Femtoscopic study on the $N\Xi$-$\Lambda\Lambda$ interaction

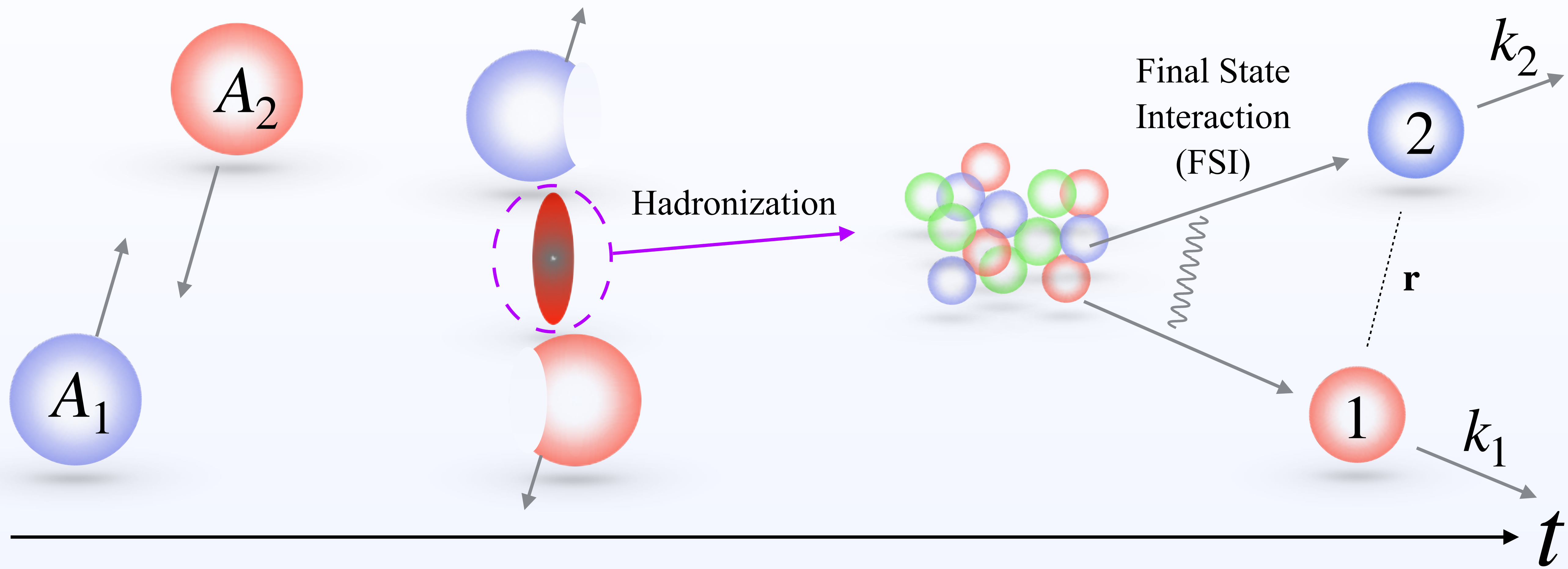
Yuki Kamiya
Institute of Theoretical Physics,
Chinese Academy of Sciences

Kenji Sasaki (CiDER, Osaka Univ.)
Tokuro Fukui (RIKEN)
Tetsuo Hyodo (Tokyo Metropolitan Univ.)
Kenji Morita (RIKEN)
Kazuyuki Ogata (RCNP,Osaka Univ.)
Tetsuo Hatsuda (RIKEN)
Akira Ohnishi (YITP, Kyoto Univ.)

HADRON 2021/07/28,
Zoom conference @ Mexico

Hadron correlation in high energy nuclear collision

- High energy nuclear collision and FSI

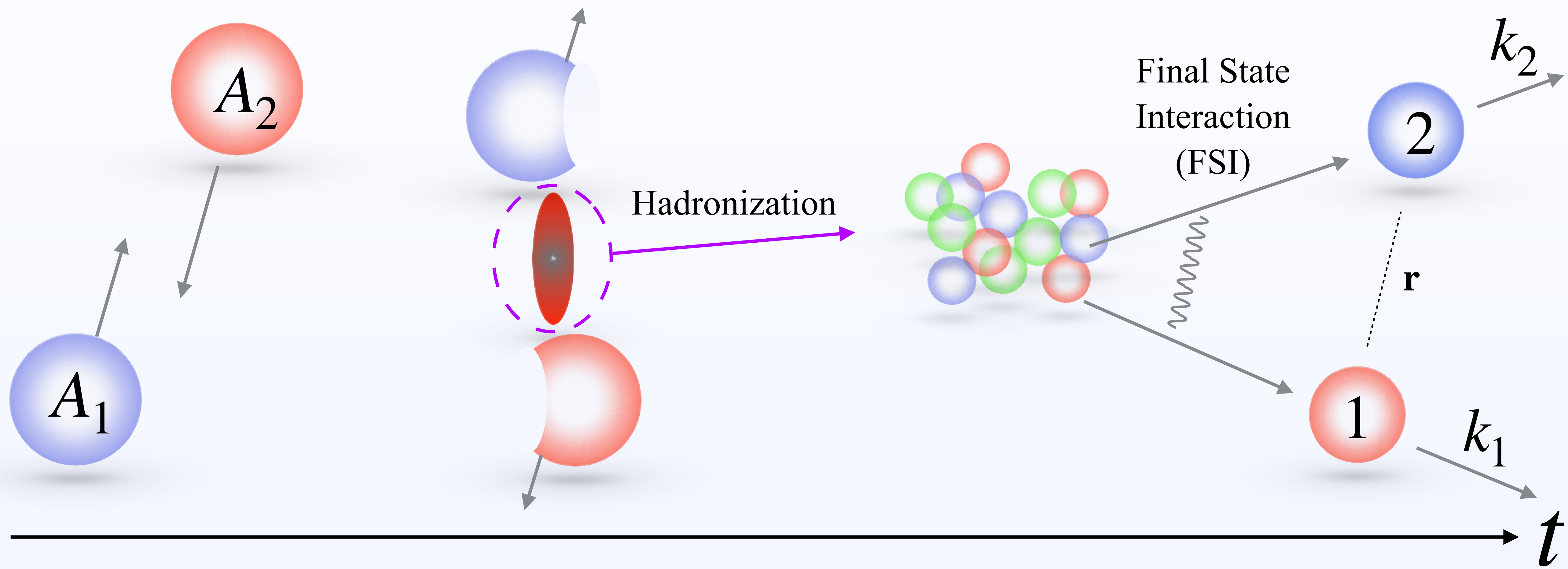


- Hadron-hadron correlation

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

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

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)

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

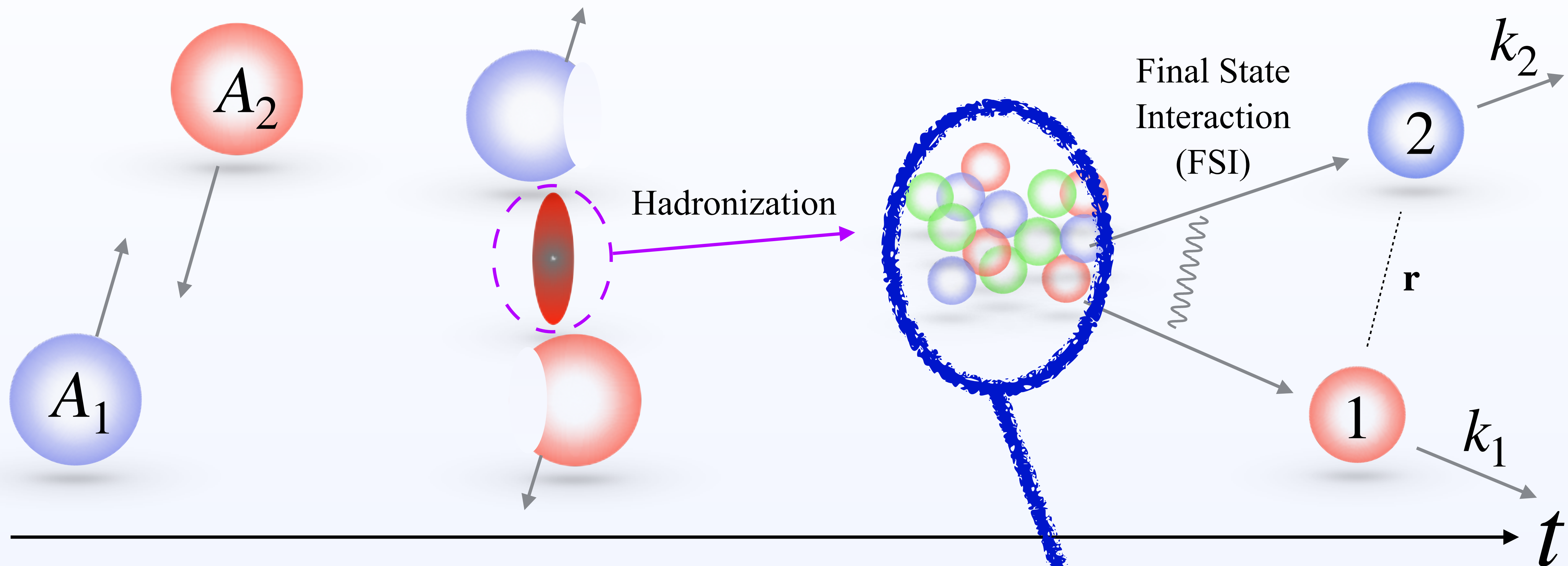
$$\mathbf{q} = (m_2\mathbf{k}_1 - m_1\mathbf{k}_2)/(m_1 + m_2)$$

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

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

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

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

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

- Depends on …

  Collision detail (A_i, energy, centrality)

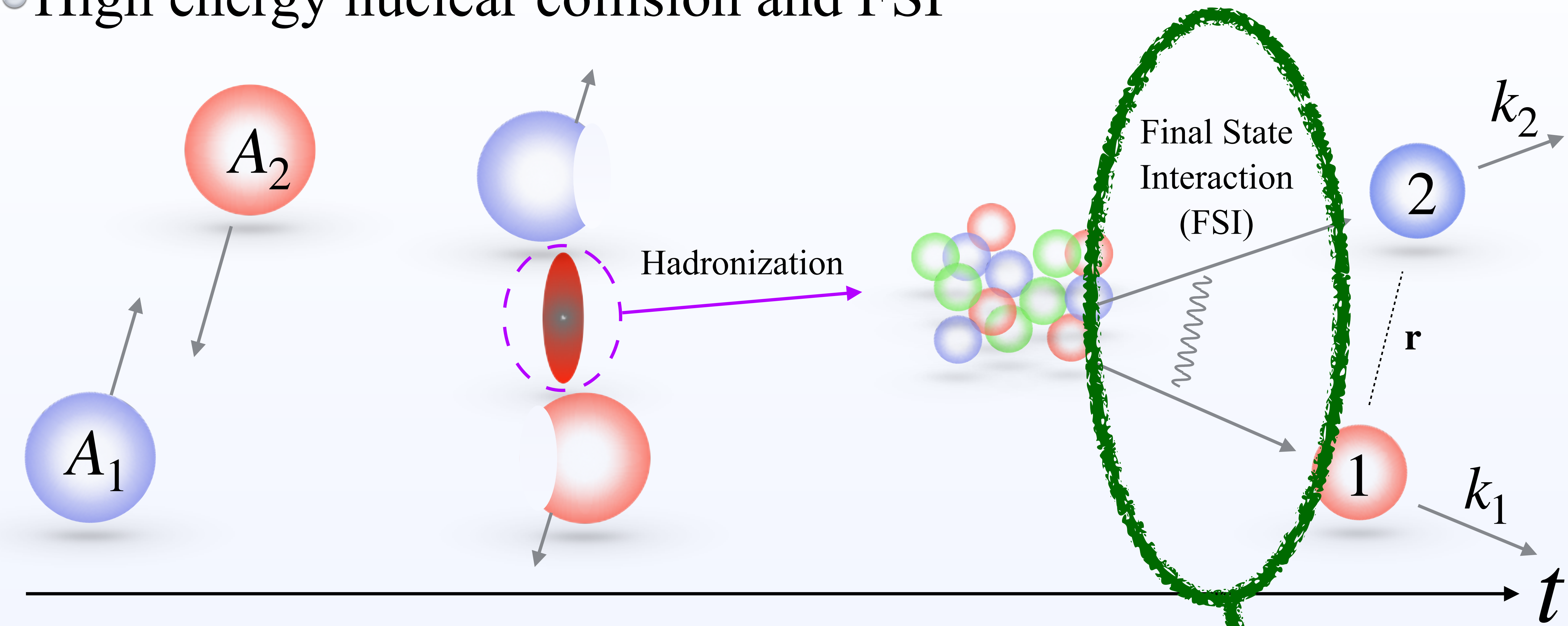
- Including information of…

  size of hadron source,

  momentum dependence, weight…

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)

