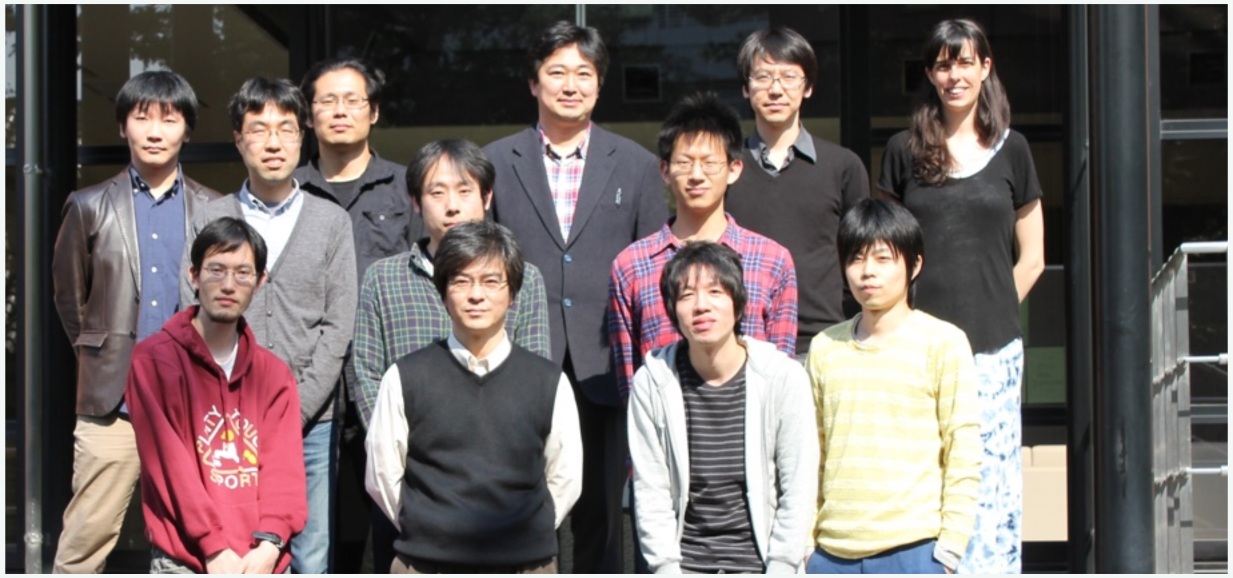
フェムトスコピー研究の発展と
大西さんとの思い出

クォーク・ハドロン・原子核物理の潮流と展望
大西さん追悼研究会　2024年3月3日

大西さんとの縁

- 2014.4〜 院生時代

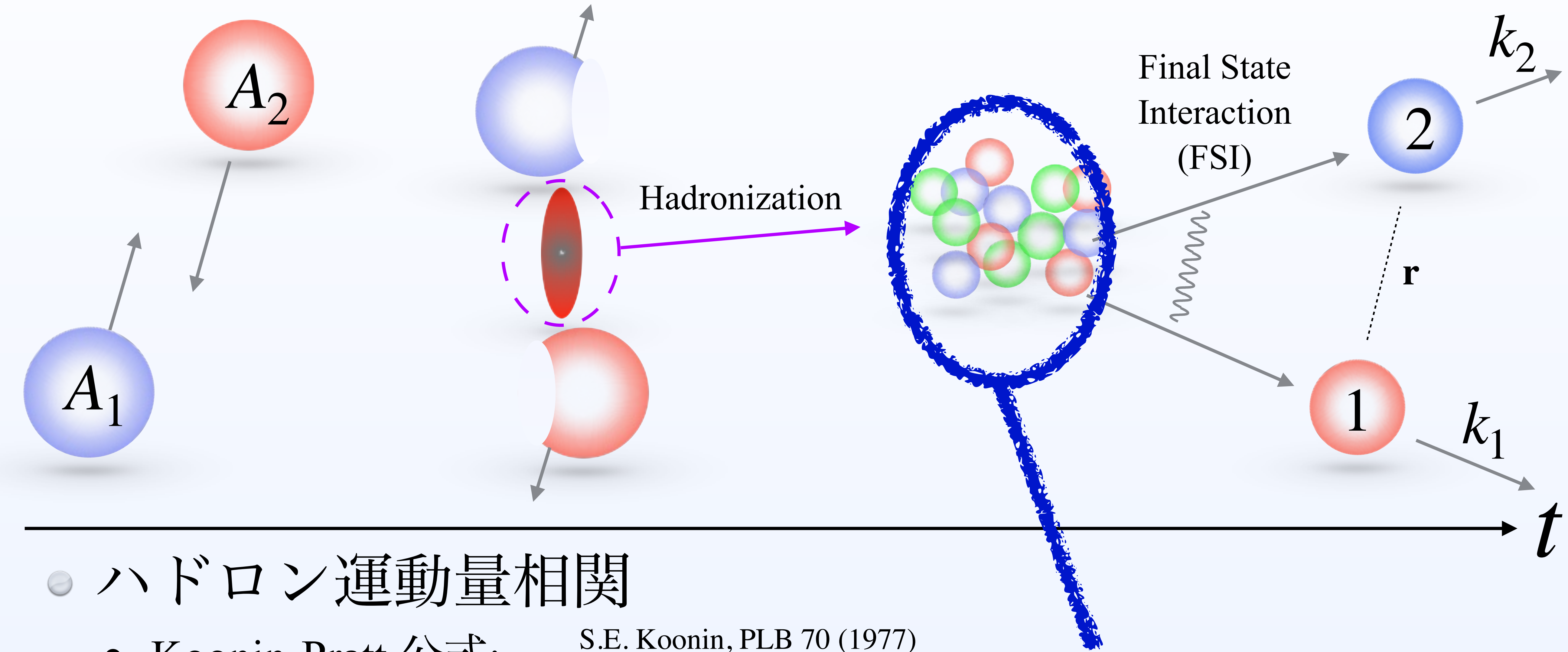


- 2019.3: YIPQS 2019＠京都
  フェムトスコピーに参入

- 2019.9 : FemTUM19 workshop @München

高エネルギー衝突実験における ハドロン運動量相関

- 高エネルギー衝突実験と終状態相互作用



- ハドロン運動量相関
  - Koonin-Pratt 公式:

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

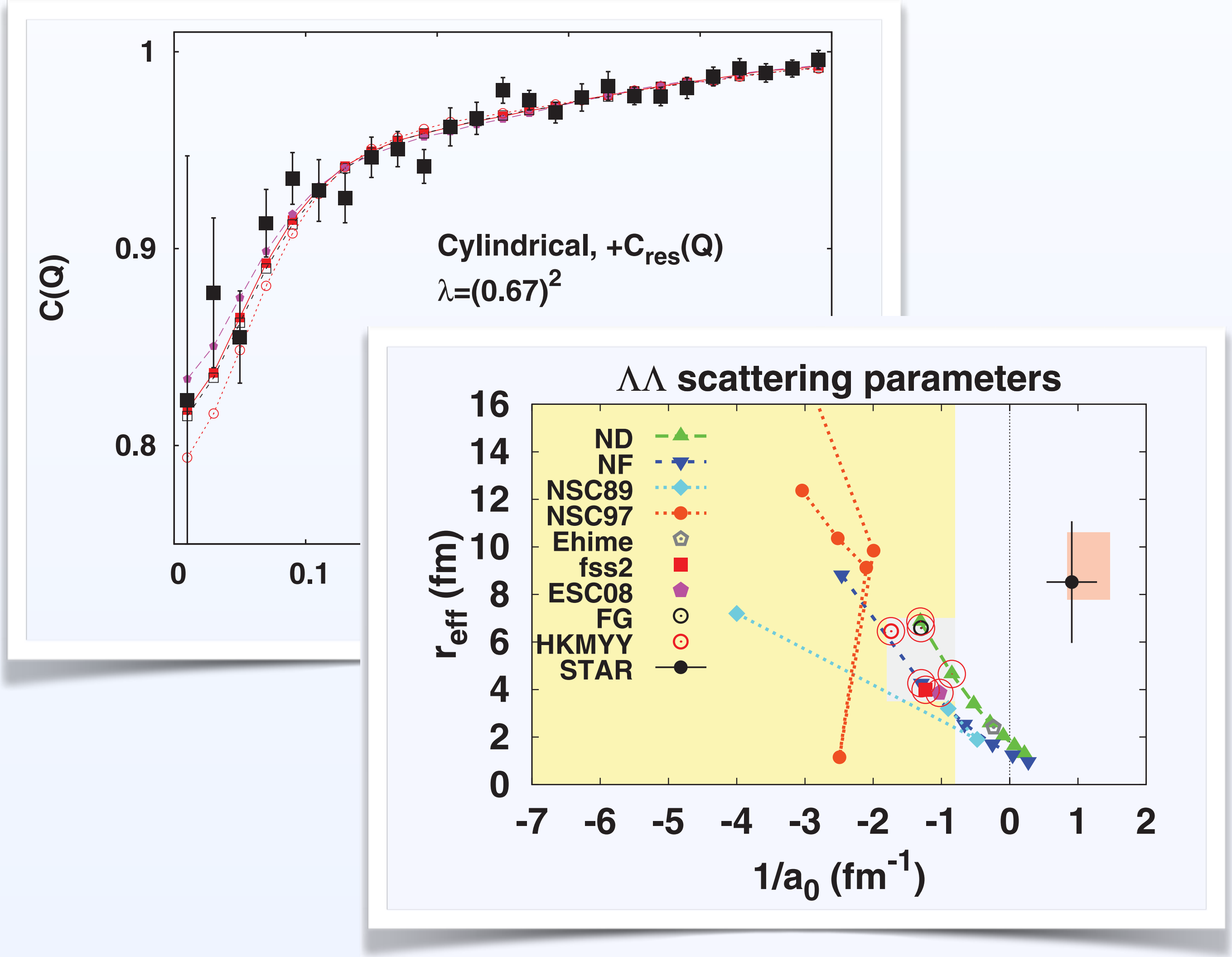
$\varphi^{(-)}(\mathbf{q},\mathbf{r})$: Relative wave function

Collision detail (Ai, energy, centrality)
size of hadron source,
momentum dependence, weight…

