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

In collaboration with
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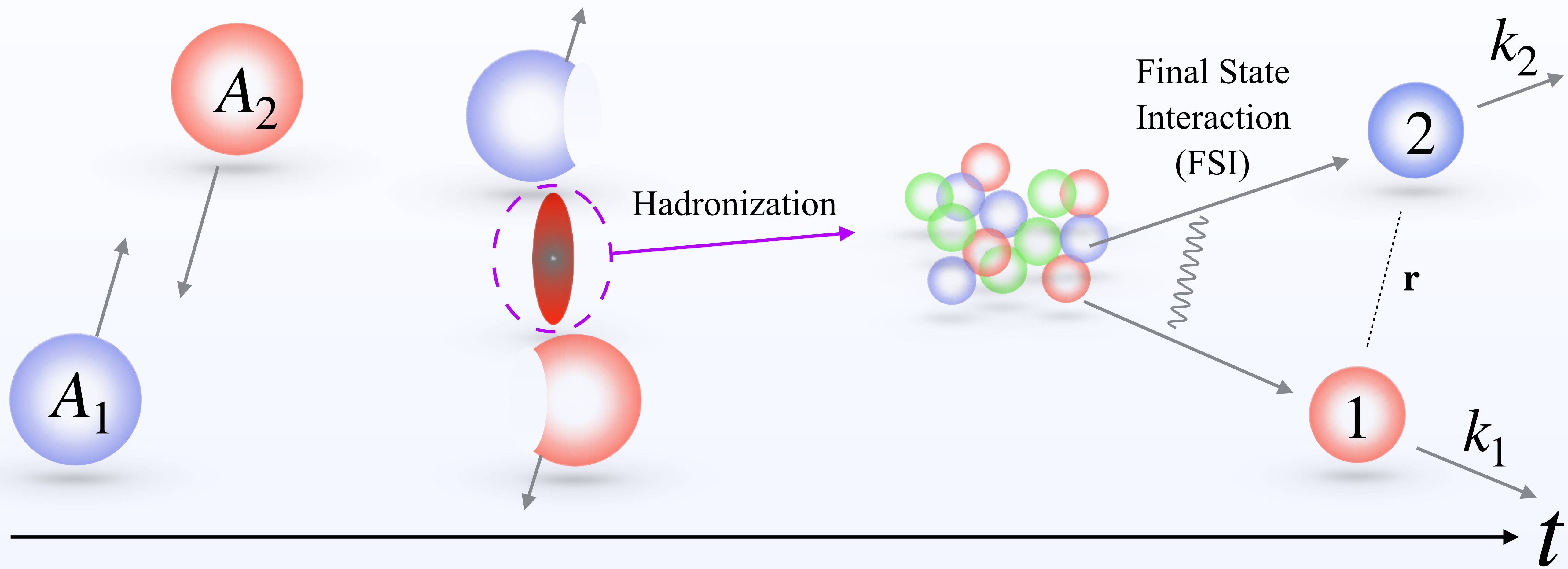
Contents

- Introduction: Hadron correlation in high energy nuclear collisions
- $K^{-}p$ correlation function with coupled-channel chiral SU(3) potential
- Comparison with ALICE $K^{-}p$ data
- Summary

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi and W. Weise, arXiv:1911.01041

- High energy nuclear collision and FSI

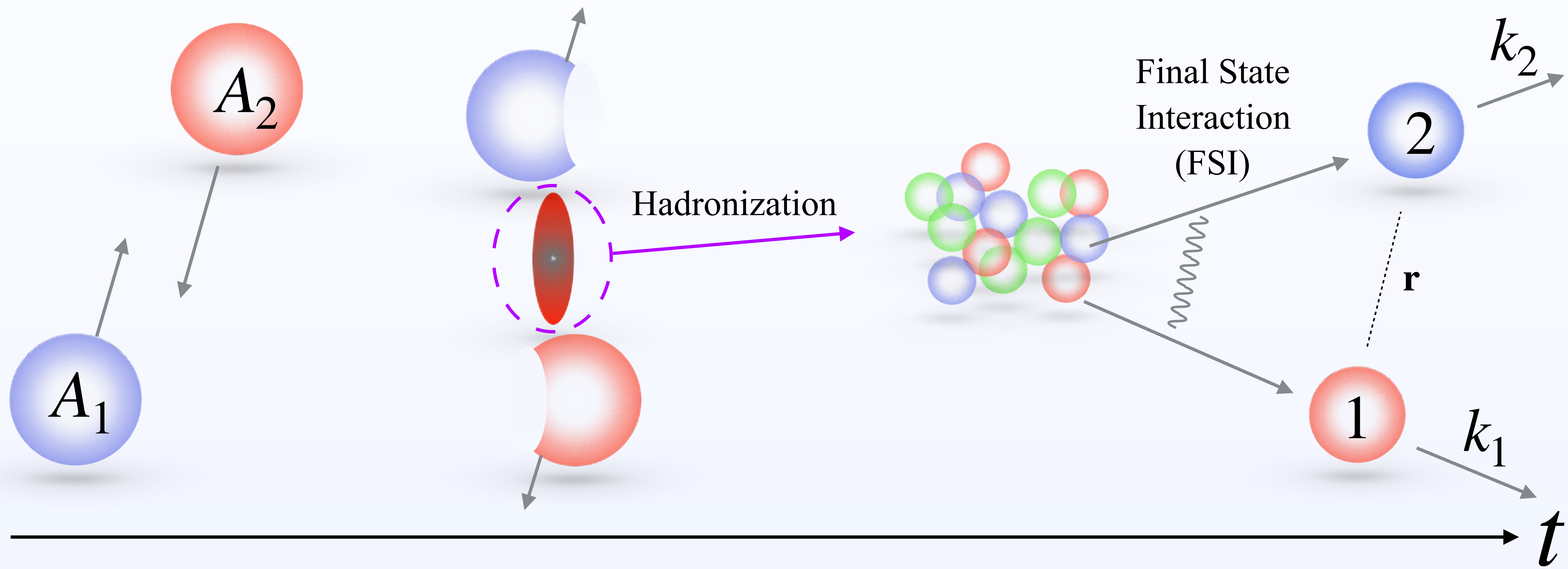


- Hadron-hadron correlation

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

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

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)

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

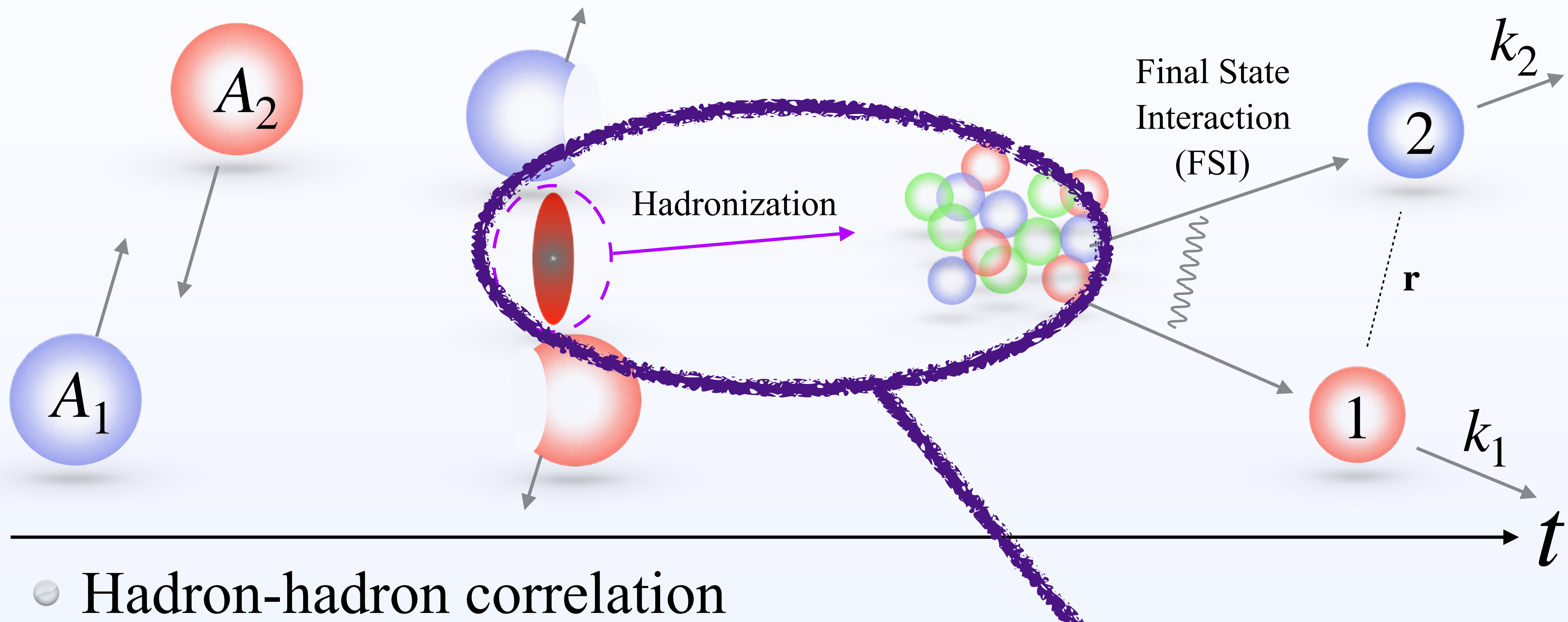
$$\mathbf{q} = (m_2\mathbf{k}_1 - m_1\mathbf{k}_2)/(m_1 + m_2)$$

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

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

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)

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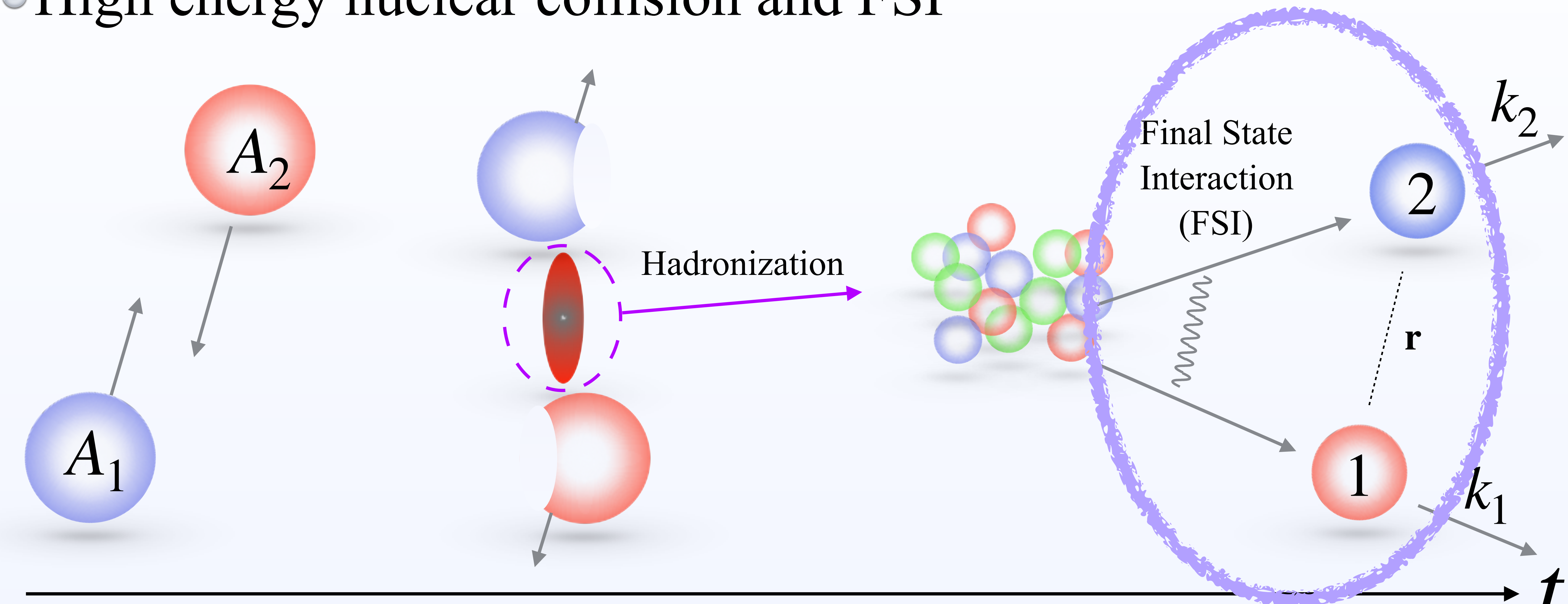
$S(\mathbf{r})$: Source function

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

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

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



- Hadron-hadron correlation
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$S(\mathbf{r})$: Source function

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

- Depends on …

  Interaction (strong and Coulomb)

  quantum statistics (Fermion, boson)

- How to study the hadron interaction

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

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

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

- Study on hadron source; $S(\mathbf{r})$
  - Source size, source shape,…

- Study on interaction; $\varphi^{(-)}(\mathbf{q},\mathbf{r})$
  - Wave function is distorted by the final state interaction of hadron pair
  - Systems with less known interaction

    (e.g. $\Lambda\Lambda$, $N\Xi$, $N\Omega$, $\bar{K}N$)
  - Advantages; rare opportunity to investigate interaction of …
    - short-lived hadrons (strangeness system, anti-baryons)
    - low-energy (low-momentum) region

How to study the hadron interaction

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

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

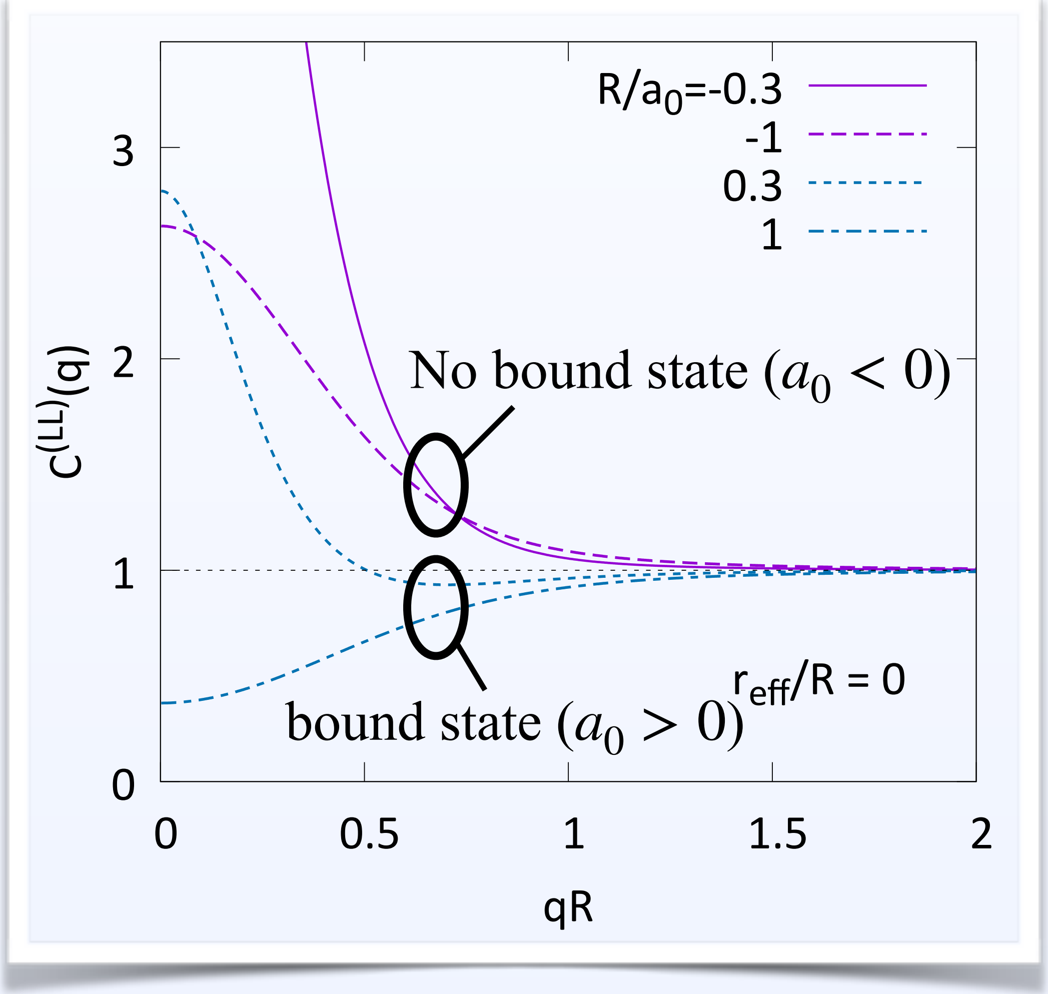
$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

- Lednicky-Lyuboshits (LL) formula

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

$$C(q) = 1 + \left[\frac{|\mathcal{F}(q)|^2}{2R^2}F_3\left(\frac{r_{\mathrm{eff}}}{R}\right) + \frac{2\mathrm{Re}\,\mathcal{F}(q)}{\sqrt{\pi}R}F_1(x) - \frac{\mathrm{Im}\,\mathcal{F}(q)}{R}F_2(x)\right]$$

