2 粒子運動量相関から探る ハドロン間相互作用

From hadron correlations to hadron interactions

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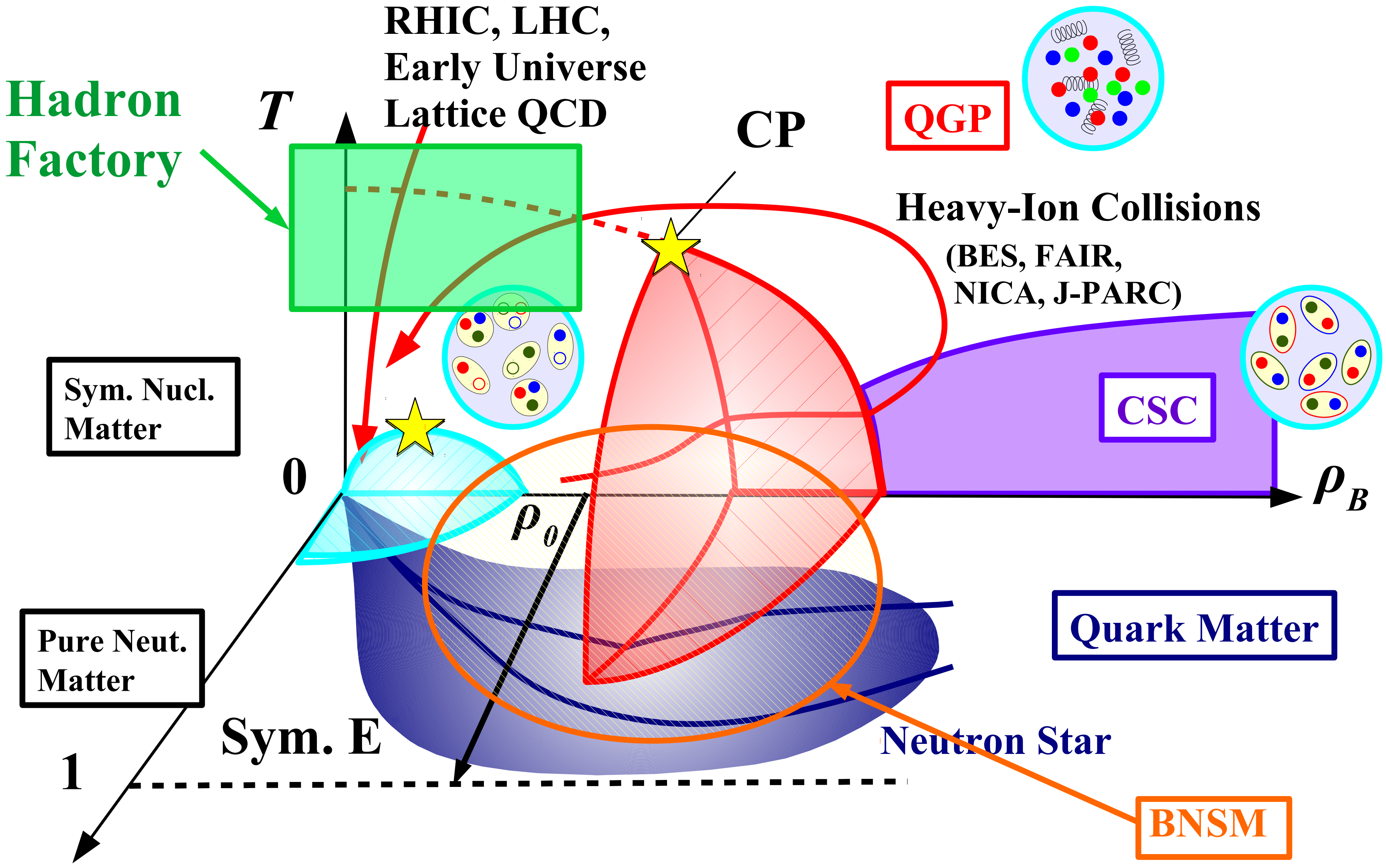
Program for ”2nd Symposium on Clustering as a window
on the hierarchical structure of quantum systems”
May 31-June 1, 2019, Tokyo Tech

Clusters & Hierarchies

公募研究 19H05151

QCD phase diagram

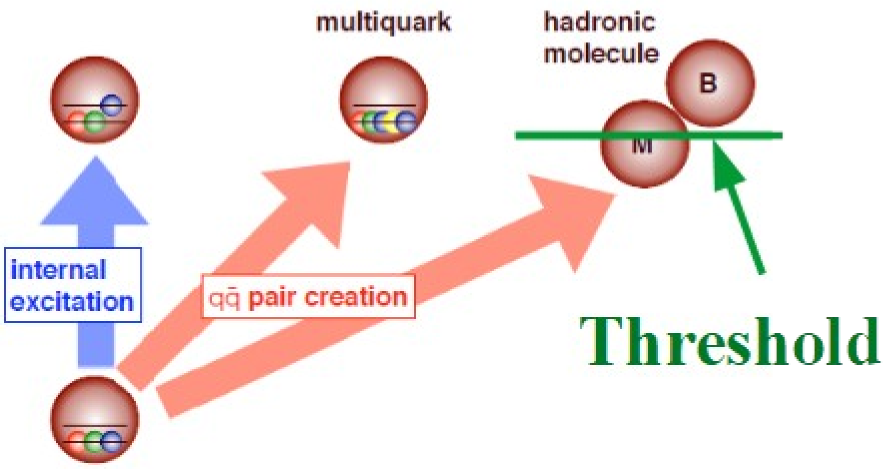


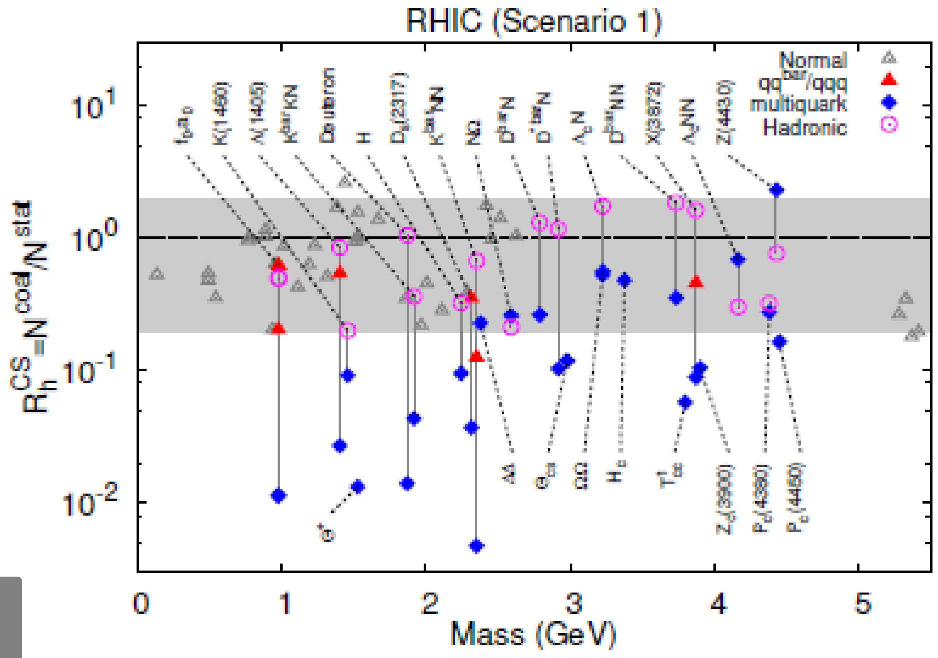
δ=(N-Z)/A (or Y_Q(hadron)=Q_h /B~(1-δ)/2)

AO, JPS Conf. Proc. 20 (2018), 011035

Hadron Production at boundaries

- **Hadron production from HIC**
  - **Chemical freezeout takes place at around the *phase* boundary**
- **Hadronic molecule states**
  - **Appear at around the *energy* boundary**
  - **Tail of wave function around threshold energy is dominated by that channel. (Ikeda diagram)**
  - **Produced as freq. as normal hadrons.**





S. Cho+, Prog. Part. Nucl. Phys. 95 ('17) 279

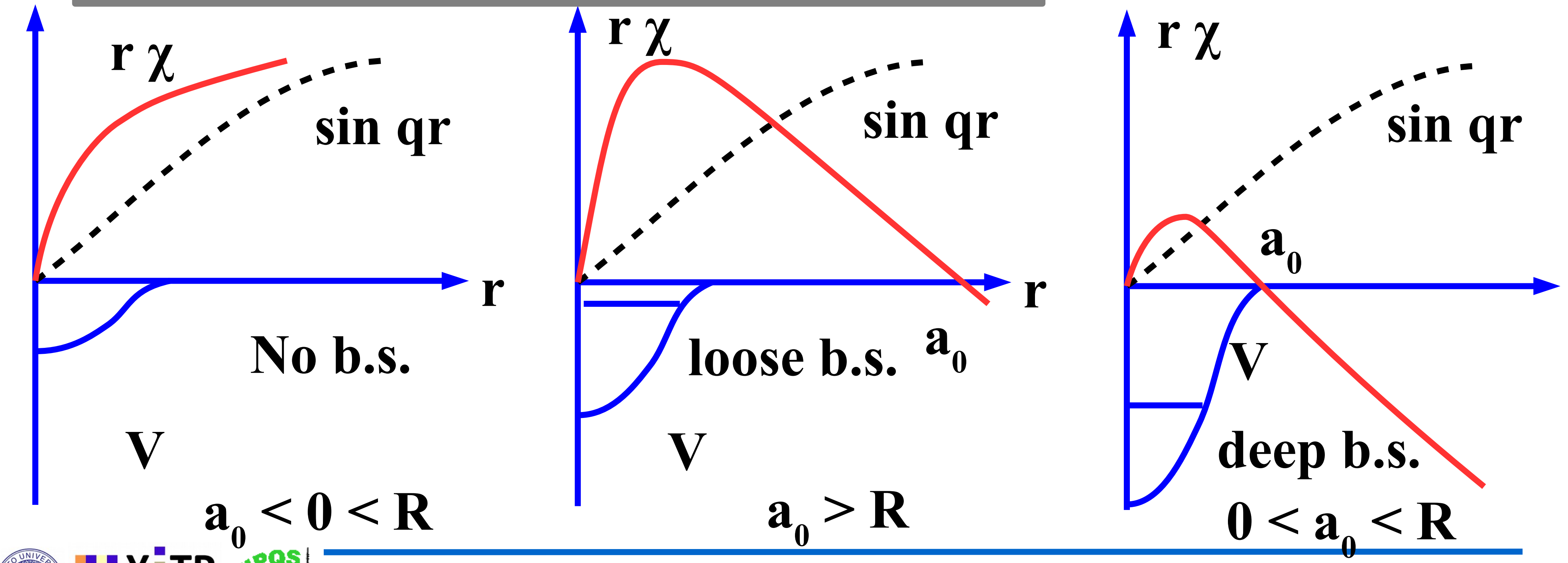
Let's study hadronic molecules formation from HIC !

Scattering wave functions around threshold (V<0)

- **No bound state ($a_0 < 0$) → Enhanced w.f.**
- **Loosely bound state (large a_0 , $a_0 > 0$) → Enhanced w.f.**
- **Deeply bound state (small a_0 , $a_0 > 0$) → Node at r ~ a_0**

How can we see the wave functions of hadronic molecule ?
→ Correlation function !