高エネルギー衝突実験における ハドロン運動量相関

- $\Lambda\Lambda$

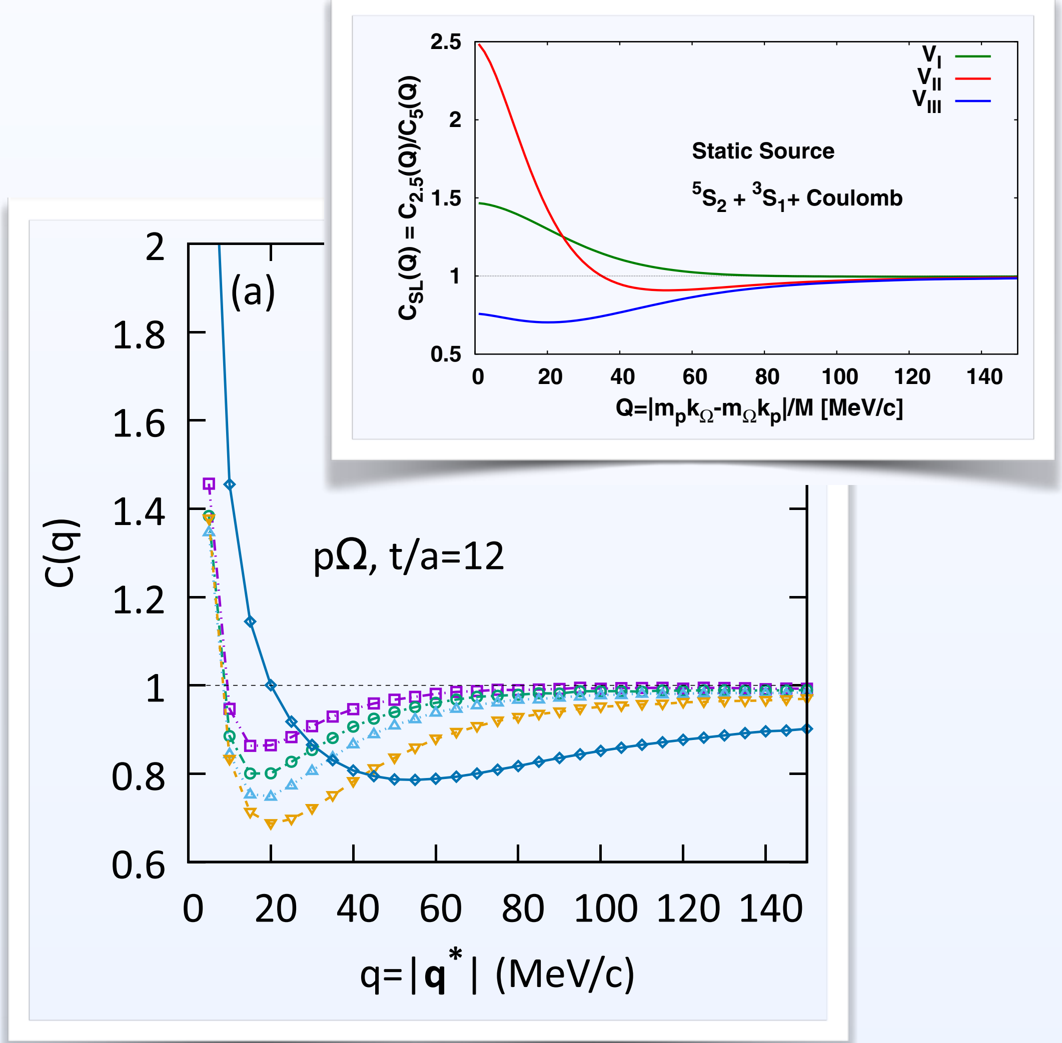
Morita, Furumoto, Ohnishi PRC **91**, 024916 (2015)



Constraint on $\Lambda\Lambda$ scattering parameters

- $p\Omega$-($\Omega\Omega$)

Morita, Ohnishi, Etminan, Hatsuda PRC101 (2020)



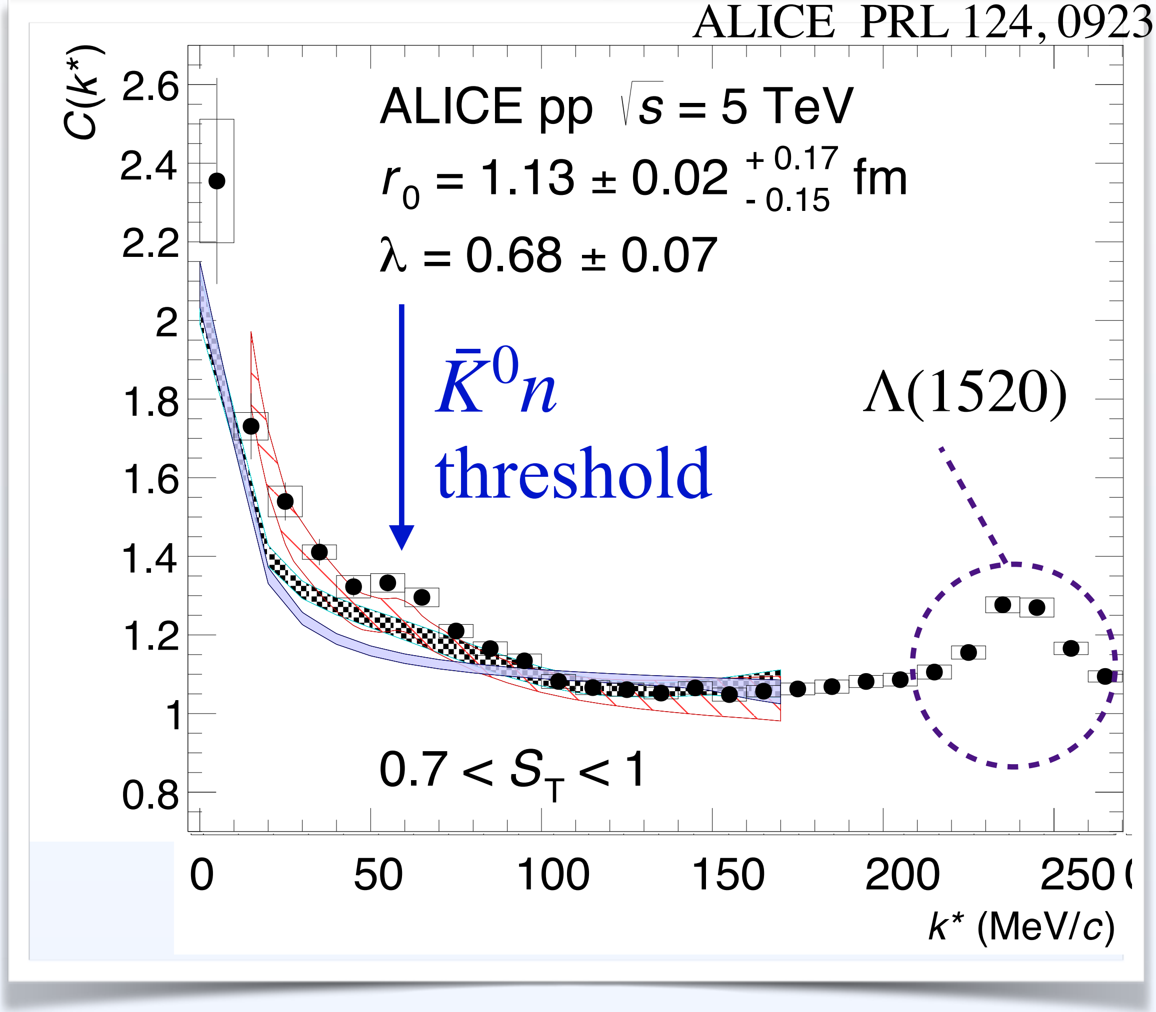
Morita, et al(Ohnishi)., PRC101 (2020)

Indication $p\Omega$ dibaryon state

$K^{-}p$相関

- pp 衝突における$K^{-}p$ 相関 by ALICE

ALICE PRL 124, 092301 (2020)



