Study of $\bar{K}N$ interaction from the hadron-hadron correlation in high-energy nuclear collisions

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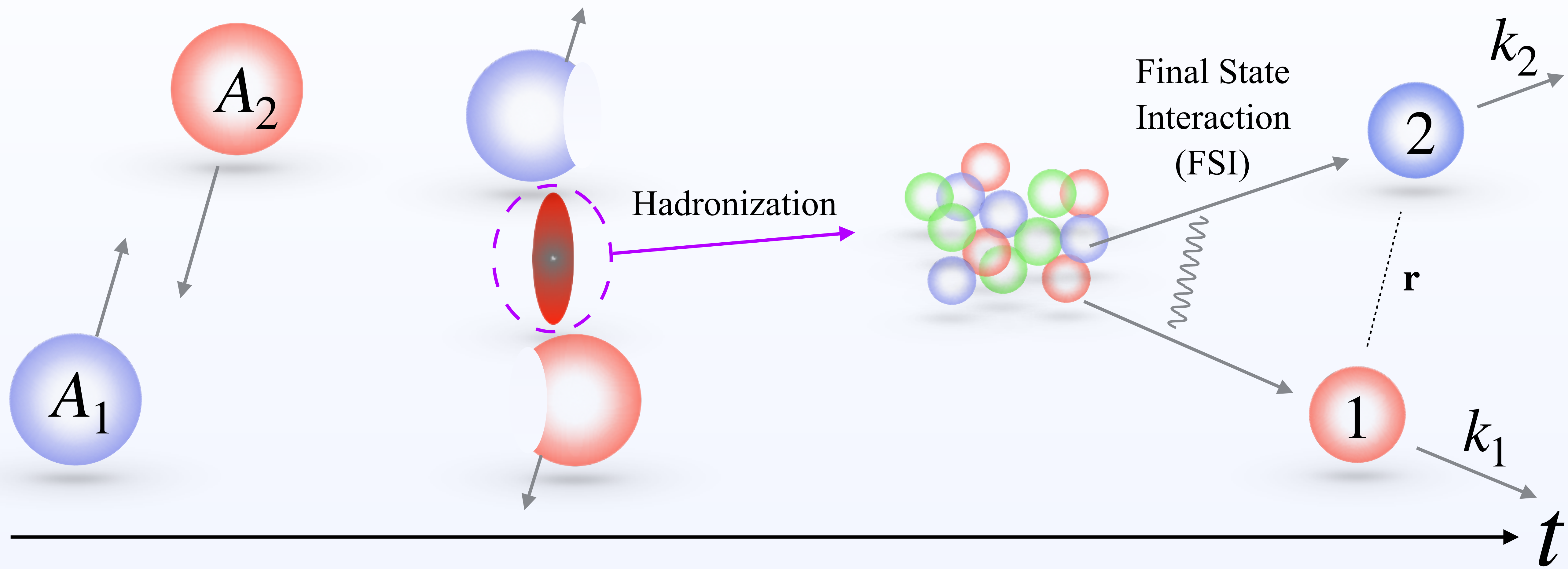
- Introduction: Hadron correlation in high energy nuclear collisions
- Introduction: $K^- p$ correlation function
- $K^- p$ correlation function with Koonin-Pratt formula
- Results and discussion

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



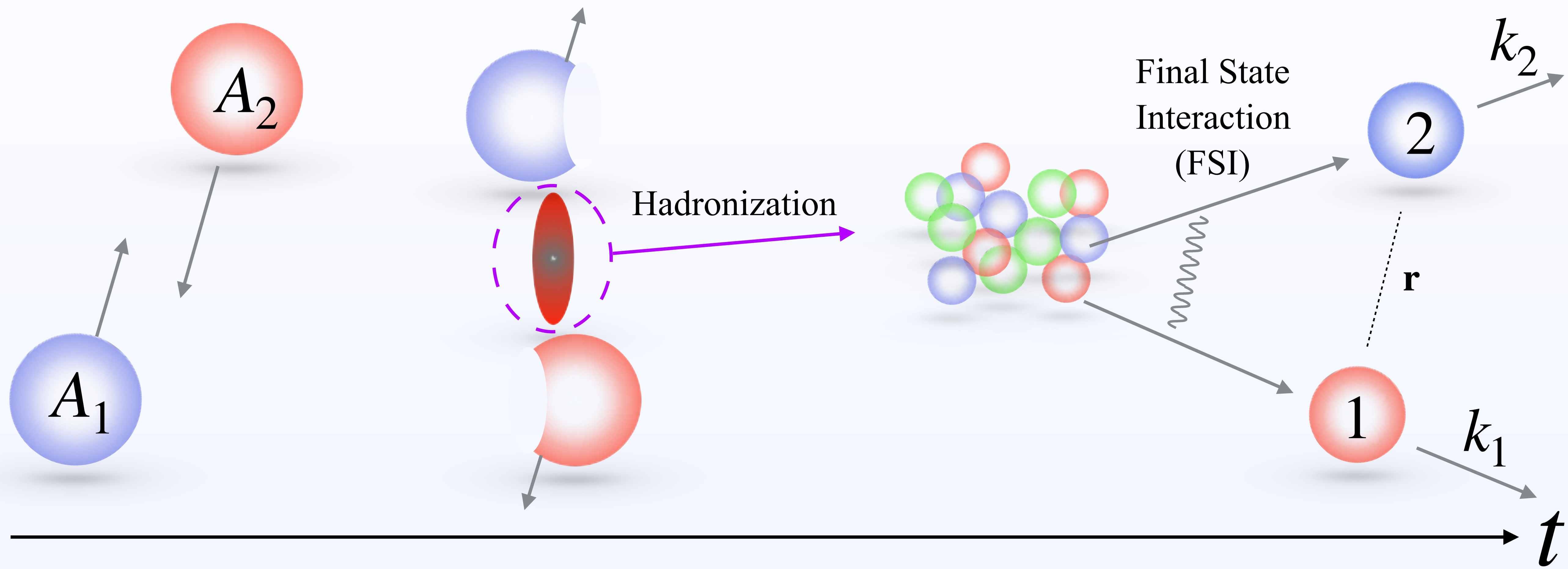
- Hadron-hadron correlation

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

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

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



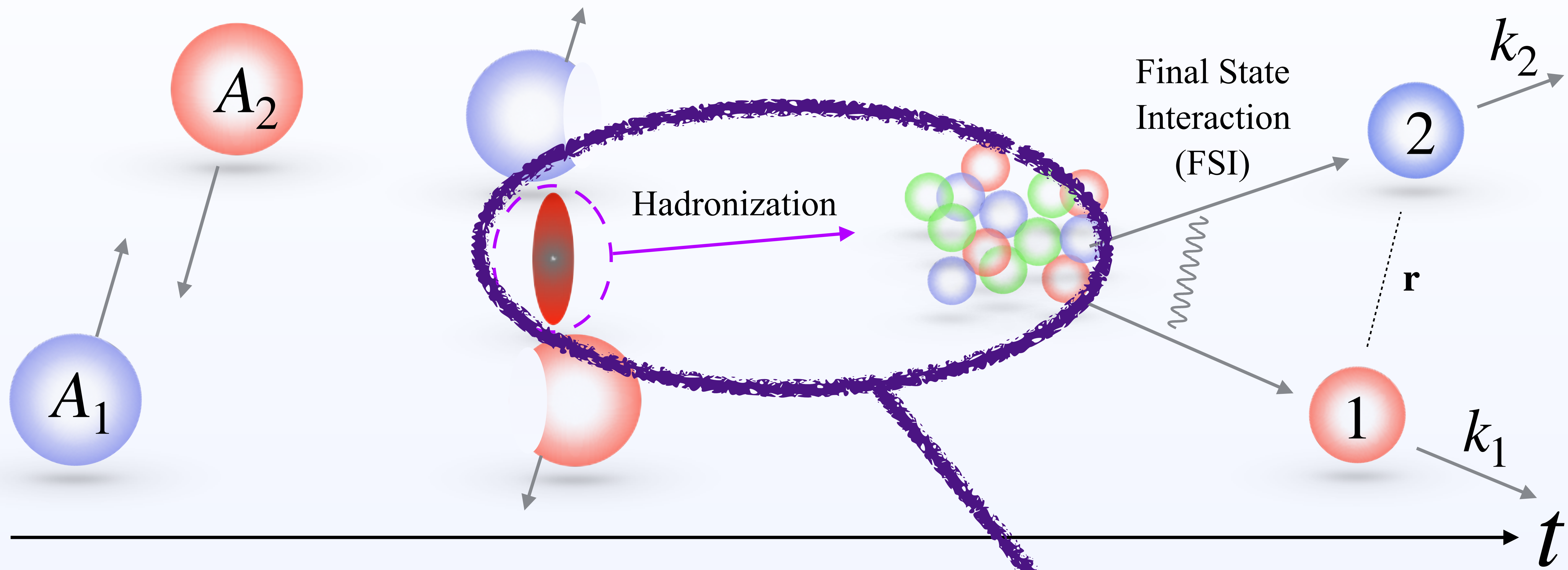
- Hadron-hadron correlation

$$C_{12}(\mathbf{k}_1,\mathbf{k}_2) = \frac{\int d^4x_1 \int d^4x_2 S_1(x_1,\mathbf{k}_1) S_2(x_2,\mathbf{k}_2) \,|\, \Psi^{(-)}(\mathbf{r},\mathbf{q}) \,|^2}{\int d^4x_1 S_1(x_1,\mathbf{k}_1) \int d^4x_2 S_2(x_2,\mathbf{k}_2)}$$

$S_i(x,\mathbf{k})$: Source function

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

High energy nuclear collision and FSI



Hadron-hadron correlation

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$S_i(x, \mathbf{k})$: Source function

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- Depends on …

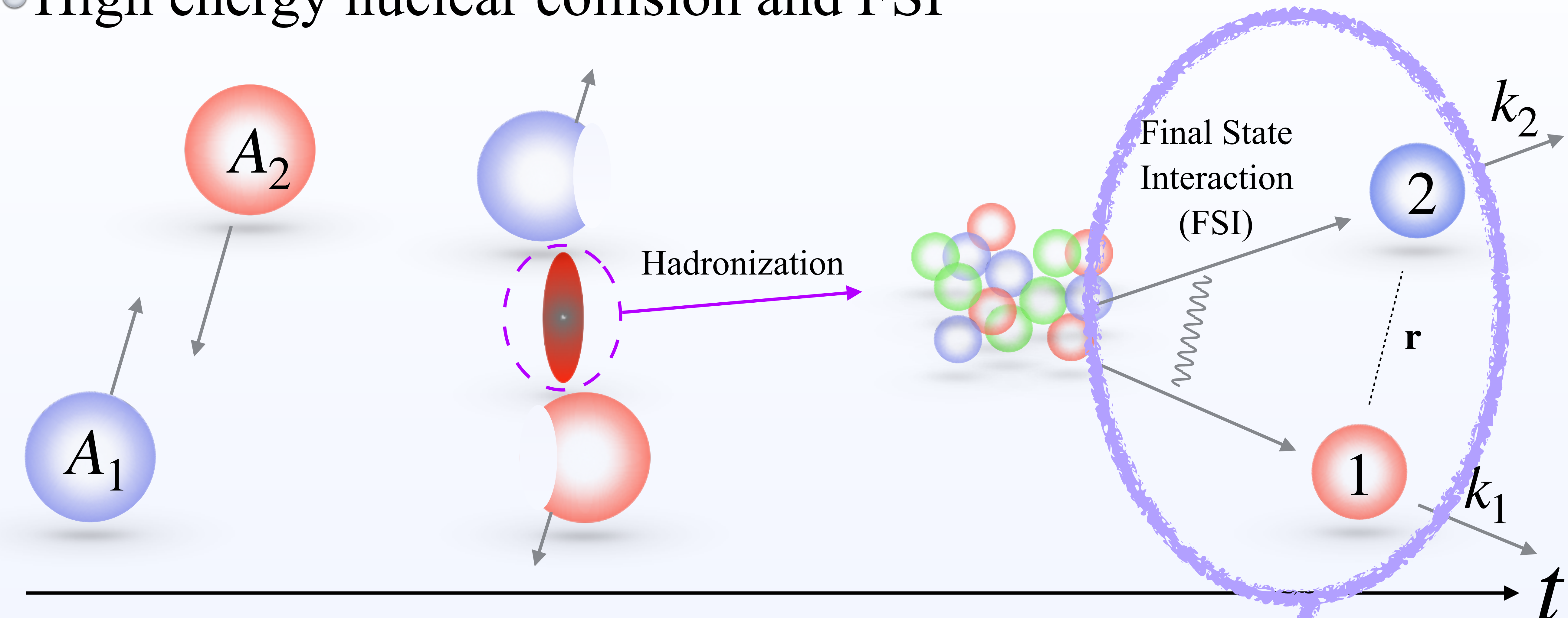
  Collision detail (Ai, energy, centrality)