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



From Hadron Correlations to Hadron Interactions

- **Correlation Function**

Koonin ('77); Pratt+('90); Lednicky+('82); Morita, Furumoto, Ohnishi ('15)

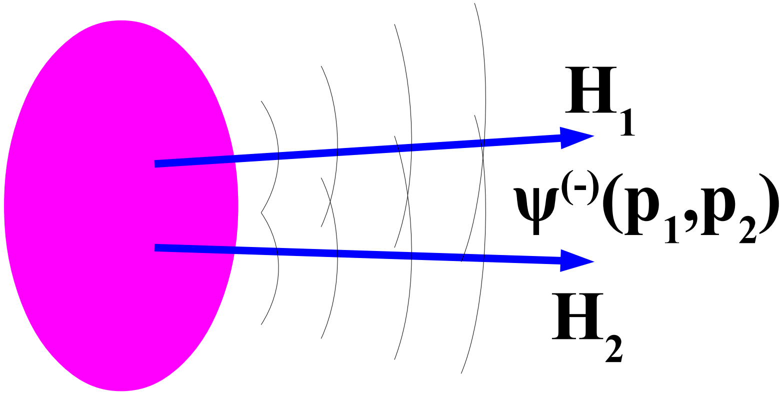
$$C(\boldsymbol{q}) = \frac{E_1 E_2 dN_{12}/d\boldsymbol{p}_1 d\boldsymbol{p}_2}{(E_1 dN_1/d\boldsymbol{p}_1)(E_2 dN_2/d\boldsymbol{p}_2)} \simeq \int d\boldsymbol{r}\, S_{12}(\boldsymbol{r}) \left|\psi_{12}^{(-)}(\boldsymbol{r},\boldsymbol{q})\right|^2$$

$$\to 1 + \int d\boldsymbol{r}\, \underbrace{S_{12}(\boldsymbol{r})}_{\text{Source fn.}} \left[\underbrace{|\chi_0(\boldsymbol{r},\boldsymbol{q})}_{\text{rel. w.f. (L=0)}}|^2 - |j_0(qr)|^2\right]$$

for Static Gaussian Source

q: Relative momentum

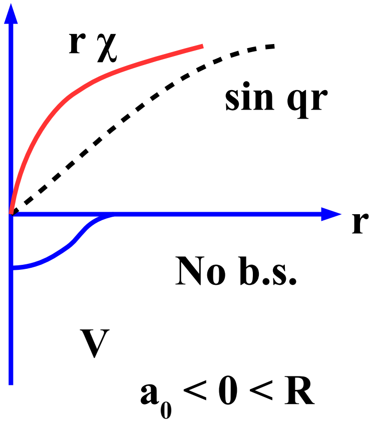
- C(q)= Same event pair prob. / Diff. event pair prob.
- CF btw identical particles has been used to determine the source size (Star, HIC).

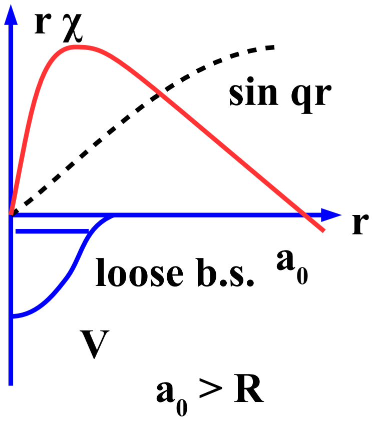


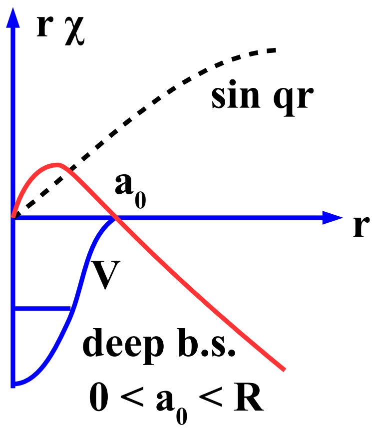
From Hadron Correlations to Hadron Interactions

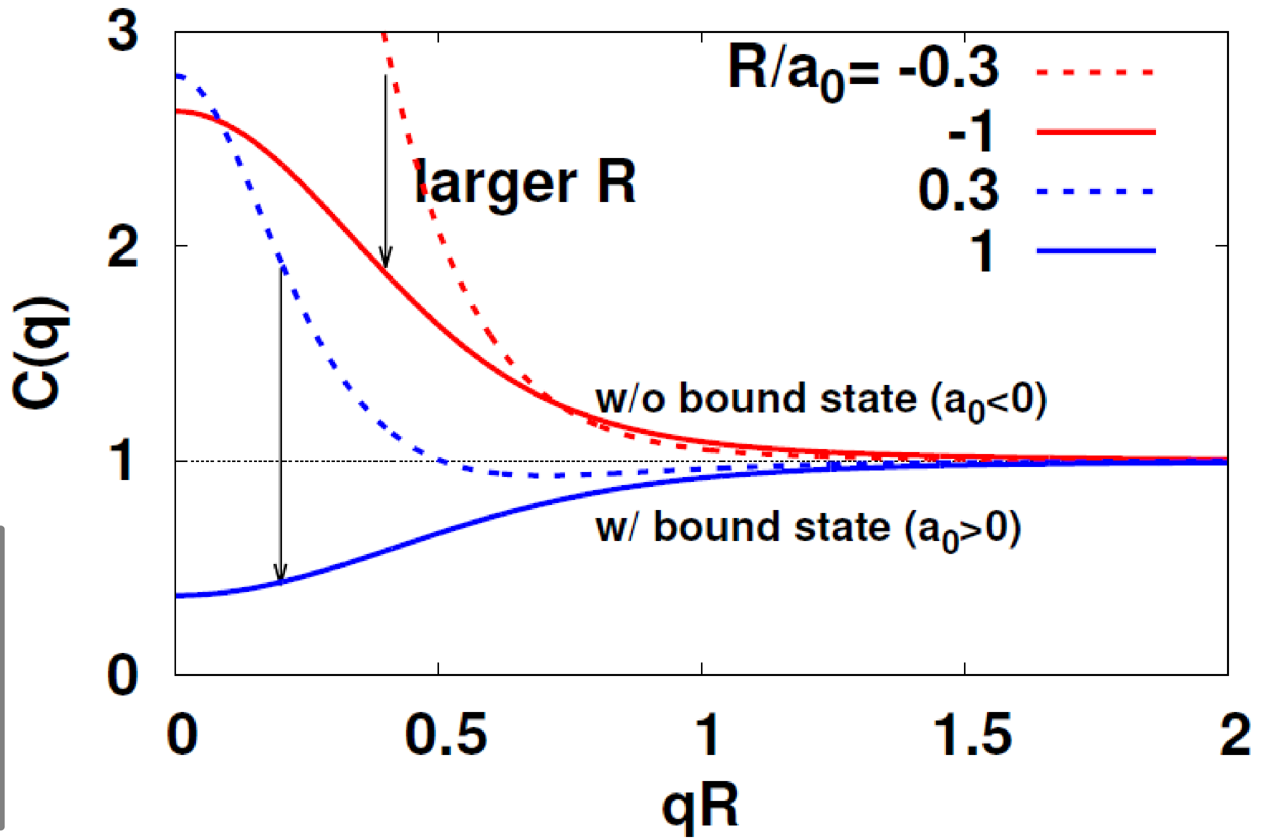
- **Scattering length dep. of w.f.**
  → Correlation function
- **Large $|a_0|$ ($|a_0| > R$)**
  → Strong enh. at small q
- **Positive a_0 ($|a_0| \sim R$)**
  → Suppressed C(q).
- **Negative a_0 ($|a_0| \sim R$)**
  → Enhanced C(q).

Strong dep. of C(q) on R/a_0
→ Please measure !









Hadronic Molecule Candidates

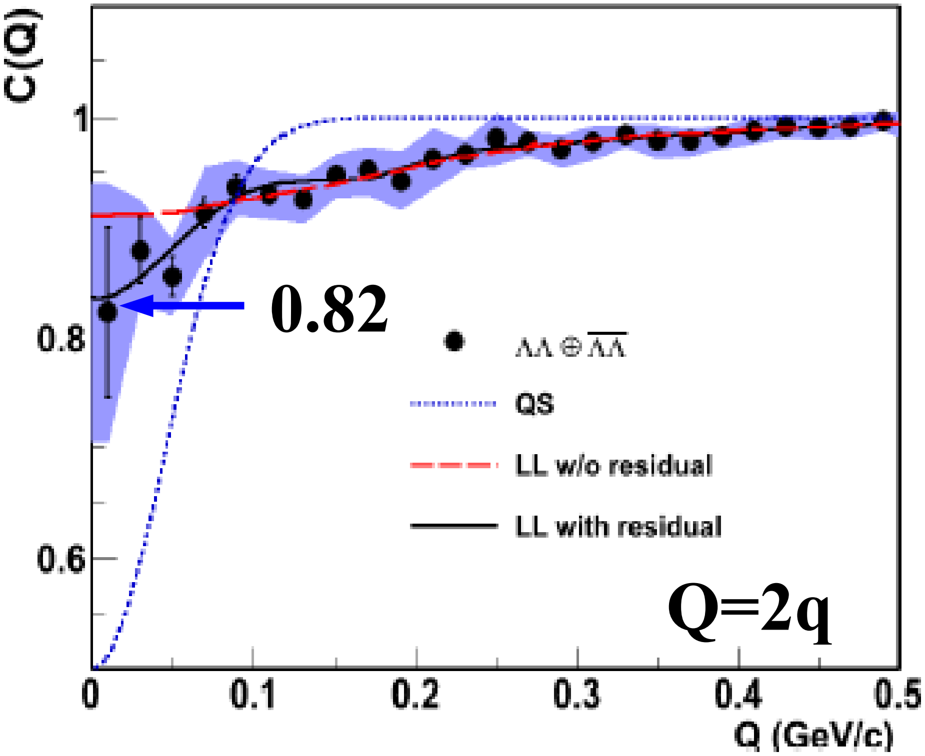
- Dibaryons
  - Not Pauli blocked and Attractive Color-spin int.
    Oka ('88), Gal ('16)
  - d*(=ΔΔ), NΣ*, H(=ΛΛ-NΞ-ΣΣ), …, NΩ
- Pentaquarks
  - Meson-baryon molecule or compact penta quark state
  - Λ(1405) ~ $\bar{K}$N bound state
    Dalitz, Wong, Rajasekaran ('67), Siegel, Weise ('88), Koch ('94), AO, Nara, Koch ('97), Akaishi, Yamazaki, Jido, Hyodo, ….
- Mesons
  - f0(980), a0(980), K(1460), Ds(2317), Tcc(3797), X(3872), Z(4430), ...

Contents

ΛΛ correlation and interaction

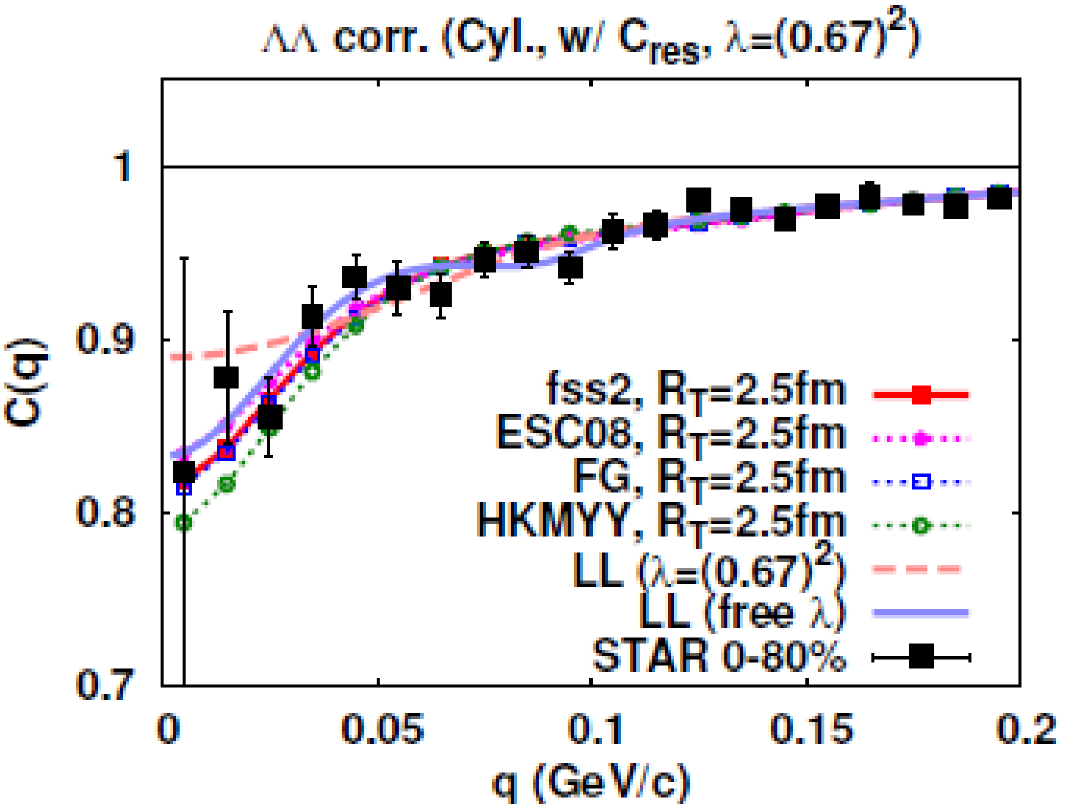
ΛΛ correlation at RHIC

- **STAR collaboration at RHIC measured ΛΛ correlation !**
  Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  - **RHIC, Au+Au ($\sqrt{s_{NN}}$=200 GeV), Weak decay vertex analysis.**
- **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.

