Yuki Kamiya
HISKP, Bonn Univ.

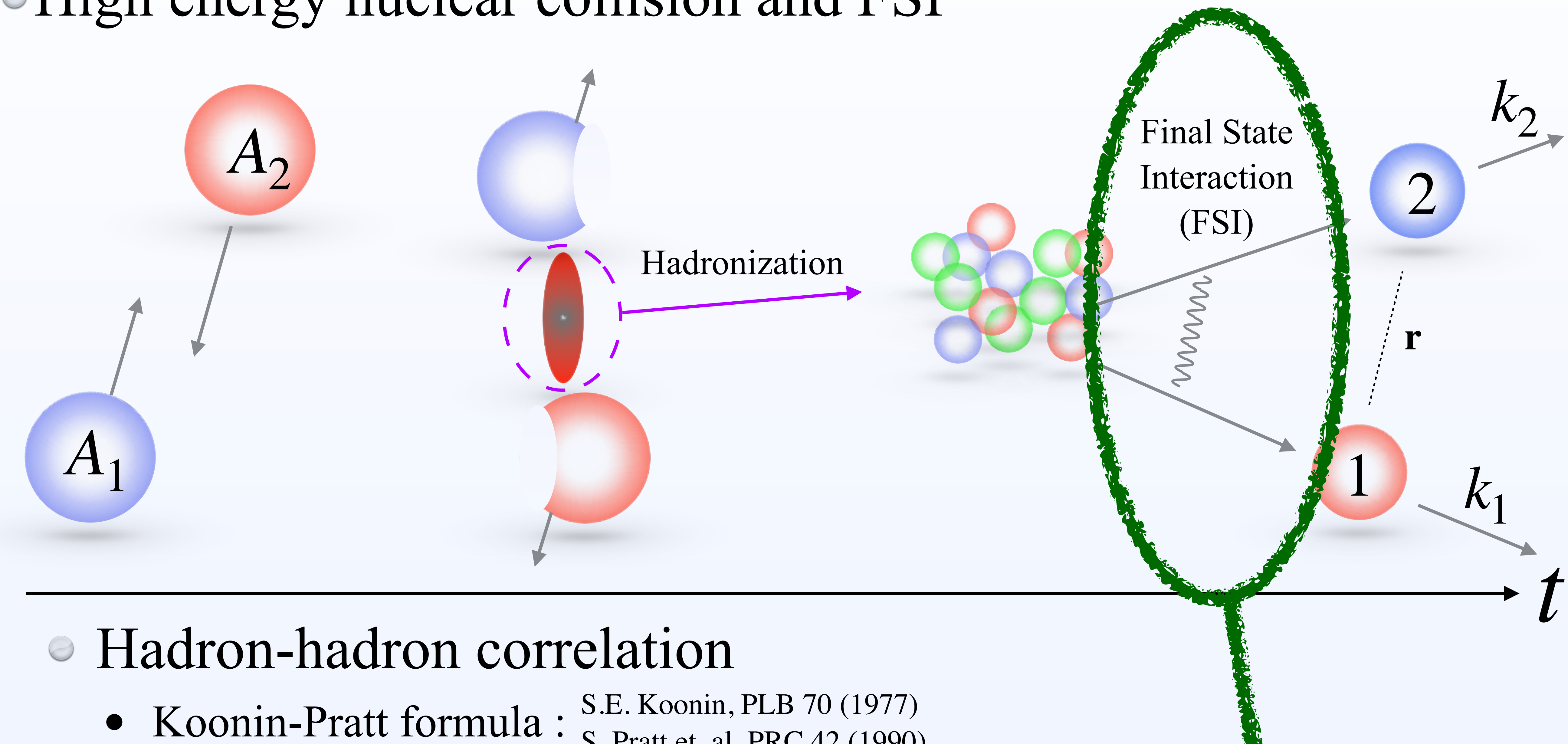
Femtoscopic studies of meson-baryon and baryon-baryon pairs with strangeness

ROCKSTAR(Towards a ROadmap of the Crucial measurements of Key observables in Strangeness reactions for neutron sTARs equation of state)

@ECT*, October 13th, 2023

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



- 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

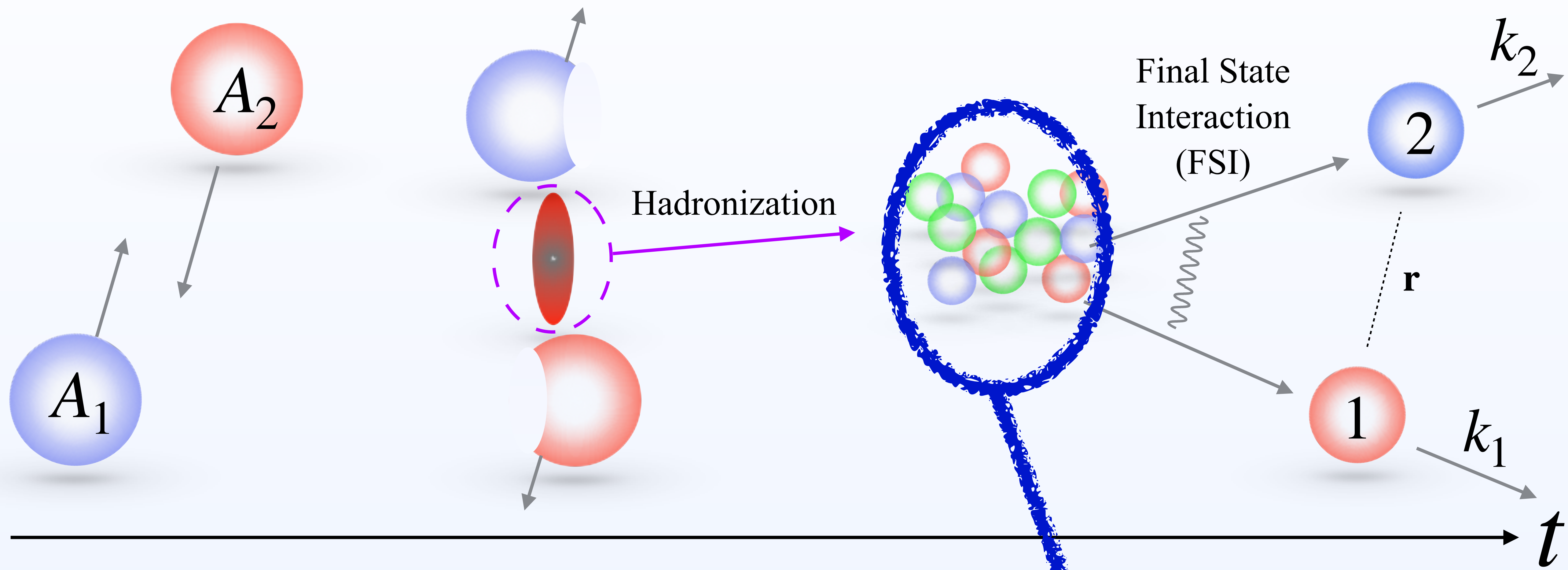
- Depends on …

  Interaction (strong and Coulomb)

  quantum statistics (Fermion, boson)

Hadron correlation in high energy nuclear collision

High energy nuclear collision and FSI



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 …

  Collision detail (A_i, energy, centrality)

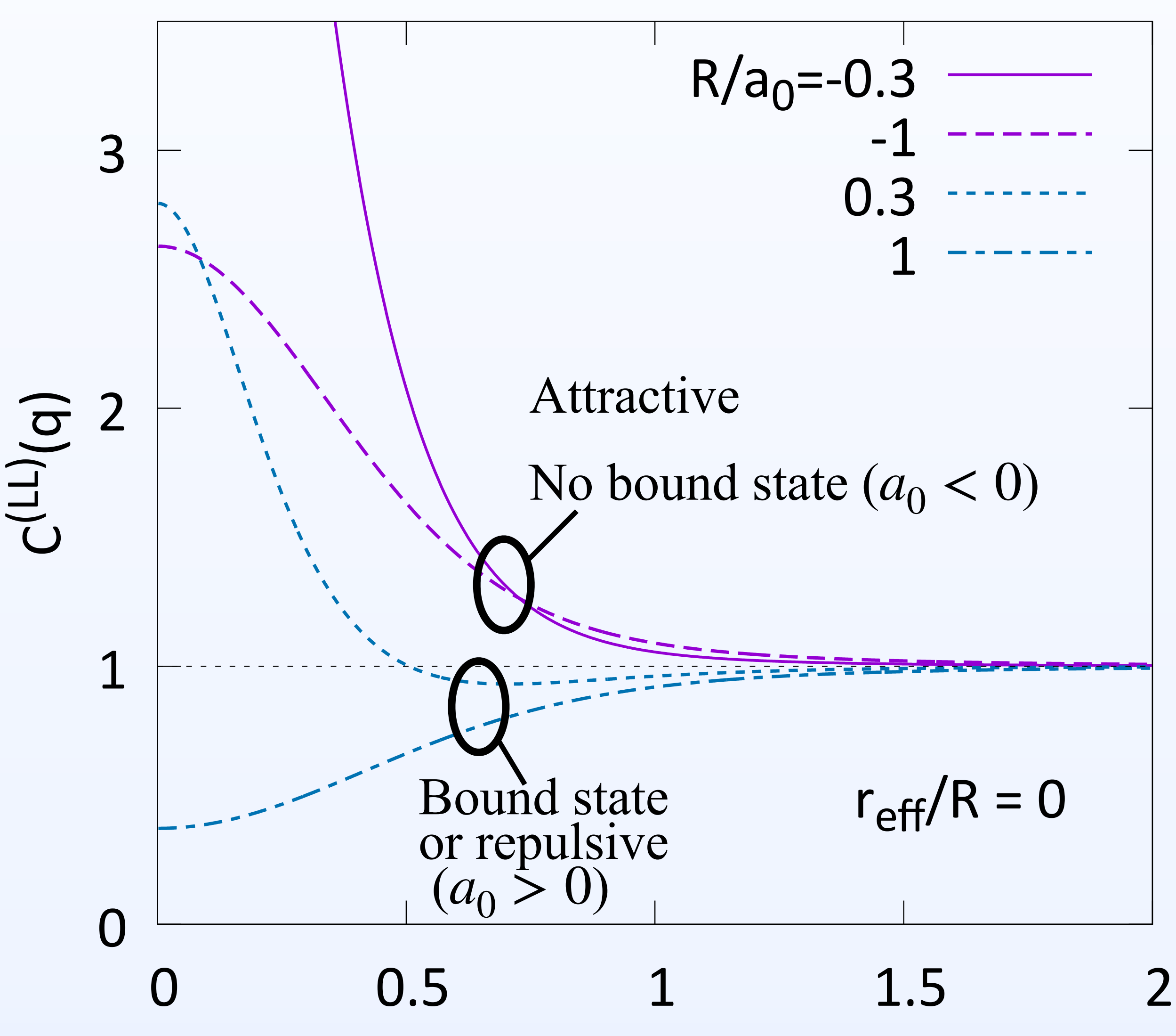
- Including information of…

  size of hadron source,

  momentum dependence, weight…

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

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



Morita, et al., PRC101 (2020)

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

- Repulsive int. ($a_0 > 0$, small $|a_0|$)

  ⇒ Suppressed $C(q)$

- Attractive int. w/ bound state ($a_0 > 0$, large $|a_0|$)

  ⇒ Suppressed $C(q)$ for Large R
  Enhanced $C(q)$ for small R

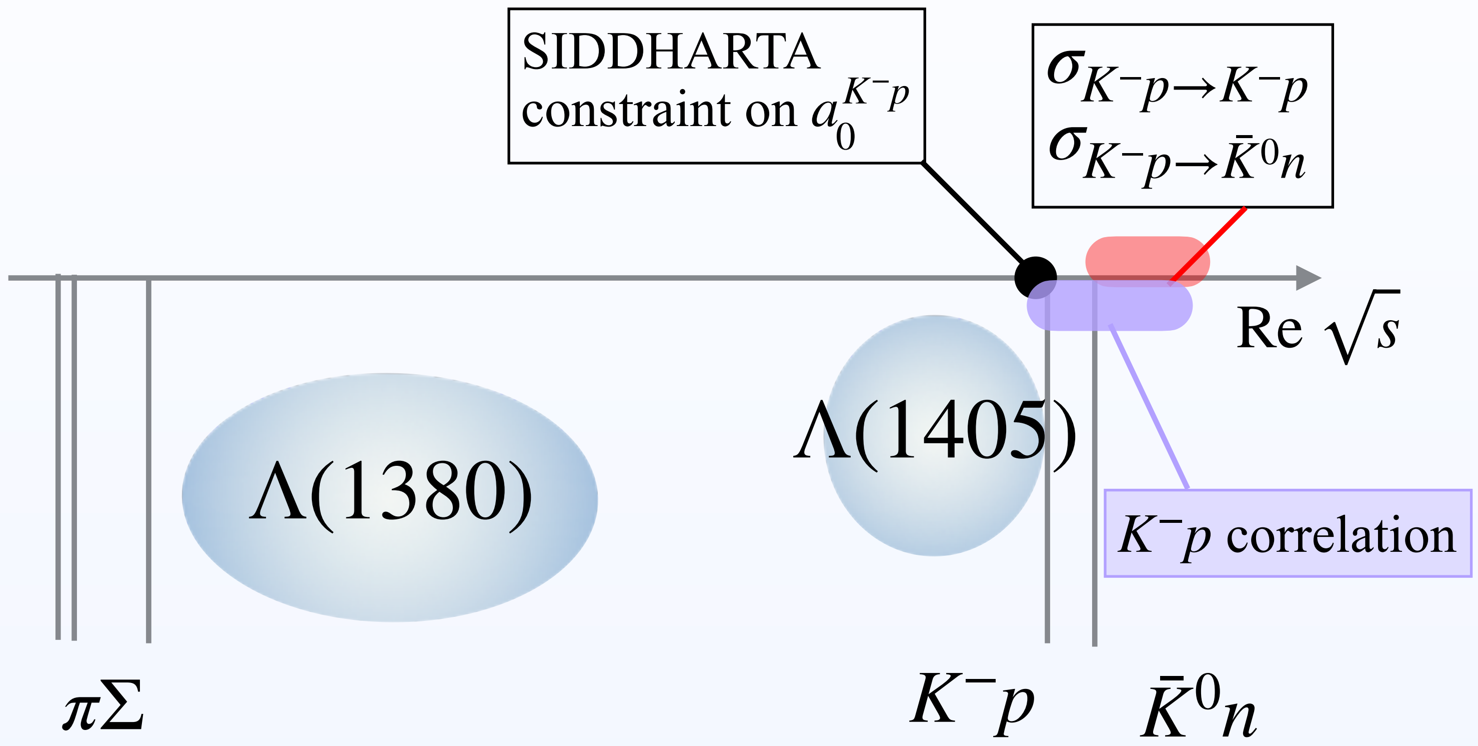
- Attractive int. w/o bound state ($a_0 < 0$)