  - Static Gaussian source
  - Asymptotic wave fcn. with effective range expansion



Morita, et al., arXiv:1908.05414

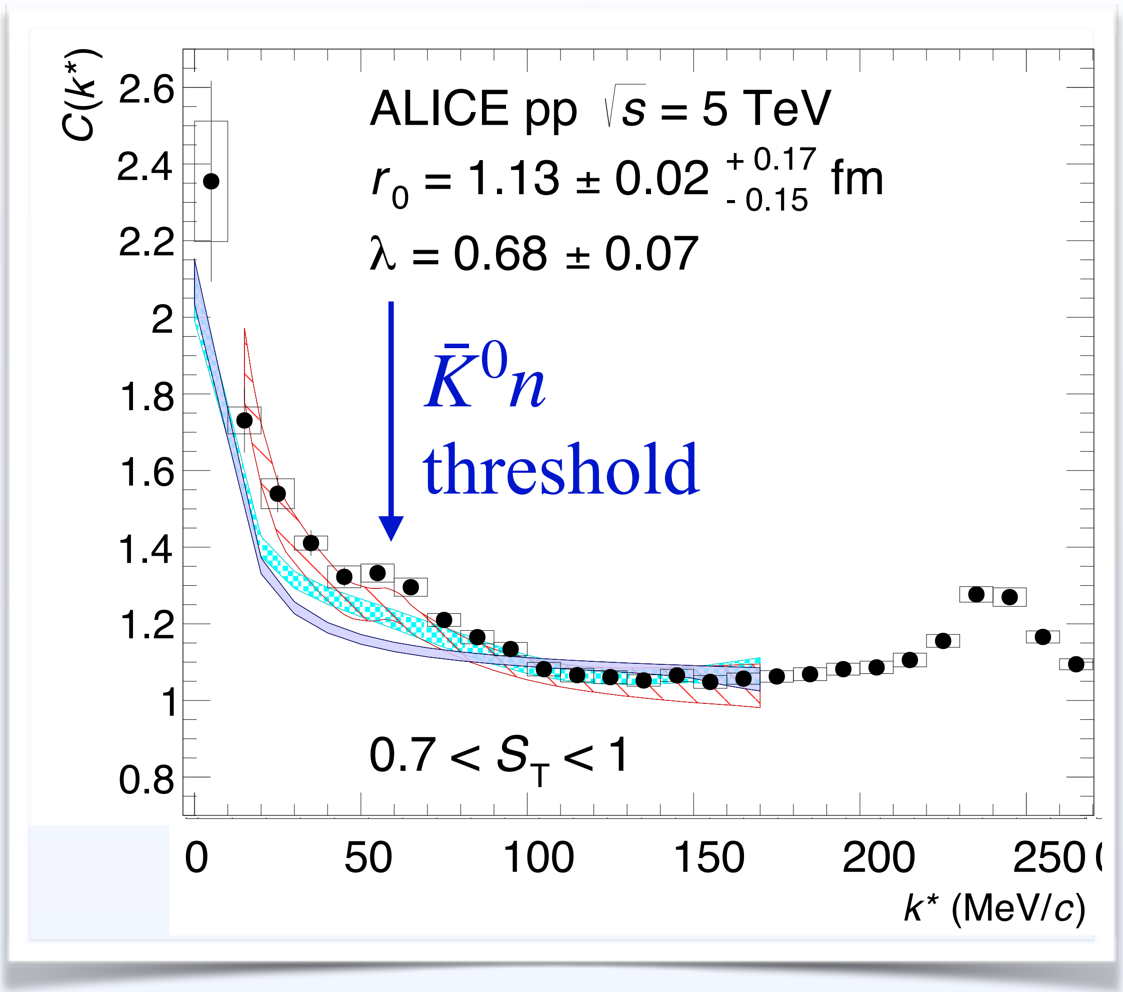
- $C(q)$ is sensitive to R/a_0
  - R : Gaussian source size
  - a_0: scattering length ($\equiv -\mathcal{F}(q=0)$)

Powerful tool to study hadron interaction in low energy region

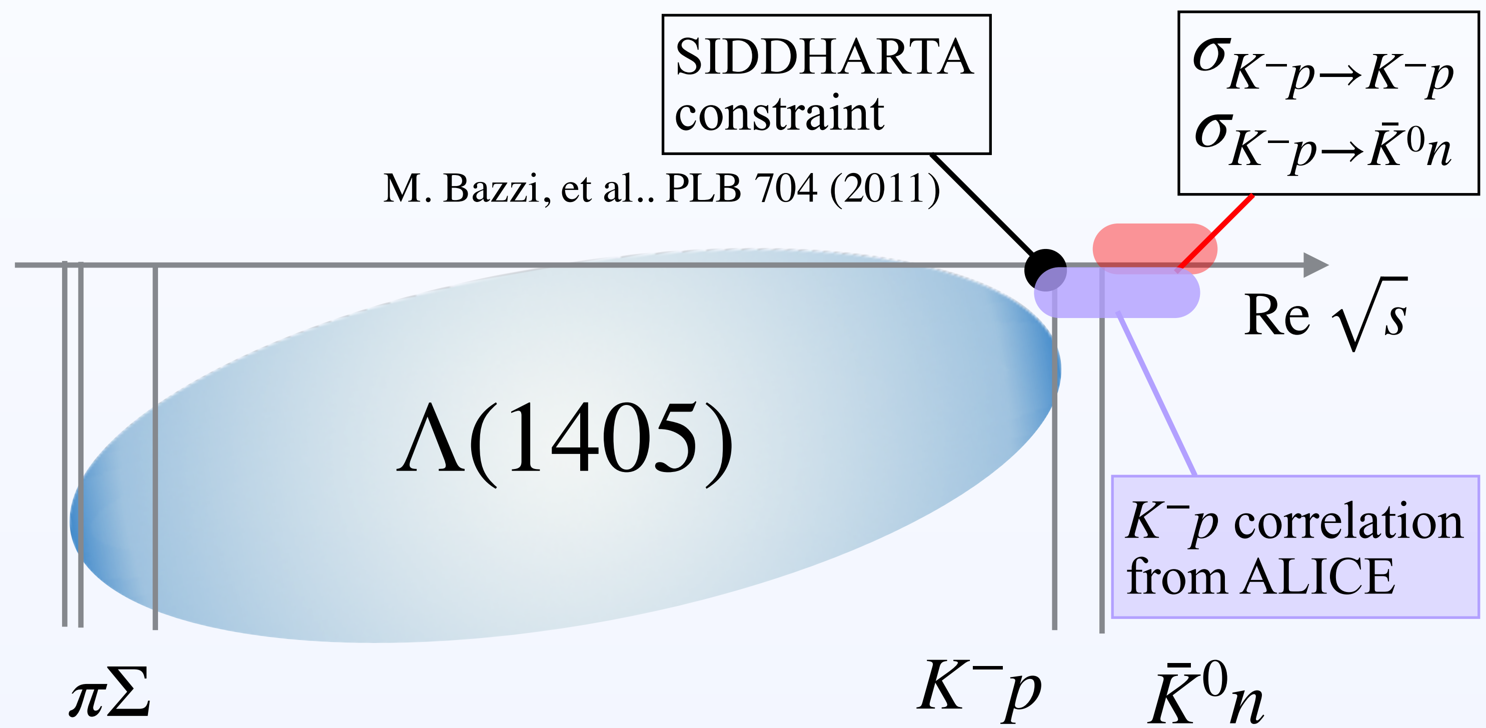
K^-p correlation

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

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



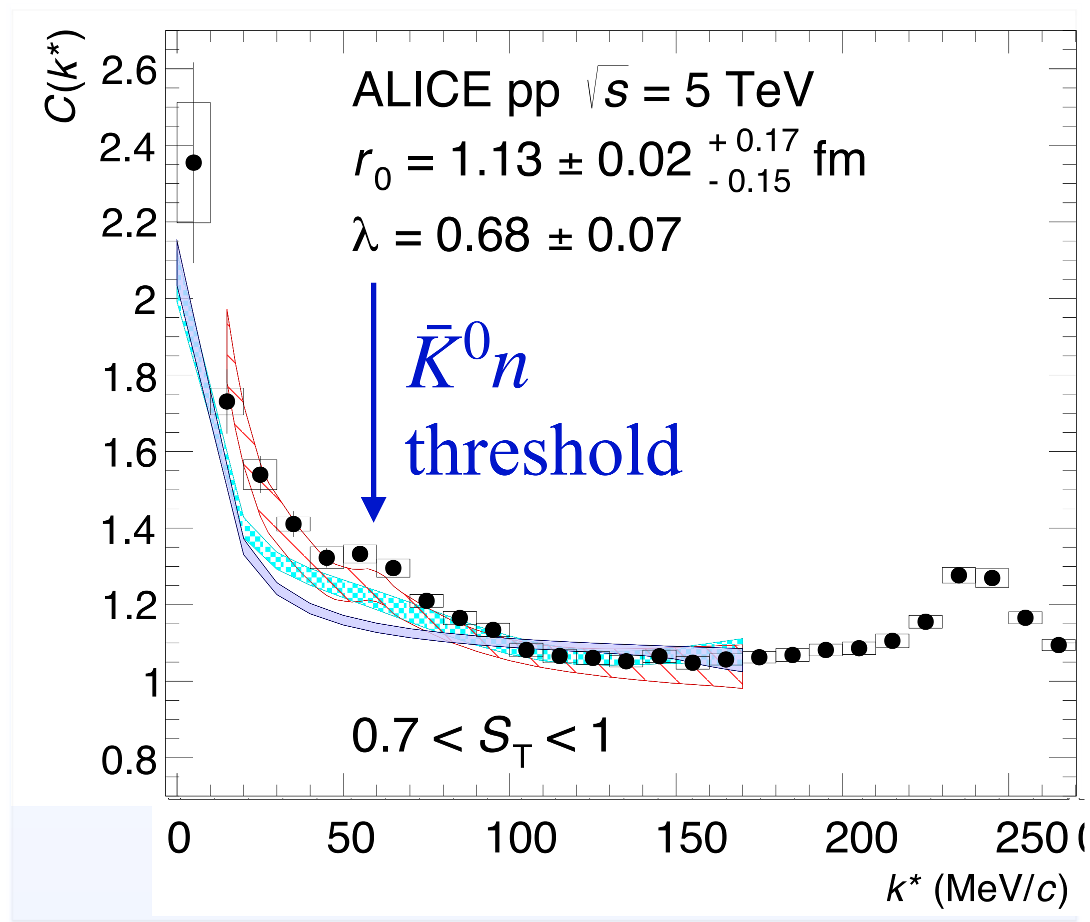
- Experimental data on $\bar{K}N$ int.



- High-multiplicity events of *pp* collisions
- Strong enhancement ($C > 1$) at small momenta ==> <u>Coulomb interaction</u>
- Deviation from with pure Coulomb case ==> Strong interaction
- Characteristic cusp at the $\bar{K}^0 n$ threshold ($k = 58$ MeV) ==> <u>isospin sym. breaking</u>

K^-p correlation

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

We update the Kyoto model to include
- Coupled-channel effect
- Coulomb interaction
- threshold energy difference of isospin multiplets

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K^-p correlation with Koonin-Pratt Formula

- Koonin-Pratt formula for K^-p correlation

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

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

- Consider only s-wave interaction
- non-identical particles

R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)
Haidenbauer NPA 981 (2018)

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\Big[\underbrace{|\varphi^{C,\text{full}}(\mathbf{q};\mathbf{r})|^2 - |\phi_0^C(qr)|^2}_{\text{Free Coulomb wave } (l \geq 1 \text{ waves})} + \underbrace{|\psi_{K^-p}^{C,(-)}(q;r)|^2}_{\text{Scattering } s\text{-wave function with Coulomb int.}}\Big] + \underbrace{\sum_{j\neq i} \omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2}_{\text{Coupled-channel source contribution}}$$

- ω_j : weight of channel j
- $\psi_j^{(-)}(q;r)$: channel j component of wave function with channel i outgoing boundary condition

K^-p correlation with Koonin-Pratt Formula

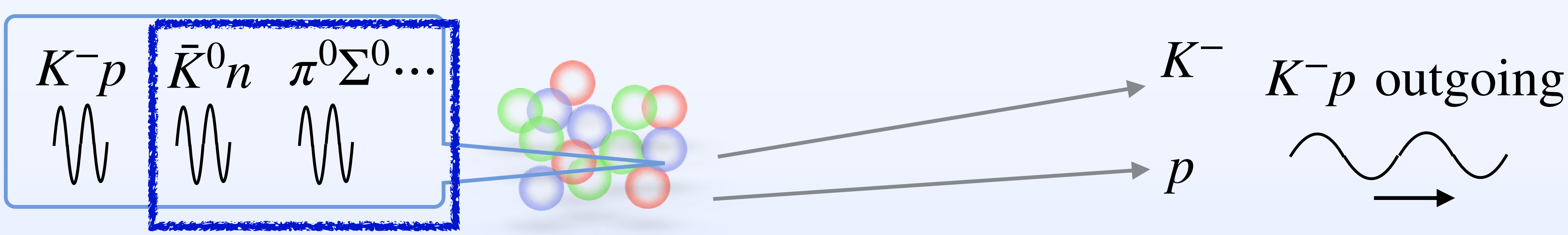
- How coupled-channel effect contributes on correlation

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\left[\,|\varphi^{C,\mathrm{full}}(\mathbf{q};\mathbf{r})|^2 - |\phi_0^C(qr)|^2 + |\psi^{C,(-)}_{K^-p}(q;r)|^2\right] + \sum_{j\neq K^-p} \omega_j \left[\int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2\right]$$

(1) Modification of wave function of observed channel: $\psi^{C,(-)}_{K^-p}$

$$\left[T + \begin{pmatrix} V_{11} & V_{12} & \cdots \\ V_{21} & V_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}\right]\begin{pmatrix} \psi_{K^-p} \\ \psi_{\bar{K}^0 n} \\ \psi_{\pi^-\Sigma^+} \\ \vdots \end{pmatrix} = E \begin{pmatrix} \psi_{K^-p} \\ \psi_{\bar{K}^0 n} \\ \psi_{\pi^-\Sigma^+} \\ \vdots \end{pmatrix}$$

(2) Contribution from coupled-channel hadron source: $S_{j\neq K^-p}$



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

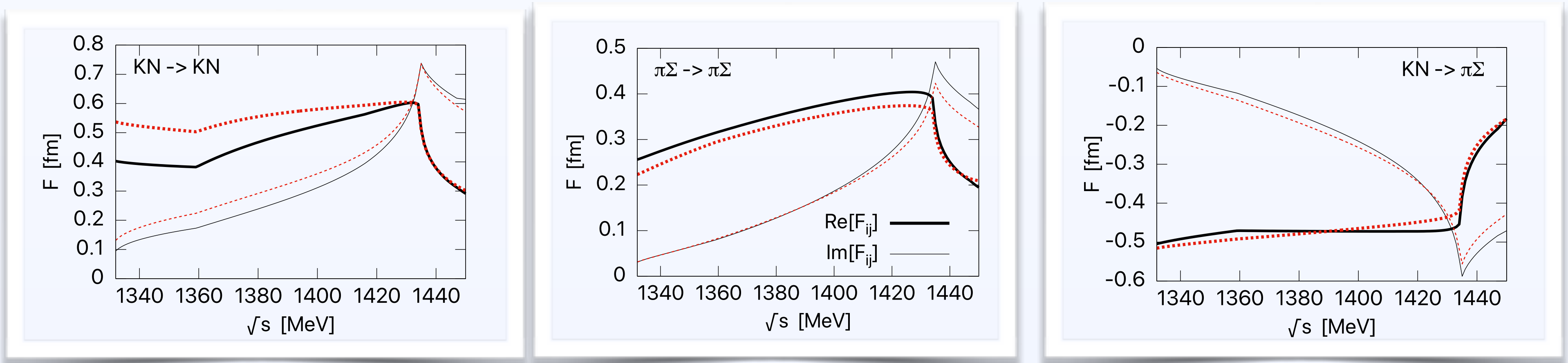
Chiral SU(3) based $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

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

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

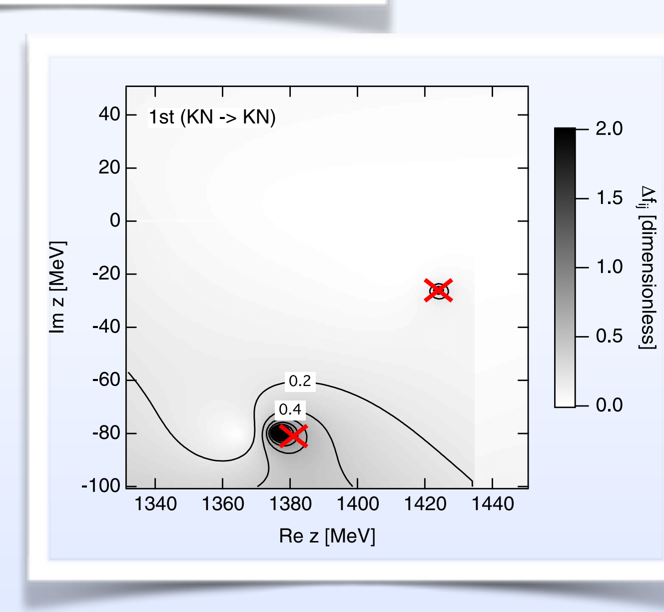
- Constructed to reproduce the chiral SU(3) amplitude around the $\bar{K}N$ sub-threshold region



- Reproduce two pole structure of $\Lambda(1405)$

High-mass pole : 1424 - 27i
Low-mass pole : 1380 - 81i

Original chiral SU(3) : 1424 - 26i
1381 - 81i



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

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

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

- Coupled-channel Schrödinger eq.

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

$$E = \frac{q_1^2}{2\mu_1} \qquad V_{ij} = V_{ij}^{\text{strong}}\ (+V^{\text{Coulomb}})$$

Δ_i ; threshold energy diff.

- Channels
  - Particle basis: K^-p, $\bar{K}^0n$, $\pi^+\Sigma^-$, $\pi^0\Sigma^0$, $\pi^-\Sigma^+$, $\pi^0\Lambda$ ($n=6$)

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

- Coupled-channel boundary condition (b.c.)

