Flavored hadron correlations and interactions from heavy ion collisions

Akira Ohnishi (YITP, Kyoto U.)

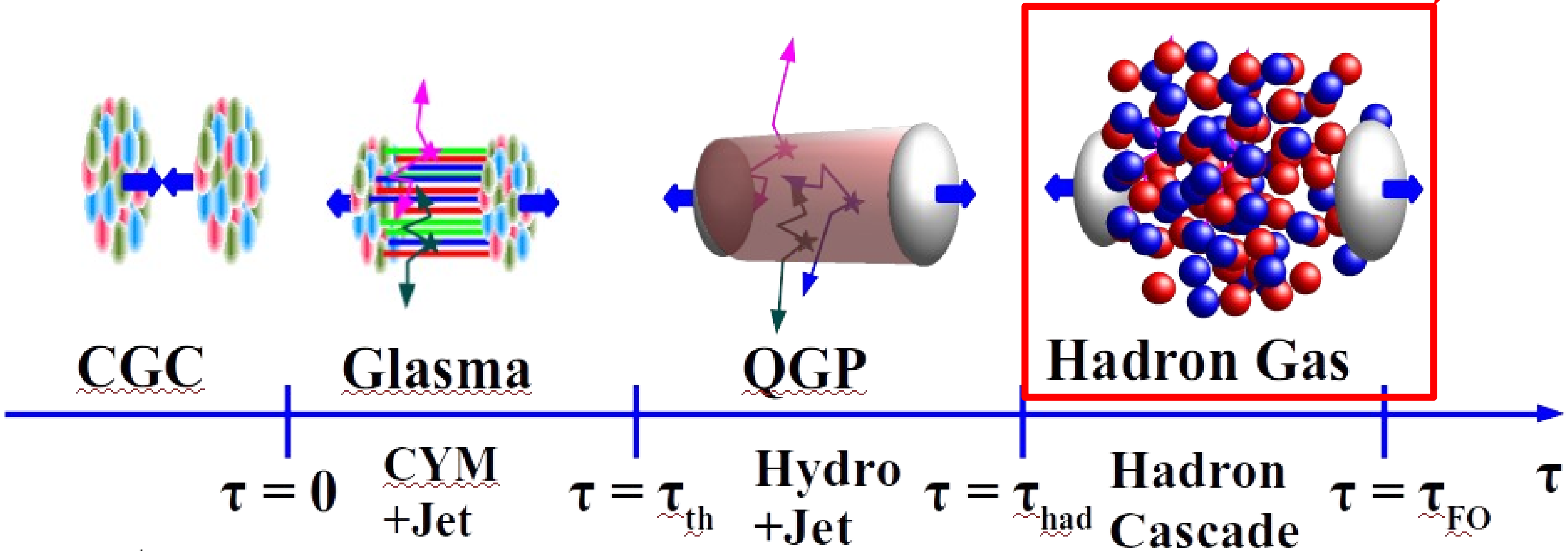
The 8th Asian Triangle Heavy-Ion Conference (ATHIC 2021), Nov.5-9, 2021, Inha U., Incheon, South Korea / Online Hybrid.

- Introduction
- Basics in femtoscopic study of hadron-hadron interactions
- Recent & Future Femtoscopic Studies of HHI
- Summary

Hadron Physics using High-Energy HIC

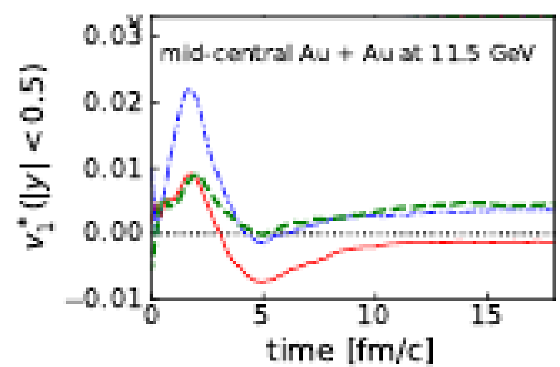
- **High-Energy Heavy-Ion Collisions**
  - **Too complex → Statistical → Simple and Clean !**
  - **High *T* & Large volume → Abundant hadrons**
  - **Nearly 4π detector / Vertex detector**

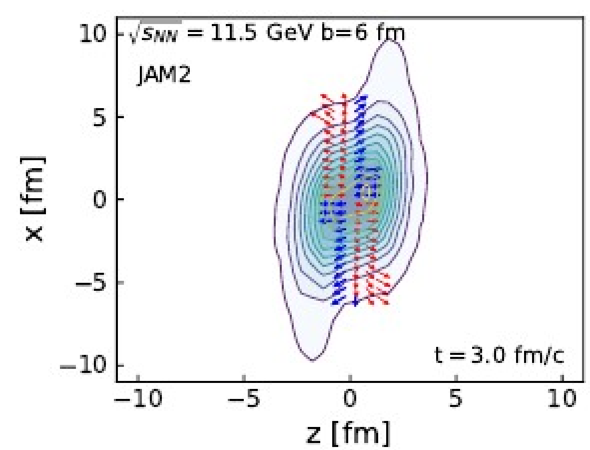
Let's study Hadron Physics
(e.g. hadron-hadron interactions and hadronic matter EOS)
by using High-Energy Nuclear Collisions as Hadron Factories.

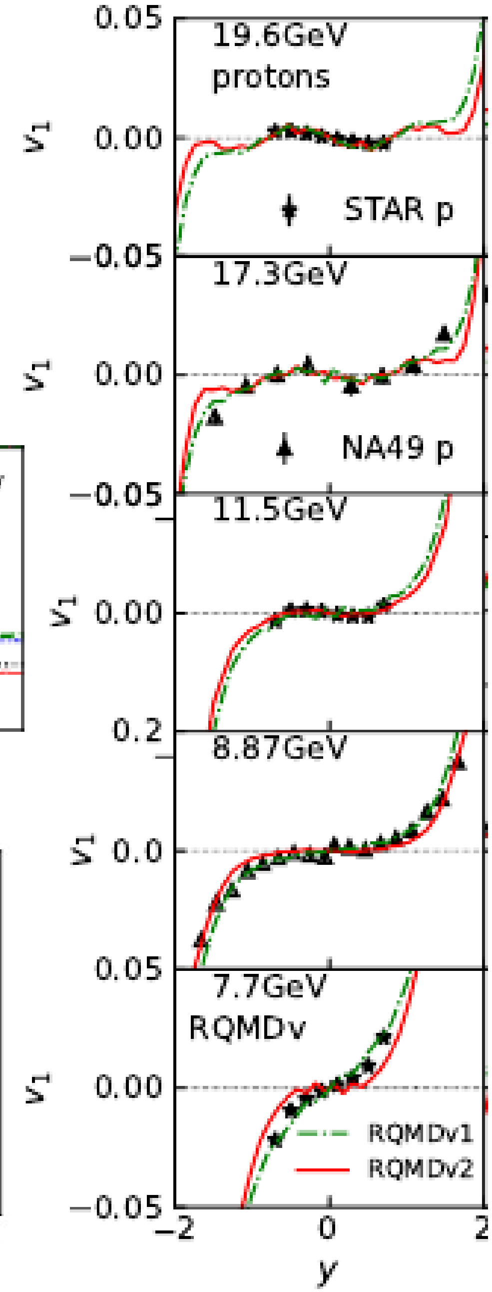


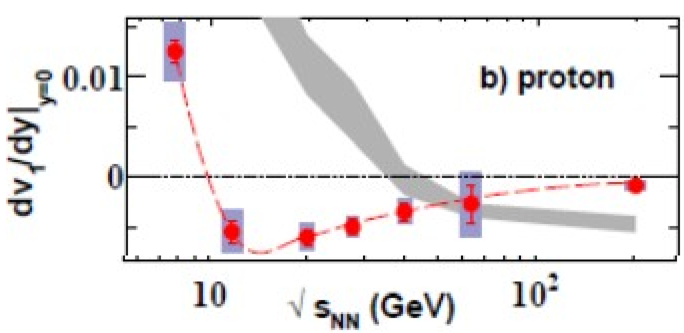
Revisiting dense hadronic matter EOS

- Collective flow → Equation of State (EOS)
  - Old but important subject in HIC
  - Non-monotonic energy dep. of proton v_1 slope
    = Unsolved puzzle *[c.f. Chun Shen (Sat.)]*
- Recent discovery *Y. Nara, AO, arXiv:2109.07594*
  - JAM2+RQMDv (EOS effect)
  - Positive flow in compression,
    Negative flow in expansion
    due to tilted ellipsoid.
  - E-dep. of dv_1/dy is explained
  - *ATHIC abst. was not accepted.*



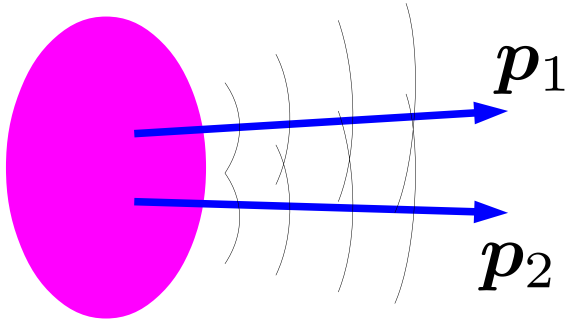






STAR, PRL112('14)162301

Femtoscopic study of hadron-hadron interaction



- **Correlation function (CF)**
  - **One can access various hadron-hadron interactions using CFs (femtoscopy).**
  - **CF=convolution of source fn. and |w.f.|^2 (Koonin-Pratt formula)** *Koonin('77), Pratt('86), Lednicky+('82)*

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1) N_2(\boldsymbol{p}_2)} \simeq \int d\boldsymbol{r} \underbrace{S(\boldsymbol{r})}_{\text{source fn.}} \underbrace{|\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2}_{\text{relative w.f.}}$$

(q=rel. mom.)

- **Source size from quantum stat. + CF (HBT-GGLP effect)**

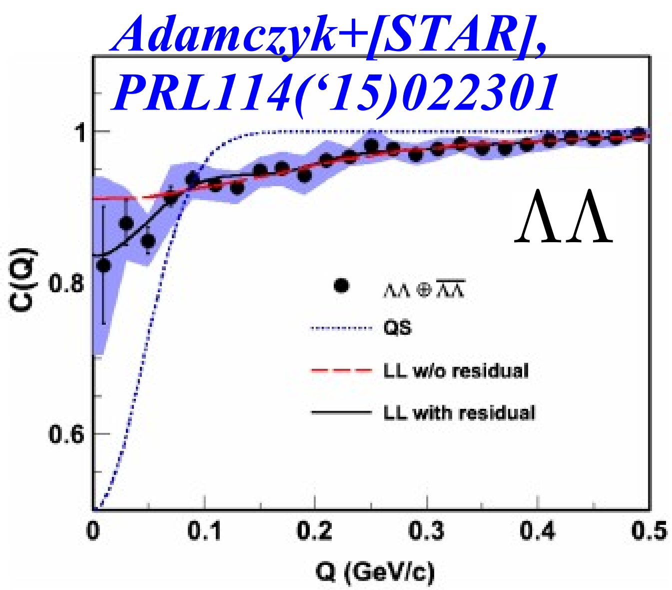
  Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)

- **Hadron-hadron interaction from source size + CF**
  - **CF of non-identical pair from static spherical source**
    Lednicky, Lyuboshits ('82); Morita, Furumoto, AO ('15)

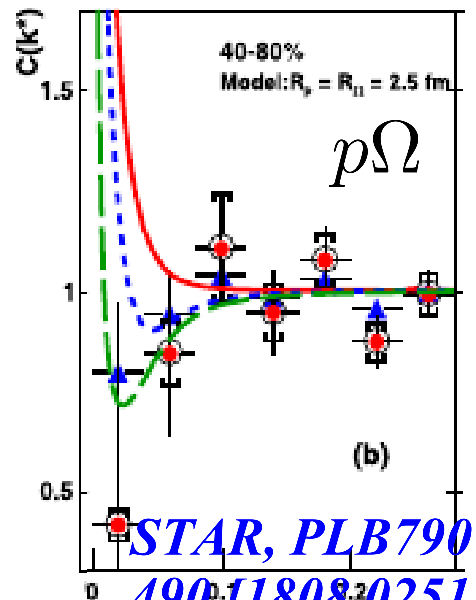
$$C(\boldsymbol{q}) = 1 + \int d\boldsymbol{r} S(r) \left\{ |\varphi_0(r)|^2 - |j_0(qr)|^2 \right\} \quad (\varphi_0 = \text{s-wave w.f.})$$

CF shows how much |φ|² is enhanced → V_{hh} effects !