Analytic model for ideal cases

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

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

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

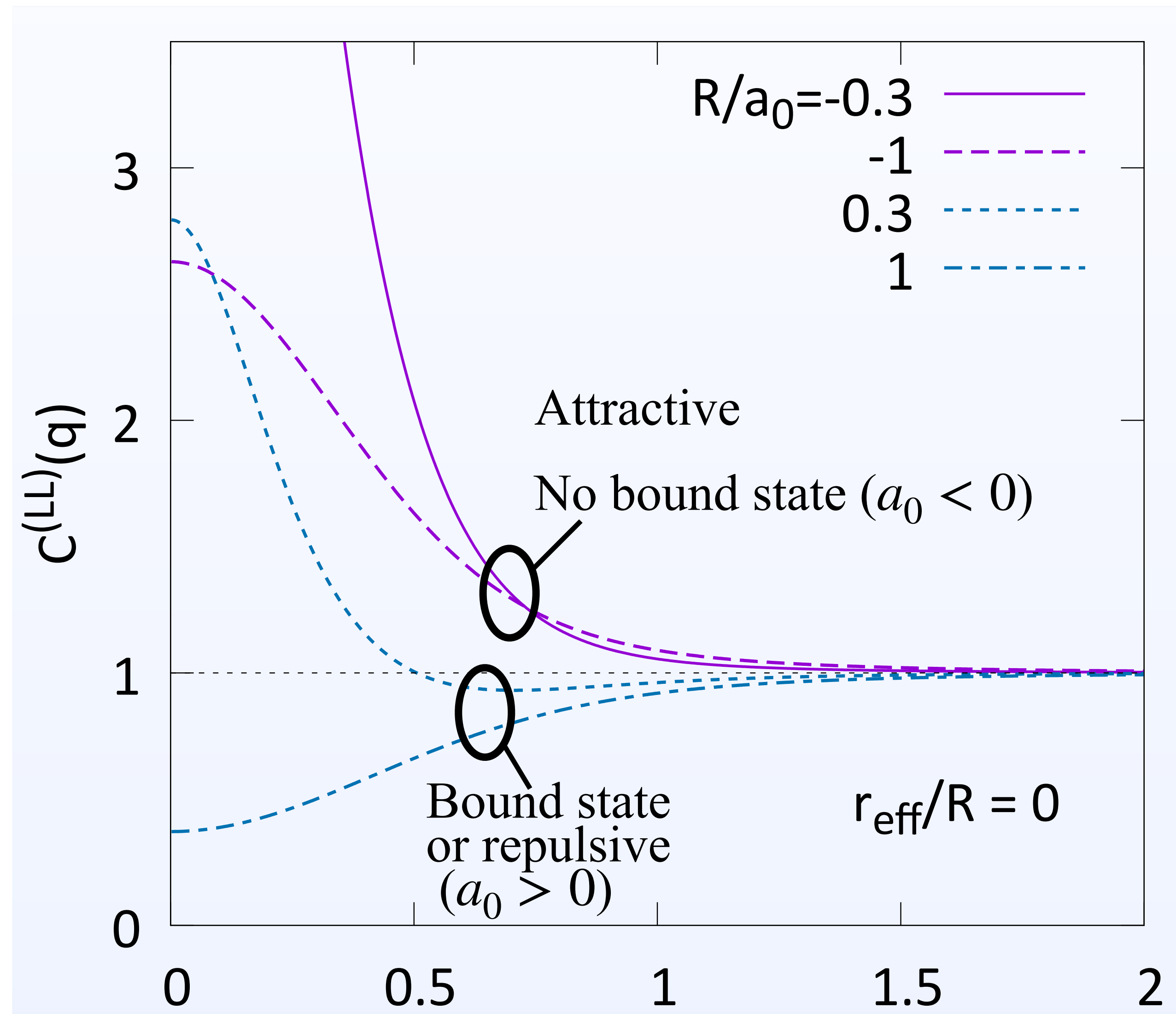
- Gaussian source with radius R
- Approximate φ by asymptotic wave func.
- $\mathcal{F}(q) = [-1/a_0 - iq]^{-1}$ with scat. length a_0

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

$$C = C(qR, R/a_0)$$

- $C(q)$ is sensitive to R/a_0 at $qR \lesssim 1$

Sgn(a_0)	Interaction
-	Attraction w/o bound state
+	Attraction w/ bound state or Repulsion



Morita, et al., PRC101 (2020)

- Clear relation between $C(q)$ and $\mathcal{F}(q)$
- Sensitive to (non)existence of bound state

Source size dependence of $C(q)$

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

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

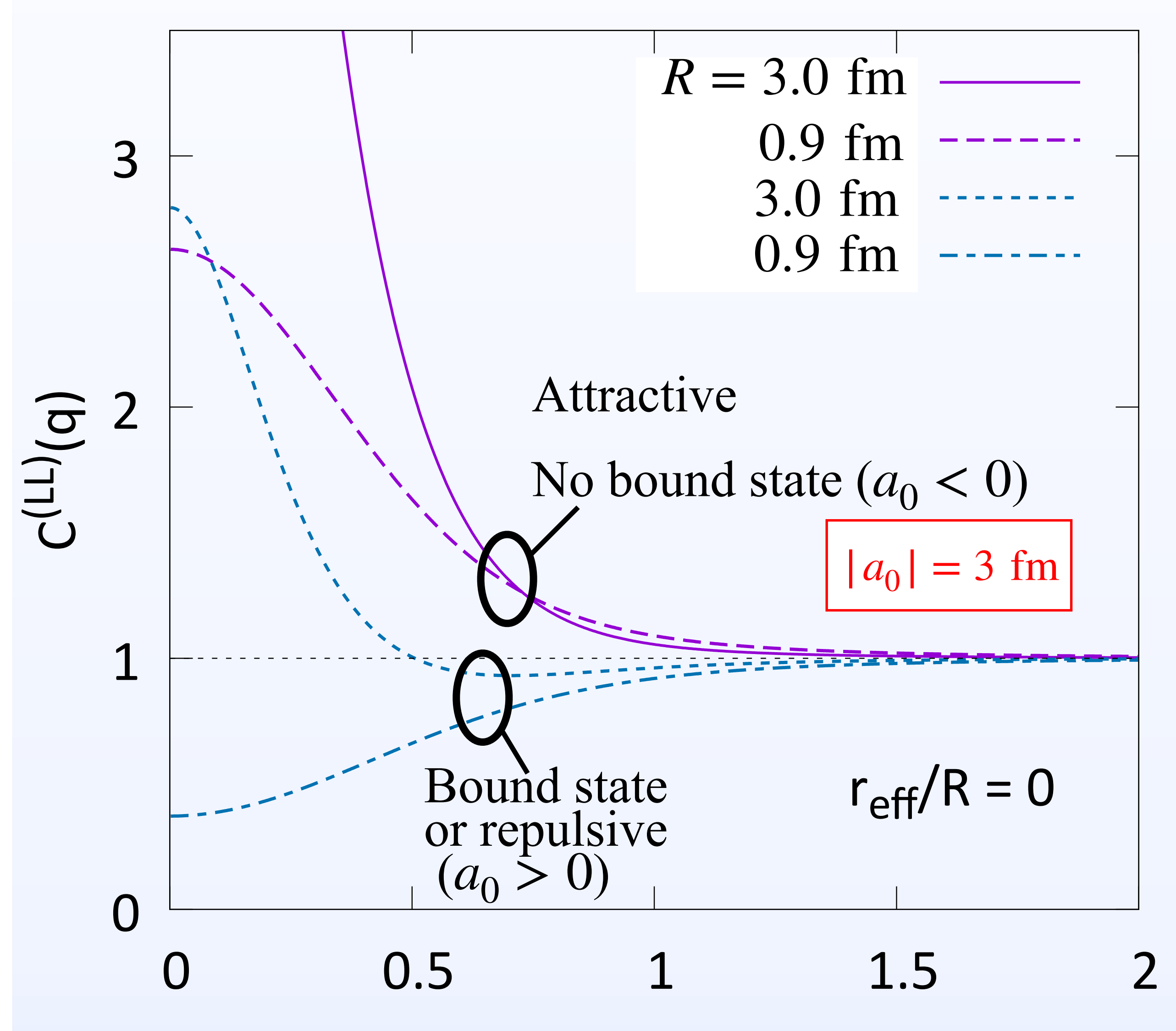
$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

$$\Rightarrow C = C(qR, R/a_0)$$

- For the specific channel (or a_0) we can get the different ratio R/a_0 from the different collision experiments

$$R \sim \begin{cases} 1 \text{ fm} & \text{(for } pp \text{ collisions)} \\ 2\text{-}5 \text{ fm} & \text{(for } AA \text{ collisions)} \end{cases}$$

- Unbound ($a_0 = -3$ fm) case
  - small source → Enhancement
  - Large source → Enhancement
- Bound ($a_0 = 3$ fm) case
  - small source → Enhancement
  - Large source → Suppression



Morita, et al., PRC101 (2020)

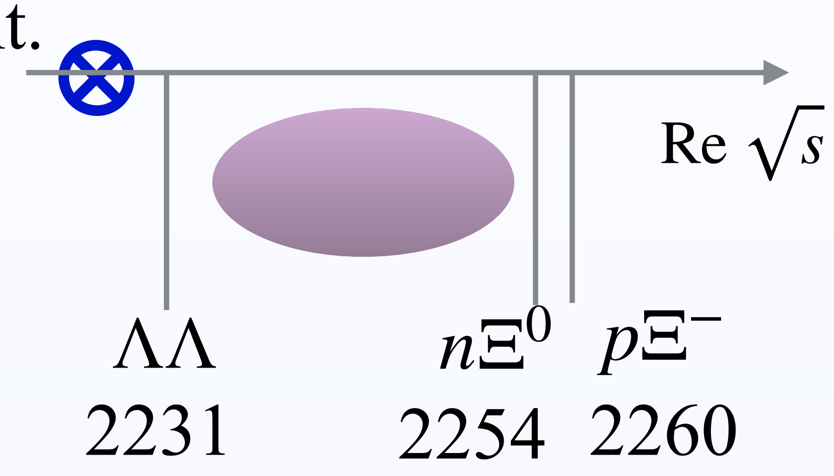
⇒ Correlation function in different collisions are very important for the detailed study.

ΛΛ-$N\Xi$ interaction and H-dibaryon state

- ΛΛ-$N\Xi$ interaction ($S = -2$) and H-dibaryon
  - $J = 0$: Unique sector in flavor Octet-Octet baryon int.

$$8 \otimes 8 = \underline{1} \oplus 8_A \oplus 8_S \oplus 10 \oplus \overline{10} \oplus 27$$

  - Pauli arrowed
  - Attractive color-magnetic int.



- Flavor-singlet dihyperon "H" R. L. Jaffe, PRL 38 (1977), 195.

  Predicted as "single hadron" below ΛΛ
  - Binding energy of double Λ hypernucleus

    Takahashi et al., PRL87 (2001) 212502

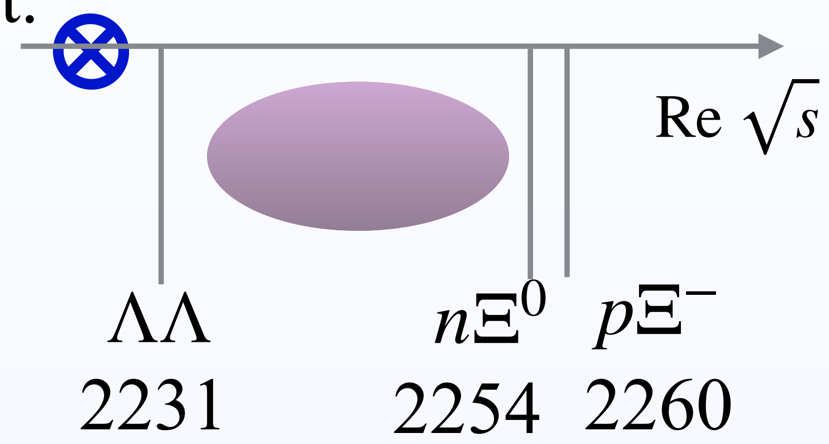
  → ΛΛ does NOT form (deep) bound state

ΛΛ-$N\Xi$ interaction and H-dibaryon state

- ΛΛ-$N\Xi$ interaction ($S = -2$) and H-dibaryon
  - $J = 0$: Unique sector in flavor Octet-Octet baryon int.

$$8 \otimes 8 = \underline{1} \oplus 8_A \oplus 8_S \oplus 10 \oplus \overline{10} \oplus 27$$

  - Pauli arrowed
  - Attractive color-magnetic int.



  - Flavor-singlet dihyperon "H" R. L. Jaffe, PRL 38 (1977), 195.