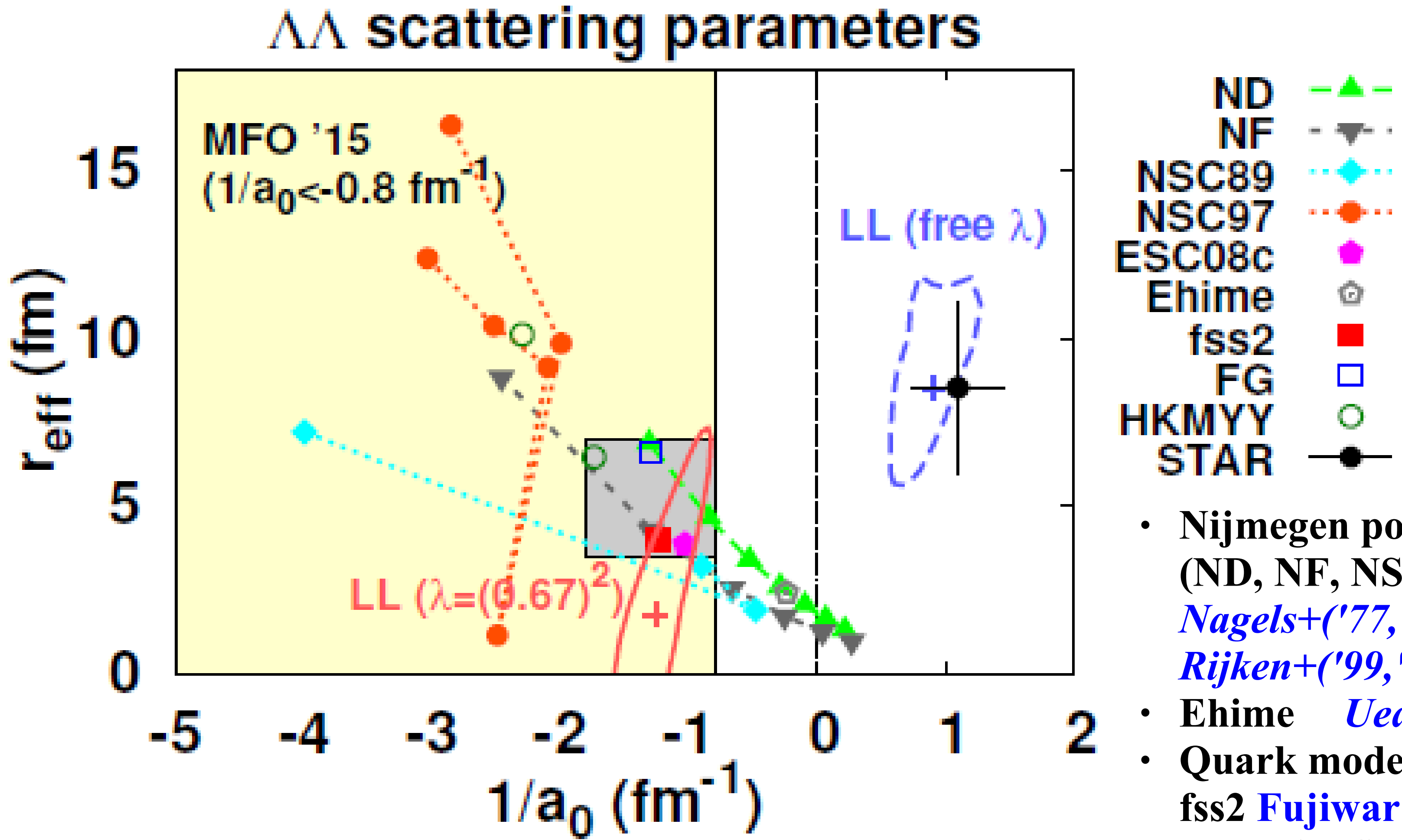


0.82

Q=2q



ΛΛ interaction from ΛΛ correlation

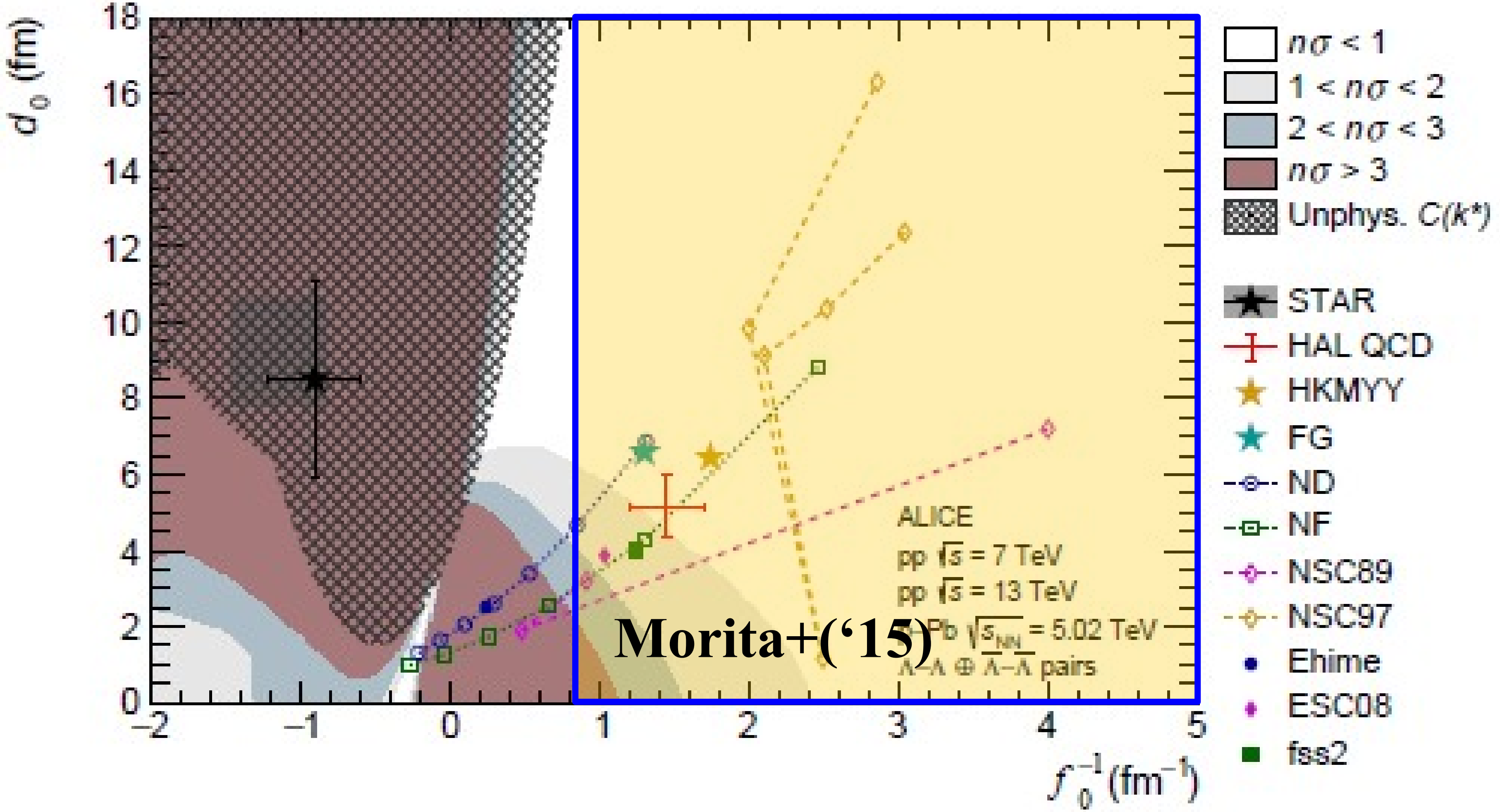


$$q \cot \delta = -1/a_0 + r_{eff}\, q^2/2 + O(q^4)$$

- **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)*

New Data from LHC-ALICE

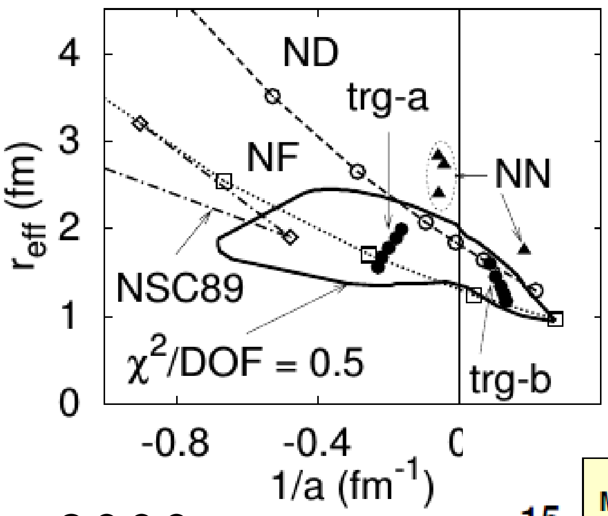
ALICE (arXiv:1905.07209)



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

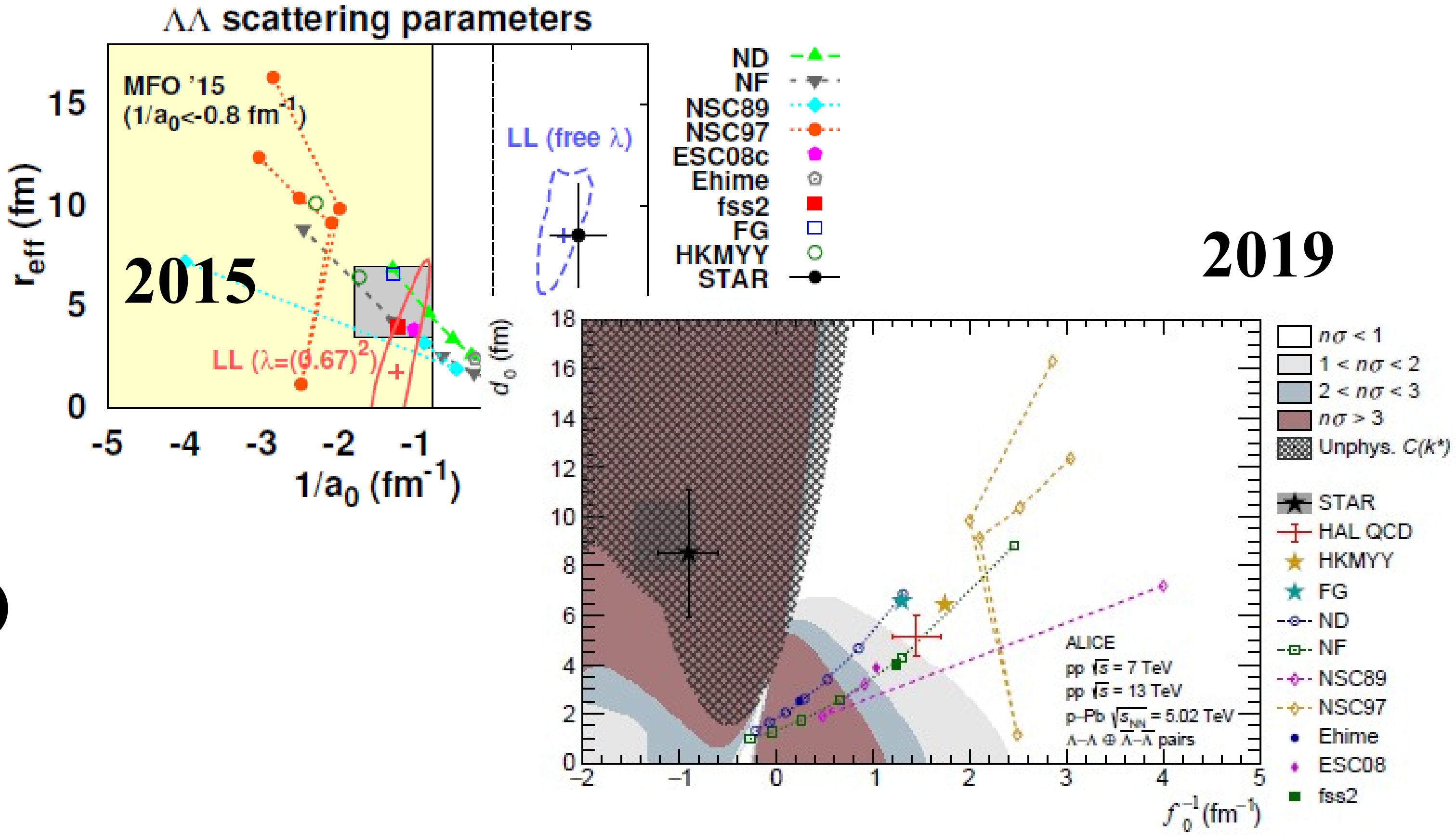
Large reff → Becomes repulisve at low relatively density.

