Hadron-hadron correlation functions and its relation to exotic hadron search

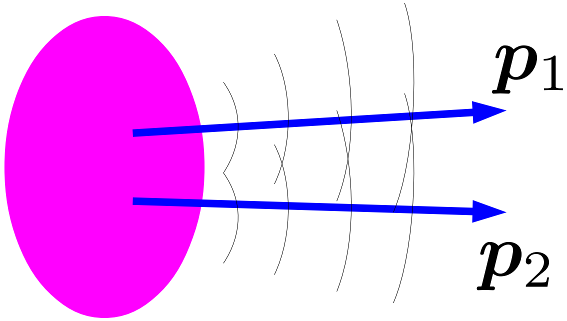
Akira Ohnishi (YITP, Kyoto U.)

ALICE Week, 9 - 13 November, 2020 (Online)

- **Introduction**
- **Survey of measured correlation function data**
  - **$\Lambda\Lambda$, $p\Omega^-$, pK^-, $p\Xi^-$.**
- **Implications of current correlation function data to the existence of hadronic molecule states**
  - **Source size dependence of the correlation funciton**
- **Correlation functions in the near future**
  - **$\Lambda\Xi^-$, Λpp, D^+p, D^-p, ...**
- **Summary**

Correlation Function (CF): Standard and Non-Std usage

- **Correlation function**
  - **Correlation from the quantum statistics and the final state int. under indep. particle production assumption lead KP formula,**
    Koonin('77), Pratt+('86), Lednicky+('82)



source fn. **relative w.f.**

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

- **Standard: Source size from CF (HBT-GGLP effects)**
  Hanbury Brown & Twiss ('56); Goldhaber, Goldhaber, Lee, Pais ('60)
  - **CF of free identical scalar bosons from spherical Gaussian source**

$$\phi(\boldsymbol{r})=\sqrt{2}\cos\boldsymbol{q}\cdot\boldsymbol{r}\to C(q)=1+\exp(-4R^2q^2)$$

- **Non-standard: hadron-hadron interaction from CF**
  - **CF of non-identical pair from Gaussian source**
    R. Lednicky, V. L. Lyuboshits ('82); K. Morita, T. 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 $|\varphi|^2$ is enhanced → V_{hh} effects !

Fermtoscopic Study of Hadron-Hadron Interaction

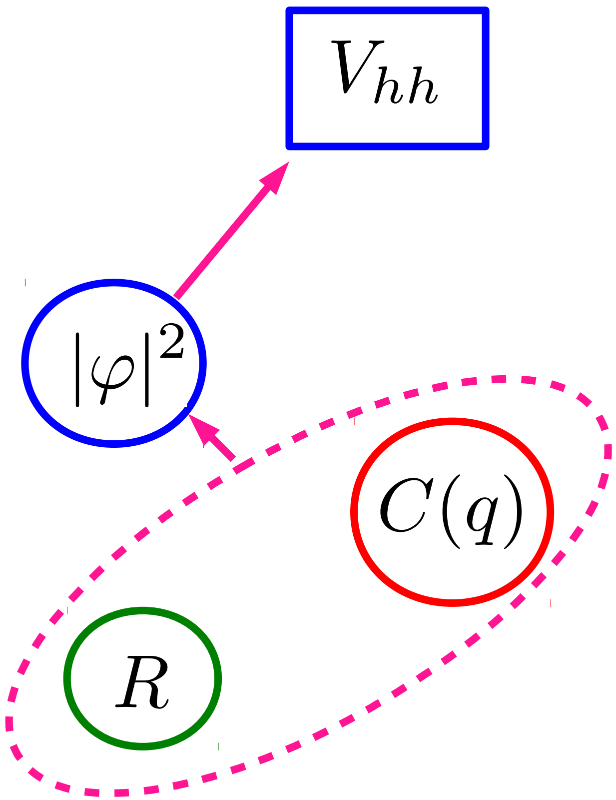
- **If CF is measured and source is well known, we may fit low E. scattering parameters to data by using Lednicky-Lyboshits (LL) formula.**

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

non-identical pair, $f(q) = (e^{2i\delta_0} - 1)/2iq$ (scatt. ampl.), $x = 2qR$, (F_i = known functions)

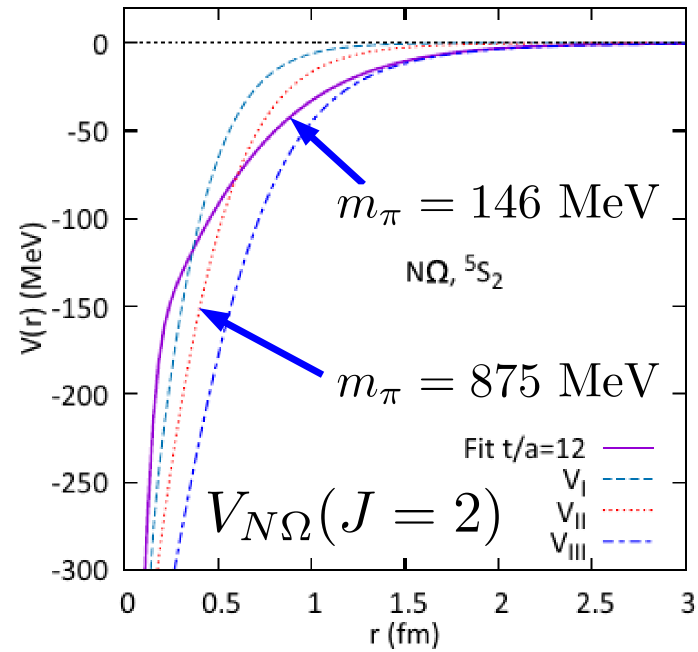
  - **Asymptotic w.f. is assumed.**

- **If reliable *V*(*r*) or *f*(*q*) exists, we may fit the source size and other parameters to data, then we can examine *V*(*r*) or *f*(*q*).**
  - **J. Haidenbauer ('19): CF from *f*(*q*)**
  - **Our approach: CF from *V*(*r*)**

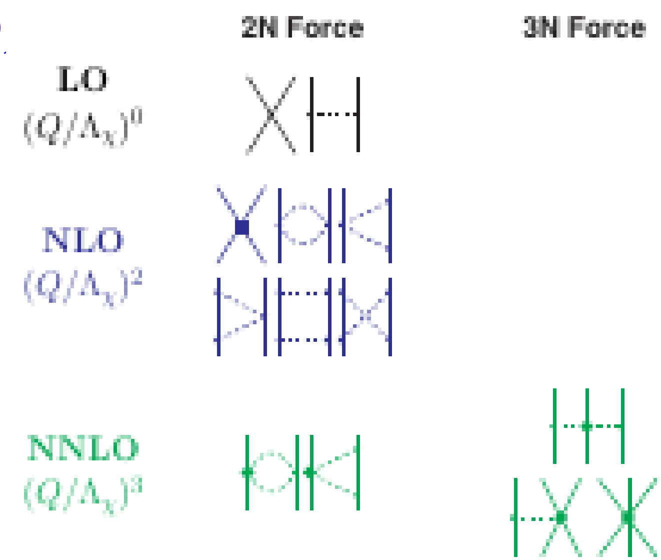


Modern Hadron-Hadron Interactions

- **Lattice QCD *hh* potential**
  - **V_{hh} is obtained from the Schrödinger eq. for the Nambu-Bethe-Salpeter (NBS) amplitude.**
    N. Ishii, S. Aoki, T. Hatsuda, PRL99('07)022001.
    → ΩΩ, NΩ, ΛΛ-NΞ potentials at phys. quark mass are published



- **Chiral EFT / Chiral SU(3) dynamics**
  - **V_{hh} at low E. can be expanded systematically in powers of Q/Λ.**
    S. Weinberg ('79);R. Machleidt, F. Sammarruca ('16)
    Y. Ikeda, T. Hyodo, W. Weise ('12).
    → NN, NY, YY, $\overline{\text{K}}$N-πΣ-πΛ, ...



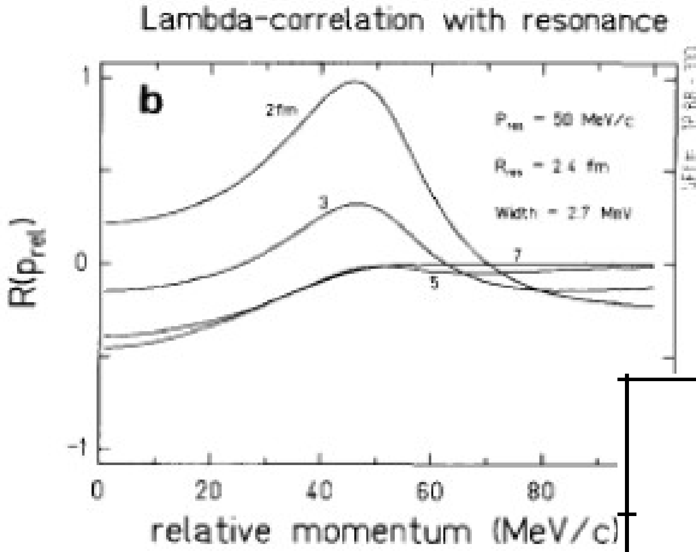
- **Quark cluster models,**
  Meson exchange models,
  More phenomenological models, …

Let us examine modern hh interactions !

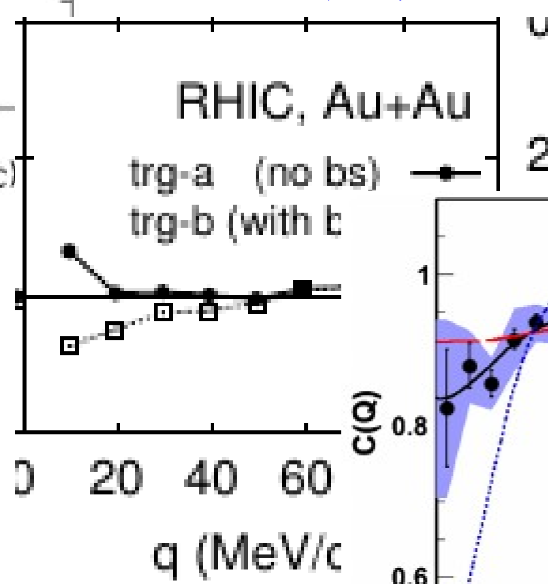
Survey of measured correlation function data

I will show some of the correlation functions which I investigated.
Details will be discussed by B. Hohlweger.

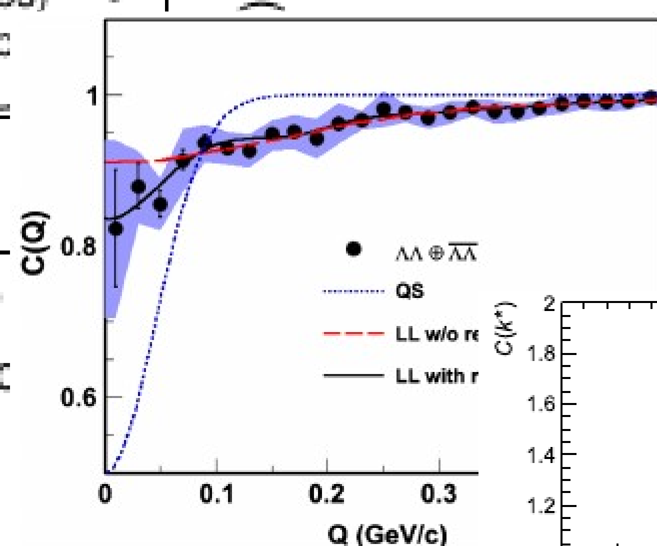
ΛΛ correlation and ΛΛ interaction



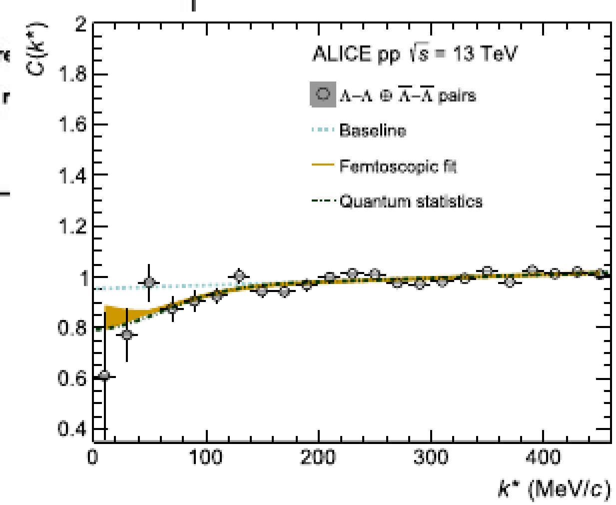
C. Greiner, B. Muller, PLB219('89)199.



AO, Hirata, Nara, Shinmura, Akaishi, NPA670('00)297c



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



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

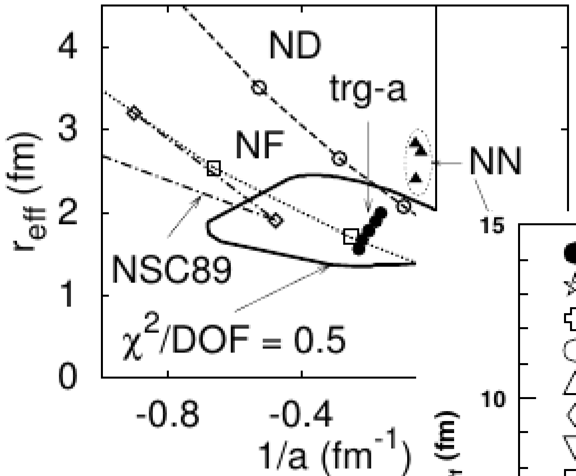
Weak enh. over quantum statistical (HBT) CF.