- 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>

⇨ 詳細な解析から$\bar{K}N$相互作用の情報を引き出せそう

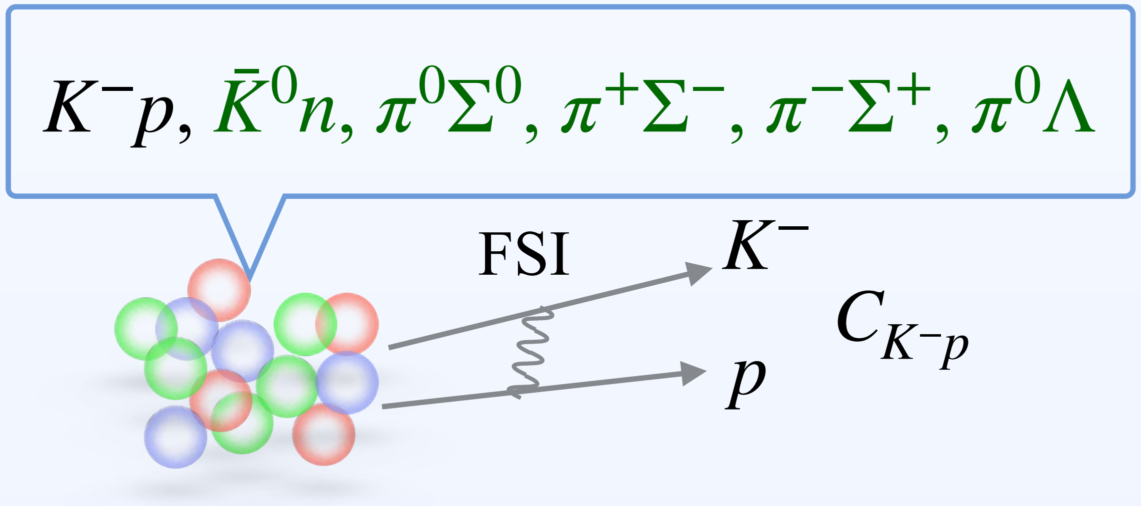
K^-p相関

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

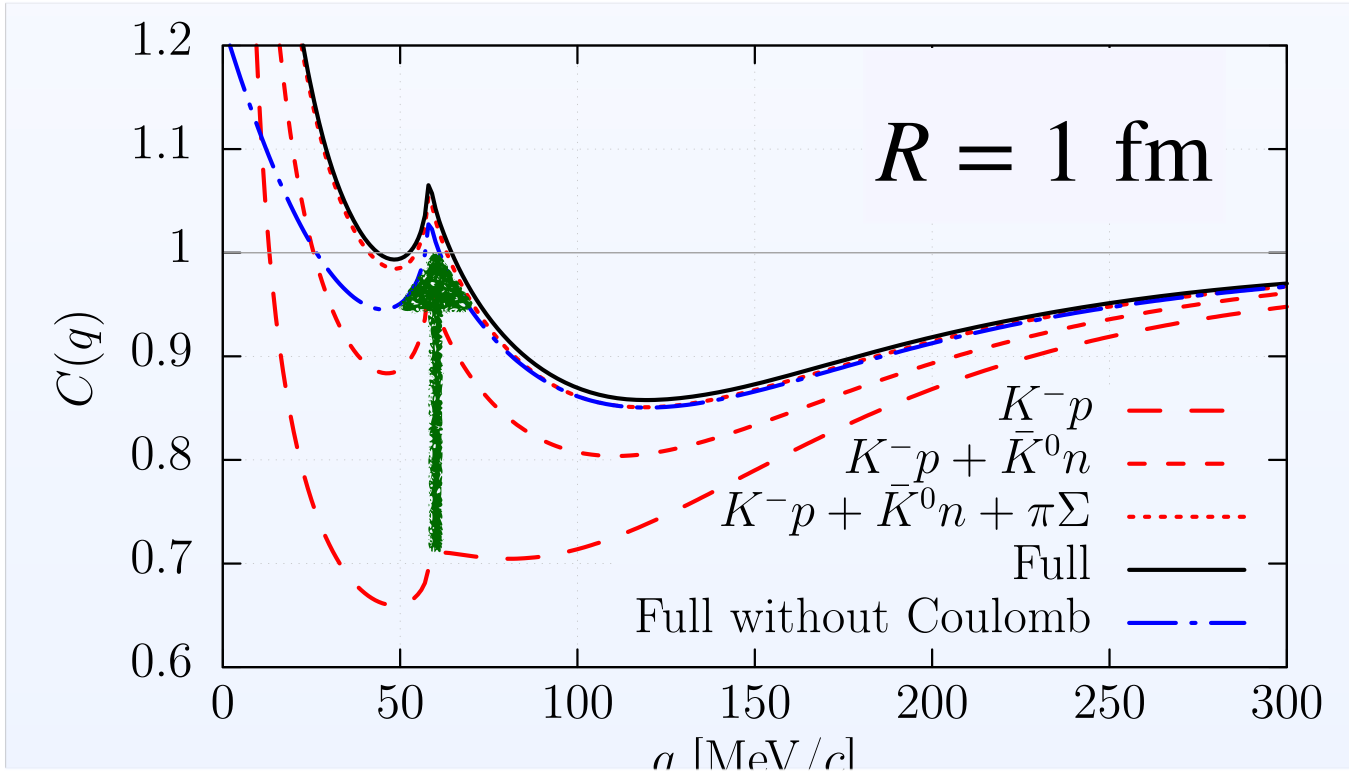
$$\boxed{C(\mathbf{q}) = \int d^3\mathbf{r}\; S(\mathbf{r})\,|\psi^{(-)}(q;r)|^2 + \sum_{j\neq i}\omega_j \int d^3\mathbf{r}\; \underline{S_j(\mathbf{r})\,|\psi_j^{(-)}(q;r)|^2}}$$

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



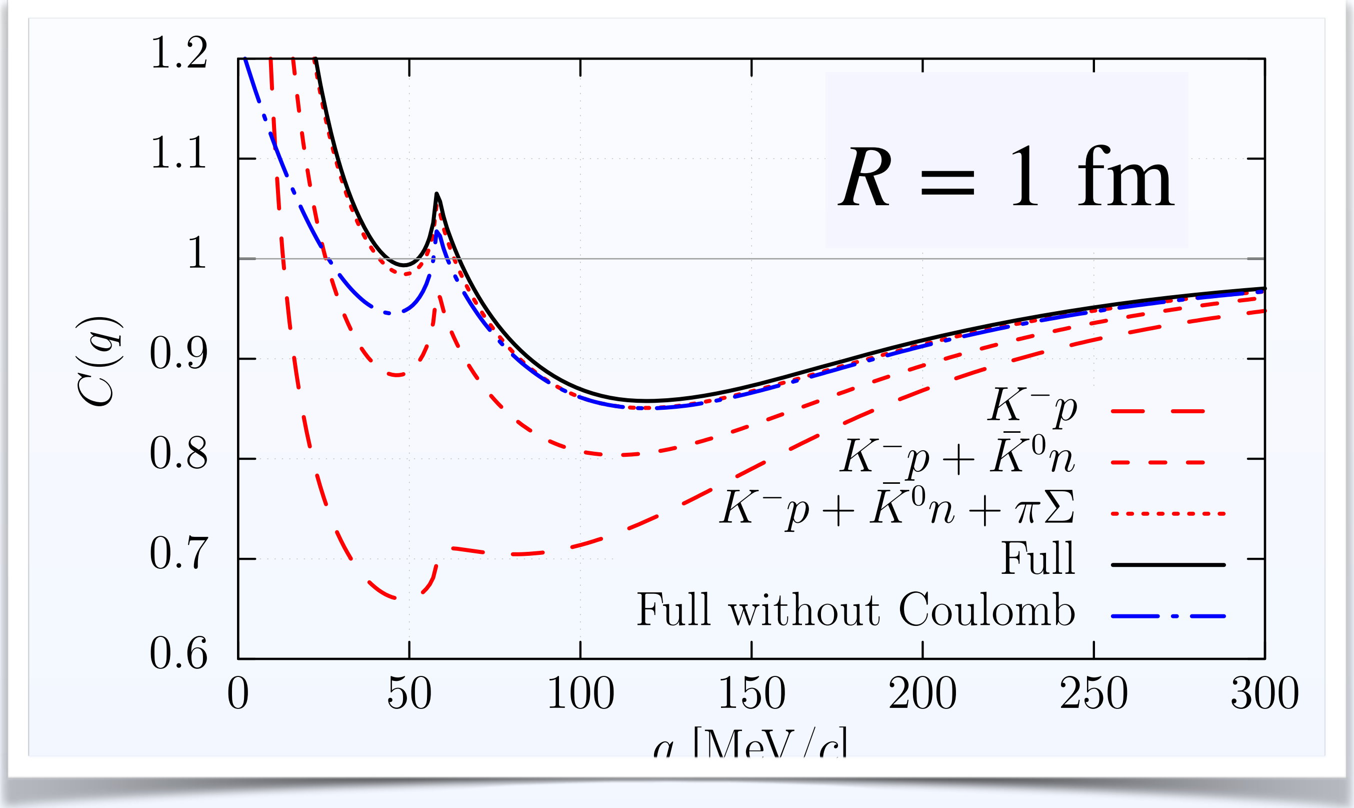
K^-p, $\bar{K}^0 n$, $\pi^0\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Lambda$

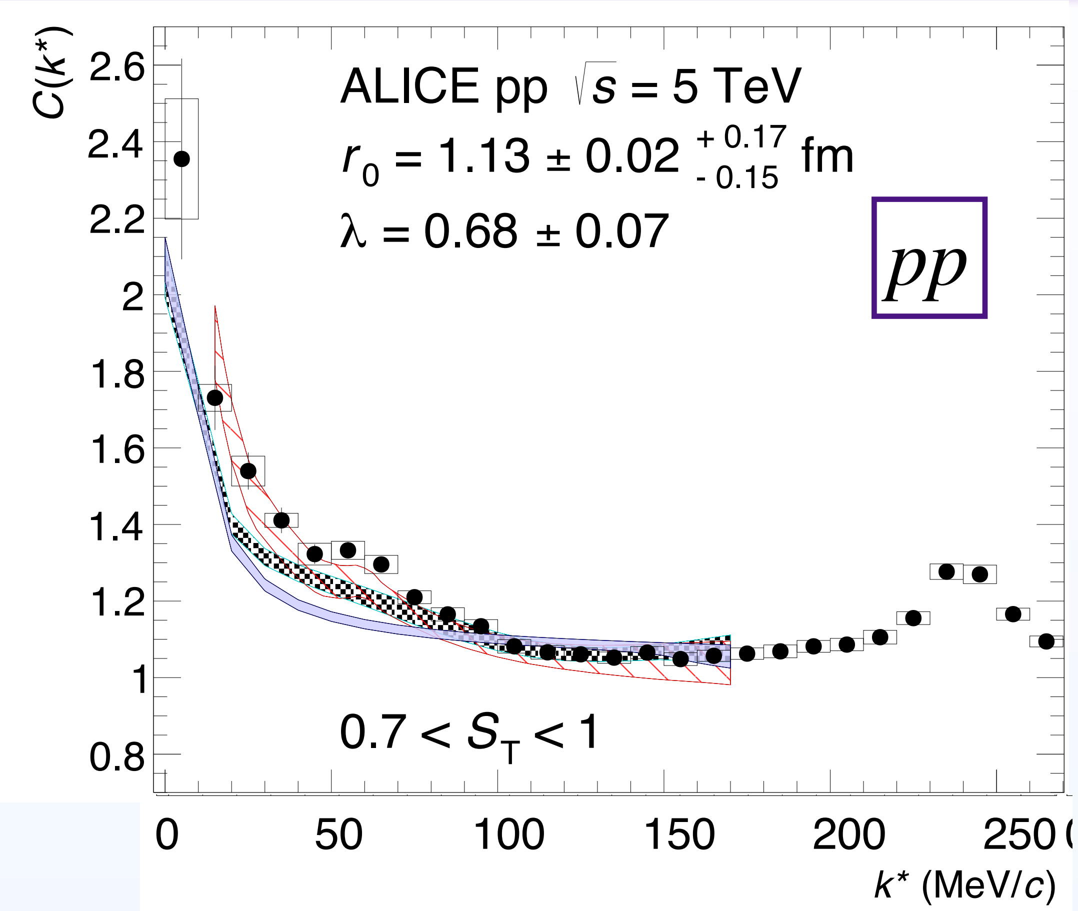


- Enhance $C(q)$
- Enhance cusp structure
- ω_i : production rate
  (compared to measured channel)

