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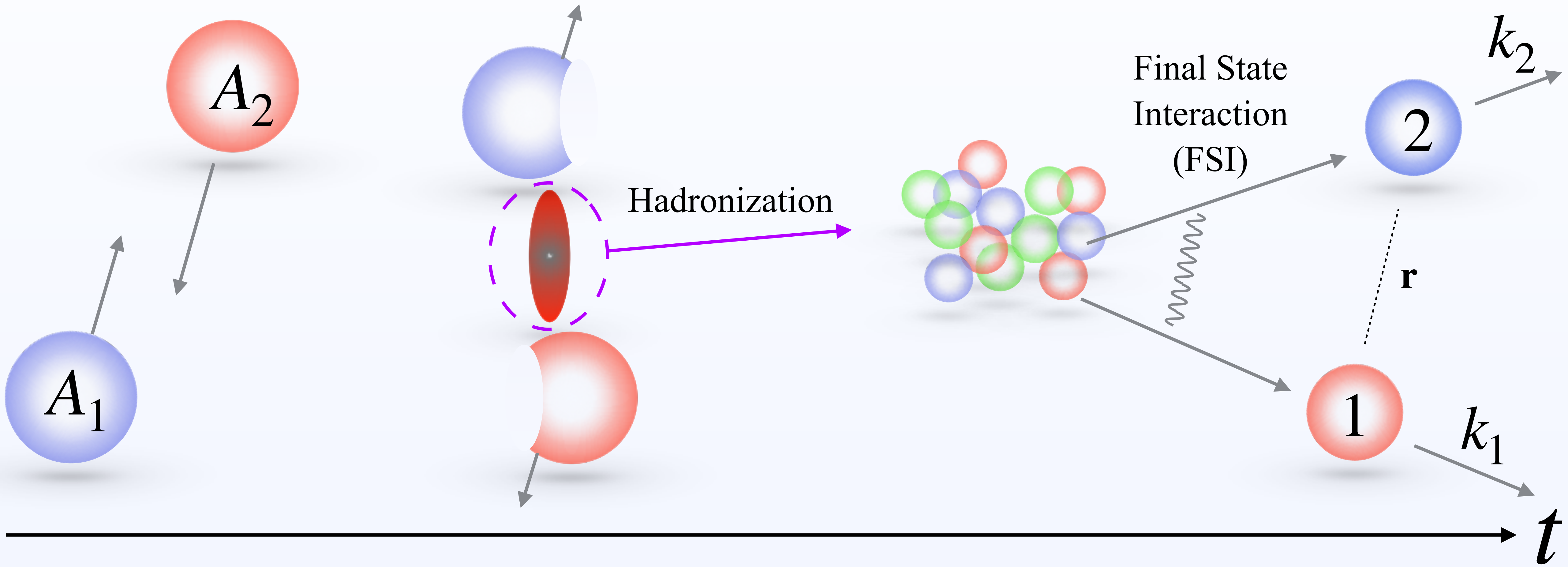
K^-p correlation function and chiral SU(3) dynamics

"EXOTICO: EXOTIc atoms meet nuclear COllisions for a new frontier precision era in low-energy strangeness nuclear physics"
@ ECT* Trento, 2022/10/18

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



- Hadron-hadron correlation

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

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

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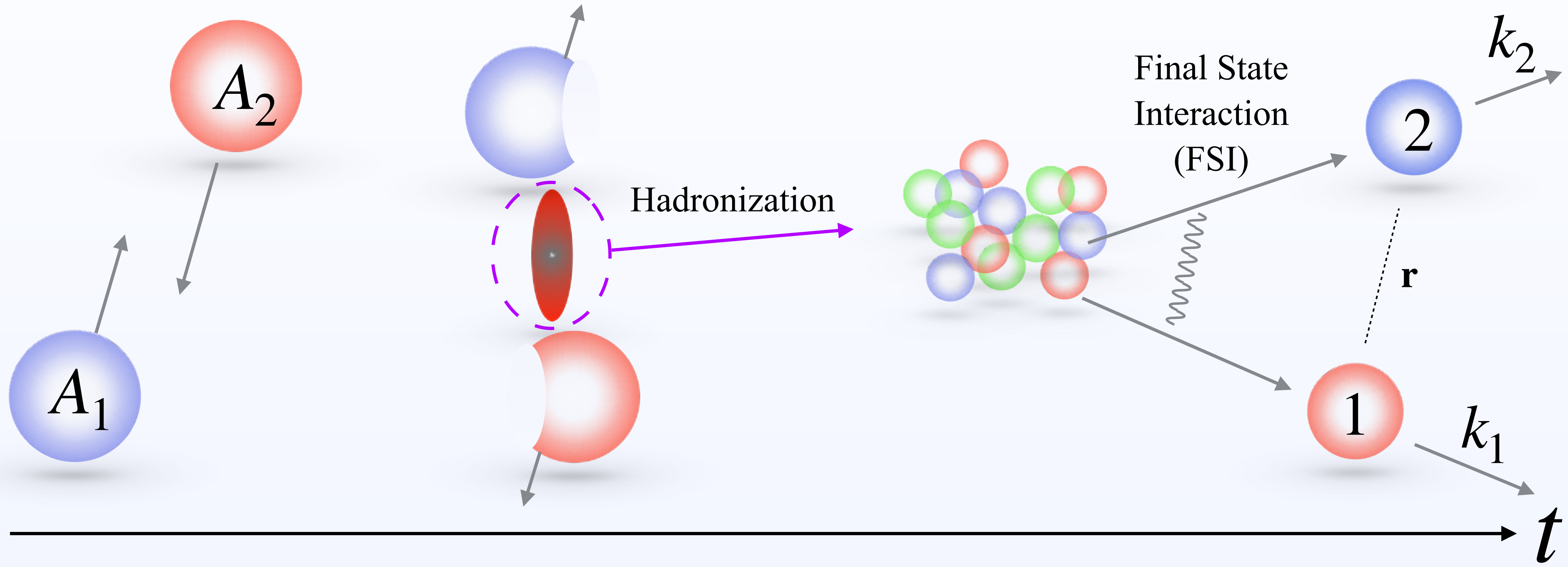

- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977) S. Pratt et. al. PRC 42 (1990)

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

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

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

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

Hadron correlation in high energy nuclear collision

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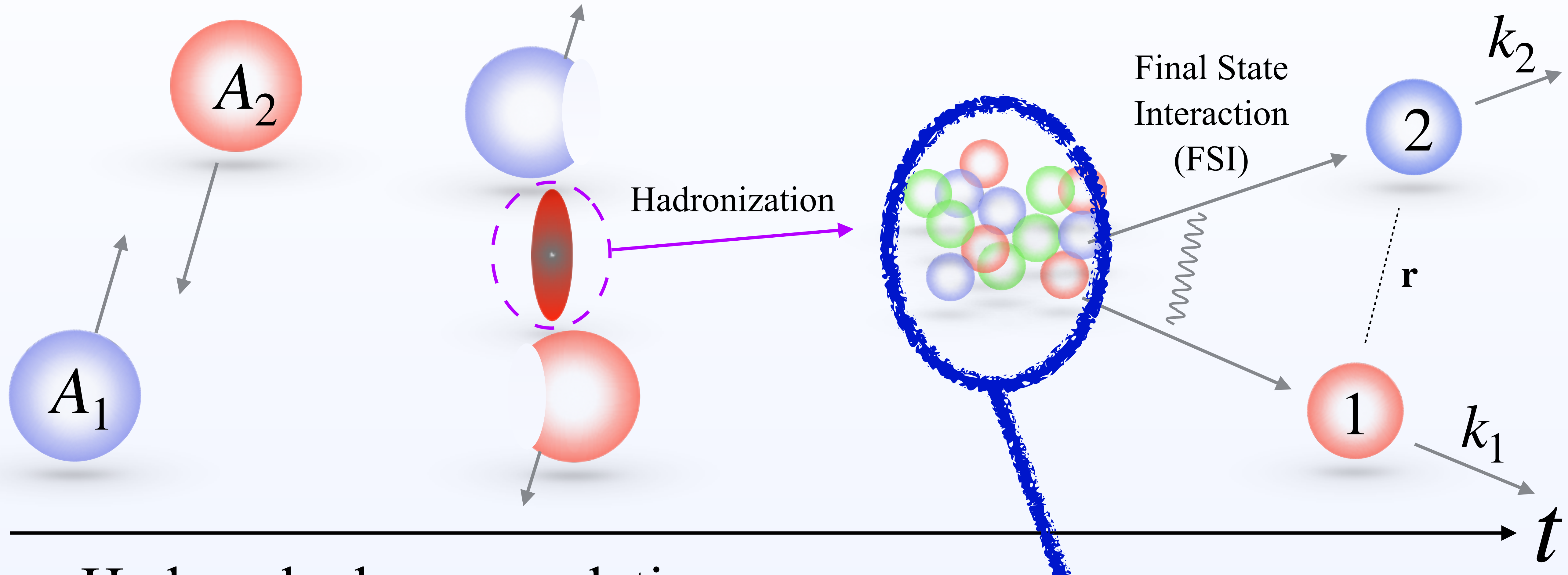

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- Depends on …

  Collision detail (Ai, energy, centrality)

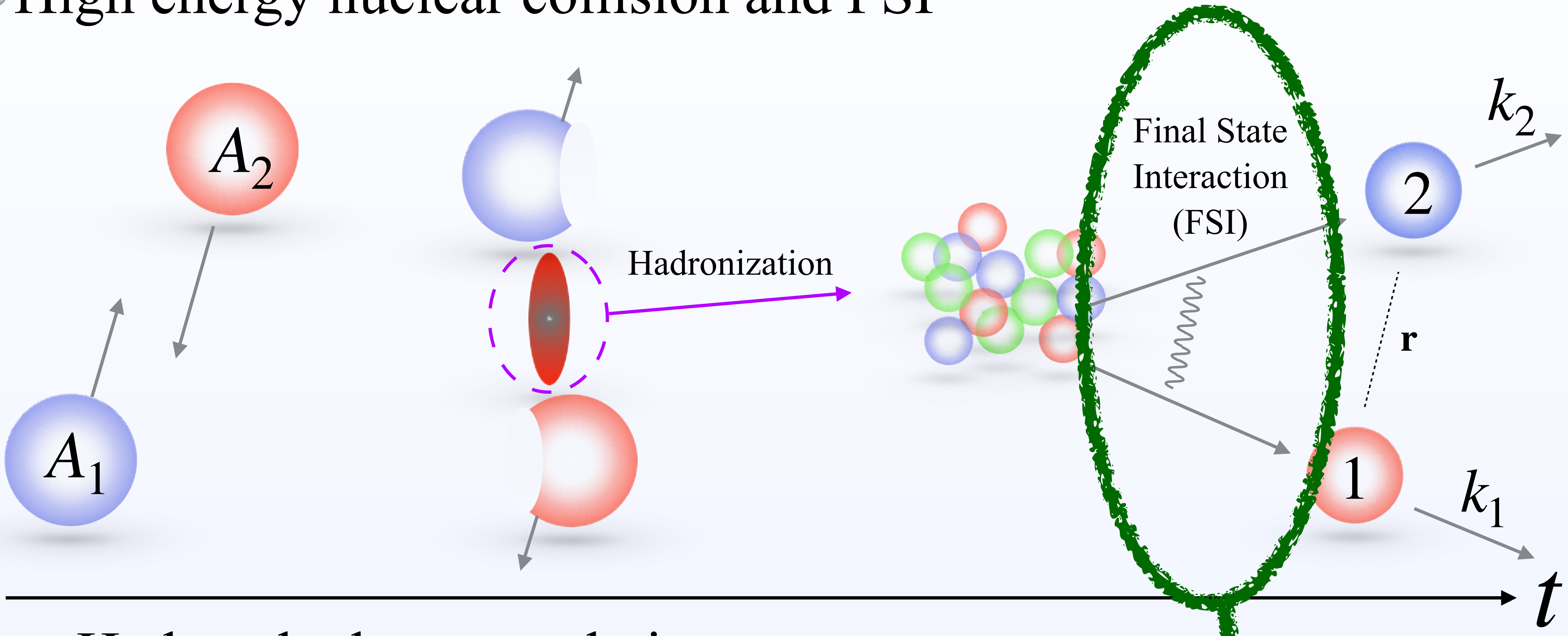
- Including information of…

  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)

