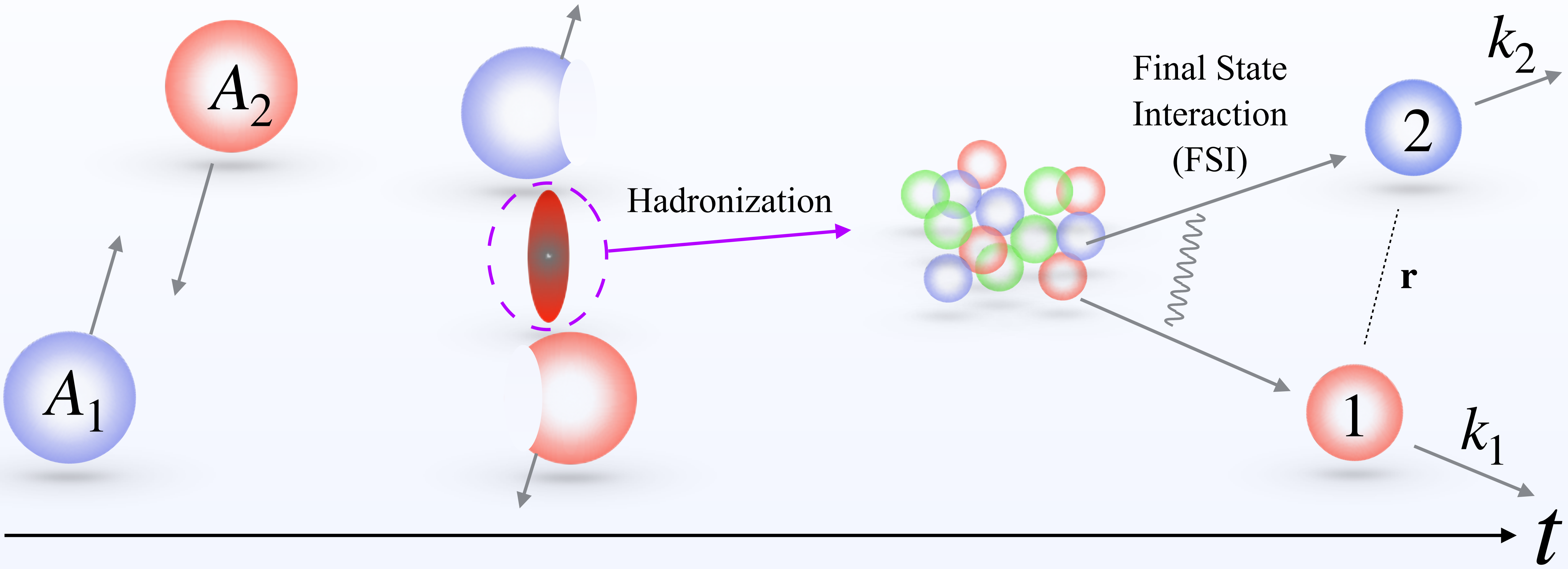
Yuki Kamiya
HISKP, Bonn Univ.

Study on hadron-hadron interaction with femtoscopic technique

14th International Conference on Hypernuclear and Strange Particle Physics (HYP2022)
@ Prague, Czech Republic, 2022/6/29

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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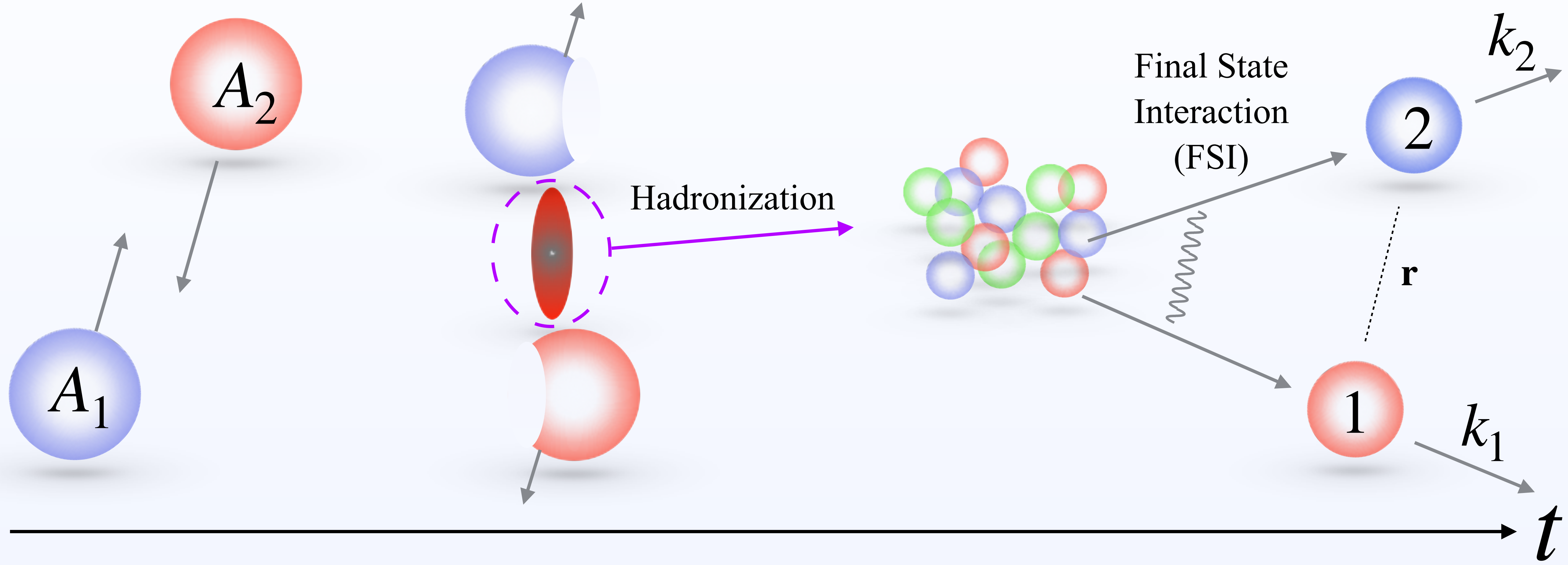

- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977) S. Pratt et. al. PRC 42 (1990)

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

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

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

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

Hadron correlation in high energy nuclear collision

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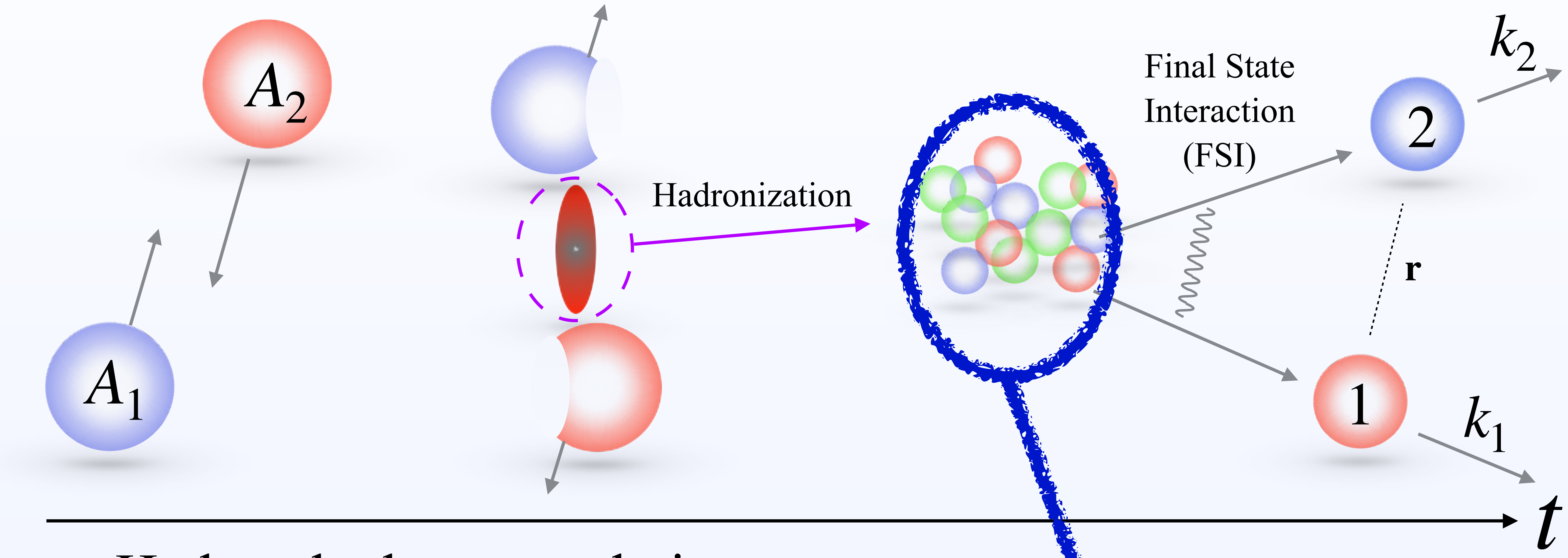

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$S(\mathbf{r})$: Source function

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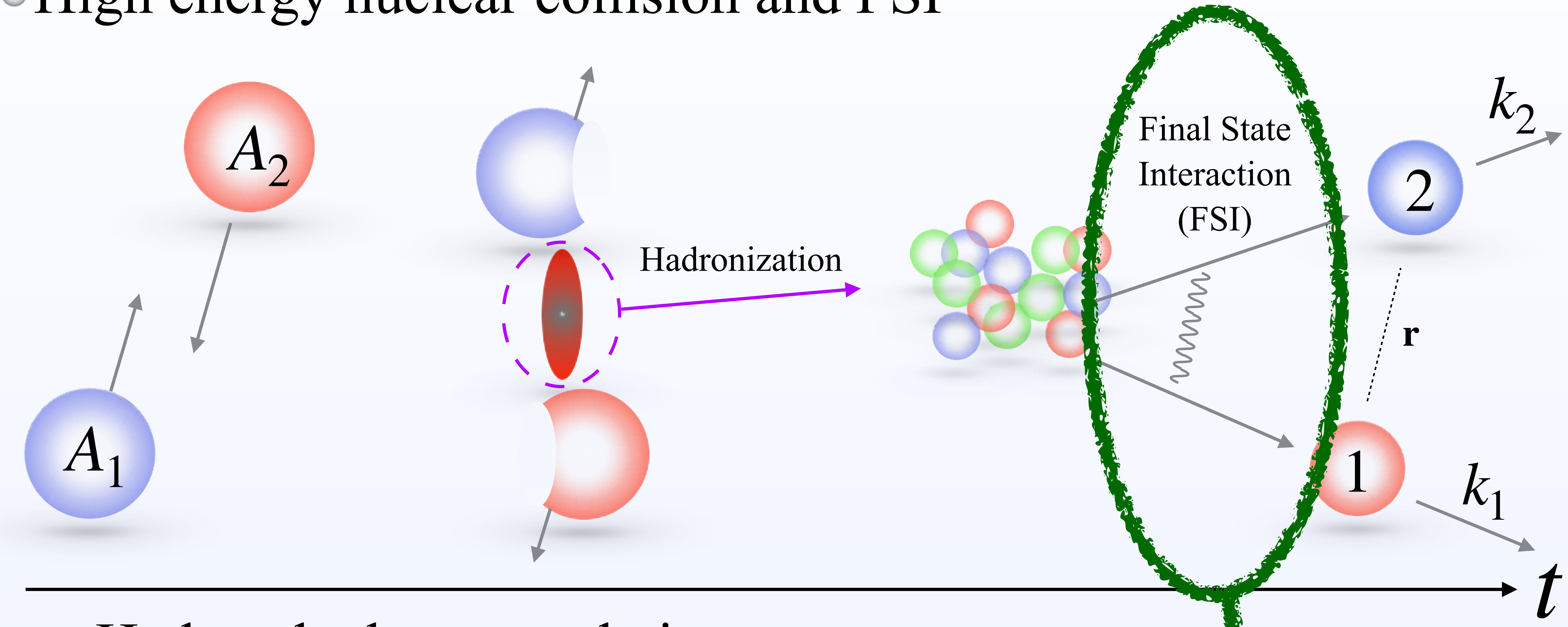
- Depends on …
  Collision detail (A_i, energy, centrality)
- Including information of…
  size of hadron source,
  momentum dependence, weight…

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



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- Depends on …

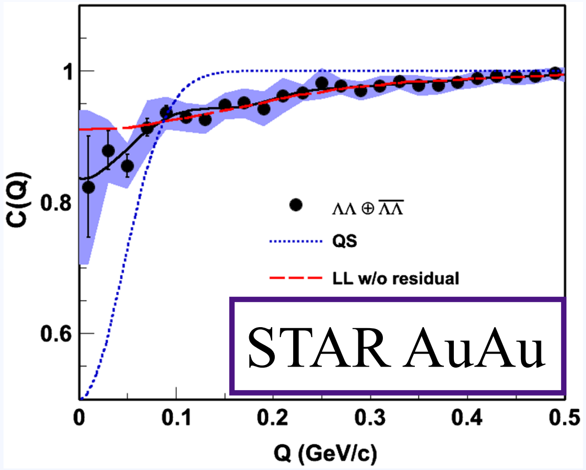
  Interaction (strong and Coulomb)

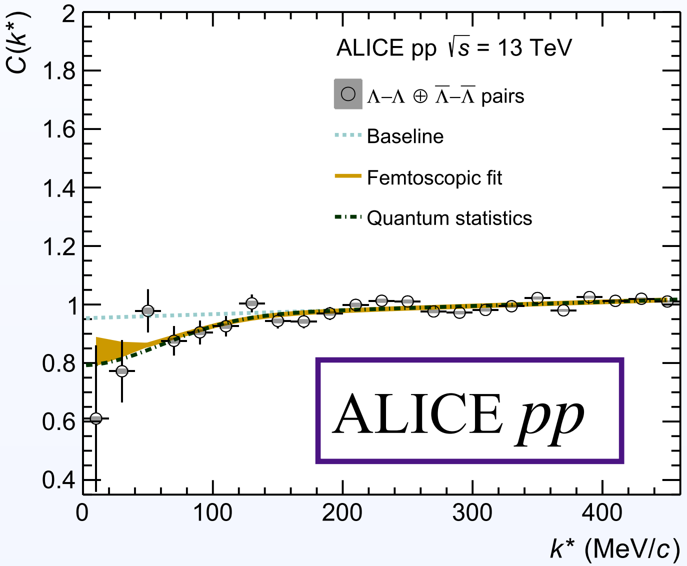
  quantum statistics (Fermion, boson)

Hadron correlation in high energy nuclear collision

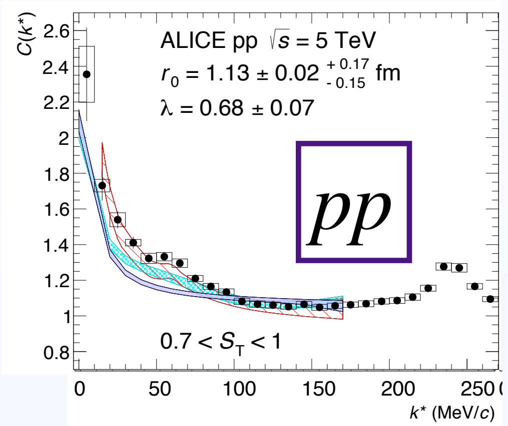
Experimental data in various sectors

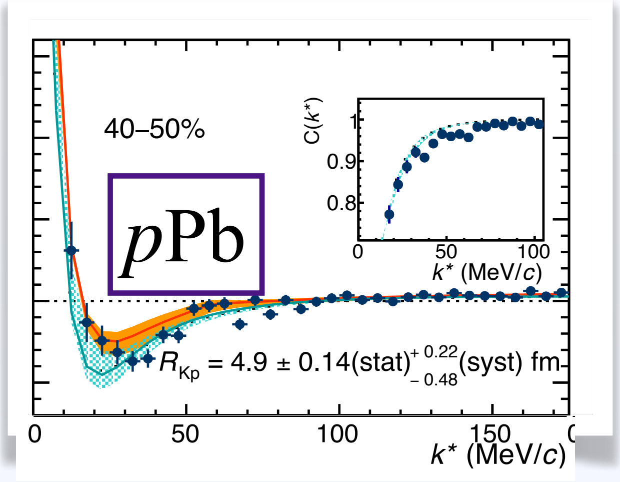
- $\Lambda\Lambda$ STAR AuAu: PRL 114,022301(2015)
  ALICE *pp*: PLB 797 (2019) 134822
  PbPb: PRC99, 024001 (2019)



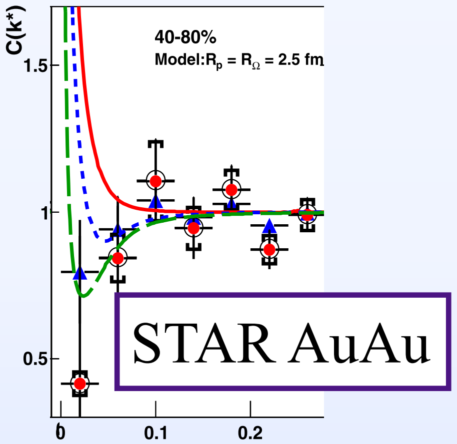


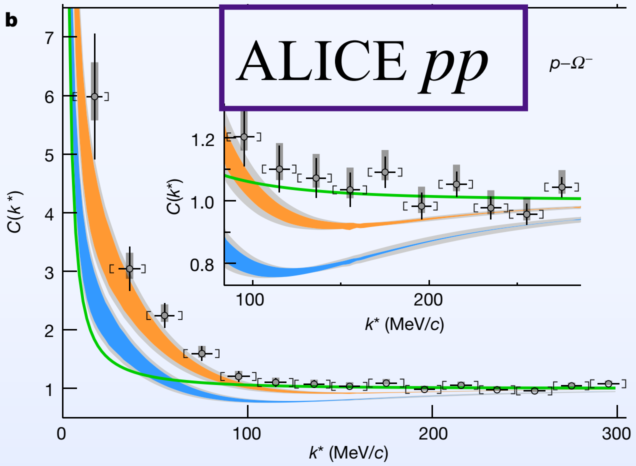
- $K^{\pm}p$ ALICE *pp*: PRL 124 (2020) 9, 092301
  PbPb: PLB 822 (2021) 136708
  STAR AuAu: NPA 982 (2019) 359



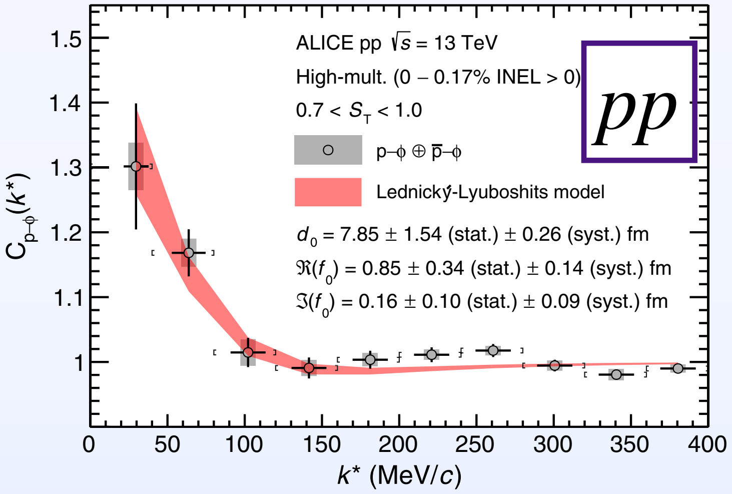


- $p\Omega$ STAR AuAu: PLB 790, 490 (2019)
  ALICE *pp*: Nature 588 (2020) 232





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



Related talks in HYP 2022

ALICE

• Dp, $D\pi$, DK	D. Battistini	(28.6 poster session)
• $p\Lambda$, $pp\Lambda$, Dp, $D\pi$	D. L. Mihaylov	(29.6, 14:30-)
• p-d, K-d, Λ-d	B. Singh	(29.6, 15:45-)
• Λ-Hadrons	G. Mantzaridis	(29.6, 17:30-)
• K^-p	R. Lea	(30.6, 9:20-)
• (Over view)	O. Vazquez Doce	(1.7 9:00-)

STAR

• $K^\pm K^\pm$, $K_s^0 K_s^0$, $K_s^0 K^\pm$	D. Pawłowska	(29.6 16:00-)

Contents

- Introduction: hadron-hadron momentum correlation function in high-energy nuclear collisions

- Key ingredients for femtoscopic study
  - Source size dependence
  - Coupled-channel effect
- Experimental and theoretical studies for various channels

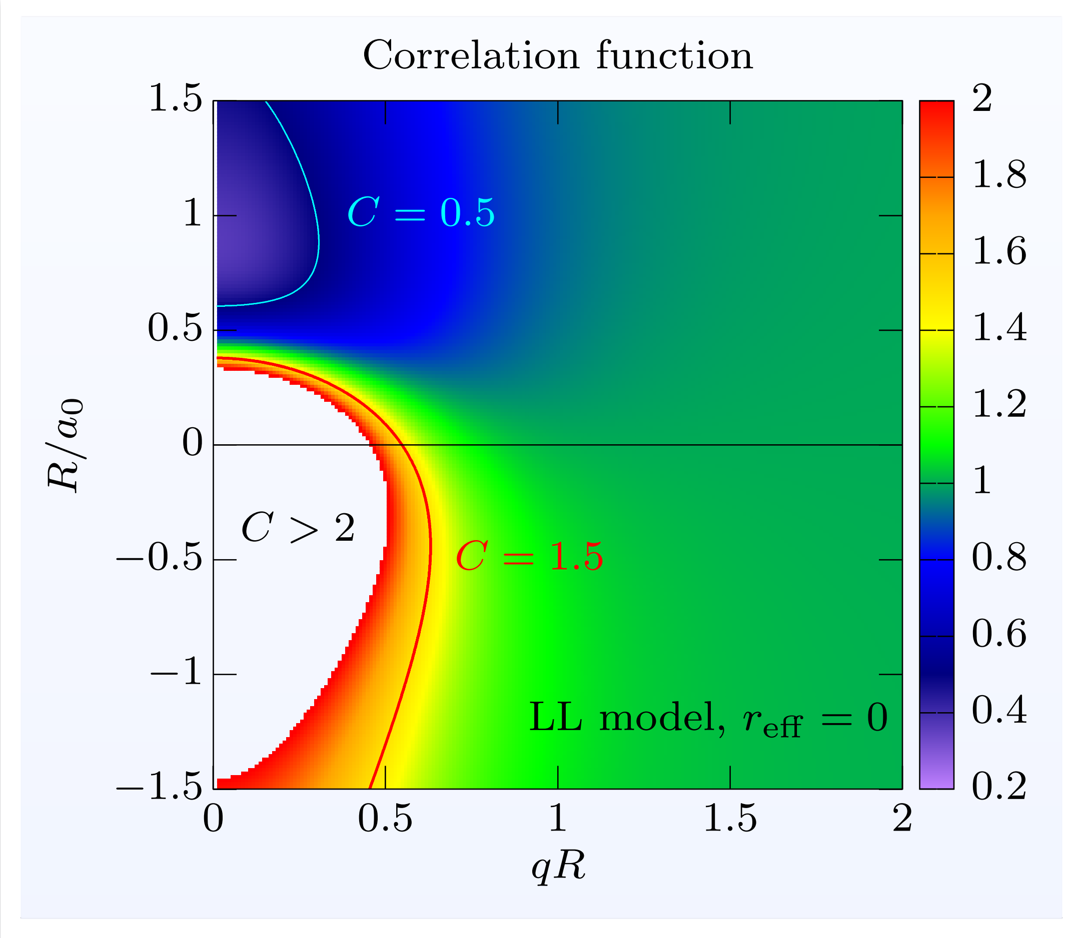
  - Strangeness sector
  - Charm sector

Hadron correlation in high energy nuclear collision

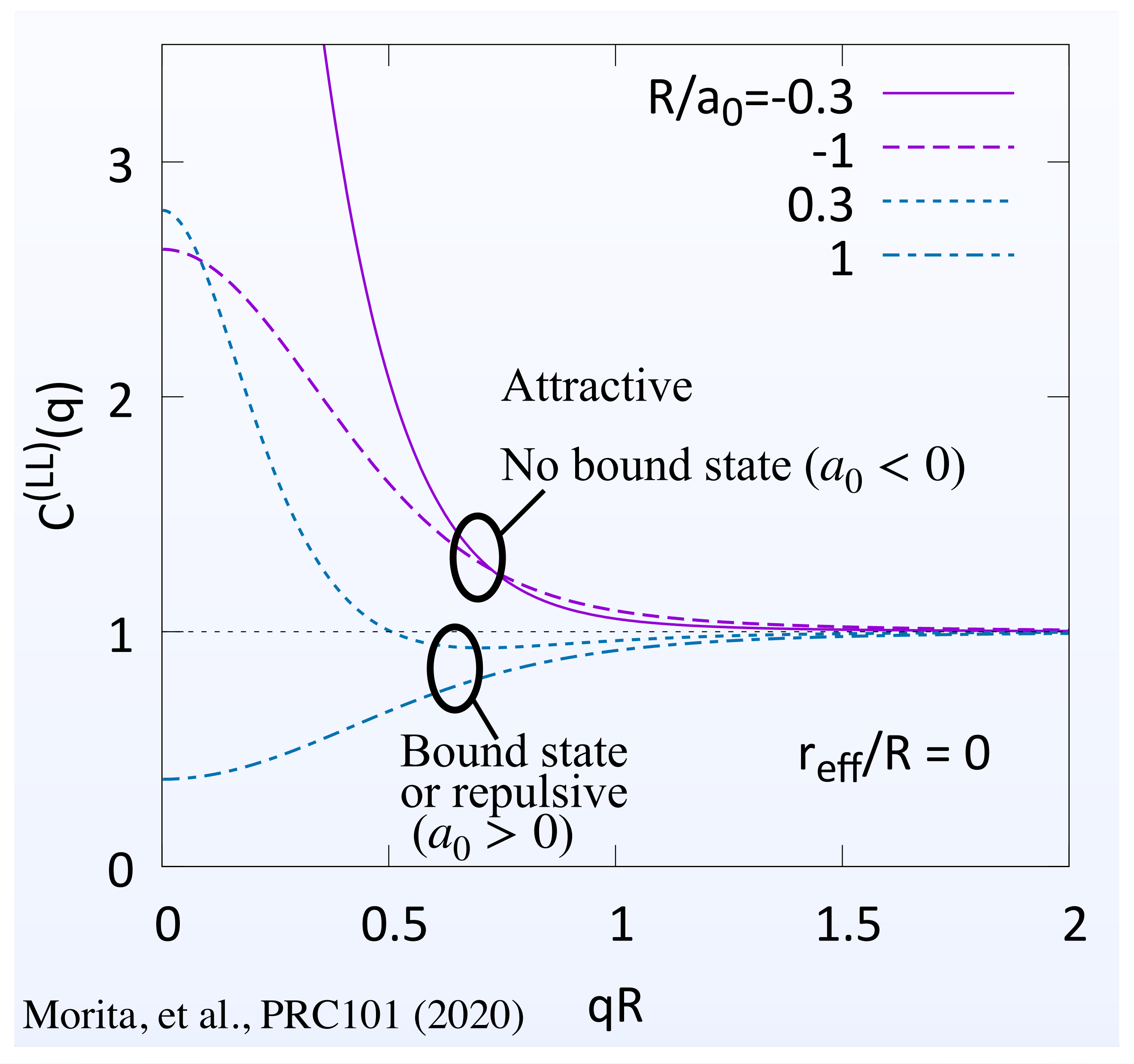
- Simple model: Lednicky-Lyuboshits (LL) formula

$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2 = C(qR, R/a_0)$$

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



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



Morita, et al., PRC101 (2020)

- Clear relation between $C(q)$ and interaction
- Sensitive to (non)existence of bound state