  ⇒ Enhanced $C(q)$

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

$\bar{K}N$ 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 $\Lambda(1405)$ and $\Lambda(1380)$
  - two pole structure
    J. A. Oller and U. G. Meißner, PLB500, 263 (2001)
  - $\bar{K}N$ molecular picture
    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
  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

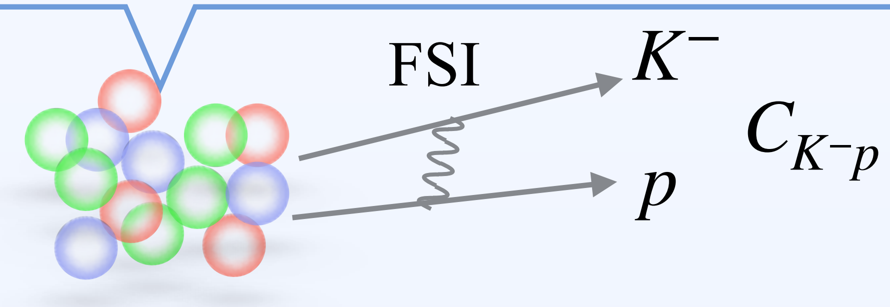
- Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula

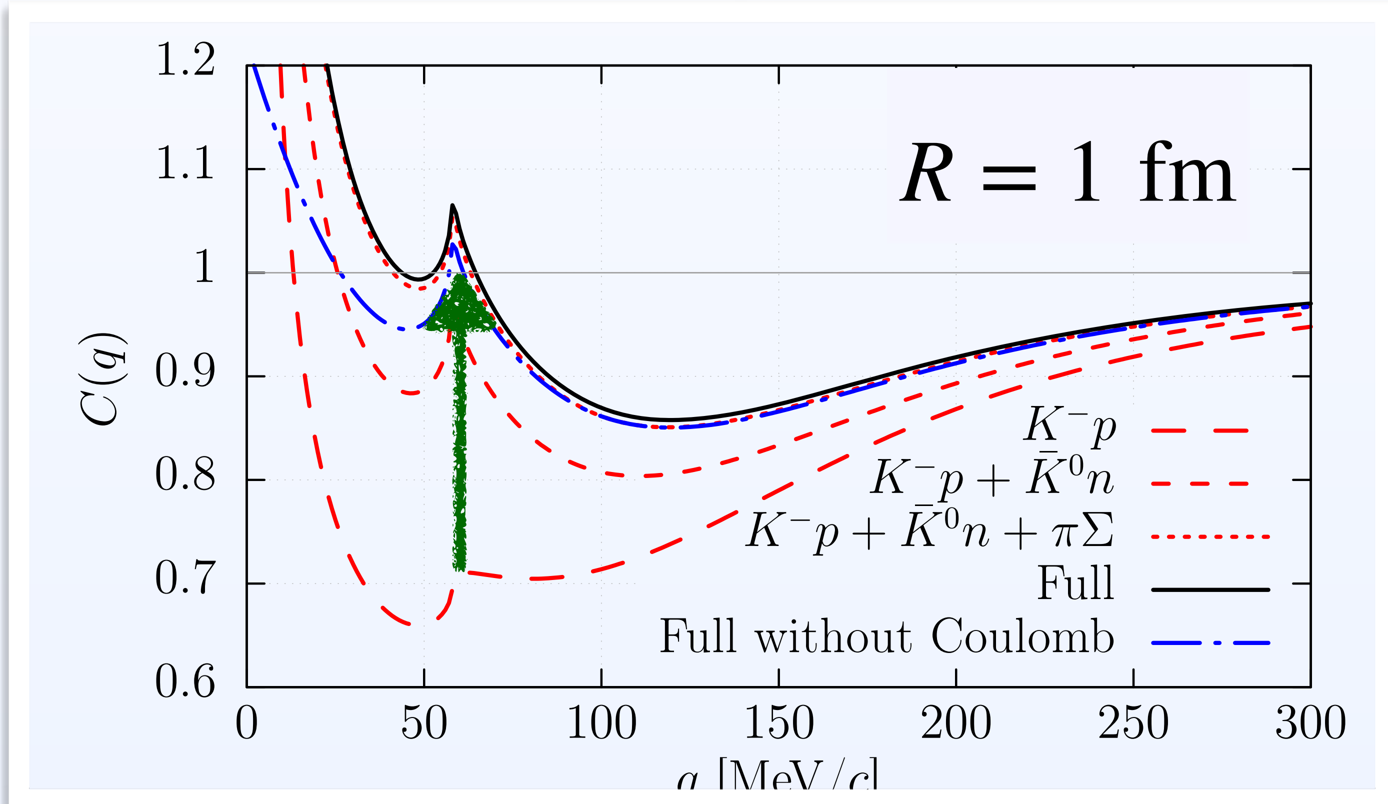
$$C(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r})\,|\psi^{(-)}(q;r)|^2 + \sum_{j\neq i} \omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{(-)}(q;r)|^2$$

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

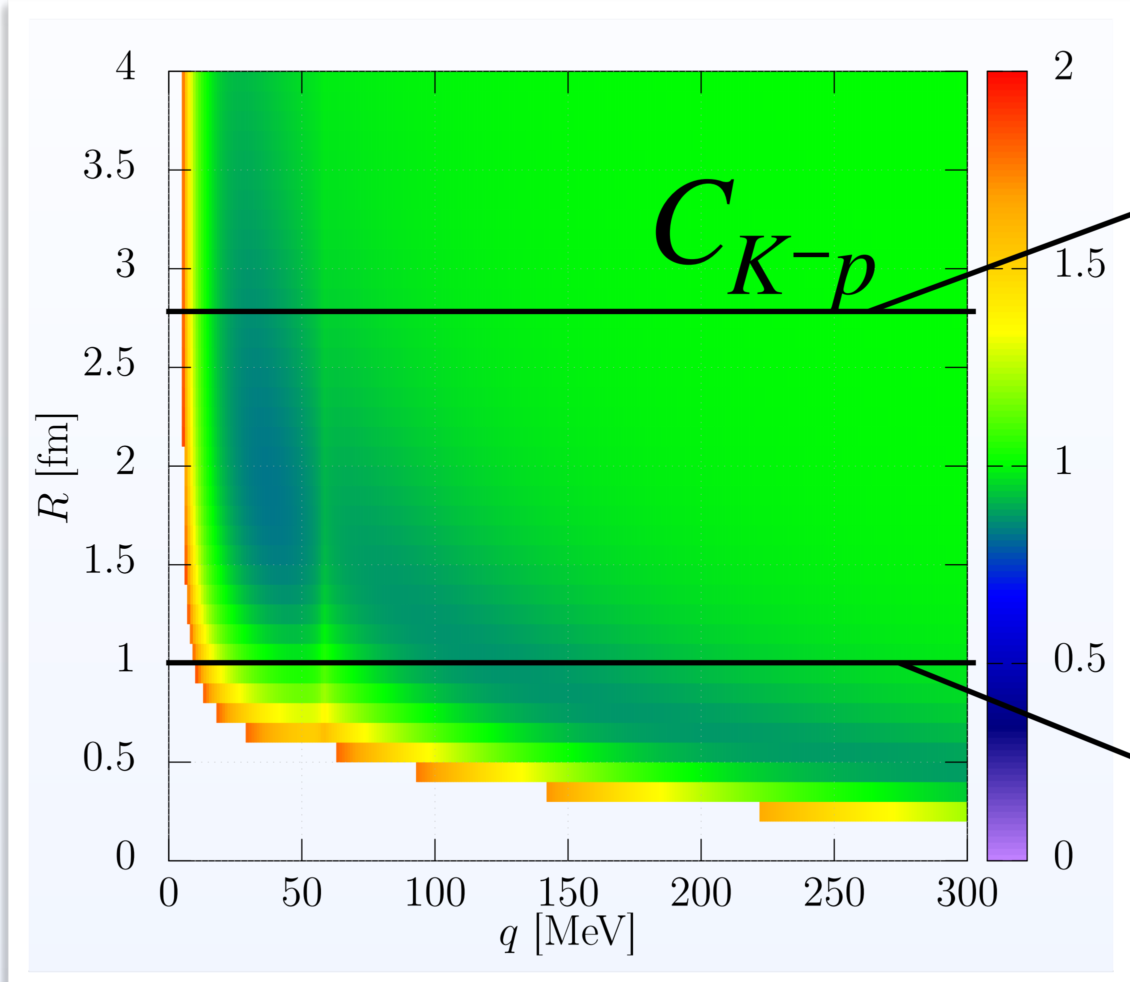


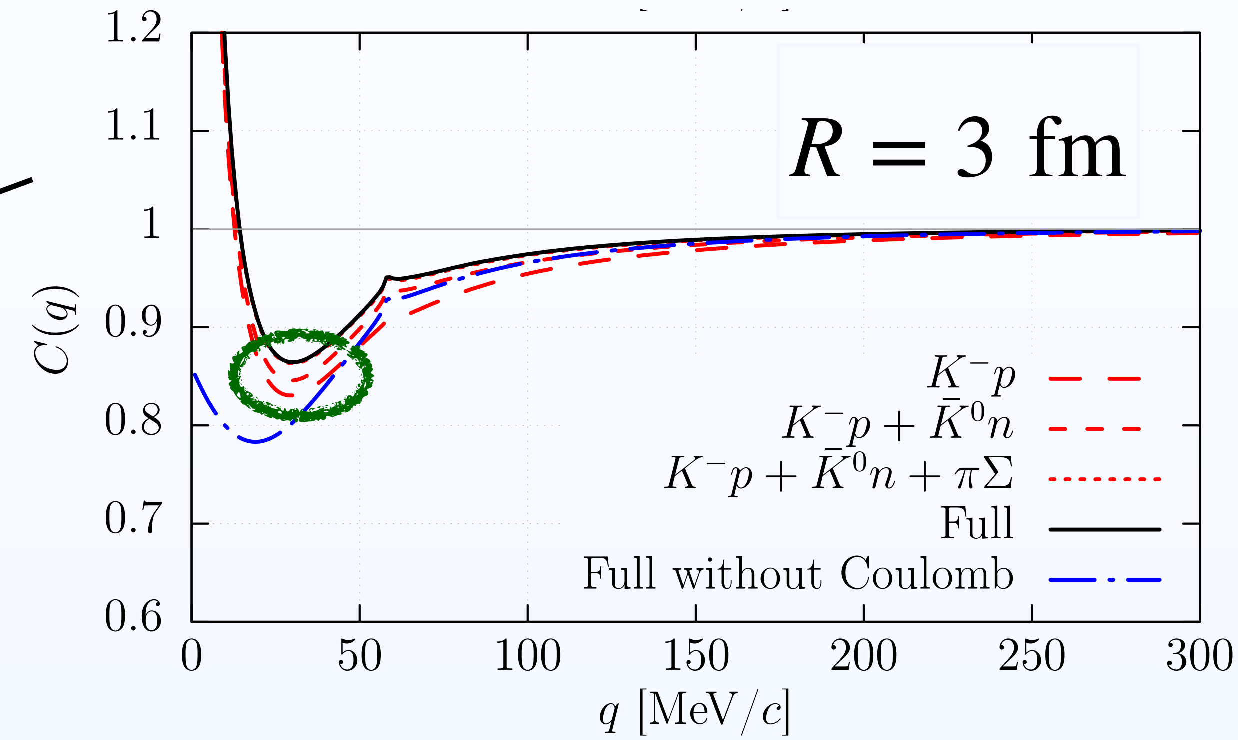


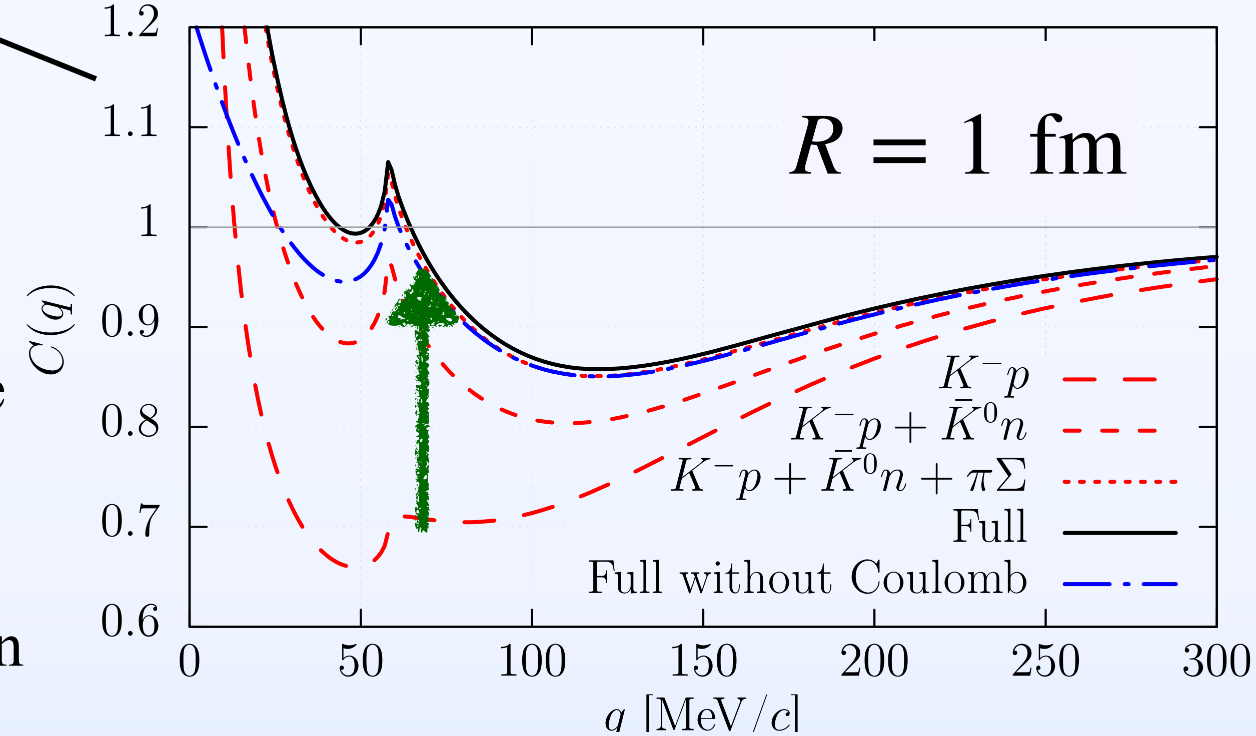
- Enhance $C(q)$
- Enhance cusp structure
- ω_i : production rate (compared to measured channel)

