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神谷　有輝

Femtoscopic study on Kaon-Nucleus correlation function

In collaboration with
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兵藤 哲雄

核力・ハドロン間相互作用と量子多体計算の進展
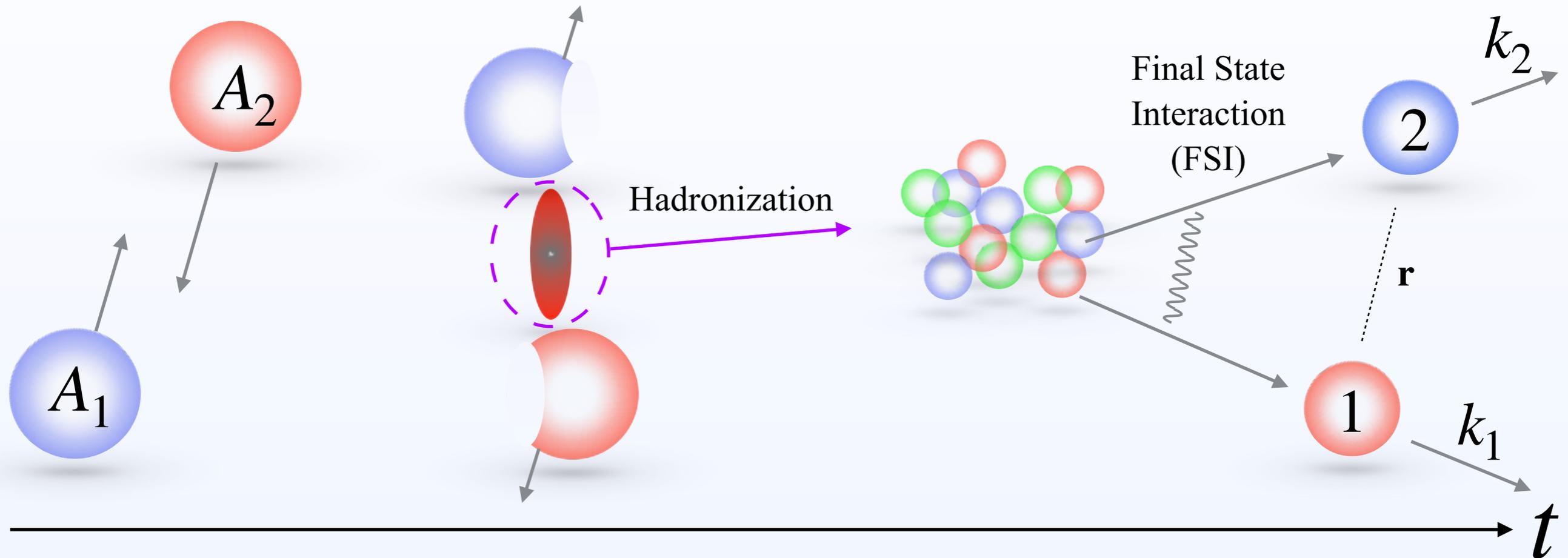
基礎物理学研究室　益川ホール

2026/2/18

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Contents

- Introduction and examples of Femtosocpic study

- K^-p femtoscopy with the chiral unitary model

- $K^-\alpha$ correlation function

- Summary

Hadron correlation in high energy nuclear collision
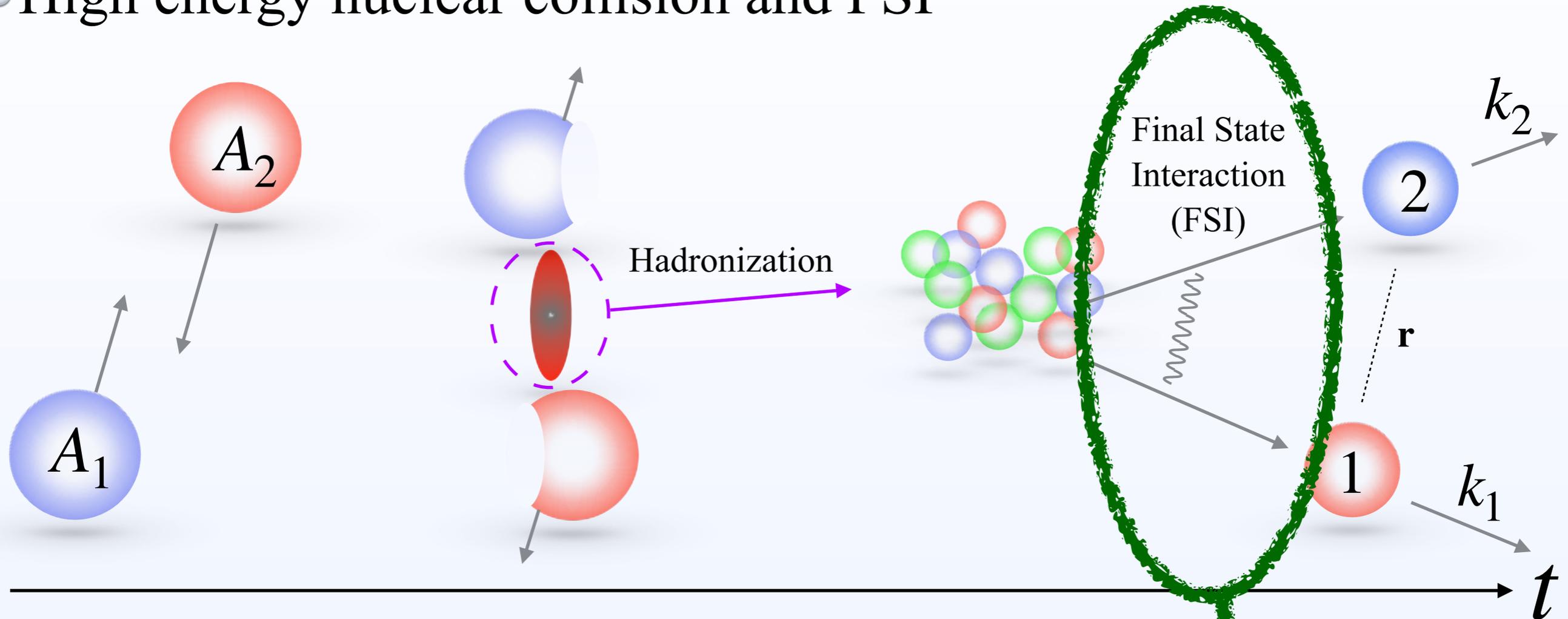
- High energy nuclear collision and FSI

- 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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High energy nuclear collision and FSI

Hadronization

Final State Interaction (FSI)

A_2

A_1

k_2

2

$\mathbf{r}$

1

k_1

t

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

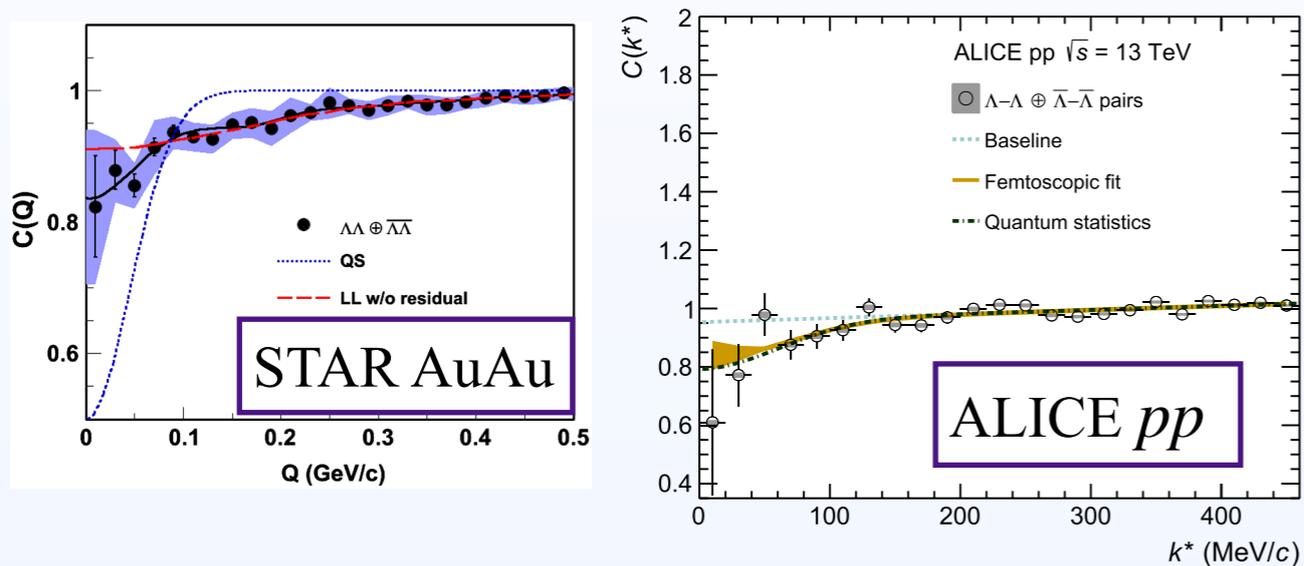$\varphi^{(-)}(\mathbf{q}, \mathbf{r})$: Relative wave function

- Depends on …

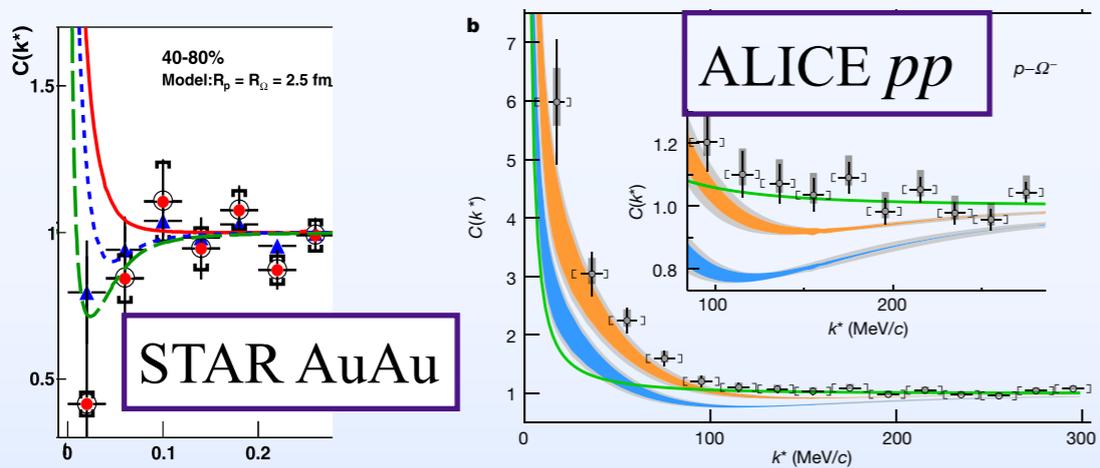 Interaction (strong and Coulomb)

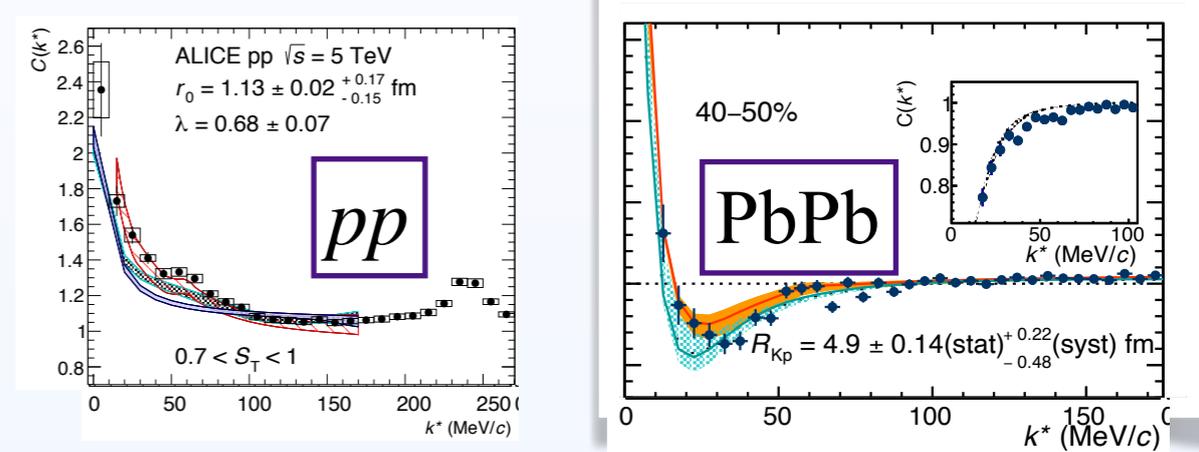 quantum statistics (Fermion, boson)

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Experimental data in various sectors

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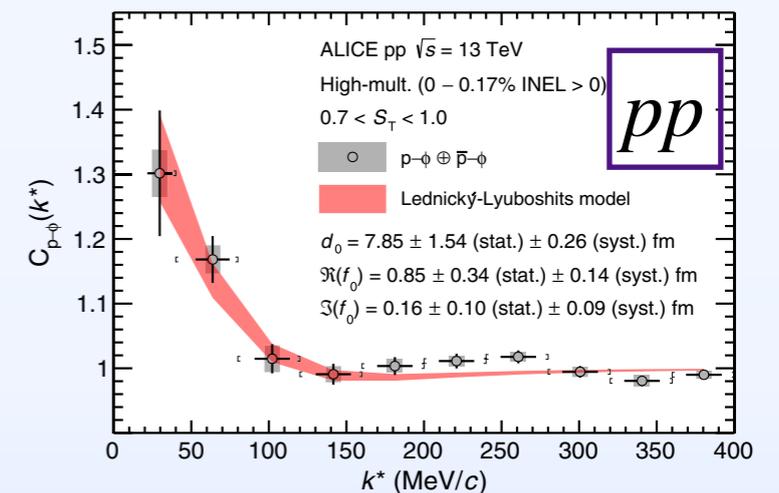 ALICE pp: PLB 797 (2019) 134822
  PbPb: PRC99, 024001 (2019)

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

STAR AuAu

ALICE pp

pp

PbPb

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

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

STAR AuAu

ALICE pp

pp

- How to control source size R

  - pp collisions
  - pPb collisions
  - PbPb collisions
    - peripheral
    - central

R

~ 1 fm ~ 1.5 fm ~ 3 fm $\gtrsim 5$ fm
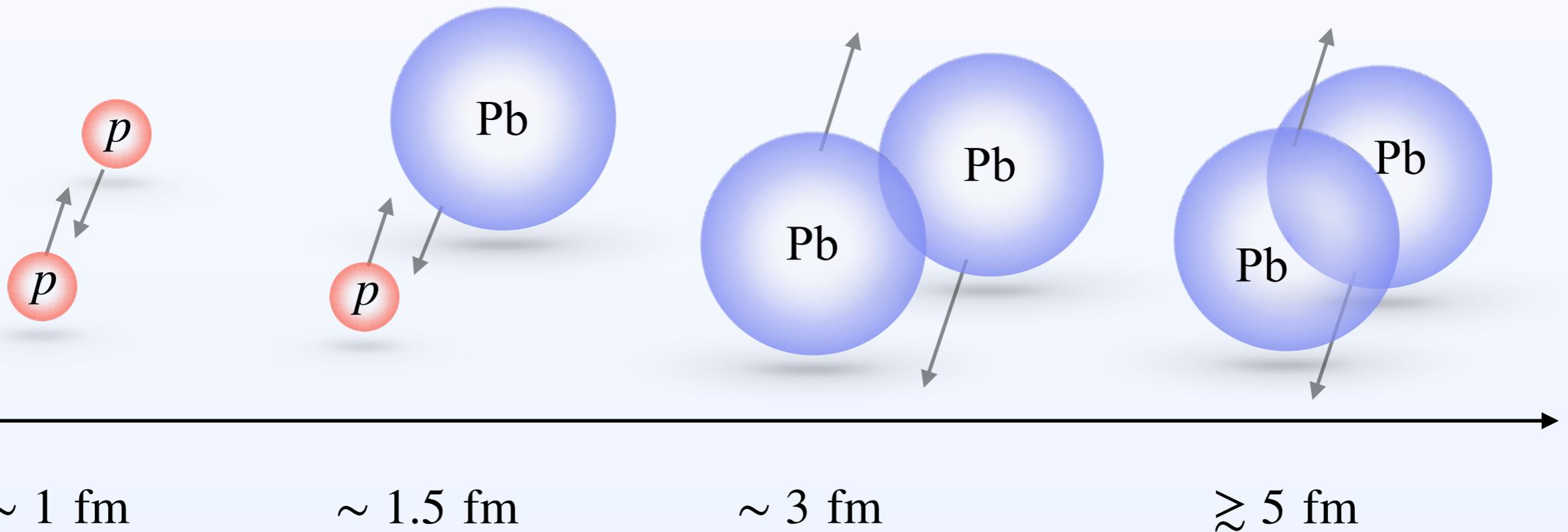
Source size dependence