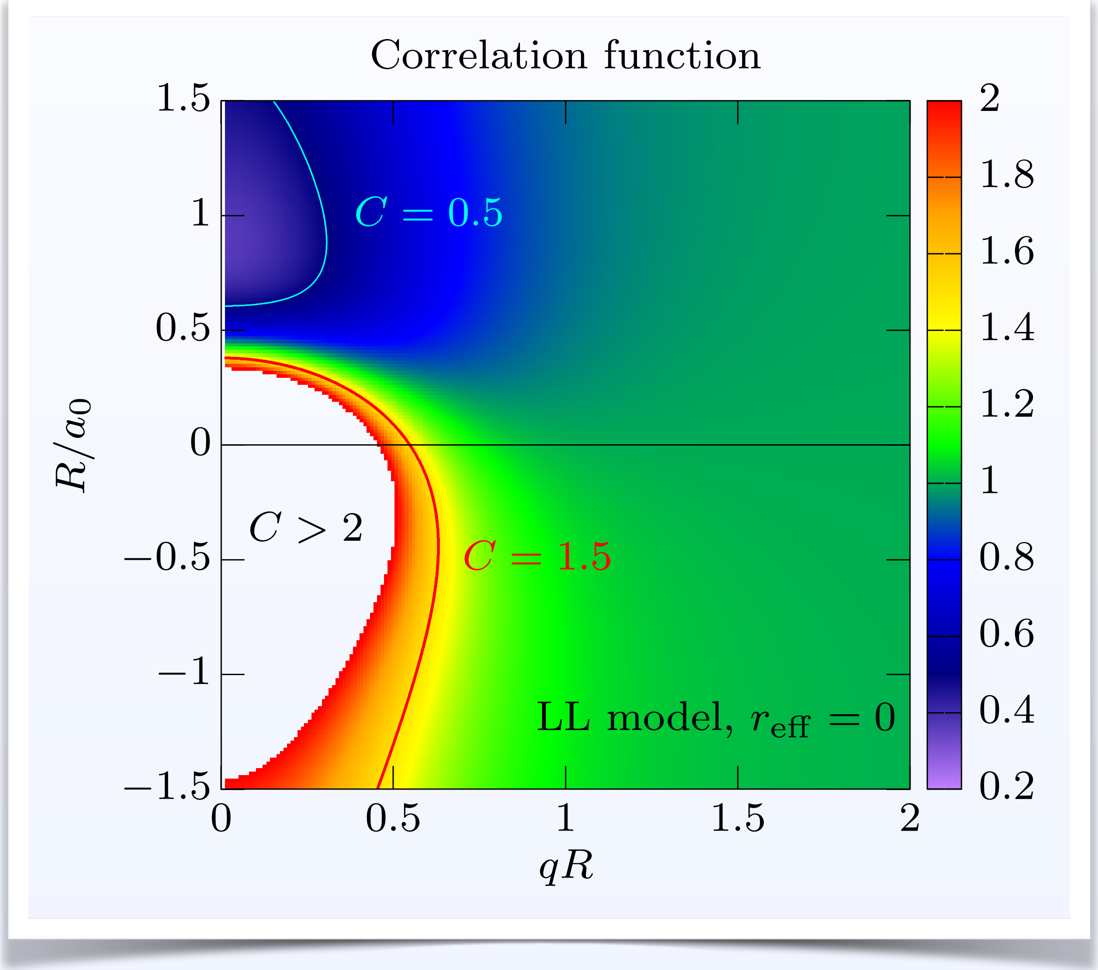
  quantum statistics (Fermion, boson)

Hadron correlation in high energy nuclear collision

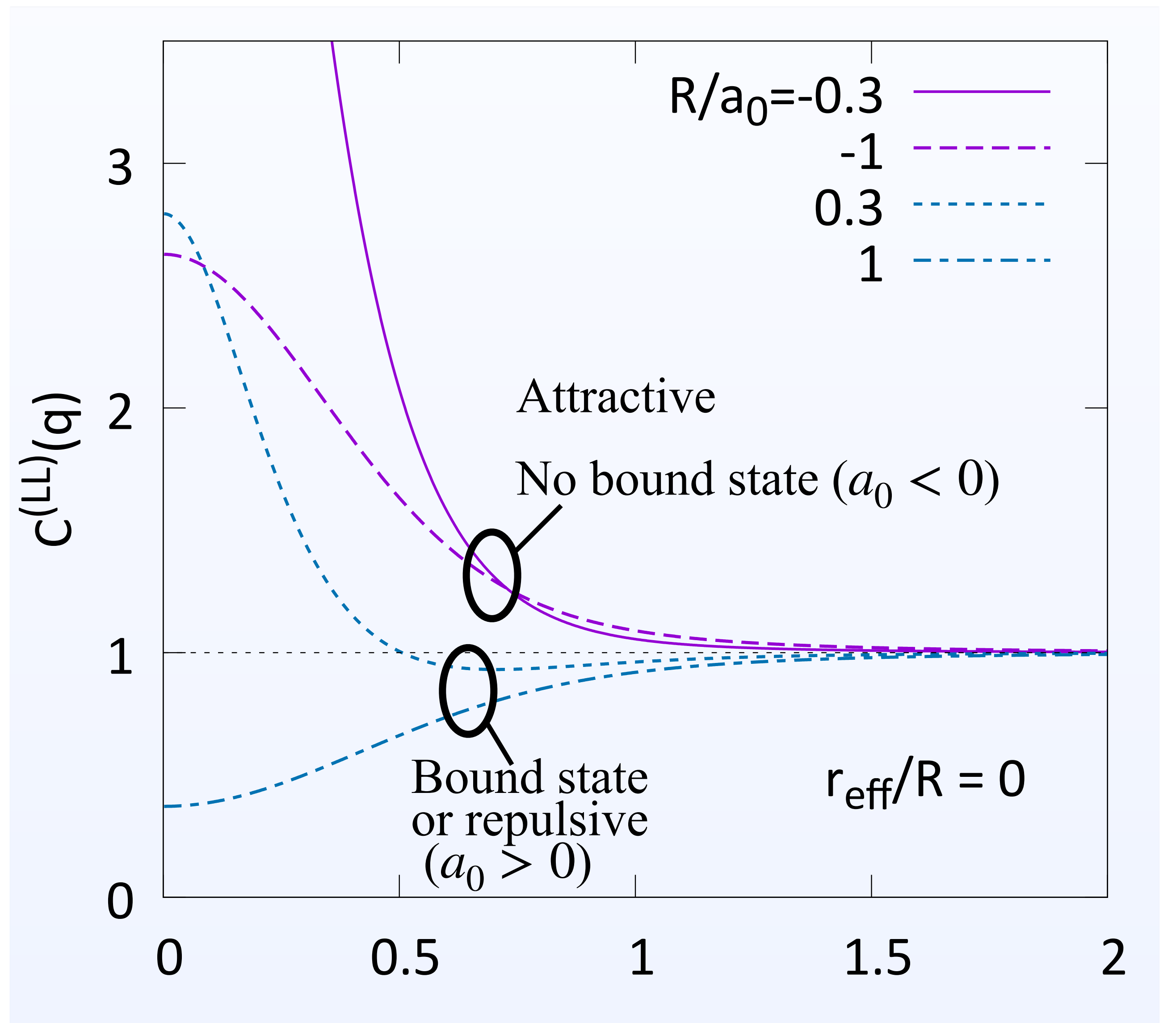
- Simple model: Lednicky-Lyuboshits (LL) formula

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

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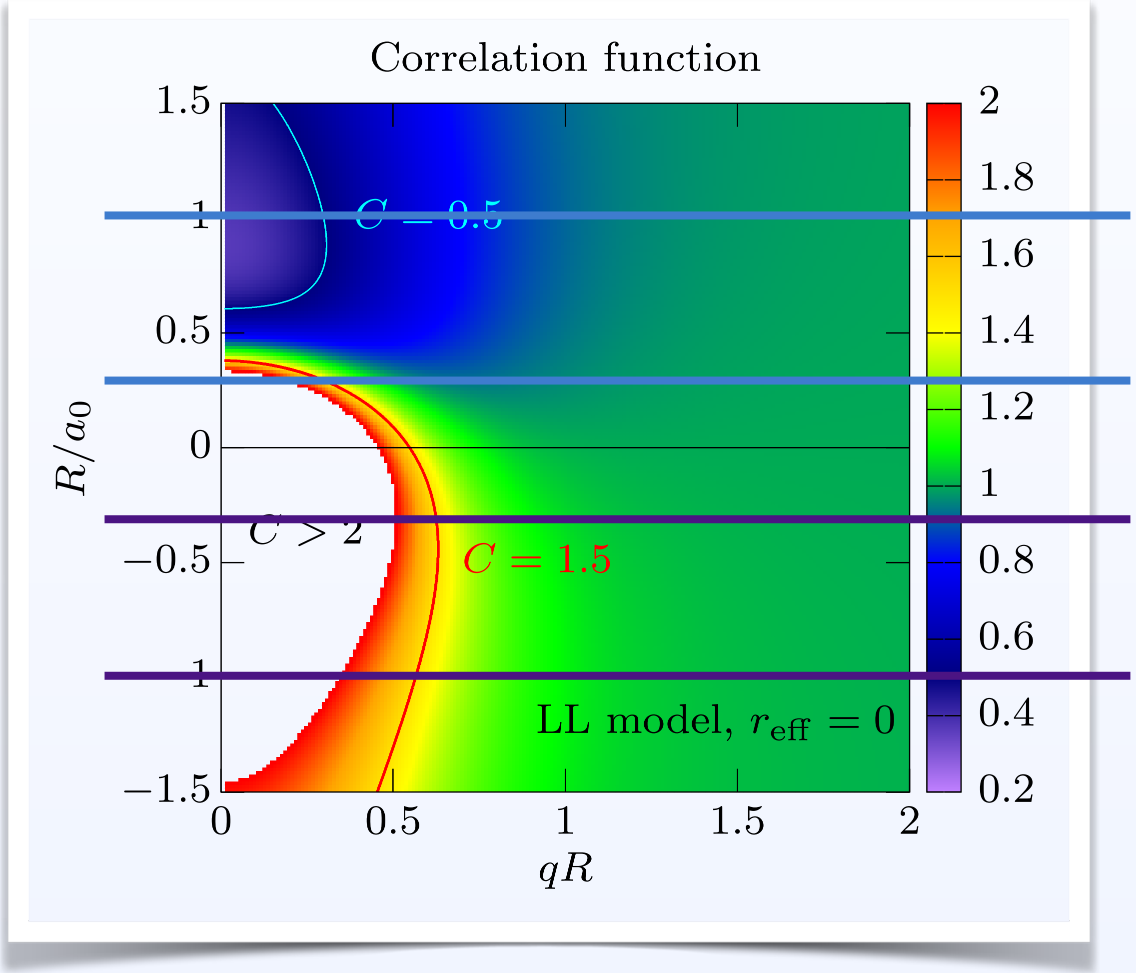