- Including information of…

  size of hadron source,

  time dependence, weight…

- High energy nuclear collision and FSI



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$S_i(x, \mathbf{k})$: Source function

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

- Depends on …

  Interaction (strong and Coulomb)

  quantum statistics (Fermion, boson)

How to study the hadron interaction

$$C_{12}(\mathbf{k}_1,\mathbf{k}_2) = \frac{\int d^4x_1 \int d^4x_2 S_1(x_1,\mathbf{k}_1) S_2(x_2,\mathbf{k}_2)\,|\varphi^{(-)}(\mathbf{r},\mathbf{q})|^2}{\int d^4x_1 S_1(x_1,\mathbf{k}_1)\int d^4x_2 S_2(x_2,\mathbf{k}_2)}$$

$S_i(x,\mathbf{k})$: Source function

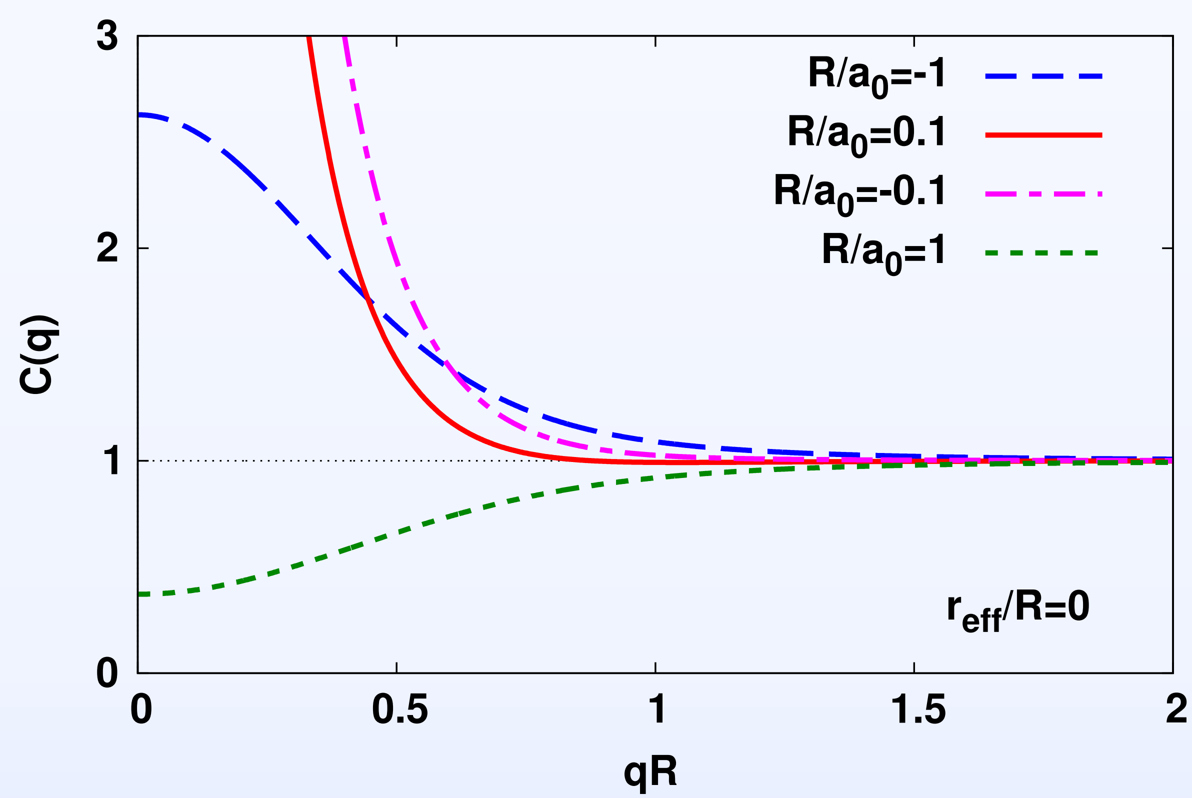
$\varphi^{(-)}(\mathbf{r},\mathbf{q})$: Relative wave function

- Introduce relative source: $S(\mathbf{k}_i)$
- Move to the center-of-mass frame

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

S.E. Koonin, PLB 70 (1977)
S. Pratt et. al. PRC 42 (1990)

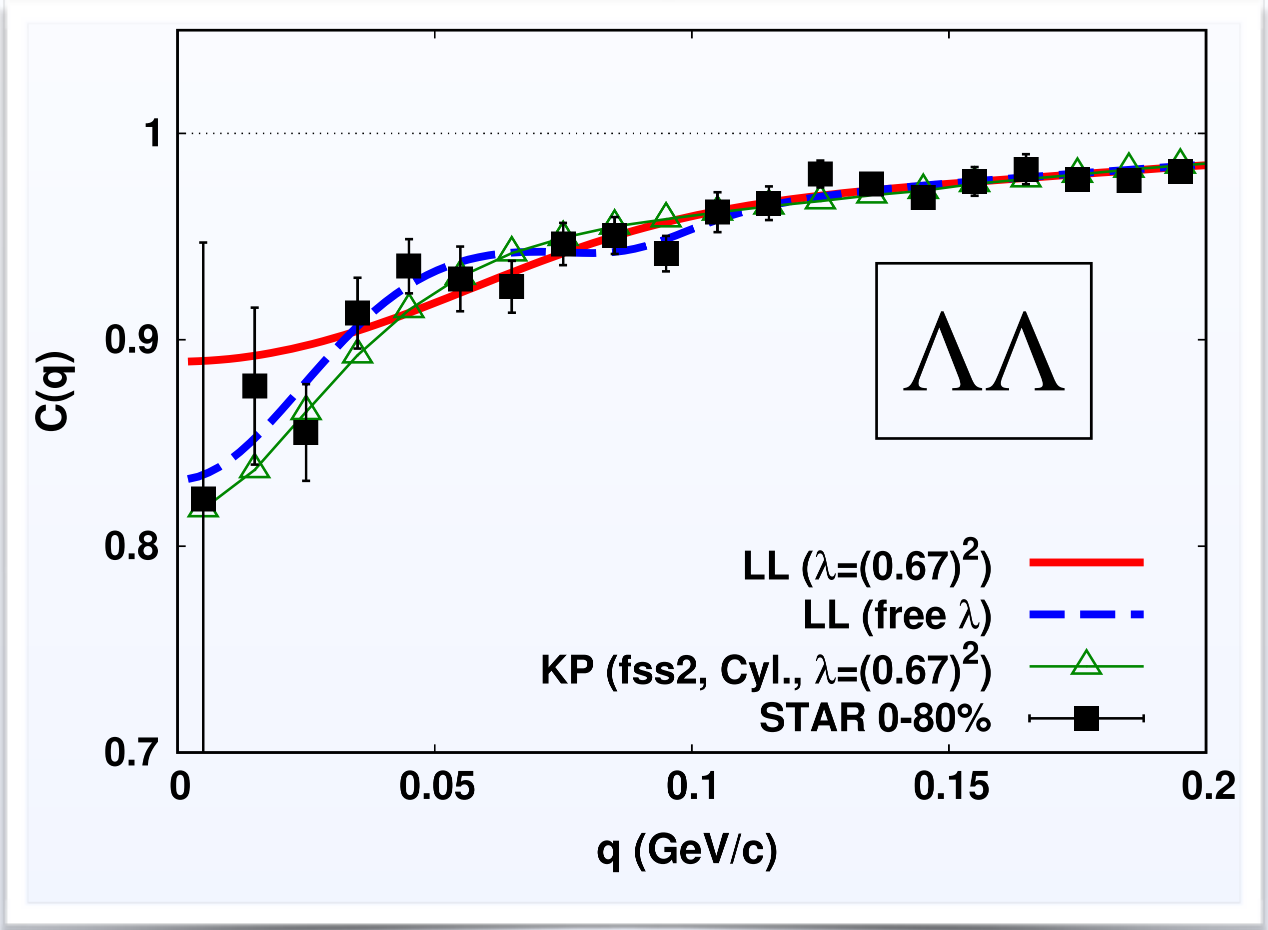
- Simple model with LL formula
  R. Lednicky, et al. Sov. J. Nucl. Phys. 35(1982).
  - Static Gaussian source
  - Effective range expansion
- $C(q)$ is sensitive to R/a_0
  - R : Gaussian source size
  - a_0: scattering length

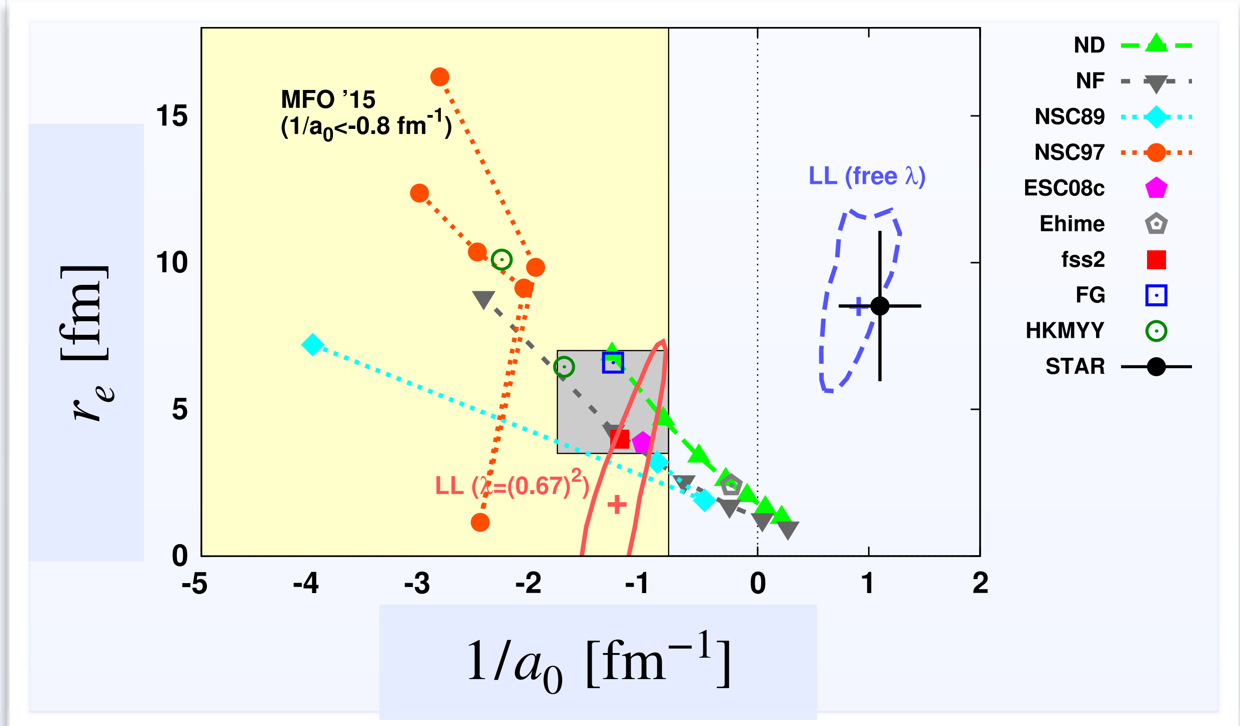


Morita, et al., arXiv:1908.05414

Powerful tool to study hadron interaction in low energy region

- Example: ΛΛ interaction from ΛΛ correlation function





Ohnishi et. al. Nuclear Physics A 954 (2016) 294–307

- ΛΛ correlation ; measured by STAR collabo. (later by ALICE collabo.)
  L. Adamczyk, et al. PRL 114 (2015). S. Acharya et al., PRC 99 (2019)

