Yuki Kamiya
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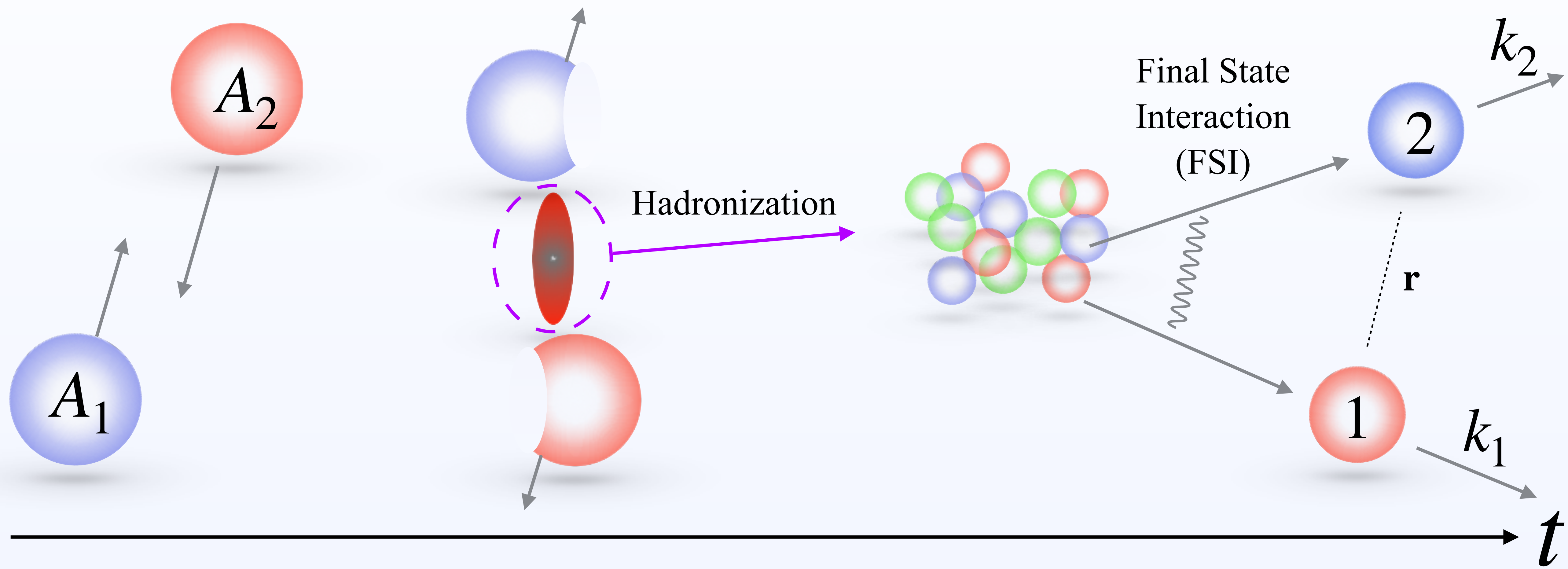
# Low-energy $\bar{K}N$ interaction from high-energy nuclear collisions

The 10th International Workshop on Chiral Dynamics
2021.11.16, Beijing (online)

# 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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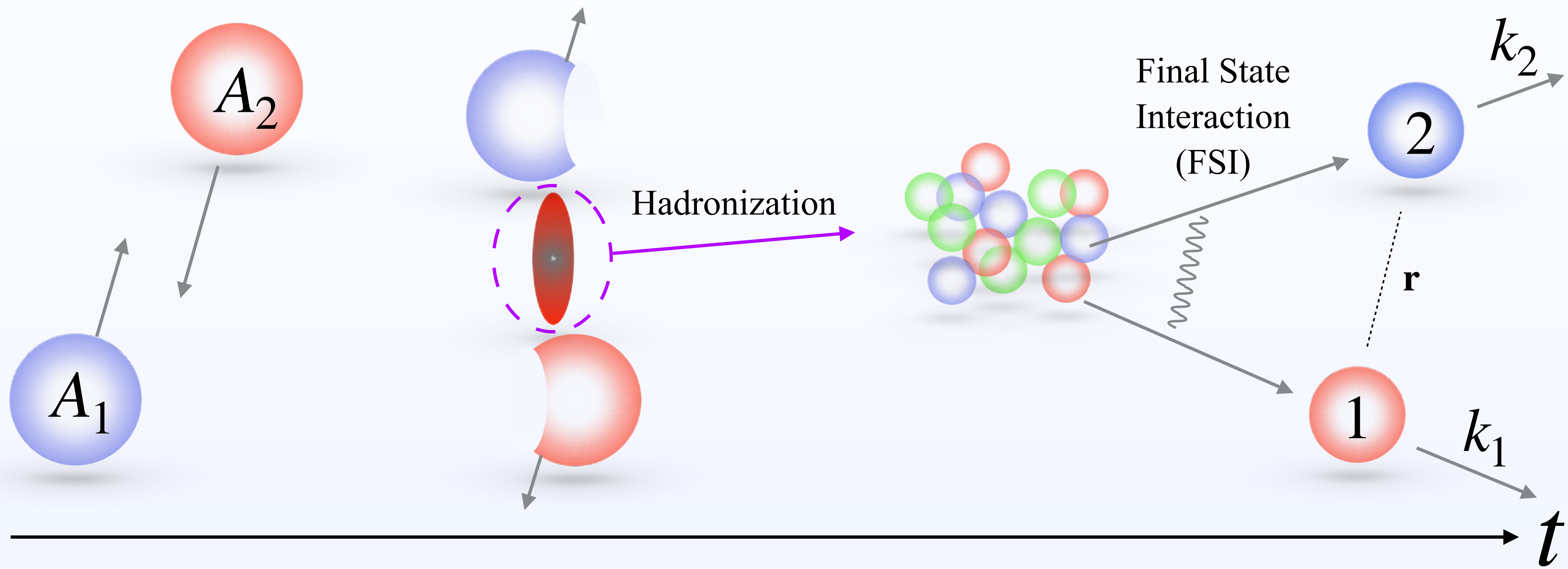



- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977) S. Pratt et. al. PRC 42 (1990)

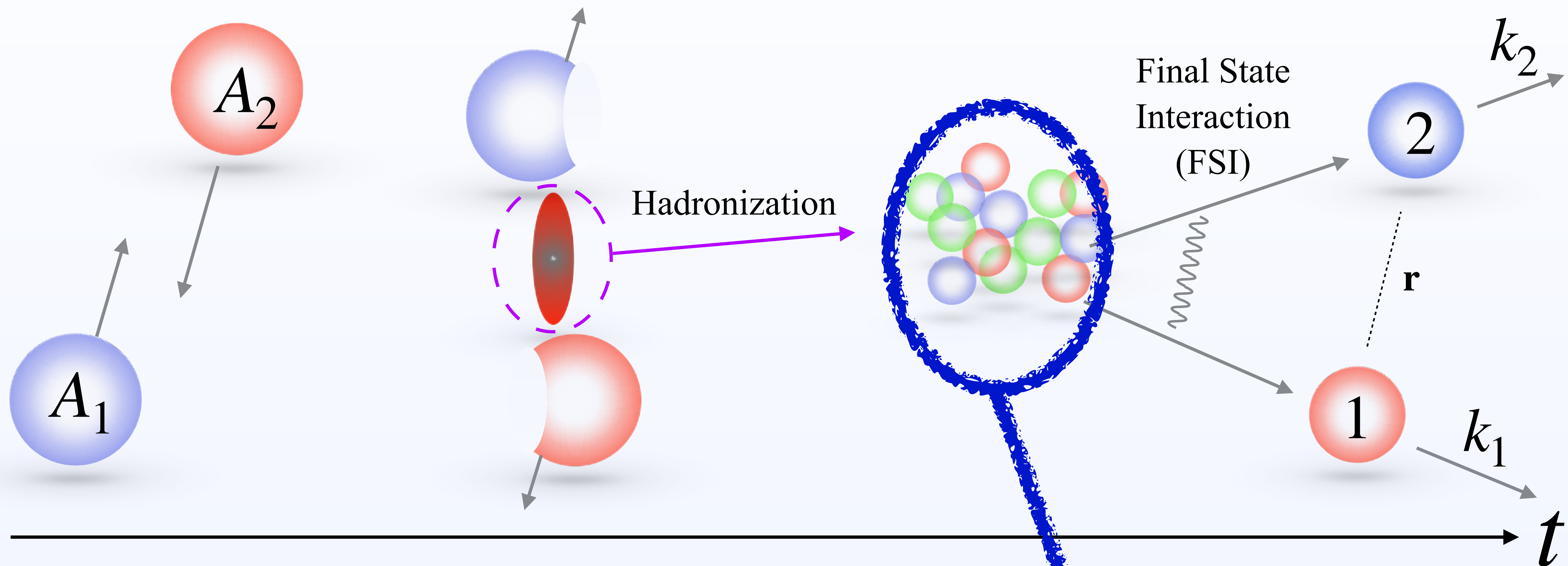
$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2$$