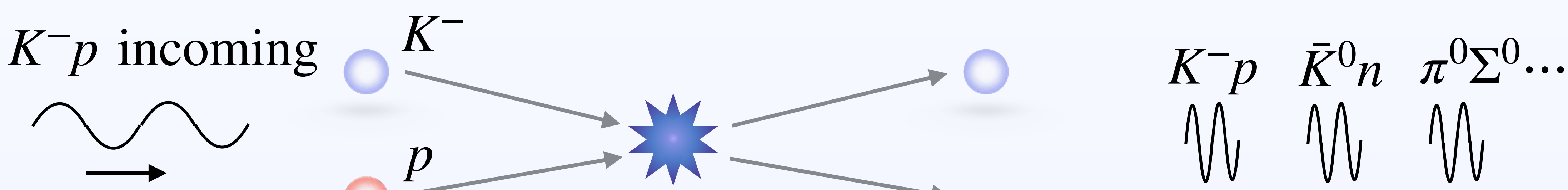
R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)

- Asymptotic waves

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

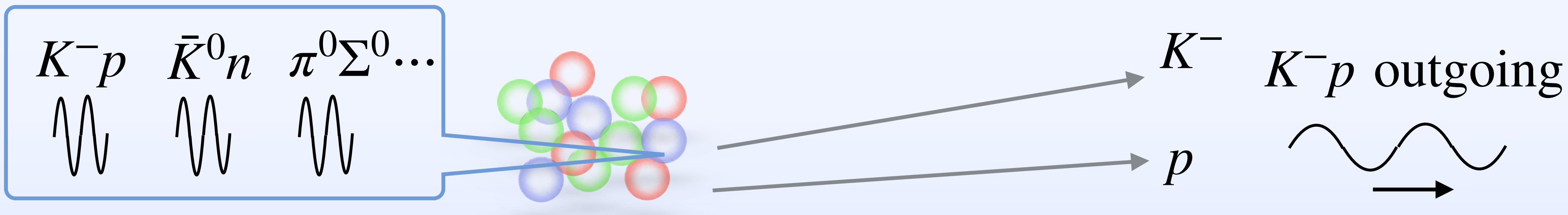
$$\text{closed channels}: \chi_j^{(C)}(r,q) \to a_j(\text{diverg. solution}) + b_j(\text{converg. solution})$$

- Scattering problem; Incoming wave b.c.



$$\Rightarrow \; |b_{K^-p}| = 1, \quad |b_{j \neq K^-p}| = 0$$

- Correlation fcn. Outgoing wave b.c.

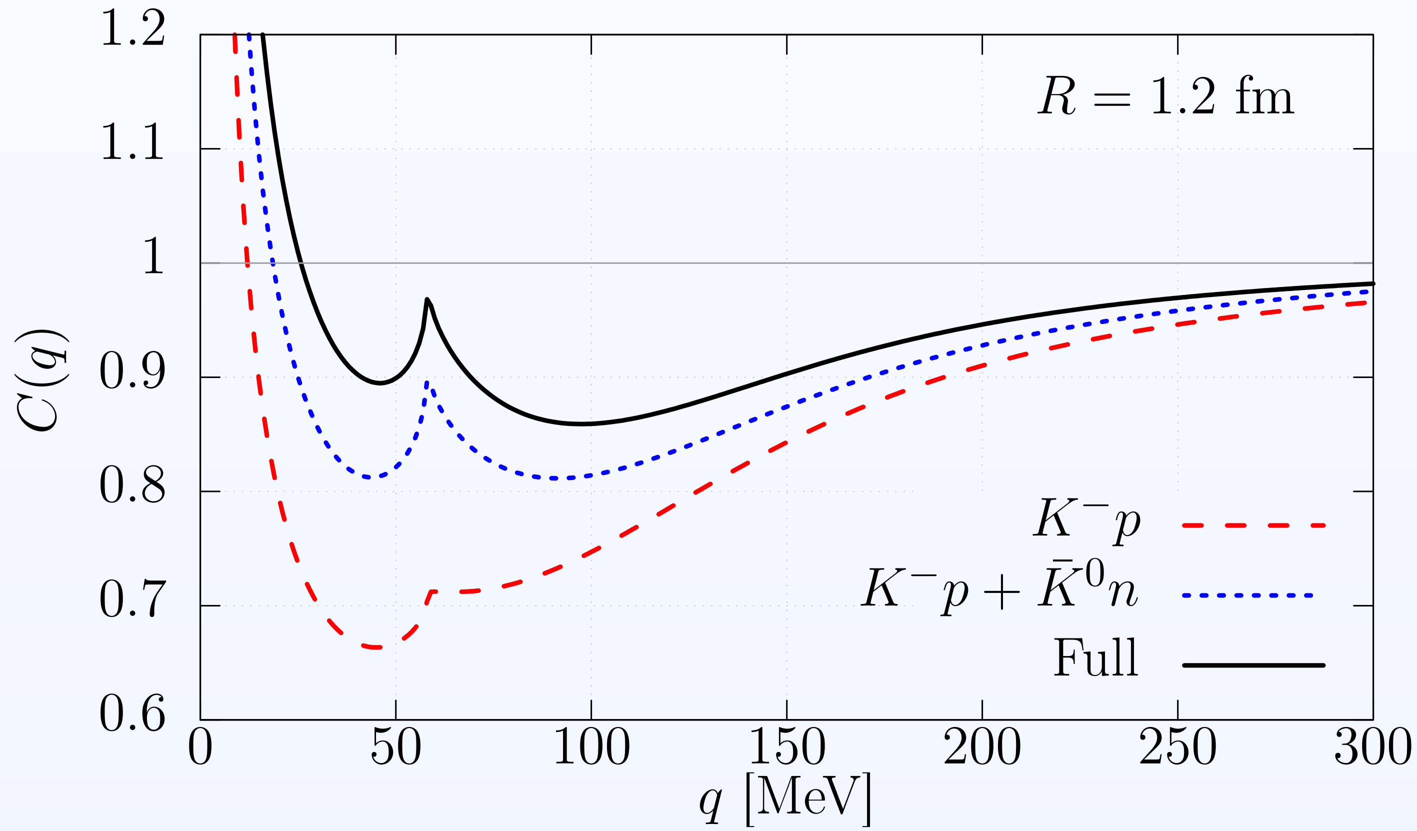


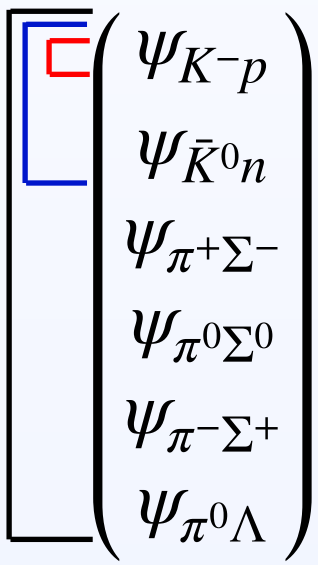
$$\Rightarrow \; |a_{K^-p}| = 1, \quad |a_{j \neq K^-p}| = 0$$

Results

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

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r}) \left[|\varphi^{C,\mathrm{full}}(\mathbf{q},\mathbf{r})|^2 - |j_0^C(qr)|^2 + |\psi^{C,(-)}_{K^-p}(q,r)|^2 \right] + \sum_j \int d^3\mathbf{r}\ S(\mathbf{r}) |\psi_j^{C,(-)}(q,r)|^2$$





* Assumptions on hadron source

- $S_j(r) \propto exp(-r^2/4R^2)$
- $\omega_j = 1$

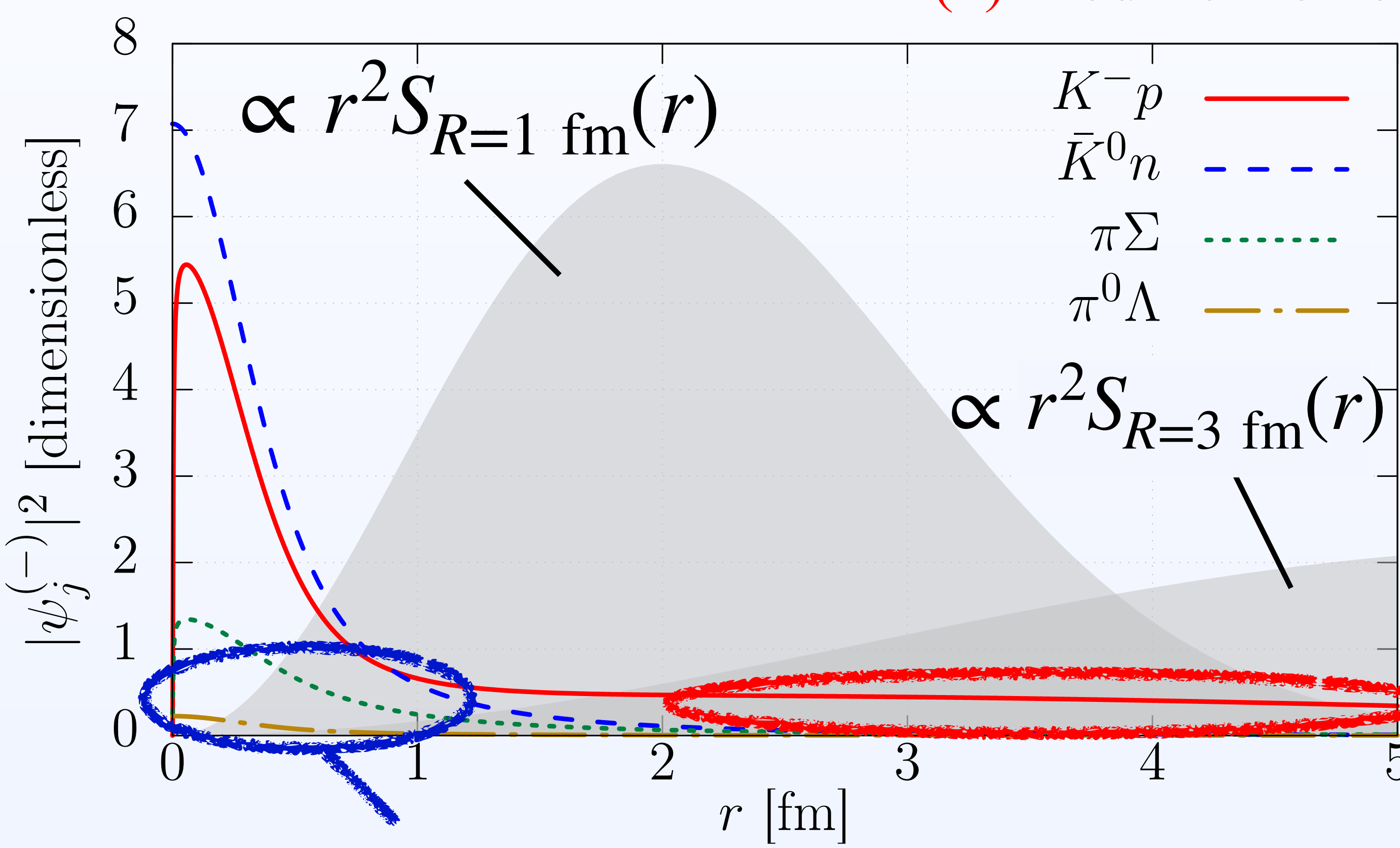
- Coupled-channel effects on $K^- p$ correlation function
  - $C(q)$ calculated with $K^- p$, $K^- p + \bar{K}^0 n$, and all of coupled-channel components
  - Inclusion of $\bar{K}^0 n$ ==> enhance correlation and the cusp structure
  - Inclusion of decay channels ==> non-negligible enhancement

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

- Coupled-channel effect and source size

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\, S_{K^-p}(\mathbf{r}) \left[|\varphi^{C,\mathrm{full}}(\mathbf{q};\mathbf{r})|^2 - |\phi_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q;r)|^2 \right] + \sum_{j\neq K^-p} \omega_j \left[\int d^3\mathbf{r}\, S_j(\mathbf{r})\, |\psi_j^{C,(-)}(q;r)|^2 \right]$$

(1) Modification of $\psi_{K^-p}^{C,(-)}$ (2) C.c. source contribution



Effect (1)
Does not depends on the source size R

$$\psi_{K^-p}^{(-)} \to \frac{1}{2iq_1 r}\left(e^{iq_1 r} - \mathcal{S}_{11}^{\dagger} e^{-iq_1 r}\right)$$

(w/o Coulomb)

Effect (2)
becomes moderate for larger source

- For the larger source, effect (2) gives just a small enhancement.

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

Coupled-channel effect and source size

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\; S_{K^-p}(\mathbf{r})\left[\,|\varphi^{C,\mathrm{full}}(\mathbf{q};\mathbf{r})|^2 - |\phi_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q;r)|^2\right] + \sum_{j\neq K^-p} \omega_j \left[\int d^3\mathbf{r}\; S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2\right]$$

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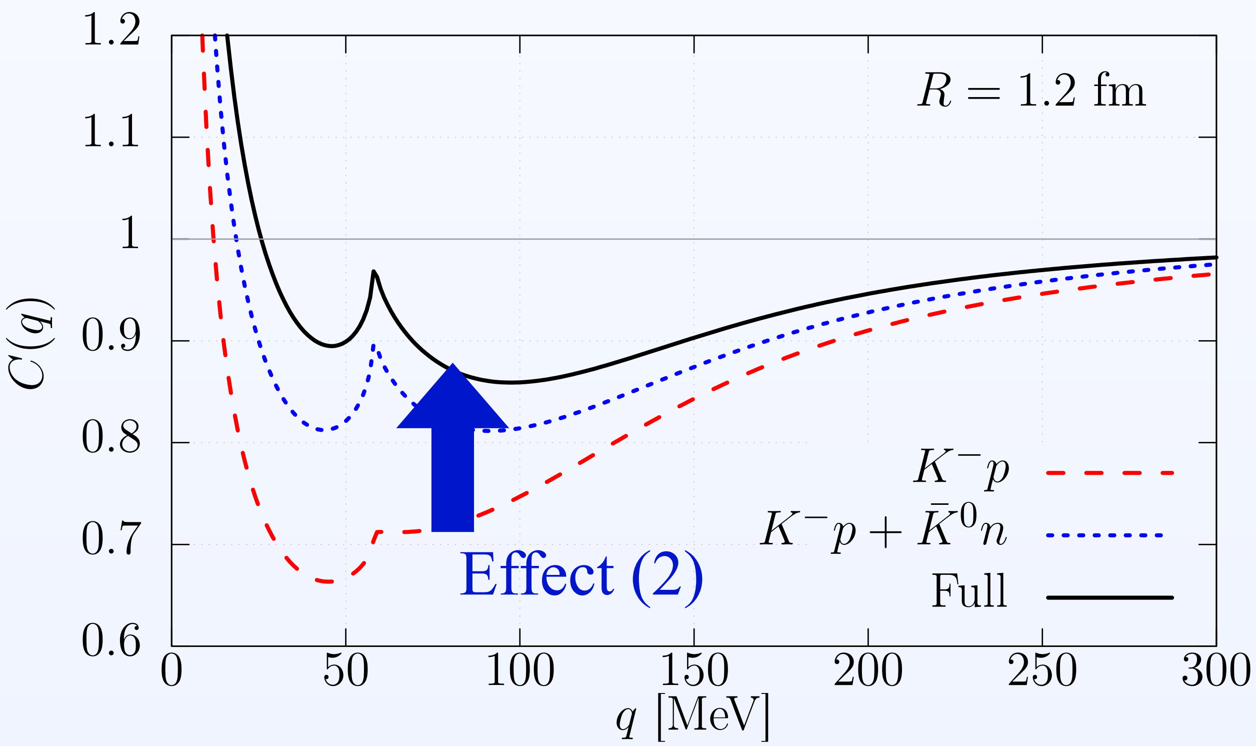
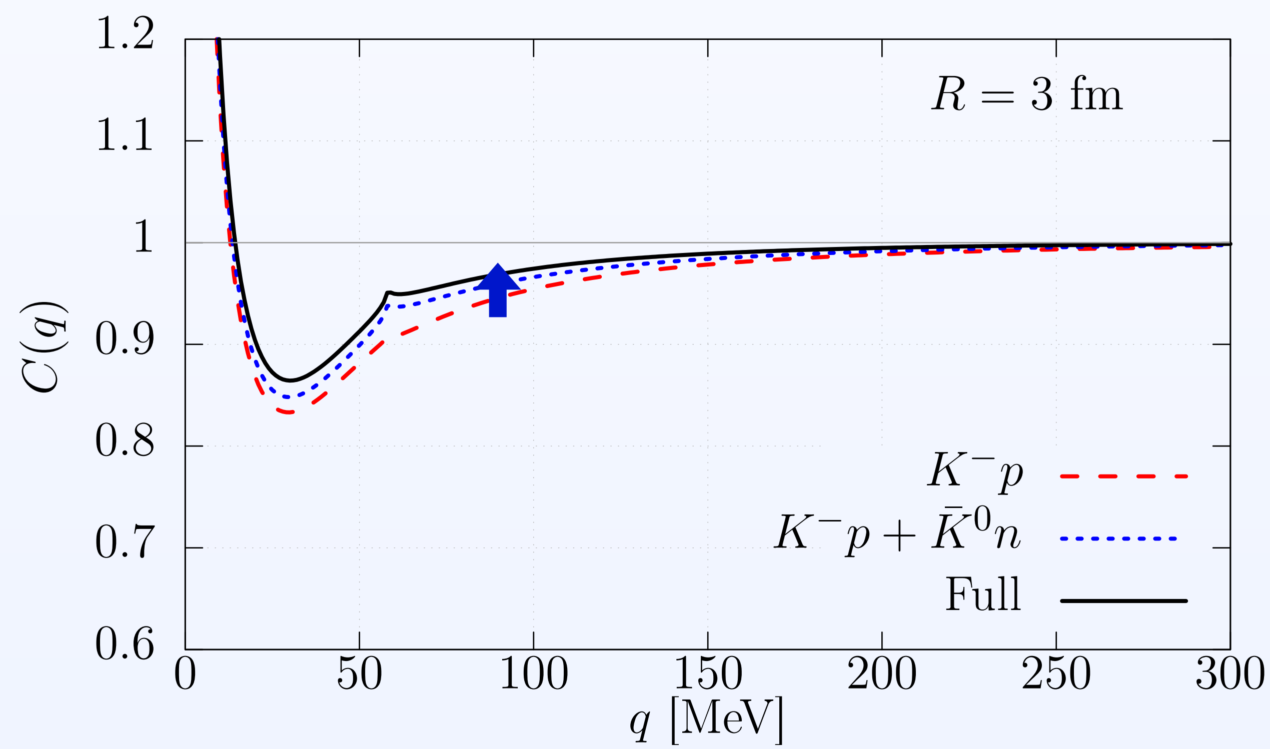
(2) C.c. source contribution