ΛΛ correlation and ΛΛ interaction

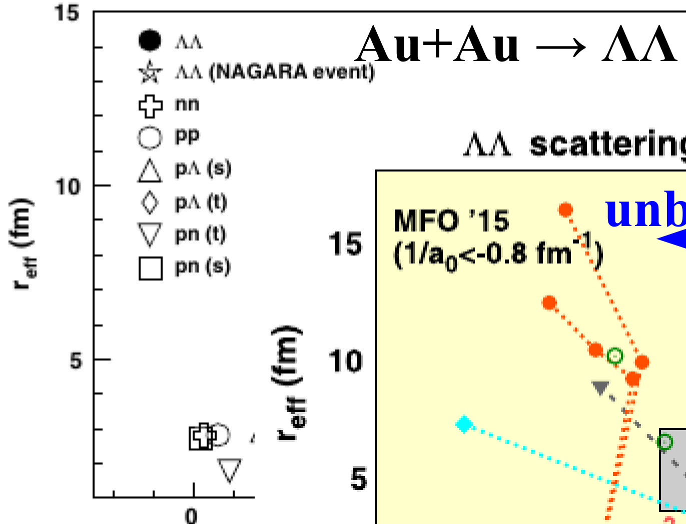
It is unlikely that ΛΛ bound state exists.

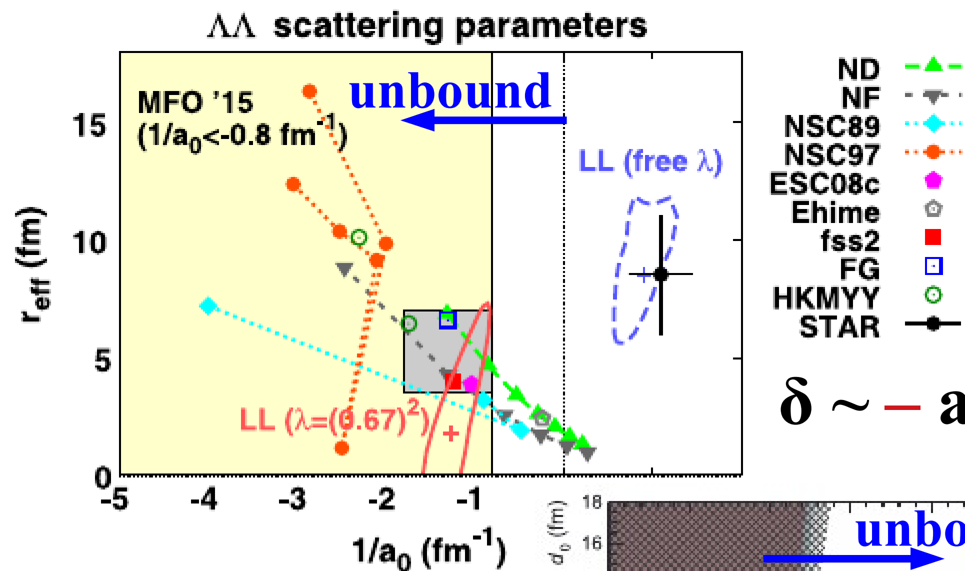
L. Adamczyk+[STAR], PRL114('15)022301

AO, K. Morita, K. Miyahara, T. Hyodo, NPA954('16)294

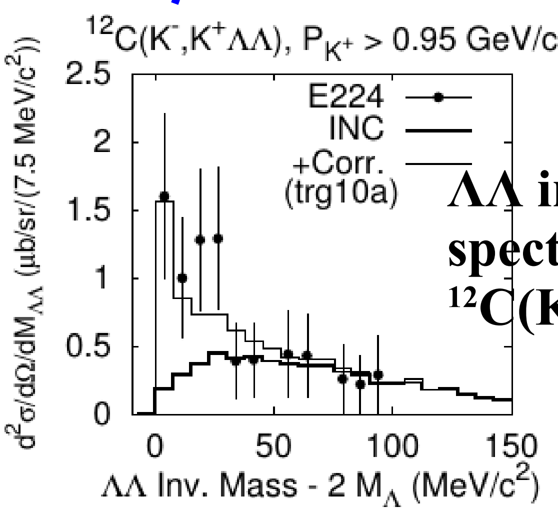


AO+('00)



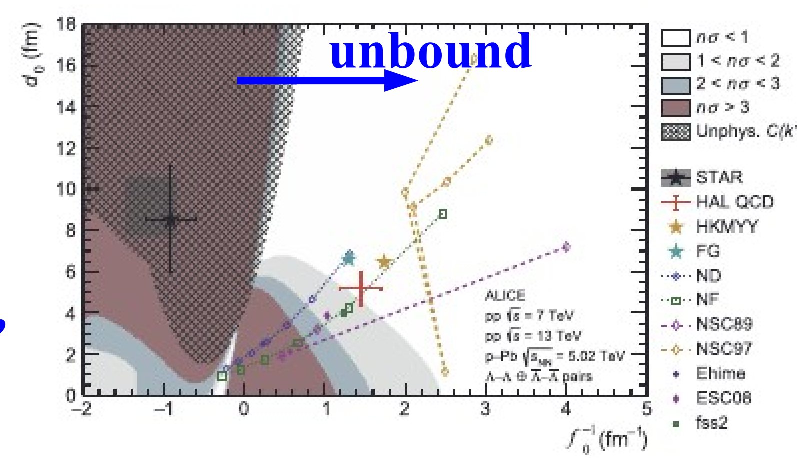


$\delta \sim - a_0 q$



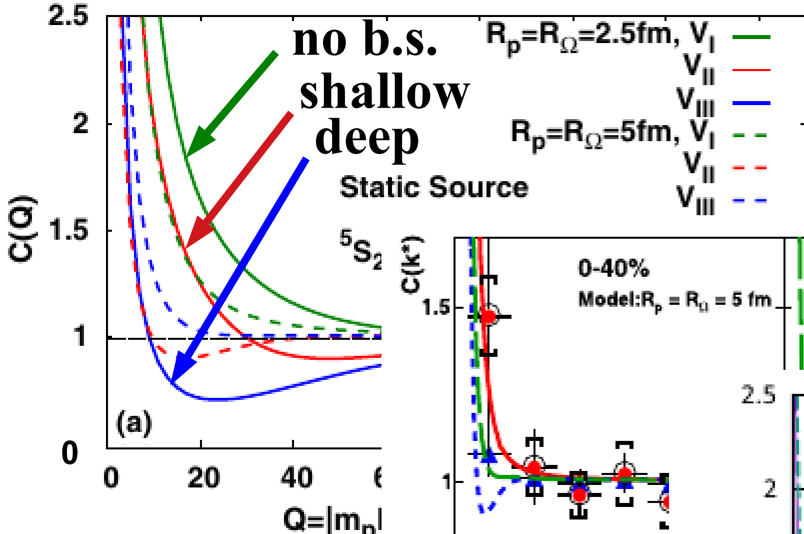
ΛΛ inv. mass spectrum from ^{12}C(K^-, K^+ΛΛ)

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

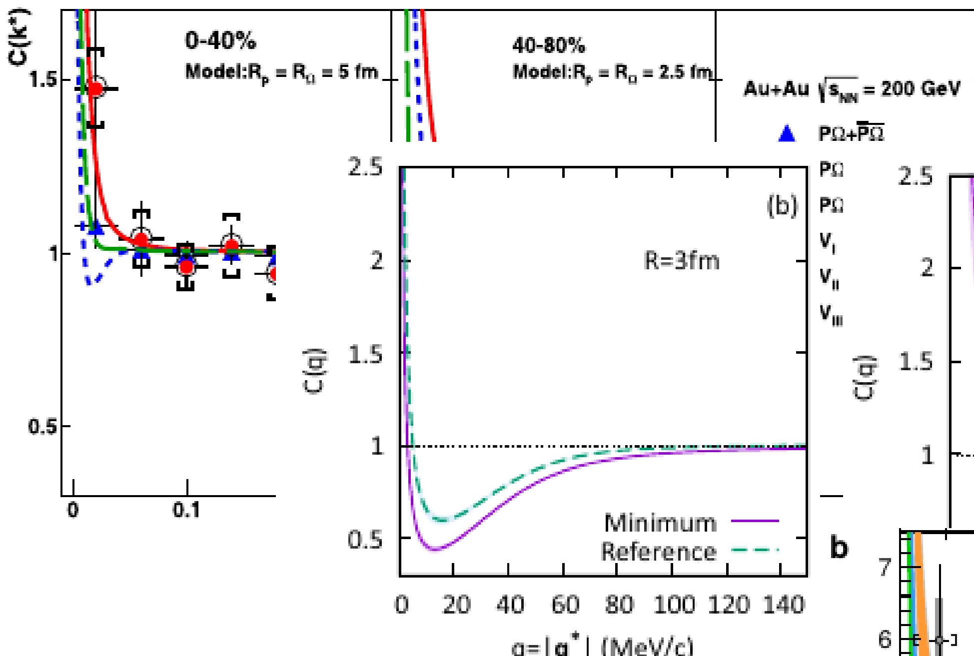


$\delta \sim + a_0 q$

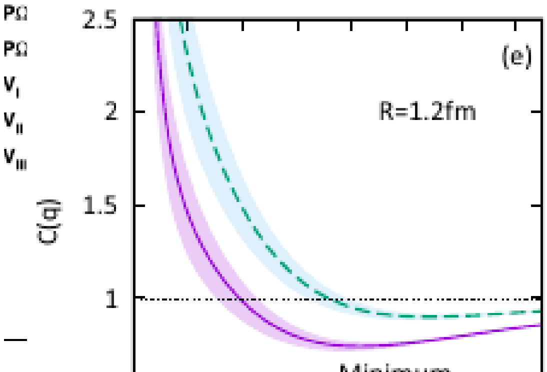
$p\Omega^-$ correlation



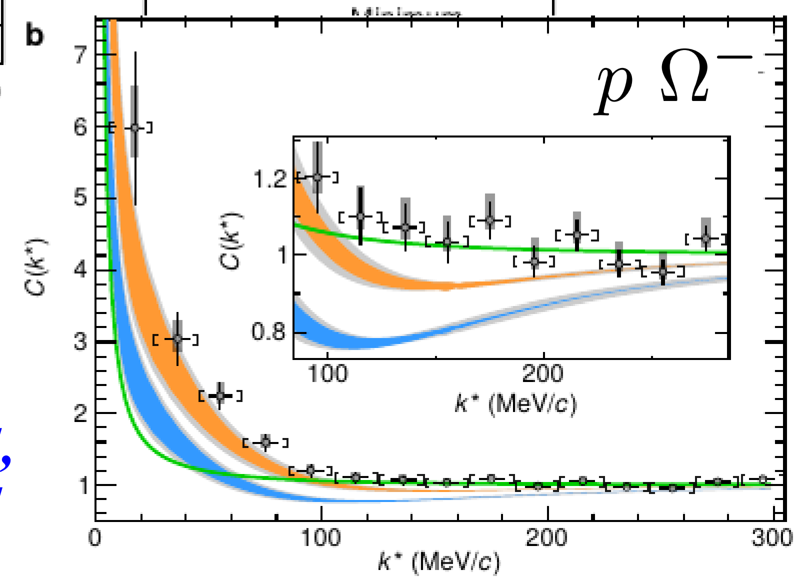
K. Morita, AO, F. Etminan,
T. Hatsuda, PRC94('16)031901(R)
(w/ Lattice potential with heavier quark mass)



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



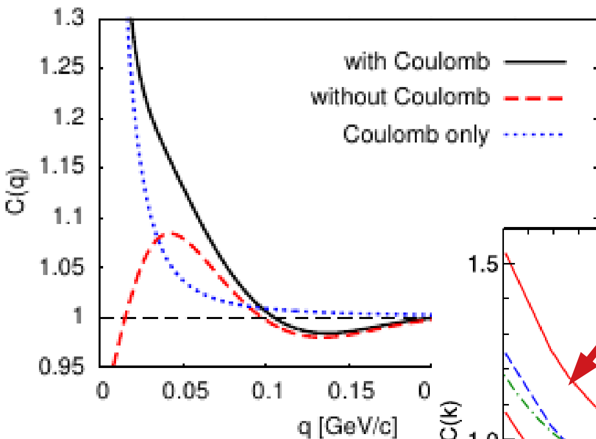
K. Morita, S. Gongyo, T. Hatsuda,
T. Hyodo, Y. Kamiya, AO,
PRC 101('20)015201. (w/ Lattice
potential at physical quark mass)



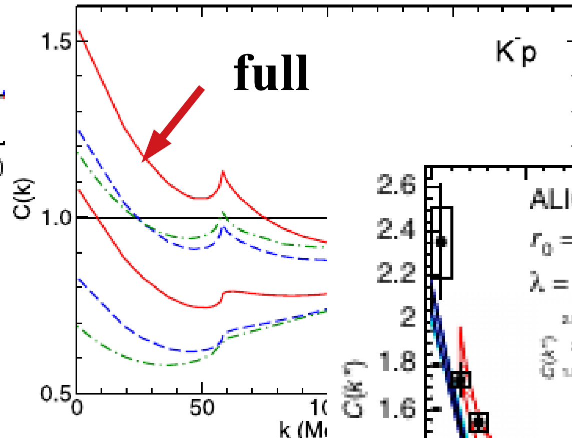
Bound state ?