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

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

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

## High energy nuclear collision and FSI

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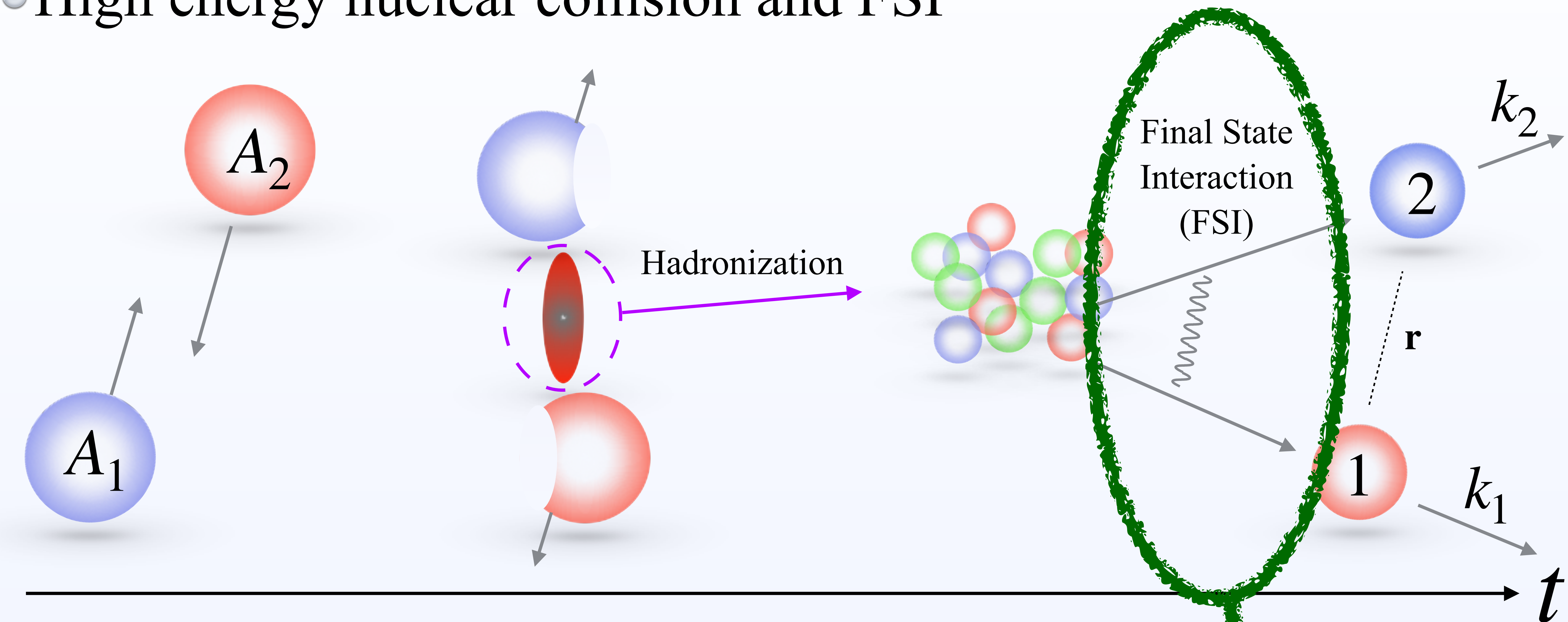
- Depends on …
  Collision detail ($A_i$, energy, centrality)
- Including information of…
  size of hadron source,
  momentum dependence, weight…

# 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)

## Qualitative feature of correlation function

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

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

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

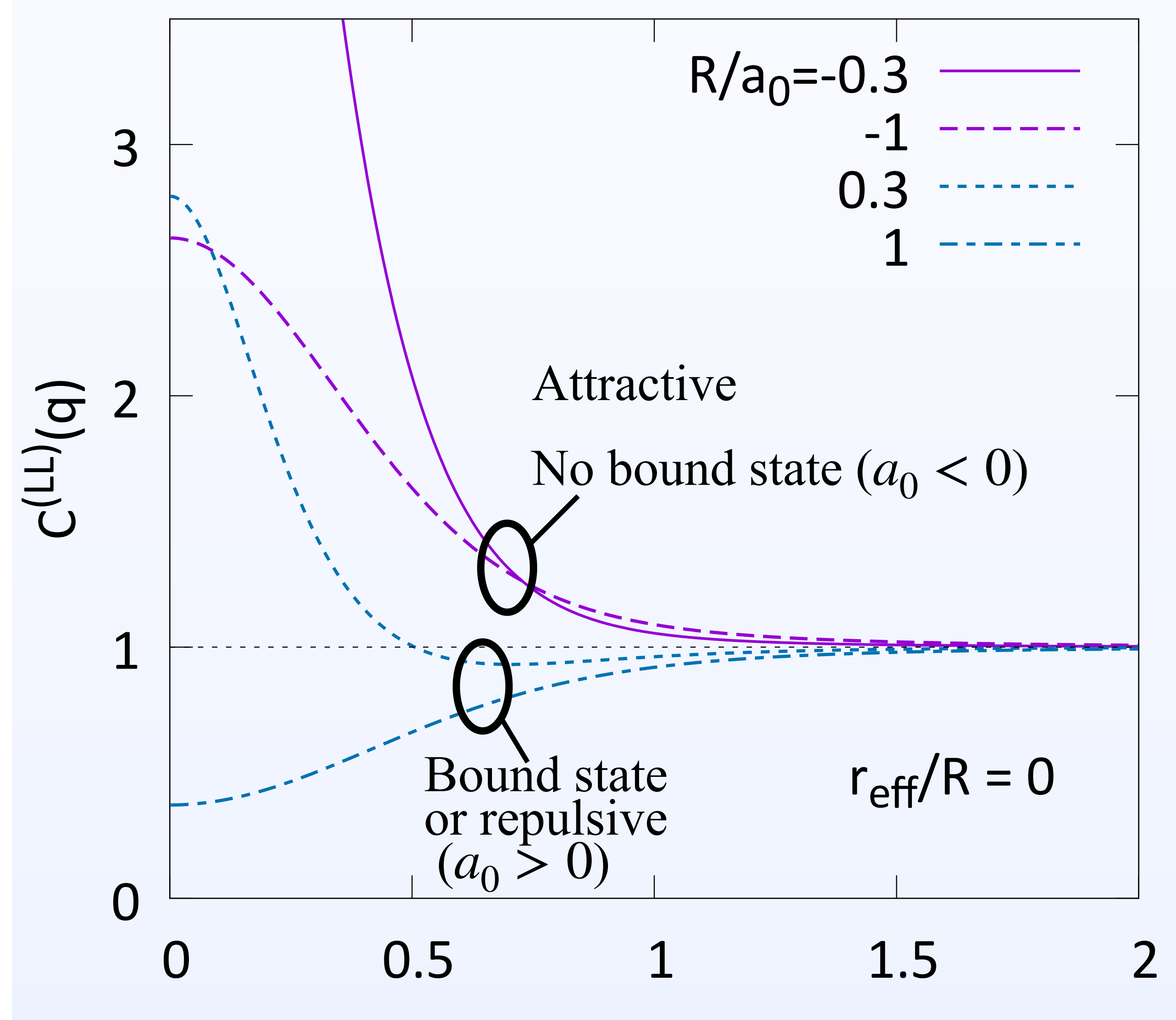
- Gaussian source with radius $R$
- Approximate $\varphi$ by asymptotic wave func.
- $\mathcal{F}(q) = [-1/a_0 - iq]^{-1}$ with scat. length $a_0$