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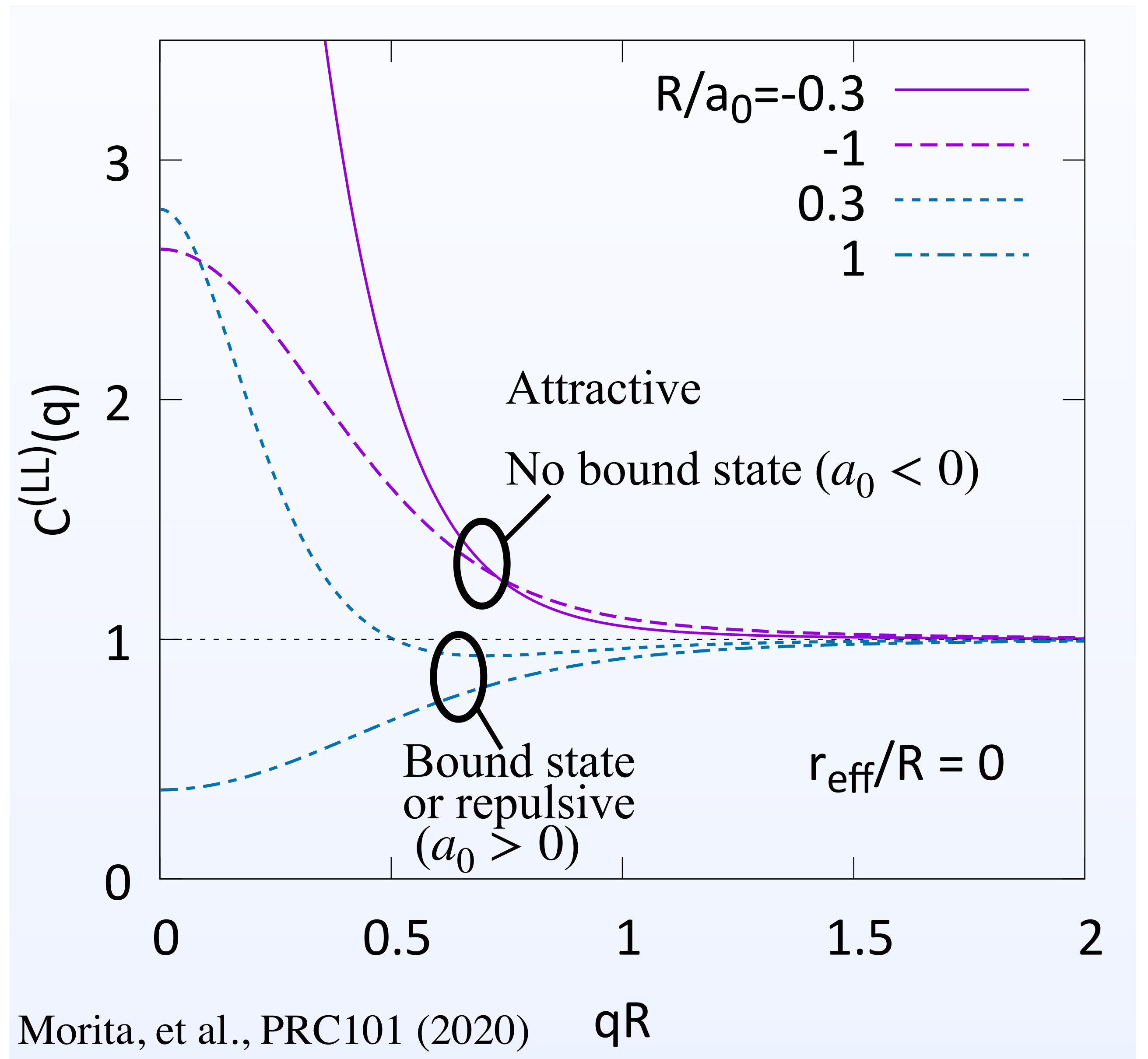

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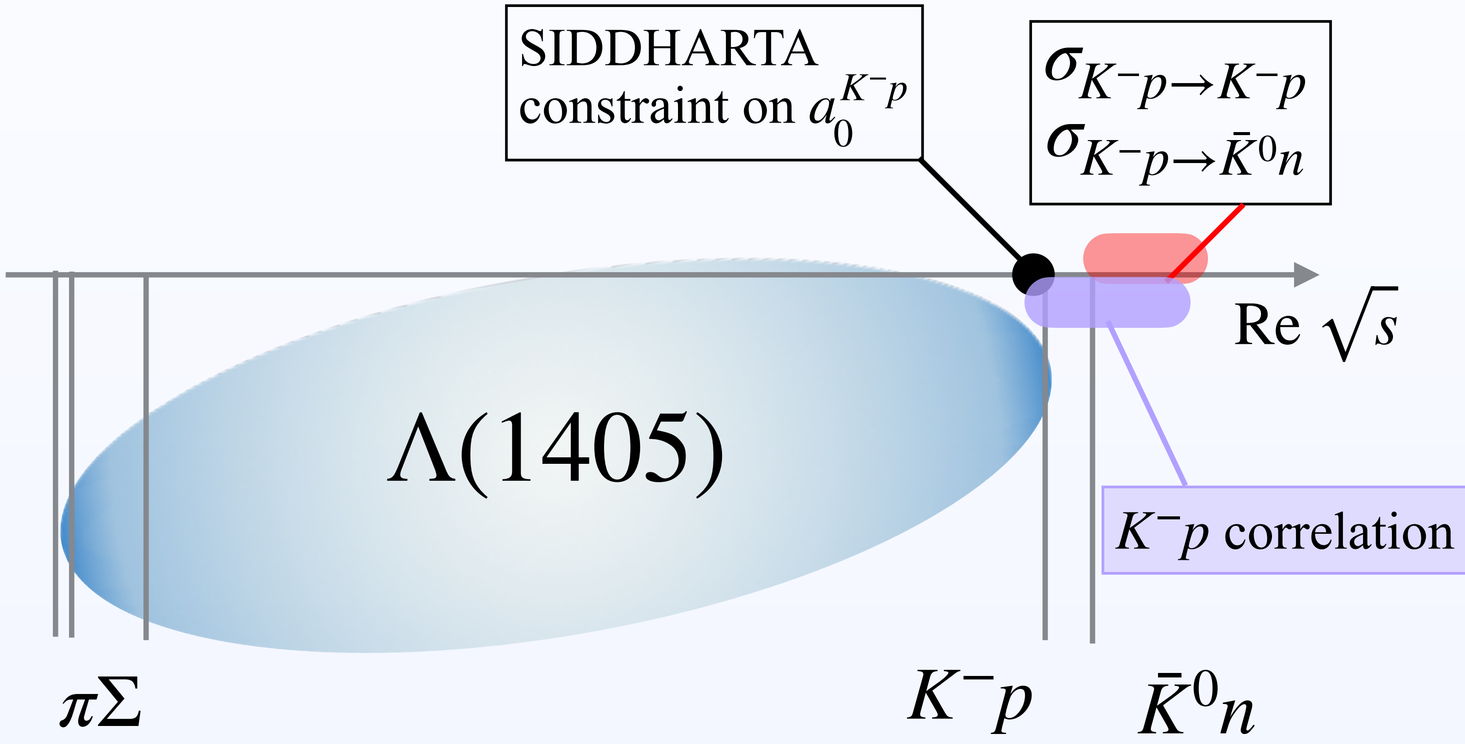
$\bar{K}N$ interaction and K^-p correlation

$\bar{K}(s\bar{l})N$ 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

Coupled-channel effect

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

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

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

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

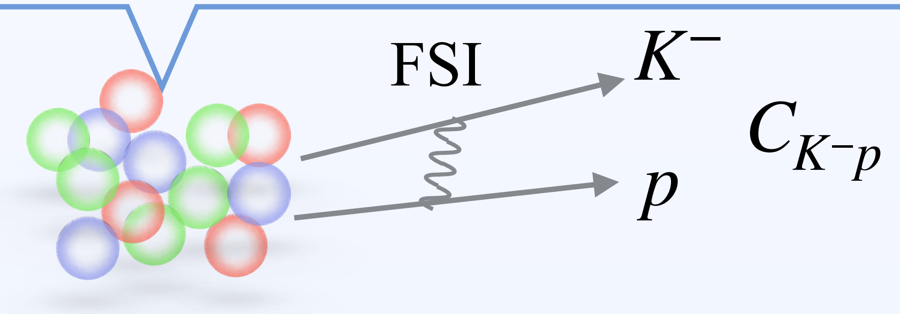
- $|S_{ij}| < 1$ —> Decrease the correlation
- At channel threshold —> Cusp structure
- ψ_i: obtained by solving the c.c. Schrödinger eq.

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

$V_{ij} = V_{ij}^{\text{strong}}\ (+V^{\text{Coulomb}})$ Δ_i ; threshold energy diff.

- Contribution from coupled-channel source

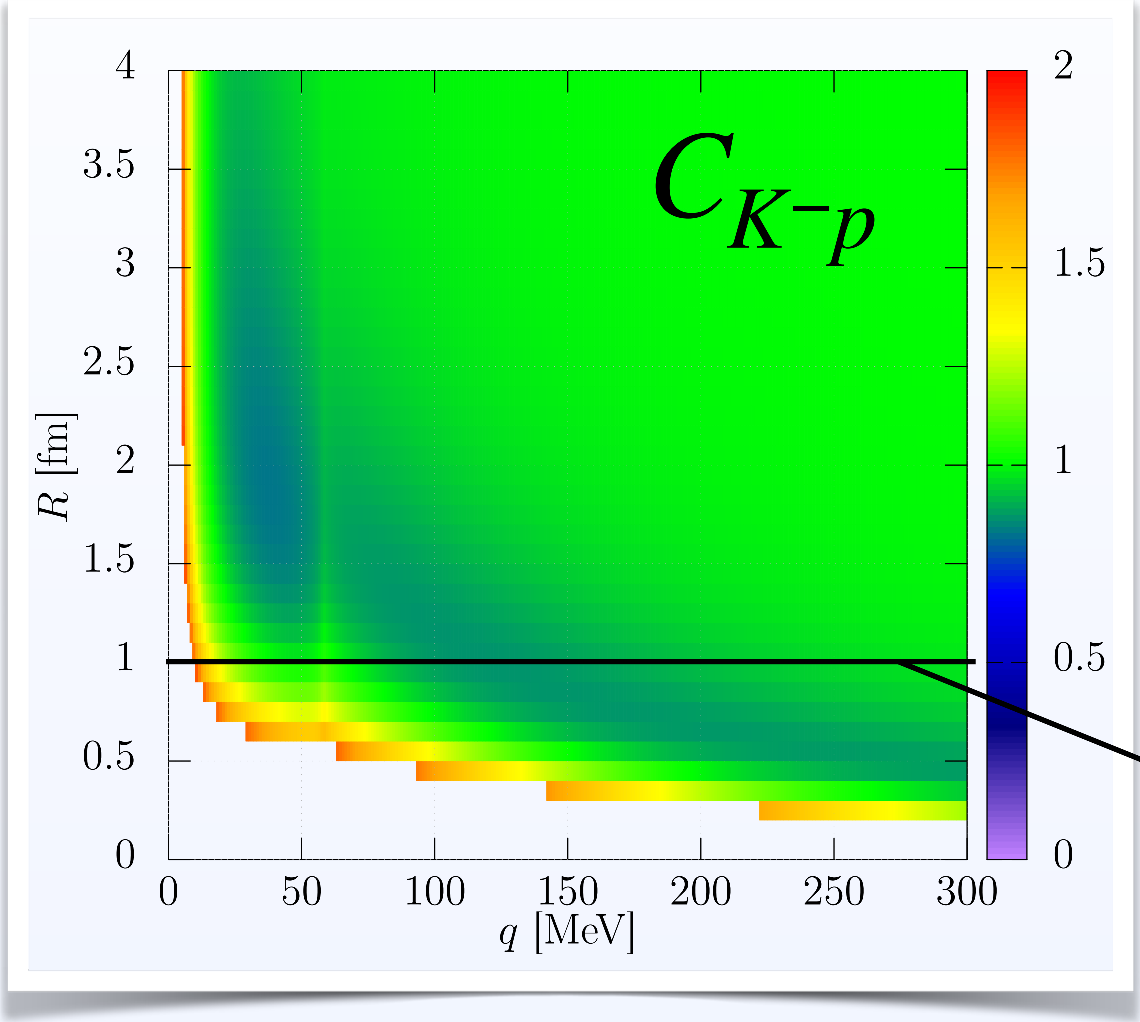
$K^-p,\ \bar{K}^0n,\ \pi^0\Sigma^0,\ \pi^+\Sigma^-,\ \pi^-\Sigma^+,\ \pi^0\Lambda$