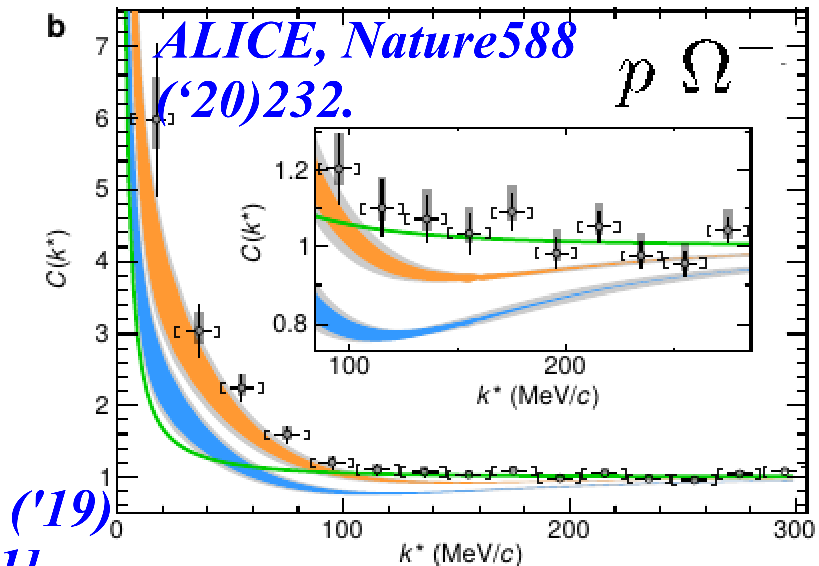
Measured Flavored Hadron CFs (examples)



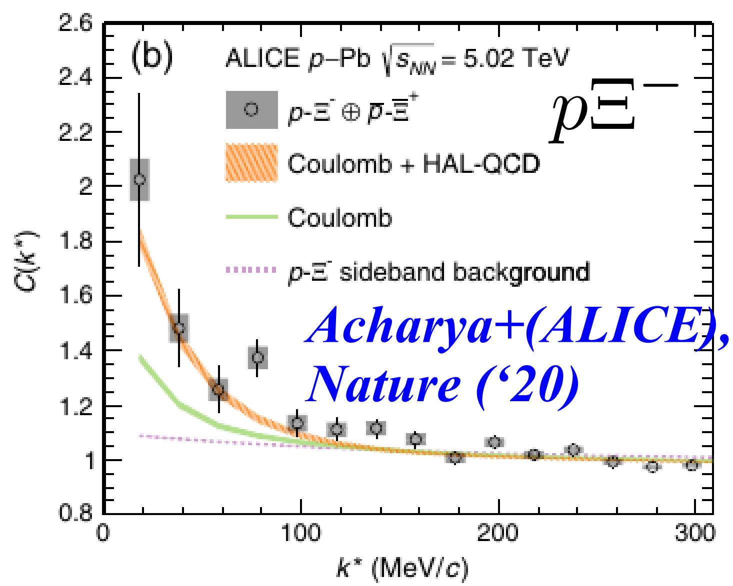
Adamczyk+[STAR], PRL114('15)022301



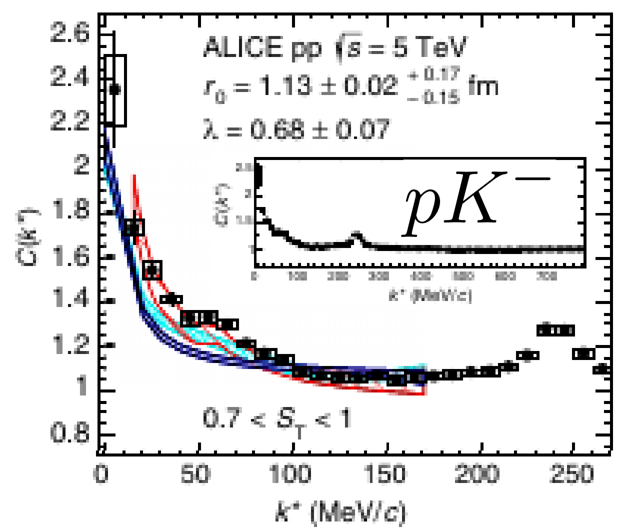
STAR, PLB790 ('19) 490 [1808.02511].



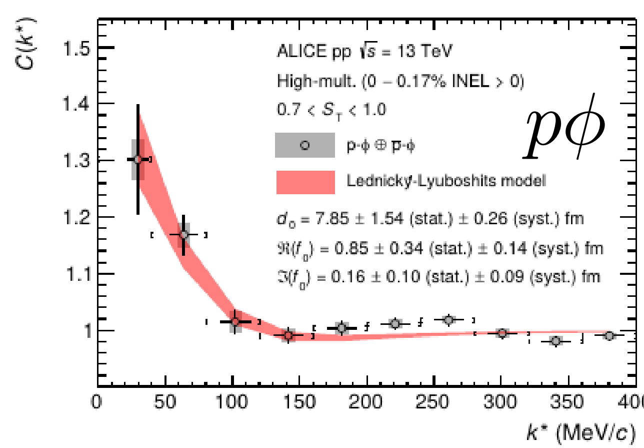
ALICE, Nature588 ('20)232.



Acharya+(ALICE), Nature ('20)

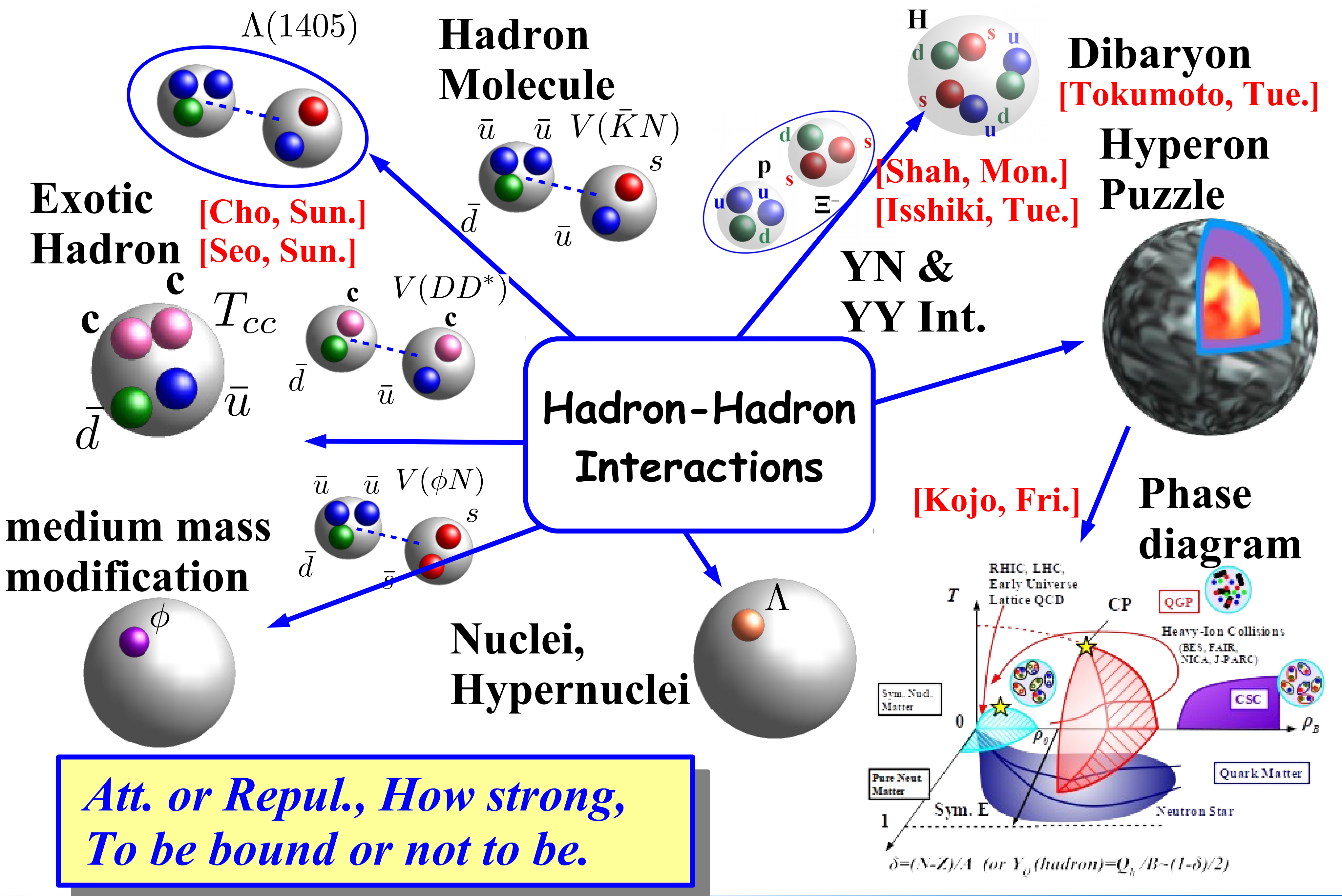


S. Acharya+[ALICE], PRL124('20)092301



ALICE, 2105.05578

Hadron-Hadron Interactions: Relevance



Basic formulae in femtoscopic study of hadron-hadron interactions

Lednicky-Lyuboshits (LL) model

- **Lednicky-Lyuboshits analytic model (Asymp. w.f.+eff. range corr.+Gaussian source)**
  Lednicky, Lyuboshits ('82)
  - **CF = a known function of f(q), R, r_{eff}, and q.**

$$\psi_0(r) \to \psi_{\rm asy}(r) = \frac{e^{-i\delta}}{qr}\sin(qr+\delta) = \mathcal{S}^{-1}\left[\frac{\sin qr}{qr} + f(q)\frac{e^{iqr}}{r}\right]$$

$$\begin{aligned} C_{\rm LL}(q) =& 1 + \int d\boldsymbol{r} S_{12}(r)\left(|\psi_{\rm asy}(r)|^2 - |j_0(qr)|^2\right) \\ =& 1 + \frac{|f(q)|^2}{2R^2}F_3\left(\frac{r_{\rm eff}}{R}\right) + \frac{2{\rm Re}f(q)}{\sqrt{\pi}R}F_1(2x) - \frac{{\rm Im}f(q)}{R}F_2(2x) \end{aligned}$$

$$(x = qR, R = \text{Gaussian size}, F_1, F_2, F_3 : \text{Known functions})$$

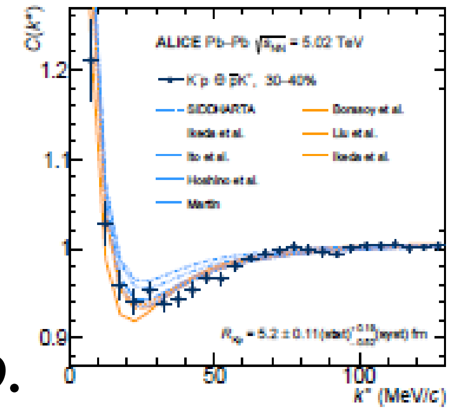
  - **Scattering amplitude at low energies**

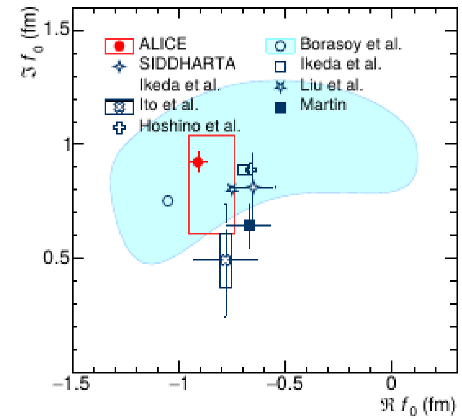
$$q\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}q^2 + \mathcal{O}(q^4) \to f(q) = (q\cot\delta - iq)^{-1}$$

From scattering length (a_0) and effective range (r_{eff}), one can calculate the correlation function !

Scattering length from CFs

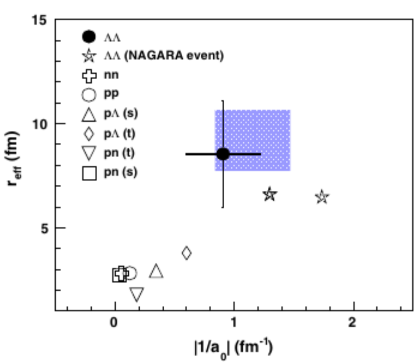
- $K^{-}p$
  - LL (w/ Coulomb) gives a_0
  - Comparable with kaonic atom data (SIDDHARTA).
  - See also Siejka+[STAR],NPA982('19)359.