Time dependence of ΛΛ interaction



$^{12}\mathrm{C}(K^-, K^+\Lambda\Lambda)$

2000

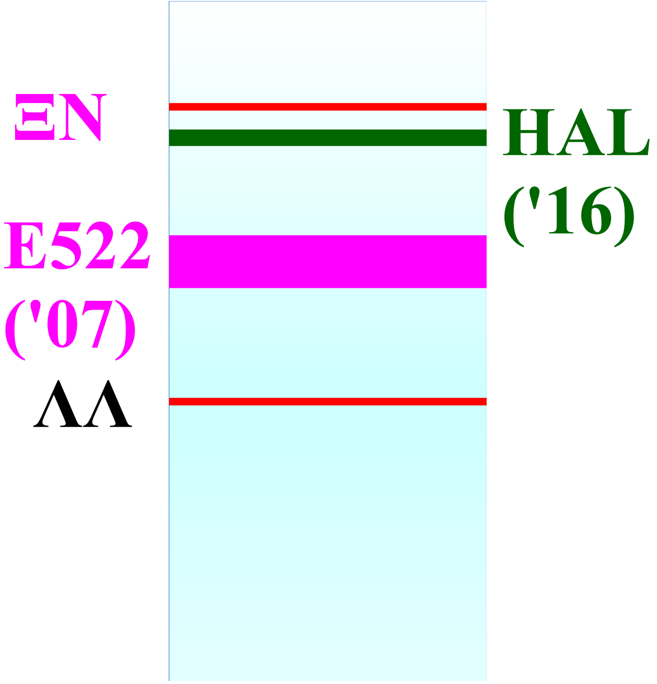


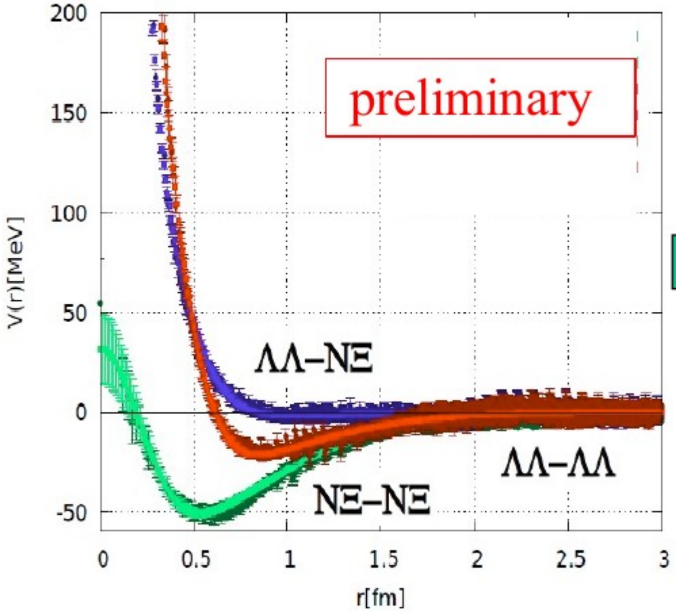
Nagara (2001)

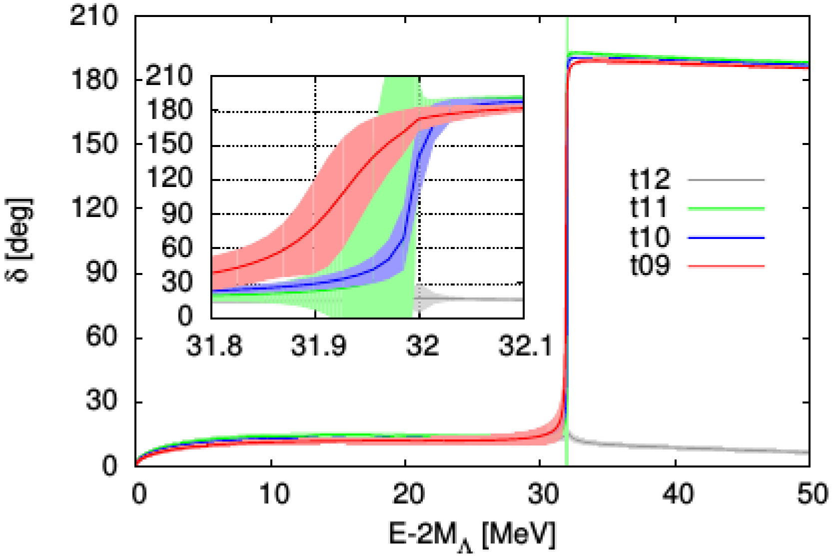
ΞN correlation and interaction

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.







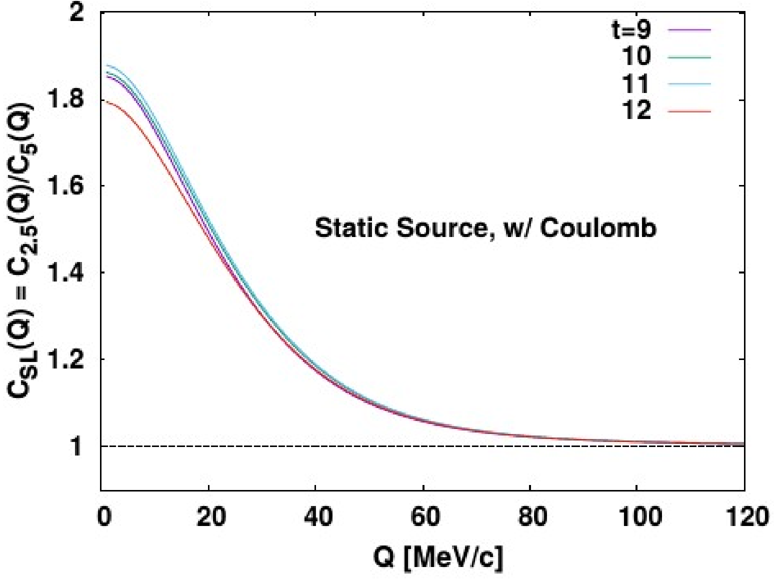
K. Sasaki et al. (HAL QCD Collab.), EPJ Web Conf. 175 (‘18) 05010.

Ξ^- p correlation

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

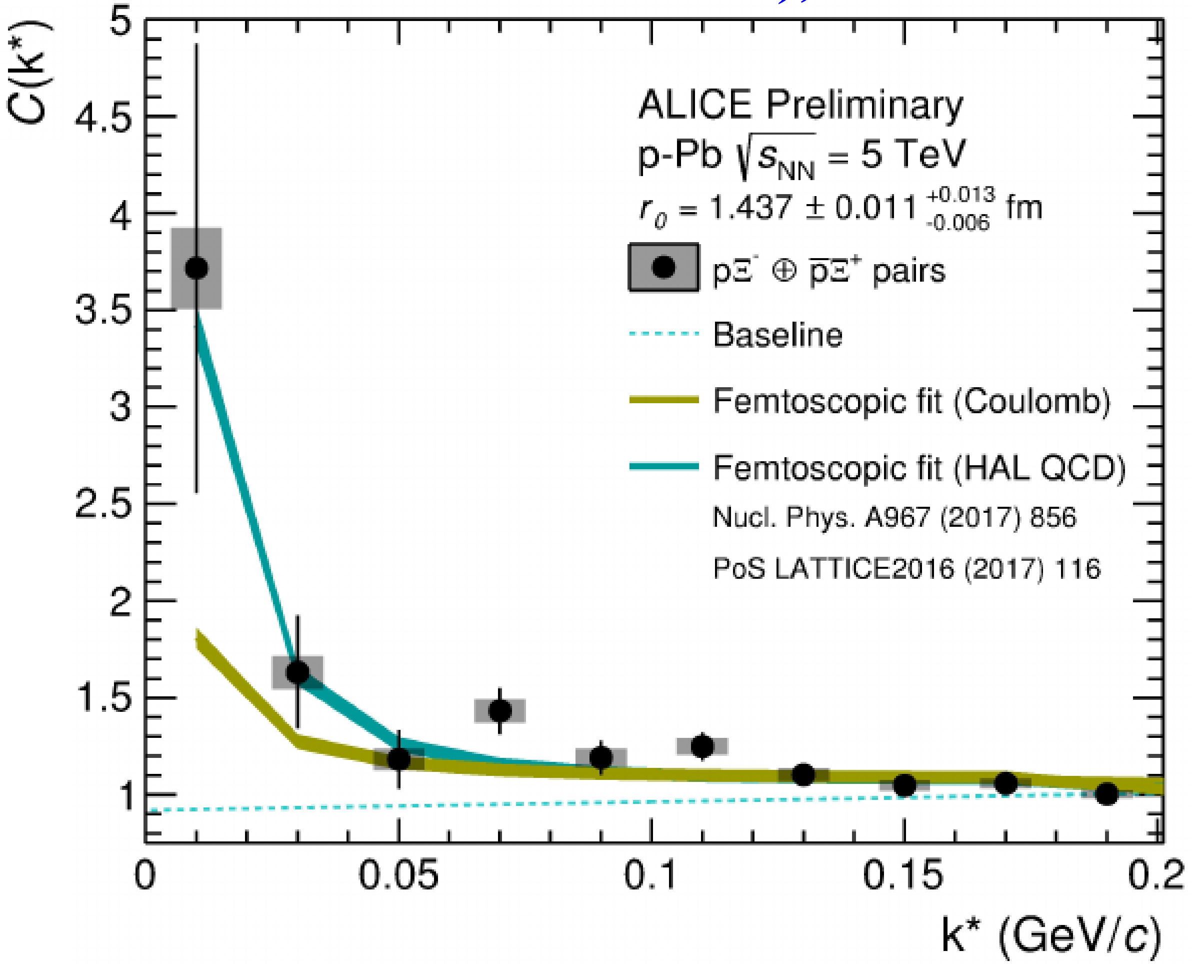
$$|\psi|^2_{\text{spin av.}} = \frac{1}{2}\sum_{I=0,1}\left[\frac{1}{4}|\psi_I^{J=0}|^2 + \frac{3}{4}|\psi_I^{J=1}|^2\right]$$

HAL prediction is examined !



