound state

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

DK and $D\bar{K}$ interaction





*All the pictures taken from Fabrizio Grosa's slide in Quark Matter 2022

$DK(\bar{K})$, $D\pi$ models:

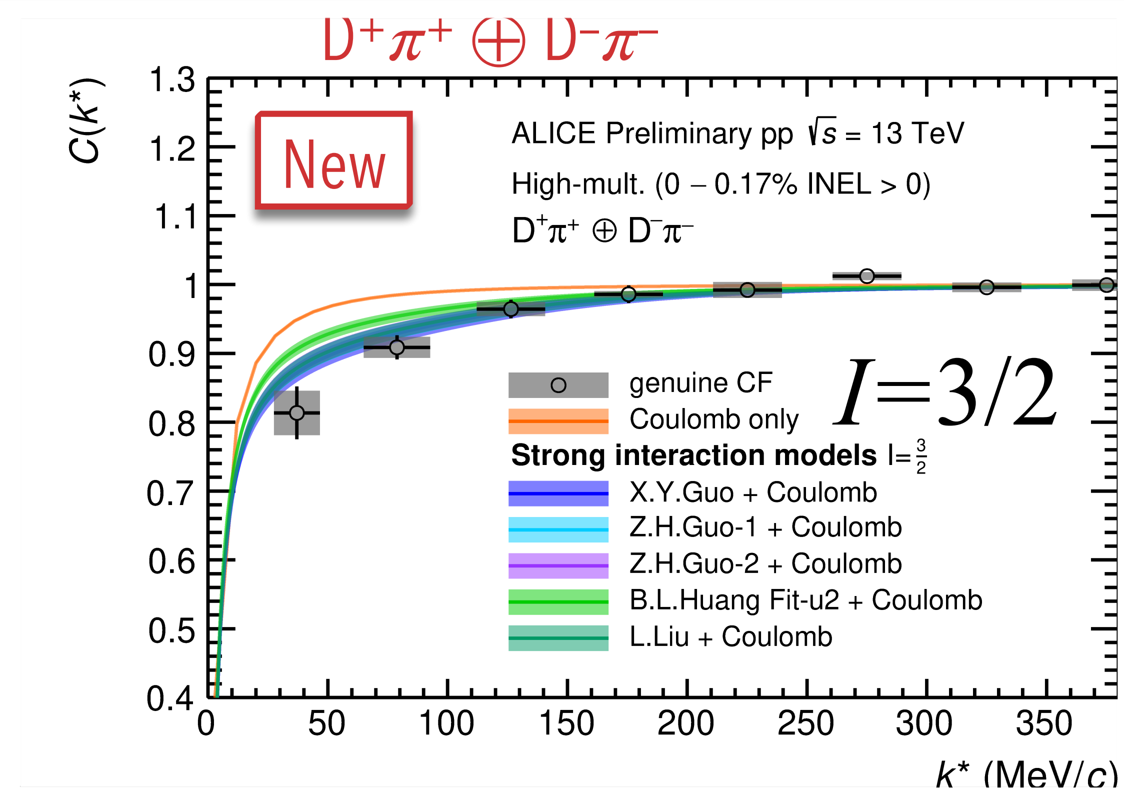
- All based on chiral Lagrangian
- Using the lattice data in DK/Dπ sector
  - L. Liu et al, Phys. Rev. D87 (2013) 014508
  - X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
  - B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
  - Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

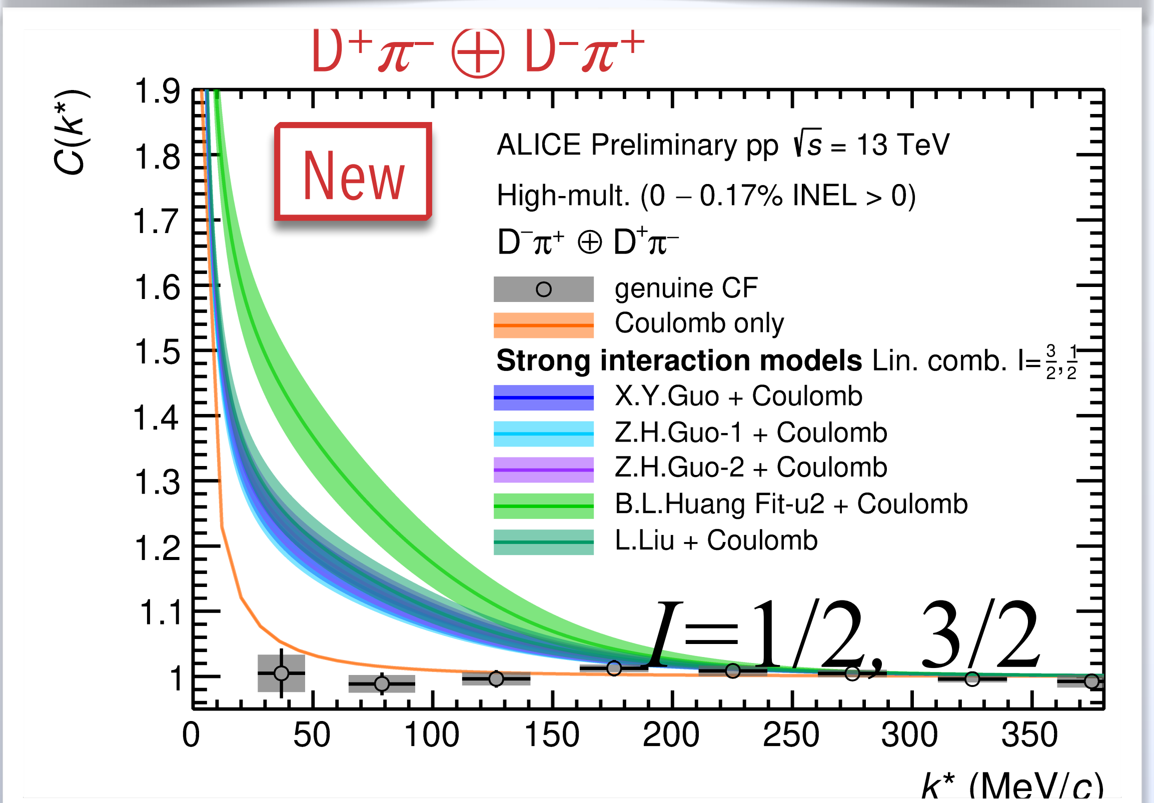
model	$DK(I=1)$	$D\bar{K}(I=1)$	$D\bar{K}(I=0)$
X.Y. Guo	-0.05	-0.22	0.46
Z.H. Guo 1	0.06+i0.30	-0.18	0.96
Z.H. Guo 2	0.05+i0.17	-0.19	0.68
B.L.Huang	-0.01	-0.24	1.81
L.Liu	0.07+i0.17	-0.20	0.84

$DK(\bar{K})$ correlation data

- No significant signals from the pure Coulomb case
- In good agreement with Chiral models

