Theory View on Hyperon-Hyperon Interactions from Correlations

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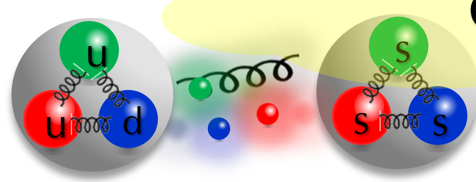


Rich for NN system
Limited for strangeness

Scattering Experiments

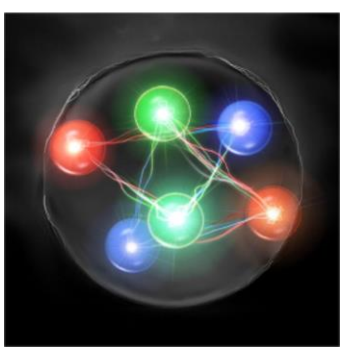
Spectroscopy

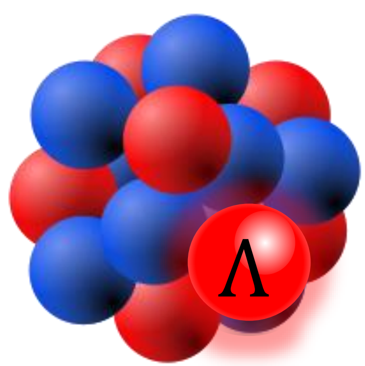
Theory: Lattice QCD

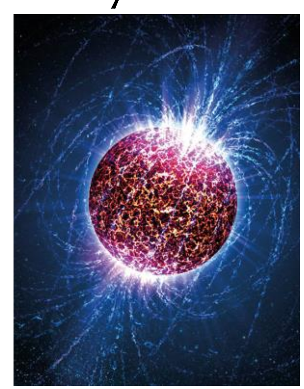
ChEFT

Various Models

Inputs to Many-body hadronic systems

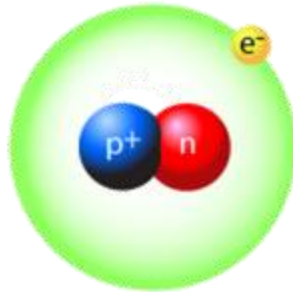




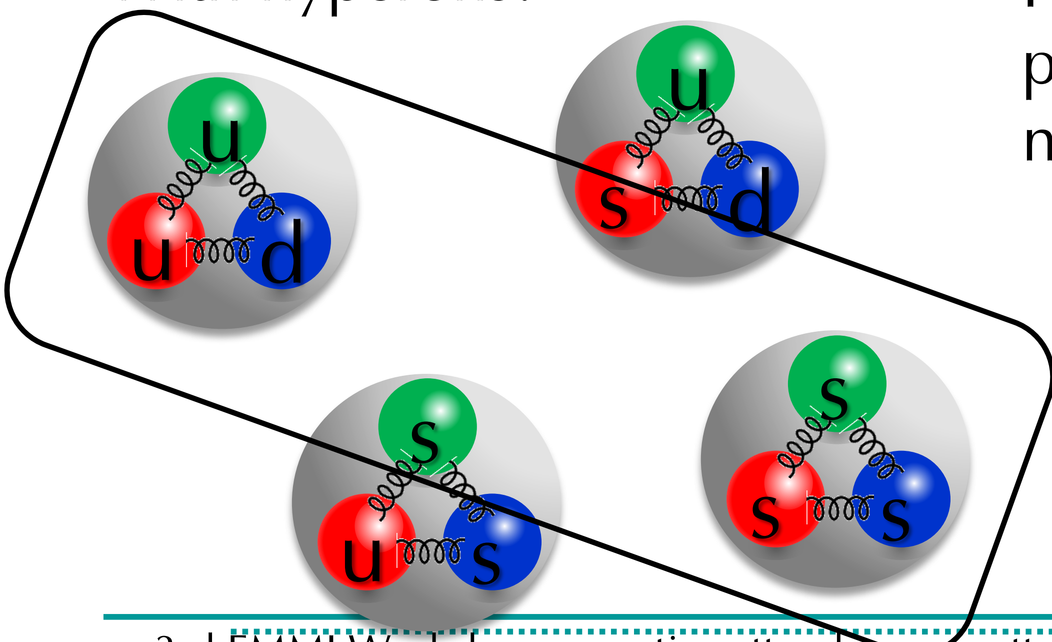


Dibaryons: Simplest BB systems

Deutron (Urey et al., 1931)



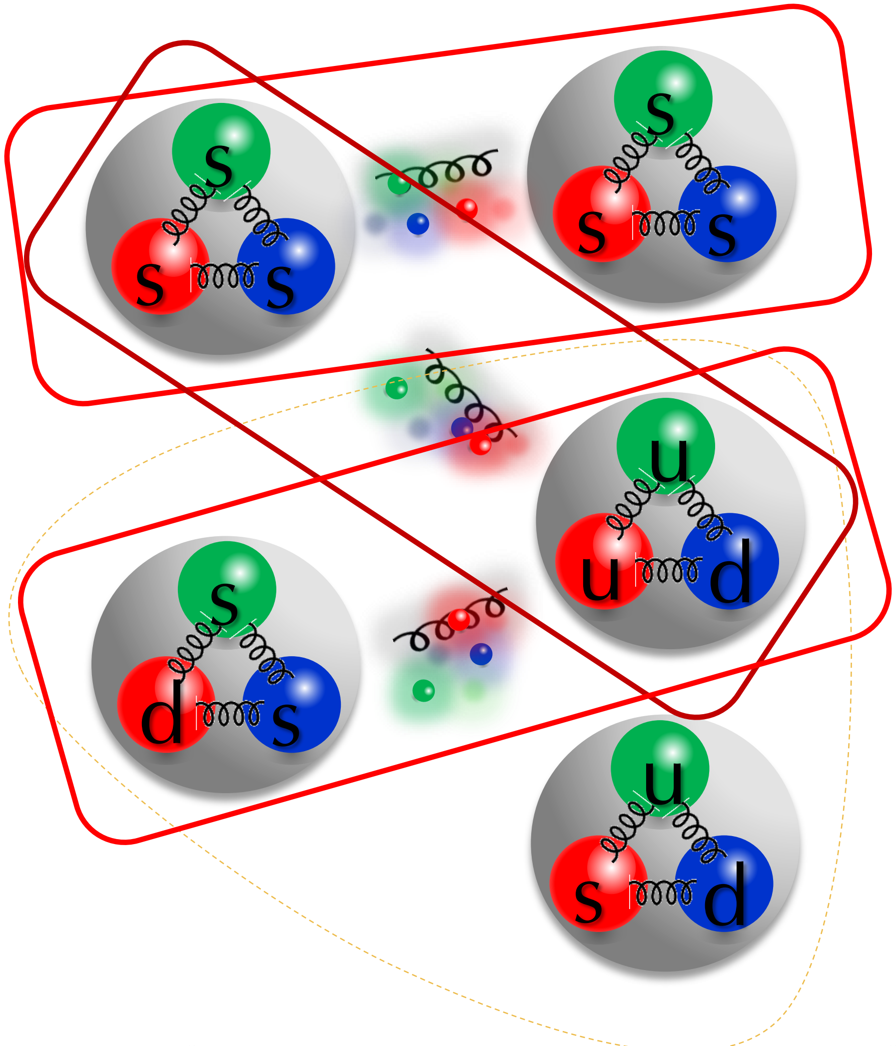
With hyperons? ----------



Flavor SU(3) classification predicts some channels with no Pauli blocking

e.g., $N\Omega$ (J=2)

Lattice QCD Studies by HAL QCD Coll.



S=-6 : Ω-Ω (J=0)
28-plet in SU(3)

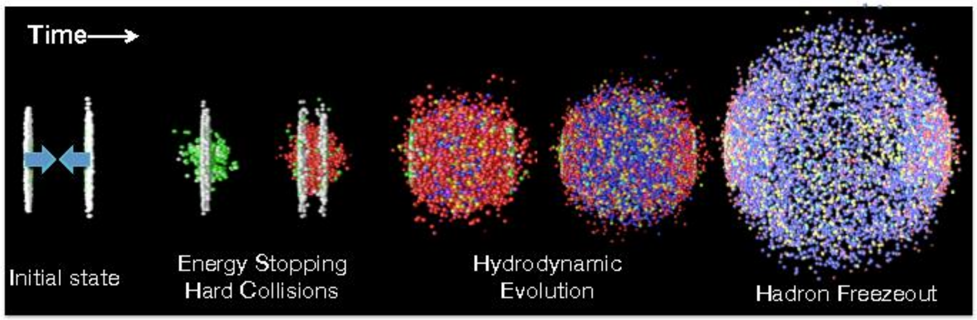
S=-3 : N-Ω (J=2)
8-plet in SU(3)

S=-2 : N-Ξ (I=0, J=0)
part of "H"
singlet in SU(3)

