２粒子・３粒子運動量相関から探る
ハドロン間相互作用

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第６回クラスター階層領域研究会

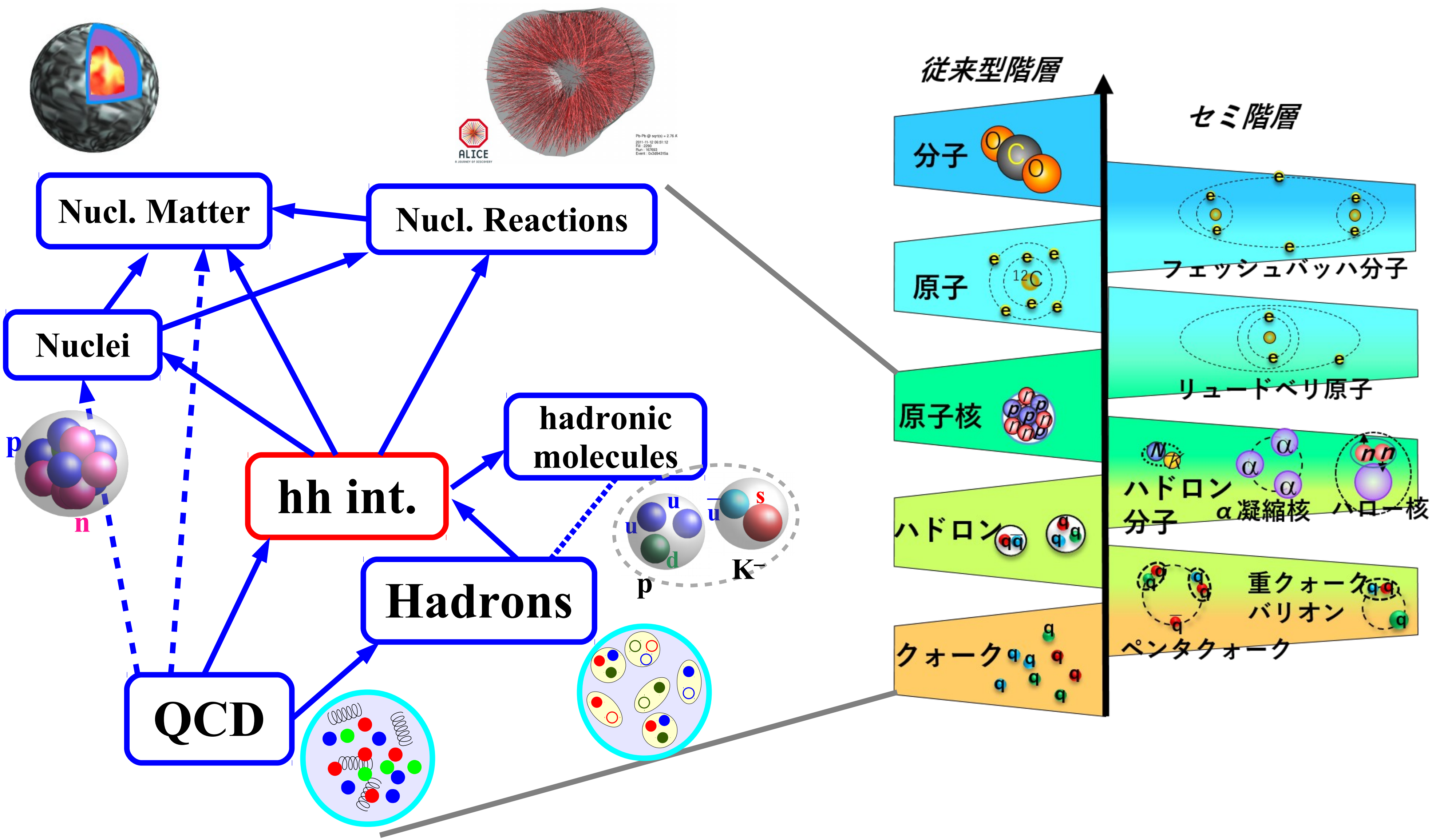
新学術領域「量子クラスターで読み解く物質の階層構造」

June 14 & 19, 2021, Online

- Introduction: 2 粒子運動量相関からハドロン間相互作用へ
- 「2 粒子運動量相関から探るハドロン間相互作用としきい値近辺の散乱振幅」の成果報告 (19H05151, 2019-20 年度 ,40+40 万円)
- 新たな課題 (21H00121, 2021-23 年度 , 30+30 万円)
  - 重陽子 - ハドロン相関、チャームハドロン、３体相関
- Summary

Clusters & Hierarchies

Cluster & Hierarchies


Nucl. Matter

Nucl. Reactions

Nuclei

hadronic molecules

hh int.

Hadrons

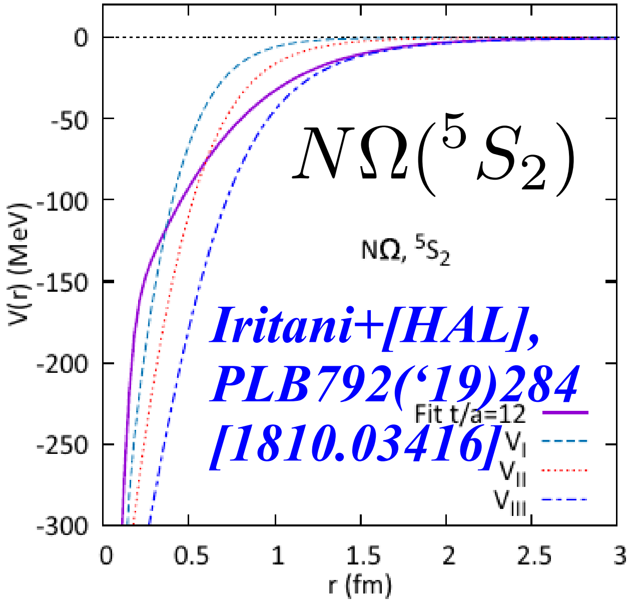
QCD

ハドロン間相互作用は原子核を含むハドロン多体問題の基礎入力

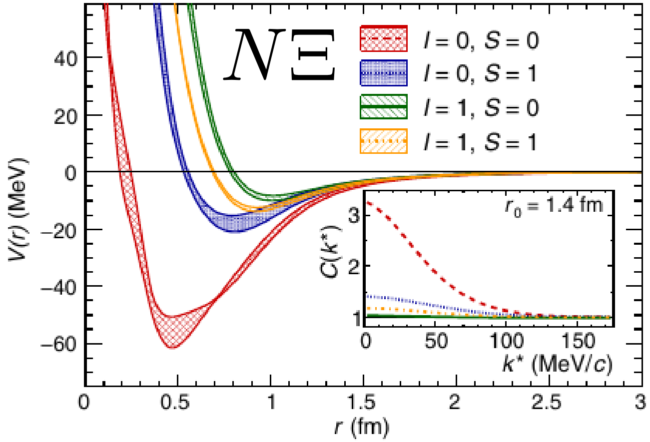
How can we access flavored hh interactions ?

- **Theoretical approaches**
  - **Nuclear force models: meson exch., quark model, … (need data)**
  - ***Ab initio*: chiral EFT (χEFT), lattice QCD (need data or CPU resources)**

Lattice

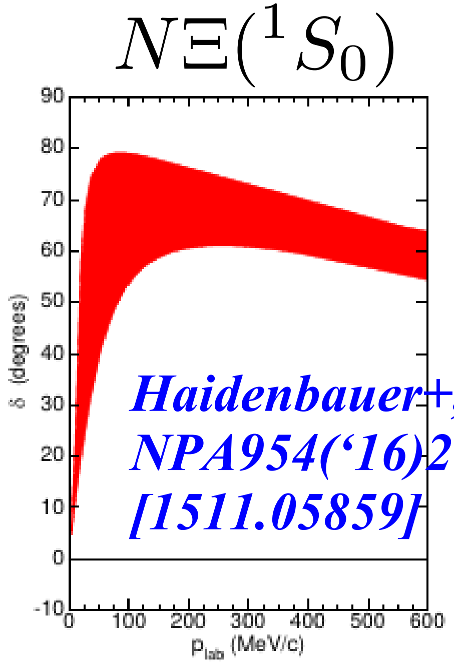


Iritani+[HAL], PLB792('19)284 [1810.03416]

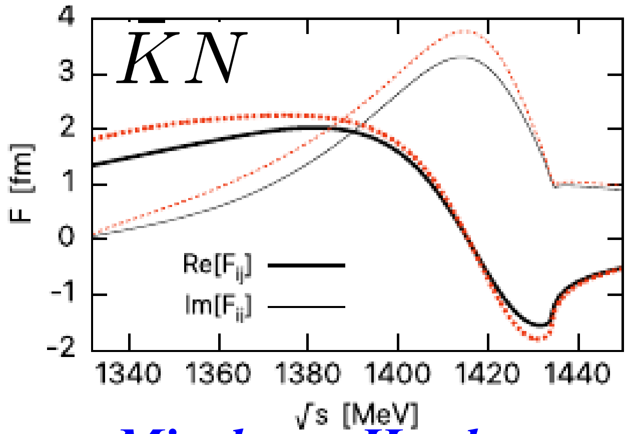


Sasaki+ [HAL], NPA998 ('20)121737 [1912.08630] (taken from ALICE('19))

Chiral



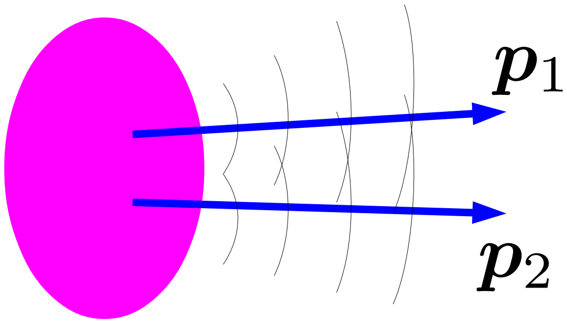
Haidenbauer+, NPA954('16)273 [1511.05859]



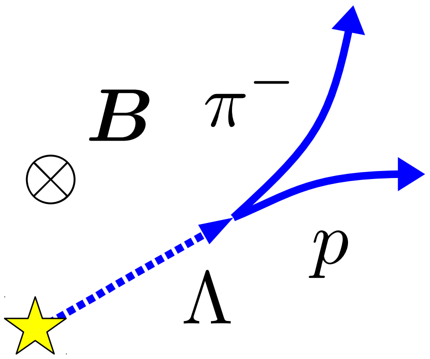
Miyahara, Hyodo, Weise, PRC98('18), 025201 [1804.08269] (Ikeda-Hyodo-Weise amplitude)

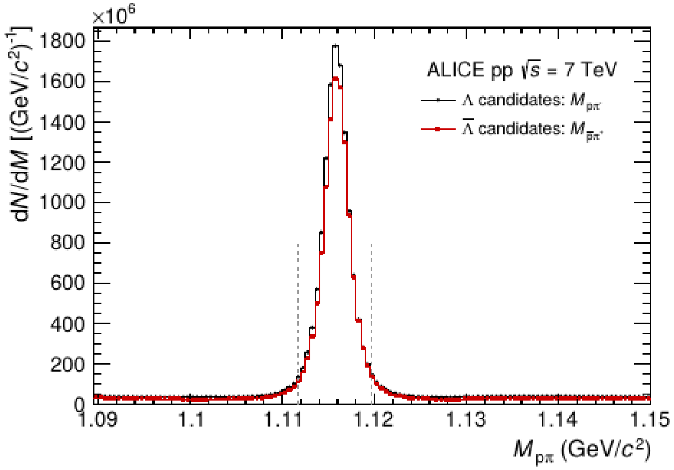
How can we access flavored hh interactions ?