$D\pi$ interaction





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$D\pi$ interaction

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 03601
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

model	$D\pi(I=3/2)$	$D\pi(I=1/2)$
X.Y. Guo	-0.11	0.33
Z.H. Guo 1	-0.101	0.31
Z.H. Guo 2	-0.099	0.34
B.L. Huang	-0.06	0.61
L.Liu	-0.10	0.37

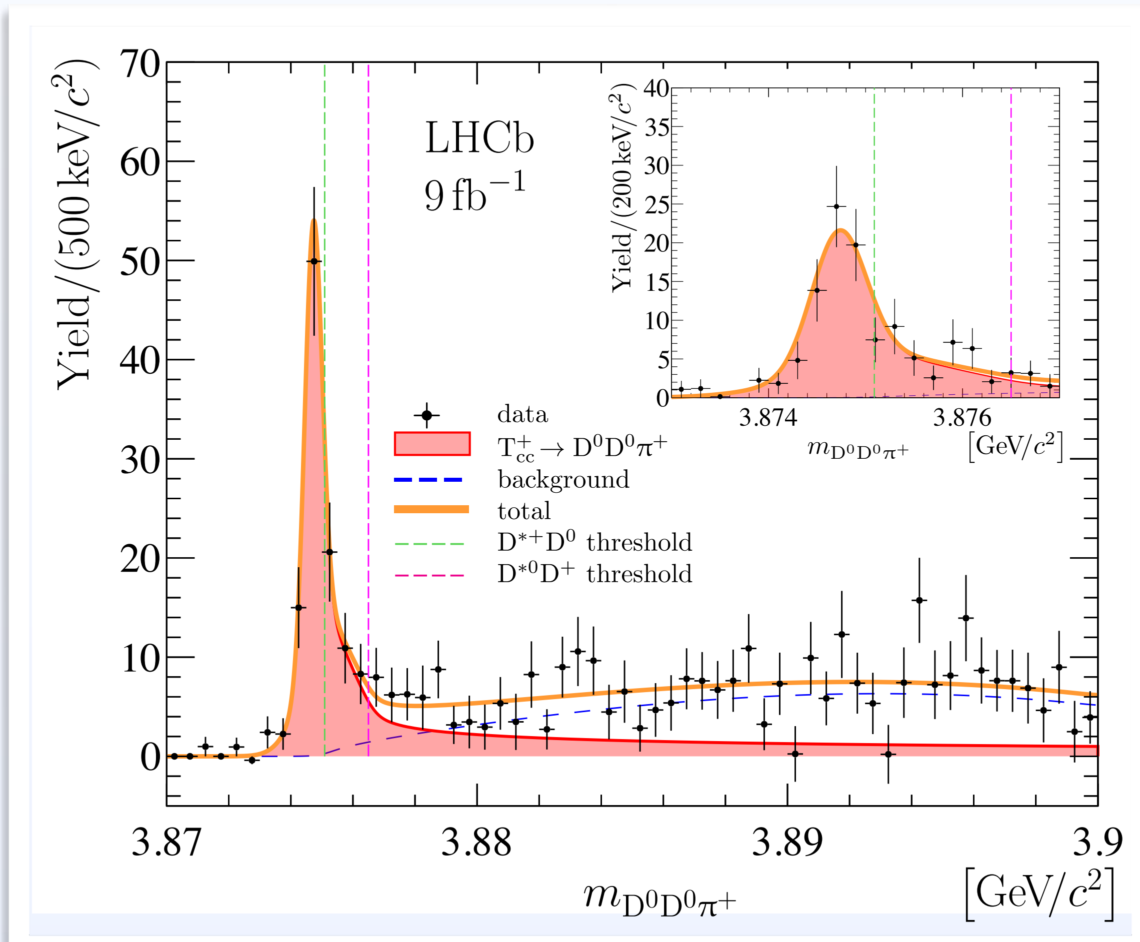
$D\pi$ correlation data

- $D^+\pi^+$ pair ($I=3/2$) is in good agreement with chiral models
- $D^+\pi^-$ pair does not show no enhancement from pure Coulomb case while all the chiral models predict enhanced CF