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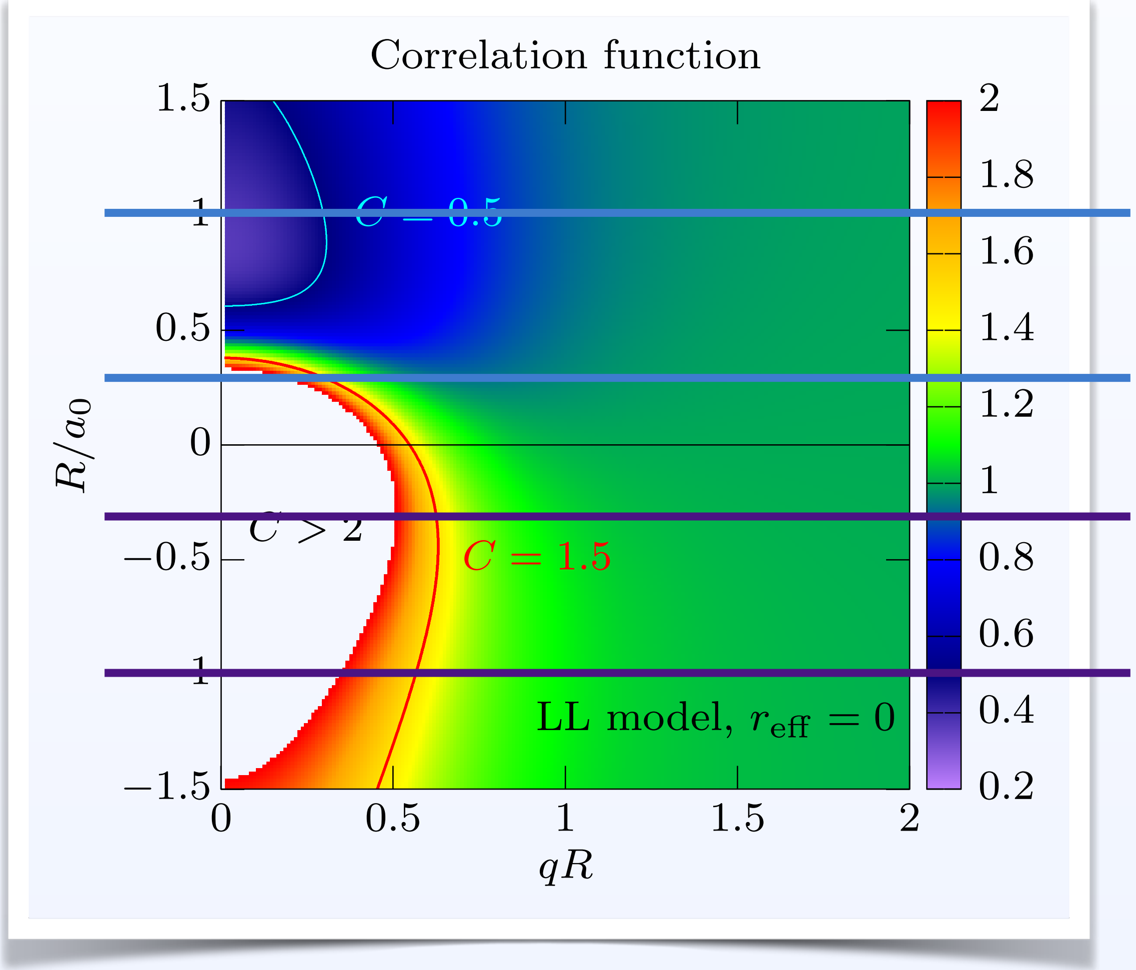

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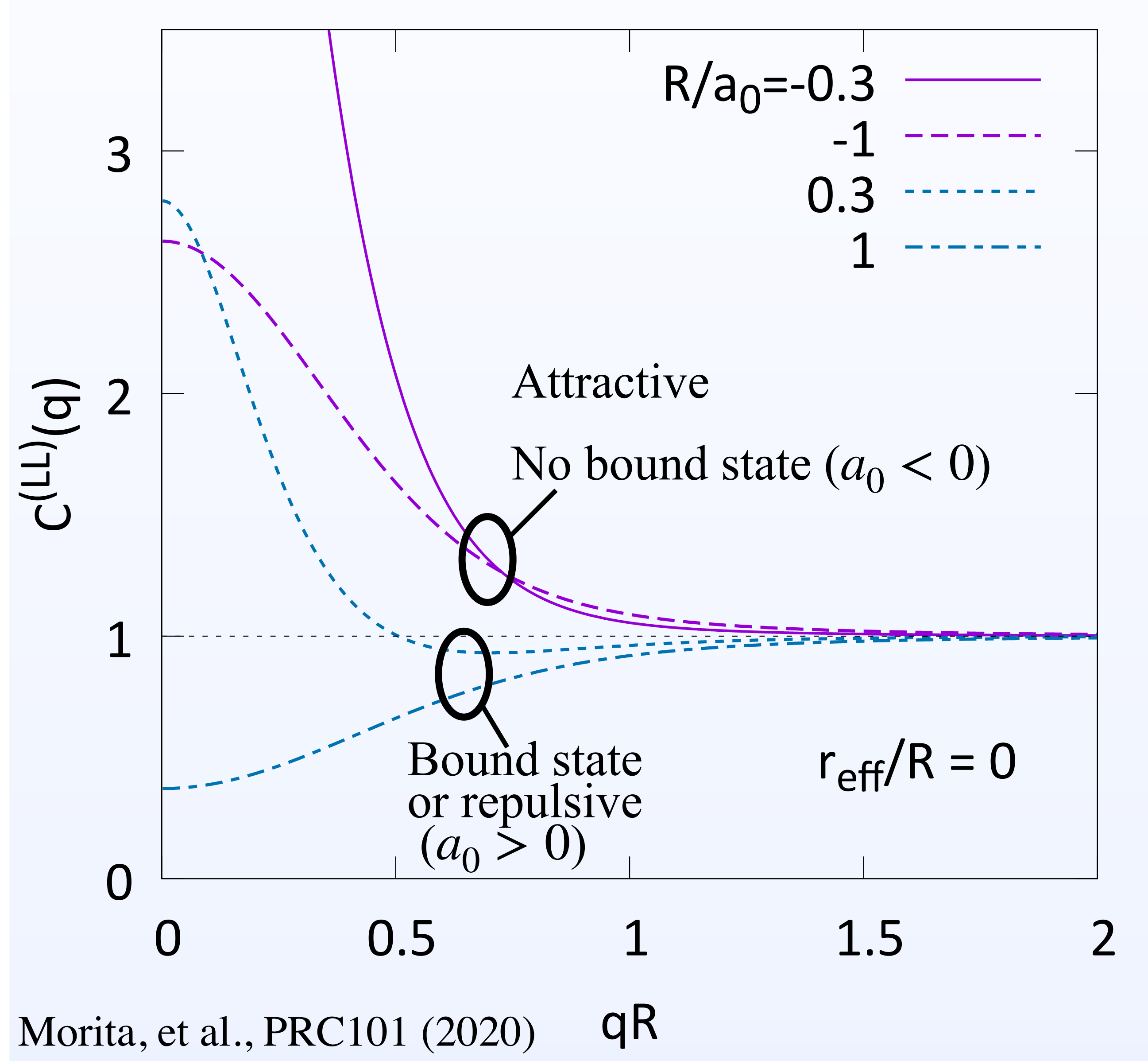
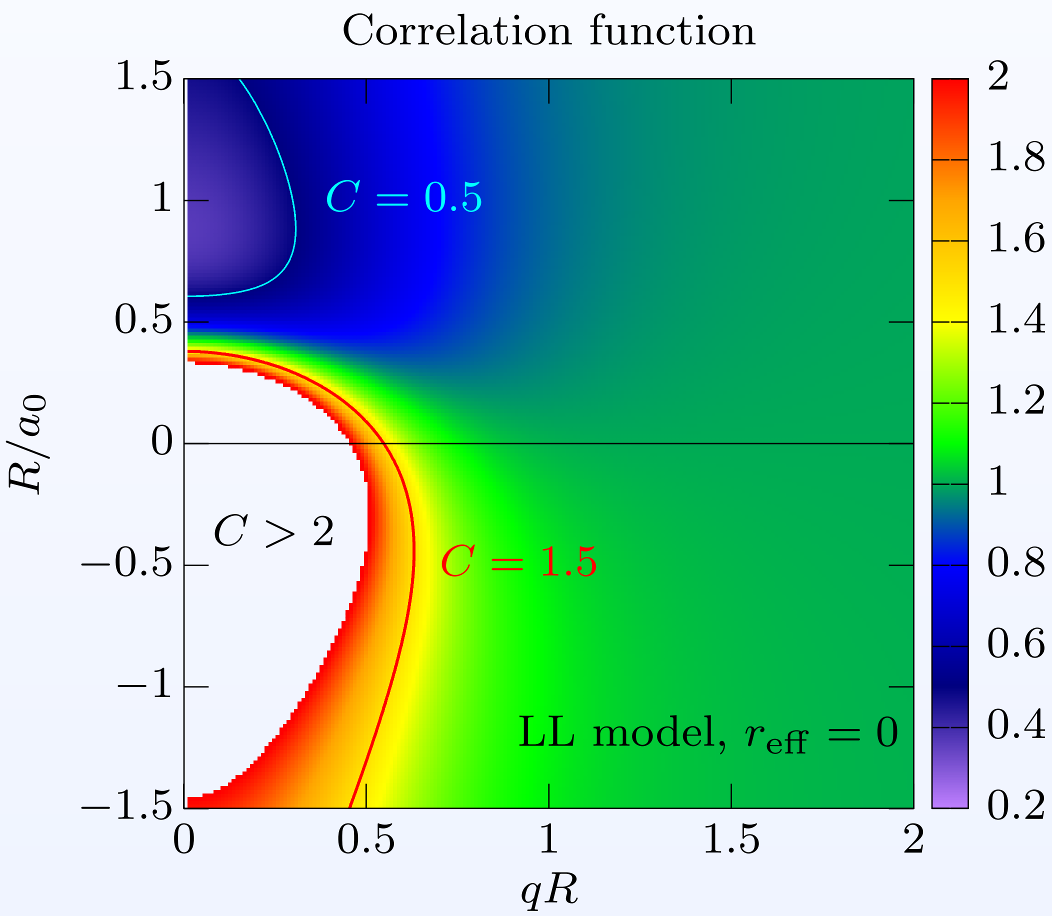


Morita, et al., PRC101 (2020)

- Clear relation between $C(q)$ and interaction
- Sensitive to (non)existence of bound state

Coulomb interaction

- Coulomb interaction with LL formula + Gamow correction
  - w/o Coulomb interaction
    - Only with strong int.
  - w/ Coulomb interaction (attractive case)
    - Coulomb int. with Gamow factor
    - Coulomb attractive case (for $p\Xi^-$)

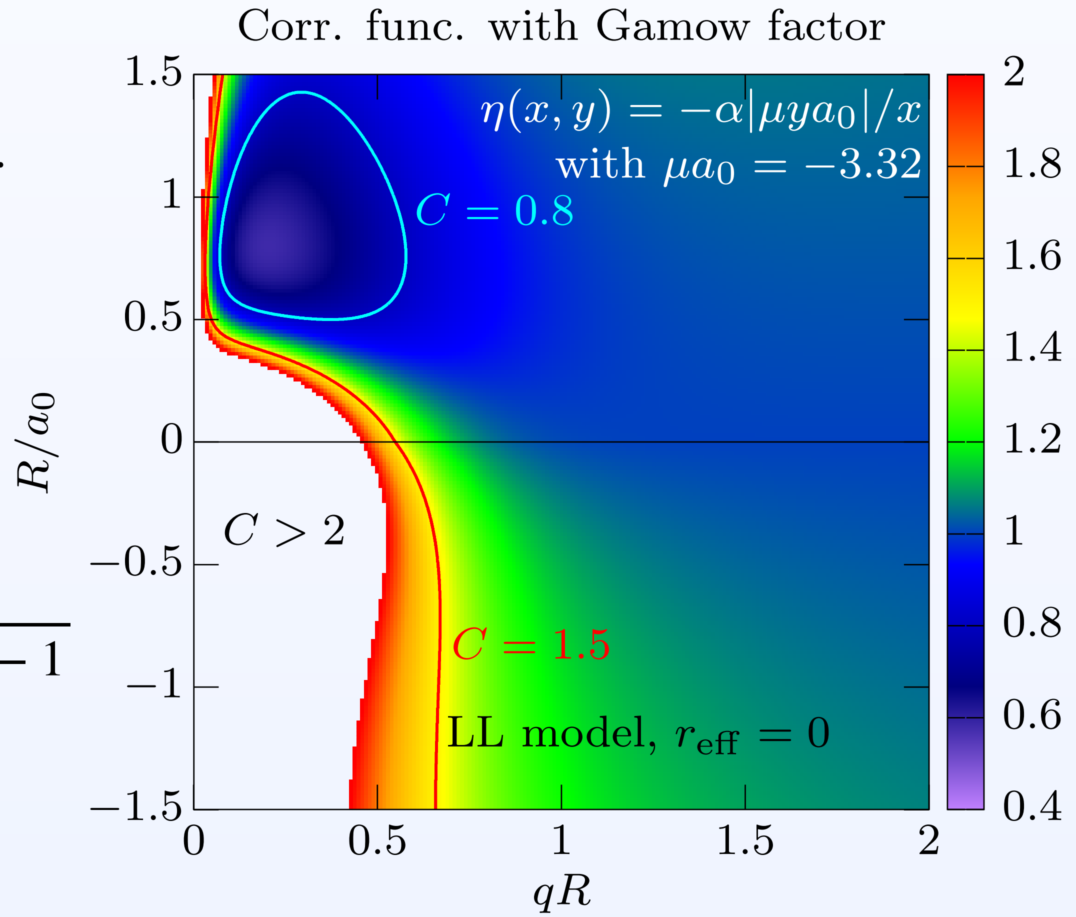


Add Coulomb int.

$\times A(q)$

$$A(q) = \frac{2\pi\eta(q)}{\exp(2\pi\eta(q)) - 1}$$

$$\eta(q) = \mu\alpha/q$$



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- Low energy region: Coulomb effect dominant
- Stonrong int. effect: found as deviation from pure Coulomb case
- Bound state signal : Suppression ==> Dip structure (attractive case)

Coupled-channel effect

- Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula

$$\boxed{C(\mathbf{q}) = \int d^3\mathbf{r}\; S(\mathbf{r})\,\underline{|\psi^{(-)}(q;r)|^2} + \sum_{j\neq i} \omega_j \underline{\int d^3\mathbf{r}\; S_j(\mathbf{r})\,|\psi_j^{(-)}(q;r)|^2}}$$

S.E. Koonin, PLB 70 (1977)
S. Pratt et. al. PRC 42 (1990)
R. Lednicky, et.al. Phys. At. Nucl. 61(1998)

Contribution from Coupled-channel Source

- Coupled-channel wave function

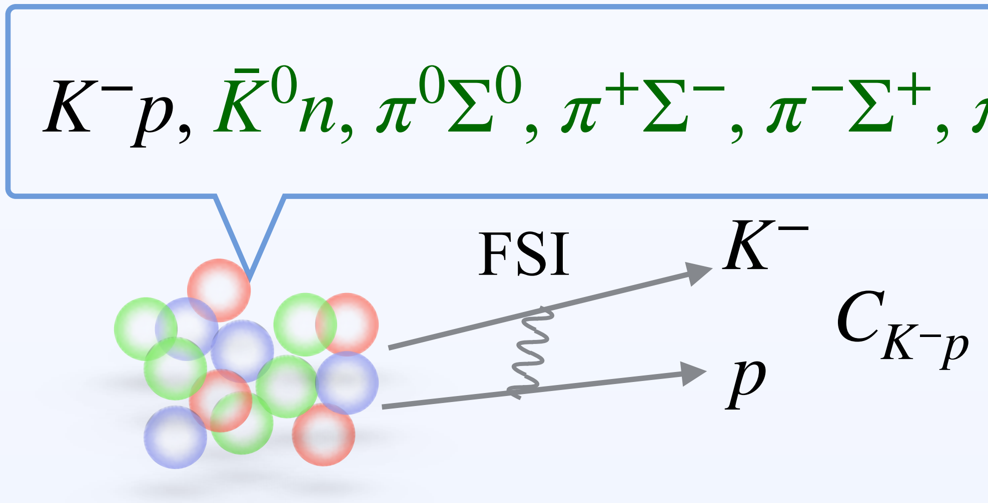
$\psi_i \to$ (out-going wave) + $S^\dagger$ (incoming wave)

- $|S_{ij}| < 1$ —> Decrease the correlation
- At channel threshold —> Cusp structure
- ψ_i: obtained by solving the c.c. Schrödinger eq.

$$\begin{pmatrix} -\frac{\nabla^2}{2\mu_1} + V_{11}(r) & V_{12}(r) & \cdots & V_{1n}(r) \\ V_{21}(r) & -\frac{\nabla^2}{2\mu_2} + V_{22}(r) + \Delta_2 & \cdots & V_{2n}(r) \\ \vdots & \vdots & \ddots & \vdots \\ V_{n1}(r) & V_{n2}(r) & \cdots & -\frac{\nabla^2}{2\mu_n} + V_{nn}(r) + \Delta_n \end{pmatrix} \Psi(q_1, r) = E\Psi(q_1, r),$$

$V_{ij} = V_{ij}^{\mathrm{strong}}\ (+V^{\mathrm{Coulomb}})$ $\quad\Delta_i$; threshold energy diff.

- Contribution from coupled-channel source



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

- Enhance $C(q)$
- Enhance cusp structure
- ω_i : production rate
  (compared to measured channel)

Coupled-channel effect

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$$\boxed{C(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r})\,|\psi^{(-)}(q;r)|^2 + \sum_{j\neq i} \underline{\omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{(-)}(q;r)|^2}}$$

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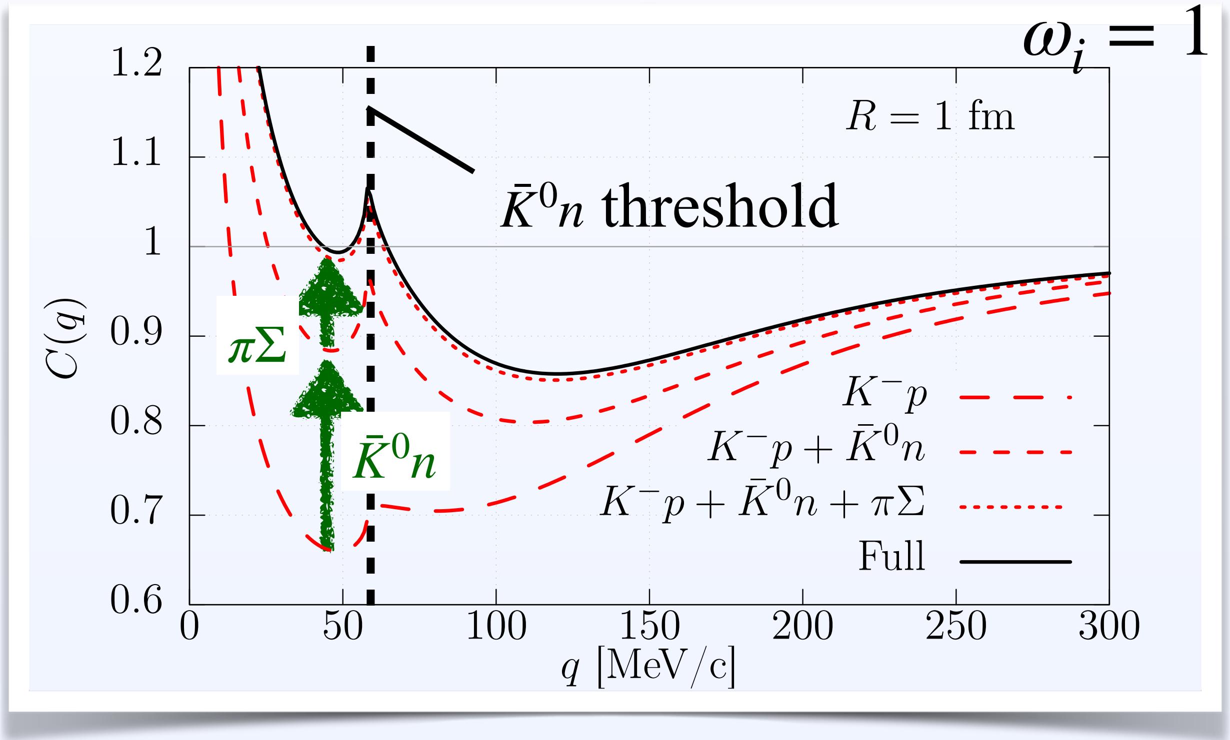
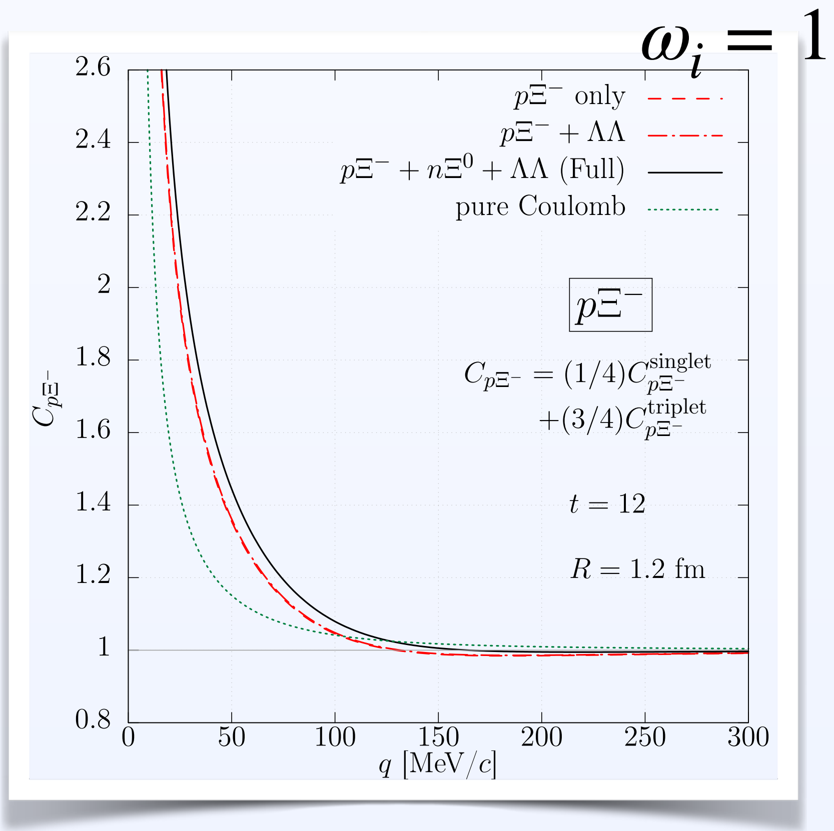
- K^-p with chiral SU(3) model
  - strongly couples to $\pi\Sigma$ and $\bar{K}^0 n$



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

- $\bar{K}^0 n$ cusp enhanced
- $\bar{K}^0 n$ and $\pi\Sigma$ source gives sizable enhancement
- $\pi\Lambda$ coupling is negligible

- $p\Xi^-$ with HAL QCD potential
  - weakly couples to $n\Xi^0$ and $\Lambda\Lambda$

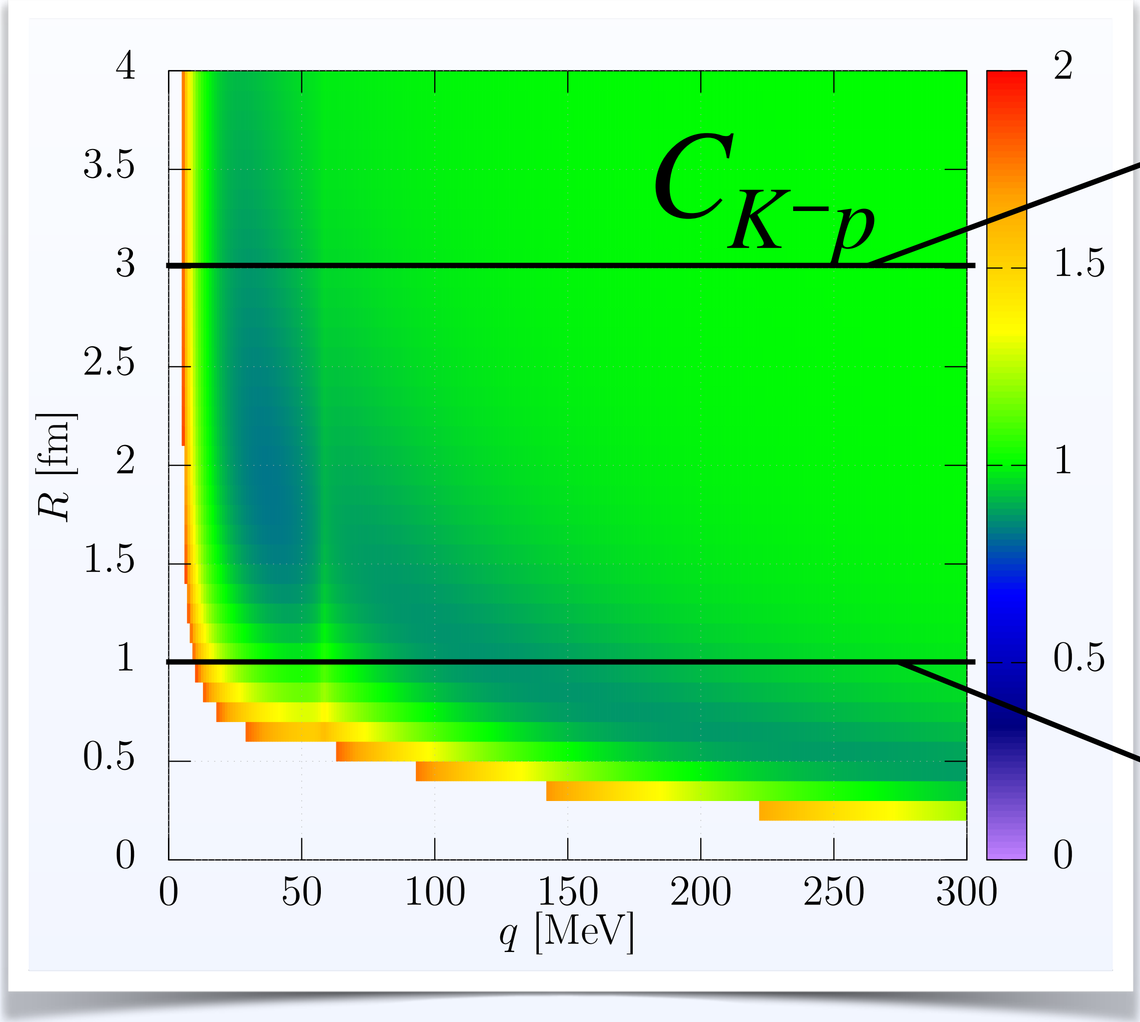


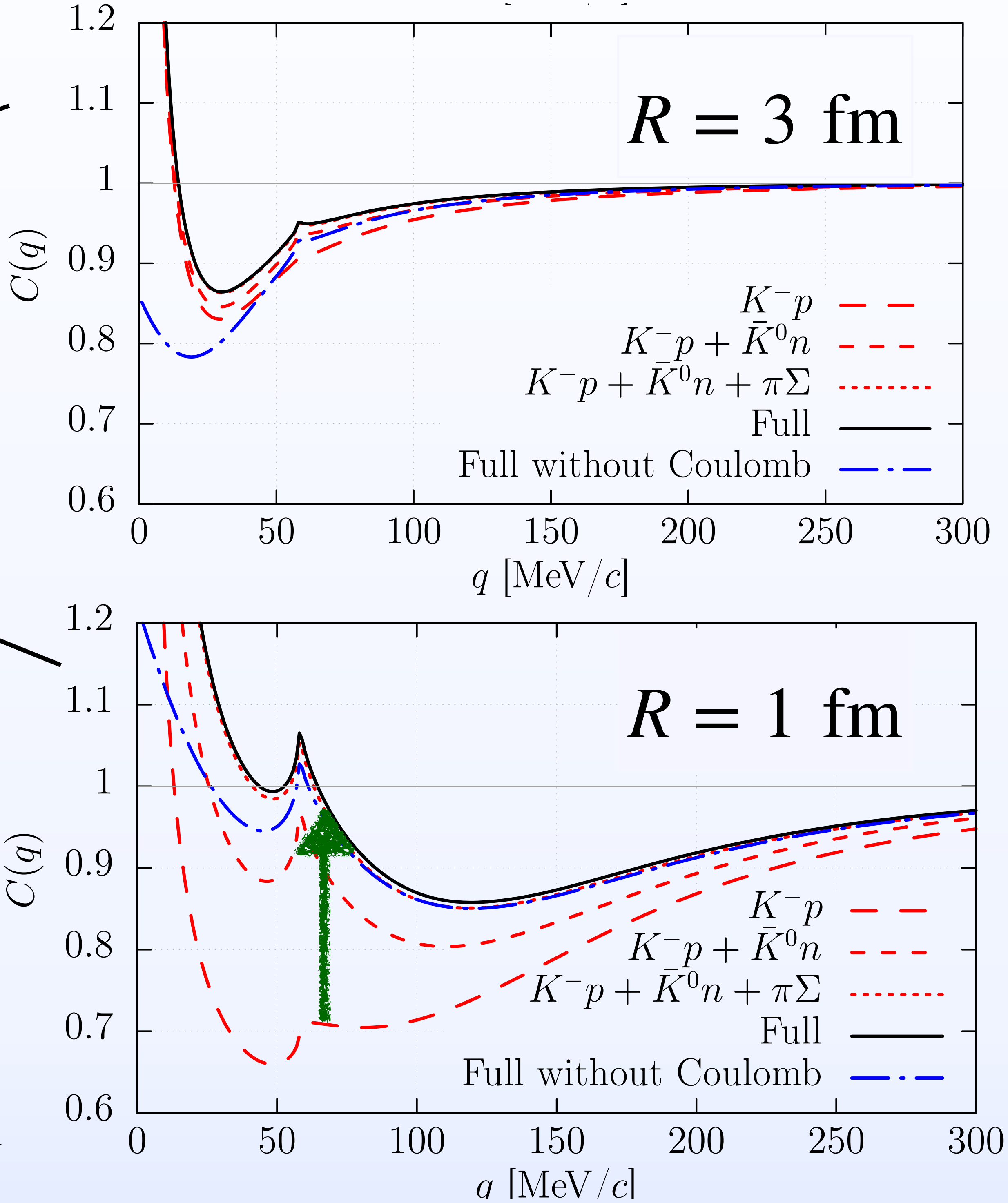
Kamiya, Sasaki, Fukui, Morita,
Ogata, Ohnishi, Hatsuda, PRC 105, 014915 (2022)