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

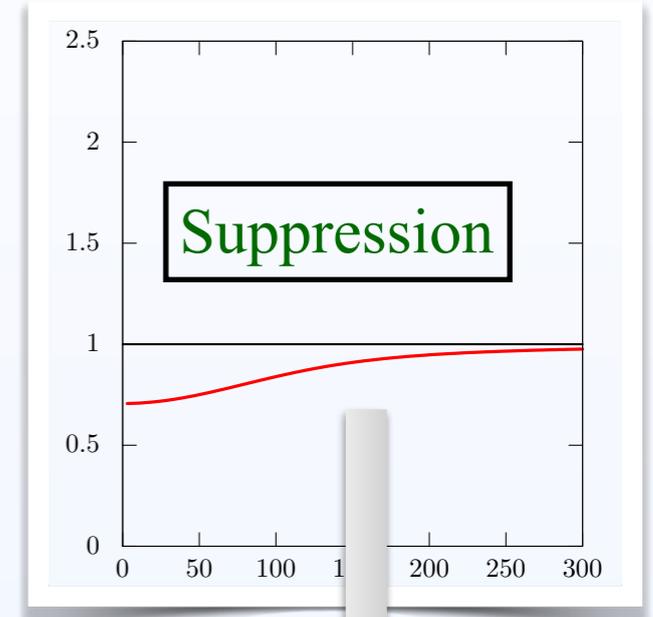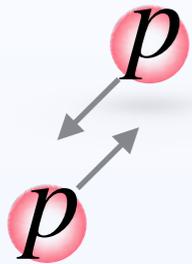• Attractive interaction
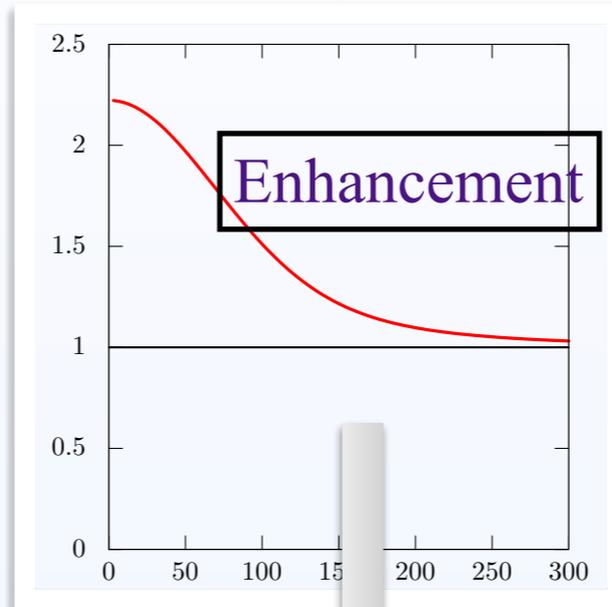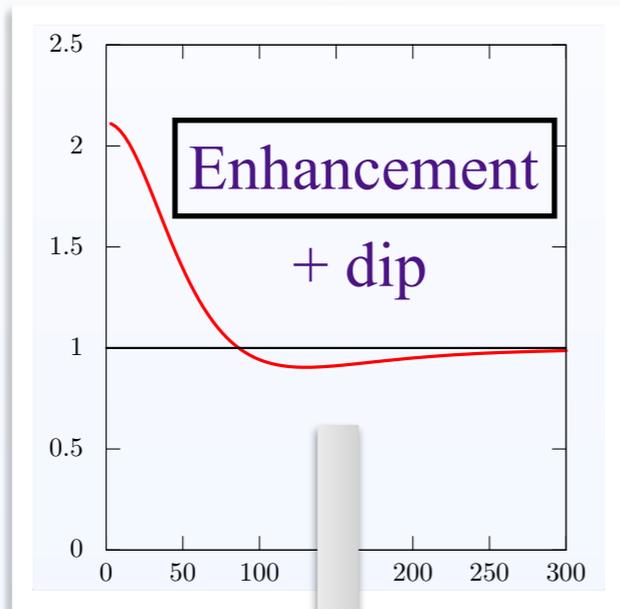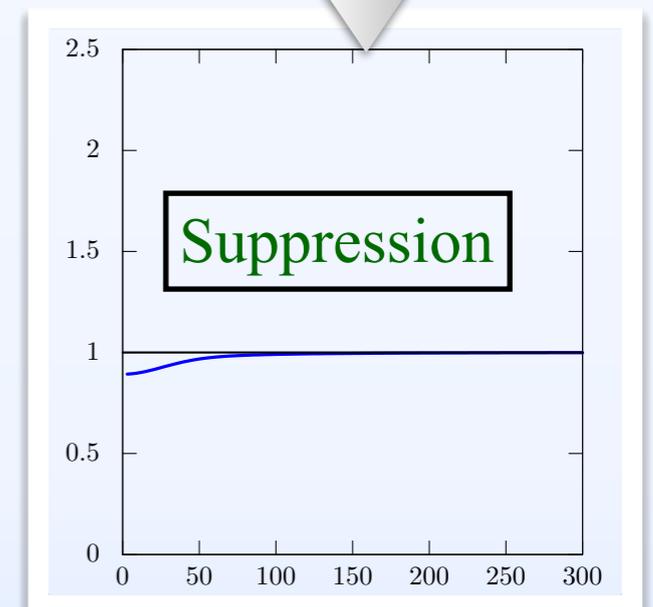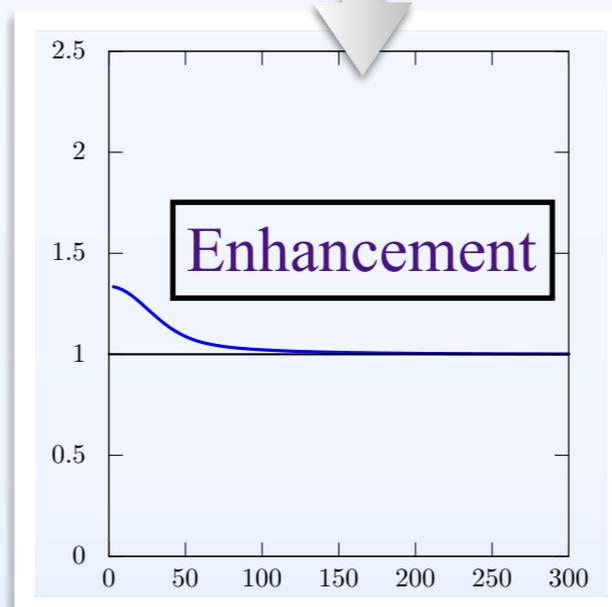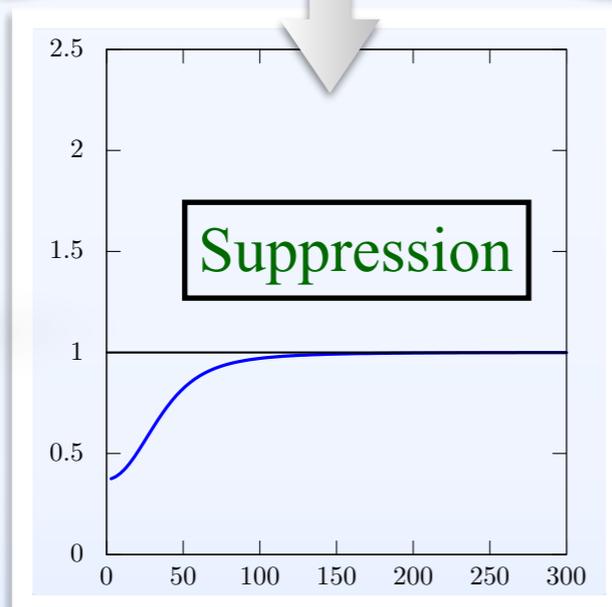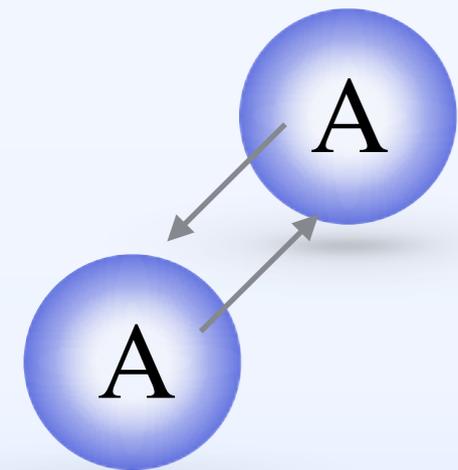
Source size dependence for typical for bound state cases!

$p\Sigma^+$ correlation

- $p\Sigma^+$ ALICE femto data and theoretical lines

$$C_{p\Sigma^+}(k^*) = \frac{1}{4}C_{\text{Singlet}}(k^*) + \frac{3}{4}C_{\text{triplet}}(k^*)$$

ALICE collabo. arXiv:2510.14448

Coulomb scattering lengths

Models	a_{sC} (fm)	a_{tC} (fm)
SMS NLO19	-3.62	0.47
SMS NLO19 (at=0.3fm)	-3.62	0.31
NSC97f	-4.35	-0.25
ESC16	-4.30	0.57
SMS NLO (sim)	-2.39	0.80
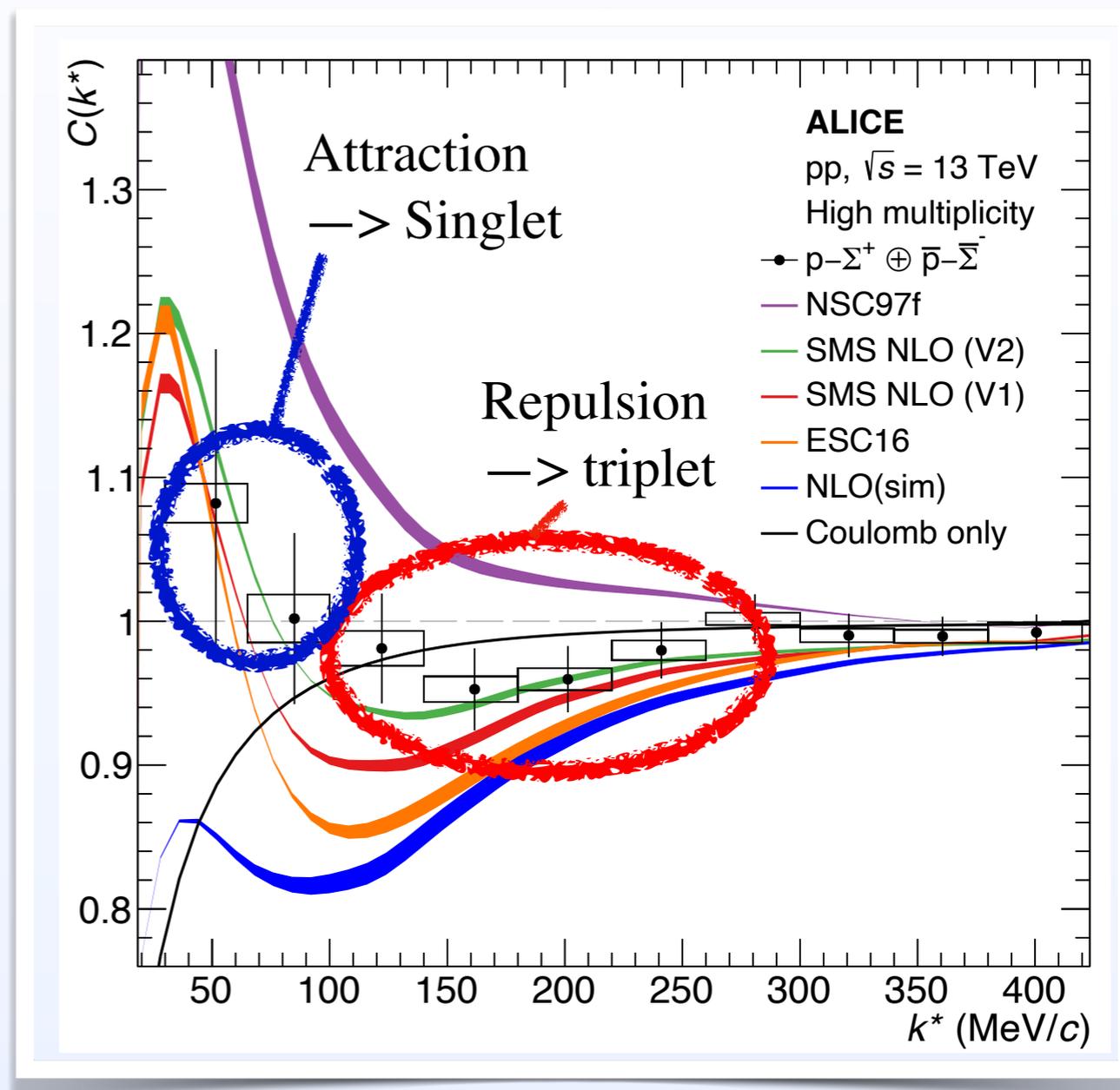
- Signal from $J = 0$ attraction and $J = 1$ repulsion are found in the different momentum region.
- NLO 19 (Chiral model) is favored by data

- Can we determine both simultaneously with data driven method?

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- $p\Sigma^+$ ALICE femto data and theoretical lines

  - Simultaneous fitting of V_{singlet} and V_{triplet}

  ALICE collabo. arXiv:2510.14448

  Gaussian parameterization of potential: $V^J(r) = V_0^J \exp(-br)$
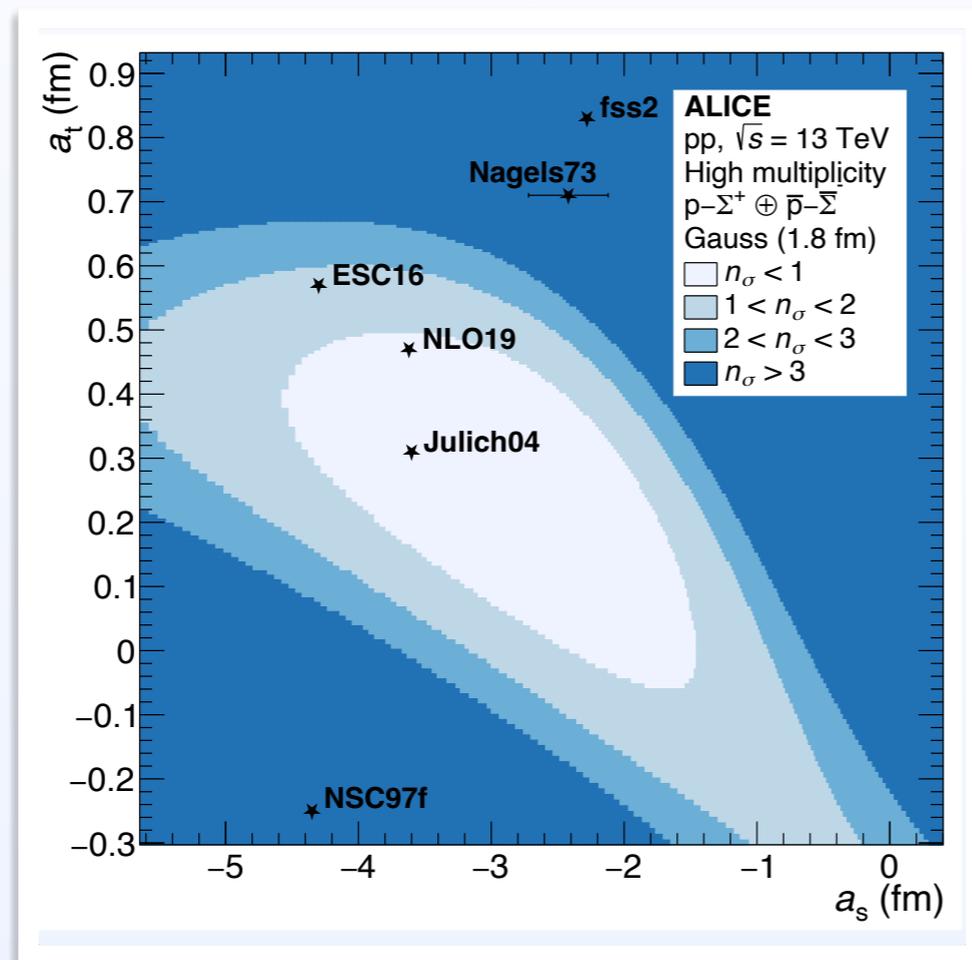
Potential	Gauss (1.8 fm)
a_{s} (fm)	$-2.82^{+0.90}_{-1.20}$
a_{t} (fm)	$0.26^{+0.19}_{-0.19}$

- Scattering length is restricted:
  —> weaker repulsion for triplet is favored.