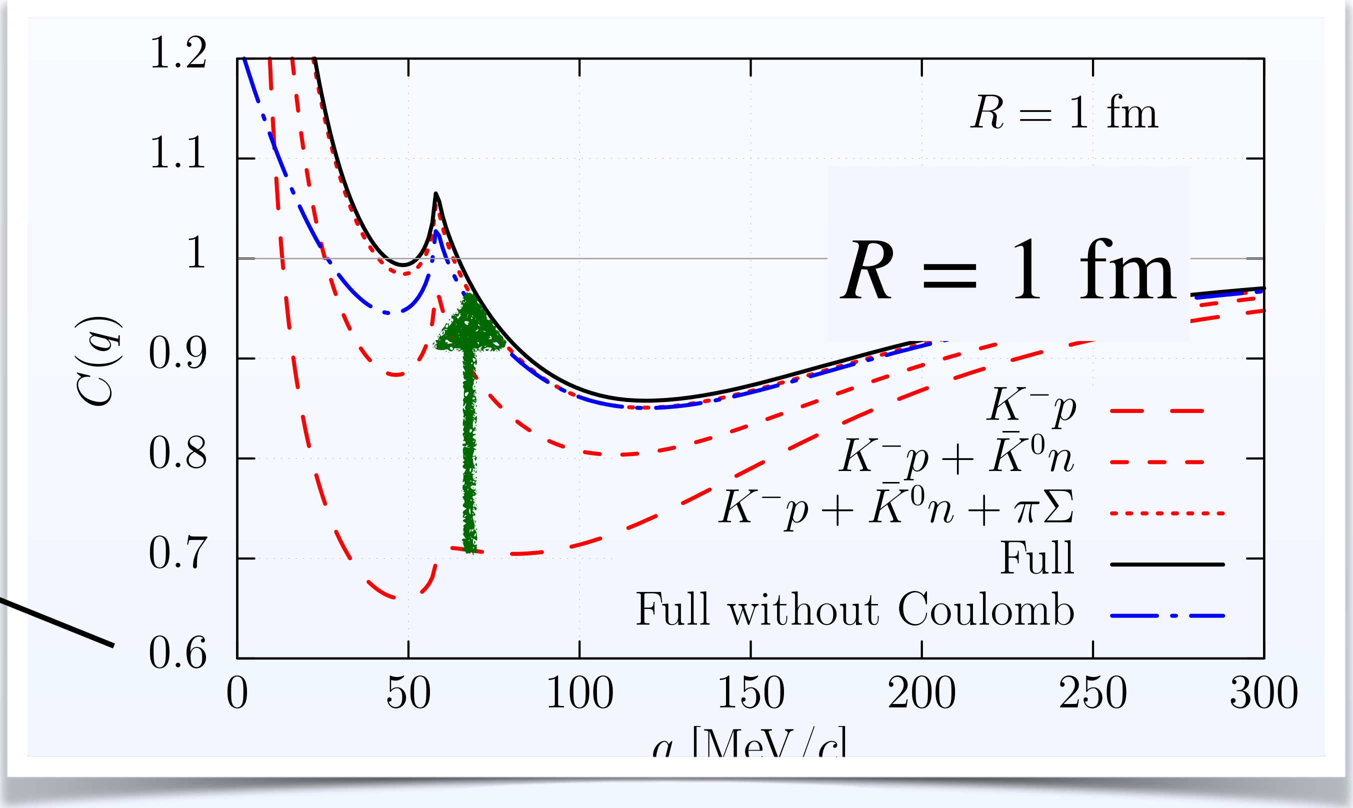


- Enhance $C(q)$
- Enhance cusp structure
- ω_i : production rate
  (compared to measured channel)

Coupled-channel effect

- Coupled-channel source effect





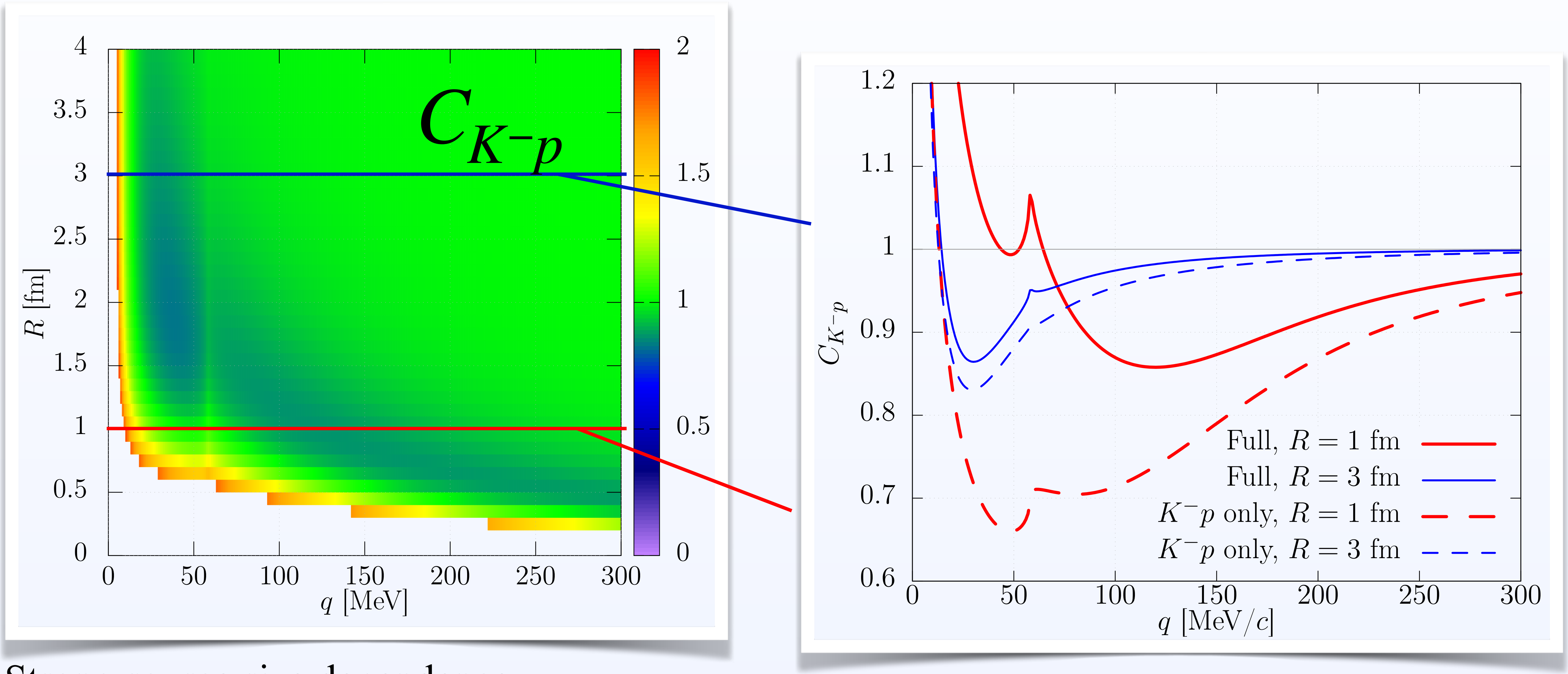
- Strong source size dependence
  < == Due to the near-threshold $\Lambda(1405)$ pole

- Coupled—channel effect
  - Enhance the correlation
  - Enhance the cusp structure
  - $\pi\Sigma$ and $\bar{K}^0 n$ w.f. components are significant

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

Coupled-channel effect

- Source size dependence of coupled-channel effect



- Strong source size dependence
  < == Due to the near-threshold $\Lambda(1405)$ pole

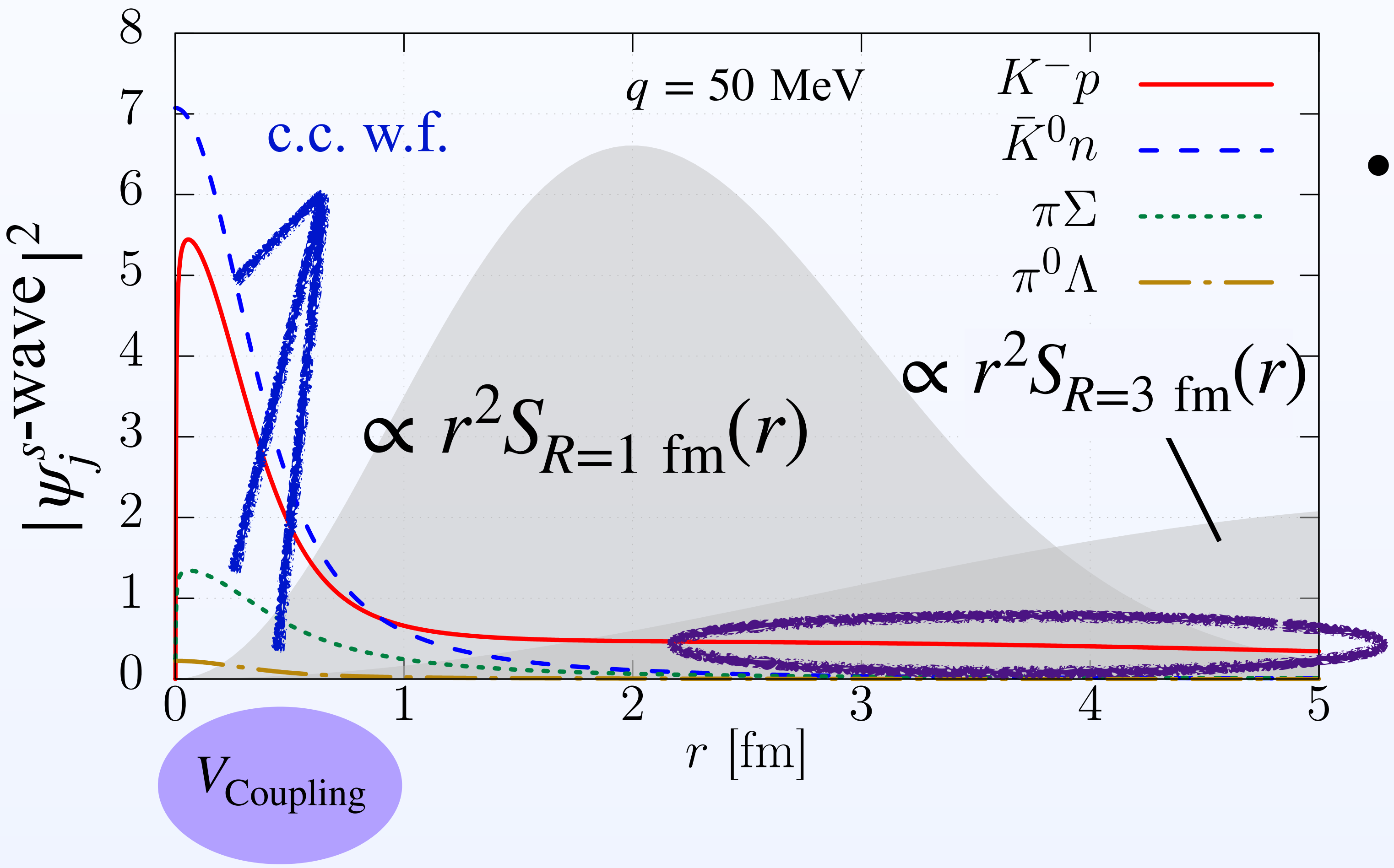
- $C(q)$ with large source
  - Less prominent cusp structure
  - Weaker coupled-channel source contribution