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

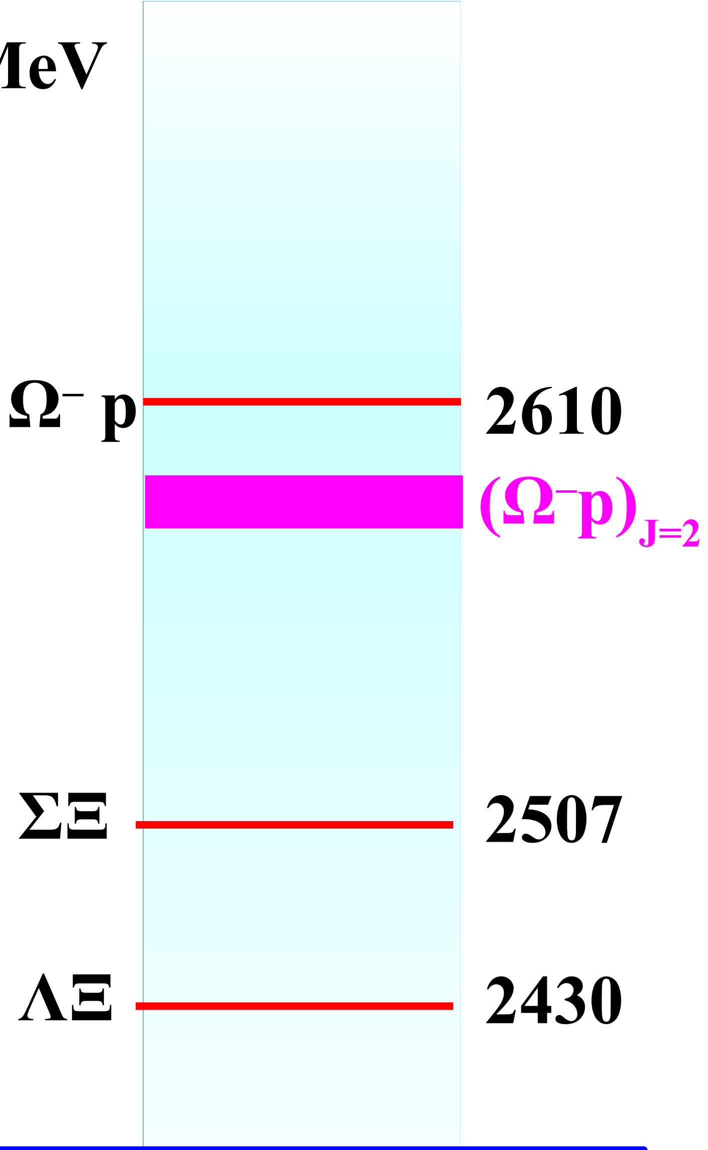
V. Mantovani-Sarti ALICE Collab.), MESONS 2018



ΩN / ΩΩ correlation and interaction

Ω^- p interaction

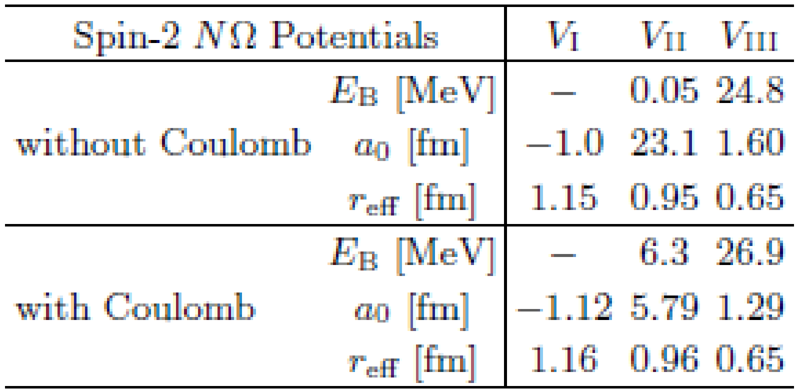
- **Ω^- : quark content=sss, J^π=3/2+, M=1672 MeV**
- **Ω^- p bound state as a S= –3 dibaryon ?**
  F.Etminan et al. (HAL QCD Collab.), NPA928('14)89.
  - **No quark Pauli blocking in ΩN, H=uuddss, and d*=ΔΔ channels.**
    Oka ('88), Gal ('16)
  - **J=2 state ($^5S_2$) couples to Octet-Octet baryon pair only with L ≥ 2**
    → Small width is expected.
    Etminan et al. (HAL QCD)('14)
  - **Correlation is measurable at RHIC !**
    Neha Shah (STAR), private commun.



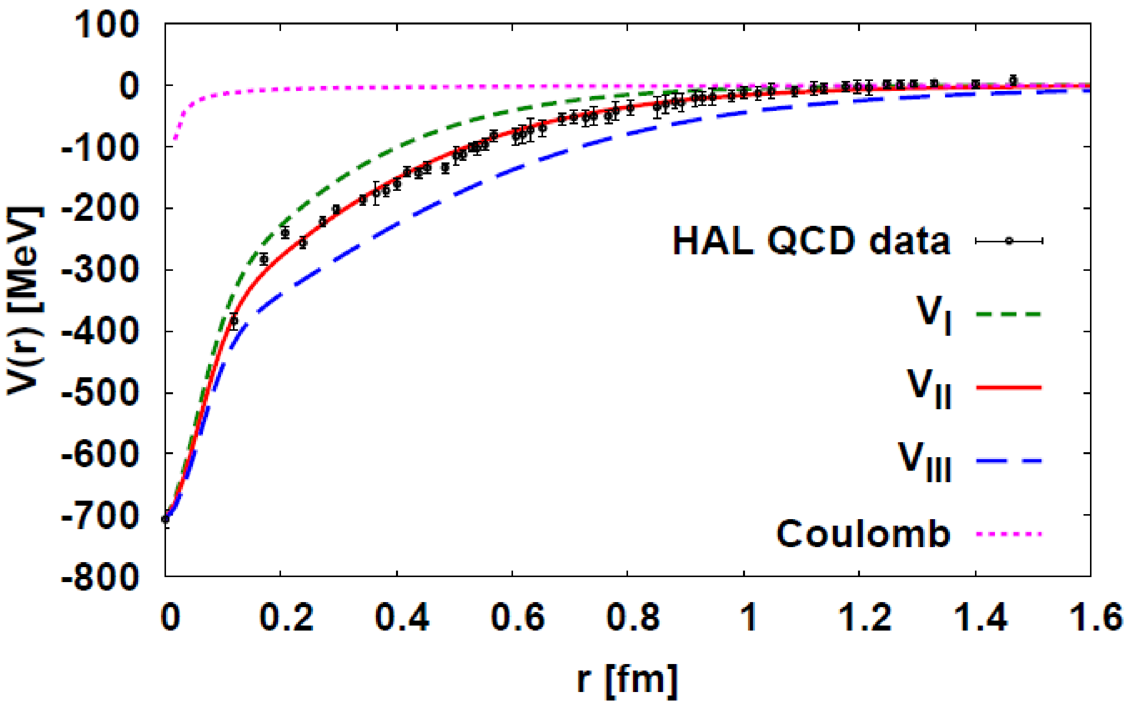
Let us try to discover the first(?) dibaryon (after deuteron) !
(First dibaryon with S<0 !)

Ω^- *p potential from lattice QCD*

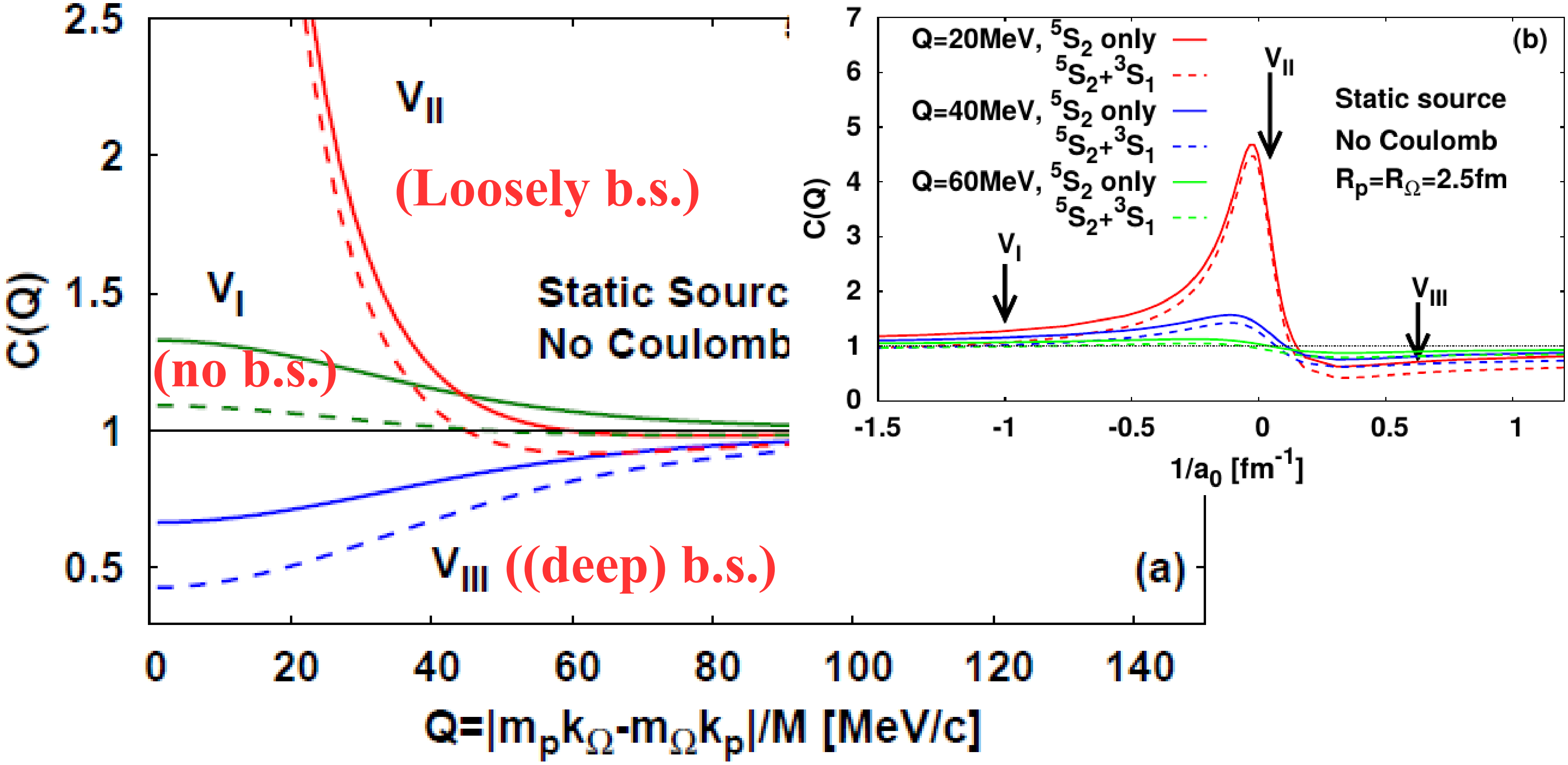
- **Lattice QCD predicts Ω^- p bound state at large quark mass, m_π=875 MeV (B.E.~ 19 MeV) in $^5S_2$ channel.**
  F.Etminan et al. (HAL QCD Collab.), NPA928('14)89.
- **Extrapolation to physical quark mass**
  - **VI → Weaker potential (no b.s.)**
  - **VII → Same potential (shallow b.s.)**
  - **VIII → Stronger potential (deep b.s.)**



Spin-2 $N\Omega$ Potentials		V_{I}	V_{II}	V_{III}
without Coulomb	E_{B} [MeV]	–	0.05	24.8
	a_0 [fm]	−1.0	23.1	1.60
	r_{eff} [fm]	1.15	0.95	0.65
with Coulomb	E_{B} [MeV]	–	6.3	26.9
	a_0 [fm]	−1.12	5.79	1.29
	r_{eff} [fm]	1.16	0.96	0.65