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

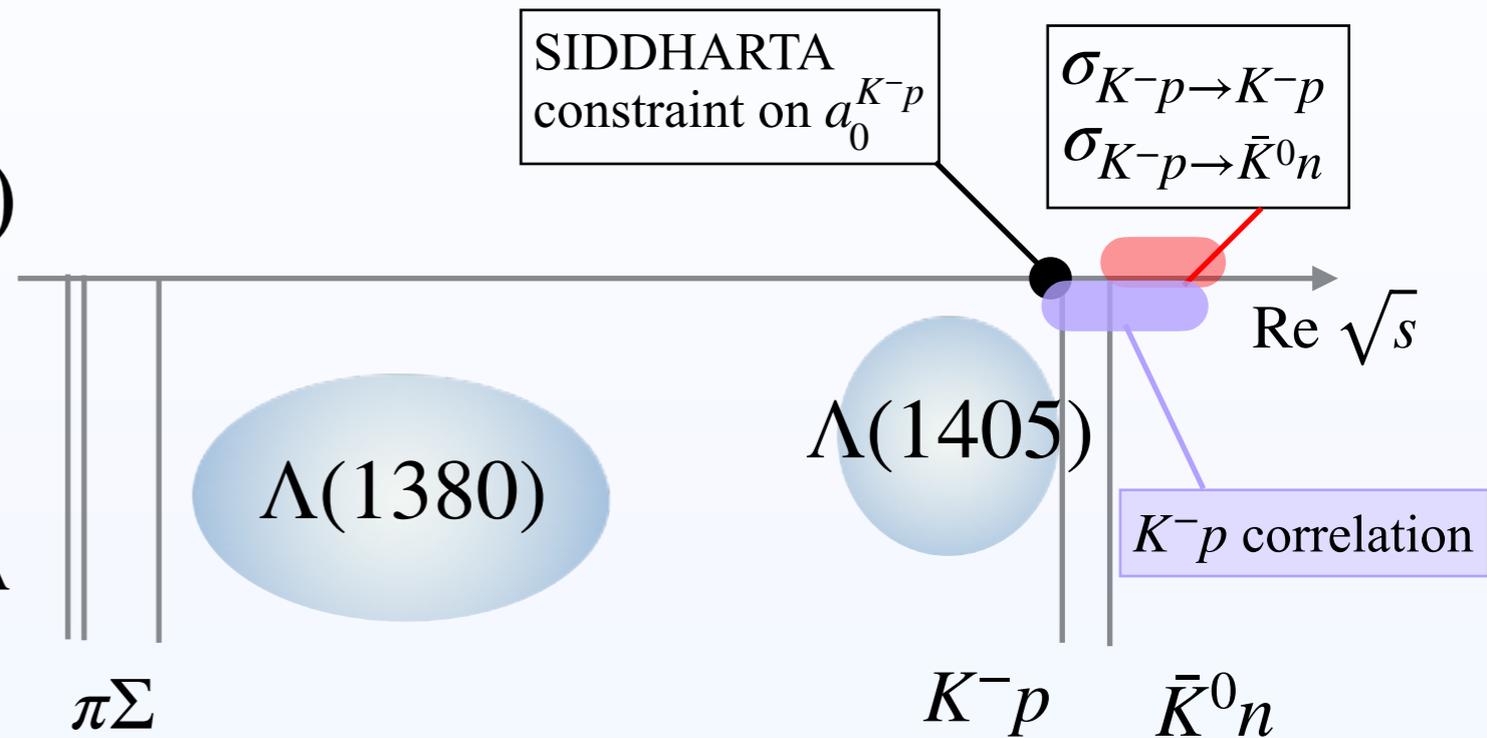## $\bar{K}N$ interaction and $\Lambda(1405)$

- 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)

SIDDHARTA constraint on $a_0^{K^-p}$

$\sigma_{K^-p \to K^-p}$
$\sigma_{K^-p \to \bar{K}^0 n}$

Re $\sqrt{s}$

$\Lambda(1380)$

$\Lambda(1405)$

K^-p correlation

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

Chiral SU(3) dynamics and effective potential

Ikeda, Hyodo, Weise, NPA881 (2012)
Miyahara, Hyodo, Weise, PRC 98 (2018)

- Constructed based on the amplitude with NLO chiral SU(3) dynamics $\longleftarrow a_0^{K^-p}, \sigma$ fitted

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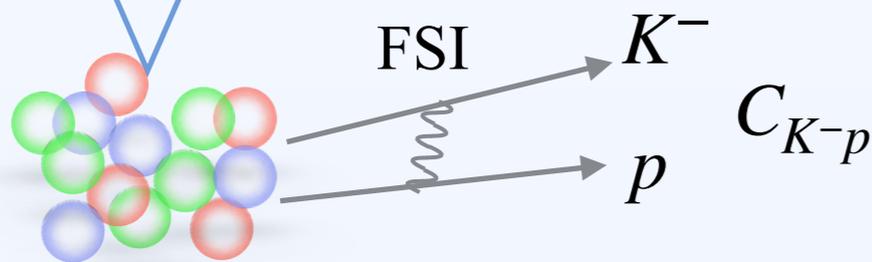
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○ Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula

$$C(\mathbf{q}) = \int d^3\mathbf{r}\, S(\mathbf{r}) |\psi^{(-)}(q;r)|^2 + \sum_{j \neq K^- p} \omega_j \int d^3\mathbf{r}\, S_j(\mathbf{r}) |\psi_j^{(-)}(q;r)|^2$$
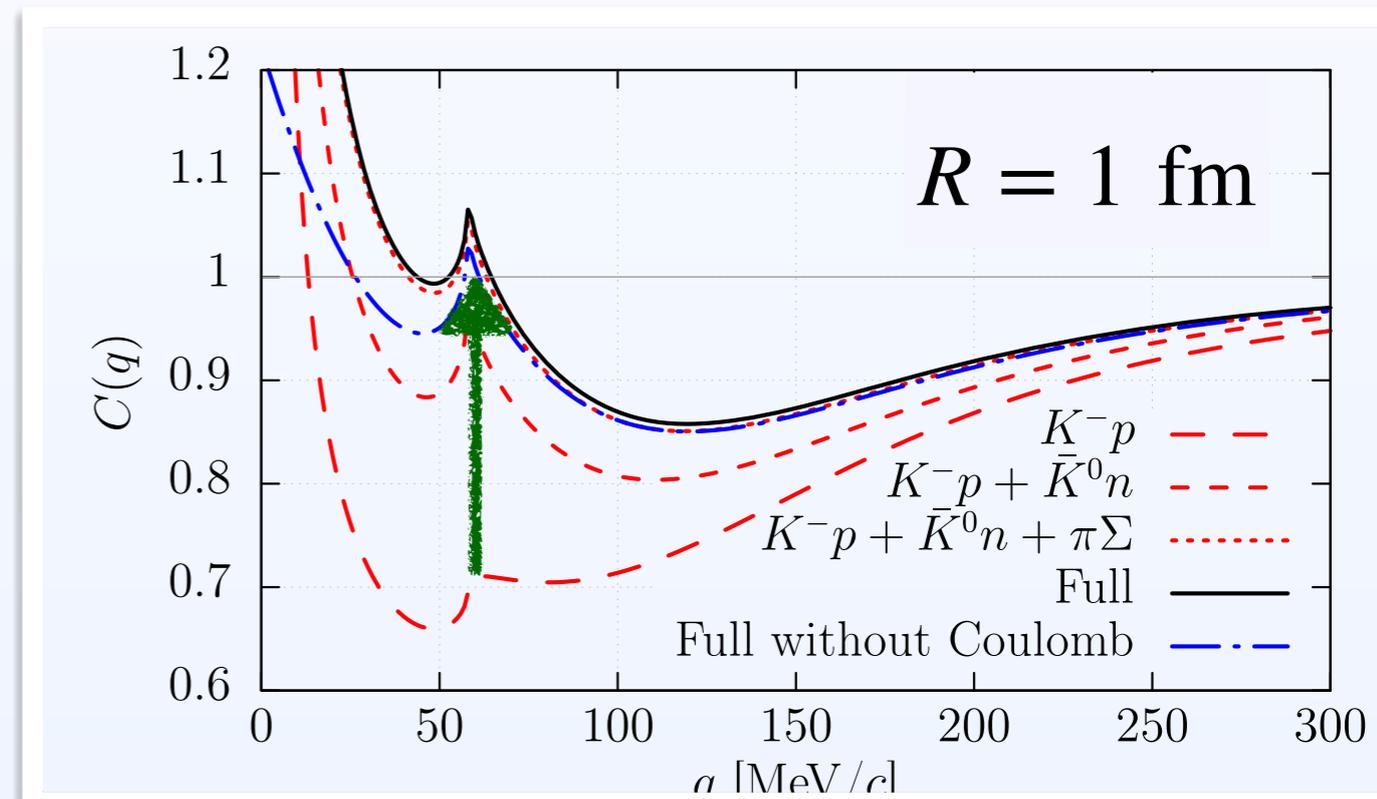
S.E. Koonin, PLB 70 (1977)
S. Pratt et. al. PRC 42 (1990)
R. Lednicky, et.al. Phys. At. Nucl. 61(1998)

● Contribution from coupled-channel source

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

FSI $\quad K^-$

$p \qquad C_{K^- p}$

$R = 1$ fm

$K^- p$
$K^- p + \bar{K}^0 n$
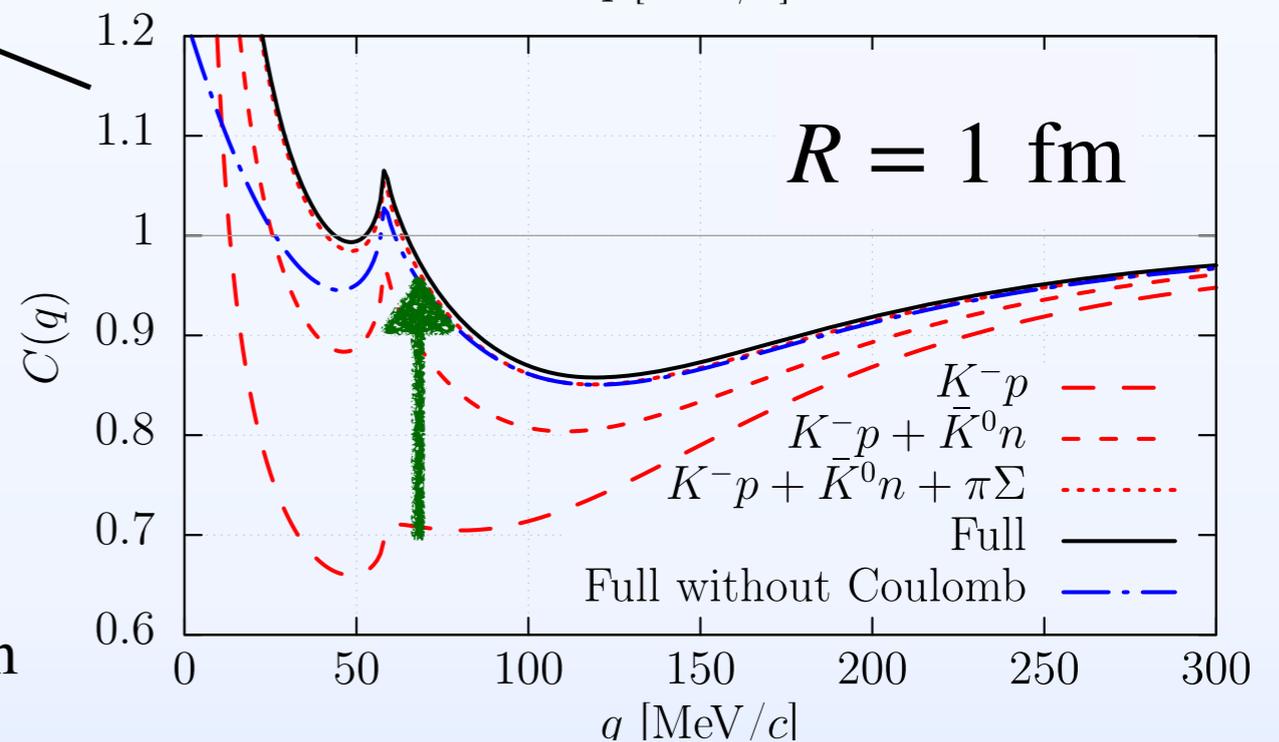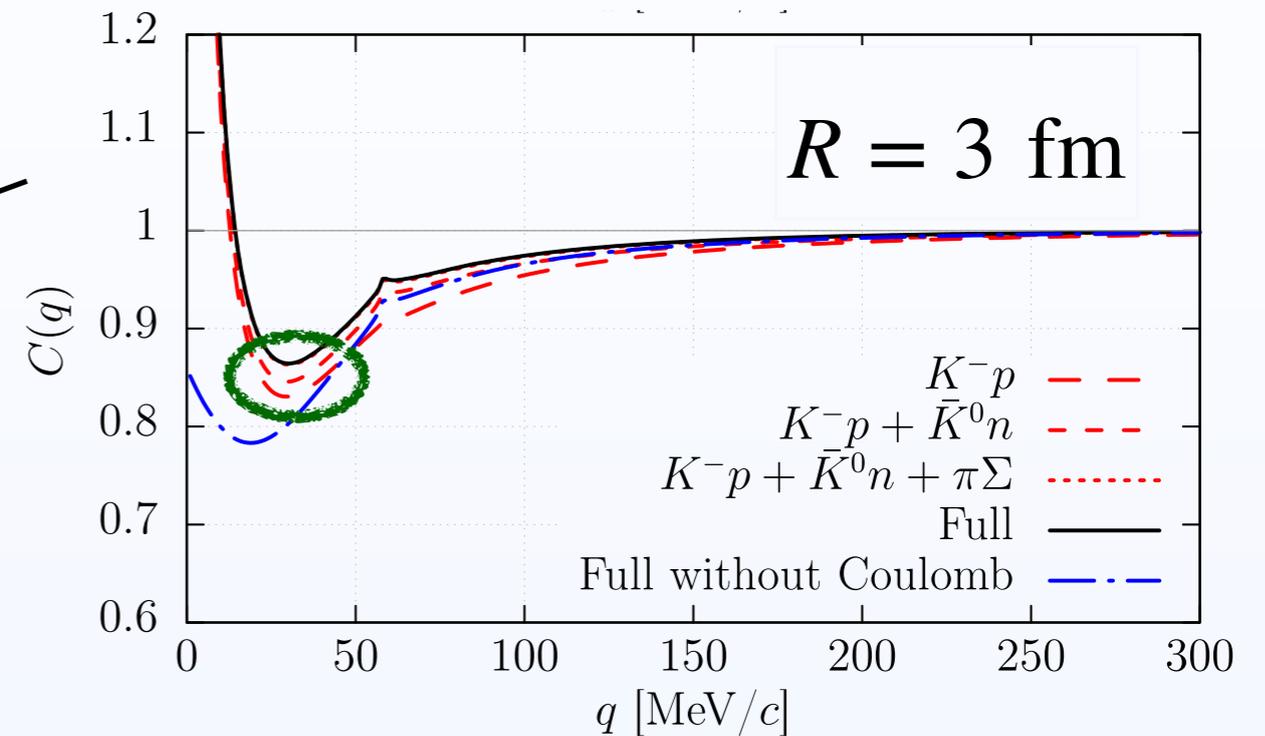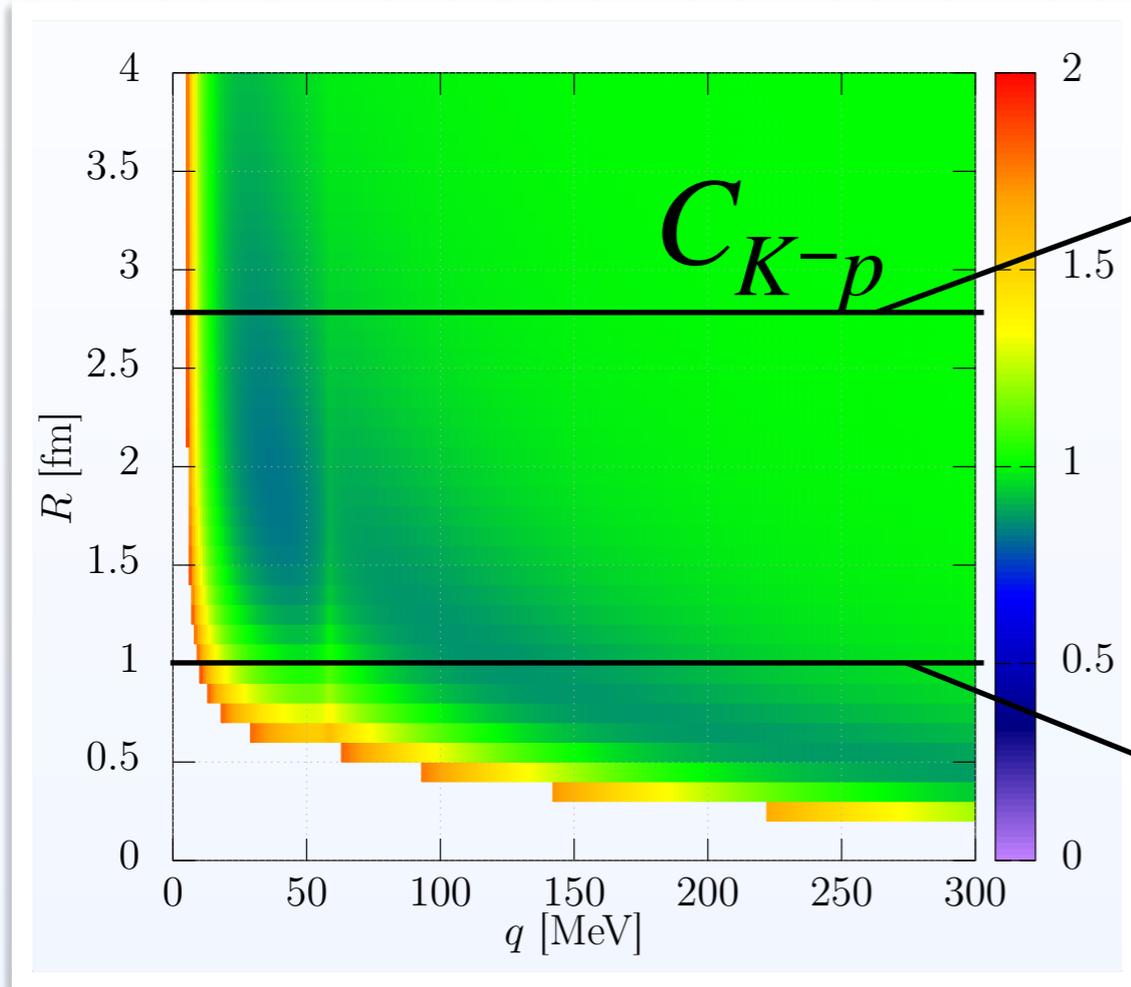$K^- p + \bar{K}^0 n + \pi \Sigma$
Full
Full without Coulomb