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

Source size dependence

- Coupled-channel wave function

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\,|\psi^{C,(-)}_{K^-p}(q;r)|^2 + \sum_{j\neq i}\omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\underbrace{\psi^{C,(-)}_j(q;r)}_{\text{Coupled-channel wave function } \bar{K}^0 n,\ \pi^0\Sigma^0,\ \cdots}|^2$$



- 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

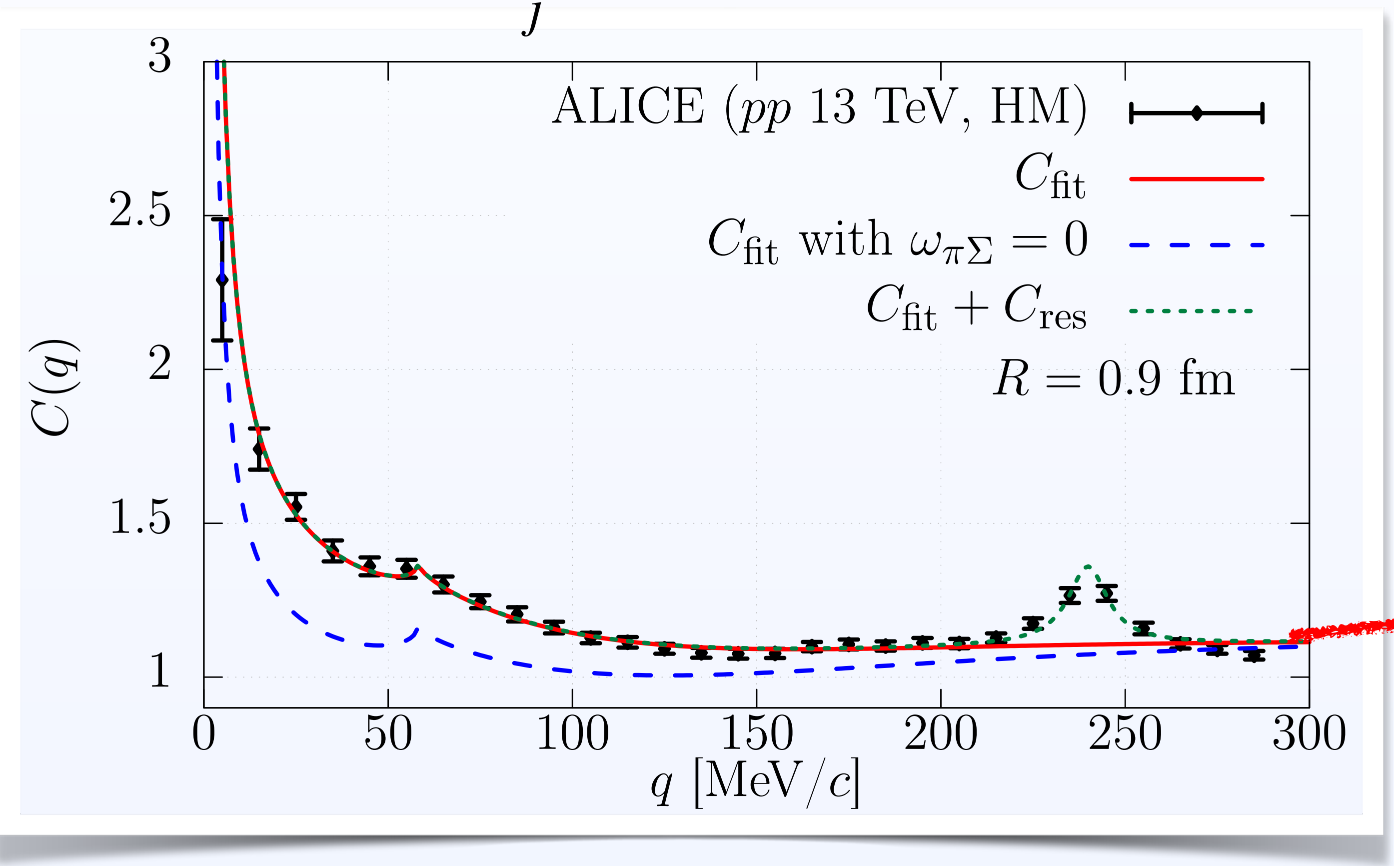
- Small source ==> W.F. of Coupled-channels counts
- Large source ==> Measured channel contribution dominant

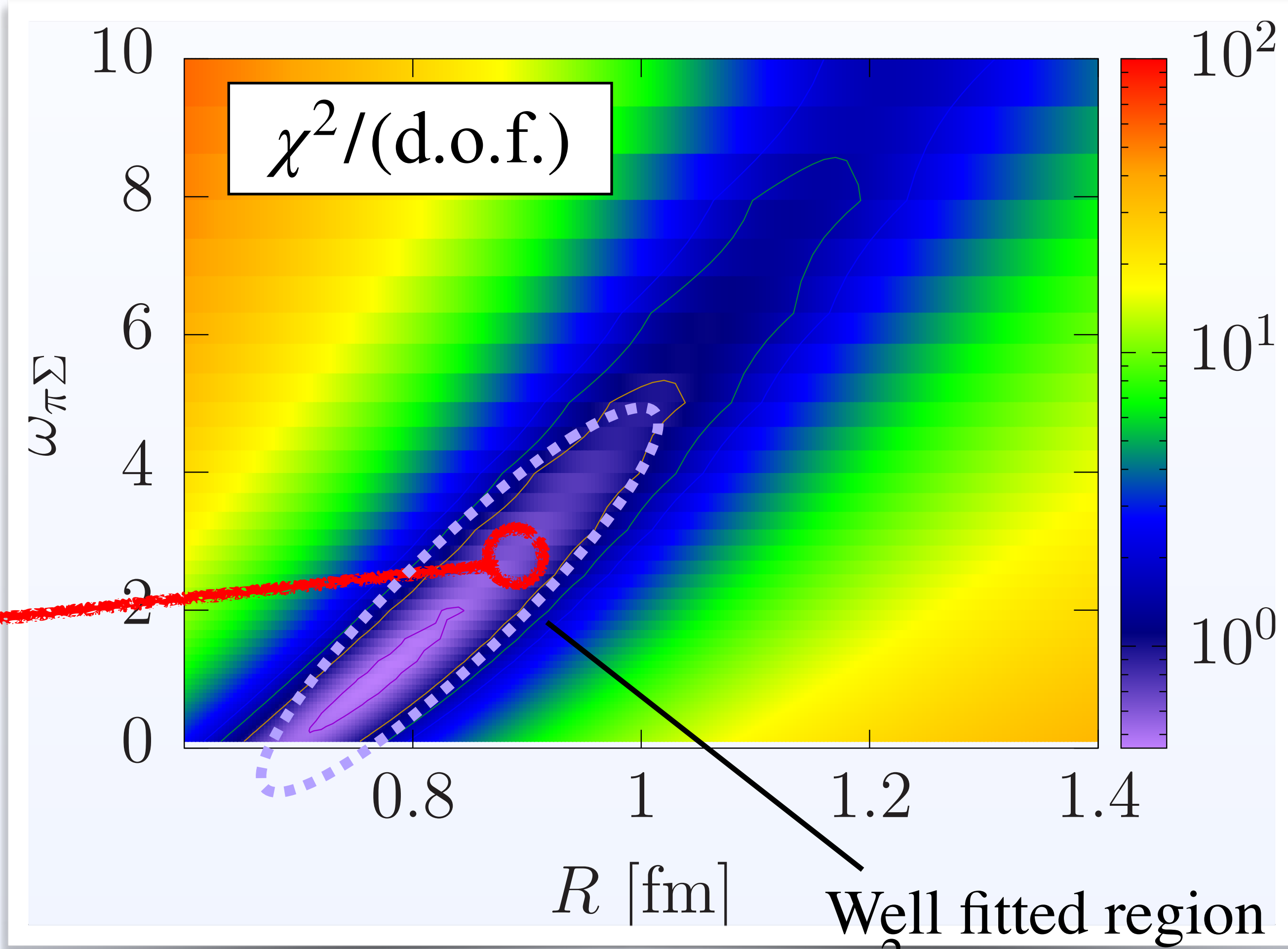
Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

Comparison with ALICE data

- Comparison to the Exp. data

$$C_{K^-p}(q) = \sum_j \underline{\omega_j} \int d^3\mathbf{r}\ \underline{S_R}(\mathbf{r})\,|\Psi_j^{C,(-)}(q,r)|^2 \Big]$$





Well fitted region
(χ^2/(d.o.f) < 1)