Coupled-channel effect

- Source size dependence of coupled-channel effect







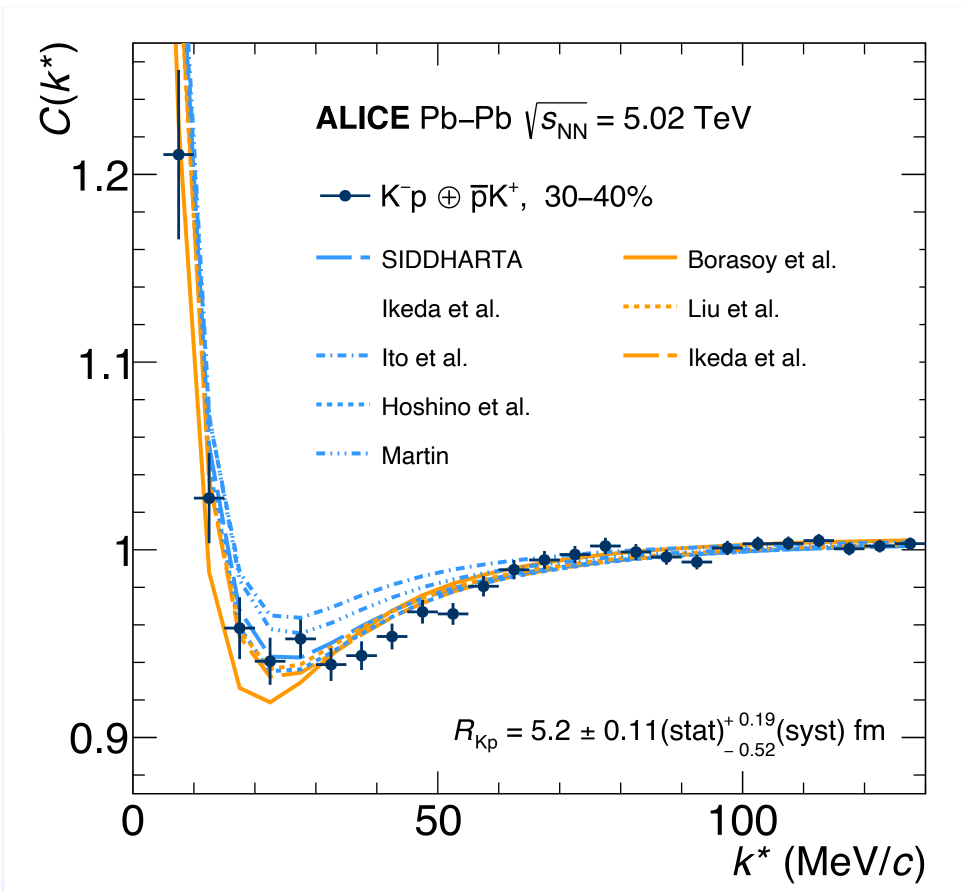
- Strong source size dependence
  <== Due to the near-threshold Λ(1405) pole
- $C(q)$ with large source
  - Less prominent cusp structure
  - Weaker coupled-channel source contribution

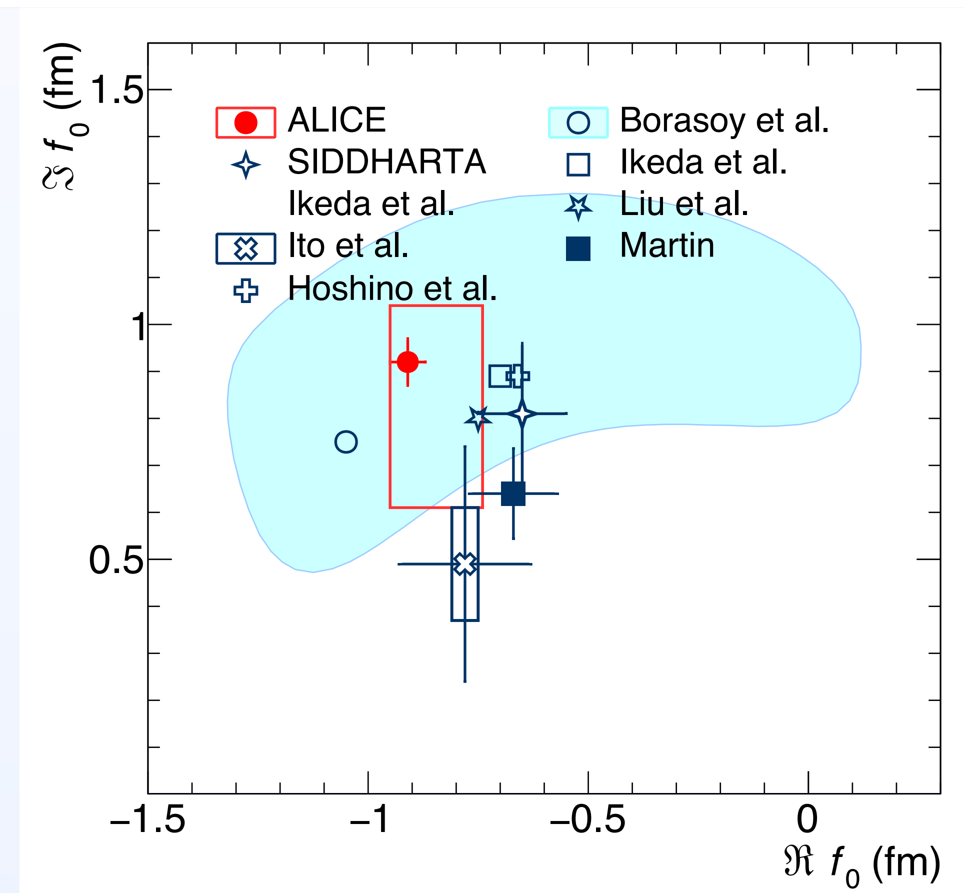
•Large source：K^-p scattering

•Small source：detailed coupled-channel effect

Coupled-channel effect

- $K^{-}p$ 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





Coupled-channel effect

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

  ALICE, EPJC 83 (2023)

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

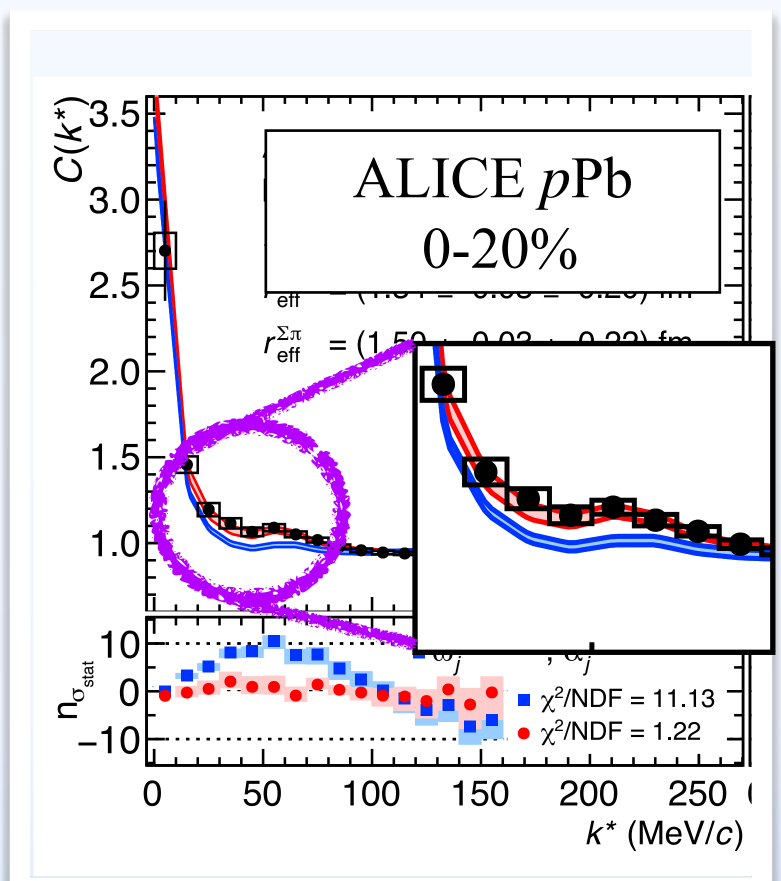
- Discrepancy around $\bar{K}^0 n$ threshold between chiral SU(3) model and exp. data for small source data

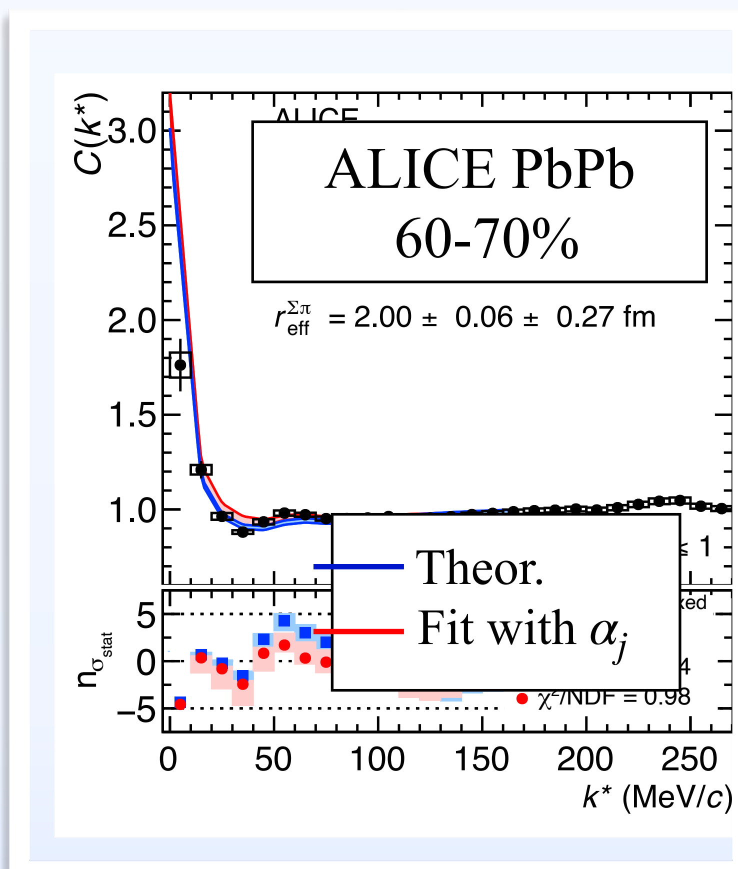
- Analysis with scale factor α_j
  - Scale the coupled-channel source contribution by scaling factor

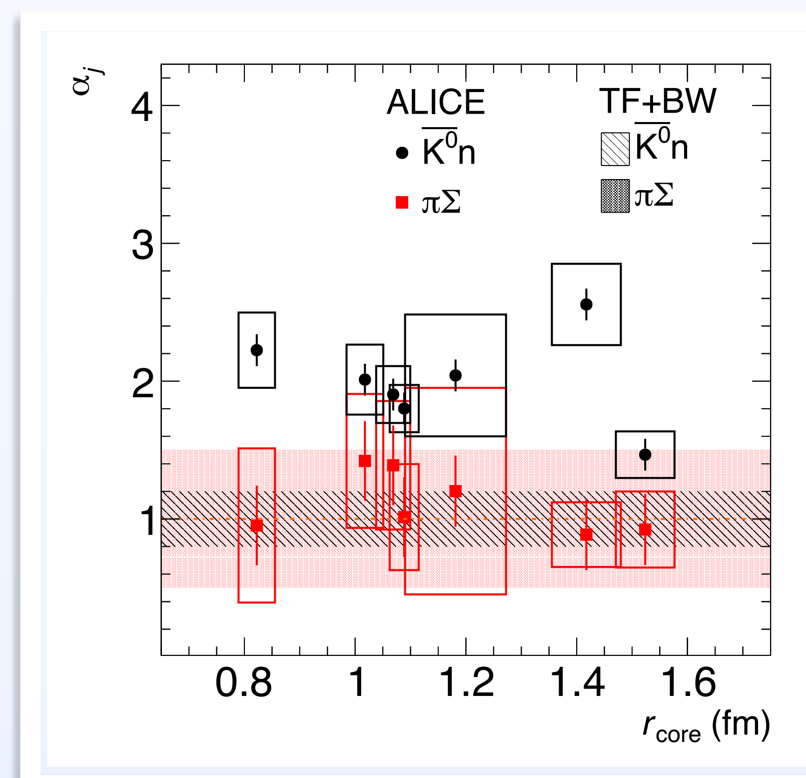
$$C_{K^-p} = C^{\mathrm{el}}_{K^-p} + \sum_j \alpha_j C^{\mathrm{inel}}_j$$