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

- Coupled-channel effect and source size

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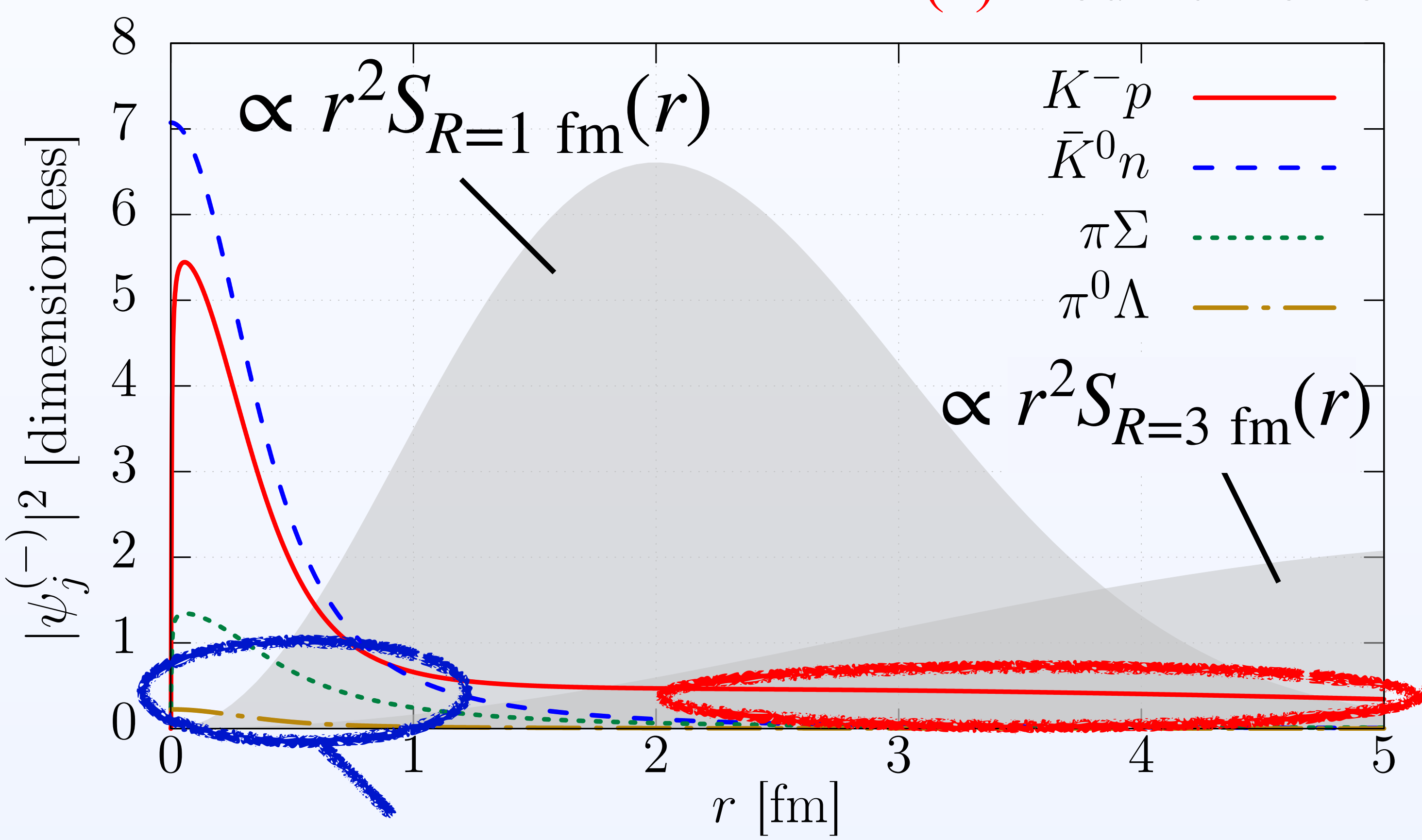
(1) Modification of $\psi_{K^-p}^{C,(-)}$ (2) C.c. source contribution



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Does not depends on the source size R

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(w/o Coulomb)

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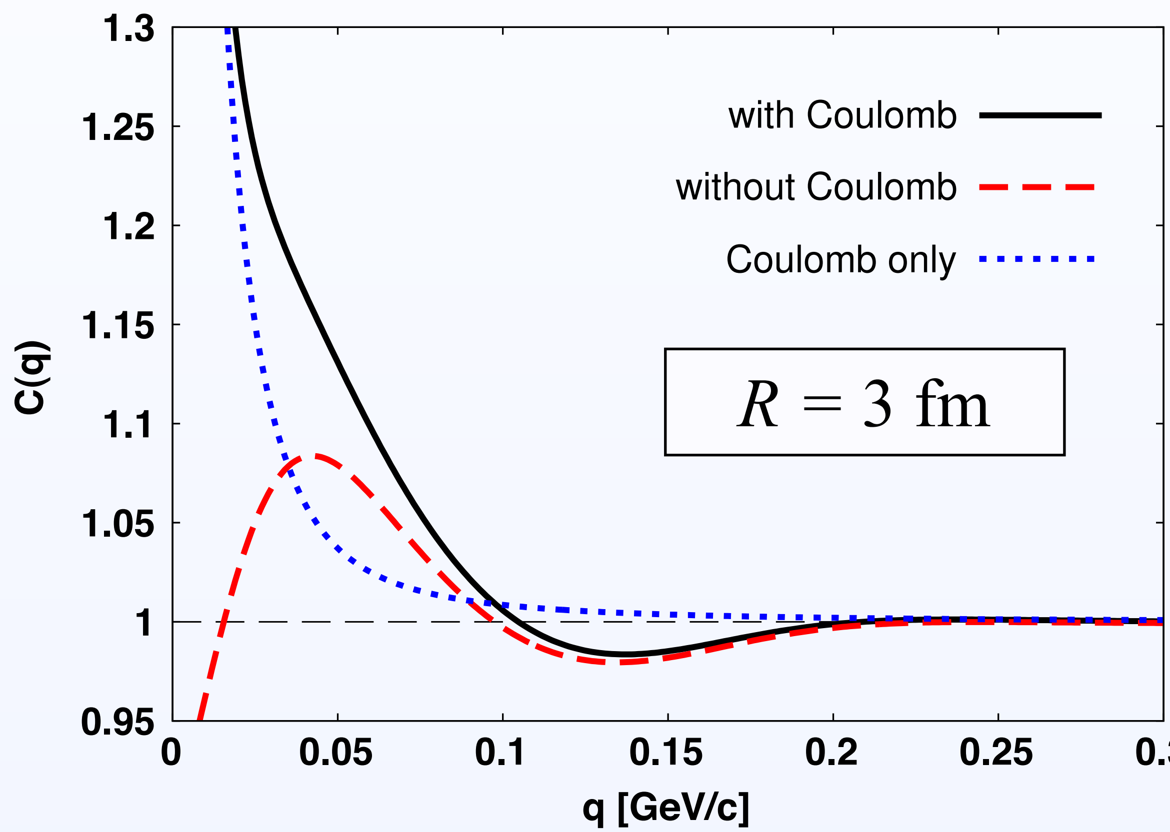
- For the larger source, effect (2) gives just a small enhancement.

Comparison with previous result

- Comparison with previous result

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

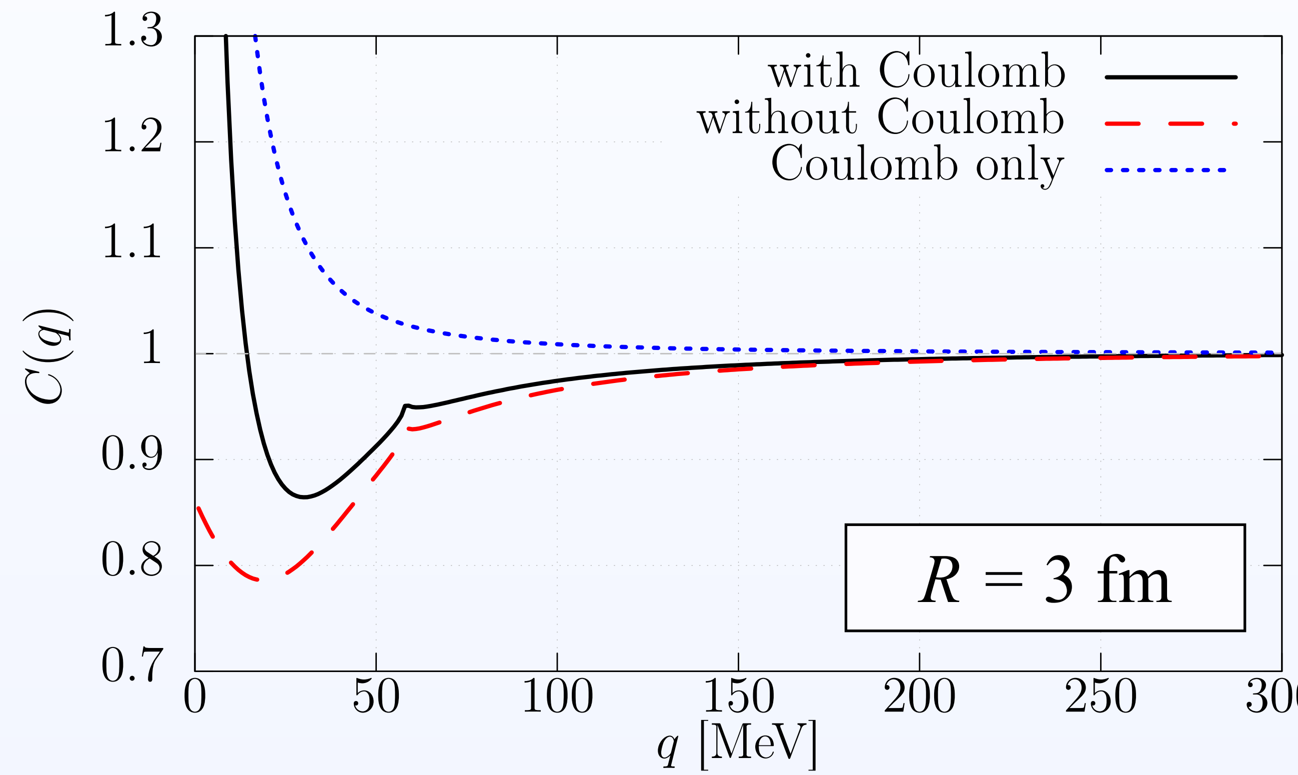


- $\bar{K}N$ $(I = 0,\ 1)$ single channel potential
- *Approximate* outgoing boundary condition (Neglect coupling to $\pi\Sigma$ and $\pi\Lambda$)

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

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

Current study — with $K^-p + \bar{K}^0 n$



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

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

Comparison with previous result

- Comparison with previous result

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

- $\bar{K}N$ single channel potential

Miyahara and Hyodo, PRC93, 015201 (2016).

$$[T_{\rm kinetic} + V^{I}_{\rm single}]\,\psi_{\bar{K}N} = E\psi_{\bar{K}N}$$

Current study

- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential

Miyahara et al., , PRC98, 025201 (2018).

$$\left[T + \begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{pmatrix}\right]\begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix} = E\begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix}$$

Integrated out

Incoming wave boundary condition

Comparison with previous result

- Comparison with previous result

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

- $\bar{K}N$ single channel potential

Miyahara and Hyodo, PRC93, 015201 (2016).

$$[T_{\text{kinetic}} + V^{I}_{\text{single}}]\ \psi_{\bar{K}N} = E\psi_{\bar{K}N}$$

Integrated out

- *Approximate* outgoing boundary condition

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

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

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

$$\begin{pmatrix} \psi_{\bar{K}N,I=0} \\ \psi_{\bar{K}N,I=1} \\ \psi_{\pi\Sigma,I=0} \\ \psi_{\pi\Sigma,I=1} \\ \psi_{\pi\Lambda} \end{pmatrix}$$

$\psi_{\bar{K}N,I=0}$, $\psi_{\bar{K}N,I=1}$ → Superposition → K^-p outgoing

$\psi_{\pi\Sigma,I=0}$, $\psi_{\pi\Sigma,I=1}$, $\psi_{\pi\Lambda}$ → outgoing

Current study

- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential

Miyahara et al., , PRC98, 025201 (2018).

$$\left[T + \begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{pmatrix}\right]\begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix} = E\begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix}$$

Incoming wave boundary condition

- *Full* outgoing boundary condition

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

$$\begin{pmatrix} \psi_{K^-p} \\ \psi_{\bar{K}^0n} \\ \psi_{\pi^+\Sigma^-} \\ \psi_{\pi^0\Sigma^0} \\ \psi_{\pi^0\Sigma^+} \\ \psi_{\pi^0\Lambda} \end{pmatrix}$$

→ Superposition → K^-p outgoing

Comparison with previous result

- Comparison with previous result

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

- $\bar{K}N$ single channel potential
  Miyahara and Hyodo, PRC93, 015201 (2016).

$$[T_{\text{kinetic}} + V^I_{\text{single}}]\ \psi_{\bar{K}N} = E\psi_{\bar{K}N}$$

- *Approxi*

$\psi_{K^-p}(r)$

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

$$\begin{pmatrix} \psi_{\bar{K}N,I=0} \\ \psi_{\bar{K}N,I=1} \\ \psi_{\pi\Sigma,I=0} \\ \psi_{\pi\Sigma,I=1} \\ \psi_{\pi\Lambda} \end{pmatrix}$$

Superposition → K^-p outgoing

→ outgoing

Current study

- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
  Miyahara et al., , PRC98, 025201 (2018).

$$\left[T + \begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{pmatrix}\right] \begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix} = E \begin{pmatrix} \psi_{\bar{K}N} \\ \psi_{\pi\Sigma} \\ \psi_{\pi\Lambda} \end{pmatrix}$$

condition

$^{-iqr}]e_{K^-p}$

$$-\sqrt{\frac{\quad}{\mu_{\bar{K}^0n}q_{\bar{K}^0n}}}\mathcal{S}_{K^-p\bar{K}^0n}\, e^{-iq_{\bar{K}^0n}r}e_{\bar{K}^0n}$$

$$\begin{pmatrix} \psi_{K^-p} \\ \psi_{\bar{K}^0n} \\ \psi_{\pi^+\Sigma^-} \\ \psi_{\pi^0\Sigma^0} \\ \psi_{\pi^0\Sigma^+} \\ \psi_{\pi^0\Lambda} \end{pmatrix}$$

Superposition → K^-p outgoing

> Two results differ so much
>
> ==> • Coupling to decay channels are not negligible
>
> • Boundary condition should be taken carefully

Contents

- Introduction: Hadron correlation in high energy nuclear collisions
- $K^- p$ correlation function with coupled-channel chiral SU(3) potential
- Comparison with ALICE $K^- p$ data
- Summary

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi and W. Weise, arXiv:1911.01041

Comparison with ALICE data

- Source function parameters

We do not have enough information for S(r)…

$$C_{K^-p}(q) = \int d^3\mathbf{r}\ S(\mathbf{r})\left[\,|\varphi^{C,\mathrm{full}}(\mathbf{q},\mathbf{r})|^2 - |j_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q,r)|^2\right] + \sum_j \omega_j \int d^3\mathbf{r}\ S(\mathbf{r})\,|\psi_j^{C,(-)}(q,r)|^2$$

- Assumptions
  - Spherical gaussian source: $S_j(r) = S_R(r) \propto \exp(-r^2/4R^2)$
  - $\omega_{\bar{K}^0N} = \omega_{\pi^0\Lambda} = 1$

- Free parameters for source function
  - Source size: R (~ 1 fm) — Normal size for pp collision
  - Source weight of $\pi\Sigma$ channel : $\omega_{\pi\Sigma}$ (~ 2) — Statistical model estimate

