Hadron-hadron correlation and interaction from high-energy nuclear collisions

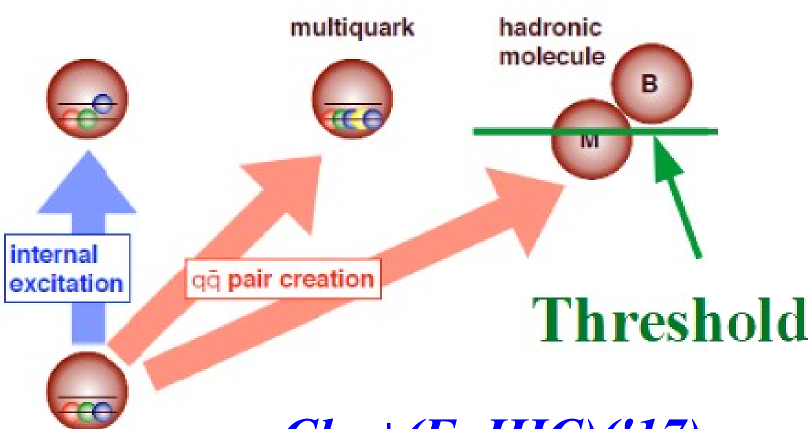
Akira Ohnishi (YITP, Kyoto U.)

The 15th Hadron Spectroscopy Cafe
"Hadron interactions and Exotics in Heavy Ion collisions",
Jan. 10, 2020, Tokyo Institute of Technology

K. Morita, T. Furumoto, AO, PRC91('15)024916 (ΛΛ)
AO, K. Morita, K. Miyahara, T. Hyodo, NPA954 ('16)294 (ΛΛ, K^-p)
K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R) (ΩN)
S. Cho et al. (ExHIC Collab.), Prog.Part.Nucl.Phys.95('17)279 (ΛΛ, K^-p)
T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17)856 (Ξ^-p)
K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101('20)015201 [1908.05414] (NΩ, ΩΩ)
Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise arXiv:1911.01041 [nucl-th] (K^-p)

Hadron Physics at High-Energy Colliders ?

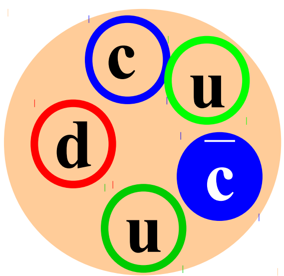
- **High-Energy Nuclear Collisions ($\sqrt{s_{NN}}$=40 GeV – 14 TeV) as a Hadron Factory**
  - **Higgs, BSM, SUSY, QGP, …**
  - **dN/dy ~ 1000 (RHIC, Au+Au) → 10^3-10^5 hadrons in one event**
  - **Various hadrons, nuclei (A<= 4) and anti-nuclei are formed.**
  - **Yield ~ Stat. Model calc.**
    (Formation processes are too complicated to be out of statistical.)
- **Trend in Hadron physics**
  - **Quark-gluon structure of hadrons (Multi-quark or Hadronic molecule)**
  - **Hadrons with heavy-quarks**
  - **Hadron-Hadron interaction**
    ΛN, ΣN, ΛΛ, ΞN, $\bar{K}$N, ….
  - **Hadrons in nuclear matter / EOS of nuclear matter**



Cho+(ExHIC)('17)

Compact Multiquark State or Hadronic Molecule

- **The answer may be “the superposition” (for pentaquarks) !**
  Y. Yamaguchi, H. García-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, arXiv:1907.04684



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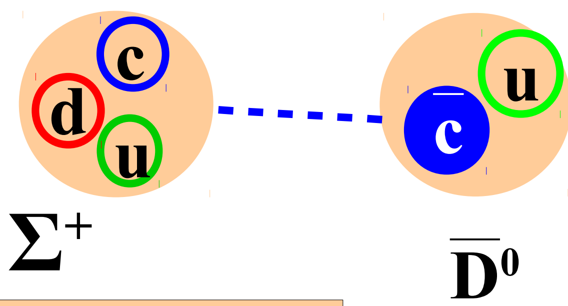
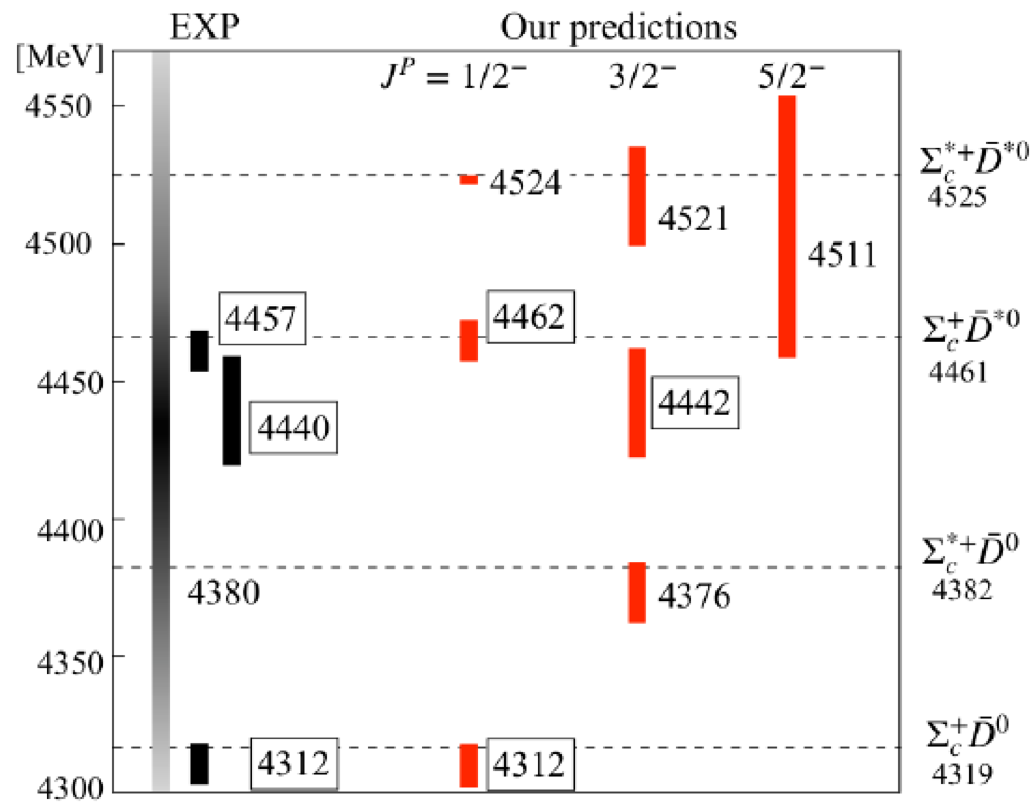


Pc (4xxx)

To confirm the structure, we need to understand scatt. amp. or potential via inv. mass spec. or corr. fn. !

E.g. Y. Ikeda et al. (HAL QCD), PRL117(‘16)242001 (Zc(3900))



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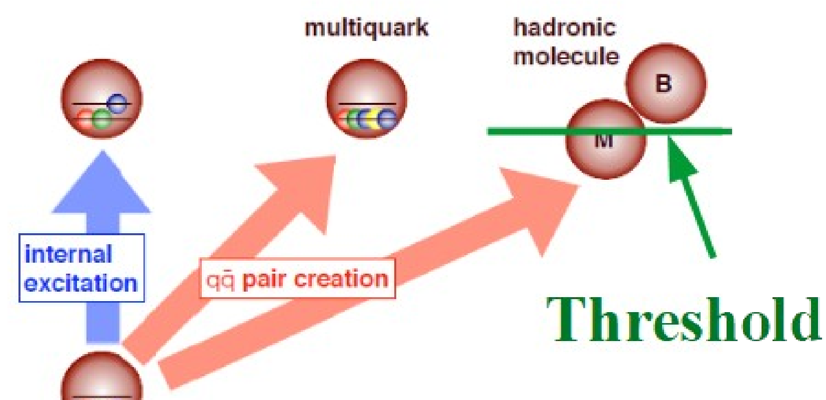
Corr. Fn.



Cho+('17)

Outline

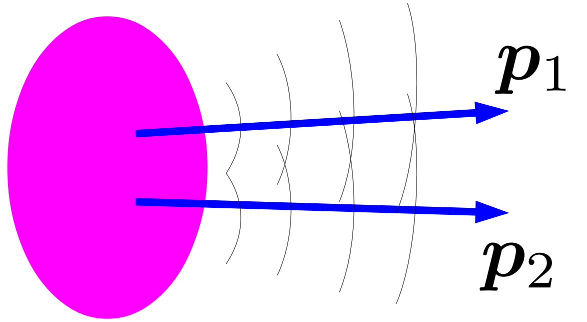
- Generic introduction: Hadron physics at Colliders ?
- Correlation function and interaction
  - Two ways to use the correlation function
  - Scattering length dependence of the correlation function
- Baryon-Baryon Interaction and Correlation Function
  - Where is dibaryon ?
  - pΩ correlation from lattice QCD potential, STAR and ALICE.
  - ($\Lambda\Lambda$, pΞ and $\Omega\Omega$ correlations)
- Kaon-Nucleon Interaction and Correlation Function
  - Coupled Channels Effects on Corr. Fn.
  - $\bar{K}$N potential and correlation from chiral SU(3) dynamics and K^-p correlation from ALICE
- Summary

Correlation Function and Interaction

Correlation Function

- **Emitting source function**

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



- **Two-particle momentum dist.**
  - **Assumption: Two particles are produced independently, and the correlation is generated by the final state int.**
    Koonin('77), Pratt+('86), Lednicky+('82)

$$N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2) \simeq \int d^4x d^4y S_1(x, \boldsymbol{p}_1) S_2(y, \boldsymbol{p}_2) \underline{|\Psi_{\boldsymbol{p}_1, \boldsymbol{p}_2}(x, y)|^2}$$

two-body w.f.

$$\simeq \int d^4x d^4y S_1(x, \boldsymbol{p}_1) S_2(y, \boldsymbol{p}_2) \underline{|\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2}$$

relative w.f.

- **Correlation function**

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{N_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)}{N_1(\boldsymbol{p}_1) N_2(\boldsymbol{p}_2)} \simeq \int d\boldsymbol{r} S_{12}(\boldsymbol{r}) |\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2$$

Correlation Function

- **Example: Free identical bosons (spin 0, non-relativistic), Gaussian source (static, simultaneous, spherical)**

$$S(\boldsymbol{x},\boldsymbol{p}) \propto \exp\left[-\frac{\boldsymbol{x}^2}{2R^2}-\frac{\boldsymbol{p}^2}{2MT}\right]$$

$$S(\boldsymbol{x},\boldsymbol{p}_1)S(\boldsymbol{y},\boldsymbol{p}_2) \propto \exp\left[-\frac{\boldsymbol{R}_{\rm cm}^2}{R^2}-\frac{\boldsymbol{r}^2}{4R^2}-\frac{\boldsymbol{P}^2}{4MT}-\frac{\boldsymbol{q}^2}{2\mu T}\right]$$

$$\Psi_{\boldsymbol{p}_1,\boldsymbol{p}_2}(\boldsymbol{x},\boldsymbol{y}) \propto \frac{1}{\sqrt{2}}\left[e^{i\boldsymbol{p}_1\cdot\boldsymbol{x}+i\boldsymbol{p}_2\cdot\boldsymbol{y}}+e^{i\boldsymbol{p}_1\cdot\boldsymbol{y}+i\boldsymbol{p}_2\cdot\boldsymbol{x}}\right]$$
$$= e^{i\boldsymbol{P}\cdot\boldsymbol{R}_{\rm cm}} \times \sqrt{2}\cos\boldsymbol{q}\cdot\boldsymbol{r}$$

- **Correlation function**

$$C(\boldsymbol{q}) = (4\pi R^2)^{-3/2}\int d\boldsymbol{r}\exp\left[-\frac{\boldsymbol{r}^2}{4R^2}\right]2\cos^2\boldsymbol{q}\cdot\boldsymbol{r}$$
$$= 1+\exp(-4q^2R^2)$$

Correlation Function → Source Size

How can we measure the radius of a star ?

- **Two photon intensity correlation**
  Hanbury Brown & Twiss, Nature 10 (1956), 1047.
  - **Simultaneous two photon observation probability is enhanced from independent emission cases**
    → angular diameter of Sirius=6.3 msec

Recent data (Wikipedia) 5.936±0.016 msec

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN
Jodrell Bank Experimental Station, University of Manchester
AND
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock

NATURE November 10, 1956 VOL. 178

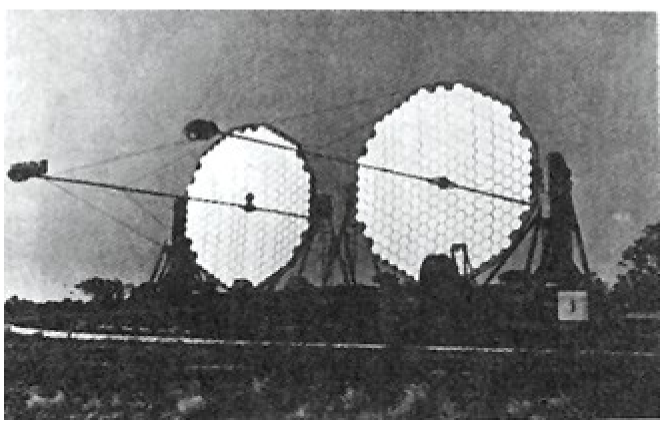
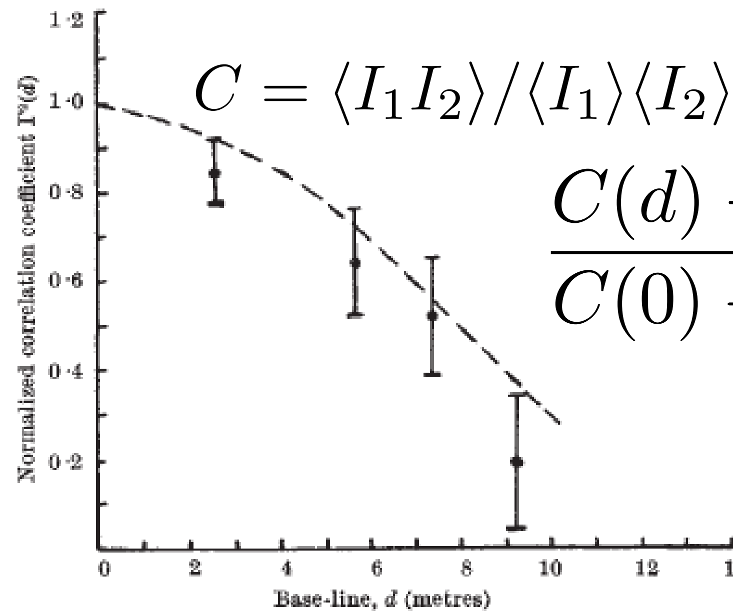


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

HBT telescope (from Goldhaber, ('91))



$$C = \langle I_1 I_2 \rangle / \langle I_1 \rangle \langle I_2 \rangle$$

$$\frac{C(d)-1}{C(0)-1}$$

Fig. 2. Comparison between the values of the normalized correlation coefficient Γ²(d) observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

HBT ('56)

Two particle intensity correlation

- **Wave function symmetrization from quantum statistics**

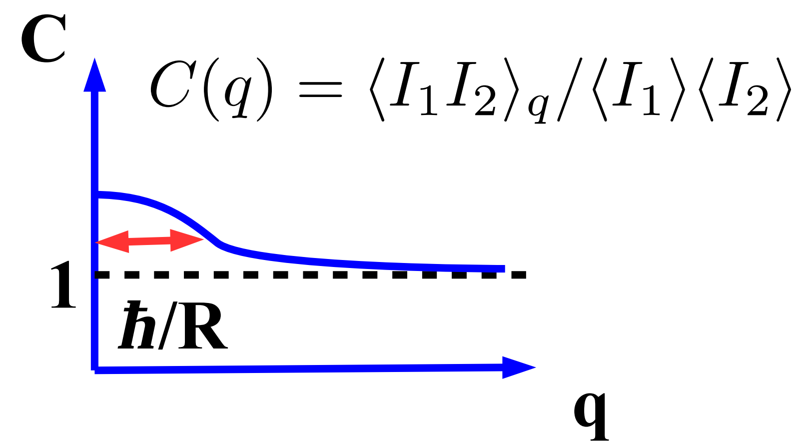
$$C(\mathbf{q}) = \int d^3r\, S(\mathbf{q},\mathbf{r}) \left| \frac{1}{\sqrt{2}} (e^{i\mathbf{q}\cdot\mathbf{r}} + e^{-i\mathbf{q}\cdot\mathbf{r}}) \right|^2 \simeq 1 + \exp(-4q^2R^2)$$

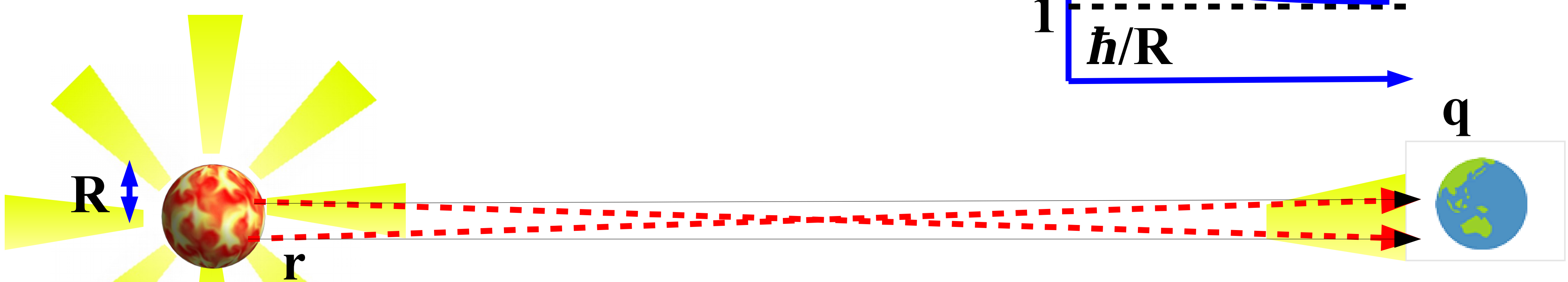
Source fn.
(r=relative coordinate)

(symmetrized w.f.)^2

Static spherical source case

→ **Small relative momenta are favored due to symmetrization of the relative wave function.**

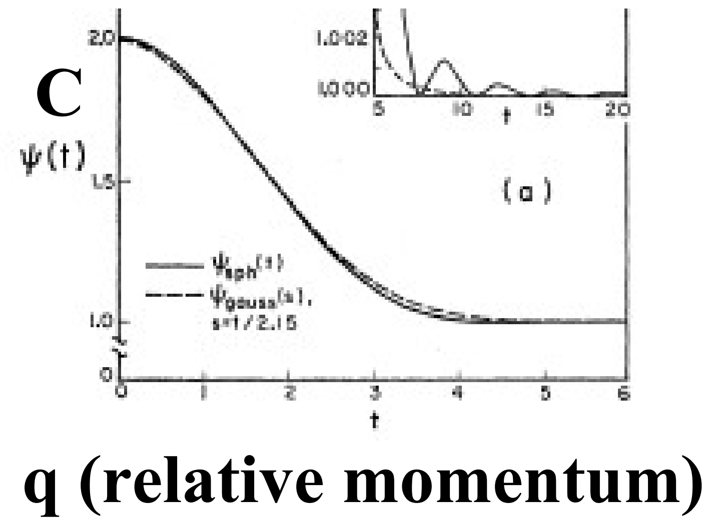




Momentum
$q=(p_1-p_2)/2$

How can we measure source size in nuclear reactions ?