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

$$C = C(qR, R/a_0)$$

- $C(q)$ 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 $\mathcal{F}(q)$
- Sensitive to (non)existence of bound state

# $\bar{K}N$ 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)
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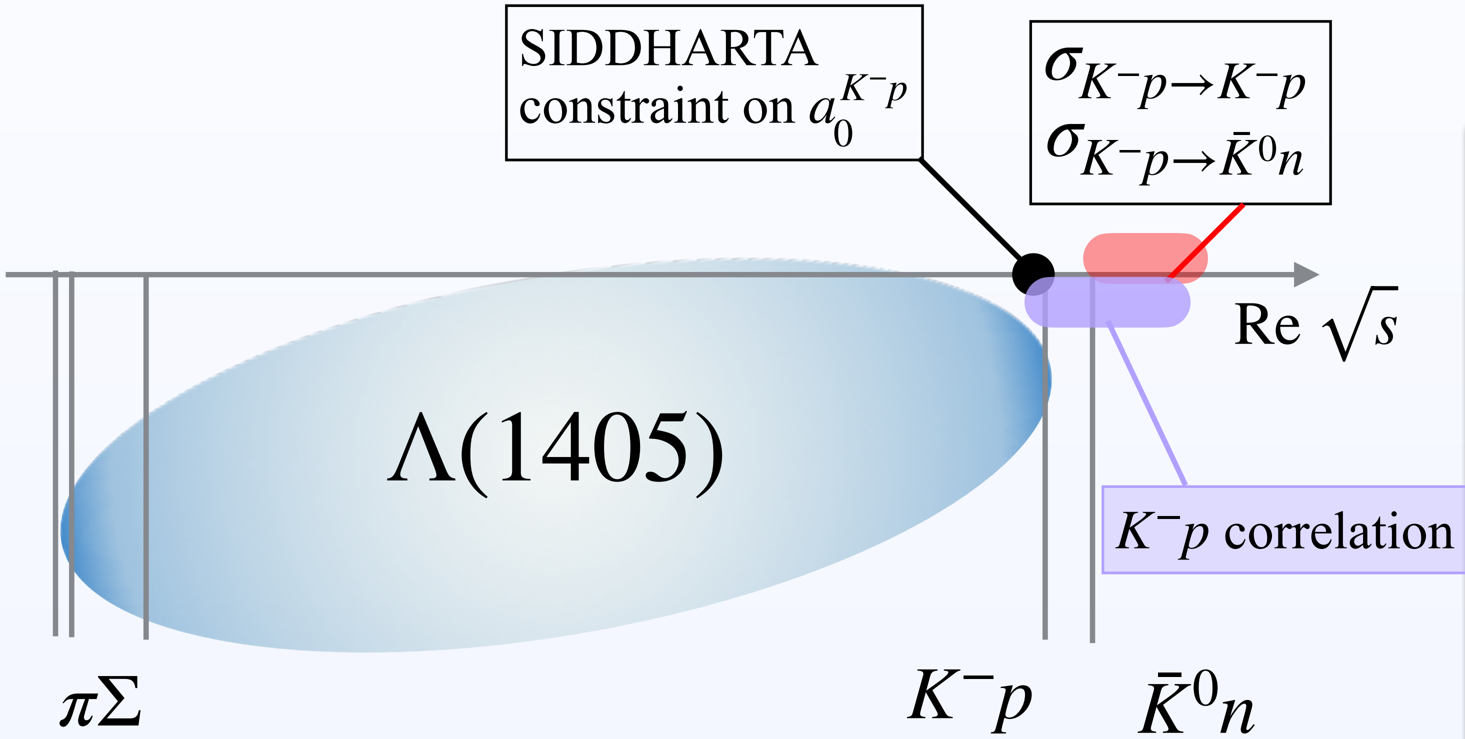


## Chiral SU(3) based $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

Miyahara, Hyodo, Weise, PRC 98 (2018)

- Constructed based on the amplitude with NLO chiral SU(3) dynamics <— $a_0^{K^-p}$, $\sigma$ fitted
  Ikeda, Hyodo, Weise, NPA881 (2012)
- Coupled-channel, energy dependent as
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$$V_{ij}^{\rm strong}(r,E) = e^{-(b_i/2+b_j/2)r^2} \sum_{\alpha=0}^{\alpha_{\rm max}} K_{\alpha,ij}\,(E/100\ {\rm MeV})^{\alpha}$$

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

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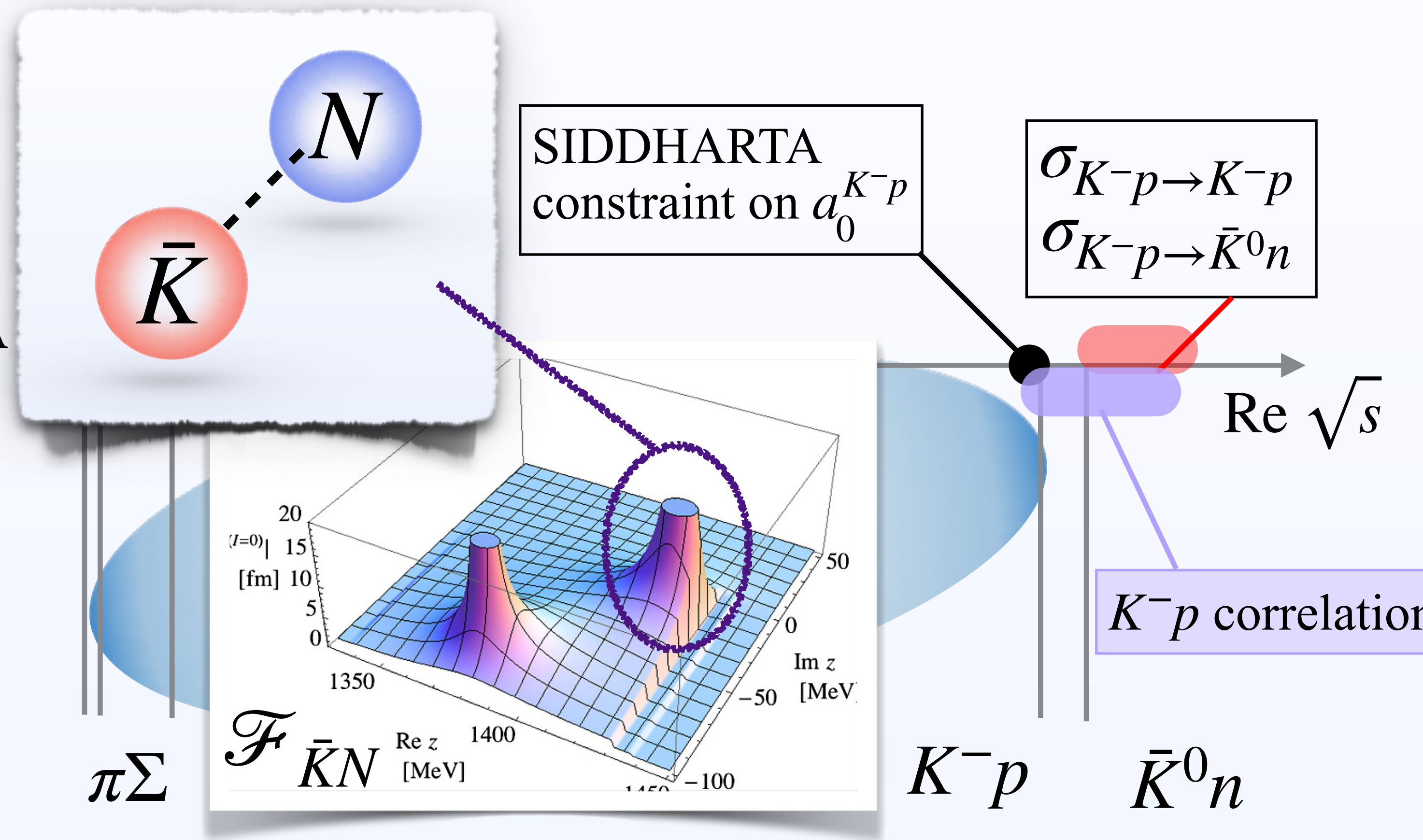