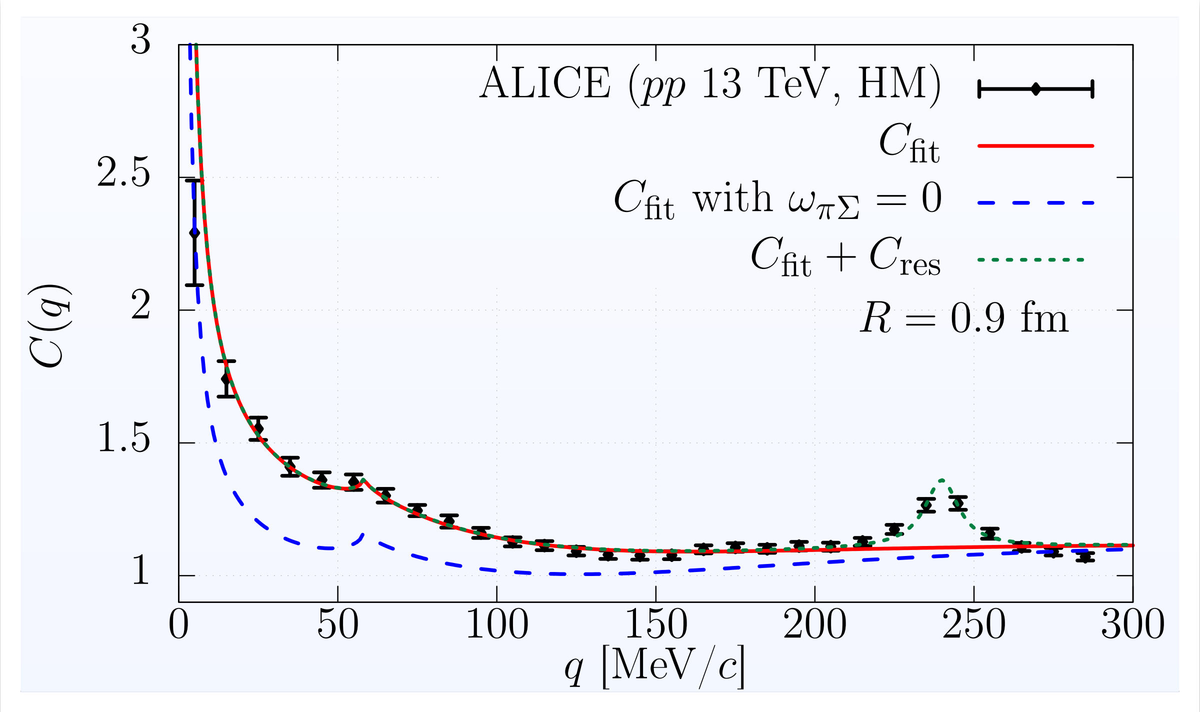
- ALICE data
  - Clear $\bar{K}^0 n$ cusp structure
  - Strong Coulomb enhancement at small q
  - $\Lambda(1520)$ peak
- Comparison with Chiral model
  - data well reproduced with the reasonable values of parameter
  - Sizable $\pi\Sigma$ source contribution

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

Source size dependence with K^-p data

- ALICE *pp* collision data

ALICE PRL 124, 092301 (2020)

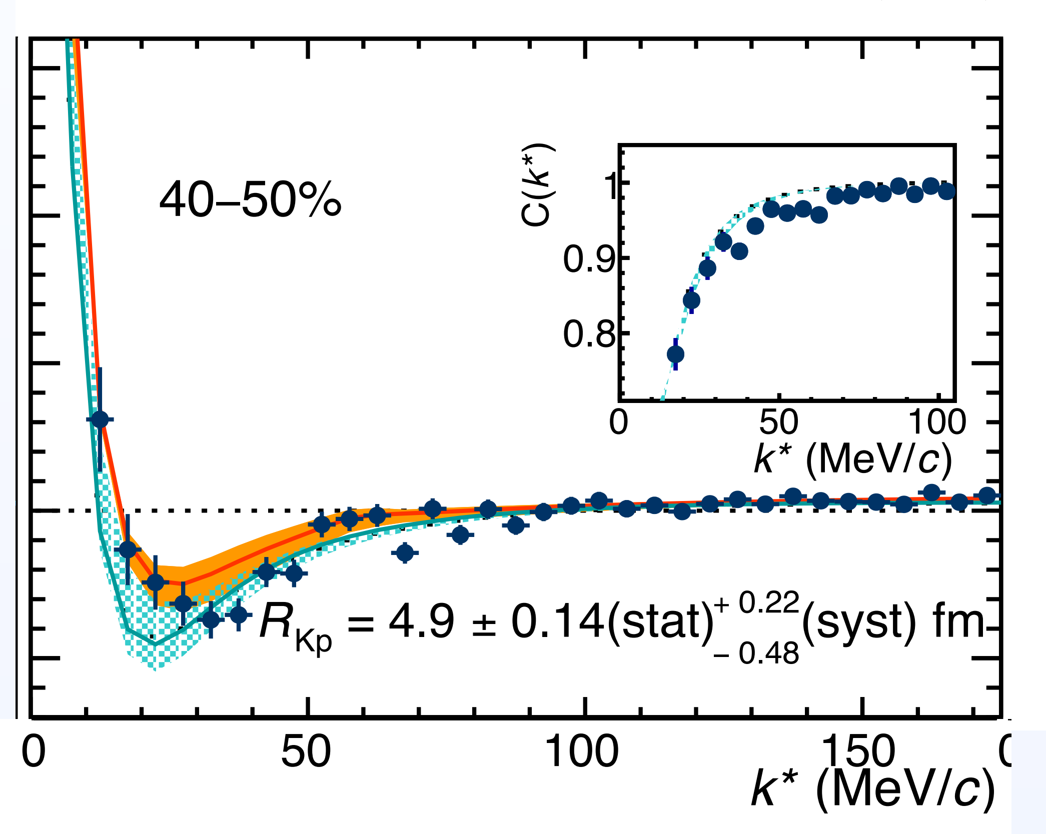


Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

- 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



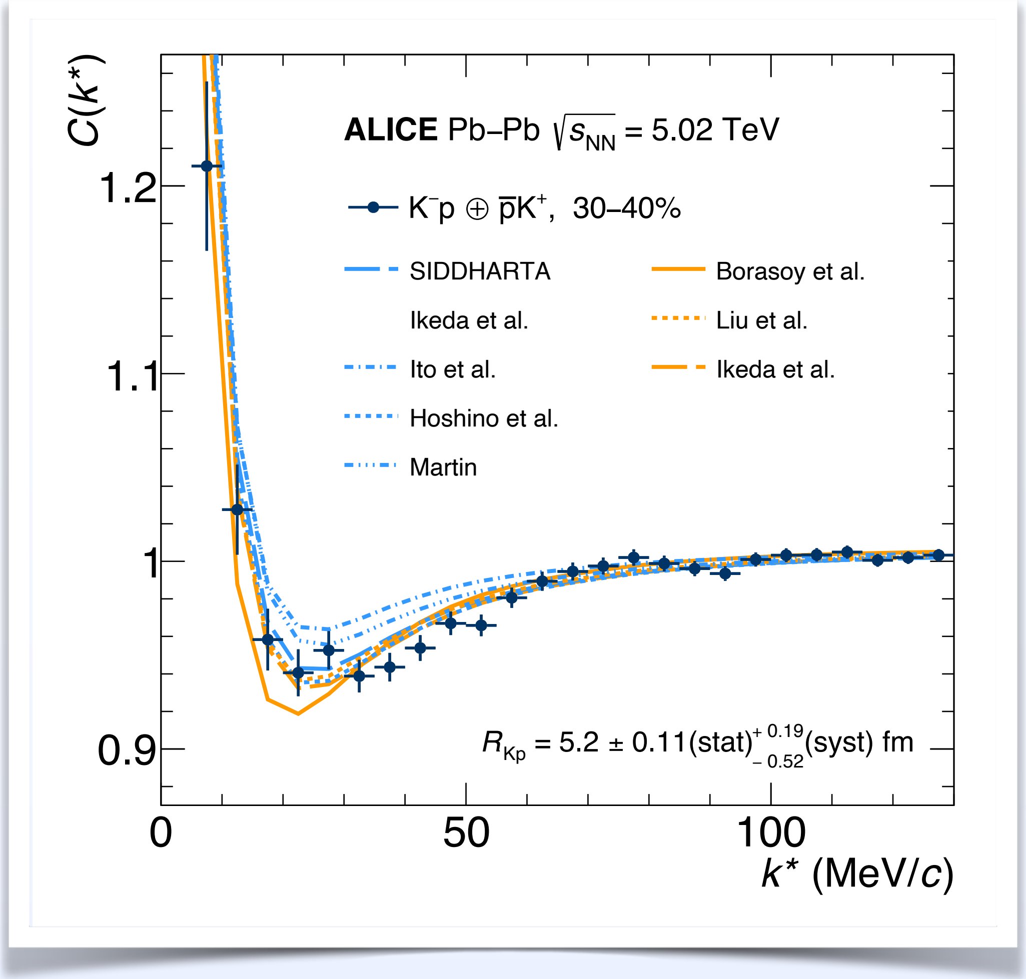
- Large source
  - Weaker cusp
  - Consistent with analysis only with K^-p source

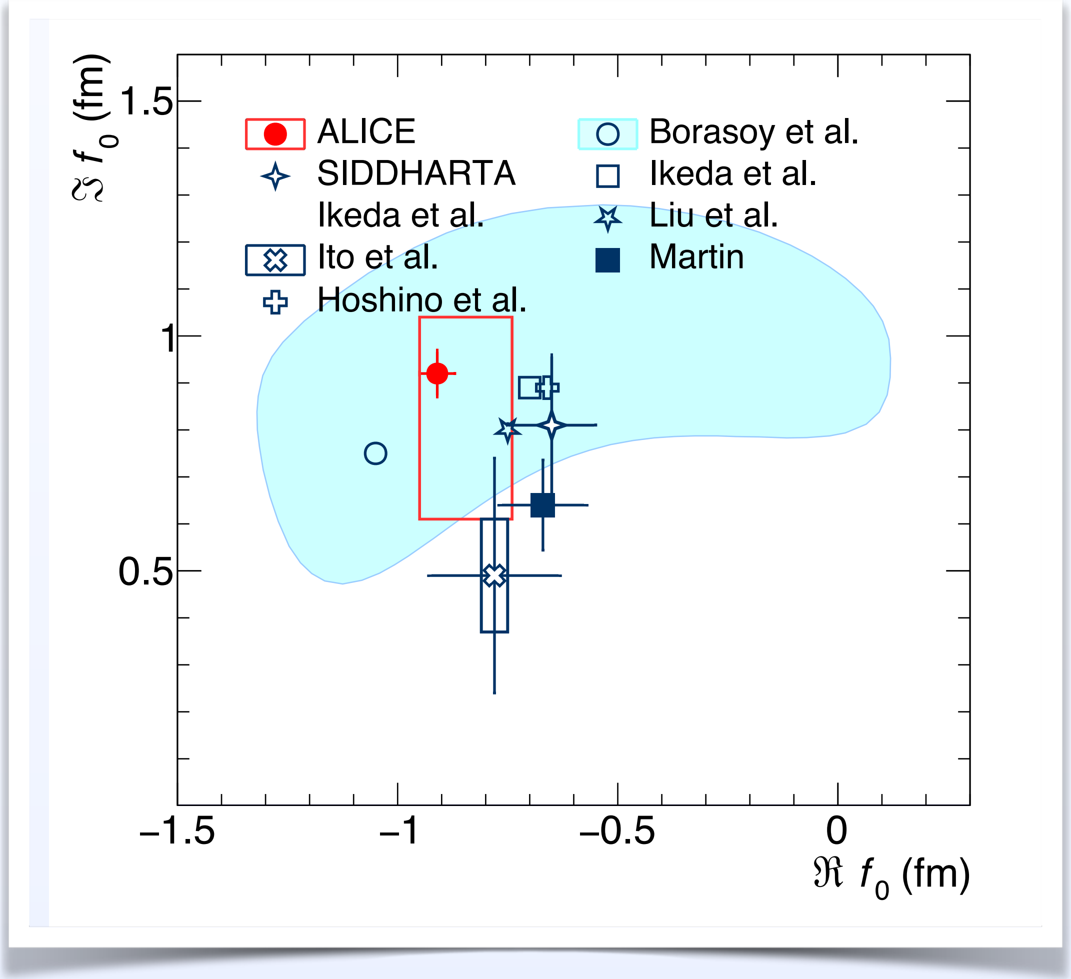
- Chiral SU(3) dynamics describes the both correlation data well.