- Other fitting parameters

$$C_{\mathrm{fit}}(q) = \mathcal{N}[1 + \lambda\{C_{K^-p}(q) - 1\}]$$

- Normalization

$N \sim 1$

- Pair purity parameter

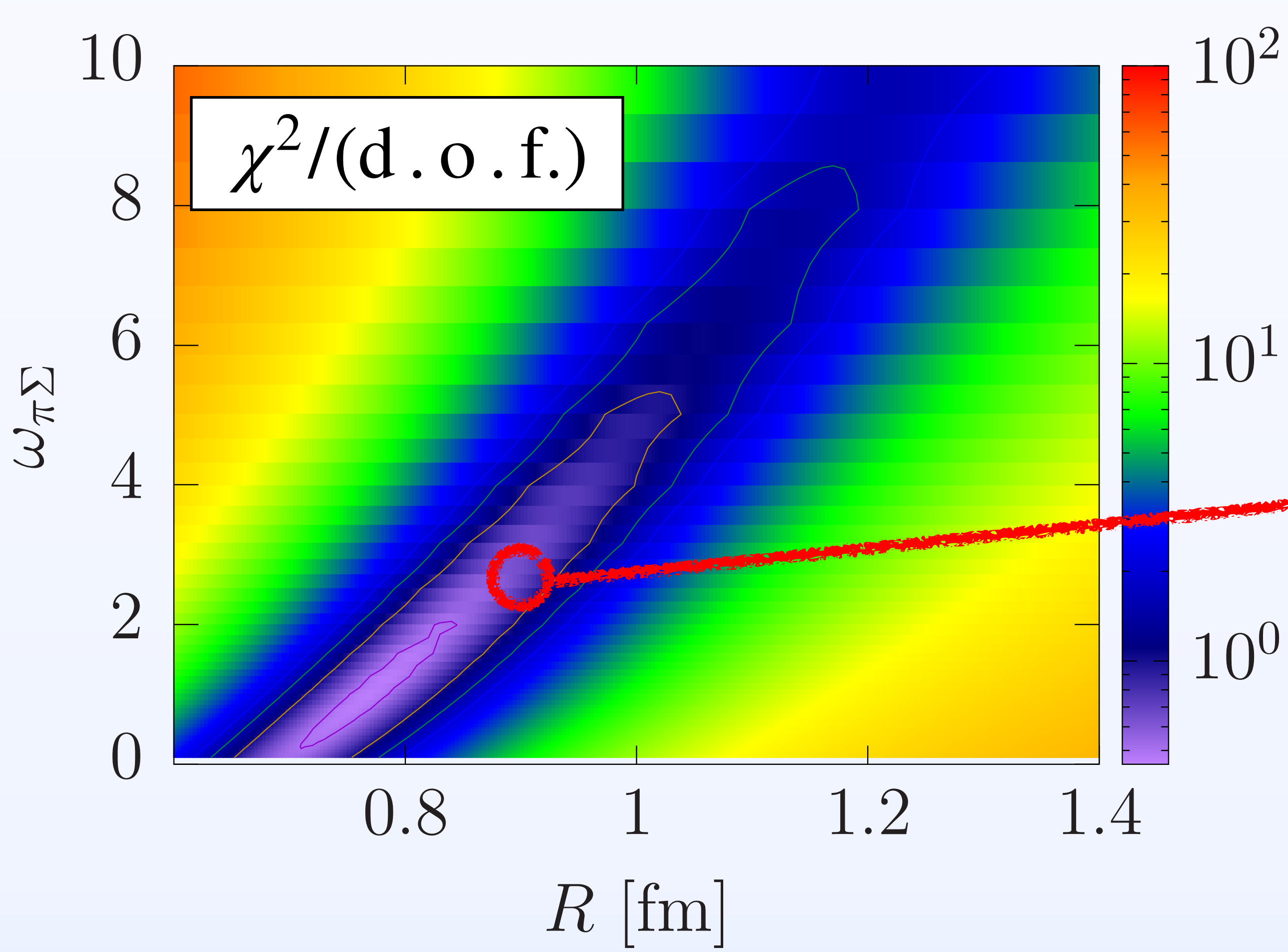
$\lambda_{\mathrm{exp}} = 0.64 \pm 0.06$

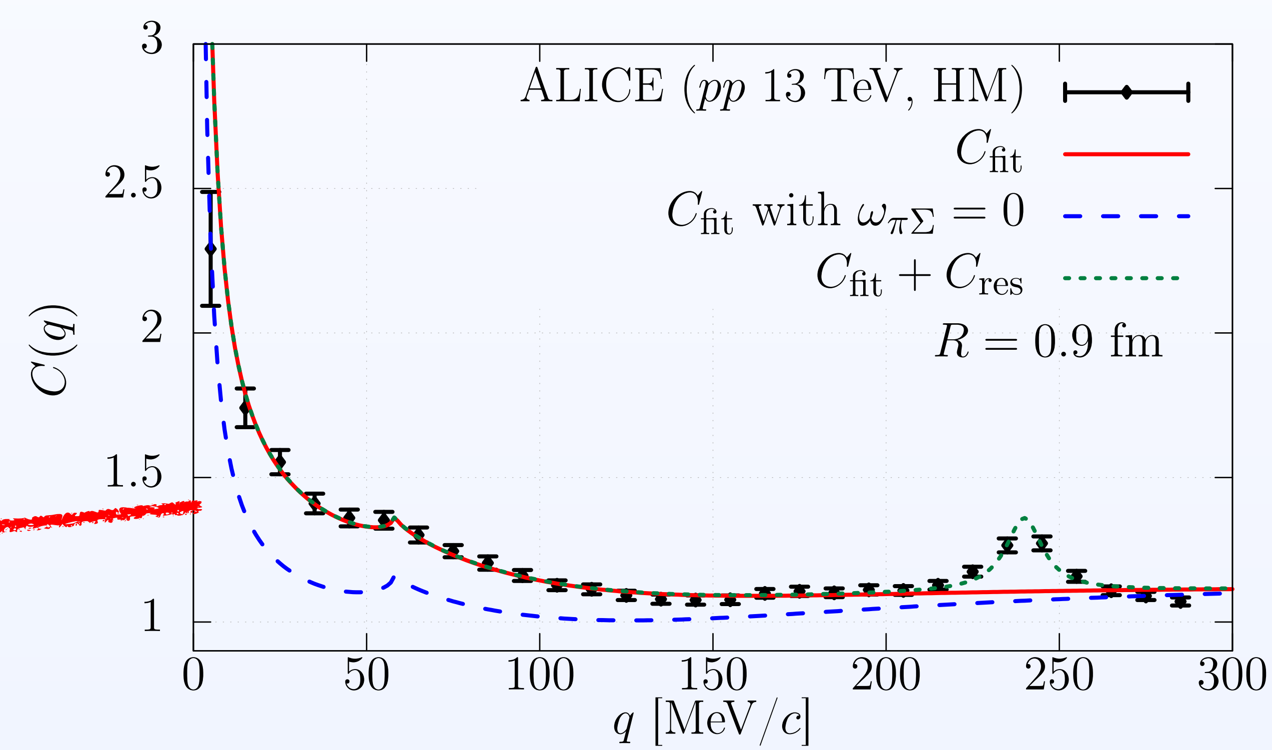
Monte calro simulation by experimental group

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

Comparison with ALICE data

- Fitting result
  - Fitting function
    $C_{\rm fit}(q) = \mathcal{N}[1 + \lambda\{C_{K^-p}(q) - 1\}]$
    $$C_{K^-p}(q) = \sum_j \omega_j \left[\int d^3\mathbf{r}\ S(\mathbf{r})\,|\Psi_j^{C,(-)}(q,r)|^2\right]$$
  - Fitting range: $q < 120$ MeV/c





$\omega_{\pi\Sigma} = 2.95, \quad \mathcal{N} = 1.13, \quad \lambda = 0.58,$

- ALICE data has been well reproduced with the reasonable values of parameters.
- C.c. source contribution is essential to reproduce the data.

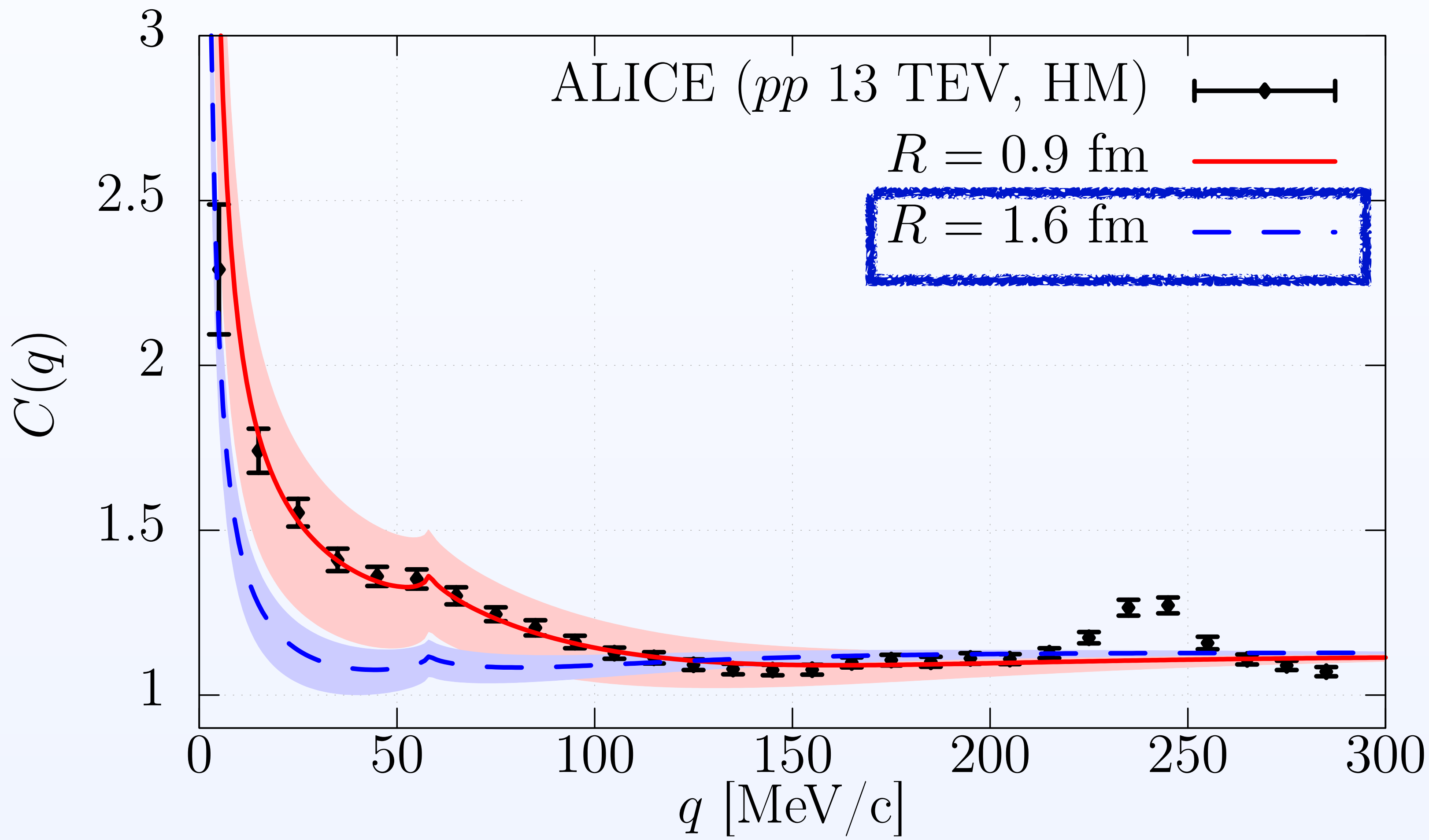
Comparison with ALICE data

- Correlation in larger source system

$$C_{\rm fit}(q) = \mathcal{N}[1 + \lambda\{C_{K^-p}(q) - 1\}] \qquad C_{K^-p}(q) = \sum_j \omega_j \int d^3\mathbf{r}\ S(\mathbf{r})\,|\,\Psi_j^{C,(-)}(q,r)\,|^2$$

∗ Same values for $\mathcal{N}$, λ, ω

∗ Shadow: $0.5 < \omega_{\pi\Sigma} < 5$



- Contribution from the coupled-channel source is weaker,
  - Moderate cusp structure
  - Weak source weight ($\omega_{\pi\Sigma}$) dependence

Summary

- To measure hadron-hadron correlation function in high energy nuclear is a powerful tool to study the (multi-)strangeness system.

- Based on Koonin-Pratt formula, we newly constructed the calculation method to include
  • Coulomb interaction,
  • coupled-channel effect,
  • threshold energy difference.

- Employing the realistic chiral SU(3) based coupled-channel potential, ALICE $K^{-}p$ data is well reproduced with the reasonable source function parameters.

- Coupled-channel effect exists various hadron-hadron systems.
  —> Careful treatment is needed for the detailed analysis.

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi and W. Weise, arXiv:1911.01041

Thank you!

K^-p correlation with Koonin-Pratt Formula

- Coupled-channel boundary condition   R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)
  - w/o Coulomb int.
  - w/o open channel (coupling only to closed channels)

- Scattering problem; In-coming wave boundary condition

$$\Psi^{\text{incoming b.c.}} \to \begin{pmatrix} \underbrace{\frac{1}{2iq_1 r} e^{-iq_1 r}}_{\text{Incoming}} - \frac{\mathcal{S}_{11}}{2iq_1 r} e^{iq_1 r} \\ -\sqrt{\frac{\mu_1 q_1}{\mu_2 q_2}} \frac{\mathcal{S}_{12}}{2iq_2 r} e^{iq_2 r} \\ \vdots \quad \text{Outgoing} \end{pmatrix}$$

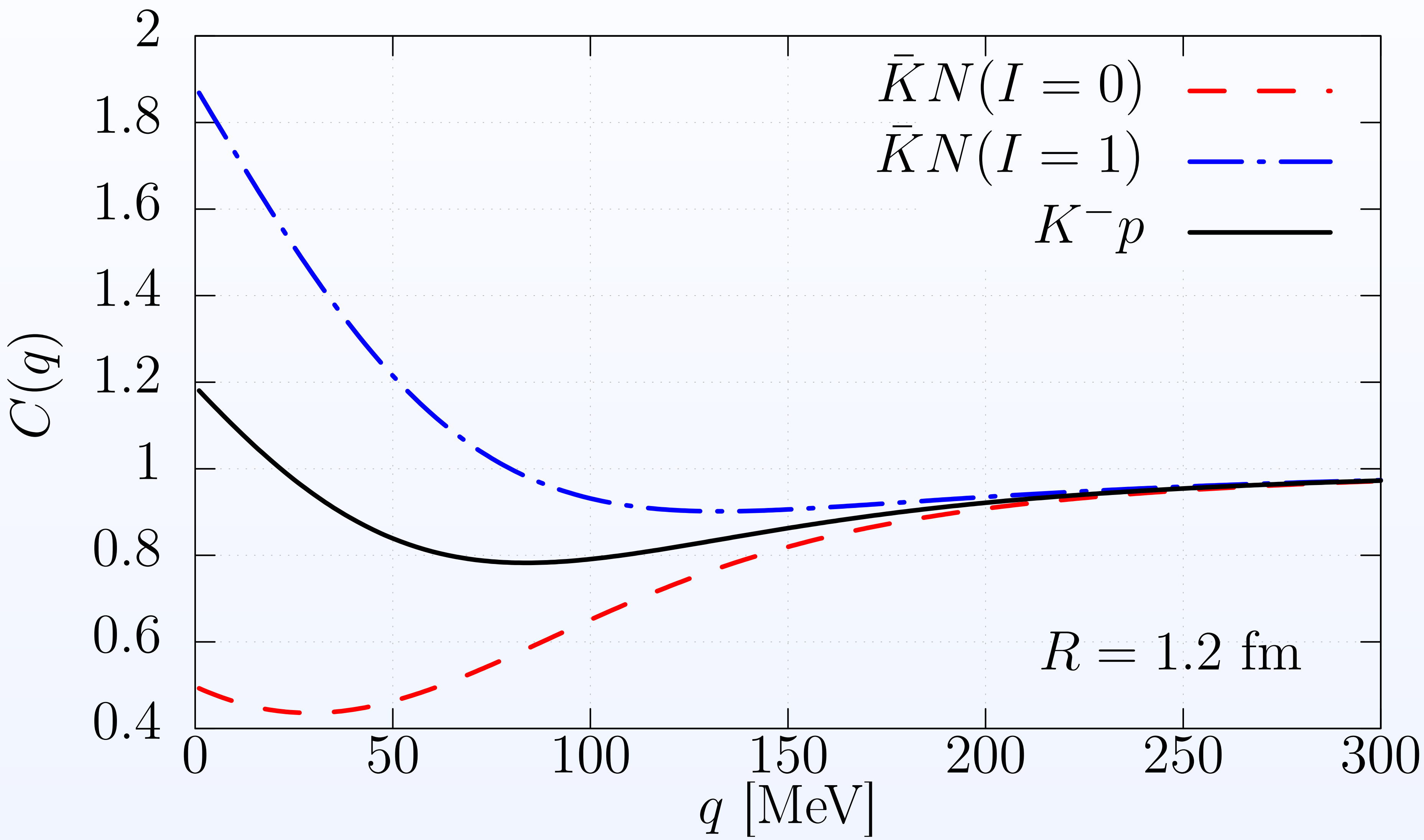
- Correlation fcn. Out-going wave boundary condition

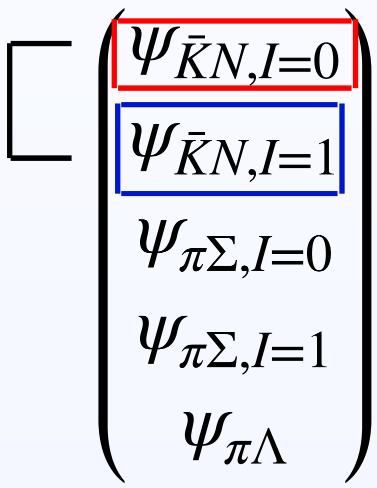
$$\Psi^{\text{outgoing b.c.}} \to \begin{pmatrix} \underbrace{\frac{1}{2iq_1 r} e^{iq_1 r}}_{\text{Outgoing}} - \frac{\mathcal{S}^\dagger_{11}}{2iq_1 r} e^{-iq_1 r} \\ -\sqrt{\frac{\mu_1 q_1}{\mu_2 q_2}} \frac{\mathcal{S}^\dagger_{12}}{2iq_2 r} e^{-iq_2 r} \\ \vdots \quad \text{Incoming} \end{pmatrix}$$

Results

Preliminary!