- moderate contribution from coupled-channels

Coupled-channel effect

- Source size dependence of coupled-channel effect





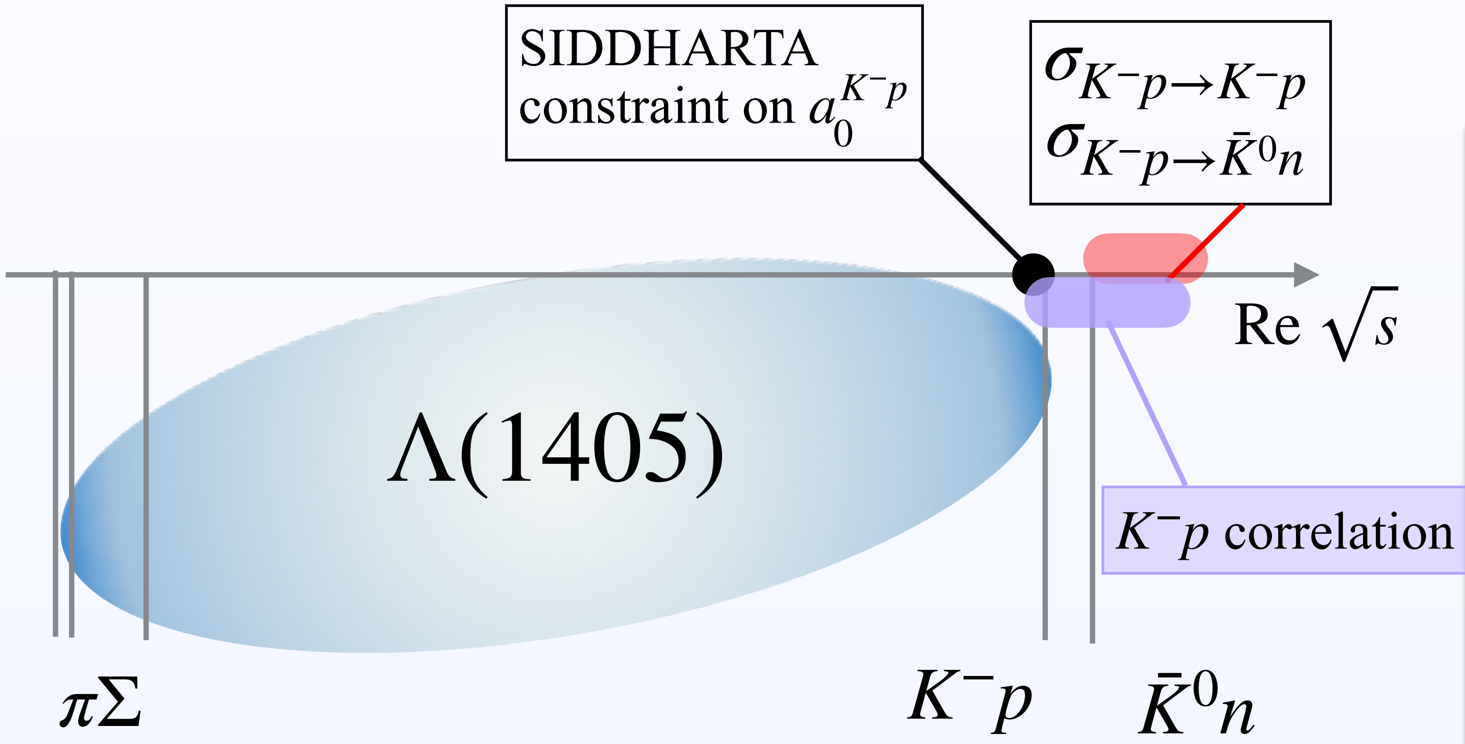
- Strong source size dependence
  $<==$ Due to the near-threshold $\Lambda(1405)$ pole
- $C(q)$ with large source
  - Less prominent cusp structure
  - Weaker coupled-channel source contribution

Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

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

$\bar{K}(s\bar{l})N$ interaction and $\Lambda(1405)$

- Coupled-channel system of $\pi\Sigma$-$\pi\Lambda$-$\bar{K}N$
- Strong attraction reproducing quasi-bound state $\Lambda(1405)$
- Strong constraint on $a_0^{K^-p}$ by SIDDHARTA experiment of Kaonic hydrogen
  M. Bazzi, et al.. PLB 704 (2011)
- Structure of $\Lambda(1405)$
  - two pole structure
    J. A. Oller and U. G. Meißner, PLB500, 263 (2001)
  - $\bar{K}N$ molecular picture (high-mass pole)
    R.H. Dalitz, S.F. Tuan, PRL 425 (1959).



Chiral SU(3) based $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

Miyahara, Hyodo, Weise, PRC 98 (2018)

- Constructed based on the amplitude with NLO chiral SU(3) dynamics <— $a_0^{K^-p}$, σ fitted
  Ikeda, Hyodo, Weise, NPA881 (2012)
- Coupled-channel, energy dependent as

$$V_{ij}^{\text{strong}}(r,E) = e^{-(b_i/2+b_j/2)r^2} \sum_{\alpha=0}^{\alpha_{\max}} K_{\alpha,ij}(E/100\ \text{MeV})^{\alpha}$$

- Constructed to reproduce the chiral SU(3) amplitude around the $\bar{K}N$ sub-threshold region

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

$\bar{K}(s\bar{l})N$ interaction and $\Lambda(1405)$ resonance

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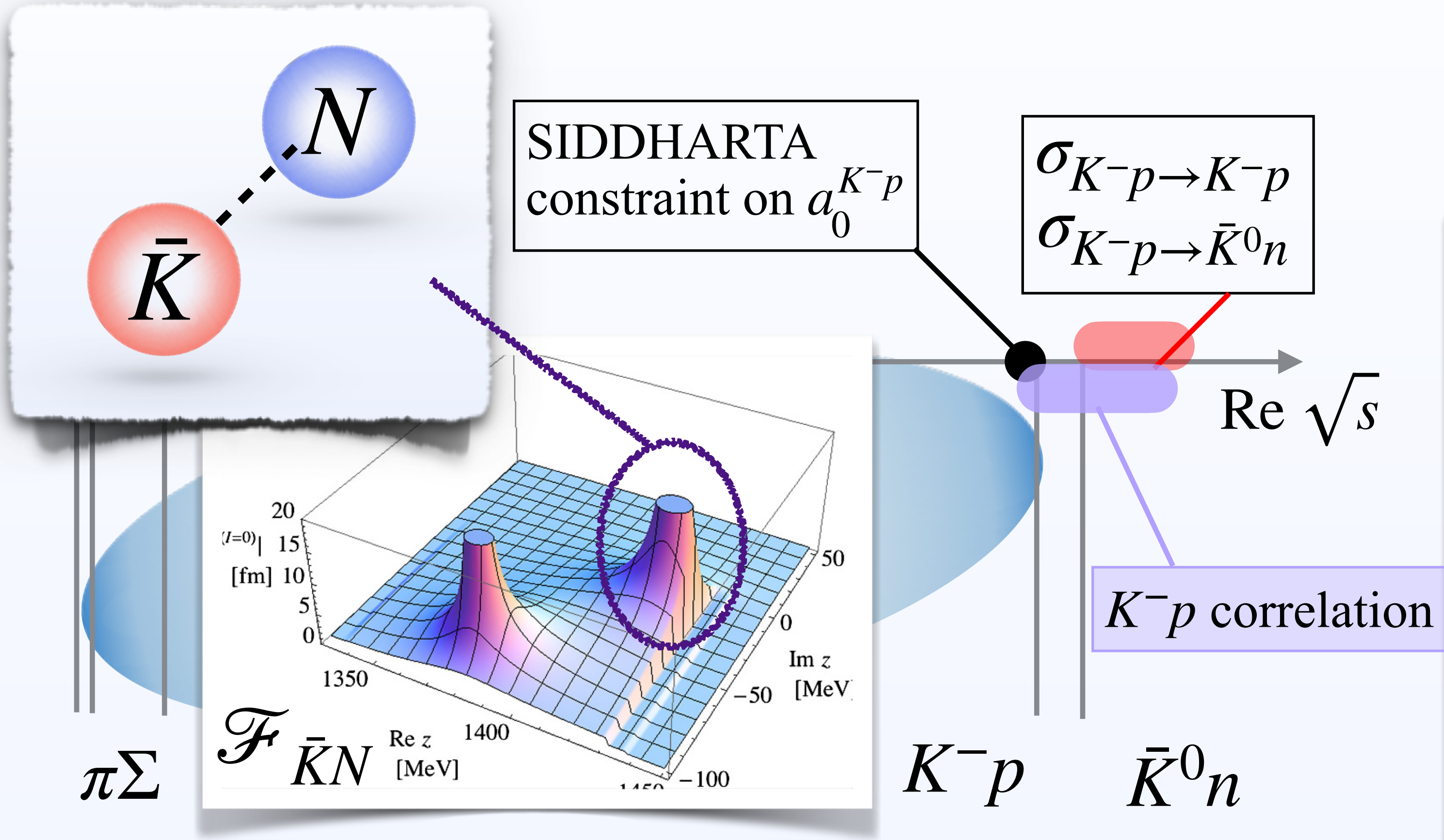

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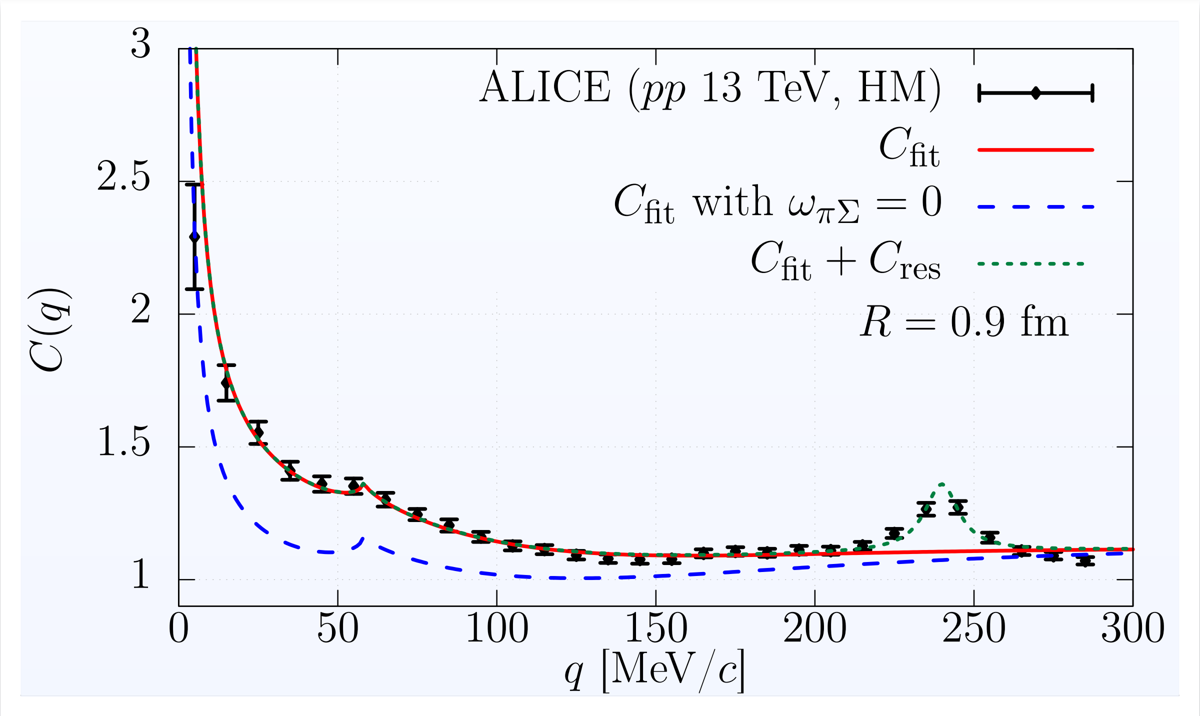
$\bar{K}N$ interaction and $K^{-}p$ correlation

Source size dependence with $K^{-}p$ data

- ALICE *pp* collision data

ALICE PRL 124, 092301 (2020)

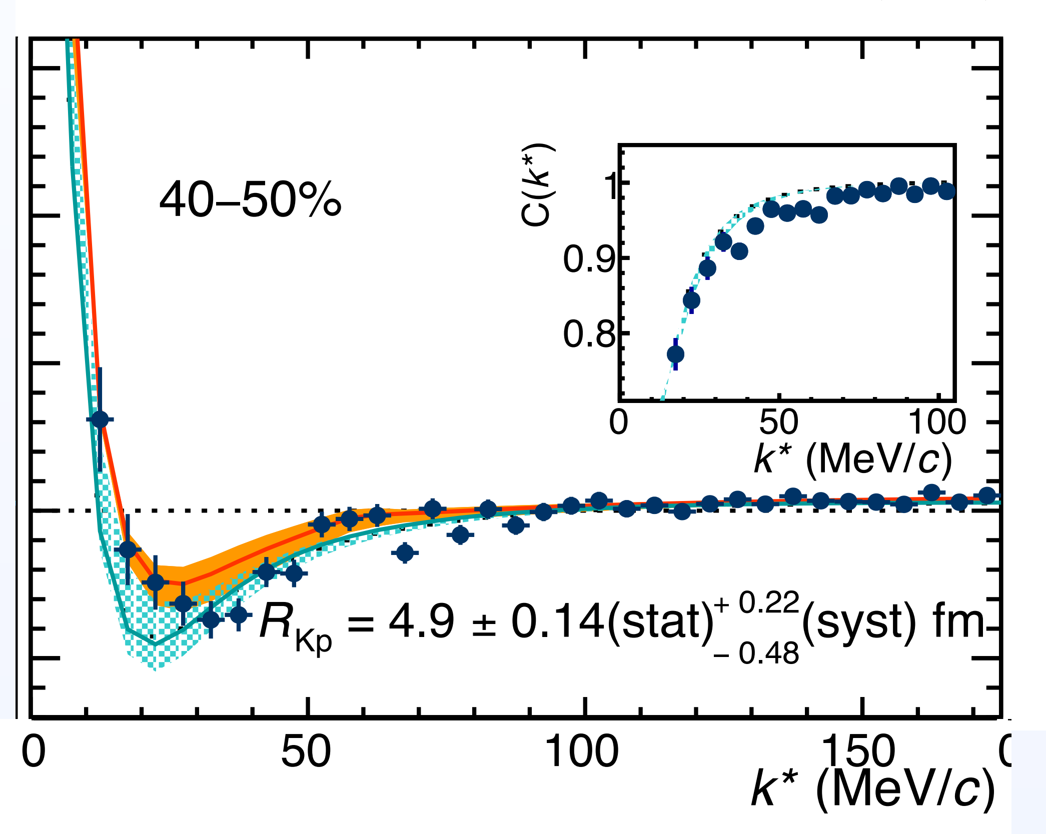


Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

- Small source
  - Clear $\bar{K}^0 n$ cusp structure
  - Sizable contribution from coupled-channel source required to reproduce data

- ALICE PbPb collision data

ALICE PLB 822 (2021) 136708



- Large source
  - Weaker cusp
  - Consistent with analysis only with $K^{-}p$ source

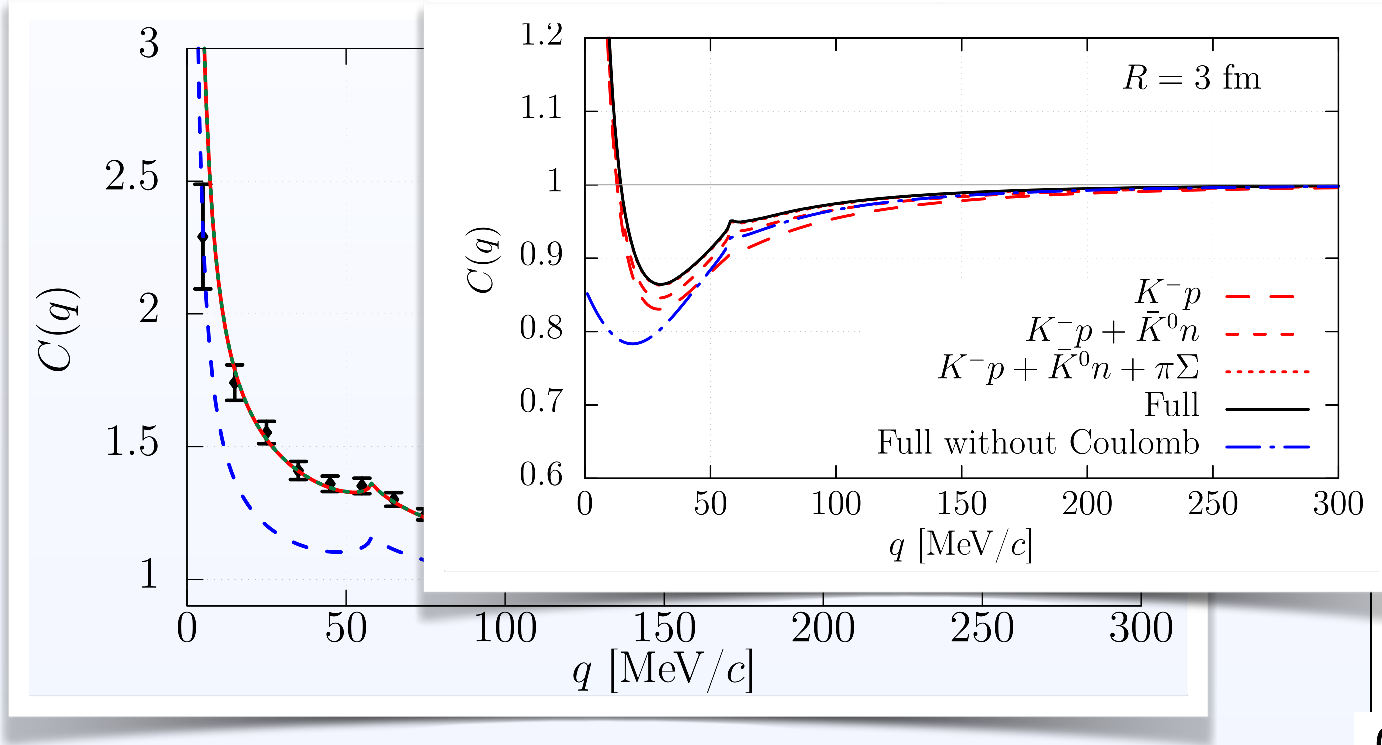
- Chiral SU(3) dynamics describes the both correlation data well.

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

Source size dependence with $K^{-}p$ data

- ALICE pp collision data

ALICE PRL 124, 092301 (2020)



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

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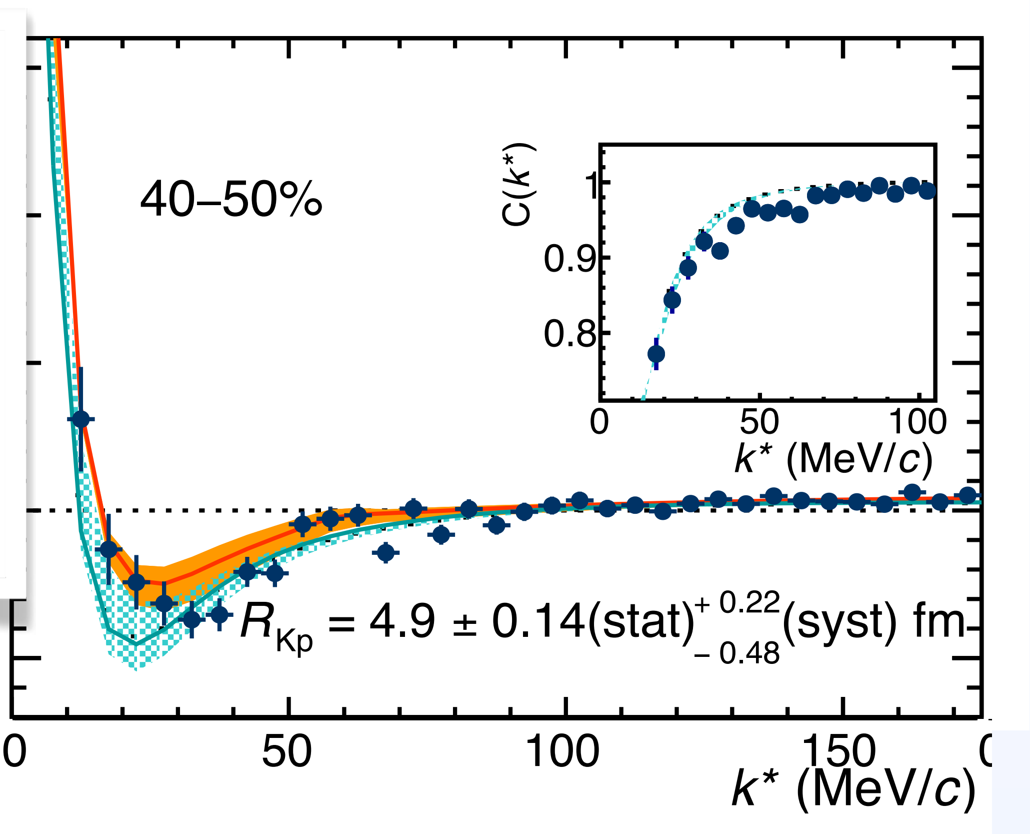
ALICE PLB 822 (2021) 136708



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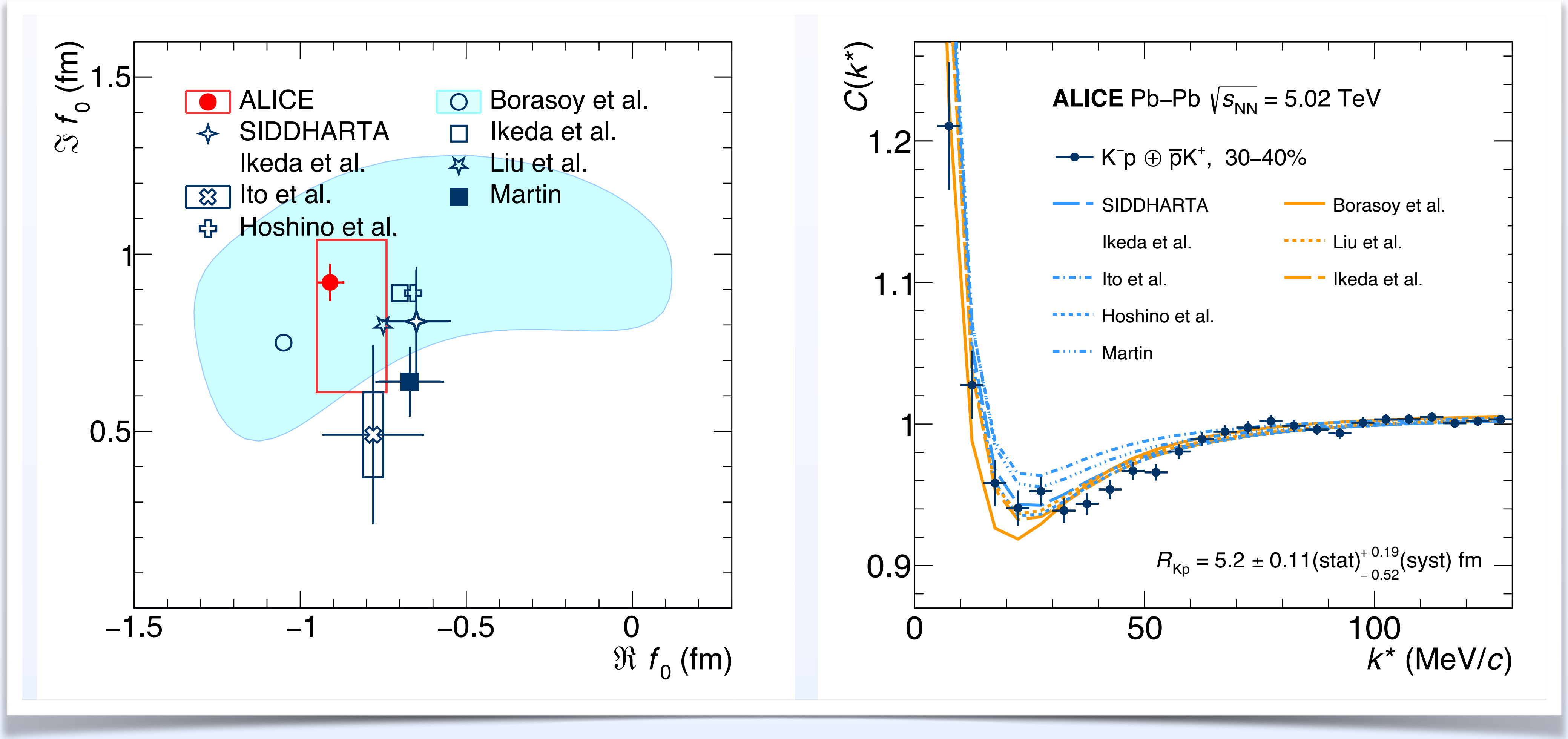
$\bar{K}N$ interaction and K^-p correlation

Source size dependence of K^-p

- ALICE data PbPb collisions data ALICE PLB 822 (2021) 136708
  - Large source —> weaker coupled-channel effect
    —> more direct approach to interaction of the measured channel
  - Extraction of the K^-p scattering length from correlation function
    * Fitting with 1 channel LL model with Gaussian source

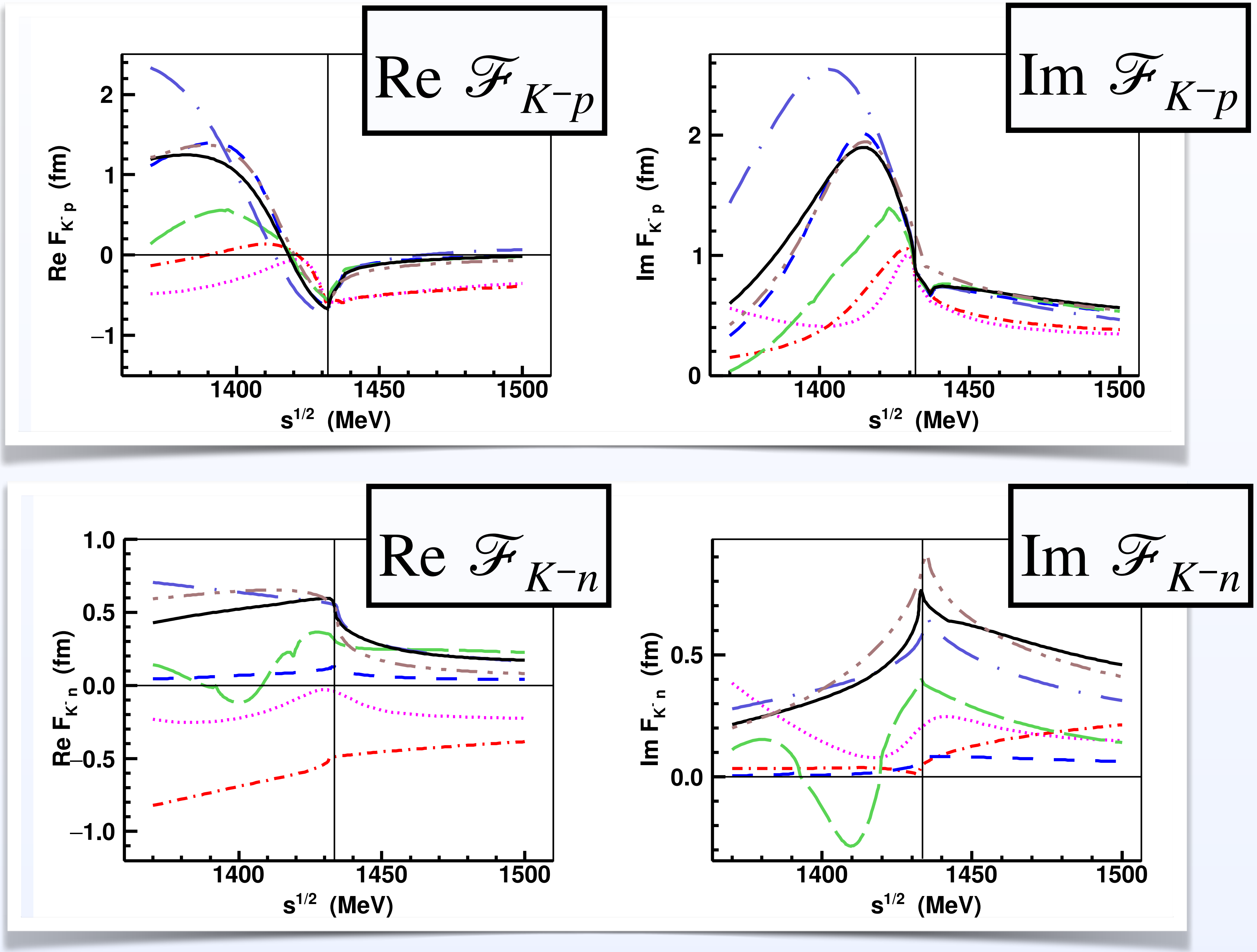


Further constraint on $\bar{K}N$ interaction?