Predicted as "single hadron" below ΛΛ

  - Binding energy of double Λ hypernucleus

Takahashi et al., PRL87 (2001) 212502

⟶ ΛΛ does NOT form (deep) bound state

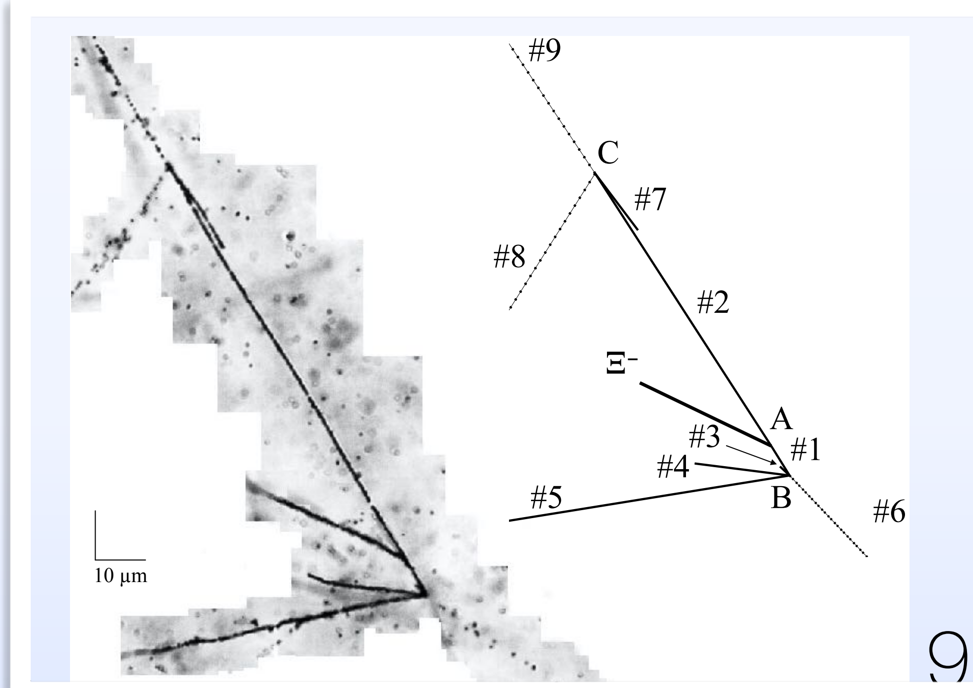
  - Ξ-^{14}N binding energy in twin-hyper nuclei

K. Nakazawa et al., PTEP 2015 (2015), 033D02

S. H. Hayakawa et al. [J-PARC E07], PRL 126 (2021) 062501 ⟶ Ibuki event

$$\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

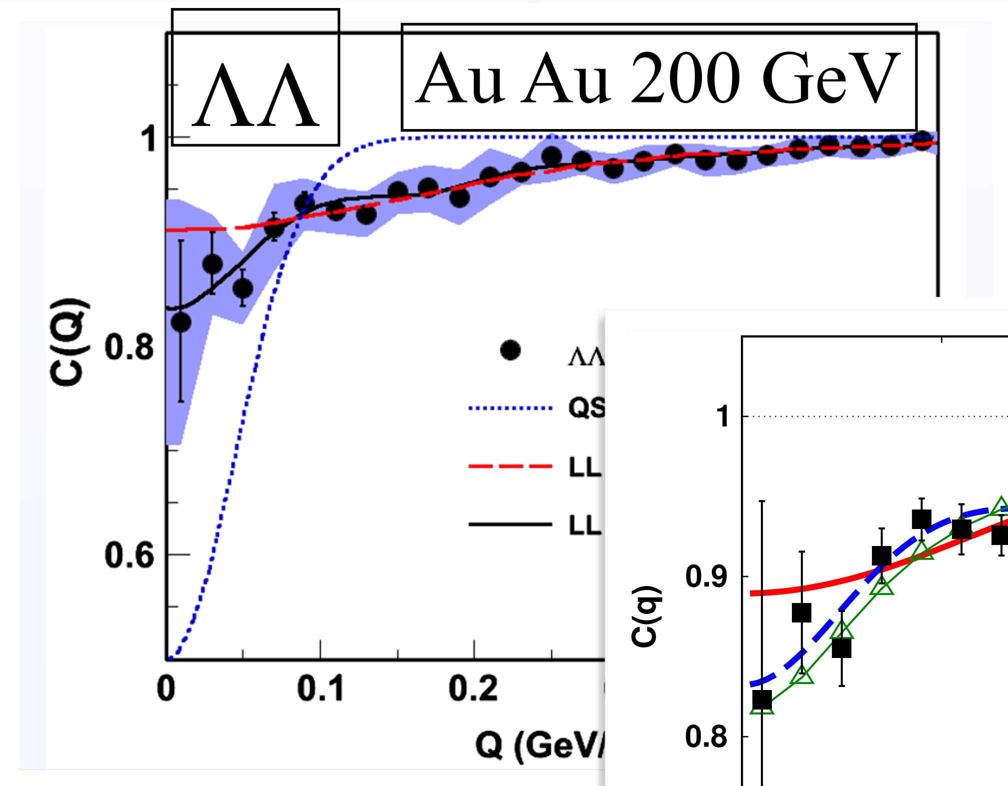
⟶ • Consistent with attractive $N\Xi$ int.



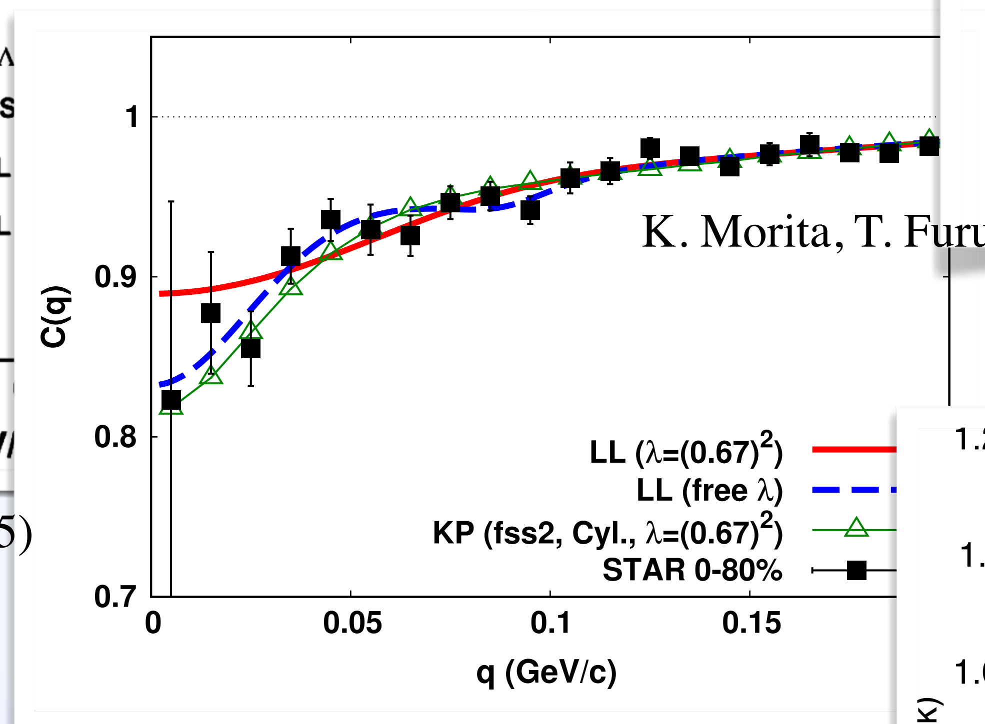
Can dibaryon state emerge as $N\Xi$ quasibound?

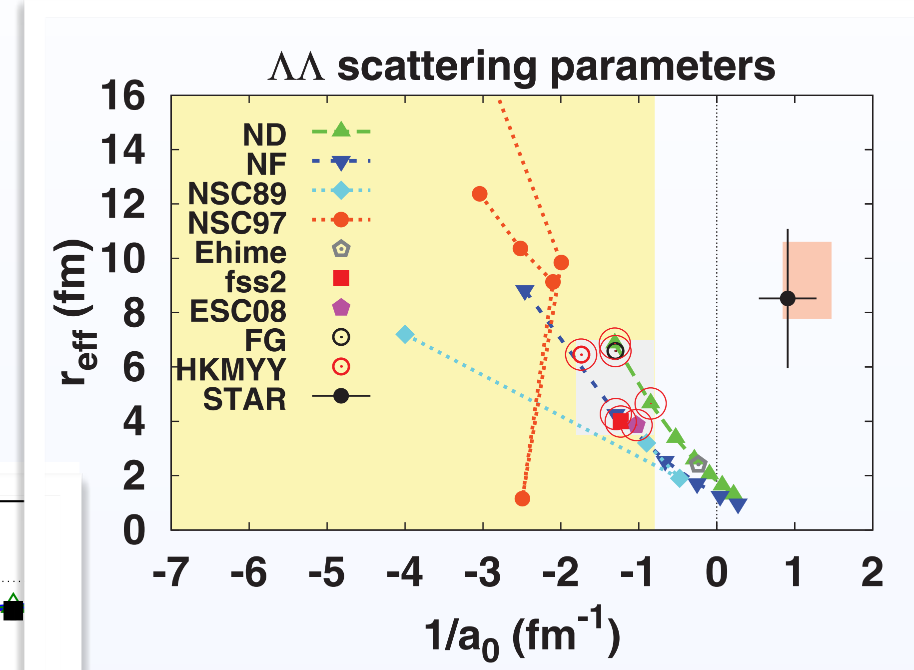
ΛΛ correlation function

- ΛΛ correlation from STAR

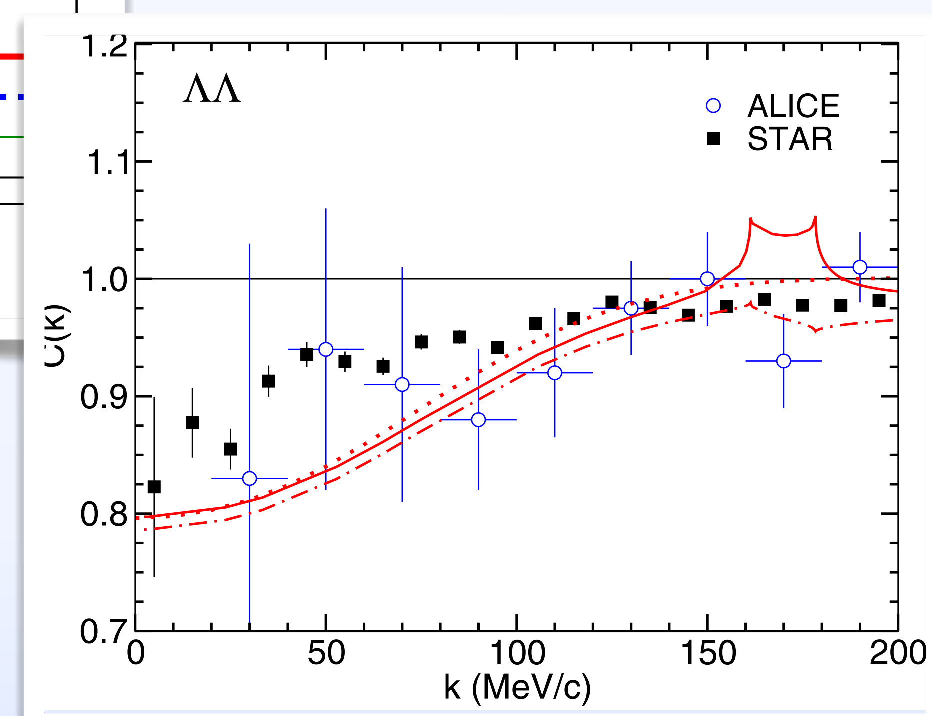


L. Adamczyk, et al. [STAR], PRL114(2015)





K. Morita, T. Furumoto, and A. Ohnishi, PRC91(2015)



J. Haidenbauer, Nucl. Phys. A 981 (2019)

- Consistent with weekly attractive ΛΛ interaction

No *H* dibaryon state below ΛΛ

ΛΛ-$N\Xi$ HAL QCD potential

- $N\Xi$-ΛΛ HAL QCD potential K. Sasaki et al. [HAL QCD], NPA 998 (2020), 121737.
  - HAL QCD method Ishii, Aoki, Hatsuda, PRL99 (2007) 022001
    N. Ishii et al Phys. Lett. B712(2012)437

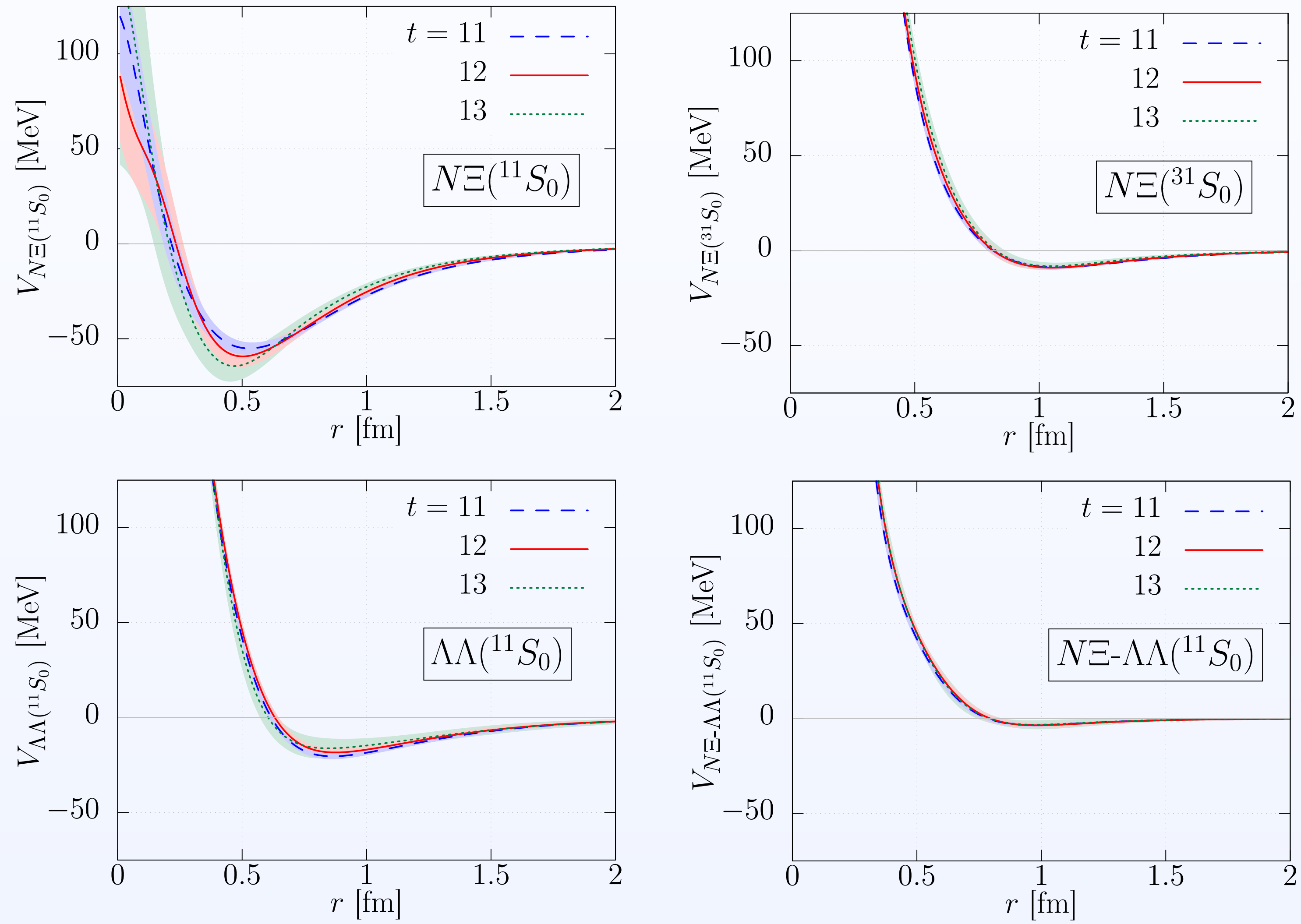
$$\langle 0 | B_1 B_2(t, \vec{r}) \bar{I}(0) | 0 \rangle = A_0 \Psi(\vec{r}, E_0) e^{-E_0 t} + \cdots$$