- **Experimental approaches**
  - **hh scattering (NN, YN, πN, KN)**
  - **Hadronic nuclei (normal nuclei, hypernuclei, kaonic nuclei) and atom (π^-, K^-, Σ^-, Ξ^-, …)**
  - **Femtoscopy**
- **Femtoscopic study of hh interactions**
  - **Applicable to various hh pairs (NN, YN, KN, DN, YY, Yd, YNN, …)**
  - **Valid when the source is chaotic**
  - **Weakly decaying particles → Good pair purity**
  - **Future measurements: Charmed hadron, hNN, ...**



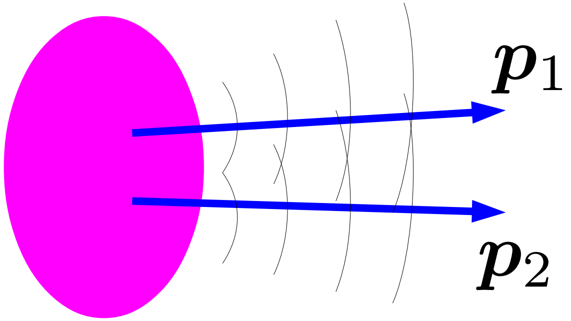
$$C(\boldsymbol{q}) = \frac{N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1) N_2(\boldsymbol{p}_2)} = \frac{N_{12}^{\mathrm{same}}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_{12}^{\mathrm{mixed}}(\boldsymbol{p}_1, \boldsymbol{p}_2)}$$





ALICE [1805.12455]

２粒子運動量相関関数



- **粒子の放出点分布関数**

$$N_i(\boldsymbol{p}) = \int d^4x S_i(x,\boldsymbol{p})$$

- **２粒子運動量相関関数**
  - **２粒子が独立に作られ、終状態の波動関数で相関が作られるとする。**

Koonin('77), Pratt+('86), Lednicky+('82)

２粒子 w.f.

$$C(\boldsymbol{q}) = \frac{N_{12}(\boldsymbol{p}_1,\boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1)N_2(\boldsymbol{p}_2)} \simeq \frac{\int d^4xd^4yS_1(x,\boldsymbol{p}_1)S_2(y,\boldsymbol{p}_2)|\boxed{\Psi_{\boldsymbol{p}_1,\boldsymbol{p}_2}(x,y)}|^2}{\int d^4xd^4yS_1(x,\boldsymbol{p}_1)S_2(x,\boldsymbol{p}_2)}$$

$$= \int d\boldsymbol{r}\underline{S(\boldsymbol{r})}|\underline{\varphi(\boldsymbol{r};\boldsymbol{q})}|^2 = 1 + \int d\boldsymbol{r}S(r)\left[|\underline{\varphi_0(\boldsymbol{r};\boldsymbol{q})}|^2 - |j_0(qr)|^2\right]$$

重心座標積分　ソース関数　相対波動関数

s 波

球対称ソース・異種粒子
・s 波のみ・クーロン無し

- **運動量相関の利用方法**
  - **相関関数＋波動関数→ソースサイズ**
    Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)
  - **相関関数＋ソース関数 → ハドロン間相互作用**
    R. Lednicky, V. L. Lyuboshits ('82); K. Morita, T. Furumoto, AO ('15)

Bird's-eye view of C(q)

- **相関関数の大まかな振る舞い→漸近形を用いた解析模型（LL 模型)**

R. Lednicky, V. L. Lyuboshits ('82)

$$C(q) = 1 + \frac{|f(q)|^2}{2R^2} F_3\left(\frac{r_{\rm eff}}{R}\right) + \frac{2{\rm Re}\, f(q)}{\sqrt{\pi}R} F_1(2qR) - \frac{2{\rm Im}\, f(q)}{R} F_2(2qR)$$

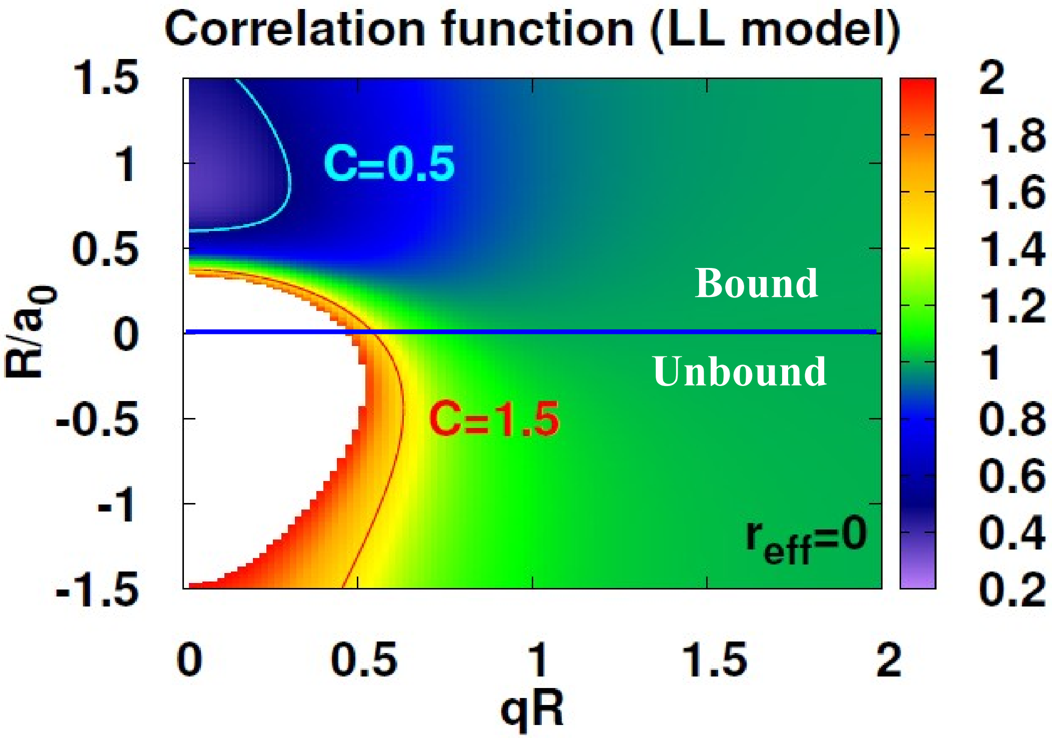
$$f(q) = [q \cot\delta - iq]^{-1},\ F_1(x) = \int_0^x dt e^{t^2-x^2}/x,\ F_2(x) = (1-e^{-x^2})/x,\ F_3(x) = 1 - x/2\sqrt{\pi}$$

(漸近形・ガウス型ソース・ s 波・クーロン無し・１チャネル・異種粒子・スピン因子無視)

- **引力 (a_0<0) による wf 増大**
  → C(q) の増大

$$C_{\rm LL}(0) = 1 - \frac{2}{\sqrt{\pi}}\left(\frac{a_0}{R}\right) + \frac{1}{2}\left(\frac{a_0}{R}\right)^2$$

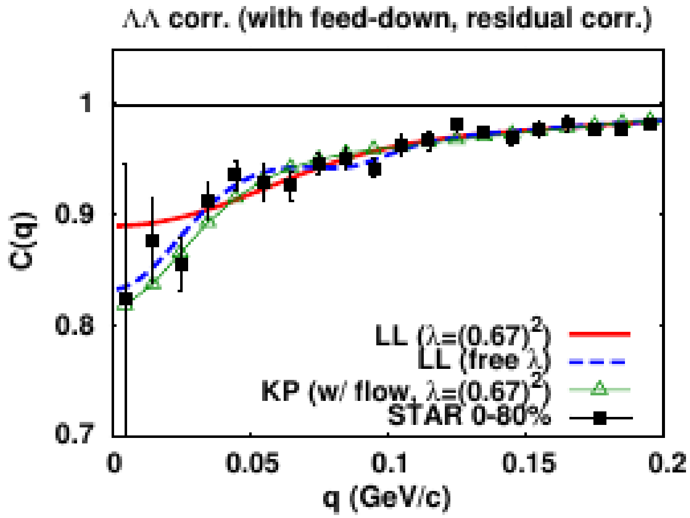
- **斥力 or 束縛状態あり (a_0>0)**
  →r ~ a_0 で wf に節
  → R ~ a_0 で C(q) の抑制

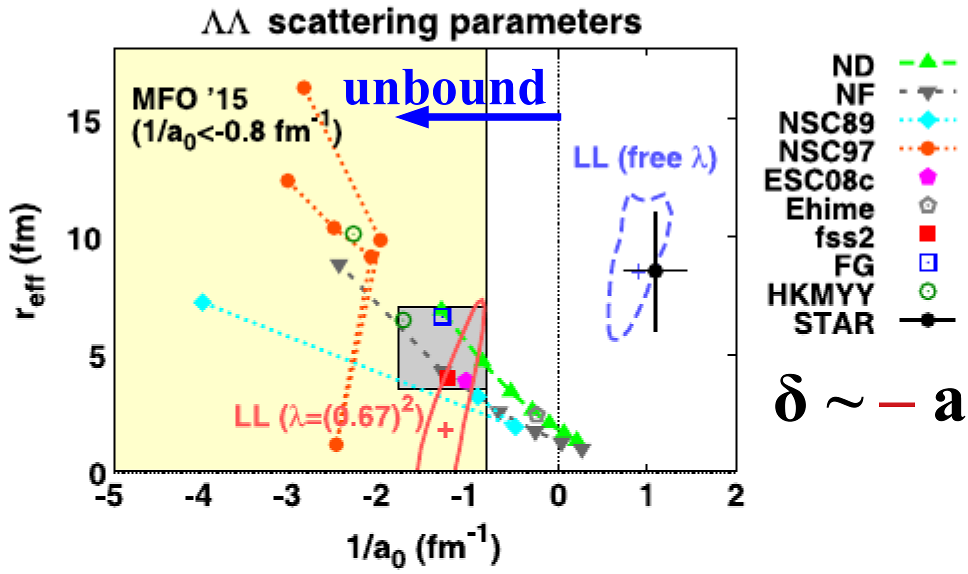


Example: ΛΛ correlation fn. and ΛΛ interaction

$$C(\boldsymbol{q}) = 1 - \frac{\lambda}{2} e^{-4q^2R^2} + \frac{\lambda}{2} \int d\boldsymbol{r} S(r) \left\{ |\varphi_0(r)|^2 - |j_0(qr)|^2 \right\}$$

λ = pair purity prob.



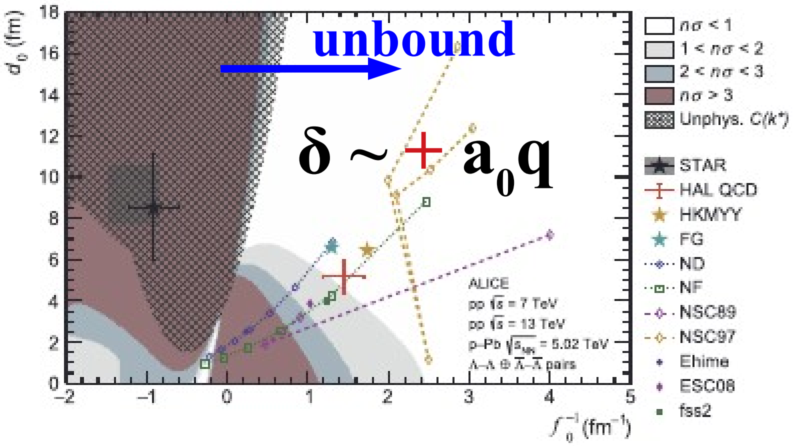


$\delta \sim - a_0 q$

-1.25 fm < a_0 < 0.

L. Adamczyk+[STAR], PRL114('15)022301;
K.Morita, T.Furumoto, AO, PRC 91('15)024916;
AO, K. Morita, K. Miyahara, T. Hyodo, NPA954('16)294.

S. Acharya+[ALICE], PLB797('19)134822



$\delta \sim + a_0 q$

２粒子運動量相関から探るハドロン間相互作用としきい値近辺の散乱振幅 *(19H05151* 成果報告 *)*

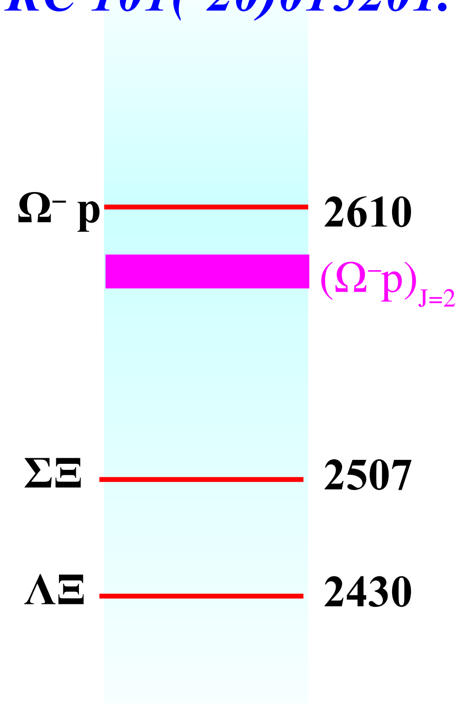
- **Probing ΩΩ and pΩ dibaryons with femotoscopic correlations in relativistic heavy-ion collisions, K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101(‘20), 015201 (Editors’ Suggestion).**
- **K^-p correlation function from high-energy nuclear collisions and chiral SU(3) dynamics, Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124 (‘20), 132501.**
- **Deuteron breakup effect on deuteron-Ξ correlation function, K. Ogata, T. Fukui, Y. Kamiya, and AO, PRC, to appear (arXiv:2103.00100).**
- **Femtoscopic study of coupled-channel N Ξ and ΛΛ interactions, Y. Kamiya, K. Sasaki, T. Fukui, T. Hatsuda, T. Hyodo, K. Morita, K. Ogata, AO, in prep.**

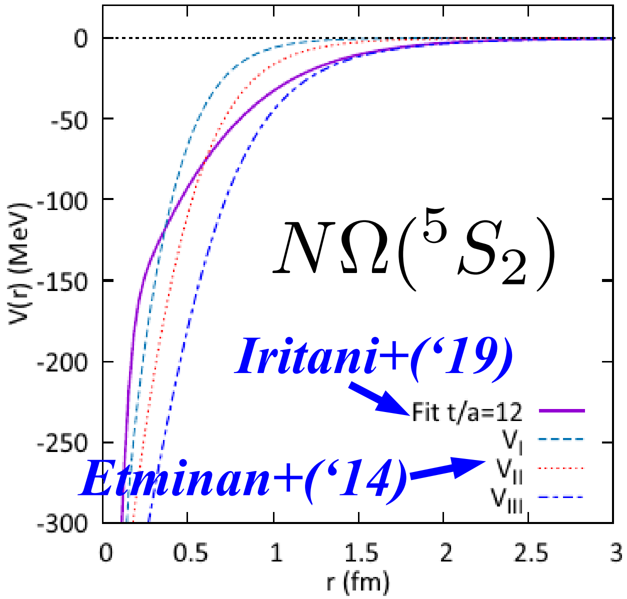
Ωp correlation function

NΩ interaction and NΩ bound state

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC 101('20)015201.

