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K^-p correlation function from high-energy nuclear collisions and chiral SU(3) dynamics

In collaboration with
Tetsuo Hyodo (Tokyo Metropolitan University)
Kenji Morita (Riken, Nishina center)
Akira Ohnishi (YITP, Kyoto University)
Wolfram Weise (Technical University of Munich)

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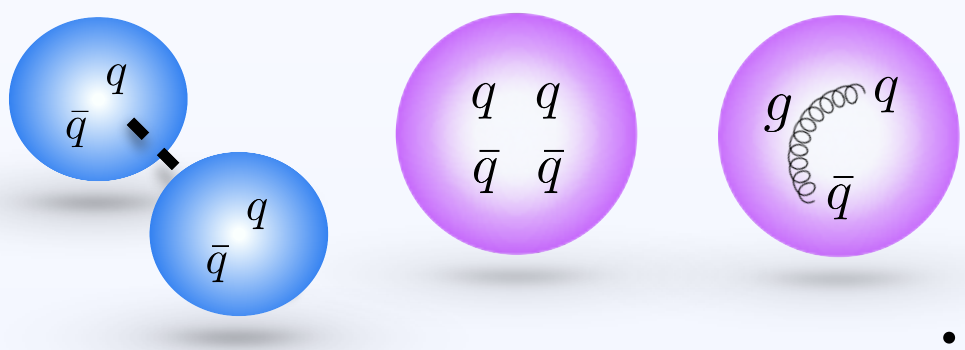
Contents

- Ordinary hadrons

- Exotic hadrons



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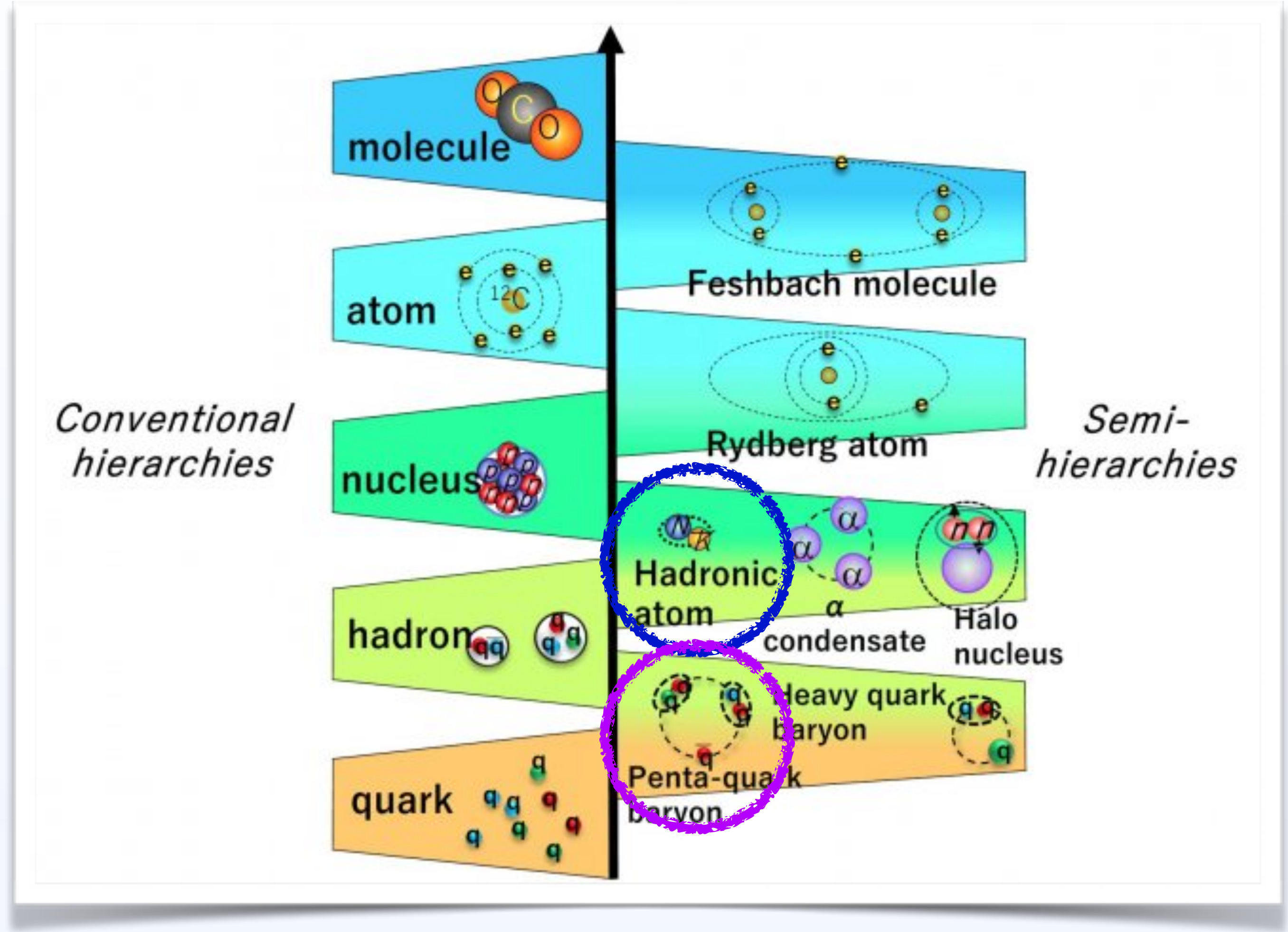

- To distinguish the internal structure of hadrons

  difficult because of the mixing of the state
  (States with the identical quantum numbers have mixing)

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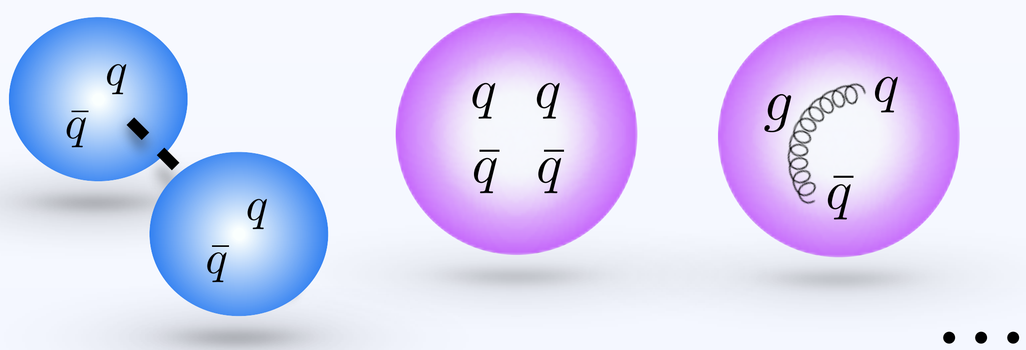