$\Psi(\vec{r}, E_0) \rightarrow V(r)$

  - Nearly physical mass calculation

$m_\pi = 146$ MeV $m_K = 525$ MeV

$^{2I+1,2s+1}L_J$



- $N\Xi$-ΛΛ $J = 0$ channel
  - Strong attraction for $N\Xi$ ($I = 0$)
  - Weak attraction for ΛΛ channel
  - Weak ΛΛ-$N\Xi$ coupling
  - Solving Schrödinger eq.with physical masses

Y. Kamiya, et al. in preparation

Scat. length : $a_0 \equiv -\mathcal{F}(E_{th})$

Virtual pole : -3.9-i0.3 MeV (from $n\Xi^0$ thr.)

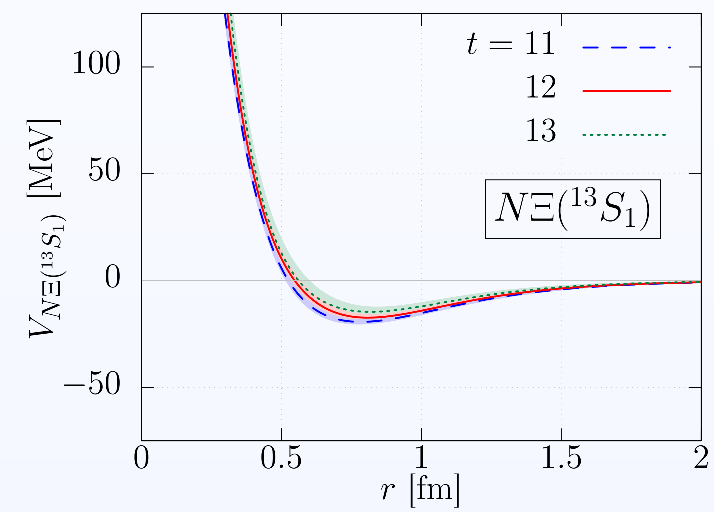
→ H dibaryon state: merely unbound

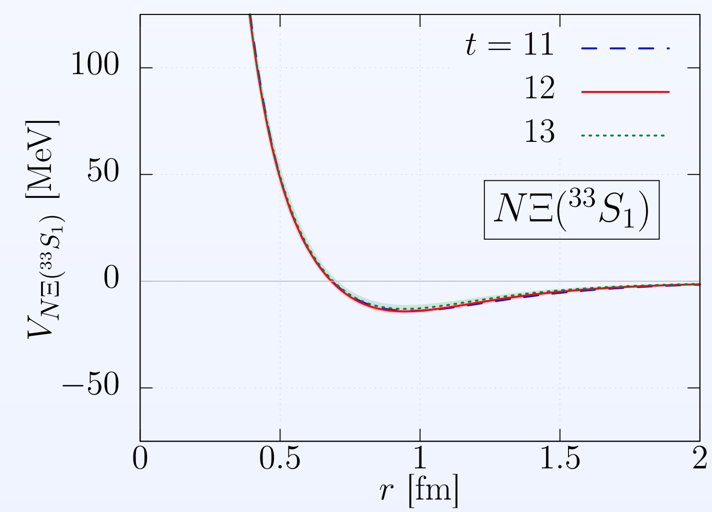
channel		a_0 [fm]
$J = 0$	$p\Xi^-$	$-1.22 \pm 0.13^{+0.08}_{-0.00} - i1.57 \pm 0.35^{+0.18}_{-0.23}$
	$n\Xi^0$	$-2.07 \pm 0.39^{+0.28}_{-0.35} - i0.14 \pm 0.08^{+0.00}_{-0.01}$
	ΛΛ	$-0.78 \pm 0.22^{+0.00}_{-0.13}$

ΛΛ-$N\Xi$ HAL QCD potential

- $N\Xi$ $J = 1$ channel K. Sasaki et al. [HAL QCD], NPA 998 (2020), 121737. Y. Kamiya, et al. in preparation

$^{2I+1,2s+1}L_J$





  - Weekly attractive
  - Similar potential for both I components

  Negligible coupling between $n\Xi^0$ and $p\Xi^-$

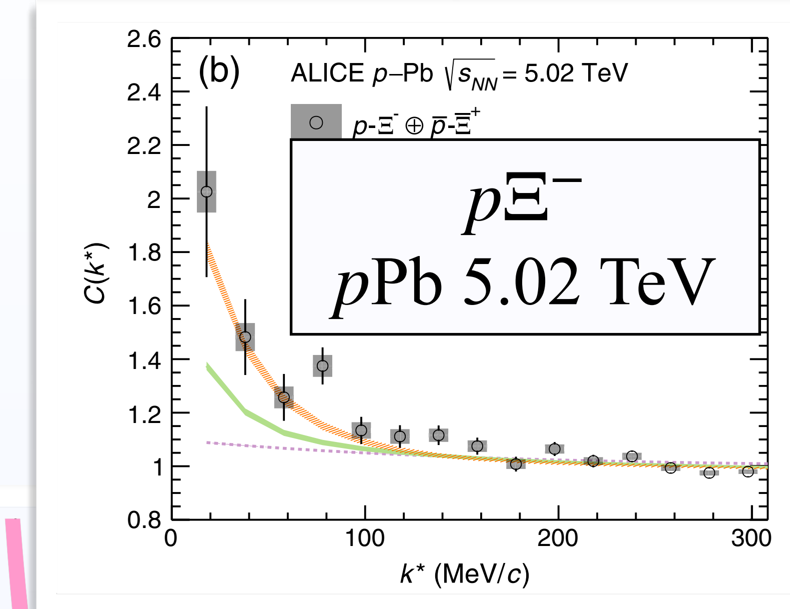
  ➡ small negative a_0

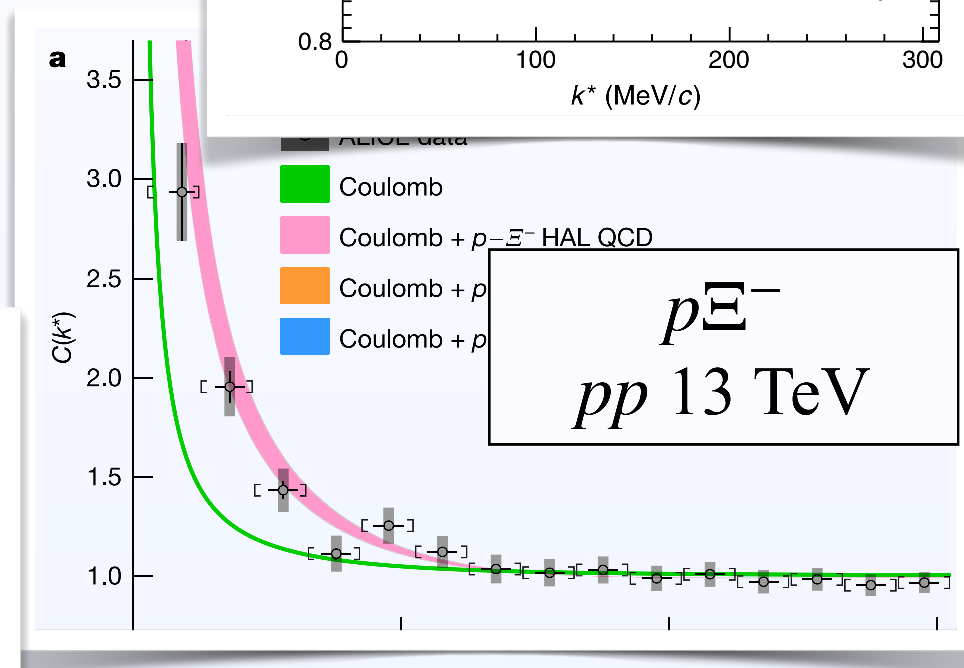
channel		a_0 [fm]
$J = 1$	$p\Xi^-$	$-0.35 \pm 0.06^{+0.09}_{-0.07} - i0.00$
	$n\Xi^0$	$-0.35 \pm 0.06^{+0.09}_{-0.07}$

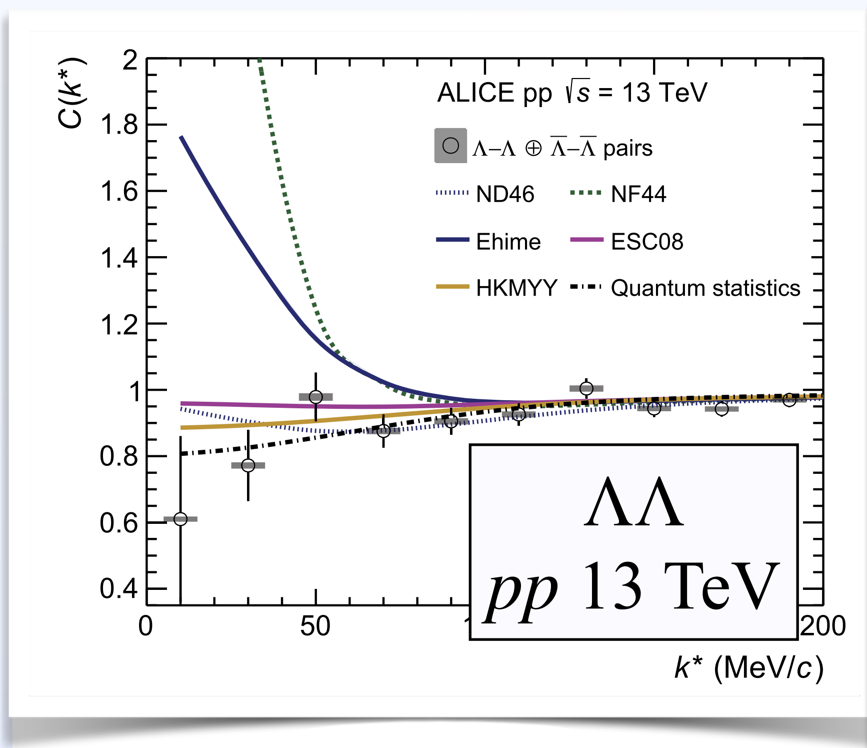
  - For calculation of $C_{p\Xi^-}$, both (J = 0 and 1) contribution must be summed up.

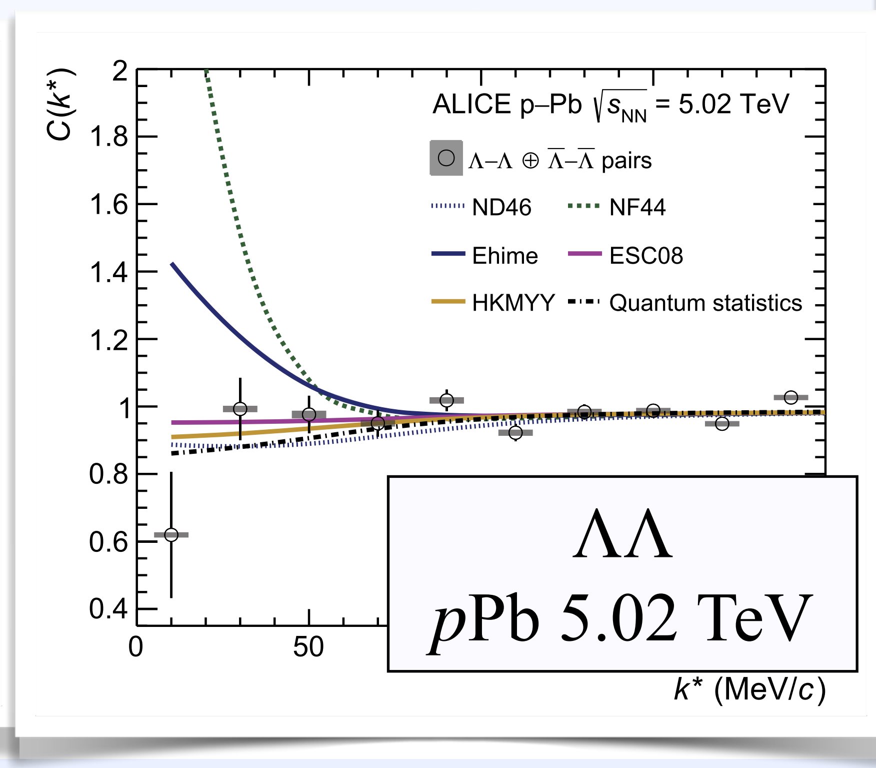
ΛΛ and $p\Xi^-$ correlation function

- $p\Xi^-$ and ΛΛ correlation from ALICE
  - $p\Xi^-$
    - pPb 5.02 TeV : ALICE, PRL, 123 (2019), 112002
    - pp 13 TeV : ALICE, Nature 588 (2020), 232-238
  - ΛΛ
    - pPb 5.02 TeV, pp 13 TeV: S. Acharya et al. [ALICE], PLB 797 (2019).