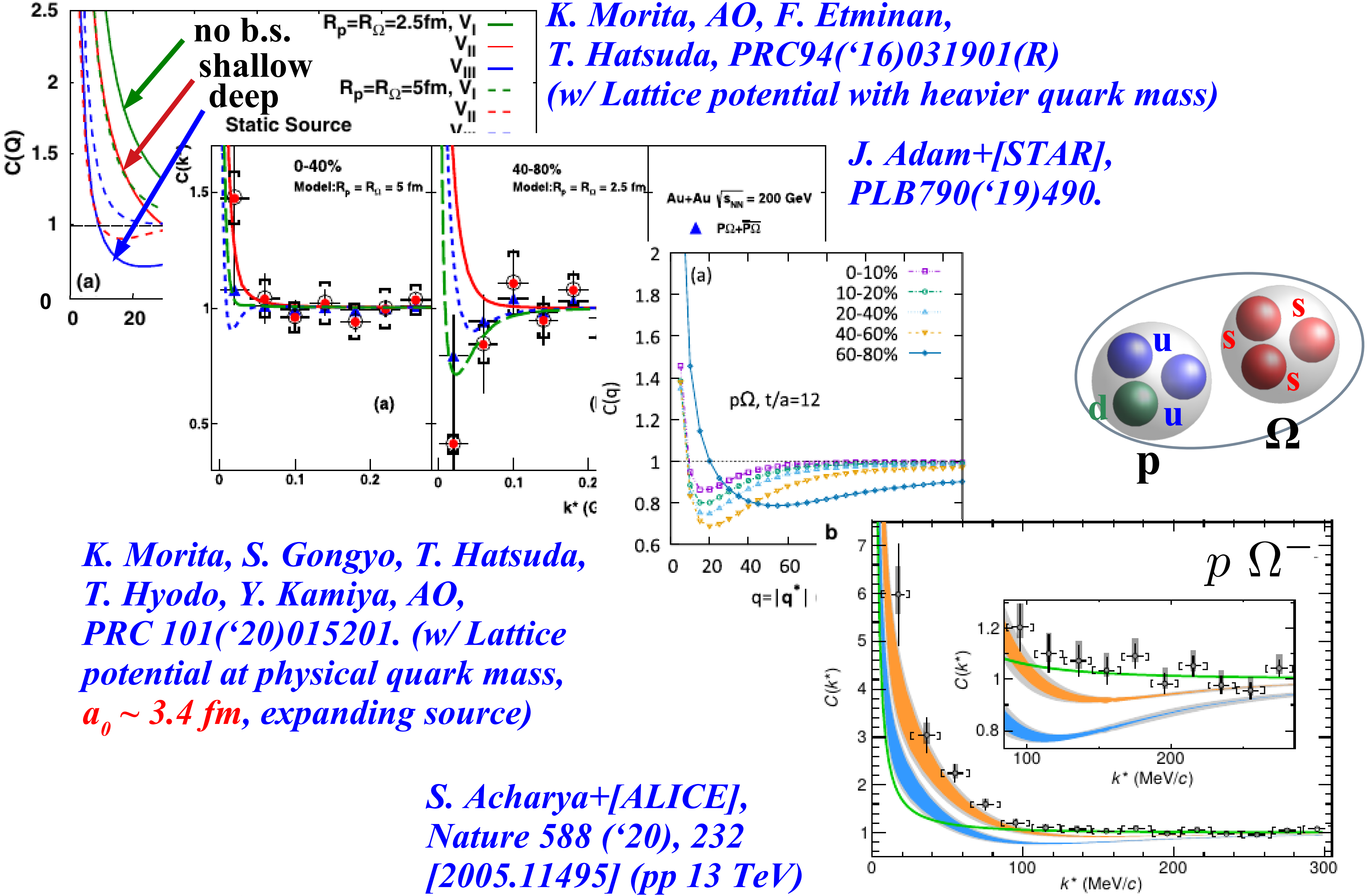
- **Ω^- (sss): J^π=3/2+, M=1672 MeV**
- **Ω^- p bound state as a S= –3 dibaryon ?**
  - **No quark Pauli blocking in ΩN, H=uuddss, and d*=ΔΔ channels.** *Oka ('88), Gal ('16)*
  - **J=2 state ($^5S_2$) couples to Octet-Octet baryon pair only with L ≥ 2 → Small width is expected.** *T. Goldman+, PRL59('87),627; F. Etminan+[HAL], NPA928('14)89; Iritani+[HAL], PLB792('19)284; Sekihara,Kamiya,Hyodo, PRC98('18)015205.*
  - **Correlation has been measured at RHIC & LHC !** *STAR ('19); ALICE ('20)*





Let us try to discover the first S<0 dibaryon !

pΩ⁻ correlation function



K. Morita, AO, F. Etminan,
T. Hatsuda, PRC94('16)031901(R)
(w/ Lattice potential with heavier quark mass)

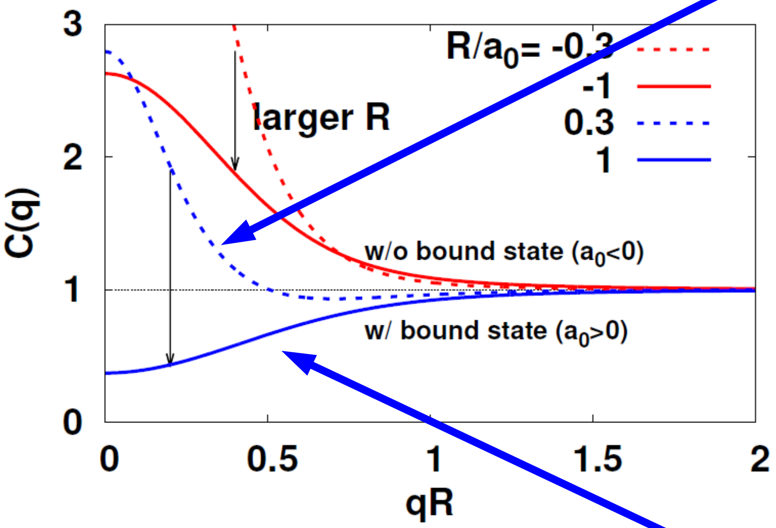
J. Adam+[STAR],
PLB790('19)490.

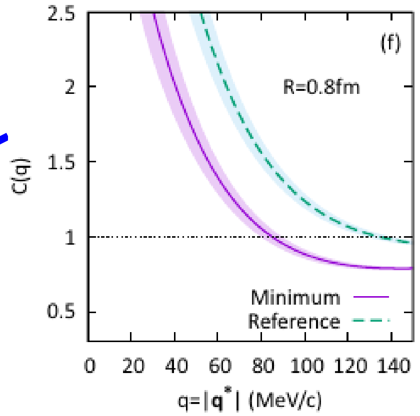
K. Morita, S. Gongyo, T. Hatsuda,
T. Hyodo, Y. Kamiya, AO,
PRC 101('20)015201. (w/ Lattice
potential at physical quark mass,
a_0 ~ 3.4 fm, expanding source)

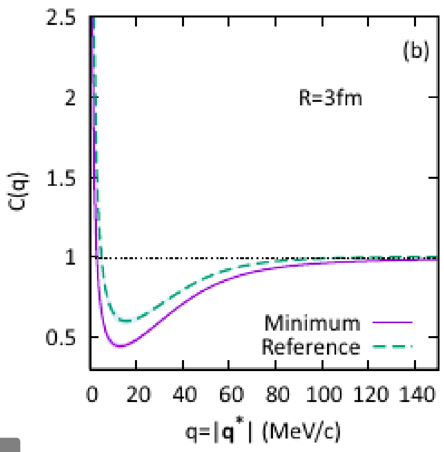
S. Acharya+[ALICE],
Nature 588 ('20), 232
[2005.11495] (pp 13 TeV)

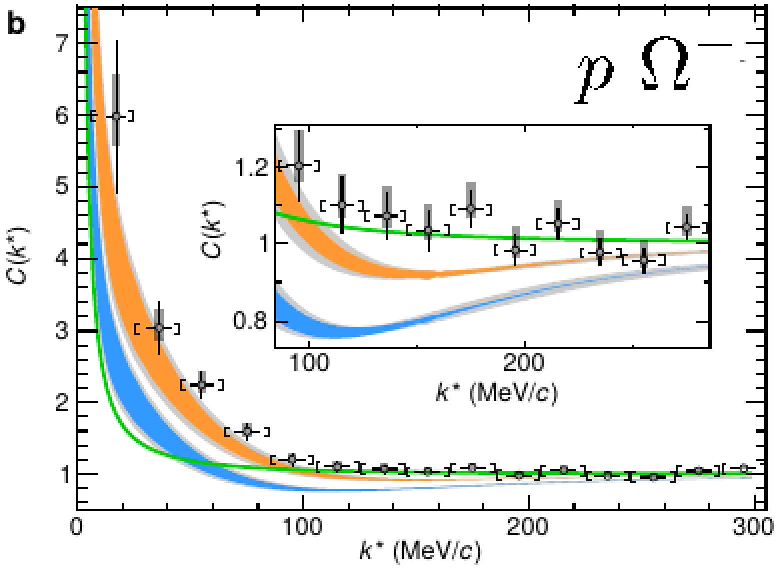
STAR+ALICE suggests a NΩ dibaryon state

Morita+, PRC101('20)015201
[1908.0414] (Gaussian source)

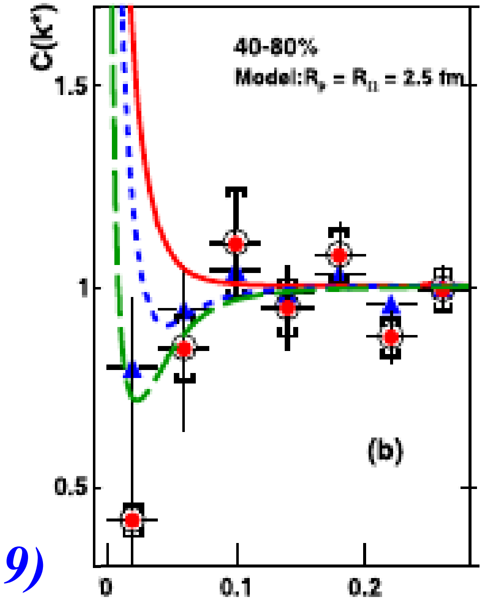








ALICE, Nature588('20)232 [2005.11495]