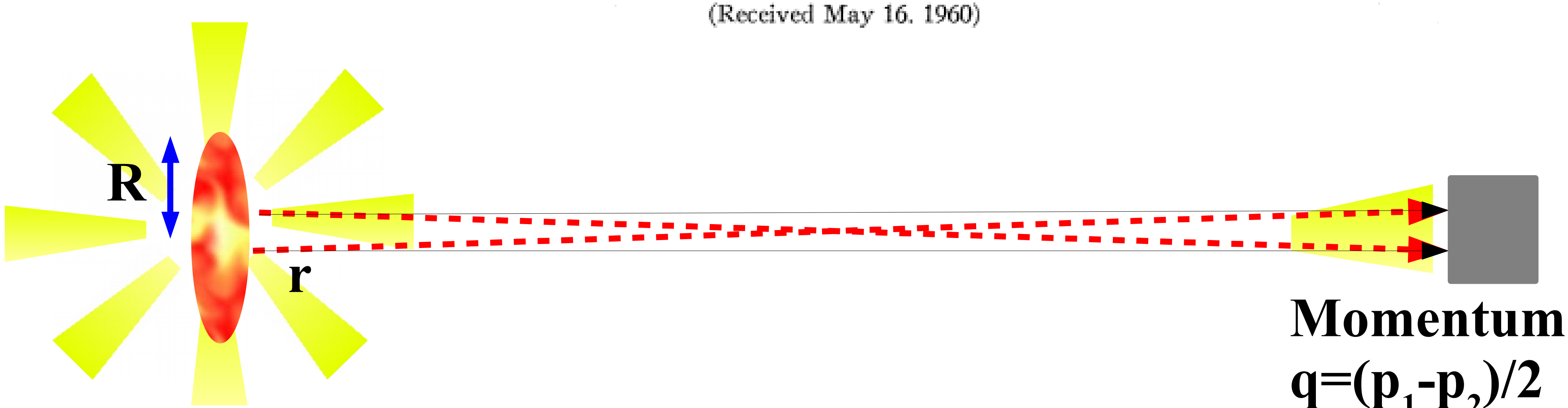
- **Two pion interferometry**
  G. Goldhaber, S. Goldhaber, W. Lee,
  A. Pais, Phys. Rev. 120 (1960), 300
  - **Two pion emission probability is enhanced at small relative momenta**
    → Pion source size ~ 0.75 ℏ / μc



PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

GERSON GOLDHABER, SULAMITH GOLDHABER, WONYONG LEE, AND ABRAHAM PAIS†
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received May 16. 1960)



Femtoscopic Study of Hadron-Hadron Interaction

- **HBT, GGLP: Corr. Fn. + w.f. → Source Size**
  Another way: Corr. Fn. + Source Size
  → wave function → hadron-hadron interaction
- **Effect of hadron-hadron interaction on the wave function**
  - **Assumption: Only s-wave (L=0) is modified.**
  - **Non-identical particle pair, Gauss source.**

$$\varphi_{\boldsymbol{q}}(\boldsymbol{r}) = e^{i\boldsymbol{q}\cdot\boldsymbol{r}} - j_0(qr) + \chi_q(r)$$

$$\to C(\boldsymbol{q}) = \int d\boldsymbol{r} S(r) |\varphi_{\boldsymbol{q}}(\boldsymbol{r})|^2$$

$$= 1 + \int d\boldsymbol{r} S(r) \left\{ |\chi_q(r)|^2 - |j_0(qr)|^2 \right\}$$

K. Morita, T. Furumoto, AO, PRC91('15)024916

Corr. Fn. shows how much squared w. f. is enhanced
→ Large CF is expected with attraction

Wave function around threshold (S-wave, attraction)

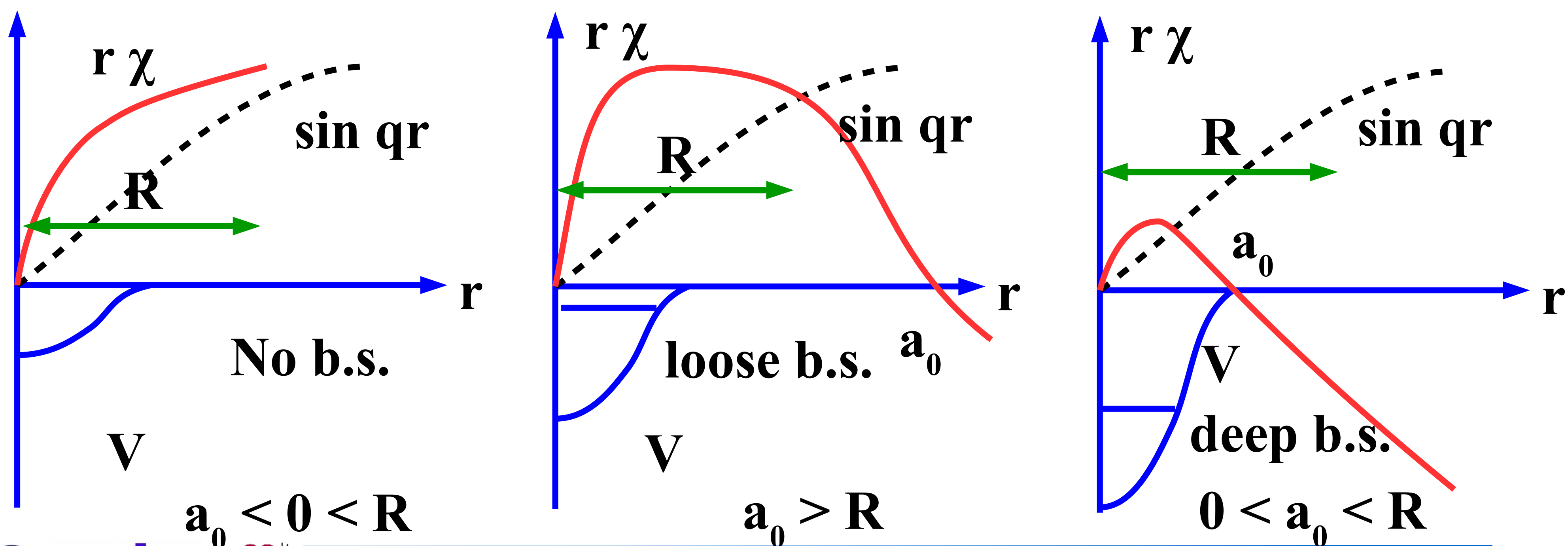
- **Low energy w.f. and phase shift**

$$u(r) = qr\chi_q(r) \to \sin(qr + \delta(q)) \sim \sin(q(r - a_0))$$

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

a_0 =scatt. length
r_{eff}=eff. range

- **Wave function grows rapidly at small r with attraction.**
- **With a bound state (a_0>0), a node appears around r=a_0**



Lednicky-Lyuboshits (LL) model

- **Lednicky-Lyuboshits analytic model**
  - **Asymp. w.f. + Eff. range corr. + $\psi^{(-)} = [\psi^{(+)}]^*$**

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

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

$$(x = 2qR, R = \text{Gaussian size}, \ F_1, F_2, F_3 : \text{Known functions})$$

- **Phase shifts**

$$q\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}q^2 + \mathcal{O}(q^4) \to \delta \simeq -a_0 q + {\rm O}(q^3)$$

$$\sin(qr+\delta) \simeq \sin(q(r-a_0)+\cdots)$$

Node at r ~ a_0 for small q

C(q) in the low momentum limit

- **Correlation function at small q (and r_{eff}=0) → F_1=1, F_2=0, F_3=1**

$$\Delta C_{\rm LL}(q) \to \frac{|f(0)|^2}{2R^2} + \frac{2{\rm Re}f(0)}{\sqrt{\pi}R} \quad (q \to 0)$$

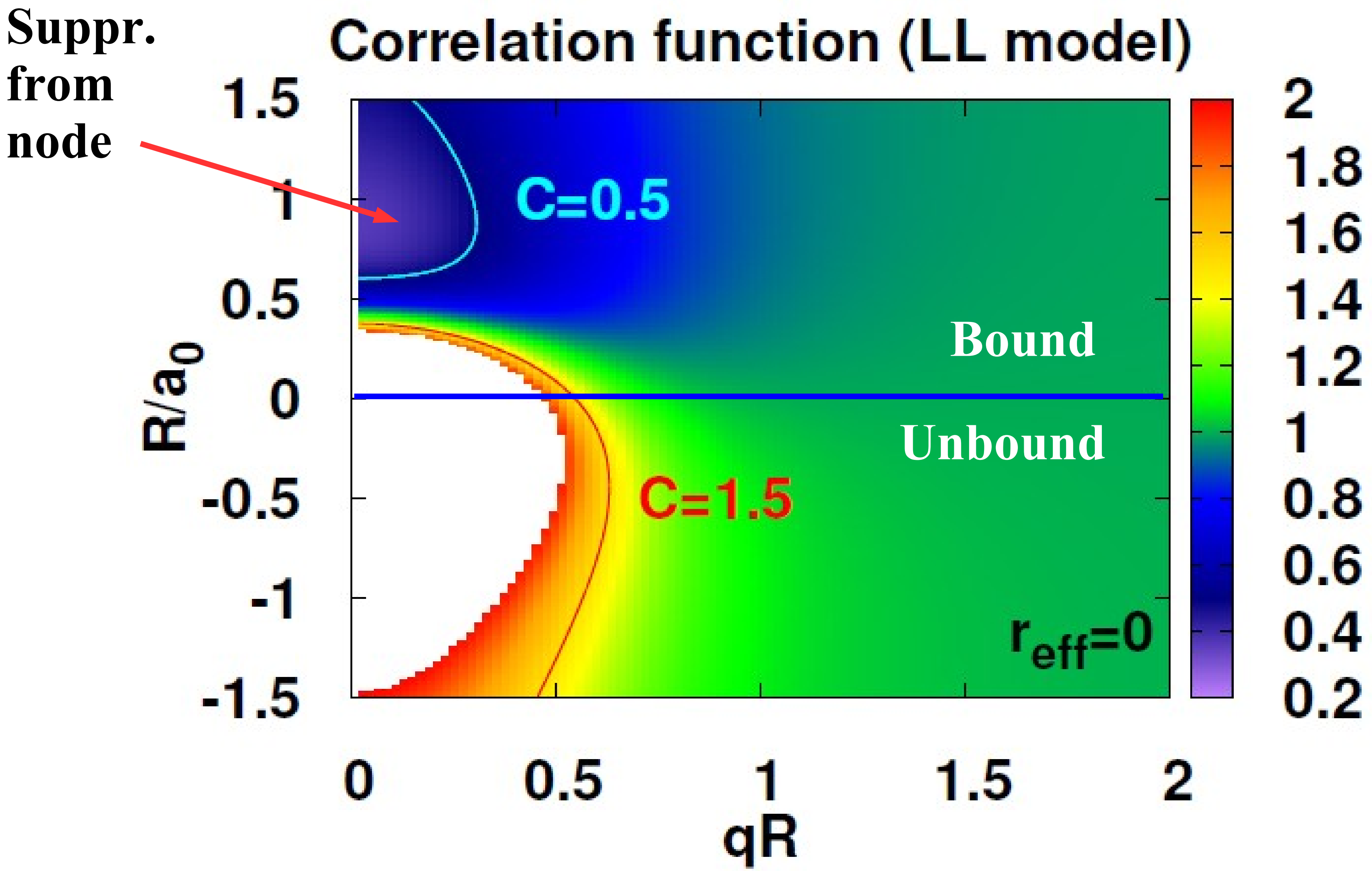
$$f(q) = (q\cot\delta - iq)^{-1} \simeq \left(-\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}q^2 - iq\right)^{-1} \to -a_0$$

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

$$1 - 2/\pi \simeq 0.36, \ \sqrt{\pi}/2 \simeq 0.89$$

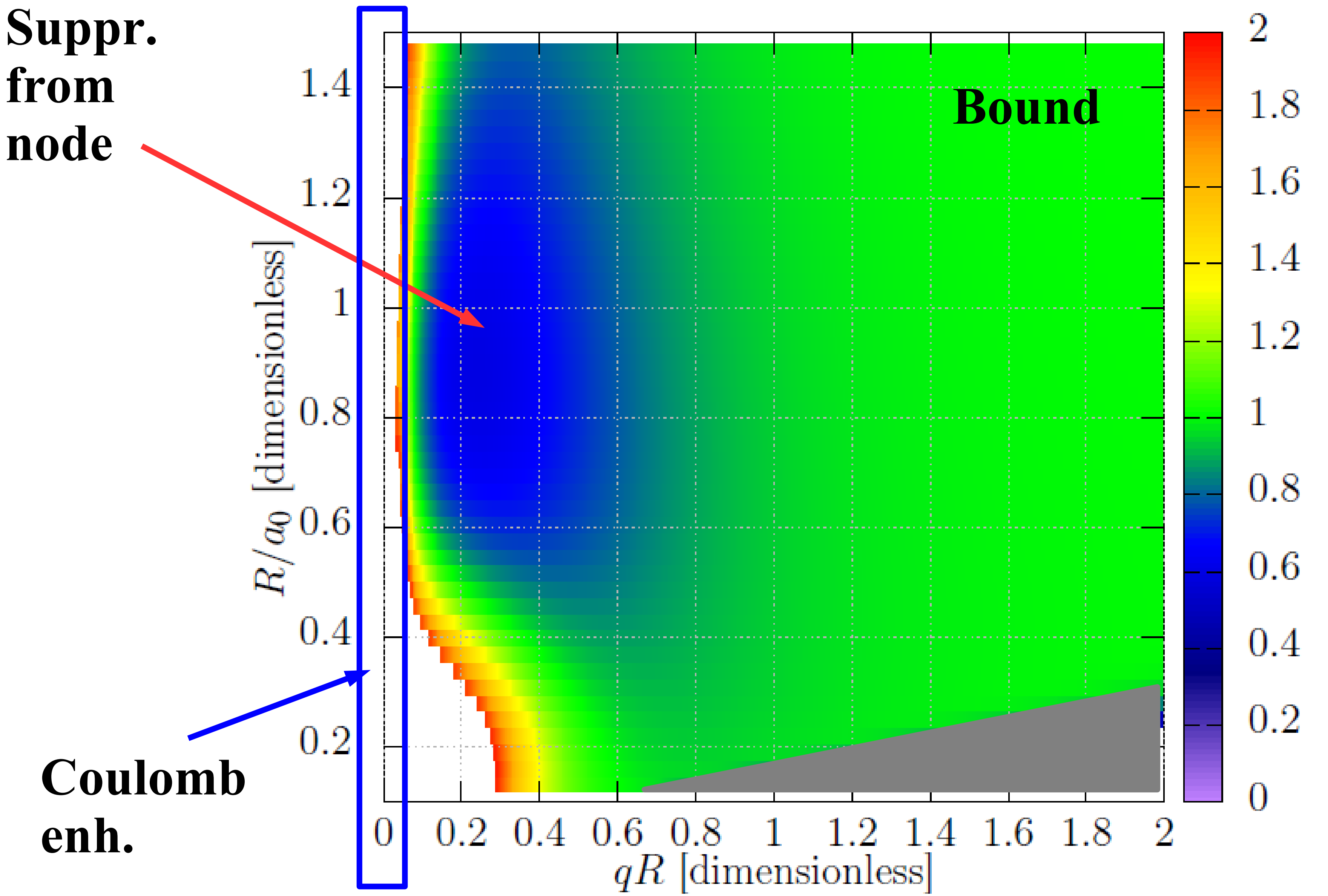
C(q → 0) takes a minimum of 0.36 at R/a_0 = 0.89 in the LL model.

Correlation Function in LL model



LL model: R. Lednicky, V. L. Lyuboshits ('82)
Similar Fig. is shown in AO, K. Morita, K. Miyahara, T. Hyodo, NPA954('16), 294.

Correlation Function with Gaussian source



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

Femtoscopic study of Hadron-Hadron Interaction

- **Correlation Function is sensitive to interaction and source (size).**
  - **If you know the source (size), it is possible to constrain the interaction parameters such as scattering length (a_0) and effective range (r_{eff}).**
- **Source size dependence of the Correlation Function**
  - **Corr. Fn. is enhanced at any R for negative a_0. (w/o bound state)**
  - **Corr. Fn. is enhanced at $R < a_0$ and suppressed at $R \sim a_0$ for positive a_0. (w/ bound state or repulsive int.)**
  - **With repulsive int., $a_0 \sim r_c$ (hard core radius), and cannot be large, and coupled channels effects generally enhances corr. fn.**
- **And many experimental data are coming…**

Recent Measurement of Hadron-Hadron Corr. Fn.

- **ΛΛ**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  S. Achara et al. (ALICE), PRC99('19), 024001; arXiv:1905.07209
  Th: K.Morita, T.Furumoto, AO, PRC91('15)024916;
  AO, K.Morita, K.Miyahara, T.Hyodo, NPA954 ('16), 294 (ΛΛ, K^-p)
  S. Cho et al. (ExHIC Collab.), Prog.Part.Nucl.Phys.95('17)279 (ΛΛ, K^-p)
  J. Haidenbauer, NPA981 ('19) 1 (ΛΛ, Ξ^-p, K^-p); Greiner,Muller('89); AO+('98)

- **Ω^-p**
  J. Adam et al. (STAR), PLB790 ('19) 490 [1808.02511]
  O. Vázquez Doce et al. (ALICE preliminary), Hadrons 2019
  Th: K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R)
  K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101('20)015201

- **Ξ^-p**
  S. Acharya et al. (ALICE), PRL123 ('19)112002
  Th: T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17)856; J. Haidenbauer ('19)

- **K^-p**
  S. Acharya et al. (ALICE), arXiv:1905.13470
  Th: AO+('16), S. Cho+(ExHIC)('17), J. Haidenbauer ('19)
  Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, arXiv:1911.01041

Baryon-Baryon Correlation Function (mainly on pΩ correlation)

Where is dibaryon ?

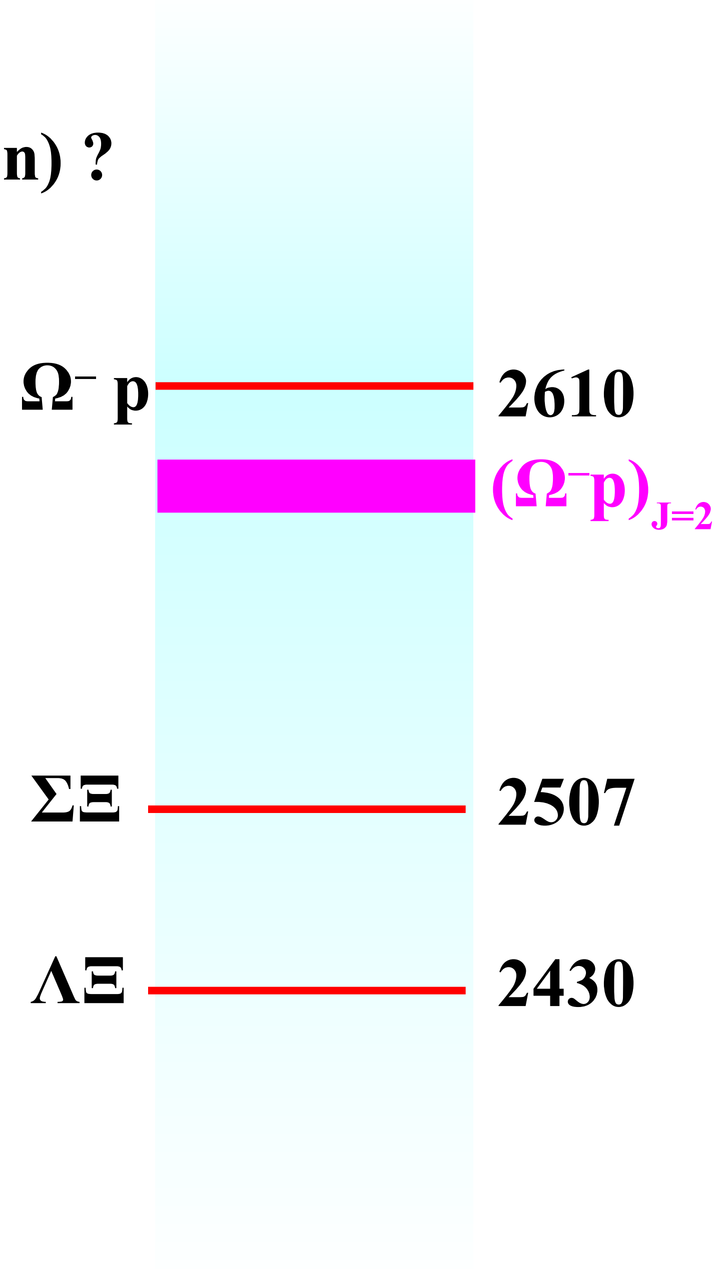
- **Deuteron = First dibaryon (pn bound state)**
- **H-particle: 6-quark state (uuddss)**
  - **Predicted (*Jaffe ('77)*), Ruled-out (ΛΛ nucl., *Takahashi+('01)*), Suggested as a resonance in exp. (*Yoon+ ('07)*) or as a bound state of ΞN (*HAL QCD ('16)*)**
- **Dibaryon would appear in channels, where *Oka ('88), Gal ('16)***
  - **The Pauli blocking of quarks does not operate,**
  - **and the Color-magnetic interaction is attractive**

Examples: H(=ΛΛ-NΞ-ΣΣ), NΩ, NΣ*, d*(=ΔΔ).

Let us examine the existence of dibaryon states by using the correlation function !