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# $\bar{K}N$ interaction and $K^-p$ correlation

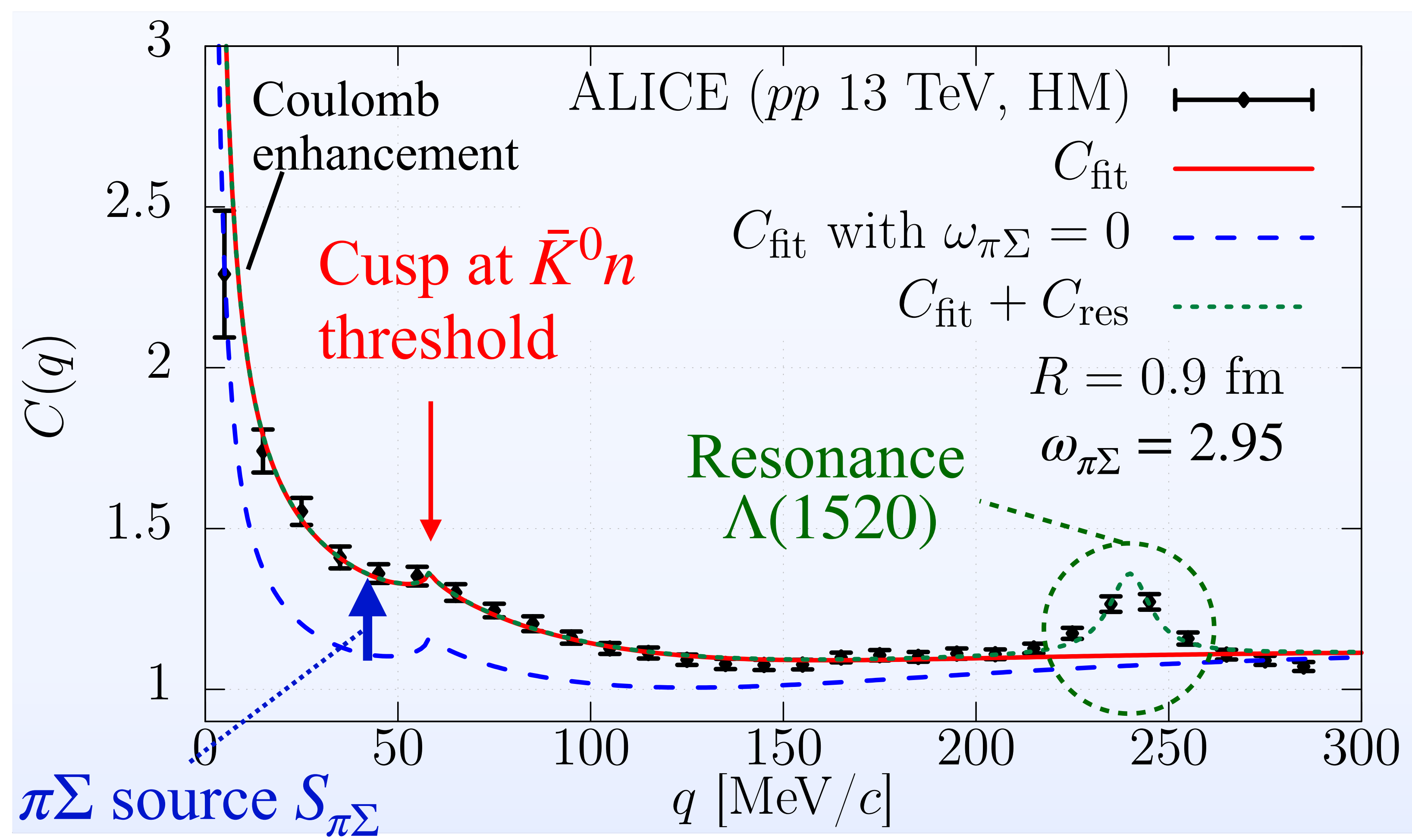
## Theoretical model for $C_{K^-p}$

Y. Kamiya, et. al. PRL 124 (2020) 13, 132501

- Interaction : Coupled-channel chiral based effective potential $V^{\bar{K}N\text{-}\pi\Sigma\text{-}\pi\Lambda}$
  Miyahara, Hyodo, Weise, PRC 98 (2018)
- Formula for $C_{K^-p}$ : coupled-channel Koonin-pratt formula R. Lednicky, et al. Sov. J. Nucl. Phys. 35(1982).
- Source function : Common static Gaussian source $S_j(r) = S_R(r) = \exp(-r^2/4R^2)/(4\pi R^2)^{3/2}$
- Channel weight : Varied around the estimation by simple statistical model: ~ twice pairs for $\pi\Sigma$

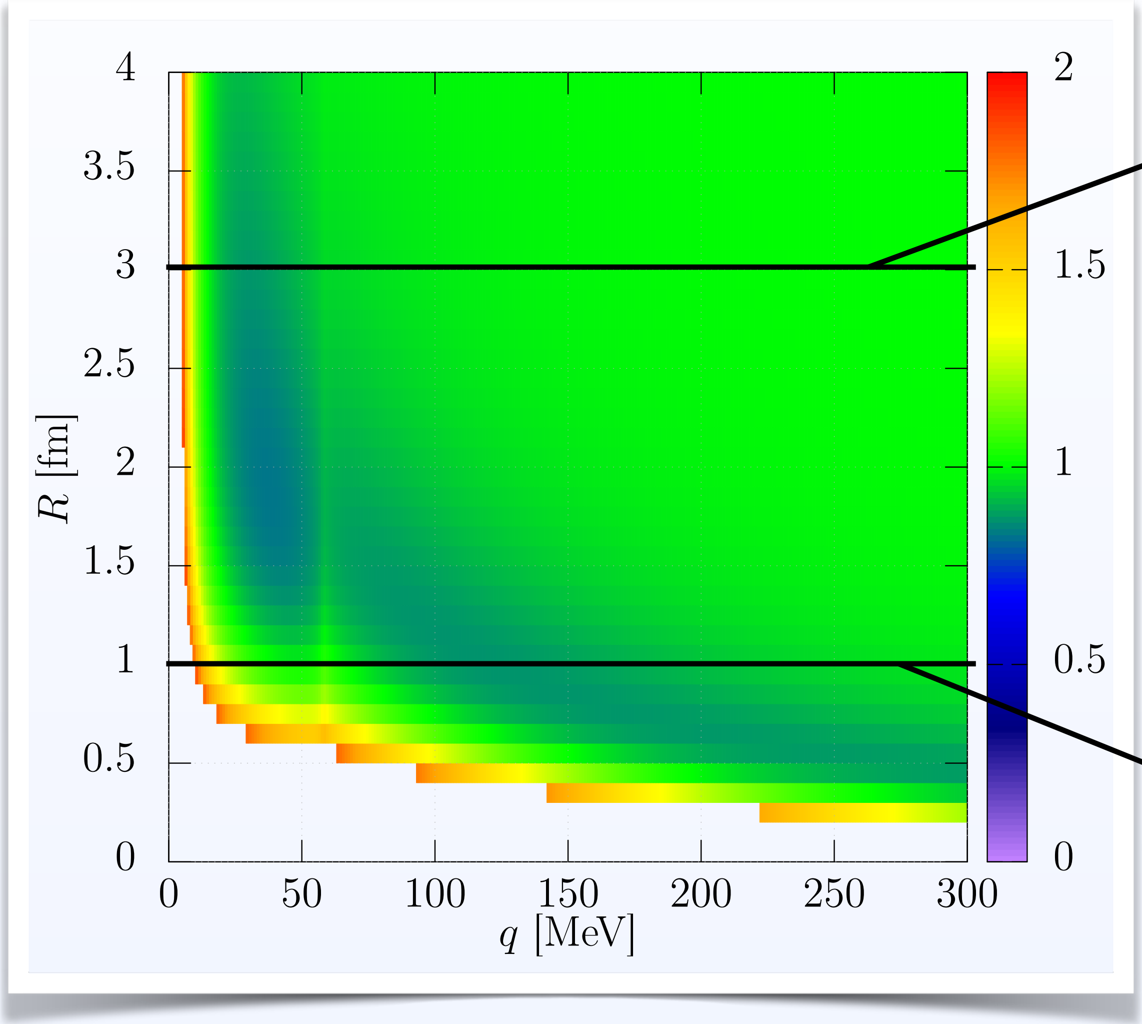
## Comparison with exp.