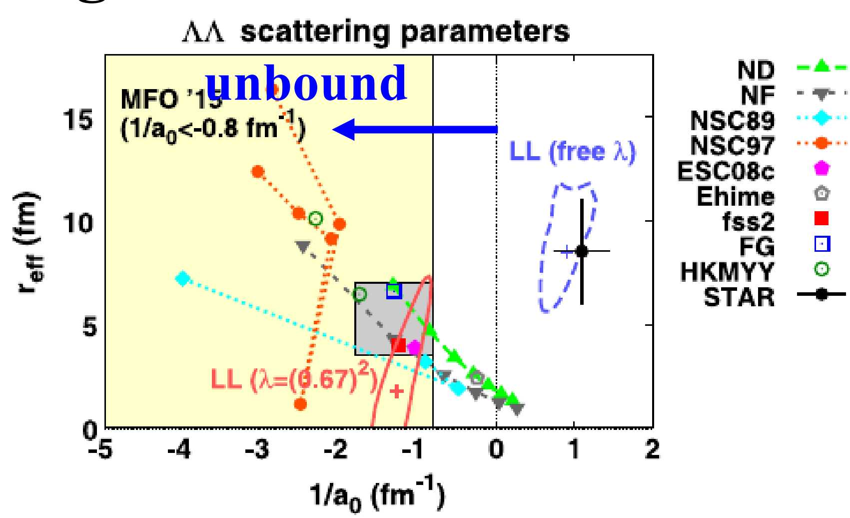


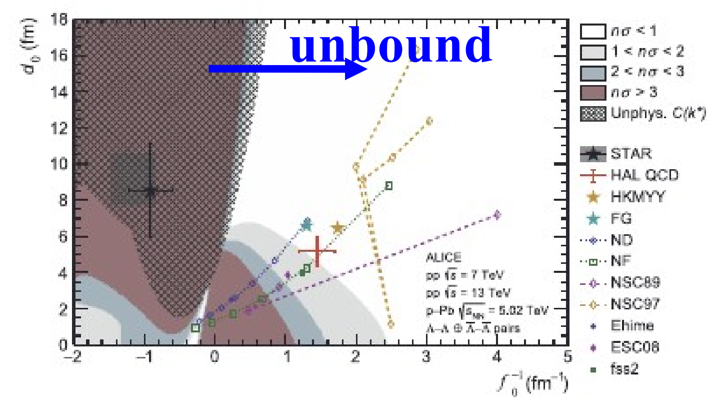


Acharya+[ALICE], PLB822('21),136708 [2105.05683] ($\delta \sim a_0 q$)

- ΛΛ
  - Quantum statistics + LL → (a_0, r_{eff}) region







L. Adamczyk+ [STAR], PRL114 ('15)022301

K.Morita, T.Furumoto, AO, PRC91 ('15) 024916; AO, Morita, Miyahara, Hyodo, NPA954('16)294 ($\delta \sim -a_0 q$)

S. Acharya [ALICE], PLB797 ('19) 134822 ($\delta \sim a_0 q$).

Femtoscopic diagnosis of bound state existence

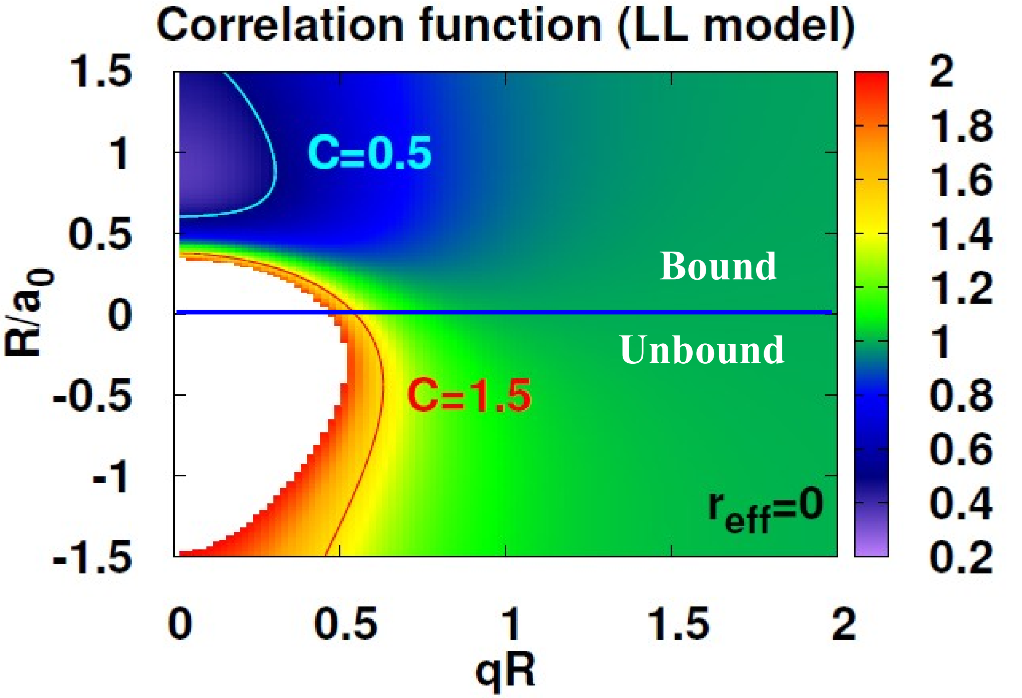
- **Lednicky-Lyuboshits model with zero effective range**
  → CF = C(qR, R/a_0)

$$r_{\rm eff} = 0 \to q\cot\delta = -1/a_0 \to f(q) = (q\cot\delta - iq)^{-1} = -\frac{R}{R/a_0 + iqR}$$

$$C(x,y) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}F_1(2x) - xF_2(2x)\right] \quad (x = qR, y = R/a_0)$$

$$= \frac{1}{2}\left(\frac{1}{y} - \frac{2}{\sqrt{\pi}}\right)^2 + 1 - \frac{2}{\pi} \quad (F_1 \to 1, F_2 \to 0 \text{ at } x \to 0)$$

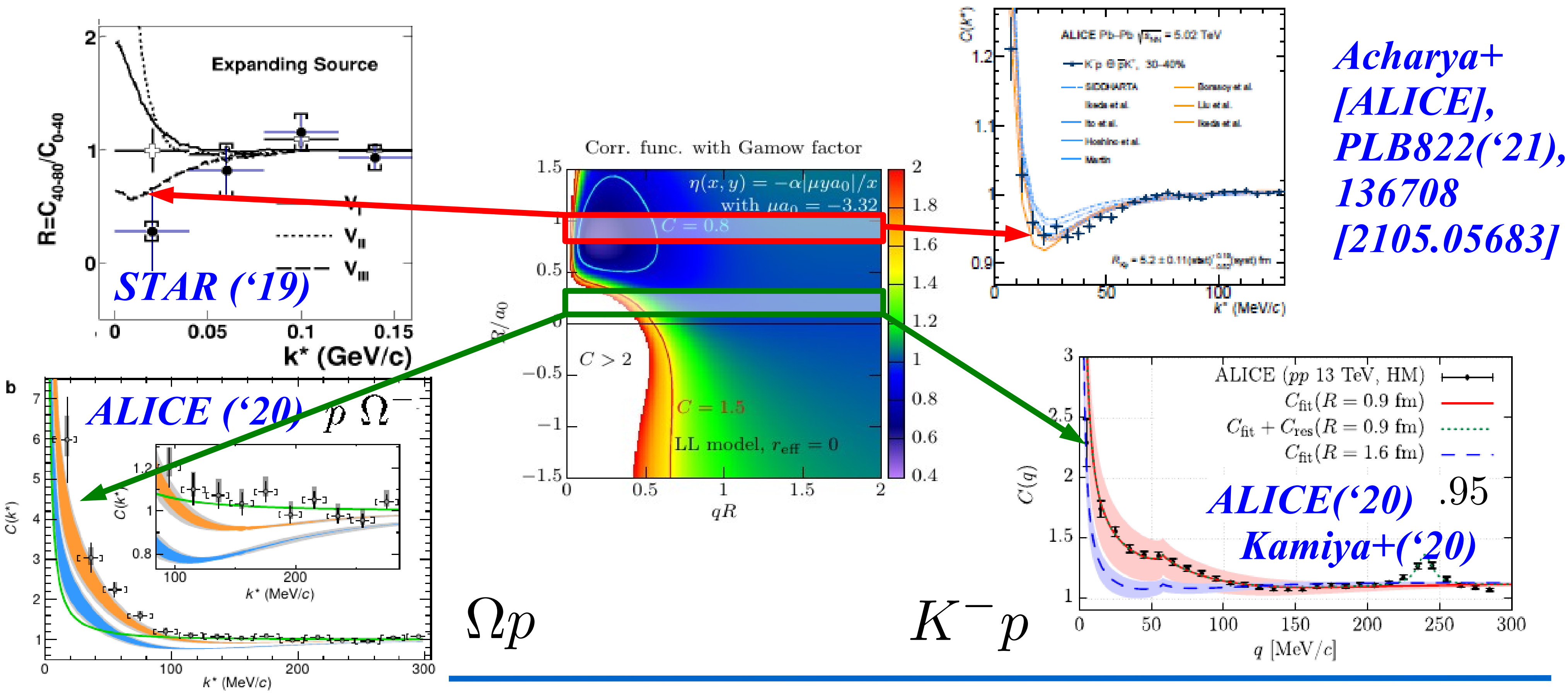
- **With a bound state, CF is suppressed at low q.**
- **Scattering w.f. needs to have a node to be orthogonal to b.s.**



E.g. AO, Morita, Miyahara, Hyodo ('16)

Hadronic molecules suggested by CFs

- Ωp and $K^- p$
  - **Bound states are expected.**
    Dalitz, Tuan ('59); Akaishi, Yamazamki ('02); Goldman+('87); Oka ('88); Etminan+[HAL QCD] ('14); Iritani+[HAL QCD]('19).
  - **Dip is expected at R ~ $|a_0|$** *Morita+('16,'20); Kamiya+('20); Haidenbauer('18)*
  - **Data support the existence of a BS.**



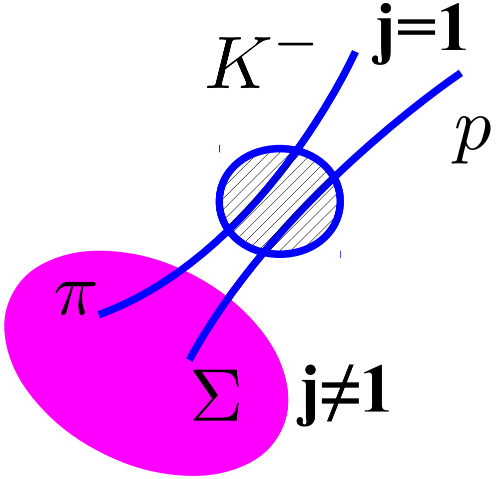
Coupled-Channel Effects

- **Correlation Function with Coupled-Channel Effects**
  - **Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula Coupled-channel contributions with ψ(-) boundary cond.**
    Lednicky, Lyuboshits, Lyuboshits, Phys. Atom. Nucl. 61 (1998), 2950;
    J. Haudenbauer, NPA981('19) 1 [1808.05049];
    Y. Kamiya, T.Hyodo, K.Morita, AO, W.Weise, PRL('20).

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

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

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



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

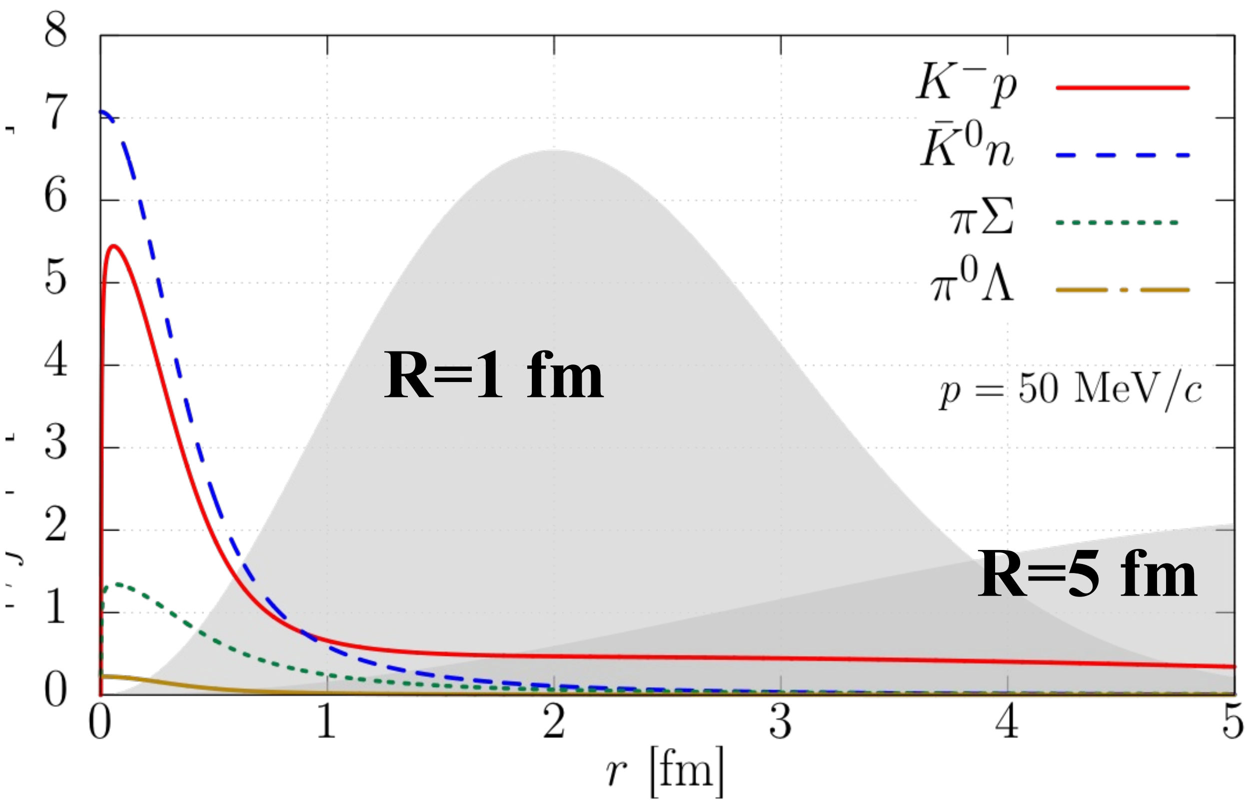
Source weight — Normalized Source fn.