S. Acharya+[ALICE],
2005.11495 [nucl-ex]
(pp 13 TeV)

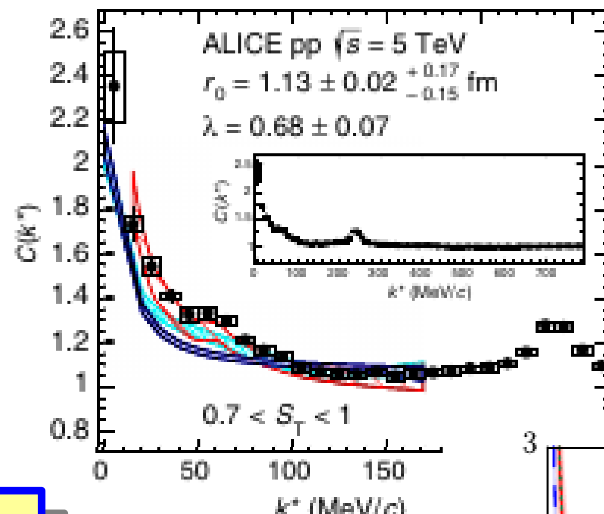
pK⁻ correlation



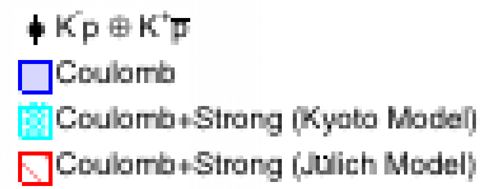
S. Cho+ [ExHIC], PPNP95('17)279.
(Insufficient coupled-channel effects)



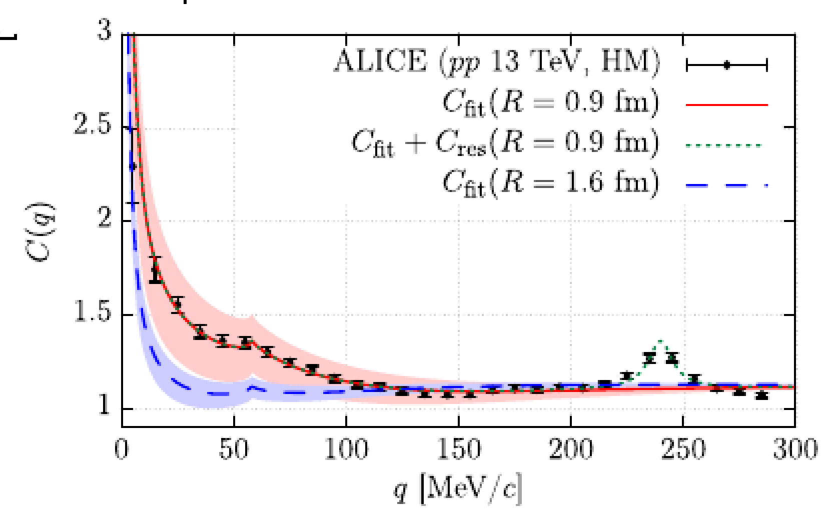
J. Haidenbauer, NPA981('19)1.
(w/ CC effects, w/o Coulomb)



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

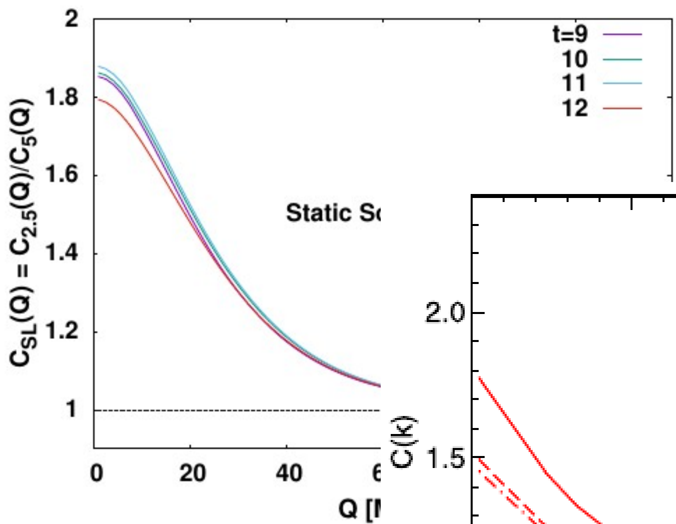


Source size dep. shows interesting feature.



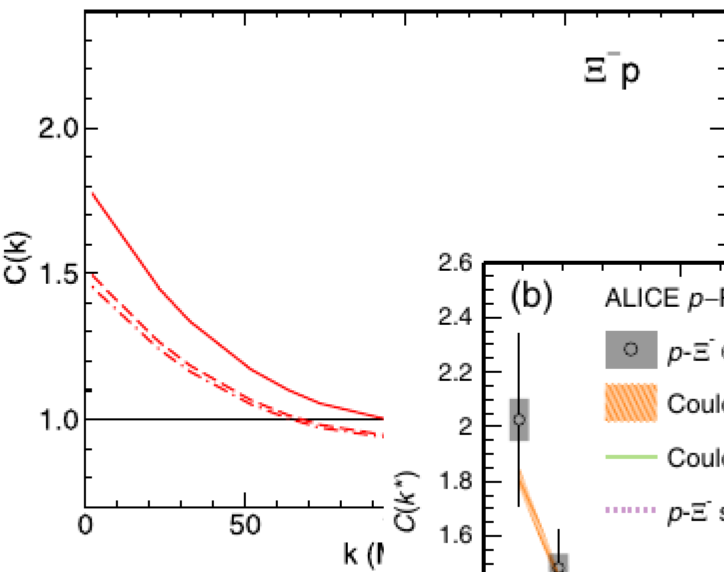
Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501.
(Chiral SU(3) dynamics)

$p\Xi^-$ correlation

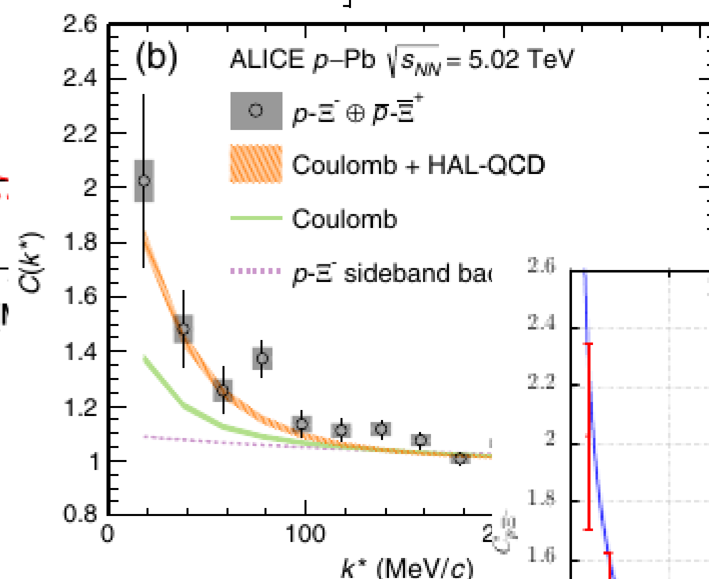


T. Hatsuda, K. Morita, AO,
K. Sasaki, NPA967('17)856.

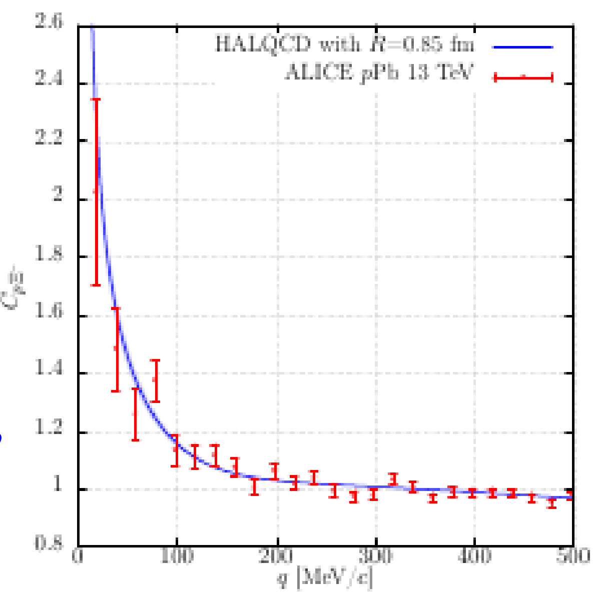
Where is H ?



J. Haidenbauer, NPA981('19)1.
(NLO(600), w/ CC effects,
w/o Coulomb)



S. Acharya+[ALICE],
PRL123('19)112002.



Y. Kamiya, K. Sasaki, T. Fukui, T. Hatsuda,
T. Hyodo, K. Morita, K. Ogata, AO, in prep.
(w/ Lattice BB pot. at phys. quark mass
and CC effects with ΛΛ)

Fermtoscopic Study of Hadron-Hadron Interaction

- **What did we learn from CF data of ΛΛ, $p\Omega^-$, pK^- and $p\Xi^-$?**
  - **CF(ΛΛ) constrain (a_0, r_{eff}) region implying small $|a_0|$.**
    It is likely that $a_0<0$ (in nucl. phys. convention, $\delta \sim -a_0 q$).
    (Consistent with double Λ hypernuclear data.)
  - **CF($p\Omega^-$) show strong enhancement at small q, imply large $|a_0|$,**
    and examine the recent lattice NΩ potential. (First info. on NΩ)
  - **CF(pK^-) show enhancement at small q, and examine potentials from the Jülich model and chiral SU(3) dynamics.**
    Coupled-channel effects with $\bar{K}^0 n$ and πΣ are large and visible, respectively (as discussed later).
  - **CF($p\Xi^-$) show strong enhancement at small q, imply large $|a_0|$,**
    and examine the chiral EFT and recent lattice NΞ potentials.
    (Nijmegen NΞ potential seems to be inconsistent with data.)
    Coupled-channel effects with ΛΛ are not large (as discussed later).
    (Consistent with Ξ-hypernuclear data ?)

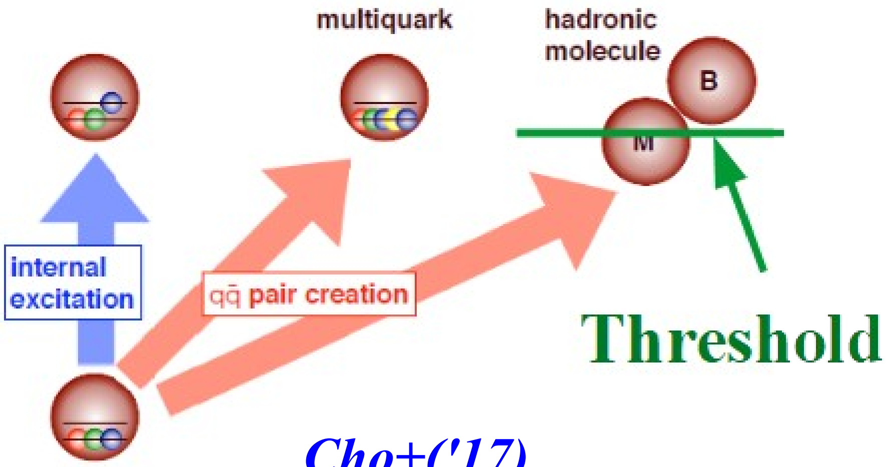
Fermtoscopic Study of Hadron-Hadron Interaction

- **These recent (2015-2020) observations of correlation functions are great achievements of RHIC and LHC.**
  We (theoretical physicists) appreciate your efforts.
  (I hope that ALICE publishes the new data more slowly…)
- **Many hadron physicists loves peaks, E and Γ of discrete poles, rather than smooth spectra. (Pc from LHCb is a good example !)**
  How can we (CF lovers) satisfy and attract them ?
  - **Relation of CF with the existence of the bound state pole.**
  - **Do coupled-channel effects modify CF and/or generate additional poles ?**
- **They also love hadronic states including heavy quarks.**
  Does silicon vertex detector specifies decay point of chamed hadrons ?
- **Many neutron star matter EOS physicists love the three-body force including hyperons. Can we access the three-body force ?**

Implications from current correlation function data to the existence of hadronic molecule states

Trend in Hadron Physics

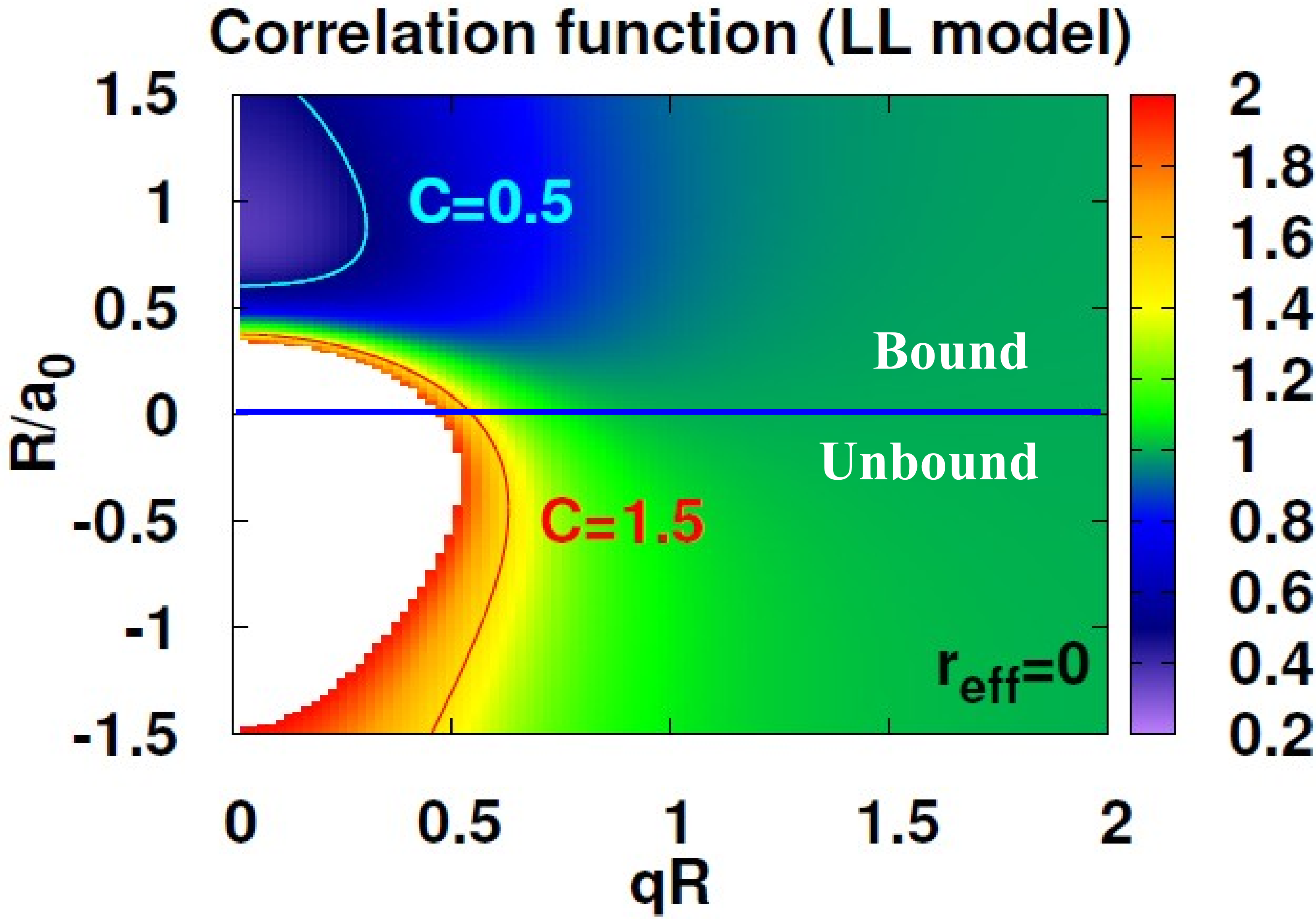
- **Hadron-Hadron interaction is closely related with ...**
  - **Quark-gluon structure of hadrons (Multi-quark or Hadronic molecule)**
    To be bound or not to be,
    That is the problem.
  - **Hadrons with heavy-quarks**
  - **Hadrons in nuclear matter and EOS of nuclear matter**