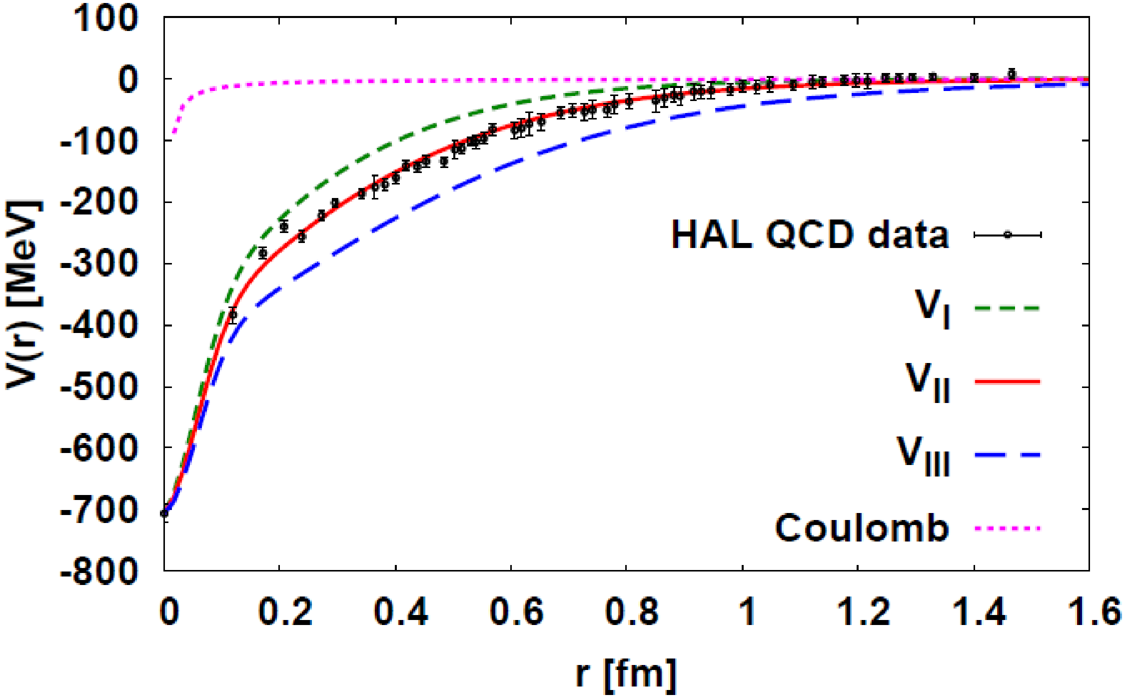
Ω N dibaryon

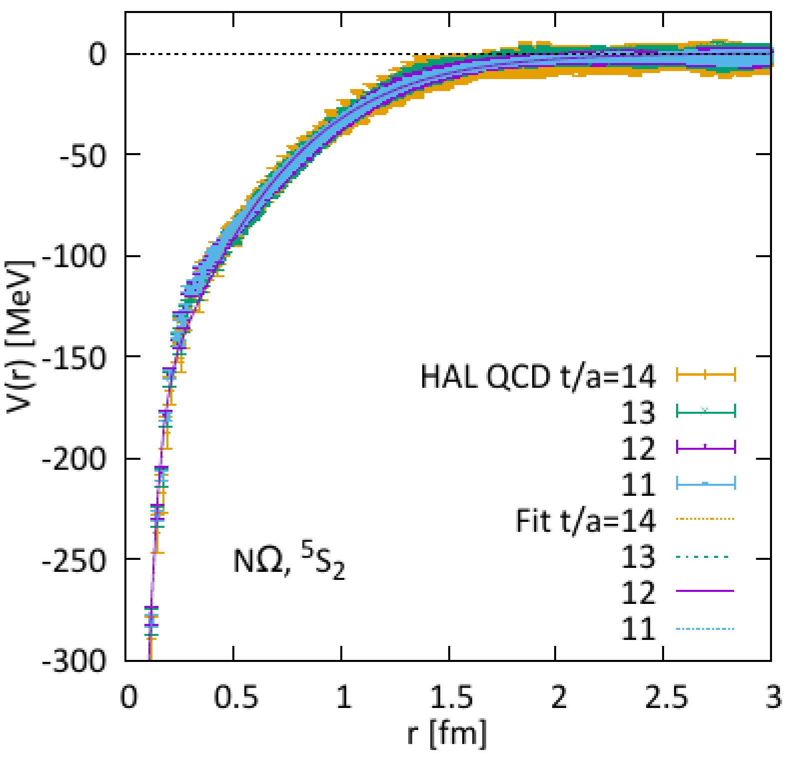
- Ω : sss, Jπ=3/2+, M=1672 MeV
- Is there an ΩN bound state (S= –3 dibaryon) ?
  - Predicted as a dibaryon candidate
    Goldman+ (‘87), Oka ('88), Gal ('16)
  - Lattice QCD predicts a bound state with narrow width for J=2 ($^5S_2$)
    (Coupling to octet-octet with L=2)
    Etminan+ (HAL QCD)('14),
    Iritani+ (HAL QCD) (‘19)
  - Meson exchange potential is also proposed
    T. Sekihara, Y. Kamiya, T. Hyodo, PRC98 (‘18) 015205
  - Correlation function is measurable !
    Adam+ (STAR)(‘19), ALICE, in prep.



ΩN potential from lattice QCD

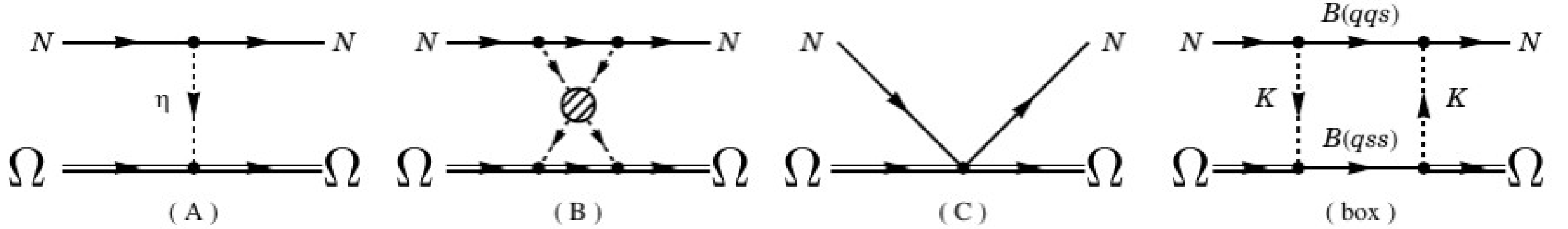
- **ΩN potential by HAL QCD Collab. (J=2)**
  - **m_π=875 MeV, B.E.~ 0.63 MeV**
    F.Etminan et al. (HAL QCD Collab.), NPA928('14)89.
  - **m_π=146 MeV, B.E.~ 2.2 MeV**
    T. Iritani et al. (HAL QCD Collab.), PLB 792('19)284.

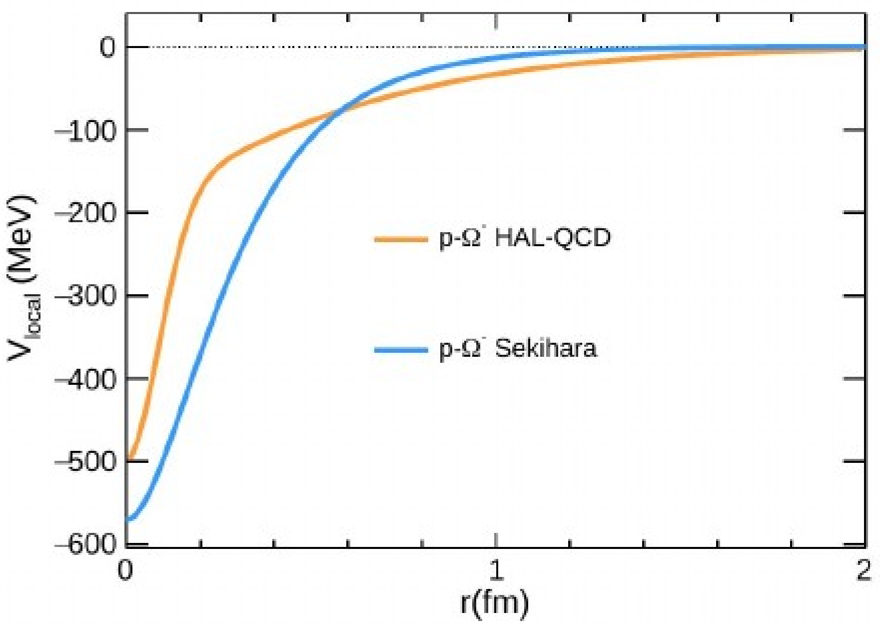




Meson Exchange Potential

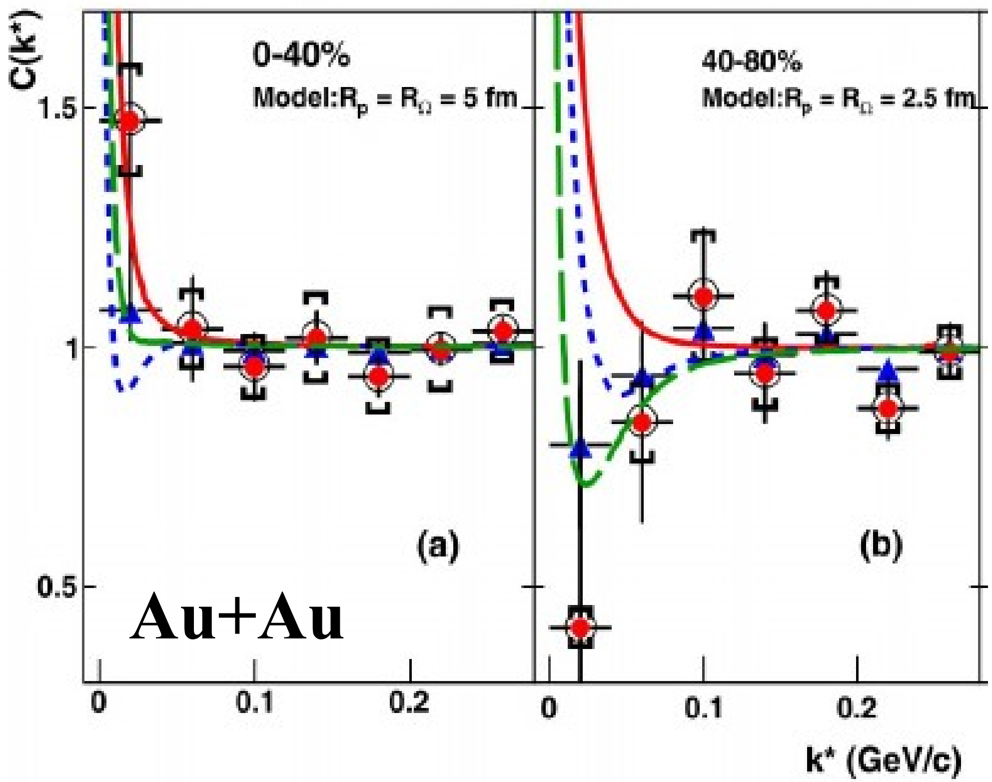
- **Meson exchange NΩ potential**
  T. Sekihara, Y. Kamiya, T. Hyodo, PRC98 ('18) 015205
  - **η meson exchange, σ exchange, contact term, box diagram.**
  - **Contact term is fitted to the scatt. length of HAL QCD potential.**

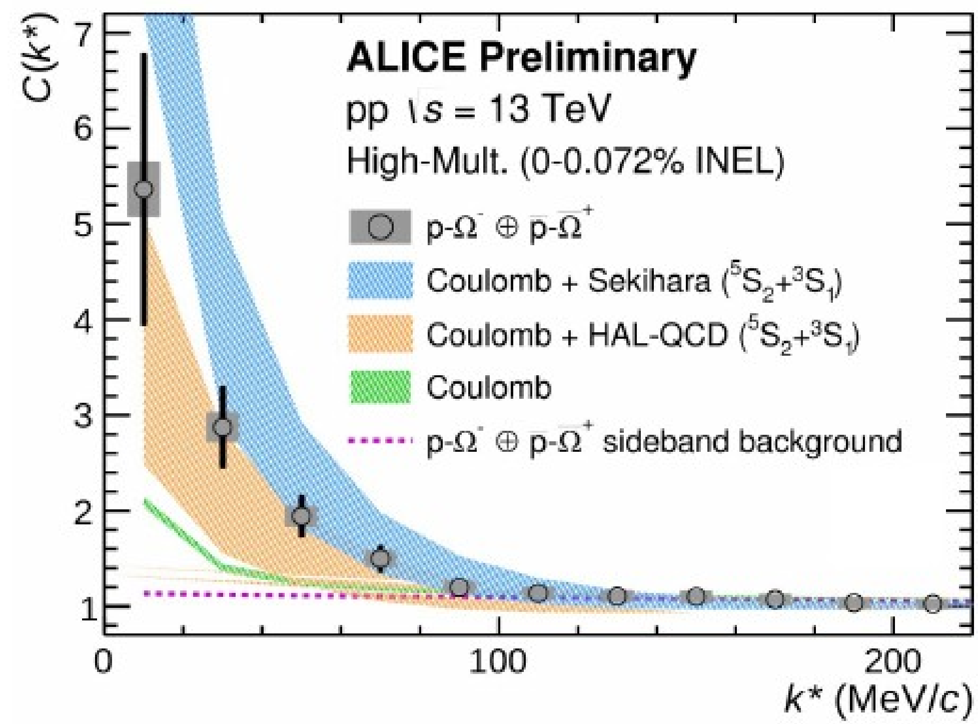




Ω^- p correlation function data

- **RHIC-STAR Collaboration**
  J. Adam et al. (STAR), PLB790 ('19) 490 [1808.02511]
- **LHC-ALICE Collaboration**
  O. Vázquez Doce et al. (ALICE, preliminary), Hadrons 2019





Suppressed & Enhanced Corr. Fn. at RHIC & LHC, resp.
Can we understand this difference ?
or Is one *(or both) of them wrong ?*

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PHYSICAL REVIEW C

covering nuclear physics

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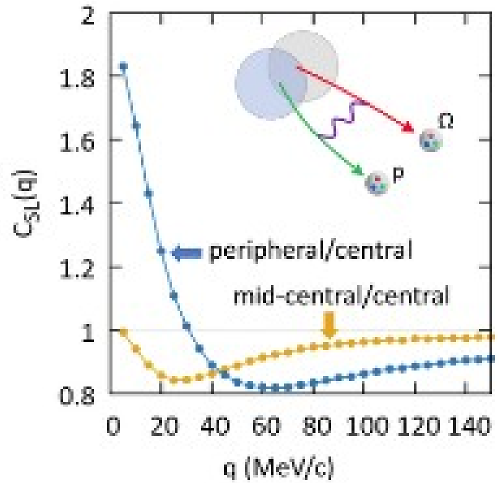


EDITORS' SUGGESTION

Probing ΩΩ and pΩ dibaryons with femtoscopic correlations in relativistic heavy-ion collisions

The authors investigate correlations between protons and Ω baryons, and between two Ω baryons, in heavy-ion collisions at RHIC and LHC. Given sufficient statistics in upcoming experiments, such measurements could provide valuable information on the existence of strange dibaryons and on the equation of state relevant to neutron stars.

Kenji Morita *et al.*

Phys. Rev. C **101**, 015201 (2020)

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101('20)015201

Calculation Details

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101('20)015201

- **NΩ potential from HAL QCD Collab.**
  Etminan+(HAL QCD) ('14), Iritani+ (HAL QCD)('19)
  - **J=1 potential is uncertain → Three models**
    Strong abs. at $r < r_0$ ($r_0 \sim 2$ fm) (*Morita+('16)*) (Standard)
    Complete absorption $\chi(J=1) = 0$ (Minimum)
    Same w.f. as that with J=2, $\chi(J=1) = \chi(J=2)$ (Reference)
  - **Statistical Error can be evaluated by using Jackknife potentials.**
- **Coulomb potential enhances CF even without strong int.**
  → Small-Large ratio of CF (*Morita+('16)*)
  - **Large source → Coulomb force dominate**
    Small source → Visible strong interaction effects
- **Source function: Blast wave, Gaussian source**

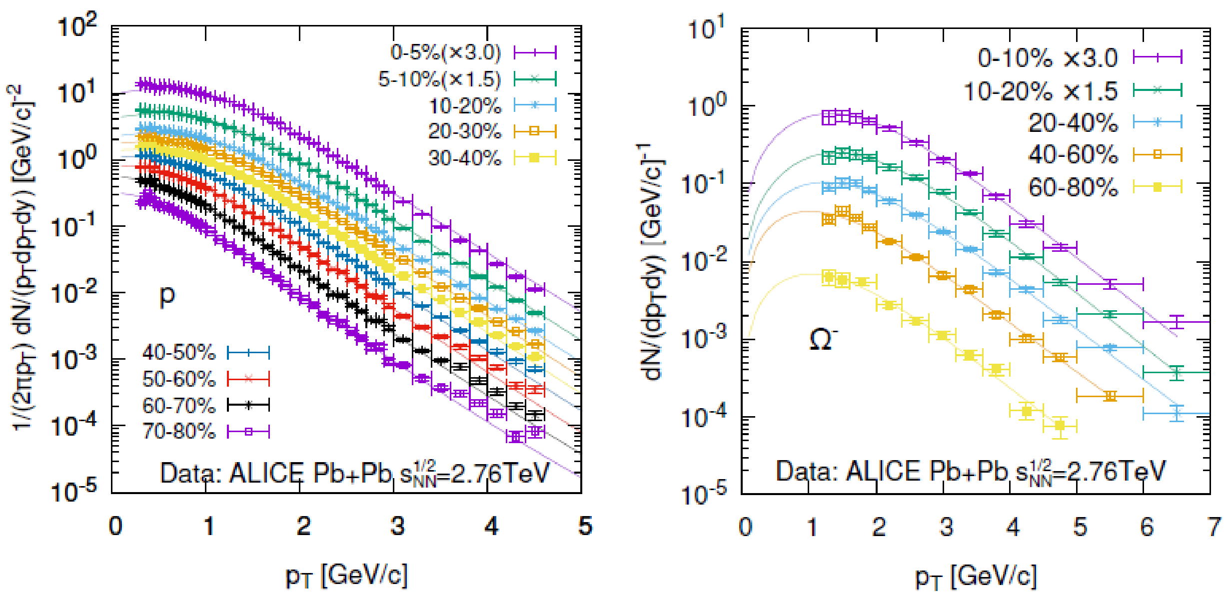
Emission Source Function

- **Gaussian Source ∝ exp(-r²/4R²), R=(0.8-4) fm [Simple and convenient]**
- **Expanding source model [Reasonably realistic]**

Flow velocity $u_\mu(x)$

$$d^4xS_i(x,p) = \tau_0 d\eta_s d^2 r_T \frac{d}{(2\pi)^3} n_f(u\cdot p, T) \exp\left(-\frac{r_T^2}{2R_T^2}\right)$$

Fermi dist.



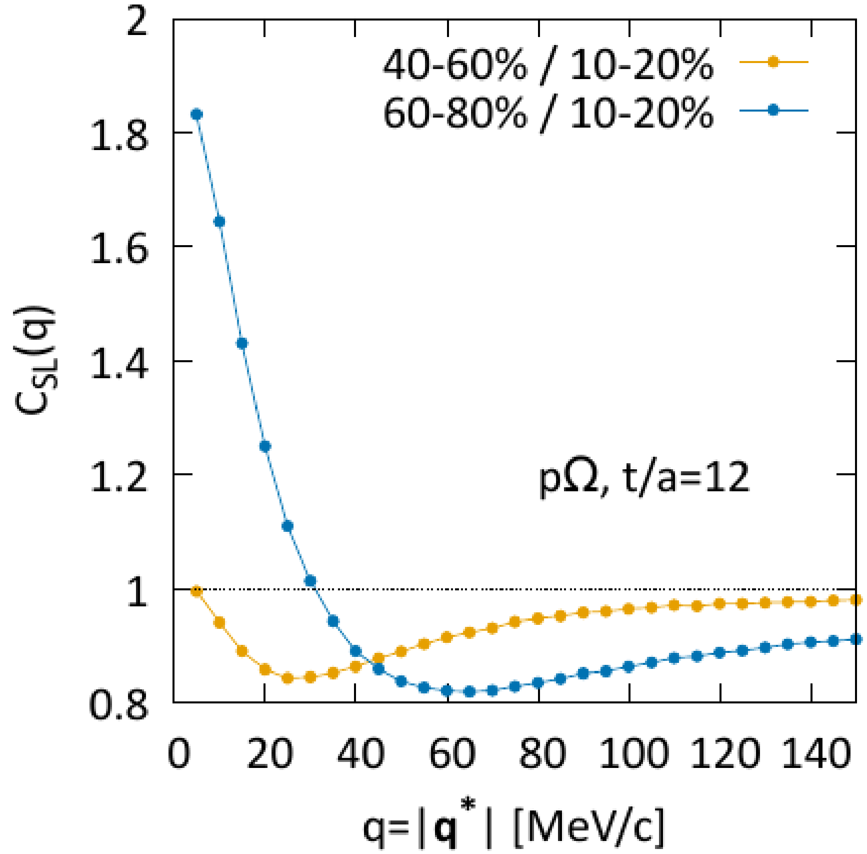
Morita+('20)

- **Transport model result [should be realistic] → Future work**

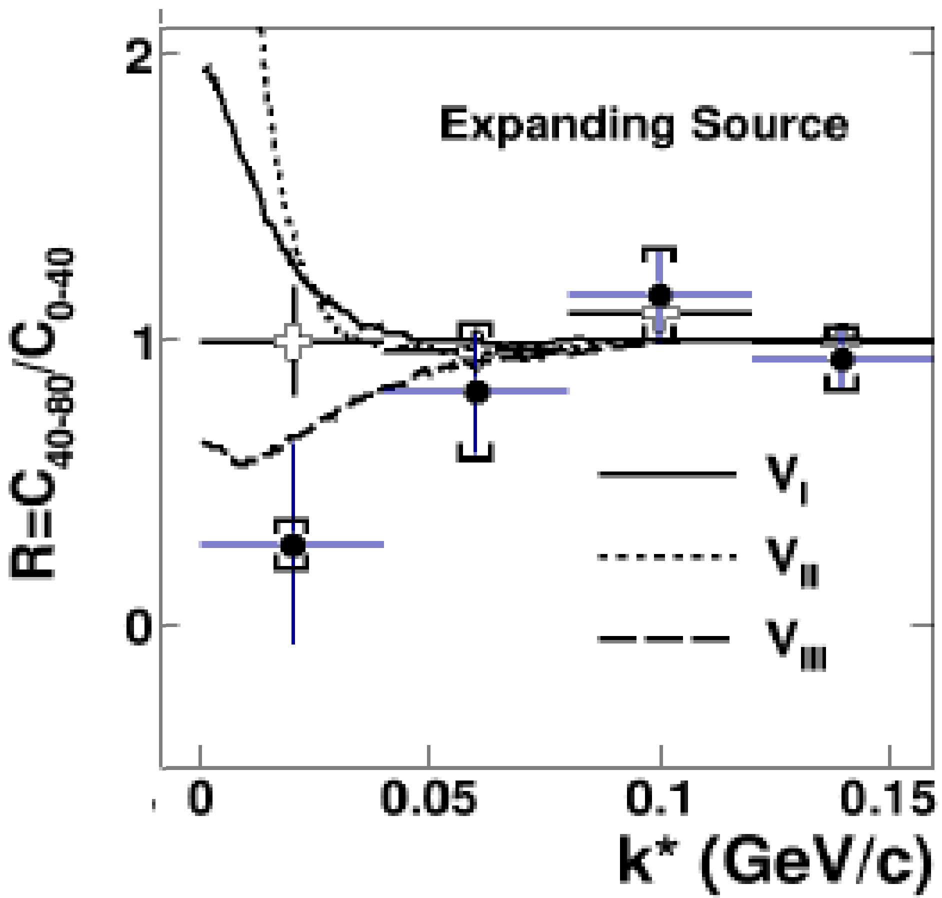
Comparison with STAR data

- **Results with potential at nearly physical quark mass (= between V_{II} and V_{III})**
  → Dip is seen but is not deep enough to explain STAR data.