(No Coulomb case)

- **Wave functions of other channels also contribute to correlation functions.**
- **Source size R and weight ω_j (j≠1) are taken as the parameter.**

Discriminating Coupled-Channel Effects

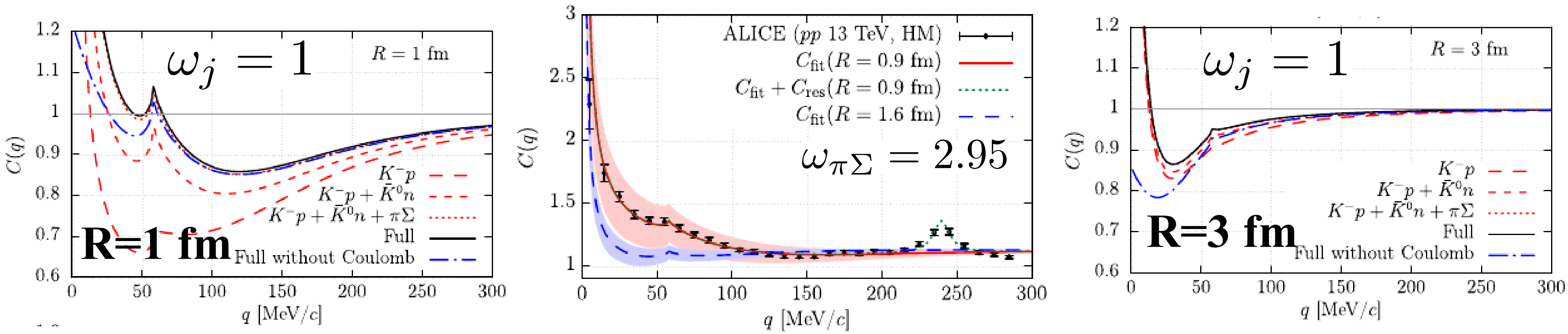
- **Source size dependence again !**
  - **Unmeasured coupled-channel wave functions disappear soon.**
    → CFs with large source is dominated
    by the measured channel wave function !
  - **Scattering parameters from CFs with large source**
    Coupled-channel effects from CFs with small source.



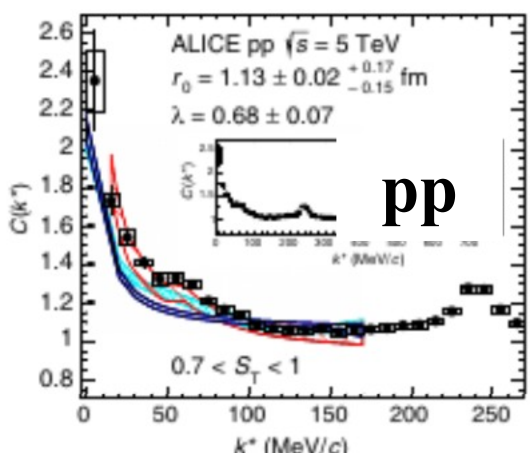
w.f. Kamiya+,arXiv:1911.01041v1

Source Size Dependence of C(K⁻p)

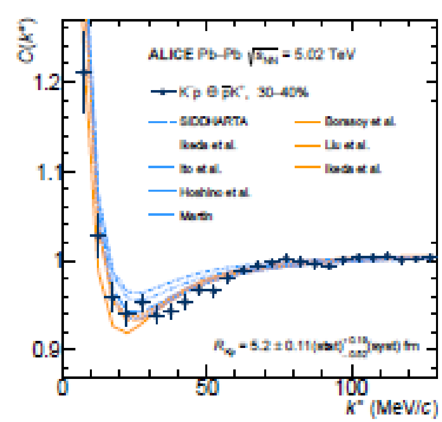
- **Coupled-channel effects are suppressed when R is large, and "pure" K^-p wave function may be observed in HIC.**



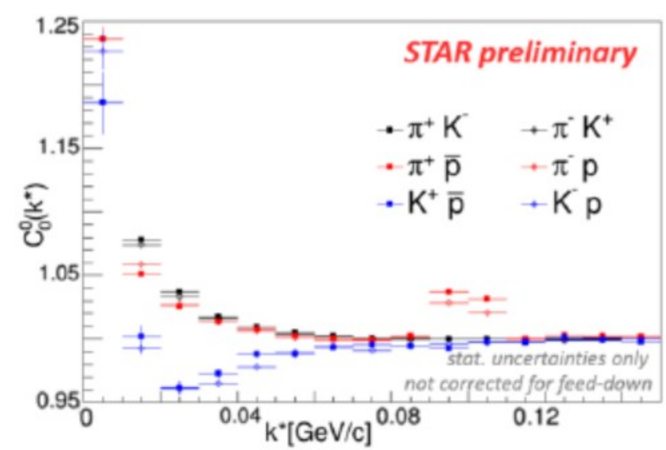
Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501.



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



S. Acharya+[ALICE], PLB822('21)136708

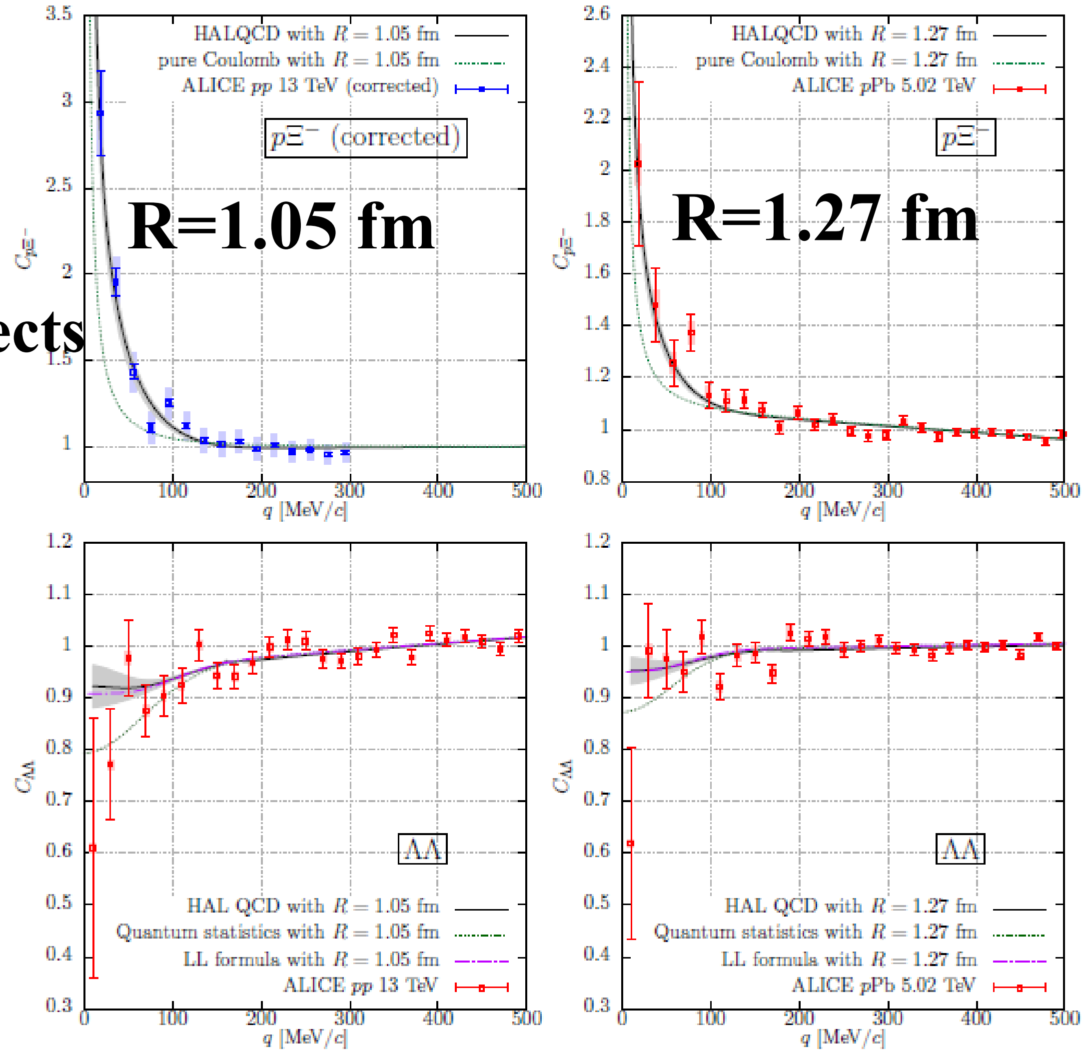


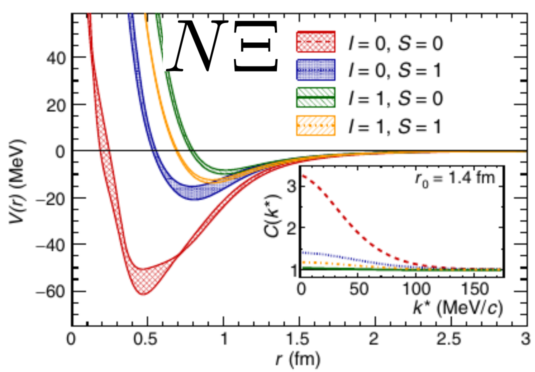
Siejka+[STAR, preliminary], NPA982 ('19)359.

Recent & Future Femtoscopic Studies of HHI

Ξ⁻p & ΛΛ correlation functions (pp and pA)

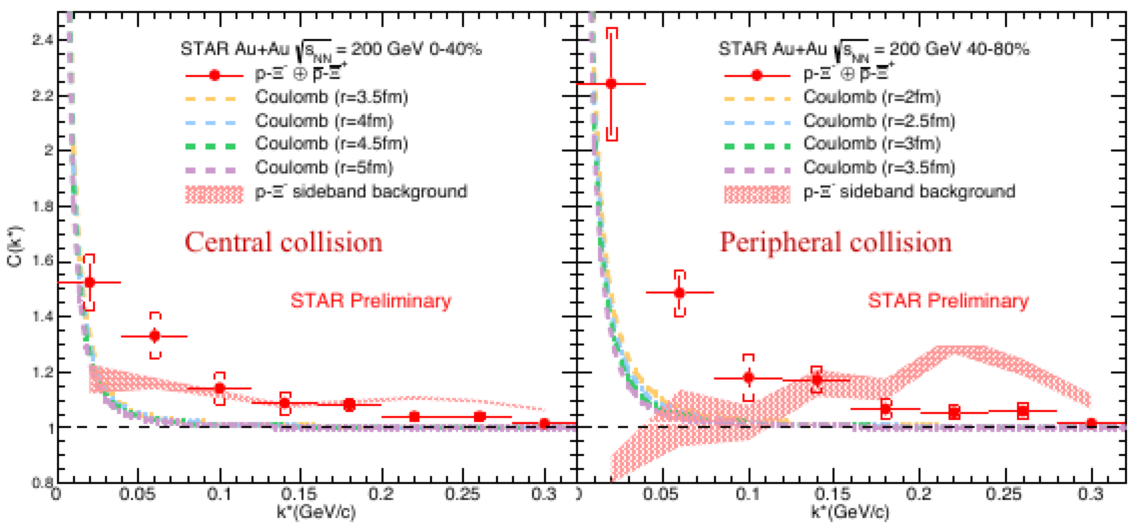
- **Correlation function data from pp and pA collisions**
  S. Acharya et al. [ALICE], PLB 797('19)134822 (ΛΛ); PRL123('19)112002 (Ξ⁻p from pA); Nature 588('20)232 (Ξ⁻p from pp).
  - CF(Ξ⁻p) is enhanced at low q. → Att. pot.
  - CF(ΛΛ) is slightly enhanced from quantum stat. result. → Weakly attractive pot.
  - CFs with coupled-channel effects using lattice QCD potential explains the data well.
    K. Sasaki [HAL QCD]('20); Y.Kamiya+, arXiv:2108.09644.