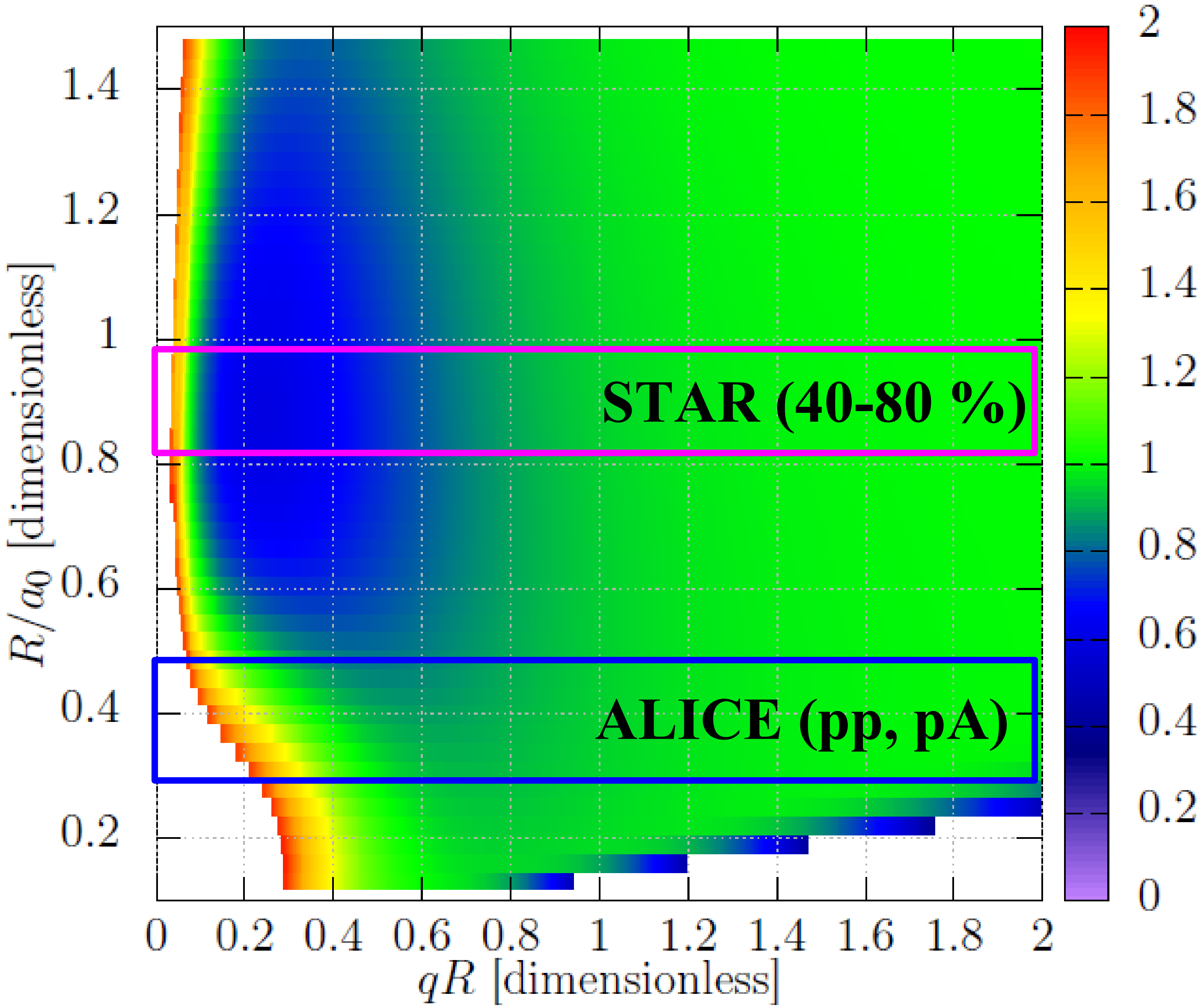
STAR, PLB790 ('19)
490 [1808.02511].

Reference: $V_{J=1}=V_{J=2}$

Minimum: $\varphi_{J=1}=0$

Dip from a bound state survives Coulomb.

Ωp Correlation Function with Gaussian source

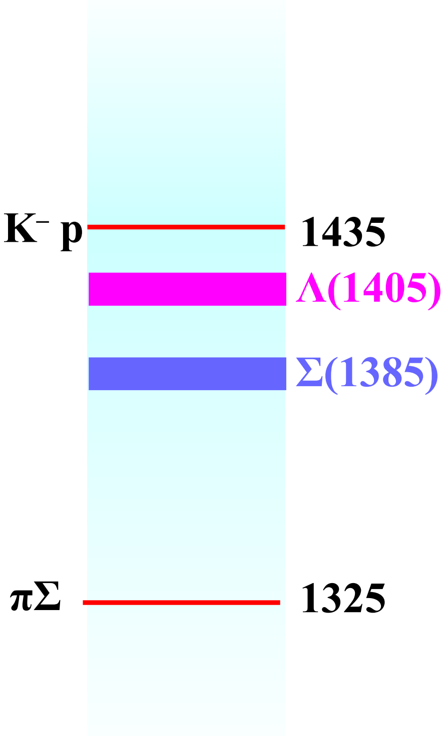


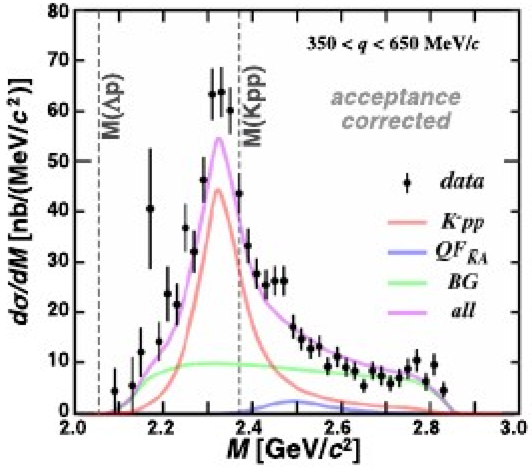
NΩ potential (J=2, HAL QCD, a_0=3.4 fm) + Coulomb

K^-p correlation function

$\bar{K}N$ interaction and pK^- correlation function

- **Λ(1405)= $\bar{K}$N quasi-bound state**
  Dalitz, Tuan ('60); Koch ('94); Kaiser, Siegel, Weise ('95); AO, Nara, Koch ('97)
  - **Positive scattering length in K^- atoms**
    M.Iwasaki et al. PRL78('97)3067;
    M.Bazzi et al. [SIDDHARTA Collab.], PLB704('11)113.
- **Kaonic nuclei ?**
  Nogami ('63); Akaishi, Yamazaki ('02); Shevchenko, Gal, Mares ('07); Ikeda, Sato ('07); Dote, Hyodo, Weise ('09);
  S.Ajimura+ [J-PARC E15], PLB 789 (2019) 620.
  → Needs precise info. on $\bar{K}$N int.
- **Scattering amplitude and Potential fitting scattering and SIDDARTA data in chiral approach**
  Ikeda, Hyodo, Weise ('11,'12);
  A. Cieplý, J. Smejkal ('12, NLO30);
  Miyahara, Hyodo, Weise ('18, CC N$\bar{K}$-πΣ-πΛ potential)





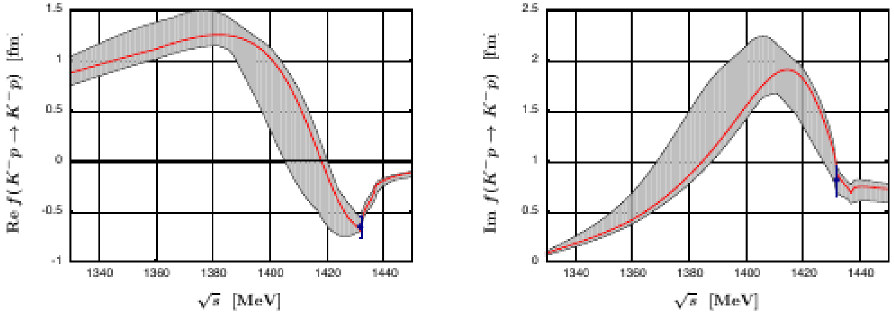
J-PARC E15 ('19)

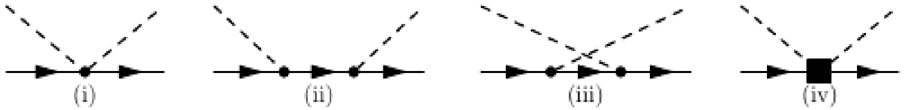
Chiral SU(3) $\bar{K}$ N interaction

- **Chiral SU(3) $\bar{K}$N scattering amplitude**

  Y. Ikeda, T. Hyodo, W. Weise, NPA881('12)98.

  - **Tomozawa-Weinberg + Born (w/ Exchange) + NLO**
  - **Fit to SIDDHARTA data of $\bar{K}$N diagonal scattering amplitude at threshold.**
  - **$\bar{K}$N-πΣ-πΛ-ηΛ-ηΣ-KΞ**

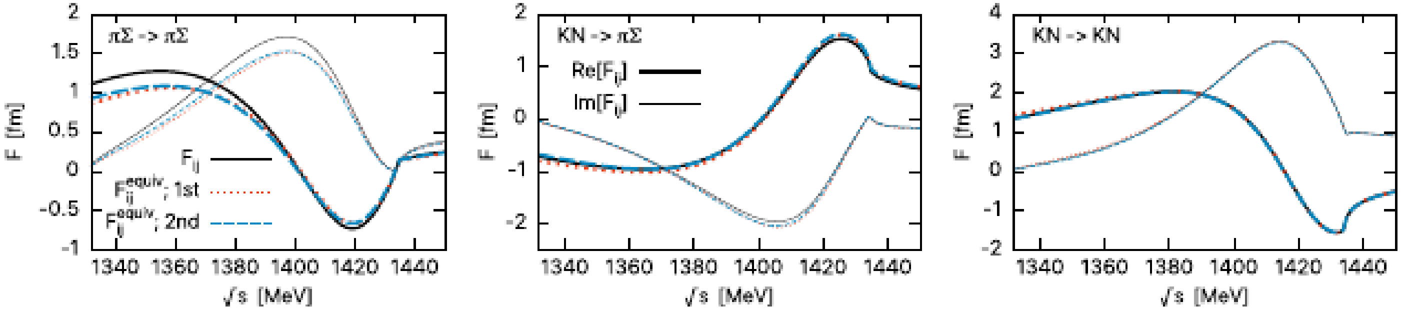


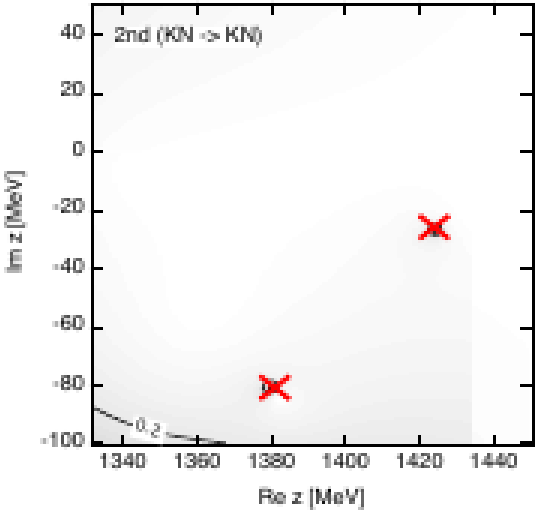


- **Coupled-channel $\bar{K}$N-πΣ-πΛ potential based on IHW amplitude**

  K. Miyahara, T. Hyodo, W. Weise, PRC98('18)025201.

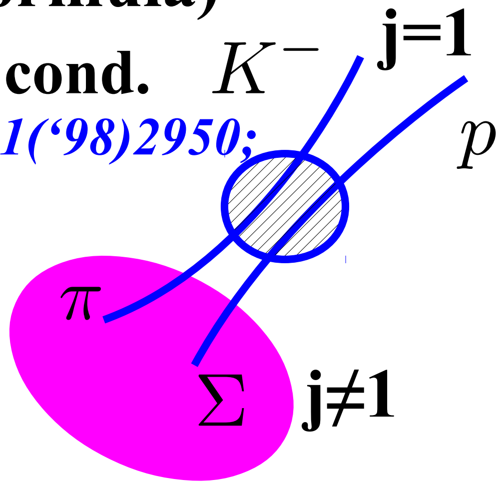
  - **Fit to IHW amplitude and pole positions of**





Correlation Function with Coupled-Channel Effects

- **To evaluate pK⁻ correlation function, we need to take account of coupled-channel effects of NK-πΣ !**
- **Correlation function formula with CC (KPLLL formula)**
  - **Coupled-channel contributions with ψ$^{(-)}$ boundary cond.**
    R.Lednicky,V.V.Lyuboshits,V.L.Lyuboshits, Phys.Atom.Nucl.61('98)2950;
    J. Haudenbauer, NPA981('19)1 [1808.05049].



$$C(\boldsymbol{q}) = \int d\boldsymbol{r} \sum_j \omega_j S_j(\boldsymbol{r}) |\Psi_j^{(-)}(\boldsymbol{r})|^2$$

$$= 1 - \int d\boldsymbol{r} S_1(r)|j_0(qr)|^2 + \int d\boldsymbol{r} \sum_j \omega_j S_j(r) |\psi_j^{(-)}(q;r)|^2$$

$$\psi_{j=1}(r) \to [e^{iqr} + A_1(q)e^{-iqr}]/2iqr \quad (\omega_1 = 1)$$

$$\psi_{j\neq1}(r) \to A_j(q)e^{-iqr}/2iqr \quad [\Psi^{(-)}\ \text{boundary condition}]$$

$$\underline{\omega_j}\,\underline{S_j(\boldsymbol{r})}|\psi_j^{(-)}(q;r)|^2$$

Source weight **Normalized Source fn.**

(No Coulomb case)

  - **Effects of coupled-channel, strong & Coulomb pot., and threshold difference are taken into account in the charge base.**
    Y. Kamiya+, PRL('20)
  - **Source size R and weight ω_j (j≠1) are taken as the parameter.**