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

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

    LHCb, Nature Com. 13 (2022) 1

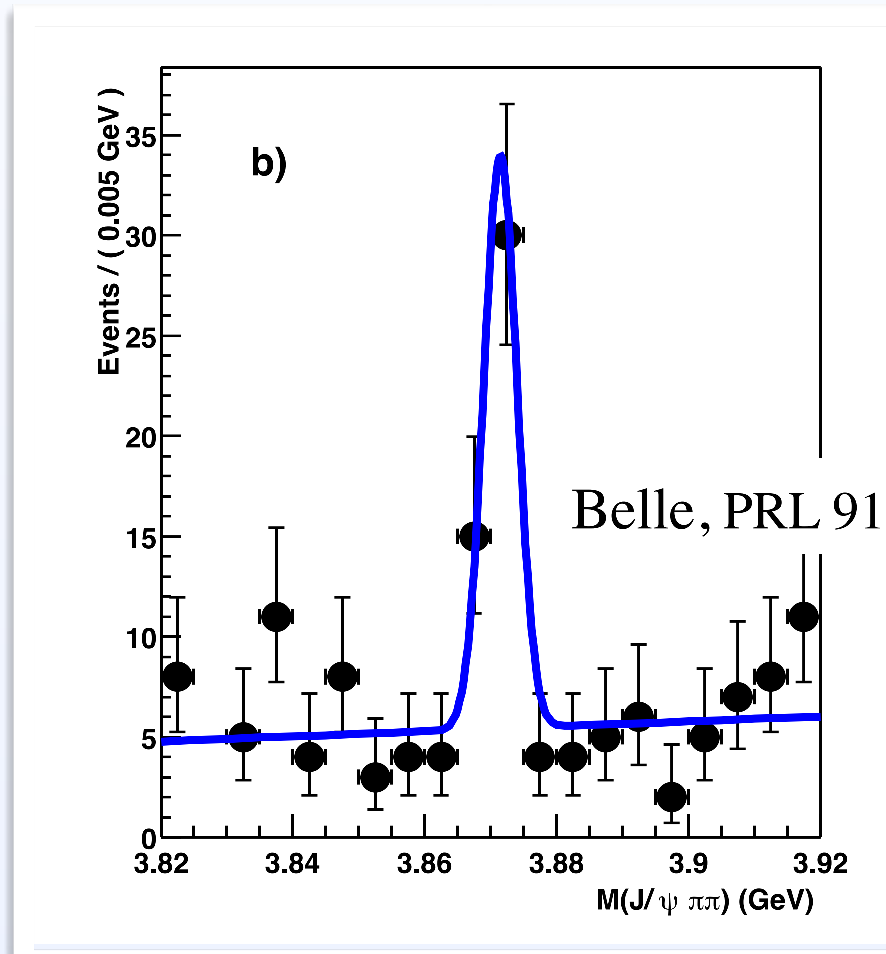


- $X(3872)$ or χ_{c1}
  - Firstly observed in $\pi\pi J/\Psi$ spectrum

    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

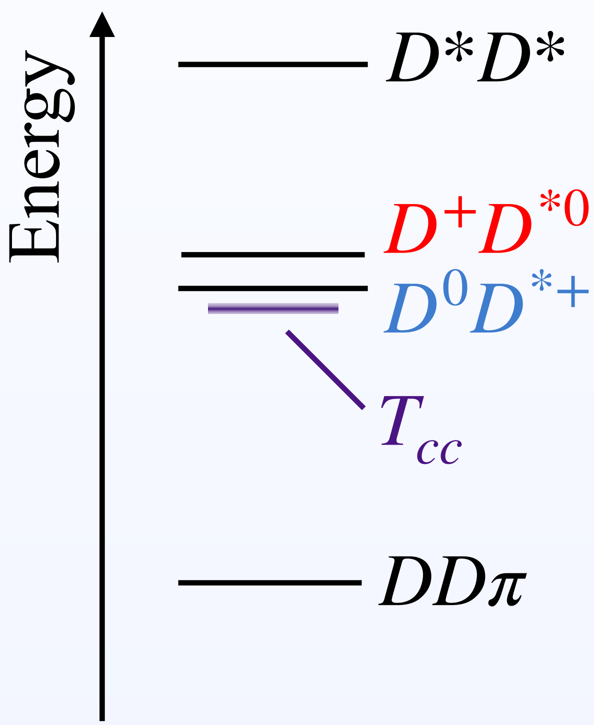
- DD^* and $D\bar{D}^*$ sector

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

+ : attractive w/o bound

- : repulsive
  or attractive w/ bound

$C = 2$



LHCb, Nature Com. 13 (2022) 1

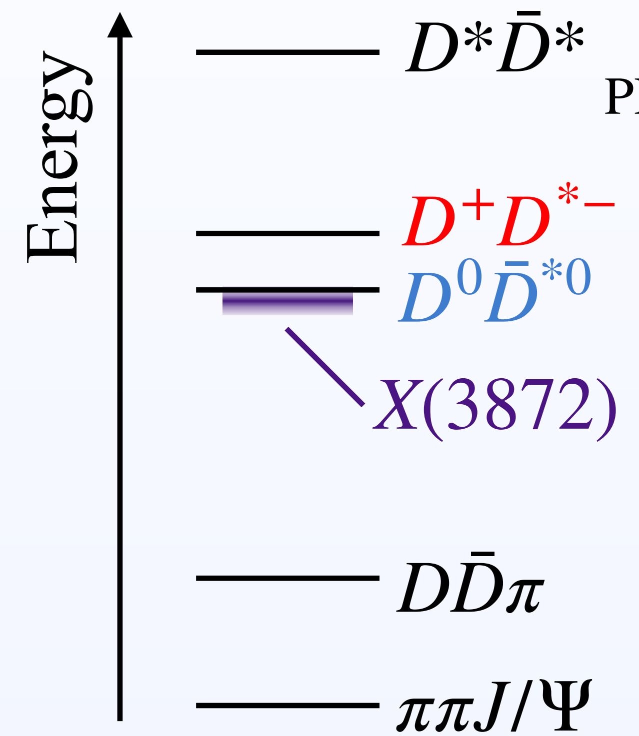
$$E_{T_{cc}} = \delta_m - \frac{i}{2}\Gamma$$

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

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

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

$C = 0$



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?

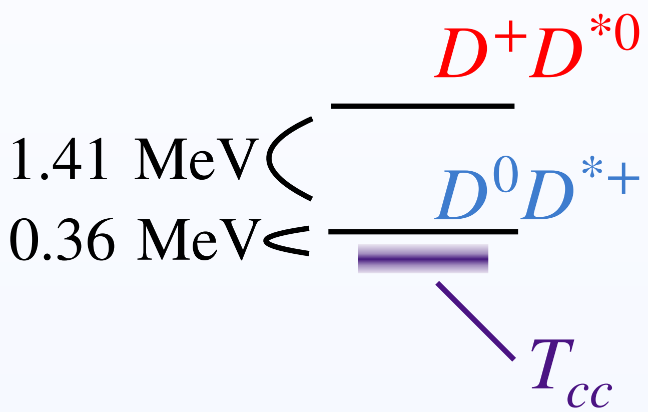
  ==>Strong attractive interaction

- Gaussian potential

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

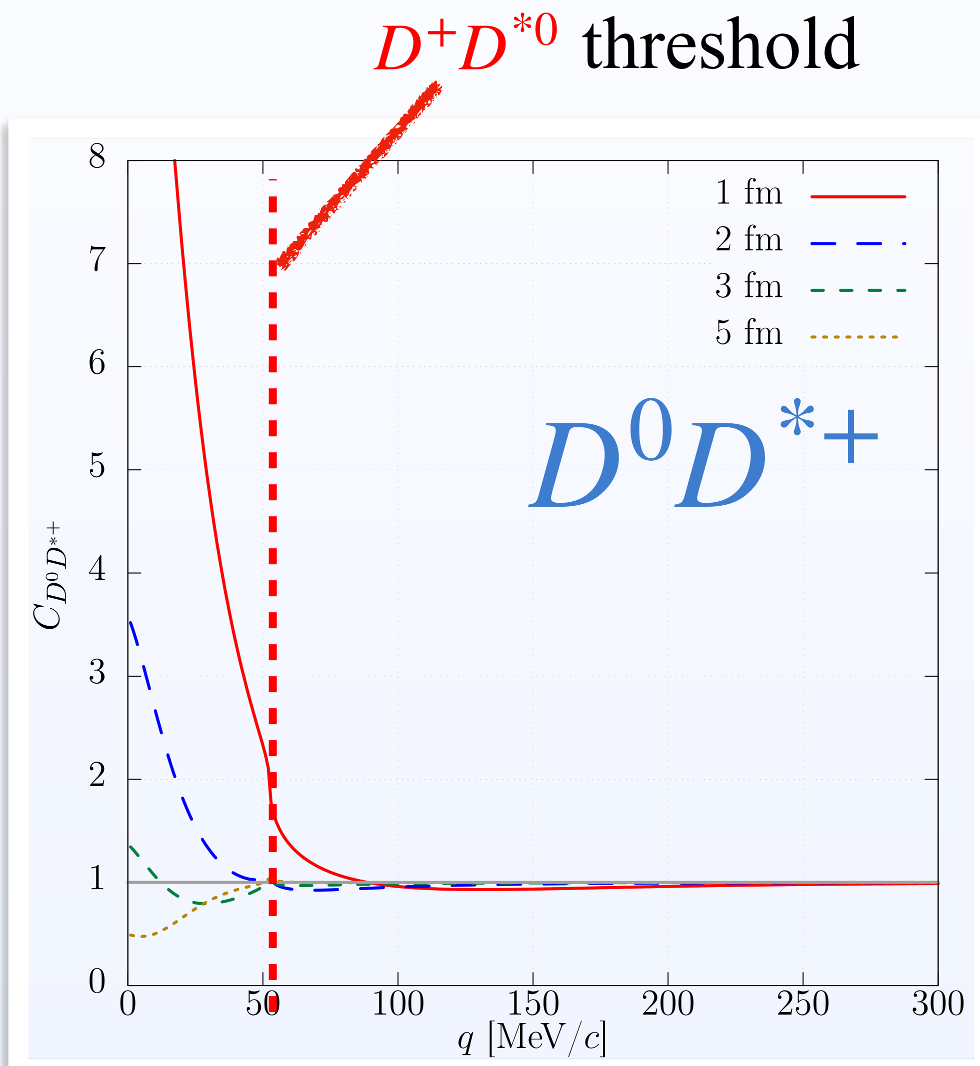
- m <— π exchange ($m = m_\pi$)
- V_0<— scattering lengths
- Assume dominant contribution from exotic channel ($I = 0$)
- Coupled-channel of two isospin channels