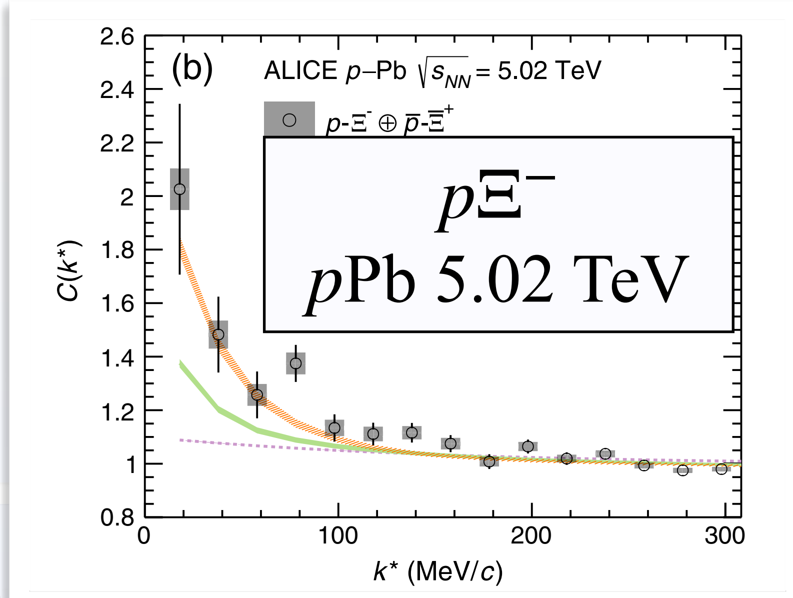
ΛΛ and $p\Xi^-$ correlation function

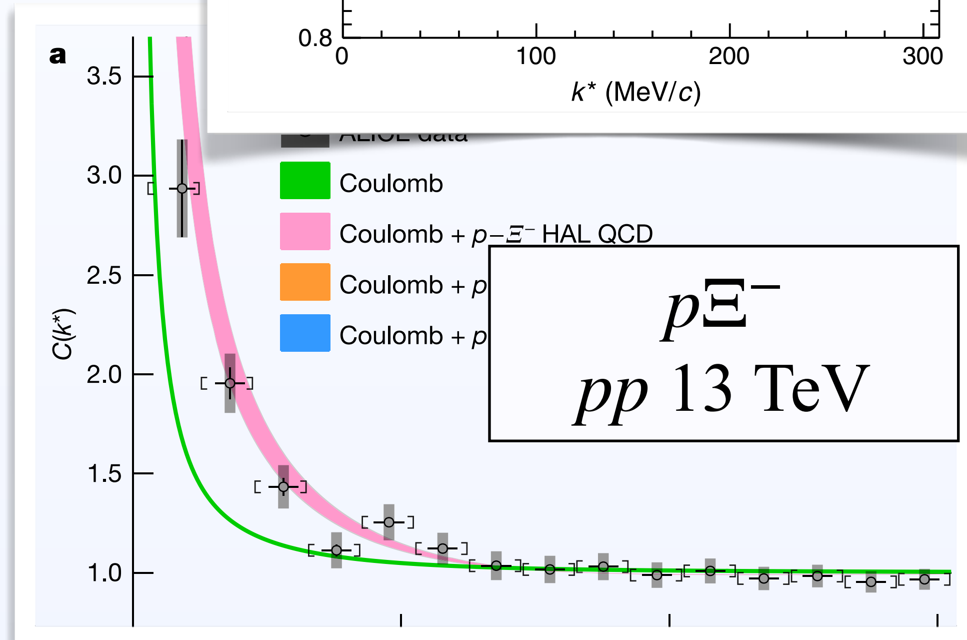
- $p\Xi^-$ and ΛΛ correlation from ALICE
  - $p\Xi^-$

    pPb 5.02 TeV : ALICE, PRL, 123 (2019), 112002
    pp 13 TeV : ALICE, Nature 588 (2020), 232-238
  - ΛΛ

    pPb 5.02 TeV
    pp 13 TeV
    S. Acharya et al. [ALICE], PLB 797 (2019).
  - Our study: Systematic analysis with including
    - Coulomb interaction
    - Coupled-channel effect
    - Threshold difference

    using latest HAL QCD coupled-channel potential





- Systematic comparison to

  ΛΛ and $p\Xi^-$ correlation from pp and pPb collisions data from ALICE

- Static spherical Gaussian with $R_{N\Xi} \sim R_{\Lambda\Lambda}$
- Fitting for comparison

$$C_{\rm fit}(q) = \underline{A_{\rm non-femt}(q)} \times [1 + \underline{\lambda}(C_{\rm Theor}(q) - 1)]$$

$A_{\rm non-femt}(q)$: $a + bq$

λ: < 1
- Miss identification
- feed-down

KP Formula for Coupled-channel systems

- Koonin-Pratt formula for coupled-channel systems

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

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

- For coupled-channel systems

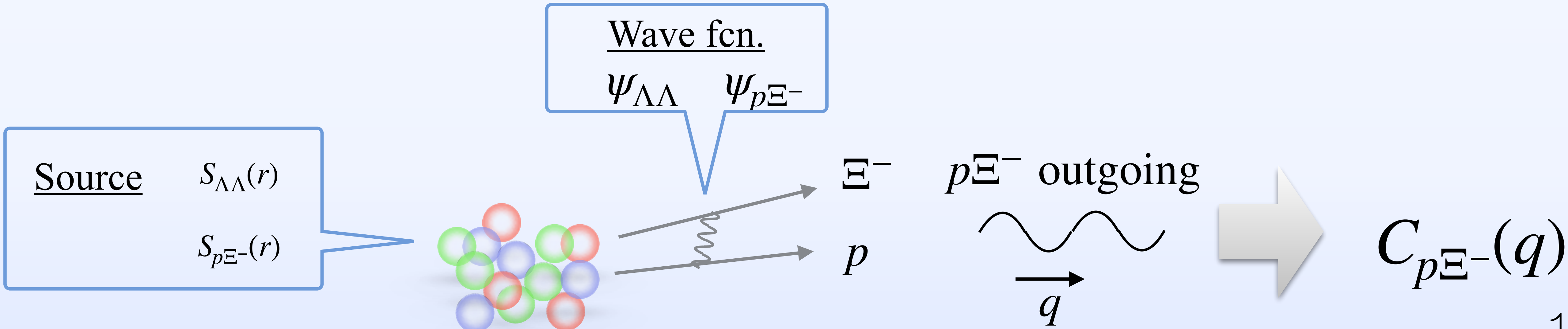
R. Lednicky, et. al. Phys. At. Nucl. 61 (1998)
Haidenbauer NPA 981 (2018)

KPLLL formula : $C_i(\mathbf{q}) = \int d^3\mathbf{r}\ S_i(\mathbf{r})\,|\,\psi_i^{C,(-)}(q;r)\,|^2 + \sum_{j\neq i} \omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\,\psi_j^{C,(-)}(q;r)\,|^2$

(**K**oonin-**P**ratt-**L**ednicky
-**L**yuboshits-**L**yuboshits)

Coupled-channel wave function

- Contribution from coupled-channel source (for $p\Xi^-$)



ΛΛ-$N\Xi$ interaction and ΛΛ and $p\Xi^-$ correlation function

- $p\Xi^-$ correlation function

$$C_{p\Xi^-} = \frac{1}{4} C_{p\Xi^-,\mathrm{singlet}} + \frac{3}{4} C_{p\Xi^-,\mathrm{triplet}}$$

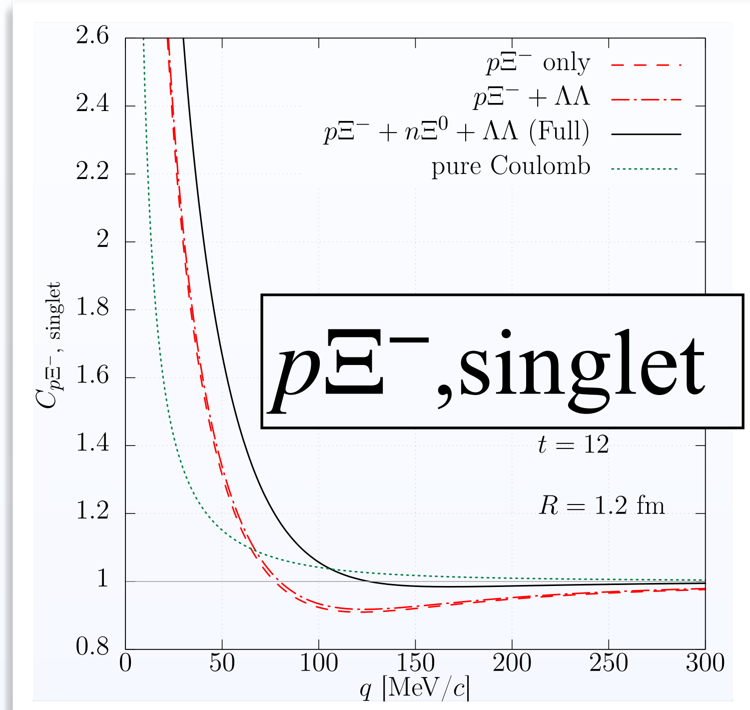
Couples to ΛΛ
(H-dibaryon channel)

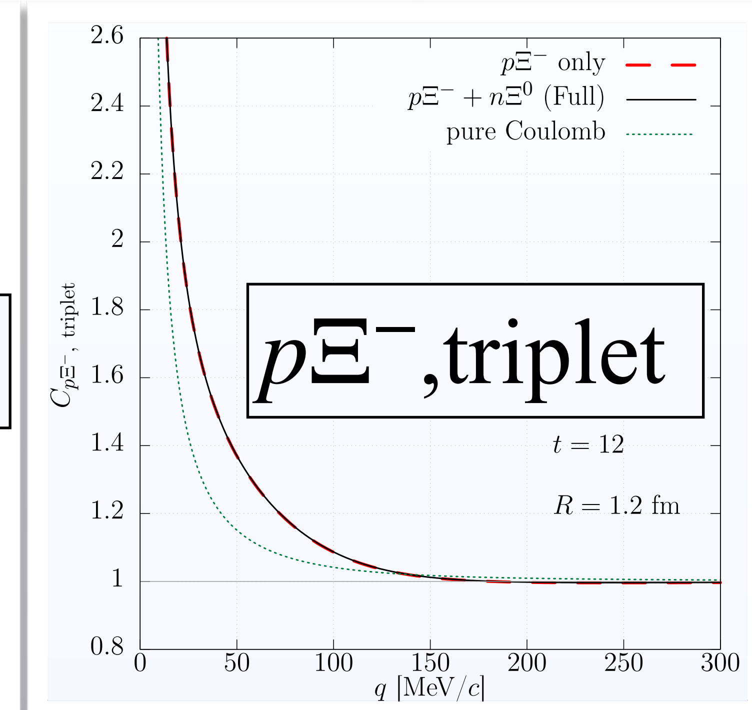
- Enhancement from pure Coulomb case
- $n\Xi^0$ source contribution