Show strong attraction at almost physical quark masses

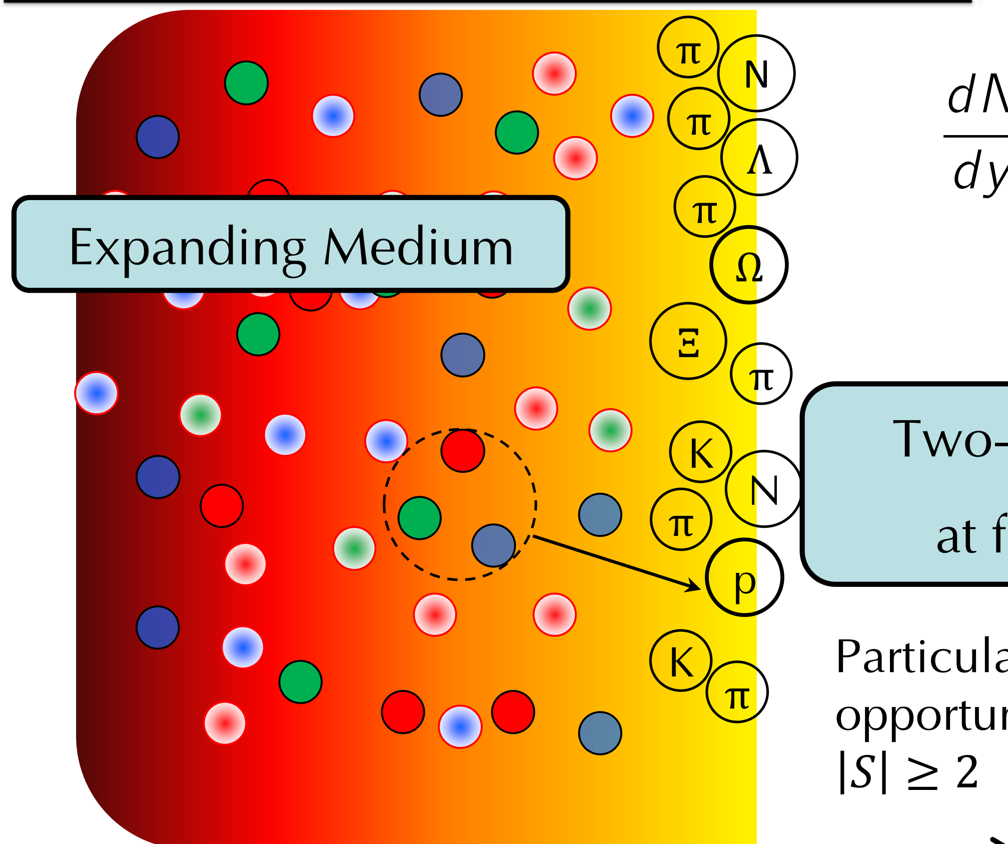
Experimental Confirmation – Pair Correlation in pp,pA and AA

High Energy Nuclear Collisions as Hadron Factory



Production of Quark-Gluon Plasma

Crossover Transition Into Hadron
Particle Abundance – Thermal Eq.

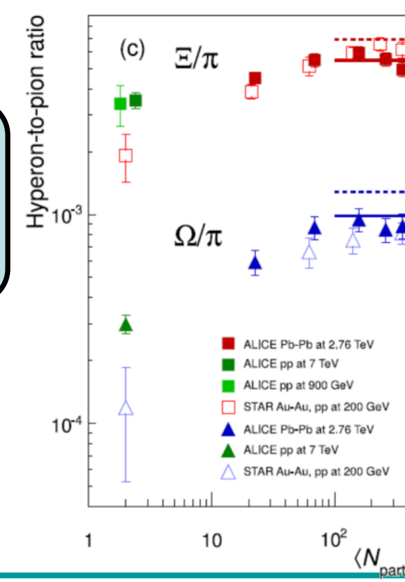


$$\left.\frac{dN}{dy}\right|_{y=0} \simeq \begin{cases} 1-26 & \Lambda(S=-1) \\ 0.12-3.3 & \Xi(S=-2) \\ 0.015-0.6 & \Omega(S=-3) \end{cases}$$

Two-particle FSI

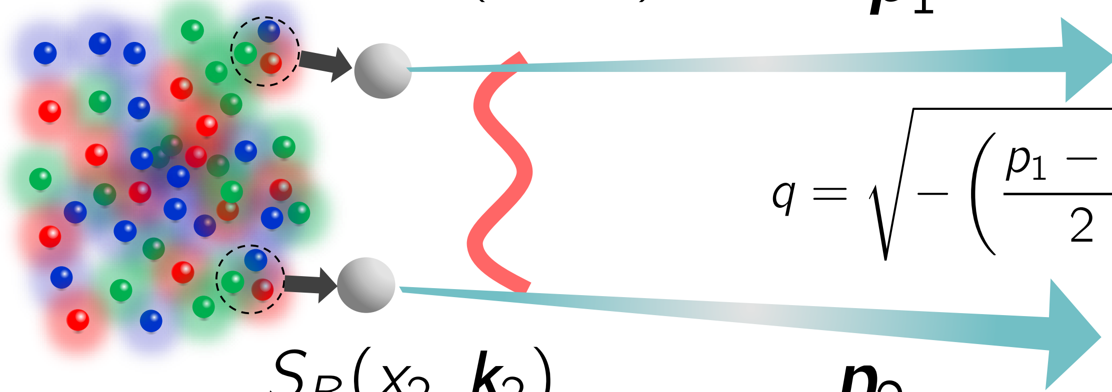
at freeze-out

Particularly unique
opportunity for
$|S| \geq 2$



Two-Particle Correlation

$S_A(x_1, \boldsymbol{k}_1)$ $\quad \boldsymbol{p}_1 \quad$ $\boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2$



$$q = \sqrt{-\left(\frac{p_1 - p_2}{2} - \frac{(p_1 - p_2)\cdot P}{P^2}P\right)^2} = |\boldsymbol{q}^*|$$

Momentum in pair rest frame

$S_B(x_2, \boldsymbol{k}_2)$ $\quad \boldsymbol{p}_2$

Measuring Pair Correlation

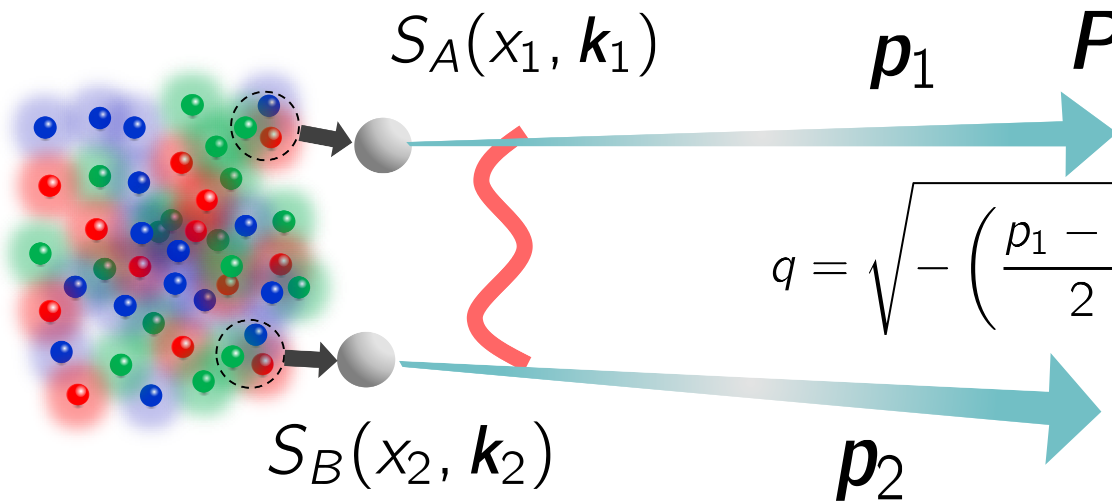
→Constrain Pairwise Interaction

$$C_{AB}(q) = \frac{N^{\text{pair}}_{AB}(q)}{N_A N_B(q)} = \begin{cases} 1 & \\ \text{Others} & \end{cases}$$

No Correlation

Interaction
Interference
etc

Two-Particle Momentum Correlation



$$\boldsymbol{P} = \boldsymbol{p}_1 + \boldsymbol{p}_2$$

$$q = \sqrt{-\left(\frac{p_1 - p_2}{2} - \frac{(p_1 - p_2)\cdot P}{P^2}P\right)^2} = |\boldsymbol{q}^*|$$

$$C_{AB}(q) \simeq \int d^3\boldsymbol{r}^* S_P^{\mathrm{rel}}(\boldsymbol{r}^*)|\psi_{AB}^{(-)}(\boldsymbol{r}^*, \boldsymbol{q}^*)|^2$$

(# of pair) = (integration over relative distribution x weight factor)

Random emission from the "Smooth" Source
Constrained from y, p_t spectrum etc

Non-relativistic scattering wave function
FSI and (a)symmetrization (for identical pairs)

More rigorous formula found in Anchishkin, Heinz, Renk, PRC57 ('98)

What we learned:

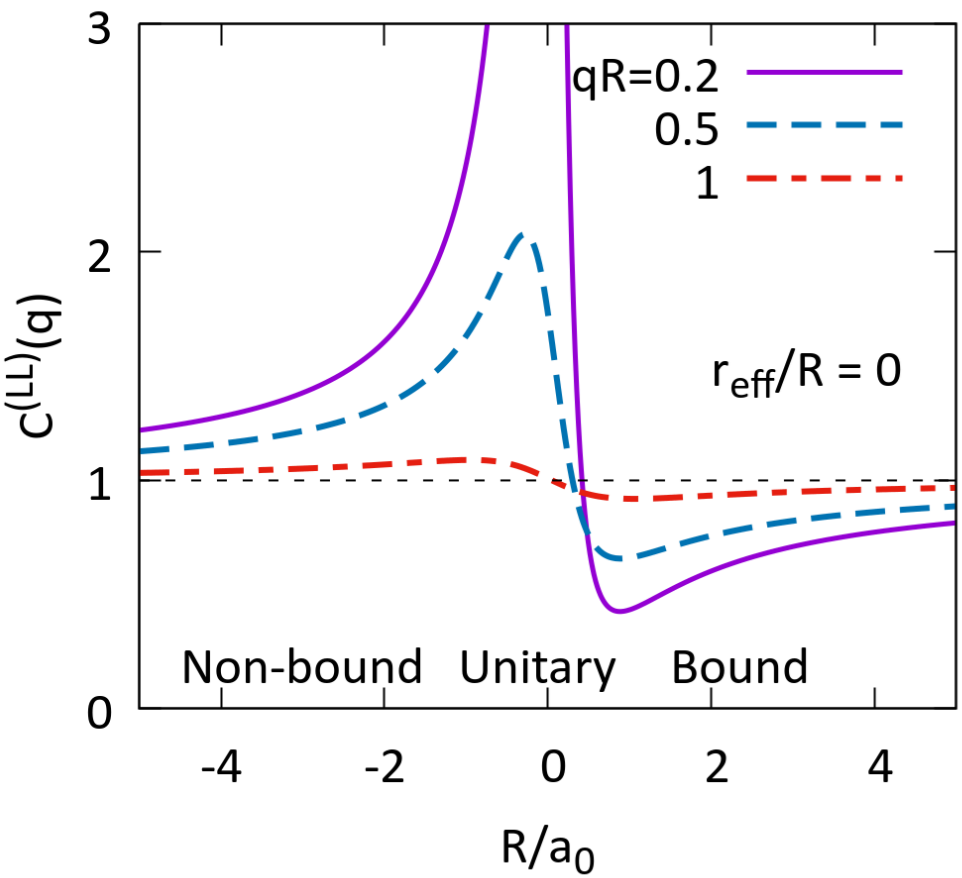
How to distinguish the nature of the interaction and existence of the bound state

Correlation from FSI

Static/Spherical Source

Lednicky+ '82

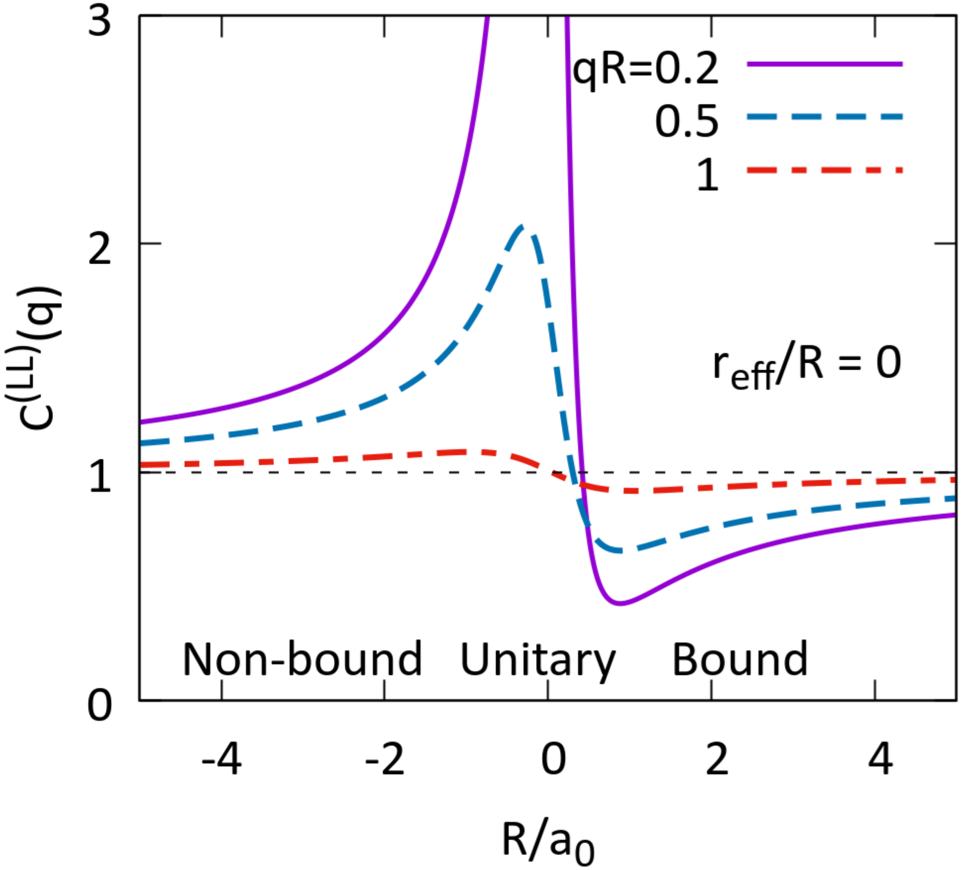
$$C_{AB}(q) = 1 + \int dr \tilde{S}^{\mathrm{rel}}(r) \left(|\chi_q(r)|^2 - |j_0(qr)|^2 \right)$$



- Assumptions
  - Gaussian Source
  - Asymptotic w.f.
  - Effective range formula
- Results
  - $C(q) = C(qR, R/a_0)$ for $r_{\mathrm{eff}}=0$
  - System size dependence – Characterized by the scattering length a_0

Recipe for Identifying Nature of Interaction

KM+ '19 (PRC in press)



- "Small" ($R \ll a_0$) system :
  always enhanced C(q) at small q

Increasing R

If a bound state exists, depletion of C(q) below 1 should be seen

- "Large" ($R \gg a_0$) system:
  Small deviation from non-FSI case

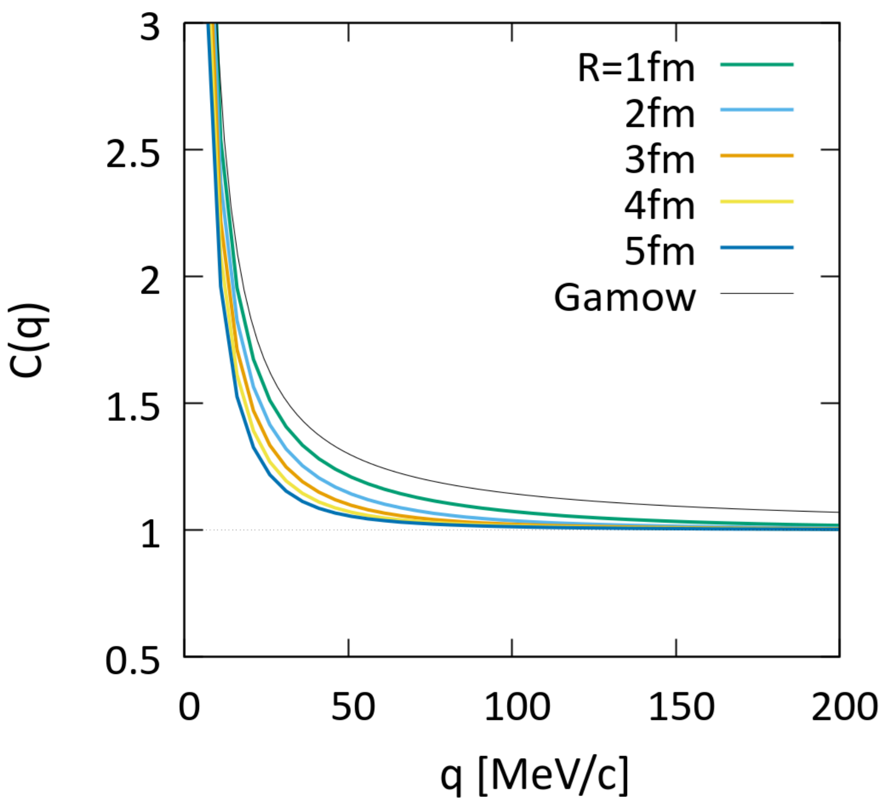
What we learned:

Other sources of the correlation
HBT / Resonance / Coulomb

Coulomb Interaction

Long-range attraction or repulsion

Coulomb Interaction Only!
N-Ω reduced mass



- Gamow factor: overcorrection
- Much less size dependent

$$C(q, R = 1\text{fm}) \sim C(q, R = 3\text{fm})$$

- Large R

$$C(q) \sim C^{\text{Coul}}(q)$$

KM+, PRC'16

- The Small-Large Ratio

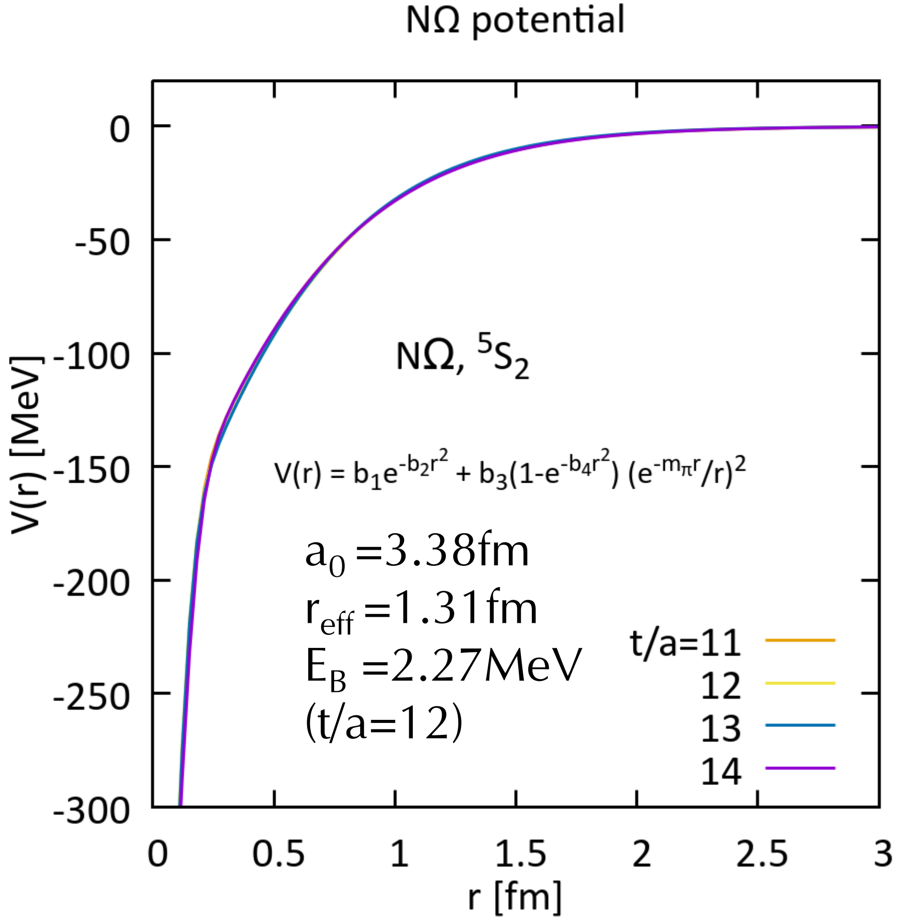
$$C_{SL}(q) = \frac{C_2^{\text{C+S}}(q)|_{\text{Small}}}{C_2^{\text{C+S}}(q)|_{\text{Large}}} \simeq \frac{C_2^{\text{C+S}}(q)|_{\text{Small}}}{C_2^{\text{C}}(q)|_{\text{Large}}}$$

$$\simeq \frac{C_2^{\text{C+S}}(q)|_{\text{Small}}}{C_2^{\text{C}}(q)|_{\text{Small}}}$$

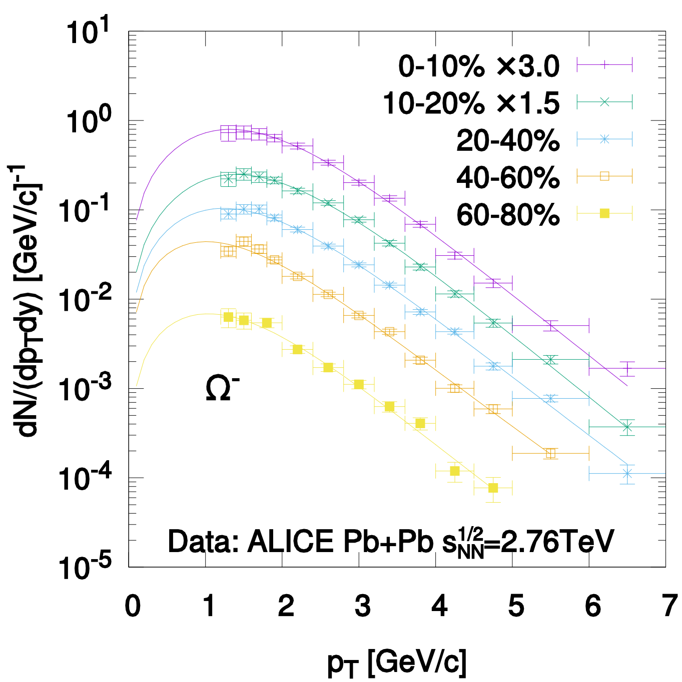
Extract strong interaction!

Example : pΩ Correlation

- Theory : HAL QCD potential + Expanding Source model

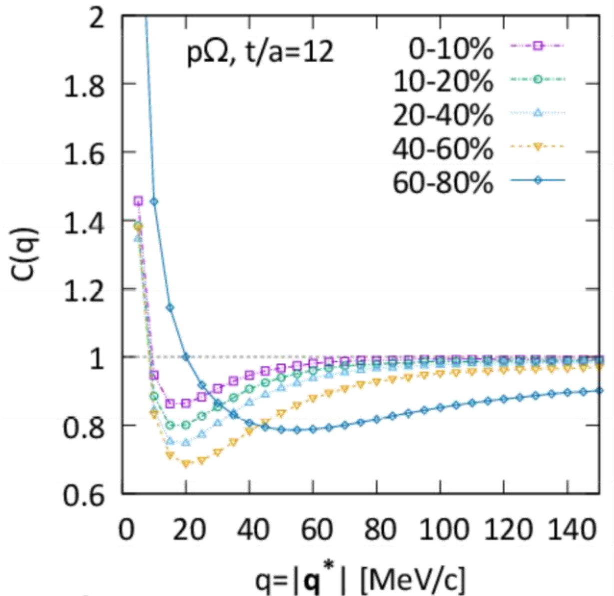


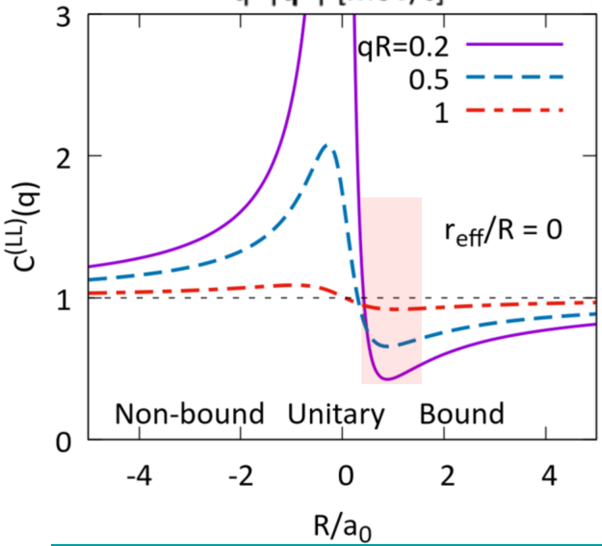
Constrained by single-particle distribution
proton HBT radii

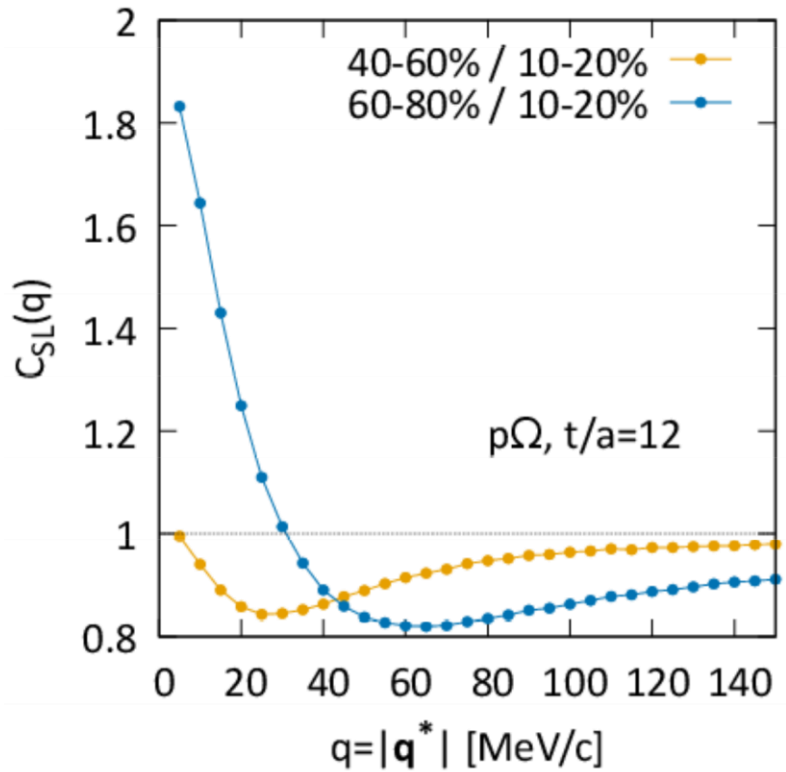


Example: pΩ Correlation

KM+ '19 (PRC in press)





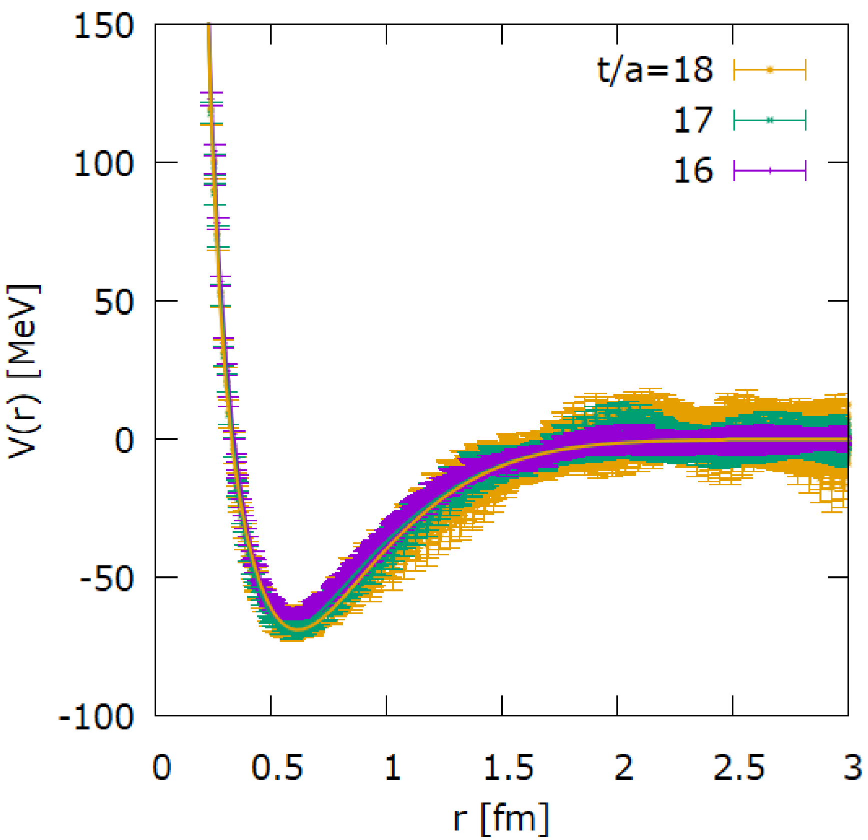


40-60% Bound regime
60-80% Unitary regime

pp unitary measured: Need HI to confirm bound regime (STAR, but more statistics!)