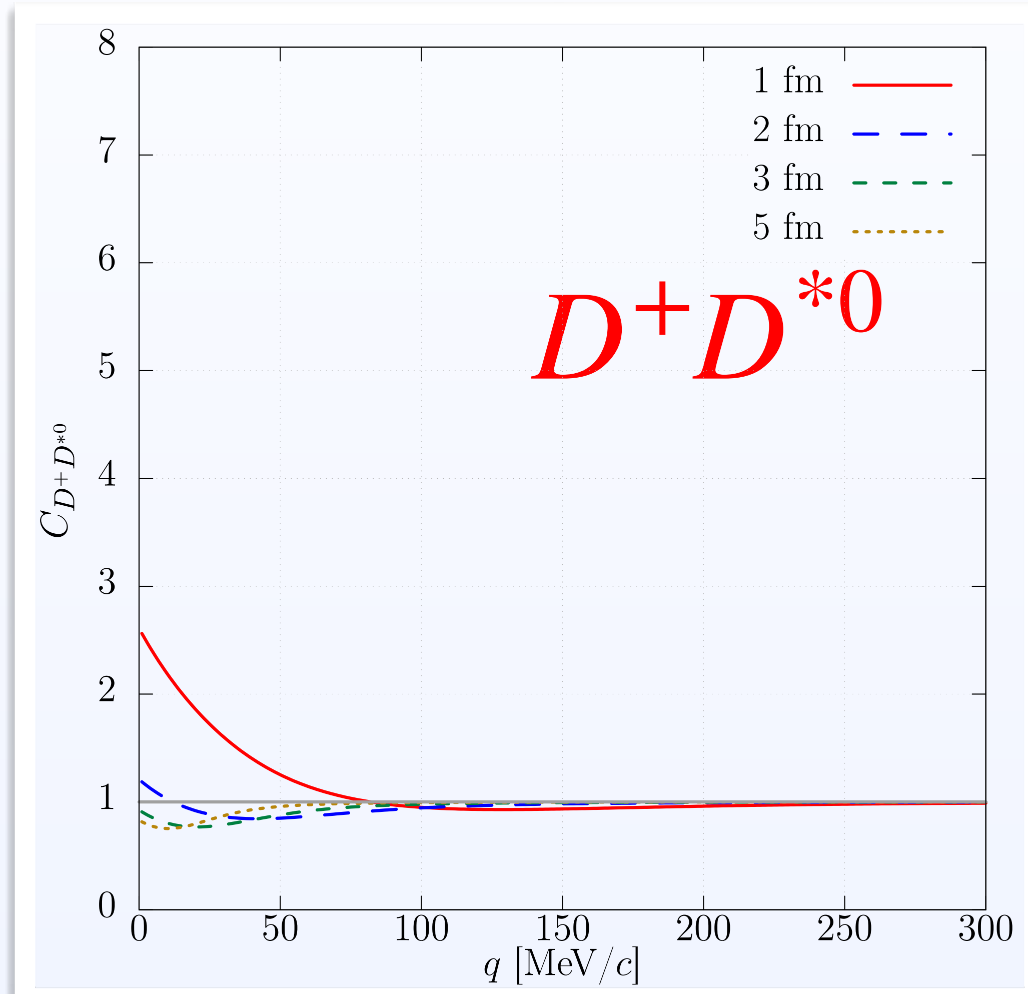
- DD^* correlation and T_{cc} state



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

LHCb, Nature Com. 13 (2022) 1

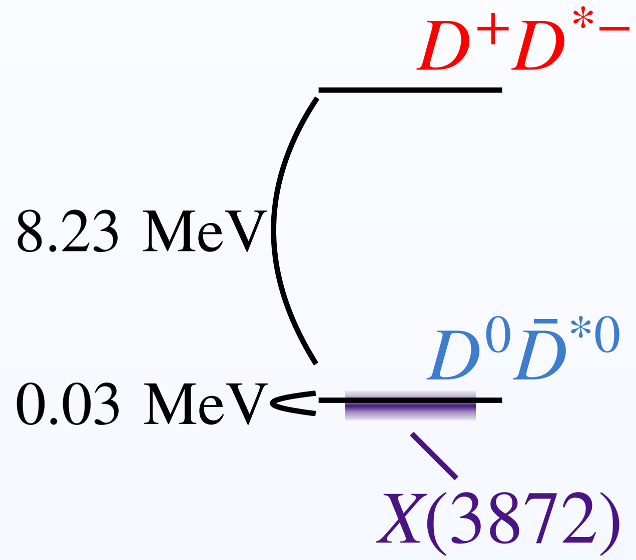




- Bound state like behavior for both pairs
- Stronger source size dep. for D^0D^{*+}
- D^+D^{*0} cusp is not prominent

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

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



PDG, PTEP 2020, 083C01 (2020)