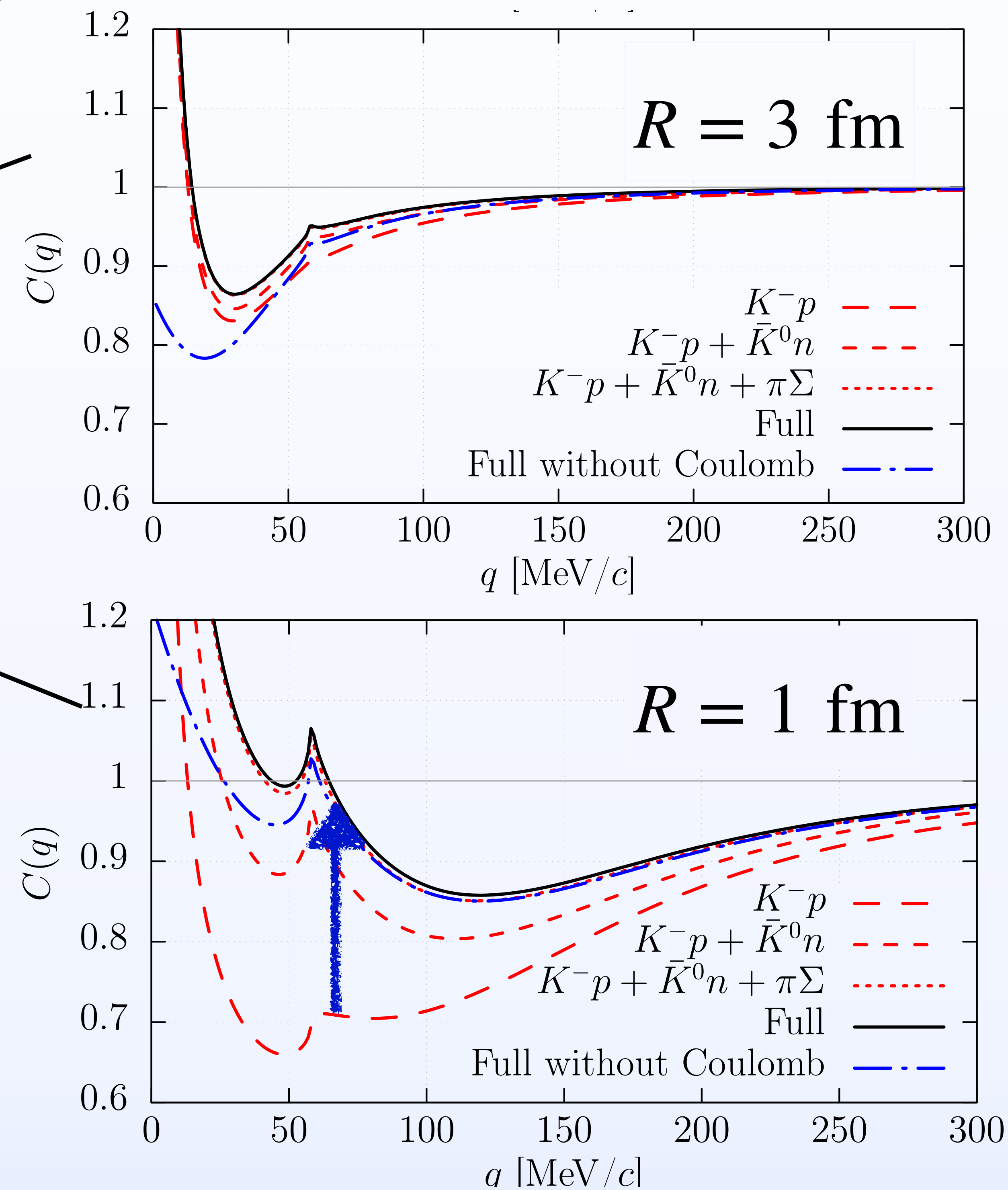
- ALICE data of $C_{K^-p}$ from $pp$ 13 TeV collisions
  ALICE PRL 124, 092301 (2020)
- Reproduces
  - Coulomb enhancement
  - $\bar{K}^0 n$ cusp structure
  - Enhancement by coupled channel sources



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

- Source size dependence of $K^-p$




- Enlarging source size
  - shifts the dip structure
  - makes cusp structure less prominent
  - reduces the c.c. source contribution

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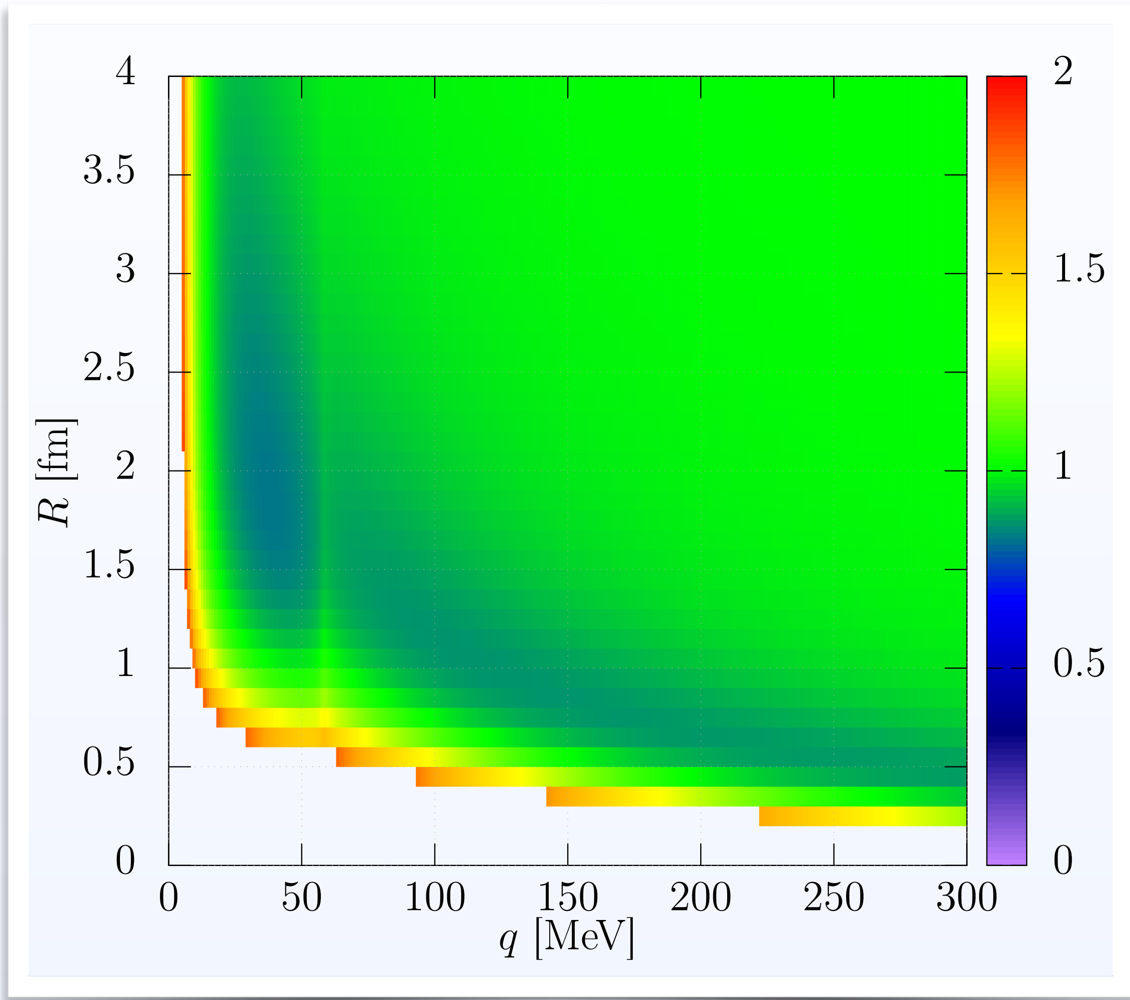