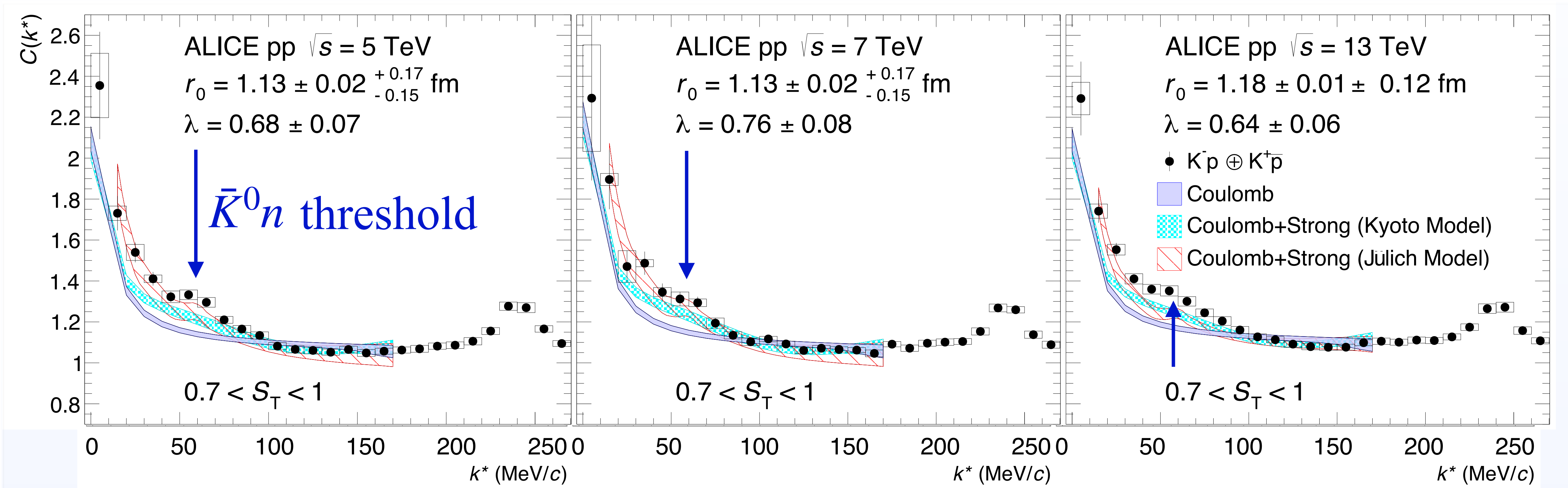
- Detailed analysis of correlation function
  Morita et al. PRC 91(2015)
  Ohnishi et. al. Nuclear Physics A 954 (2016)

Constraint to the ΛΛ threshold parameters (a_0, r_e)

$K^- p$ correlation

- $K^- p$ correlation: measured by ALICE collab.

ALICE, S. Acharya et al., (2019), 1905.13470.



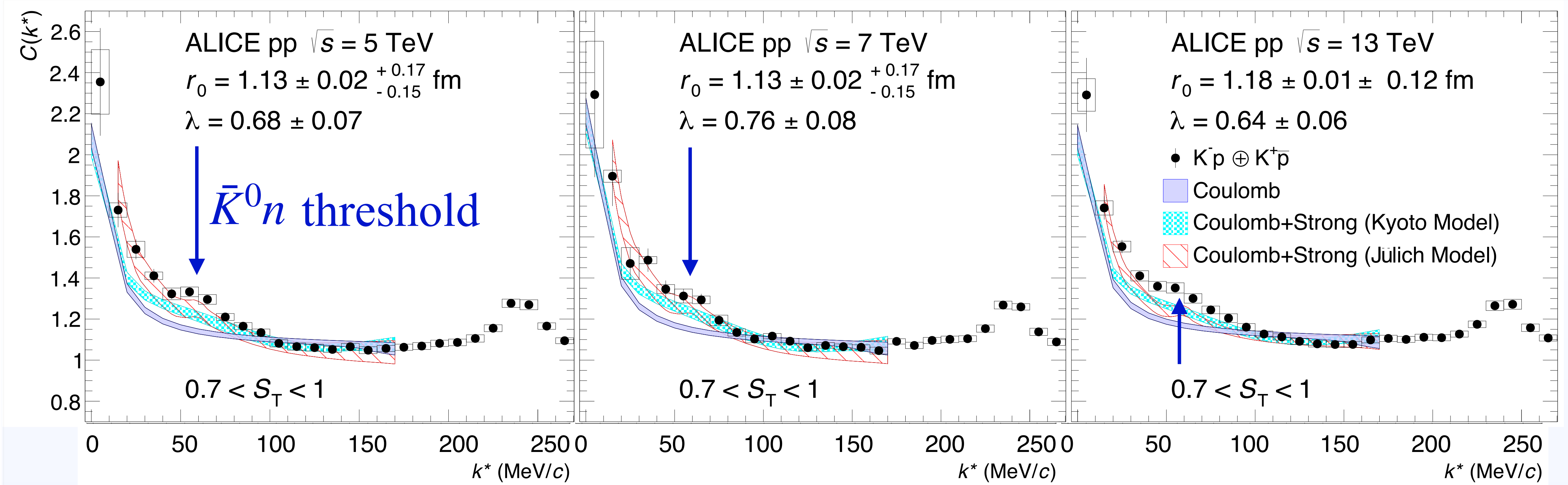
- $p+p$ collision at $\sqrt{s} = 5,\ 7,\ 13$ TeV, source radius $R = 1.13$ fm - 1.18 fm
- Strong enhancement ($C > 1$) at small momenta ==> Coulomb interaction
- But larger than prediction with pure Coulomb ==> Strong interaction
- Characteristic cusp at the $\bar{K}^0 n$ threshold ($k = 58$ MeV) ==> isospin sym. breaking

Can we derive constraint on $\bar{K}N$ interaction from $K^- p$ correlation?

$K^- p$ correlation

- $K^- p$ correlation: Comparison with theoretical models

ALICE, S. Acharya et al., (2019), 1905.13470.



Kyoto Model

Ohnishi et al. NPA 954 (2016)
Cho, et al., PPNP 95 (2017)

- Interaction: Based on Chiral SU(3) dynamics
  Ikeda, Hyodo, Weise, NPA881 (2012)
- Calculated with
  - Coulomb + Strong int.
  - $\bar{K}N$ ($K^-p + \bar{K}^0 n$) w/ isospin ave. mass

Jülich Model

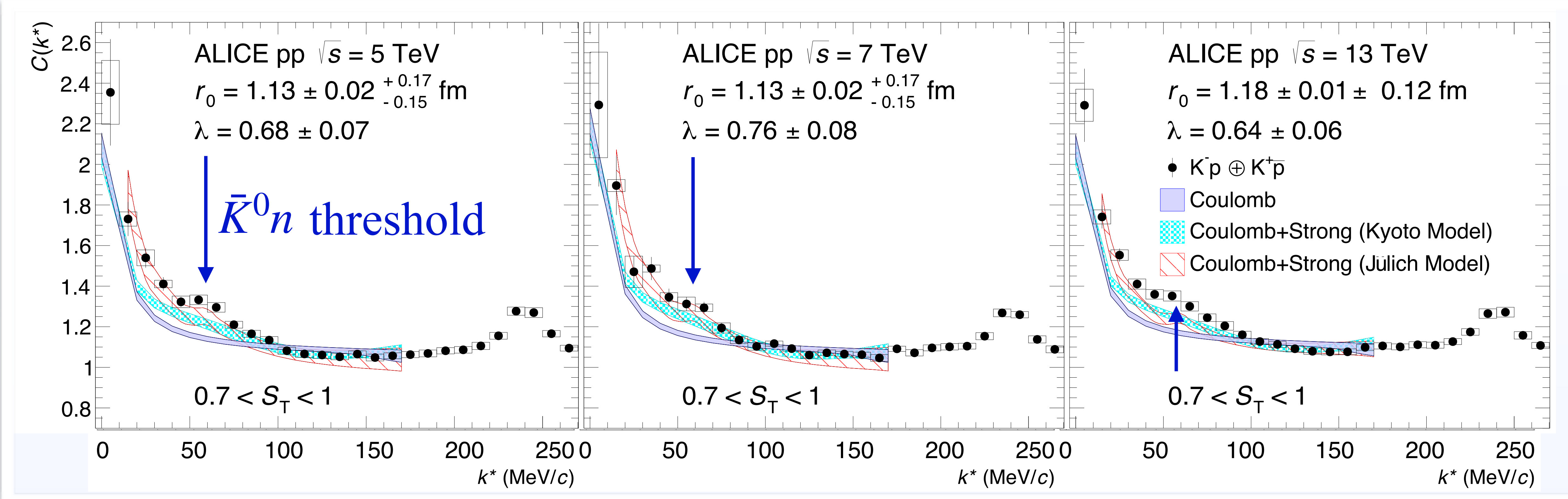
Haidenbauer NPA 981 (2018)

- Interaction: Jülich meson exchange model
  Refitted ver. of Müller-Groeling, et al., NPA 513 (1990)
- Calculated with
  - Coulomb (Gamow) + Strong int.
  - $\bar{K}N + \pi\Sigma + \pi\Lambda$ with particle mass

K^-p correlation

- K^-p correlation: Comparison with theoretical models

ALICE, S. Acharya et al., (2019), 1905.13470.



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- What we need to include
  - Coulomb interaction
  - Coupled-channel (decay channels)
  - Threshold energy difference (K^-p, $\bar{K}^0n$) and open channel contribution ($\bar{K}^0n$)

⇒ We update the Kyoto model calculation and discuss the coupled-channel effect and interaction dependence.