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



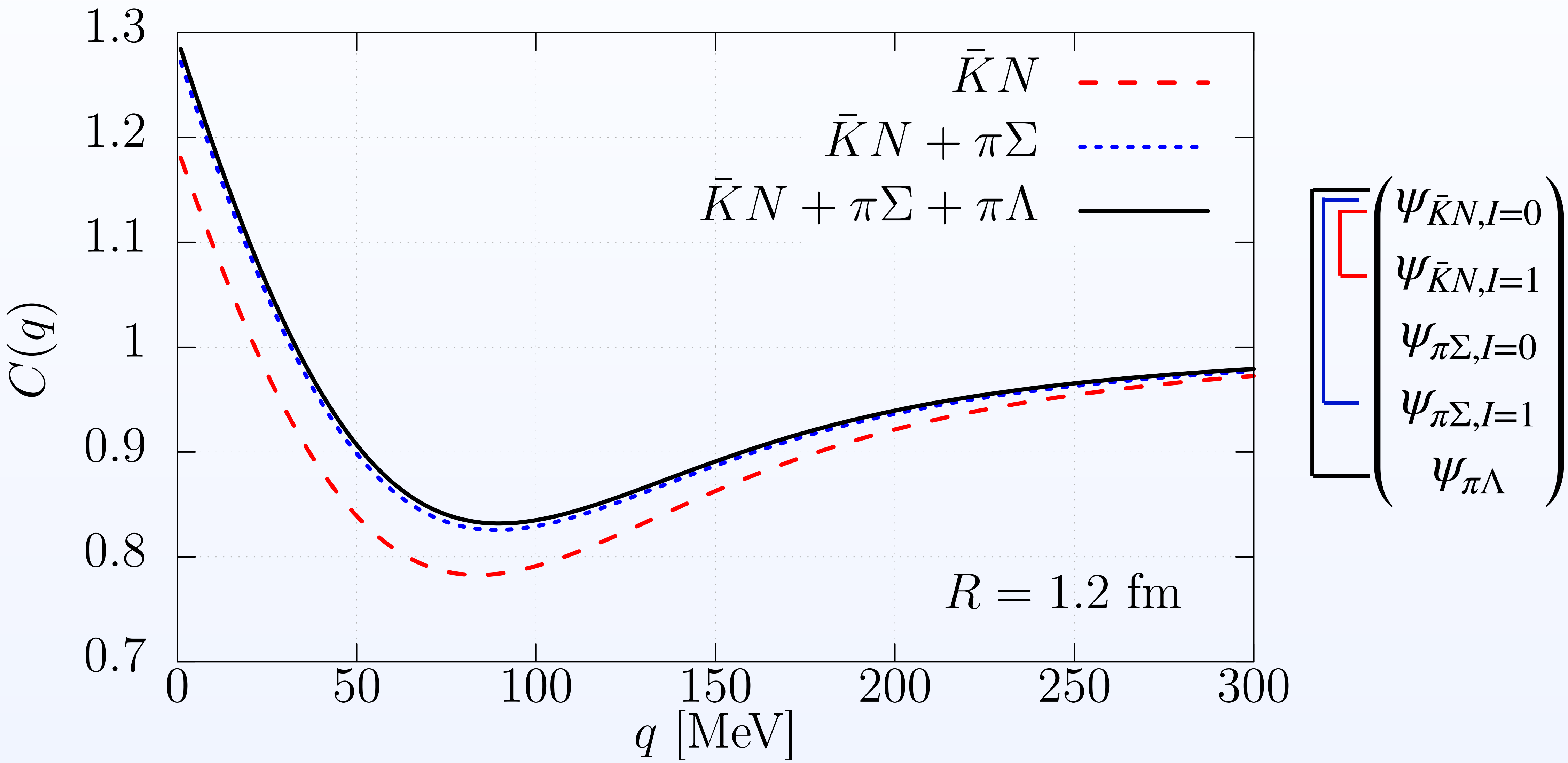


- $C(q)$ calculated only with $\bar{K}N$ ($K^{-}p + \bar{K}^{0}n$) component with $R = 1.2$ fm
- Re $a_0^{I=0} > 0 \Rightarrow C_{\bar{K}N}^{I=0} < 1$, Re $a_0^{I=1} < 0 \Rightarrow C_{\bar{K}N}^{I=1} > 1$ at small q
- $C_{K^-p}(q) = (C_{\bar{K}N}^{I=0} + C_{\bar{K}N}^{I=1})/2$

Results

Preliminary!

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

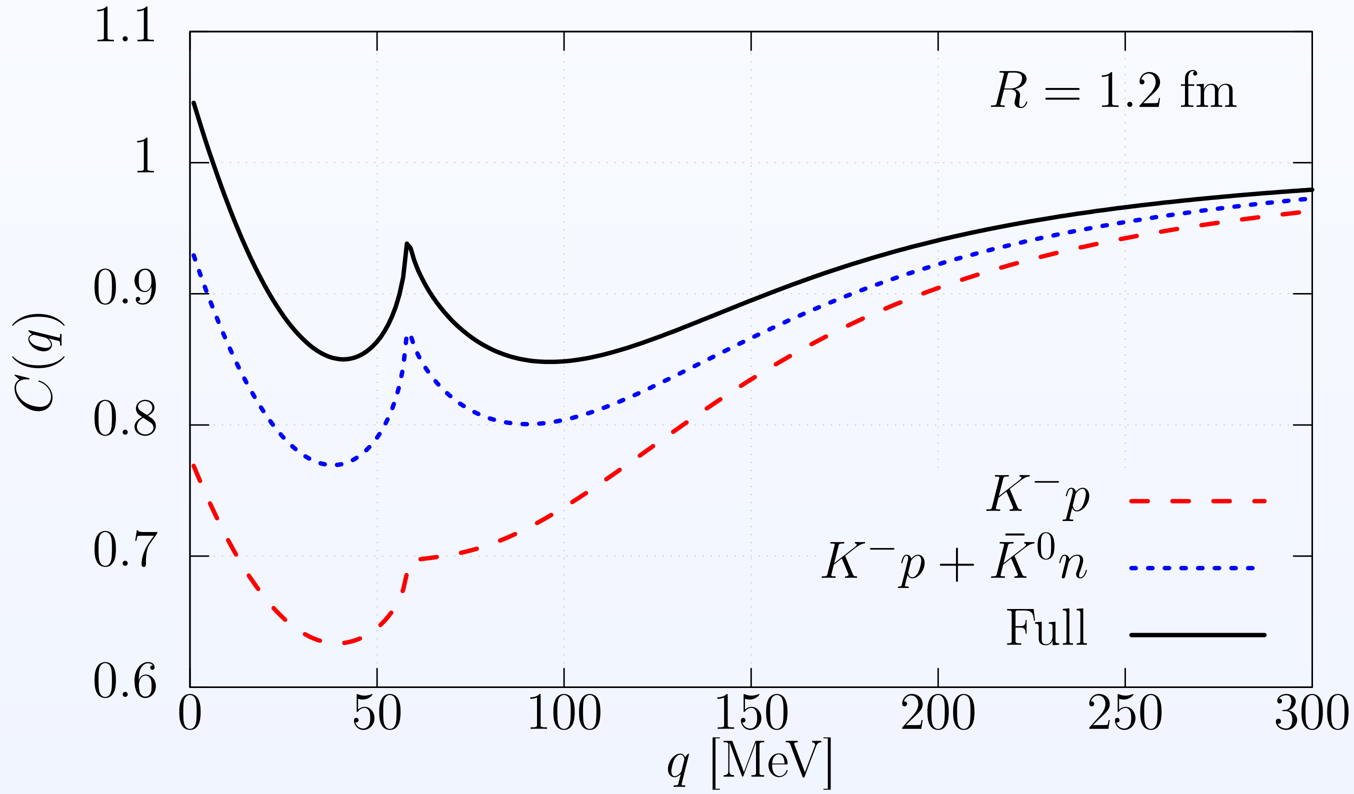


- Coupling to $\pi\Sigma$: Enhancement
- Coupling to $\pi\Lambda$: Negligible enhancement

Results

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

$$C_{K^-p}(q) = \int d^3\mathbf{r}\ S(\mathbf{r})\left[\,|\varphi^{\mathrm{full}}(\mathbf{q};\mathbf{r})|^2 - |j_0(qr)|^2 + |\psi^{(-)}_{K^-p}(q;r)|^2\right] + \sum_j \int d^3\mathbf{r}\ S(\mathbf{r})\,|\psi^{(-)}_j(q;r)|^2$$



$$\begin{pmatrix} \psi_{K^-p} \\ \psi_{\bar{K}^0 n} \\ \psi_{\pi^+\Sigma^-} \\ \psi_{\pi^0\Sigma^0} \\ \psi_{\pi^-\Sigma^+} \\ \psi_{\pi^0\Lambda} \end{pmatrix}$$

* Assumptions on hadron source

- $S_j(r) \propto exp(-r^2/4R^2)$
- $\omega_j = 1$

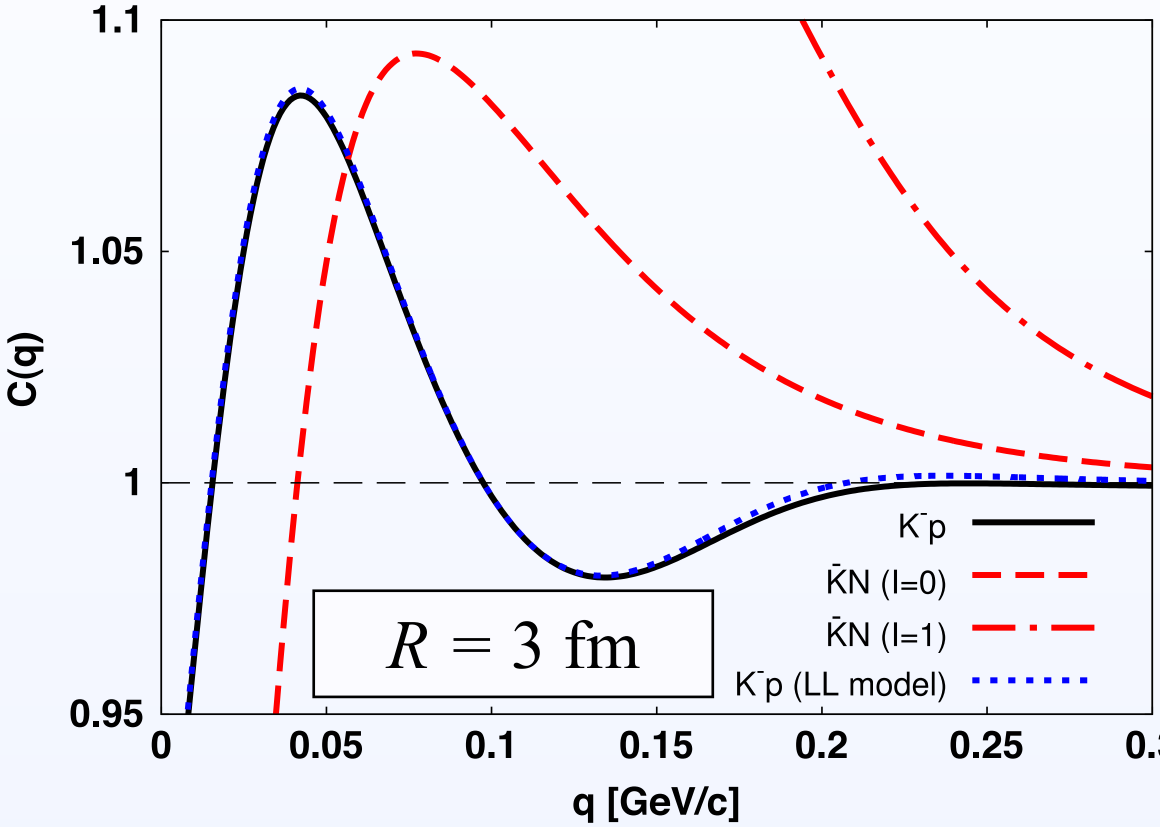
- Coupled-channel effects on $K^{-}p$ correlation function
  - $C(q)$ calculated with $K^{-}p$, $K^{-}p + \bar{K}^0 n$, and all of coupled-channel components
  - Inclusion of $\bar{K}^0 n$ ==> enhance correlation and the cusp structure
  - Inclusion of decay channels ==> non-negligible enhancement

c.f. Haidenbauer NPA 981 (2018)

Comparison with previous result

- Comparison with previous result

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



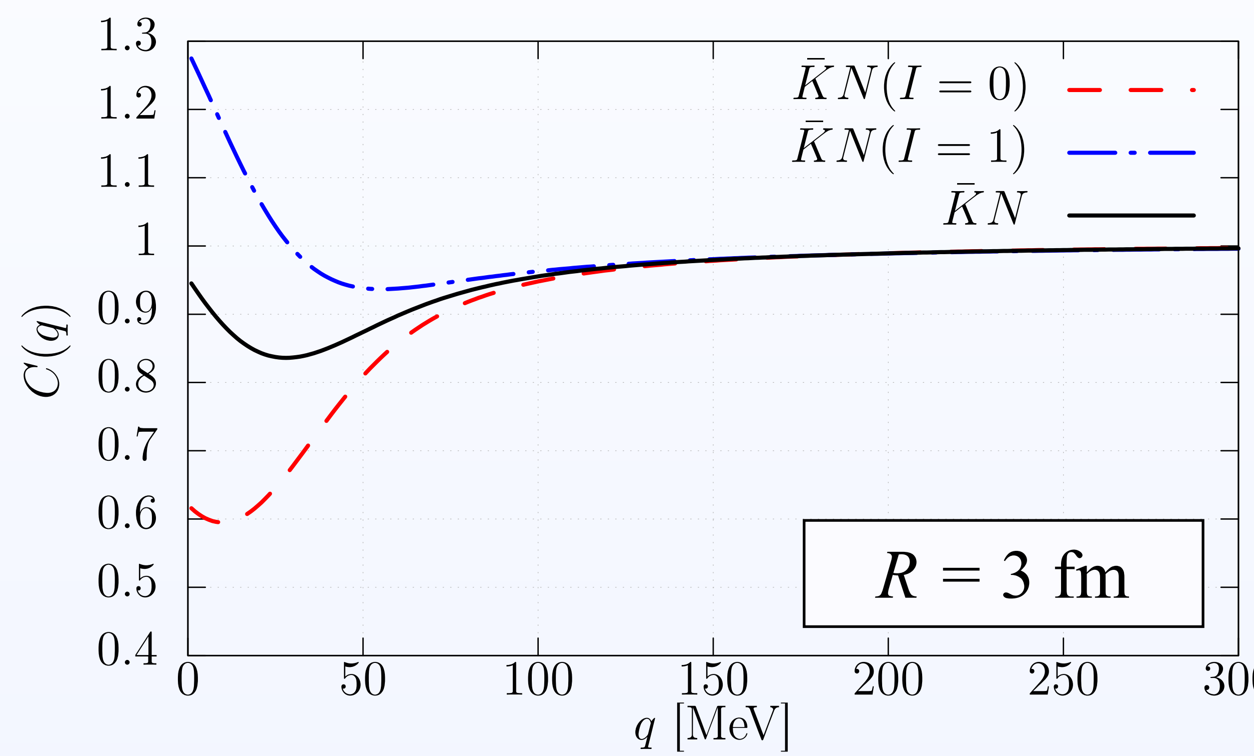
- $\bar{K}N$ single channel potential
- *Approximate* outgoing boundary condition

(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

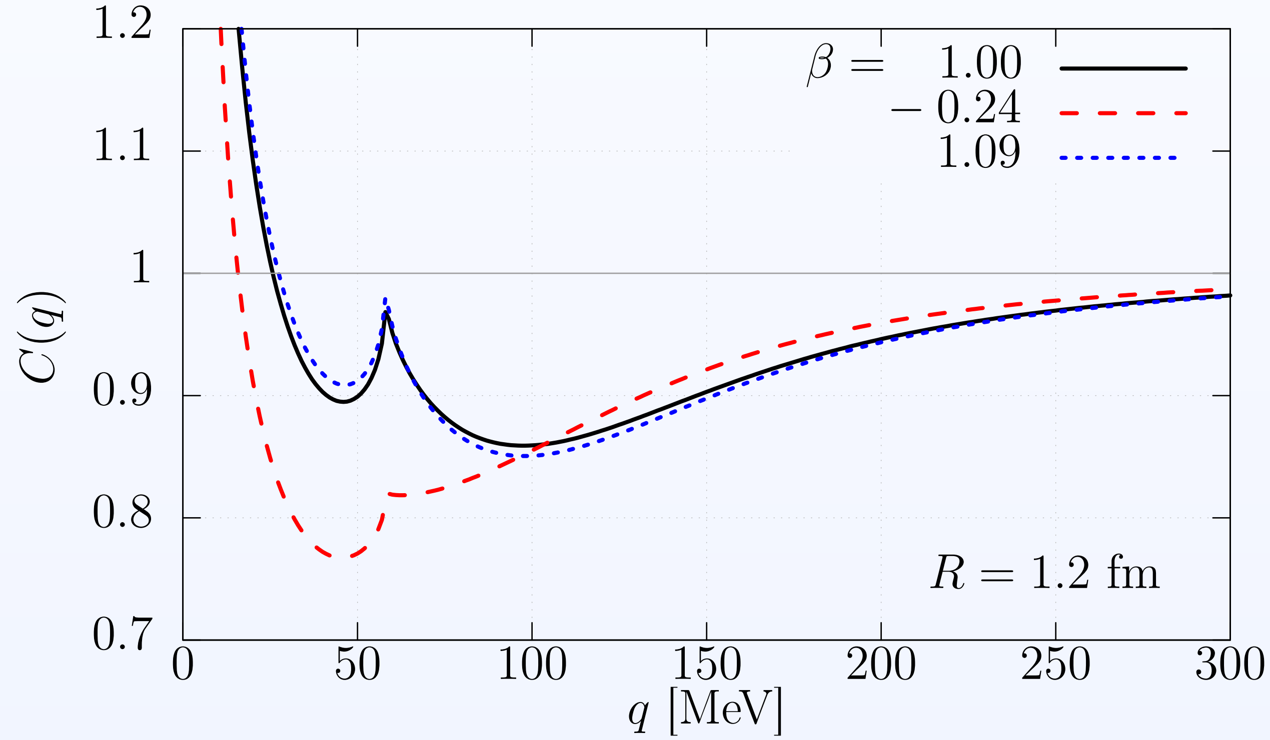


- $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channel potential
- *Full* outgoing boundary condition