- Enlarging source size
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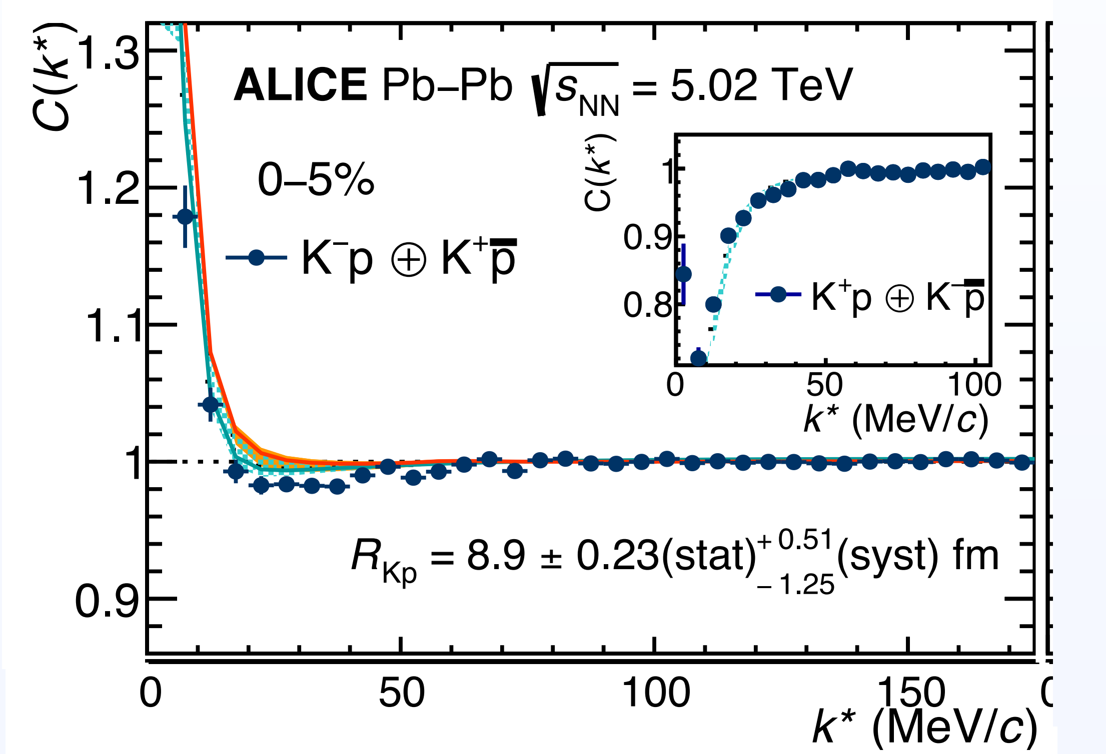
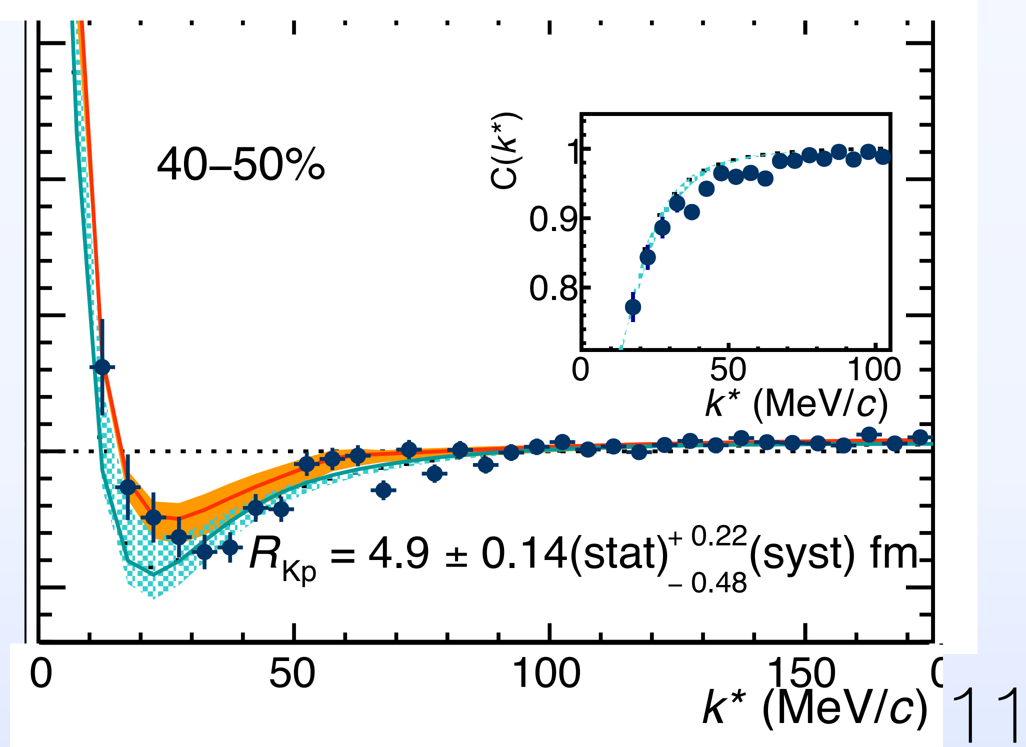
- PbPb data: in good agreement with qualitative features

- ALICE data PbPb collisions data

ALICE [arXiv:2105.05683v1]



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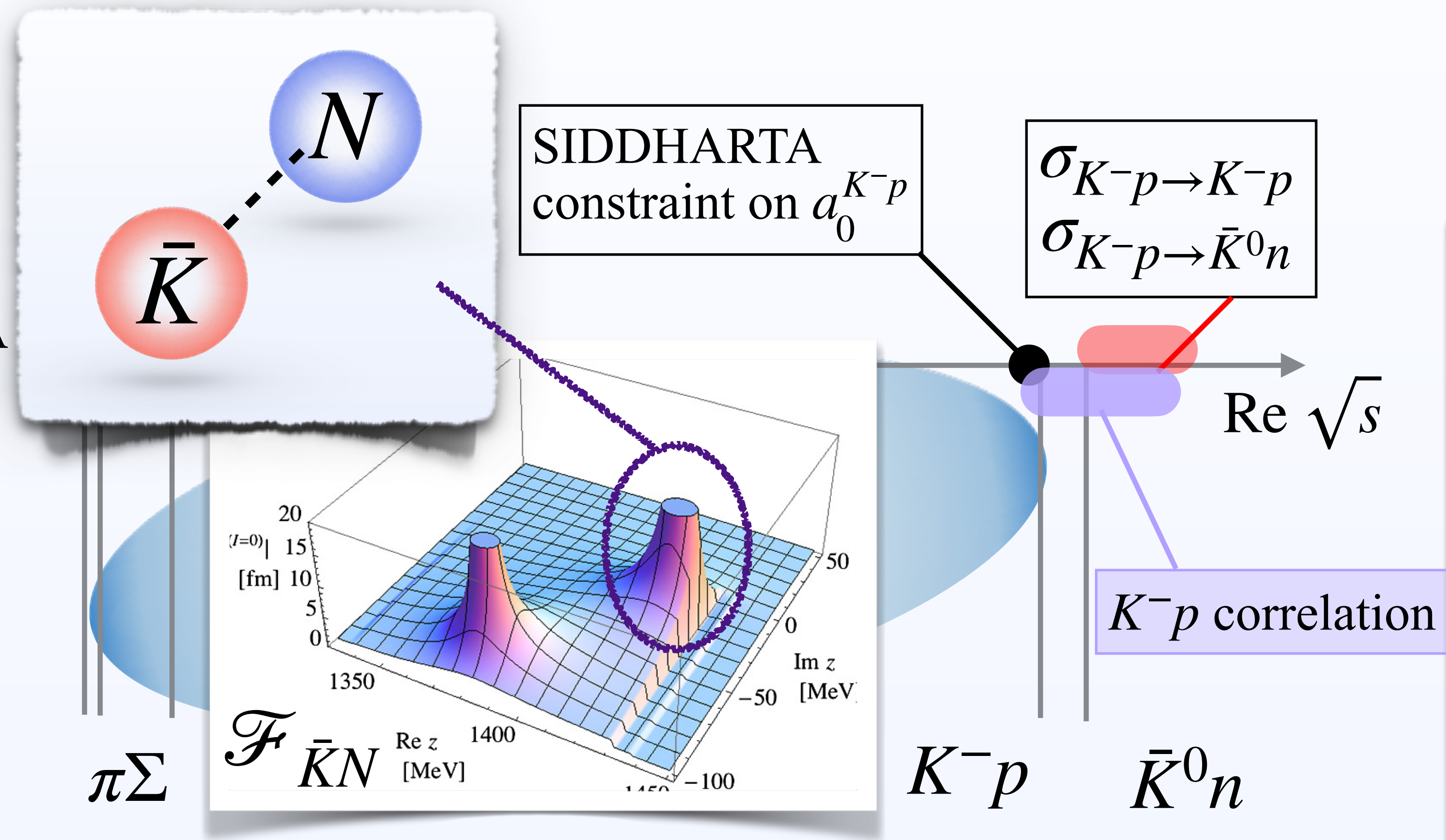