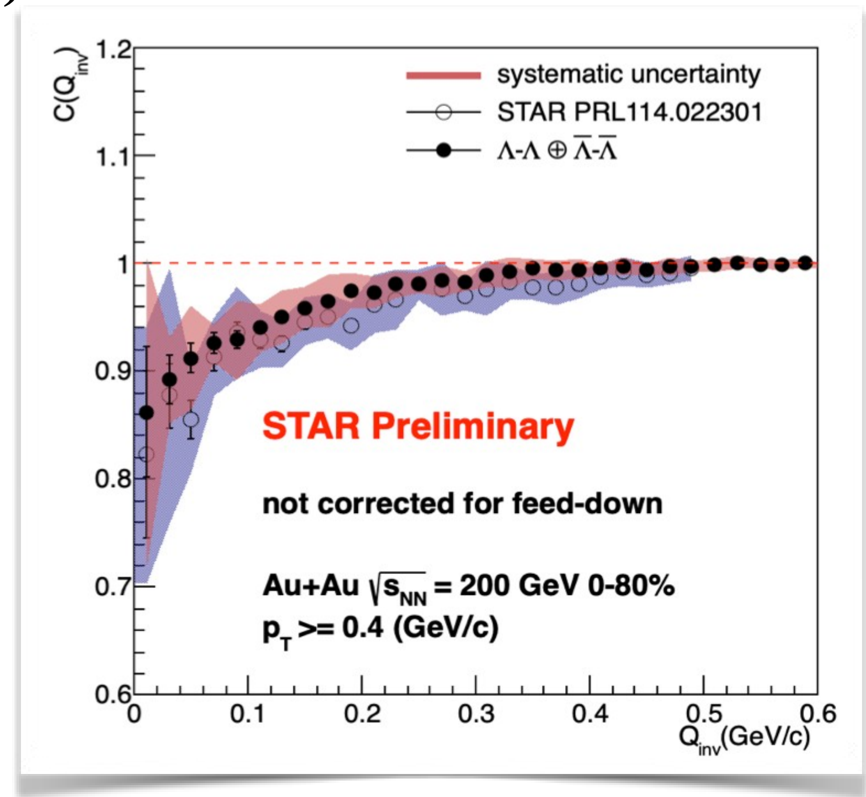


Ξ^-p & ΛΛ correlation functions (AA)

- **Correlation function data from AA collisions**
  [c.f. Shah, Mon., Isshiki, Tue.]
  K. Mi+(STAR, preliminary), Au+Au 200 AGeV, APS2021.
  Moe Isshiki+ (STAR, preliminary), Strangeness physics workshop, 2021.
  - **We do not see a dip in C(Ξ^- p) from Au+Au.**
    → There will be no bound state of Ξ^- p.
  - **Much higher statistics data of C(ΛΛ) from Au+Au are obtained.**
    → LL formula fit will be possible.



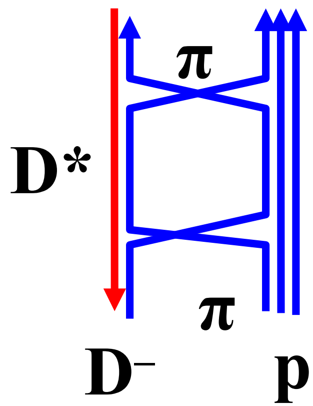
K. Mi+(STAR, preliminary),
Au+Au 200 AGeV, APS2021.
(No Dip at larger R)



Moe Isshiki+ (STAR, preliminary).

Charmed Hadron Interactions

- **Charmed hadron interactions are extremely important in exotic hadron physics.**
- **Example: D^- p correlation**
  - **Proposed potentials generally predict weak or repulsive interaction.**
    Hofmann, Lutz ('05) (repulsive); Haidenbauer+('07) (repulsive); Yamaguchi+('11) (att., w/ bs); Fontoura+('13) (repulsive)
  - **Attraction from pion exchange**
    S. Yasui, K. Sudoh, PRD80('09)034008.



Model	$a^{I=0}_{\bar{D}N}$	$a^{I=1}_{\bar{D}N}$	$a_{\bar{D}}$
SU(4) contact [185]	−0.16	−0.26	−0.24
Meson exchange [194]	0.07	−0.45	−0.32
Pion exchange [192]	−4.38	−0.07	−1.15
Chiral quark model [219]	0.03–0.16	-(0.20-0.25)	-(0.14-0.15)

1. Hoffmann, Lutz ('05)
2. Haidenbauer+ ('07)
3. Yamaguchi+('11)
4. Fontoura+('13)

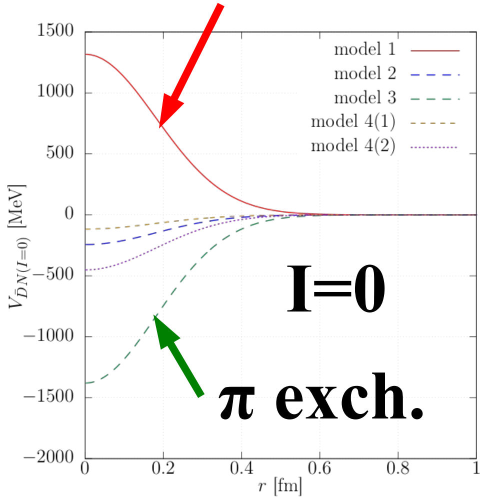
Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, PPNP96('17)88

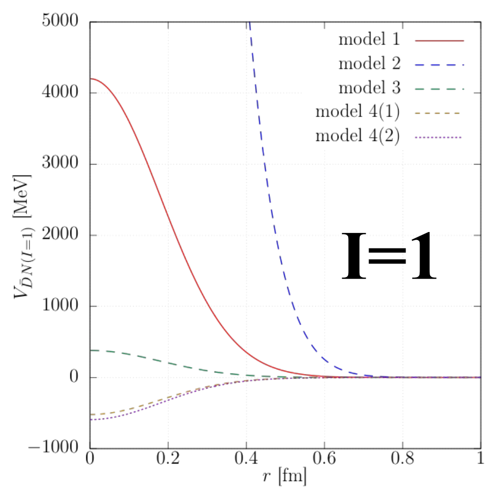
Which picture is correct ?

Charmed Hadron Interactions

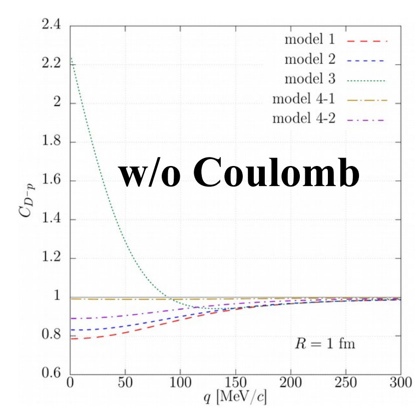
- **D⁻ p CFs from proposed scattering length** ***Kamiya, Hyodo, AO (in prog.)***
  - **One-range Gaussian potential strength is fitted to proposed a0 with the range of ρ meson exchange.**
  - **Measurable difference is found.**

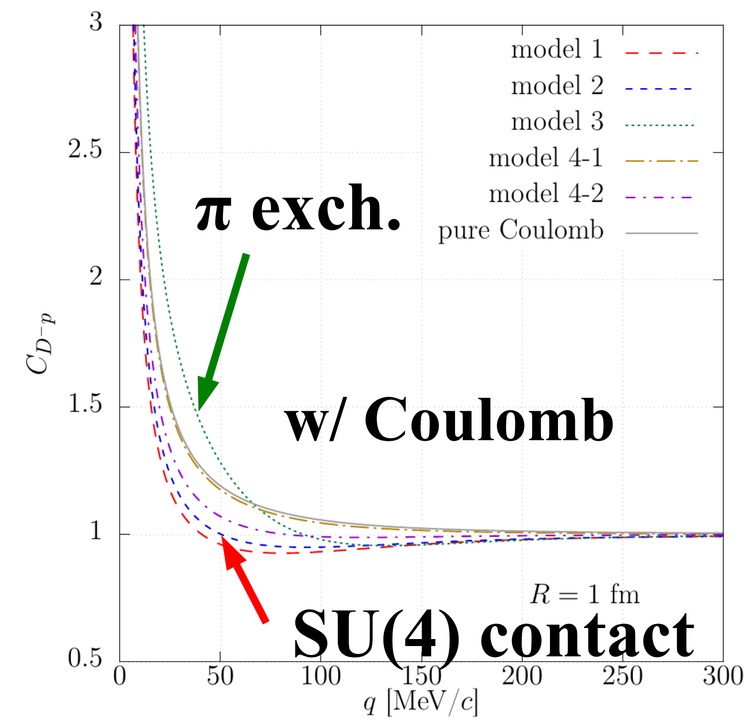
SU(4) Contact





1. Hoffmann, Lutz ('05)
2. Haidenbauer+ ('07)
3. Yamaguchi+('11)
4. Fontoura+('13)



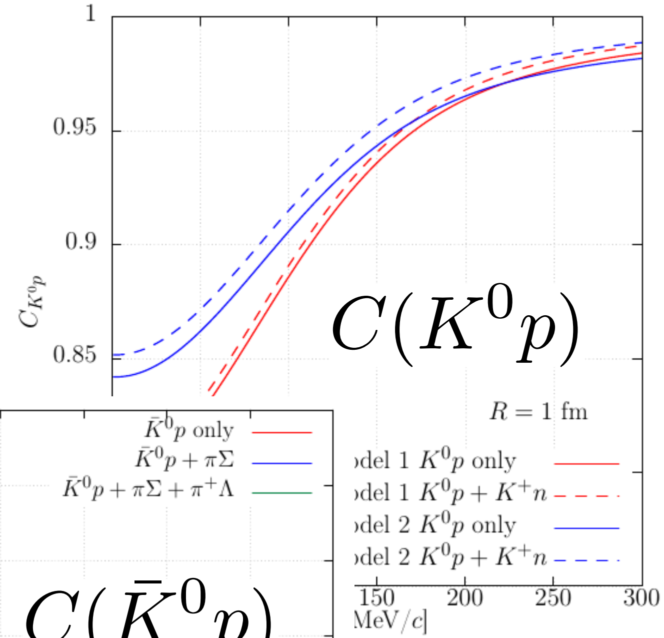


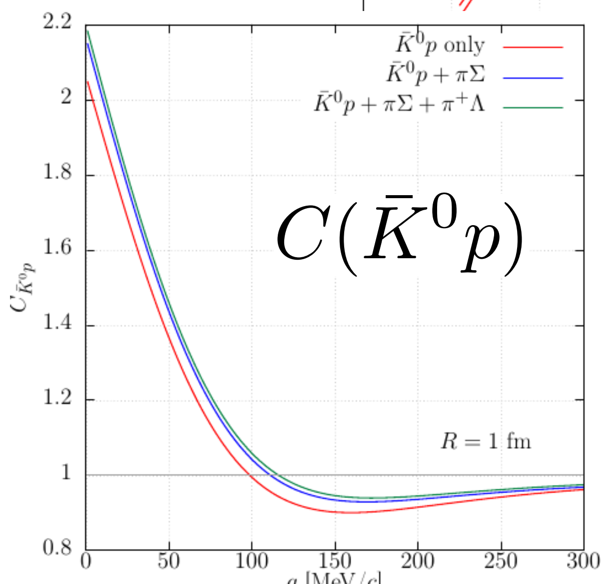
Data will discriminate these potentials !

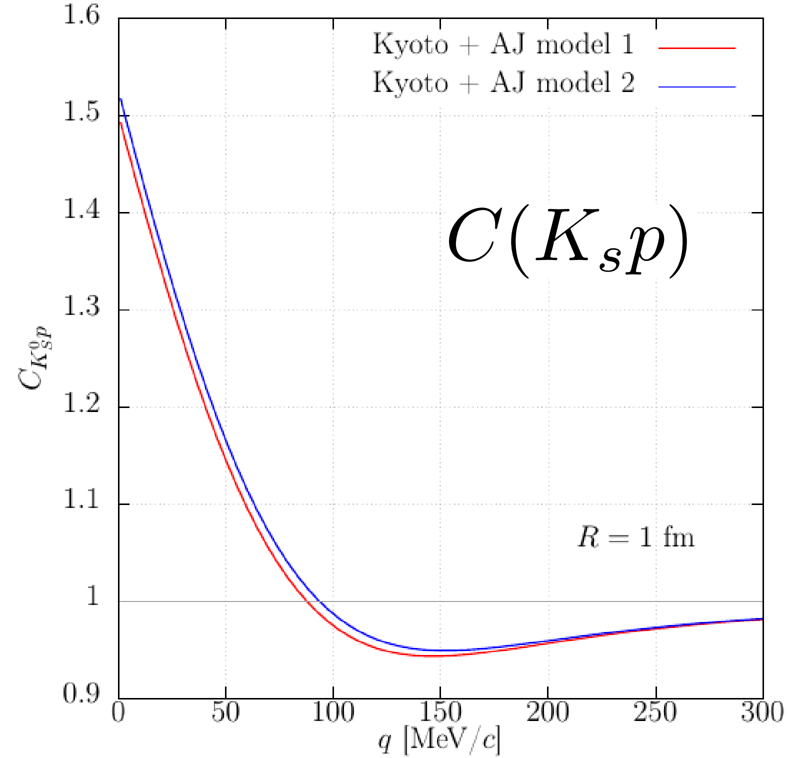
Ks p correlation function

- **Ks wave function** ***Kamiya+(in prep.)***

$$|K_s\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right] \to C(K_s p) = \frac{1}{2}\left[C(K^0 p) + C(\bar{K}^0 p)\right]$$







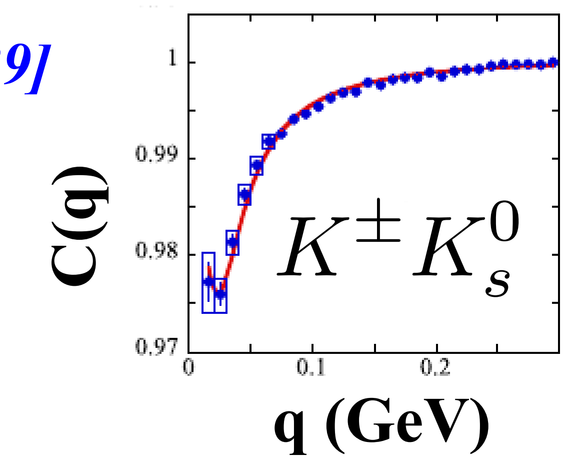
$K^-p, K^+p, K_sp,$ and K^-n or $K^+\bar{n}$ (missing)
to obtain KN and $\bar{K}N$ interactions with $I = 0, 1$