Ω^- p correlation



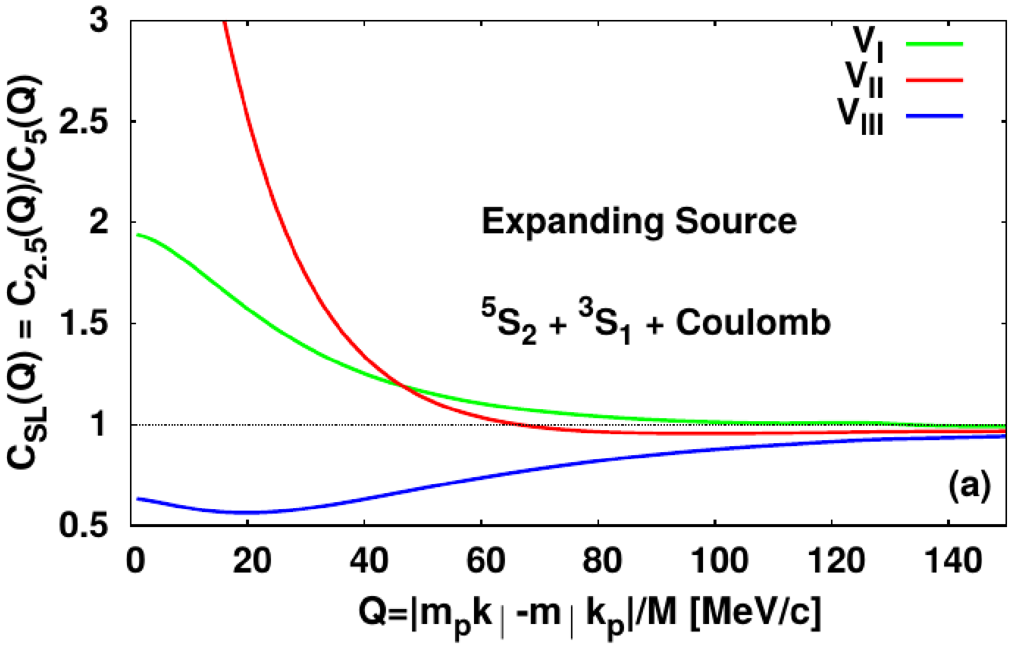
(w/o Coulomb, Strong absorption at r< 2 fm in $^3S_1$ (decay to 8-8 in S-wave))

K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R) [arXiv:1605.06765 [hep-ph]]

Data from STAR

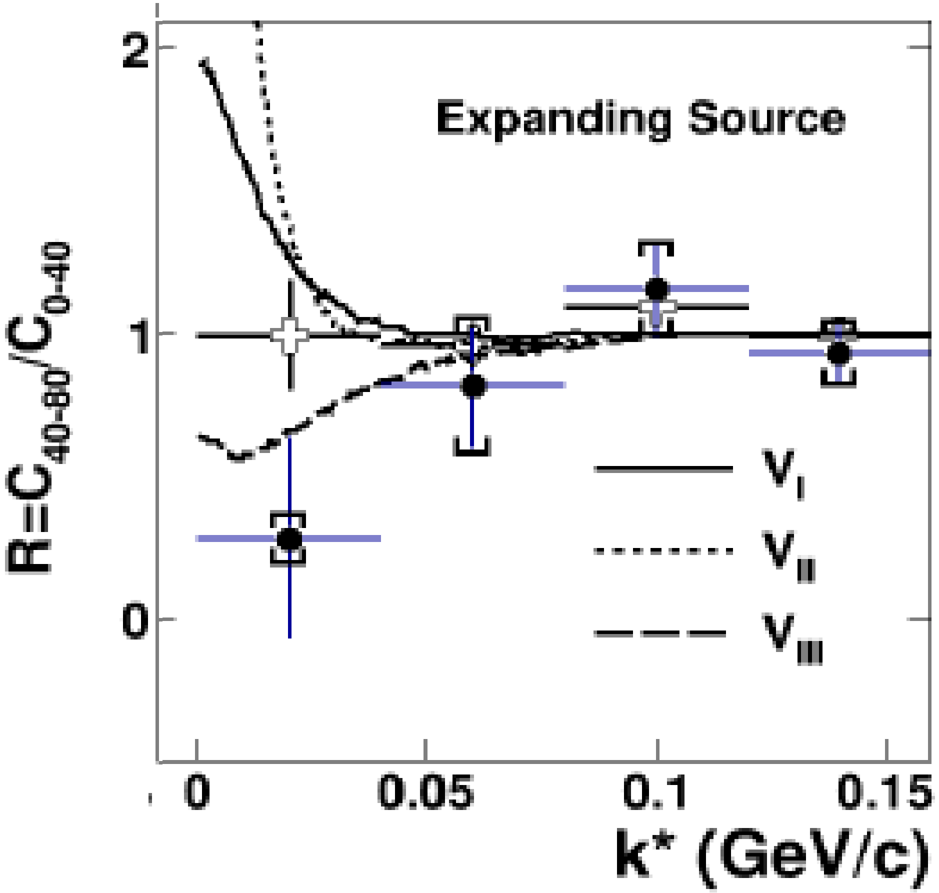
- **ΩN bound state may exist.**

C(R=2.5 fm)/C(R=5 fm)



Morita, AO, Etminan, Hatsuda ('16)

STAR (1808.02511
PLB790 ('19) 490)

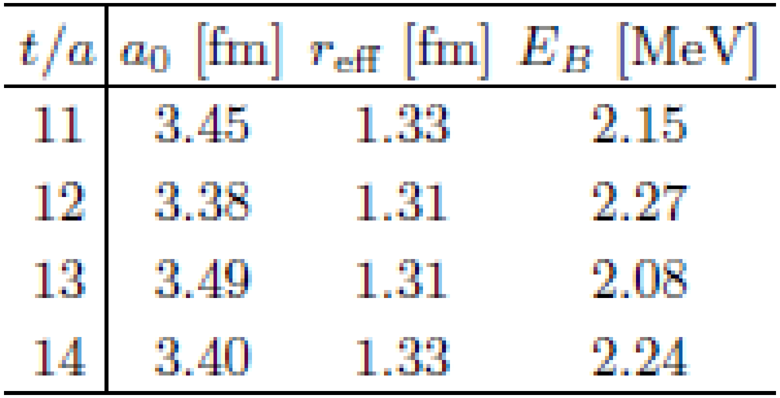


We may have a dibaryon state in ΩN channel

Results with updated HAL QCD potential

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

- **Updated HAL QCD NΩ potential**
  T. Iritani et al. (HAL QCD Collab.), PLB792 ('19)284 (1810.03416)
  Almost physical point m_π = 146 MeV



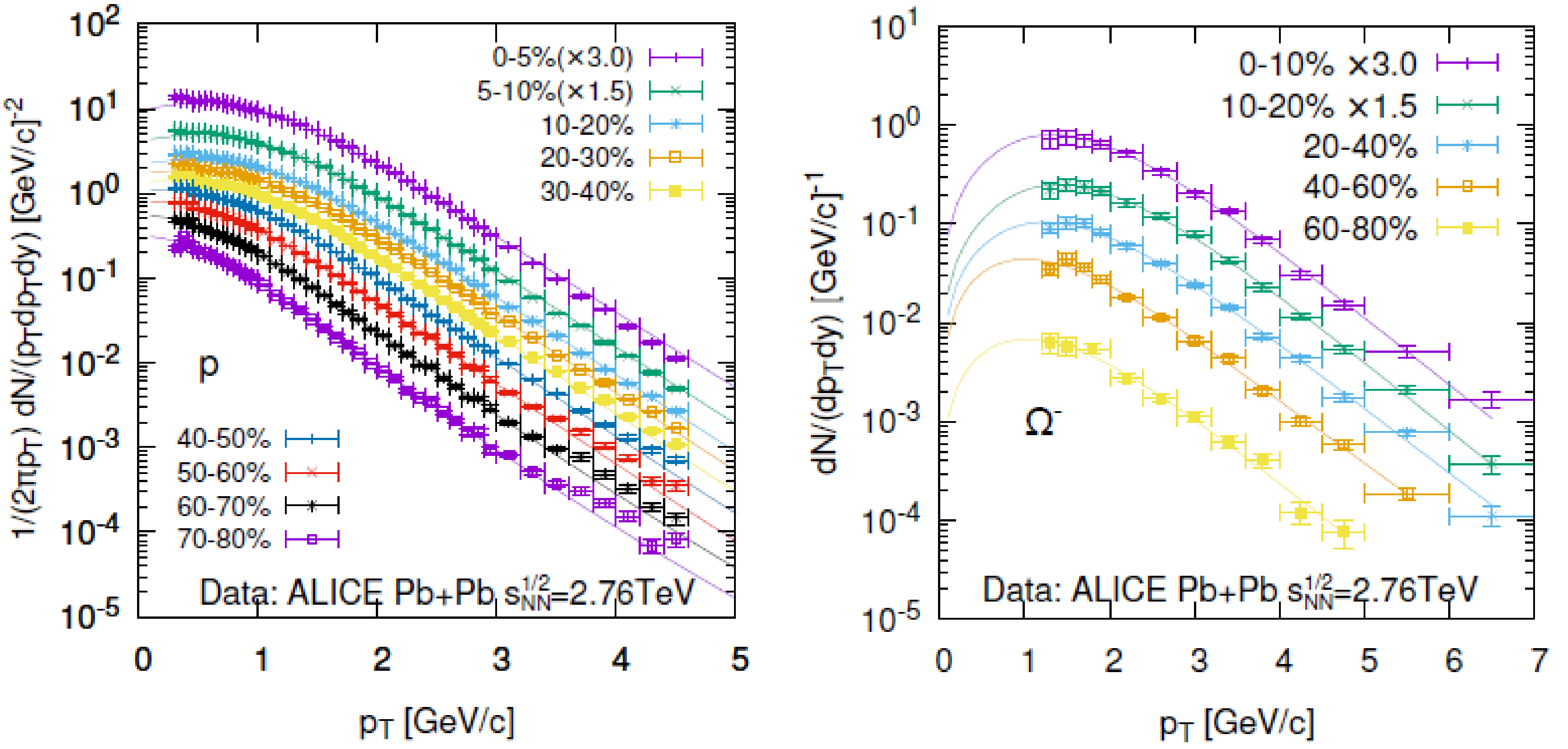
t/a	a_0 [fm]	$r_{\rm eff}$ [fm]	E_B [MeV]
11	3.45	1.33	2.15
12	3.38	1.31	2.27
13	3.49	1.31	2.08
14	3.40	1.33	2.24

- **Cylindrical source with radial transverse flow**
  → pT spectra of protons and Ωs
- **Small-Large ratio to suppress the Coulomb effects**
  & Absorptive potential in J=1 channel
  K. Morita, AO, F. Etminan, T. Hatsuda, PRC94('16)031901(R) [arXiv:1605.06765 [hep-ph]]