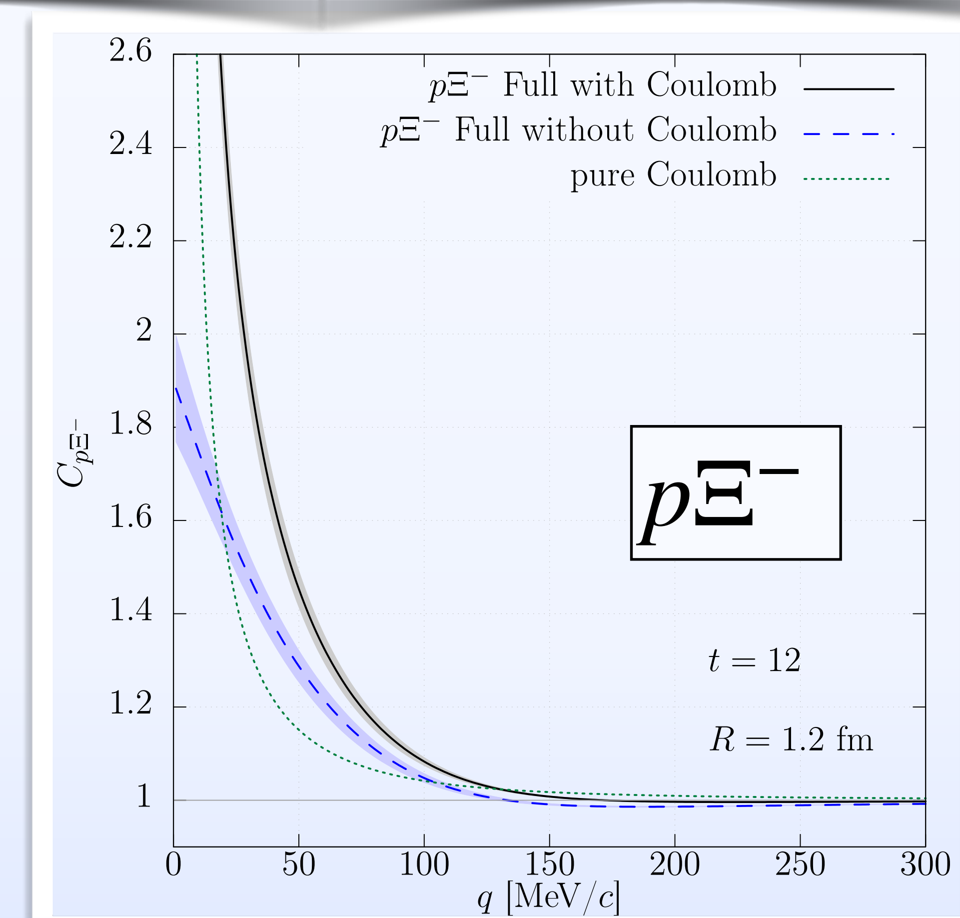
  Singlet (J=0) : sizable enhancement

  Triplet (J=1) : negligible

- ΛΛ source contribution : Negligible







ΛΛ-$N\Xi$ interaction and ΛΛ and $p\Xi^-$ correlation function

- $p\Xi^-$ correlation function

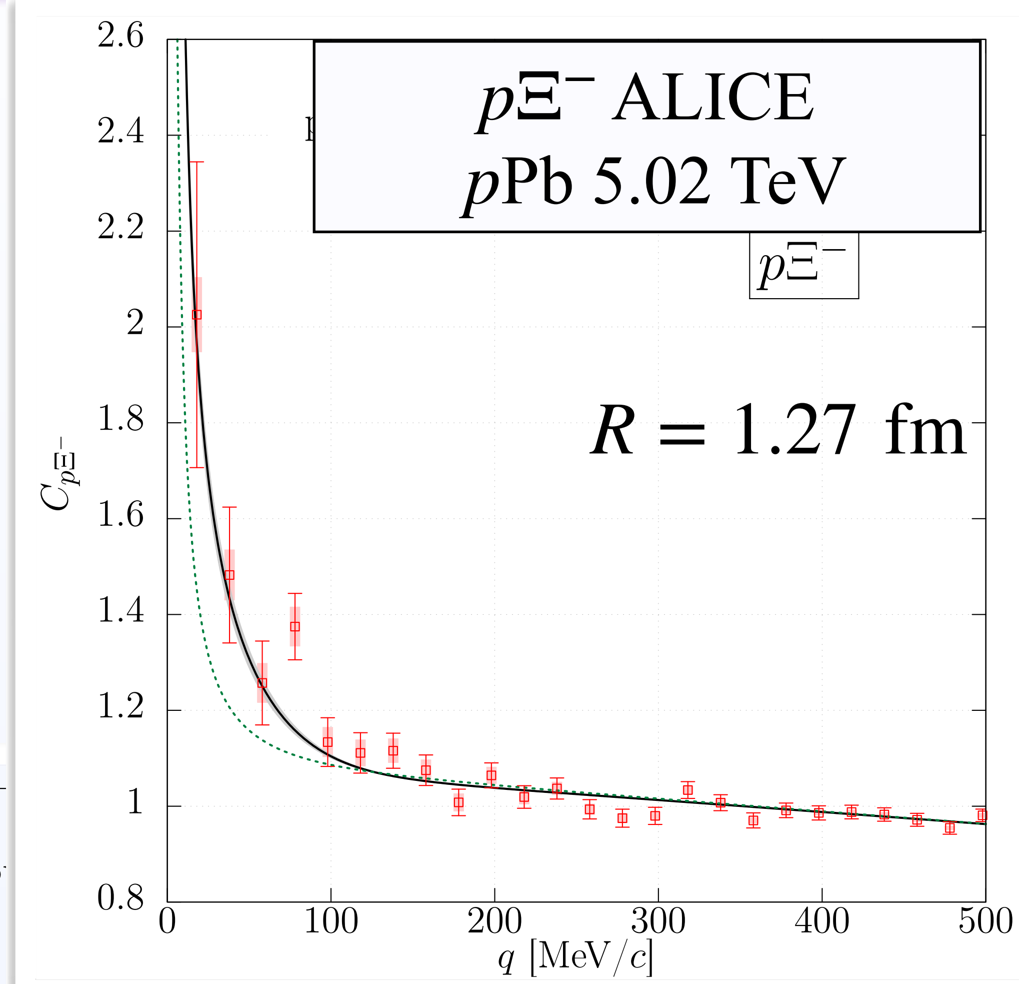
$$C_{p\Xi^-} = \frac{1}{4} C_{p\Xi^-,\mathrm{singlet}} + \frac{3}{4} C_{p\Xi^-,\mathrm{triplet}}$$

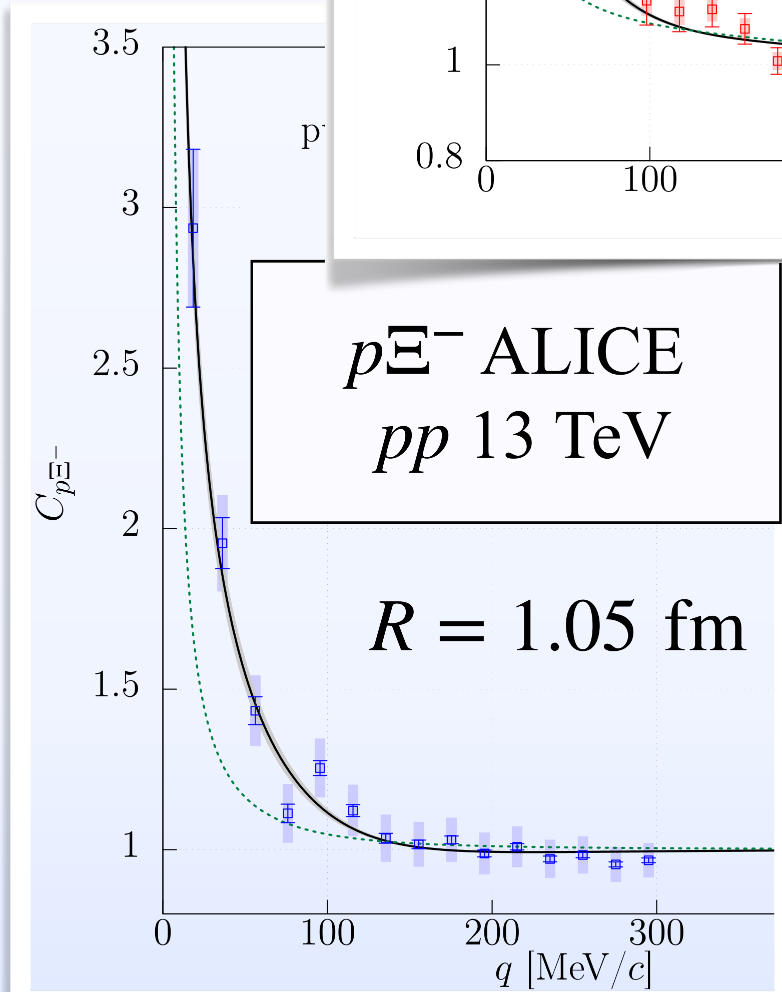
Couples to ΛΛ
(H-dibaryon channel)

- Enhancement from pure Coulomb case
- $n\Xi^0$ source contribution
  Singlet (J=0) : sizable enhancement
  Triplet (J=1) : negligible
- ΛΛ source contribution : Negligible
- Comparison with ALICE data
  pPb 5.02 TeV : ALICE, PRL, 123 (2019), 112002
  pp 13 TeV : ALICE, Nature 588 (2020), 232-238

$$C_{\mathrm{fit}}(q) = C_{\mathrm{non-femt}}(q) \times C_{\mathrm{theor}}(q)$$

Well reproduced with enhancement from pure Coulomb





$\Lambda\Lambda$-$N\Xi$ interaction and $\Lambda\Lambda$ and $p\Xi^-$ correlation function

- $\Lambda\Lambda$ correlation function

$$C_{\Lambda\Lambda} = 1 - \frac{1}{2}\underline{\exp(-4q^2R^2)} + \underline{\Delta C_{\Lambda\Lambda}}$$

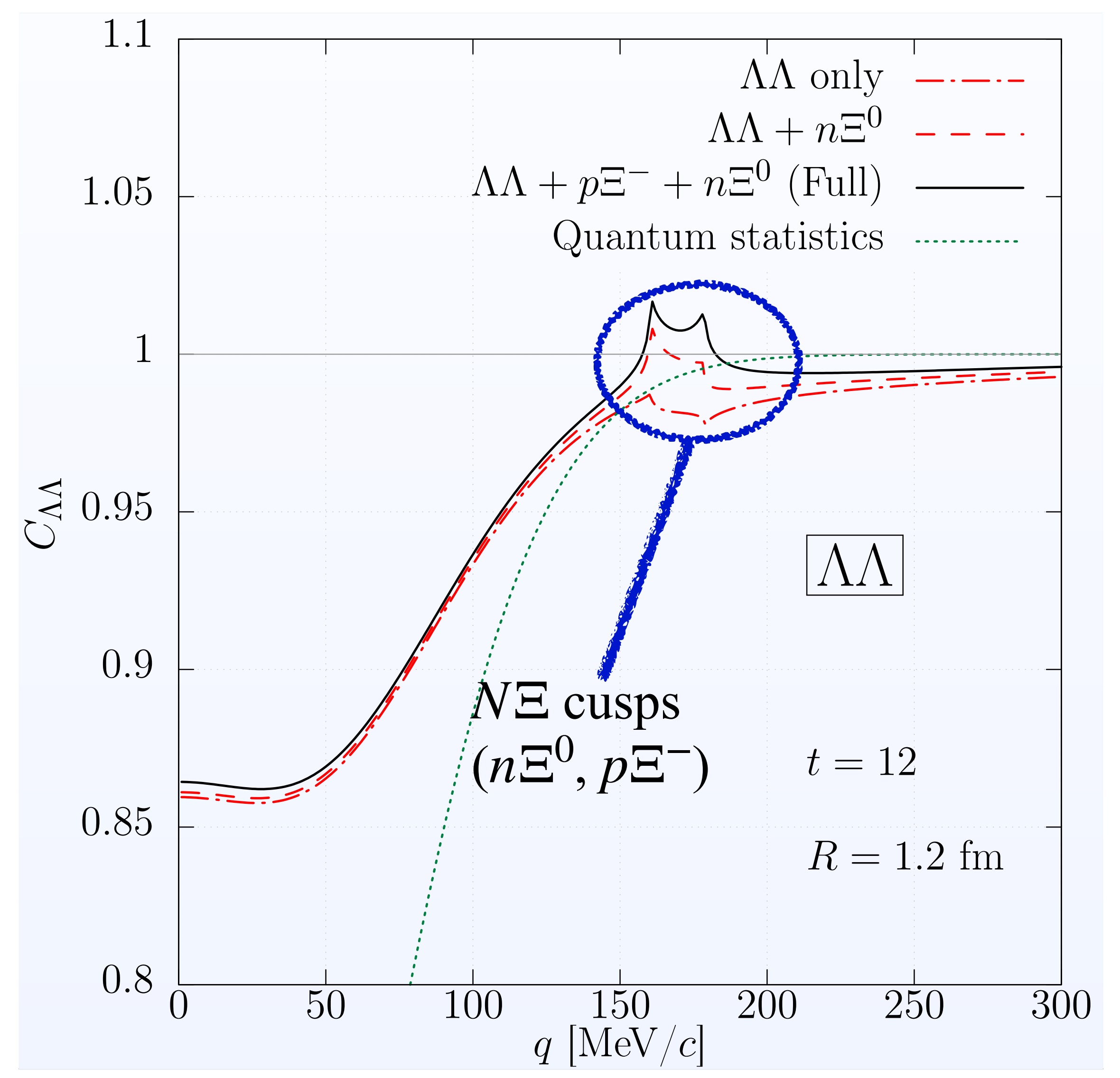
Quantum statistics — Strong int.

- Enhancement form quantum statistics
  week attractive interaction

- $N\Xi$ cusps related to the coupling and existence of H-dibaryon

J. Haidenbauer, Nucl. Phys. A 981 (2019),

→ Almost invisible with HAL-QCD potential (small coupling)



ΛΛ-$N\Xi$ interaction and ΛΛ and $p\Xi^-$ correlation function

- ΛΛ correlation function

$$C_{\Lambda\Lambda} = 1 - \underline{\frac{1}{2}\exp(-4q^2R^2)} + \underline{\Delta C_{\Lambda\Lambda}}$$

Quantum statistics   Strong int.