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

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

- Source size dependence of coupled-channel effect

C_{K^-p}

$R = 3$ fm

$C(q)$ — q [MeV/c]

K^-p
$K^-p + \bar{K}^0 n$
$K^-p + \bar{K}^0 n + \pi\Sigma$
Full
Full without Coulomb

$R = 1$ fm

$C(q)$ — q [MeV/c]

K^-p
$K^-p + \bar{K}^0 n$
$K^-p + \bar{K}^0 n + \pi\Sigma$
Full
Full without Coulomb

- 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
    - Large source：K^-p scattering
    - Small source：detailed coupled-channel effect

- Femtoscopic data
- High statics data
- Data from various sources

ALICE, PRL 124, 092301 (2020)
- pp: 5, 7, 13 TeV

ALICE, EPJC 83 (2023)
- pPb : 0-20%, 20-40% 40-100%
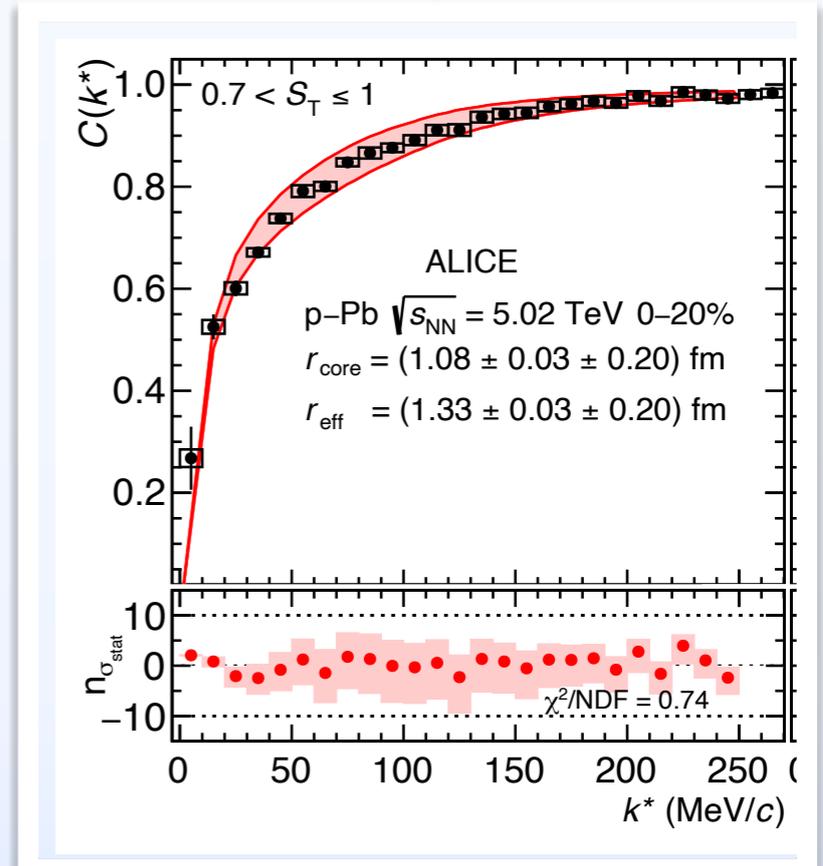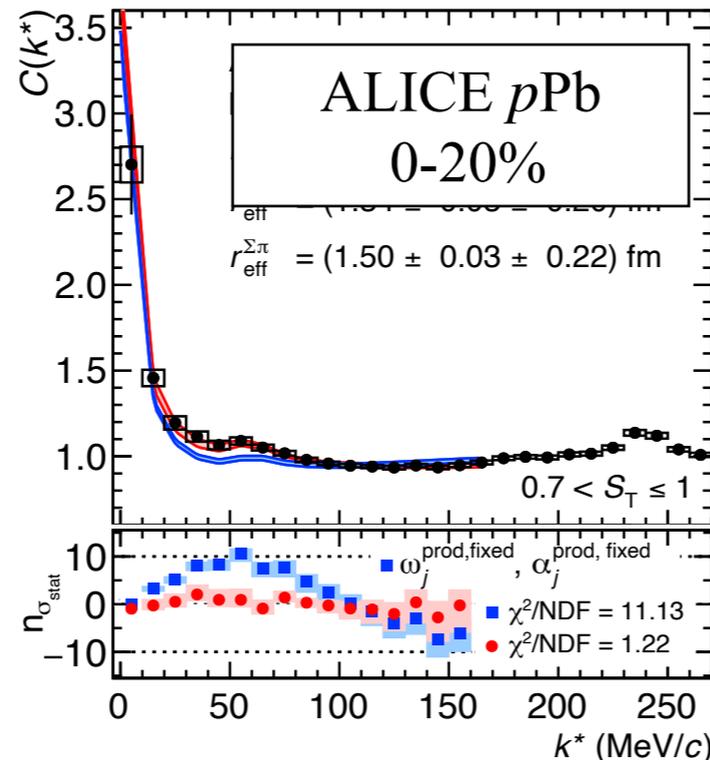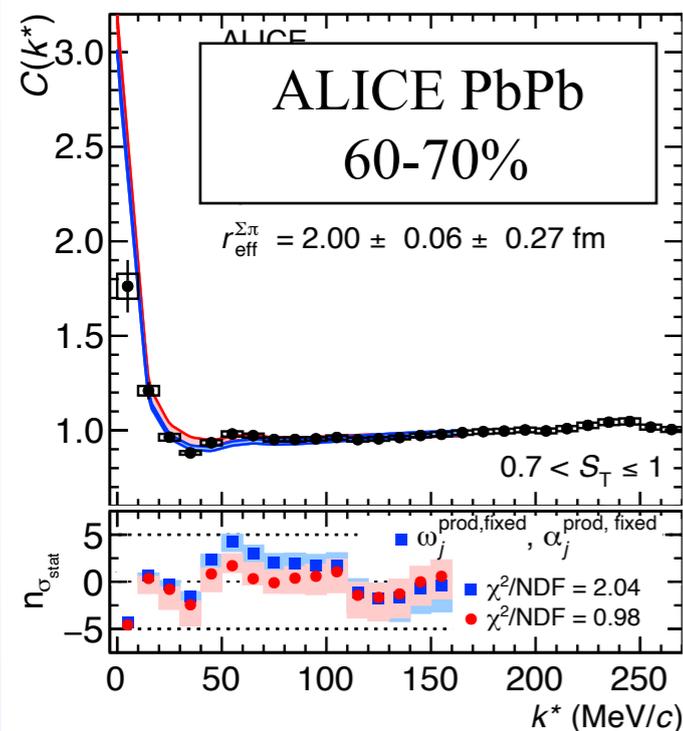- PbPb : 60-70%, 70-80% 80-90%

ALICE, PLB 822 (2022)
- PbPb : 0-5%, 5-10%, 10-20%,
   20-30%, 30-40%, 40-50%

- Source determination by K^-p

- KN int.: Well constrained
   by scattering exp.

- C_{K^+p}: Good observable to determine
   source size R
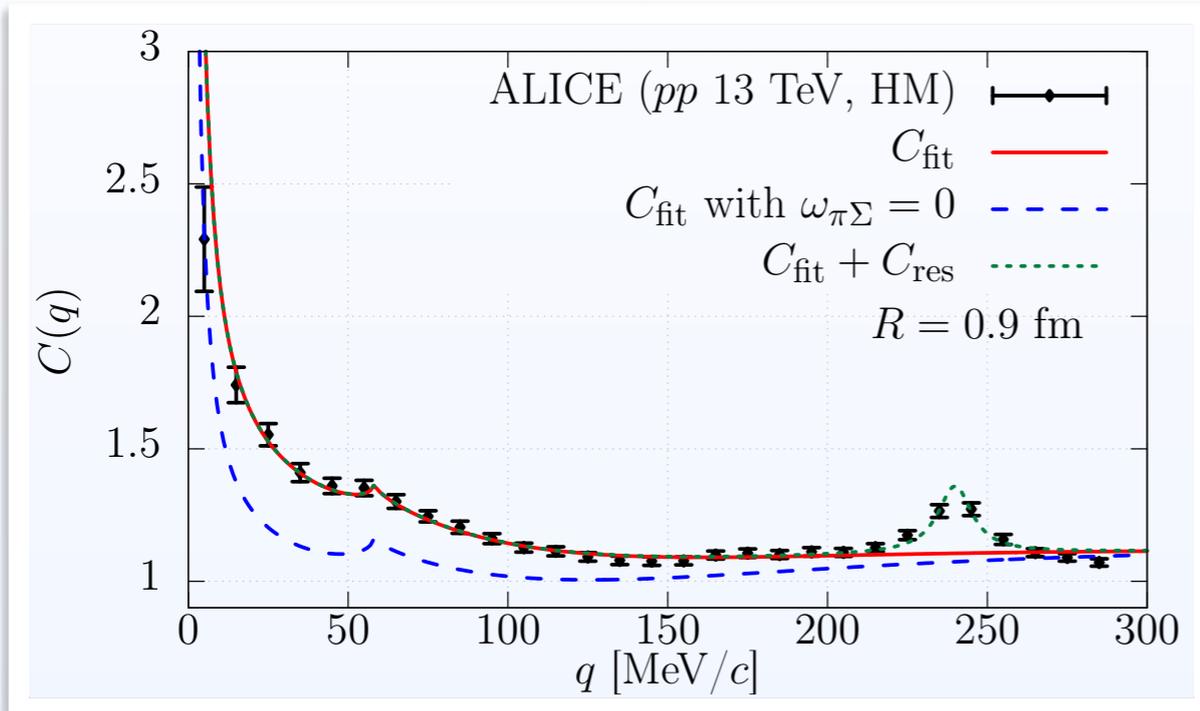
$$S_{K^+p} \simeq S_{K^-p}$$

- $K^- p$ femto data and chiral model

- 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
  - $\pi\Sigma$ enhancement needed

- ALICE Pb–Pb collision data

ALICE PLB 822 (2021) 136708

ALICE Pb–Pb $s_{NN} = 5.02$ TeV

0–5%

$R_{Kp} = 8.9 \pm 0.23(\text{stat})^{+0.5}_{-1.25}(\text{syst})$ fm

40–50%

$R_{Kp} = 4.9 \pm 0.14(\text{stat})^{+0.22}_{-0.48}(\text{syst})$ fm

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

- Good agreement with the chiral NLO dynamics for every collisions system's data

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K^-p correlation from large source

- 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
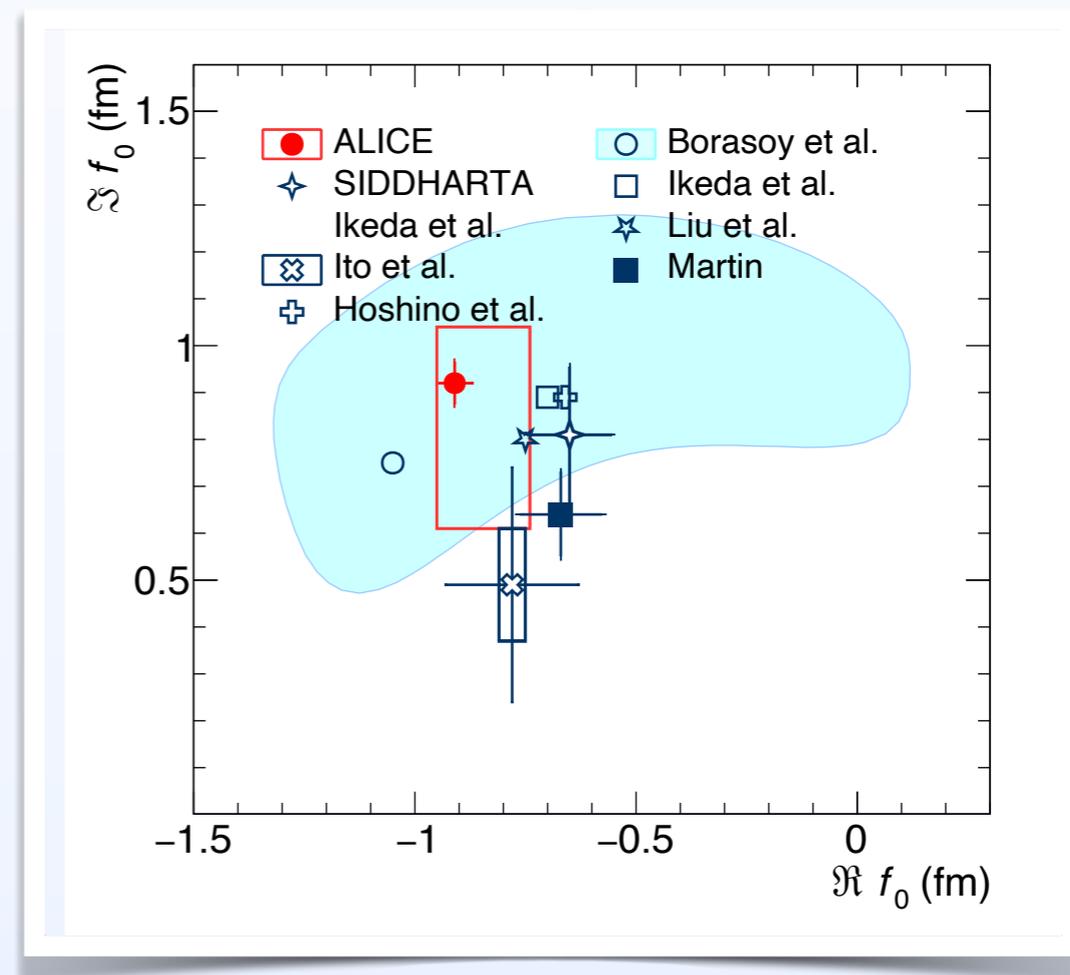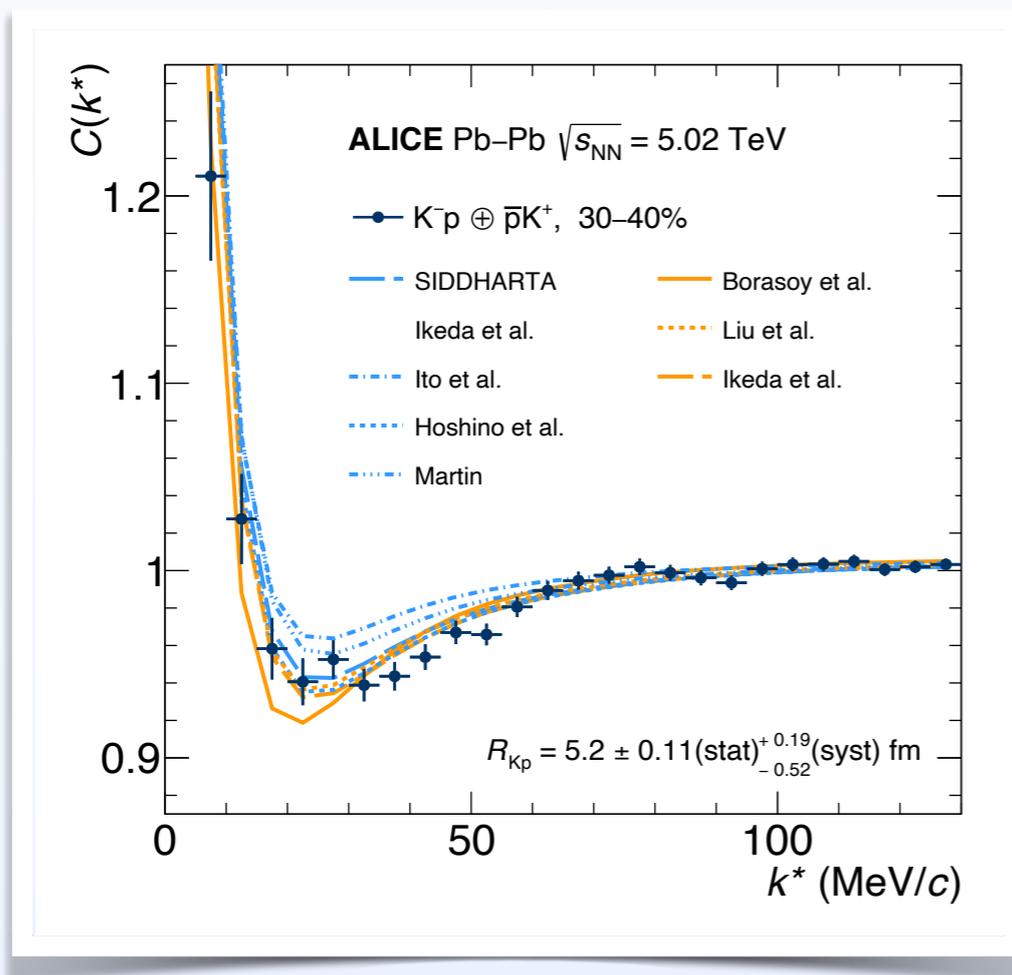
$K_S^0 p$ correlation