Morita, Gongyo, Hatsuda, Hyodo, Kamiya, AO, PRC101('20)015201 [1908.05414]

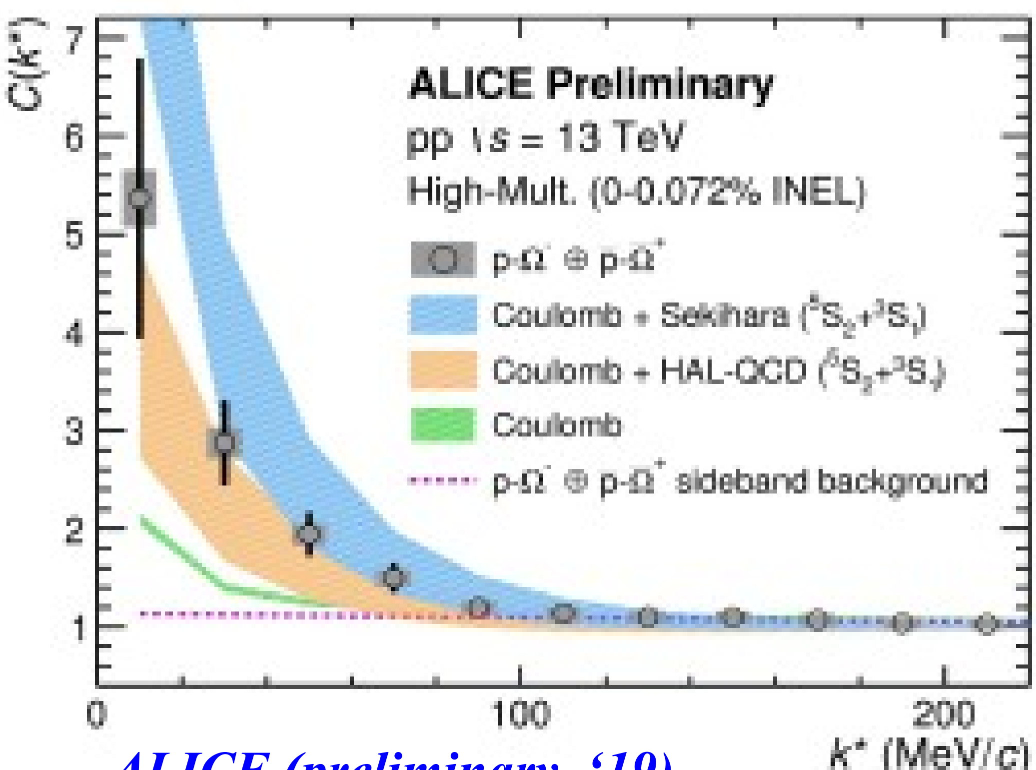


STAR (1808.02511, PLB790 ('19) 490)

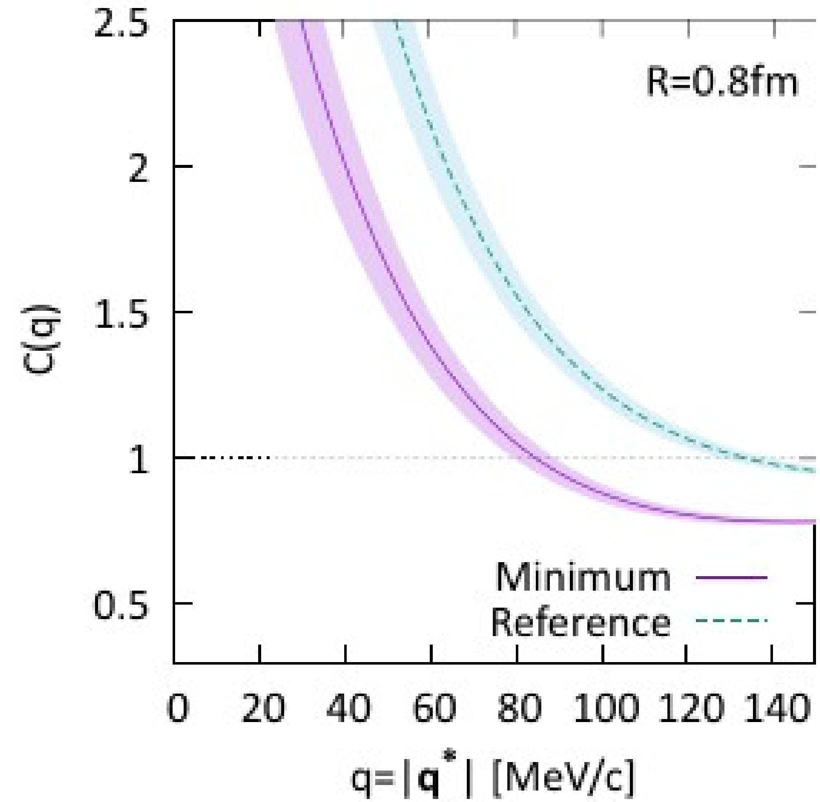


ALICE Preliminary

- **pp 13 TeV high-multiplicity events in ALICE**
  → Strong enhancement of CF at small q
  O. Vázquez Doce et al. (ALICE), Hadrons 2019
- **Lattice QCD potential roughly explains the data.**

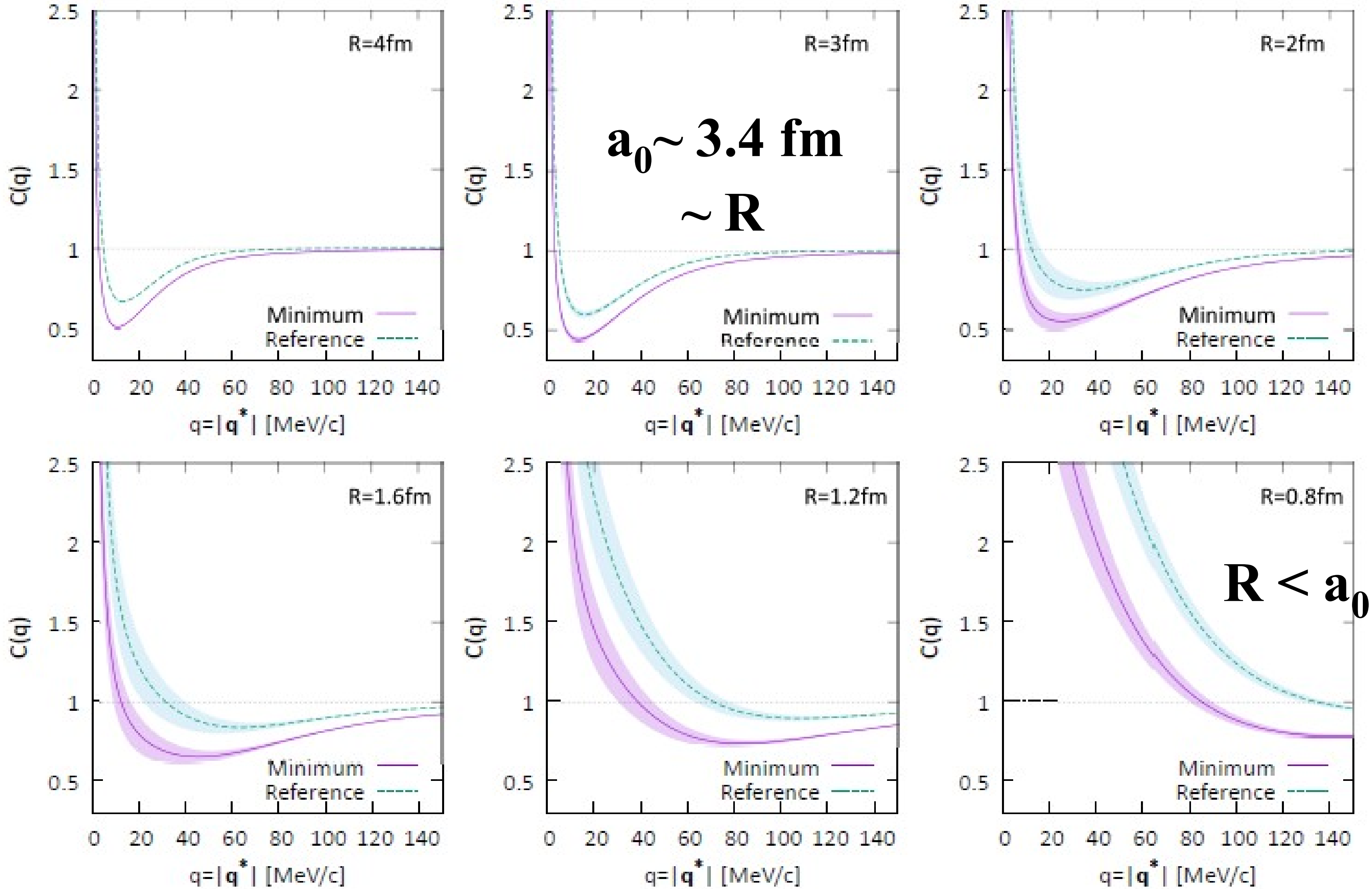


ALICE (preliminary, '19)



Morita+ ('20)

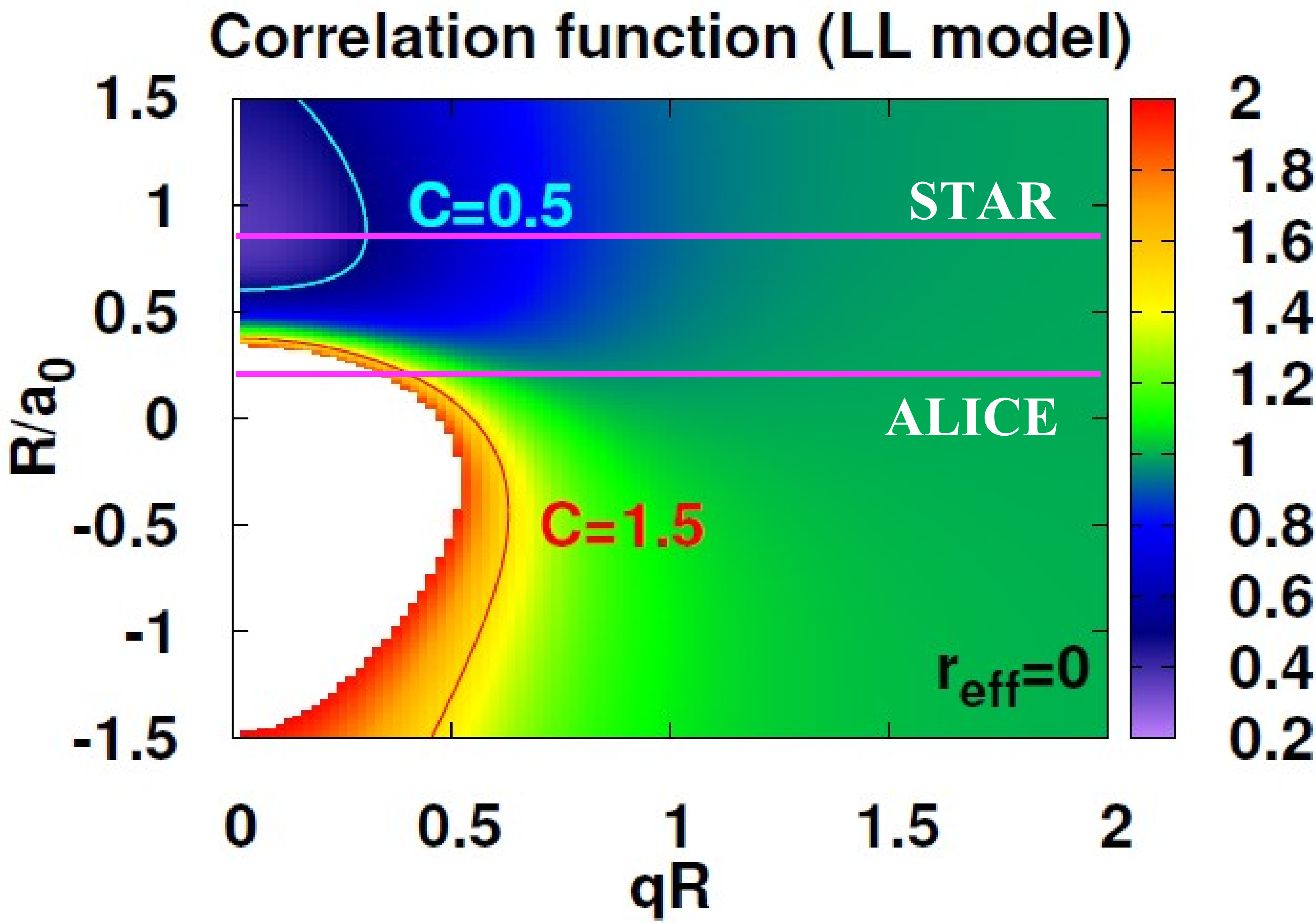
Source Size Dependence of Correlation Function



Gaussian Source

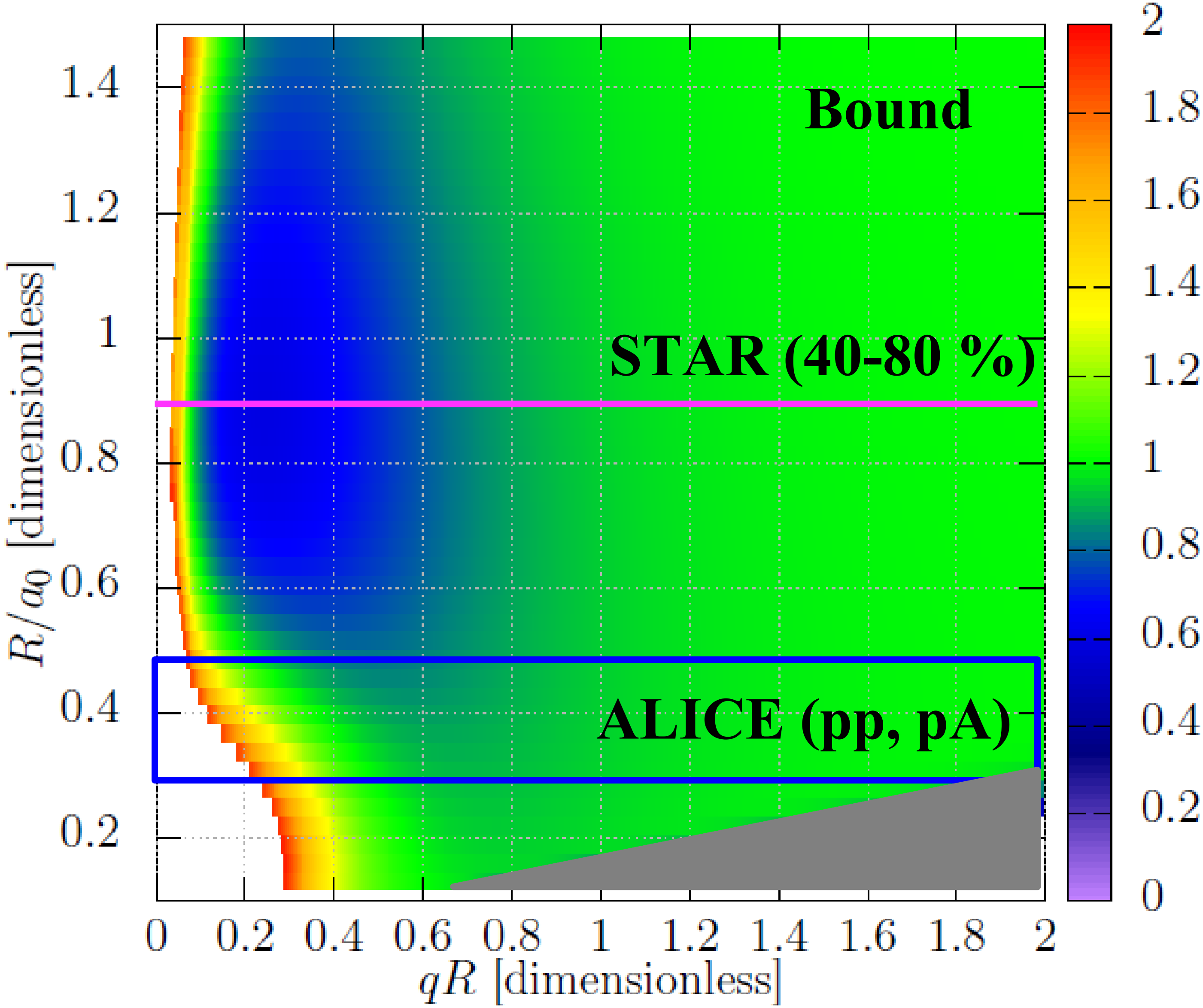
K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO ('20)

Correlation Function in LL model



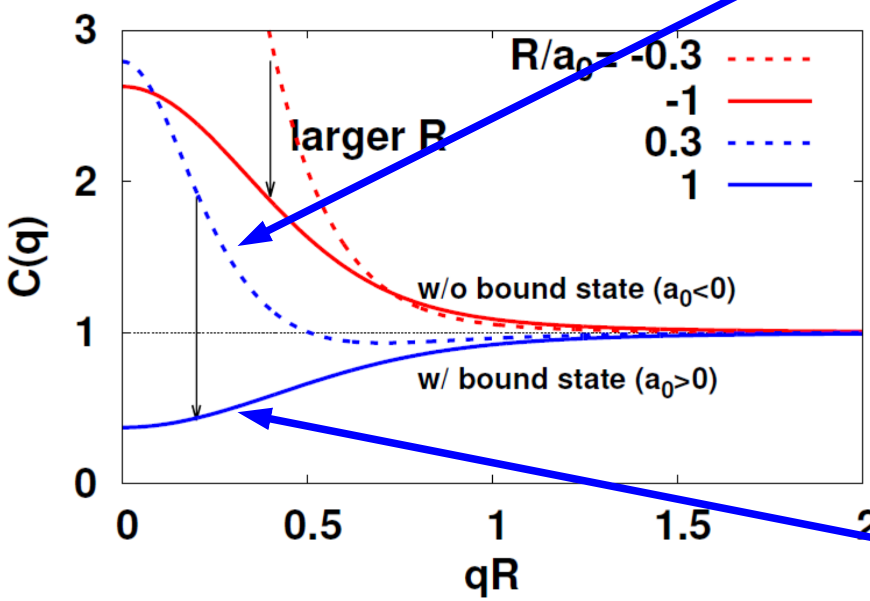
a_0 (pΩ)~ 3.4 fm, R(ALICE)~0.7 fm, R(STAR)~3 fm

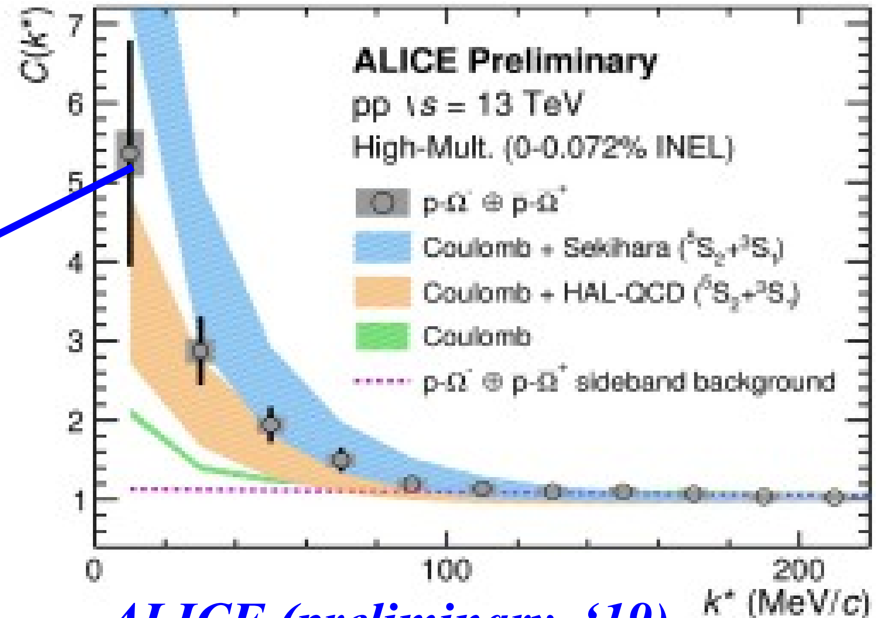
Correlation Function with Gaussian source



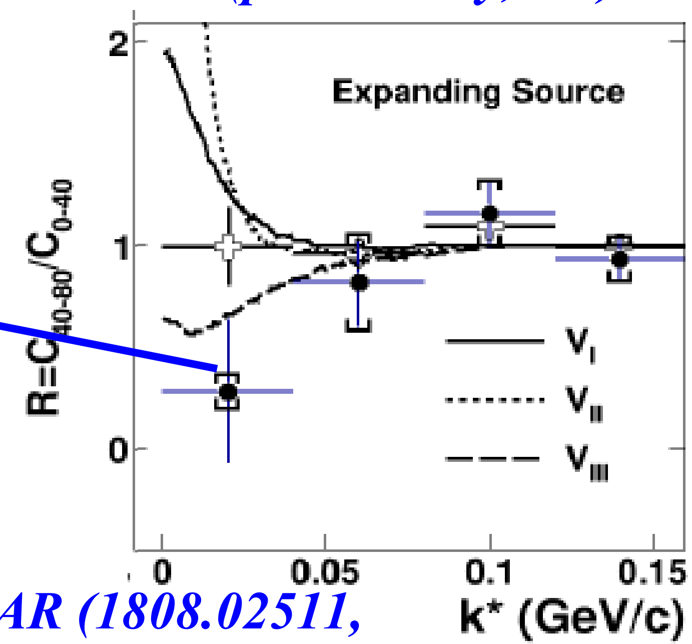
NΩ potential (J=2, HAL QCD, a_0=3.4 fm) + Coulomb