$K^- p$ correlation with Koonin-Pratt Formula

- Koonin-Pratt formula

$$C(\mathbf{k}_1, \mathbf{k}_2) = \frac{\int d^4x_1 \int d^4x_2 S_1(x_1, \mathbf{k}_1) S_2(x_2, \mathbf{k}_2) |\varphi^{(-)}(\mathbf{r}, \mathbf{q})|^2}{\int d^4x_1 S_1(x_1, \mathbf{k}_1) \int d^4x_2 S_2(x_2, \mathbf{k}_2)}$$

- Introduce relative source: $S(\mathbf{k}_i)$
- Move to the center-of-mass frame

$$\boxed{\text{Koonin-Pratt formula} : C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r}) |\varphi^{(-)}(\mathbf{r}, \mathbf{q})|^2}$$

S.E. Koonin, PLB 70 (1977)
S. Pratt et. al. PRC 42 (1990)

- Static Gaussian source function: $S \propto \exp\left(-r^2/4R^2\right)$
  - R : Relative source radius
- Consider only s-wave
- Single-channel, no Coulomb int., non-identical particles

$$\boxed{C(\mathbf{q}) = 1 + \int d^3\mathbf{r}\ S(\mathbf{r}) \left[- |j_0(qr)|^2 + |\chi^{(-)}(r, q)|^2 \right]}$$

Free s-wave:
(Spherical Bessel fcn.)

Scattering wave function:
obtained by solving the Schrödinger Eq.

$K^- p$ correlation with Koonin-Pratt Formula

$$C(\mathbf{q}) = \underline{1} + \int d^3\mathbf{r}\; S(\mathbf{r}) \left[- \underline{|j_0(qr)|^2} + \underline{|\chi^{(-)}(r,q)|^2} \right]$$

- With Coulomb interaction: $V_{\text{Coulomb}} = \alpha / r$

$$C(\mathbf{q}) = \int d^3\mathbf{r}\; S(\mathbf{r}) \left[\underline{|\varphi^{C,\text{full}}(\mathbf{r},\mathbf{q})|^2} - \underline{|j_0^{C}(qr)|^2} + \underline{|\chi^{C,(-)}(r,q)|^2} \right]$$

Full Coulomb wave

Coulomb s-wave:

Scattering wave function with Coulomb int.

Known fcn.
(Confluent hypergeometric fnc.)

Schrödinger Eq. with
$V = V_{\text{strong}} + V_{\text{Coulomb}}$

$K^- p$ correlation with Koonin-Pratt Formula

$$C(\mathbf{q}) = \underline{1} + \int d^3\mathbf{r}\; S(\mathbf{r})\left[-\underline{|j_0(qr)|^2} + \underline{|\chi^{(-)}(r,q)|^2} \right]$$

- With Coulomb interaction: $V_{\text{Coulomb}} = \alpha / r$

$$C(\mathbf{q}) = \int d^3\mathbf{r}\; S(\mathbf{r})\left[\underbrace{|\varphi^{C,\text{full}}(\mathbf{r},\mathbf{q})|^2}_{\text{Full Coulomb wave}} - \underbrace{|j_0^C(qr)|^2}_{\text{Coulomb s-wave:}} + \underbrace{|\chi^{C,(-)}(r,q)|^2}_{\text{Scattering wave function with Coulomb int.}} \right]$$

- Coupled channel case:

$$C_i(\mathbf{q}) = \int d^3\mathbf{r}\; S_i(\mathbf{r})\left[\underline{|\varphi^{C,\text{full}}(\mathbf{r},\mathbf{q})|^2} - \underline{|j_0^C(qr)|^2} + \underline{|\chi_i^{C,(-)}(r,q)|^2} \right] + \sum_{j\neq i} \underbrace{\omega_j \int d^3\mathbf{r}\; S_j(\mathbf{r})\, |\chi_j^{C,(-)}(r,q)|^2}_{\text{Coupled channel effect}}$$

R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)

- ω_j : weight of channel j ==> We assume $\omega_j = 1$.
- $\chi_j^{(-)}(r,q)$: channel j component of wave function with channel i outgoing boundary condition

K^-p correlation with Koonin-Pratt Formula

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

Miyahara, Hyodo, Weise, PRC 98 (2018)

- Constructed based on the amplitude with chiral SU(3) dynamics
  Ikeda, Hyodo, Weise, NPA881 (2012)
- Coupled-channel, energy dependent as

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

- Reproduce the coupled-channel amplitude around the $\bar{K}N$ sub-threshold region

Coupled-channel boundary condition

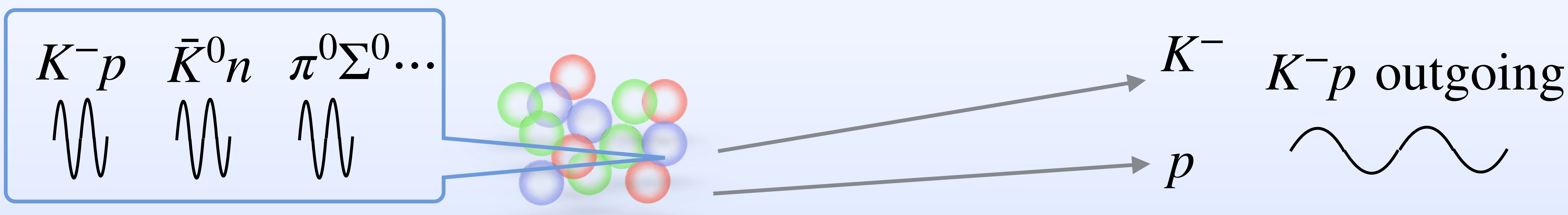
R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)

- Asymptotic waves

$$\text{open channels : } \chi_j^{(C)}(r,q) \to a_j(\text{outgoing wave}) + b_j(\text{incoming wave})$$

$$\text{closed channels : } \chi_j^{(C)}(r,q) \to a_j(\text{diverg. solution}) + b_j(\text{converg. solution})$$

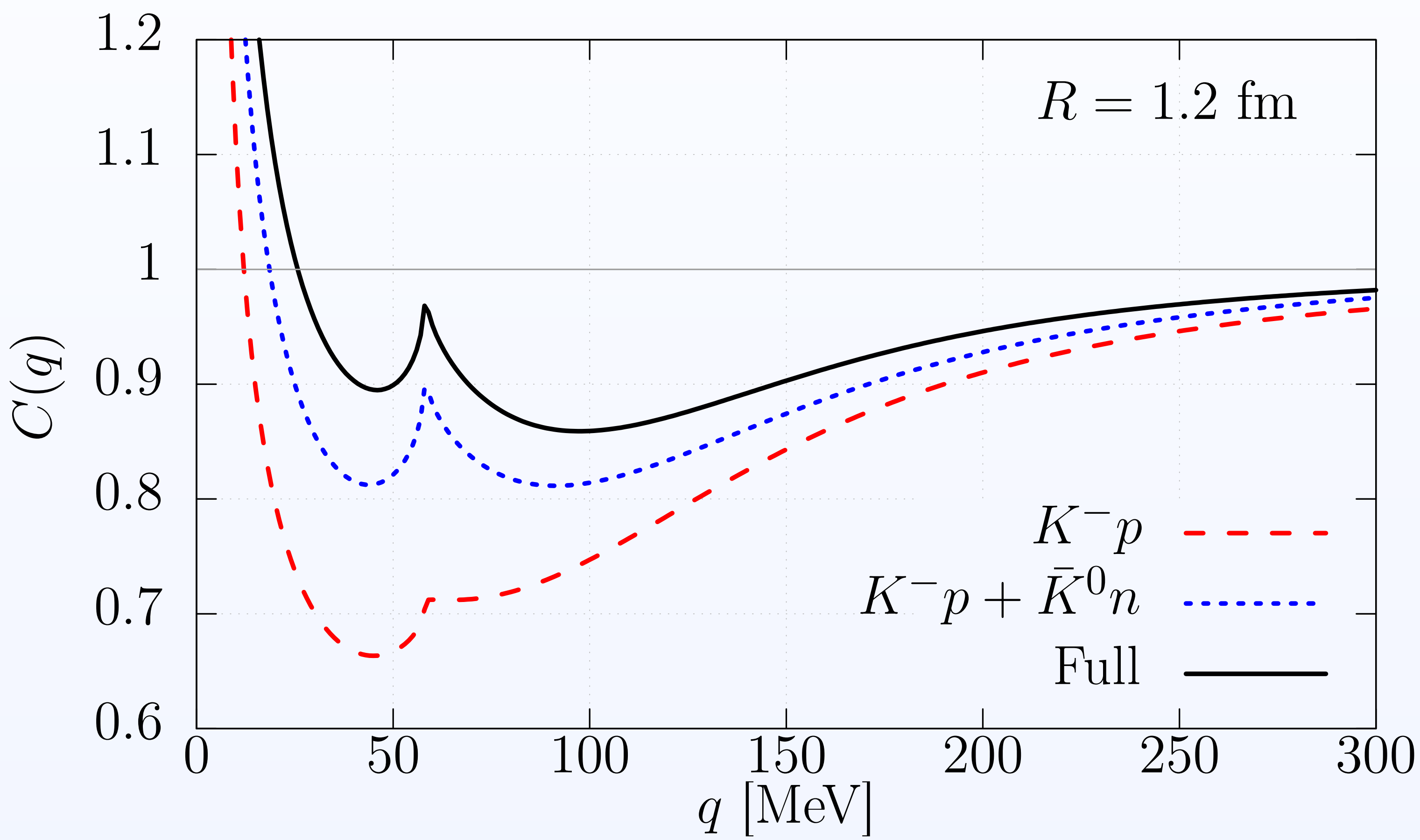
- Out-going wave boundary condition for K^-p channel ; $|a_{K^-p}| = 1, \quad |a_{\text{others}}| = 0$



Results

Preliminary!

- $K^{-}p$ correlation in particle basis w/ Coulomb



- $C(q)$ calculated with $K^{-}p$, $K^{-}p + \bar{K}^0 n$, $\bar{K}N + \pi\Sigma + \pi\Lambda$ components
- Inclusion of $\bar{K}^0 n$ ==> enhance correlation and the cusp structure
- Inclusion of decay channels ==> non-negligible enhancement

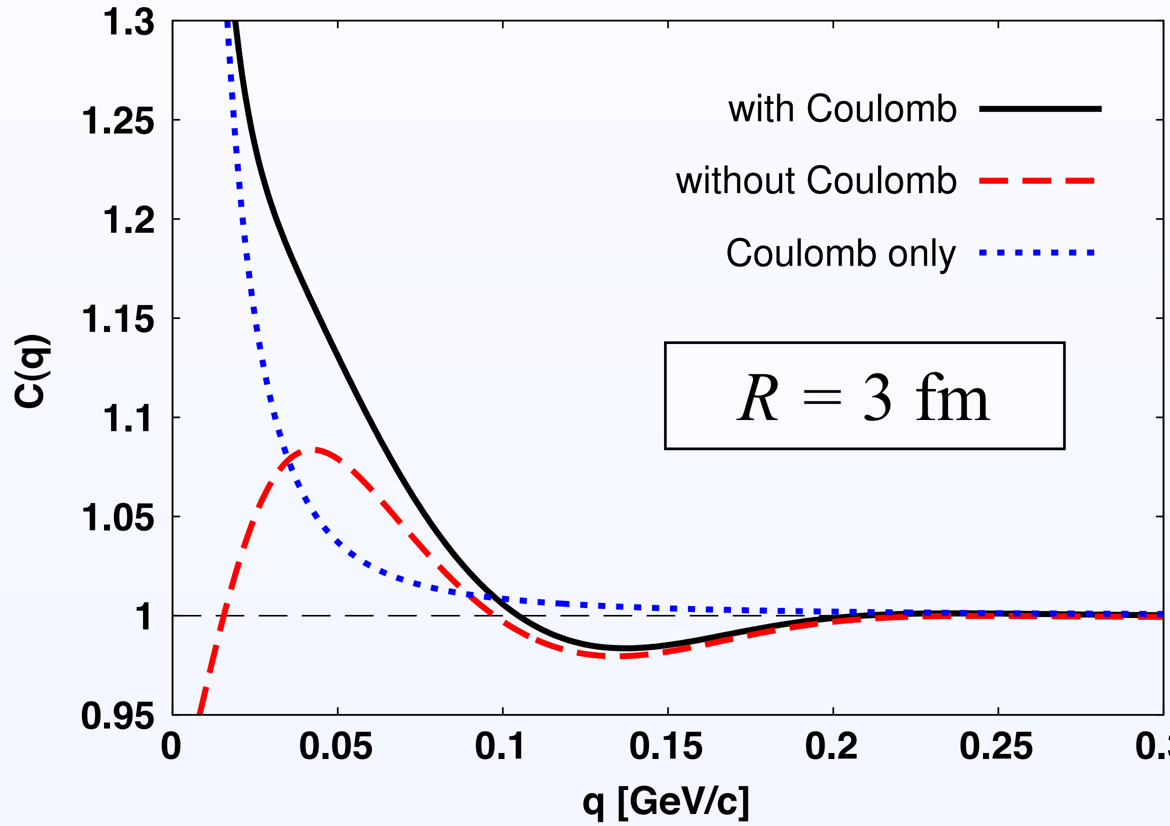
⇨ Inclusion of coupled channel effect is essential for $K^{-}p$ correlation

Results

Preliminary!