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

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

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

$KN, I = 0, 1$

- $I = 1$ component only
- Chiral amplitude

  Ikeda, Hyodo, Weise, NPA881 (2012)

- Effective potential

  Miyahara, Hyodo, Weise, PRC 98 (2018)
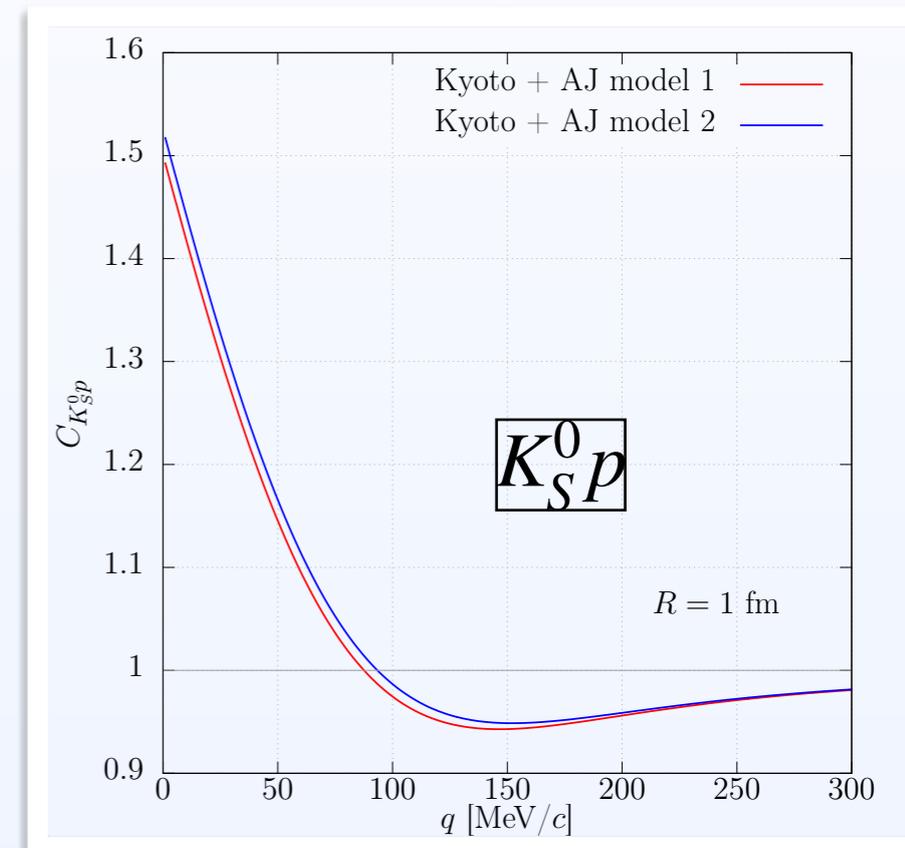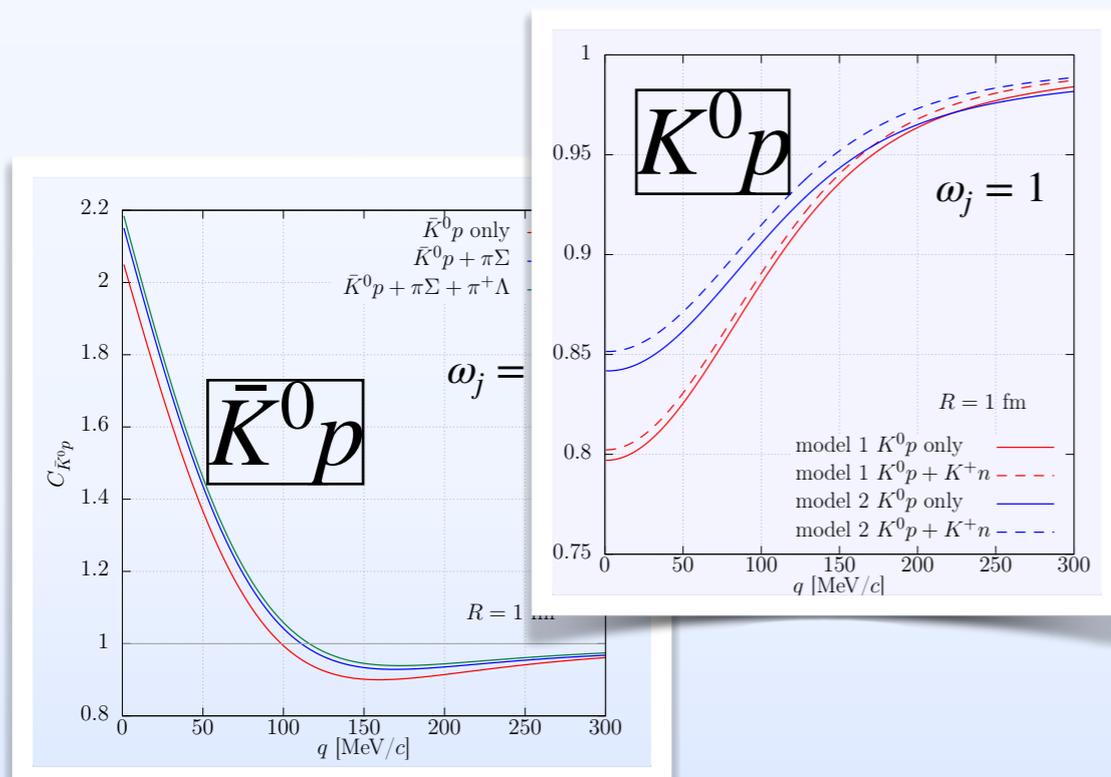
- Well determined with scat. exp.
- Chiral amplitude

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

- Effective potential

  Constructed from chiral amp.

$\bar{K}^0 p$

$K^0 p$

$K_S^0 p$

$R = 1$ fm

- Enhancement by $\bar{K}^0 p (\bar{K}N\ I = 1)$ is sizable.

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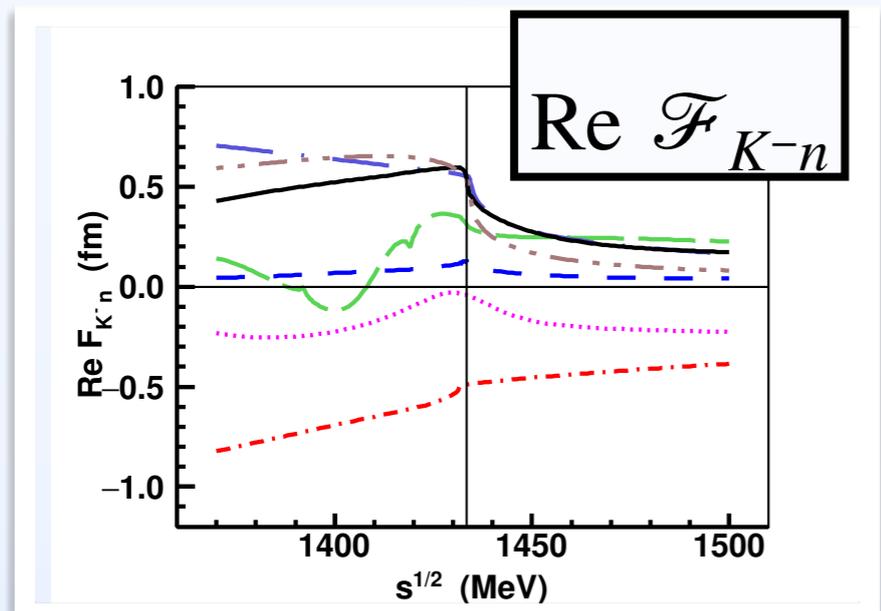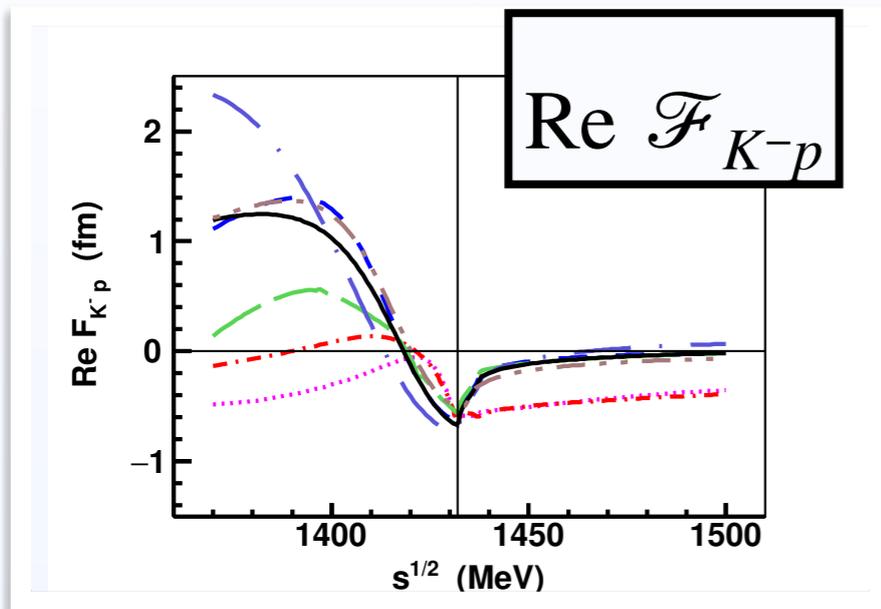# Contents

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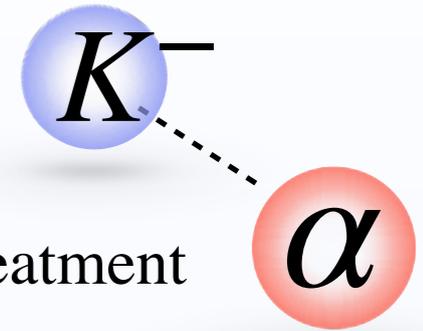
- $K^-\alpha$ correlation function

- Summary

$\bar{K}N$ interaction

- Large uncertainty remains in $I = 1$

Re $\mathscr{F}_{K^-n}$

$\bar{K}\alpha$ interaction

- Large binding energy of α
  —> • Good description by two body treatment

K^-

α

- $V_{\bar{K}\alpha}$ interaction

$$V_{K^-p} = \frac{1}{2}\left[V_{I=0} + V_{I=1}\right] \longrightarrow V_{\bar{K}\alpha} \sim \frac{1}{4}\left[V_{I=0} + 3V_{I=1}\right]$$

- Large $I=1$ contribution

- $^4_{\bar{K}}$H: bound state of $K^-\alpha$ system

- Predicted by the few body calculation
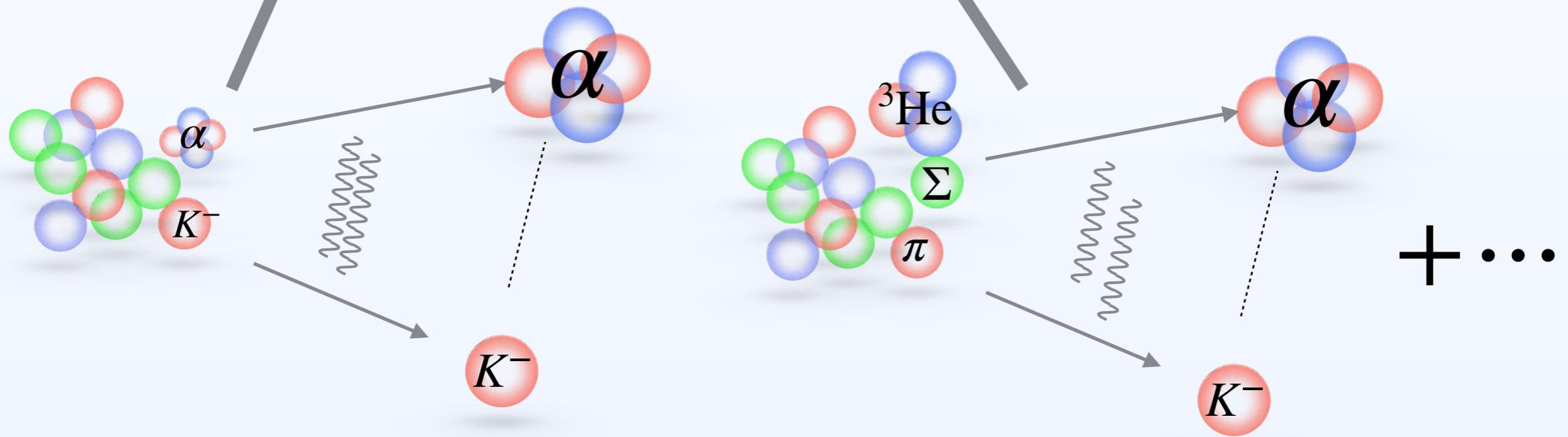- B, Γ: large uncertainty with the calculation/potential

TABLE V. Properties of the calculation for $^4_{\bar{K}}$He system with $J^\pi = 0^-$.

Model	$^4_{\bar{K}}$He ($J^\pi = 0^-$)		AY
	SIDDHARTA		
	Type I	Type II	
B [MeV]	67.9	72.7	85.2
Γ [MeV]	28.3	74.1	86.5

Cieply and Mai, EPJ Web Conf. 130, 02001 (2016)   S. Ohnishi, et al PRC95, 065202 (2017)

$K^-\alpha$ correlation

- Coupled-channel Source effect?