STAR + ALICE = NΩ Dibaryon





ALICE (preliminary, '19)



STAR (1808.02511, PLB790 ('19) 490)

STAR + ALICE = NΩ Dibaryon

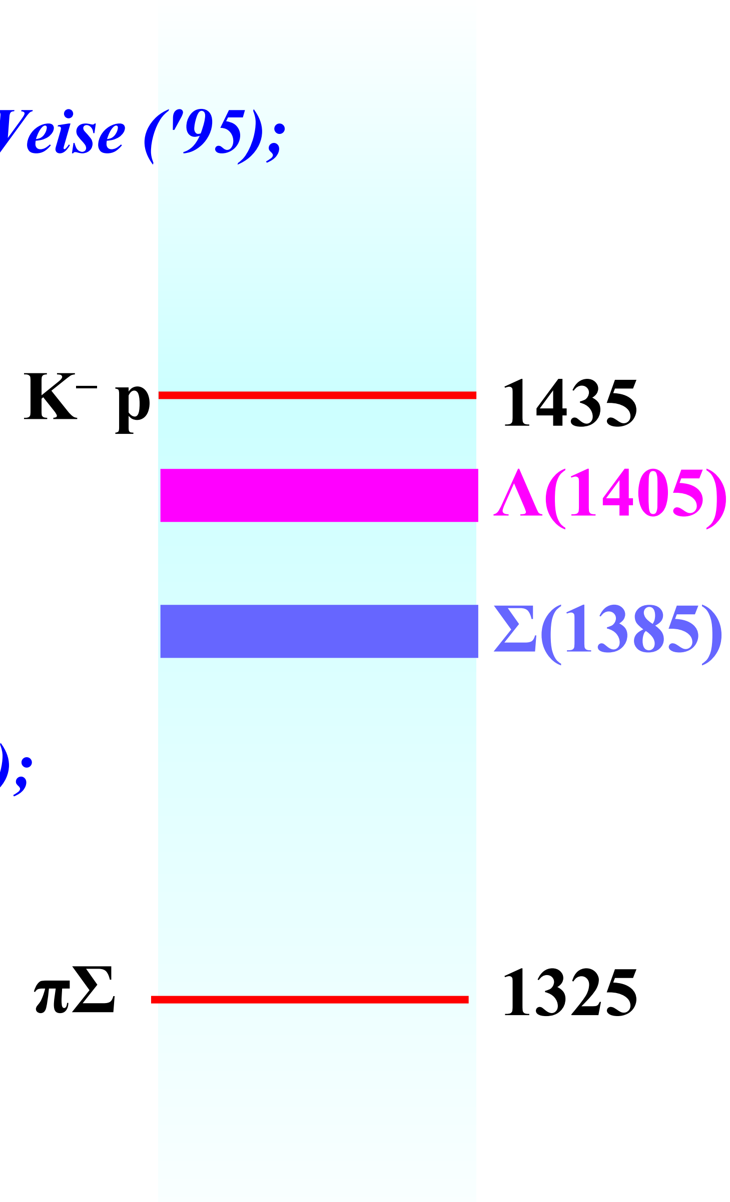
- **Theory**
  - **Corr. Fn. is enhanced at any R for negative a_0. (w/o bound state)**
  - **Corr. Fn. is enhanced at R < a_0 and *suppressed* at R ~ a_0 for positive a_0. (w/ bound state or repulsive int.)**
  - **With repulsive int., $a_0 \sim r_c$ (hard core radius), and cannot be large, and coupled channels effects generally enhances corr. fn.**
- **Experiment**
  - **pΩ corr. fn. is *suppressed* at small q in HIC at RHIC.**
  - **pΩ corr. fn. is strongly enhanced in high mult. pp events at LHC.**

There should be (a) bound state(s) in pΩ,
whose scatt. length is around the source size of HIC.
Any other possibility ?

$K^{-}p$ correlation

K^- p interaction

- **Λ(1405) $\bar{K}$N quasi-bound state**
  Dalitz, Tuan ('60); Koch ('94); Kaiser, Siegel, Weise ('95); AO, Nara, Koch ('97); Jido+('03)
  - **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)
  → 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), Miyahara, Hyodo ('16)



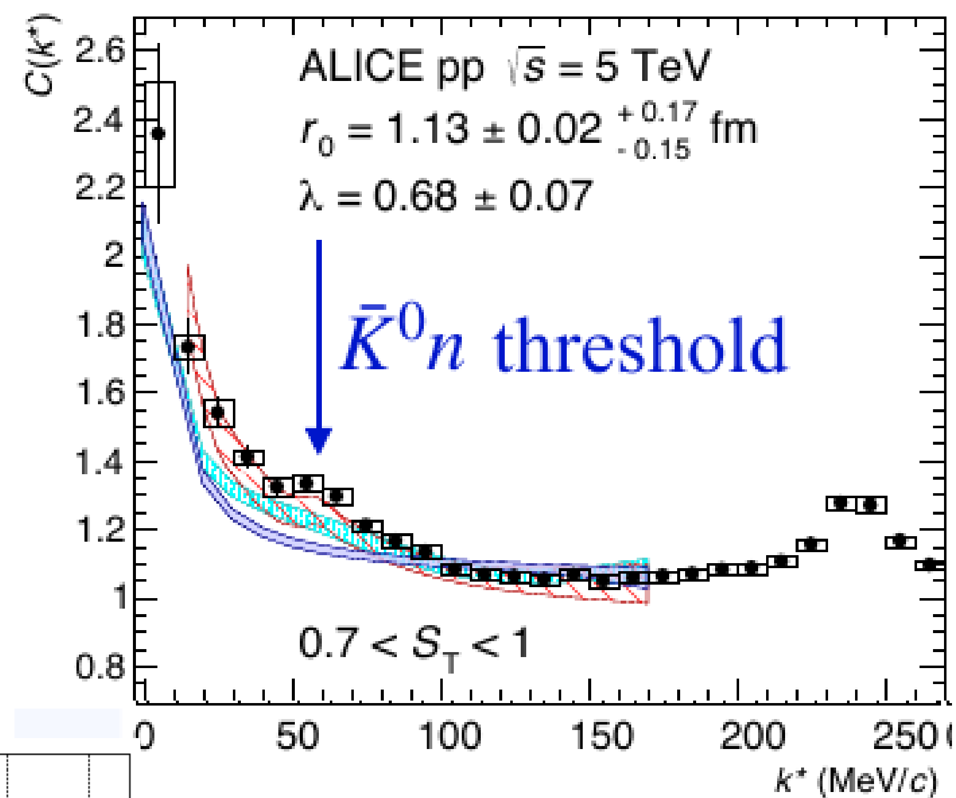
How about K^- p correlation ?

K^-p correlation function data

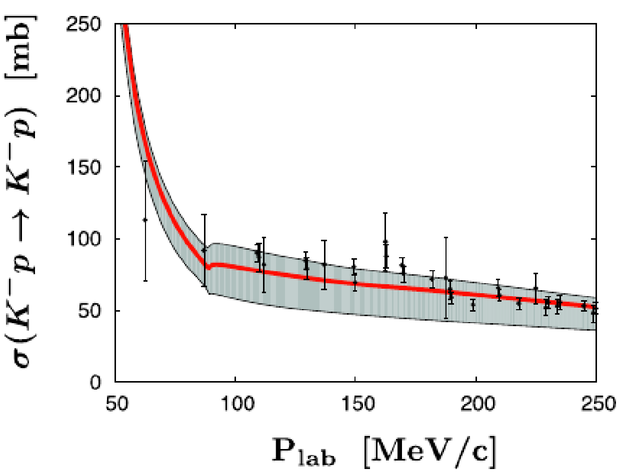
- **K – p correlation function from high-multiplicity events of pp collisions**

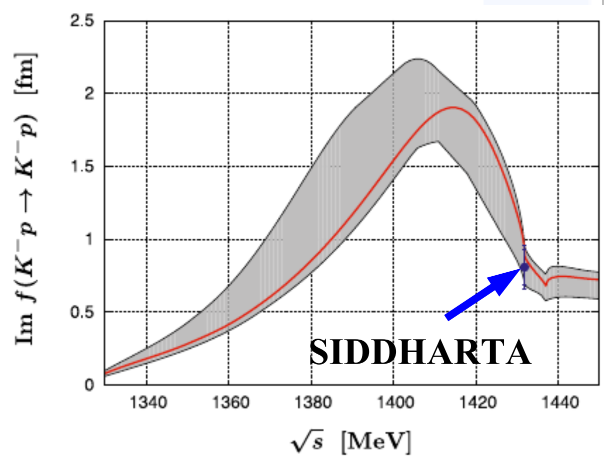
  S. Acharya et al. (ALICE), arXiv:1905.13470

  - **High precision data from low to high momentum ! c.f. Previous scatt. data & Kaonic atom data.**
  - **Enhanced at low k, cusp, Λ(1520), ...**



Red:Kyoto model
Blue: Julich model
grey: Coulomb

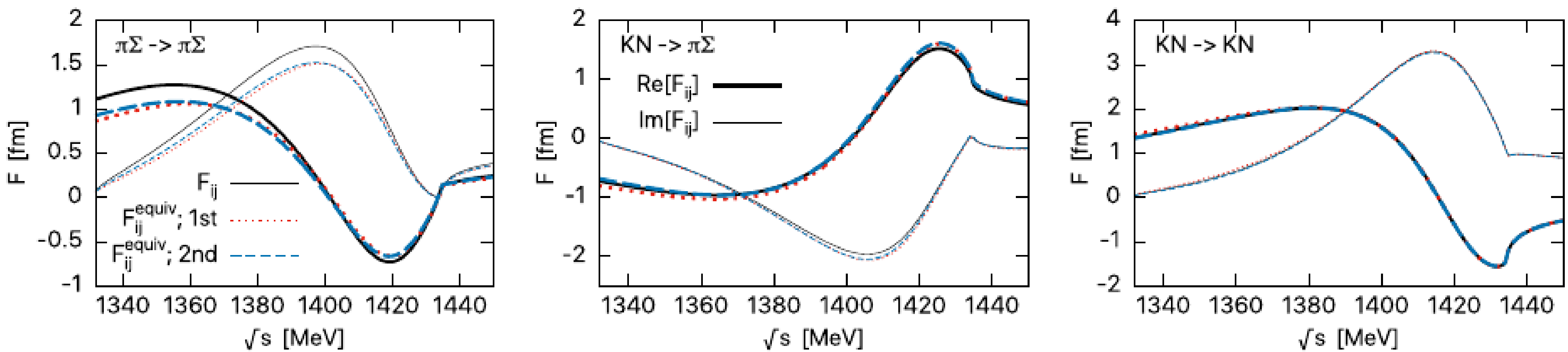




Y. Ikeda, T. Hyodo, W. Weise,NPA881 ('12) 98

$\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ Scattering Amplitude and Potential

- **Amplitude in chiral SU(3) coupled-channels dynamics**
  Y. Ikeda, T. Hyodo, W. Weise,NPA881 (‘12) 98
  - **NLO meson-baryon effective Lagrangian ($\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$)**
    + fit of Kaonic Hydrogen, Cross Section, Threshold branching ratio
- **Coupled-channels potential**
  K. Miyahara, T. Hyodo, W. Weise, PRC98(‘18)025201
  - **Potential fitted to IHW amplitude**



Y. Ikeda, T. Hyodo, W. Weise,NPA881 (‘12) 98
K. Miyahara, T. Hyodo, W. Weise, PRC98(‘18)025201

Correlation Function with Coupled-Channels Effects

J. Haidenbauer, NPA 981('19)1; R. Lednicky, V. V. Lyuboshits, V. L. Lyuboshits, Phys. At. Nucl. 61('98)2950.

- **Single channel, w/o Coulomb (non-identical pair)**

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

- **Single channel, w/ Coulomb**

$$C(\boldsymbol{q}) = \int d\boldsymbol{r} S(\boldsymbol{r}) \left[\underline{|\varphi^{C,\mathrm{full}}(\boldsymbol{q},\boldsymbol{r})|^2} + \underline{|\chi^{C,(-)}(r,q)|^2} - \underline{|j_0^C(qr)|^2} \right]$$

Full free Coulomb w.f. — **s-wave w.f. with Coul.** — **s-wave Coul. w.f.**

- **Coupled channel, w/ Coulomb**

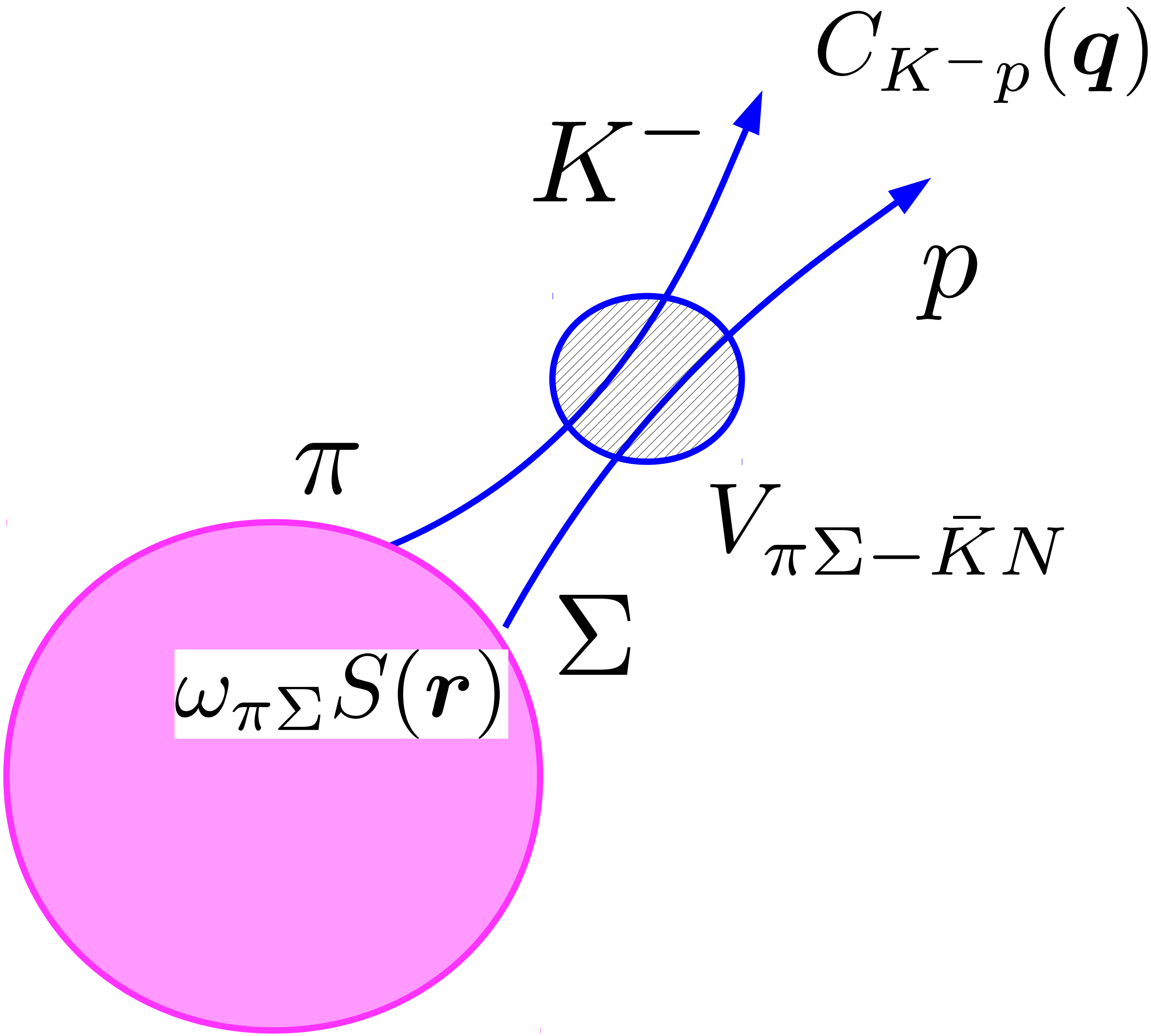
$$C_i(\boldsymbol{q}) = \int d\boldsymbol{r} S_i(\boldsymbol{r}) \left[\underline{|\varphi^{C,\mathrm{full}}(\boldsymbol{q},\boldsymbol{r})|^2} + \underline{|\chi_i^{C,(-)}(r,q)|^2} - \underline{|j_0^C(qr)|^2} \right]$$

$$+ \sum_{j \neq i} \omega_j \int d\boldsymbol{r} S_j(\boldsymbol{r}) \underline{|\chi_j^{C,(-)}(r,q)|^2}$$

s-wave w.f. in j-th channel

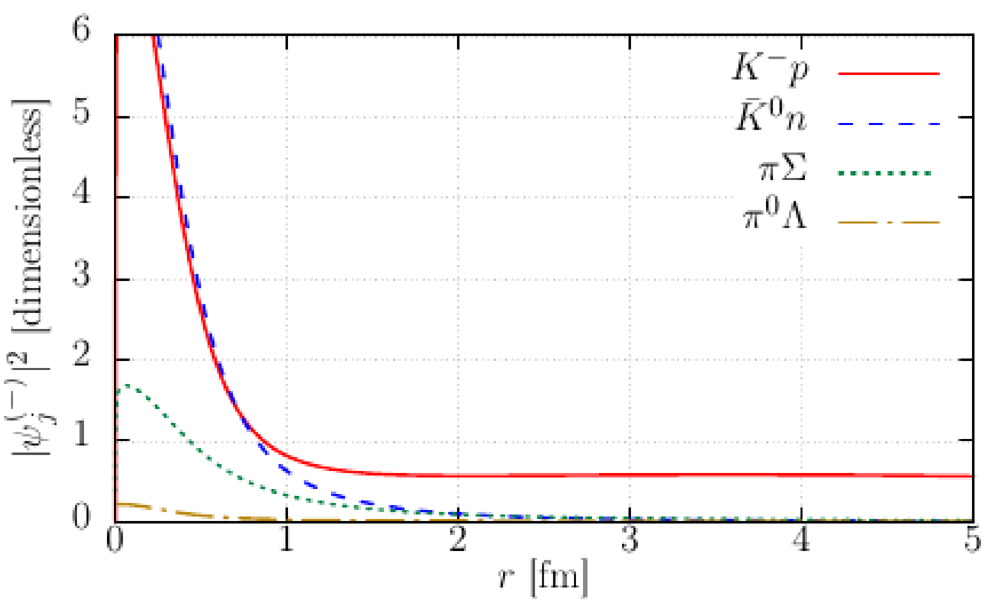
Outgoing B.C. in the i-th channel, ω_j = Source weight (ω_j=1)

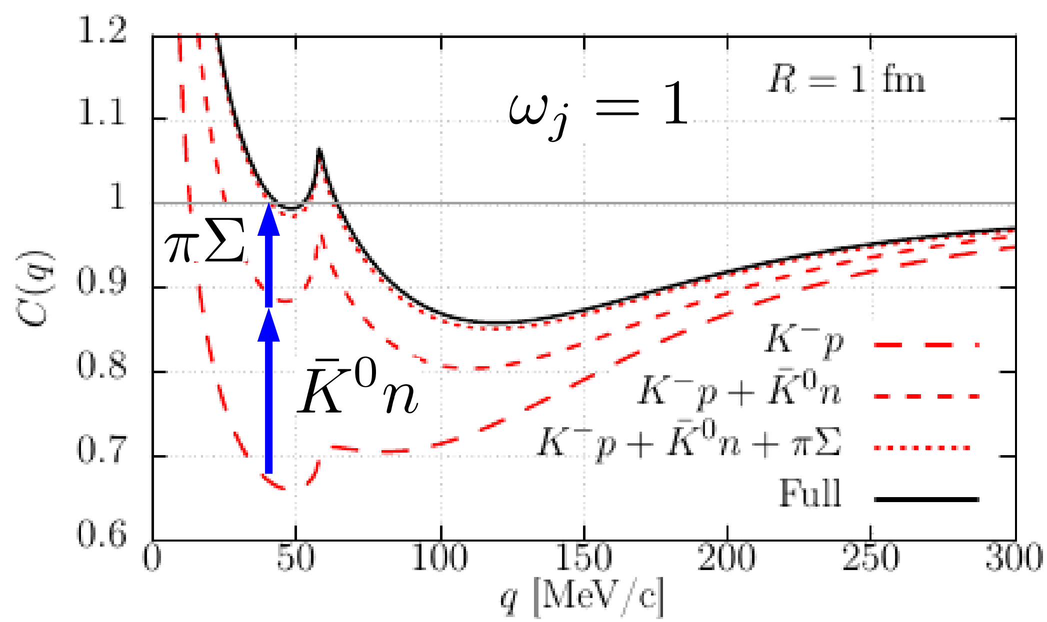
Correlation Function with Coupled-Channels Effects



Correlation Function from Chiral SU(3) Potential (1)