Comparison with ALICE data

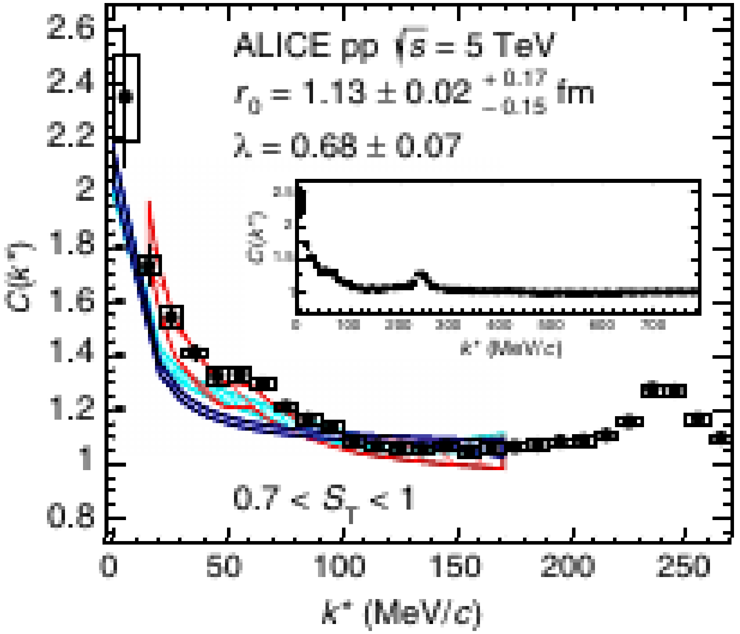
- 物理パラメータ　= R and $\omega_{\pi\Sigma}$
  - ALICE value (single channel) R=1.13 fm (K$^+$p 相関関数 (Jülich+Gamow) で決定)
  - R はチャネルに依存しないと仮定し、(R, $\omega_{\pi\Sigma}$) 平面で実験をよく説明する領域を決定
- 観測パラメータ　= N and λ

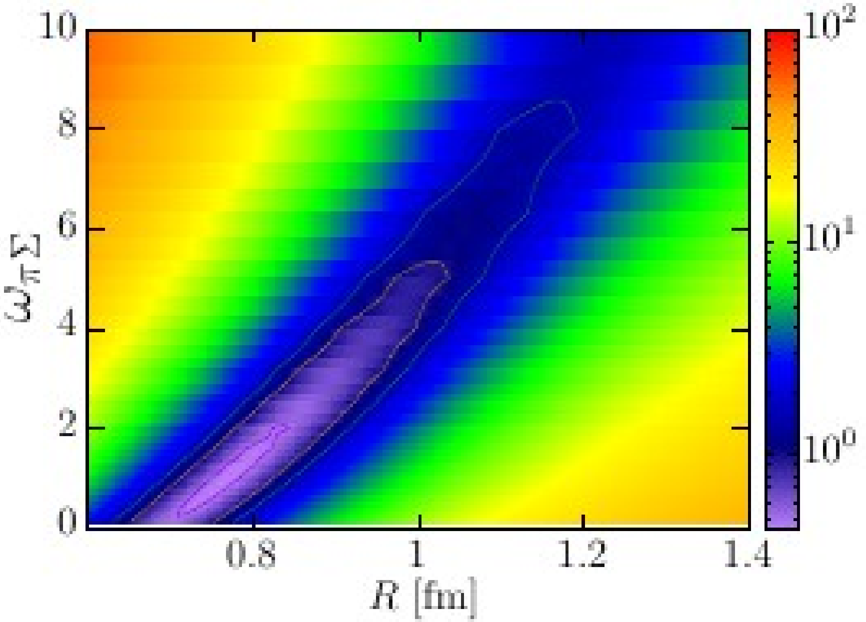
$$C_{\rm fit}(q) = \mathcal{N}\left[1+\lambda(C(q)-1)\right]$$

  - 規格化パラメータ (N) と pair purity (λ, 直接生成された pK$^-$の割合) は観測による

→ (R, $\omega_{\pi\Sigma}$) ごとに fit して決定

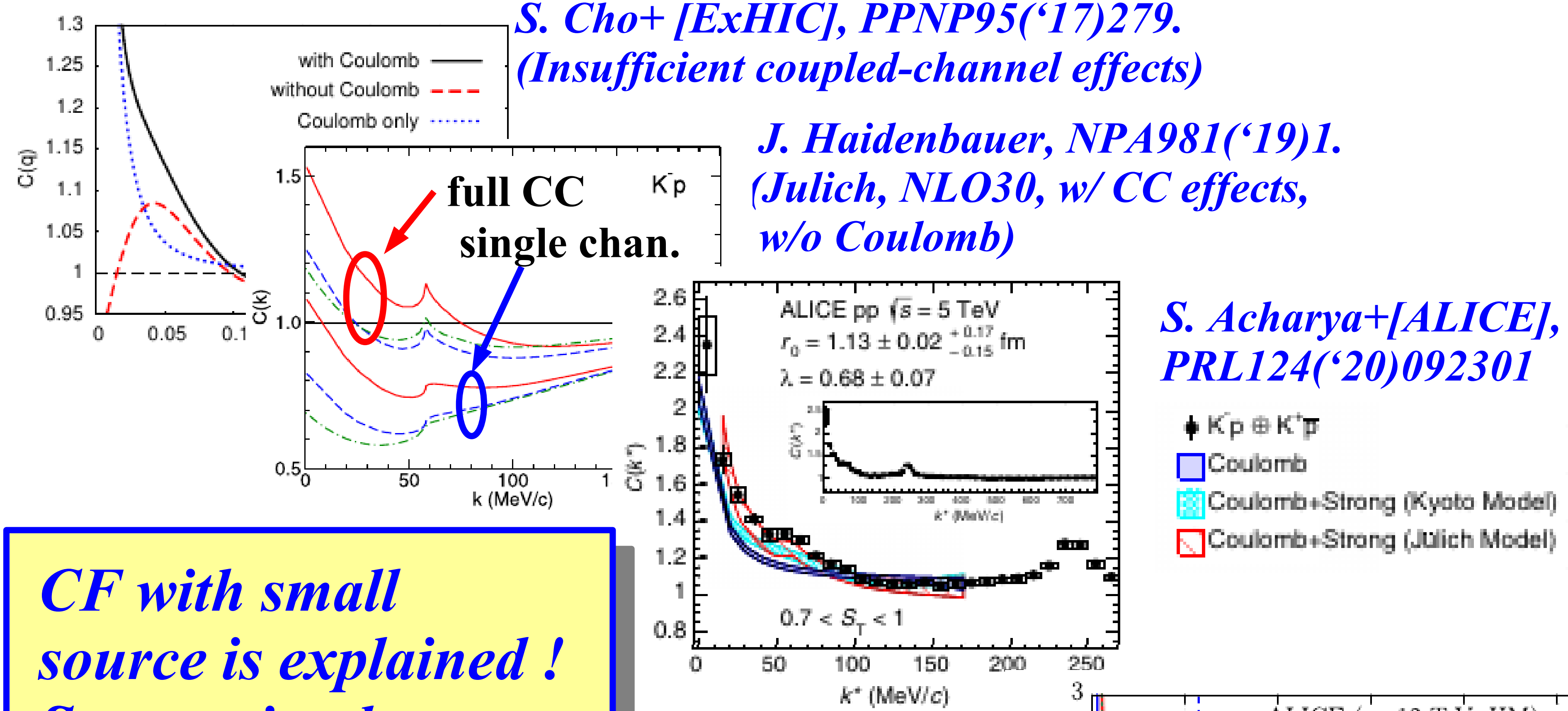
S. Acharya+[ALICE],PRL124('20)092301.





Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501.

pK^- correlation

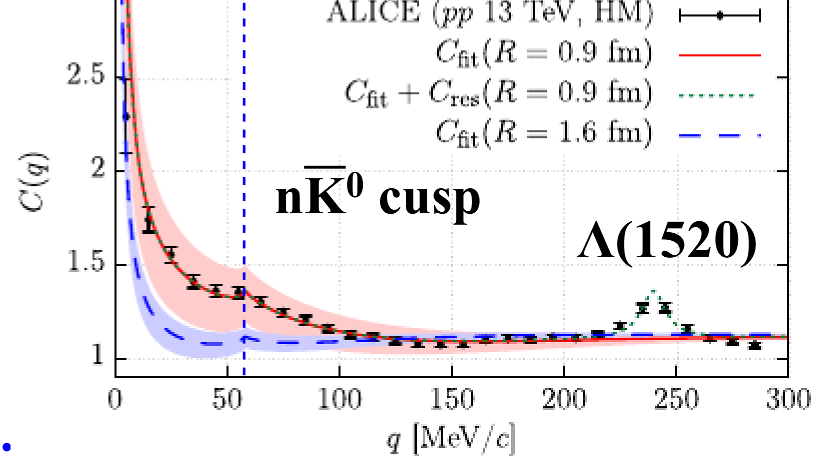


S. Cho+ [ExHIC], PPNP95('17)279.
(Insufficient coupled-channel effects)

J. Haidenbauer, NPA981('19)1.
(Julich, NLO30, w/ CC effects,
w/o Coulomb)

S. Acharya+[ALICE],
PRL124('20)092301

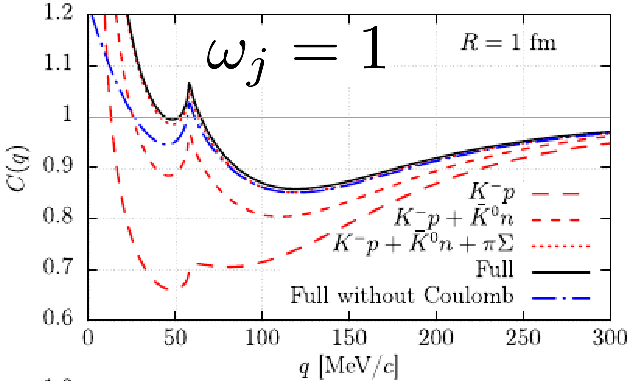
CF with small source is explained !
Source size dep. may clarify bound state nature of Λ(1405).

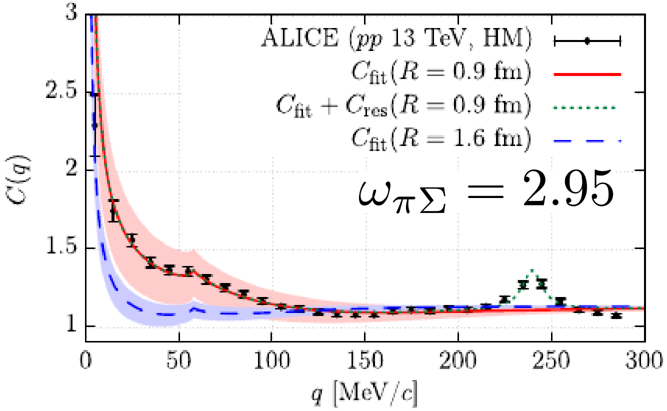


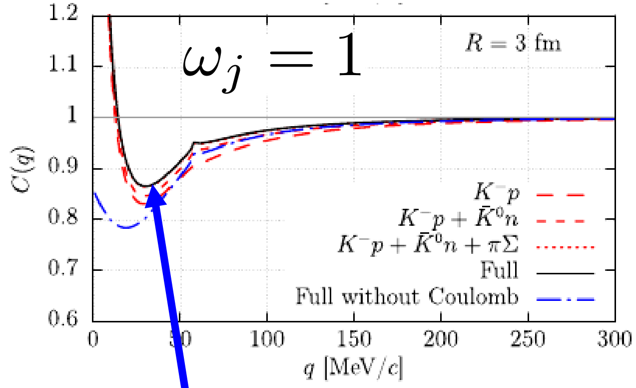
Y. Kamiya, T. Hyodo, K. Morita, AO,
W. Weise, PRL124('20)132501
[1911.01041] (Chiral SU(3) dynamics).

Source Size Dependence of C(pK$^-$)

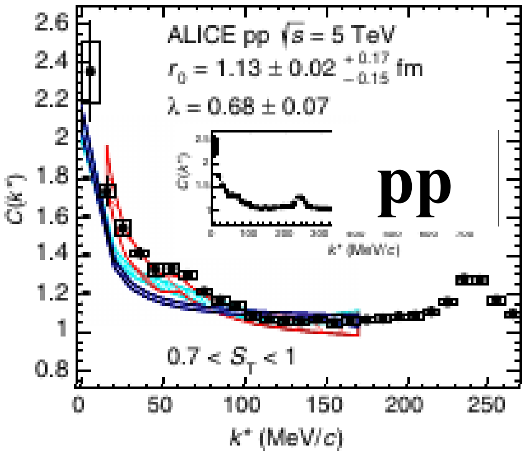
- **Coupled-channel effects are suppressed when R is large, and "pure" pK$^-$ wave function may be observed in HIC.**



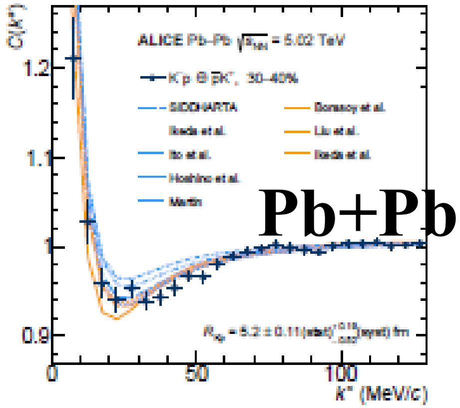




Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501.