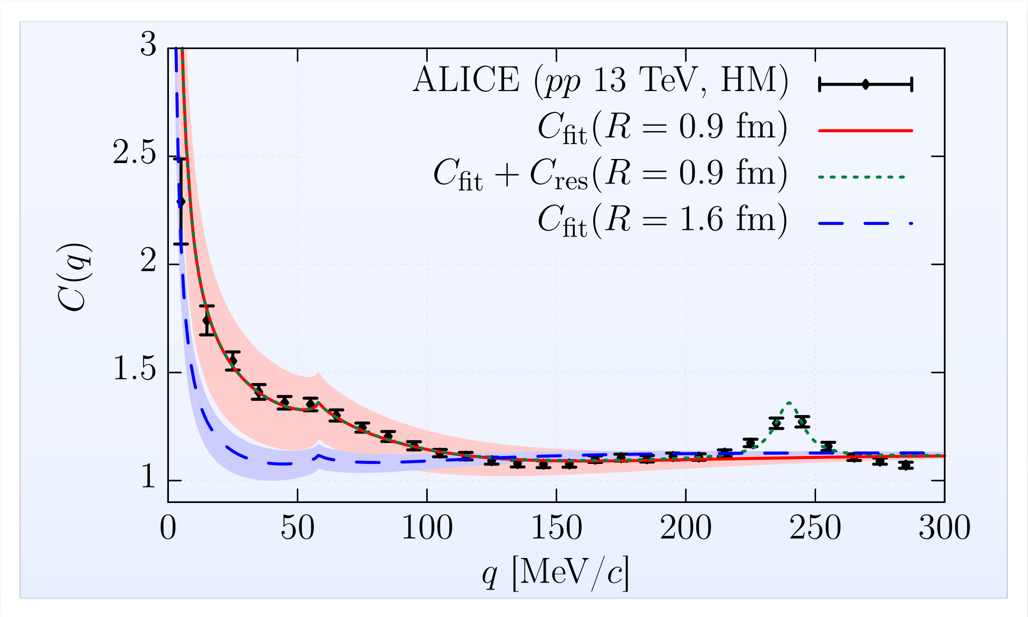
K^-p相関

- FEM-TUM workshop 2019 @ Munich





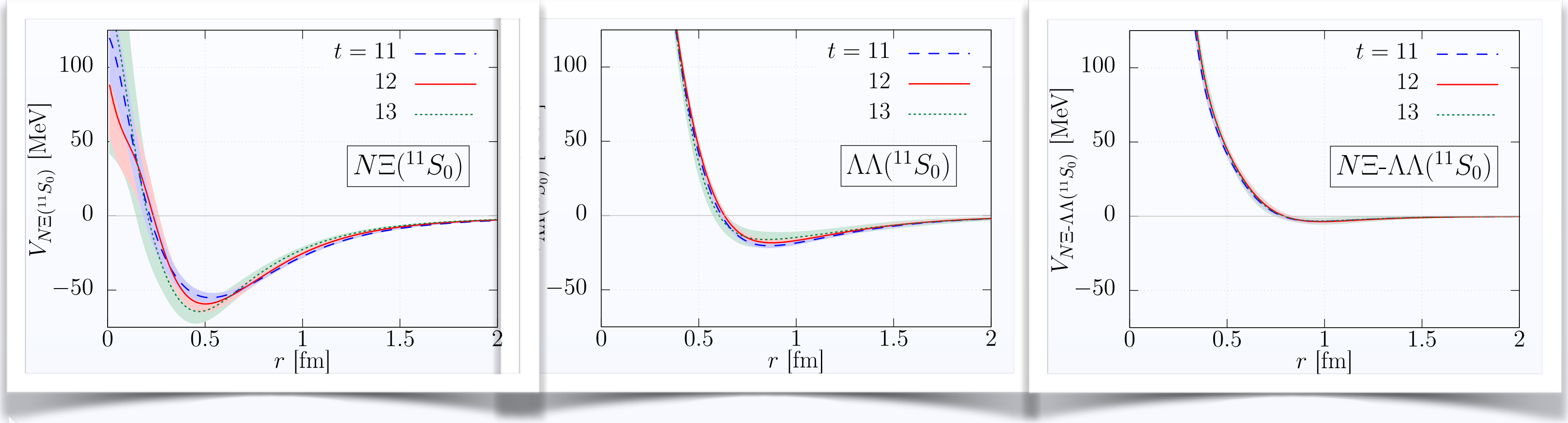
- データまでフィットしよう！
- 使える全データ点を使いたい！



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

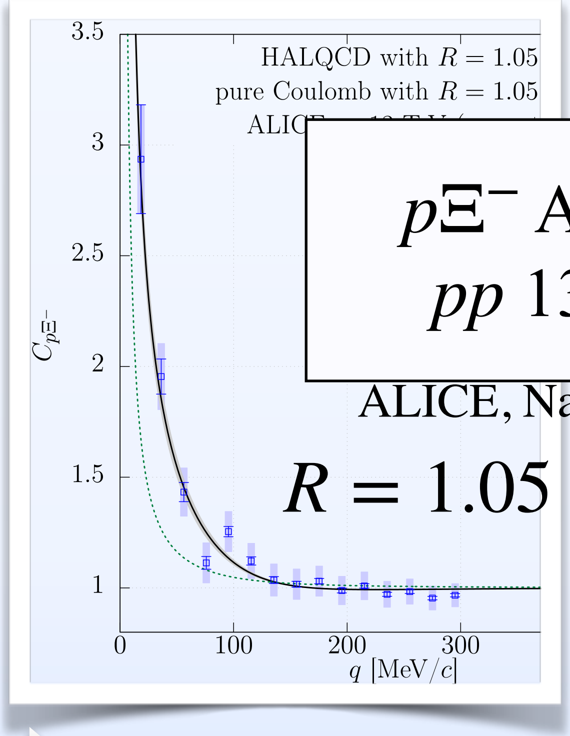
$N\Xi$-$\Lambda\Lambda$相関

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



H ダイバリオン:$N\Xi$付近のunphysical pole(ぎりぎり束縛しない)

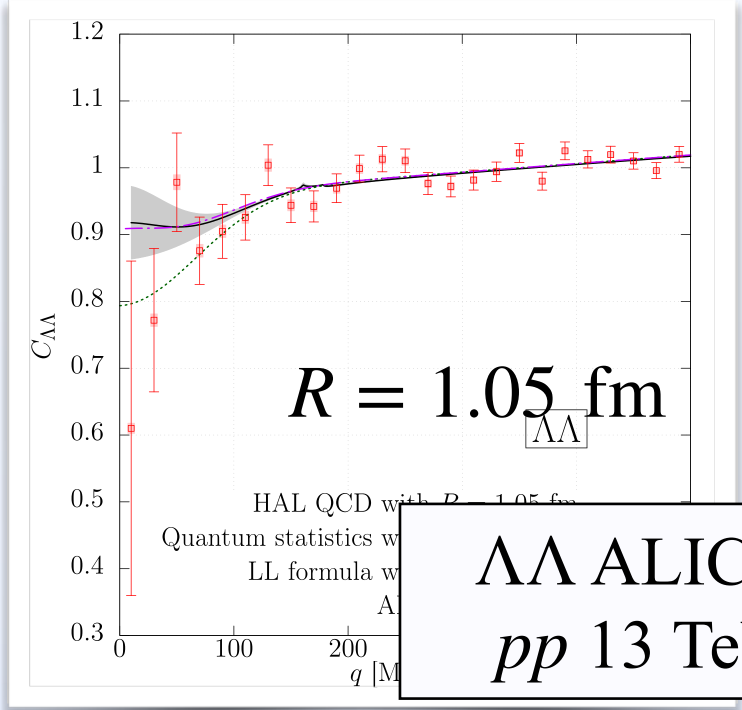
- $p\Xi^-$-$\Lambda\Lambda$相関 YK, K. Sasaki, T. Fukui, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda, *Phys.Rev.C* 105 (2022) 1, 014915



$p\Xi^-$ ALICE
pp 13 TeV

ALICE, Nature 588 (2020), 232-238

$R = 1.05$ fm



$R = 1.05$ fm

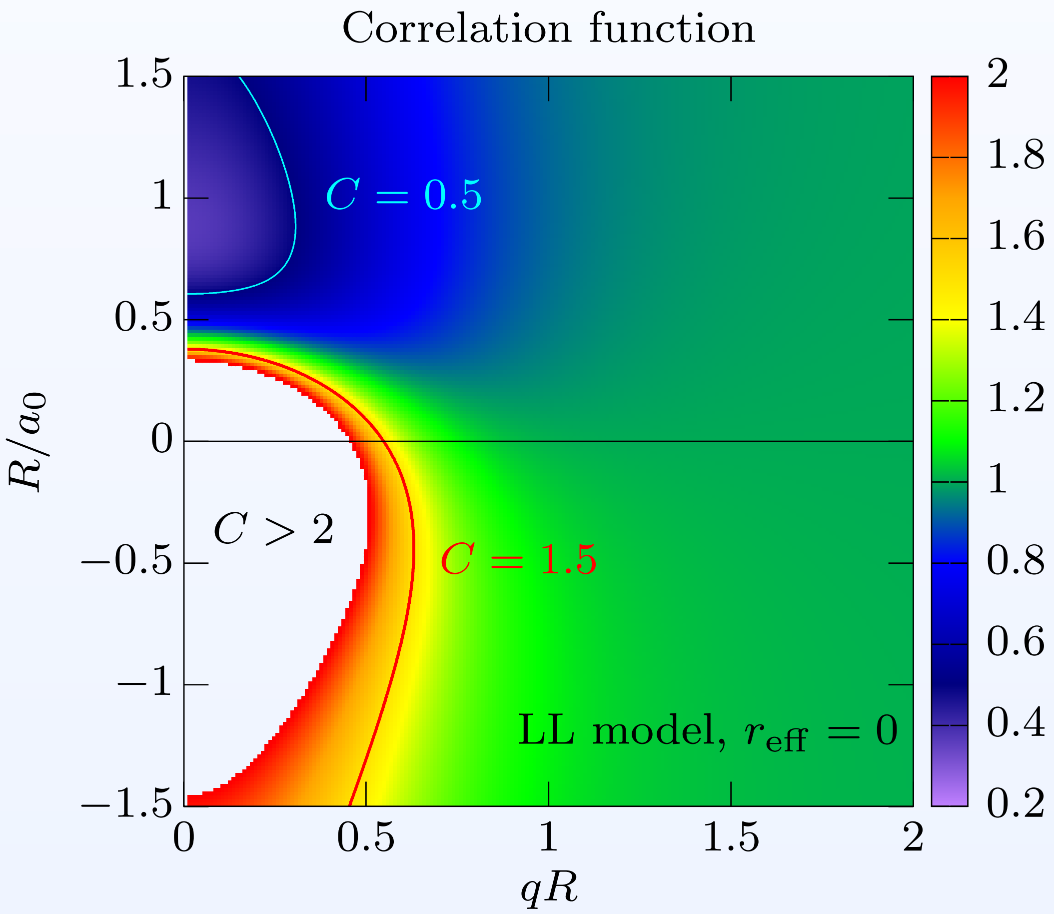
$\Lambda\Lambda$ ALICE
pp 13 TeV

S. Acharya et al. [ALICE], PLB 797 (2019).

H ダイバリオンが存在しないモデルとコンシステント

ユニタリ極限近傍のクーロン効果

- Coulomb interaction with LL formula + Gamow correction
  - クーロンなし
    - LLモデル
  - クーロンあり（引力の場合）
    - クーロンはガモフファクター