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

Interaction dependence

- 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

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

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

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

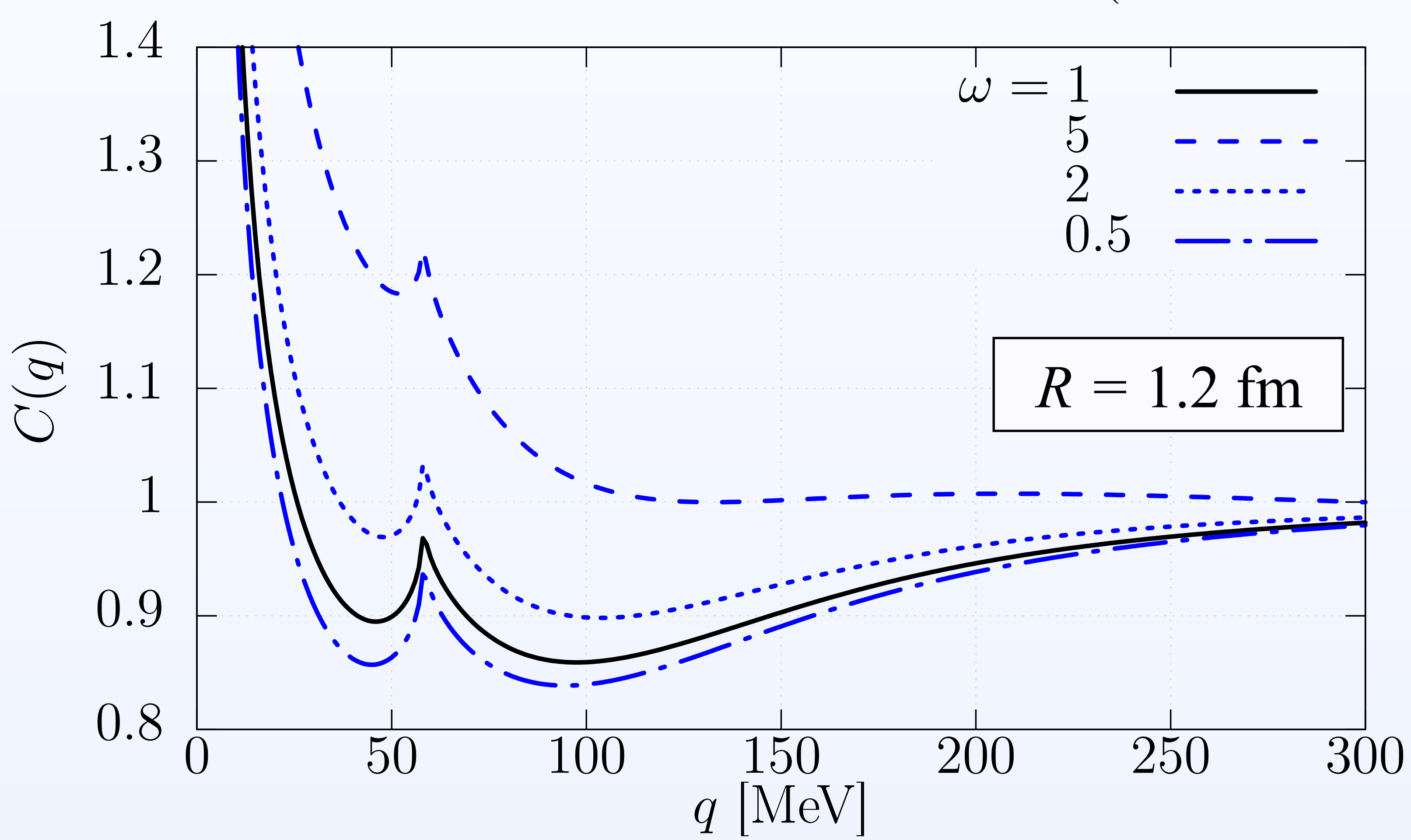
Source dependence

- Channel weight dependence of $K^- p$ correlation

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r})\left[\,|\varphi^{C,\mathrm{full}}(\mathbf{q},\mathbf{r})|^2 - |j_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q,r)|^2\right] + \sum_j \omega_j \int d^3\mathbf{r}\ S(\mathbf{r})\,|\psi_j^{C,(-)}(q,r)|^2$$

- Vary the source weight of the $\pi\Sigma$ channel:

(* $\pi\Lambda$ source contribution is negligible)



- Increase $\omega_{\pi\Sigma}$ ==> • weaken dip at $q \sim 40$ MeV

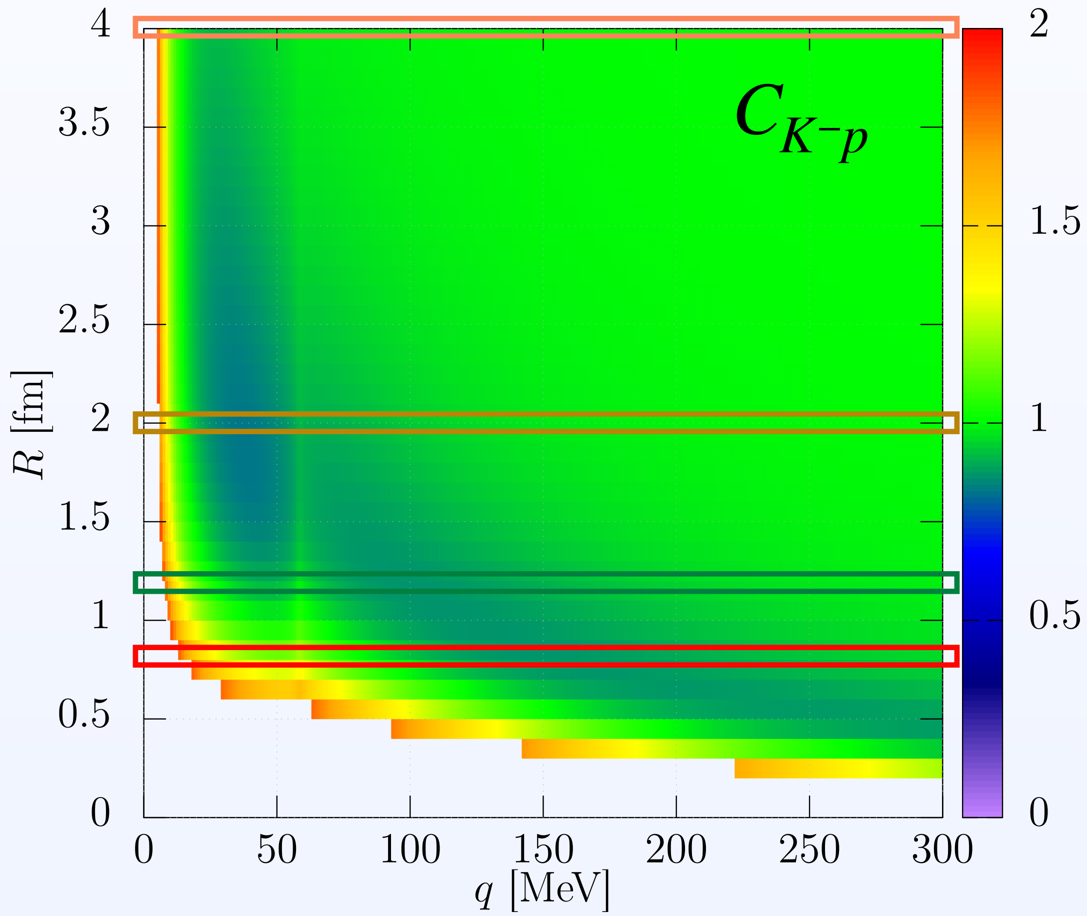
Channel weight must be determined for the detailed analyses!

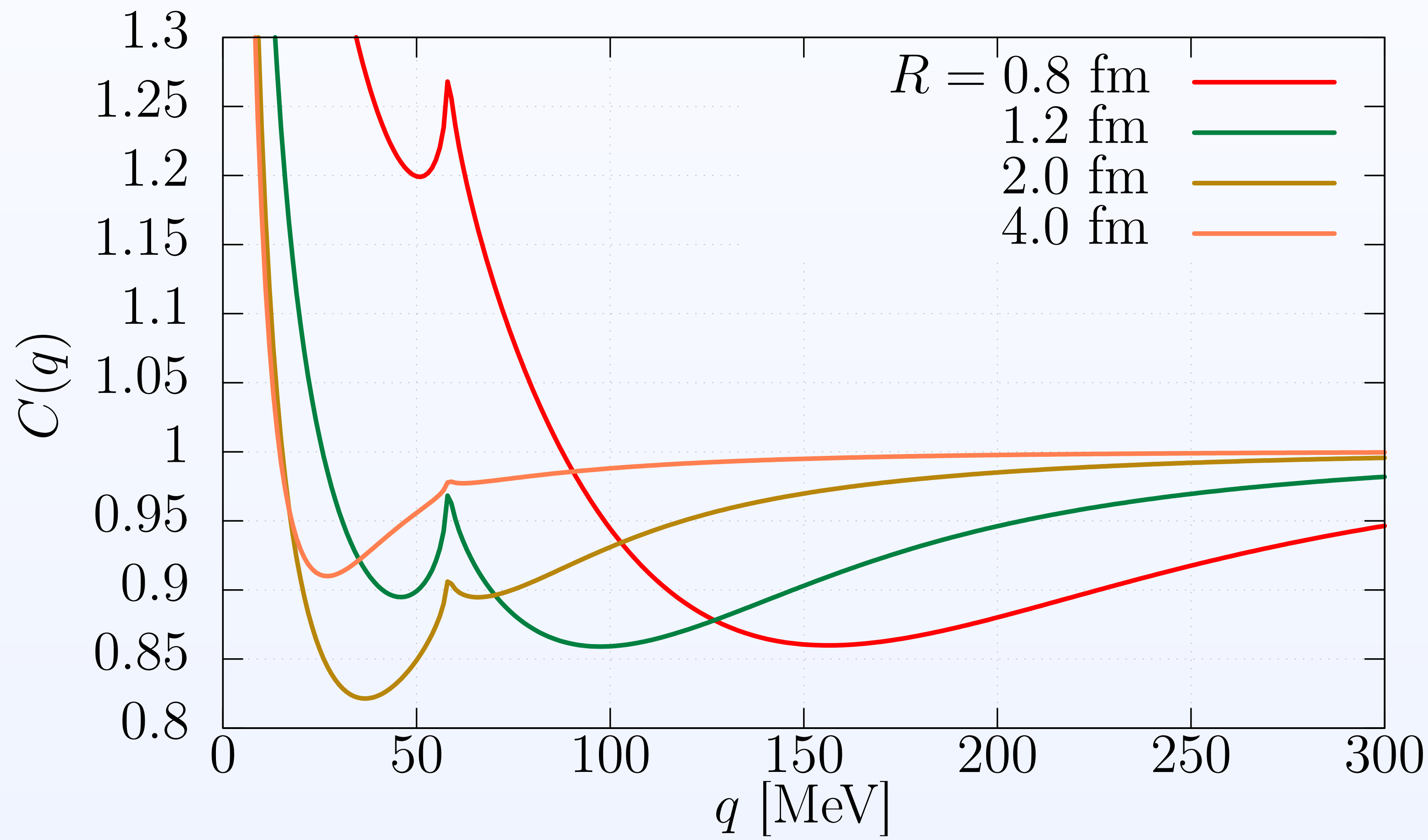
Source dependence

- Source size dependence of K^-p correlation

$$C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\, S(\mathbf{r}) \left[|\varphi^{C,\mathrm{full}}(\mathbf{q},\mathbf{r})|^2 - |j_0^C(qr)|^2 + |\psi_{K^-p}^{C,(-)}(q,r)|^2 \right] + \sum_j \omega_j \int d^3\mathbf{r}\, S(\mathbf{r}) |\psi_j^{C,(-)}(q,r)|^2$$

$$S(r) \propto \exp\left(-r^2/4R^2\right)$$





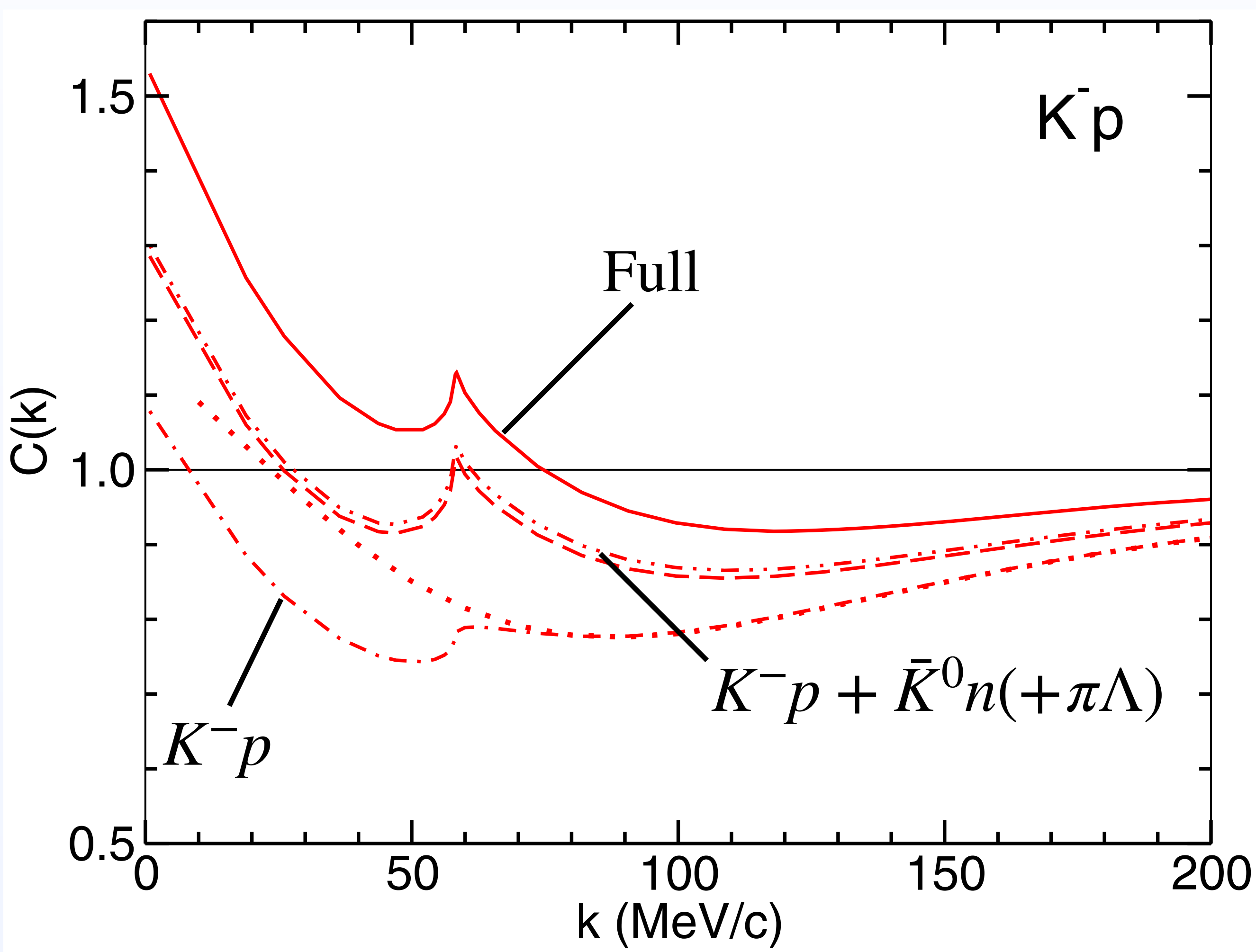
- Strong dependence around $R \sim 1.0$ fm
  <== • Sensitive region: $|R/a_0| \lesssim 1$.
- Larger system: cusp effect is moderate

Measurement of the K^-p in other size systems are important!

Comparison with Jülich model

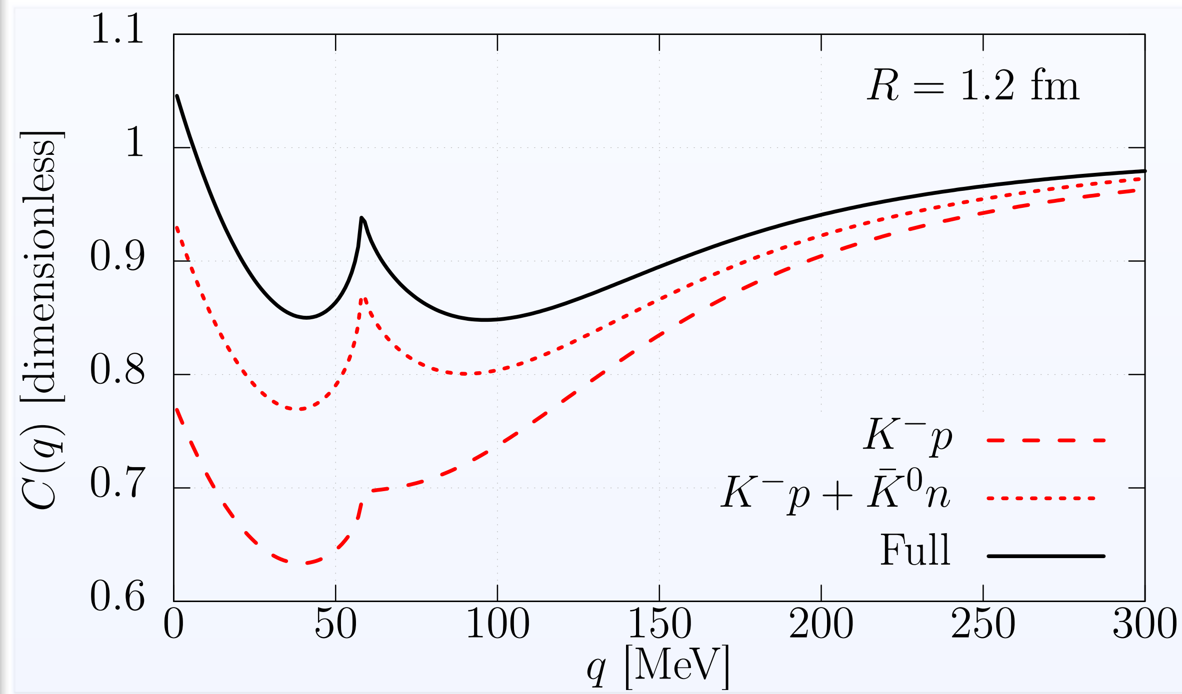
- Comparison with Jülich model: coupled-channel effect

Jülich Model



c.f. Haidenbauer NPA 981 (2018)