- $\bar{K}N$ interaction

$\mathcal{F}_{\bar{K}N,I=0}$

$\mathcal{F}_{\bar{K}N,I=1}$



B2, B4: Mai, Meißner, EPJA 51 (2015)

M1, MII: Guo, Oller, PRC 87 (2013)

PNLO: Cieplý, Smejkal, NPA 881 (2012)

KMNLO: Ikeda, Hyodo Weise NPA 881 (2012)

Ciepły and Mai, EPJ Web Conf. 130, 02001 (2016)

- Can we constrain $\bar{K}N$ $I = 1$ interaction / amplitude from femtoscopy?

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

- Latest K^-p correlation results

  ALICE [2205.10258]

  - pPb : 0-20%, 20-40% 40-100%
  - PbPb : 60-70%, 70-80% 80-90%

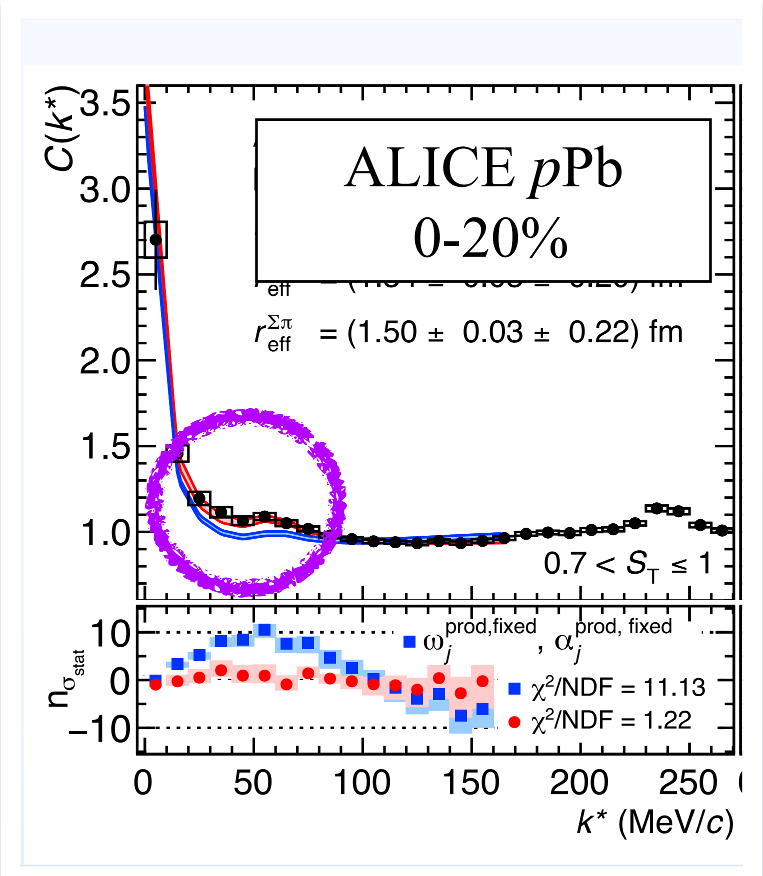
- Discrepancy around $\bar{K}^0n$ threshold between chiral SU(3) model and exp. data for small source data

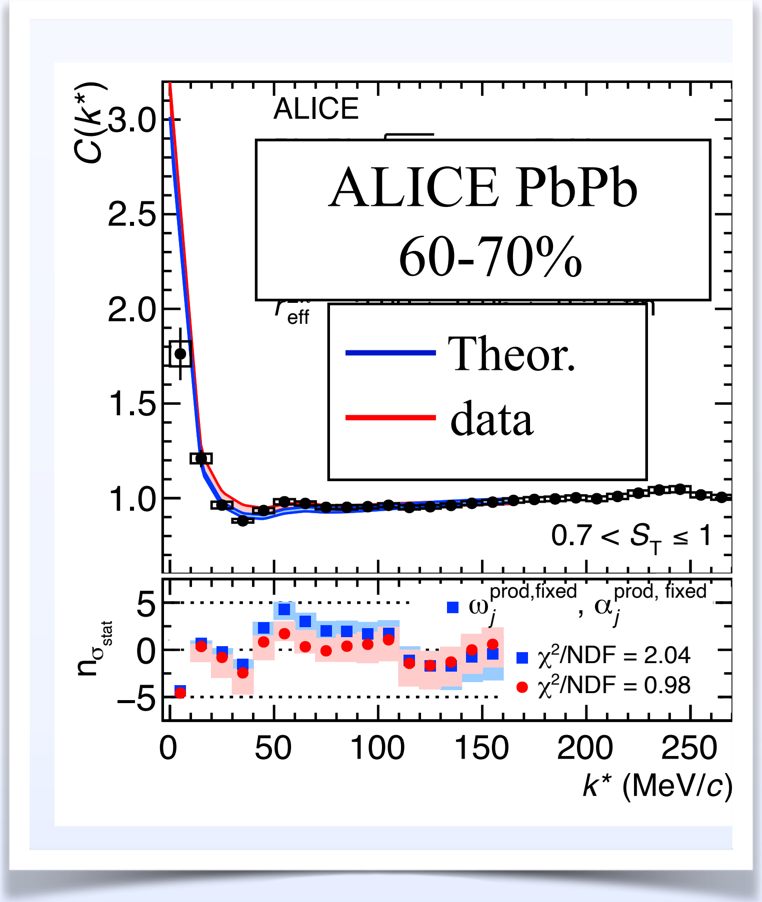
- Analysis with scale factor α_j
  - Scale the coupled-channel source contribution by scaling factor

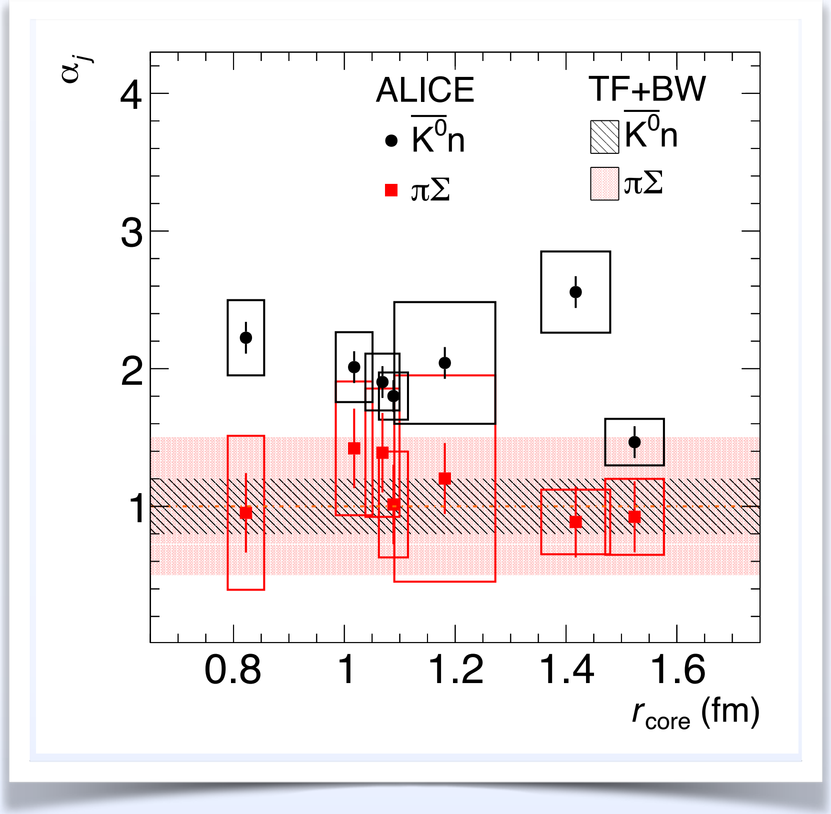
$$C_{K^-p} = C^{\rm el}_{K^-p} + \sum_j \alpha_j C^{\rm inel}_j$$

  - $\alpha_{\bar{K}^0n} \sim 2$ gives better agreement

    implying the stronger coupling







Detail —> Talk by R. Lea 9am on Thursday!

$\bar{K}N$ interaction from $K^0_S p$ correlation function

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

$K^0_S p$ correlation

$$|K^0_S p\rangle = [\,|\underset{\underline{\bar{K}N,\, I=1}}{\bar{K}^0 p}\rangle - |\underset{\underline{KN,\, I=0,\,1}}{K^0 p}\rangle]/\sqrt{2} \quad \Rightarrow \quad C_{K^0_S p} = [C_{\bar{K}^0 p} + C_{K^0 p}]/2$$

- $I = 1$ component only
- Chiral amplitude

Ikeda, Hyodo, Weise, NPA881 (2012)

- Effective potential

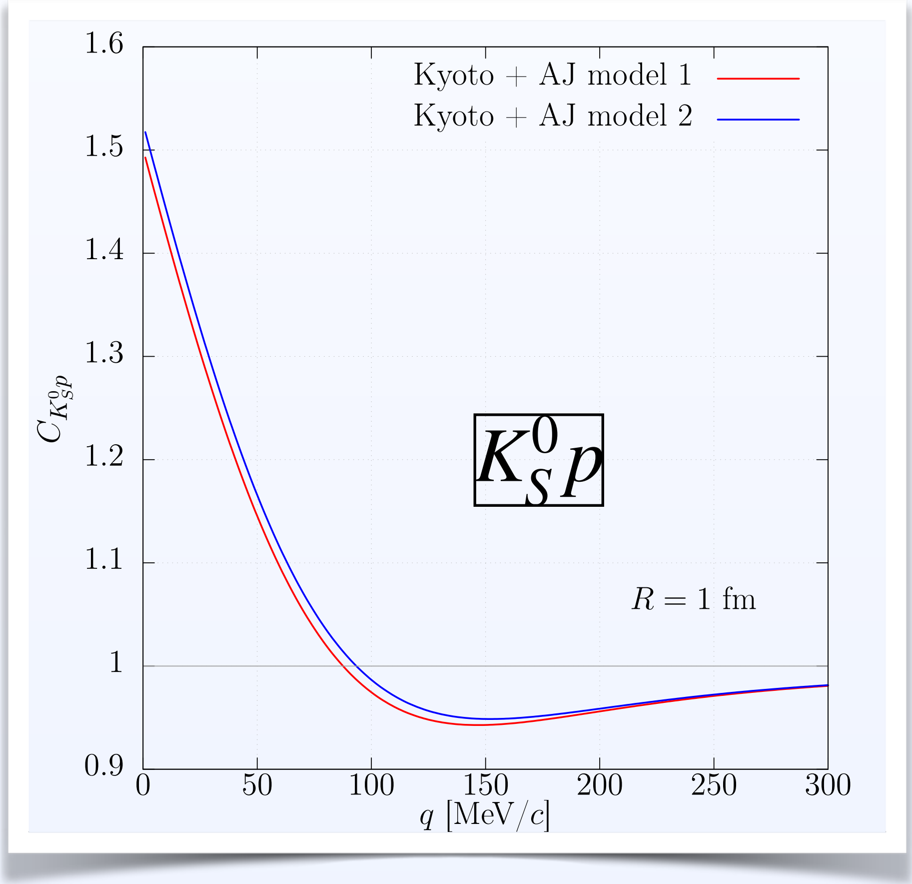
Miyahara, Hyodo, Weise, PRC 98 (2018)

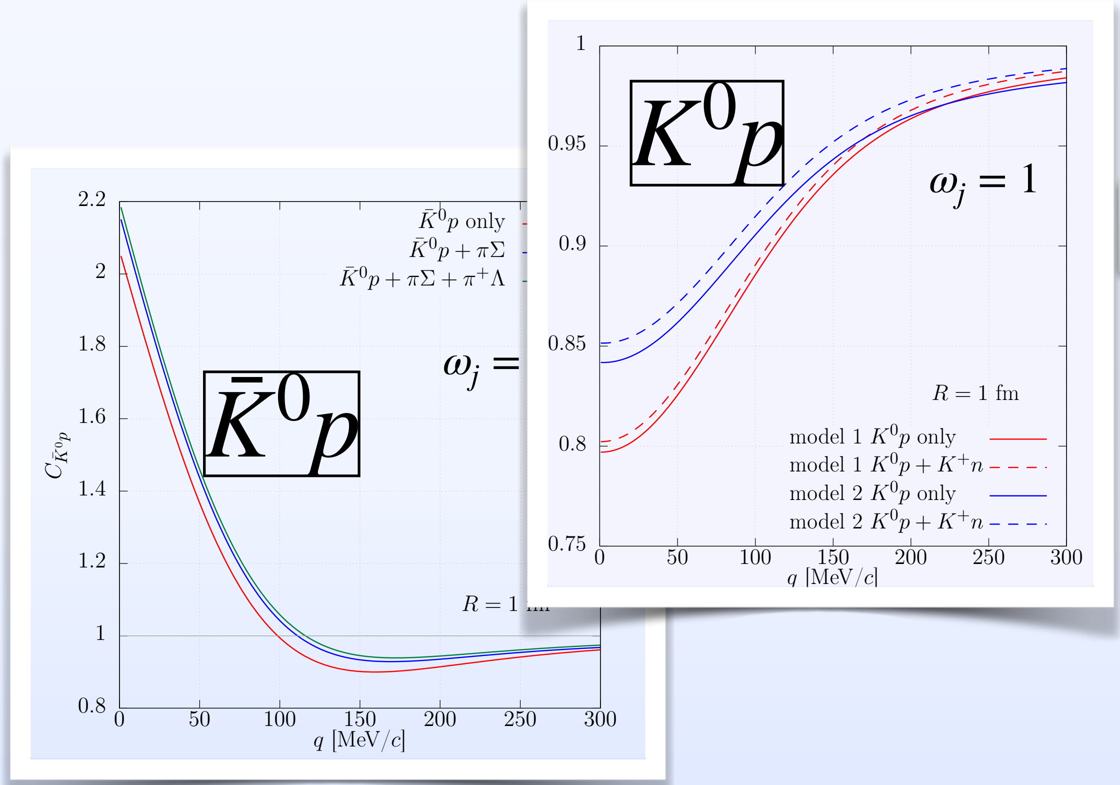
- Well determined with scat. exp.
- Chiral amplitude

K. Aoki and D. Jido, PTEP (2019)

- Effective potential

Constructed from chiral amp.

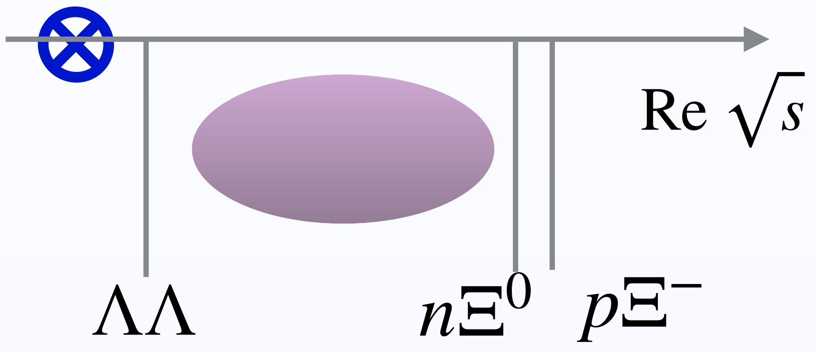




- Enhancement by $\bar{K}^0 p (\bar{K}N\ I = 1)$ is sizable.
- Prediction for the future $K_0 p$ data

$\Lambda\Lambda$-$N\Xi$ interaction and $\Lambda\Lambda$ and $p\Xi^-$ correlation function

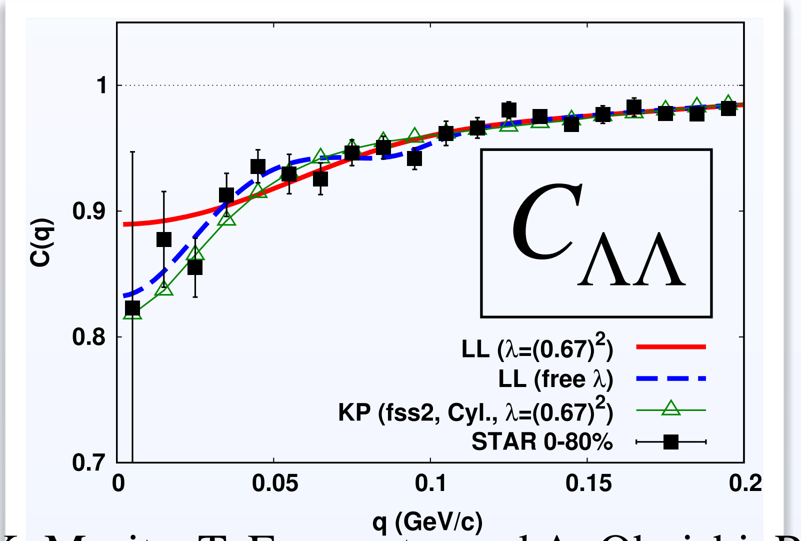
$\Lambda\Lambda$-$N\Xi$ interaction ($S = -2$) and H-dibaryon



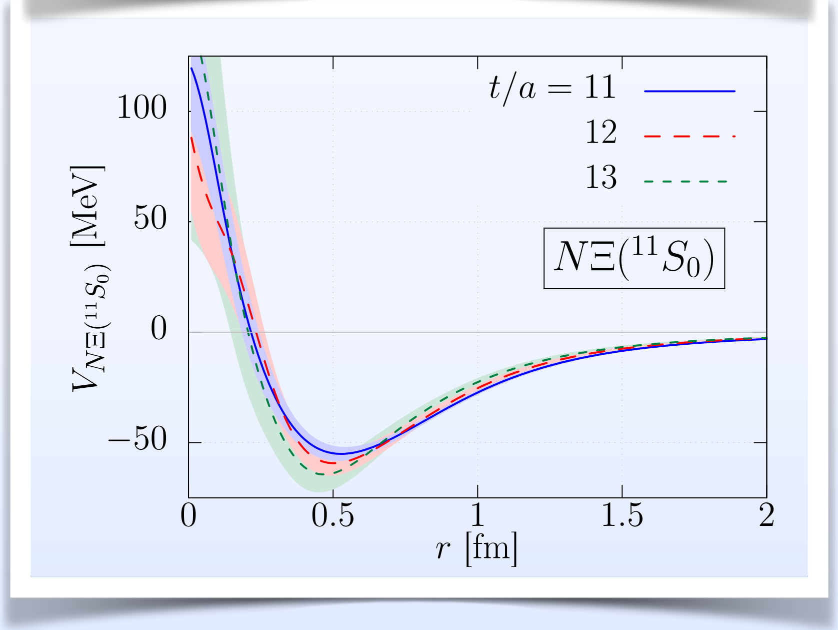
- Long history of discussion on $(J, I) = (0,0)$ sector related to $H(uuddss)$-dibaryon.
  R. L. Jaffe, PRL 38 (1977), 195.
- Binding energy of double Λ hypernucleus
  ⟶ $\Lambda\Lambda$ does NOT (deeply) bound
  Takahashi et al., PRL87 (2001) 212502.
- STAR $\Lambda\Lambda$ correlation
  L. Adamczyk et al. [STAR] PRL 114 (2015).
  ⟶ weak $\Lambda\Lambda$ interaction
- $\Lambda\Lambda$-$N\Xi$ coupled-channel system
  ⟶ Possibility of $N\Xi$ quasibound
- 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.



K. Morita, T. Furumoto, and A. Ohnishi, PRC91(2015)



Fate of H-dibaryon?

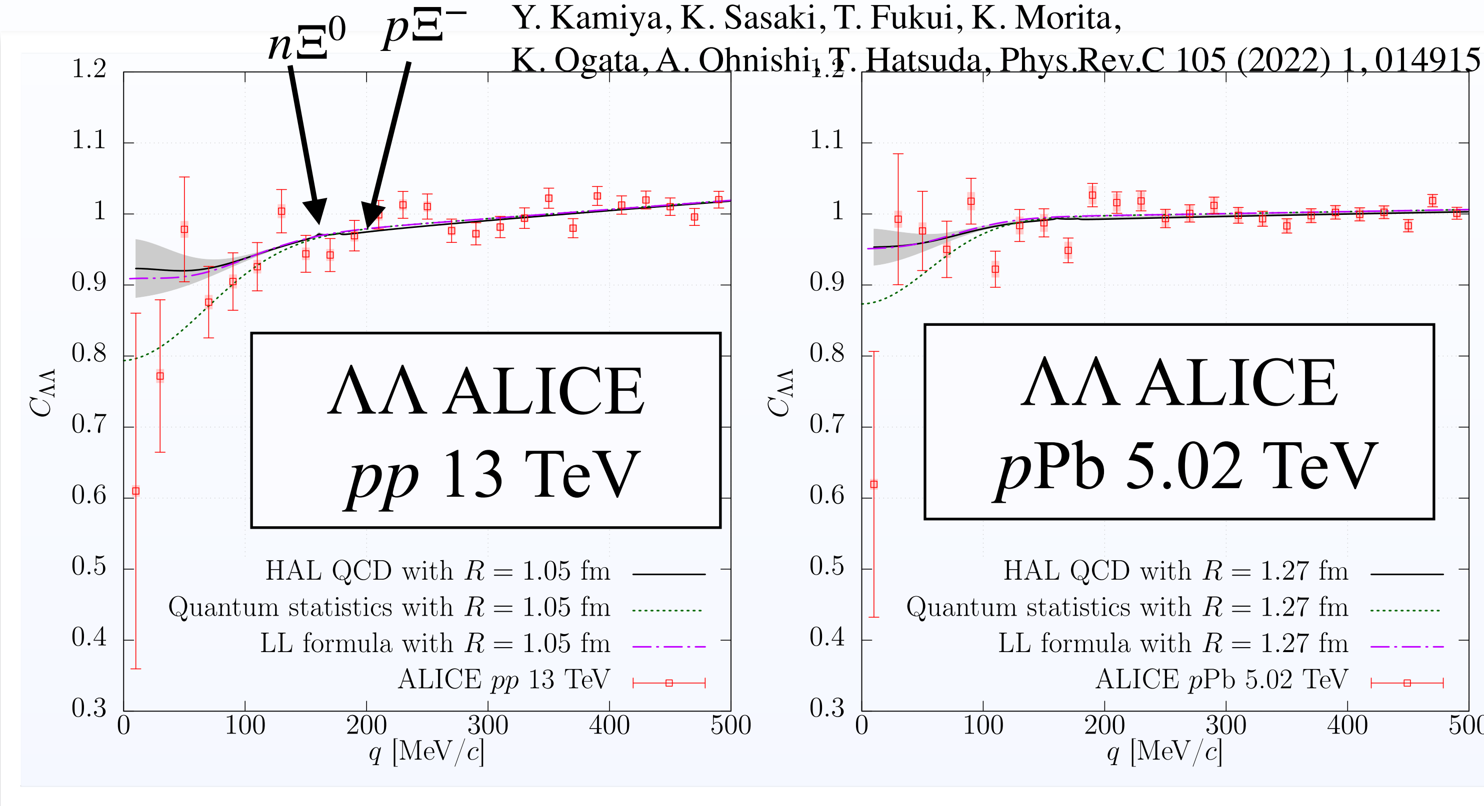
$\Lambda\Lambda$-$N\Xi$ interaction and $\Lambda\Lambda$ and $p\Xi^-$ correlation function

$\Lambda\Lambda$ correlation function

$$C_{\Lambda\Lambda} = 1 - \underline{\frac{1}{2}e^{-4q^2R^2}}$$

Quantum statistics (QS) for octet-octet

$$+\frac{1}{2}\sum_j \omega_j \int d^3r S_j(r)[\,|\psi_{j,s}(r)|^2 - |j_0(r)|^2\delta_{j1}]$$