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

  → implying the stronger coupling

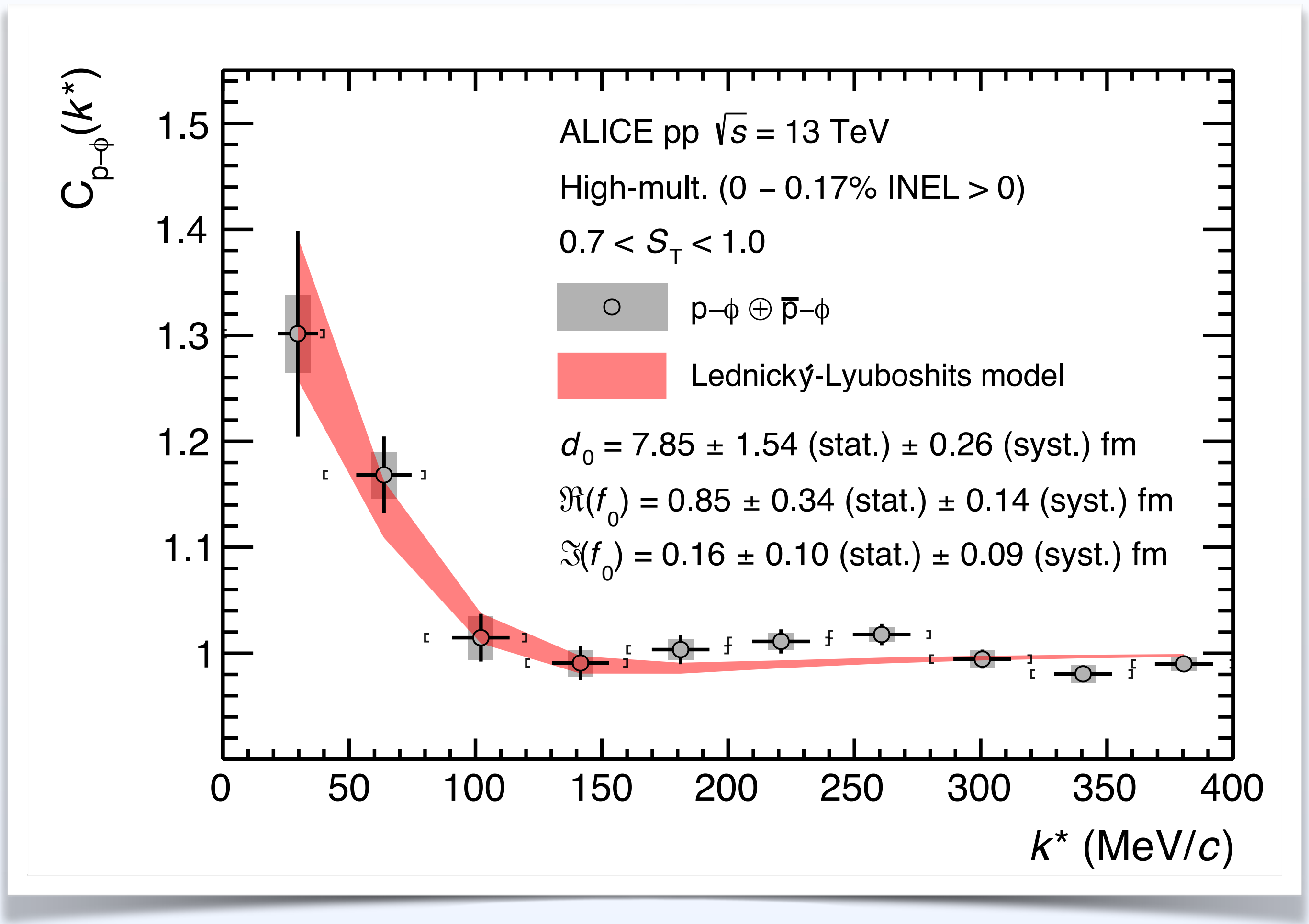






$N\phi$ interaction

- $p\phi$ correlation data from pp collisions



ALICE, PRL 127 (2021) 17, 172301

- Enhancement in the low momentum region
  - attractive $p\phi$ interaction
- Analysis with Lednický–Lyuboshits formula

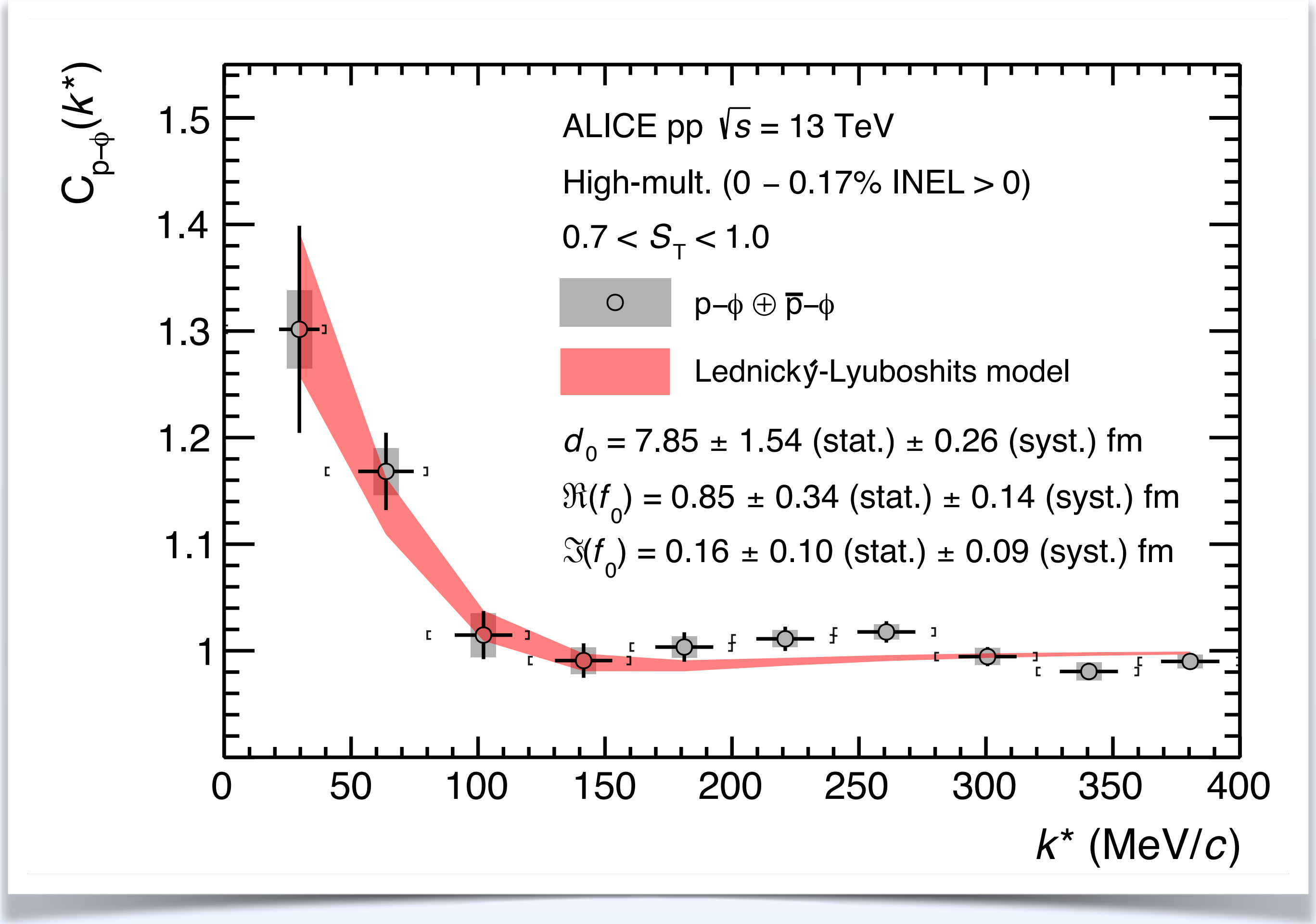
$$\mathrm{Re}\ a_0 = -0.85 \pm 0.34(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{fm}$$
$$\mathrm{Im}\ a_0 = -0.16 \pm 0.10(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\ \mathrm{fm}$$

- Decomposition for spin channels?

$$C_{p\phi}(k^*) = \frac{2}{3}C_{3/2}(k^*) + \frac{1}{3}C_{1/2}(k^*)$$

$N\phi$ interaction

- $p\phi$ correlation data from pp collisions



ALICE, PRL 127 (2021) 17, 172301

- Enhancement in the low momentum region
  - attractive $p\phi$ interaction
- Analysis with Lednický–Lyuboshits formula

$$\mathrm{Re}\ a_0 = 0.85 \pm 0.34(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})\ \mathrm{fm}$$
$$\mathrm{Im}\ a_0 = 0.16 \pm 0.10(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})\ \mathrm{fm}$$

- Decomposition for spin channels?

$$C_{p\phi}(k^*) = \frac{2}{3}C_{3/2}(k^*) + \frac{1}{3}C_{1/2}(k^*)$$

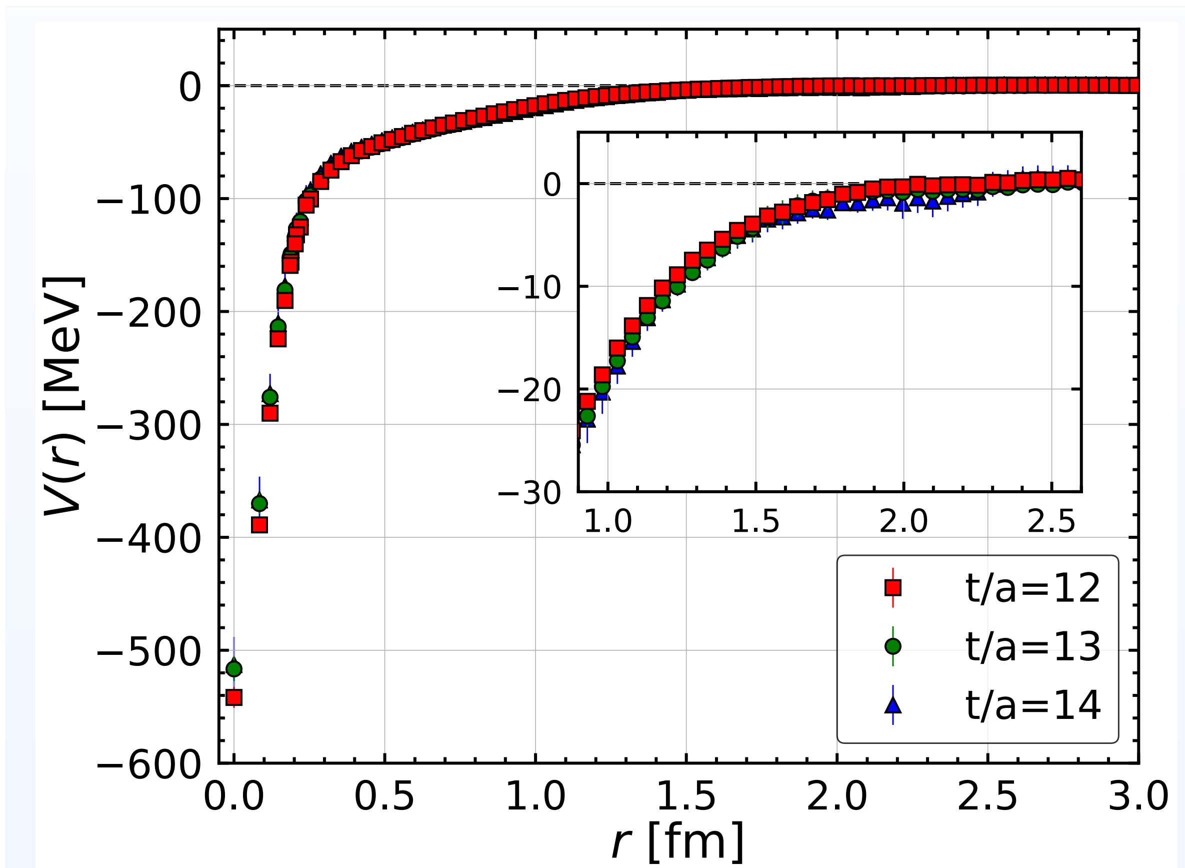
use the latest lattice potential   determine from data

Reanalyze data to extract spin 1/2 int.

$N\phi$ interaction

- HAL QCD potential for spin 3/2

Y. Lyu *et al*, PRD 106, 074507 (2022).



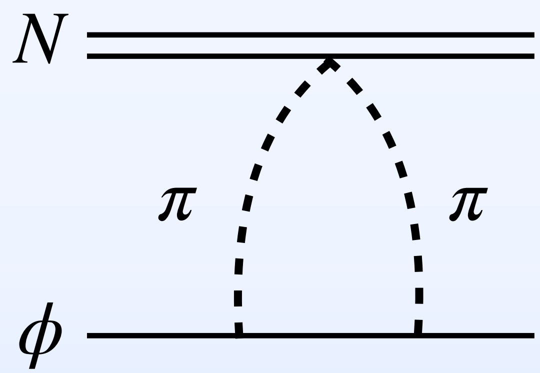
- Fitting function

$$V_{\rm fit}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3)\frac{e^{-2m_\pi r}}{r^2}$$

short range part — 2π exchange int.

- Decay effect to $\Lambda K/\Sigma K$: strongly suppresses by *d*-wave coupling
  → well described with real potential
- Long range tail
  → $2\,\pi$ exchange int.