Cho+('17)

- **High-Energy Nuclear Collisions ($\sqrt{s_{NN}}$=40 GeV – 14 TeV) are favorable as a Hadron Factory !**
  - **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.)

Source Size Dependence of Correlation Function



LL model: R. Lednicky, V. L. Lyuboshits ('82)

Wave function around threshold (S-wave, attraction)

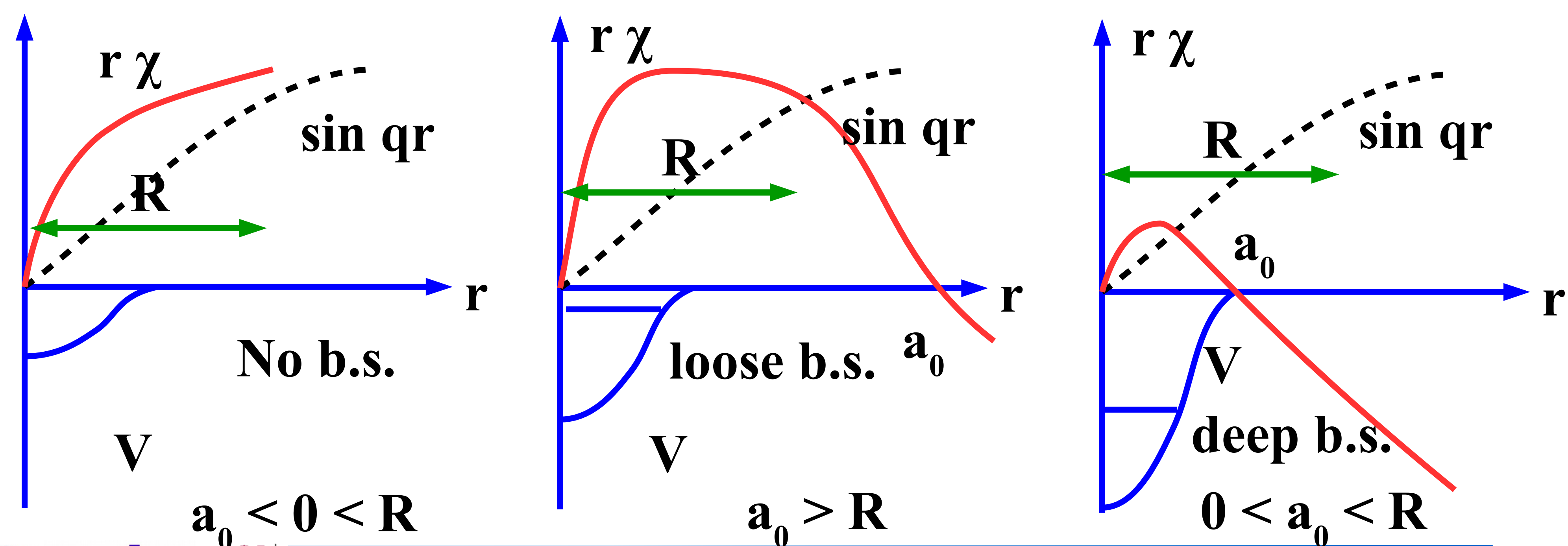
- **Low energy w.f. and phase shift**

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

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

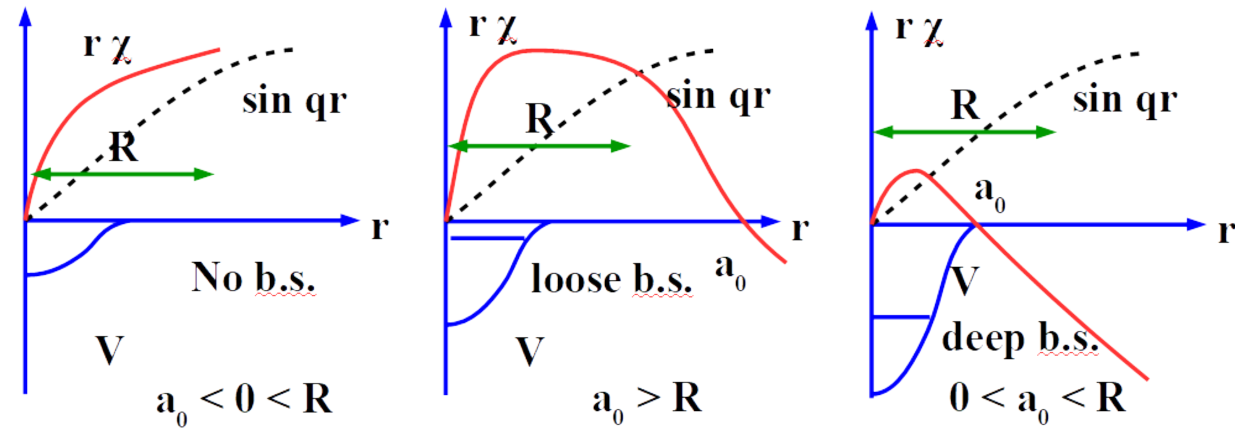
a_0 =scatt. length
r_{eff}=eff. range

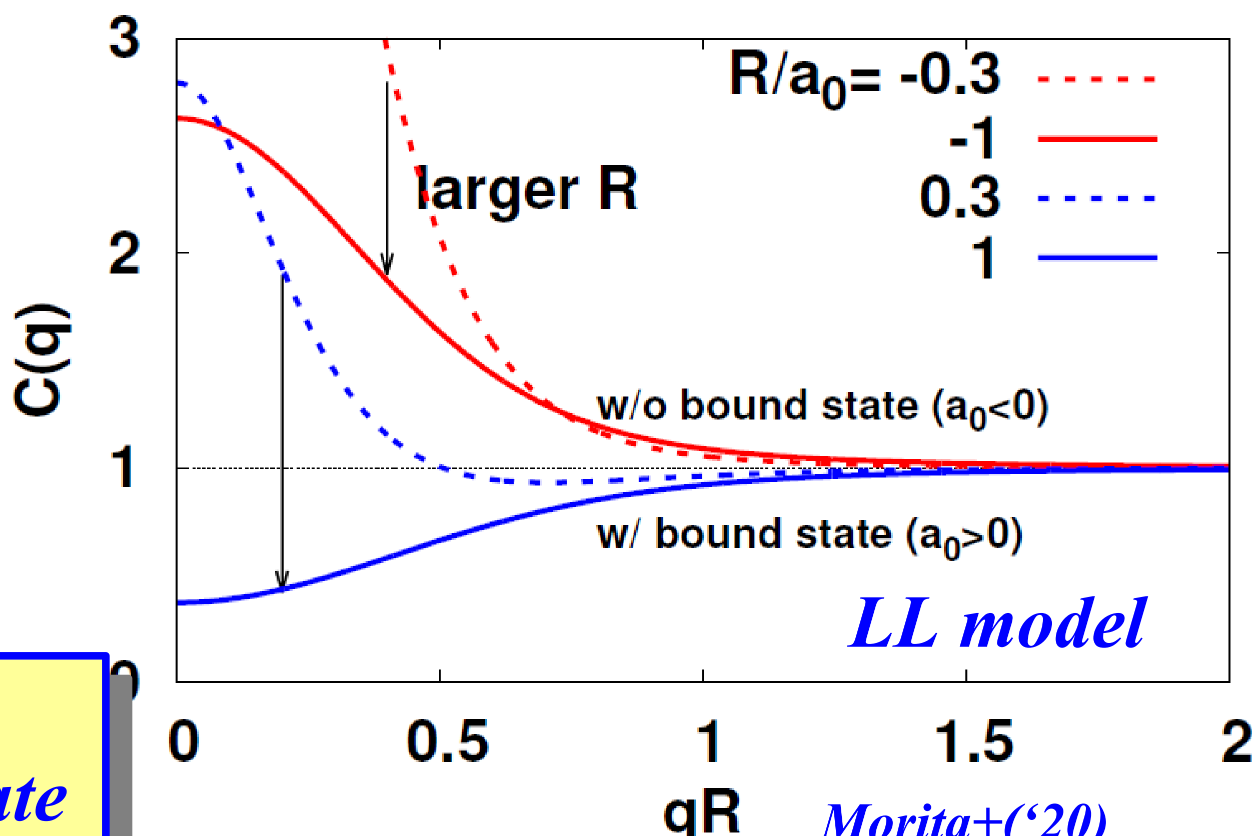
  - **Wave function grows rapidly at small r with attraction.**
  - **With a bound state (a_0>0), a node appears around r=a_0**



From correlation function to hadron-hadron interaction

- **Large $|a_0|$ ($|a_0| > R$)**
  → Large C(q)
  (unitary regime)
- **w/o bound state**
  ($a_0 < 0$, $|a_0| \sim R$)
  → C(q) > 1
- **With bound state**
  ($a_0 > 0$, $|a_0| \sim R$)
  → Region with
  C(q) < 1 appears

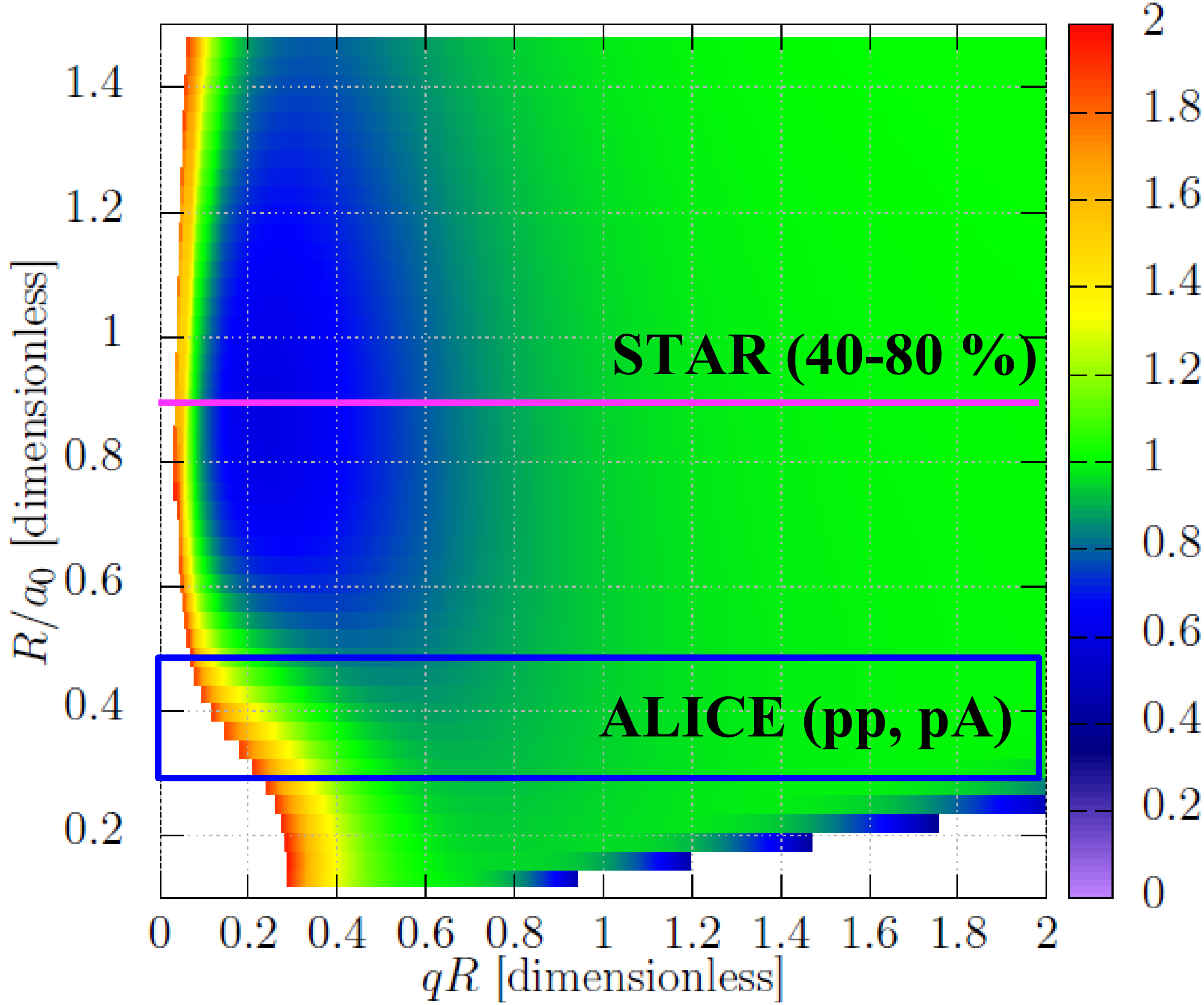




Morita+('20)