ΩΩ (S=-6) : Coulomb+HBT+Unitary

$^1S_0$ bound state from Lattice QCD



Gongyo+, (HAL QCD), PRL'18

m_π=146MeV, m_Ω=1713MeV

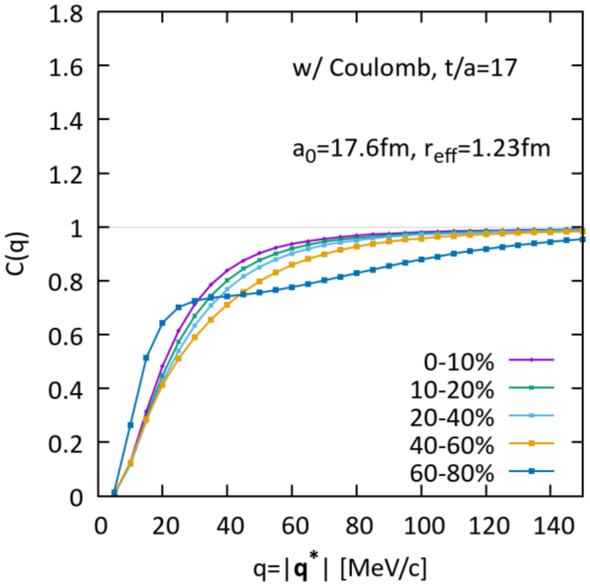
+Coulomb repulsion

t/a	a_0 [fm]	r_{eff} [fm]	E_B [MeV]
16	65.3	1.29	0.1
17	17.6	1.23	0.5
18	11.7	1.21	1.0

⇩

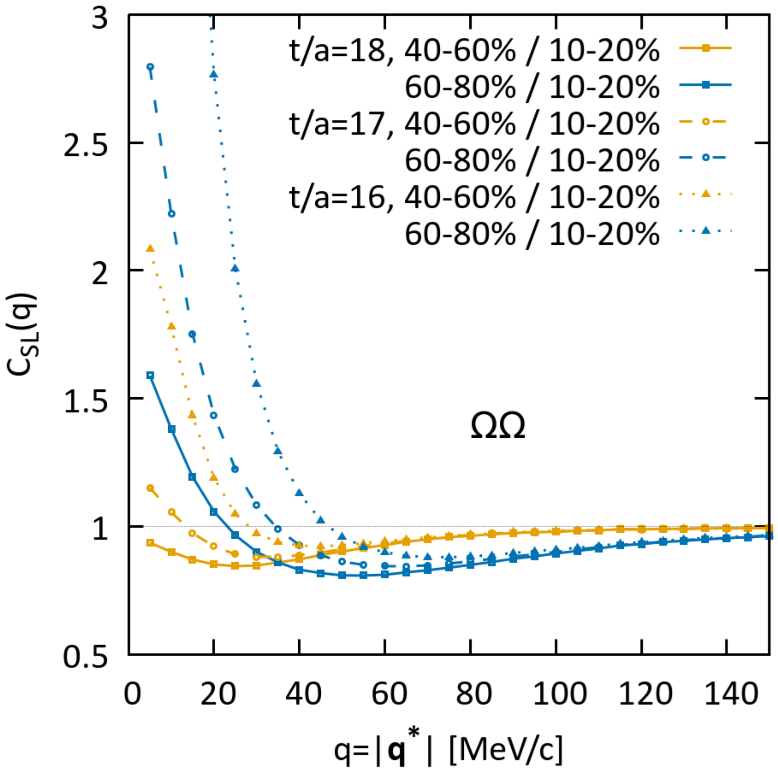
Unitary regime in typical source size for HIC

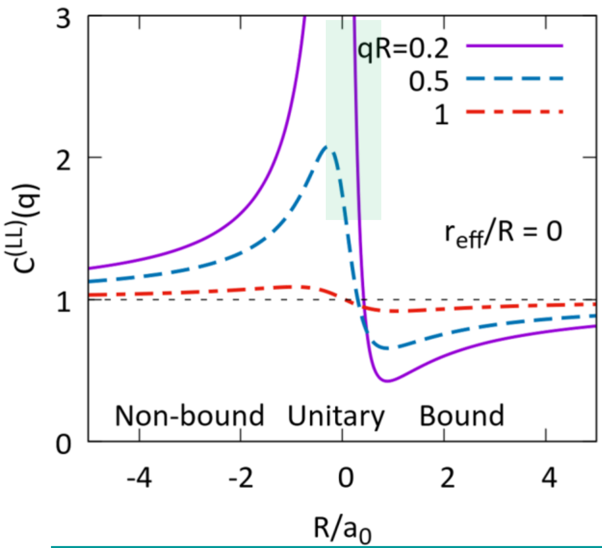
ΩΩ Correlation: Coulomb+HBT+Unitary



HBT gives suppression of C(q) for larger system

Small spin-0 contribution : unseen in C(q) despite large a_0





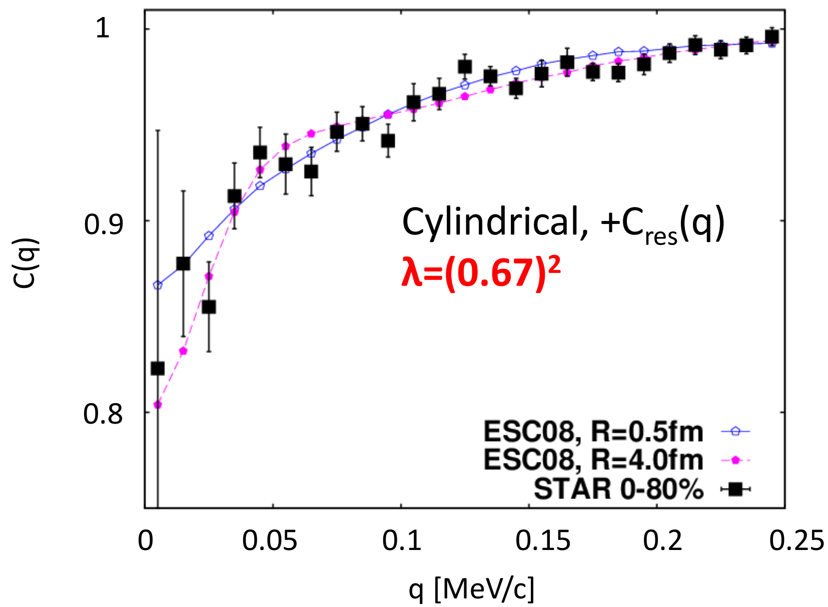
Highly challenging: statistics of di-Omega events

Too large system required for bound regime

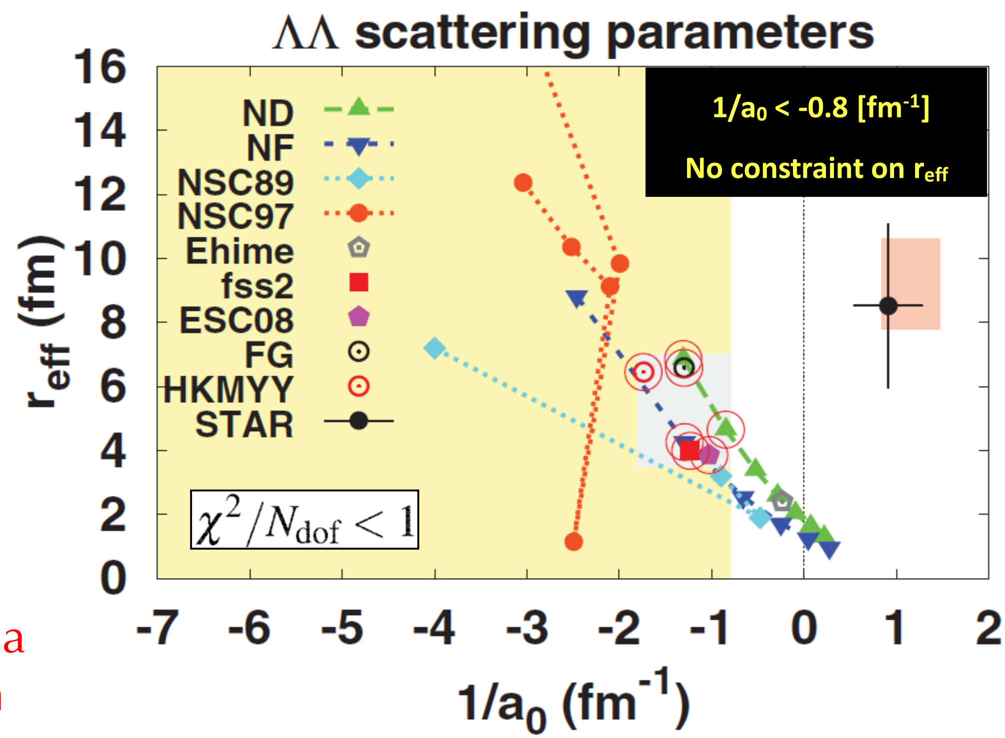
ΛΛ Correlation (HBT+resonance)