J. Tarrús Castella` and G. a. Krein, PRD 98, 014029 (2018).



- Threshold parameters from fitted potential

m_π [MeV]	$a_0^{(3/2)}$ [fm]	$r_{\rm eff}^{(3/2)}$ [fm]
146.4	$-1.43(23)_{\rm stat.}\left(^{+36}_{-06}\right)_{\rm syst.}$	$2.36(10)_{\rm stat.}\left(^{+02}_{-48}\right)_{\rm syst.}$
138.0	$\simeq -1.25$	$\simeq 2.49$

- Strongly attractive but no bound state (nuclear physics convention for a_0)

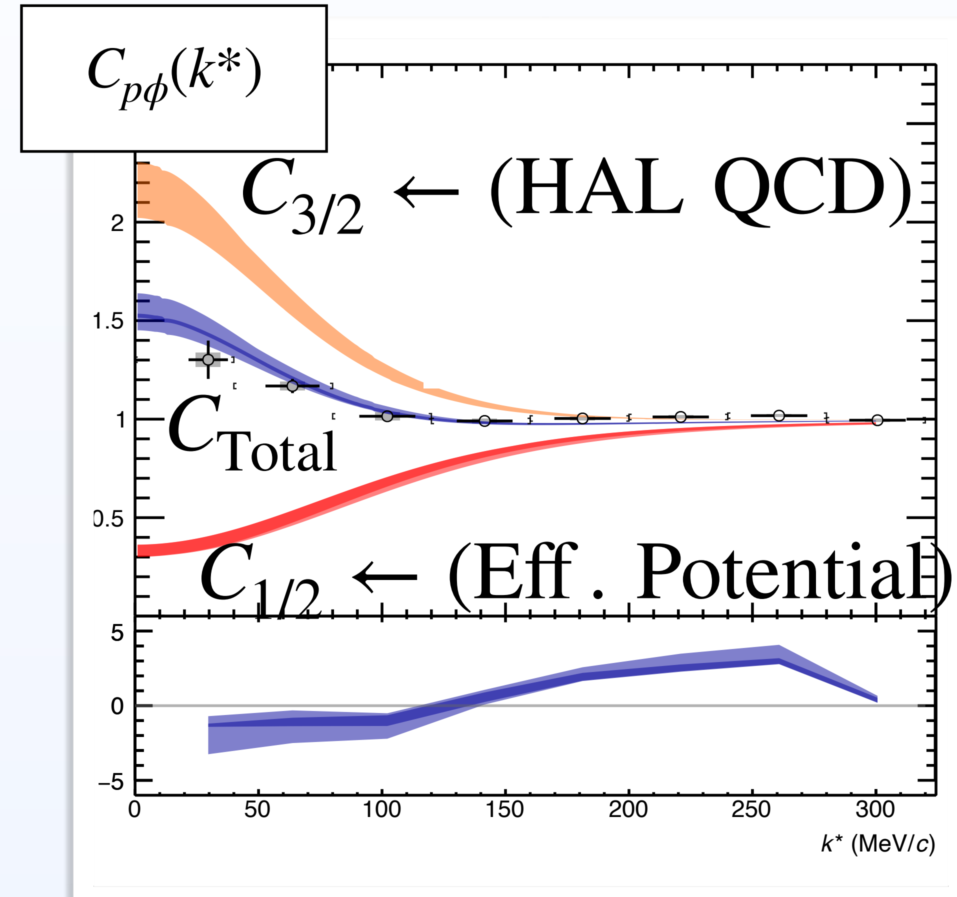
$N\phi$ interaction

- Spin 1/2 $N\phi$ int. from femtoscopic data and HAL QCD potential

$$C_{\text{Total}} = C_{1/2} + C_{3/2}$$

E.~Chizzali, et. al. [arXiv:2212.12690 [nucl-ex]].

HAL QCD ($C_{1/2}$) — Fit with effective potential ($C_{3/2}$)



- Fitting function for spin 1/2 potential

$$V_{1/2} = \beta \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r; b_3) \frac{e^{-2m_\pi r}}{r^2} + i\gamma \sqrt{f(r; b_3)} \frac{e^{-m_K r}}{r}$$

  - Inspired by HAL QCD potential for spin 3/2:
  - Two fitting parameters

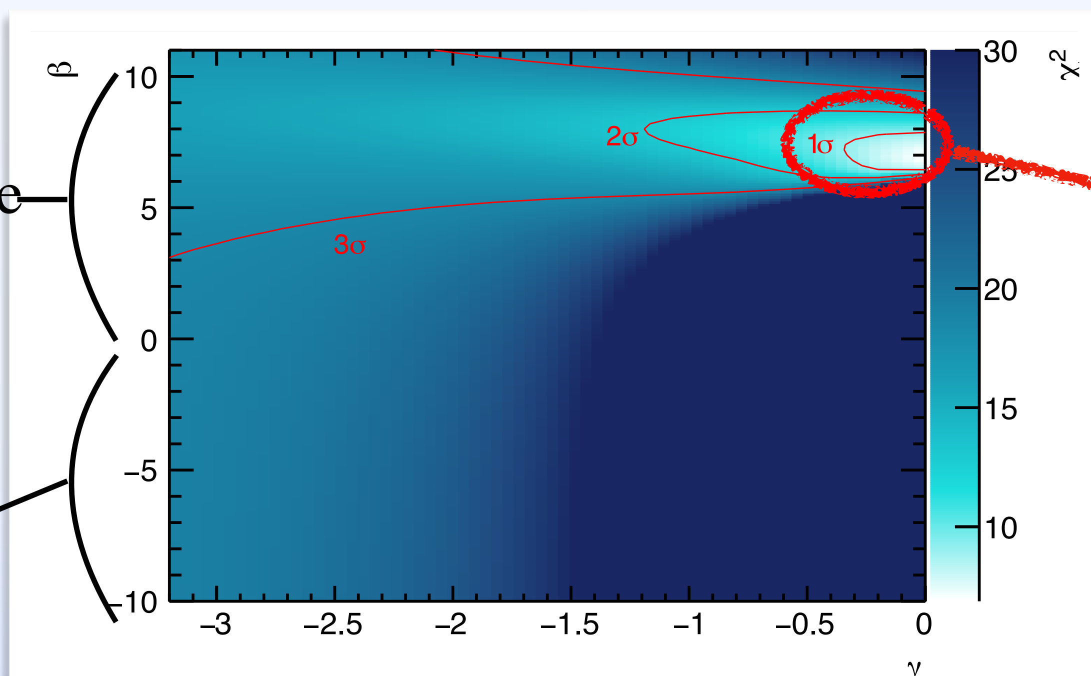
    β: relative strength of short range int.

    γ: strength of imaginary part

- Fitting result

Attractive ($\beta > 0$)

Repulsive ($\beta < 0$)



- Well fitted range

  $\beta = 7.0^{+0.8}_{-0.2}(\text{stat.})^{+0.2}_{-0.2}(\text{syst.})$

  $\gamma = 0.0^{+0.0}_{-0.2}(\text{stat.})^{+0.0}_{-0.2}(\text{syst.})$

- No good parameter sets for repulsive interactions

→ Strongly attractive interaction with small decay effect

$N\phi$ interaction

Analysis with fitted potential

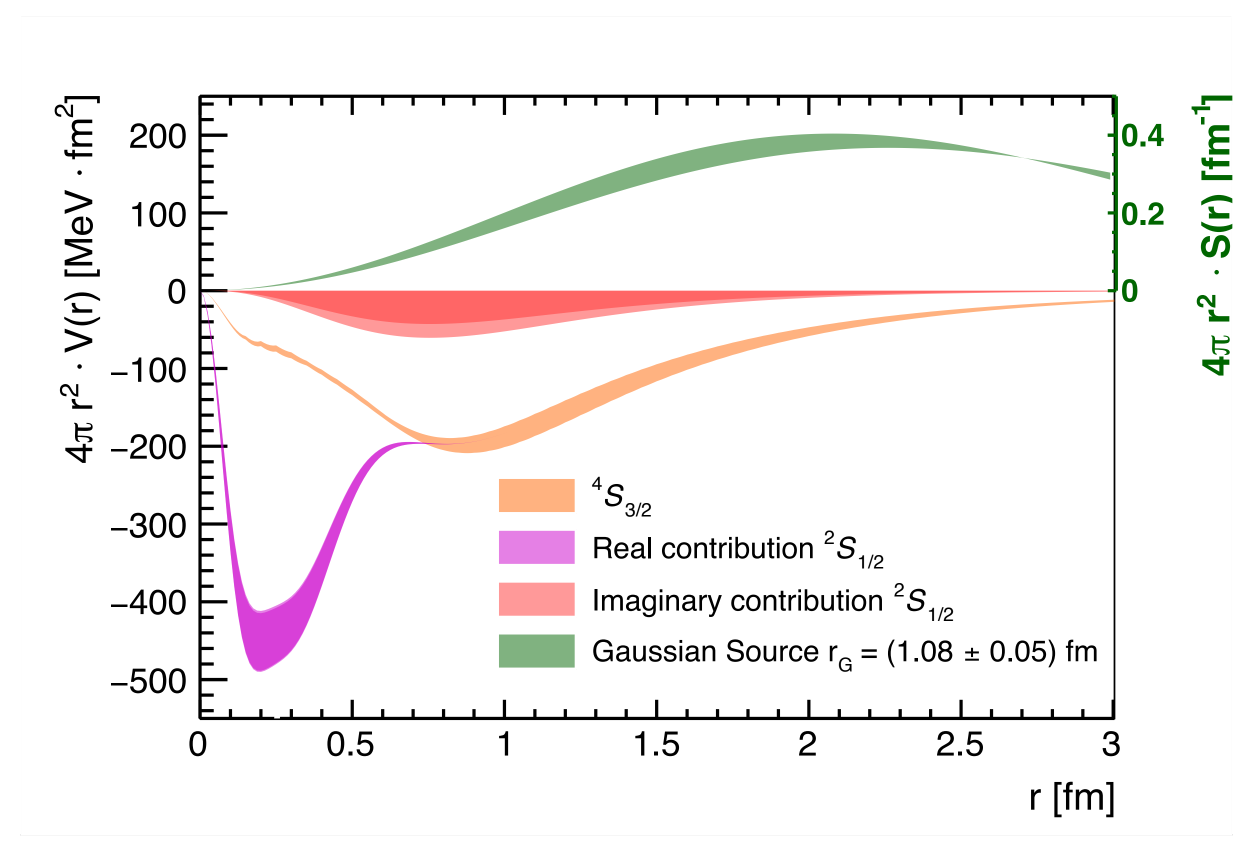
E.~Chizzali, et. al. [arXiv:2212.12690 [nucl-ex]].

- Threshold parameters (high energy phys. convention)
  - Scattering length

$$\text{Re } a_0 = \quad 1.47^{+0.44}_{-0.37}(\text{stat.})^{+0.14}_{-0.17}(\text{syst.}) \text{ fm}$$

$$\text{Im } a_0 = -0.00^{+0.26}_{-0.00}(\text{stat.})^{+0.15}_{-0.00}(\text{syst.}) \text{ fm}$$

$\longrightarrow$ indicating bound state



- Eigenenergy of quasibound state

$$E = -26.6^{+10.5}_{-29.4}(\text{stat.})^{+5.5}_{-6.2}(\text{syst.})$$
$$-i0.0^{+0.0}_{-7.8}(\text{stat.})^{+0.0}_{-6.6}(\text{syst.}) \text{ [MeV]}$$

$\longrightarrow$ <u>ϕN spin 1/2 bound state below the threshold found!</u>

- Comparable or larger binding energy compared to model calculations

QCD van der Waals attractive potential (Yukawa-type) $\longrightarrow E_B = 1.8$ MeV

H. Gao, T.-S. H. Lee, and V. Marinov, PRC 63, 022201 (2001).

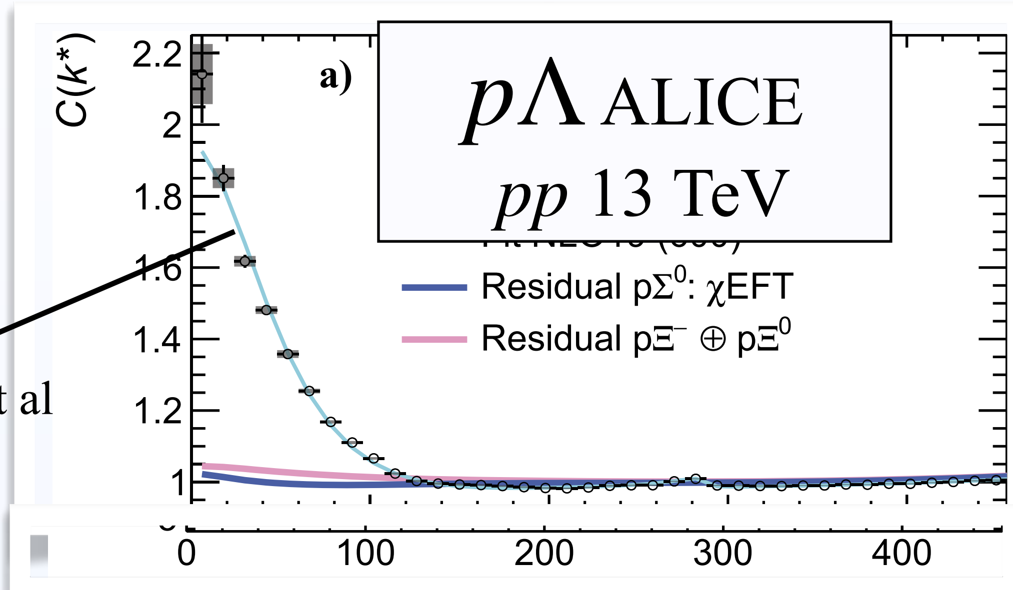
SU(3) chiral quark model $\longrightarrow E_B \sim 3$ MeV

F. Huang, Z. Y. Zhang, and Y. W. Yu, PRC 73, 025207 (2006).

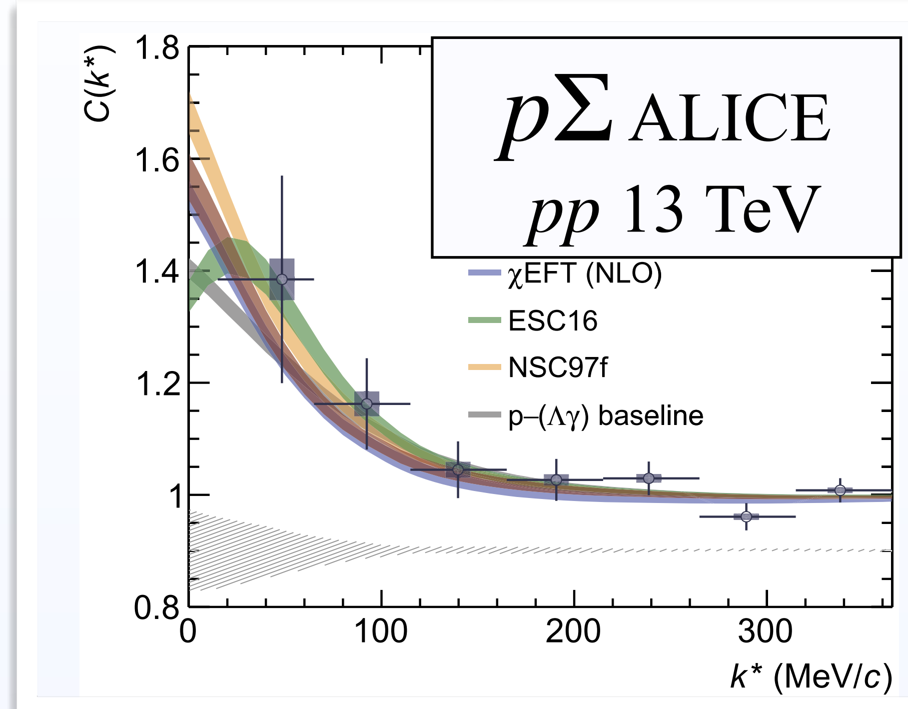
Y-$N(Y)$ correlation

- $S = -1$

NLO 19
J. Haidenbauer, et al
EPJA 56(2020)