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

- ALICE pPb, pp collisions data

S. Acharya et al. [ALICE], PLB 797 (2019).

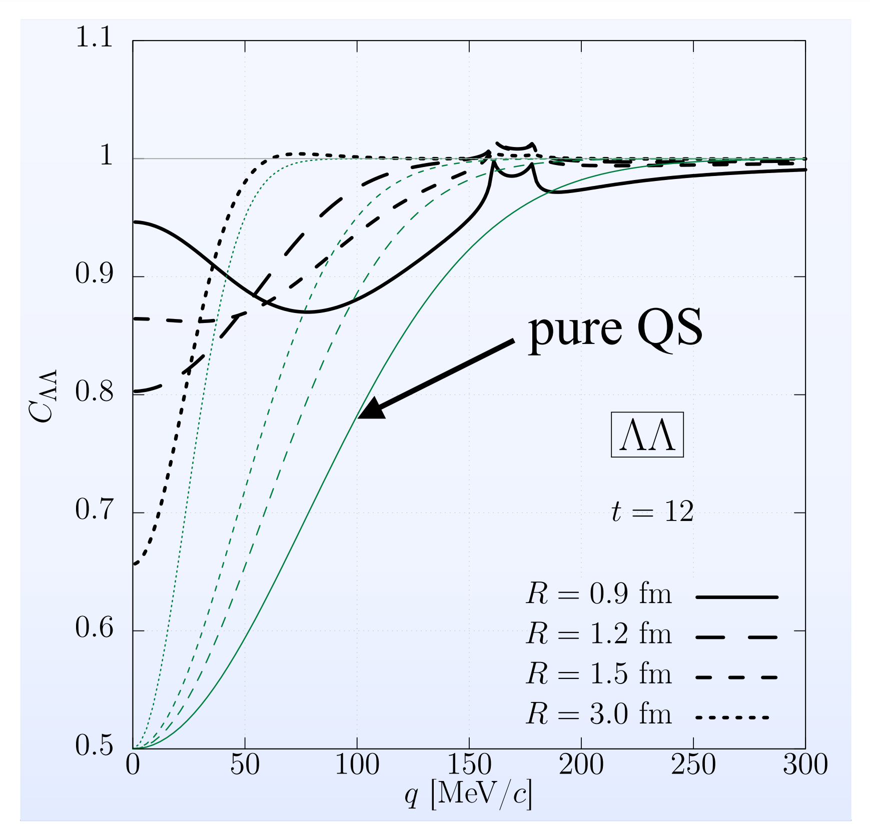
- $N\Xi$ cusps related to the coupling and existence of H-dibaryon

J. Haidenbauer, Nucl. Phys. A 981 (2019),

⟶ Almost invisible due to small coupling

- Small source size dependence
- Small deviation from QS effect

Due to the small scat. length: $a_0 = -0.78$ fm



⇨ Weak attraction of $\Lambda\Lambda$ confirmed
There is no signal of H-dibaryon

$\Lambda\Lambda$-$N\Xi$ interaction and $\Lambda\Lambda$ and $p\Xi^-$ correlation function

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

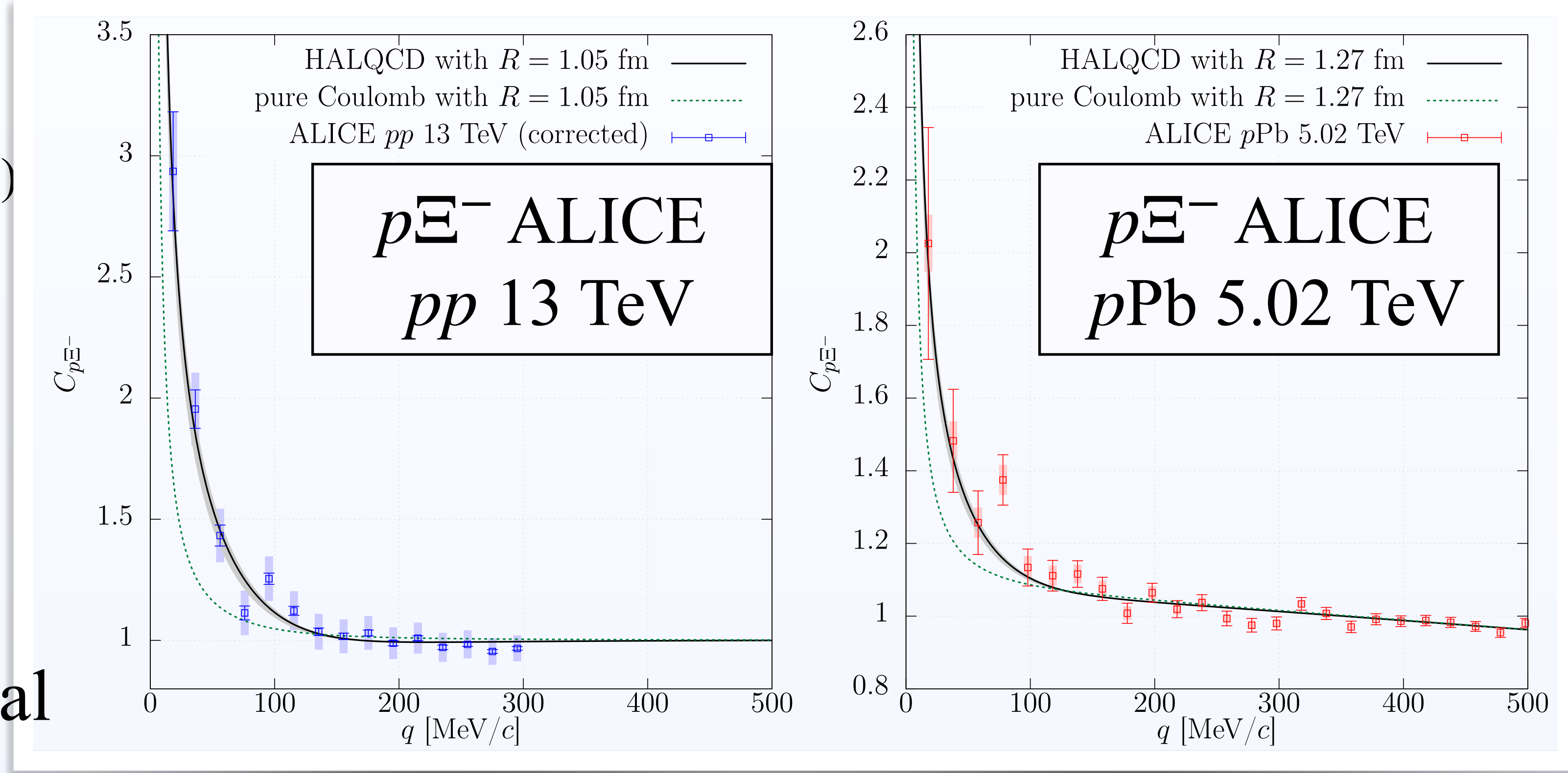
- $p\Xi^-$ correlation function

$$C_{p\Xi^-} = \frac{1}{4}\underbrace{C_{p\Xi^-,\mathrm{singlet}}}_{} + \frac{3}{4}C_{p\Xi^-,\mathrm{triplet}}$$

Couples to $\Lambda\Lambda$
(H-dibaryon channel)

- ALICE data
  - pp: ALICE Nature 588 (2020)
  - pPb: ALICE PRL 123 (2019).

  in good agreement w/ HAL potential



- Small coupled-channel source effect
- No dip structure for every source sizes

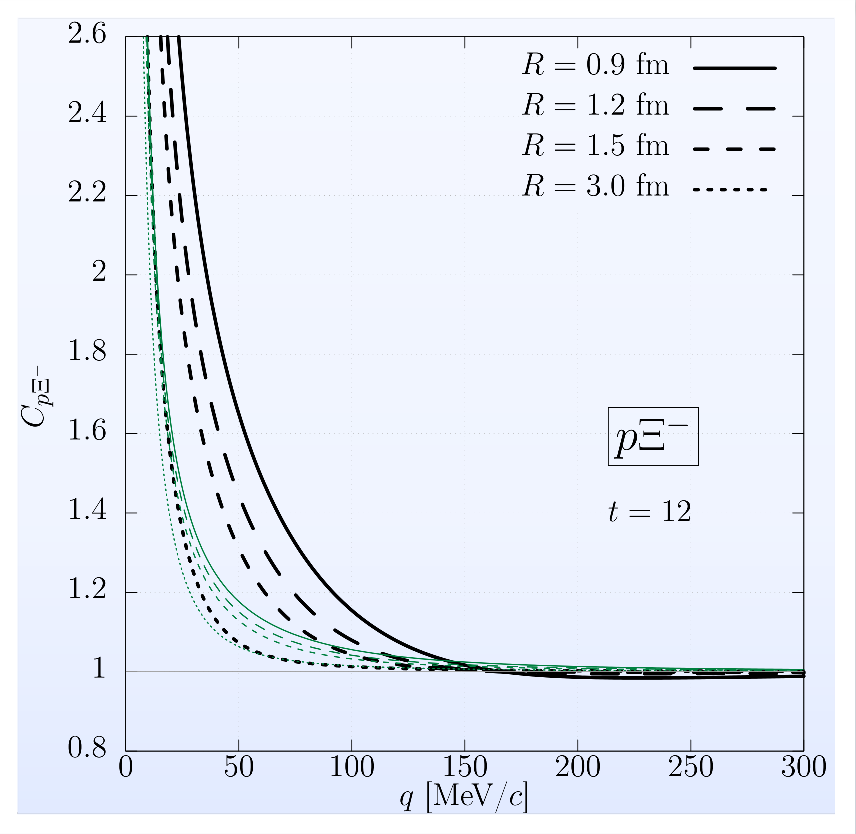
  ⟶ No dibaryon state

- Source size dependence

  Small R: sizable enhancement (from Coulomb)

  Large R: Coulomb effect dominant

⇨ Barely unbound scenario:
Good agreement for both channels($\Lambda\Lambda$, $p\Xi^-$)



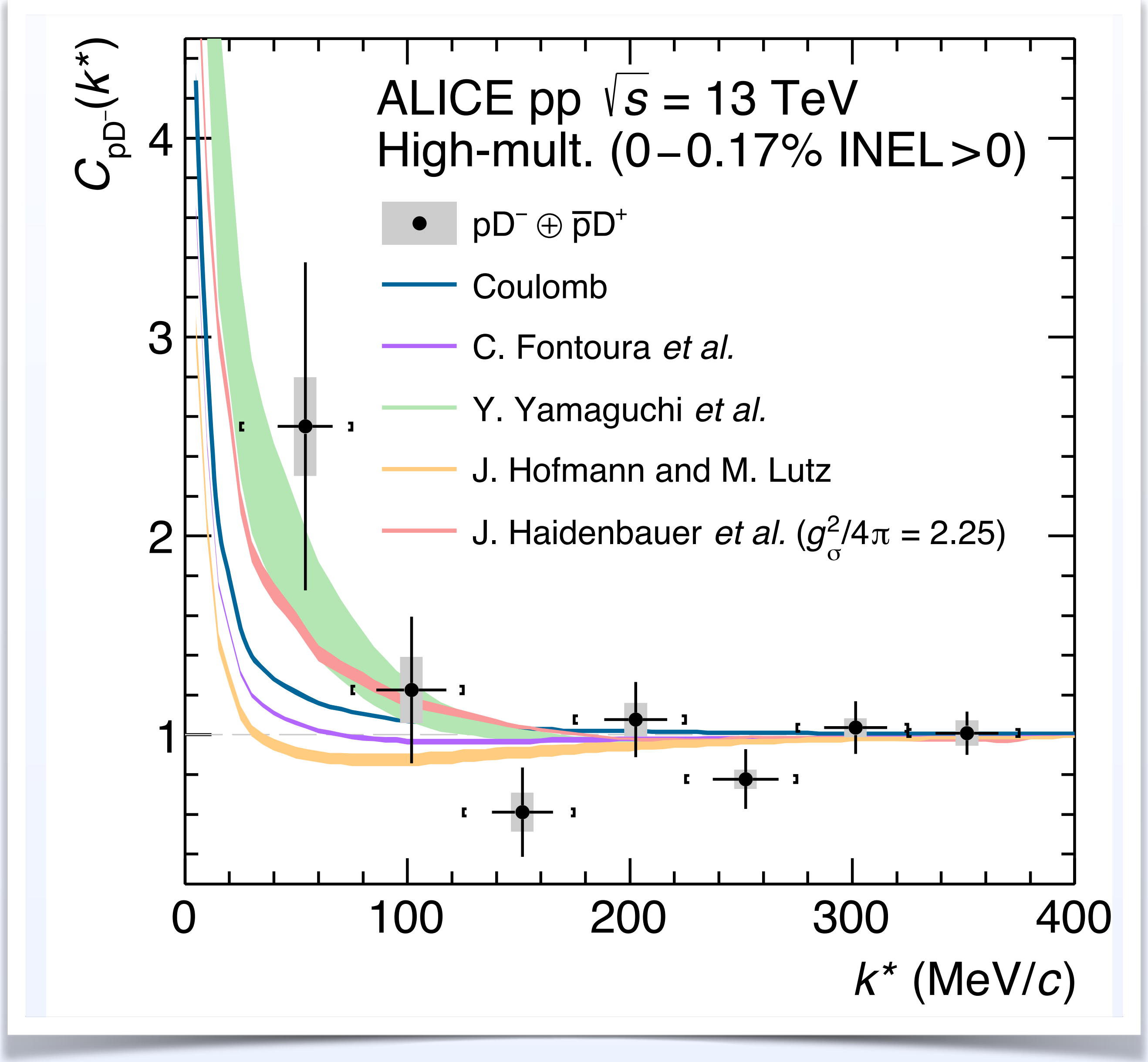
$\bar{D}N$ interaction and D^-p correlation function

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

Poster by D. Battistini

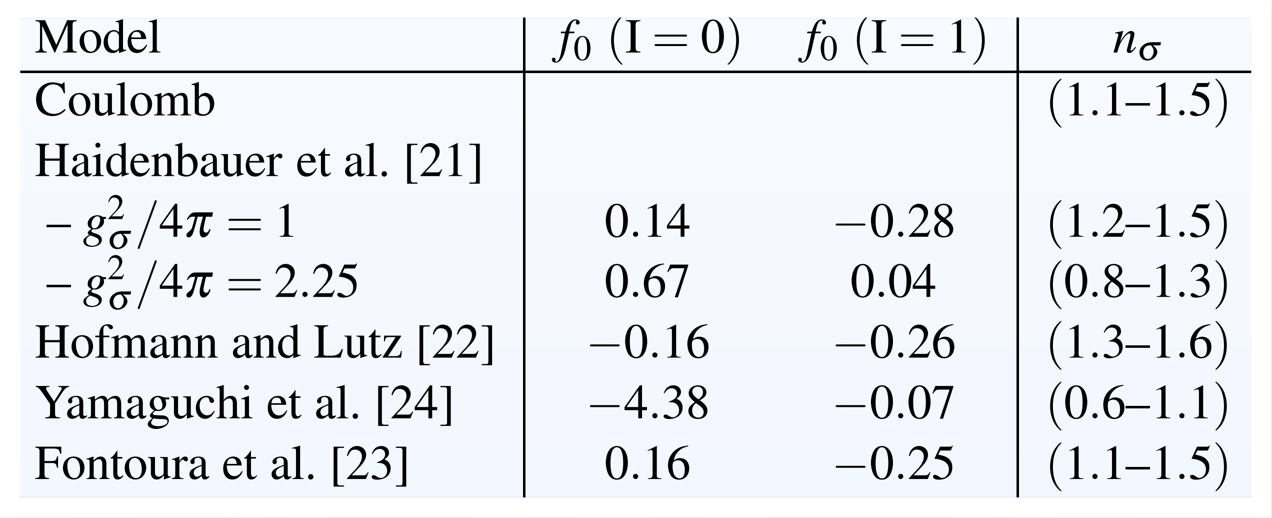
$f_0 \equiv \mathscr{F}(E = E_{\rm th})$
+ : attractive w/o bound
- : repulsive
or attractive w/ bound

- D^-p correlation function ALICE arXiv [2201.05352]



* 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

ALICE arXiv [2201.05352]

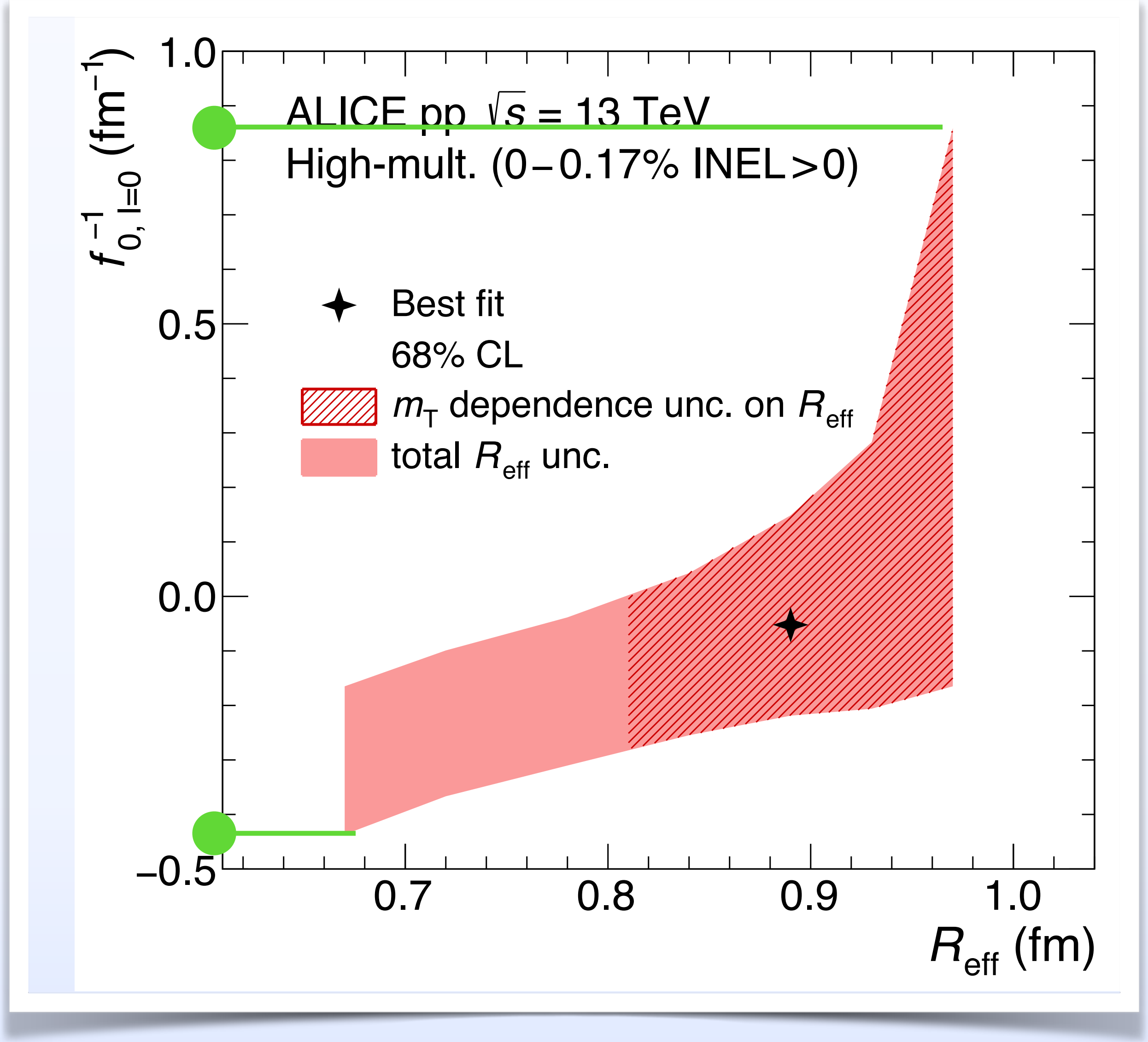
$f_0 \equiv \mathcal{F}(E = E_{\mathrm{th}})$
+ : attractive w/o bound
- : repulsive
or attractive w/ bound

- 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.

DN interaction and D^+p correlation function

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

- Model scattering lengths ($I=1$)

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

+ : attractive w/o bound

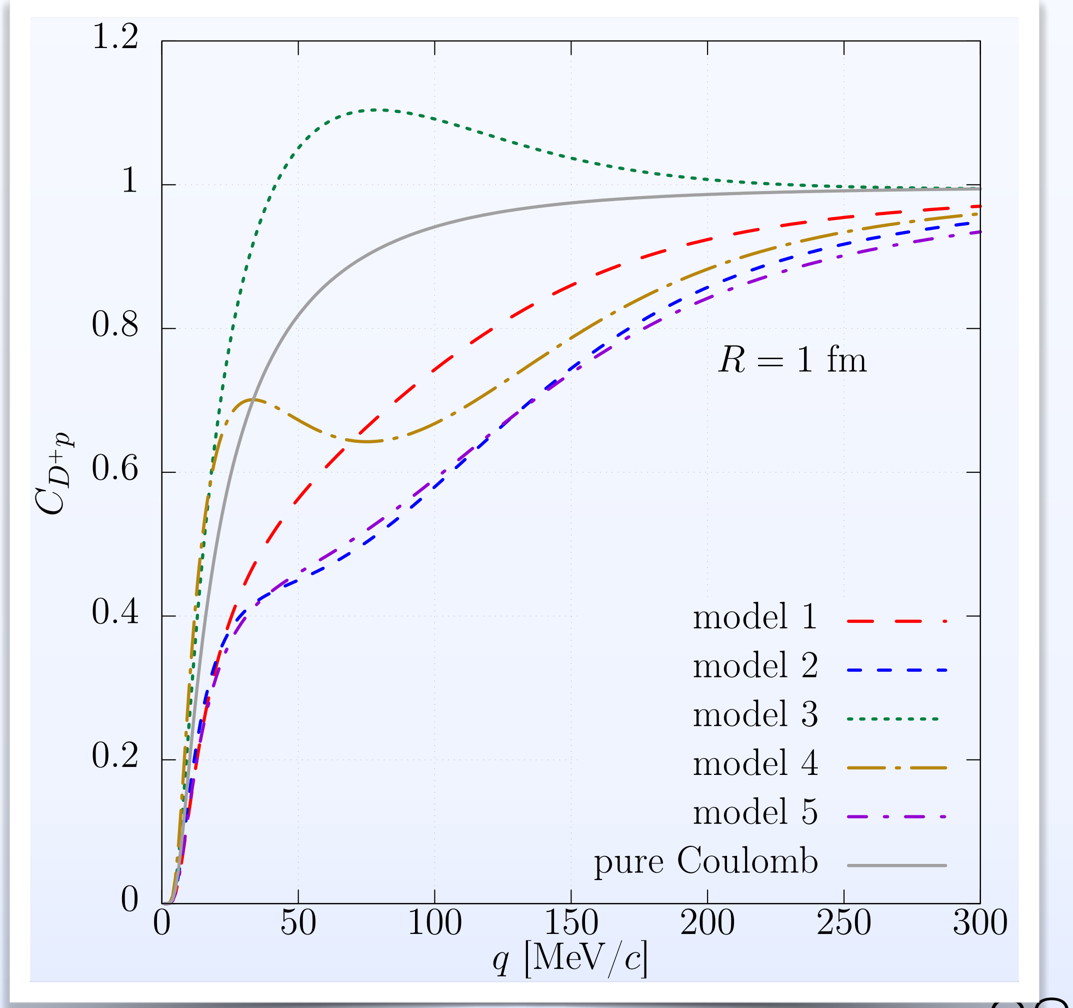
- : repulsive
  or attractive w/ bound

Moldes	$a_0^{DN(I=1)}$ [fm]	bound state ($I=1$)
[1] J. Hofmann and M. Lutz, NPA 763 (2005).	-0.41	$2620 - i1$
[2] T. Mizutani and A. Ramos, PRC 74 (2006).	$-1.47 + i0.65$	$2695 - i77$
[3] C. Garcia-Recio et al., PRD 79 (2009).	$0.33 + i0.05$	$2637 - i40$
[4] J. Haidenbauer, et. al. EPJA 47 (2011).	$-2.07 + i0.57$	$2793 - i6$
[5] U. Raha, et. al.. PRC98 (2018).	$-0.764 + i0.615(D^0n)$	$2806 - i72$

- D^+p channel: only $I=1$ interaction
- Complex value of a_0 due to decay channels
- Large uncertainty for pole position and scat. lengths

D^+p correlation

- Gaussian potential ($I=1$) and Gaussian source
- Depending on the interaction (scattering length), C_{D^+p} shows enough enhancement, suppression.



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

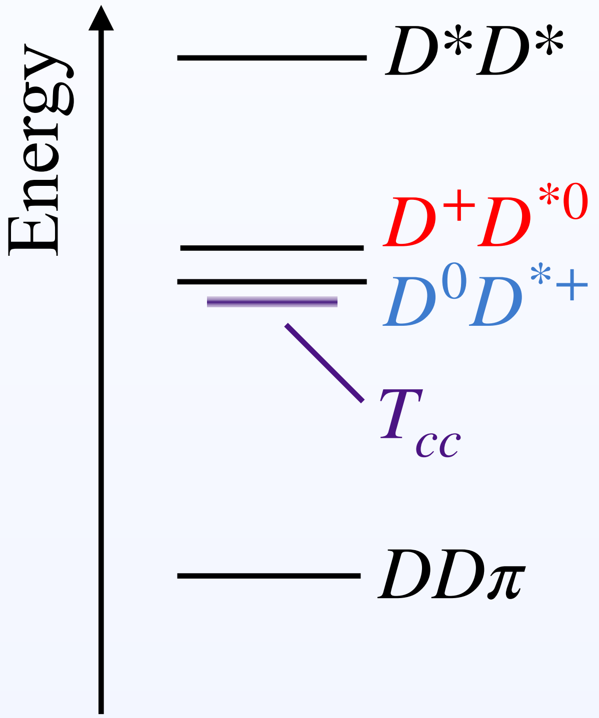
- DD and $D\bar{D}$ sector

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

+ : attractive w/o bound

- : repulsive
  or attractive w/ bound

$C = 2$



LHCb, Nature Com. 13 (2022) 1

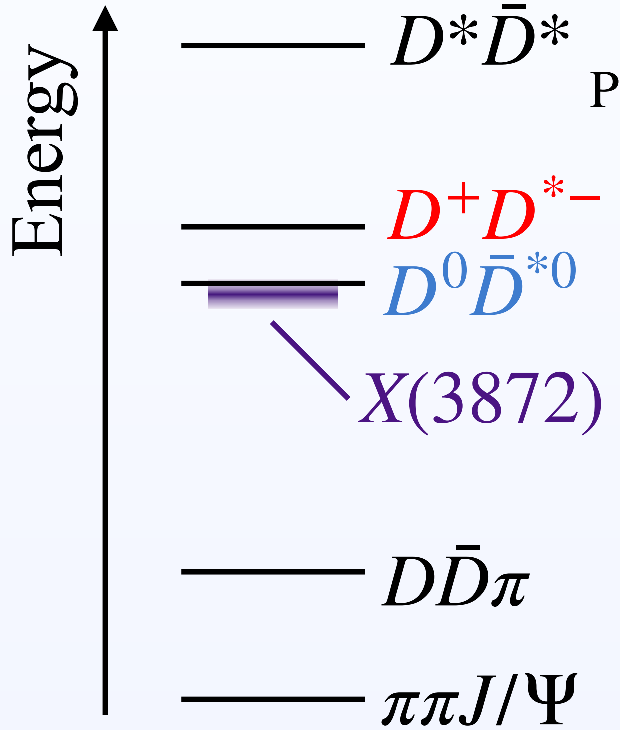
$$E_{T_{cc}} = \delta_m - \frac{i}{2}\Gamma$$

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

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

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

$C = 0$



PDG, PTEP 2020, 083C01 (2020).

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

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

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

$$\downarrow$$

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

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

  ==> meson-meson molecule?