- Enhancement form quantum statistics week attractive interaction

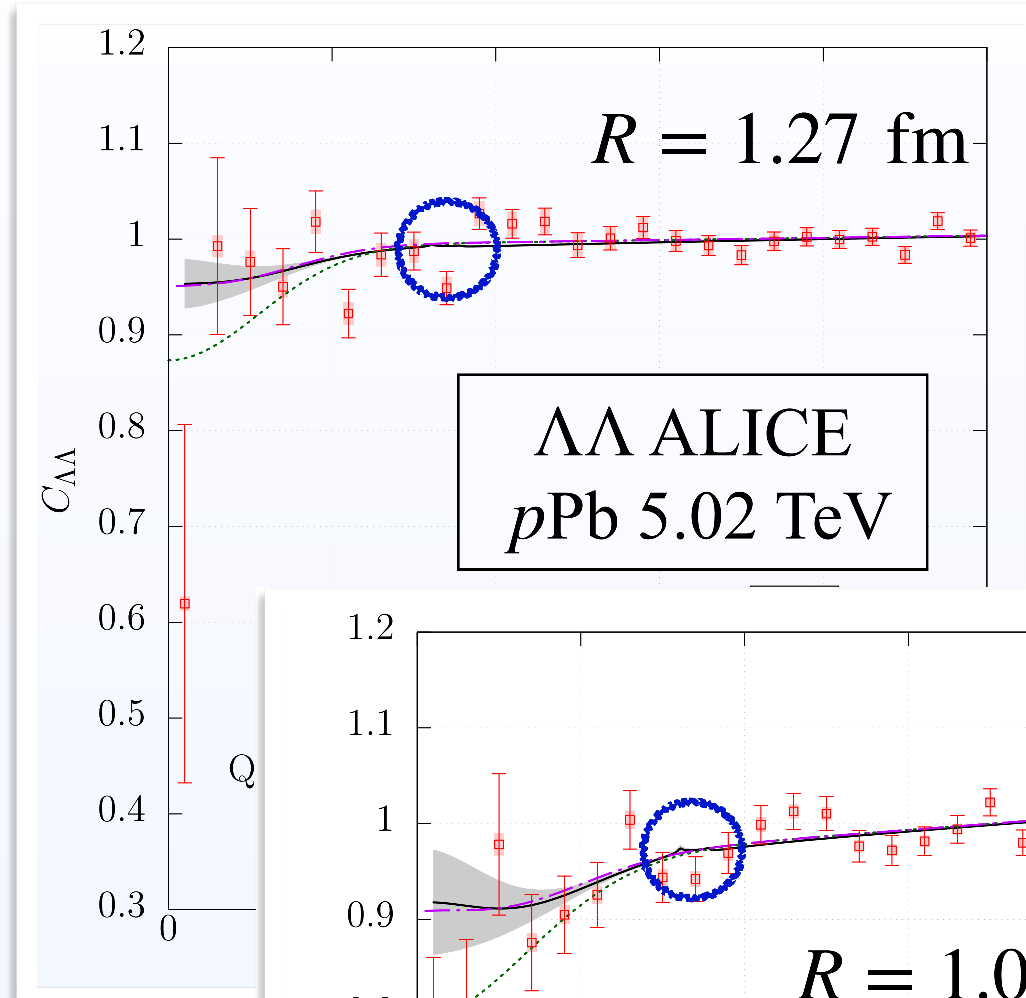
- $N\Xi$ cusps related to the coupling and existence of H-dibaryon

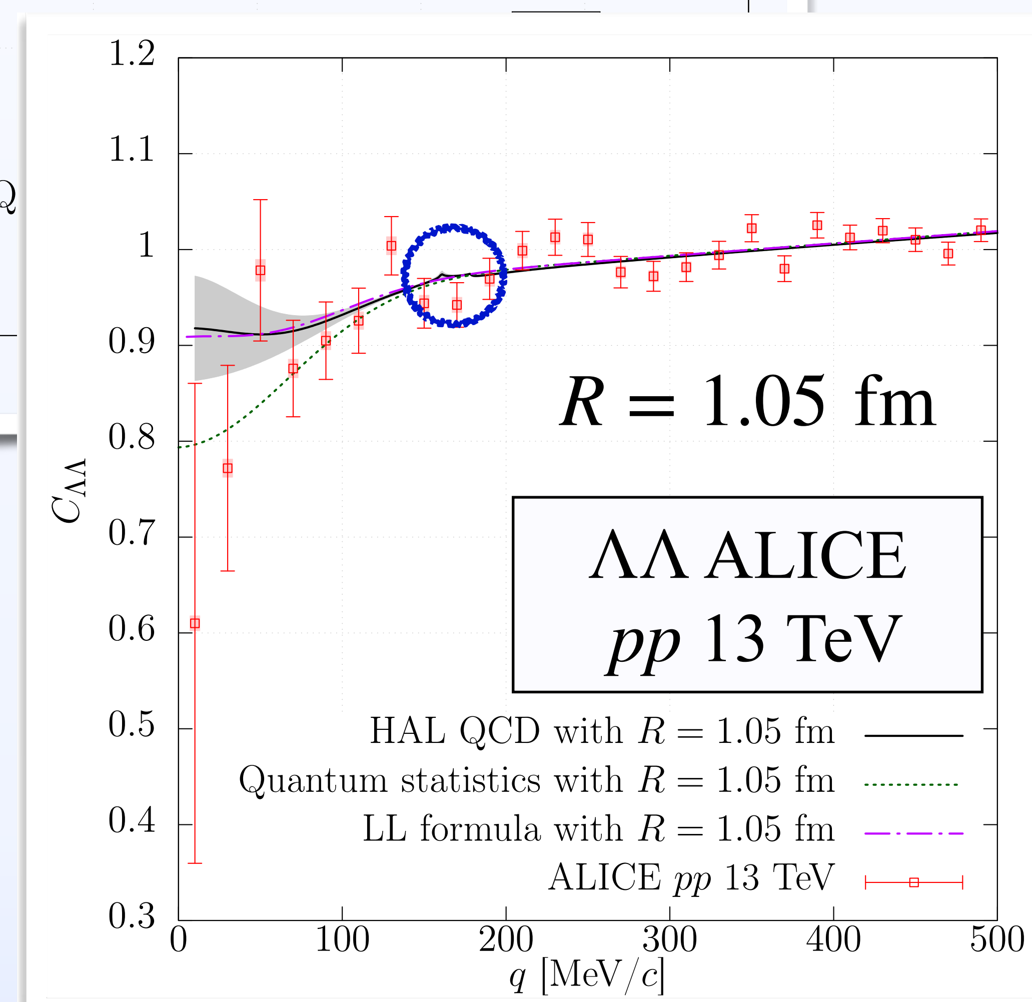
  J. Haidenbauer, Nucl. Phys. A 981 (2019),

  → Almost invisible with HAL-QCD potential (small coupling)

- Comparison with ALICE data

  pPb 5.02 TeV, *pp* 13 TeV collisions :
  S. Acharya et al. [ALICE], PLB 797 (2019).