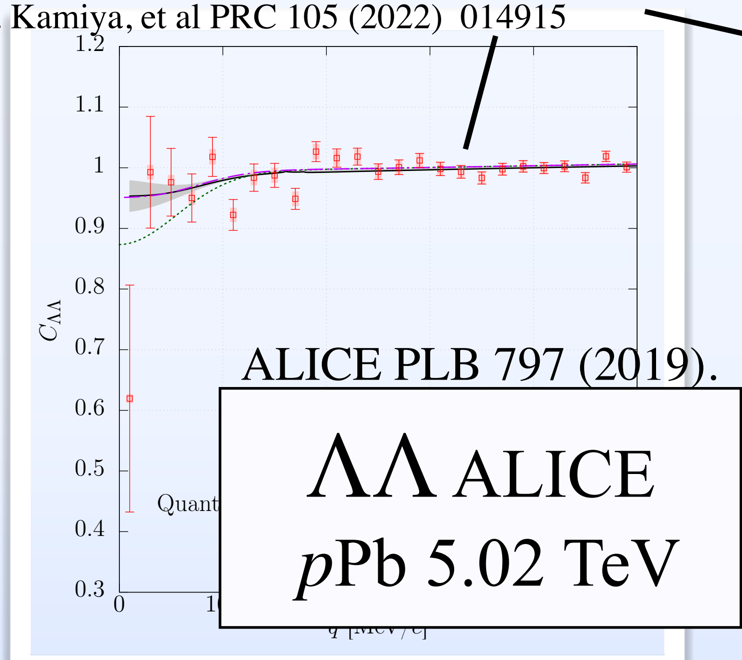
ALICE PLB 805 (2020) 135419



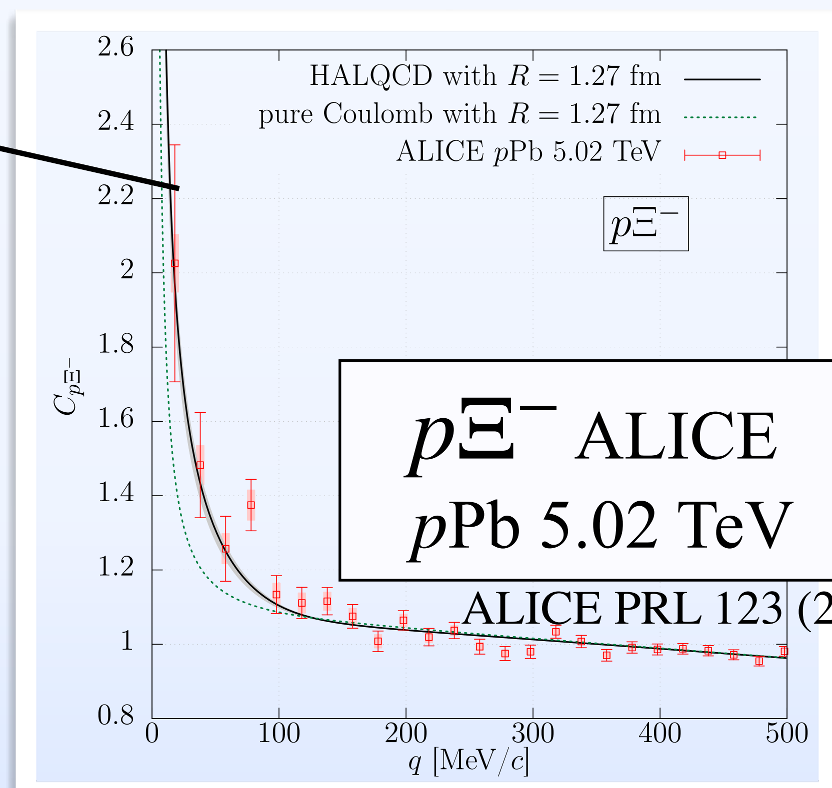
PLB 833 (2022) 137272

- $S = -2$

HAL QCD at almost physical m_π
K. Sasaki et al., NPA, 121737 (2019).
Y. Kamiya, et al PRC 105 (2022) 014915



ALICE PLB 797 (2019).



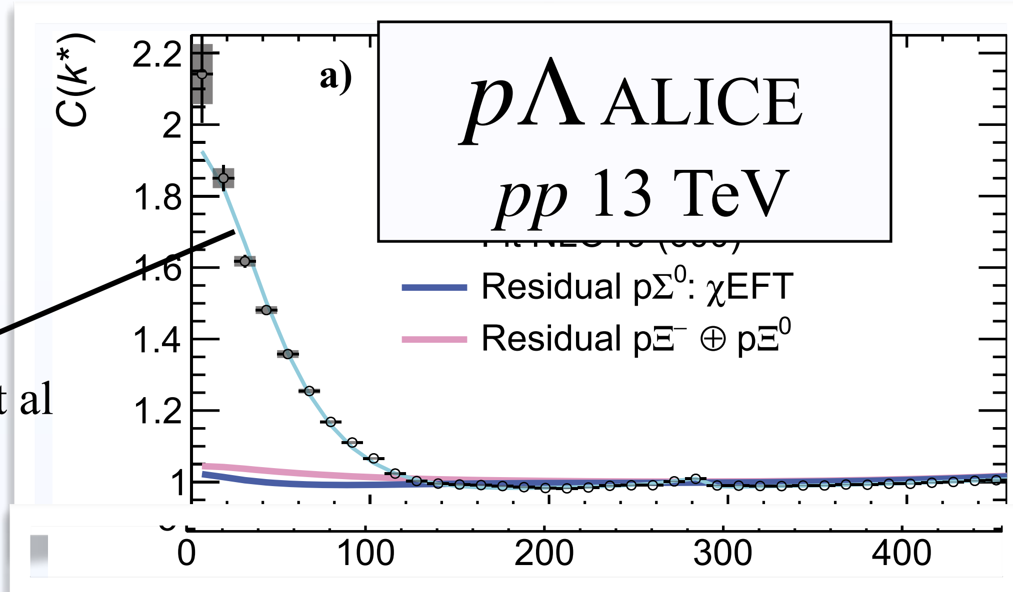
ALICE PRL 123 (2019).

- In good agreement data and theor. model
- Further constraint on the $YN(YY)$ int?

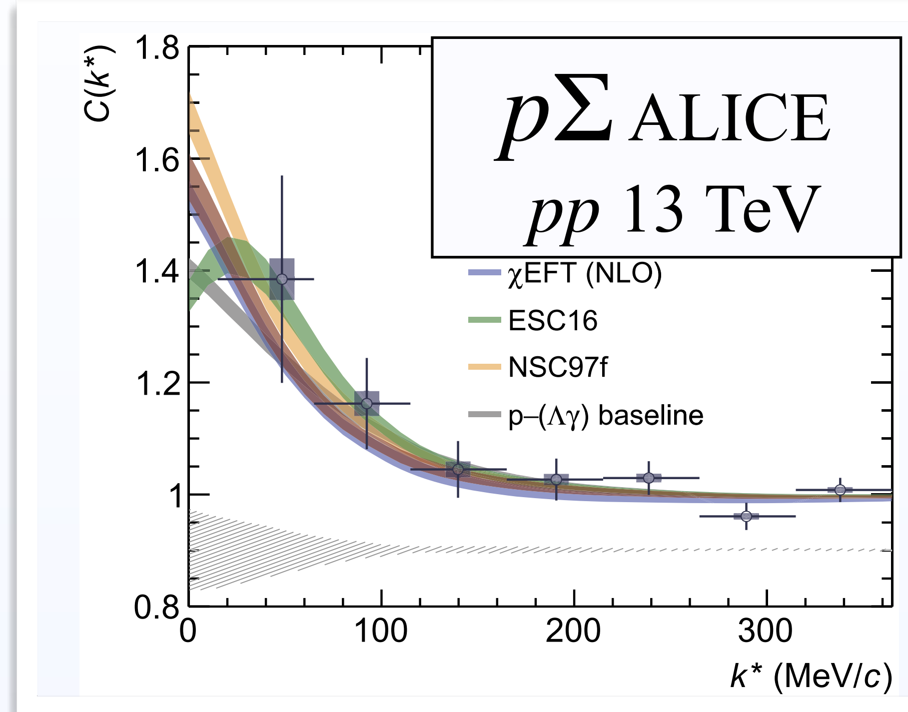
Y-N(Y) correlation

- $S = -1$

NLO 19
J. Haidenbauer, et al
EPJA 56(2020)



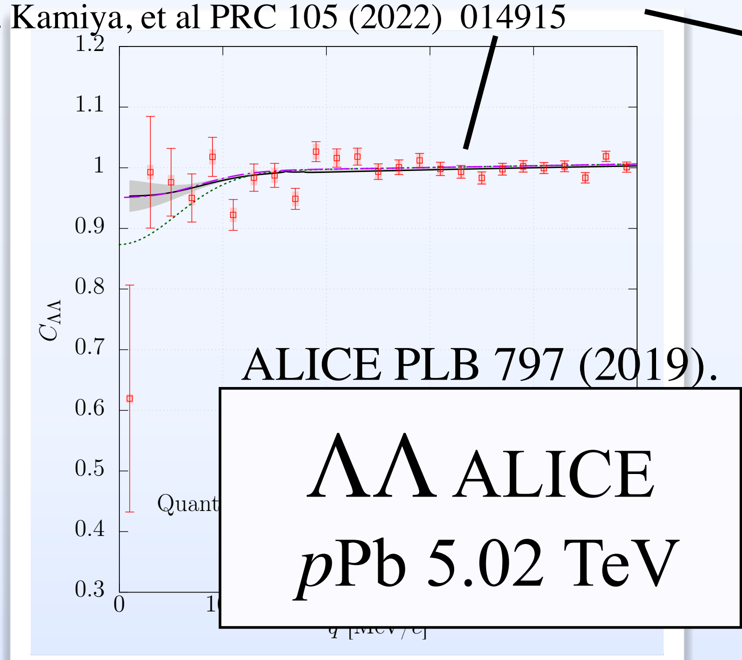
ALICE PLB 805 (2020) 135419



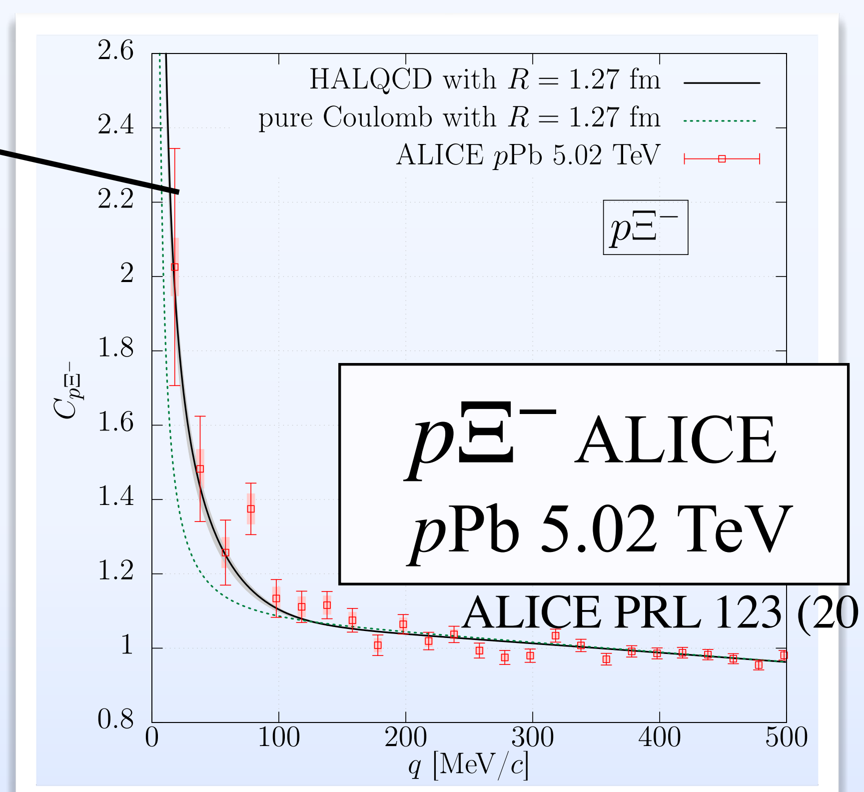
PLB 833 (2022) 137272

- $S = -2$

HAL QCD at almost physical m_π
K. Sasaki et al., NPA, 121737 (2019).
Y. Kamiya, et al PRC 105 (2022) 014915



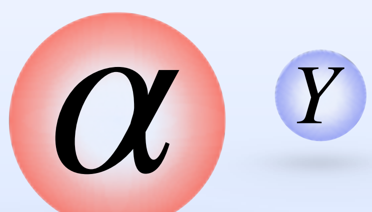
ALICE PLB 797 (2019).



ALICE PRL 123 (2019).

- In good agreement data and theor. model
- Further constraint on the $YN(YY)$ int?

→ αY pair?