- Comparison with previous result

Previous study S. Cho et al., PPNP 95 (2017)

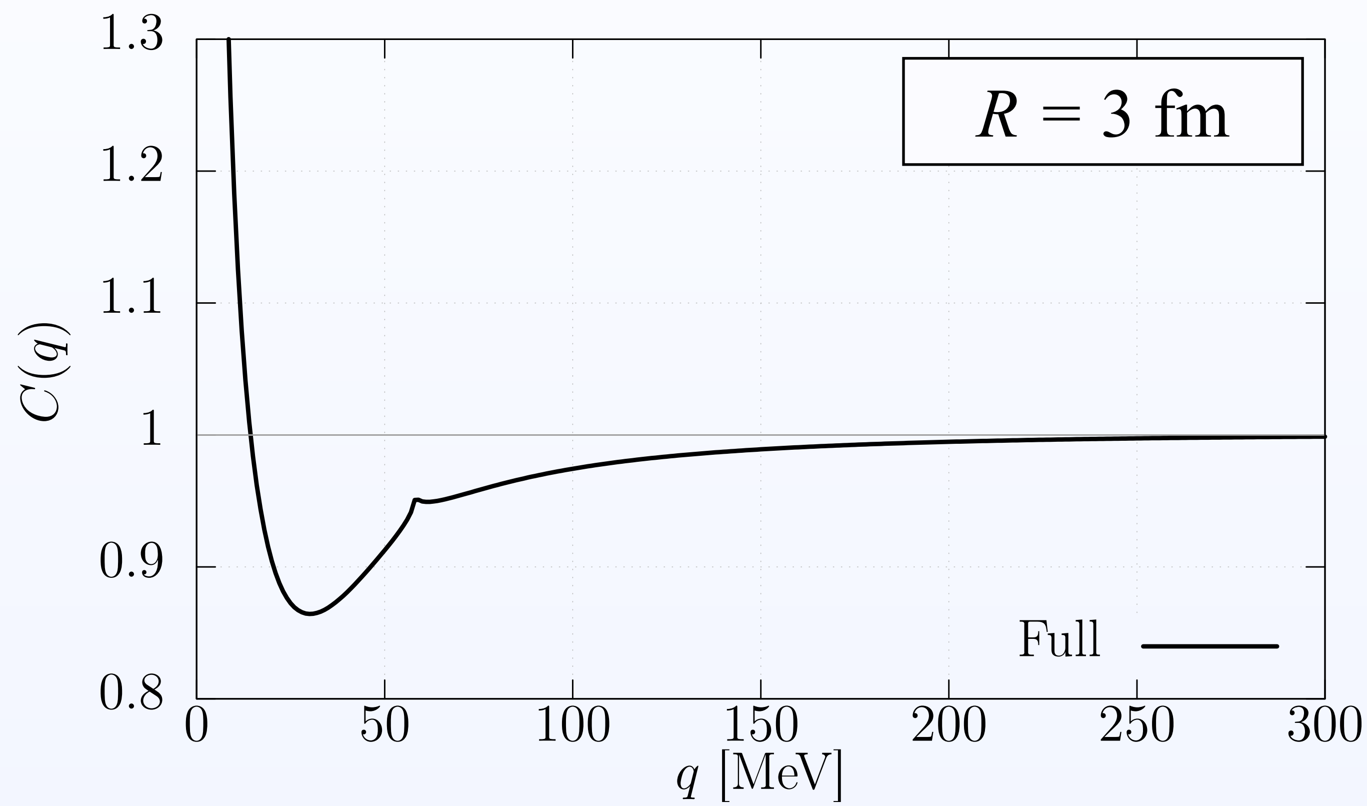


- $\bar{K}N$ single channel potential
- *Approximate* outgoing boundary condition
  (Neglect coupling to $\pi\Sigma$ and $\pi\Lambda$)

$$\psi_{K^-p}(r) \to \frac{1}{2iqr}\left[e^{iqr} - \tilde{\mathcal{S}}^{-1}_{K^-p}\, e^{-iqr}\right]$$

$$\tilde{\mathcal{S}}_{K^-p} = 2\left(\mathcal{S}_0^{-1} + \mathcal{S}_1^{-1}\right)^{-1}, \quad \mathcal{S}_I = e^{2i\delta_I}$$

Current study



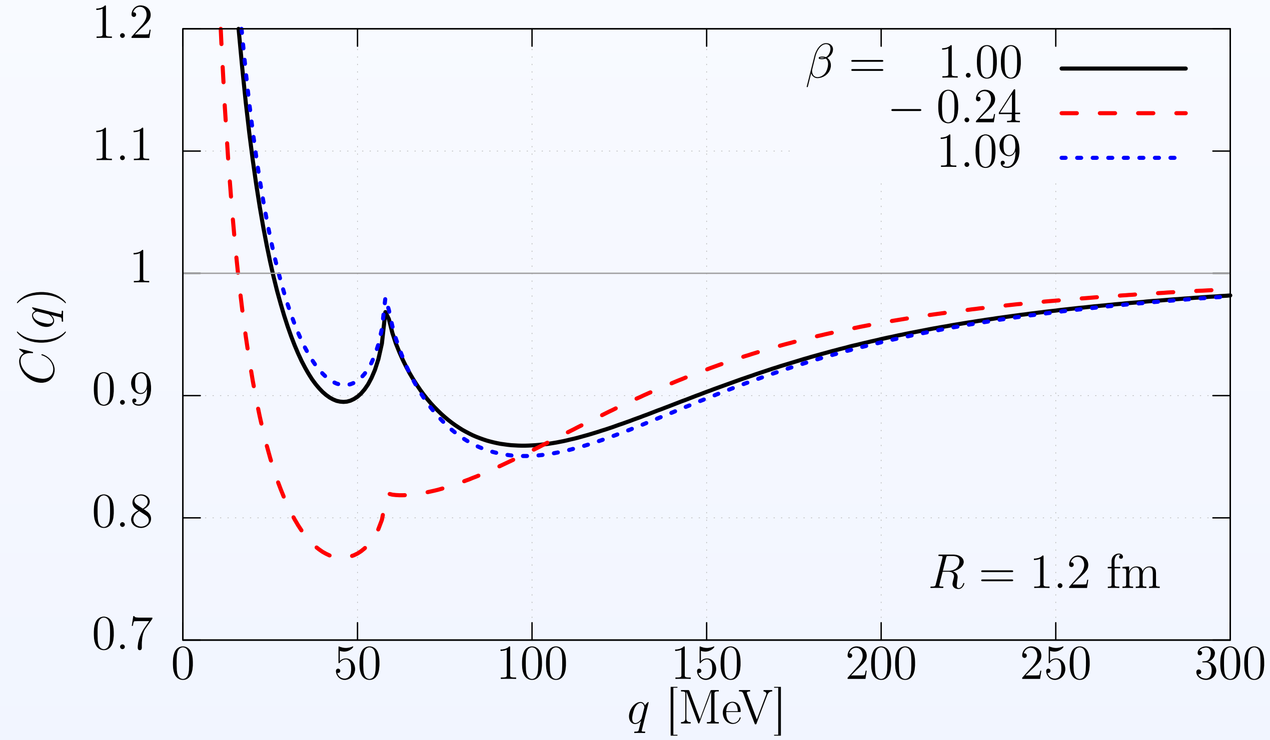
- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
- *Full* outgoing boundary condition

$$\psi \to \frac{1}{2iqr}\left[e^{iqr} - \mathcal{S}^{\dagger}_{K^-pK^-p}\, e^{-iqr}\right] e_{K^-p} - \sqrt{\frac{\mu_{K^-p}\, q}{\mu_{\bar{K}^0 n}\, q_{\bar{K}^0 n}}}\, \mathcal{S}^{\dagger}_{K^-p\bar{K}^0 n}\, e^{-iq_{\bar{K}^0 n} r}\, e_{\bar{K}^0 n}$$

Results

Preliminary!

- Interaction dependence of $\bar{K}N$ correlation
  - $I = 0$ $\bar{K}N$ interaction <== strongly constrained by the SIDDHARTA constraint
    M. Bazzi, et al., NPA 881 (2012)
  - $I = 1$ $\bar{K}N$ interaction is not well known ==> vary $V^{I=1}_{\bar{K}N-\bar{K}N} \to \beta V^{I=1}_{\bar{K}N-\bar{K}N}$
  - SIDDHARTA constraint on $a_0^{K^-p}$ ==> Varied region of β as $-0.24 < \beta < 1.09$



β	$a_0^{K^-p}$ [fm]	$a_0^{\bar{K}N,I=1}$ [fm]
-0.24	0.75-i0.69	-0.07-i0.13
1.00	0.65-i0.91	0.61-i0.78
1.09	0.65-i0.96	0.64 -i0.95

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

- For $\beta = -0.24$,
  - Remarkable suppression around $\bar{K}^0 n$ threshold ($q \simeq 58$ MeV)
  - Moderate cusp structure

$\boxed{I = 1\ \bar{K}N \text{ interaction can be determined with the detailed analysis!}}$

Conclusion

- Hadron correlation in high energy nuclear collisions is a powerful tool to study the interaction of strangeness systems.

- $K^- p$ correlation function has been studied with the Koonin-Pratt formula and interaction based on chiral dynamics, including Coulomb interaction, coupled-channel effect, and threshold energy difference between $K^- p$ and $\bar{K}^0 n$. Characteristic cusp structure is found at $\bar{K}^0 n$ threshold, as found in ALICE data.

- $C(q)$ is also sensitive to $I = 1$ $\bar{K}N$ interaction, so that detailed analysis of $K^- p$ correlation can give the constraint on $I = 1$ interaction.

- Detailed comparison with experimental data ==> Future study

Kamiya, Hyodo, Morita and Ohnishi in preparation

Thank you!