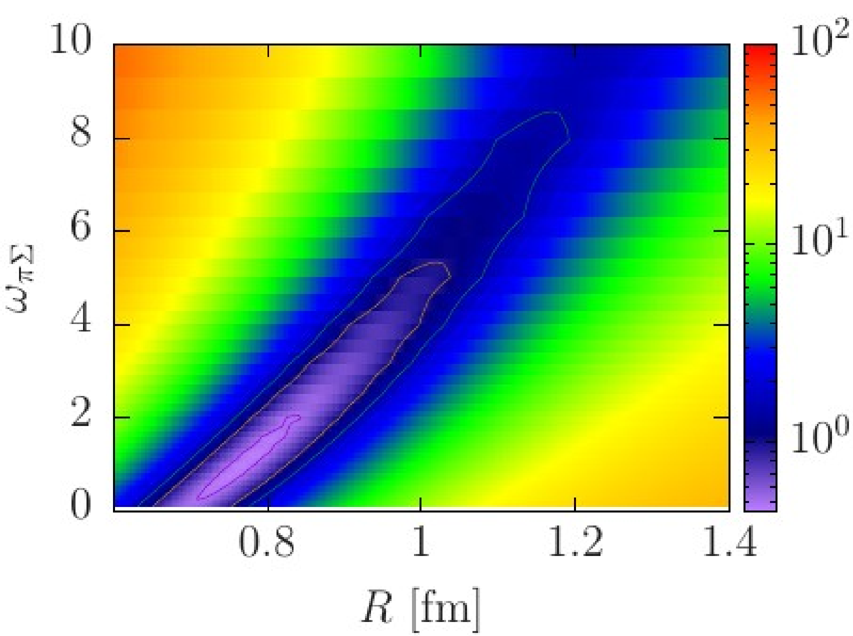
- **Corr. Fn. from Chiral SU(3) coupled-channels potential + Coulomb + threshold difference (for the first time !)**
  Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, arXiv:1911.01041
- **Coupled-channels effect**
  - **W.f. of other channels than K^-p decay in r < 1 fm.**
  - **But they contribute to corr. fn. meaningfully.**

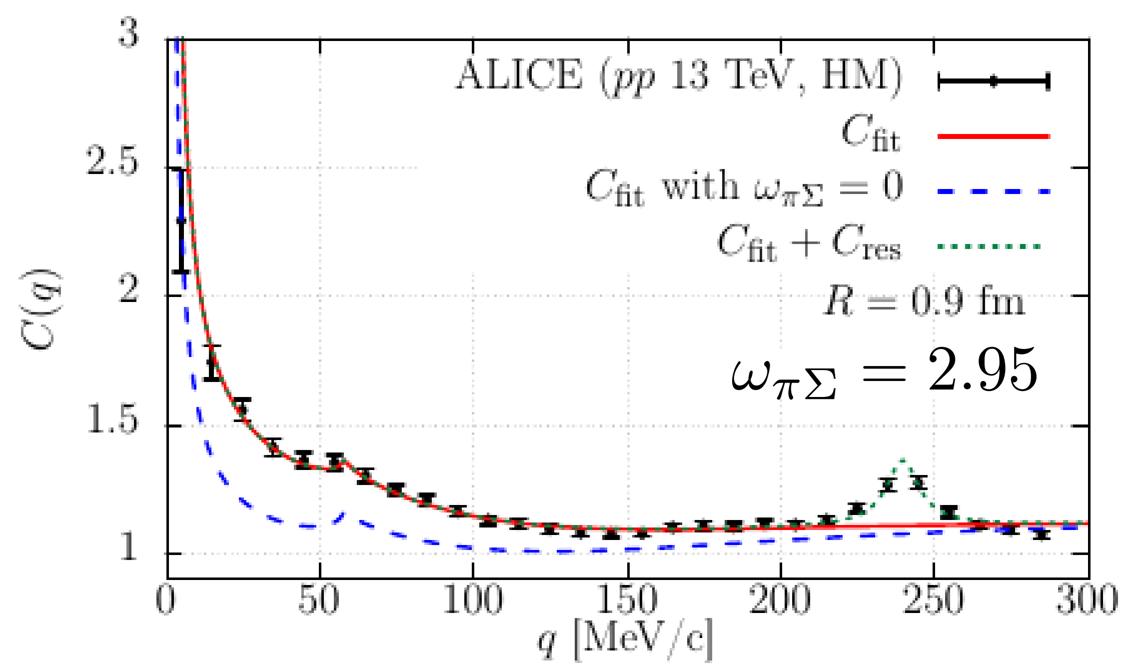




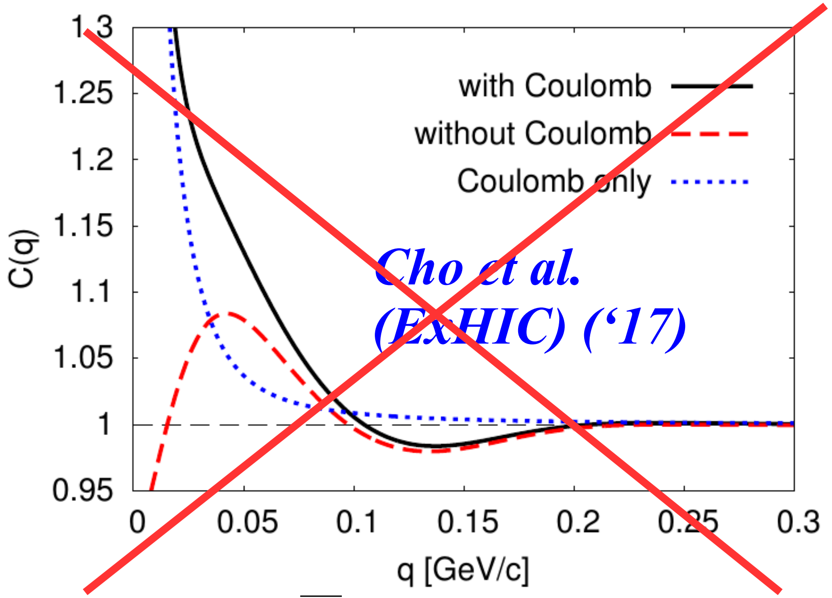
Correlation Function from Chiral SU(3) Potential (2)

- **"Free" parameters**
  = Source Size R, Source Weight ω_j ← Th+Exp.
  + Normalization + Pair purity (λ) ← Exp.
  - **Larger R → Smaller couple-channels effect from $\pi\Sigma$**
    (Favorable values of R and ω_j are correlated)
  - **Simple statistical model esitmate**
    $\omega_{\pi\Sigma} \sim \exp[(m_K+m_N-m_\pi-m_\Sigma)/T] \sim 2.$

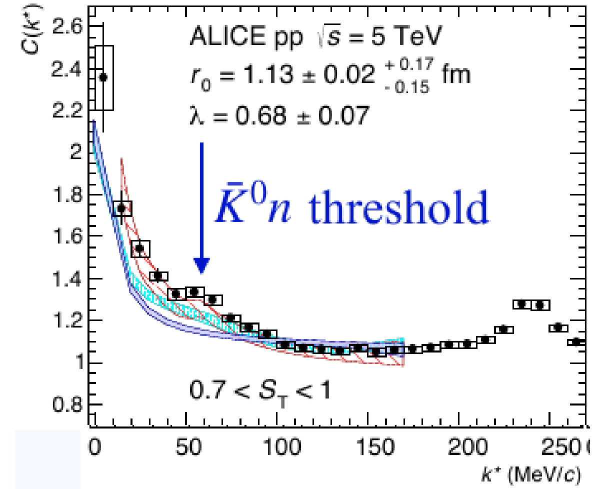




Comparison with other estimates

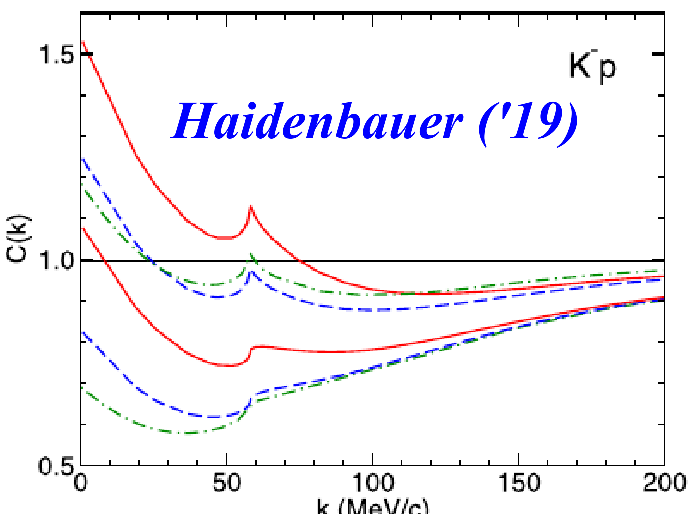


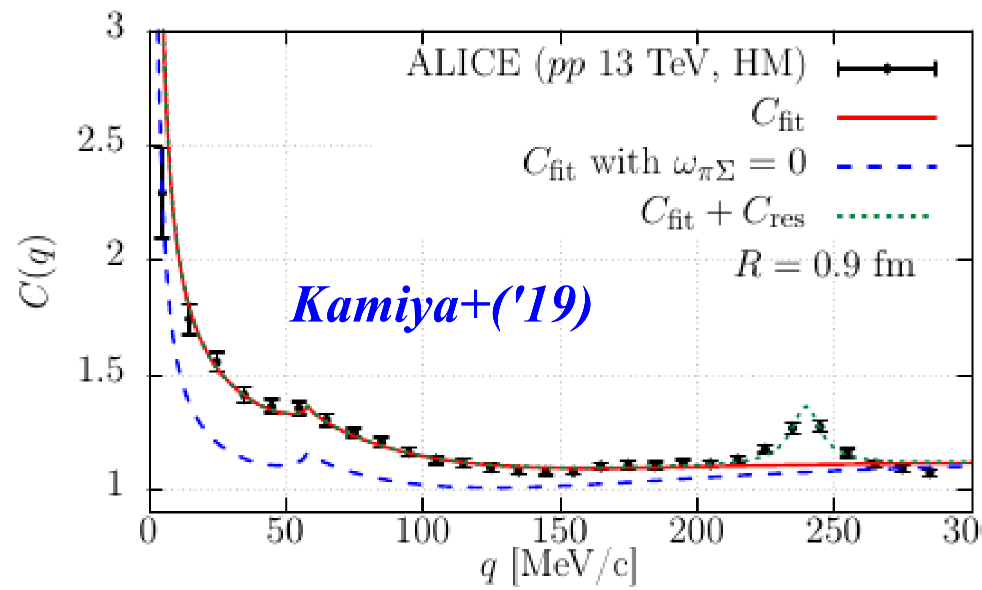
No $\overline{K}^0 n$, $\pi\Sigma$ source
No threshold diff.



ALICE

Kyoto model (~Cho+('17))→ accident
Julich model (Blue) Gamow corr. for Coulomb

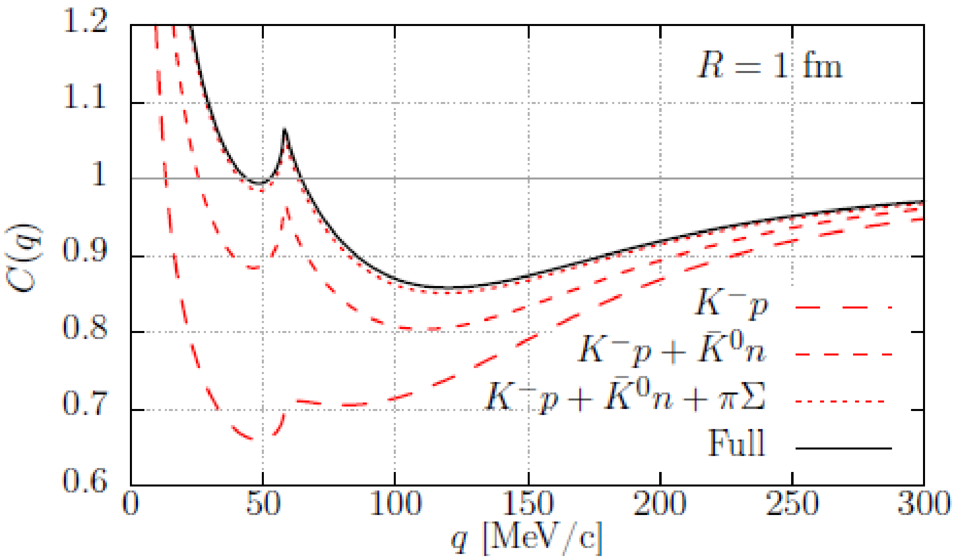


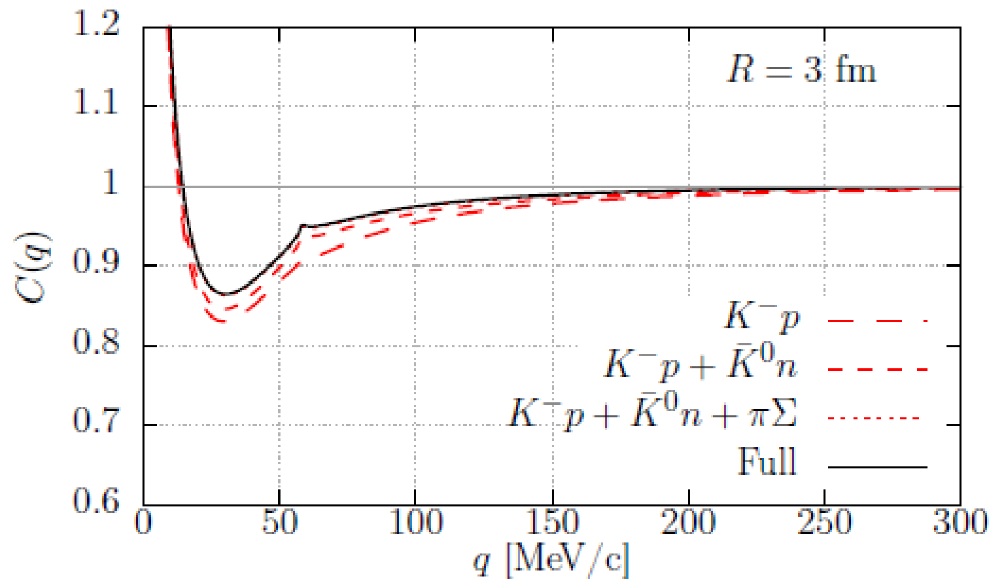


Julich amplitude
Consistent with Kamiya+('19) w/o Coulomb

Source Size Dependence (2)

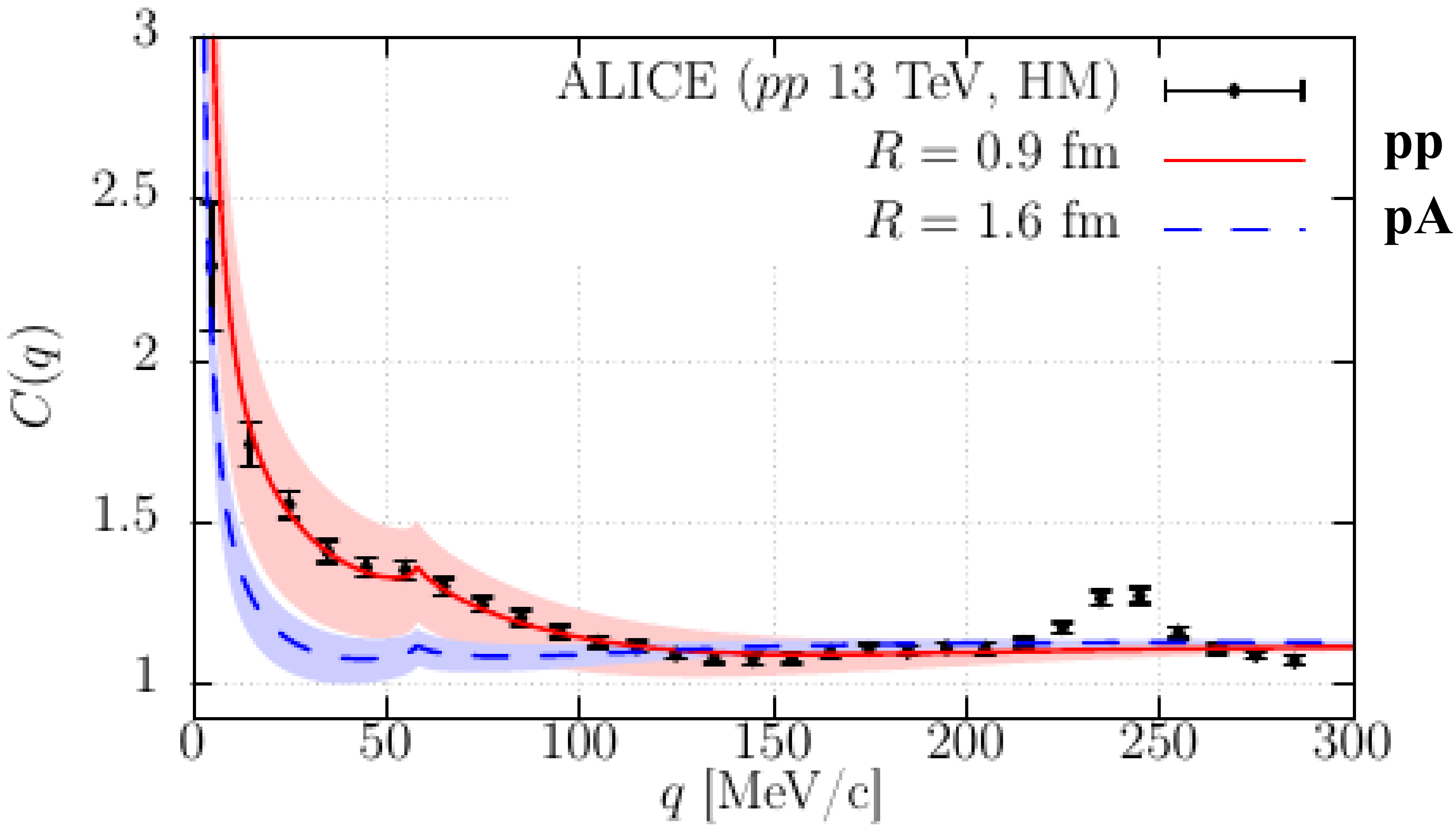
- **Experimental confirmation of coupled-channels contribution → Source size dependence**
  - **Channel w.f. other than $K^- p$ are localized at around r=0. (Outgoing boundary condition for $K^- p$)**
  - **Contribution of πΣ source is suppressed for larger R.**





Source Size Dependence (2)

- Corr. Fn. from pA & AA collisions will elucidate the role of πΣ
  - R ~ 1.6 fm → πΣ effects are suppressed.



Summary

- High-energy nuclear collisions can be utilized as a hadron factory.
- Two-hadron correlation functions are useful to get knowledge of hadron-hadron interaction.
  E.g. Large corr. fn. at small q implies large $|a_0|/R$, and the source size dependence may show the sign of a_0, to be or not to be bound.
- Measured corr. fn. tell us many things !
  - ALICE and STAR data strongly suggest the existence of S= –3 dibaryon as a bound state of NΩ.
  - ALICE data are consistent with chiral SU(3) $\bar{K}N$-πΣ-πΛ amplitudes.
  - STAR and ALICE data confirm weakly attractive ΛΛ int.
  - ALICE data of Ξ^-p implies large $|a_0|/R$, and the existence of some kind of pole (b.s., res., virtual) around the threshold.

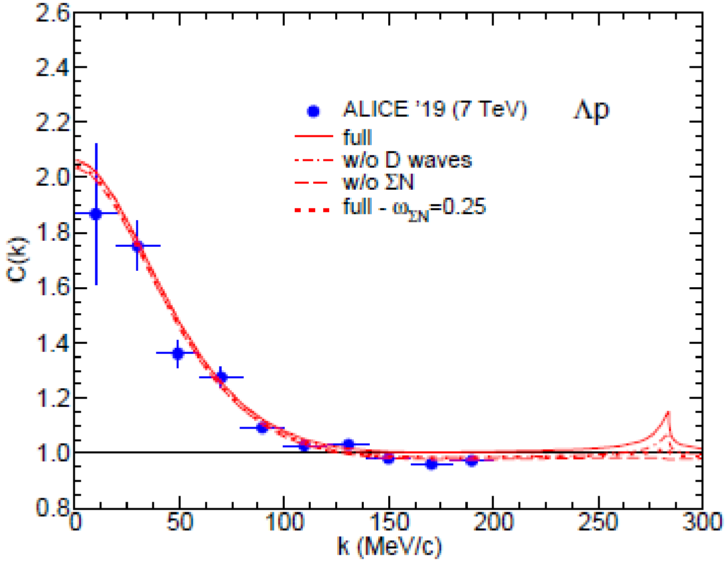
Future works and challenges

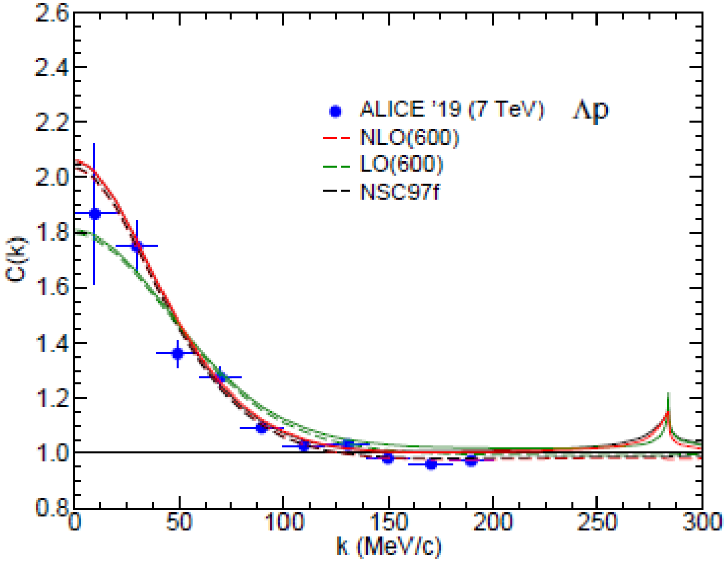
- **To do**
  - **Ξ^- p corr. fn. with updated HAL QCD potential**
    K. Sasaki et al. (HAL QCD), arXiv:1912.08630
  - **Corr. Fn. of S= –1 BB pair, especially Σ^0 p,**
    using Lattice QCD BB potential.
    S. Acharya et al. (ALICE), arXiv:1910.14407
  - **$\pi\Sigma$ corr. fn. ($\pi\Sigma$ interaction is not constrained !)**
  - **$\pi^\pm$Y, $K^\pm$Y (Y=Λ, Ξ^-, Ω^-) will be measurable. Interesting physics ?**
- **Challenges**
  - **$\Omega\Omega$ (experimentally challenging)**
  - **Deuteron: K^- d (T=1 ampl.), Λd (3ΛH lifetime, ΛNN 3BF),**
    Ξ^- d (already measured (analyzed) ?), ...
    → Break up effects of deutron via CDCC would be helpful (Ogata, ...)