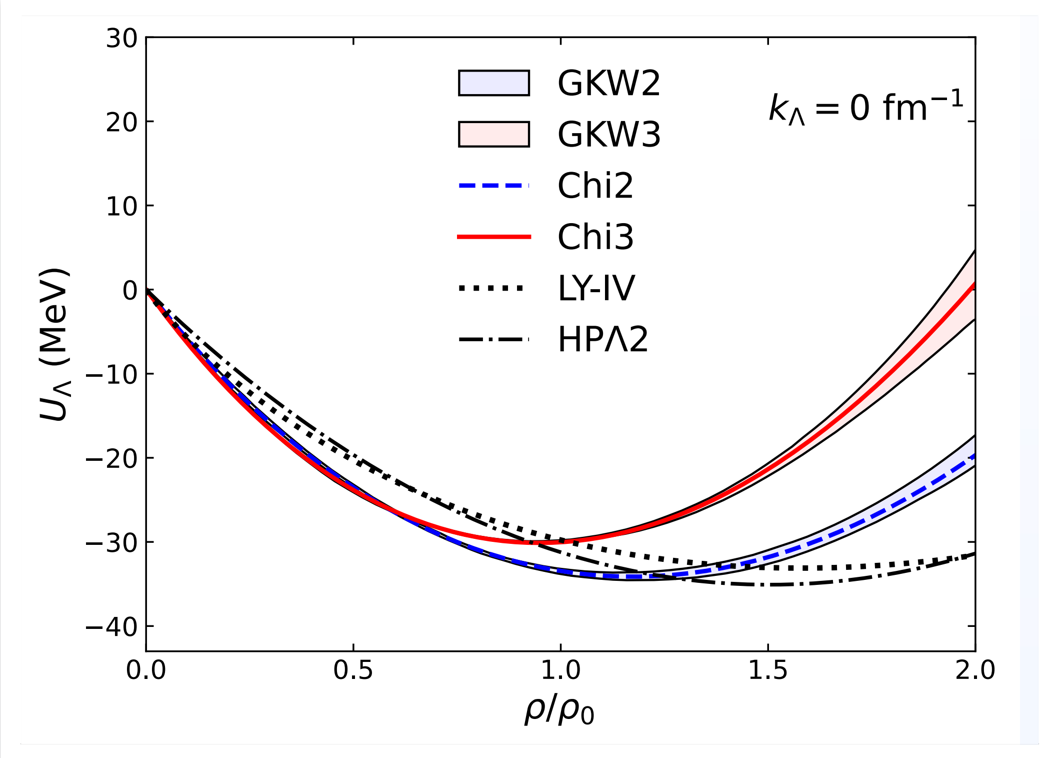
$\alpha\Lambda$ correlation

$N\Lambda$ interaction at finite density

- Key to solve the Hyperon puzzle
- Chiral EFT with NLO   D. Gerstung, N. Kaiser, W. Weise, EPJA 55 (2020)
  —> ΛNN three body interaction gives the additional repulsion
  —> stiffer EOS
- Chi3: Skyrme type Λ potential based on Chiral EFT with three body
  A. Jinno. K. Murase, Y. Nara, and A. Ohnishi arXiv:2306.17452

$$U_\Lambda^{\rm local} = a_1^\Lambda \rho_N + a_2^\Lambda \tau_N - a_3^\Lambda \triangle \rho_N + a_4^\Lambda \rho_N^{4/3} + a_5^\Lambda \rho_N^{5/3}$$

  - Well reproduces the binding energy of Λ in hypernuclei
- $N\Lambda$ potential model with different density dependence
  - LY-IV
    D. E. Lanskoy and Y. Yamamoto, PRC 55, 2330 (1997)
  - HPΛ2
    N. Guleria, S. K. Dhiman, and R. Shyam, Nucl. Phys. A 886, 71 (2012)



$\alpha\Lambda$ potential

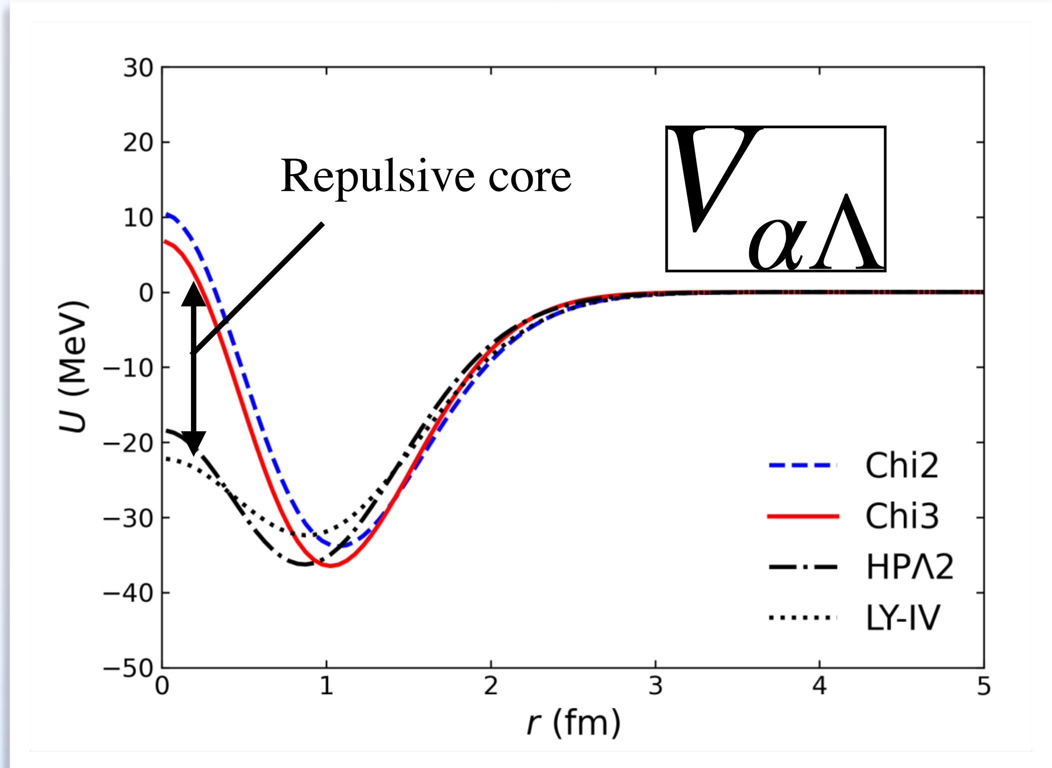
- Nucleon density with Gaussian form:

$$\rho(r) = A(2\nu_c/\pi)^{3/2} e^{-2\nu_c r^2}$$

  - high central density ~ $2\rho_0$

Can we see the effect of repulsion core?

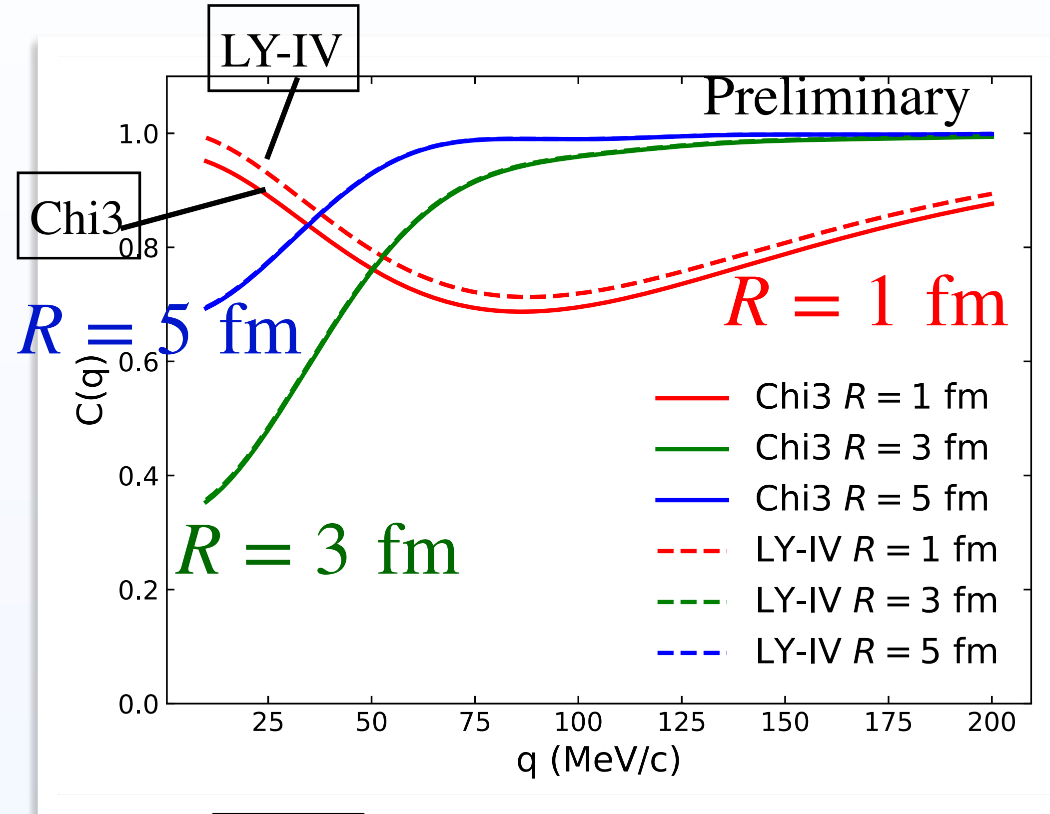
- Unknown a_3^Λ: fit to reproduce the ${}^5_\Lambda$He experimental $E_B = 3.12$ MeV



$\alpha\Lambda$ correlation

$\alpha\Lambda$ correlation with Chi3 model

- Characteristic lineshapes for weak binding system (${}^{5}_{\Lambda}$He)
    - Strong source size dependence
    - Dip structure
- $C(q)$ with Chi3 is slightly suppressed from that with LY-IV
    - Effect of the repulsive core emerges in small source size

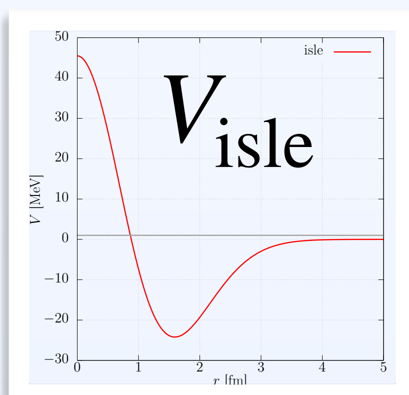


Model with strong repulsive core

- $N\Lambda$ Isle potential
  Kumagai-Fuse, S. Okabe, Y. Akaishi, PLB 345 (1995)

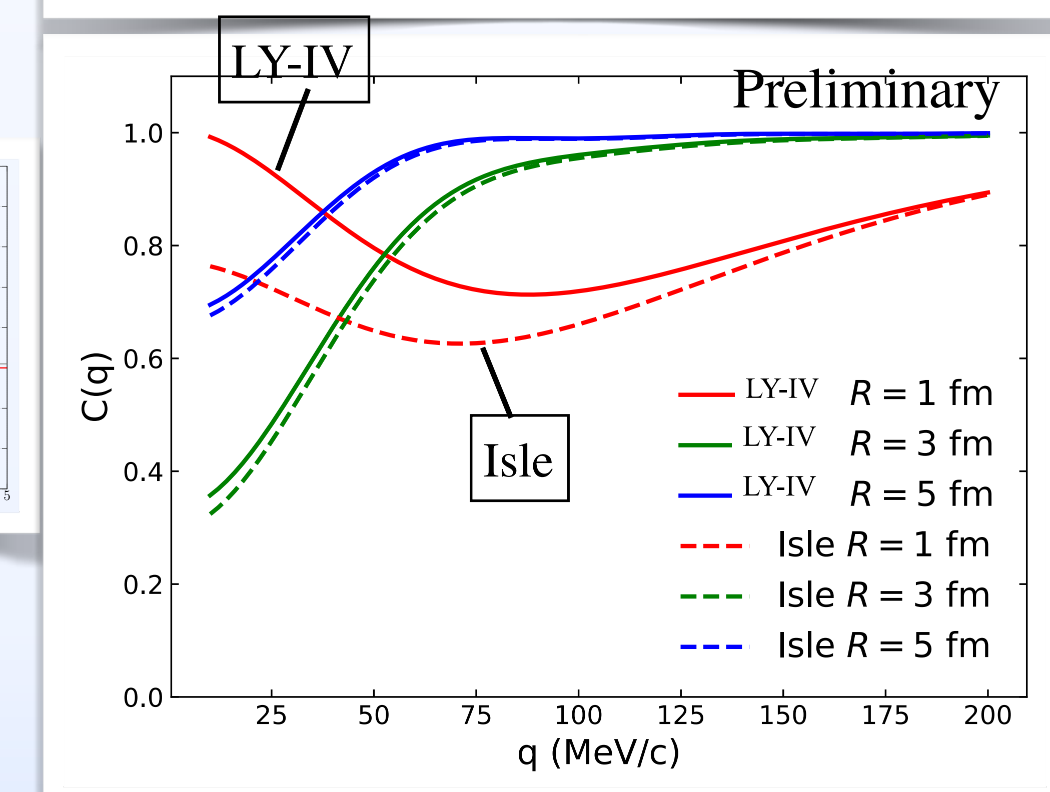
$$V(r) = V_1 e^{-r^2/b_1^2} + V_2 e^{-r^2/b_2^2}$$

repulsive core (short range) — attractive part (long range)



- $C(q)$: Much stronger suppression compared to LY-IV

Strength of the repulsive core can be tested with $C_{\alpha\Lambda}(q)$ from small source!



A. Jinno, Y. Kamiya, T. Hyodo, A. Ohnishi in prep.

$\alpha\Xi$ correlation

$\alpha\Xi$ bound state ($^{5}_{\Xi}$H)

- $N\Xi$ shows strong attraction
  —> $\alpha\Xi$ pair may form a bound state: $^{5}_{\Xi}$H (not observed)

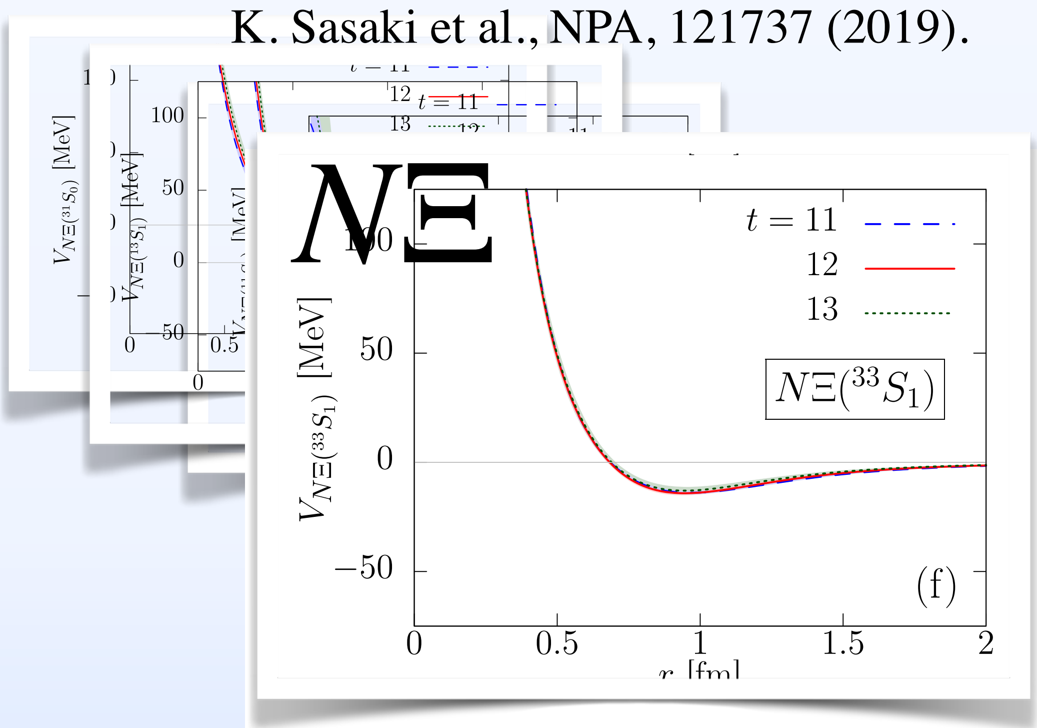
- HAL QCD $N\Xi$ potential based folding potential
  Coulomb assisted weakly bound state:
  $E_B = 0.45$ MeV
  E. Hiyama, et al PRC 106, 064318 (2022).
  K. Sasaki et al., NPA, 121737 (2019).