  ==>Strong attractive interaction

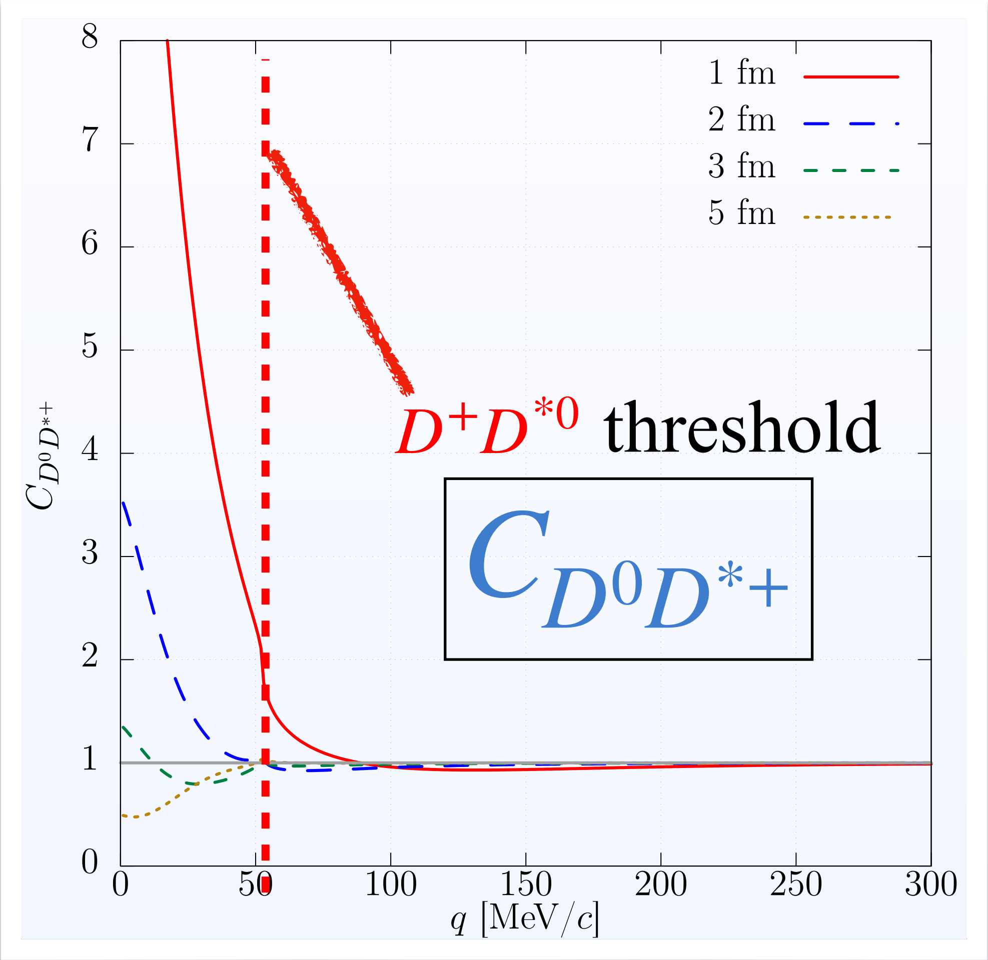
- Gaussian potential

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

- m <— ρ exchange ($m = m_\rho$)
- 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



- $D\bar{D}$

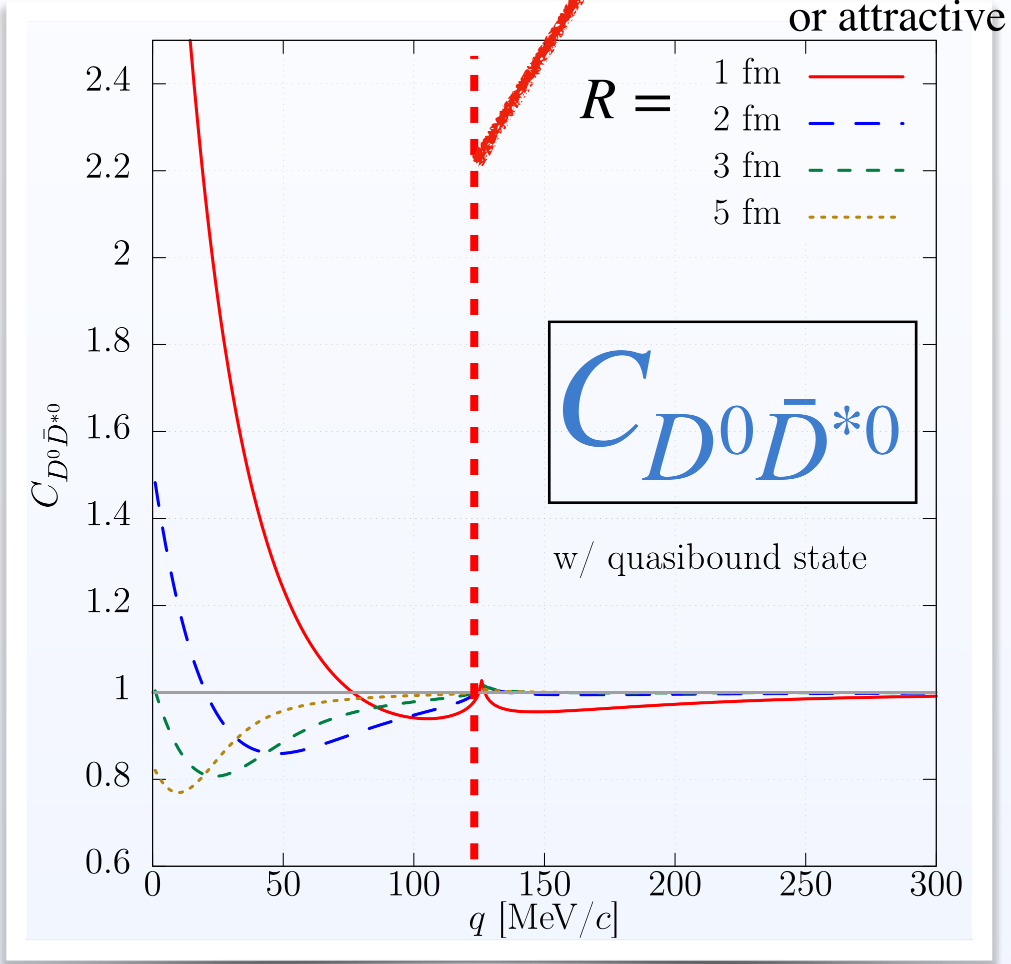
D^+D^{*-} threshold

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

+ : attractive w/o bound

- : repulsive

or attractive w/ bound



- Larger signal in the lower channels
- Bound state like behavior for both pairs
- Clear source size dependence
- Moderate D^+D^{*0}/D^+D^{*-} cusp

Y. Kamiya, T. Hyodo, A. Ohnishi, [2203.13814]

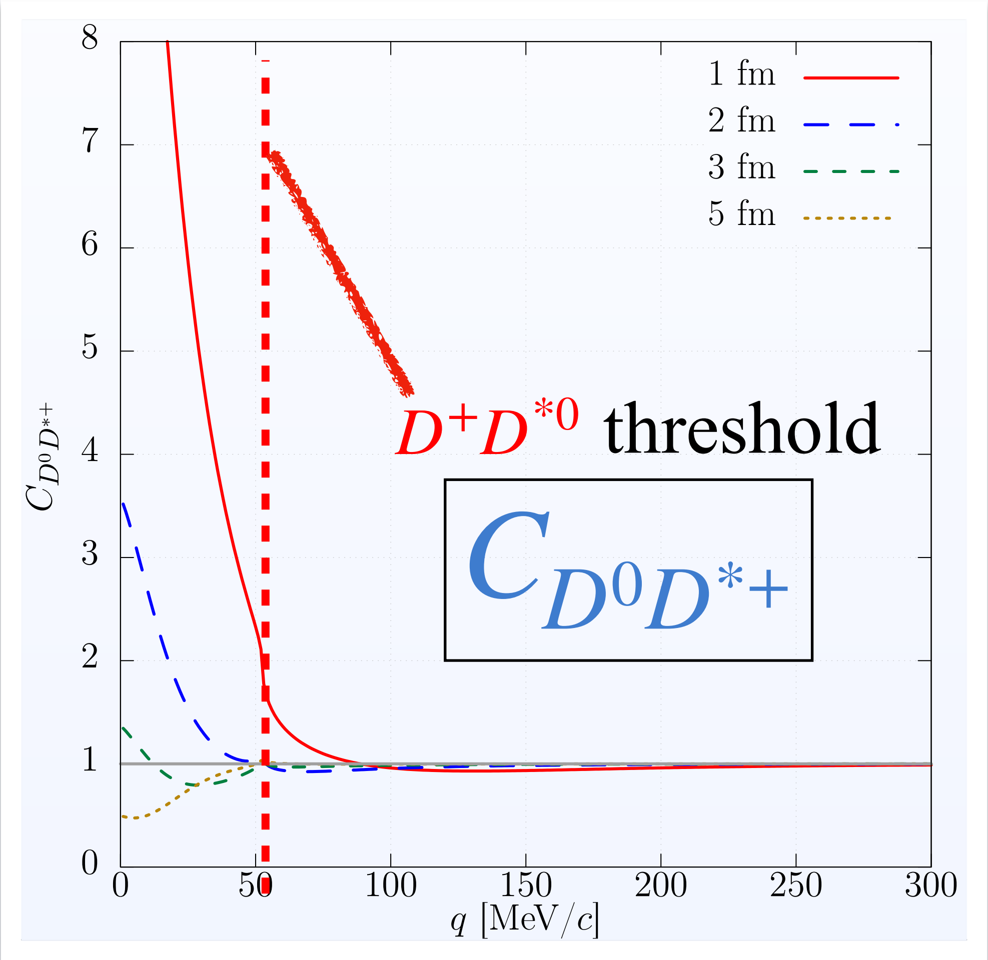
DD^* and $D\bar{D}^*$ int. from femtoscopy

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

+ : attractive w/o bound

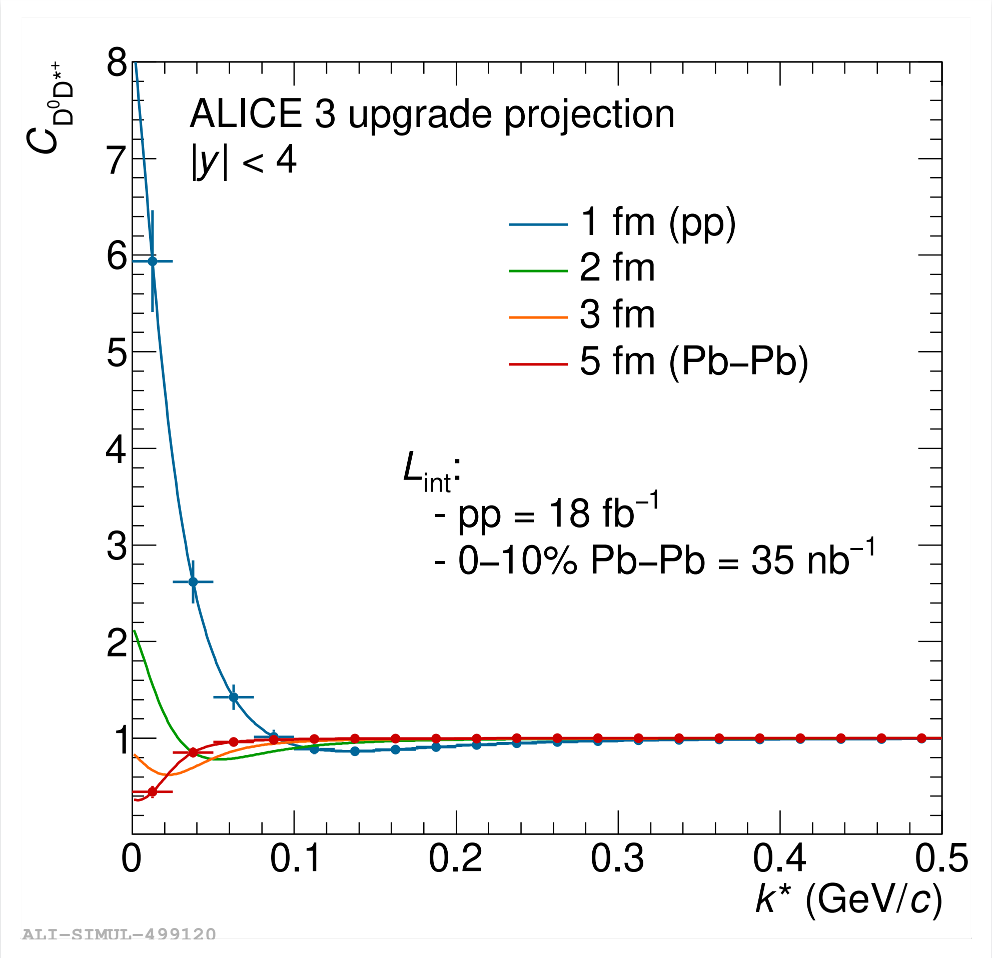
- : repulsive
  or attractive w/ bound

- ***DD***



D^+D^{*0} threshold

$C_{D^0D^{*+}}$



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

- Larger signal in the lower channels
- Bound state like behavior for both pairs
- Clear source size dependence
- Moderate D^+D^{*0}/D^+D^{*-} cusp

- Well investigated
  with future ALICE 3 upgrade

Y. Kamiya, T. Hyodo, A. Ohnishi, [2203.13814]

Summary

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the hadron-hadron interaction.
- Source size dependence is important to see the interaction detail especially for the coupled-channel case.
- $K^- p$
  Chiral SU(3) dynamics model is consistent with the large source data while small deviation is found in small source data.
- $\Lambda\Lambda$-$p\Xi^-$
  Coupled-channel HAL-QCD potential is consistent with current data from pp and pPb collisions.
- $D^- p$
  Non-interacting model dan 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.

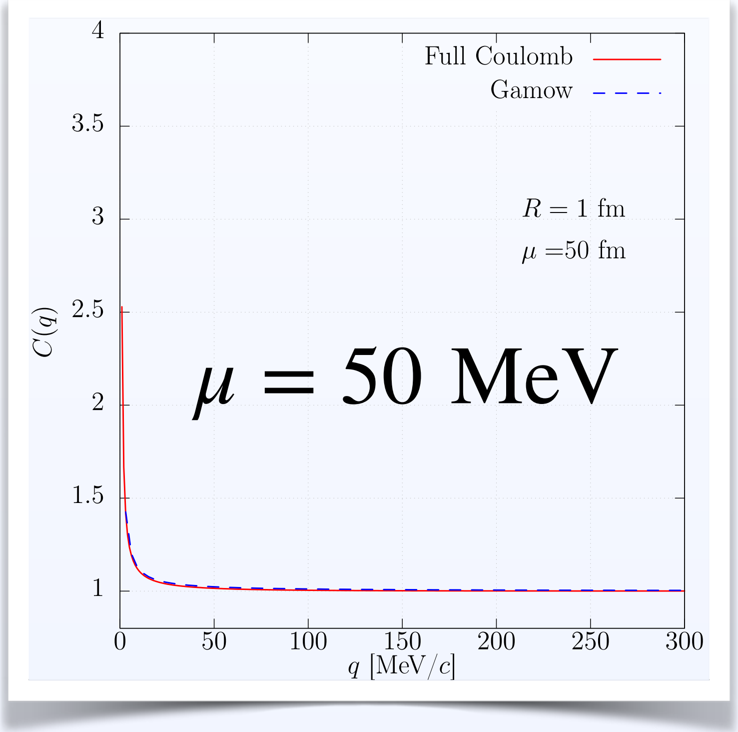
Thank you for your attention!

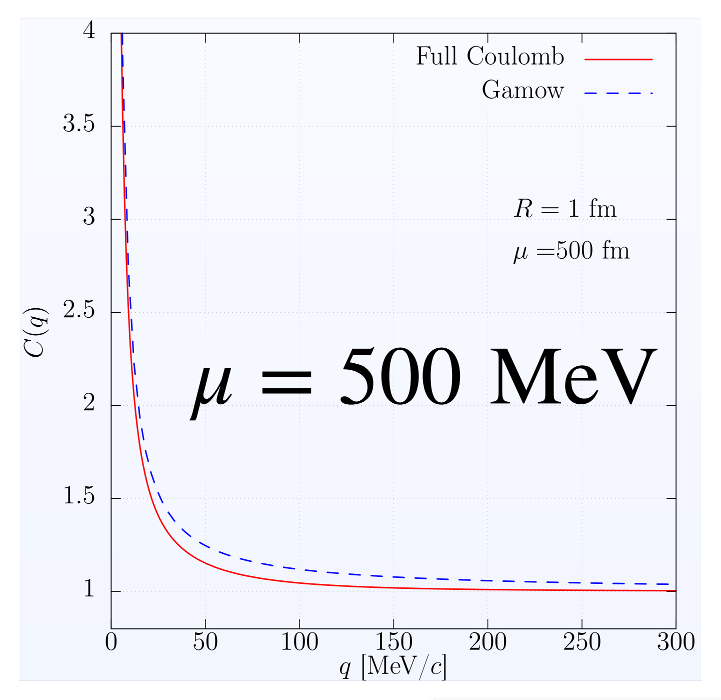
Thank you!

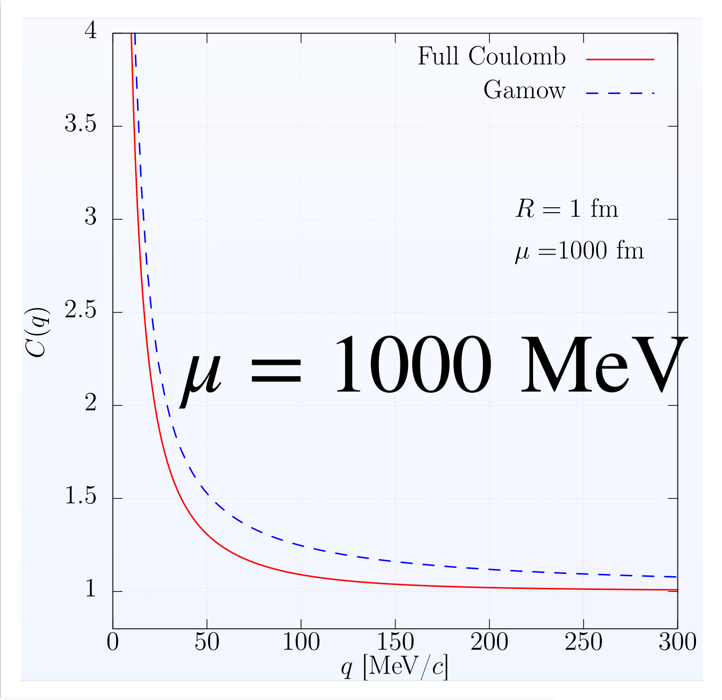
Coulomb interaction

Coulomb interaction: Full calculation

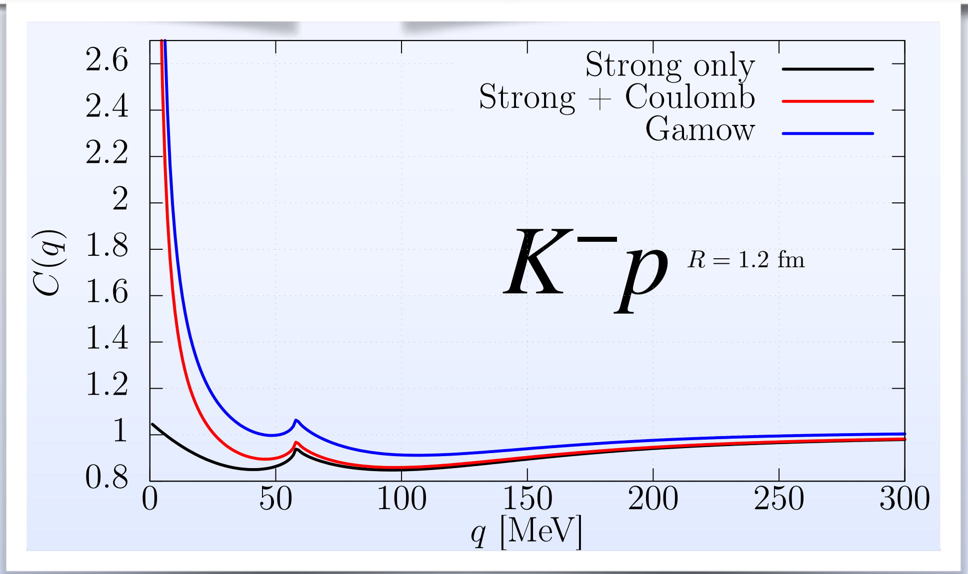
- For the quantitative discussion, fully calculated Coulomb w.f. ψ^C is needed:
  - $[H_0 + V]\psi^C = E\psi^C$ with $V = V_{\text{strong}} + V_{\text{Coulomb}}$
- Pure Coulomb cases ($V_{\text{strong}} = 0$)
  - LL formula over estimates the Coulomb int. for heavy particle pairs.







- With strong int. ($V_{\text{strong}} \neq 0$)
  - Interference of V_{strong} and V_{Coulomb}



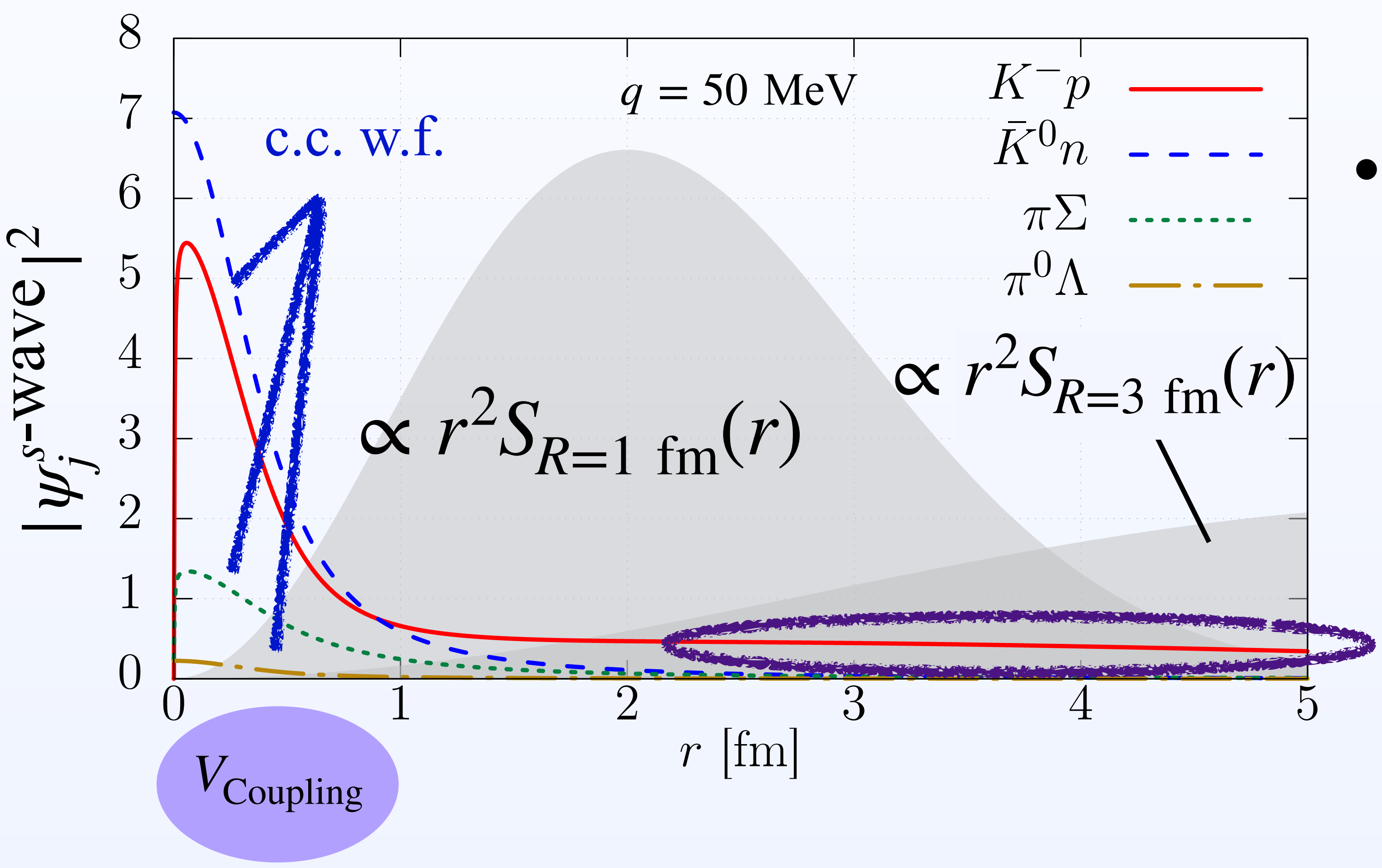
- For the femtoscopic study, full calculation is mandatory.

Source size dependence

- Coupled-channel wave function

$$\boxed{C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\,|\psi^{C,(-)}_{K^-p}(q;r)|^2 + \sum_{j\neq i}\omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\underbrace{\psi^{C,(-)}_j(q;r)}_{}|^2}$$

Coupled-channel
wave function $\bar{K}^0 n$, $\pi^0\Sigma^0$, ⋯



- Coupled-channel wave function satisfies the out-going boundary condition
  - Measured channel (K^-p) has out going wave
  - Coupled-channel w.f. emerges only in int. region

- Small source ==> W.F. of Coupled-channels counts
- Small source ==> Measured channel contribution dominant

Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

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

Chiral SU(3) based $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

Miyahara, Hyodo, Weise, PRC 98 (2018)

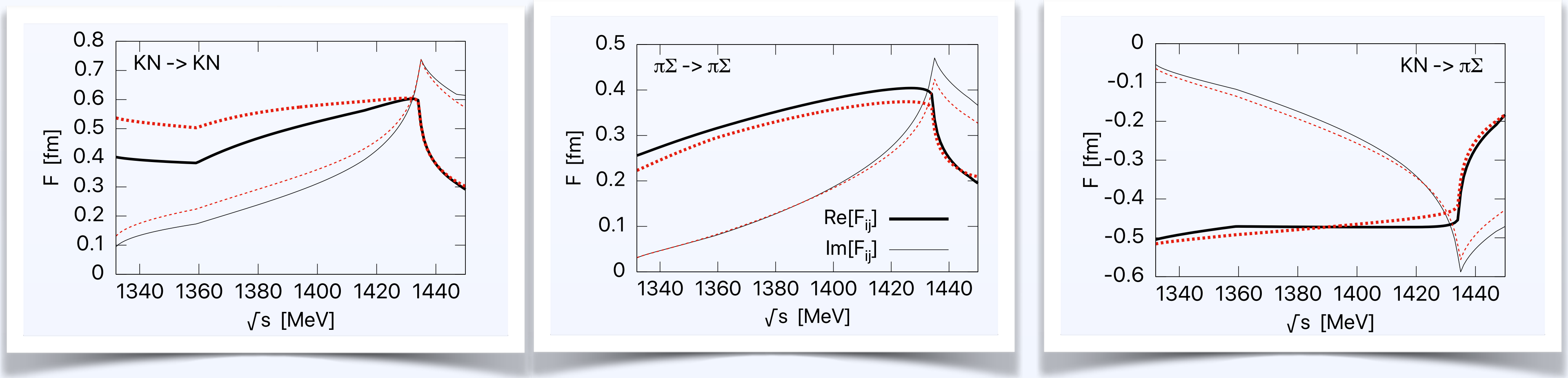
- Constructed based on the amplitude with NLO chiral SU(3) dynamics

Ikeda, Hyodo, Weise, NPA881 (2012)

- Coupled-channel, energy dependent as

$$V_{ij}^{\mathrm{strong}}(r,E) = e^{-(b_i/2+b_j/2)r^2}\sum\nolimits_{\alpha=0}^{\alpha_{\mathrm{max}}} K_{\alpha,ij}\,(E/100\ \mathrm{MeV})^{\alpha}$$

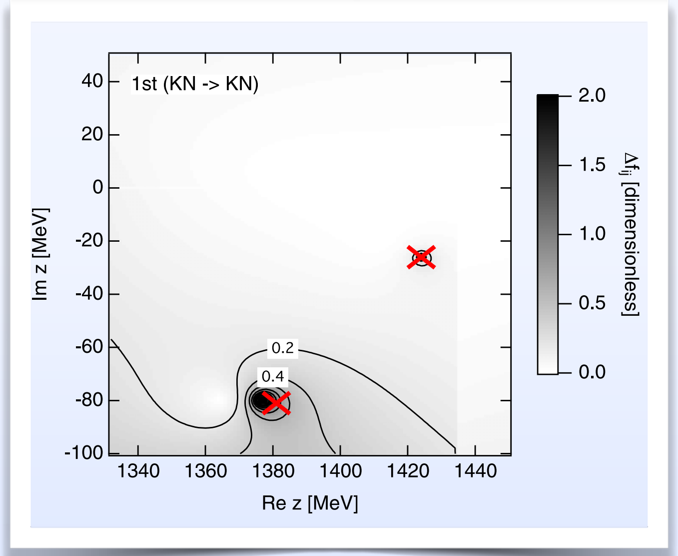
- Constructed to reproduce the chiral SU(3) amplitude around the $\bar{K}N$ sub-threshold region