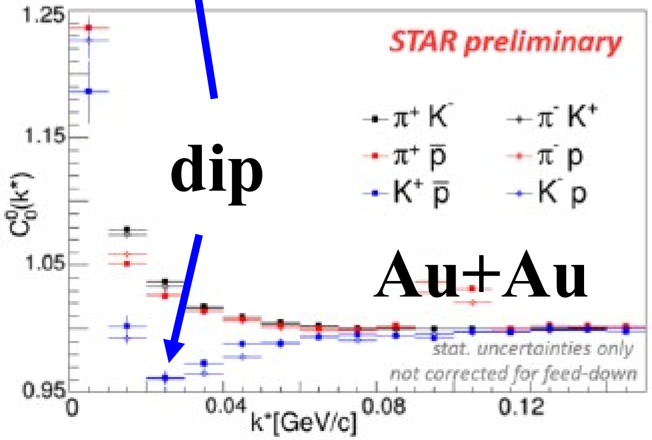
pA



S. Acharya+[ALICE], PRL124('20)092301

S. Acharya+[ALICE], 2105.05683

dip



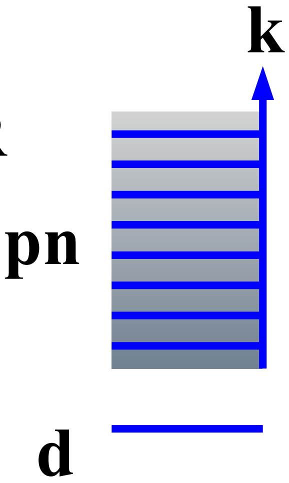
Siejka+[STAR, preliminary], NPA982 ('19)359.

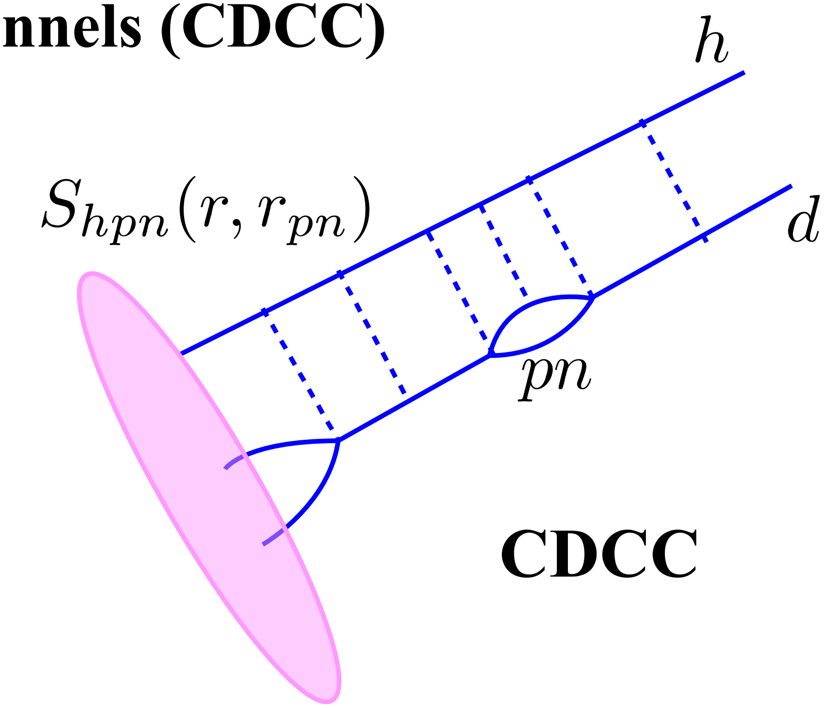
STAR(prel.) & new ALICE data show dip at small q.

Ξ^-d correlation function

Hadron-Deuteron correlation function

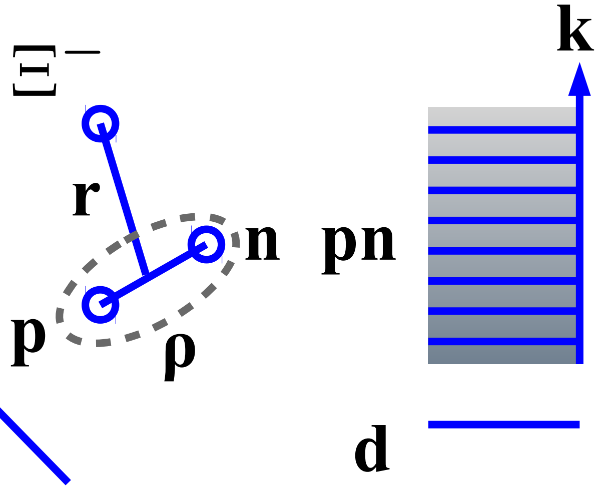
- **Hadron-deuteron correlation (Λd, K⁻d, Ξ⁻d, Ω⁻d, …)**
  S.Mrówczyński, Patrycja Słoń, Acta Phys.Polon.B51('20),1739 [1904.08320](K-d,pd); J.Haidenbauer, PRC102('20)034001[2005.05012](Λd); F.Etminan+[2006.12771](Ωd).
  - **Scattering length data of these are important to evaluate**
    - **binding energy and lifetime of hyper triton (Λd)**
    - **I=1 $\bar{\mathrm{K}}$N interaction (K⁻d, Ξ⁻d)**
    - **and the existence of a bound state.**
  - **Problem: *Breakup and Dynamical Formation of d* (d ↔ pn)**
    → Continuum-discretized coupled-channels (CDCC)
    M.Kamimura+('86); N. Austern+('87);
    M.Yahiro, K.Ogata, T.Matsumoto, K.Minomo, PTEP 2012 (2012) 01A206.
  - **Measurable at LHC-ALICE and (probably) RHIC-STAR**





Ξ^-d C(q) using CDCC

- **Three-body wave functions (s-wave)**



$$\psi^{(-)}(r,\rho;q)=\sum_n\sum_k A_{kn}\underline{\varphi_k(\rho)}\,\underline{\chi_{nk}(r;q_{nk})}$$

J, spin, isospin, ...

intrinsic momentum bin

kinematic factor

normalized pn w.f. in k-th bin

Ξ^--pn w.f.

- **Ξ^-d Correlation function**

$$C(q)=\underline{C^{\mathrm{C}}_{\ell>0}(q)}+\underline{\frac{1}{2\cdot 3}}\int d\boldsymbol{r}\,S(r)\sum_{nk}|\chi_{nk}(r;q_{nk})|^2$$

pure Coulomb

$1/(2J_1+1)/(2J_2+1)$

“Ξ^-d” source fn.

- **Potential = HAL QCD potential at almost physical quark masses**

K. Sasaki et al. [HAL QCD Collab.], NPA 998 (‘20) 121737 (1912.08630)

(coupling with ΛΛ is ignored).

Ξ^-d correlation function: Result

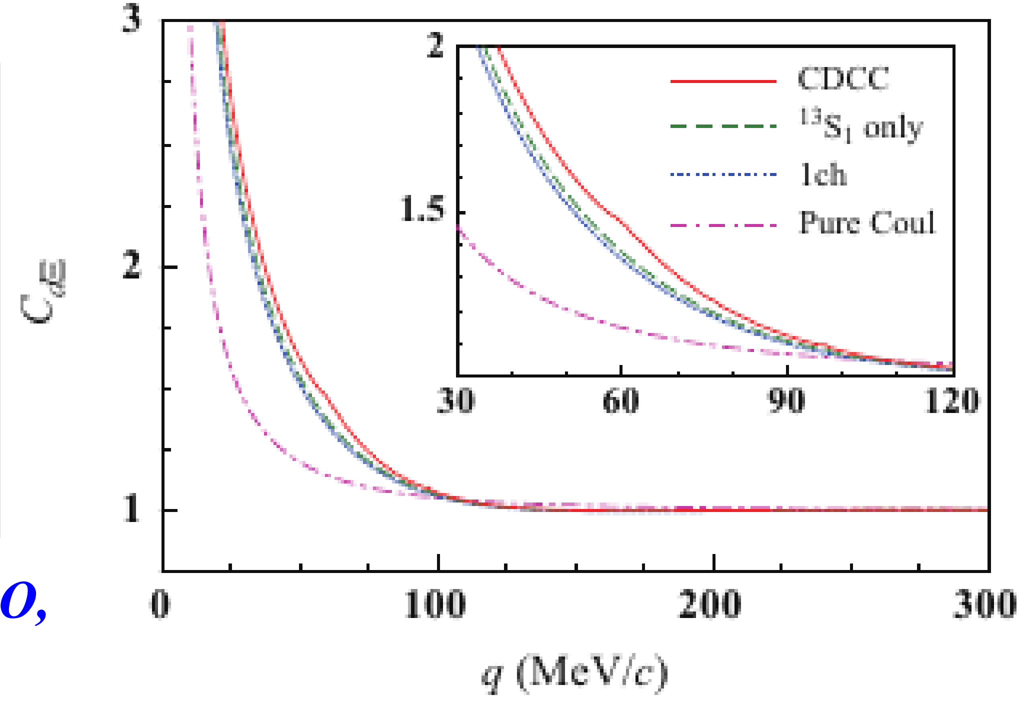
- **CDCC results of Ξ^-d correlation function**
  - **Enhancement from pure Coulomb C(q) by ΞN interaction from HAL QCD potential.**
  - **Breakup & Reformation effects ~ 10 % (Barely measurable)**
  - **Dynamical formation of deuteron is (maximally) included.**

$$\text{Implicit assumption: } \int d\boldsymbol{\rho} S(\rho)|\varphi_k(\rho)|^2 \simeq \text{const.}$$

  - **Threshold cusp at d → pn threshold is seen, but not prominent.**

Single channel description may not be bad.
→ Bound or Unbound in Ξd from Experimental data (if measured).

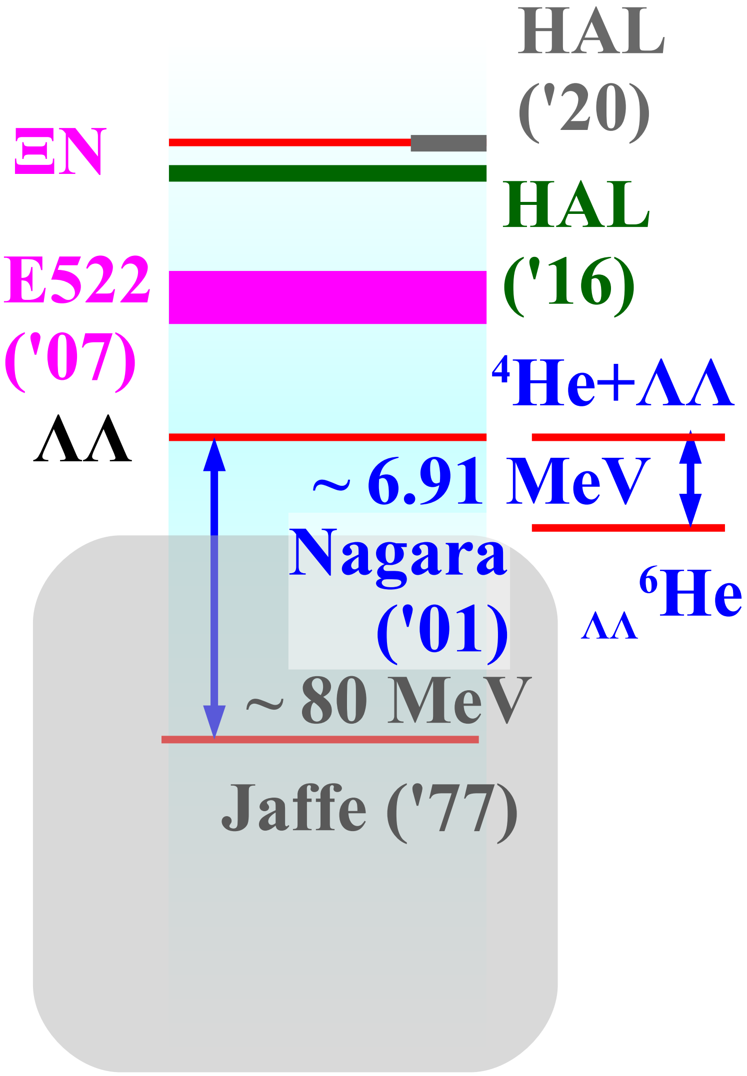
K. Ogata, T. Fukui, Y. Kamiya, and AO, PRC, to appear (arXiv:2103.00100).