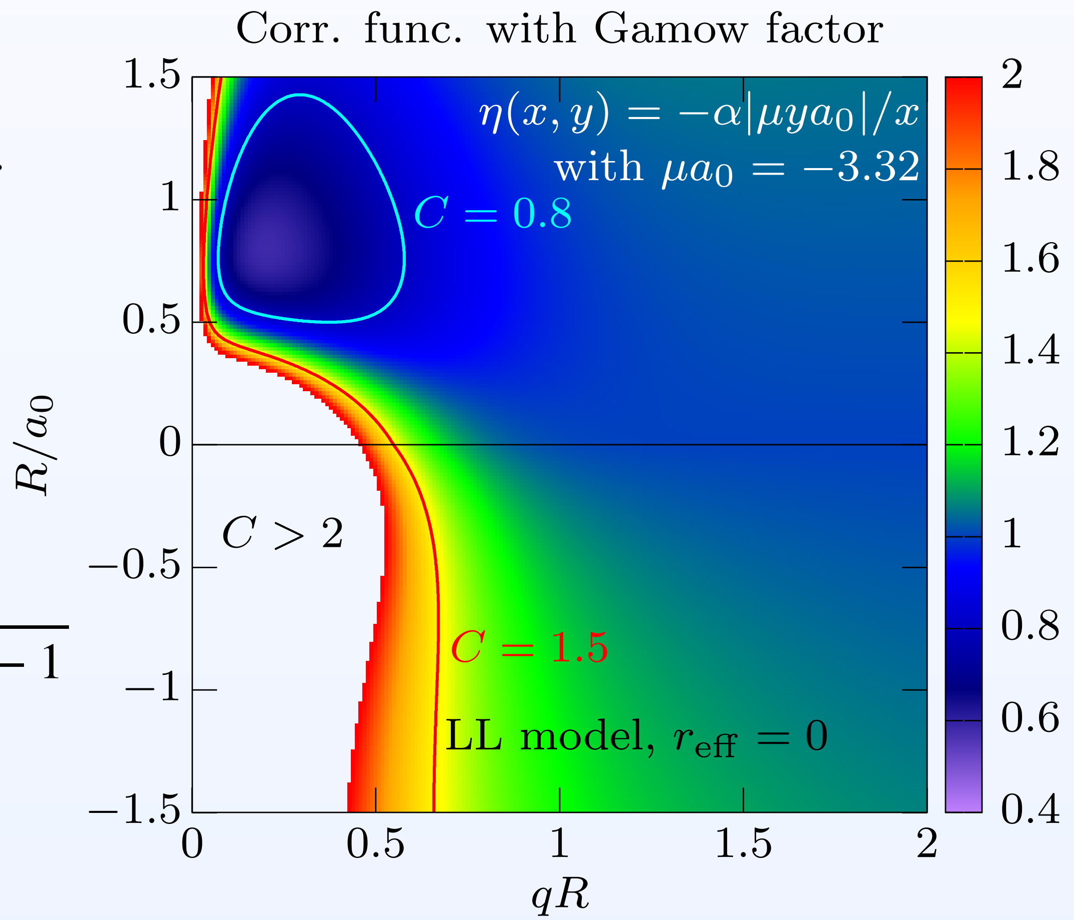


Add Coulomb int.

$\times A(q)$

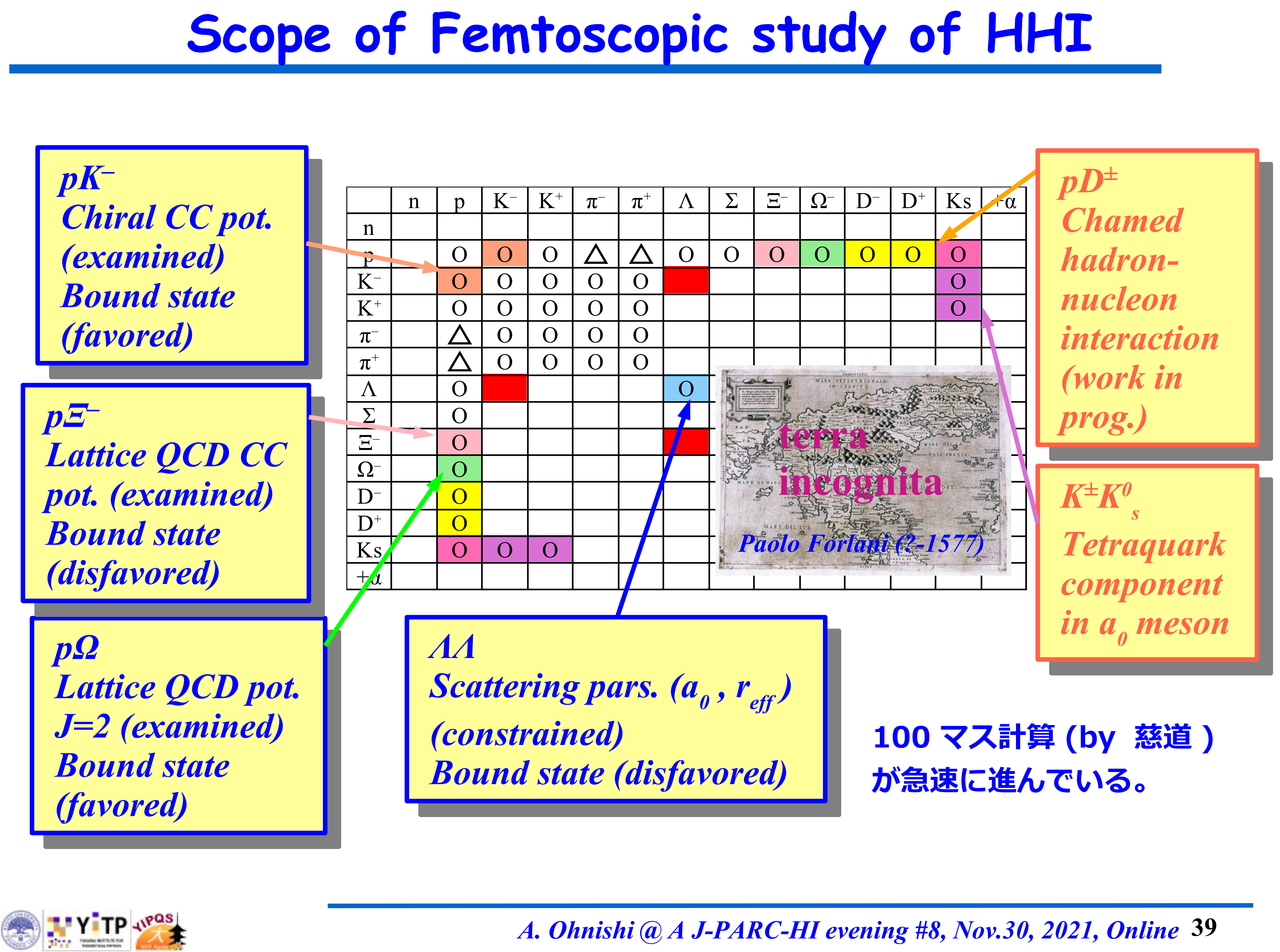
$$A(q) = \frac{2\pi\eta(q)}{\exp(2\pi\eta(q)) - 1}$$

$$\eta(q) = \mu\alpha/q$$



YK, K. Sasaki, T. Fukui, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda, *Phys.Rev.C* 105 (2022) 1, 014915

- 低運動量: クーロン効果が支配的
- 束縛状態($a_0 > 0$): ==> ディップ



Scope of Femtoscopic study of HHI

pK^-
Chiral CC pot. (examined)
Bound state (favored)

$p\Xi^-$
Lattice QCD CC pot. (examined)
Bound state (disfavored)

$p\Omega$
Lattice QCD pot. J=2 (examined)
Bound state (favored)

	n	p	K⁻	K⁺	π⁻	π⁺	Λ	Σ	Ξ⁻	Ω⁻	D⁻	D⁺	Ks	+α
n														
p		O	O	O	△	△	O	O	O	O	O	O	O	
K⁻		O	O	O	O	O	🟥						O	
K⁺		O	O	O	O	O							O	
π⁻		△	O	O	O	O								
π⁺		△	O	O	O	O								
Λ		O	🟥				O							
Σ		O												
Ξ⁻		O					🟥							
Ω⁻		O												
D⁻		O												
D⁺		O												
Ks		O	O	O										
+α														

terra incognita

Paolo Forlani (?-1577)

$pD^{\pm}$
Chamed hadron-nucleon interaction (work in prog.)

$K^{\pm}K^0_s$
Tetraquark component in a_0 meson

$\Lambda\Lambda$
Scattering pars. (a_0, r_{eff}) (constrained)
Bound state (disfavored)

100 マス計算 (by 慈道) が急速に進んでいる。

A. Ohnishi @ A J-PARC-HI evening #8, Nov.30, 2021, Online **39**

Ohnishi-san’s talk slide @ J-PARC-HI 8th

$DD^* / D\bar{D}^*$ 相関(チャーム系)

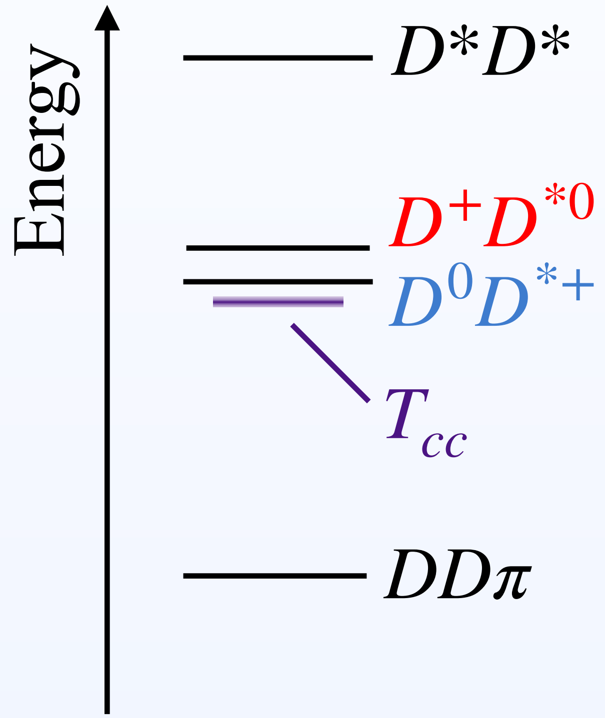
- DD^* and $D\bar{D}^*$ sector

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

+ : attractive w/o bound

- : repulsive
  or attractive w/ bound

$C = 2$



LHCb, Nature Com. 13 (2022) 1

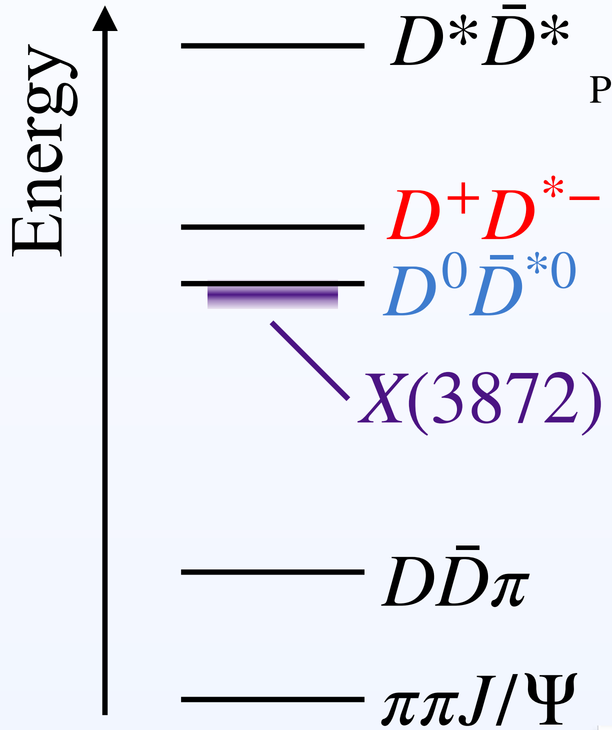
$$E_{T_{cc}} = \delta_m - \frac{i}{2}\Gamma$$

$$\delta m = -0.36\ \mathrm{MeV}$$

$$\Gamma = 0.048\ \mathrm{MeV}$$

$$a_0 = -7.16 + i1.85\ \ \mathrm{fm}$$

$C = 0$



PDG, PTEP 2020, 083C01 (2020).