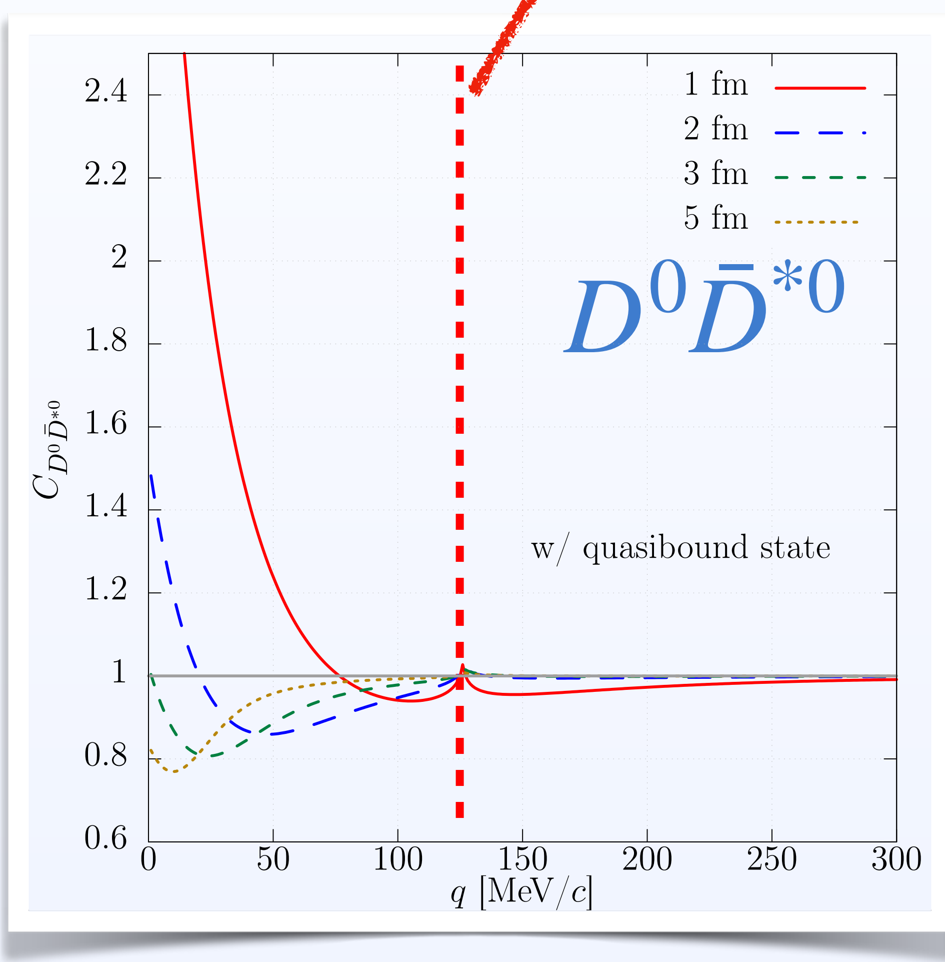
$$E_{X(3872)} = \delta_m - \frac{i}{2}\Gamma$$

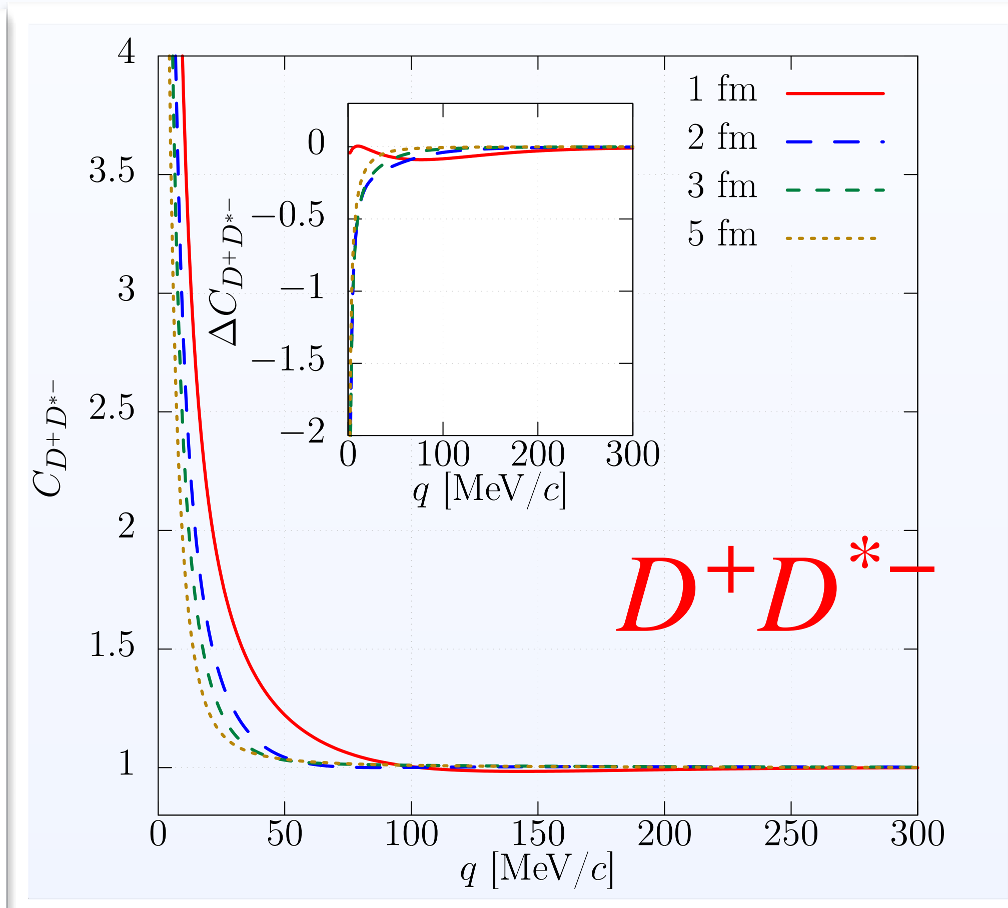
$$\delta m = -0.04\ \text{MeV}$$

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

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

D^+D^{*-} threshold

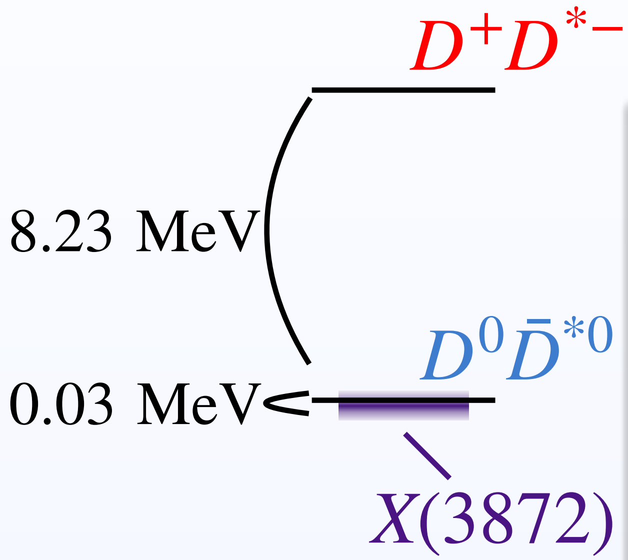




- D^0D^{*+} : Strong source size dep.
- D^+D^{*-} : Small effect of the strong int. (Coulomb int dominance)
- Moderate D^+D^{*+} cusp