Correlation Function Studies by Jülich Group

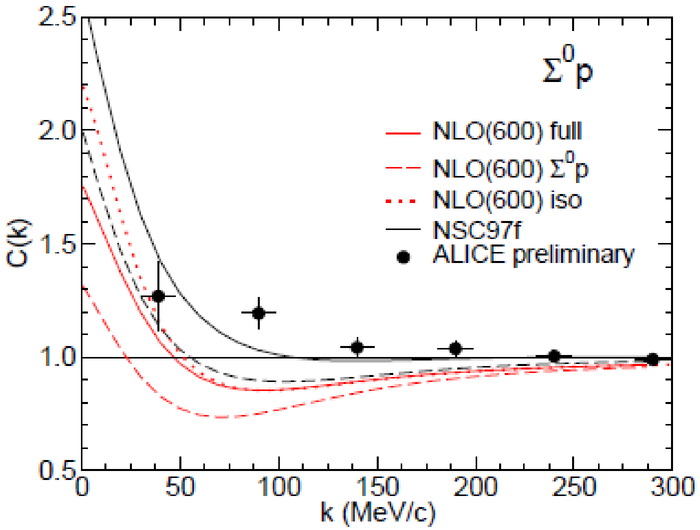
- **Λp correlation (chiral EFT, NLO)**

J. Haidenbauer, FemTUM2019

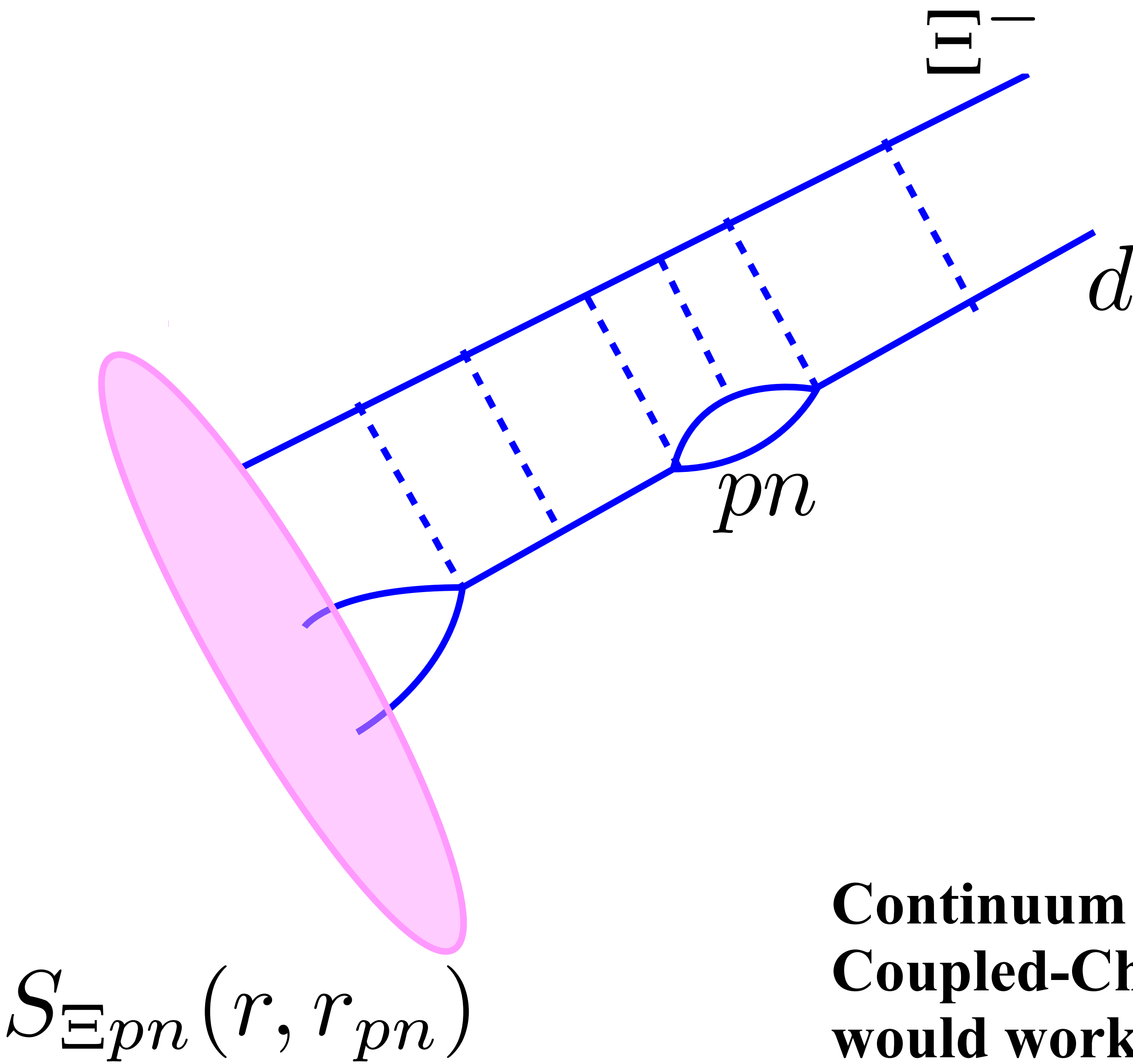




- **Σ^0p correlation**



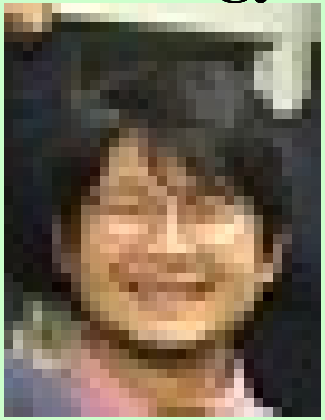
Break up effect of deuteron



Continuum Discretized Coupled-Channel (CDCC) would work

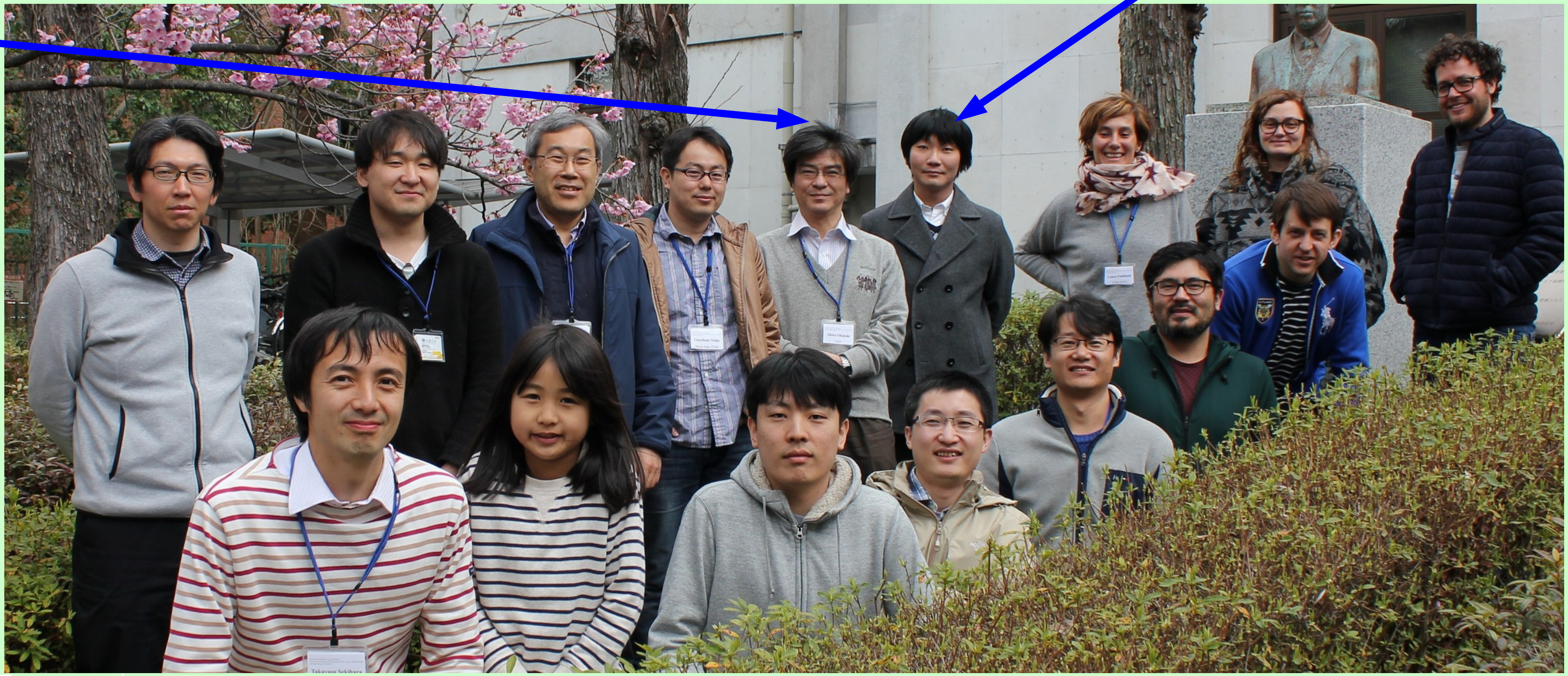
Thank you for attention !

Coauthors of arXiv:1908.05414

K. Morita	S. Gongyo	T. Hatsuda	T. Hyodo
			

Y. Kamiya

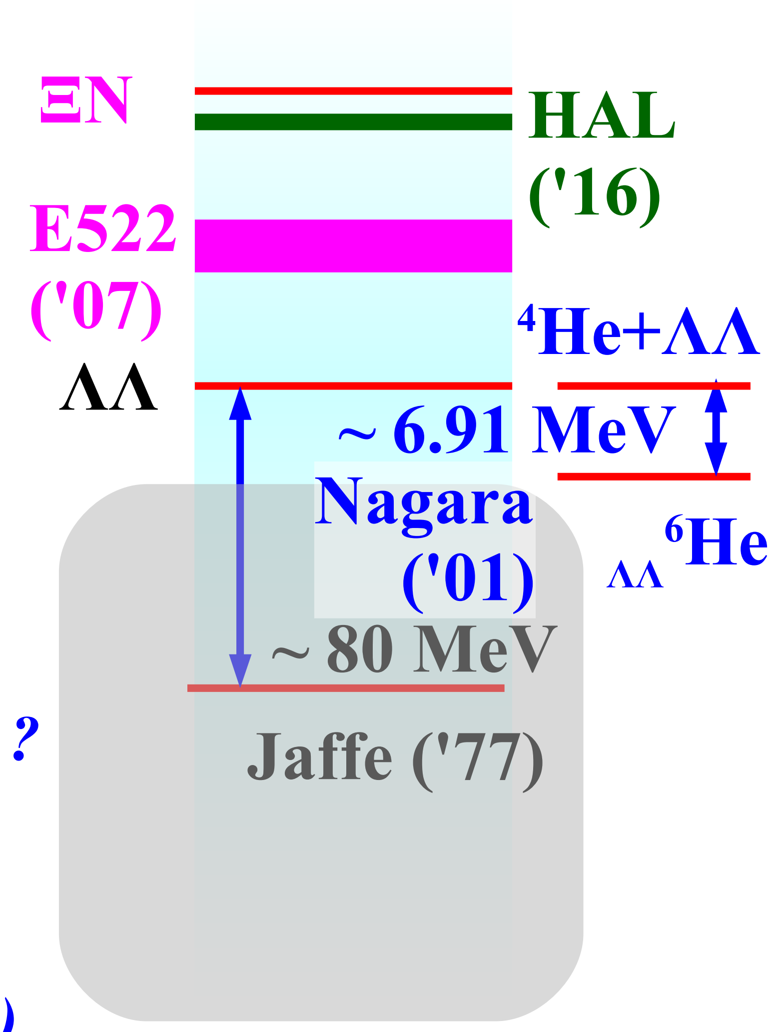
AO



Do I have time ?

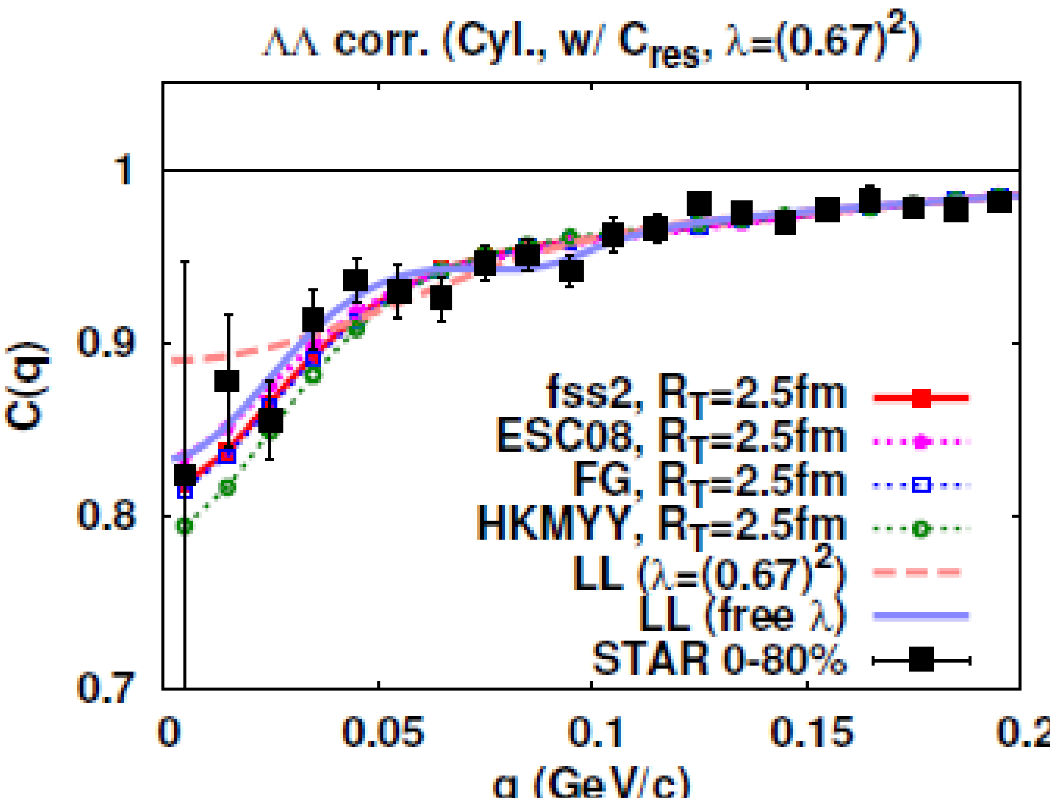
Relevance of ΛΛ interaction to physics

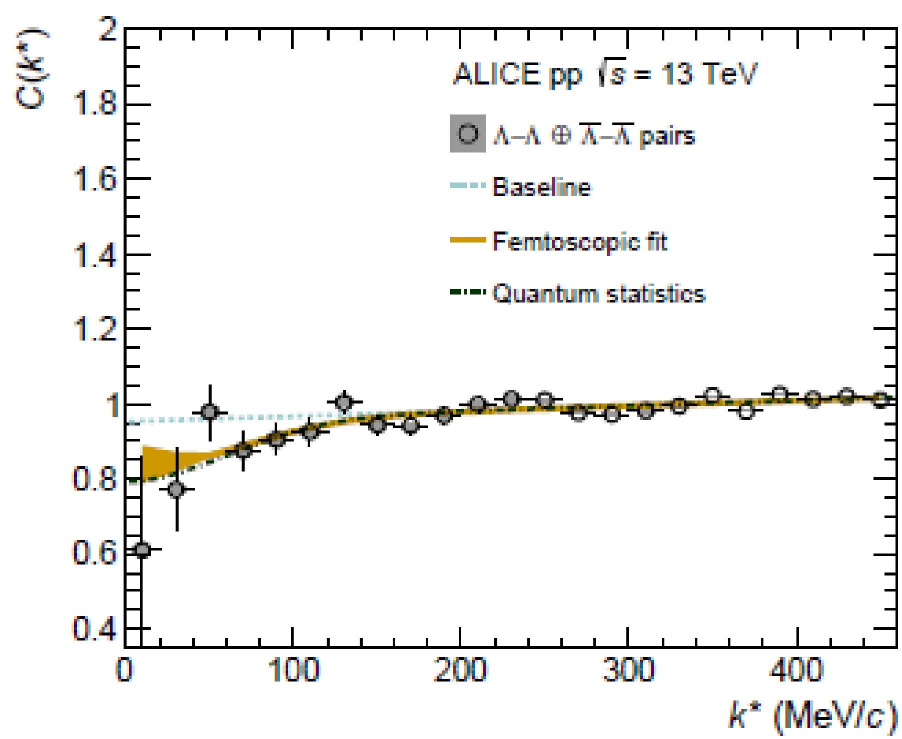
- H-particle: 6-quark state (uuddss)
  - Prediction: *R.L.Jaffe, PRL38(1977)195*
  - Ruled-out by double Λ hypernucleus
    Takahashi et al.,PRL87('01) 212502
  - Resonance or Bound "H" ?
    Yoon et al.(KEK-E522)+AO ('07)
  - Lattice QCD
    HAL QCD & NPLQCD ('11)
    HAL QCD ('16): H as a loosely bound ΞN ?
- Neutron Star Matter EOS
  - Hyperon Puzzle
    Demorest et al. ('10), Antoniadis et al. ('13)
  - Cooling Puzzle (ΛΛ superfluidity)
    T. Takatsuka, R. Tamagaki, PTP 112('04)37



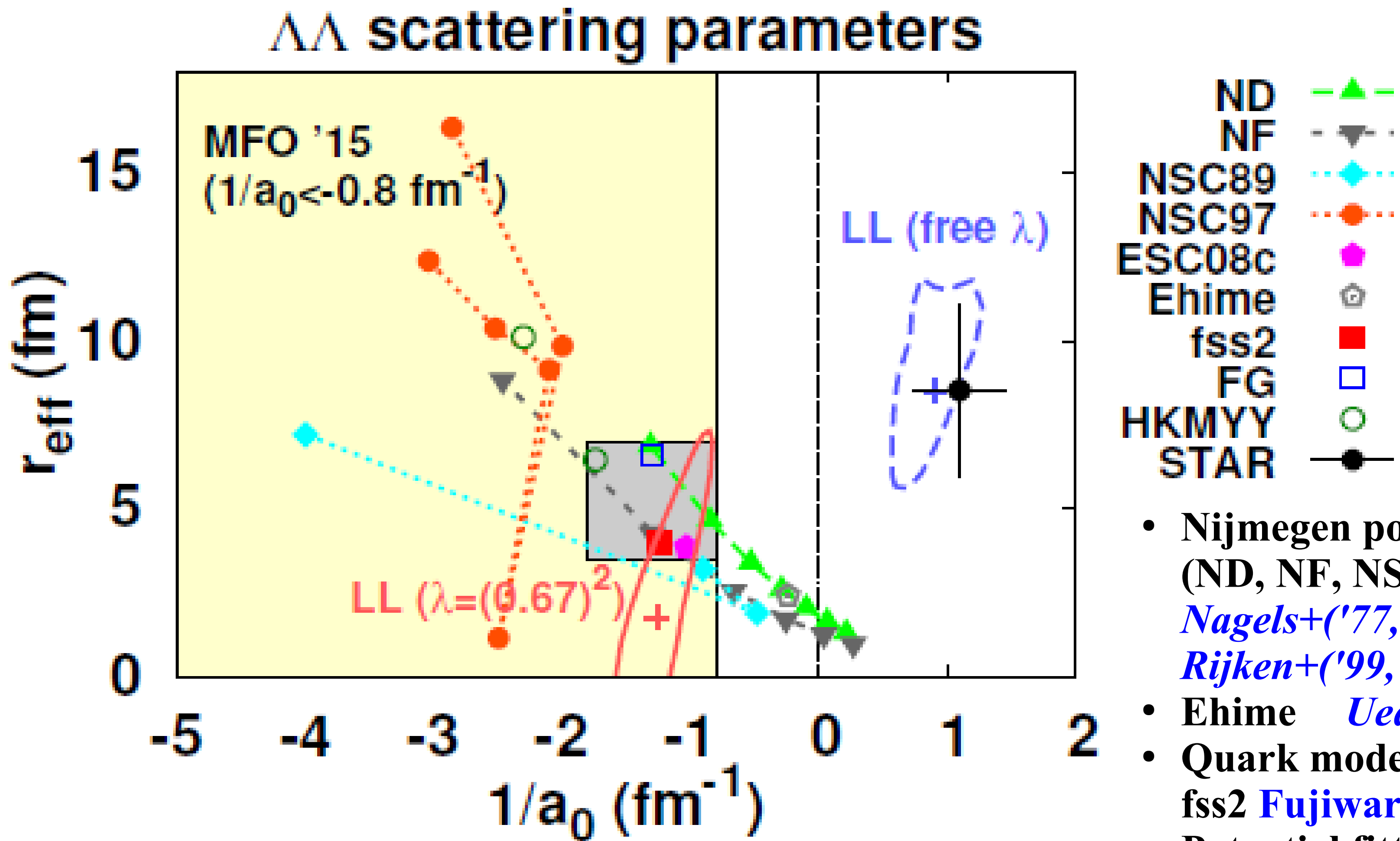
ΛΛ correlation at RHIC

- **STAR collaboration at RHIC measured ΛΛ correlation !**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
- **Theoretical Analysis well explains the data**
  K.Morita et al., T.Furumoto, AO, PRC91('15)024916;
  AO, K.Morita, K.Miyahara, T.Hyodo, NPA954 ('16), 294.
- **New Data from ALICE**
  S. Achara+(ALICE), PRC99('19), 024001; arXiv:1905.07209