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

H dibaryon state, to be bound or not to be bound ?

- **H-dibaryon: 6-quark state (uuddss)**
  - **Prediction:** *R.L.Jaffe, PRL38(1977)195*
  - **Ruled-out by double Λ hypernucleus**
    Takahashi et al.,PRL87('01) 212502
  - **Resonance or Bound "H" ?**
    Yoon et al.(KEK-E522)+AO ('07)
- **Lattice QCD results**
  - **Bound (below ΛΛ threshold):**
    HALQCD('11), NPLQCD('11,'13), Mainz('19)
    (heavier quark mass or SU(3) limit)
  - **Resonance (Bound state of NΞ):**
    HAL QCD ('16,18) **(HAL preliminary)**
  - **Virtual Pole (around NΞ threshold)**
    HAL QCD ('20) **(almost physical m_q)**

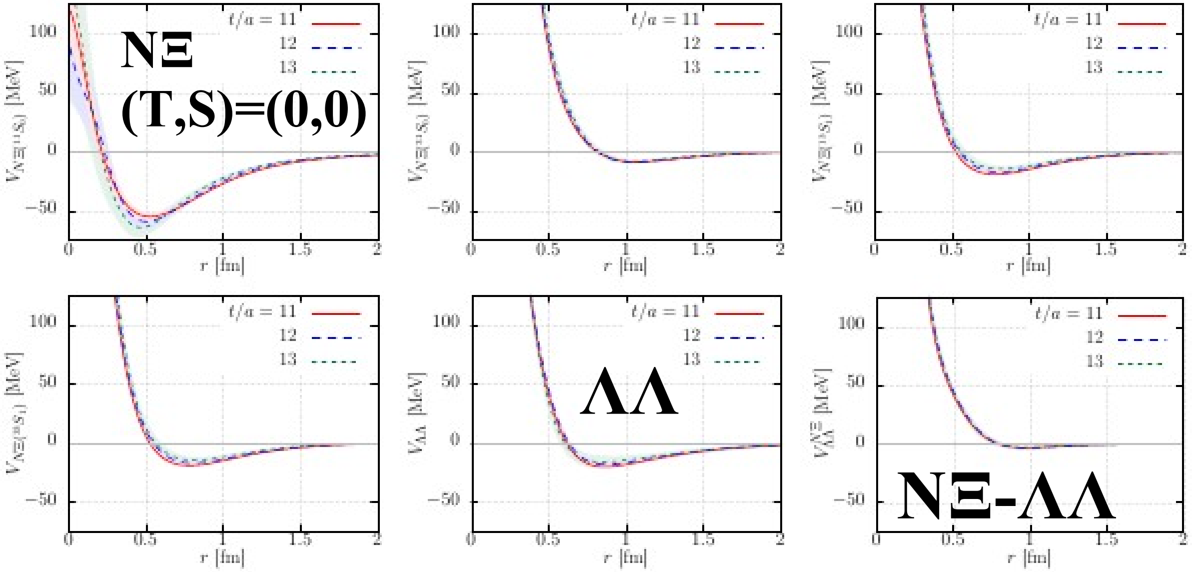


We examine LQCD NΞ-ΛΛ potential and discuss H using CF !

NΞ-ΛΛ potential from Lattice QCD

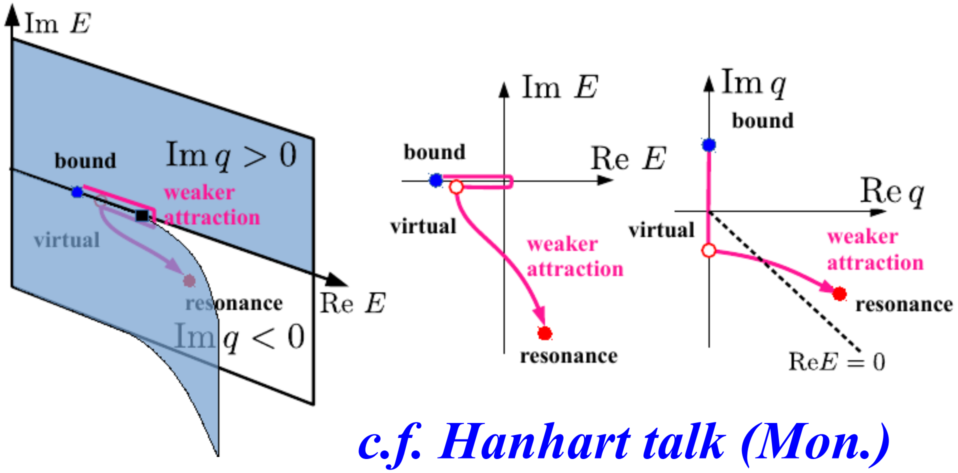
- **NΞ-ΛΛ potential at almost physical quark mass (m_π=146 MeV) by HAL QCD Collaboration**

K. Sasaki et al. [HAL QCD Collab.], NPA 998 ('20) 121737 (1912.08630)



- **Strong attraction in (T,S)=(0,0) of NΞ**
- **Weak attraction in ΛΛ (Coupling with NΞ causes ΛΛ attraction)**
- **There is no bound state in NΞ-ΛΛ system (except for Ξ^- atom), but there is a virtual pole around the NΞ threshold (3.93 MeV below $n\Xi^0$ threshold) on the irrelevant Riemann sheet, (+, –, +) [relevant=(–,+,+)]**

sign of Im(eignen momentum)



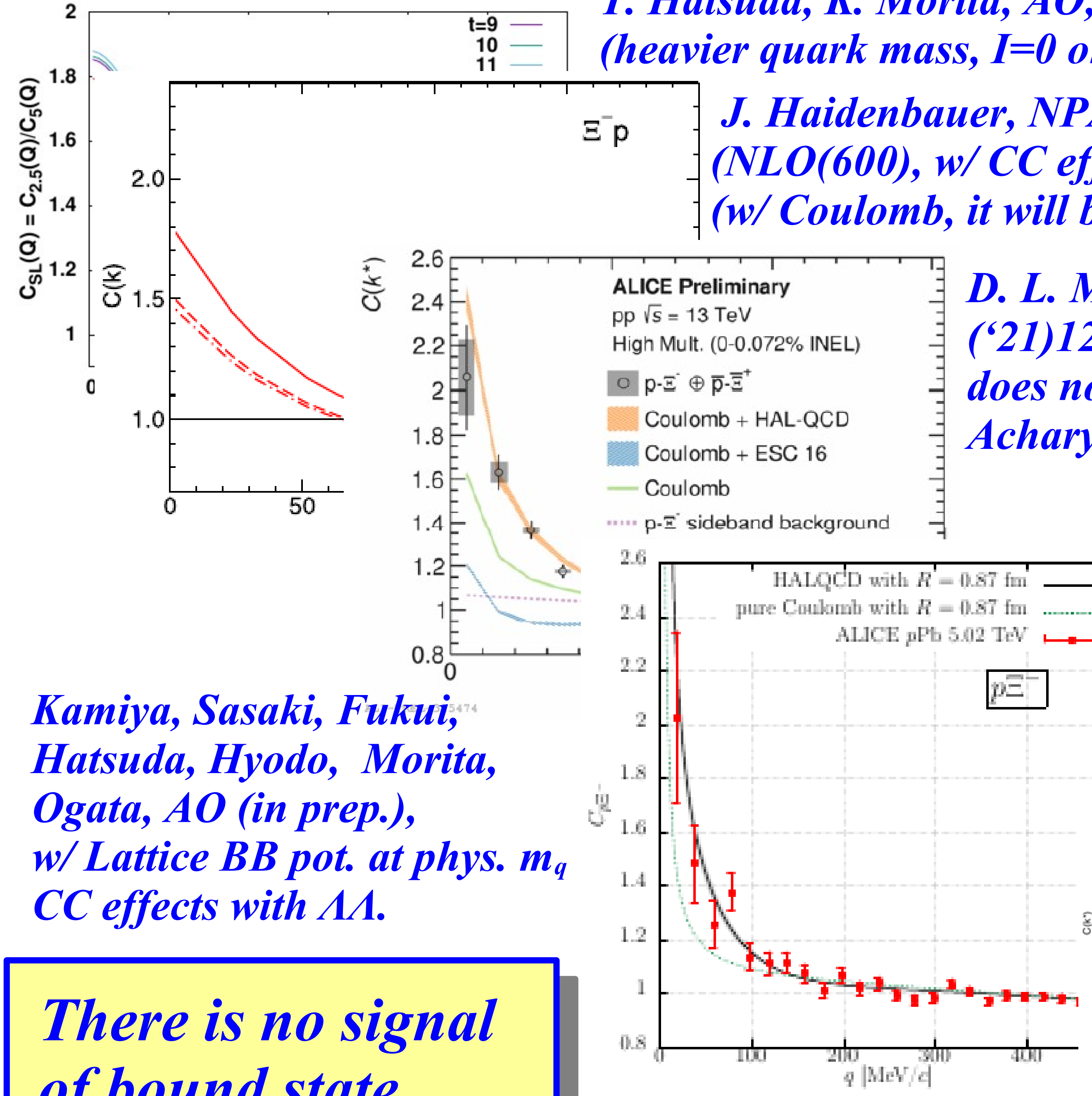
c.f. Hanhart talk (Mon.)

$p\Xi^-$ correlation function

T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17)856.
(heavier quark mass, I=0 only, w/o CC effects)

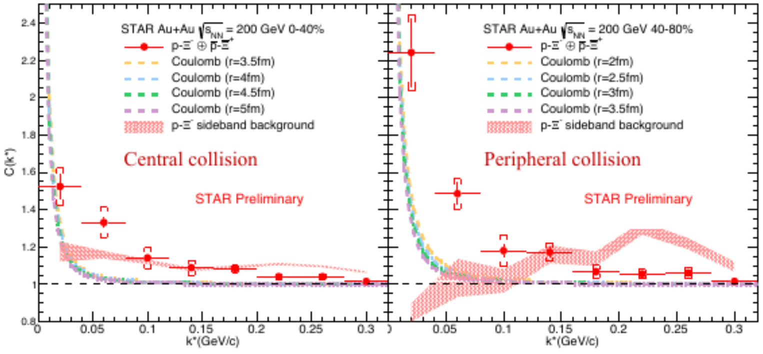
J. Haidenbauer, NPA981('19)1.
(NLO(600), w/ CC effects, w/o Coulomb)
(w/ Coulomb, it will be comparable with data.)

D. L. Mihairov+[ALICE], NPA 1005 ('21)121760 (QM2019). (Nijmegen pot. does not explain the data. w/o CC)
Acharya+(ALICE), Nature ('20)