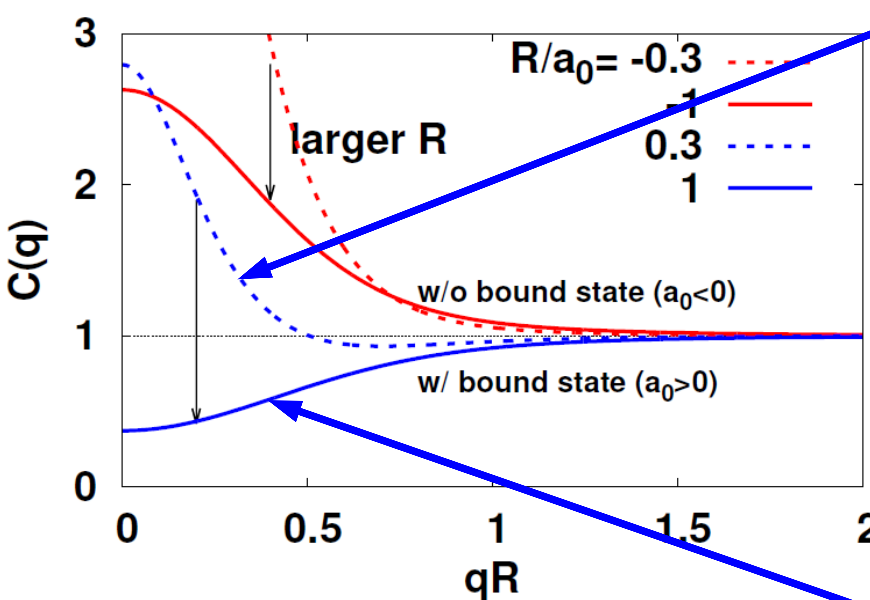
Source size dep. of CF
→ Existence of bound state

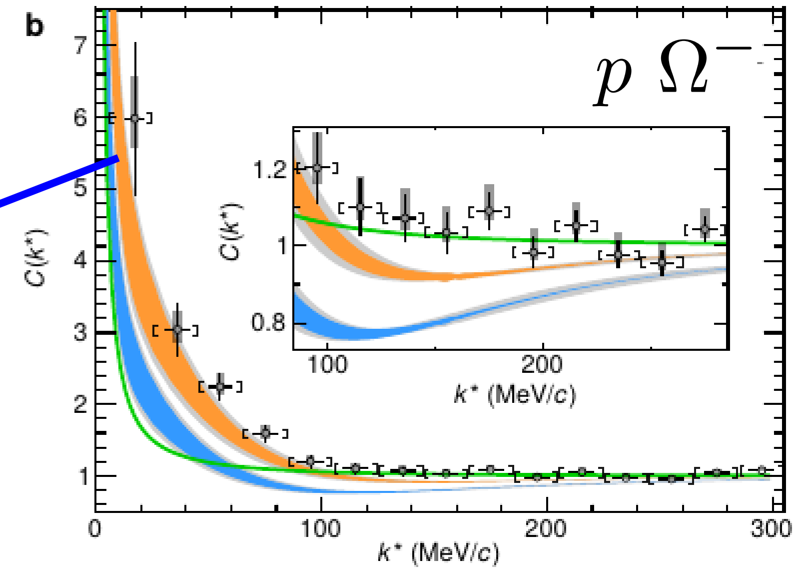
Correlation Function with Gaussian source



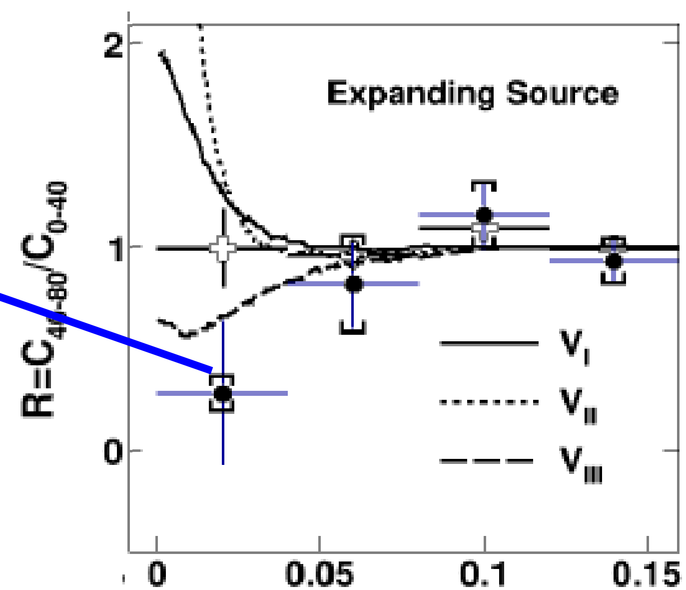
NΩ potential (J=2, HAL QCD, a_0=3.4 fm) + Coulomb

STAR + ALICE = NΩ Dibaryon





ALICE, 2005.11495

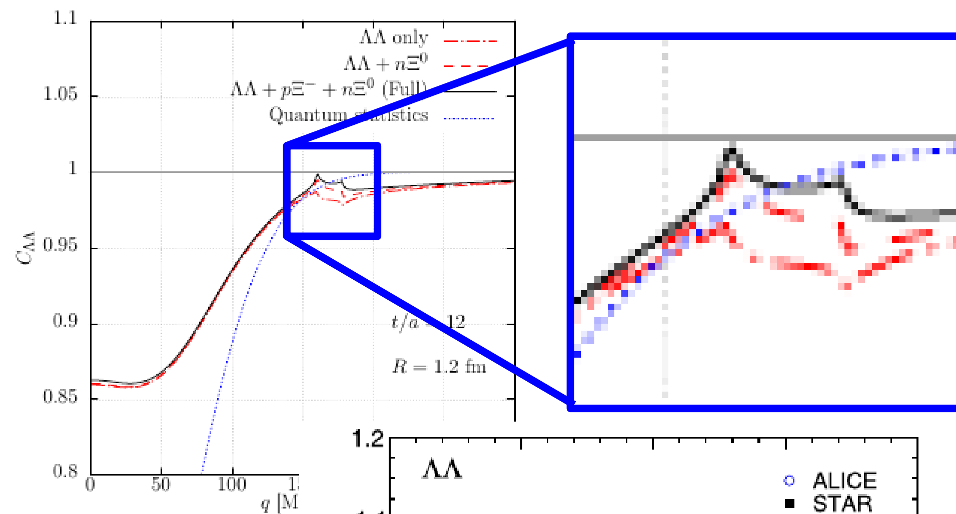


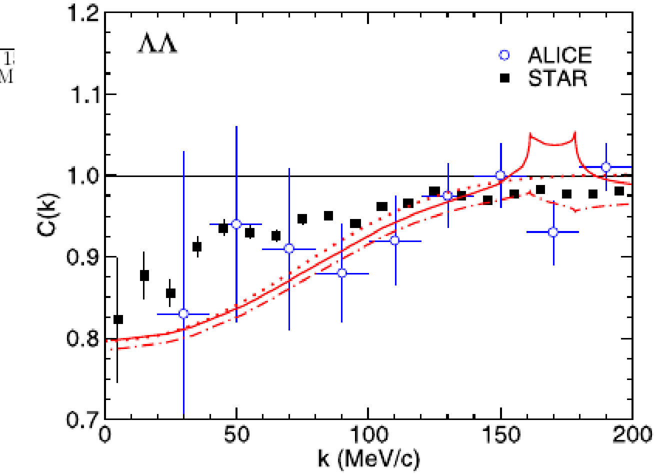
STAR (1808.02511, PLB790 ('19) 490)

Do you know any mechanism to suppress C(q) other than the existence of bound state, when the interaction is attractive ? (Strong flow, ...)

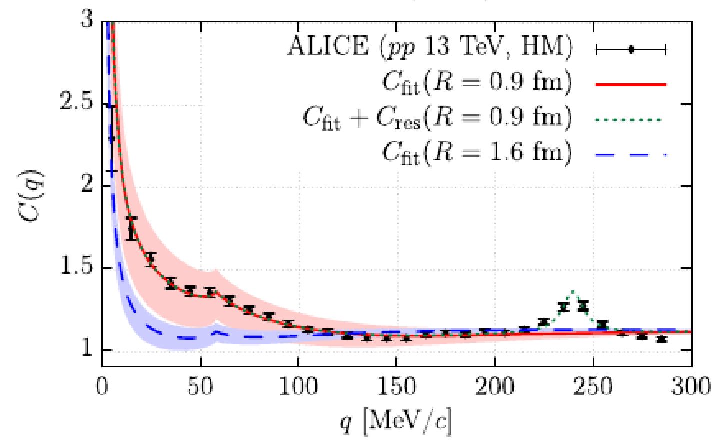
Other bound states ?

- **ΛΛ-NΞ**
  - **$C_{\Lambda\Lambda}(q)$ in AA(RHIC) and pp(LHC) are similar (No b.s. below ΛΛ).**
  - **LQCD predicts a virtual 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+, in prep.; Haidenbauer('19).



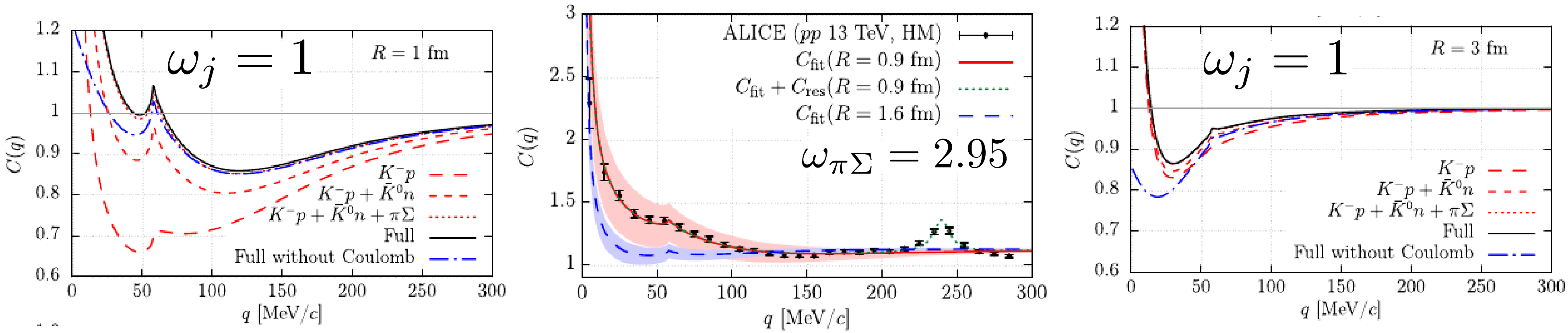


- **$\bar{K}N$**
  - **Λ(1405) is believed to be the bound state of $\bar{K}N$, and "dip" is expected at $R \sim a_0$.**
  - **However, Coulomb and coupled-channel effects modify the dip-like behavior.**
    Kamiya+ ('20).

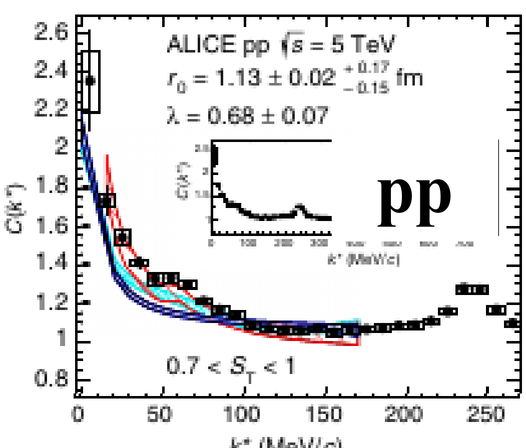


Source Size Dependence of C(pK⁻)

- **Coupled-channel effects are suppressed when R is large, and "pure" pK⁻ wave function may be observed in HIC.**
- **Can we deduce (Re a_0, Im a_0) at precision comparable to that in SIDDHARTA kaonic hydrogen data ?**



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



pA

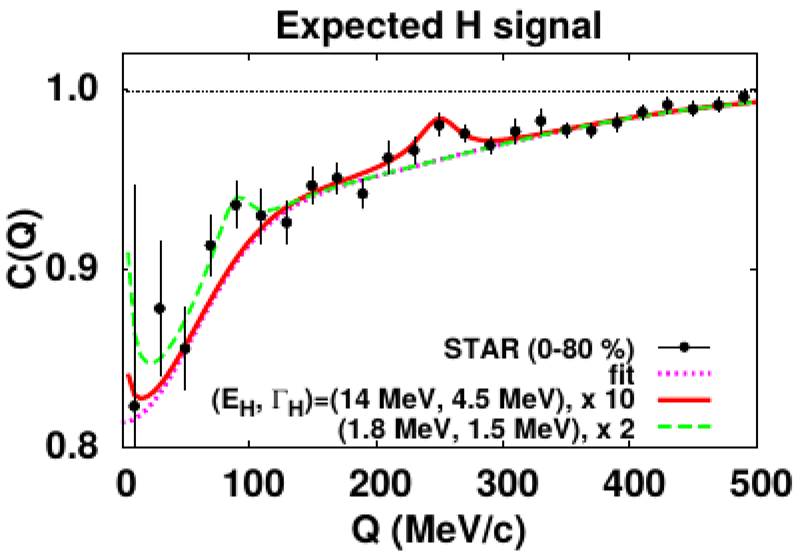
AA

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

Correlation functions in the near future

CF from ALICE in the near future

- S=-3 baryon-baryon correlation (e.g. $\Lambda\Xi^-$)
  - Important to confirm NΩ bound state as a peak in $C_{\Lambda\Xi}(q)$.
  - Statistically challenging.
    In $C_{\Lambda\Lambda}$ data from STAR, statistical fluc. is 10 times larger than expected signal from statistical model estimate.