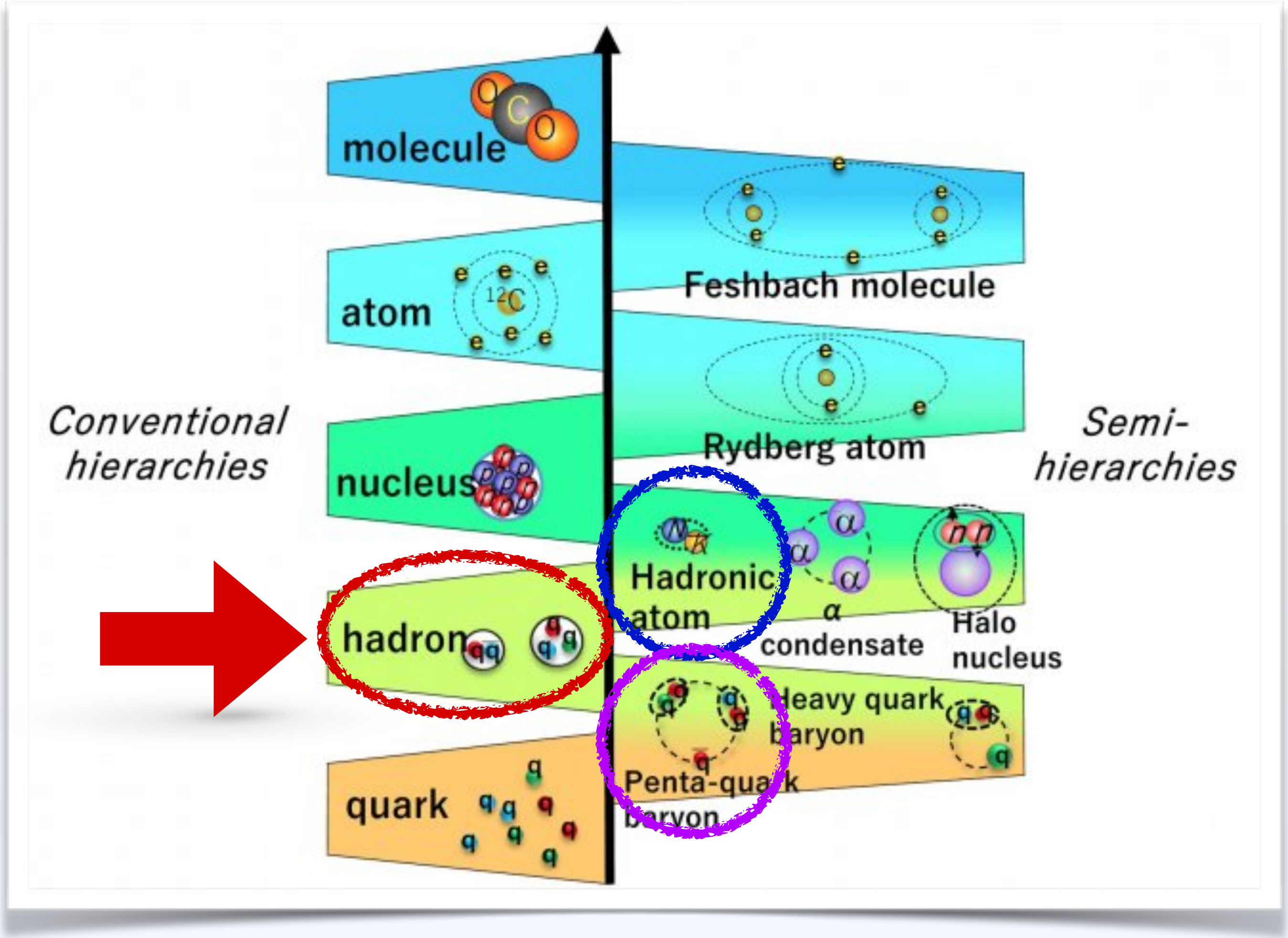

- To distinguish the internal structure of hadrons

difficult because of the mixing of the state
(States with the identical quantum numbers have mixing)

- Key: detailed study on the hadron-hadron interaction
(potential, amplitude, …)

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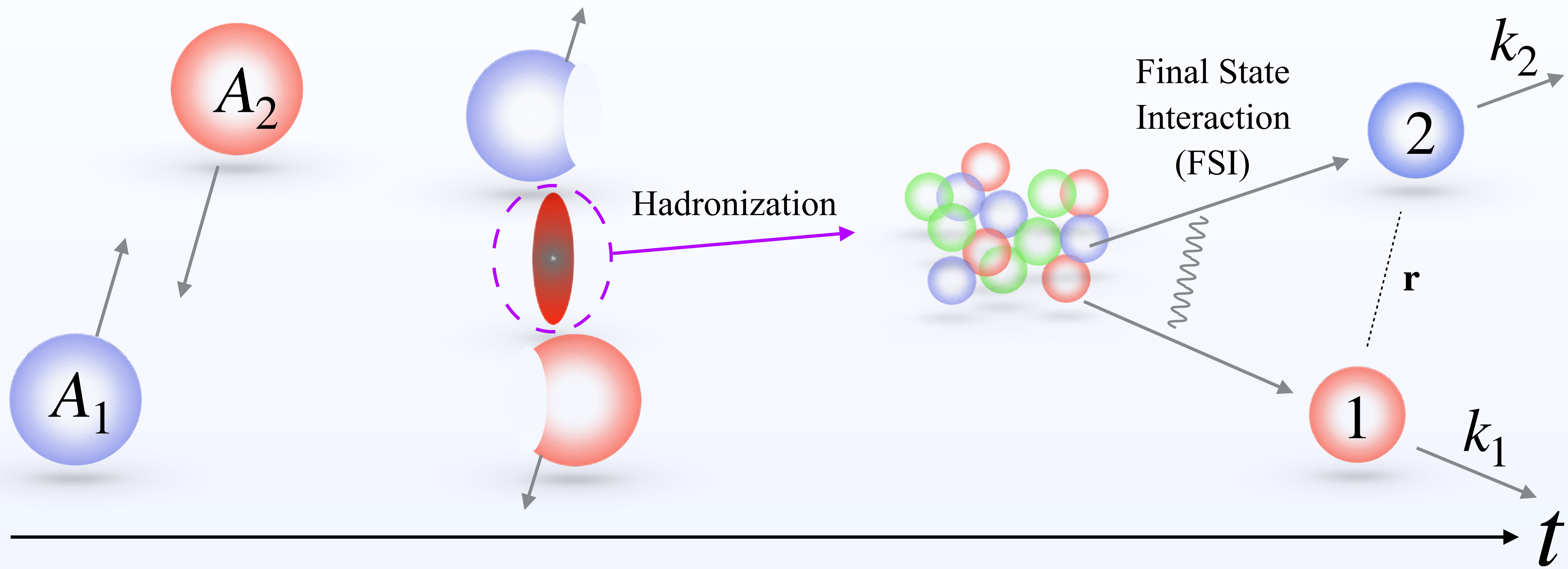
Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi and W. Weise, arXiv:1911.01041

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI



- Hadron-hadron correlation

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

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

Hadron correlation in high energy nuclear collision

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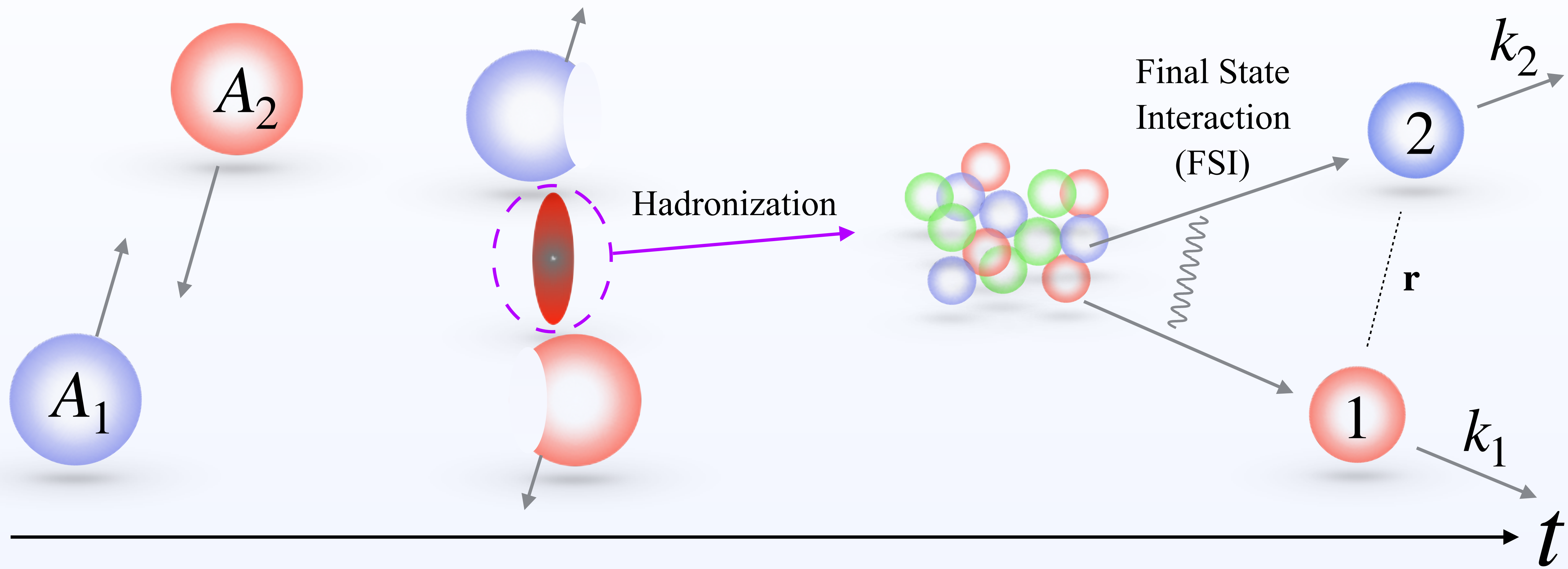


- Hadron-hadron correlation
  - Koonin-Pratt formula : S.E. Koonin, PLB 70 (1977) S. Pratt et. al. PRC 42 (1990)