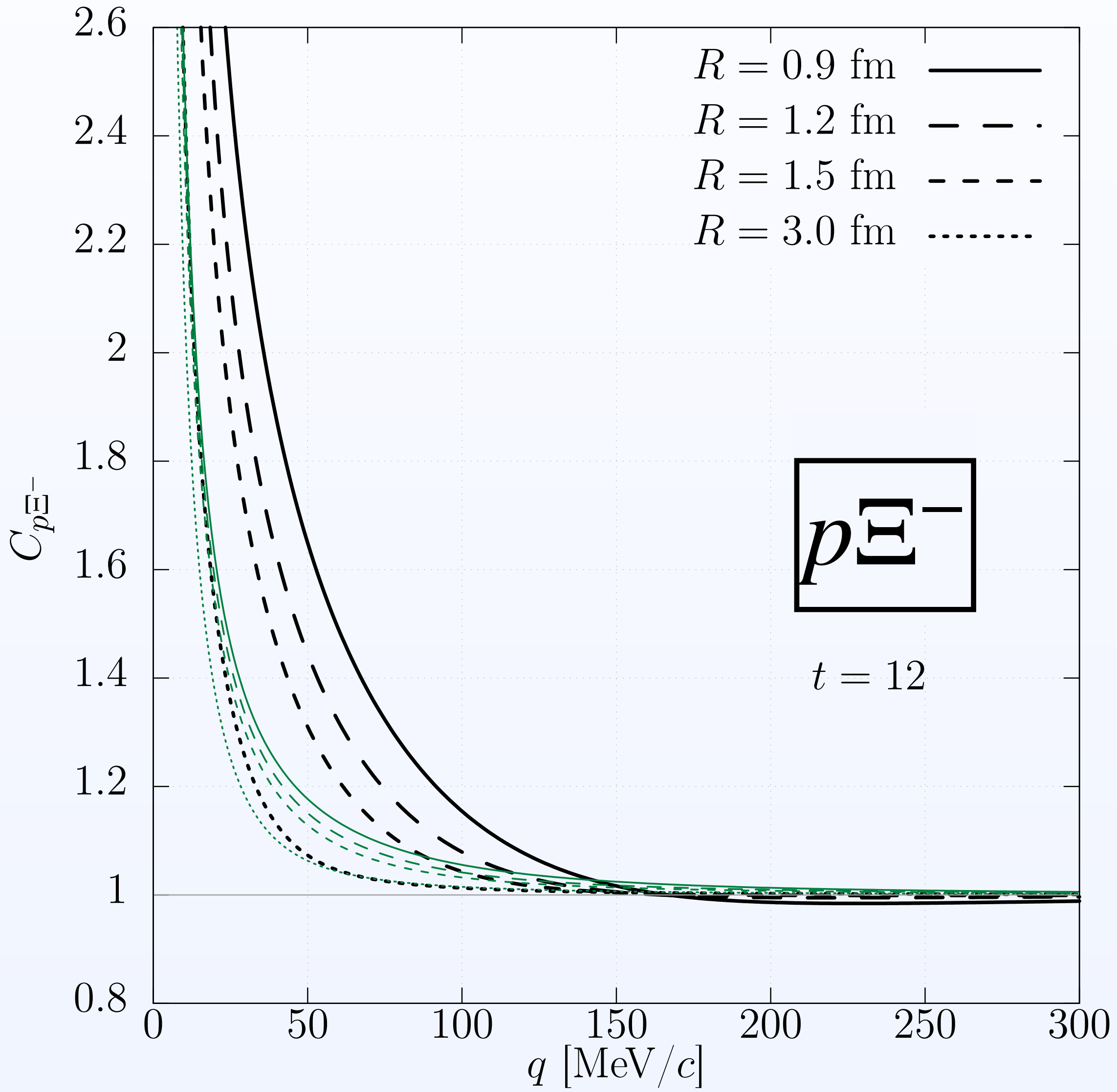


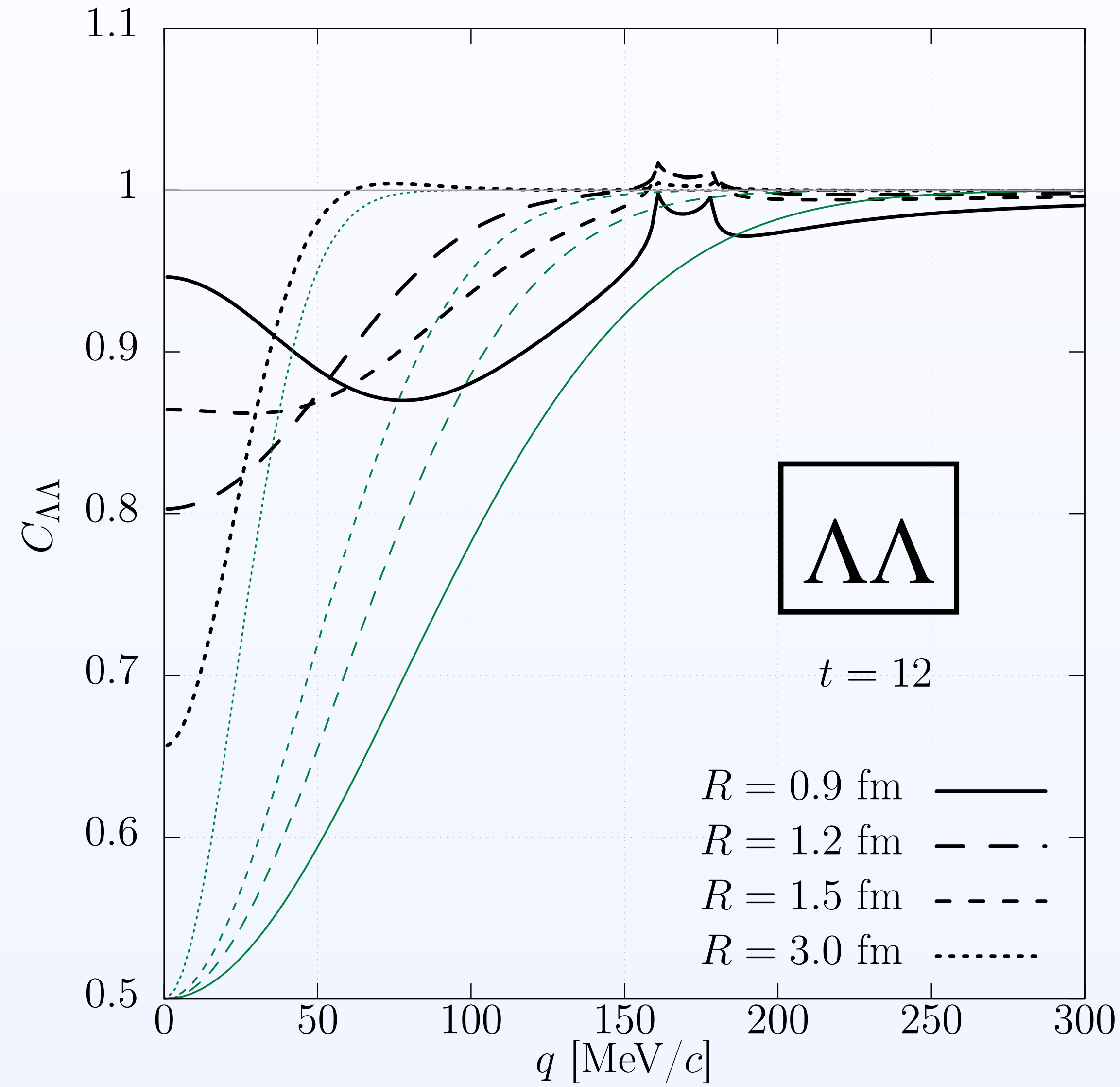


→ • Weak attraction of ΛΛ int.
• There is no signal of H-dibaryon

ΛΛ-$N\Xi$ interaction and ΛΛ and $p\Xi^-$ correlation function

- Source size dependence

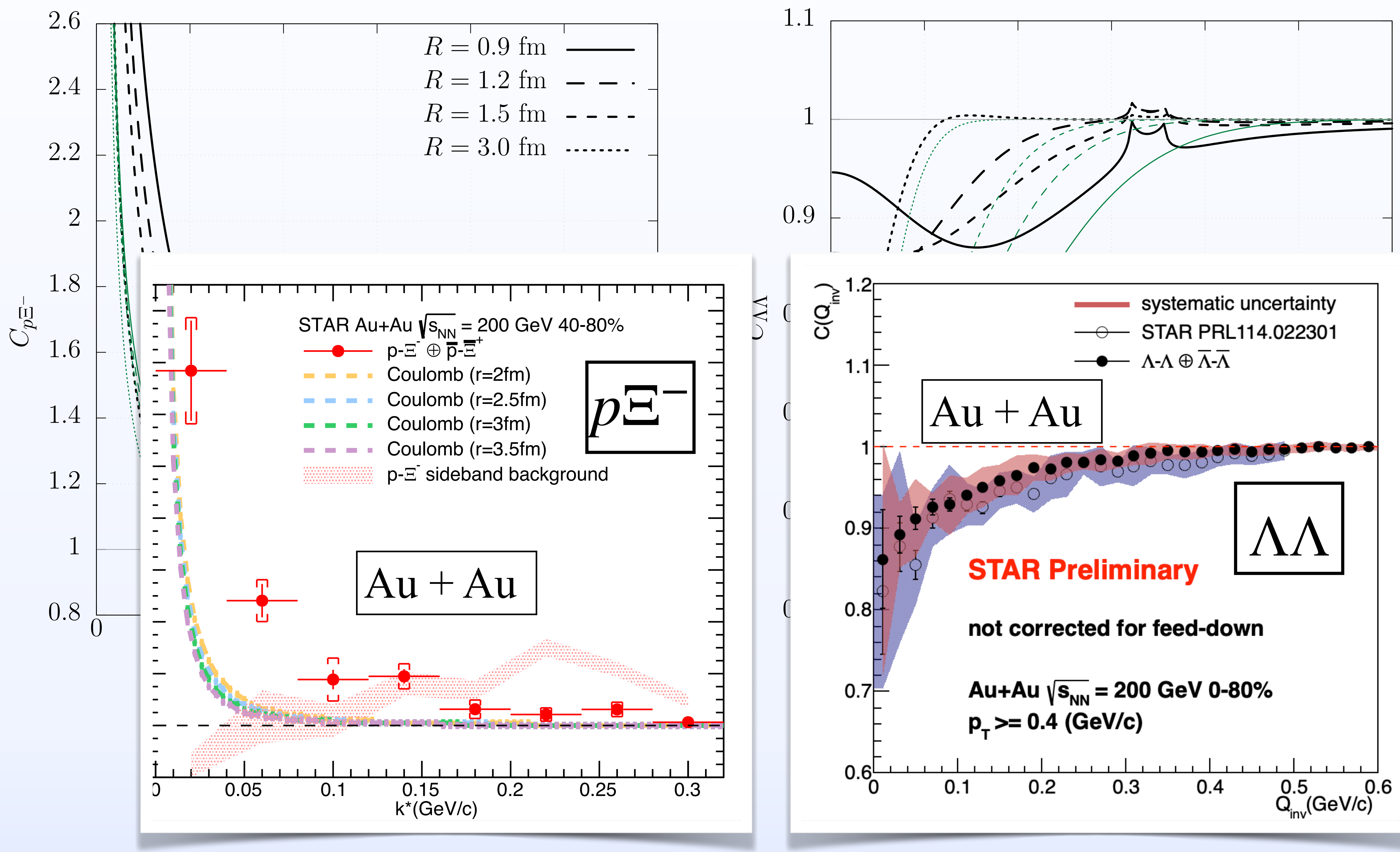




- $p\Xi^-$
  - small enhancement for large (R ~ 3 fm) case w/o any dip
- ΛΛ
  - To see source size dependence at small q is mandatory to see the week interaction

ΛΛ-$N\Xi$ interaction and ΛΛ and $p\Xi^-$ correlation function

- Source size dependence



M. Isshiki [STAR] talk slide in SQM 2021

$d\Xi^-$ correlation function

- Three body system of $d(np)\Xi$

K. Ogata, T. Fukui, Y. Kamiya, and A. Ohnishi, arXiv:2103.00100

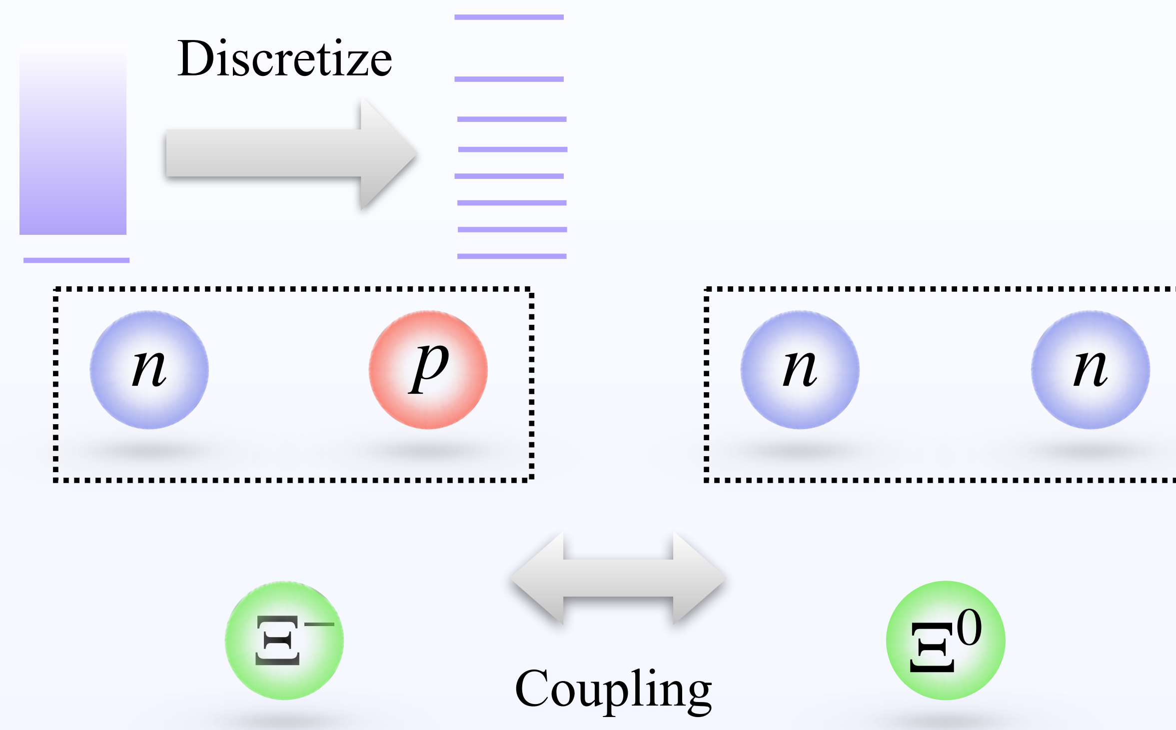
  - Three body problem :
    continuum-discretized
    coupled-channels method (CDCC)

    N. Austern, M. Yahiro, and M. Kawai, PRL 63 2649(1989)
    N. Austern, M. Kawai, and M. Yahiro, PRC 53 314 (1996)

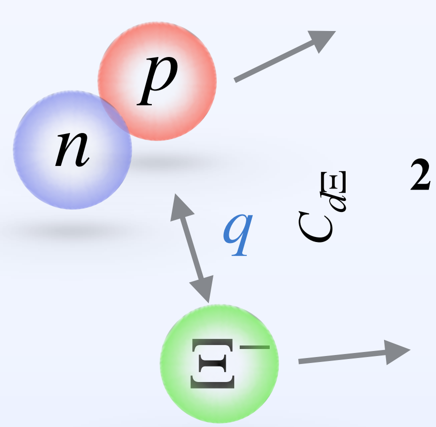
    ==> d-Ξ relative wave function

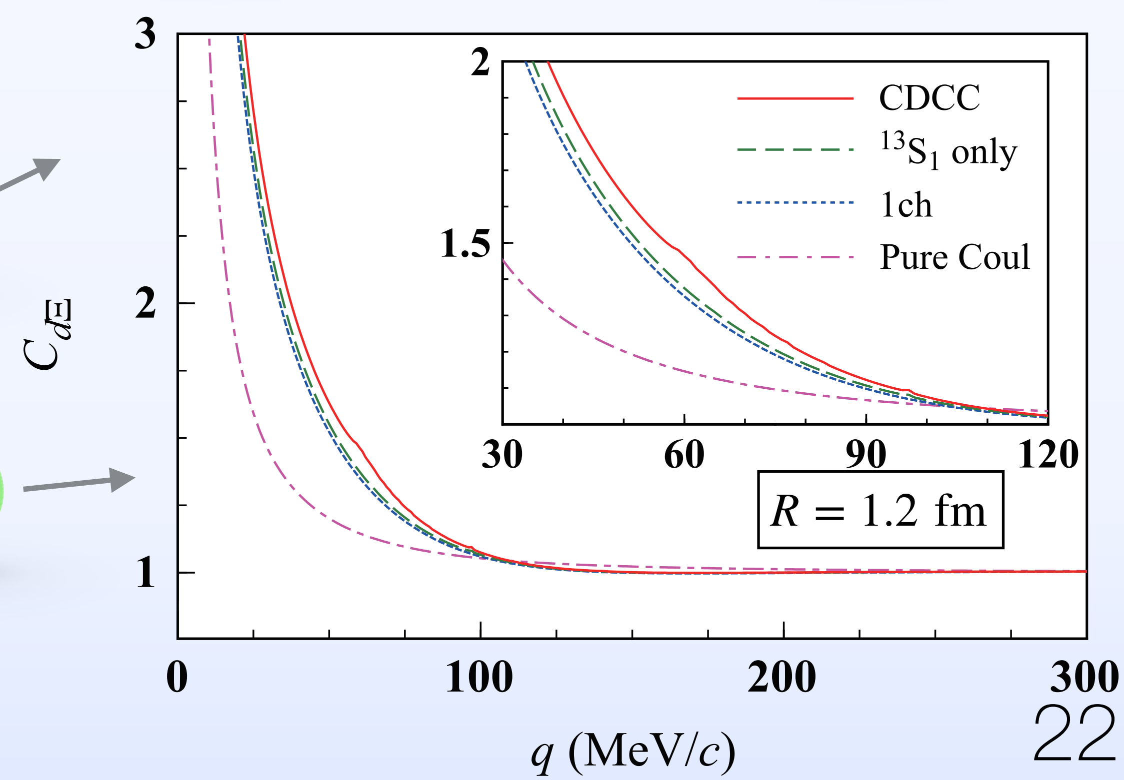
  - $N\Xi$ interaction : HAL QCD potential
    K. Sasaki et al. [HAL QCD], NPA 998 (2020), 121737.

  - Coupling between $np\Xi^-$-$nn\Xi^0$ included



- Theoretical model for $C_{d\Xi^-}$
  - Strong enhancement compared to pure Coulomb case
  - Coupling effect by $np\Xi^-$-$nn\Xi^0$ is estimated to be 6–8 %





Summary

Summary

Y. Kamiya, K. Sasaki, T. Fukui, T. Hyodo, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda in prep.

- Femtoscopic correlation function in high energy nuclear collisions is a powerful tool to investigate the hadron-hadron interaction.
- With the latest HAL QCD potential, the *H* state does not exist as physical state but emerges as virtual pole in amplitude.
- $\Lambda\Lambda$ and $p\Xi^-$ correlation function is studied with including full coupled-channel effect and Coulomb interaction in the consistent manner. The result shows good agreement with ALICE data (*pp* and *p*Pb collisions).
- For the further determination of interactions, to extract the source size dependence is important using other collisions systems.

Thank you for your attention!