$V(\bar{K}N)$:Chiral SU(3) (Kyoto-Münich) model (Miyahara, Hyodo, Weise ('18))

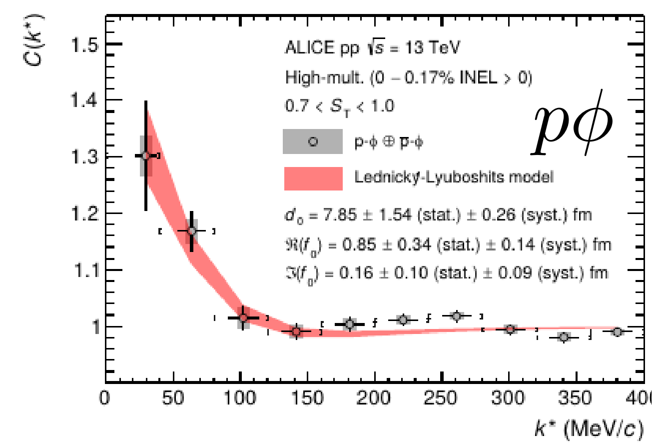
$V(KN)$:Chiral SU(3) based model (Aoki, Jido ('19))

Other Correlation Functions

- $\bar{p}\bar{p}, p\bar{\Lambda}$ *E.g. A. Kisiel [ALICE], Acta Phys.Polon.Supp. 6 ('13)519*
- **$K^{\pm}K^0_s$** *S.Acharya+ [ALICE], PLB774 ('17)64 [1705.04929]*
  - **Slightly suppressed at low q**
    Tetraquark component of a_0 meson



- **pϕ** *Acharya+[ALICE], PRL127('21)172301[2105.05578]*
  - **Attractive potential which may be responsible to medium mass reduction**
- **$p\bar{\Lambda}, \Lambda\bar{\Lambda}$ [2105.05190],**
  $p\Sigma^0$ ['20 [1910.14407]] [ALICE]
- **deuteron-hadron CF**
  S. Mrówczyński and P. Słoń,
  Acta Phys.Polon.B51('20)1739 [1904.08320];
  F. Etminan, M. M. Firoozabadi, [1908.11484];
  J. Haidenbauer, PRC102('20)034001 [2005.05012];
  K.Ogata, T.Fukui, Y.Kamiya, AO [2103.00100].



Acharya+[ALICE], PRL127 ('21) 17, 172301[2105.05578]

Summary

- **Correlation function from heavy-ion collisions (including high-energy pp and pA collisions) are useful to access hadron-hadron interactions.**
  - **One can obtain the basic properties of HHIs such as Attractive or Repulsive, Strength, To be bound or not to be.**
  - **Source size dependence is useful in deducing the existence of a bound state and in discriminating the coupled-channel effects.**

- **We are sorry for using a static Gaussian source functions.**
  - **Flavored hadron CFs are measured in 1D (as a function of |q|), m_T dependence is not yet discussed, and errors are still large.**
  - **Effects of flow, elongated shape, and others are expected to be renormalized in changing the source size at present.**

- **Many hadron physicists are waiting for your data.**

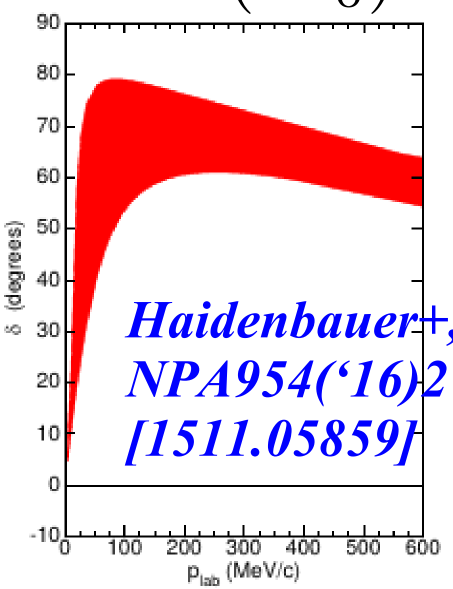
Thank you for your attention !

Theoretical Approaches to HHI

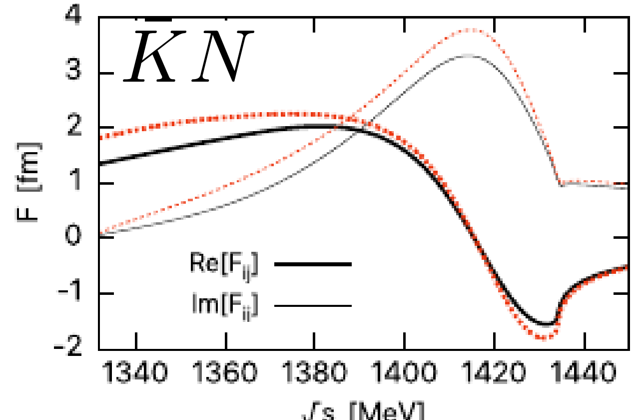
- **Nuclear force models: meson exch., quark model, … (need data)**
- ***Ab initio*: chiral EFT, lattice QCD (need data or CPU resources)**

Chiral

$N\Xi(^1S_0)$

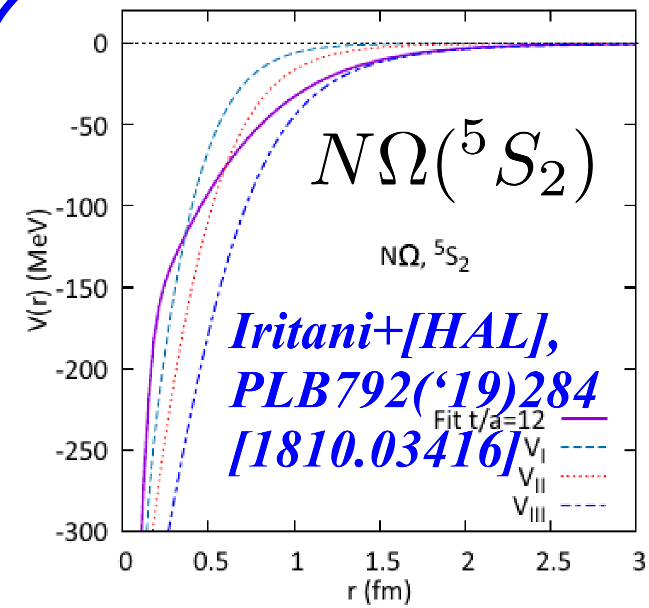


Haidenbauer+, NPA954('16)273 [1511.05859]

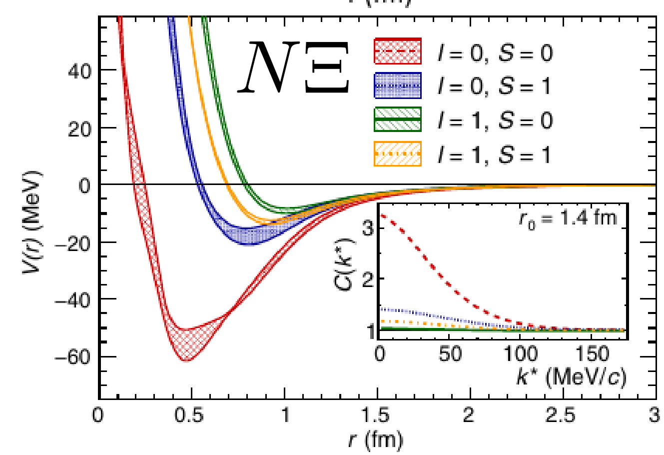


Miyahara, Hyodo, Weise, PRC98('18), 025201 [1804.08269] (Ikeda-Hyodo-Weise amplitude)

Lattice



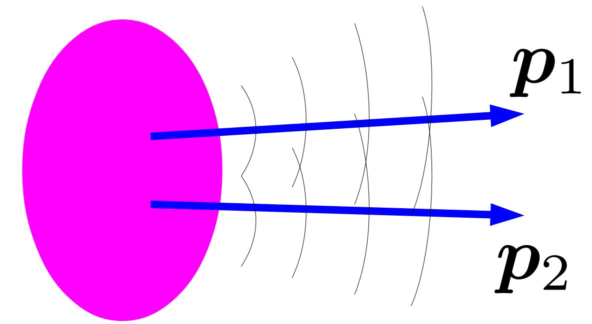
Iritani+[HAL], PLB792('19)284 [1810.03416]



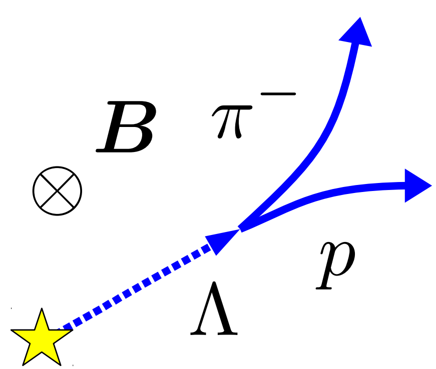
Sasaki+ [HAL], NPA998 ('20)121737 [1912.08630] (taken from ALICE('19))

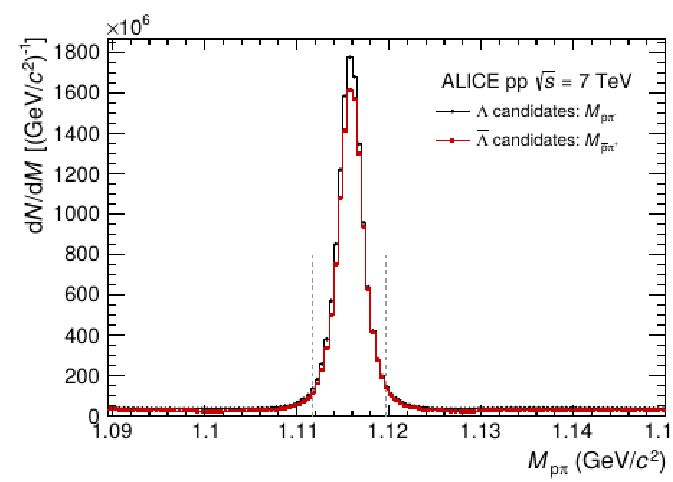
Experimental Approaches to HHI

- **Experimental approaches**
  - **hh scattering (NN, YN, πN, KN)**
  - **Hadronic nuclei (normal nuclei, hypernuclei, kaonic nuclei)**
  - **Hadronic 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, ...**



$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1)N_2(\boldsymbol{p}_2)}$$





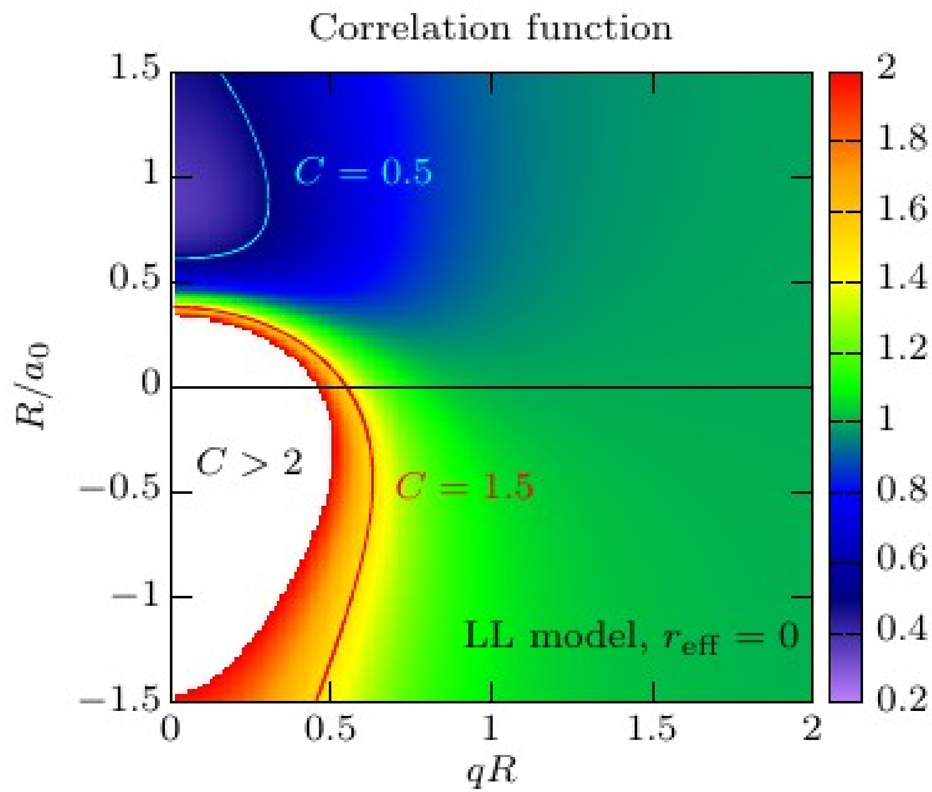
ALICE [1805.12455]