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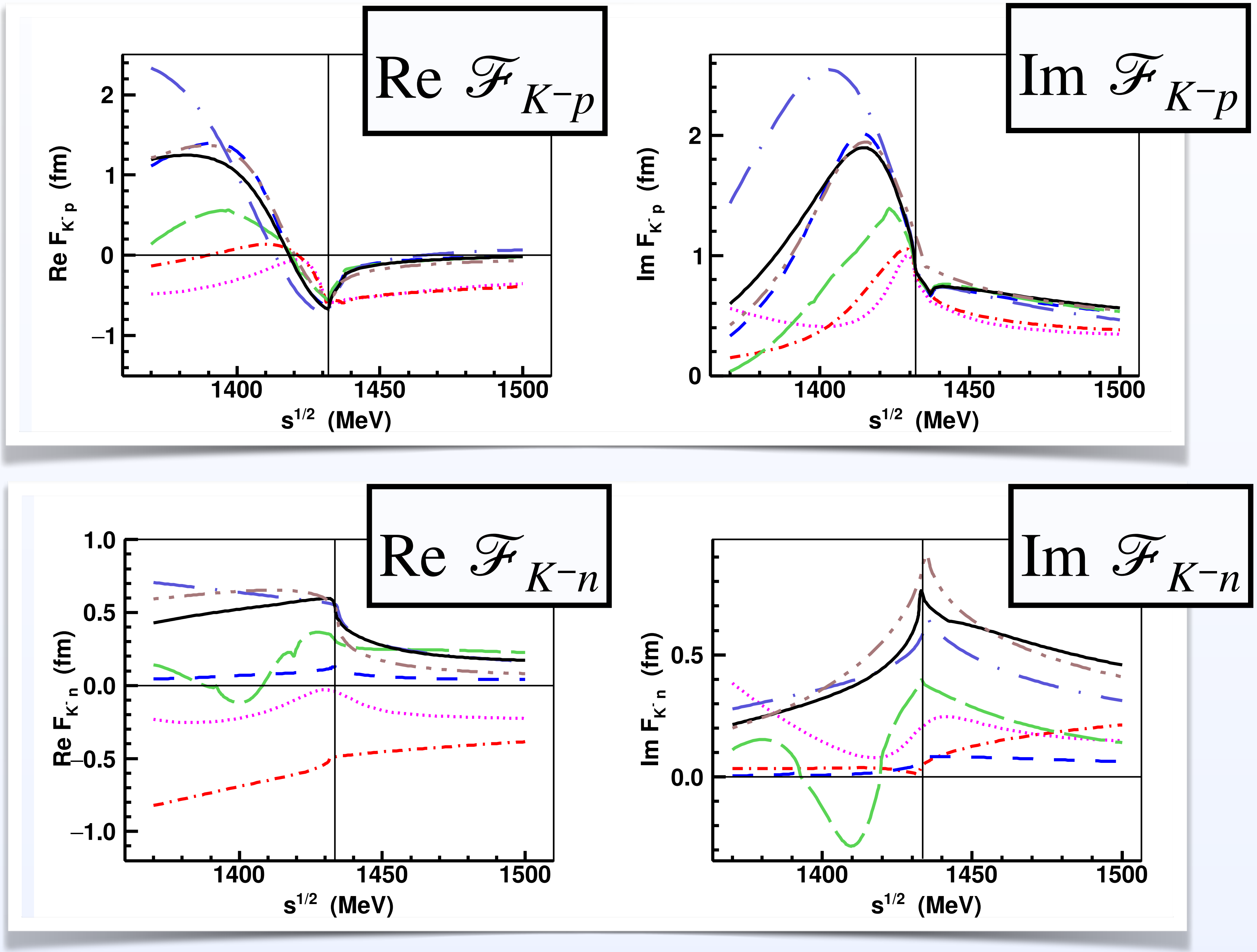
# Further constraint on $\bar{K}N$ interaction?

- $\bar{K}N$ interaction

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

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




Ciepły 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, et. al. in preparation

- $K^0_S p$ correlation

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

$\bar{K}N, I=1$ ↗ ↖ $KN, I=0,1$

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

$\bar{K}N, I=1$:

- $I = 1$ component only
- Chiral amplitude

  Ikeda, Hyodo, Weise, NPA881 (2012)
- Effective potential

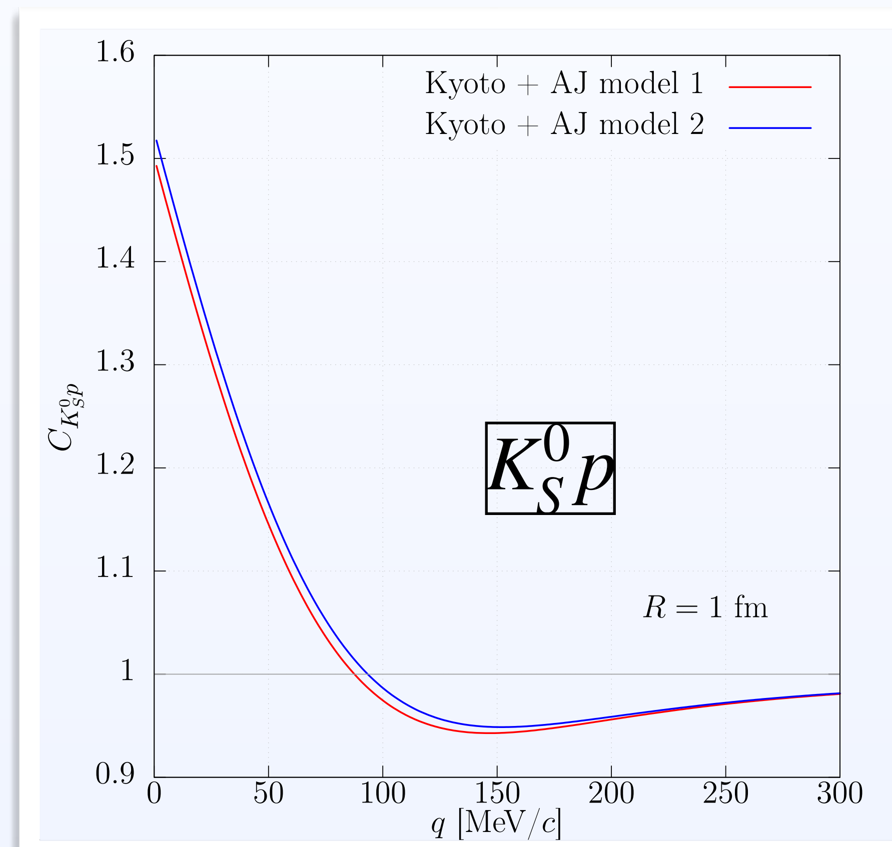
  Miyahara, Hyodo, Weise, PRC 98 (2018)