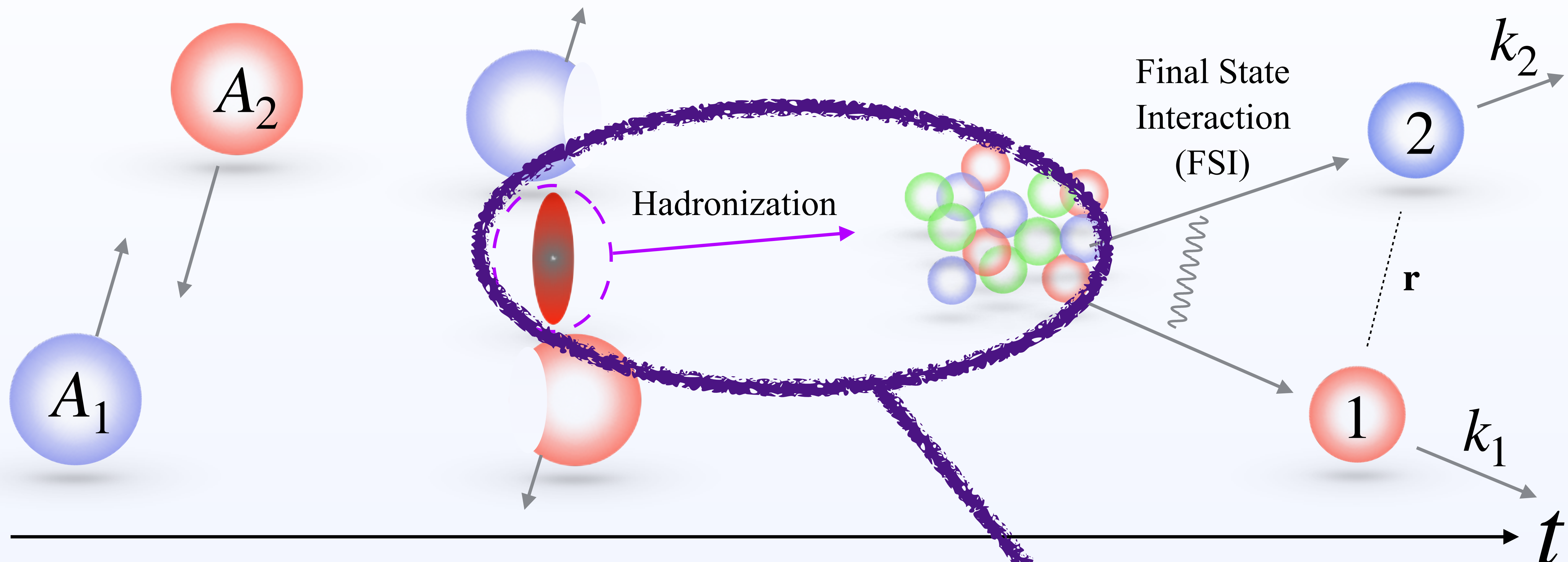
$$C(\mathbf{q}) \simeq \int d^3\mathbf{r}\ S(\mathbf{r})\,|\varphi^{(-)}(\mathbf{q},\mathbf{r})|^2$$

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

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

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

- High energy nuclear collision and FSI



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- Depends on …

  Collision detail (Ai, energy, centrality)

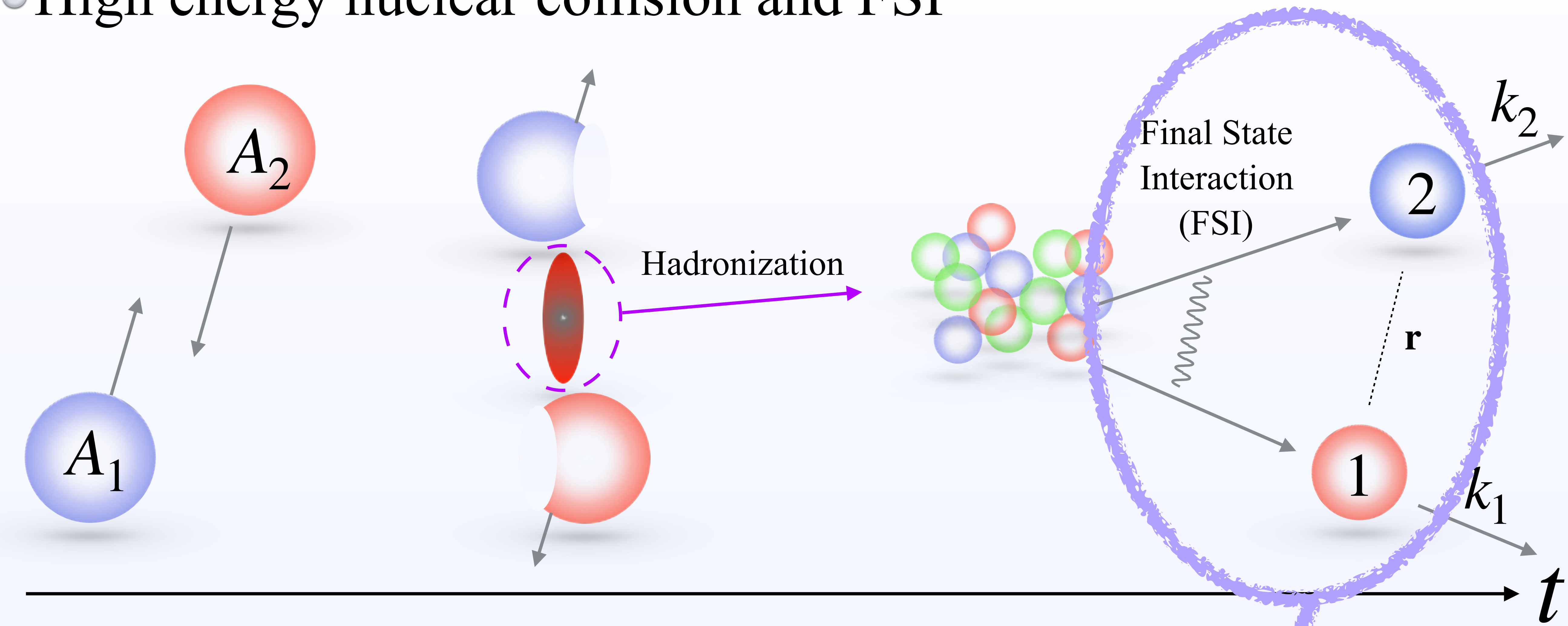
- Including information of…

  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

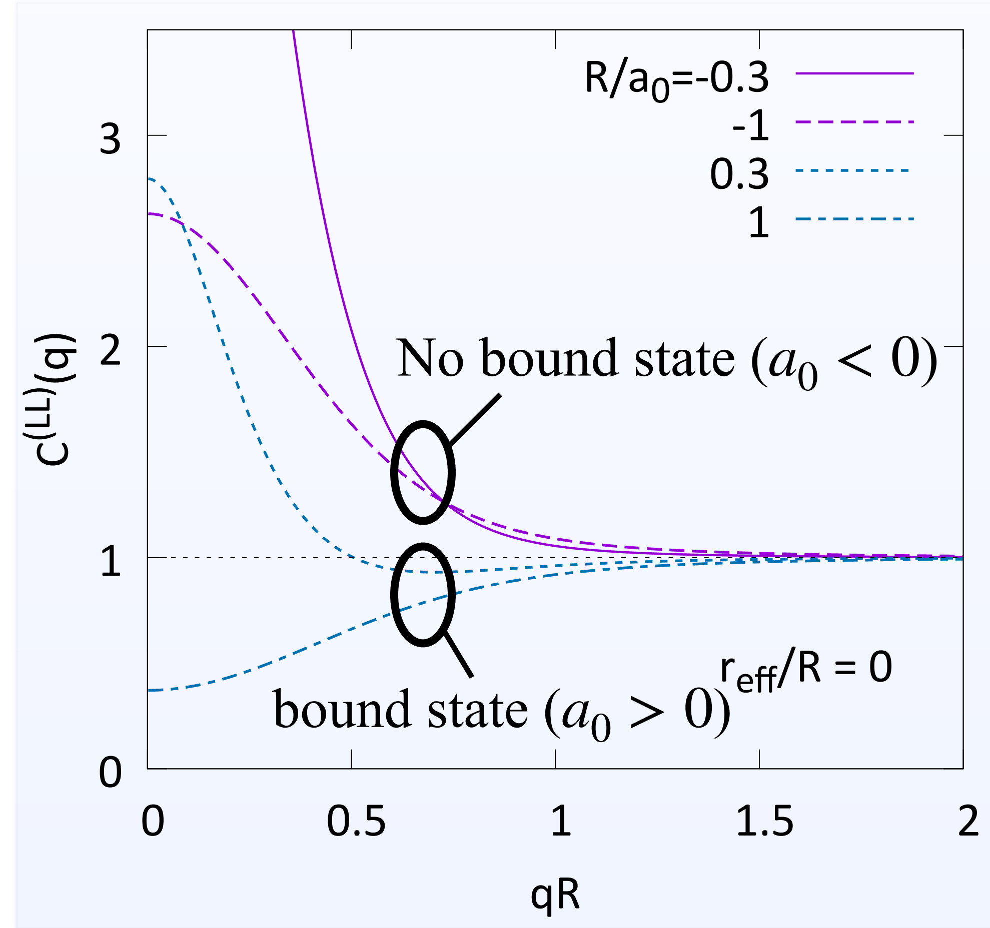
$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