KM+ '15

Constraint from the STAR measurement



Favor weakly attracting ΛΛ pair

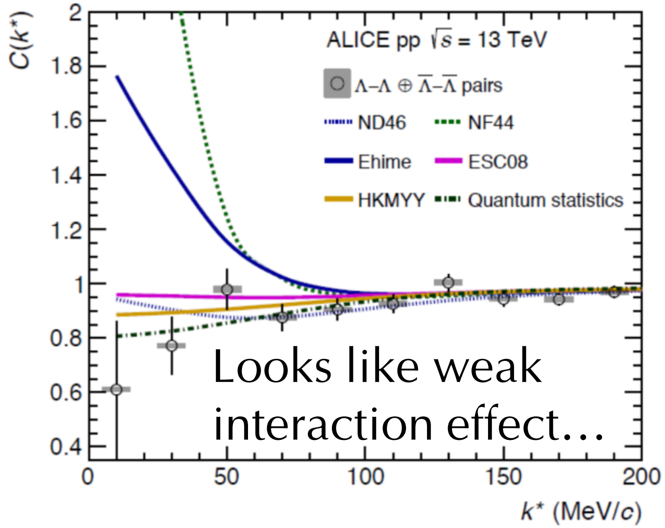


Fix λ from $\Sigma^0 \to \Lambda\gamma$ contribution
Dilution of C(q) (reduction of C(0))

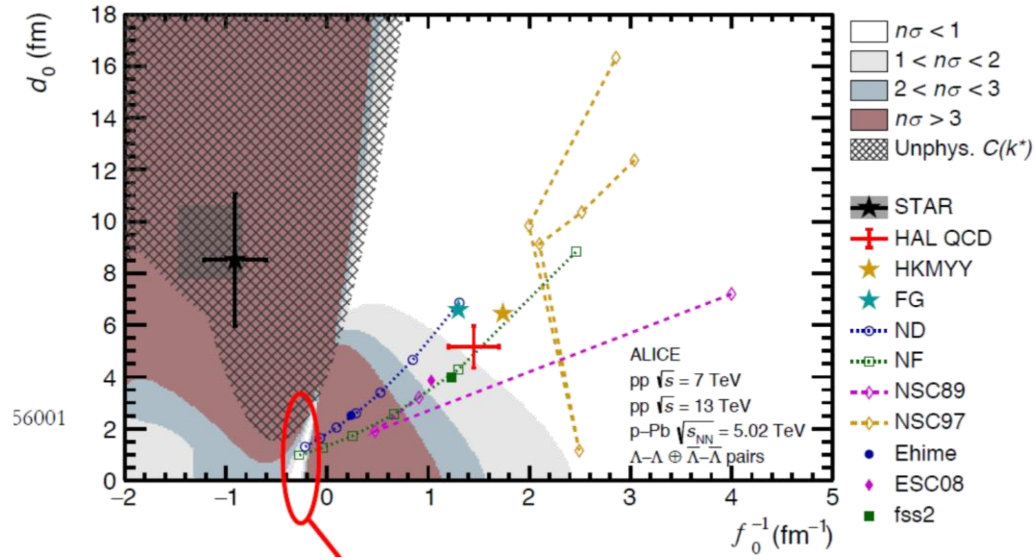
Free(fitting parameter) λ can lead to a global but physically false minimum

ΛΛ Correlation @LHC

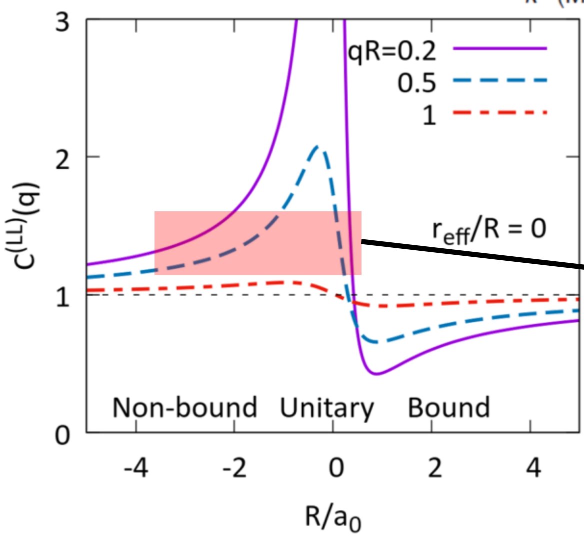
ALICE pp (7 and 13TeV) and p+Pb (5TeV)



Version 2019 (Fabbietti, QM2019)



Allow H-dibaryon as ΛΛ bound state



Probably we're here.
Larger system (HI) can kill (or confirm) the bound regime
(Statistics at q < 50MeV crucial)

What should we do next?

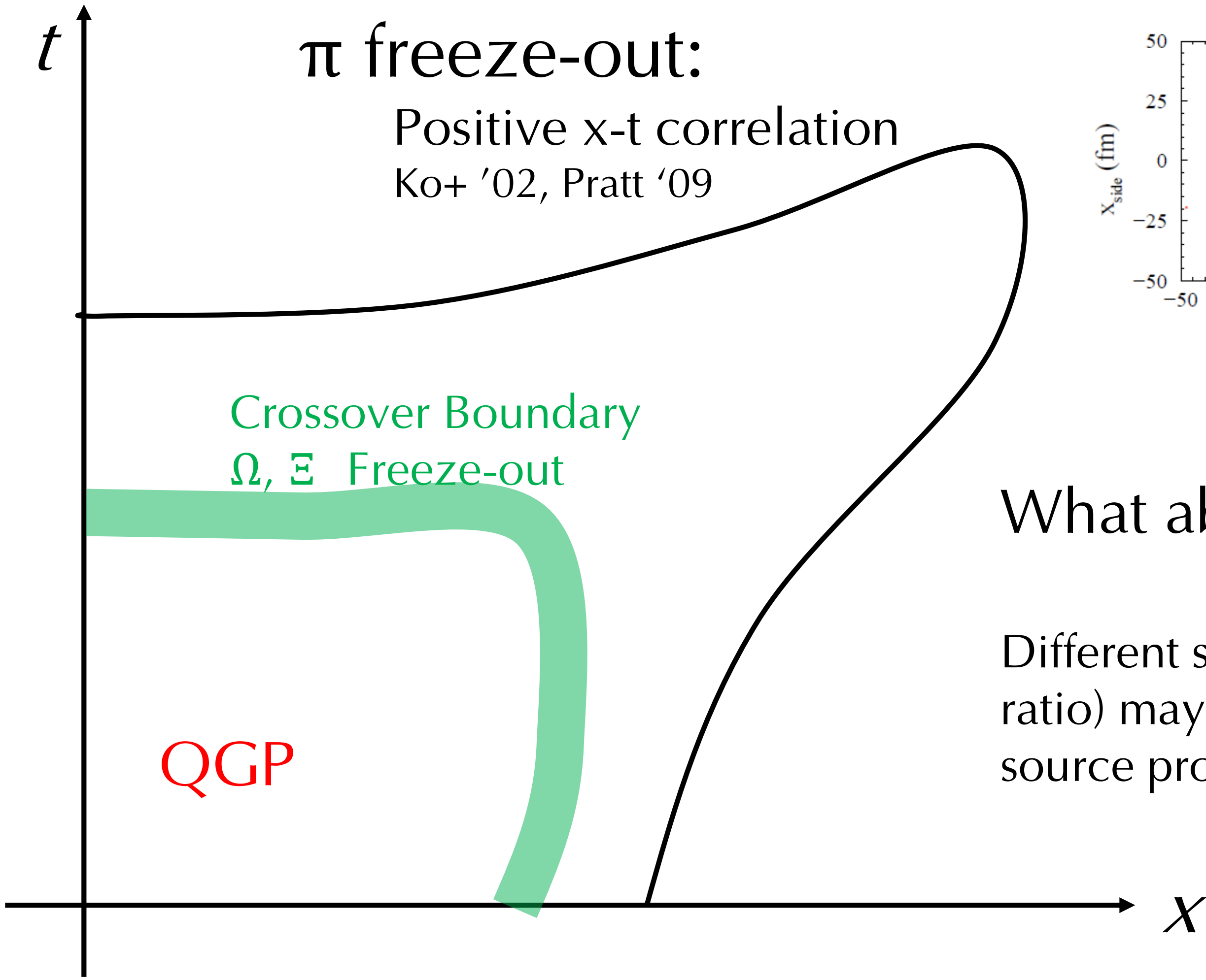
Trivial things :

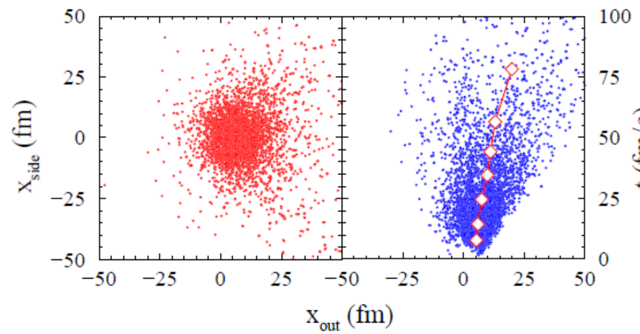
statistics

improving experimental technique

Things to Check : Source function in HIC

Recollection: the HBT puzzle in ππ





What about p, Λ, K etc…?