How to study the hadron interaction

$$C_{12}(\mathbf{k}_1, \mathbf{k}_2) = \frac{\int d^4x_1 \int d^4x_2 S_1(x_1, \mathbf{k}_1) S_2(x_2, \mathbf{k}_2) |\varphi^{(-)}(\mathbf{r}, \mathbf{q})|^2}{\int d^4x_1 S_1(x_1, \mathbf{k}_1) \int d^4x_2 S_2(x_2, \mathbf{k}_2)}$$

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

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- Simple model with LL formula

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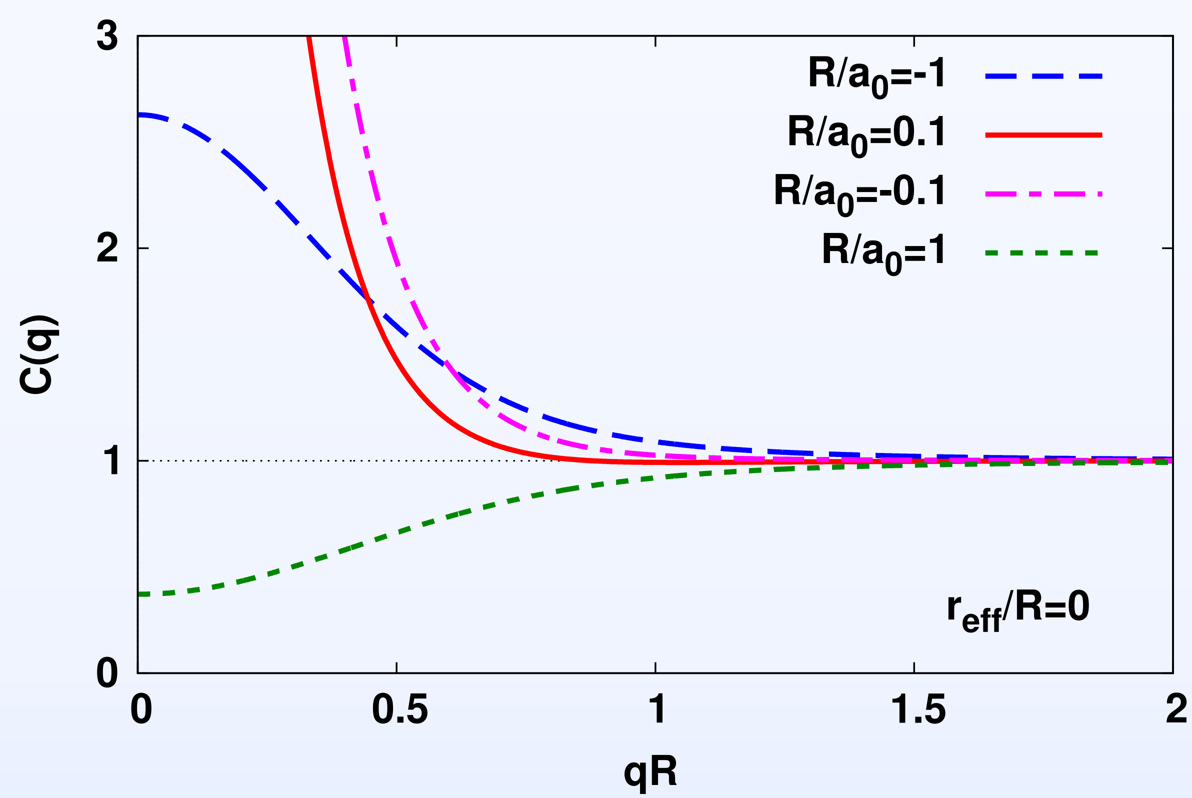


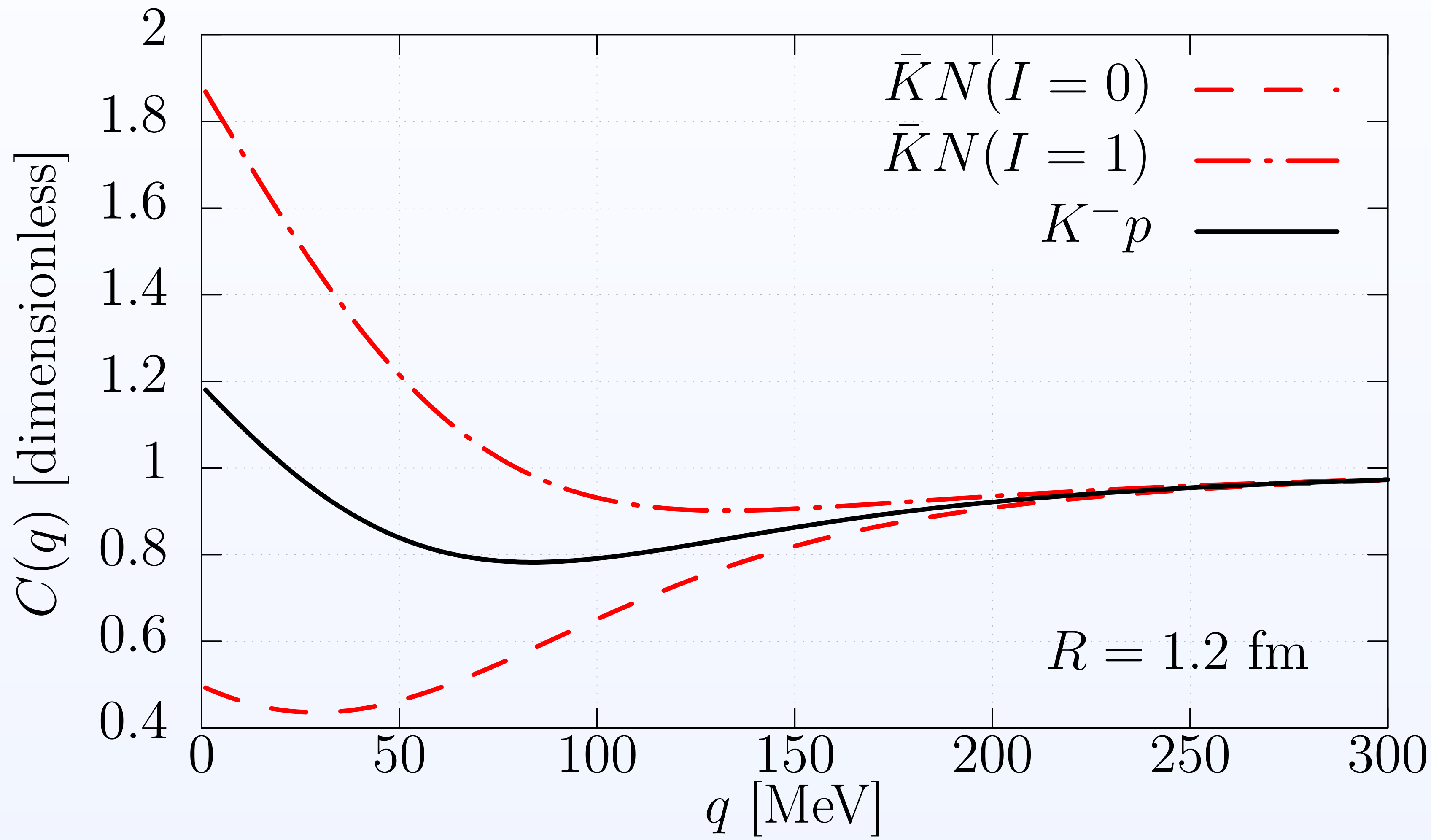
Morita, et al., arXiv:1908.05414

Powerful tool to study hadron interaction in low energy region

Results

Preliminary!

- $K^- p$ correlation in isospin basis w/o Coulomb

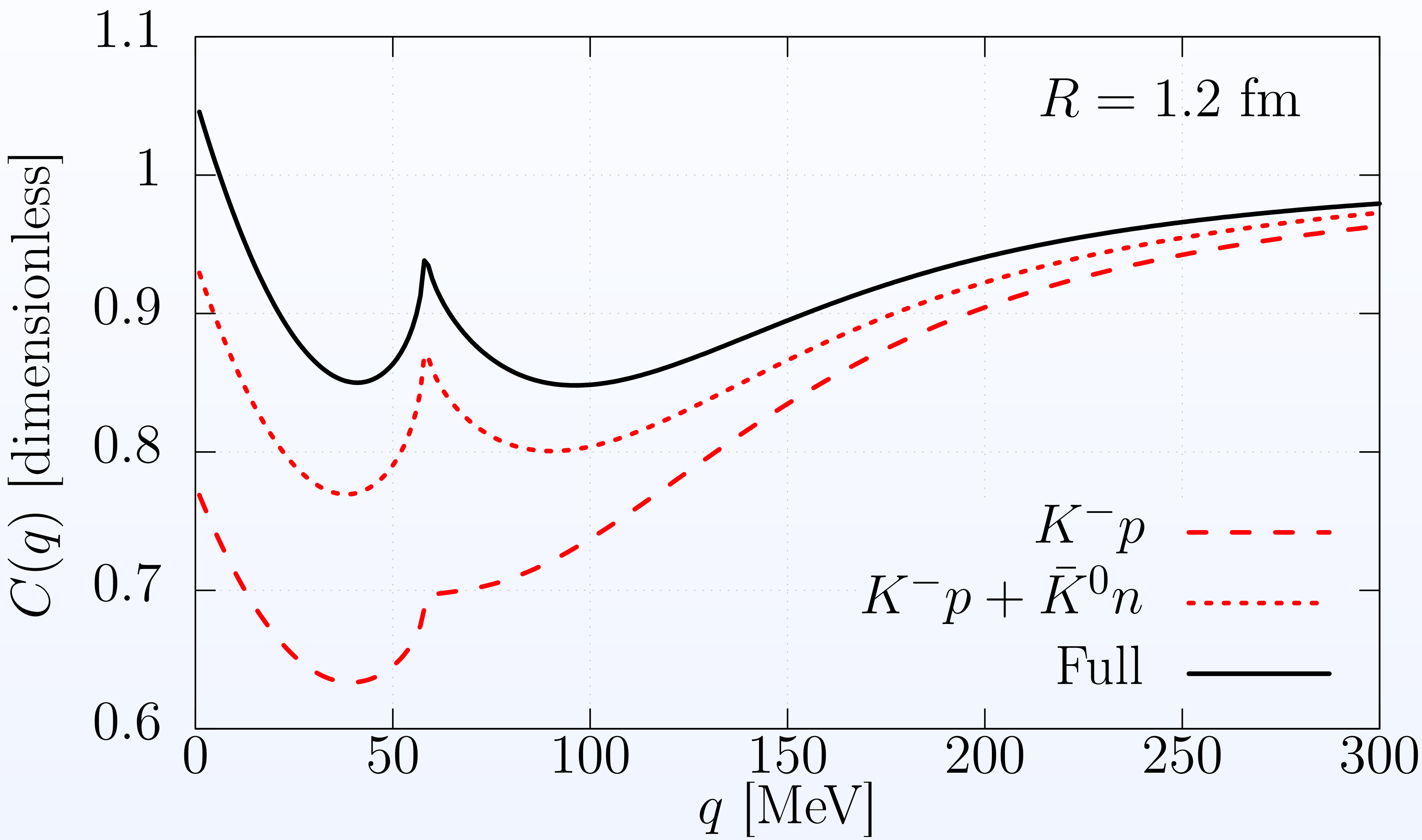


- $C(q)$ calculated only with $\bar{K}N$ ($K^- p + \bar{K}^0 n$) component with $R = 1.2$ fm
- $\mathrm{Re}\ a_0^{I=0} > 0 \Rightarrow C_{\bar{K}N}^{I=0} < 1$, $\mathrm{Re}\ a_0^{I=1} < 0 \Rightarrow C_{\bar{K}N}^{I=1} > 1$ at small q
- $C_{K^- p}(q) = (C_{\bar{K}N}^{I=0} + C_{\bar{K}N}^{I=1})/2$

Results

Preliminary!