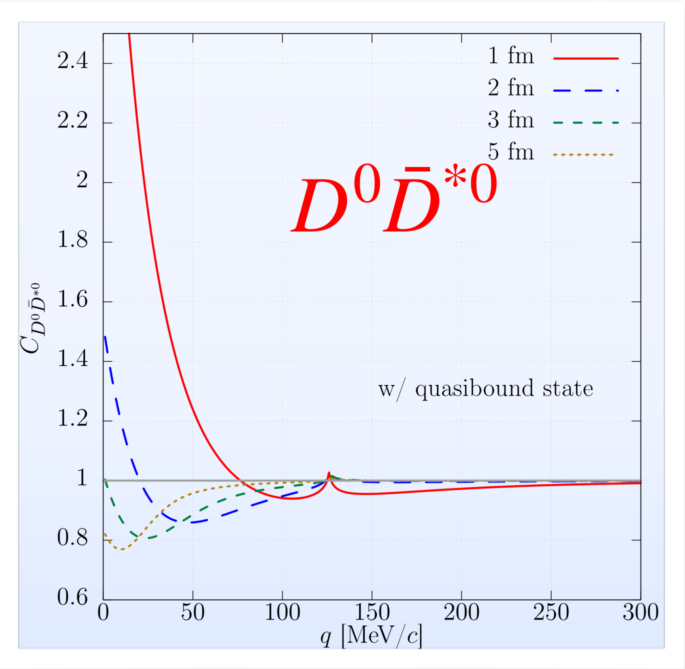
$$E_{X(3872)} = \delta_m - \frac{i}{2}\Gamma$$

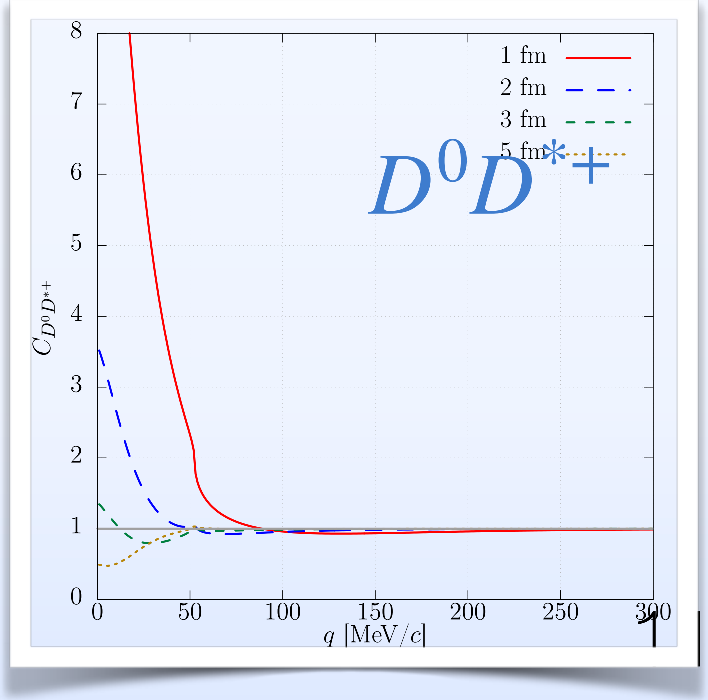
$$\delta m = -0.04\ \mathrm{MeV}$$

$$\Gamma = 1.19\ \mathrm{MeV}$$

$$a_0^{D^0\bar{D}^{*0}} = -4.23 + i3.95\mathrm{fm}$$

- 散乱長から$DD^*/D\bar{D}^*$ポテンシャルを
  - 閾値に近いペア（$D^0\bar{D}^{*0}/D^0\bar{D}^{*+}$）で顕著な相関
  - 散乱長に応じたソースサイズ依存性
  - 将来の実験データから内部構造の判別が可能