- Lednicky-Lyuboshits (LL) formula

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

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

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



Morita, et al., arXiv:1908.05414

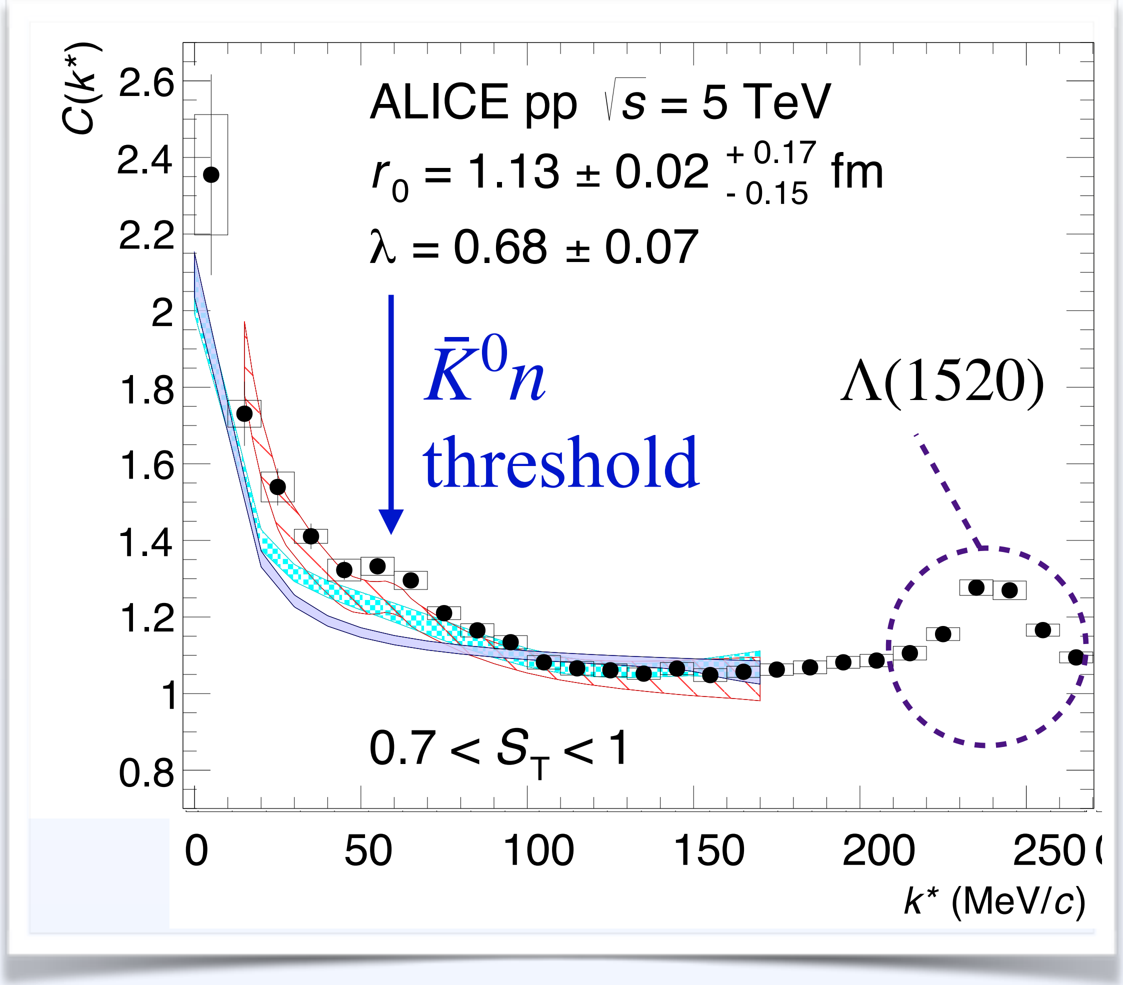
- $C(q)$ is sensitive to R/a_0
  - R : Gaussian source size
  - a_0: scattering length $(\equiv -\mathcal{F}(q=0))$