- $K^- p$ correlation in particle basis w/o Coulomb



- $C(q)$ calculated with $K^- p$, $K^- p + \bar{K}^0 n$, all of coupled-channel components
- Inclusion of $\bar{K}^0 n$ ==> enhance correlation and the cusp structure
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Results

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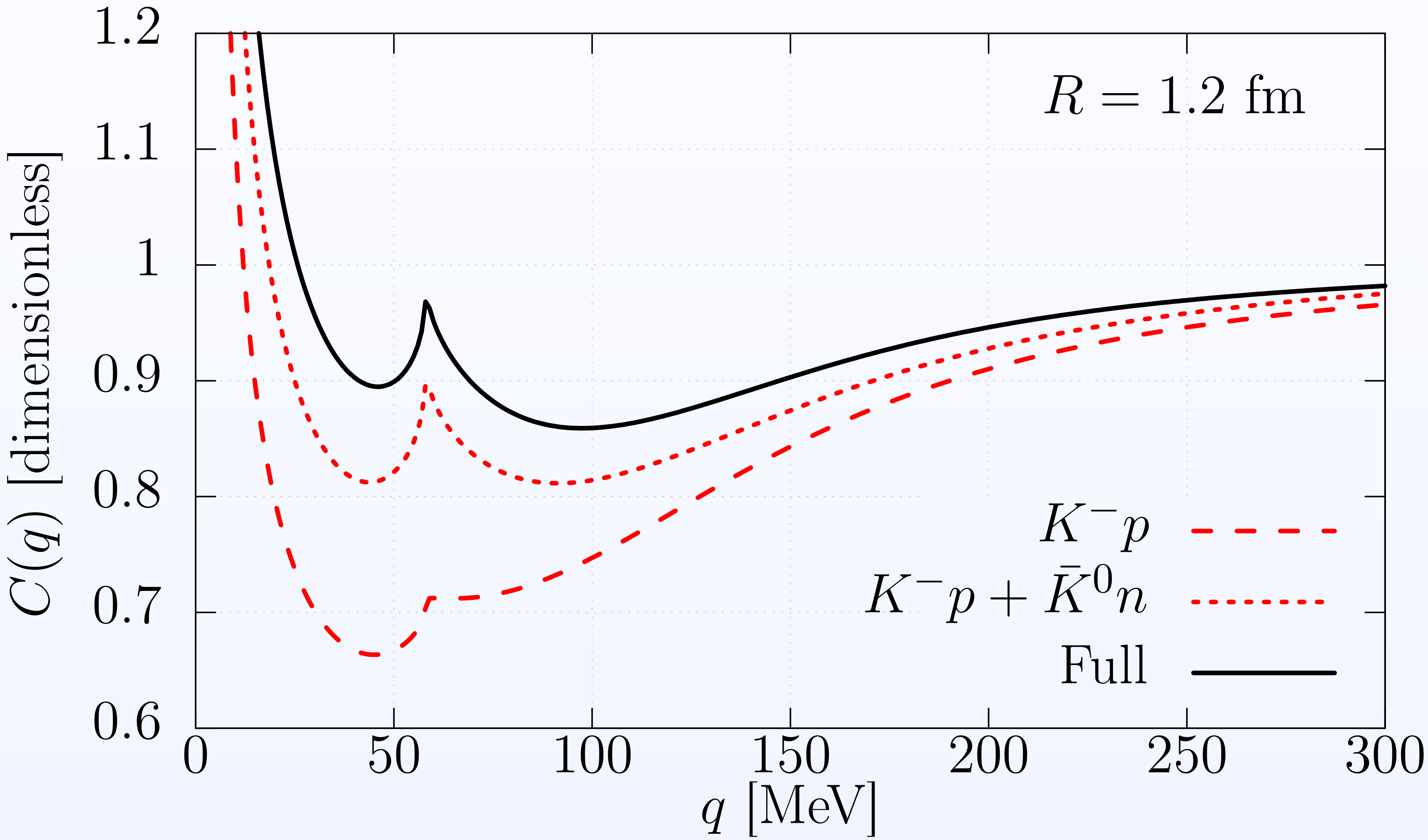
- K^-p correlation in particle basis w/ Coulomb

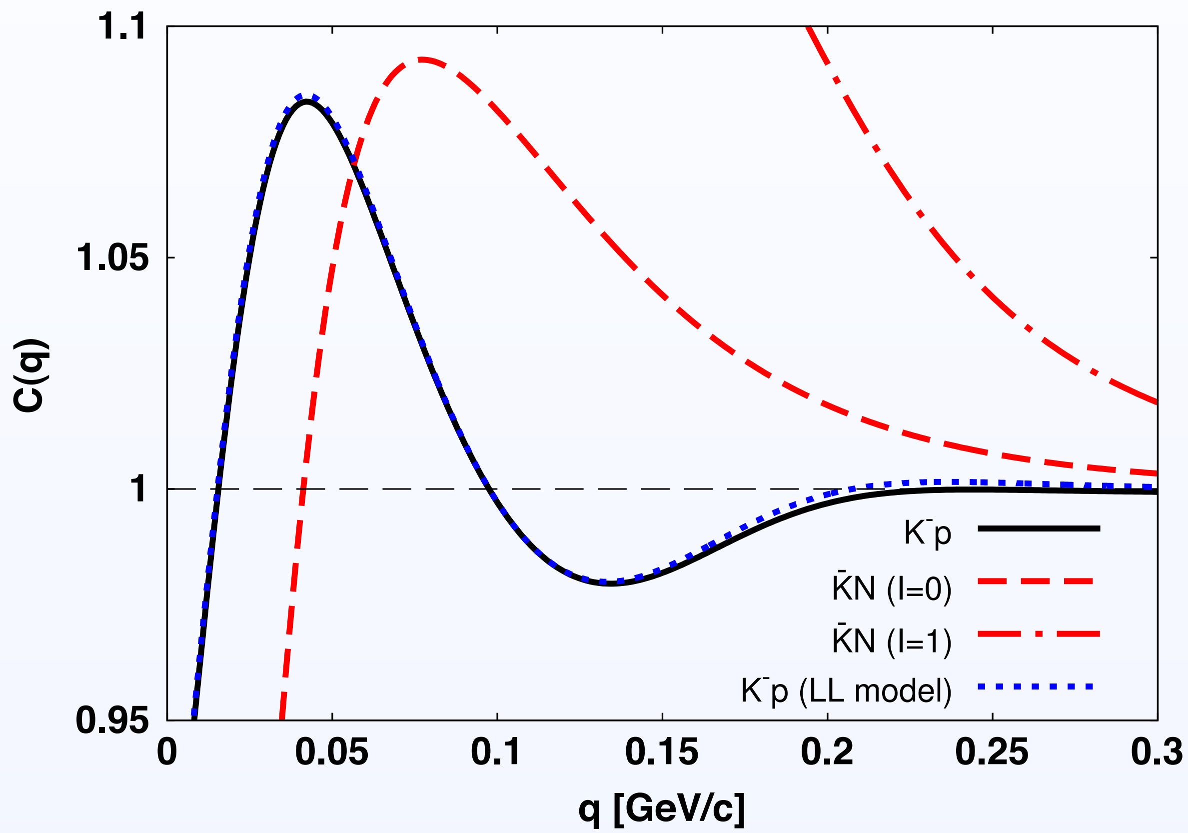


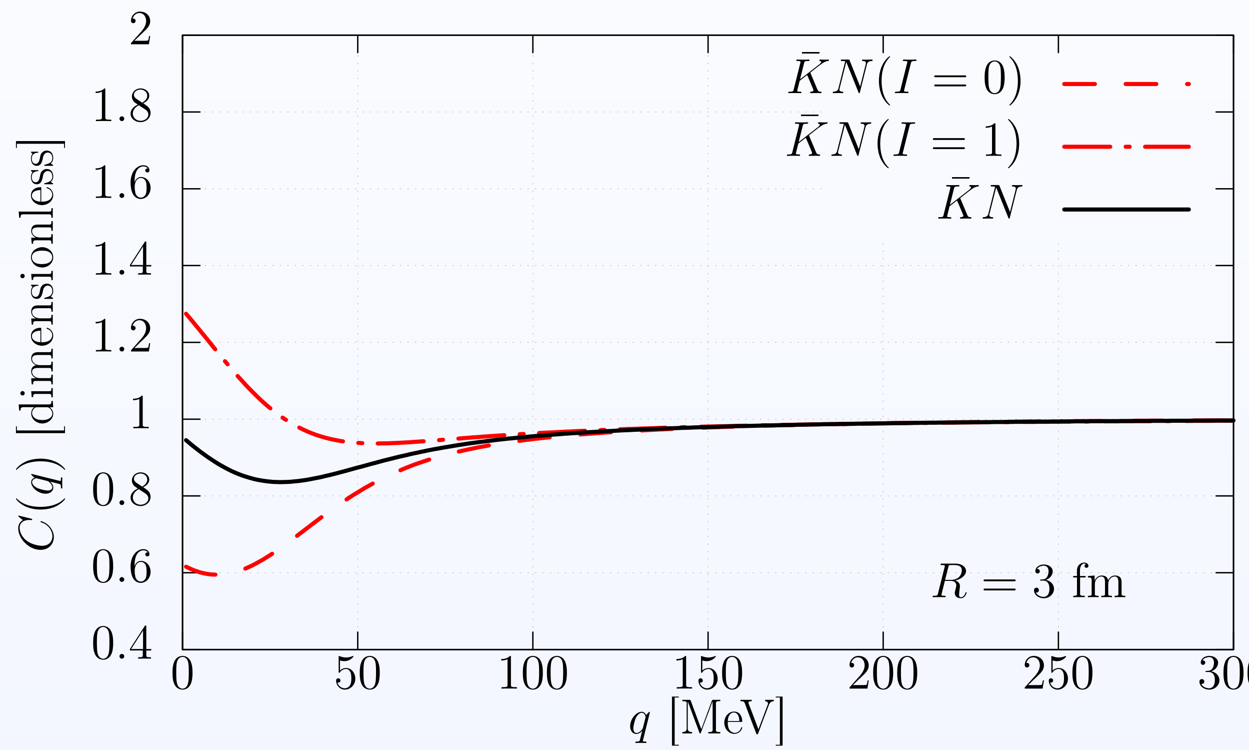
- $C(q)$ calculated with K^-p, $K^-p + \bar{K}^0 n$, all of coupled-channel components
- Strong enhancement at the small $q \lesssim 20$ MeV
- Cusp structure is still clear

Comparison with previous result

- Comparison with previous results

S. Cho et al., Prog. Part. Nucl. Phys. 95, 279 (2017)]





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  (Neglect coupling to $\pi\Sigma$ and $\pi\Lambda$)

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$$\tilde{\mathcal{S}}_{K^-p} = 2\left(\mathcal{S}_0^{-1} + \mathcal{S}_1^{-1}\right)^{-1}, \quad \mathcal{S}_I = e^{2i\delta_I}$$

- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
- *Full* outgoing boundary condition

$$\psi \to \frac{1}{2iqr}[e^{iqr} - \mathcal{S}^{\dagger}_{K^-pK^-p} e^{-iqr}] e_{K^-p}$$
$$-\sqrt{\frac{\mu_{K^-p} q}{\mu_{\bar{K}^0 n} q_{\bar{K}^0 n}}} \mathcal{S}^{\dagger}_{K^-p\bar{K}^0 n} e^{-iq_{\bar{K}^0 n} r} e_{\bar{K}^0 n}$$

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Preliminary!