• Coupled-channel KP formula

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

$+\cdots$

• Coupled-channel source: considered to be negligible

• Decay effect → introduced via optical complex $\bar{K}N$ potential

$K^-\alpha$ correlation

- ### $\bar{K}\alpha$ potential with chiral $\bar{K}N$ potential

- Chiral base $\bar{K}N$ potential

  Miyahara, Hyodo, PRC 93, 015201 (2016)

  $$V_{\bar{K}N}^{\text{Kyoto}}(r, E) = e^{-(r/b)^2} C(E) \sum_{\alpha=0}^{\alpha_{\max}} K_\alpha (E/100 \text{ MeV})^\alpha$$

  - Fitted to the low-energy $\bar{K}N$ chiral amplitude of chiral unitary model
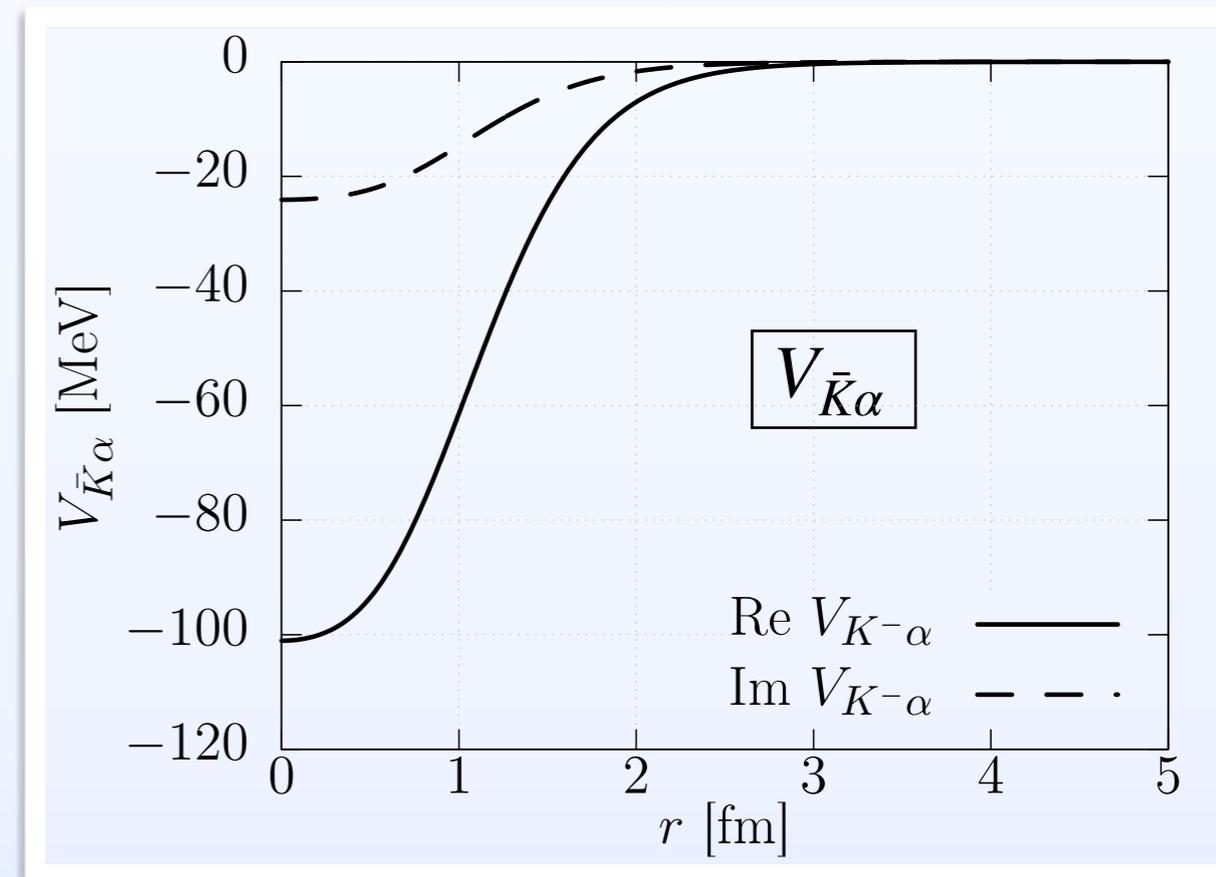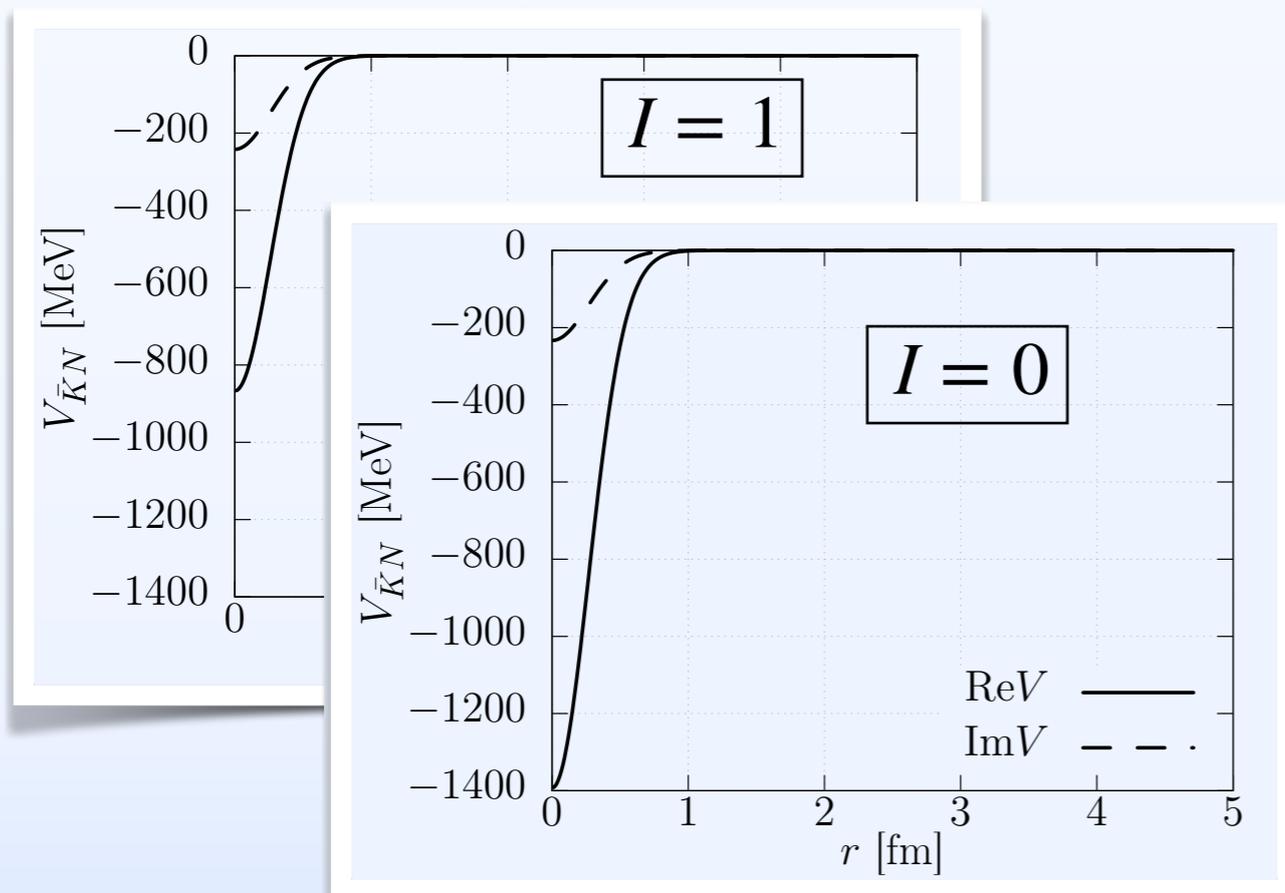
    Ikeda, Hyodo, Weise, NPA881 (2012)

  - Energy dependent and complex potential

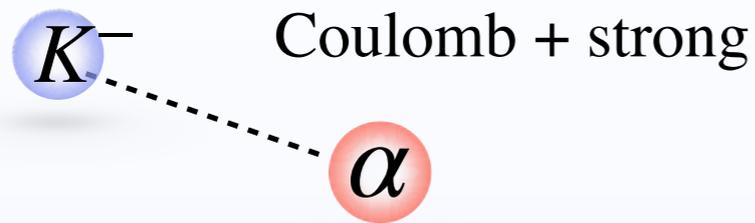- Folding $\bar{K}\alpha$ potential

  $$V_{\bar{K}\alpha}(\mathbf{r}) = \int d\mathbf{r}' \rho_N(\mathbf{r}') \frac{1}{4} \left[V_{I=0}(|\mathbf{r} - \mathbf{r}'|) + 3V_{I=1}(|\mathbf{r} - \mathbf{r}'|) \right]$$

  - Potential is dilated by the nuclear distribution $\rho(r)$
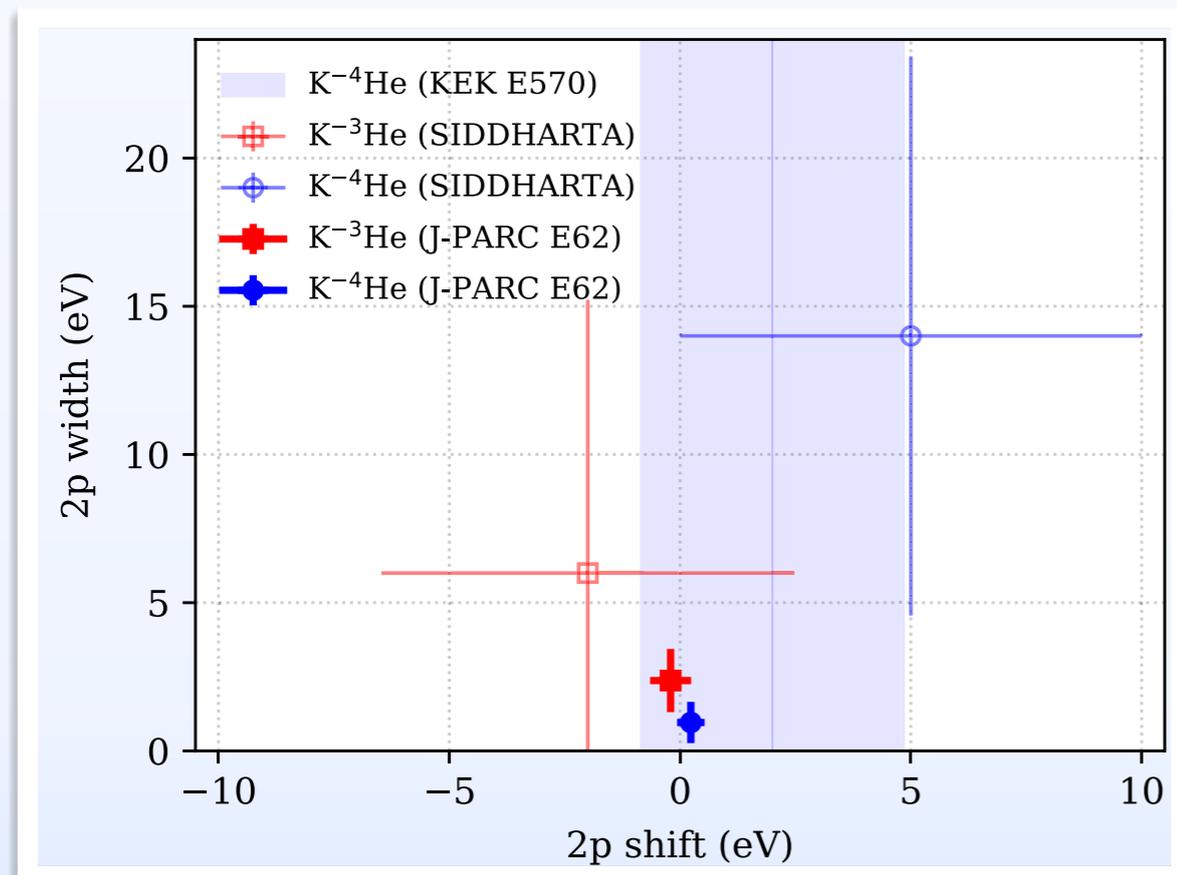

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$K^-\alpha$ correlation

○ Phenomenological optical $\bar{K}$-atom potential

K^- Coulomb + strong

α

● J-PARC E62 data of energy level
  shift and width K^{-3}He and K^{-4}He

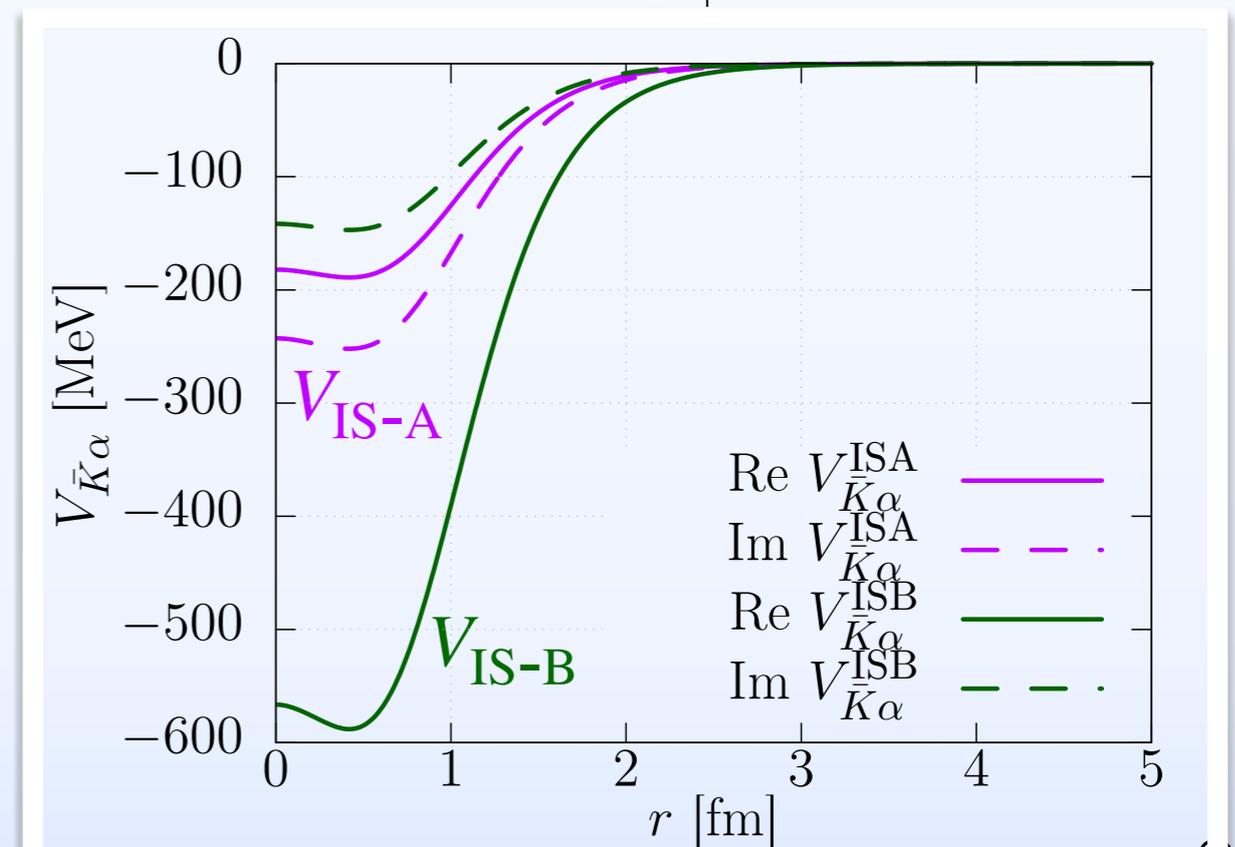T. Hashimoto et al. [J-PARC E62], PRL 128, 112503 (2022)

● Fitted optical $\bar{K}$-atom potential (strong int.)