ΛΛ interaction from ΛΛ correlation

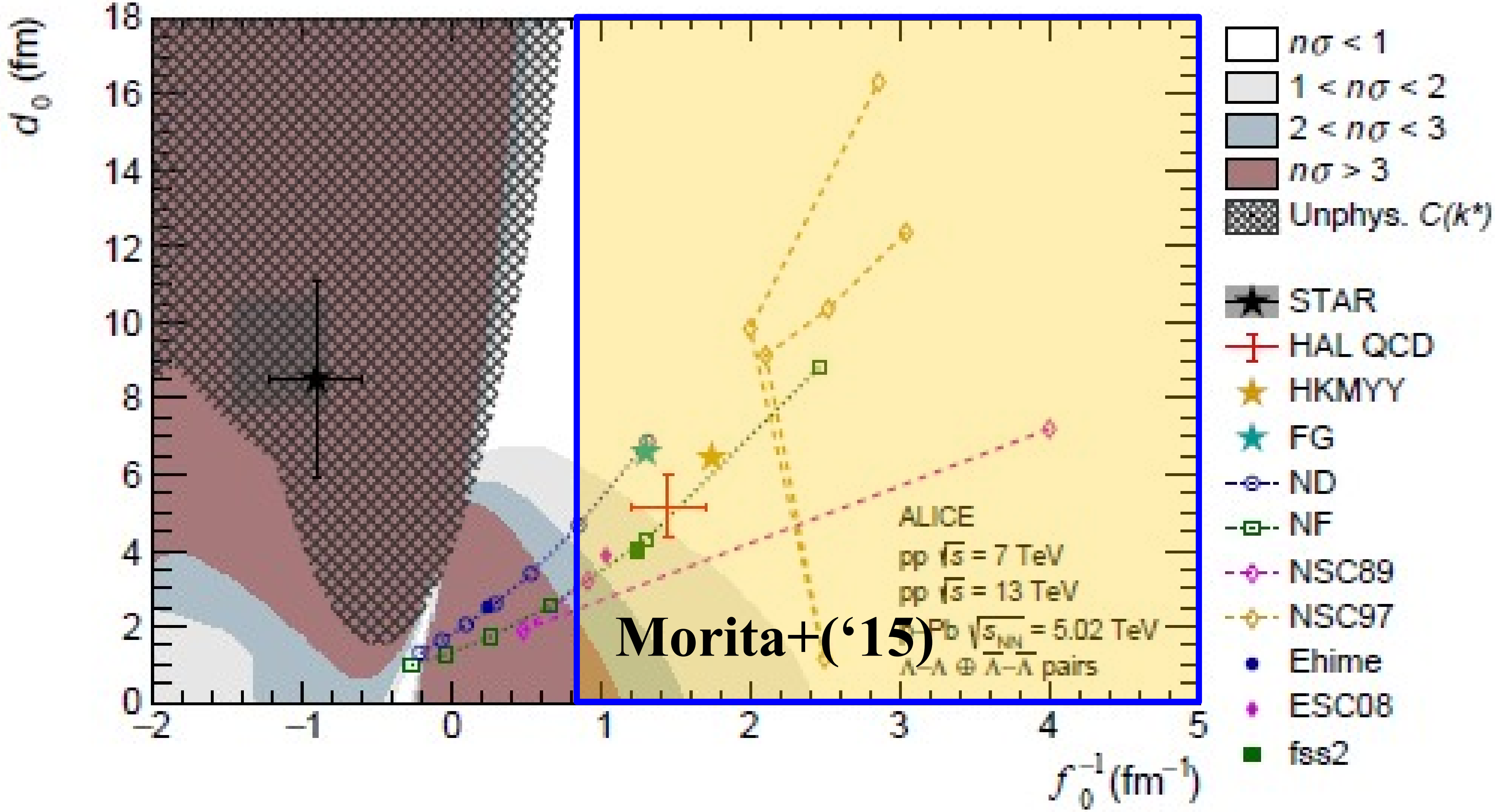


- **Nijmegen potentials (ND, NF, NSC89, NSC97, ESC08)** *Nagels+('77, '79), Maessen+('89), Rijken+('99,'10)*
- **Ehime** *Ueda et al. ('98)*
- **Quark model interaction: fss2** Fujiwara et al.('07)
- **Potential fitted to Nagara** *Filikhin, Gal ('02) (FG), Hiyama et al. ('02, '10)(HKMYY)*

$$q \cot \delta = -1/a_0 + r_{eff}\, q^2/2 + O(q^4)$$

New Data from LHC-ALICE

ALICE (arXiv:1905.07209)

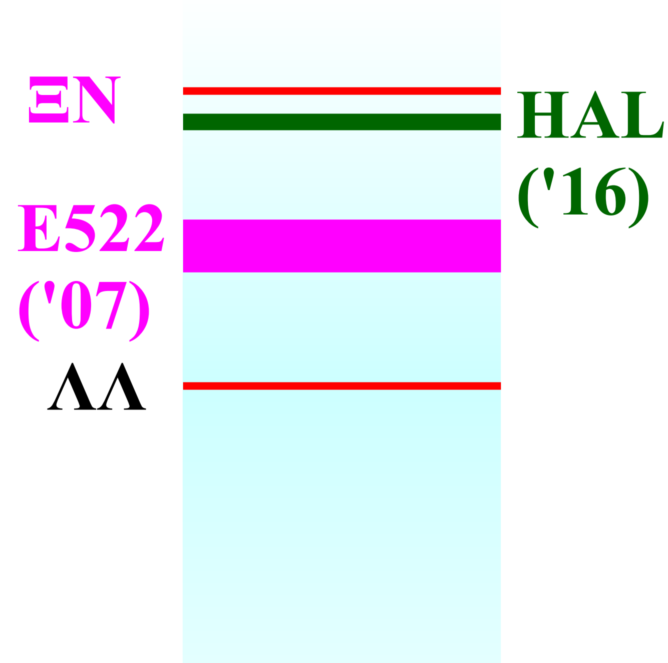


Weakly attractive $V_{\Lambda\Lambda}$.

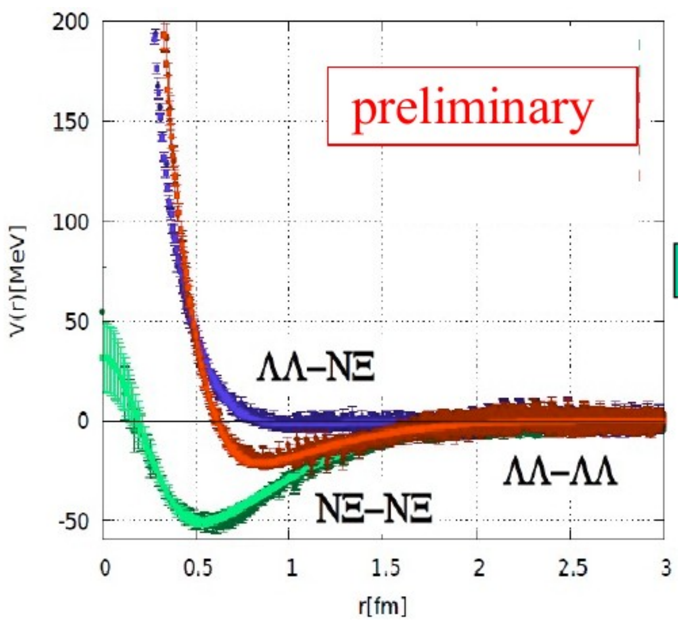
Large reff → Becomes repulisve at low relatively density.

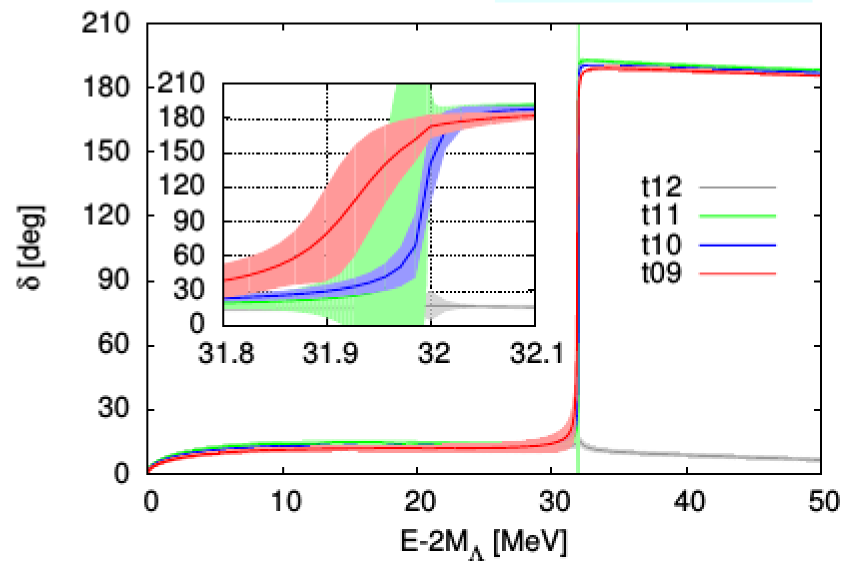
Relevance of ΞN interaction to physics

- **H-particle: 6-quark state (uuddss) may be realized as a loosely bound state of ΞN (I=0)**
  K. Sasaki et al. (HAL QCD, '16,'17)



- **Repulsive ΞN interaction (I=1) may help to support 2 $M_\odot$ Neutron Star**
  Weissborn et al., NPA881 ('12) 62.





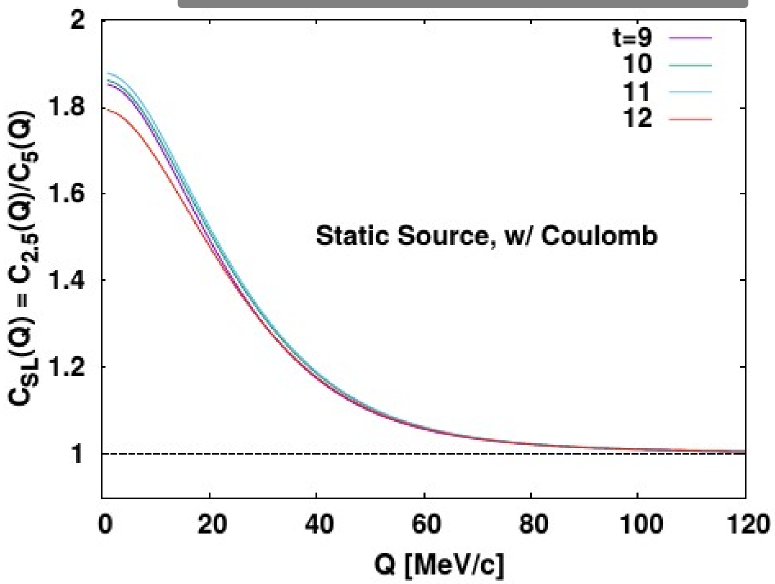
K. Sasaki et al. (HAL QCD Collab.), EPJ Web Conf. 175 ('18) 05010.

$\Xi^- p$ correlation

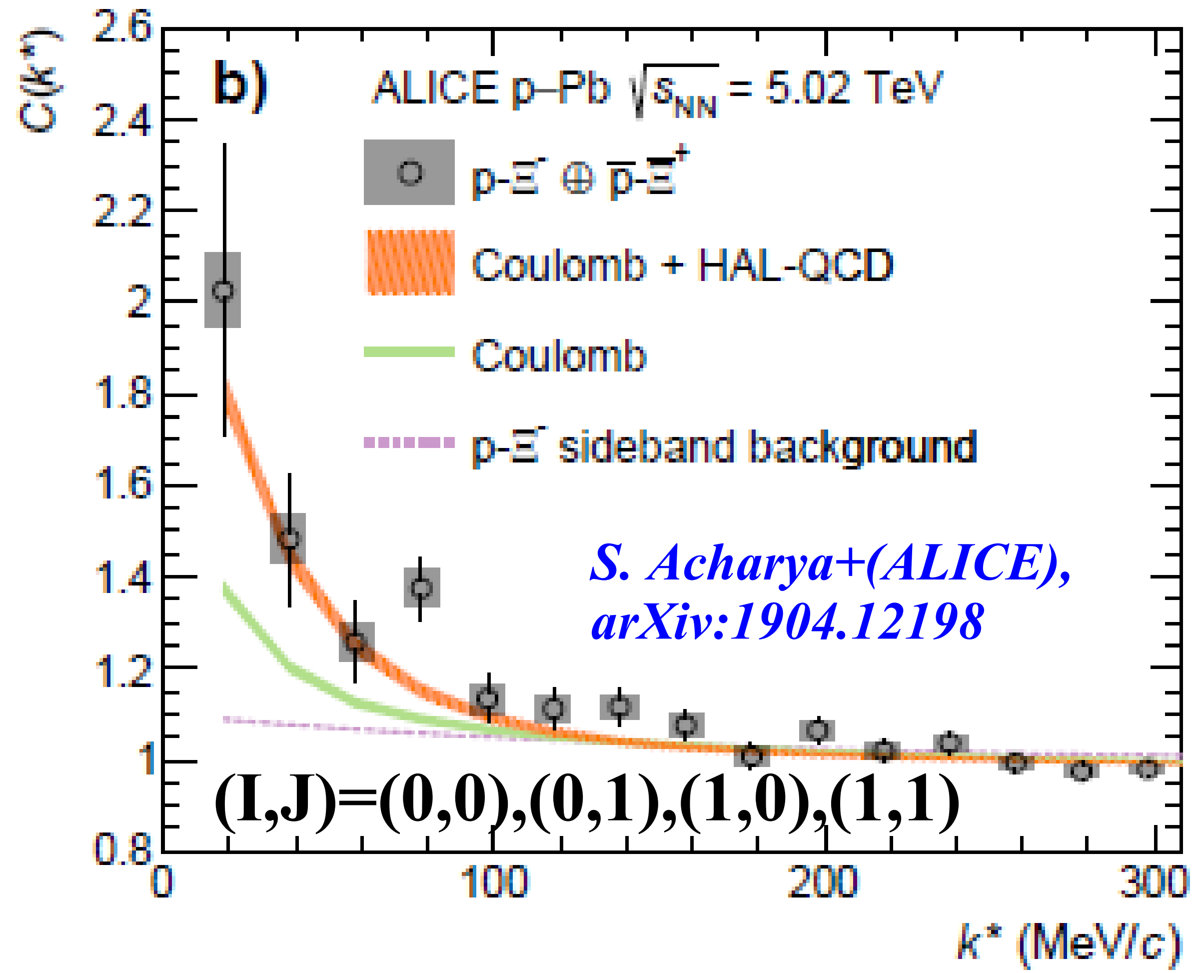
- **Prediction of the correlation function by using ΞN potential (HAL QCD Collab.) + Coulomb potential**

$$|\psi|^2_{\text{spin av.}} = \frac{1}{2}\sum_{I=0,1}\left[\frac{1}{4}|\psi_I^{J=0}|^2 + \frac{3}{4}|\psi_I^{J=1}|^2\right]$$

HAL prediction is examined !



T. Hatsuda, K. Morita, AO, K. Sasaki, NPA967('17), 856.

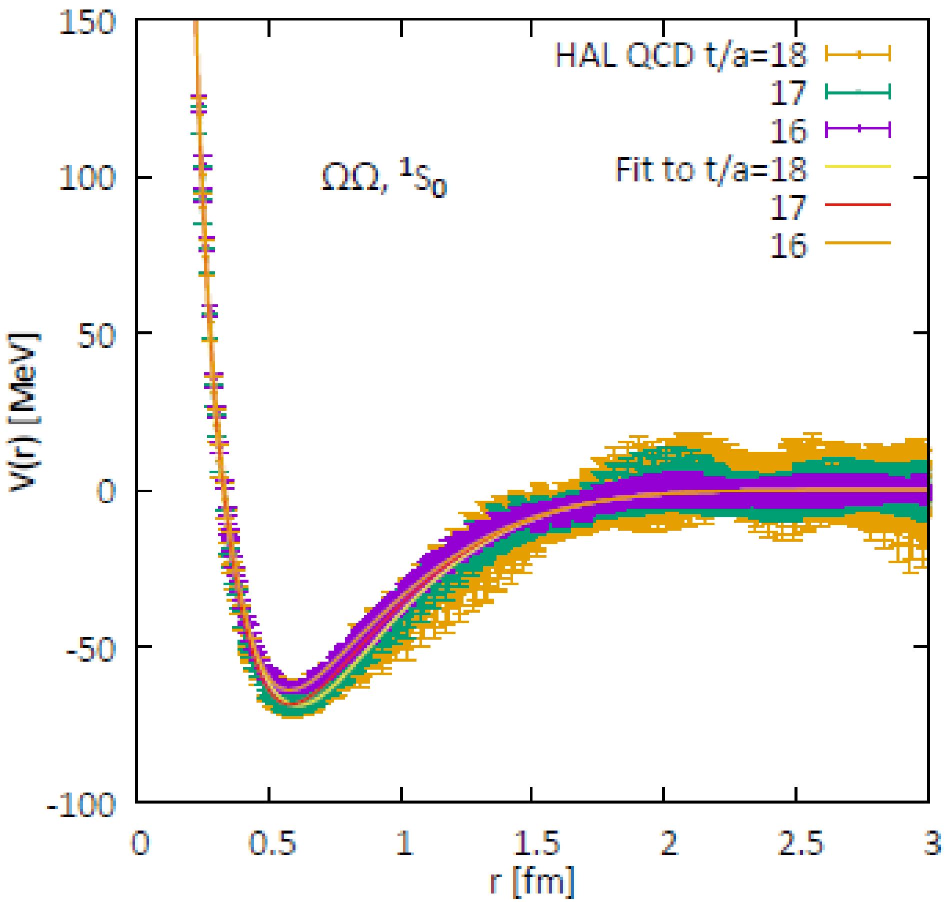


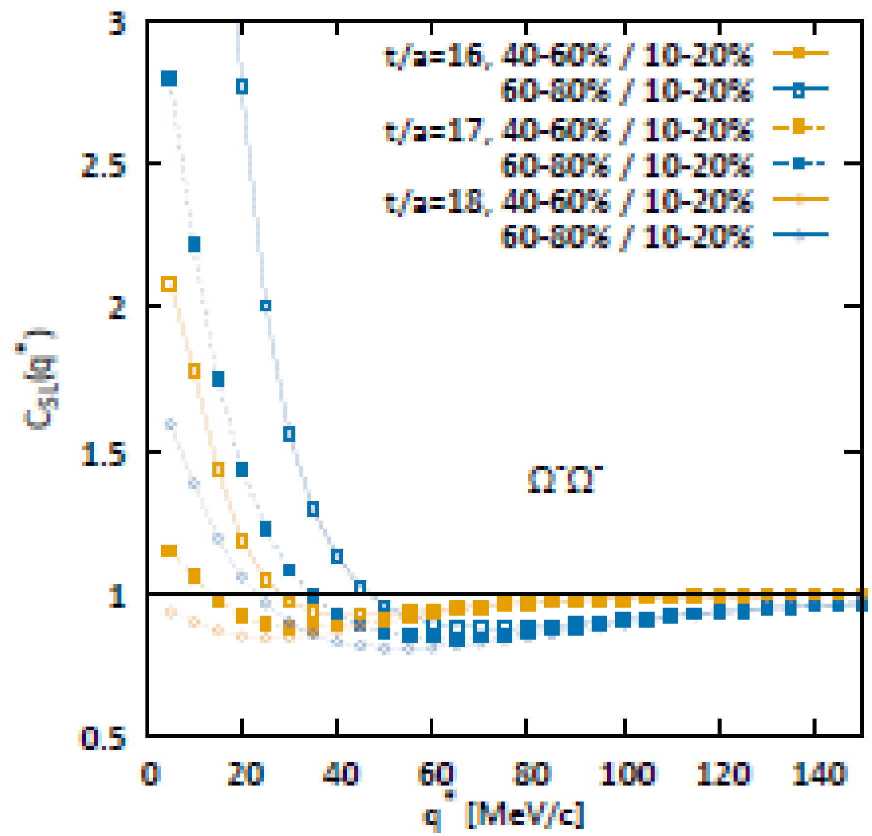
S. Acharya+(ALICE), arXiv:1904.12198

(I,J)=(0,0),(0,1),(1,0),(1,1)

ΩΩ correlation

ΩΩ potential: S. Gongyo et al. (HAL QCD Collab), Phys. Rev. Lett. 120, 212001 (2017), 1709.00654.





K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, Y. Kamiya, AO, PRC101('20)015201 [1908.05414]

Thank you for your attention !