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

Source size dependence of K^-p data

- 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





$\bar{K}N$ 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%

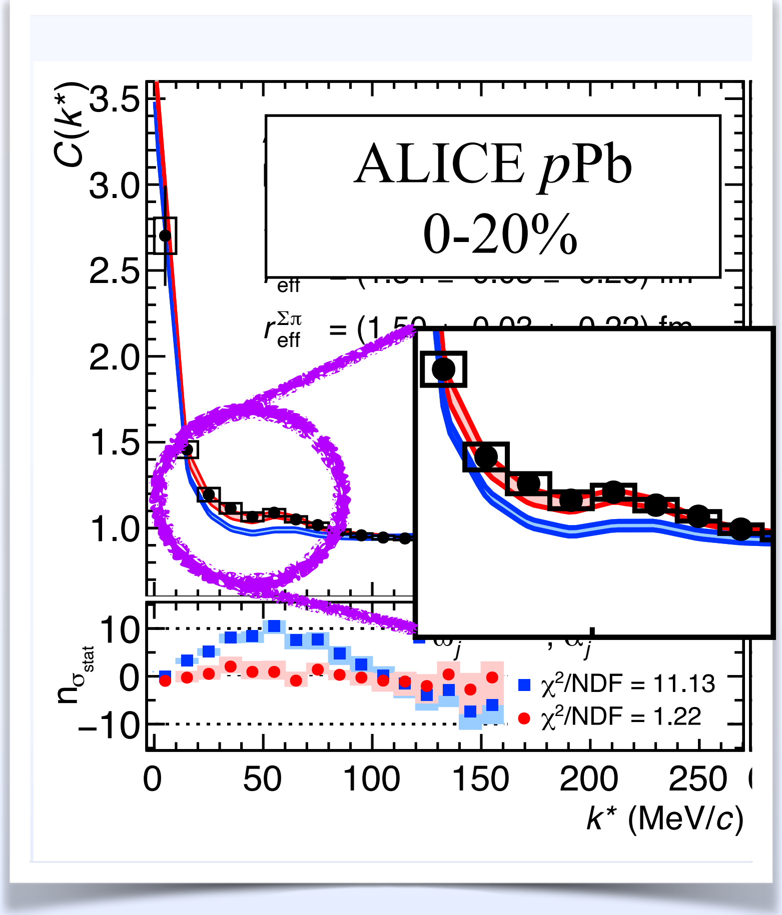
- Discrepancy around $\bar{K}^0n$ threshold between chiral SU(3) model and exp. data for small source data

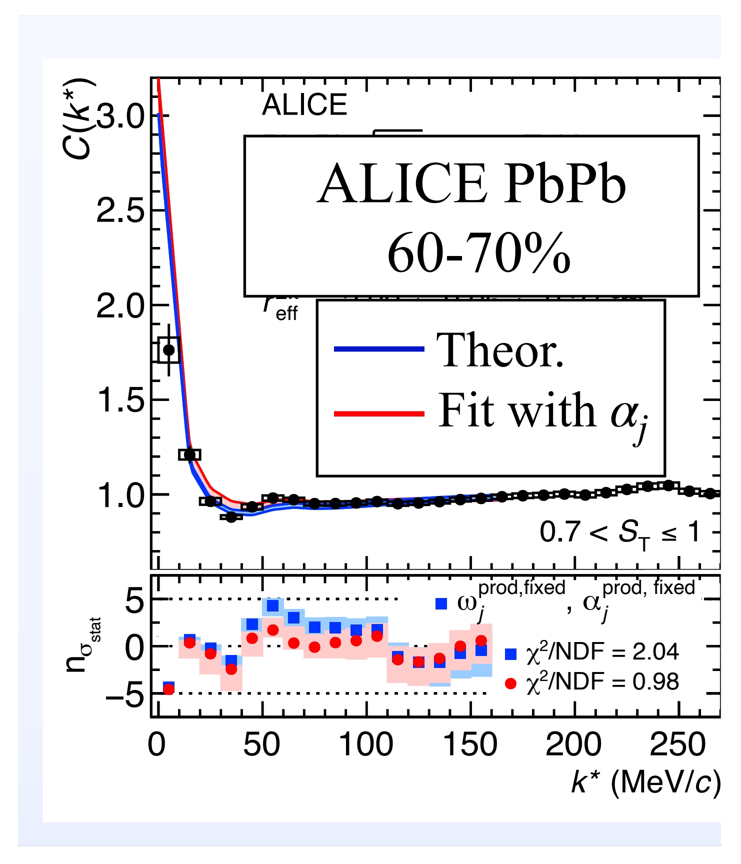
- Analysis with scale factor α_j
  - Scale the coupled-channel source contribution by scaling factor

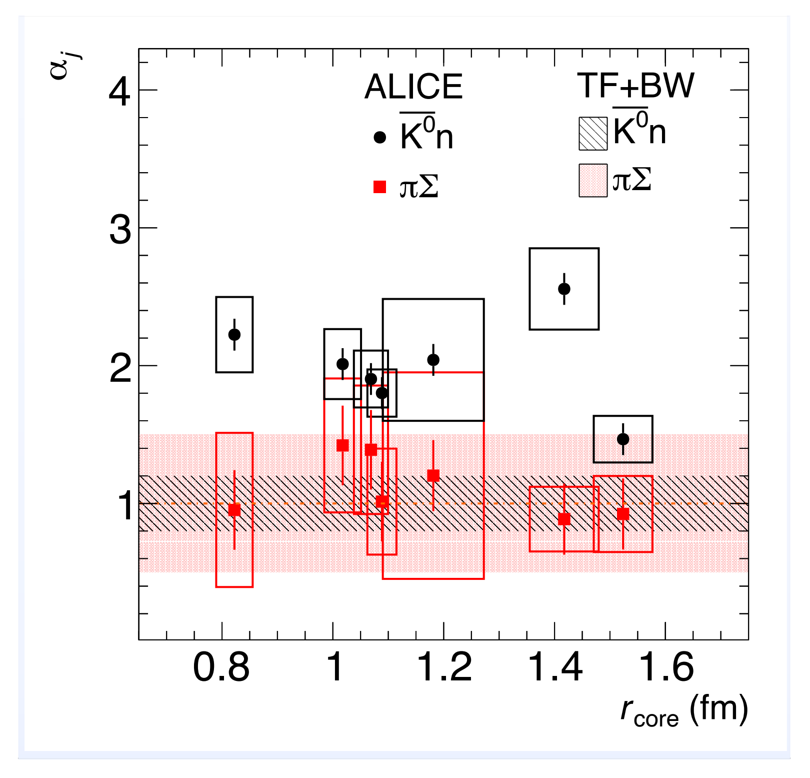
    $$C_{K^-p} = C^{\rm el}_{K^-p} + \sum_j \alpha_j C^{\rm inel}_j$$

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

  implying the stronger coupling







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

- Latest $K^{-}p$ correlation results

ALICE [2205.10258]

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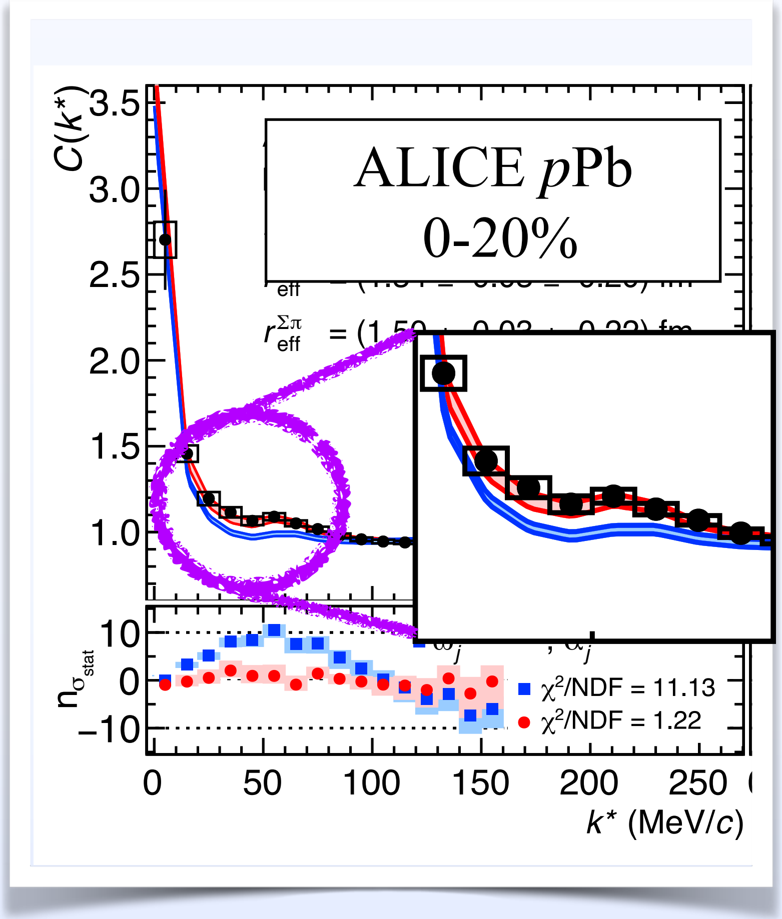
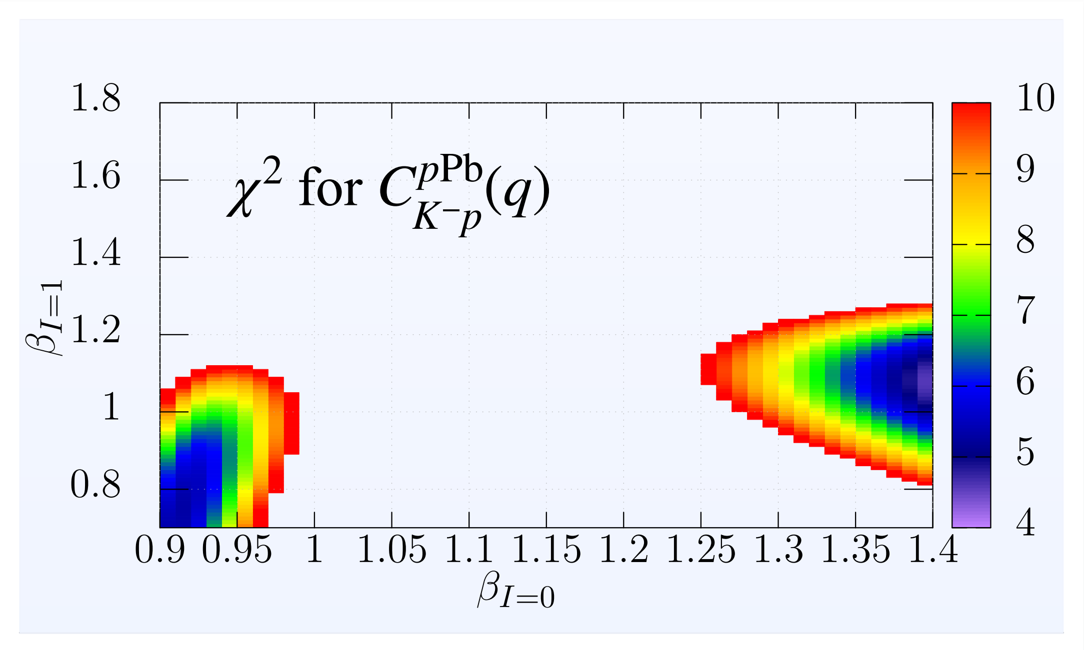