Different size comparison (e.g., S-L ratio) may be free from the realistic source problem, but better to know

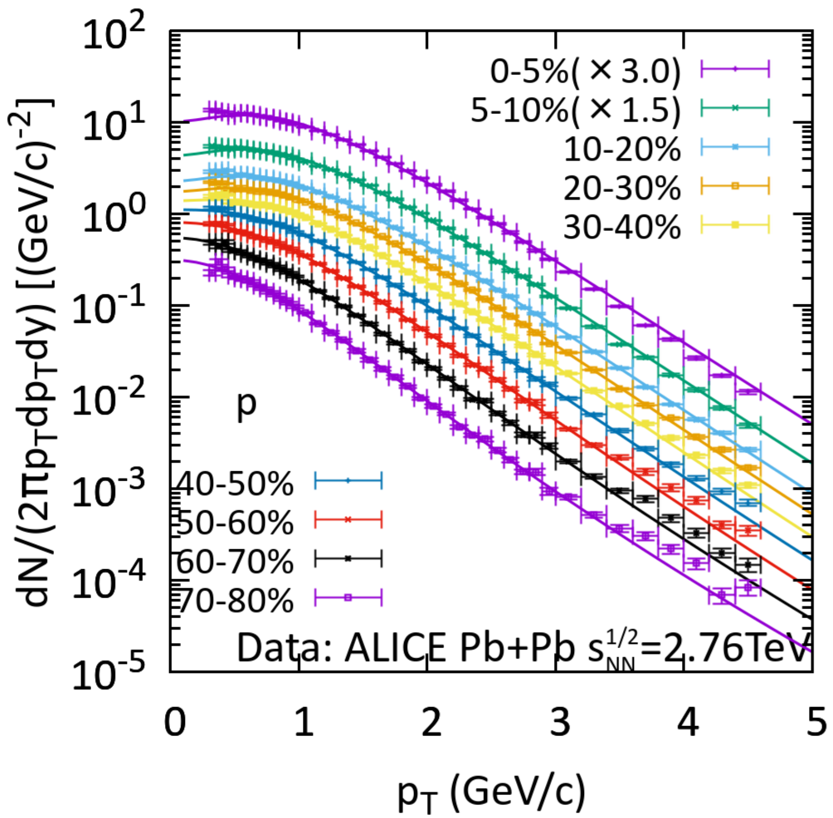
Constraint on p Source Function

Csörgő+ '95

$$\frac{dN}{dy p_T dp_T 2\pi} = \frac{d}{(2\pi)^3} 2m_T V \int_0^\infty d\rho \rho e^{-\rho^2/2} I_0\left(\frac{p_T}{T}\sinh y_T\right) K_1\left(\frac{m_T}{T}\cosh y_T\right)$$

$$V = 2\tau_0 \pi R^2, \quad y_T = \alpha \rho^\beta, \; \rho = \frac{r}{R}$$

+2-body decay from m_{res} <2GeV



KM+ '19

relative distance distribution

Reasonable size at T=155MeV
HBT radii (~4fm)

Momentum dependence

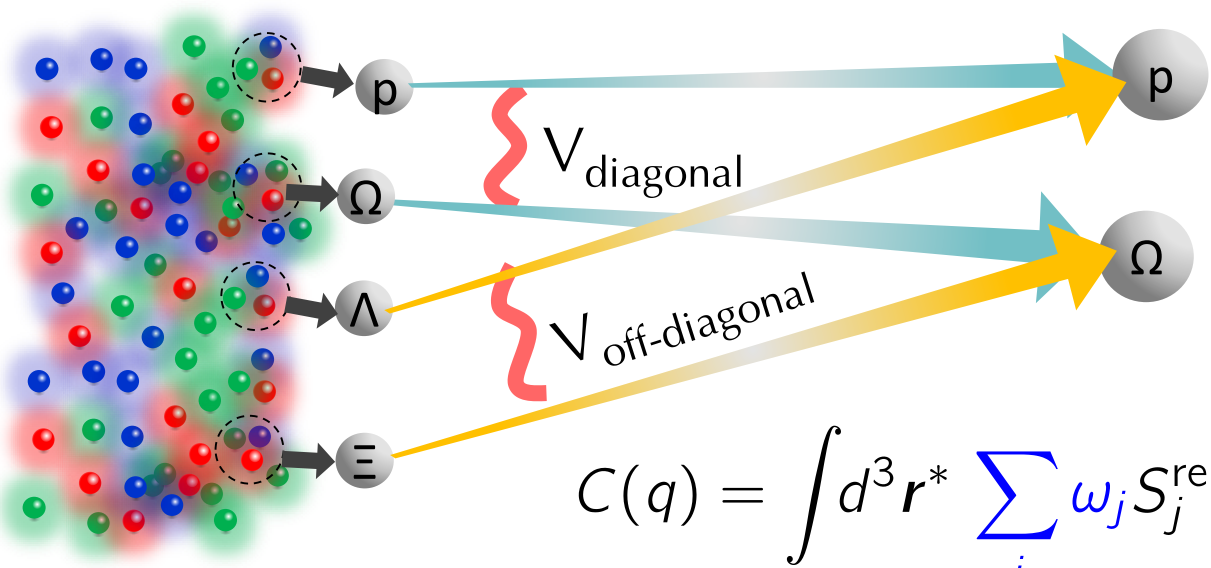
Well reproduce pt-spectrum

Is this Gaussian model sufficient?

Maybe not, when one wants to have relative source function with different particle species.

Coupled Channel

- Most of YN, YY systems are C.C. systems!



Lednicky +'82
Haidenbauer '18

$$C(q) = \int d^3\boldsymbol{r}^* \sum_j \omega_j S_j^{\mathrm{rel}}(\boldsymbol{r}^*) |\psi_j^{(-)}(\boldsymbol{r}^*, \boldsymbol{q}^*)|^2$$

Additional contribution (weight ω_j) and modification of Ψ though Schrödinger Equation
→ Y. Kamiya (K^-p correlation / Thursday)

Caveat – Small $V_{\text{off-diagonal}}$ does <u>not</u> mean small influence on C(q), if close to unitary regime (Sekihara+ '18)

Concluding Remarks

Single-channel analysis is established

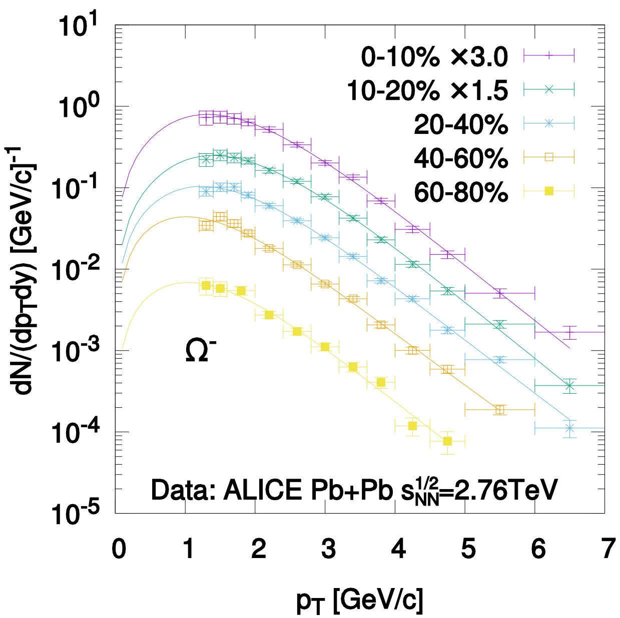
- Correlation : complementary, sometimes unique approach to get insights into BB interaction.
- C(q) in small systems is more sensitive to FSI.
- System size scan to confirm bound state.
- Toward precision era – consider baryon source functions in HIC and coupled channel analyses.