Powerful tool to study hadron interaction in low energy region

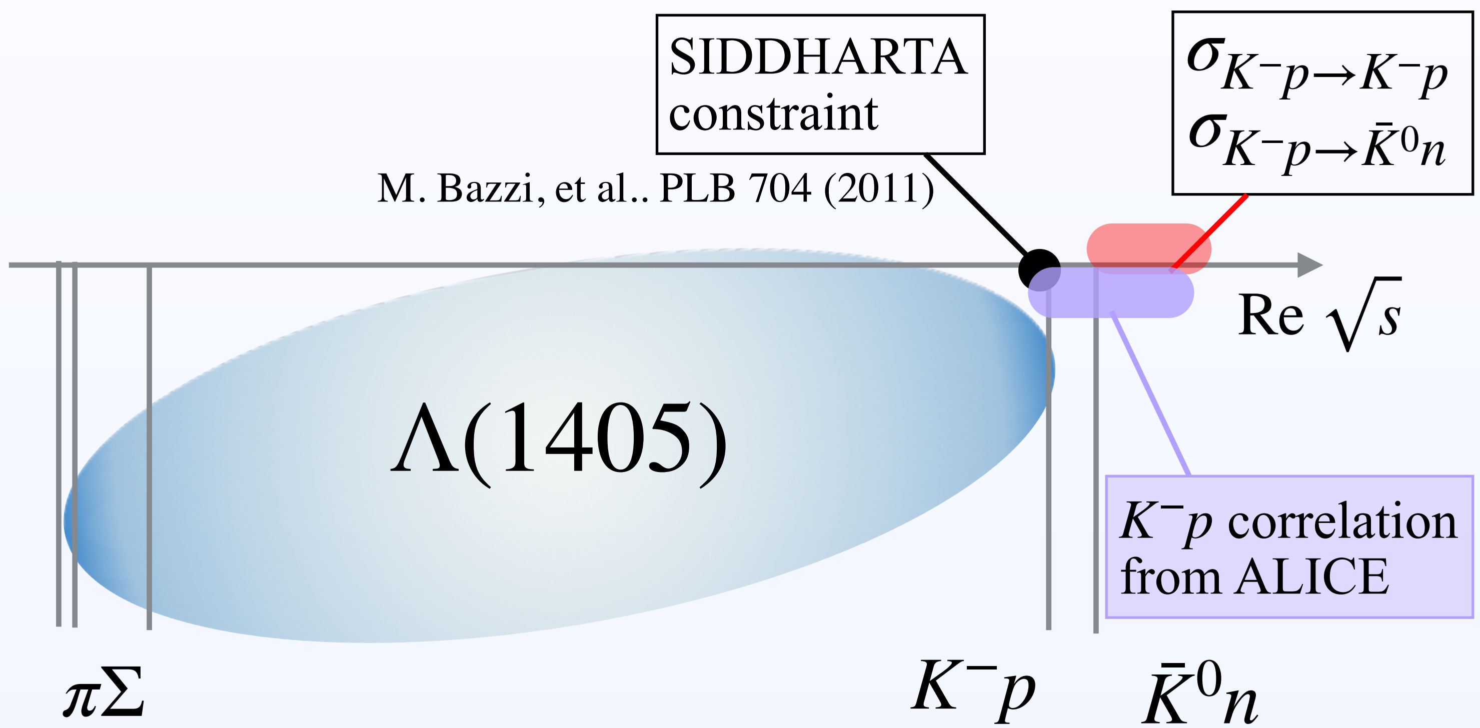
K^-p correlation

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

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



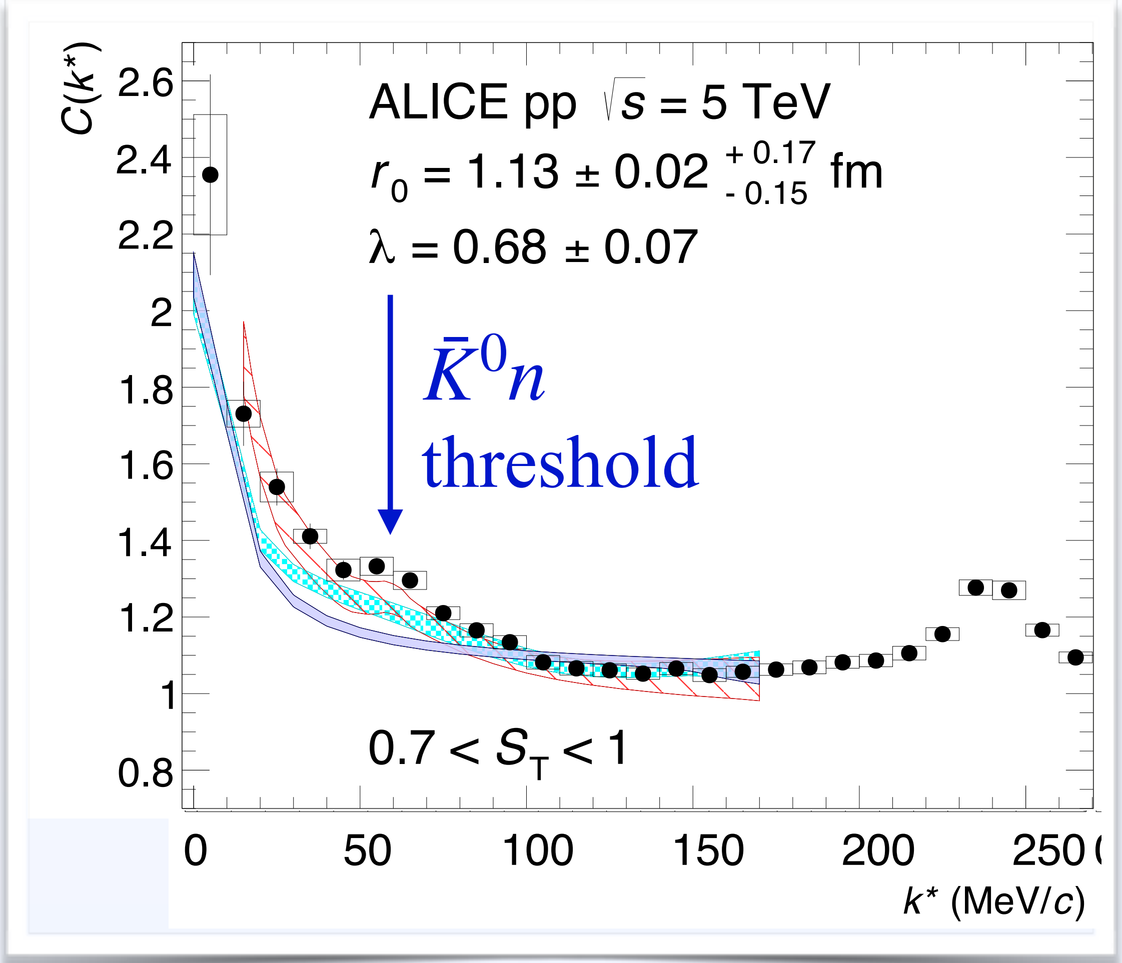
- Experimental data on $\bar{K}N$ int.



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

$K^- p$ 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 try 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

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

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)

$$\boxed{C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\left[\sum_{l\geq 1}|\varphi_l^C(\mathbf{q};\mathbf{r})|^2 + |\psi_{K^-p}^{C,(-)}(q;r)|^2\right] + \sum_{j\neq i}\omega_j\int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{C,(-)}(q;r)|^2}$$

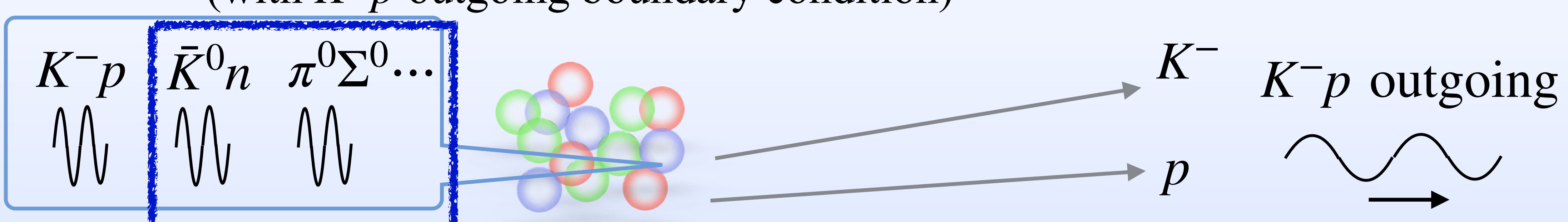
K^-p $l \geq 1$ waves (Coulomb)

K^-p s-wave (Coulomb + Strong)

Coupled-channel wave function (s-wave)

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

(with K^-p outgoing boundary condition)



K^-p correlation with Koonin-Pratt Formula

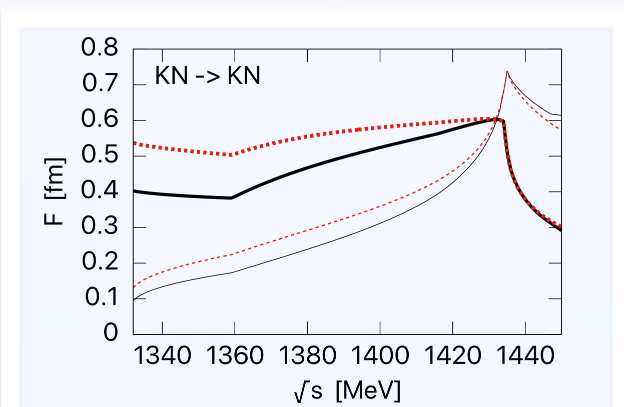
Chiral SU(3) based $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ potential

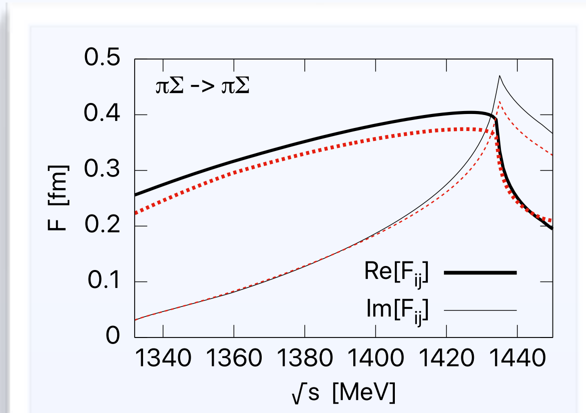
Miyahara, Hyodo, Weise, PRC 98 (2018)

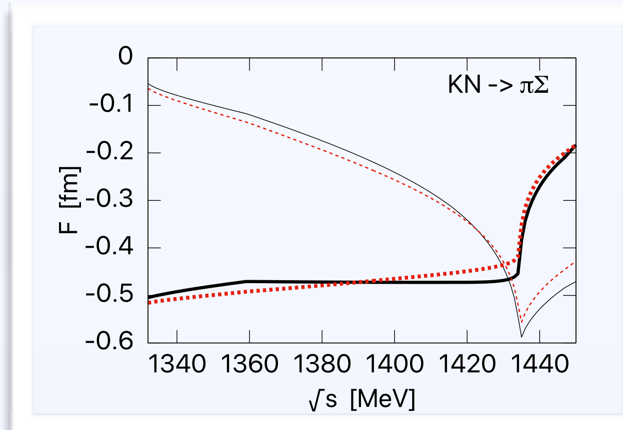
- Constructed based on the amplitude with NLO chiral SU(3) dynamics
  Ikeda, Hyodo, Weise, NPA881 (2012)
- Coupled-channel, energy dependent as

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

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



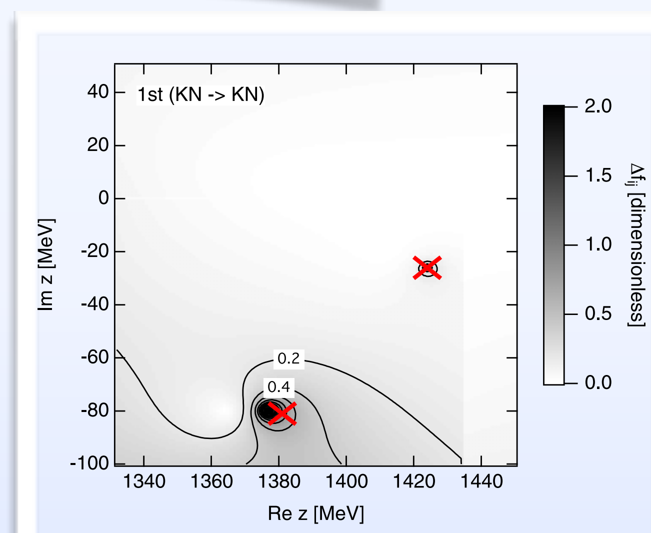




- Reproduce two pole structure of $\Lambda(1405)$

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

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



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Coupled-channel Schrödinger eq.