- Two pole structure of $\Lambda(1405)$: well reproduced

High-mass pole : 1424 - 27i
Low-mass pole : 1380 - 81i

Original chiral SU(3) : 1424 - 26i
1381 - 81i

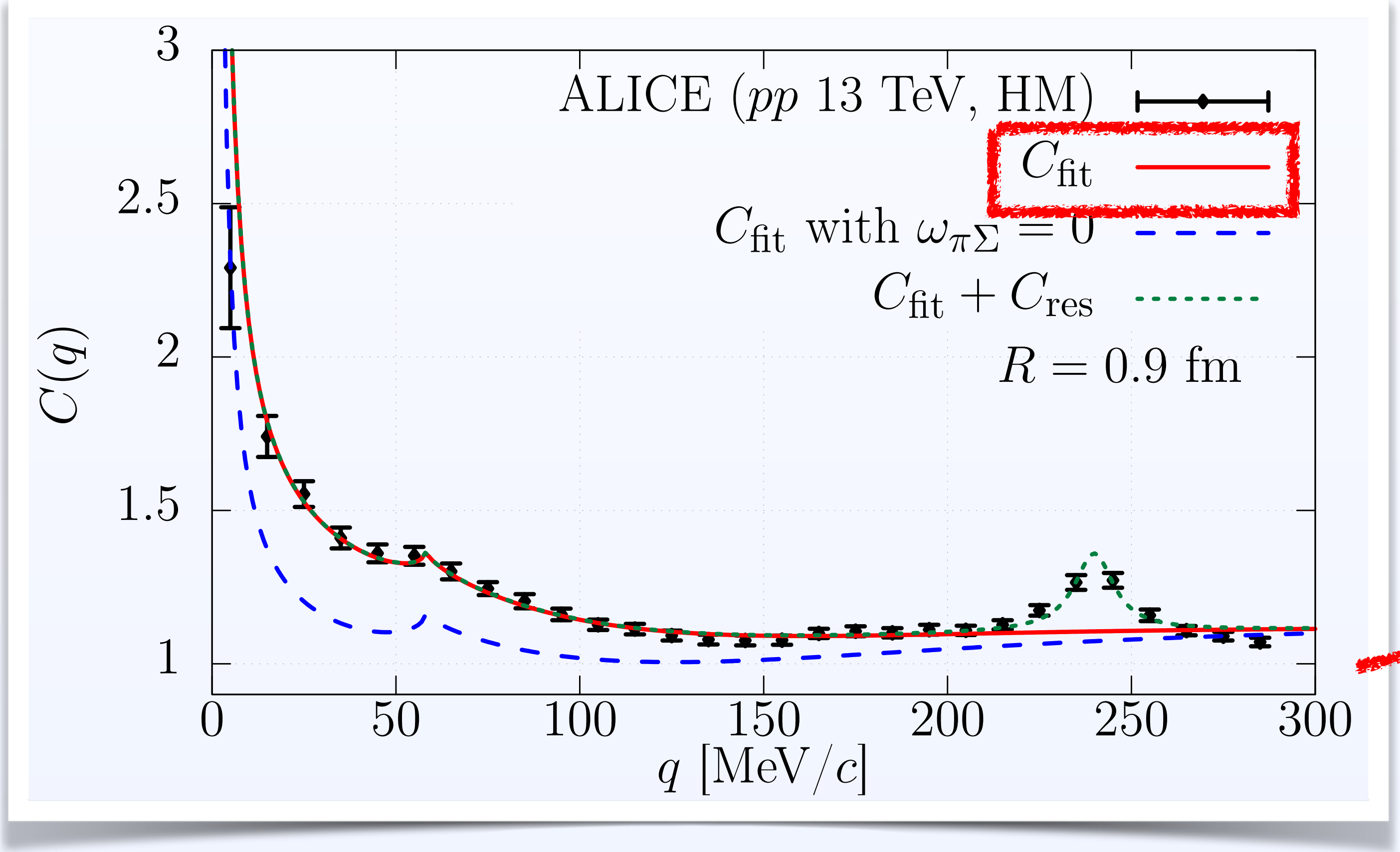


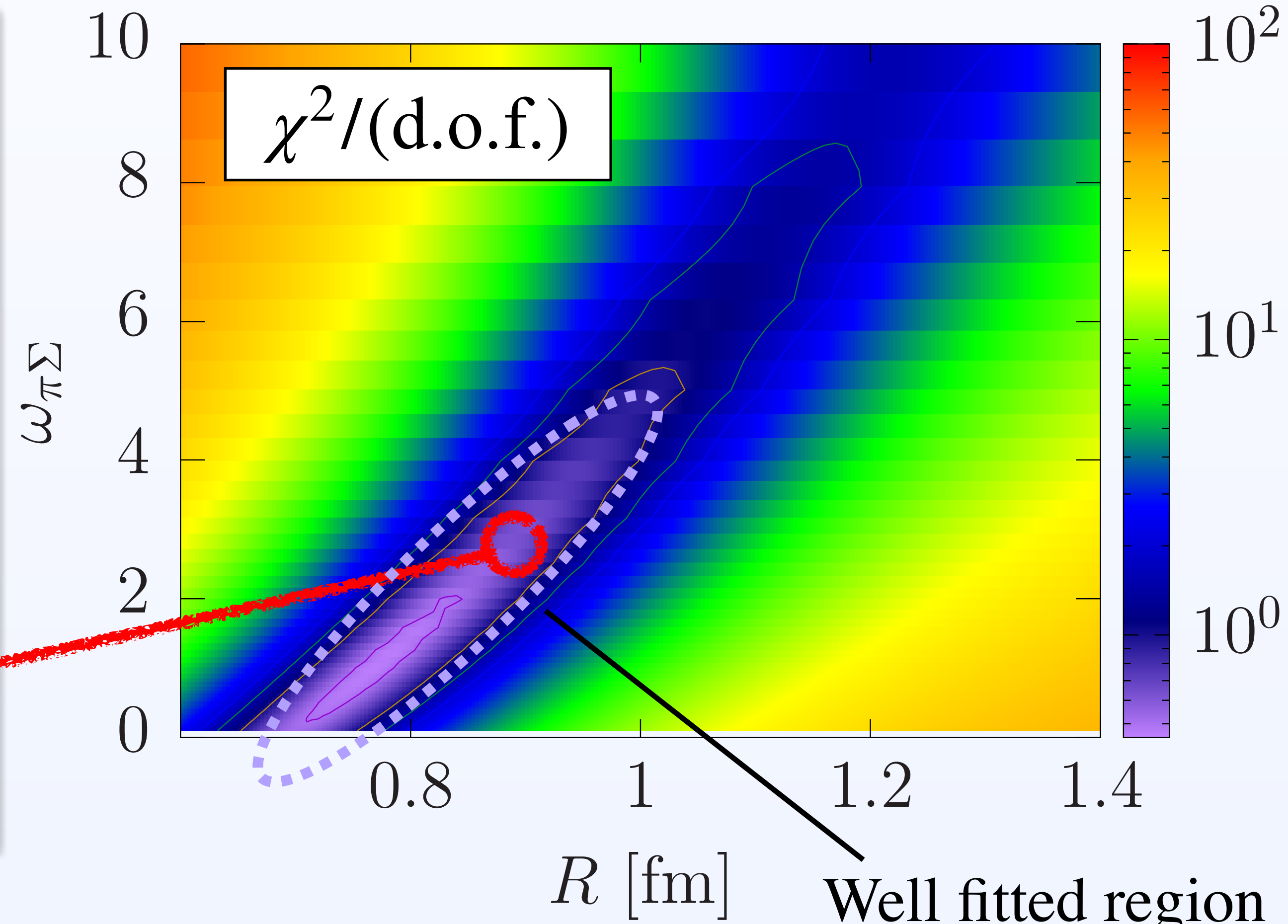
Comparison with ALICE data

- Fitting result
  - Fitting function

$$C_{\text{fit}}(q) = \mathcal{N}[1 + \lambda\{C_{K^-p}(q) - 1\}] \qquad C_{K^-p}(q) = \sum_j \omega_j \left[\int d^3\mathbf{r}\; S(\mathbf{r})\,|\Psi_j^{C,(-)}(q,r)|^2\right]$$

  - Fitting range: $q < 120$ MeV/c





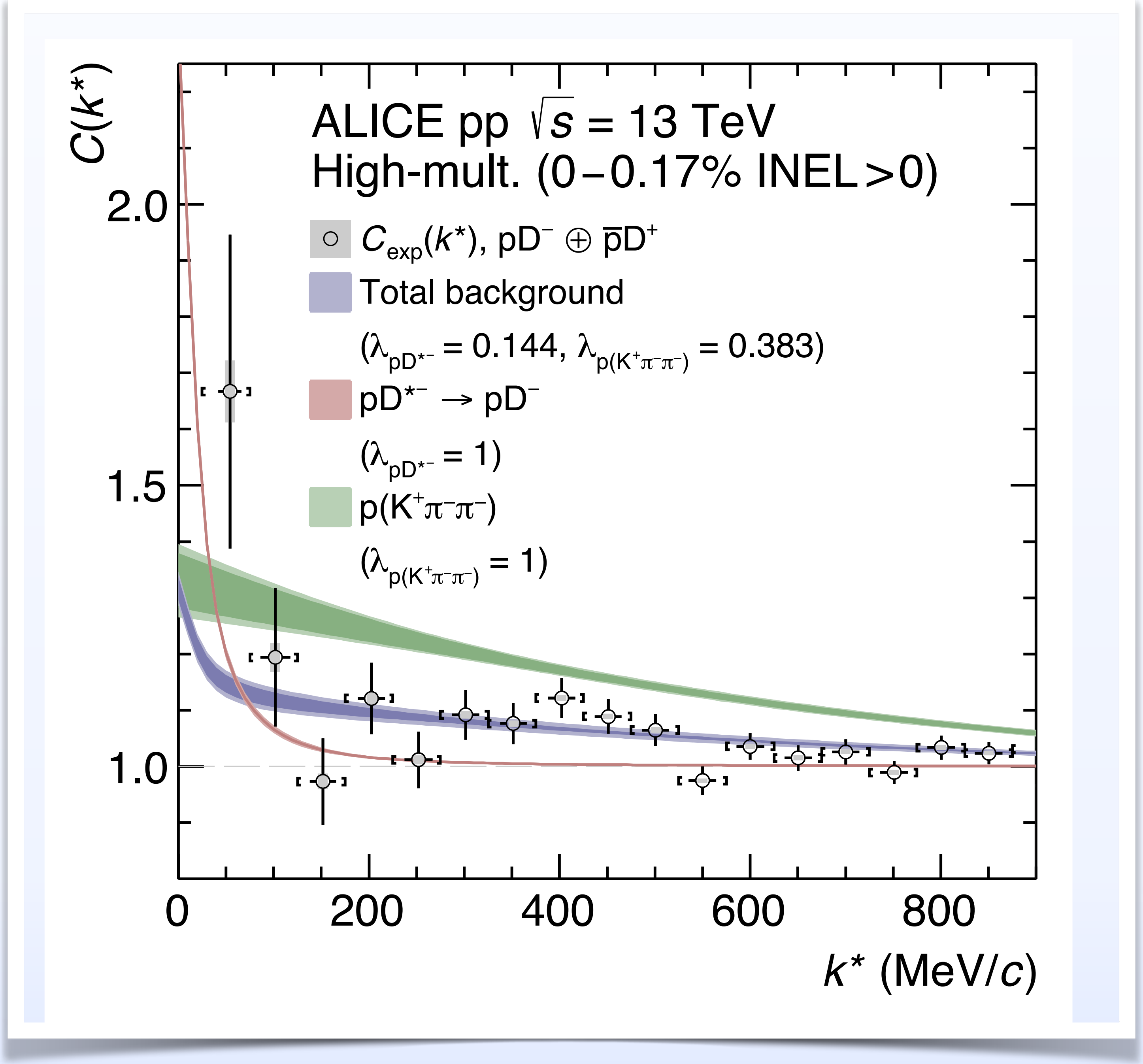
Well fitted region
(χ^2/(d.o.f) < 1)

- ALICE data has been well reproduced with the reasonable values of parameters.
- Coupled-channel source contribution is essential to reproduce the data.

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

- Background for D^-p correlation function

ALICE arXiv [2201.05352]



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

$f_0 \equiv \mathscr{F}(E = E_{\rm th})$

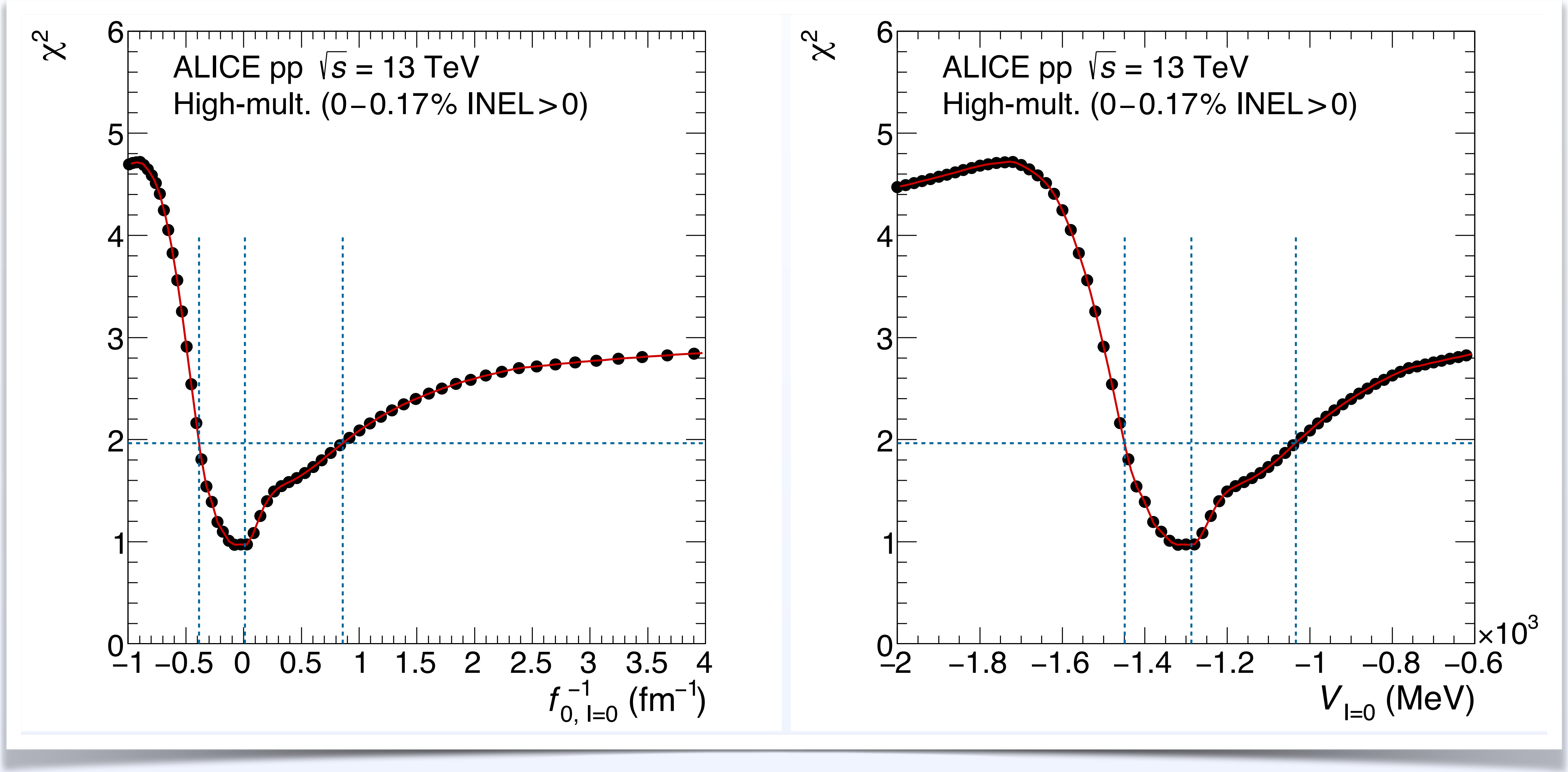
+ : attractive w/o bound

- : repulsive

or attractive w/ bound

- Constraint on $I = 0$ scattering length f_0

ALICE arXiv [2201.05352]



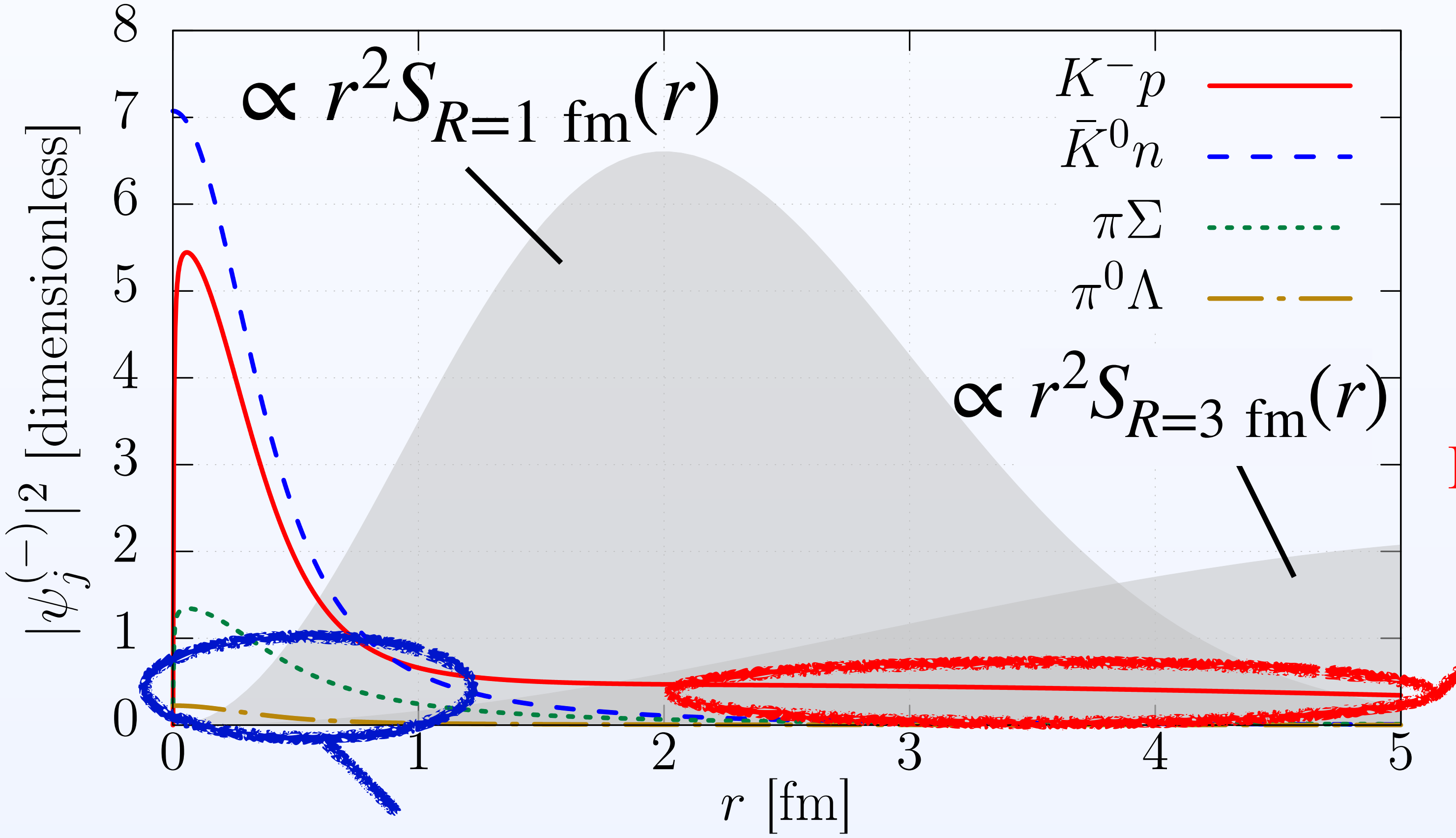
K^-p correlation with Koonin-Pratt Formula

- Coupled-channel effect and source size

$$\boxed{C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\; S_{K^-p}(\mathbf{r})\Big[\sum_{l\geq 1}|\varphi_l^C(\mathbf{q};\mathbf{r})|^2 + \underline{|\psi_{K^-p}^{C,(-)}(q;r)|^2}\Big] + \sum_{j\neq i}\omega_j \underline{\int d^3\mathbf{r}\; S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2}}$$

(1) Modification of $\psi_{K^-p}^{C,(-)}$

(2) C.c. source contribution



Effect (2)
becomes moderate for larger source

Effect (1)
Does not depends on the source size R

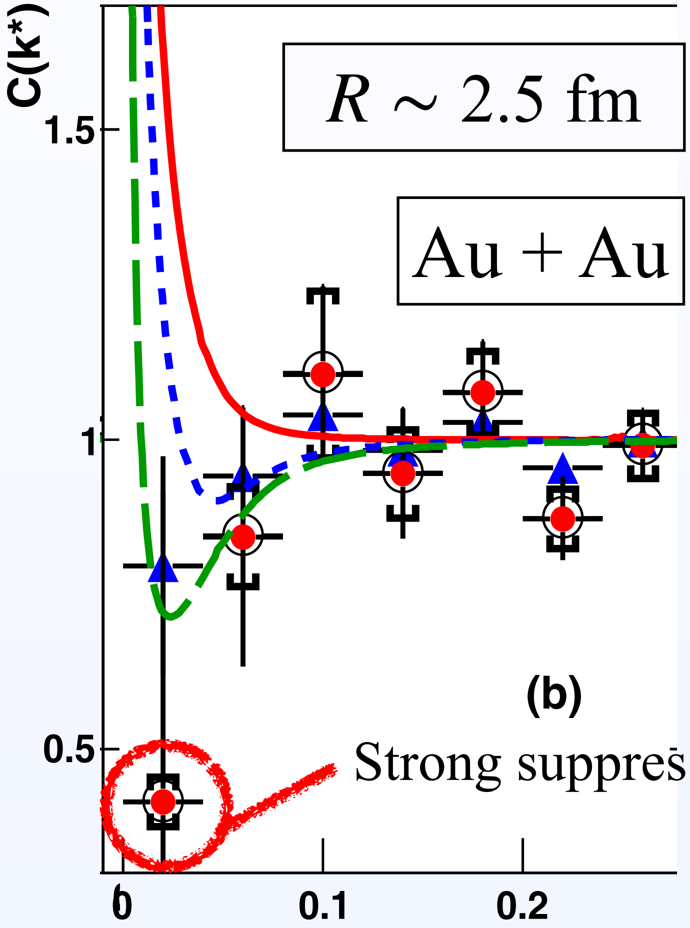
$$\psi_{K^-p}^{(-)} \to \frac{1}{2iq_1 r}\left(e^{iq_1 r} - \mathcal{S}_{11}^{\dagger} e^{-iq_1 r}\right)$$

(w/o Coulomb)

- For the larger source, effect (2) gives just a small enhancement.

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

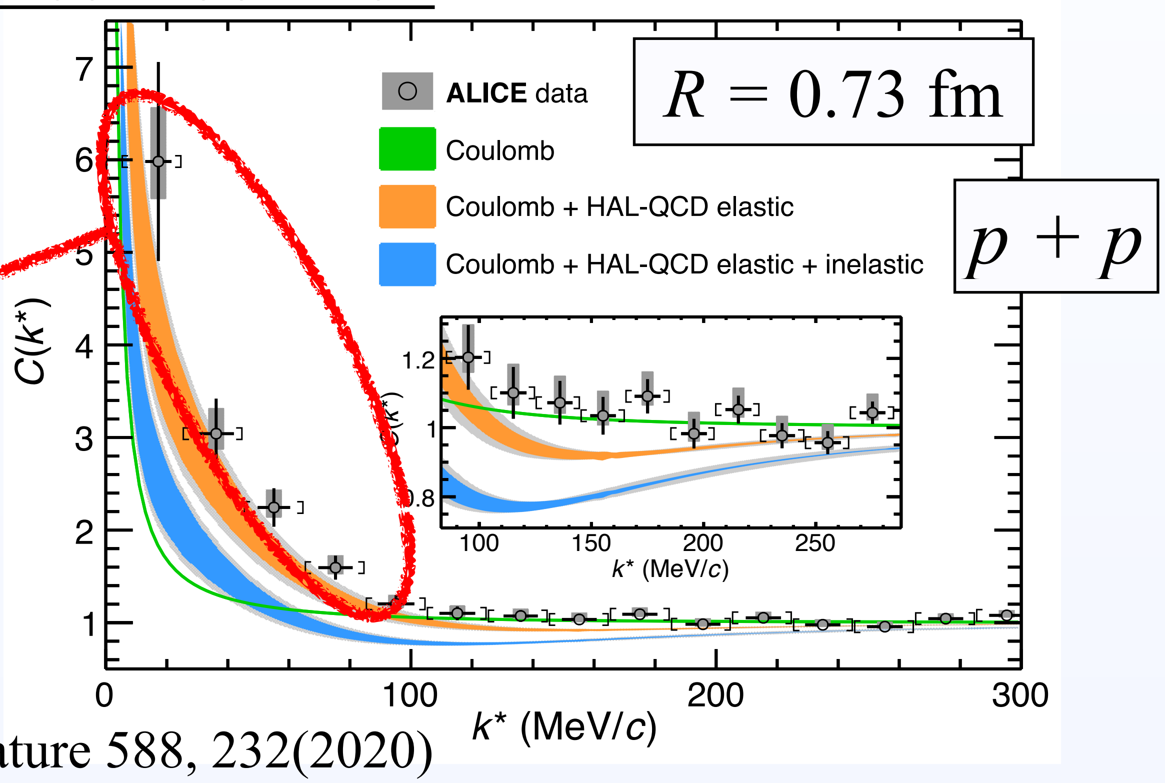
- Current situation of experimental data of $p\Omega$ corrleaiton
  - STAR collaboration
  - ALICE collaboration



Strong suppression

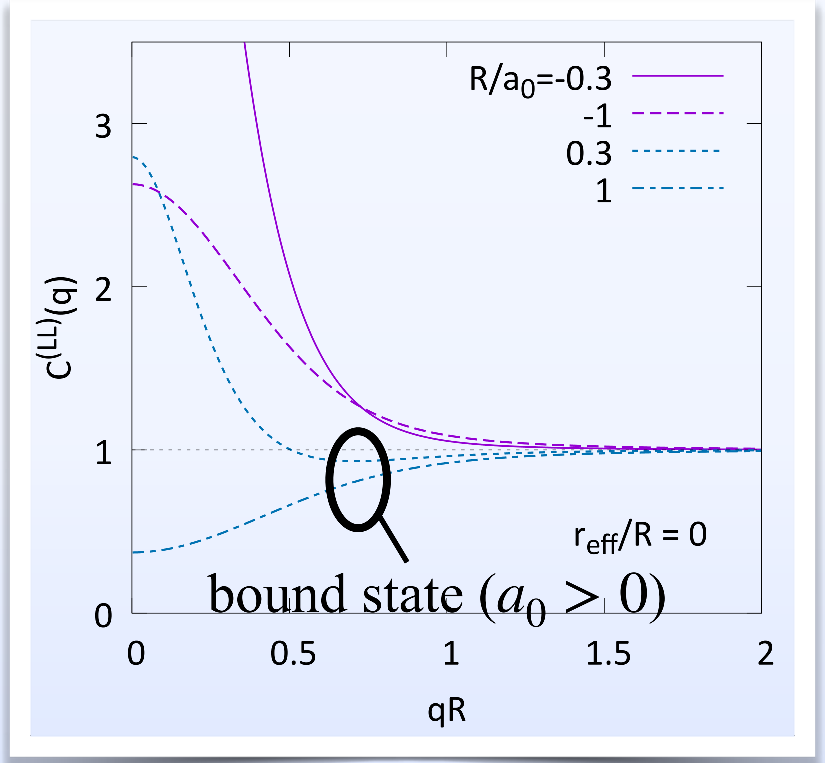
Adam et. al.PLB 790 (2019)

Enhancement



ALICE, Nature 588, 232(2020)

Fabbietti, et.al. [2012.09806]



bound state ($a_0 > 0$)

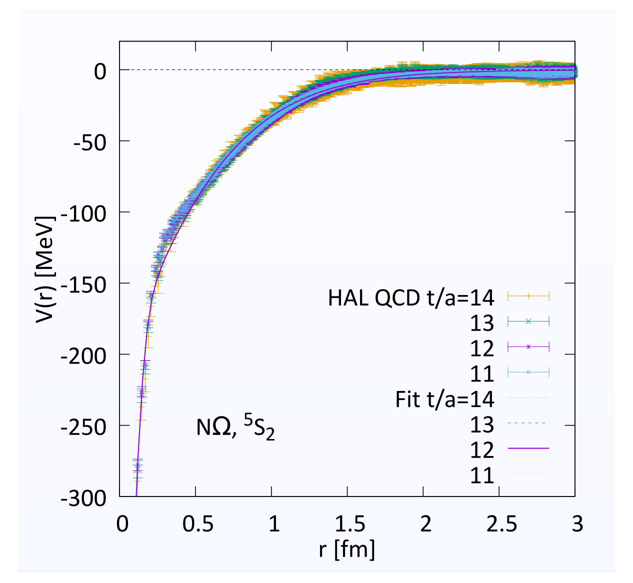
- Strong source size dependence ==> large $|a_0|$
- Strong suppression at larger source (R=2.5 fm)

  ==> $p\Omega$ dibaryon state?