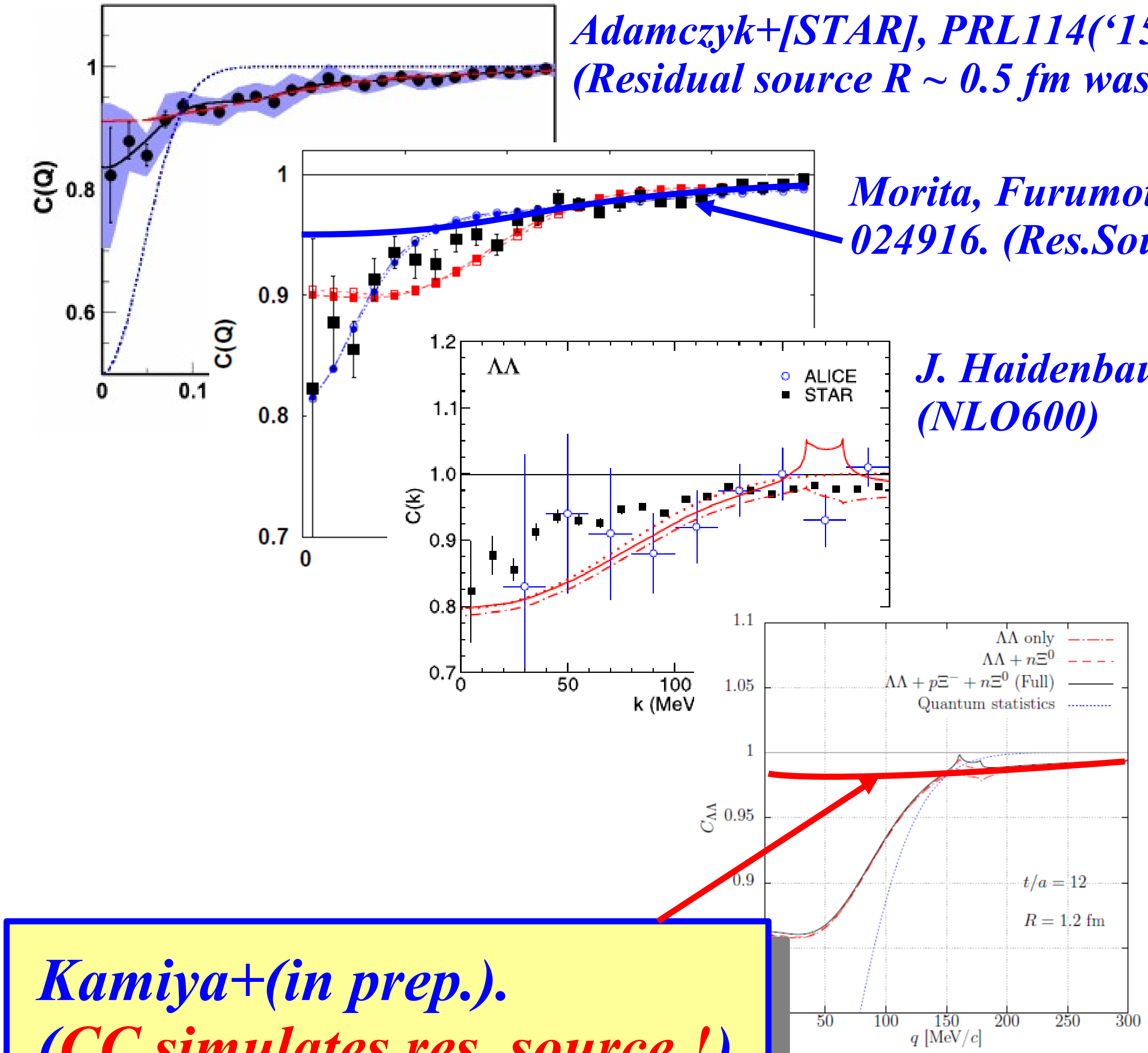
Kamiya, Sasaki, Fukui, Hatsuda, Hyodo, Morita, Ogata, AO (in prep.), w/ Lattice BB pot. at phys. m_q
CC effects with ΛΛ.

K. Mi+(STAR, preliminary), Au+Au 200 AGeV, APS2021.
(No Dip at larger R)



There is no signal of bound state.

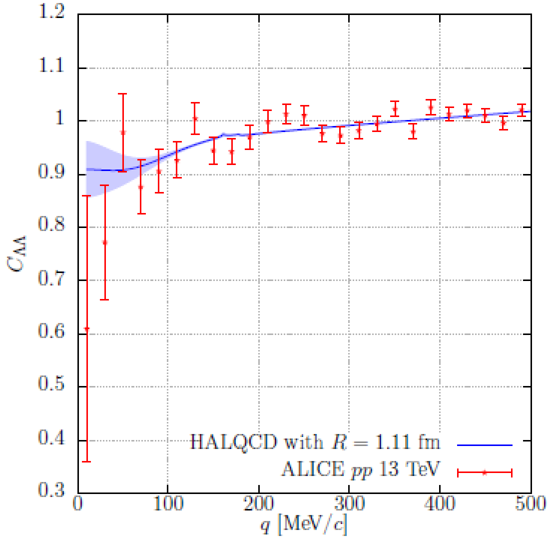
ΛΛ correlation function



Adamczyk+[STAR], PRL114('15)022301
(Residual source R ~ 0.5 fm was assumed.)

Morita, Furumoto, AO,PRC91('15) 024916. (Res.Source + flow)

J. Haidenbauer, NPA981('19)1. (NLO600)



Kamiya+(in prep.).
(CC simulates res. source !)

Summary of 19H05151

- **Correlation function is useful to access hadron-hadron interactions as well as to deduce the existence of a bound state.**

	n	p	K⁻	K⁺	π⁻	π⁺	Λ	Σ	Ξ⁻	Ω⁻	D⁻	D⁺	Ks	d	pp	+α
n																
p		O	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		O						O	
Σ		O						O								
Ξ⁻		O												🟦		
Ω⁻		O														
D⁻		O														
D⁺		O														
Ks			O	O												
d		O							🟦							
pp		O					O									
+α																

未開の沃野

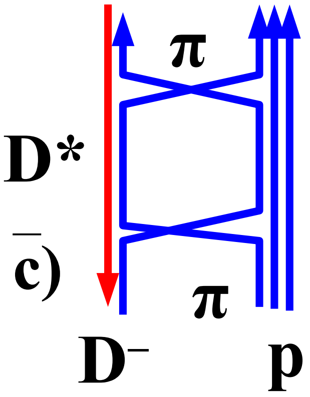
terra incognita

Paolo Forlani (?-1577)

21H00121

チャーム・ハドロン ＆ ３体相関

Correlation functions of Charmed Hadron and Nucleon



- **CF including charmed hadron**
  - **Extremely important in recent hadron physics.**
  - **$D^-(\bar{c}d)$-p(uud) correlation**
    - **Probes $\Theta_c(\bar{c}$-ud-ud) state (replace $\bar{s}$ in $\Theta(\bar{s}$-ud-ud) with $\bar{c}$)**

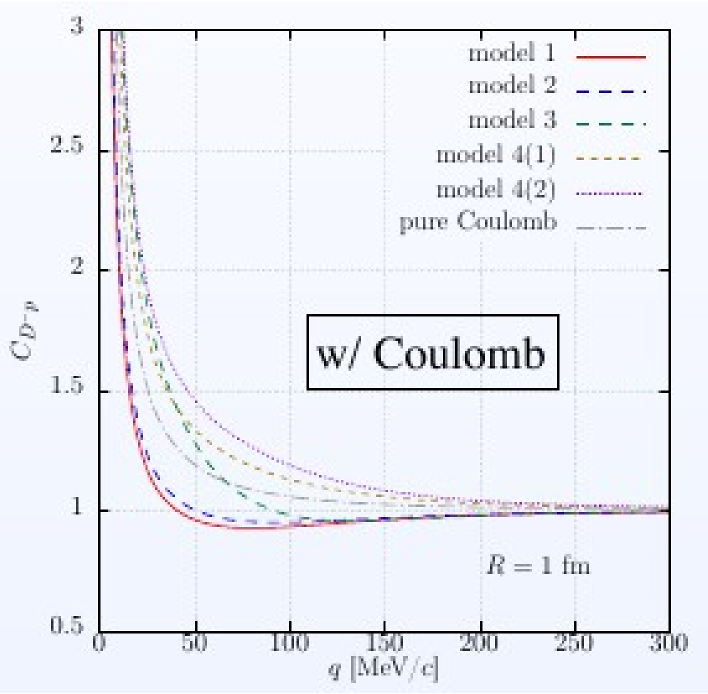
      D. O. Riska, N. N. Scoccola, PLB299('93)338 (pred.);
      A. Aktaset+ [H1], PLB588('04)17 (positive);
      J. M. Linket+ [FOCUS], PLB622('05)229 (negative).
    - **Attraction from two pion exchange**

      S. Yasui, K. Sudoh, PRD80('09)034008.
    - **Easy to calculate the potential in LQCD.**

      Y. Ikeda et al. (private communication)
- **$D^-(\bar{c}d)$-p(uud) CFs from proposed potentials**

  Hofmann, Lutz ('05) (repulsive);
  Haidenbauer+('07) (repulsive);
  Yamaguchi+('11) (att., w/ bs); Fontoura+('13) (repulsive)

Data will discriminate these potentials !



Kamiya, Hyodo, AO (in prog.)

Three-body correlation functions

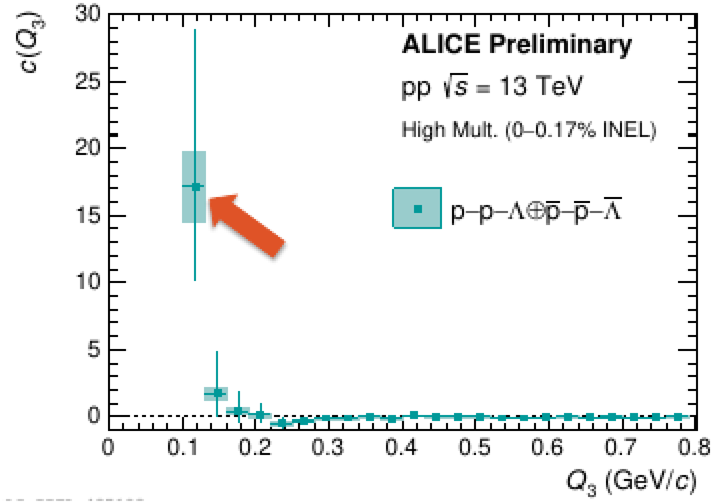
- **Three-body correlation functions are measured and discussed; ppp, Λpp, pd, …**
- **Continuum Three-body w.f. at various momenta with Coulomb.**
  - **Riverside approximation (3π)**
    E.g. E. O. Alt, T. Csorgo, B. Lorstad, J. Schmidt-Sorensen, PLB458 ('99)407.

$$\Psi_{123} = \psi(\boldsymbol{q}_{12})\psi(\boldsymbol{q}_{23})\psi(\boldsymbol{q}_{31})$$

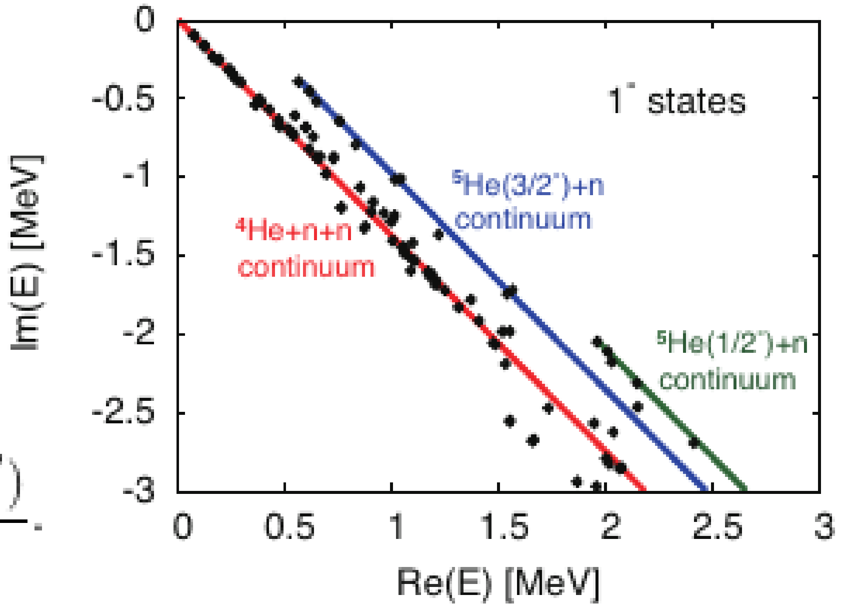
    → Does not give free correct w.f.
  - **Complex Scaling ?**
    Y. Kikuchi, T. Myo, M. Takashina, K. Kato, K. Ikeda, PTP122 ('09) 499;
    T.Myo, AO, K.Kato, PTP99('98)801.

$$\mathcal{G}^\theta(E;\xi,\xi') = \left\langle \xi \left| \frac{1}{E-\hat{H}^\theta} \right| \xi' \right\rangle = \sum\!\!\!\!\!\!\int_n \frac{\chi_n^\theta(\xi)\tilde{\chi}_n^\theta(\xi')}{E-E_n^\theta}.$$

  - **Other idea ?**



V. Mantovani Sarti @SQM2021



Summary

- **相関関数を用いたハドロン間相互作用の研究を進めている。**
  - **19H05151 (2019-2020): ほぼ計画通り**
    - **Ωp, $\Omega\Omega$ (K.Morita+(‘20)), K^-p (Y.Kamiya+(‘20)),
Ξ^-d (K.Ogata+(to appear)), Ξ^-p, $\Lambda\Lambda$ (Y.Kamiya+(in prep.)).**
    - **HAL QCD, Chiral SU(3) dynamics からの相互作用を用いた相関関数**
    - **結合チャネル効果を含む相関関数を求める手法を実装**
    - **Continuum Discretized Coupled-Channels (CDCC) の利用**
  - **21H00121 (2021-2022):**
    - **$p\Lambda$, $p\Sigma^0$, $\Lambda\Xi^-$ → HAL QCD potential を用いて C(q) を計算**
    - **D^-p, D^+p → 既存のポテンシャルを利用。 Pentaquark states ?**
    - **3 体相関関数 → アイデア募集中。**

Thank you for your attention !

Coauthors of arXiv:1908.05414 ($p\Omega$, $\Omega\Omega$) and arXiv:1911.01041 (pK^-), arXiv:2103.00100 ($d\Xi^-$), and next paper on $p\Xi^-$-$\Lambda\Lambda$ (Y. Kamiya, K. Sasaki, T. Fukui, T. Hatsuda, T. Hyodo, K. Morita, K. Ogata, AO, in prep.)

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