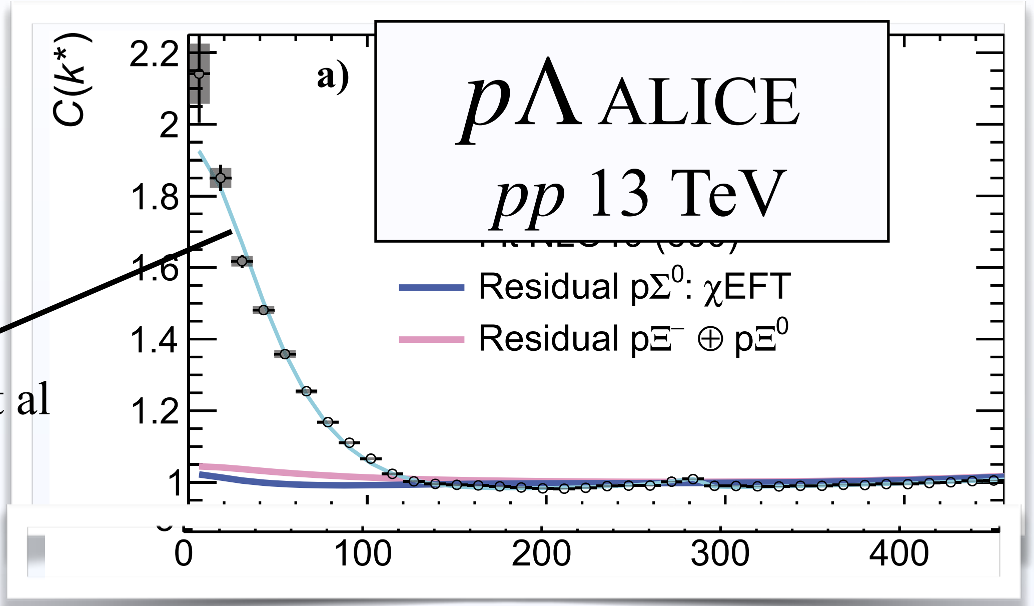


YK, T. Hyodo, A. Ohnishi, Eur.Phys.J.A 58 (2022

ハイペロン(Y)相関

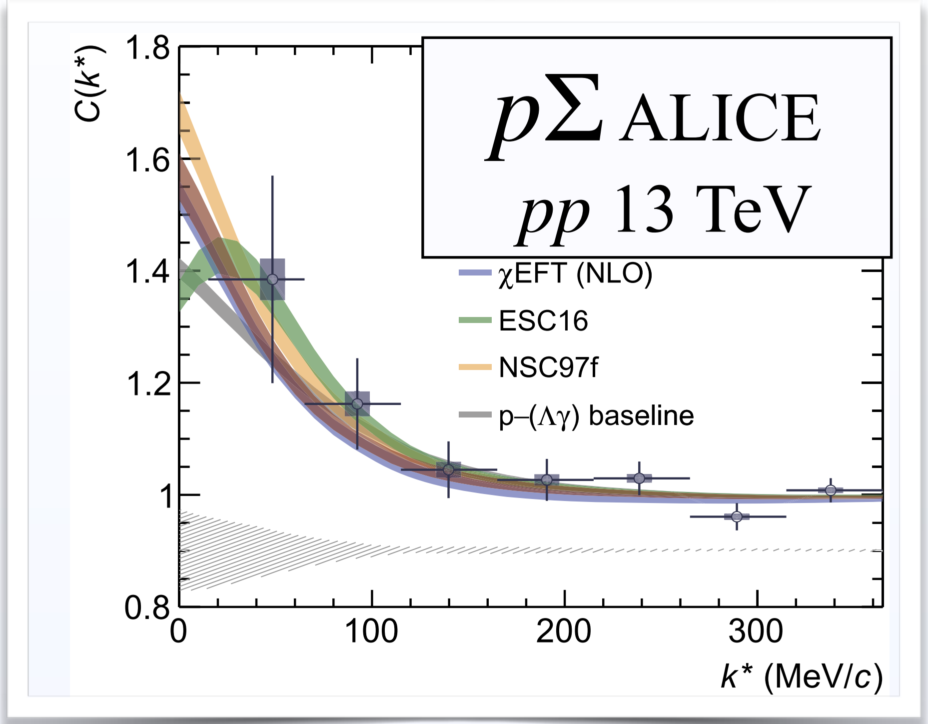
- $S = -1$

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



$p\Lambda$ ALICE
pp 13 TeV

ALICE PLB 805 (2020) 135419



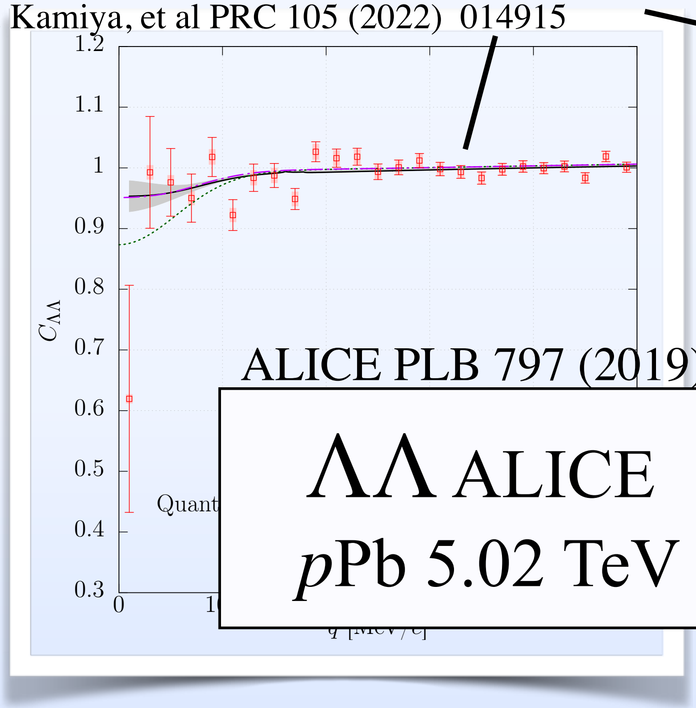
$p\Sigma$ ALICE
pp 13 TeV

PLB 833 (2022) 137272

- $S = -2$

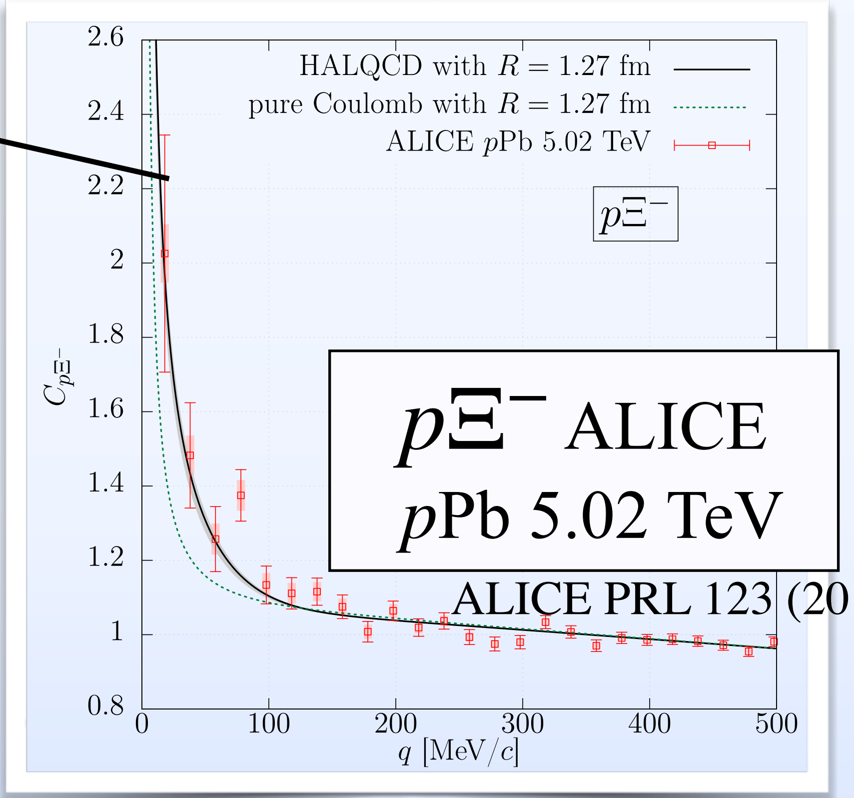
HAL QCD at almost physical m_π

K. Sasaki et al., NPA, 121737 (2019).
Y. Kamiya, et al PRC 105 (2022) 014915



ALICE PLB 797 (2019).

$\Lambda\Lambda$ ALICE
pPb 5.02 TeV

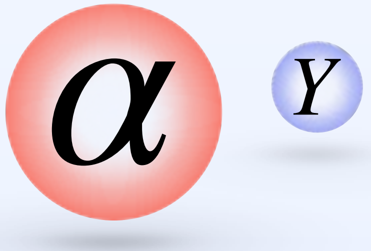


$p\Xi^-$ ALICE
pPb 5.02 TeV

ALICE PRL 123 (2019).

- ハイペロン相関はOK
- 相関を用いた詳細な相互作用の決定?

⇒ αY相関? $\rightarrow$ $\alpha\Lambda, \alpha\Xi$



$\alpha\Lambda$ 相関

有限密度での$N\Lambda$相互作用

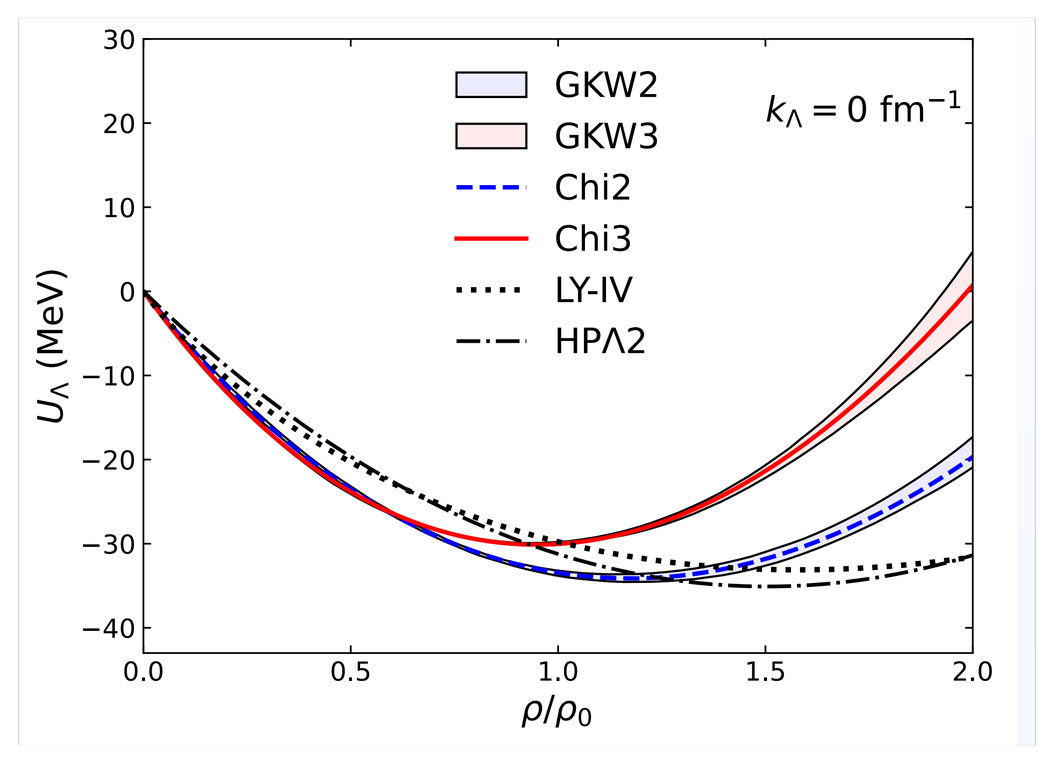
- ハイペロンパズル解決の鍵
- Chiral EFT with NLO D. Gerstung, N. Kaiser, W. Weise, EPJA 55 (2020)
  —> ΛNN 三体力による斥力
  —> stiffer EOS
- Chi3モデル: スキルムΛ ポテンシャル<— Chiral EFT w/ 三体力
  A. Jinno. K. Murase, Y. Nara, and A. Ohnishi arXiv:2306.17452

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

- Well reproduces the binding energy of Λ in hypernuclei

- $N\Lambda$ ポテンシャルモデル
  - 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)

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



$\alpha\Lambda$ポテンシャル

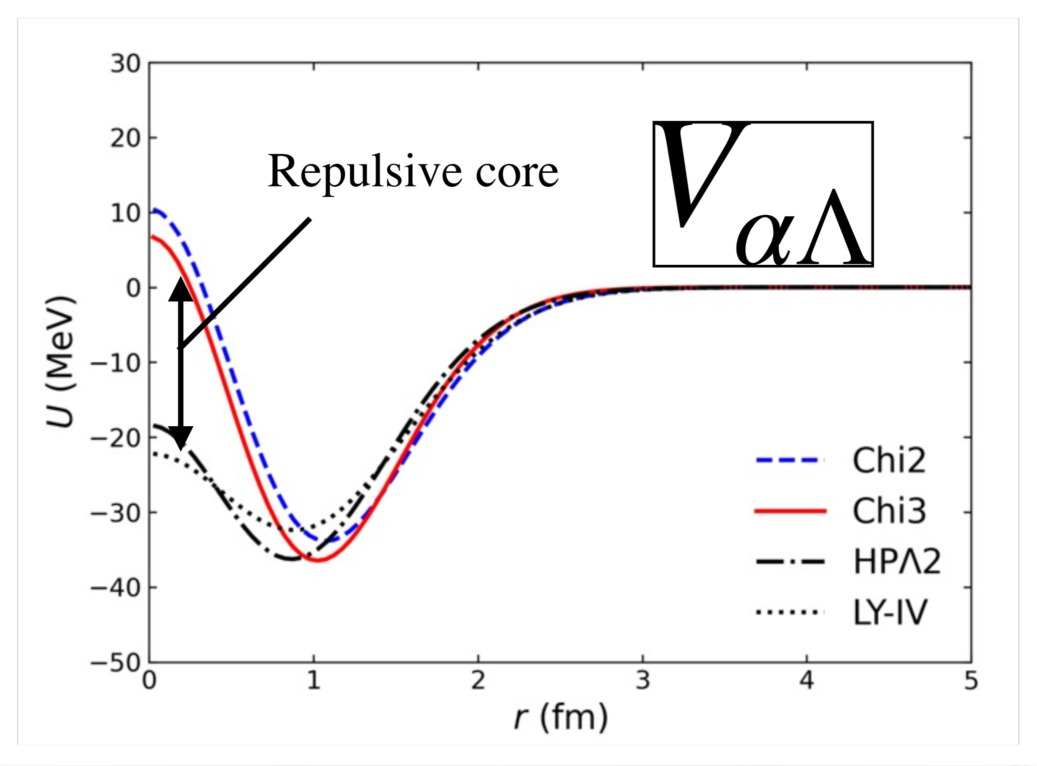
- Nucleon density with Gaussian form:

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

  - high central density ~ $2\rho_0$

Can we see the effect of repulsion core?

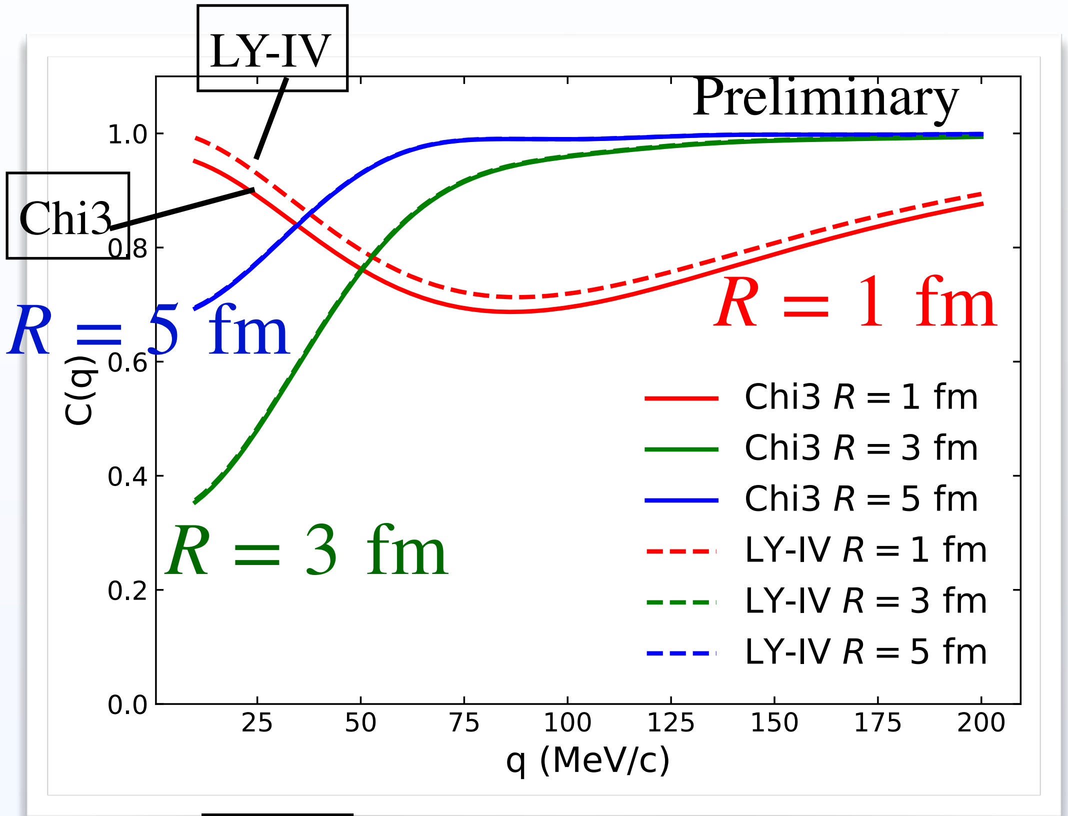
- Unknown a_3^Λ: fit to reproduce the ${}^5_\Lambda$He experimental $E_B = 3.12$ MeV