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

- Updated $^5S_2$ $N\Omega$ potential by HAL QCD

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



  - Nearly physical quark mass: $m_\pi = 146$ MeV, $m_K = 525$ MeV
  - No repulsive core ← $N(lll)$ $\Omega(sss)$
  - Strong attraction with $N\Omega$ dibaryon $B = 1.54(0.30)(^{+0.04}_{-0.10})$ MeV

—> Next Dr. Sasaki's talk

$(a_0 \simeq 5.3 \text{ fm})$

- $p\Omega^-$ correlation function with HALQCD potential

Morita, et al., PRC101 (2020)

  - Neglect the channel coupling
  - Two assumptions on $J = 1$ wave function $\varphi^{(-)}_{J=1}$

$$C_{p\Omega}(\mathbf{q}) \simeq \frac{5}{8}\int d^3\mathbf{r}\ S(\mathbf{r})\,|\,\varphi^{(-)}_{J=2}(\mathbf{q};\mathbf{r})\,| + \frac{3}{8}\int d^3\mathbf{r}\ S(\mathbf{r})\,|\,\varphi^{(-)}_{J=1}(\mathbf{q};\mathbf{r})\,|^2$$

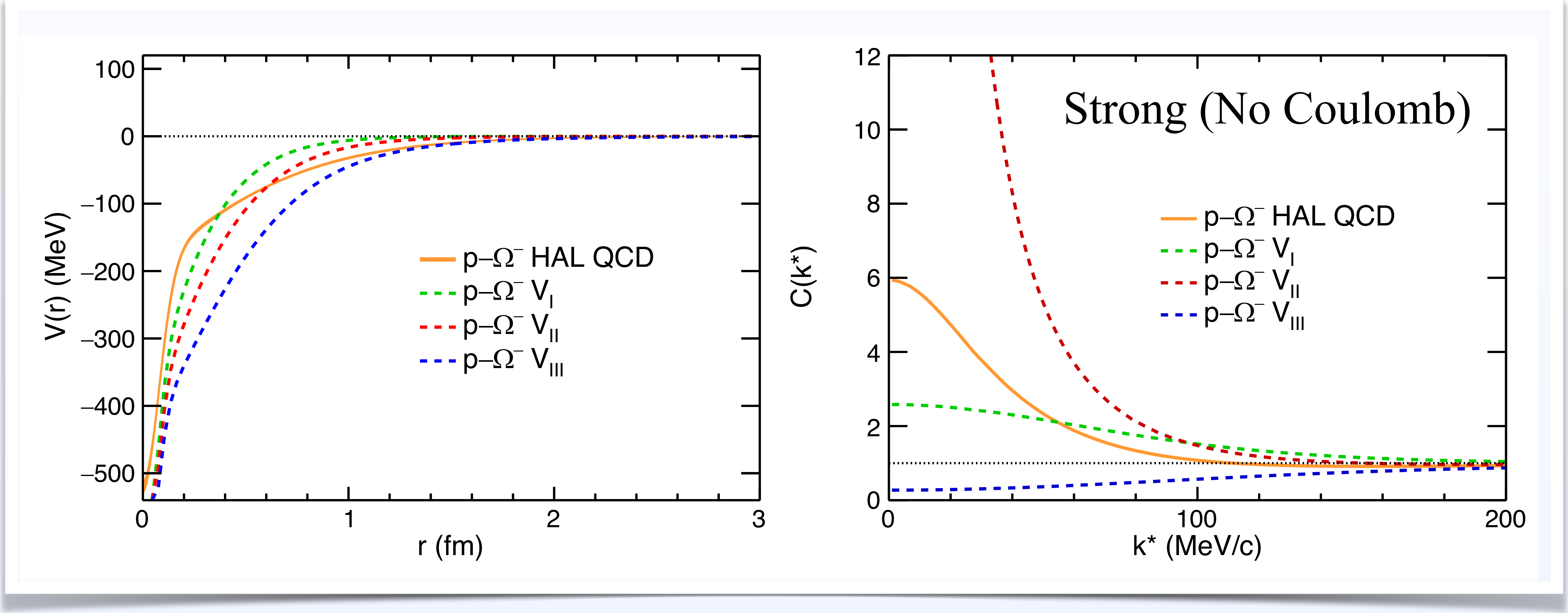
Reference : $\varphi^{(-)}_{J=1} = \varphi^{(-)}_{J=2}$ (Same attraction for $J = 1$ channel)

Minimum : $\varphi^{(-)}_{J=1,\text{s-wave}} = 0$ (Suppressed by channel coupling)

Difference of "Reference" and "Minimum" can be regarded as theoretical uncertainty from the unknown $J = 1$ interaction.

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

- Comparison with previous results



Fabbietti, et.al. [2012.09806]

	Strong	Strong + Coulomb
V_I	–	–
V_{II}	0.05 MeV	0.63 MeV
V_{III}	24.8 MeV	26.9 MeV

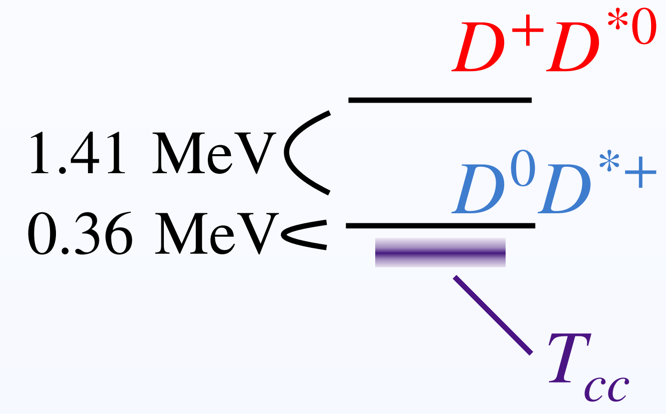
Morita K, Ohnishi A, Etminan F, Hatsuda T. PRC 94 (2016)

Morita K, et al. PRC (2020)

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

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

- DD^* correlation and T_{cc} state



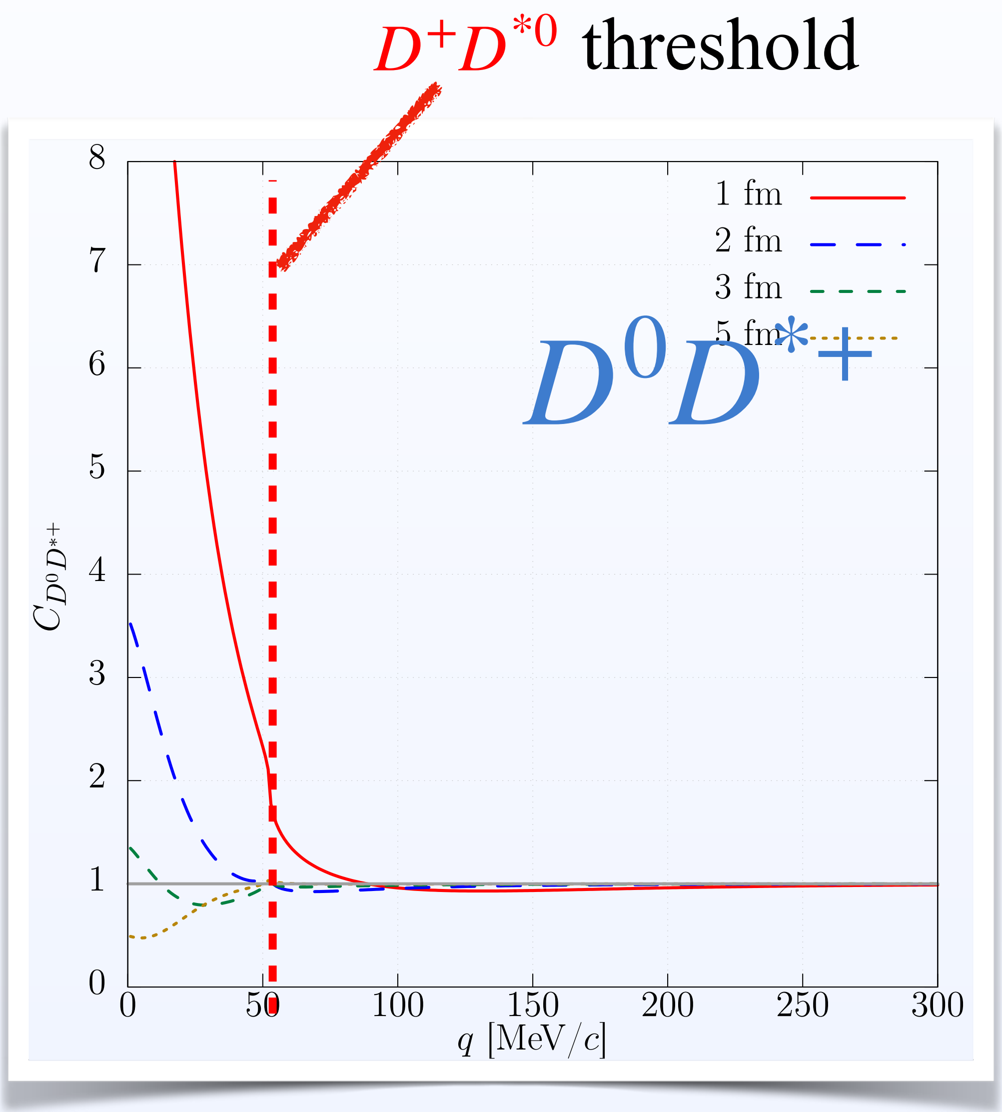
$$E_{T_{cc}} = \delta m - \frac{i}{2}\Gamma,$$

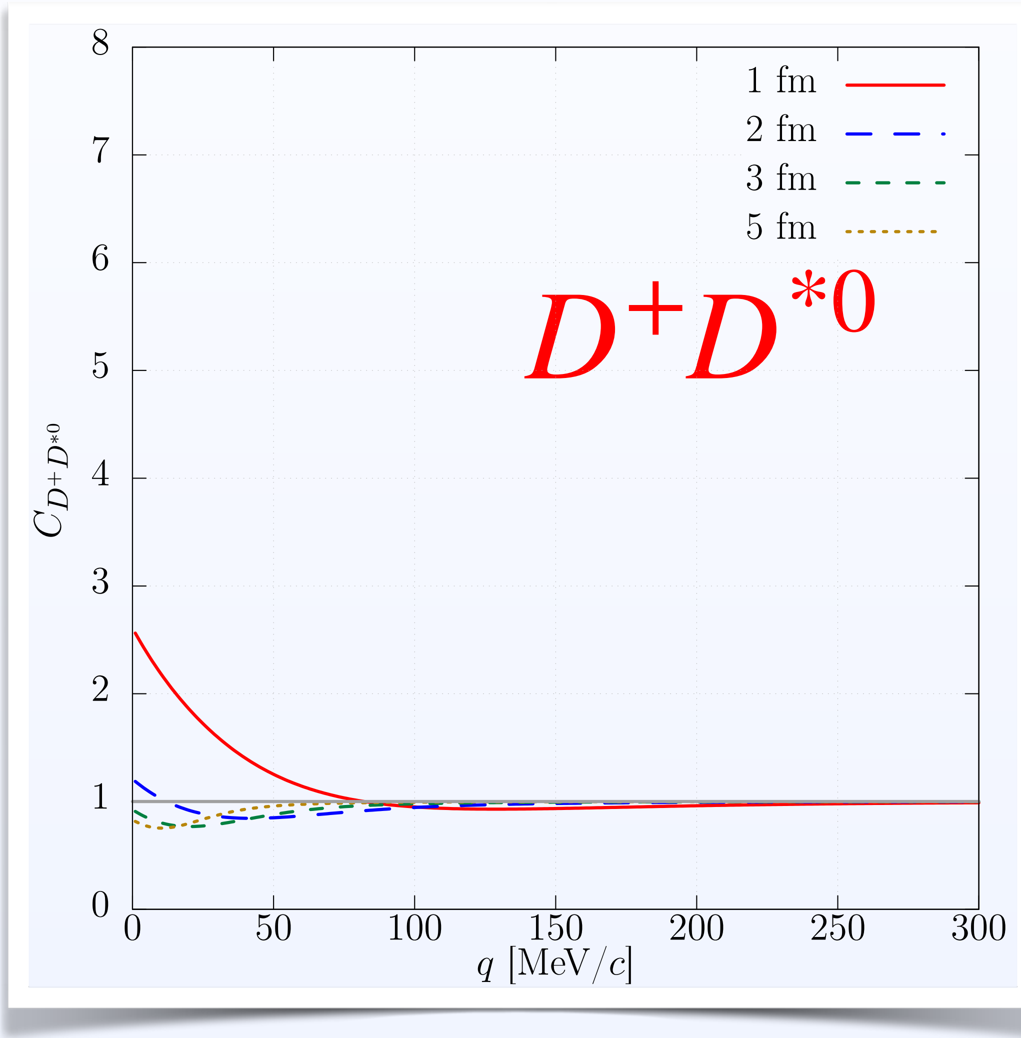
$$\delta m = -360 \ \mathrm{keV},$$

$$\Gamma = 48 \ \mathrm{keV}$$

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

LHCb, arXiv2109.01056



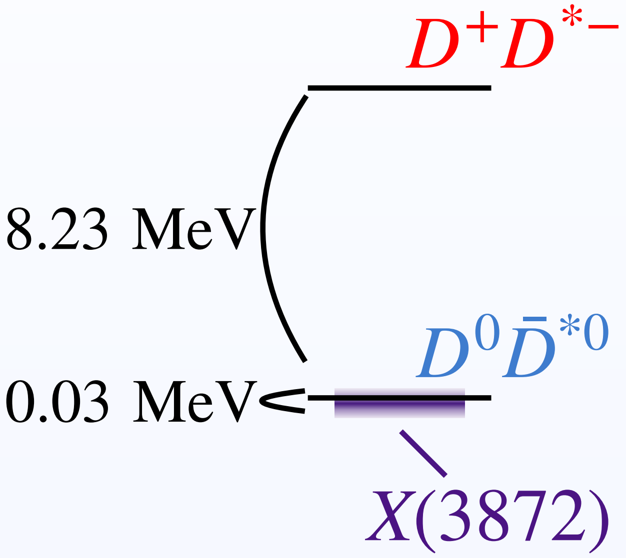


- Bound state like behavior for both pairs
- Stronger source size dep. for D^0D^{*+}
- D^+D^{*0} cusp is not prominent

Y. Kamiya, T. Hyodo, A. Ohnishi, [2203.13814]

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

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



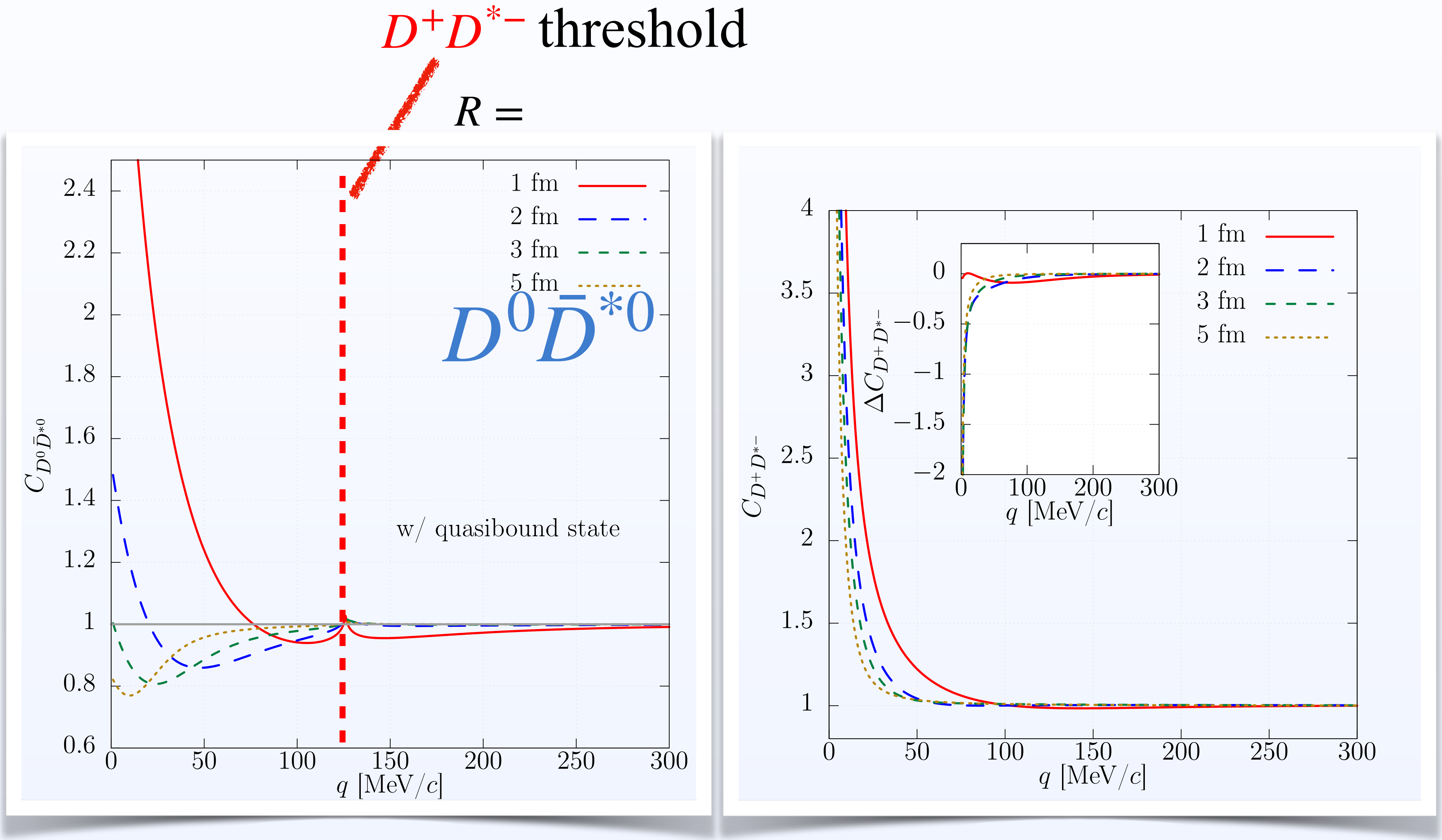
PDG, PTEP 2020, 083C01 (2020)

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

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

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

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

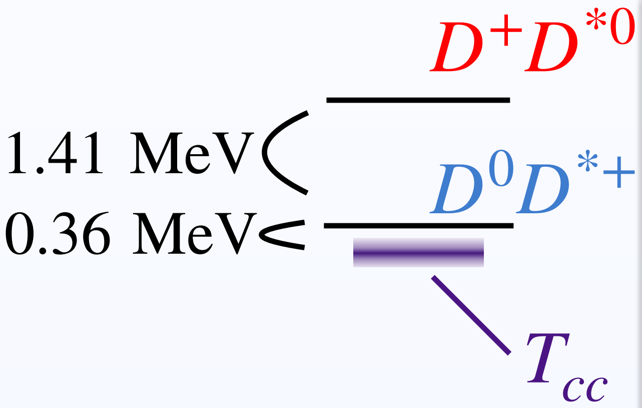


- D^0D^{*+} : Strong source size dep.
- D^+D^{*-} : Small effect of the strong int. (Coulomb int dominance)
- Moderate D^+D^{*+} cusp

Y. Kamiya, T. Hyodo, A. Ohnishi, [2203.13814]

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

- DD^* correlation and T_{cc} state



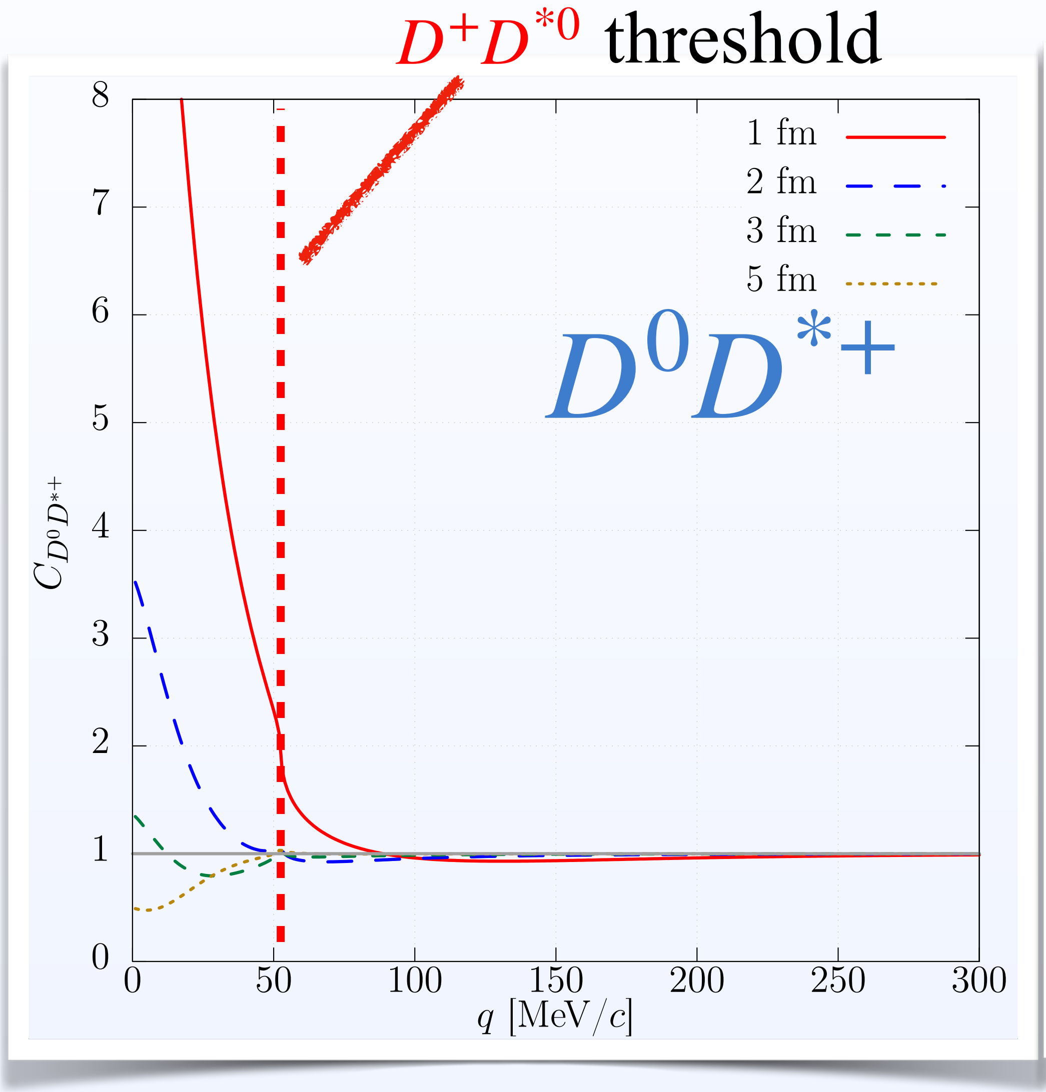
$$E_{T_{cc}} = \delta m - \frac{i}{2}\Gamma,$$

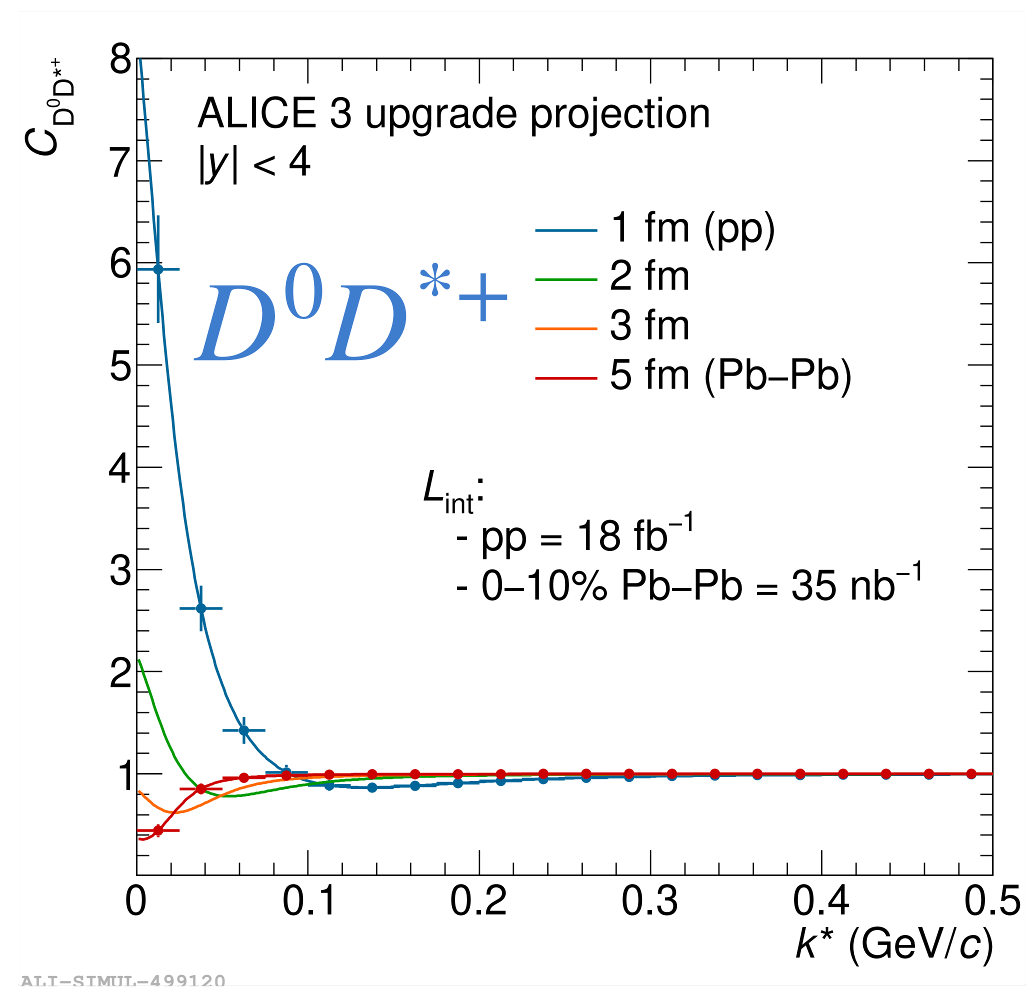
$$\delta m = -360 \text{ keV},$$

$$\Gamma = 48 \text{ keV}$$

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

LHCb, arXiv2109.01056





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

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

Y. Kamiya, T. Hyodo, A. Ohnishi, [2203.13814]