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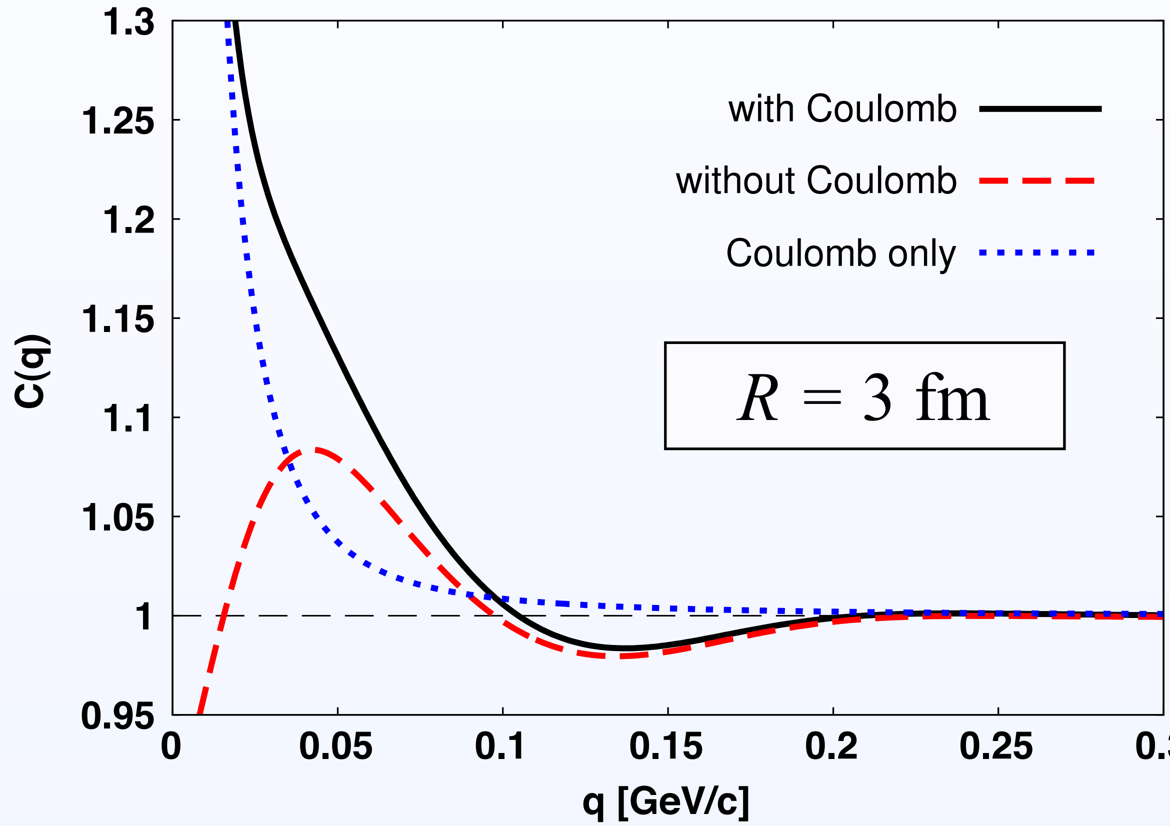
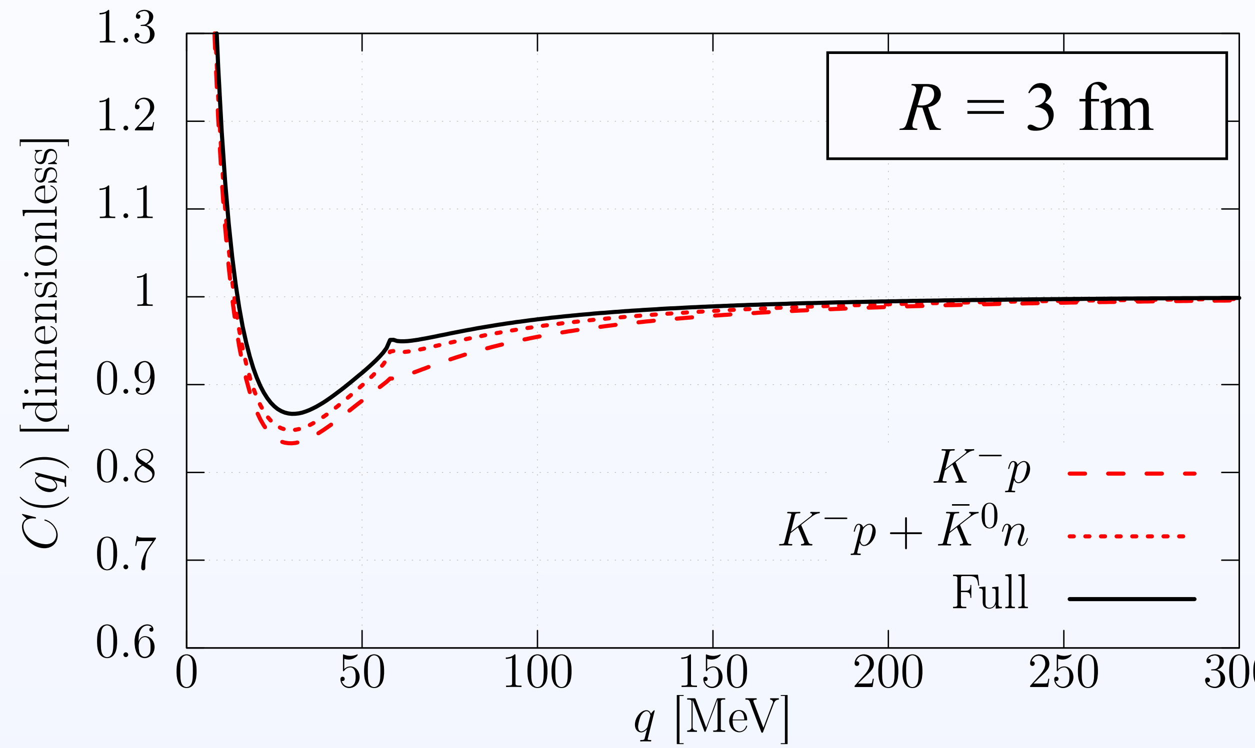


Current study



- $\bar{K}N$ single channel potential
- <u>*Approximate* outgoing boundary condition</u>

  (Neglect coupling to $\pi\Sigma$ and $\pi\Lambda$)

$$\psi_{K^-p}(r) \to \frac{1}{2iqr}\left[e^{iqr} - \tilde{\mathcal{S}}^{-1}_{K^-p} e^{-iqr}\right]$$

$$\tilde{\mathcal{S}}_{K^-p} = 2\left(\mathcal{S}_0^{-1} + \mathcal{S}_1^{-1}\right)^{-1}, \quad \mathcal{S}_I = e^{2i\delta_I}$$

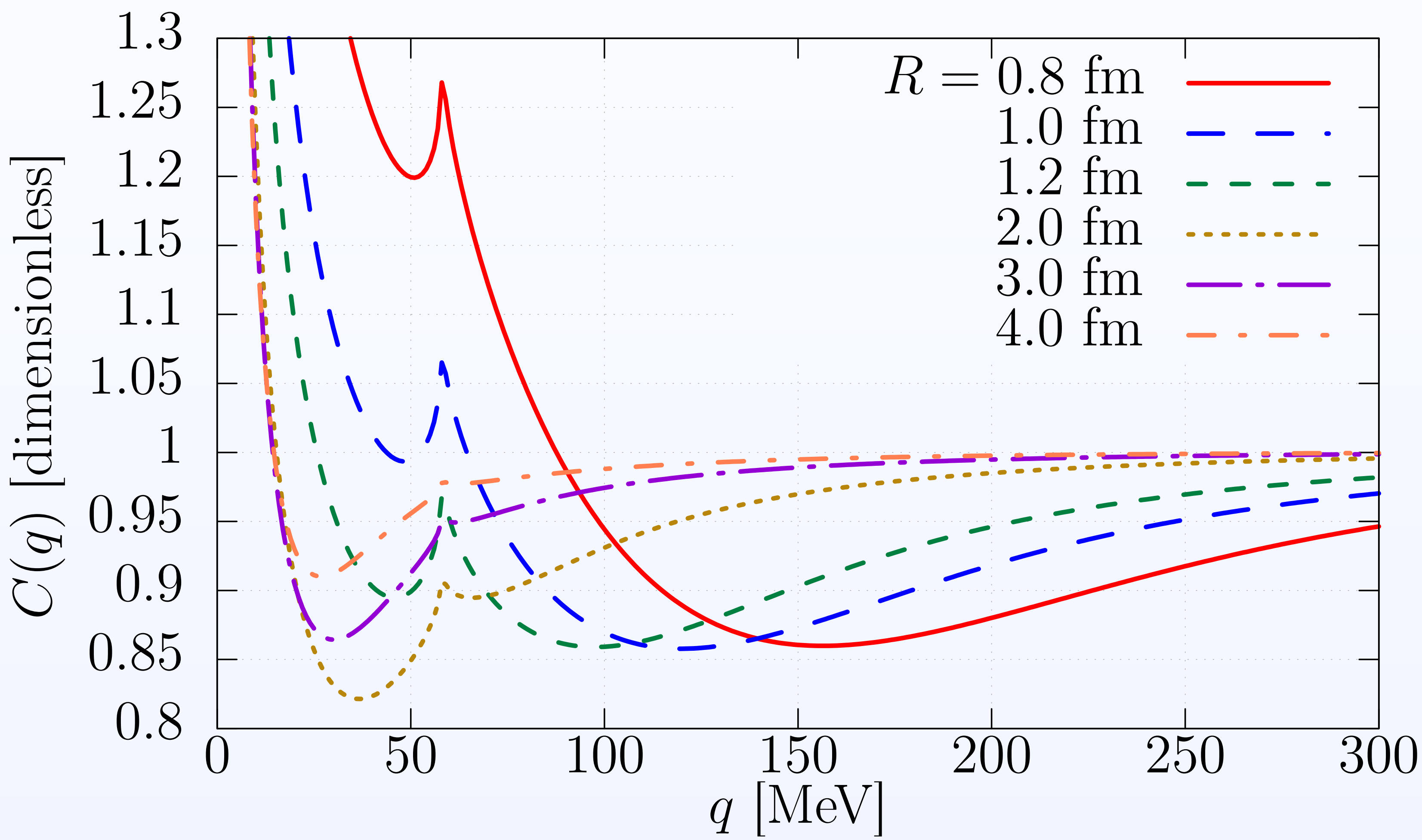
- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
- <u>*Full* outgoing boundary condition</u>

$$\psi \to \frac{1}{2iqr}[e^{iqr} - \mathcal{S}^{\dagger}_{K^-pK^-p} e^{-iqr}] e_{K^-p}$$
$$- \sqrt{\frac{\mu_{K^-p} q}{\mu_{\bar{K}^0 n} q_{\bar{K}^0 n}}} \mathcal{S}^{\dagger}_{K^-p\bar{K}^0 n} e^{-iq_{\bar{K}^0 n} r} e_{\bar{K}^0 n}$$

Results

Preliminary!

- Source size dependence of $K^{-}p$ correlation



- Strong dependence around $R \sim 1.0$ fm
  <== • Sensitive region: $|R/a_0| \lesssim 1.$
- Larger system (> 3 fm) : cusp effect is moderate