- Analysis with the effective Kyoto potential

Vary the interaction with the factor β as

$$V_{\bar{K}N,I=1} \to \beta_{I=0} V_{\bar{K}N,I=1}$$
$$V_{\bar{K}N,I=0} \to \beta_{I=1} V_{\bar{K}N,I=0}$$

Check the consistency with $a_0^{\mathrm{SIDDHARTA}}$ and ALICE pPb data $C_{K^-p}^{p\mathrm{Pb}}(q)$



- No parameter sets reproduces $a_0^{\mathrm{SIDDHARTA}}$ and $C_{K^-p}^{p\mathrm{Pb}}(q)$

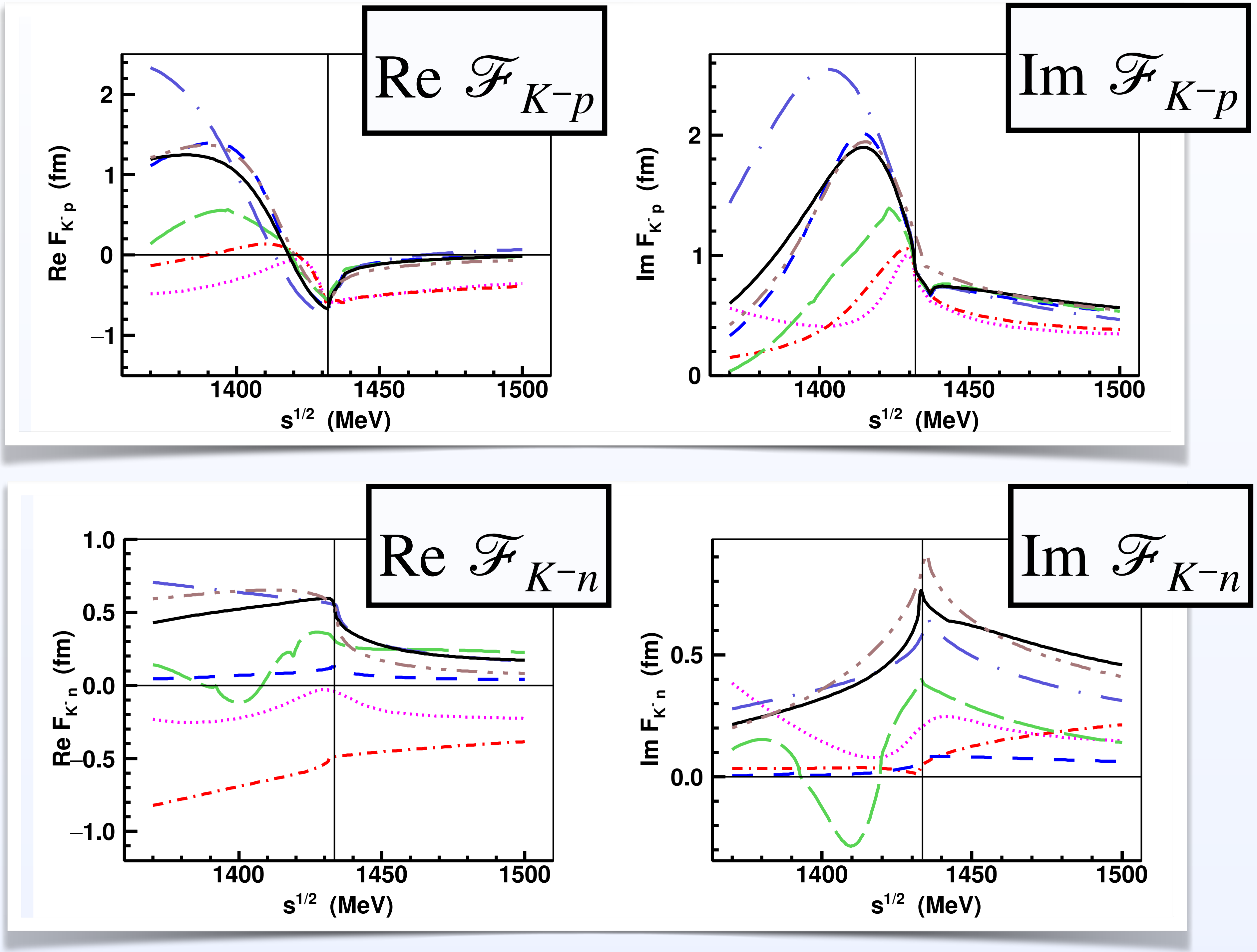
More detailed theoretical analysis is needed.

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

- $\bar{K}N$ interaction

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

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



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

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)

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

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

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

- $K^0_S p$ correlation

$$|K^0_S p\rangle = [\,|\bar{K}^0 p\rangle - |K^0 p\rangle]/\sqrt{2}$$

$\bar{K}N, I = 1$ $\quad$ $KN, I = 0, 1$

$$C_{K^0_S p} = [C_{\bar{K}^0 p} + C_{K^0 p}]/2$$

- $I = 1$ component only
- Chiral amplitude

Ikeda, Hyodo, Weise, NPA881 (2012)

- Effective potential

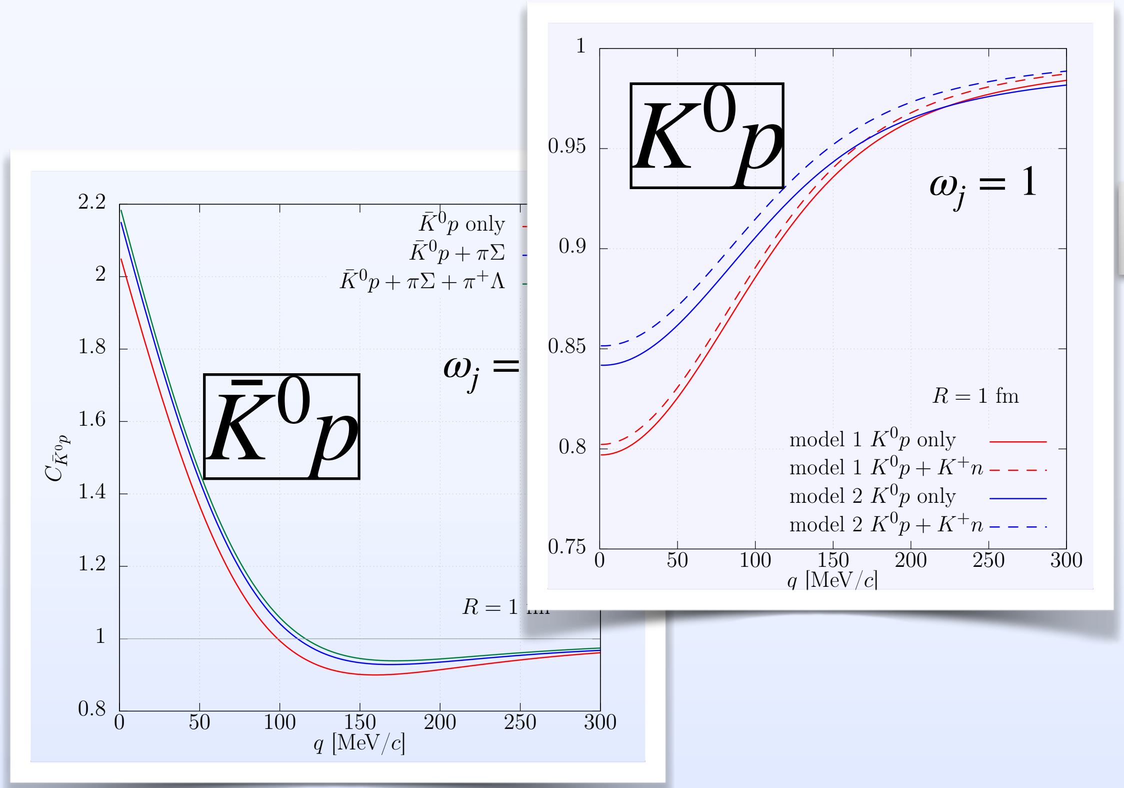
Miyahara, Hyodo, Weise, PRC 98 (2018)

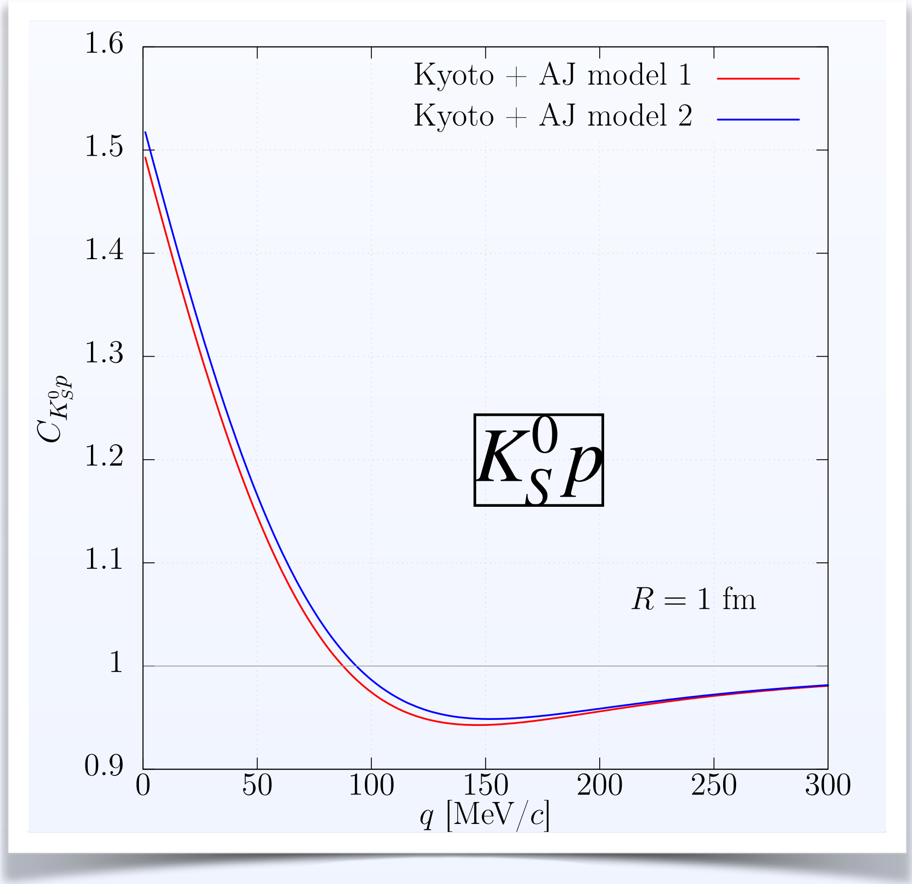
- Well determined with scat. exp.
- Chiral amplitude

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.

Summary

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the hadron-hadron interaction.
- Chiral SU(3) based effective potential model reproduces the ALICE K^-p correlation data from *pp* collisions with the reasonable by including the coupled-channel source effect.
- Detailed source size dependence can be investigated with the latest data from the different collision experiments.
  • Large source: Good agreement with the chiral model of K^-p channel
  • Small source: Finite deviation indicates the need for the modification of the coupled-channel interaction.
- $K_s^0 p$ correlation is useful to directly see the $I = 1$ $\bar{K}N$ interaction.

Thank you for your attention!

Thank you!