Source function

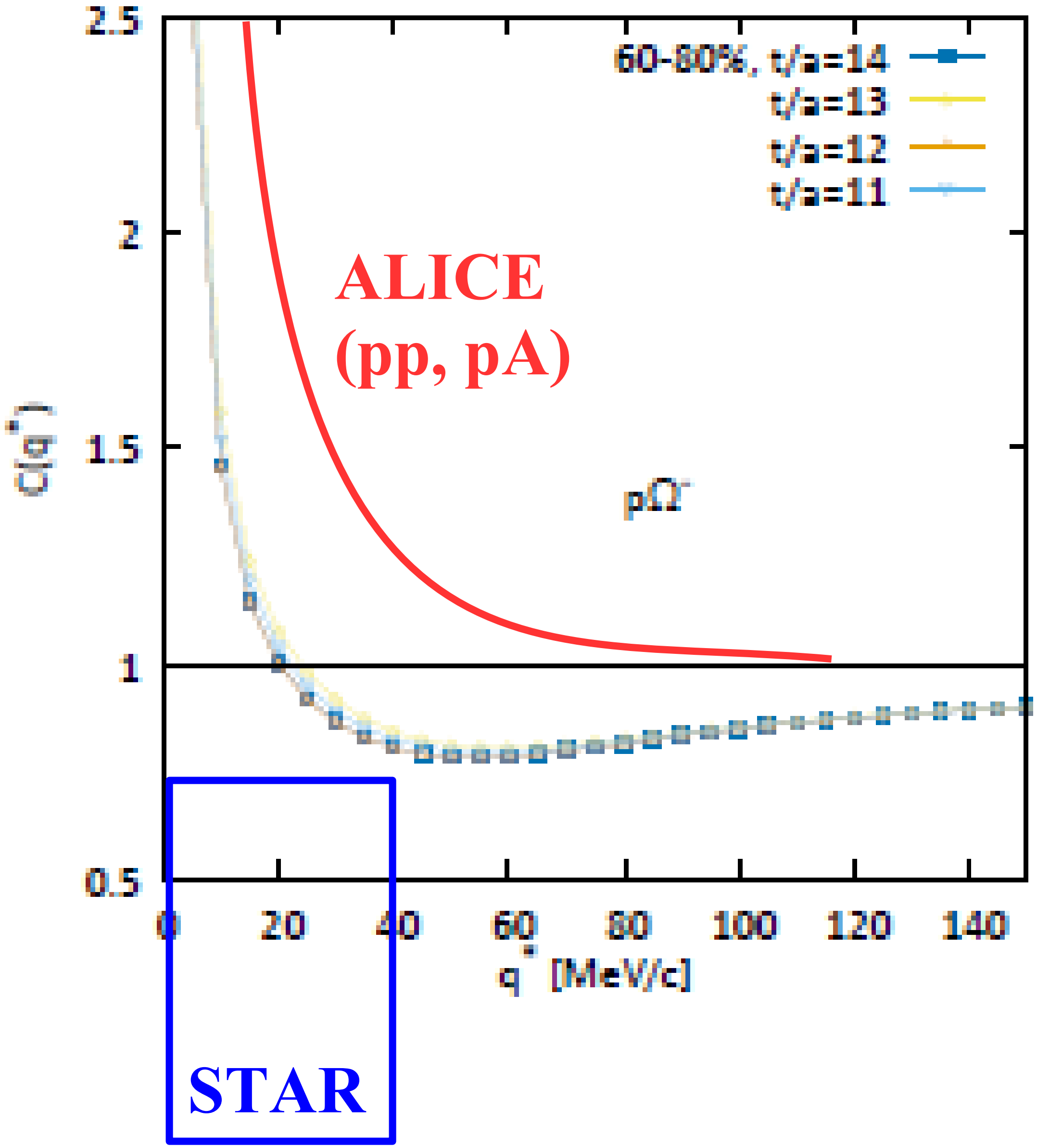
- **Blast wave model fit**

$$d^4 x S_i(x,p) = \tau_0 d\eta_s d^2 r_T \frac{d}{(2\pi)^3} \underbrace{n_f(\overset{\text{Flow velocity}}{u}\cdot p, T)}_{\text{Fermi dist.}} \exp\left(-\frac{r_T^2}{2R_T^2}\right)$$

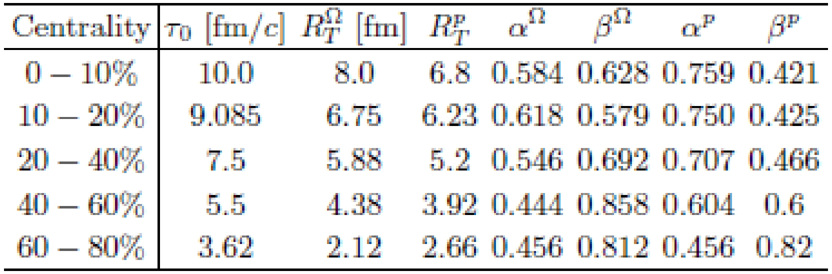


K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

Correlation function from heavy-ion collisions



Peripheral collisions
(R ~ (2-3) fm)
→ Strong enh. at small q,
+ Suppression at finite q

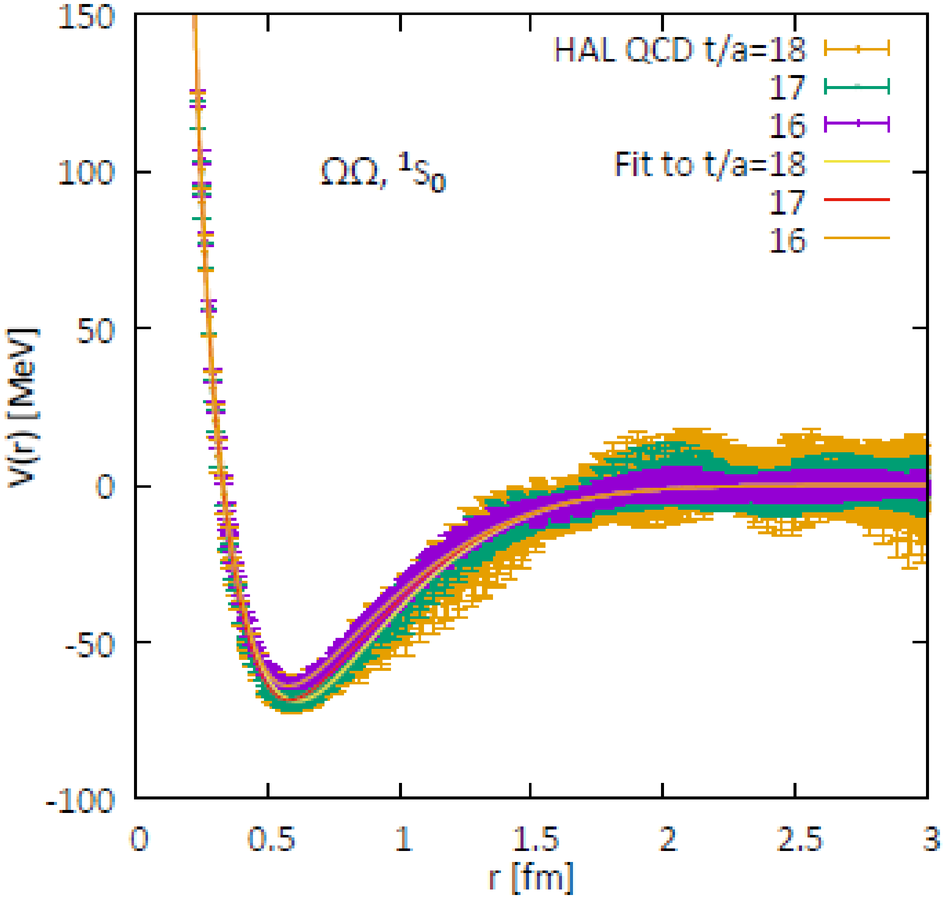


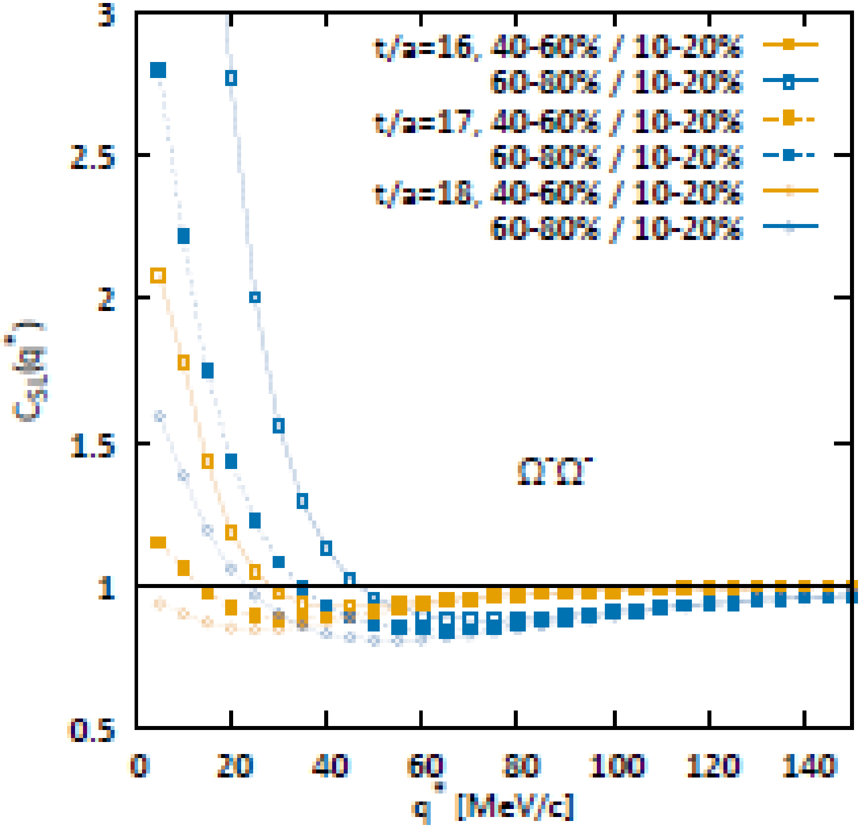
Centrality	τ_0 [fm/c]	R_T^Ω [fm]	R_T^p	α^Ω	β^Ω	α^p	β^p
0 – 10%	10.0	8.0	6.8	0.584	0.628	0.759	0.421
10 – 20%	9.085	6.75	6.23	0.618	0.579	0.750	0.425
20 – 40%	7.5	5.88	5.2	0.546	0.692	0.707	0.466
40 – 60%	5.5	4.38	3.92	0.444	0.858	0.604	0.6
60 – 80%	3.62	2.12	2.66	0.456	0.812	0.456	0.82

K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

ΩΩ correlation

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



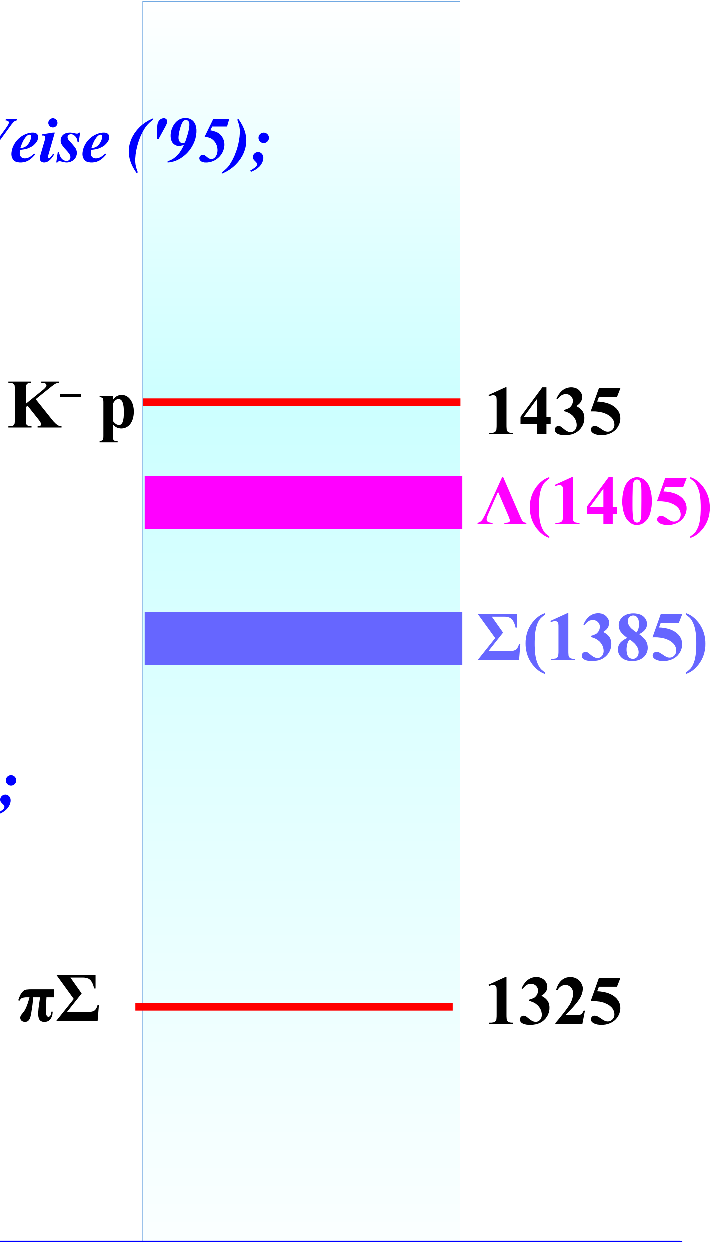


K. Morita, S. Gongyo, T. Hatsuda, T. Hyodo, T. Iritani, AO, K. Sasaki, in prep.

$\bar{K}N$ correlation and interaction

K^- p interaction

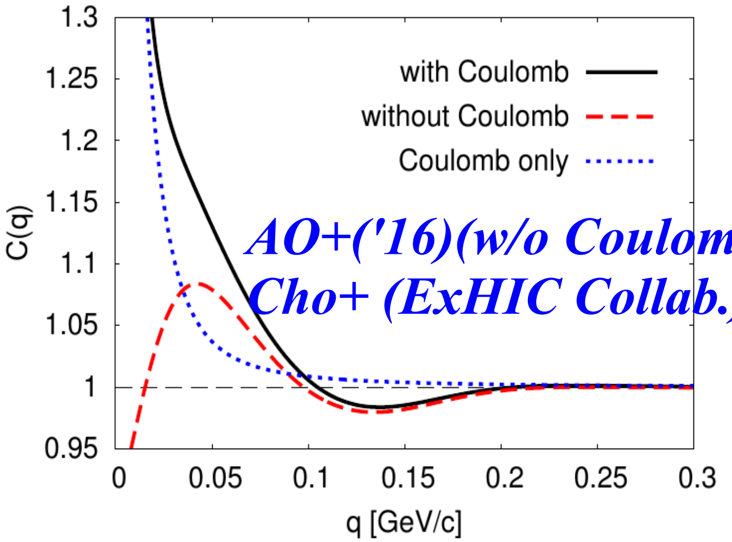
- **Λ(1405) $\bar{K}N$ quasi-bound state**
  Dalitz, Tuan ('60); Koch ('94); Kaiser, Siegel, Weise ('95); AO, Nara, Koch ('97)
  - **Positive scattering length in K^- atoms**
    M.Iwasaki et al. PRL78('97)3067; M.Bazzi et al. [SIDDHARTA Collab.], PLB704('11)113.
- **Kaonic nuclei ?**
  Nogami ('63); Akaishi, Yamazaki ('02); Shevchenko, Gal, Mares ('07); Ikeda, Sato ('07); Dote, Hyodo, Weise ('09)
  → 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)