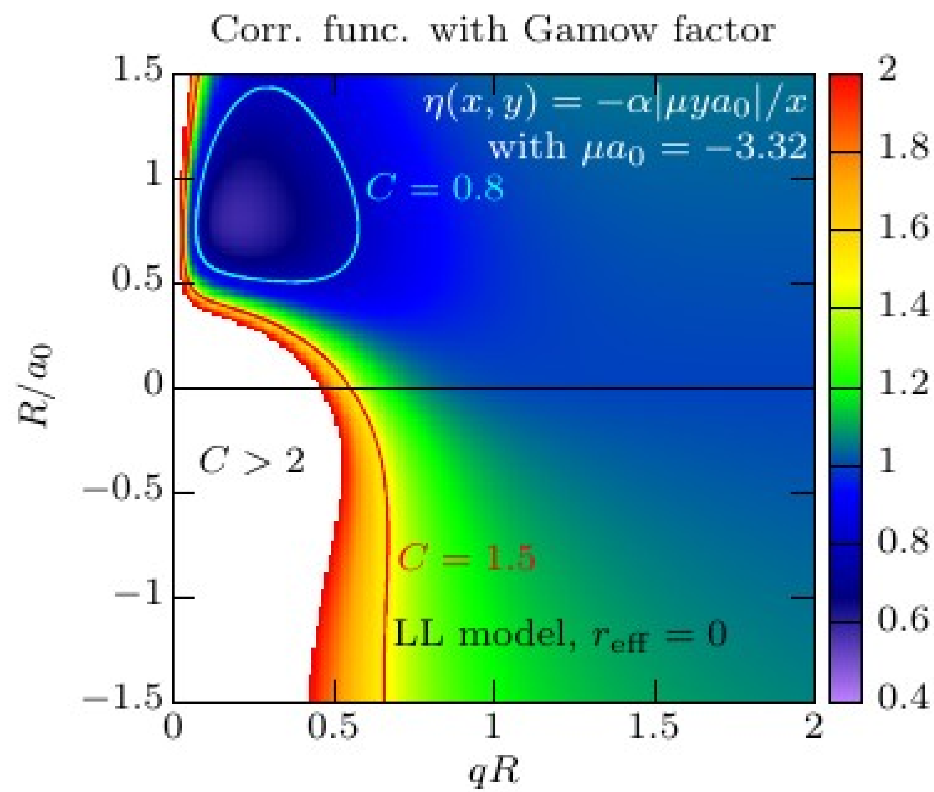
Femtoscopic Diagnosis of Bound State

- **With Coulomb attraction, a bound state causes a dip.**
  - **E.g. LL formula and the Gamow factor**

$$C(q) \to C_{\mathrm{strong}}(q) \times A_{\mathrm{Gamow}}(\eta)$$

$$A_{\mathrm{Gamow}}(\eta) = 2\eta/(\exp(2\eta) - 1) \ (\eta = Z_1 Z_2 \mu |y a_0|/x)$$

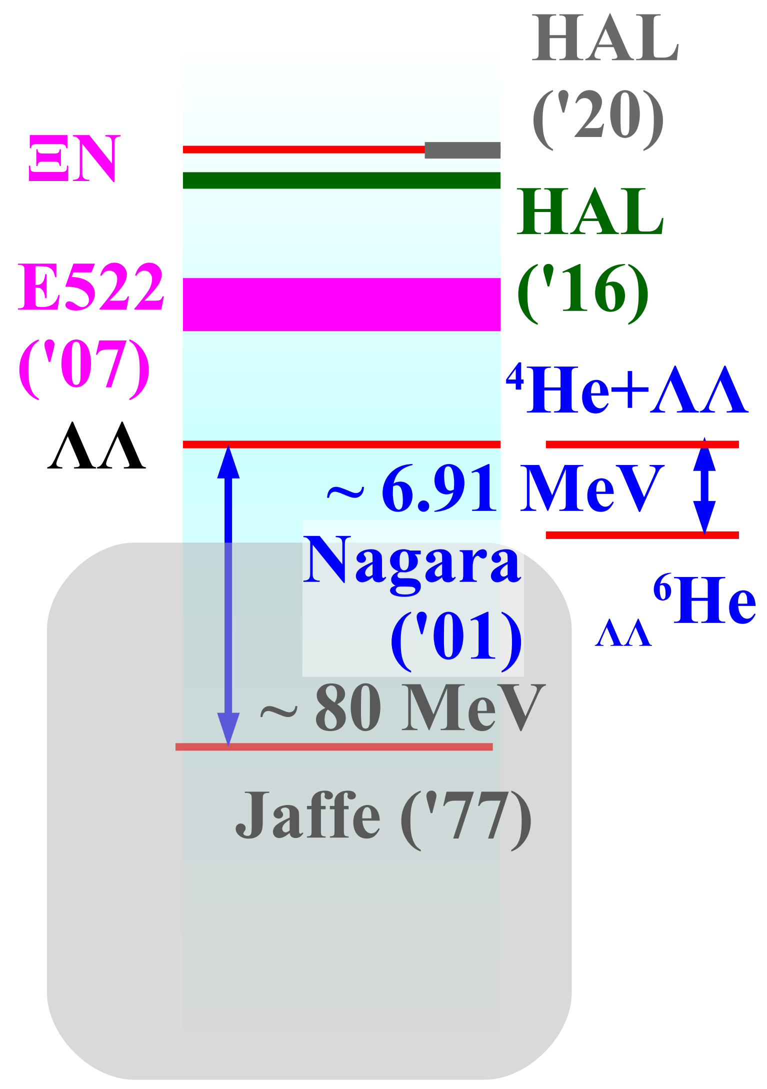




Kamiya+('21), 2108.09644

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)**



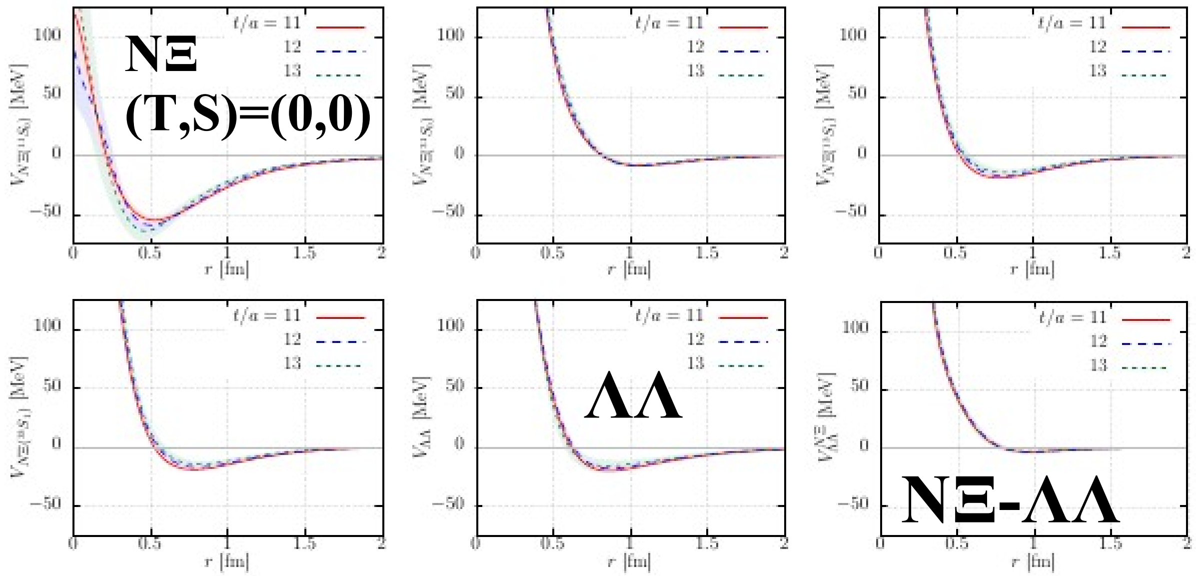
We examine LQCD NΞ-ΛΛ potential and discuss H using CF !

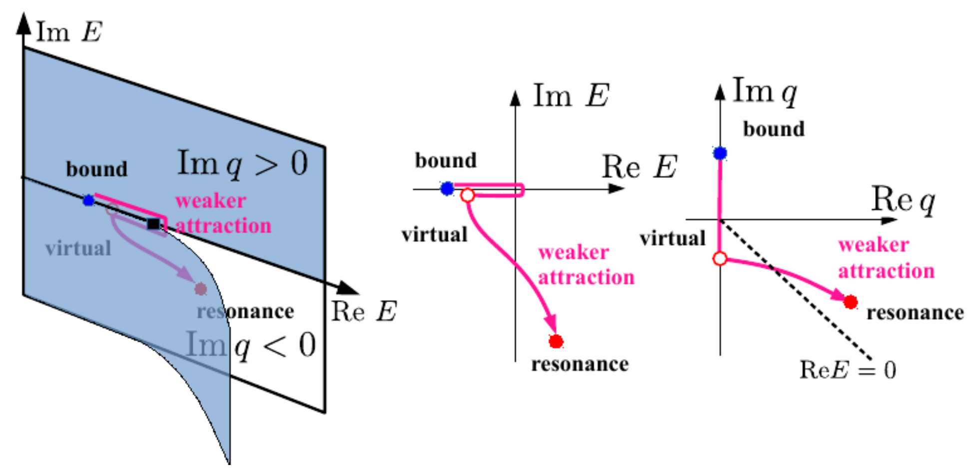
NΞ-ΛΛ potential from Lattice QCD

- **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 (eigenmomentum))**

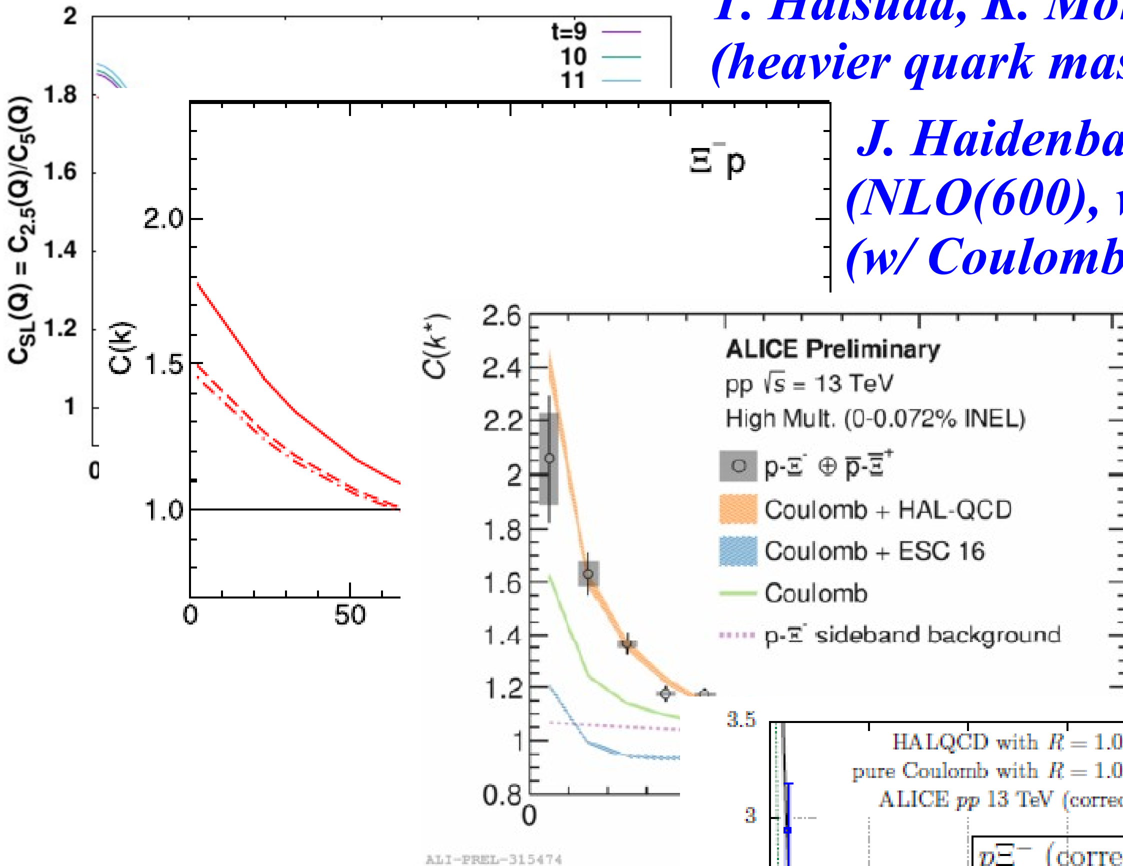




Ξ⁻p correlation function

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

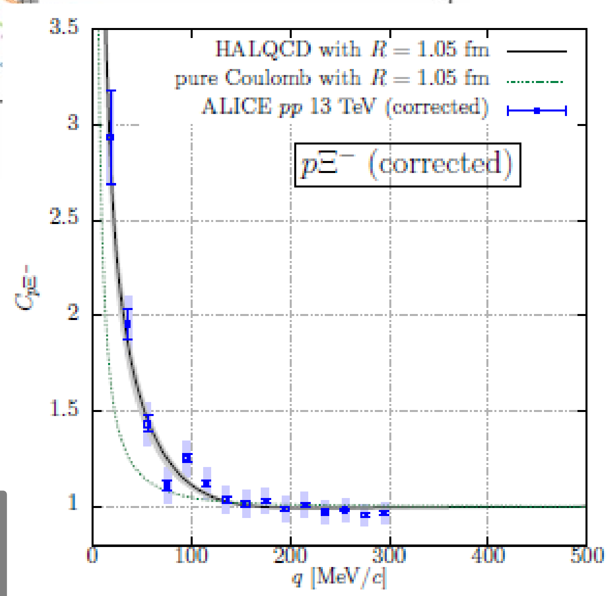
J. Haidenbauer, NPA981('19)1.
(NLO(600), w/ CC effects, w/o Coulomb)
(w/ Coulomb, it will be comparable with data.)