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

$$E = \frac{q_1^2}{2\mu_1} \qquad V_{ij} = V_{ij}^{\text{strong}}\ (\ +V^{\text{Coulomb}}) \qquad \Delta_i\ ;\ \text{threshold energy diff.}$$

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

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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)…

$$\boxed{C_{K^-p}(\mathbf{q}) = \int d^3\mathbf{r}\ S_{K^-p}(\mathbf{r})\Big[\sum_{l\geq 1}|\varphi_l^C(\mathbf{q};\mathbf{r})|^2 + |\psi_{K^-p}^{C,(-)}(q;r)|^2\Big] + \sum_{j\neq i}\omega_j\int d^3\mathbf{r}\ S_j(\mathbf{r})|\psi_j^{C,(-)}(q;r)|^2}$$

- 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 ($\sim$ 1 fm)
  - Source weight of $\pi\Sigma$ channel : $\omega_{\pi\Sigma}$ ($\sim$ 2)

Normal size for *pp* collision

Statistical model estimate

- Phenomenological parameters

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

- Normalization

$N \sim 1$

- Pair purity parameter

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

Monte calro simulation by experimental group

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

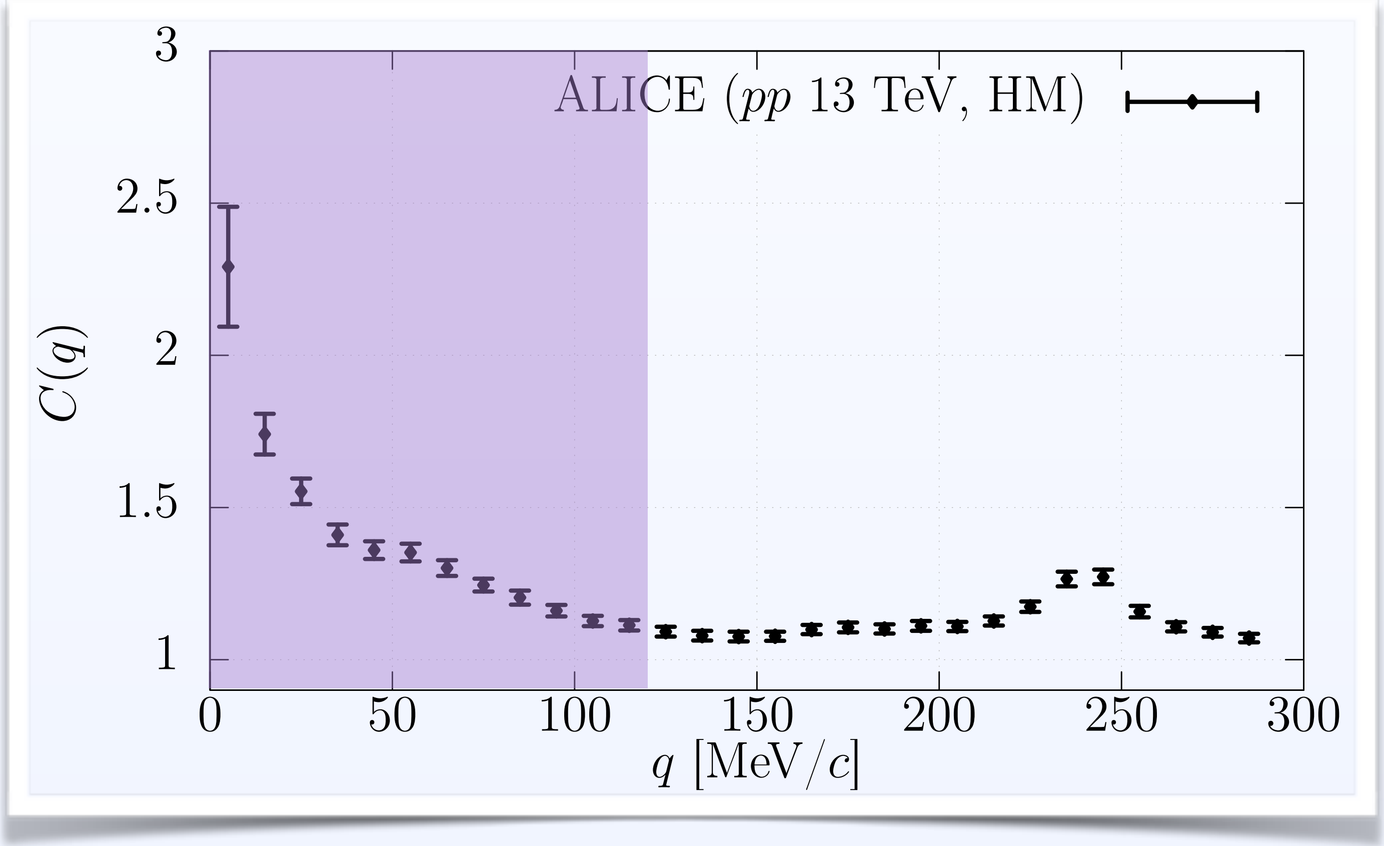
Comparison with ALICE data

- 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



Comparison with ALICE data

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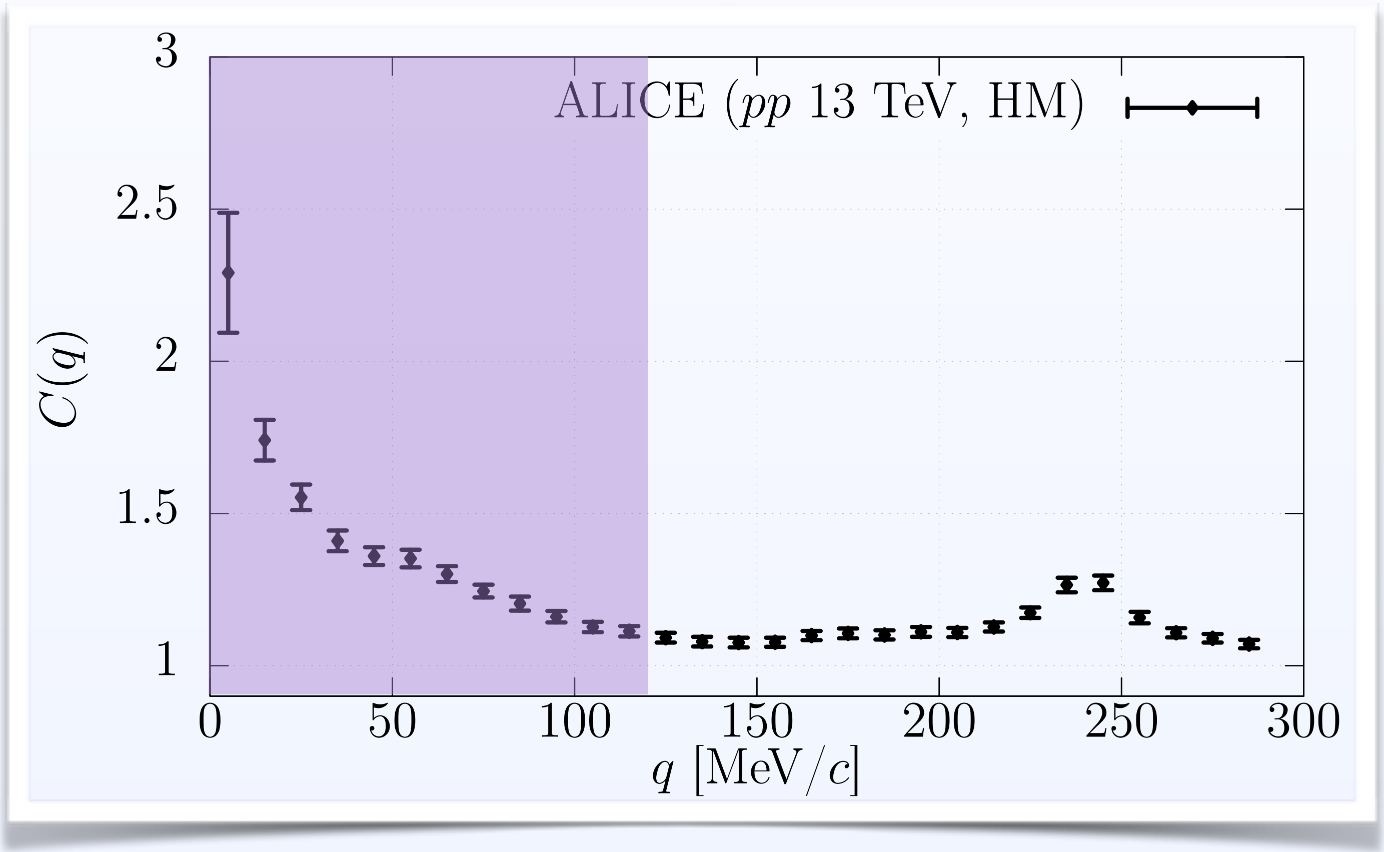