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

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



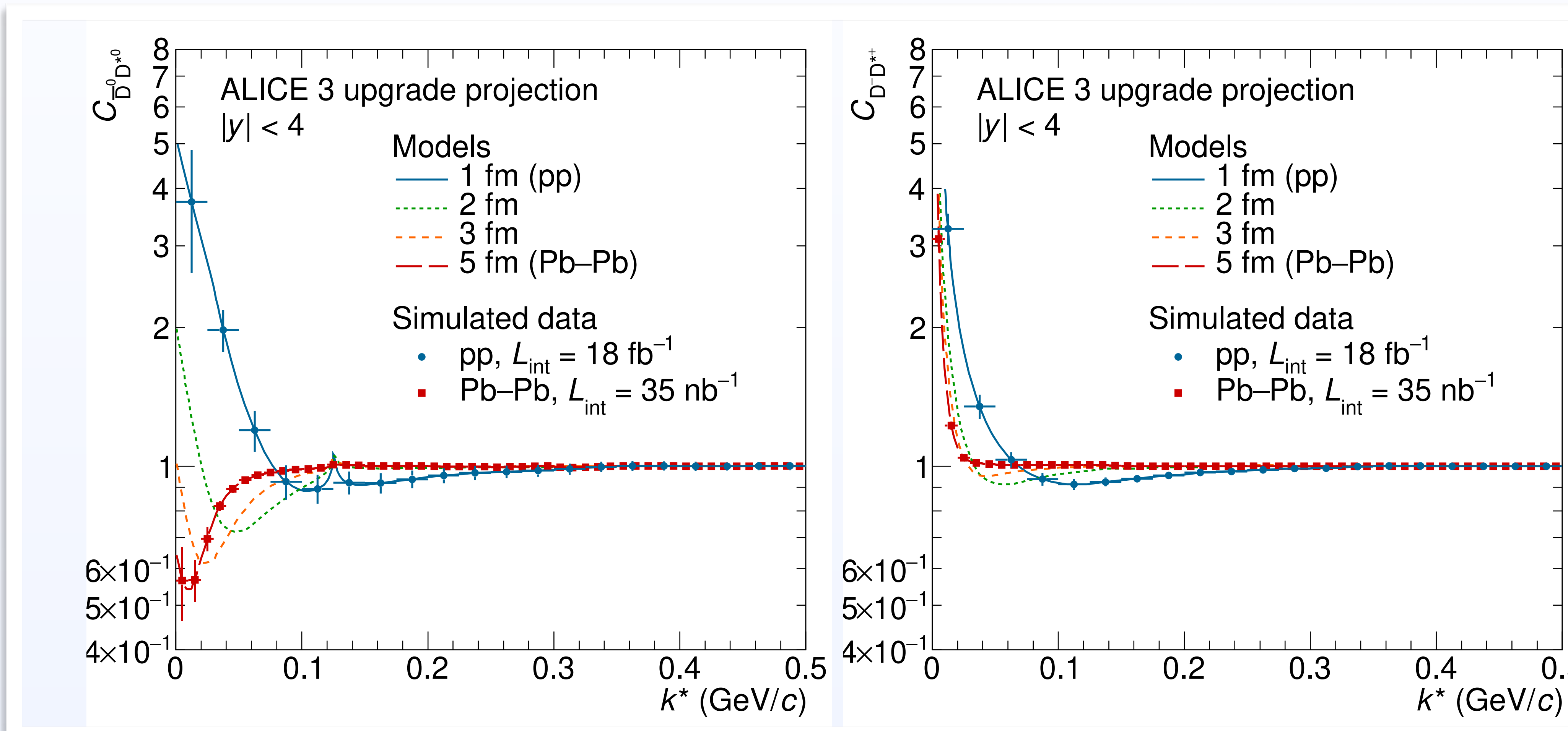
PDG, PTEP 2020, 083C01 (2020)

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

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

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

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



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

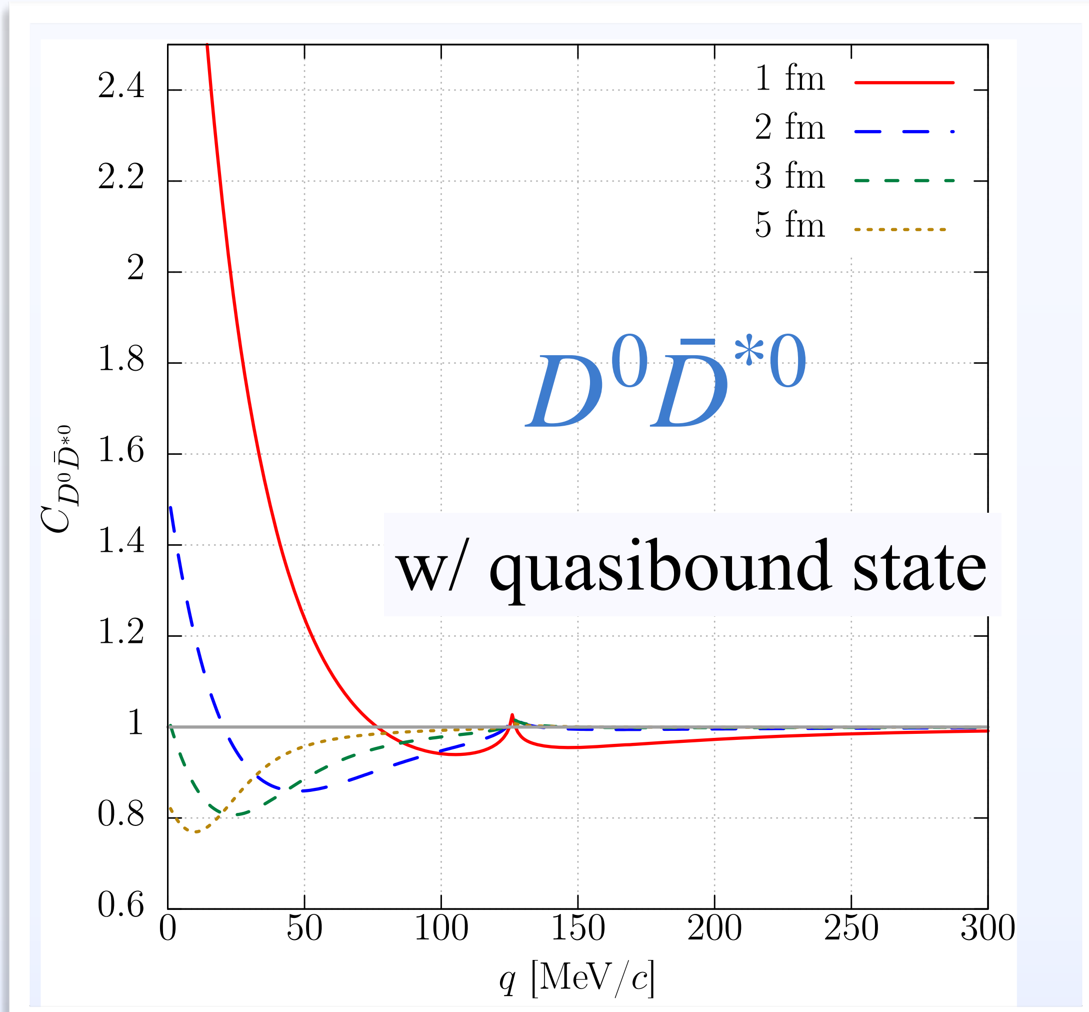
$a_0 \equiv \mathscr{F}(E = E_{\text{th}})$
+ : attractive w/o bound
- : repulsive
  or attractive w/ bound