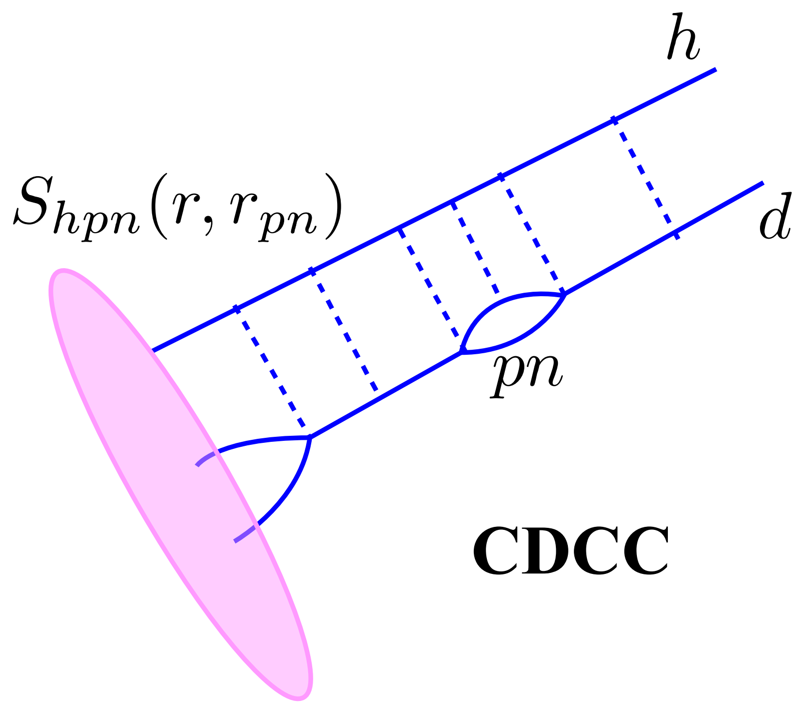


- Three-body correlation (e.g. Λpp)
  - Extremely important to neutron star matter EOS, if we can extract three-body force.
  - We may need to develop a framework beyond the "Riverside approximation" to include *hh* and *hhh* interaction.
    E. O. Alt, T. Csorgo, B. Lorstad, J. Schmidt-Sorensen, PLB458 ('99)407 for 3π.

(I got the info. mainly from Laura, Valentina and Oton, but I never told it to people other than CF collaborators of mine.)

CF from ALICE in the near future (cont.)

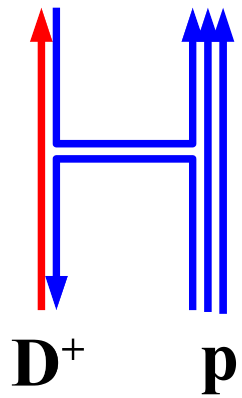
- **Hadron-deuteron correlation (Λd, K$^-$d, Ξ^-d, Ω^-d, …)**
  - **Scattering length data of these are important to evaluate binding energy and lifetime of hyper triton (Λd), I=1 $\bar{K}$N interaction (K$^-$d), and the existence of a bound state.**
    Etminan+ (2006.12771); J. Haidenbauer, PRC102('20)034001.
  - **For serious estimate, deuteron breakup effects (d ↔ pn) need to be accounted for. I asked two low-energy few-body nuclear physicists (K. Ogata, T. Fukui) to apply the few-body reaction framework (Continuum-discretized coupled-channels (CDCC)) to hadron-deuteron correlation.**



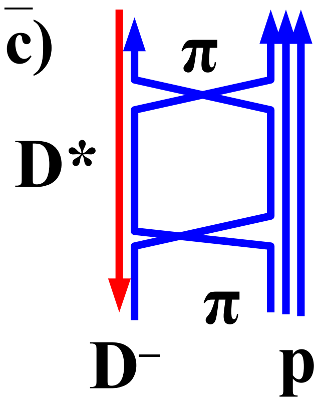
(I got the info. mainly from Laura, Valentina and Oton, but I never told it to people other than CF collaborators of mine.)

CF from ALICE in the near future (cont.)

- **CF including charmed hadron**
  - **Extremely important in recent hadron physics.**
  - **$D^+(c\bar{d})$-p(uud) correlation**
    $q\bar{q}$ can annihilate, and D^+p couples with many other channels. (LQCD calc. is difficult.)



  - **$D^-(\bar{c}d)$-p(uud) correlation**
    Probes Θ_c($\bar{c}$-ud-ud) state (replace $\bar{s}$ in Θ($\bar{s}$-ud-ud) with $\bar{c}$)
    Two pion exchange can induce attraction.
    Provides production-mechanism-free (thermal) result.
    Easy to calculate the potential in LQCD.
    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).



(I got the info. mainly from Laura, Valentina and Oton, but I never told it to people other than CF collaborators of mine.)

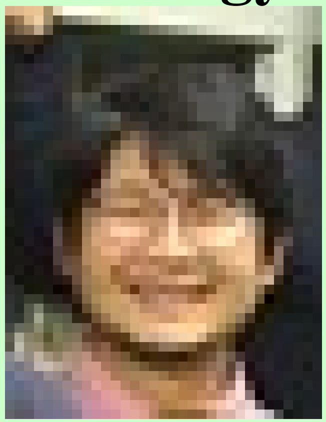
Summary

- Correlation functions (CFs) can be utilized to constrain / examine the hadron-hadron interactions (V_{hh}), provided that
  - the pair purity (λ) is not very small,
  - and V_{hh} dominates the correlation.
- Recent data from ALICE and STAR enable us to access V_{hh} unexplored in previous works.
- Source size (R) dependence of CF is important to get knowledge of the existence of a bound state around the threshold.
  - With a bound state, CF shows suppression at qR~1 for $a_0/R \sim 1$ in single-channel problems.
  - Coupled-channel effects are suppressed for larger R.
- CFs involving charmed hadrons are charming and would attract many hadron physicists.

Thank you for attention !

Coauthors of arXiv:1908.05414 (pΩ, ΩΩ) and arXiv:1911.01041 (pK⁻)

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

Y. Kamiya

K.Sasaki

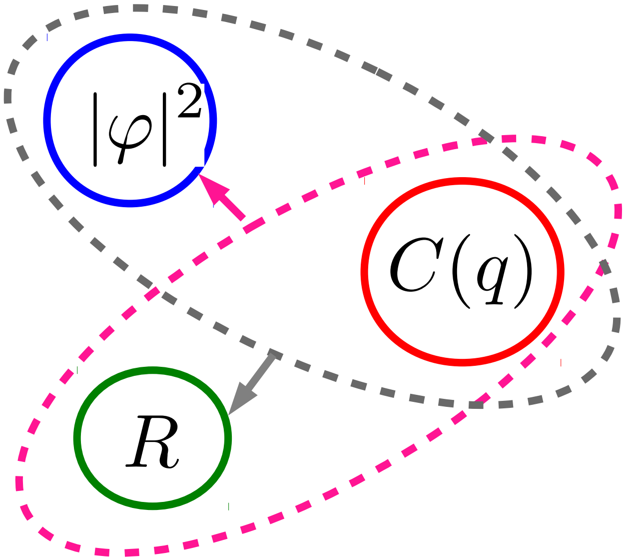
ALICE

(My) Homeworks

- pΛ, pΣ^0 and $\Lambda\Xi^-$ correlation functions using the updated LQCD potentials.
- CF involving deuteron (K. Ogata, T. Fukui).
- Developing a framework to handle three-body correlations.
- Interactions between hadrons with charm.
- Simple Gaussian source function should be improved to include resonance decay effects as done in CATS.
(c.f. B. Hohlweger's talk)
- ...

Correlation Function (CF): Non-standard usage

- **HBT, GGLP: CF + w.f. → Source Size**
  Another way: CF + Source Size → w.f. → hh 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

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**

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

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

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

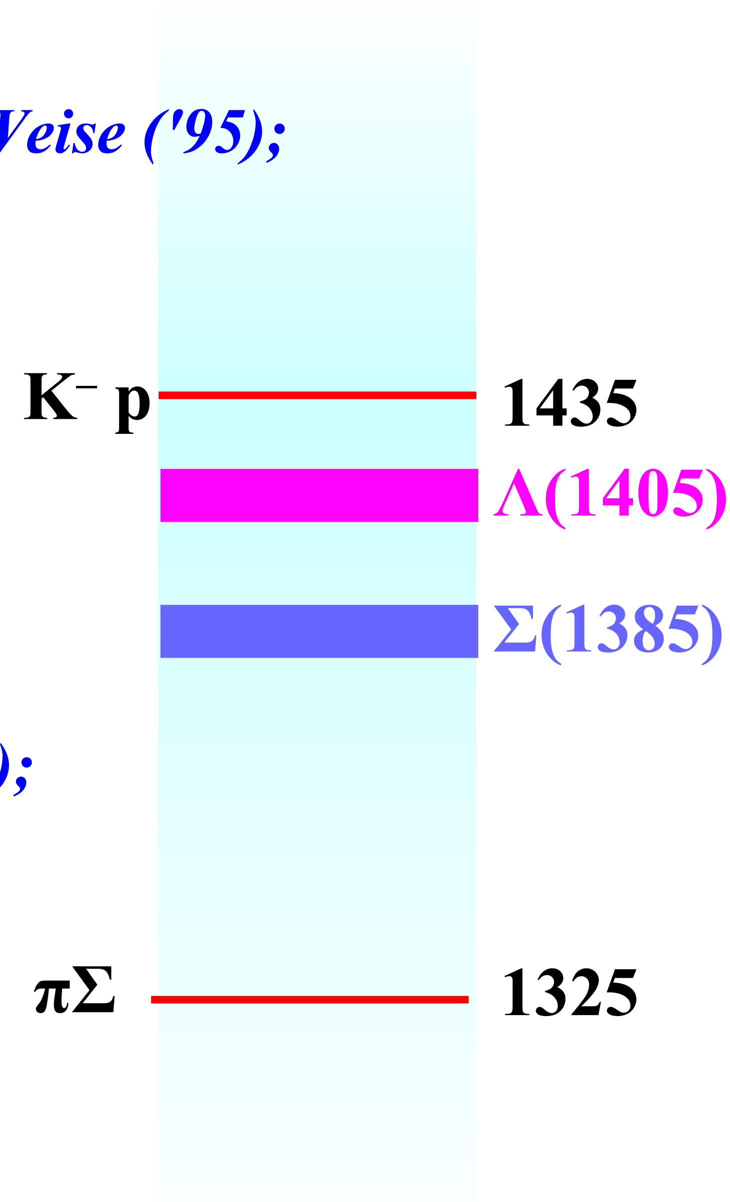
$$1 - 2/\pi \simeq 0.36,\ \sqrt{\pi}/2 \simeq 0.89$$

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

$K^{-}p$ correlation

K^- p interaction

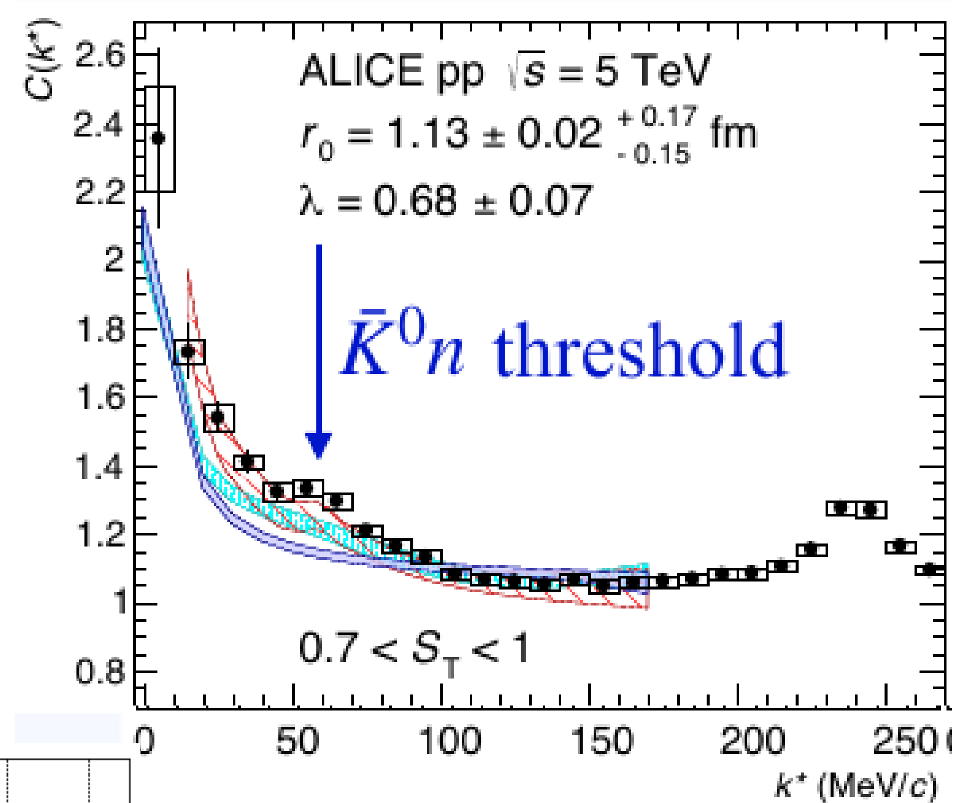
- **Λ(1405) $\bar{K}$N quasi-bound state**
  Dalitz, Tuan ('60); Koch ('94); Kaiser, Siegel, Weise ('95); AO, Nara, Koch ('97); Jido+('03)
  - **Positive scattering length in K^- atoms**
    M.Iwasaki et al. PRL78('97)3067; M.Bazzi et al. [SIDDHARTA Collab.], PLB704('11)113.
- **Kaonic nuclei ?**
  Nogami ('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)



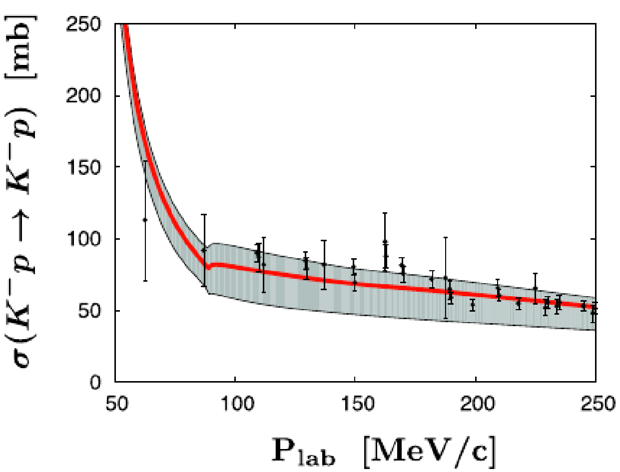
How about K^- p correlation ?