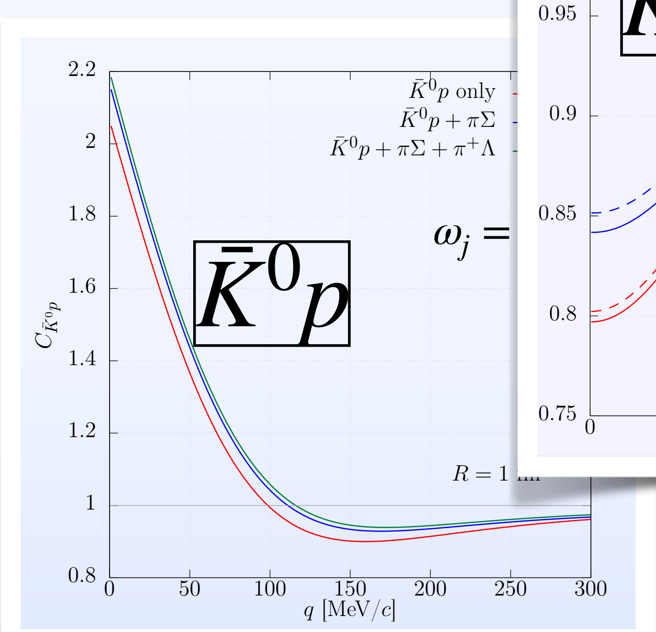
$KN, I=0,1$:

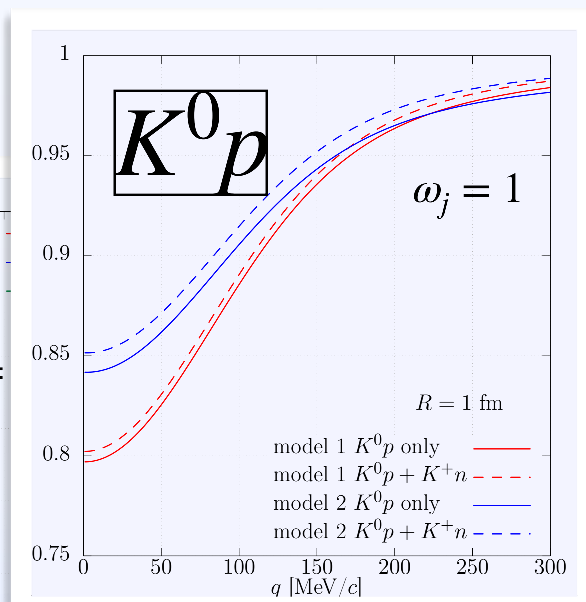
- Well determined with scat. exp.
- Chiral amplitude

  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

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

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

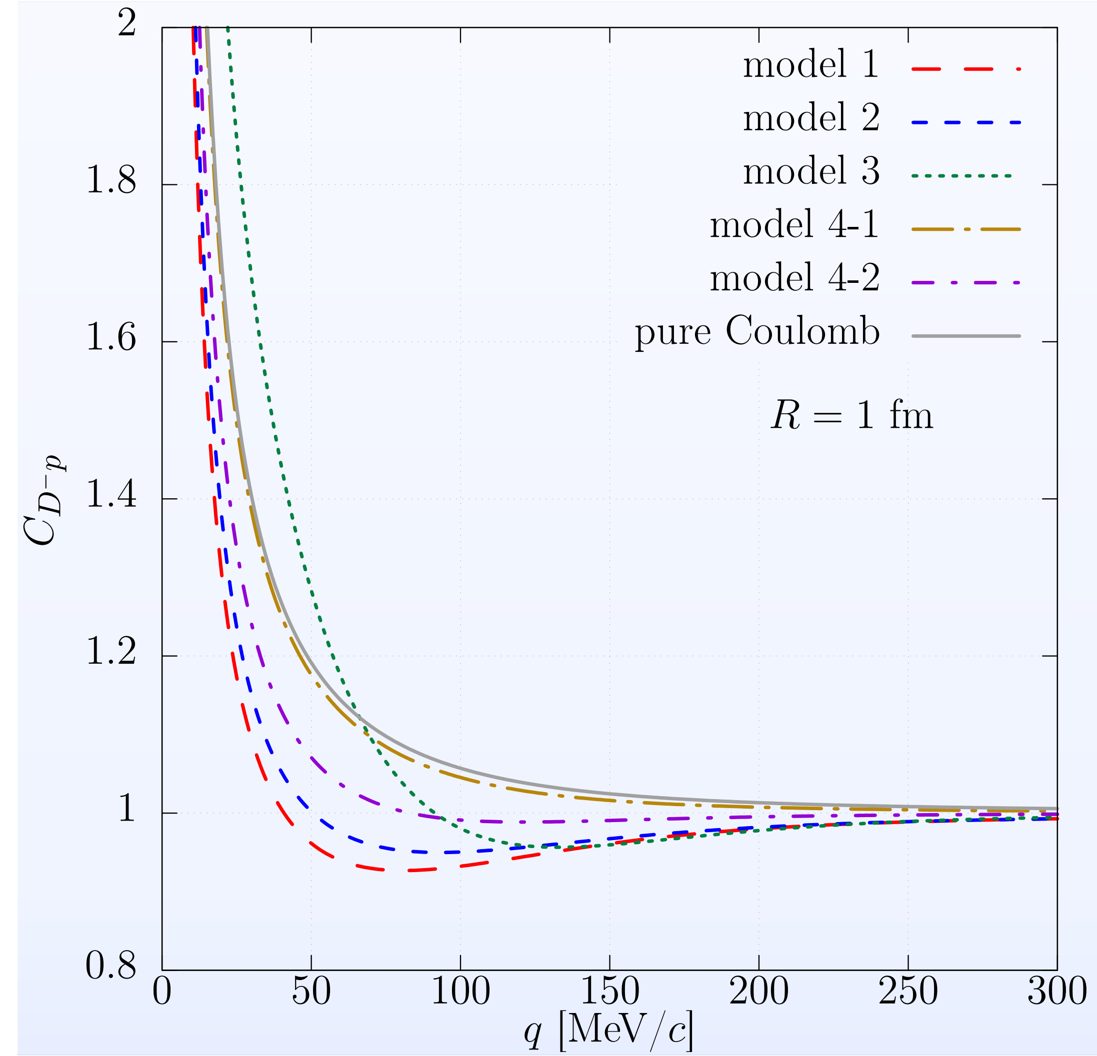
$a_0 \equiv \mathscr{F}(E = E_{th})$
+ : attractive w/o bound
- : repulsive
or attractive w/ bound

| Moldes | $a_0^{\bar{D}N(I=0)}$ [fm] | $a_0^{\bar{D}N(I=1)}$ [fm] | boutnd state (I=0) | bound state (I=1) |
|---|---|---|---|---|
| [1] J. Hofmann and M. Lutz, NPA 763 (2005) | -0.16 | -0.26 | None | None |
| [2] J. Haidenbauer, et. al. EPJA 33(2007) | 0.07 | -0.45 | None | None |
| [3] Y. Yamaguchi, et. al. PRD 84 (2011) | -4.38 | -0.07 | 2804 | None |
| [4] C. Fontoura, et. al. PRC 87 (2013) | 0.03-0.16 | 0.20-0.25 | None | None |

- Not well determined due to lack of scat. data
- One model predicts bound state in $I = 0$ channel

## $D^{-}p$ correlation

- Coulomb attractive
- Construct effective potential $V$ from models
  - Coupling between $D^{-}p$ and $\bar{D}^0 n$ $(I = 0,1)$
- Bound state case —> dip structure
- Can be tested by experimental data in future




Y. Kamiya, et. al. in preparation

# Summary

## Summary

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the hadron-hadron interaction.
- Chiral dynamics based $\bar{K}N$ correlation function model gives the good description for the $K^-p$ correlation function.
- Further study on $\bar{K}N$ interaction for $I = 1$ from femtoscpic study with $\bar{K}^0_S p$ correlation.
- Femtoscopic method can be applicable to charm sector in future study.

*Thank you for your attention!*

Thank you!