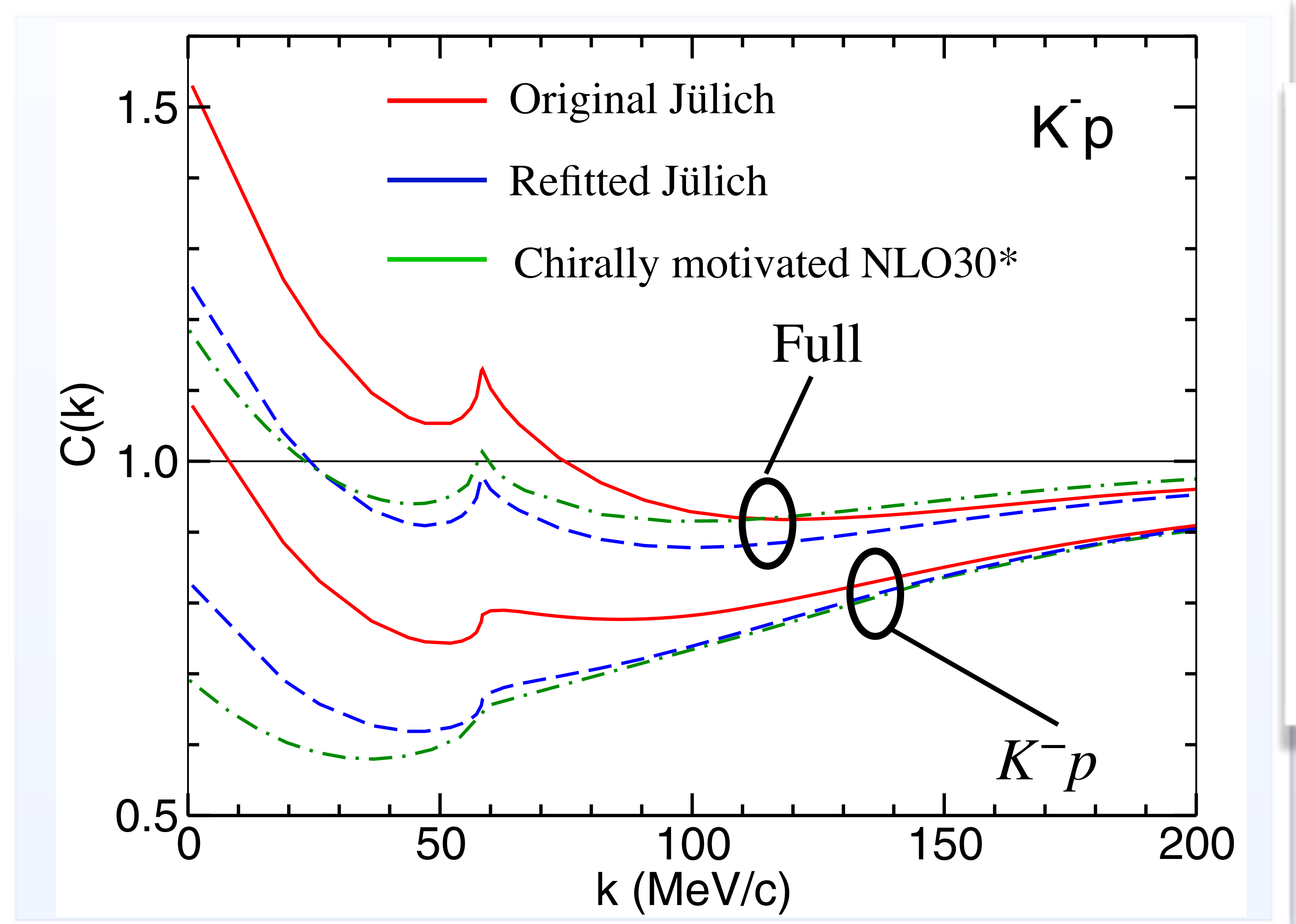
Our result



Comparison with Jülich model

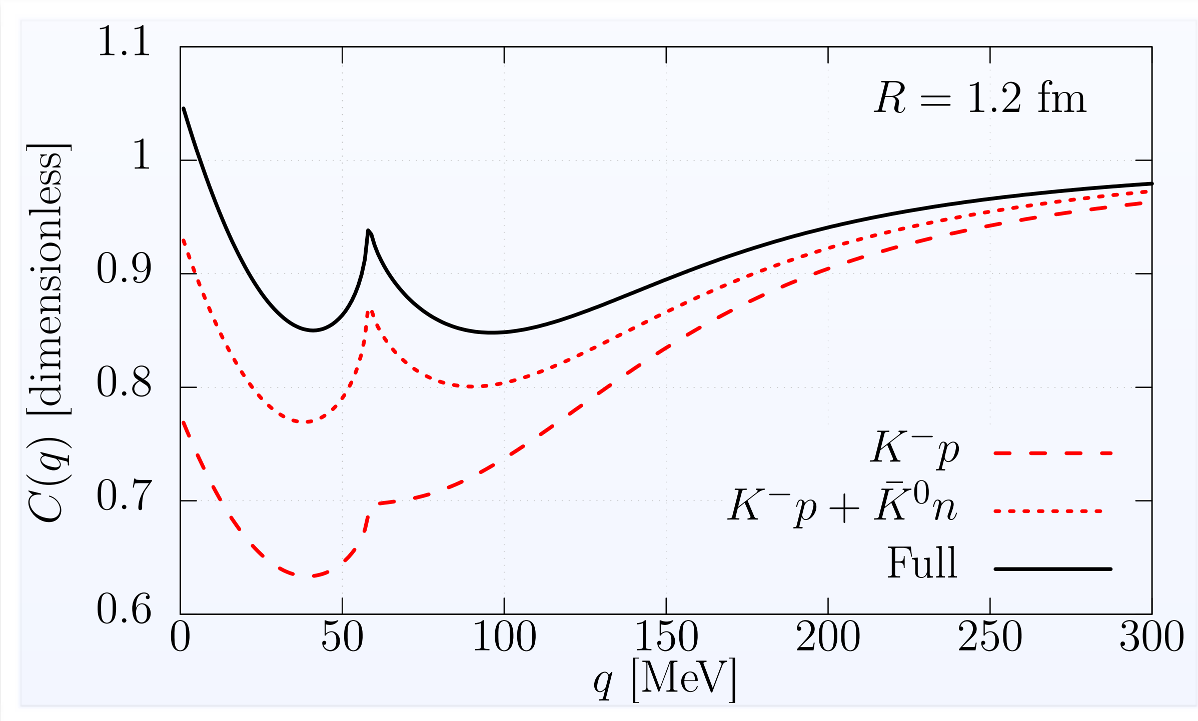
- Comparison with Jülich model: refitted model

Jülich Model



c.f. Haidenbauer NPA 981 (2018)

Our result



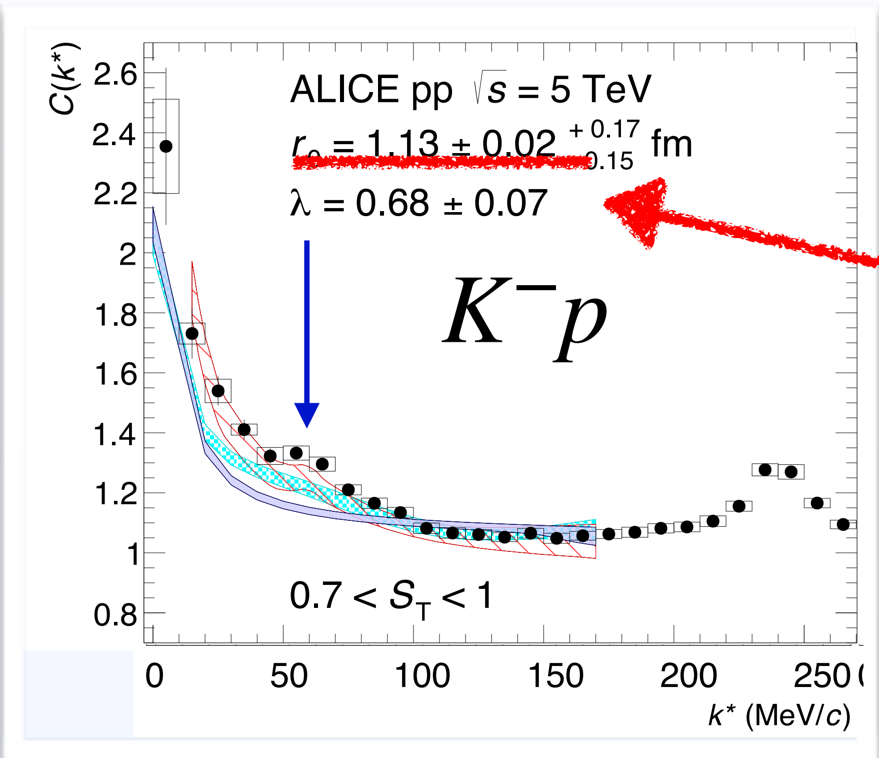
- Refitted Jülich model: constructed to reproduce $a_{K^-p}^{\mathrm{SIDDHARTA}}$

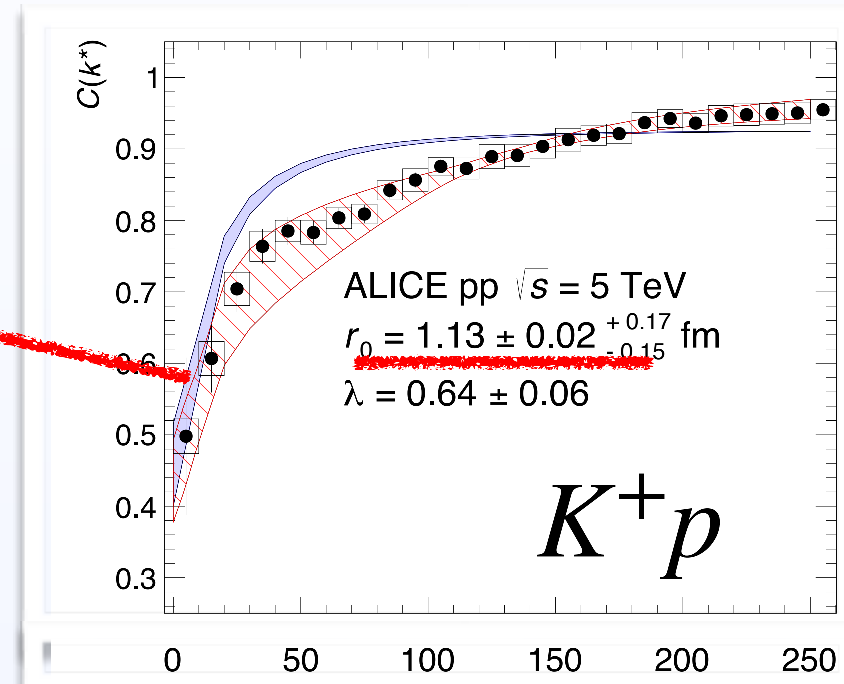
*A. Cieplý, et.al, NPA881(2012)

Comparison with ALICE data

- About the source size

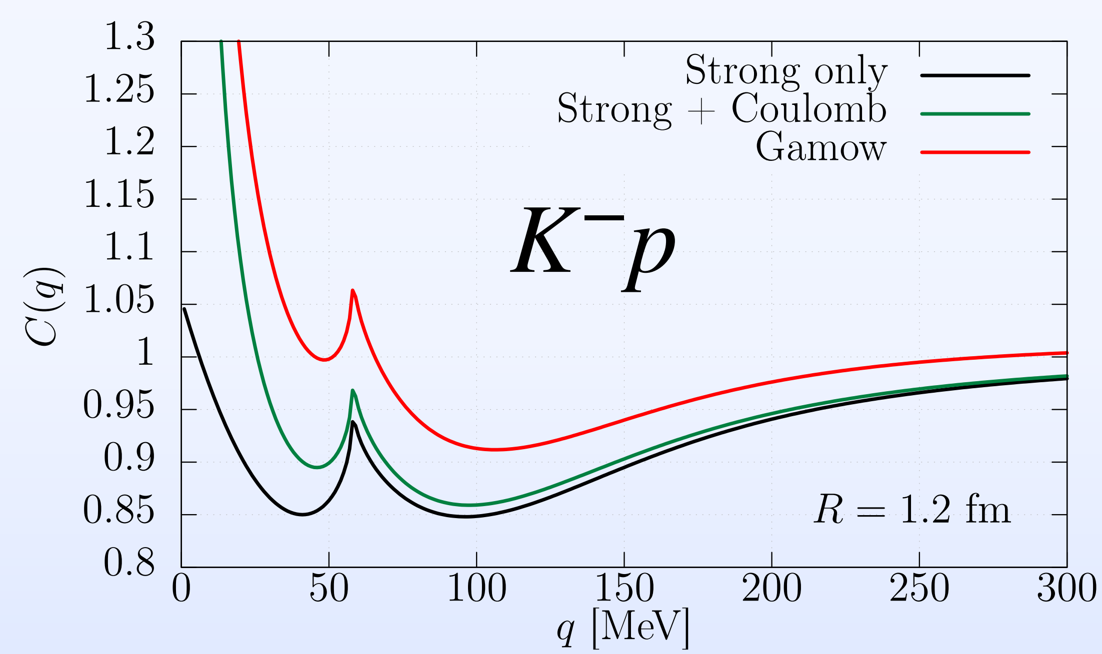
In ALICE analysis, the source size is determined from the K^+p correlation.





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

- But… Coulomb effect for K^+p correlation is
  - Relative source size is channel dependent:
    In general, $R_{\bar{K}N} \neq R_{KN}$
  - Gamow collection may over estimate the Coulomb int.



Comparison with ALICE data

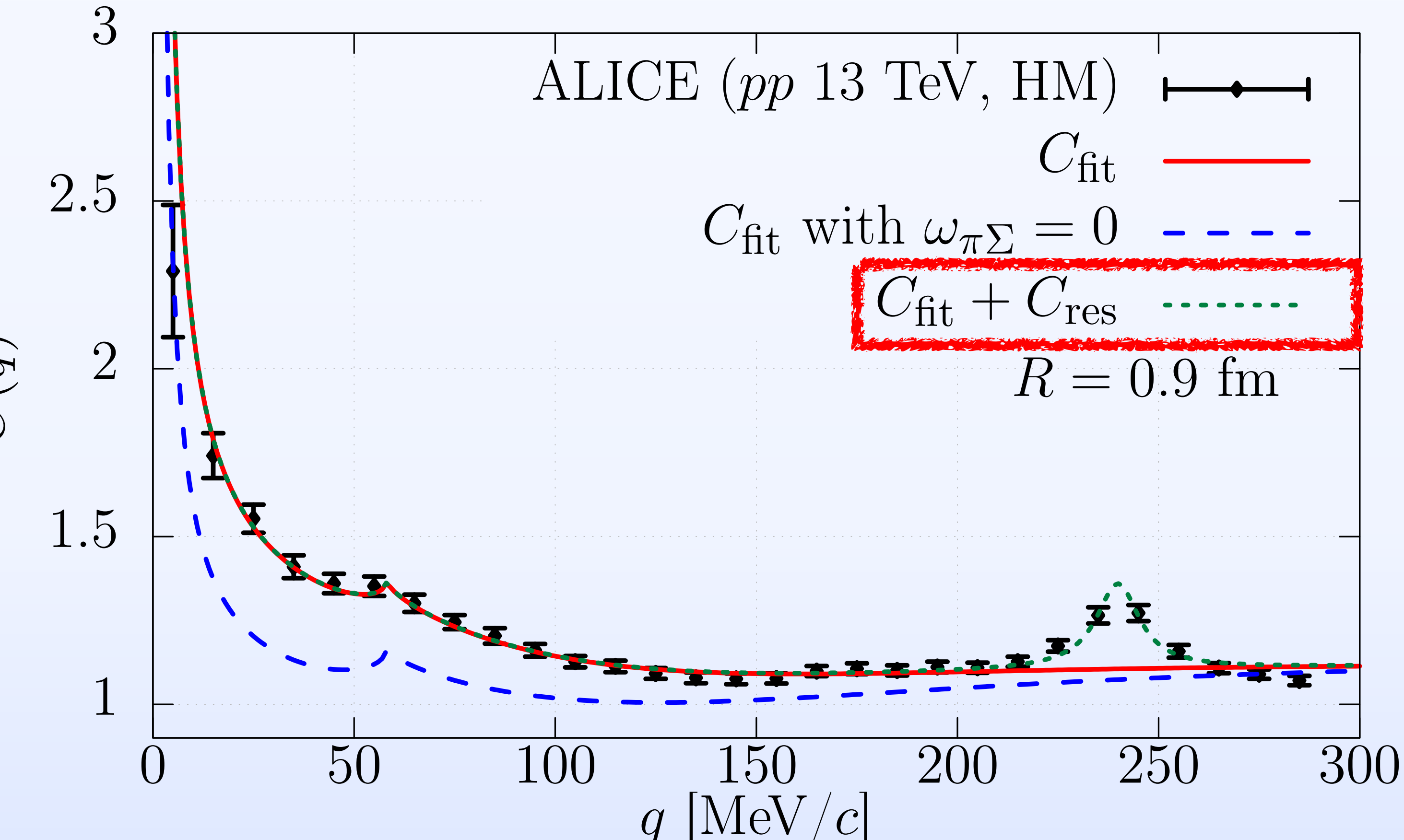
- $\Lambda(1520)$ contribution
  - Fit the remnant part of data ($C_{\text{data}} - C_{\text{fit}}$) by Breit-Wigner function

$$C_{\text{res}}(q) = \frac{b\Gamma^2}{(q^2/2\mu_{K^-p} + m_p + m_{K^-} - E_R)^2 + \Gamma^2/4}$$

  - Result

$$E_R = 1520.9 \text{ MeV}$$

$$\Gamma = 9.7 \text{ MeV}$$



- PDG pole position

$\Lambda(1520)$ $3/2^-$

REAL PART

VALUE (MeV)

1517 $^{+4}_{-4}$

$-2\times$IMAGINARY PART

VALUE (MeV)

15 $^{+10}_{-8}$

PDG PRD98 (2018)