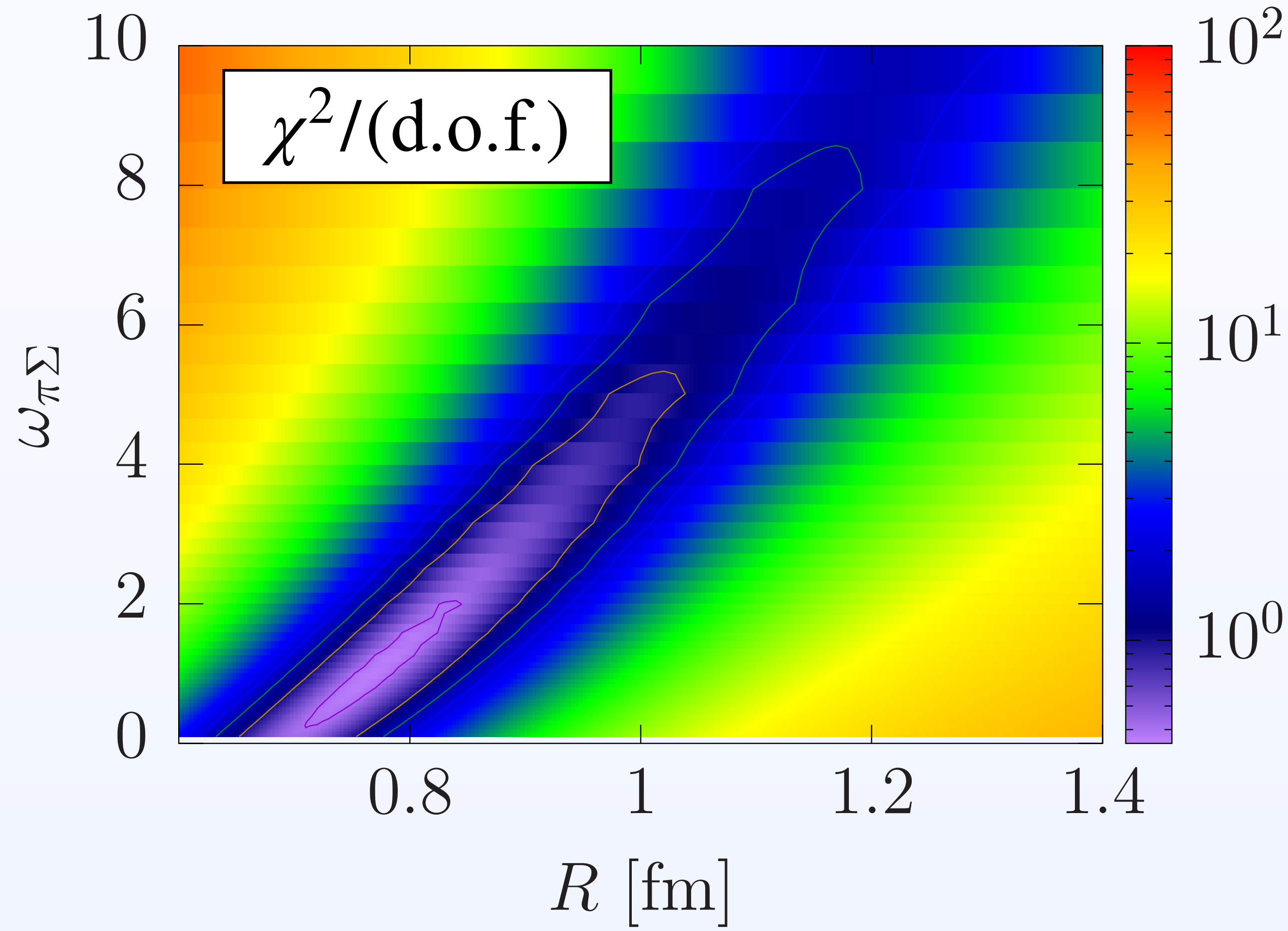

- ALICE data has been well reproduced with the reasonable values of parameters.
- C.c. source contribution is essential to reproduce the data.

Comparison with ALICE data

- Fitting result
  - Fitting function

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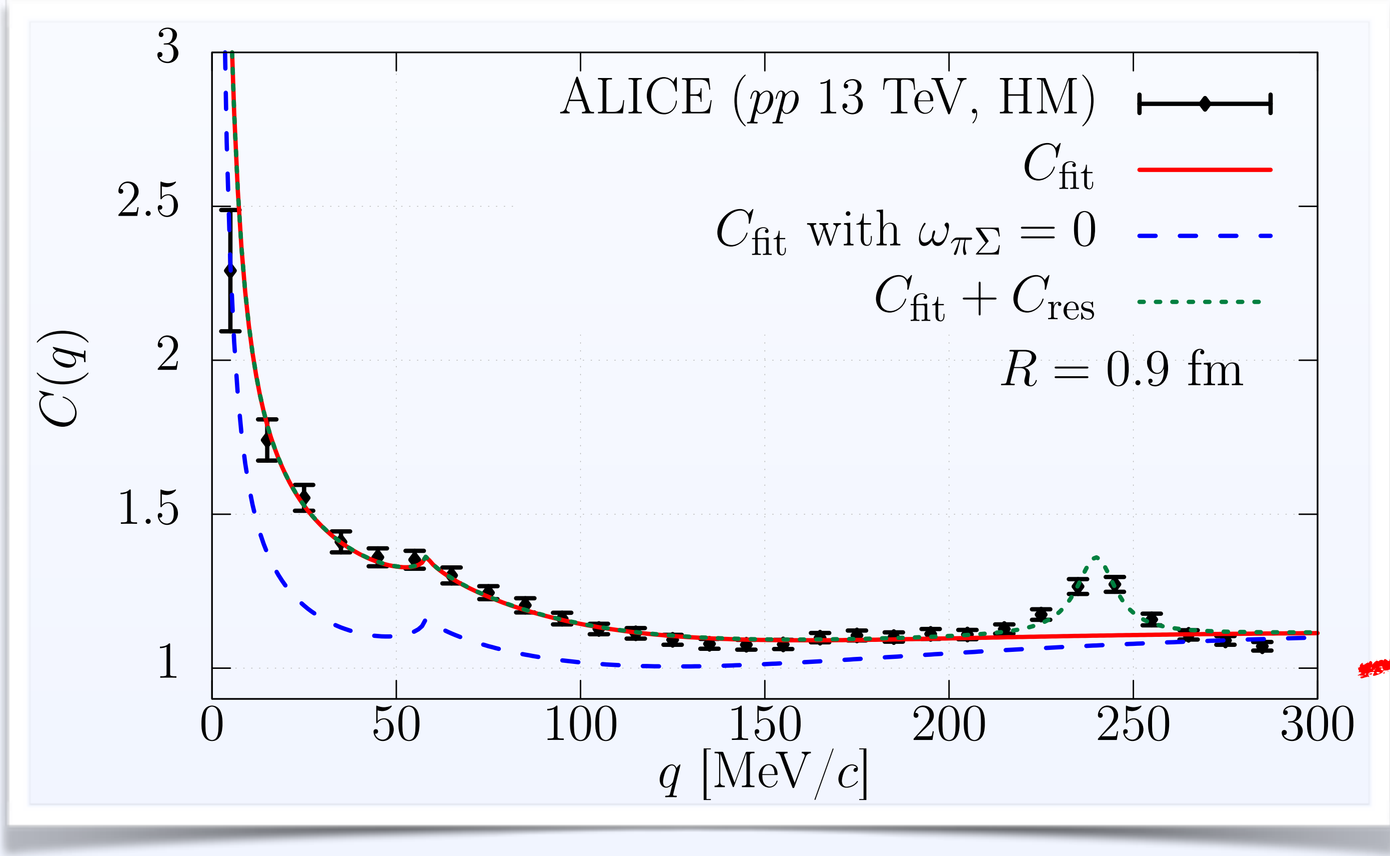