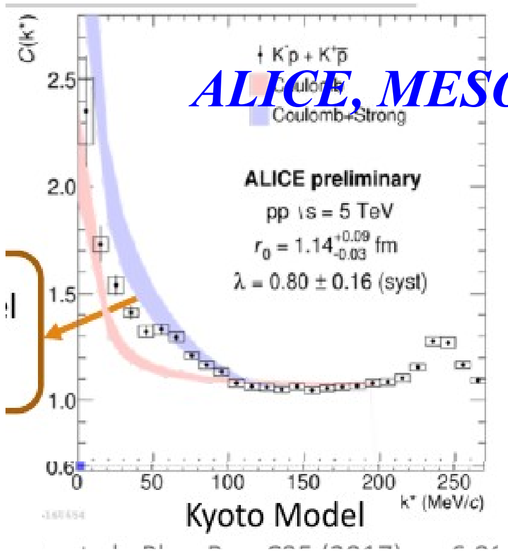
How about K^- p correlation ?

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

- **K^-p correlation (w/ a bound state Λ(1405) Chiral dyn.+Coulomb)**



AO+('16)(w/o Coulomb);
Cho+ (ExHIC Collab.) (‘17)

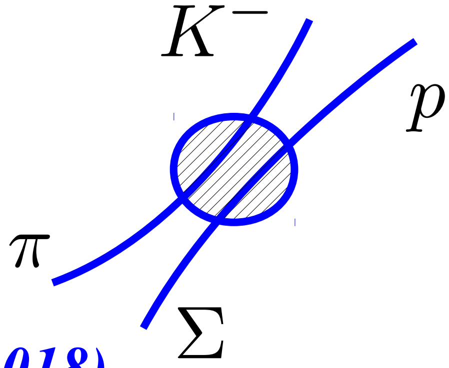


ALICE, MESONS 2018

- **Calc. results seem to explain the data qualitatively,**
  but coupled channel effects with πΣ were not taken into account.
  J. Haidenbauer, arXiv:1808.05049

Correlation Function with Coupled Channels

- **Contribution of the source in other channels**



$$C_\alpha(\boldsymbol{q}) = \sum_\beta \int d\boldsymbol{r}\, \underline{S_\beta(\boldsymbol{r})} \left|\psi^{(-)}_{\beta\alpha}(\boldsymbol{r},\boldsymbol{q})\right|^2$$

Source fn.

- **Asymptotic wave function**

  K. Miyahara, T. Hyodo, W. Weise, Phys. Rev. C 98, 025201 (2018), arXiv:1804.08269.

$$|\Psi^{(\pm)}_\alpha\rangle = \sum_\beta \psi^{(\pm)}_{\beta\alpha} |\beta\rangle$$

No outgoing w.f. for β !=α

$$\psi^{(+)}_{\beta\alpha}(r) \to \frac{-1}{2ik_\alpha}\left[\delta_{\beta\alpha}\frac{e^{-ik_\beta r}}{r} - \sqrt{\frac{v_\alpha}{v_\beta}} S_{\beta\alpha}\frac{e^{ik_\beta r}}{r}\right] \quad (v_\alpha = k_\alpha/\mu_\alpha)$$

- **Asymptotically outgoing wave function**

$$\psi^{(-)}_{\beta\alpha}(r) = \frac{1}{k_\alpha}\sum_\gamma \psi^{(+)}_{\beta\gamma}(r) S^\dagger_{\gamma\alpha} k_\gamma \sqrt{\frac{v_\alpha}{v_\gamma}} \to \frac{1}{2ik_\alpha}\left[\delta_{\beta\alpha}\frac{e^{ik_\beta r}}{r} - \sqrt{\frac{v_\alpha}{v_\beta}} S^\dagger_{\beta\alpha}\frac{e^{-ik_\beta r}}{r}\right]$$

Updated Results of K^-p correlation

- **Strong (Chiral SU(3))**

  Miyahara, Hyodo, Weise ('18)

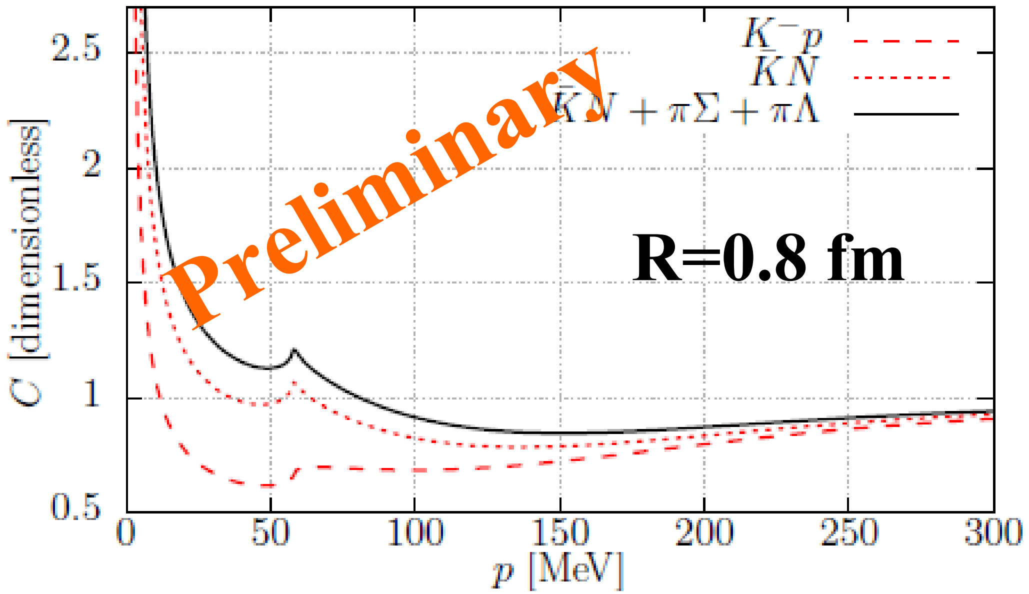
  + Coulomb

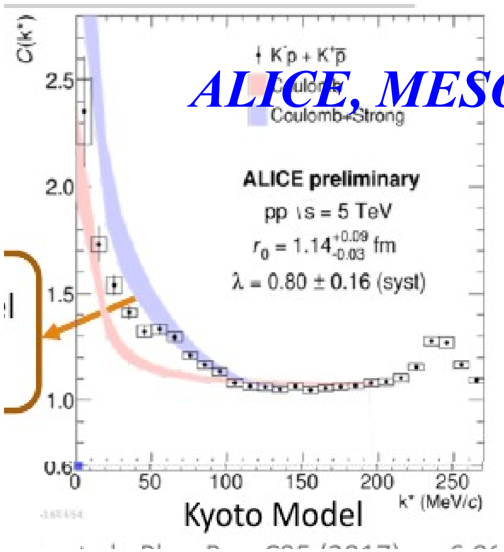
  + Coupled-Channel

  + Different Threshold

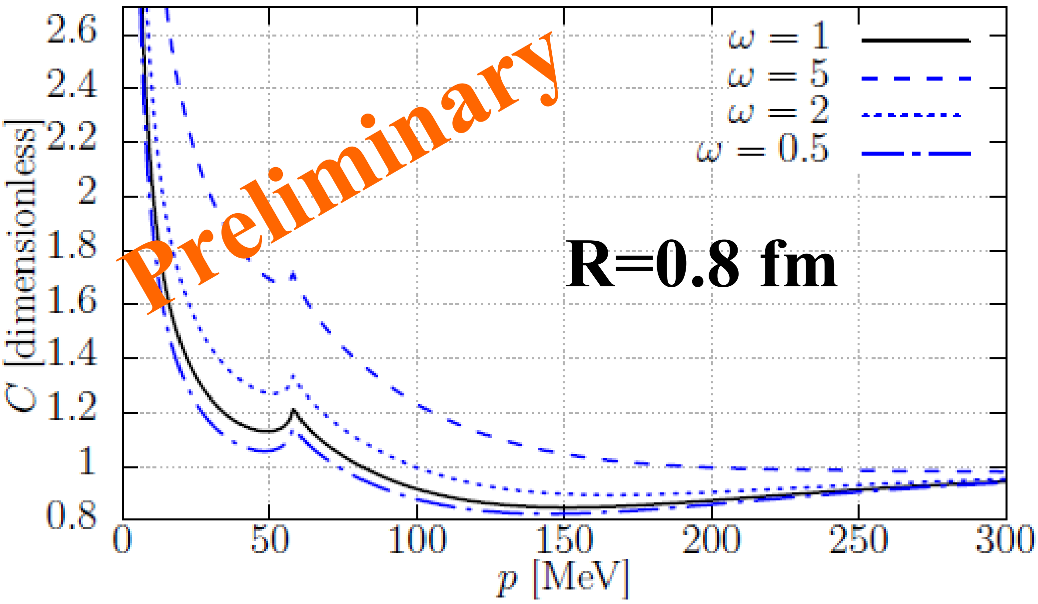
  + Source Strength of $\pi\Sigma$

- **Results with $S_{\pi\Sigma} \sim 2\ S_{K-p}$ agree with data.**





ALICE, MESONS 2018



Kamiya, Morita, Hyodo, AO (in prep.)

Summary

- Hadronic molecule states appear at around the threshold, and constitute the semi-hierarchy between hadron and nucleus. Heavy-ion collisions are useful to produce hadronic molecules.
- Hadron-Hadron correlation contains information on interactions.
  - Correlations in various pairs have been measured: $\pi\pi$, KK, pp, nn, $\bar{p}\,\bar{p}$, $\Lambda\Lambda$, Λp, $K^- p$, $\Omega^- p$, $\Xi^- p$, …
  - When the pair purity and the scattering length are large enough, corr. fn. has sensitivity to hh interaction.
- Some of hh correlations have been discussed.
  - $\Lambda\Lambda$ potential is weakly attractive, and consistent with Nagara.
  - Scattering lengths of $\Xi^- p$ and $\Omega^- p$ should be large. We need to know the source size dep. to determine the sign of a_0.
  - $K^- p$ correlation data are useful to constrain $\bar{K}N$ interaction.
- Many other type of pairs are waiting for us.

To do

- Plan in the proposal of 19H05151
  - Ωp, K^- p → preliminary results are already obtained.
  - Ξ^-p → to be done with updated HAL QCD potential
  - Numerical program to obtain correlation function including effects of Coulomb, coupled channel, threshold difference as well as strong interaction → almost done
    (神谷くん、速い！)
- Additional plan
  - $\Omega\Omega$ → to be completed soon
  - Λ p → precise data are obtained by ALICE
  - Σ^0 p → preliminary data are obtained by ALICE
  - K^- d, Λ d → STAR is planning to analyze

Thank you for your attention !