J.Yamagata-Sekihara et al., PTEP 013D02 (2025)

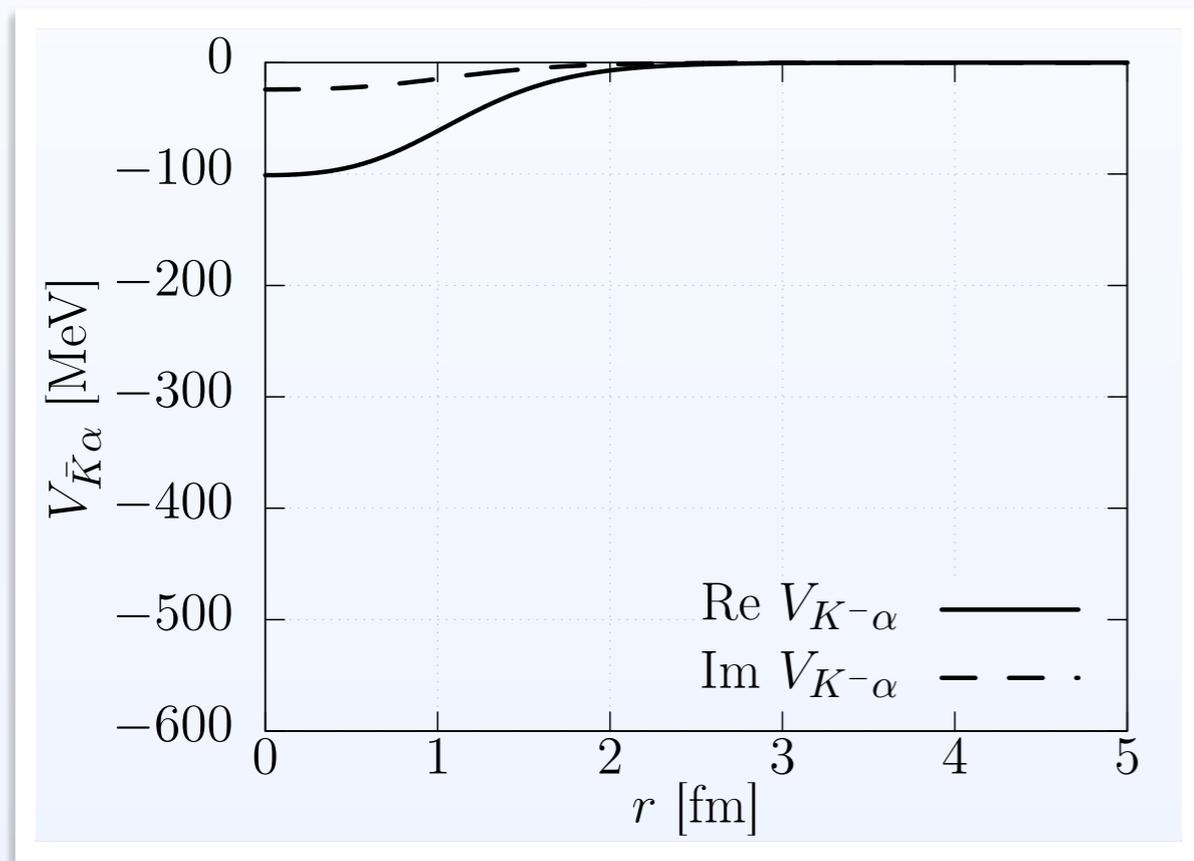$$U(r) = \left(V_0 + iW_0\right)\frac{\rho_N(r)}{\rho_0}$$

$V_0,\ W_0$: Fitted to E62 data

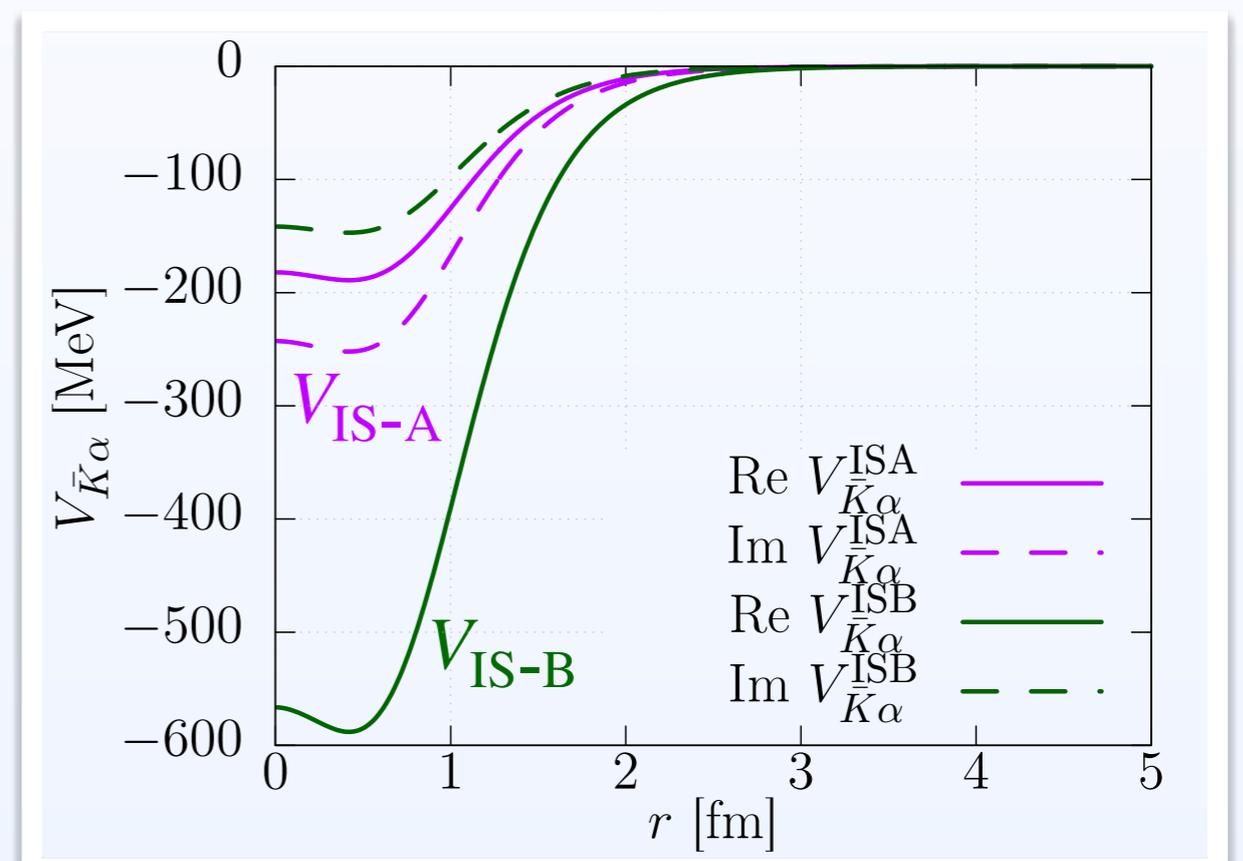| potential	V_0	W_0
IS–A	-90	-120
IS–B	-280	-70

$K^-\alpha$ correlation

- ## Comparison of V_{folding} and $V_{\text{Pheno.}}$

- Chiral based folding $\bar{K}\alpha$ potential

- Fitted optical $\bar{K}$-atom potential

J.Yamagata-Sekihara et al., PTEP 013D02 (2025)

- Large difference between the two potentials
  —> How $C(q)$ differs?

$K^-\alpha$ correlation

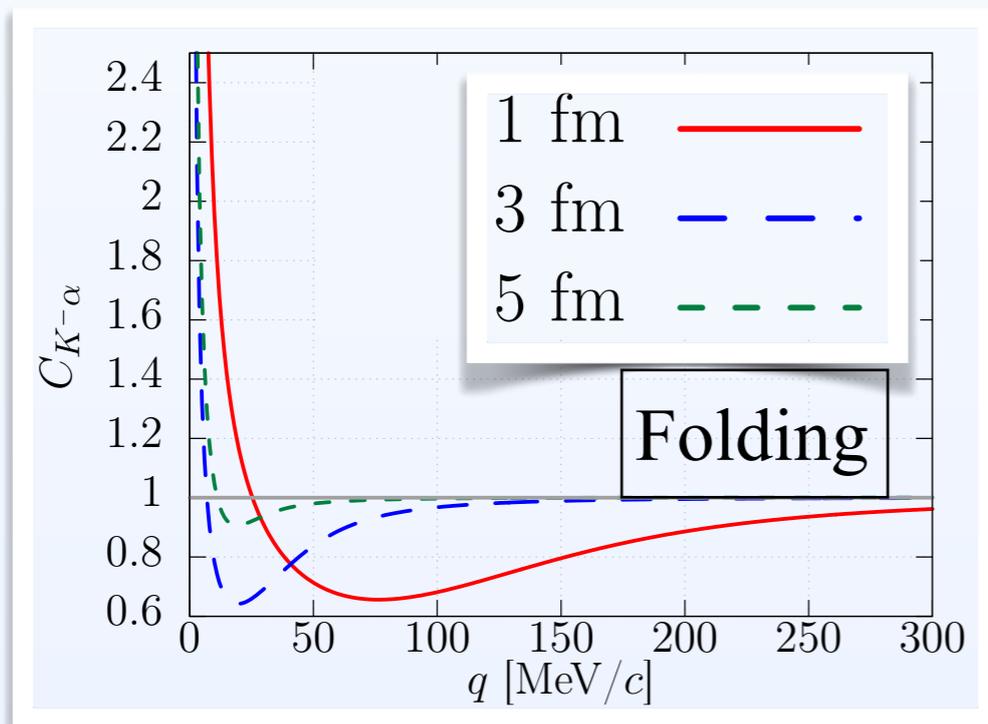## $K^-\alpha$ correlation function

- Koonin-Prat foramula analysis
  - Solve Schrödinger equation
  $$V_{\bar{K}\alpha} + V_C \xrightarrow{r\,[\text{fm}]} \varphi_{\bar{K}\alpha}$$
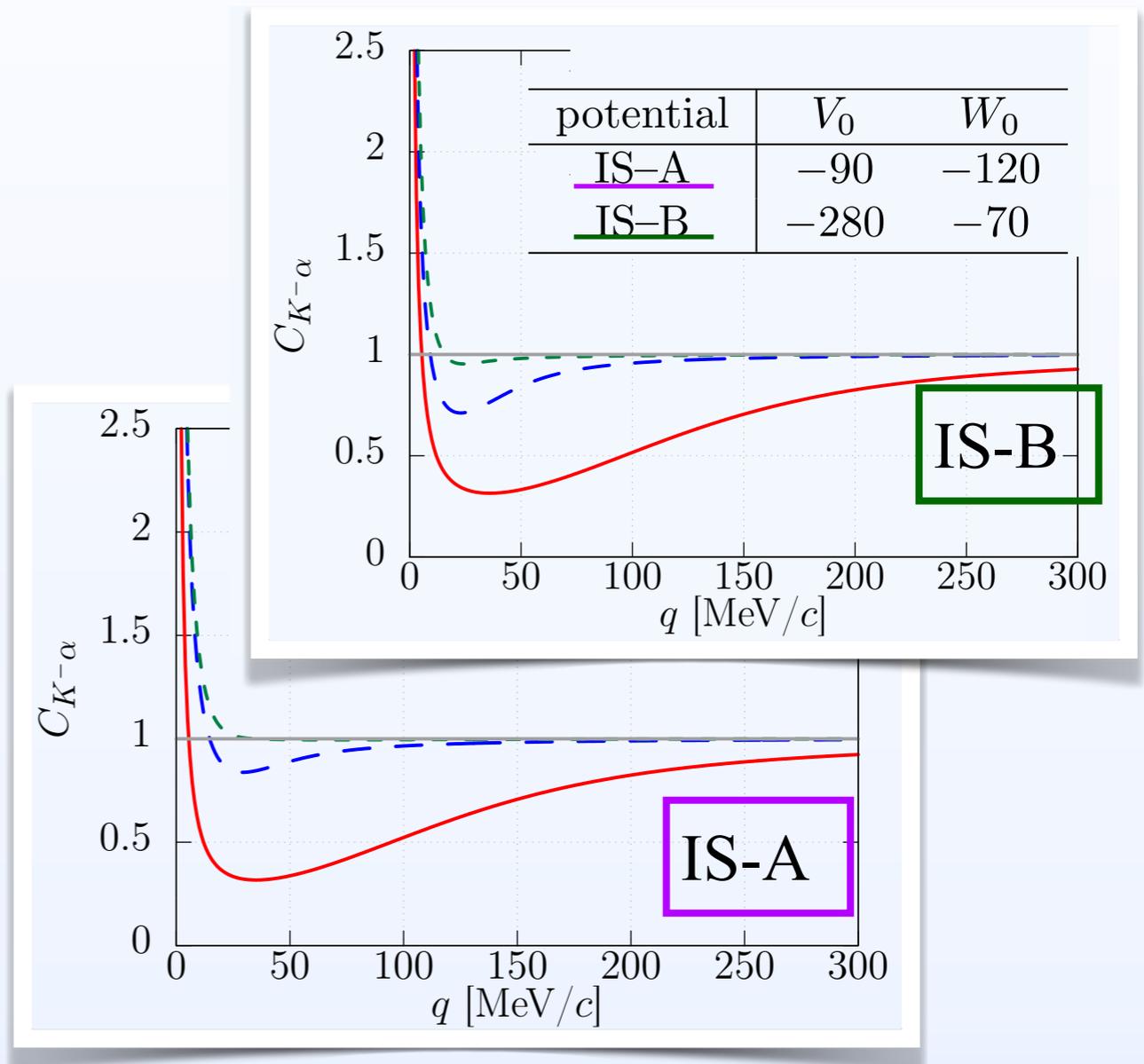 - $C(q)$ model with KP formula
  $$C(\mathbf{q}) = \int d^3\mathbf{r}\; S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2$$

- Chiral folding potential

- Phenomenological optical $\bar{K}$-atom potential

potential	V_0	W_0
IS–A	-90	-120
IS–B	-280	-70

Re $V_{\bar{K}\alpha}^{\text{ISA}}$
Im $V_{\bar{K}\alpha}^{\text{ISA}}$
Re $V_{\bar{K}\alpha}^{\text{ISB}}$
Im $V_{\bar{K}\alpha}^{\text{ISB}}$

1 fm
3 fm
5 fm

Folding

IS-B

IS-A

- Significant difference between C_{Folding} and C_{Pheno} for every source size!