- Chiral NLO potential with no core shell model
  Bound state: $E_B = 2.16$ MeV
  H. Le, et al EPJA (2021)

→ $C_{\alpha\Xi}(q)$ can be used to see $^{5}_{\Xi}$H?

Interaction

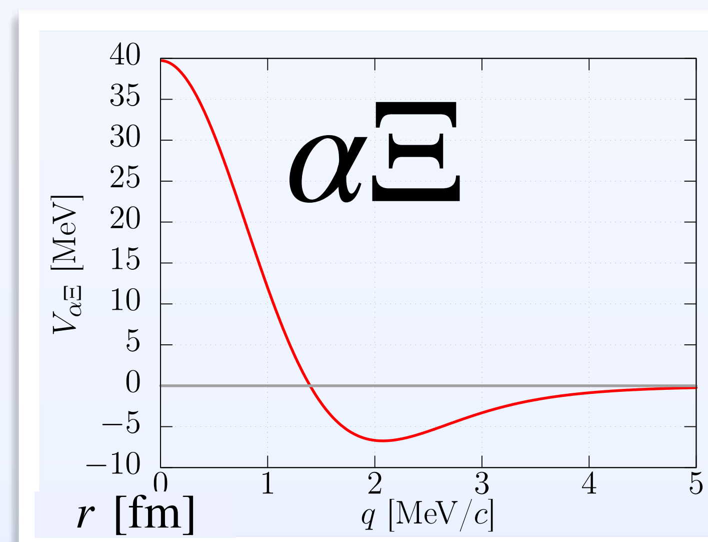
- HAL QCD $N\Xi$ potential
  K. Sasaki et al., NPA, 121737 (2019).



- Folding $\alpha\Xi$ potential with HAL QCD pot.
  E. Hiyama, M. Isaka, T. Doi, and T. Hatsuda, PRC 106, 064318 (2022).

Folding →

$[V(^{11}S_0) + 3V(^{13}S_1)$
$3V(^{31}S_0) + 9V(^{33}S_1)]/16$



- Effect of long range attractive int.?
- Effect of repulsive core?

$\alpha\Xi$ correlation

$\alpha\Xi^-$ correlation and ${}^{5}_{\Xi}$H binding energy

Preliminary

- Folding potenital and variations

potential	E_B [MeV]	Model
Vfolding	0.45	HAL QCD base folding V (original)
2 Vfolding	2.16	E_B chiral model (H. Le, et al EPJA(2021))
Vfolding / 2	(Unbound)	Weaker interaction case

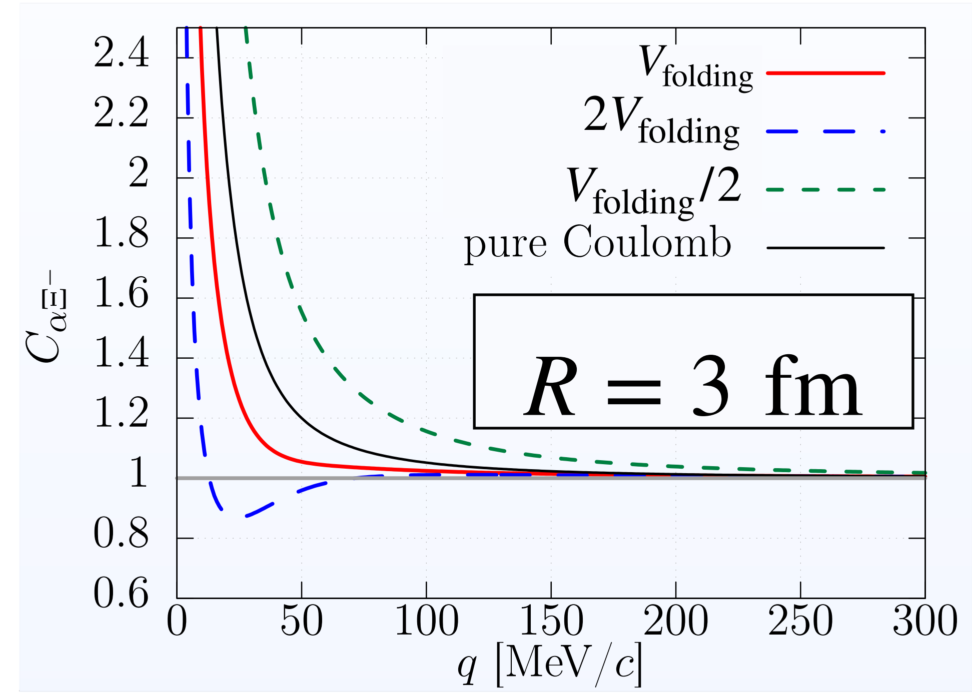
- Result with mid source ($R = 3$ fm)
  - V_{folding}: suppression from Coulomb
  - $2V_{\text{folding}}$: bump structure around $q \sim 100$ MeV/c
  - $V_{\text{folding}}/2$: enhancement from Coulomb

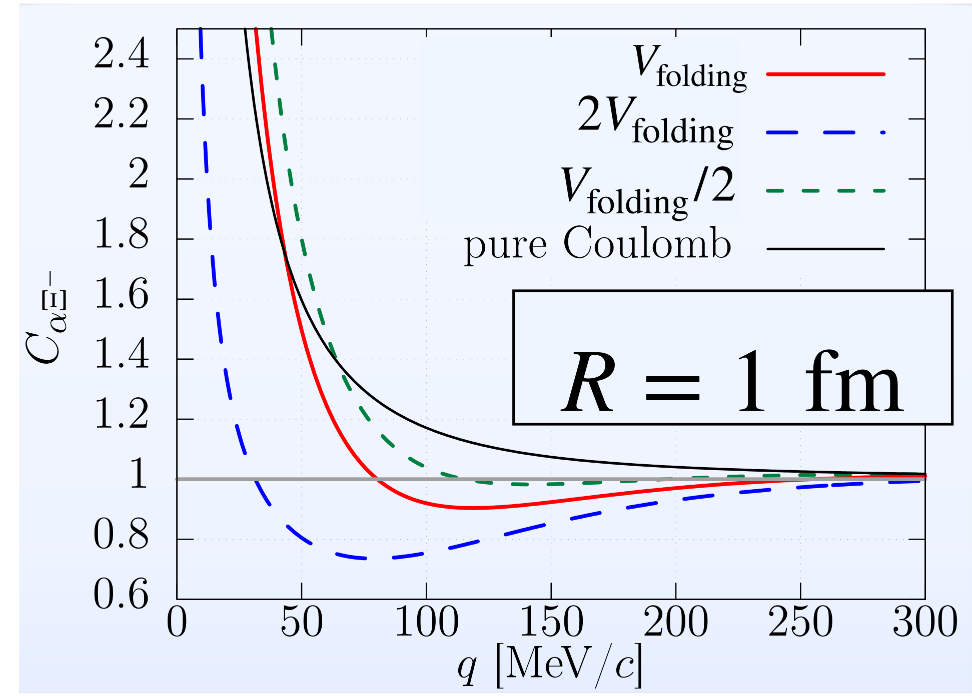
→ ${}^{5}_{\Xi}$H can be distinguished by the source size dependence

- Result with small source ($R = 1$ fm)
  - V_{folding} and $V_{\text{folding}}/2$ unnatural bump at $q \sim 100$ MeV/c
  - $2V_{\text{folding}}$: deep bump structure

→ Effect by the strong repulsion core?

∗ Coulomb int. included





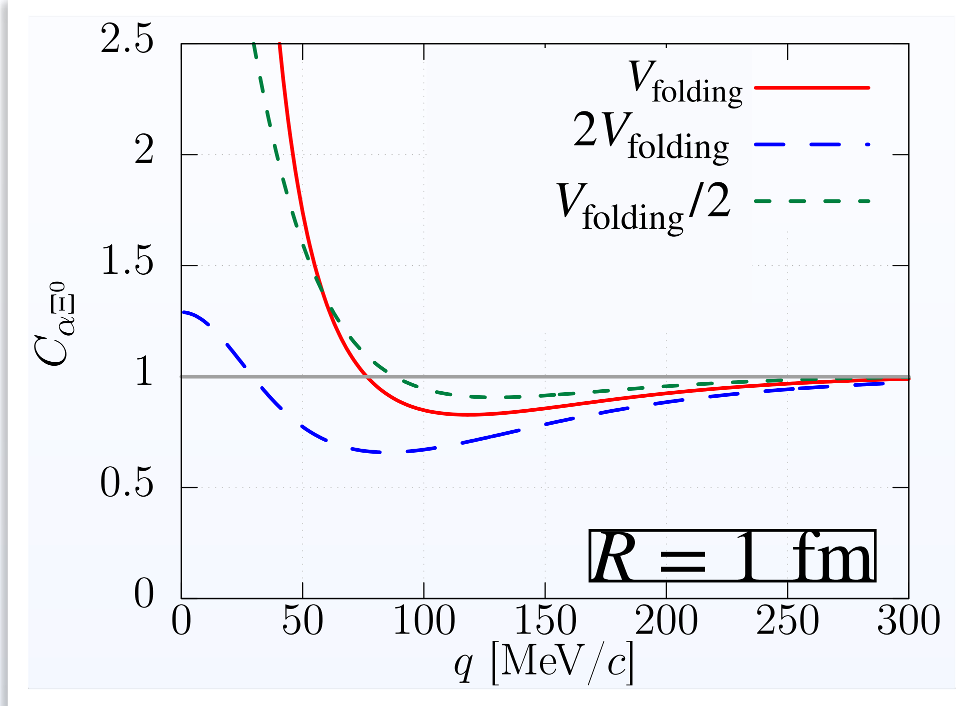
Y. Kamiya, A. Jinno, T. Hyodo, A. Ohnishi in prep.

$\alpha\Xi$ correlation

- $\alpha\Xi^0$ correlation and potential detail

No Coulomb: Good to see the effect of detailed potential

potential	E_B [MeV]
Vfolding	(Unbound)
2 Vfolding	1.15
Vfolding / 2	(Unbound)



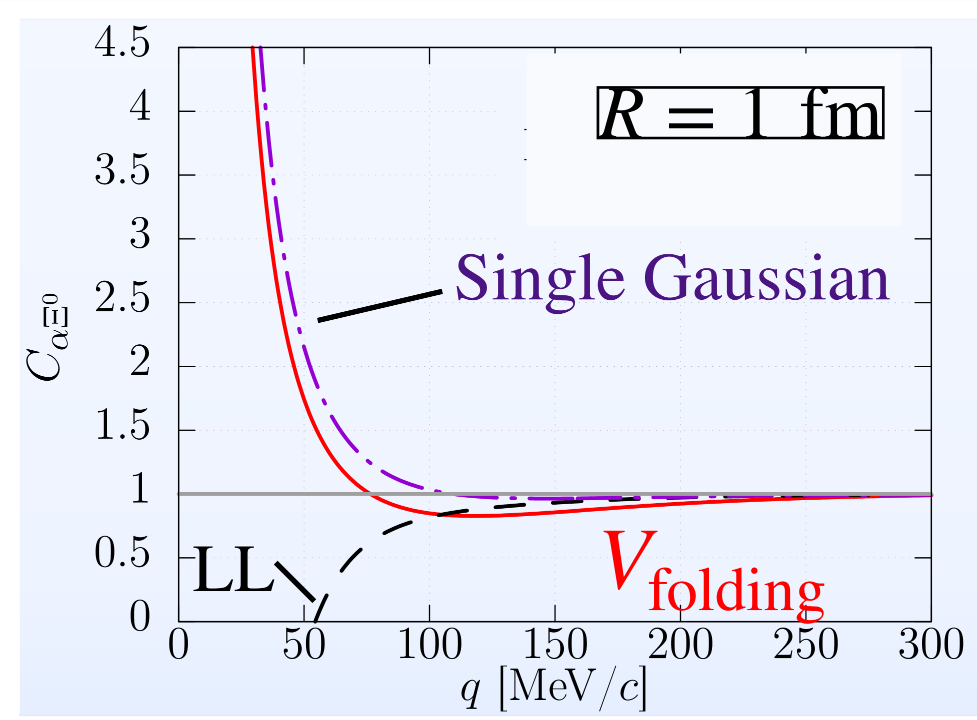
- Dip in $q \sim 100$ MeV/c for V_{folding} and $V_{\mathrm{folding}}/2$
- Long tail for $2V_{\mathrm{folding}}$

—> Effect of the repulsive core

- Single Gaussian potential model $V \propto e^{-r^2/b^2}$
—> purely enhanced $C(q)$

- Lednicky-Lyuboshits(LL) formula
—> Largely underestimate $C(q)$ due to the large effective range

Detailed potential shape can be tested by $C(q)$ from small source!



Y. Kamiya, A. Jinno, T. Hyodo, A. Ohnishi in prep.

Summary

- Femtoscopic study on the hadron interaction
  - Direct approach to the low-energy interaction
  - Sensitive to the near-threshold resonance

- $K^{-}p$ correlation
  - Chiral SU(3) model give the good agreement with the various $K^{-}p$ data
  - Finite deviation in small source indicates the stronger coupling

- ϕN correlation
  - Spin 1/2 interaction extracted with femto data and lattice spin 3/2 potential
  - Strong attractive interaction supporting a bound state indicated

- α-Hyperon correlation
  - Good observable to test the interaction detail of Y-N interaction
  - $\alpha\Lambda$: Suppression by the repulsive core
  - $\alpha\Xi$: Existence of ${}^{5}_{\Xi}\mathrm{H}$ can be tested

    Dip structure in mid momentum by the repulsion core

Thank you for your attention!