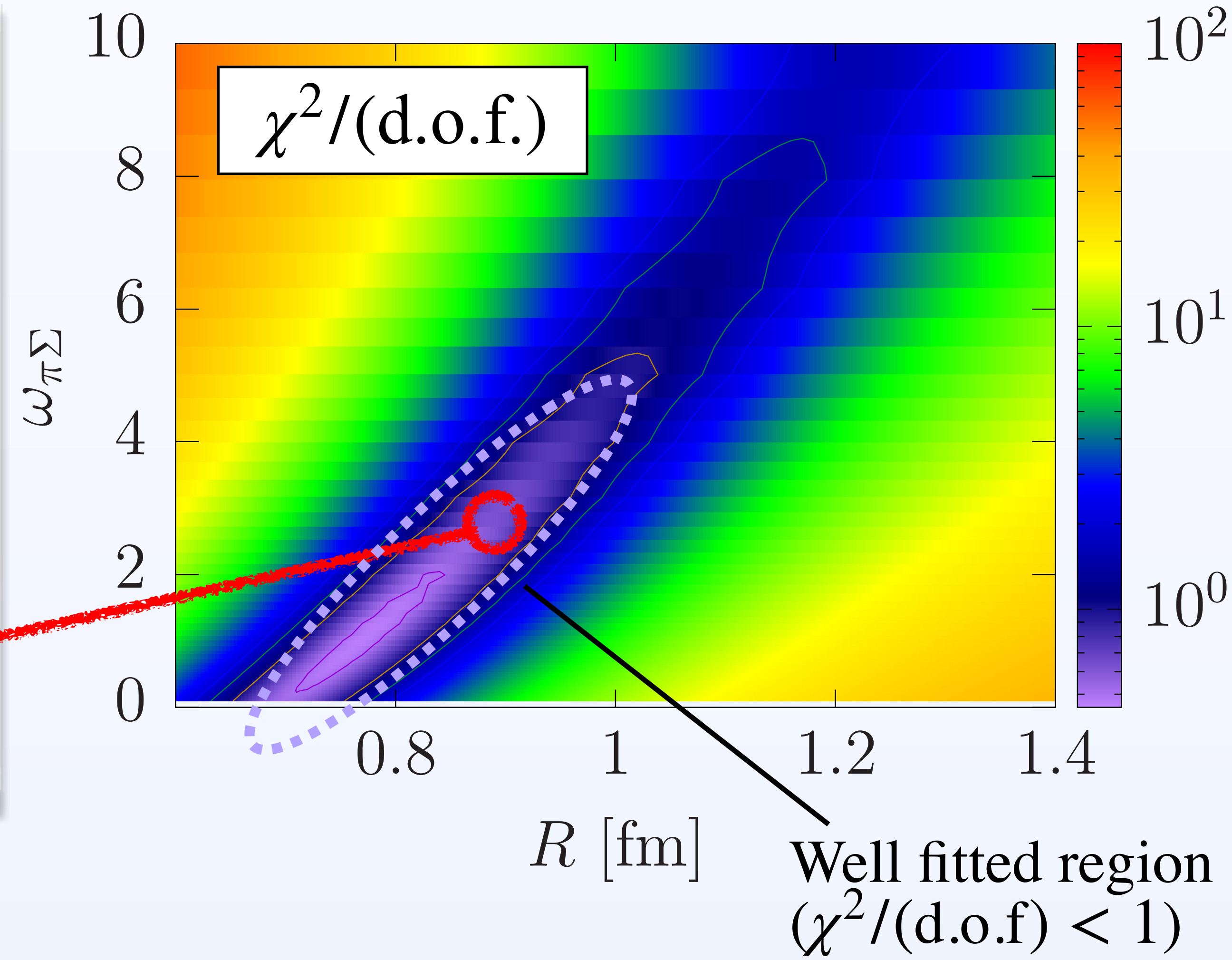

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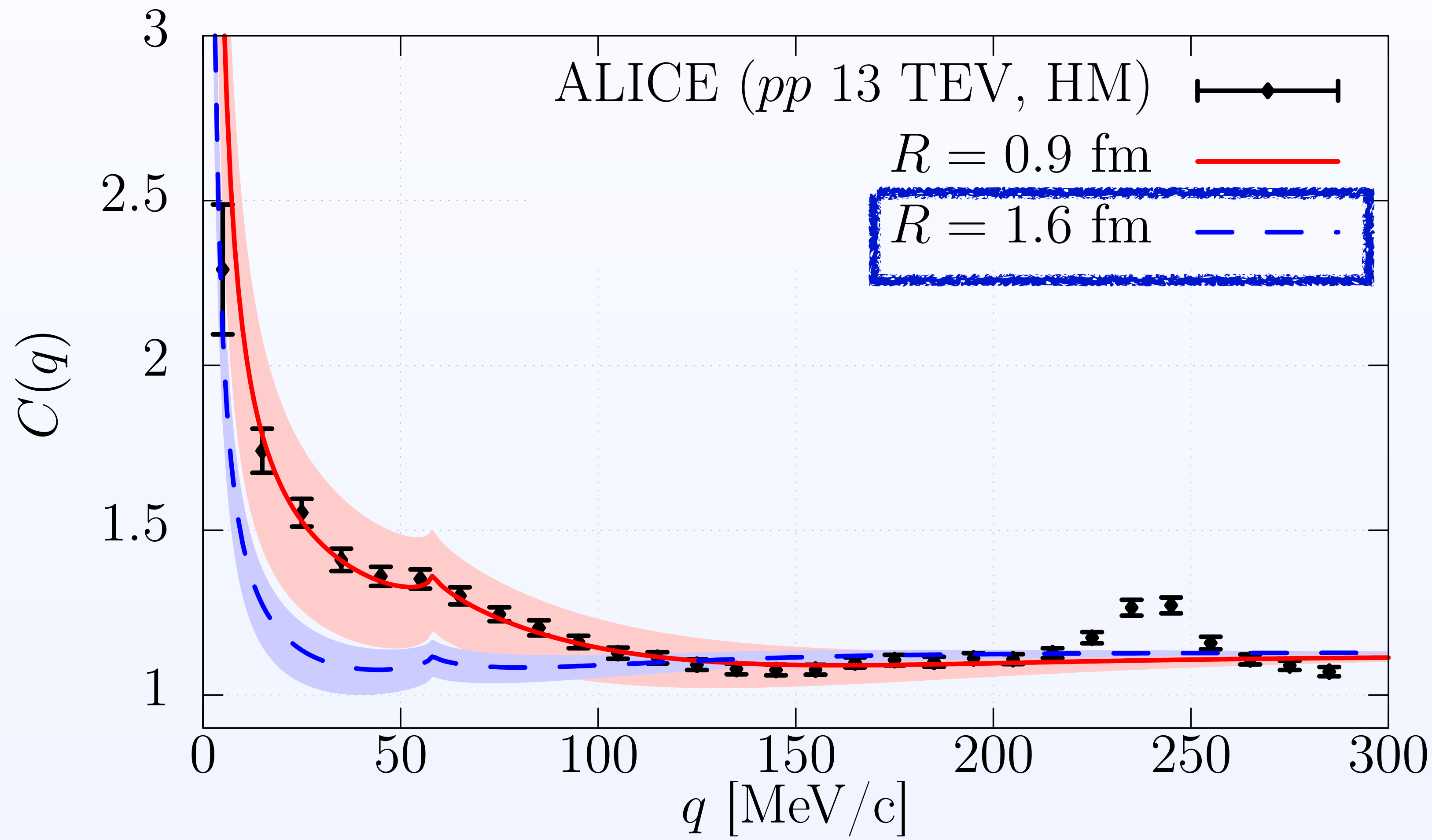
Comparison with ALICE data

- Correlation in larger source system

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



* Same values for $\mathcal{N}$, λ, ω

* Shadow: uncertainties by $\omega_{\pi\Sigma}$ $(0.5 < \omega_{\pi\Sigma} < 5)$

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

Summary

- Hadron correlation function in high energy nuclear collisions 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.

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

Thank you!