$K^+\alpha$ correlation

- ## $K\alpha$ folding potential with chiral unitary KN potential

- Chiral base KN potenital

$$V_{KN}(r, E) = e^{-(r/b)^2} C(E) \sum_{\alpha=0}^{\alpha_{max}} K_\alpha (E/100 \text{ MeV})^\alpha$$
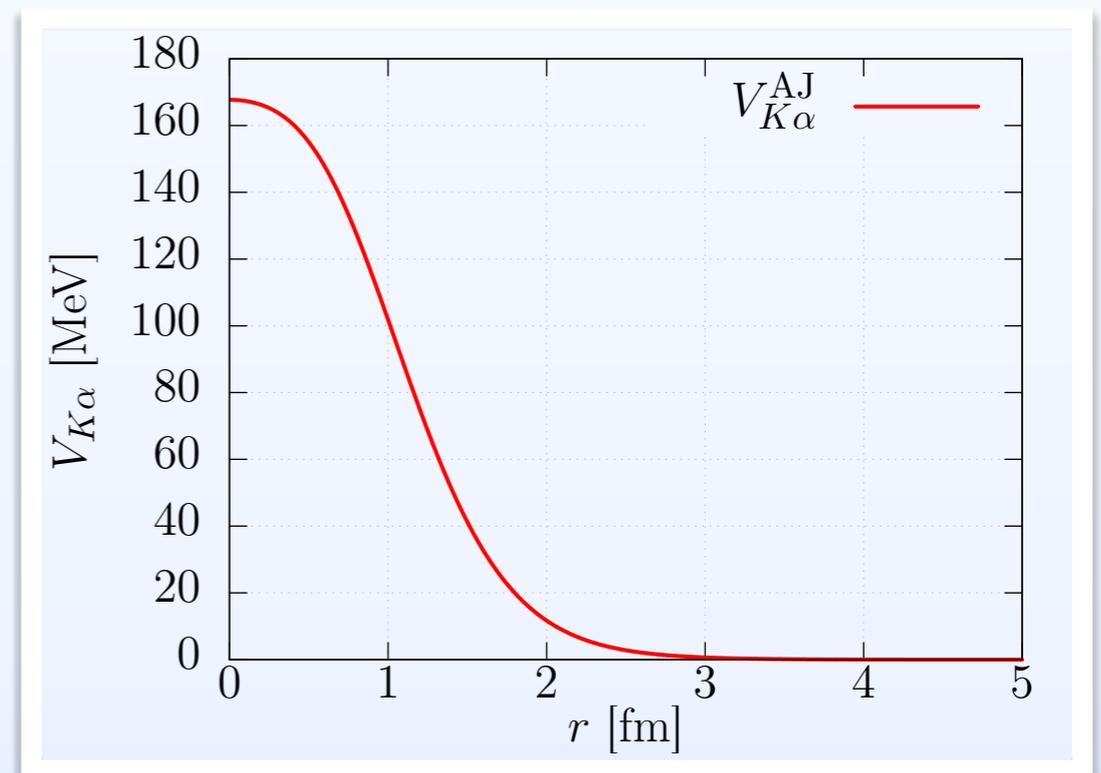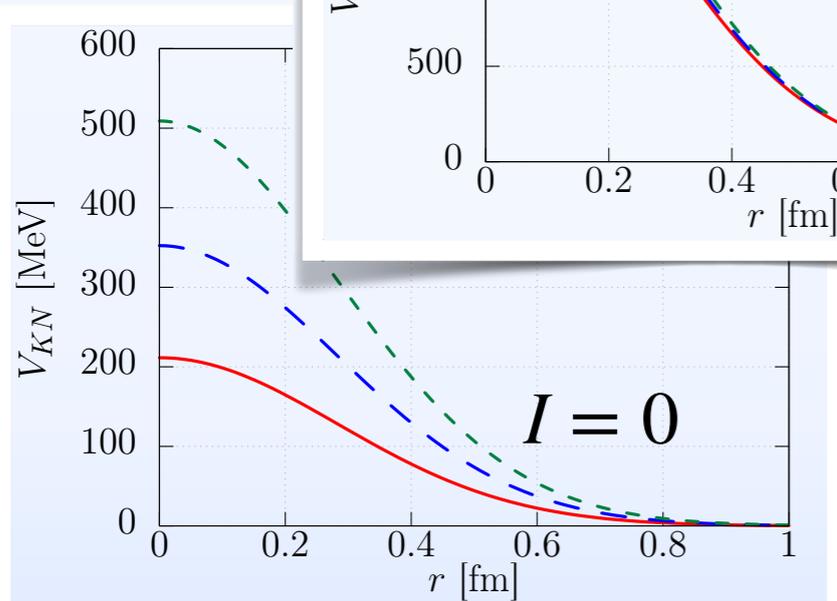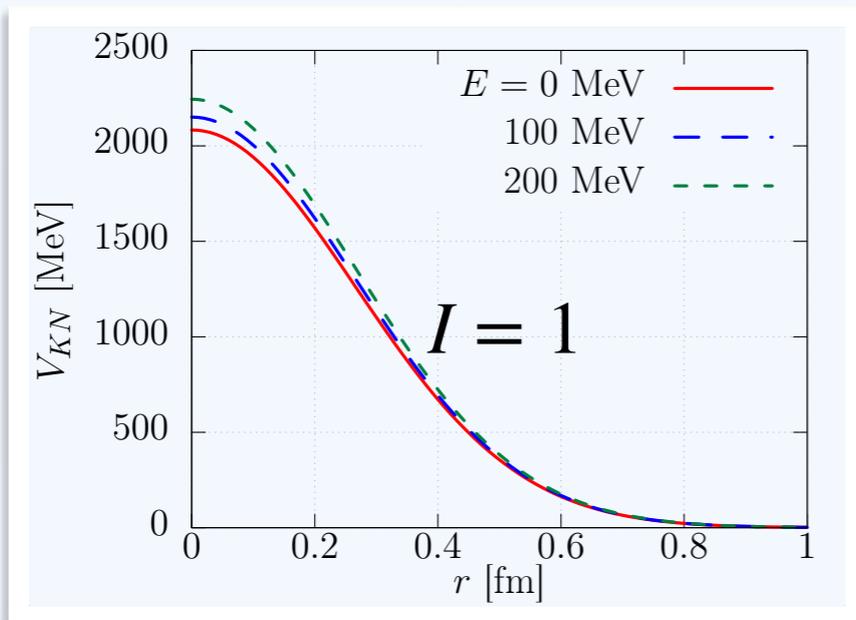
  - Fitted to the low-energy KN chiral amplitude of chiral unitary model

    K. Aoki and D. Jido, PTEP 2019, 013D01 (2019)

- Folding $K\alpha$ potential

$$V_{K\alpha}(\mathbf{r}) = \int d\mathbf{r}' \rho_N(\mathbf{r}') \frac{1}{4} \left[V_{I=0}(|\mathbf{r} - \mathbf{r}'|) + 3V_{I=1}(|\mathbf{r} - \mathbf{r}'|) \right]$$

  - Potential is dilated by the nuclear distribution $\rho(r)$
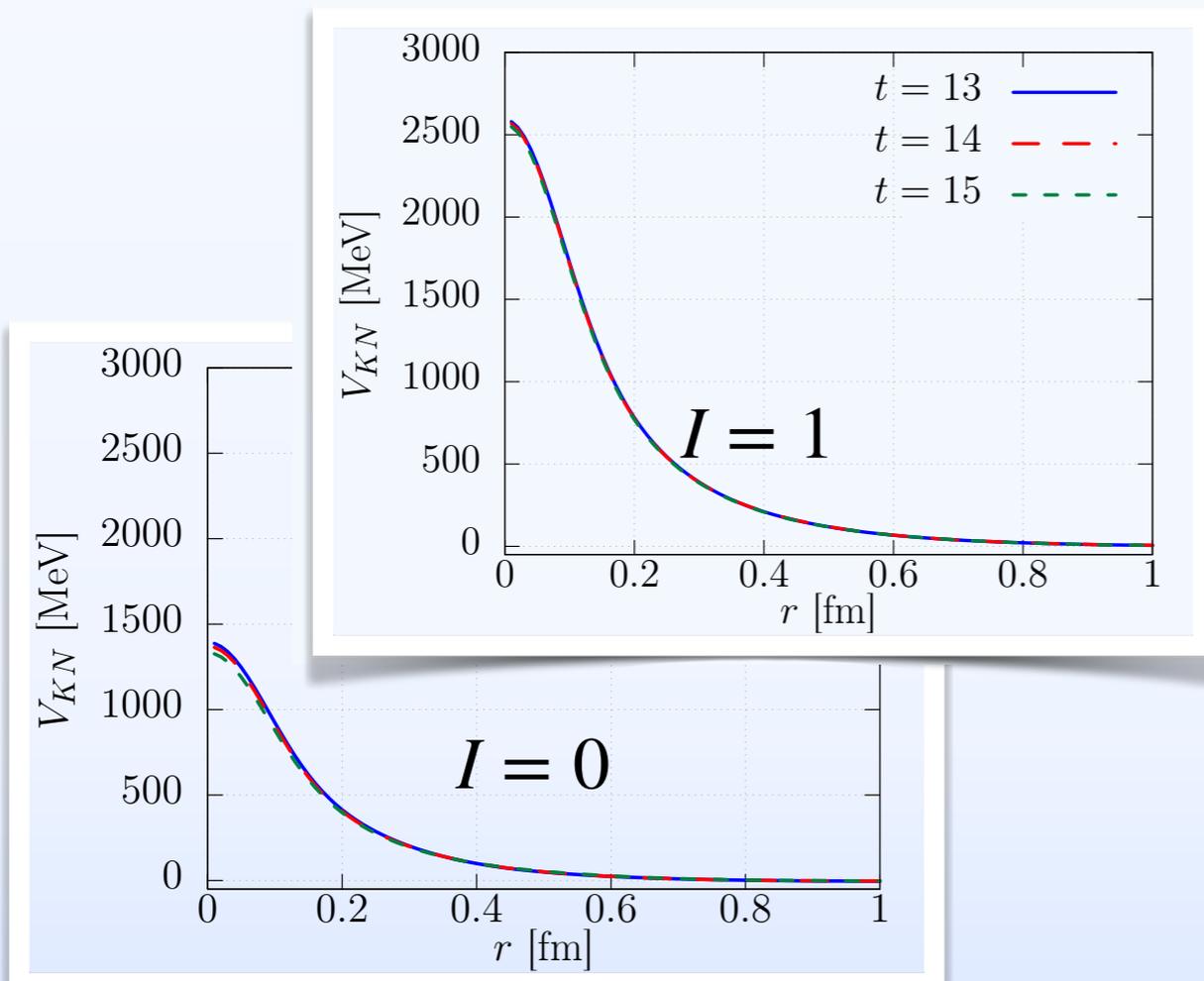

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$K^+\alpha$ correlation

- *$K\alpha$* folding potential with lattice QCD *KN* potential
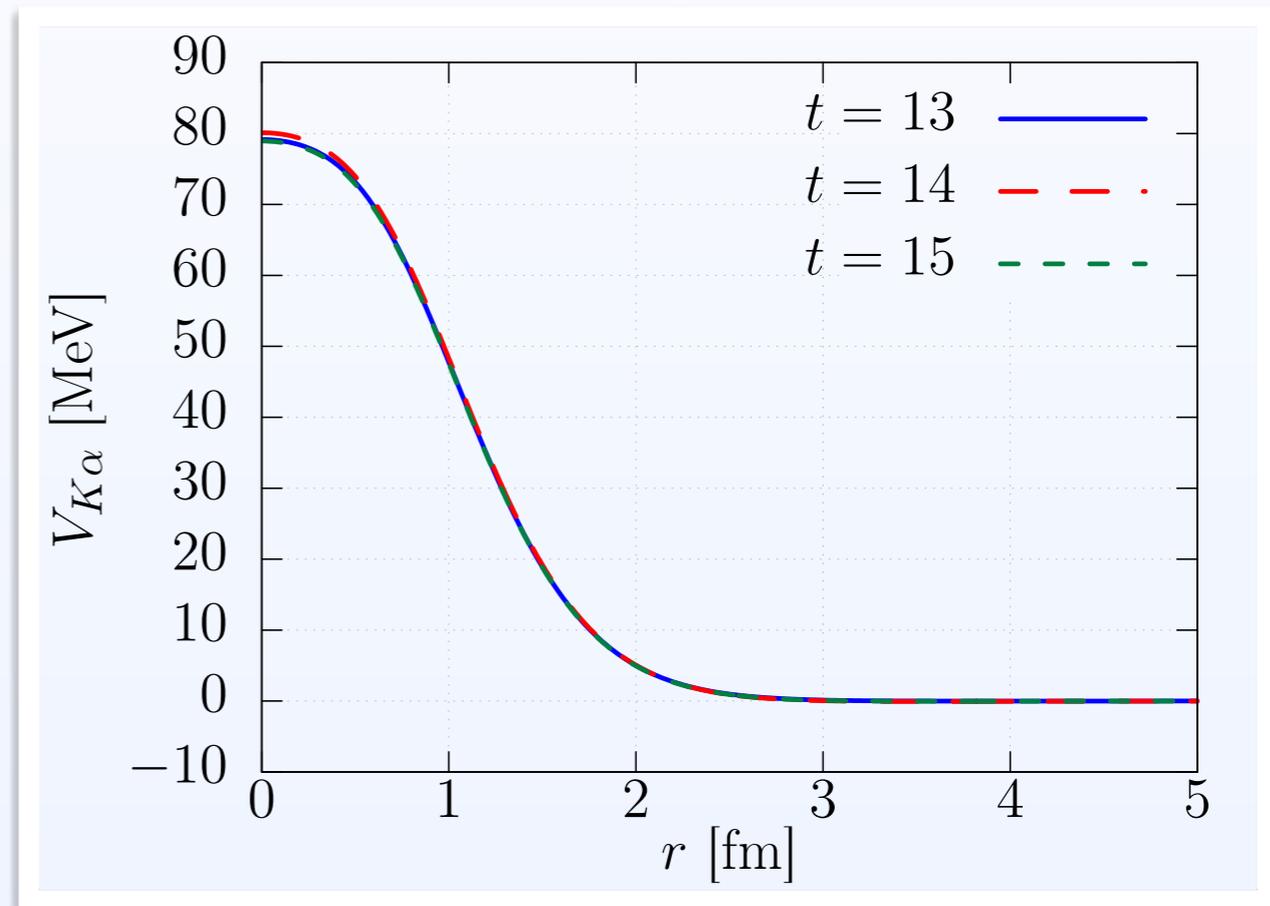
● HAL QCD *KN* potential

● Folding *$K\alpha$* potenital

$$V_I^{4G}(r) = \sum_{i=1}^{4} a_i^I \exp\left(-r^2/b_i^{I^2}\right)$$

● Weaker repulsion compared to chiral model
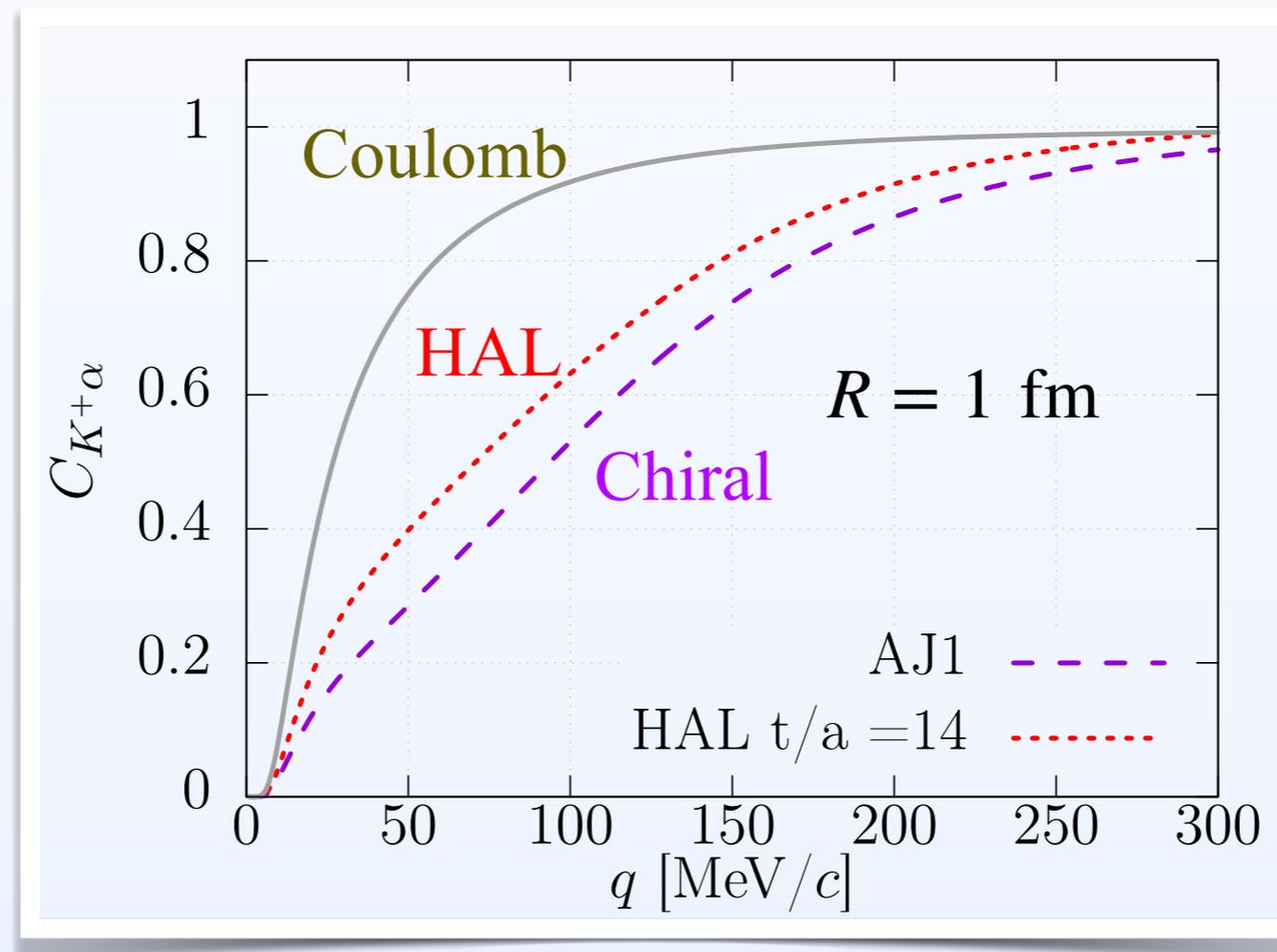
$K^+\alpha$ correlation

- ## $K^+\alpha$ correlation function

  • Sizable suppression by the strong interaction
    —> Good observable to determine the source size

  • HAL folding potential: weaker signal compared to Chiral model

Summary

- Femtoscopy: new tool for the hadron interaction
  - Useful for the strangeness/charm sector
  - Sensitive to the low-energy interaction

- K^-p correlation function
  - Strong source size dependence due to $\Lambda(1405)$ quasibound state
  - Coupled-channel source effect for small source data
  - Good agreement with the chiral dynamics model $C(q)$

- $K^-\alpha/K^+\alpha$ correlation function
  - Large difference between the chiral folding potential and phenomenological optical potential
  - $C_{K^-\alpha}(q)$ shows significant signal with strong dependence on R for both potential models.
  - $C_{K^+\alpha}(q)$ useful for determine the source

Thank you for your attention!

Thank you!