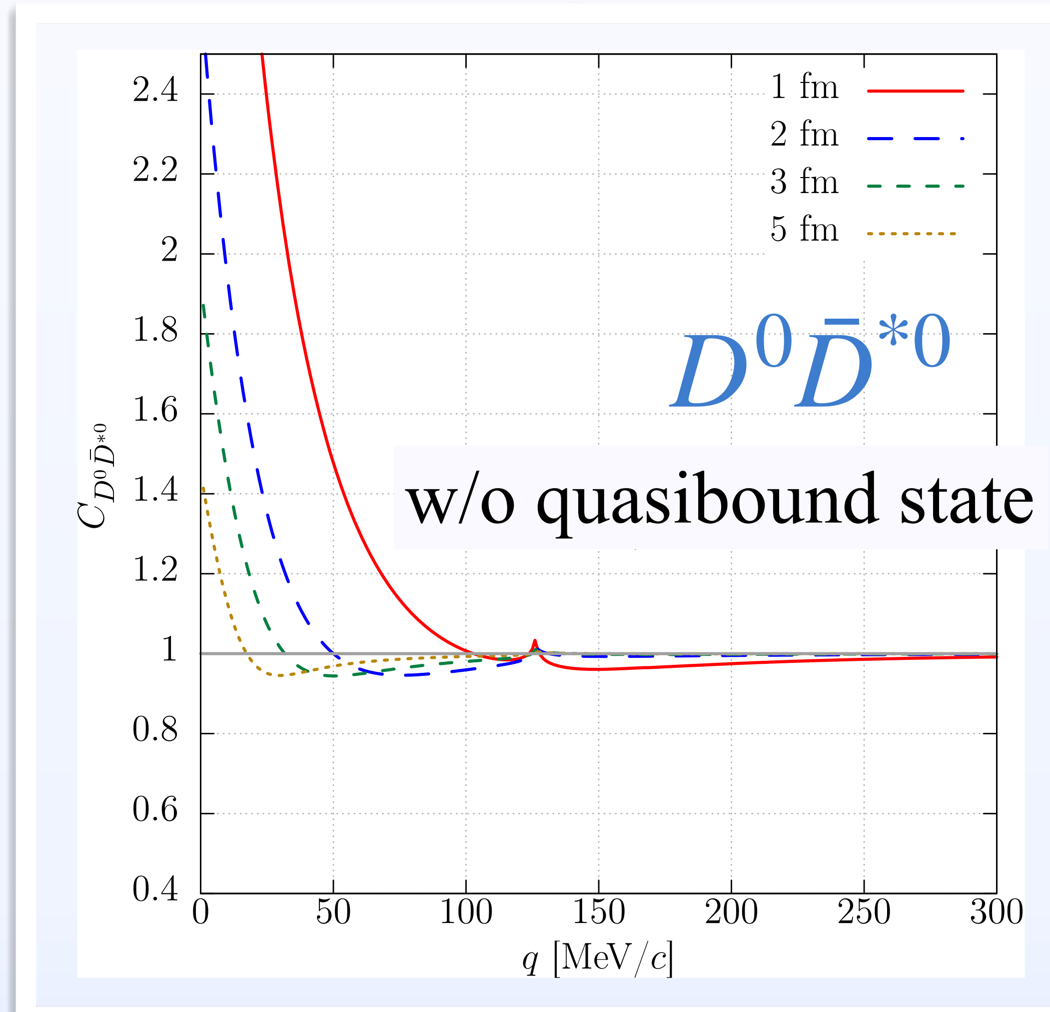
- $X(3872)$ as cusp
  - Empirical scattering length

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

weaken interaction

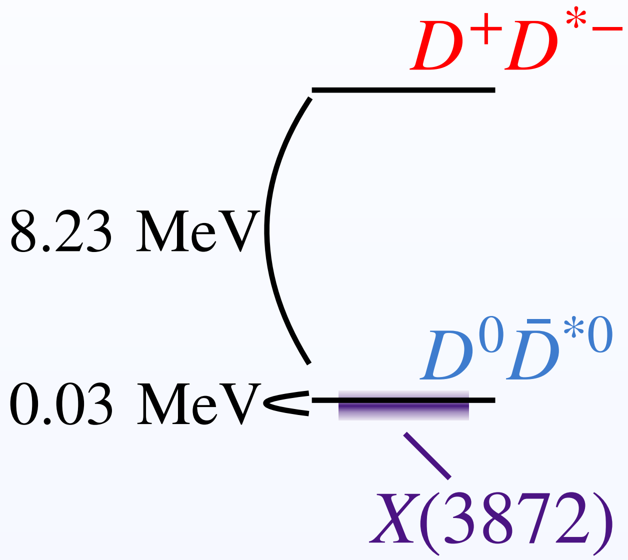
$a_0^{D^0\bar{D}^{*0}} = 2.30 + i4.00 \text{ fm}$





X(3872) with various assumptions

- $X(3872)$ with short range force



PDG, PTEP 2020, 083C01 (2020)