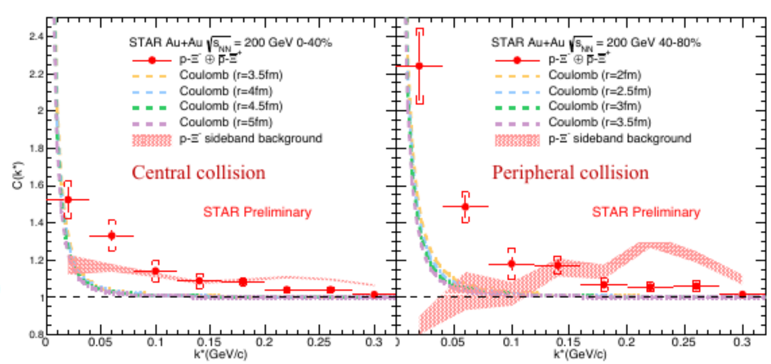


D. L. Mihairov+[ALICE], NPA 1005 ('21)121760 (QM2019). (Nijmegen pot. does not explain the data. w/o CC)
Acharya+(ALICE), Nature ('20)

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

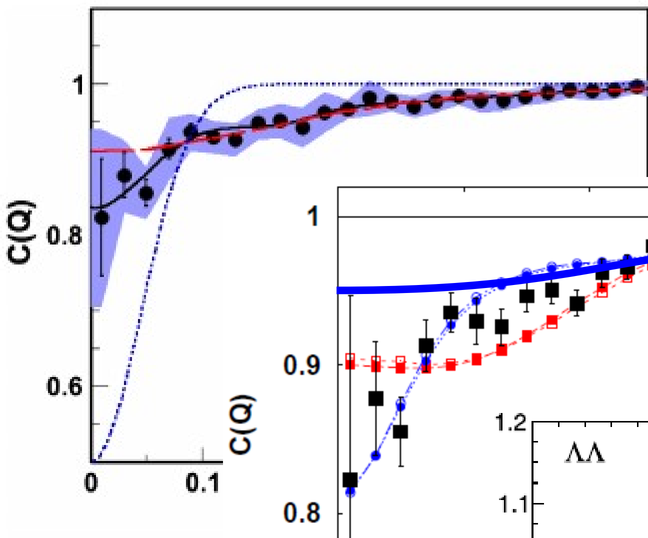
Kamiya+, 2108.09644
w/ Lattice BB pot. at phys. m_q
CC effects with ΛΛ.



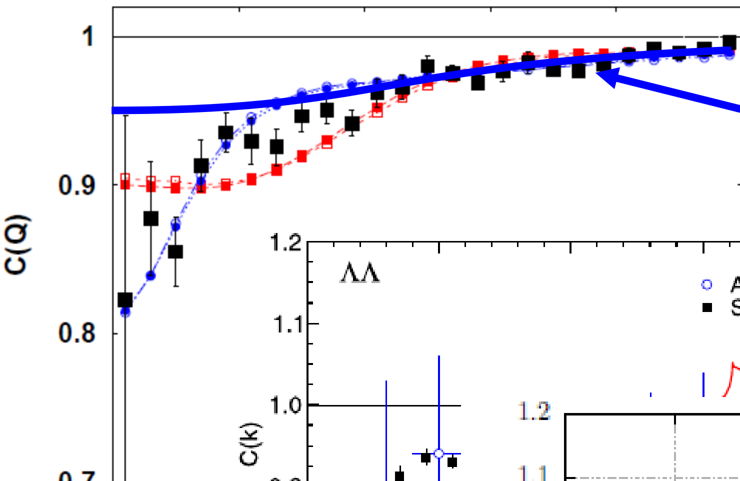


There is no signal of bound state.

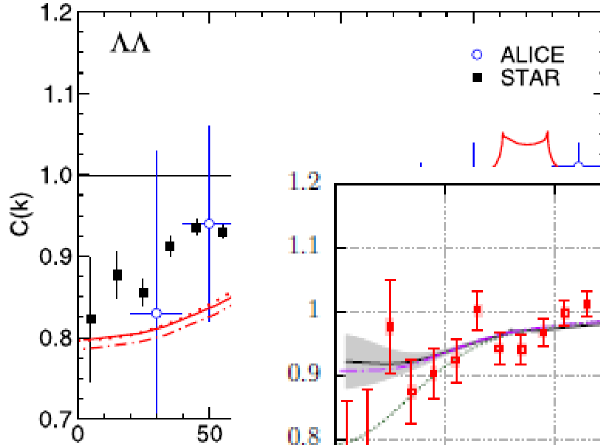
ΛΛ correlation function



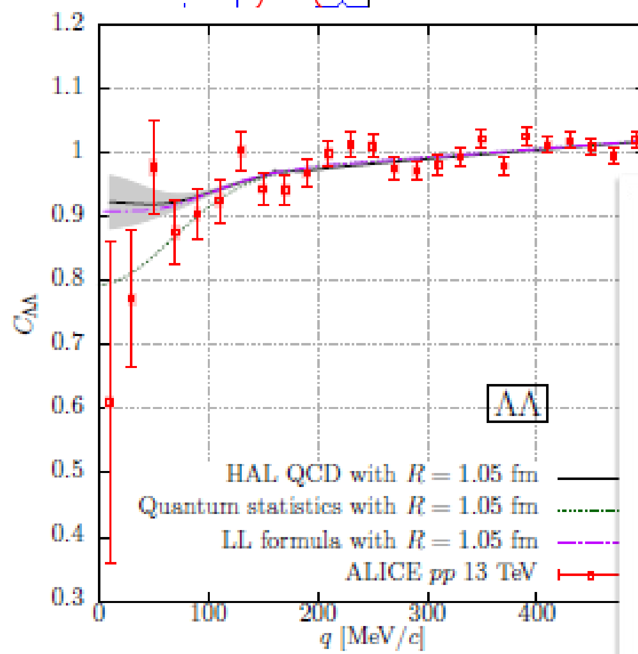
Adamczyk+[STAR], PRL114('15)022301
(Residual source R ~ 0.5 fm was assumed.)



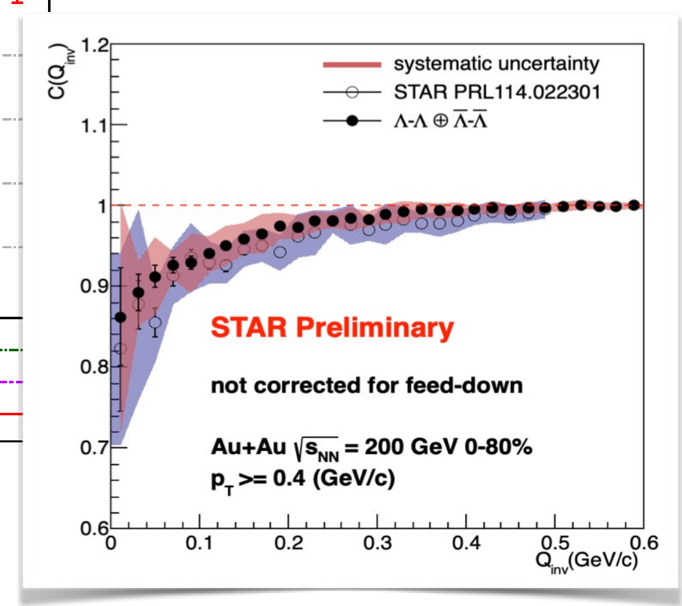
Morita, Furumoto, AO,PRC91('15) 024916. (Res.Source + flow)



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



Moe Isshiki+[STAR], preliminary.



Kamiya+, 2108.09644
w/ Lattice BB pot. at phys. m_q
CC effects with ΛΛ.

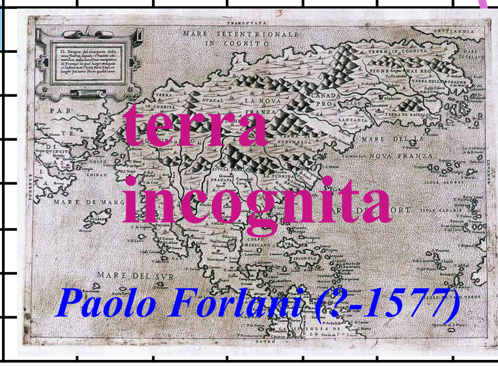
Scope of Femtoscopic study of HHI

pK⁻
Chiral CC pot. (examined)
Bound state (favored)

pΞ⁻
Lattice QCD CC pot. (examined)
Bound state (disfavored)

pΩ
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		
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										
+α														



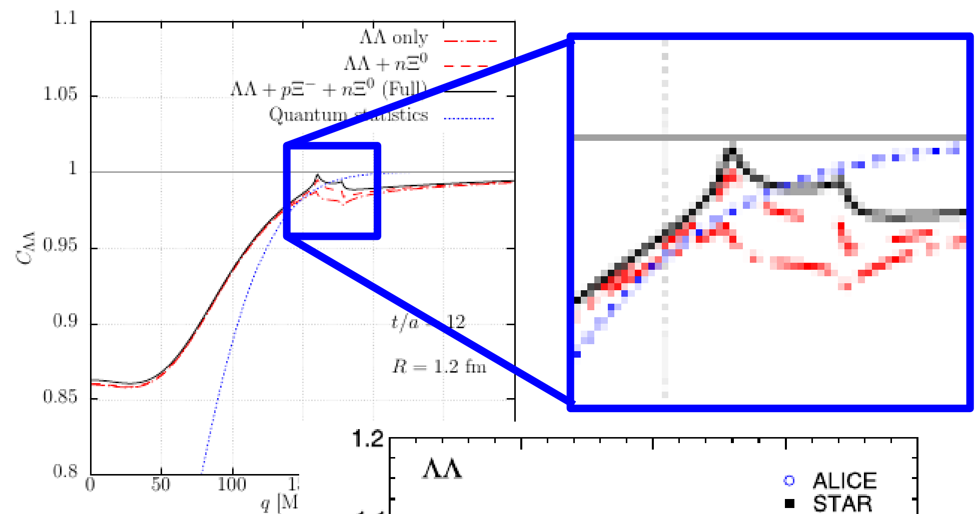
ΛΛ
Scattering pars. (a_0, r_{eff}) (constrained)
Bound state (disfavored)

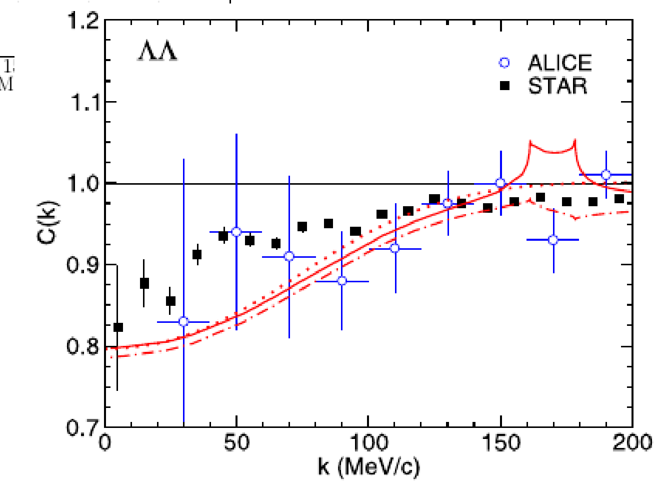
pD±
Chamed hadron-nucleon interaction (work in prog.)

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

Other bound states ?

- **ΛΛ-NΞ**
  - **$C_{\Lambda\Lambda}(q)$ in AA(RHIC) and pp(LHC) are similar (No b.s. below ΛΛ).**
  - **LQCD predicts a virtural pole near NΞ threshold, which can be detected as the cusp in $C_{\Lambda\Lambda}(q)$.**
    NLO(600) potential predicts the same.
    (The fate of H particle)
    K. Sasaki+[HAL QCD], NPA998('20)121737;
    Y. Kamiya+, 2108.09644; Haidenbauer('19).





- **$K^{bar}N$**
  - **Λ(1405) is believed to be the bound state of $K^{bar}N$ and "dip" is expected at $R \sim a_0$.**
  - **However, Coulomb and coupled-channel effects modify the dip-like behavior.**
    Kamiya+ ('20).