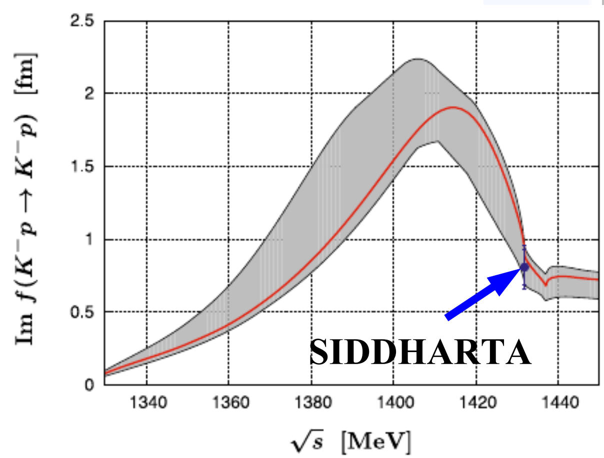
K^-p correlation function data

- **K – p correlation function from high-multiplicity events of pp collisions**
  S. Acharya et al. (ALICE), PRL124('20)092301 [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

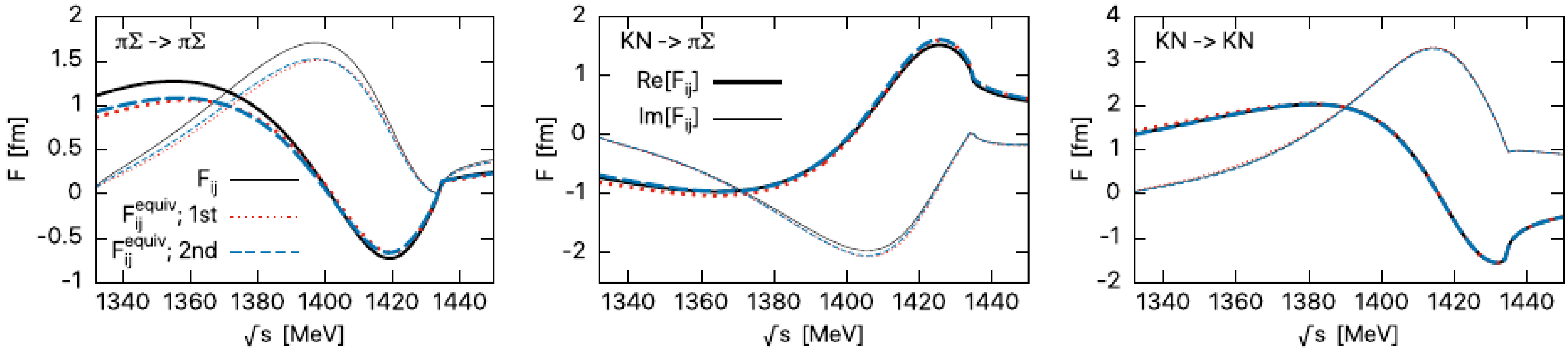




Y. Ikeda, T. Hyodo, W. Weise,NPA881 ('12) 98

$\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ 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**

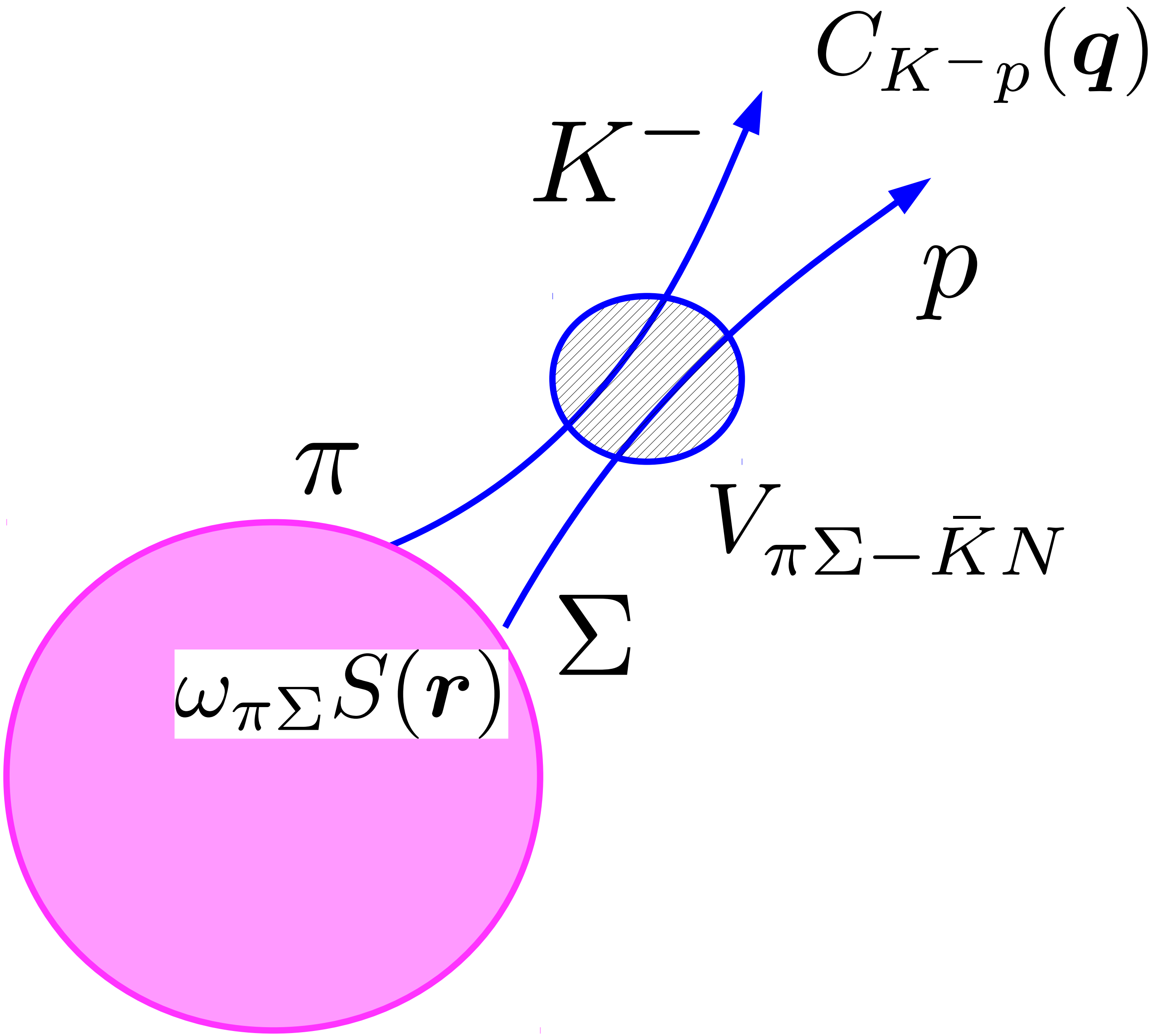
$$C_i(\boldsymbol{q}) = \int d\boldsymbol{r} S_i(\boldsymbol{r}) \left[\underline{|\varphi^{C,\mathrm{full}}(\boldsymbol{q},\boldsymbol{r})|^2} + \underline{|\chi_i^{C,(-)}(r,q)|^2} - \underline{|j_0^C(qr)|^2} \right]$$

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

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

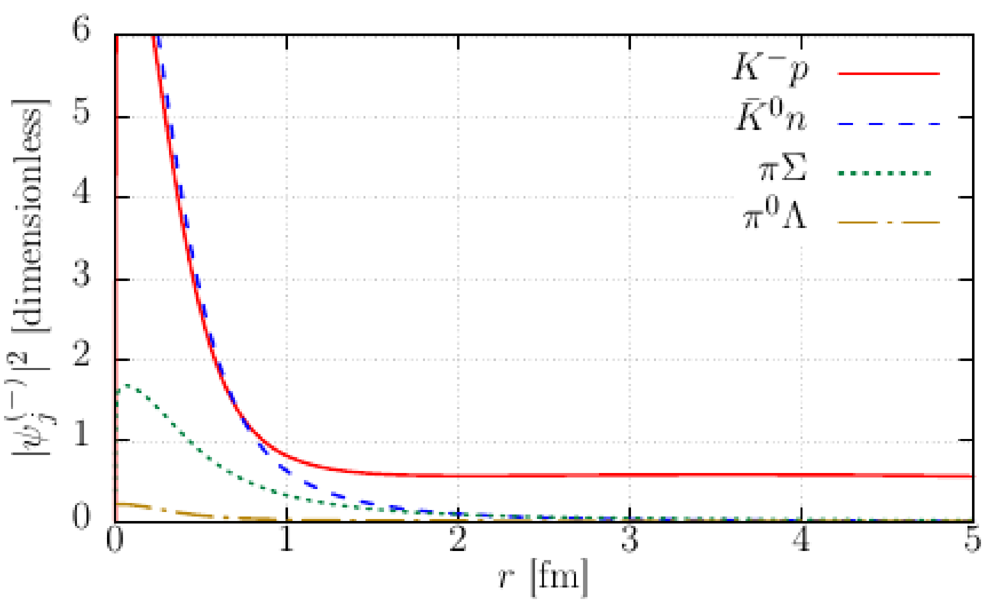
Outgoing B.C. in the i-th channel, ω_j = Source weight (ω_j=1)

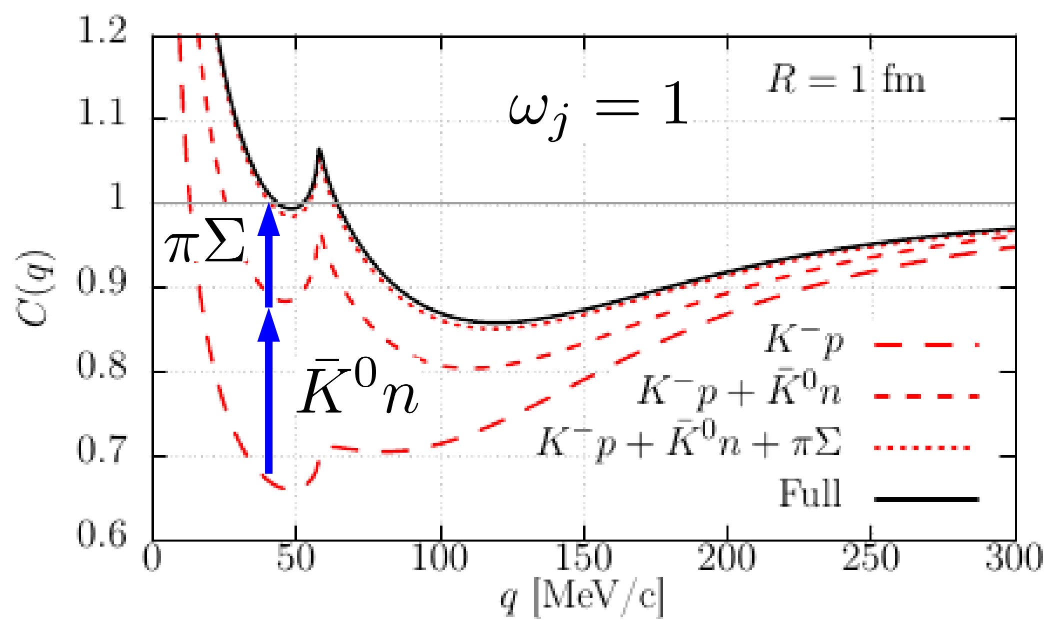
Correlation Function with Coupled-Channels Effects