$\alpha\Lambda$ 相関

$\alpha\Lambda$ 相関 with Chi3 model

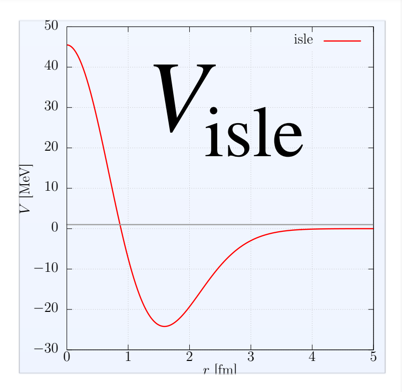
- Characteristic lineshapes for weak binding system ($^5_\Lambda$He)
    - Strong source size dependence
    - Dip structure
- $C(q)$ with Chi3 is slightly suppressed from that with LY-IV
    - Effect of the repulsive core emerges in small source size



斥力芯効果

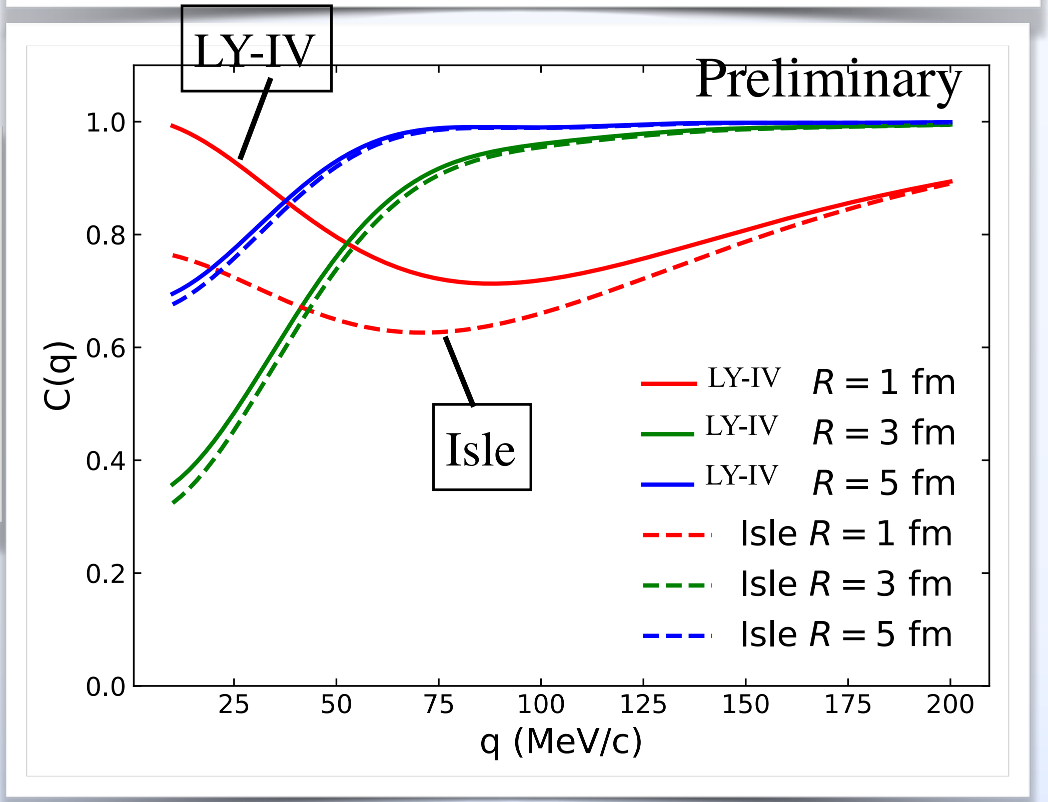
- $N\Lambda$ Isle potential
  Kumagai-Fuse, S. Okabe, Y. Akaishi, PLB 345 (1995)

$$V(r) = \underbrace{V_1 e^{-r^2/b_1^2}}_{\text{repulsive core (short range)}} + \underbrace{V_2 e^{-r^2/b_2^2}}_{\text{attractive part (long range)}}$$



- $C(q)$: 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.

$\alpha\Xi$ 相関

$\alpha\Xi^-$ 相関と ${}^{5}_{\Xi}\mathrm{H}$

Preliminary

- $\alpha\Xi$ foldingポテンシャル with HAL QCD

K. Sasaki et al., NPA, 121737 (2019).

E. Hiyama, M. Isaka, T. Doi, and T. Hatsuda, PRC (2022).

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

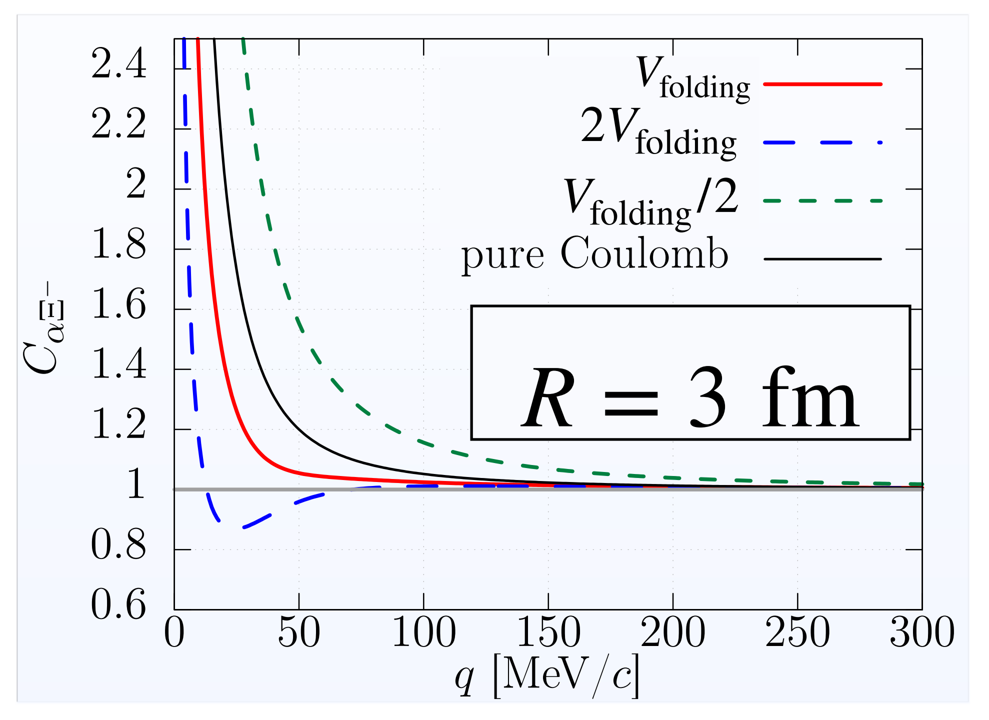
- Result with mid source ($R = 3$ fm)
  - V_{folding}: suppression from Coulomb
  - $2V_{\text{folding}}$: bump structure around $q \sim 100$ MeV/c
  - $V_{\text{folding}}/2$: enhancement from Coulomb

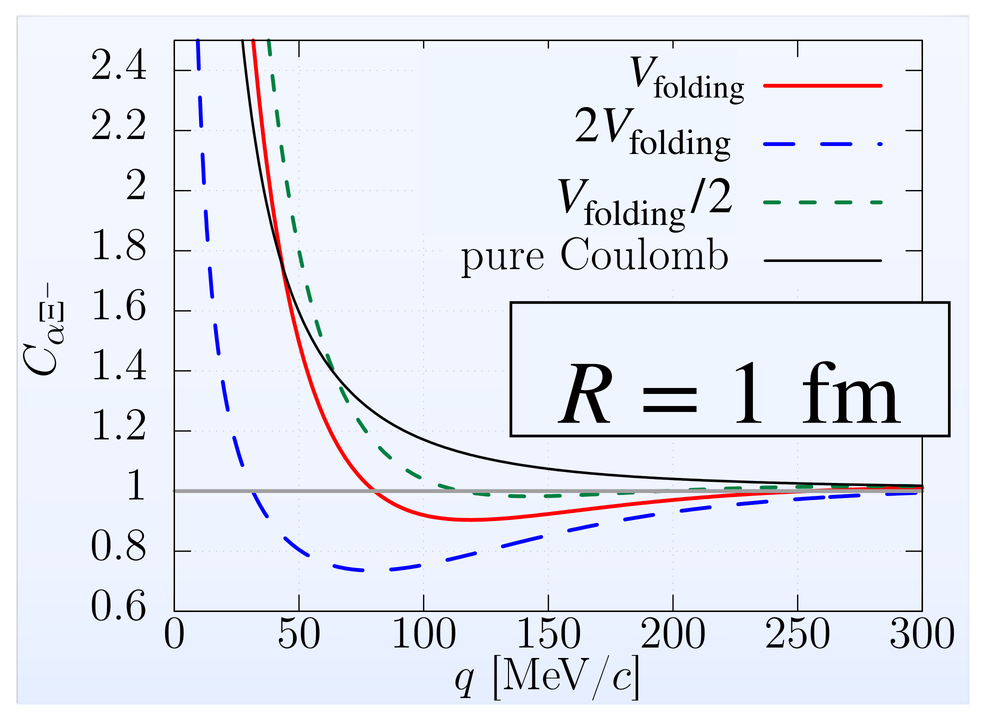
➡ ${}^{5}_{\Xi}\mathrm{H}$ can be distinguished by the source size dependence

- 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.

大西さん安らかにお眠りください