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

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

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

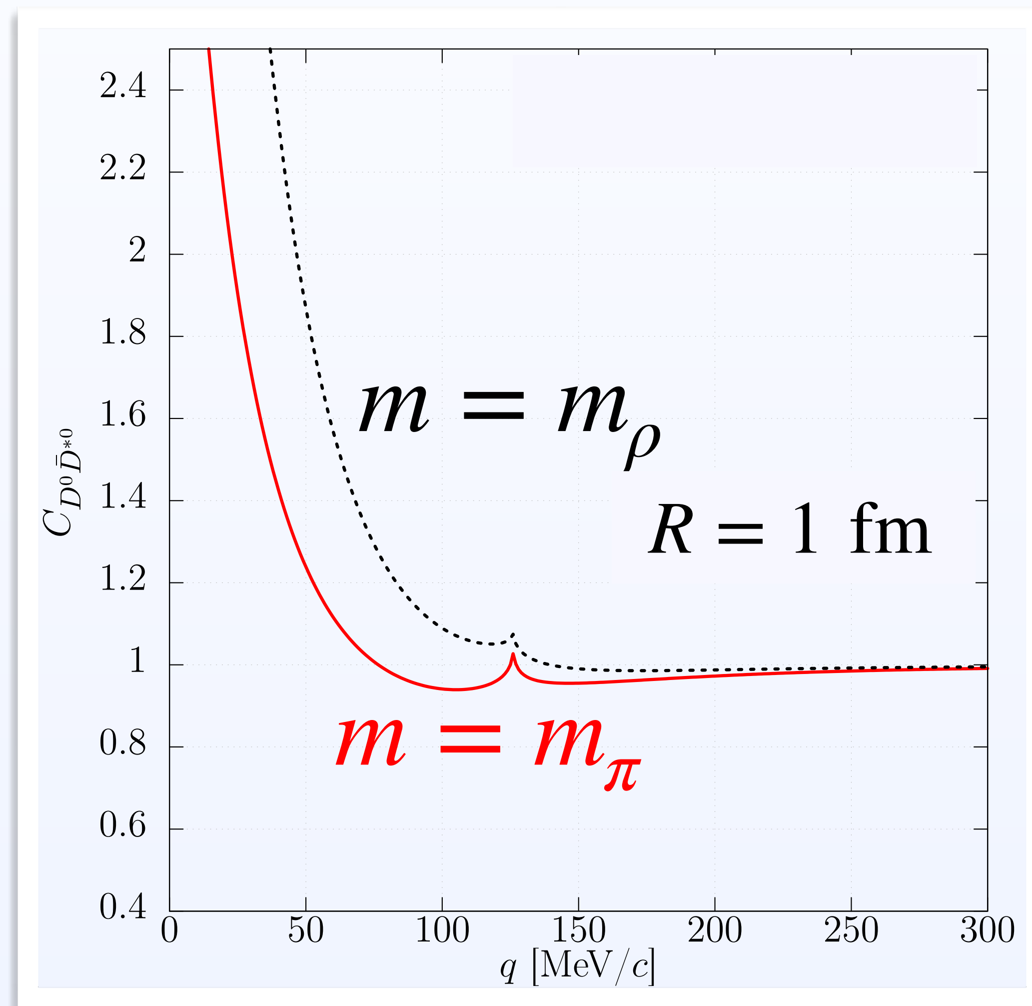
- Potential shape dependence

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

Two potentials fitted to same scattering length

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

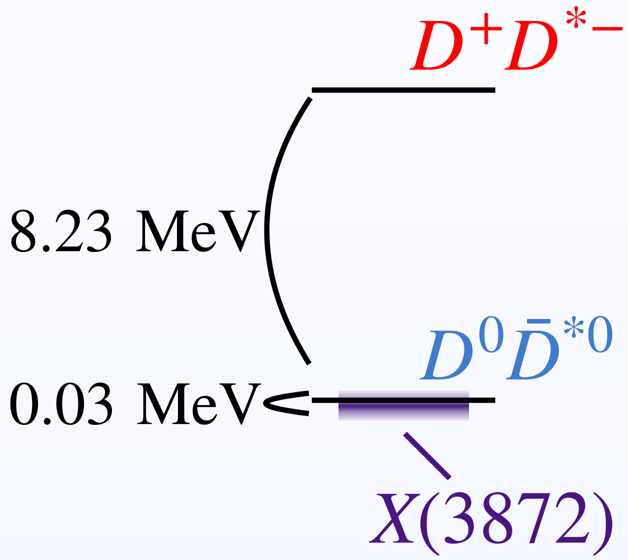
- Long range pot. : $m = m_\pi$
- Short range pot. : $m = m_\rho$



Change of the interaction range gives moderate enhancement

$X(3872)$ with various assumptions

- $X(3872)$ with $I = 1$ interaction



PDG, PTEP 2020, 083C01 (2020)

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

$\delta m = -0.04$ MeV

$\Gamma = 1.19$ MeV

- π exchange interaction
  - $\propto I \cdot I'$ ==> $V_{I=0}/V_{I=1} = -3$
  - Fit $a_0^{D^0\bar{D}^{*0}}$ for each case

repulsive $V_{I=1}$

$$V_{I=1} = -\mathrm{Re}\ V_{I=0}/3$$

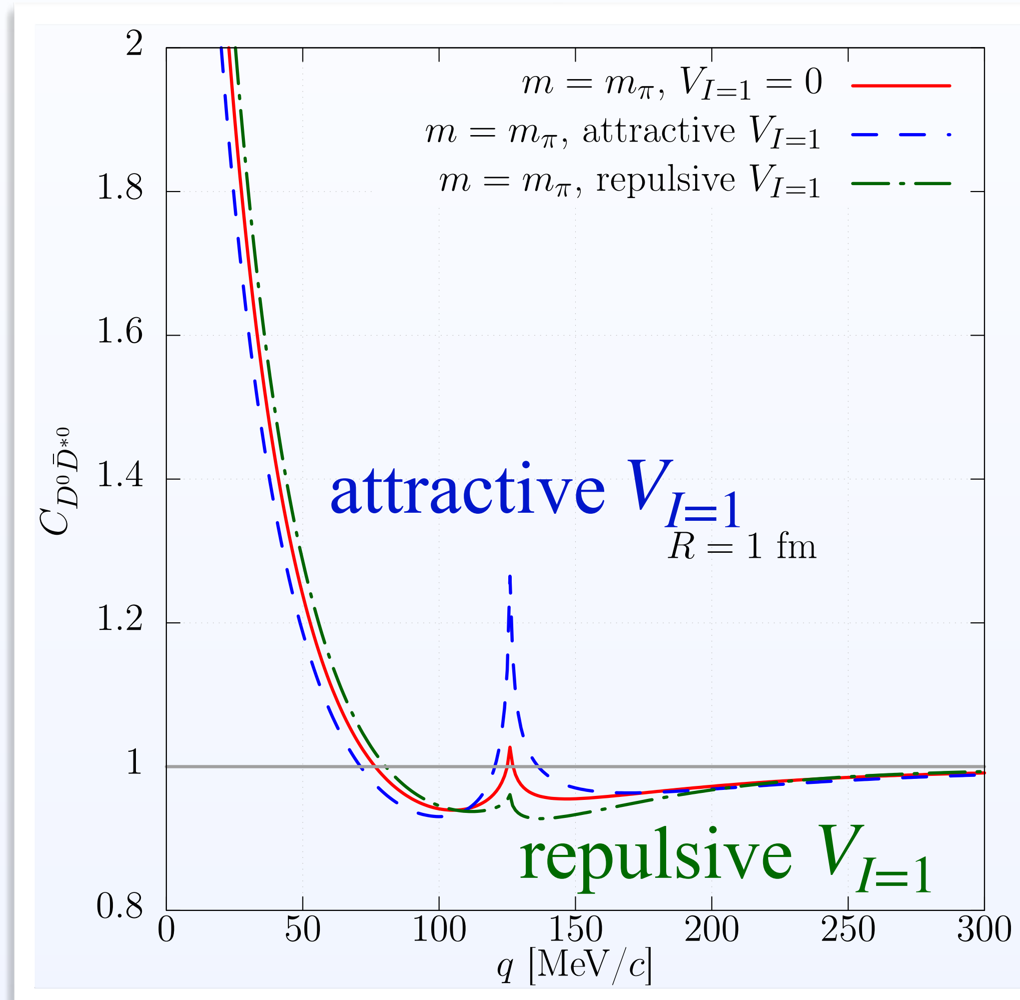
==> Weaker cusp

attractive $V_{I=1}$

$$V_{I=1} = \mathrm{Re}\ V_{I=0}/3$$

==> prominent cusp

* Due to the additional virtual pole around D^+D^{*-} threshold



The strength of the cusp depends on the detailed isospin structure of the interaction.

Summary

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the nature of bound state.
  - Comparison to model prediction
  - Direct extraction from $C(q)$ data

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

- $DK(\bar{K})$: Coulomb int. dominant and consistent with chiral models
  $D\pi$: Opposite-charge pair shows the discrepancy from chiral models

- $DD^{*}/D\bar{D}^{*}$
  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!