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

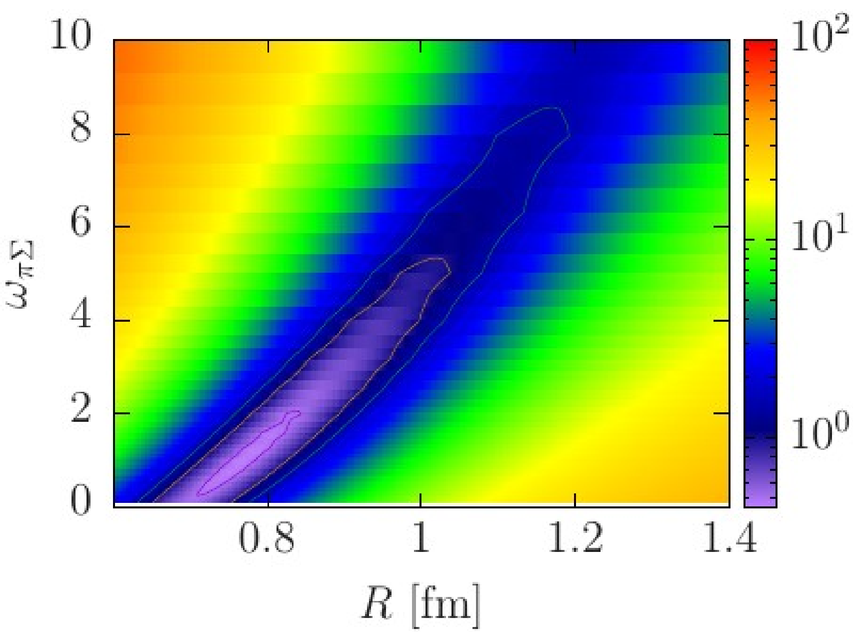
- **Corr. Fn. from Chiral SU(3) coupled-channels potential + Coulomb + threshold difference (for the first time !)**
  Y. Kamiya, T. Hyodo, K. Morita, AO, W. Weise, PRL124('20)132501 [1911.01041].
- **Coupled-channels effect**
  - **W.f. of other channels than K⁻ p decay in r < 1 fm.**
  - **But they contribute to corr. fn. meaningfully.**

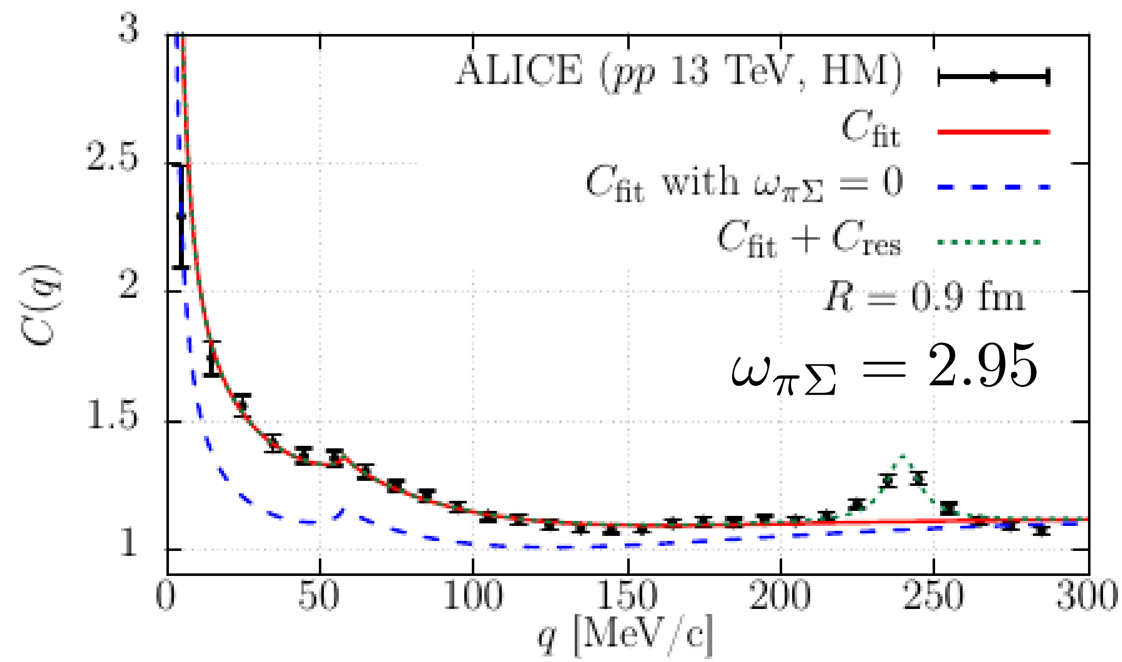




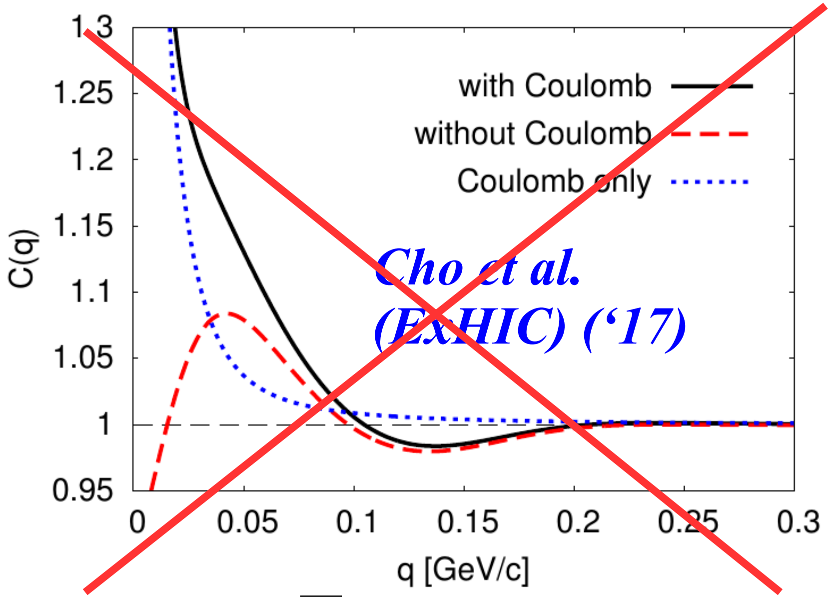
Correlation Function from Chiral SU(3) Potential (2)

- **"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**
    $\omega_{\pi\Sigma} \sim \exp[(m_K+m_N-m_\pi-m_\Sigma)/T] \sim 2.$



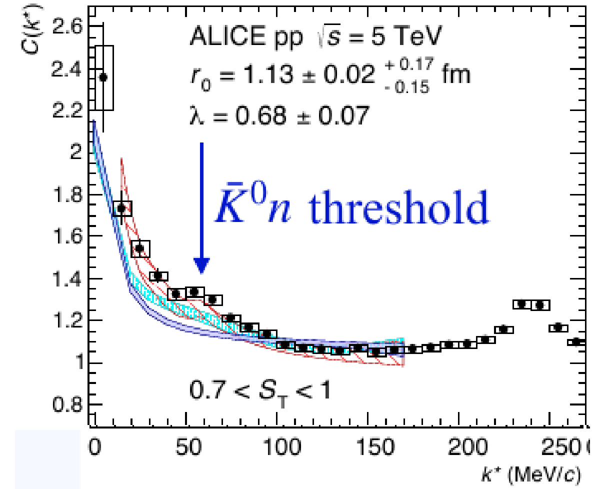


Comparison with other estimates

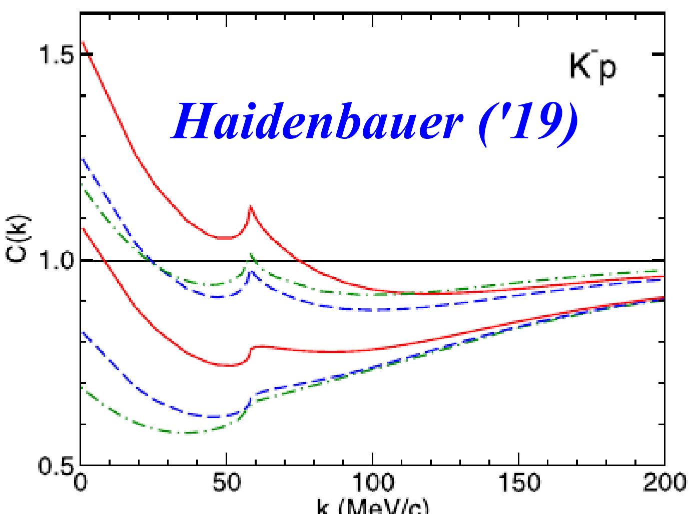


No $\overline{K}^0$n, πΣ source
No threshold diff.

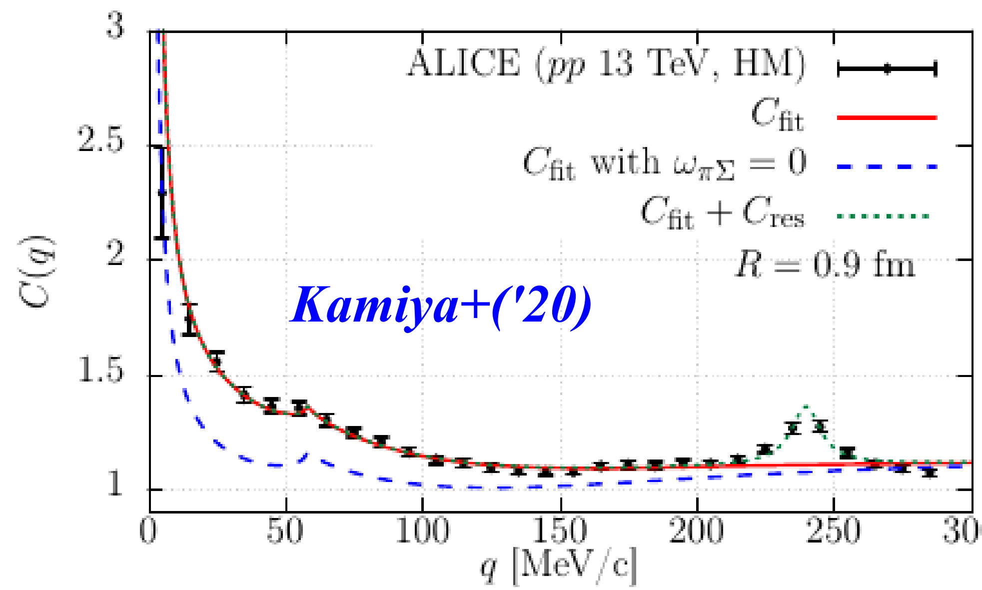
ALICE



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

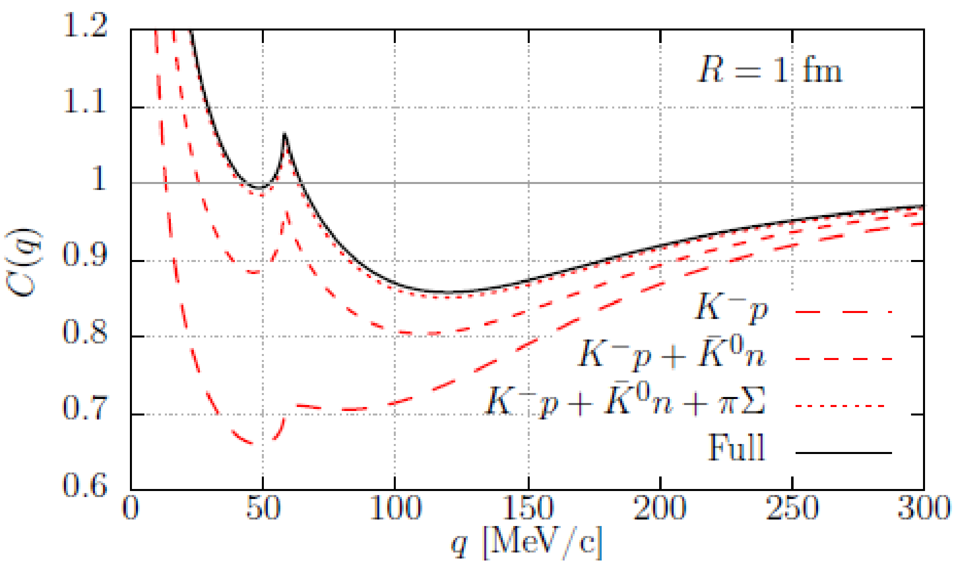


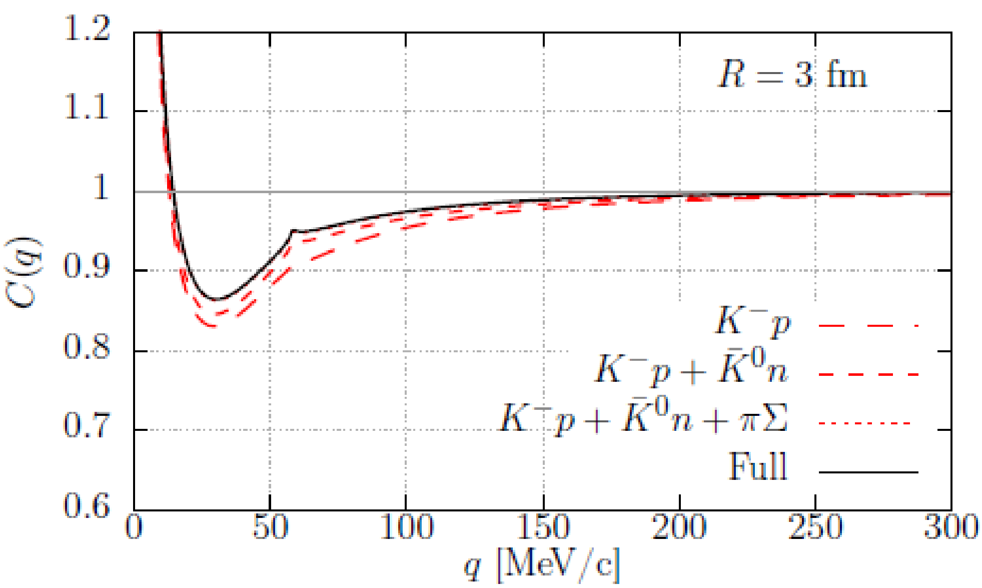
Julich amplitude
Consistent with Kamiya+('19) w/o Coulomb



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.**