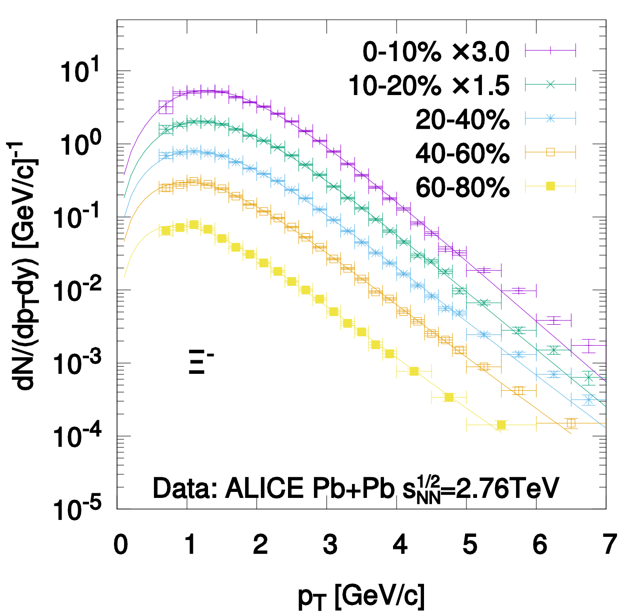
Comment on each channels

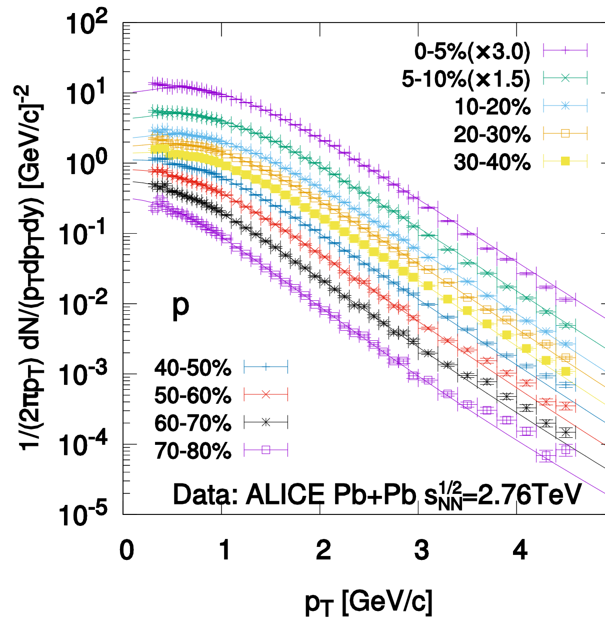
- ΩΩ – most likely unitary regime even in HIC. Enhancement over Coulomb+HBT. Waiting for J=1,2,3 on the lattice.
- pΩ – from unitary (pp,pA,peripheral) to bound regime (AA). Coupled channel analysis necessary for quantitative determination.
- ΛΛ – Full coupled channel and system size scan for further constraint.
- K^-p – Testing ground of the full coupled channel framework.

Backup

Spectra@ T=155MeV







Direct only
V = 103 – 4160 fm^3
(60-80%) (0-10%)

Include Ξ(1530) decay
V = 171 - 4100 fm^3
(60-80%) (0-10%)

Include m* < 2GeV
V = 110 – 3500 fm^3
(60-80%) (0-10%)

Fix τ_0 = 10 fm for 0-10% and use $\tau_0 \sim (dN/dy)^{1/3} \longrightarrow$ Fix R

⇨ R= 2 – 8 fm, $R_{\text{proton-HBT}} \sim$ 4 fm (Consistent w/ ALICE)

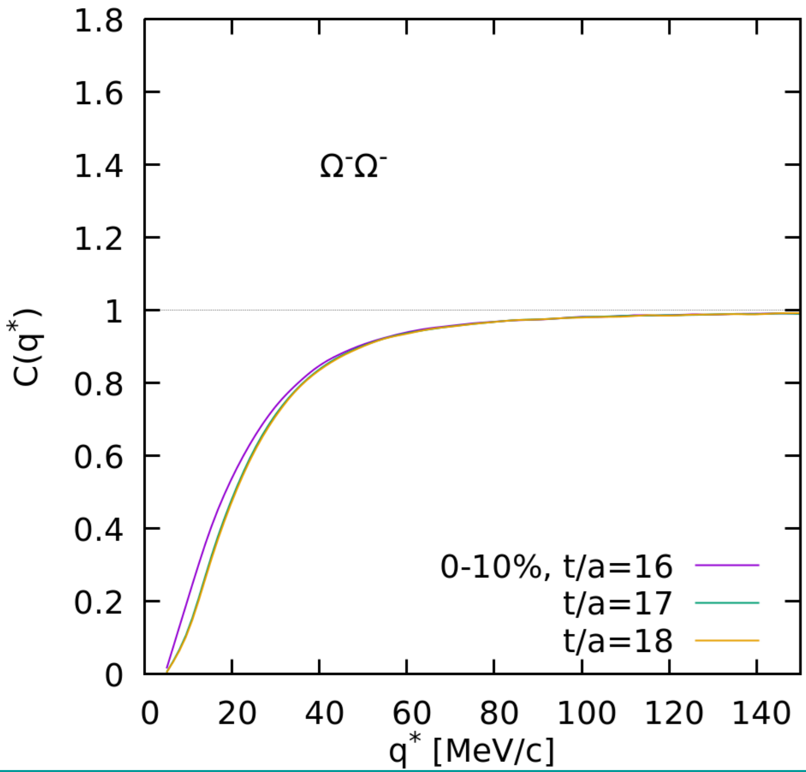
ΩΩ Correlation

- Wave function

$$|\varphi_{\Omega\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{1}{16}|\varphi(J=0)|^2 + \sum_{J=1}^{3} \frac{2J+1}{16}|\varphi(J)|^2$$

FSI+Coulomb+symmetrization Coulomb+(a)symmetrization

- Correlation function



System is too large
Coulomb+HBT dominate

Further suppressed by the spin degeneracy factor 1/16

ΩΩ Correlation

Wave function

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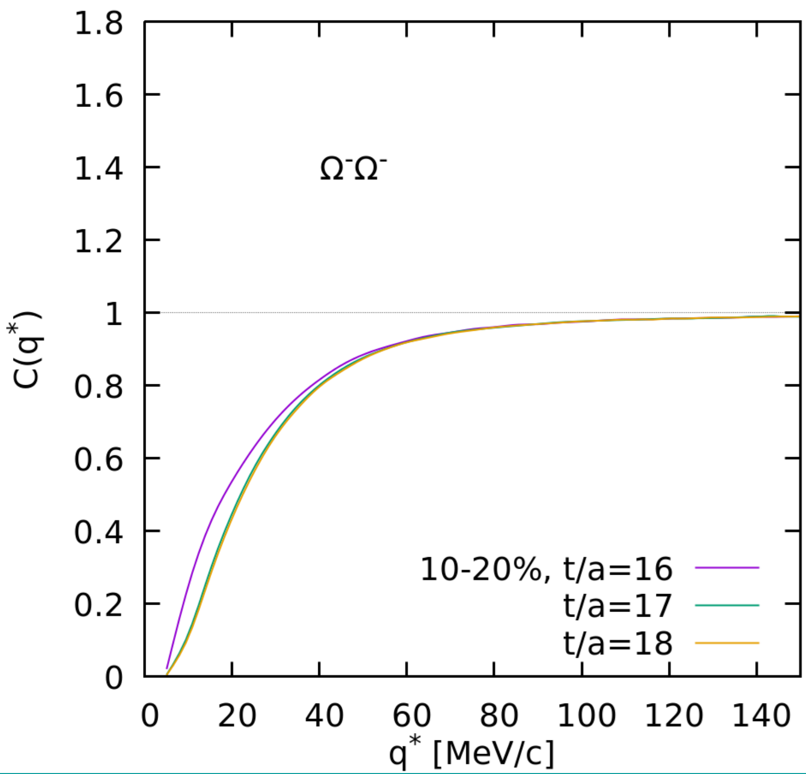
FSI+Coulomb+symmetrization   Coulomb+(a)symmetrization

Correlation function



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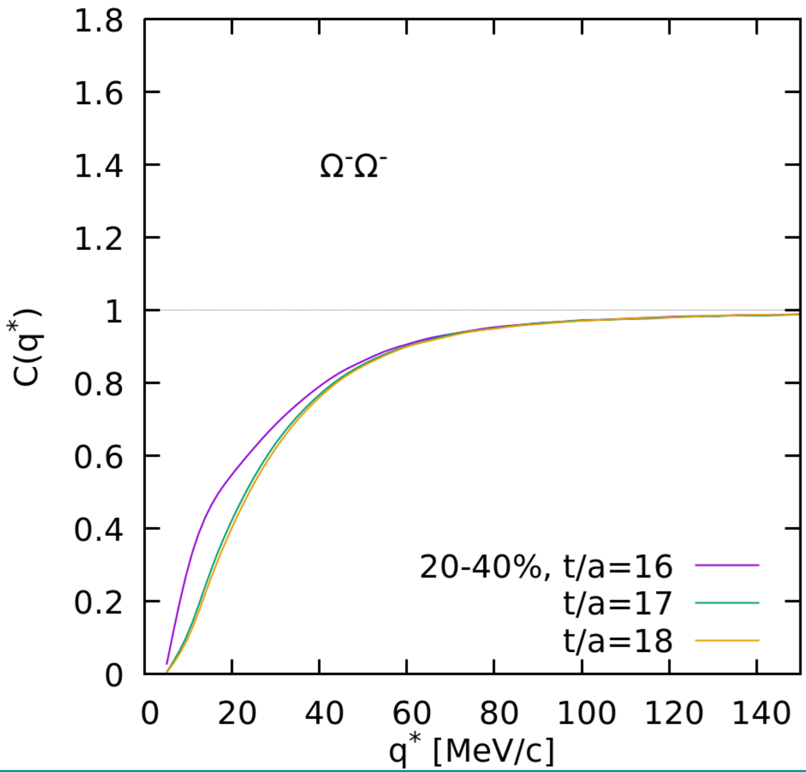


System is too large
Coulomb+HBT dominate

Further suppressed by the spin degeneracy factor 1/16

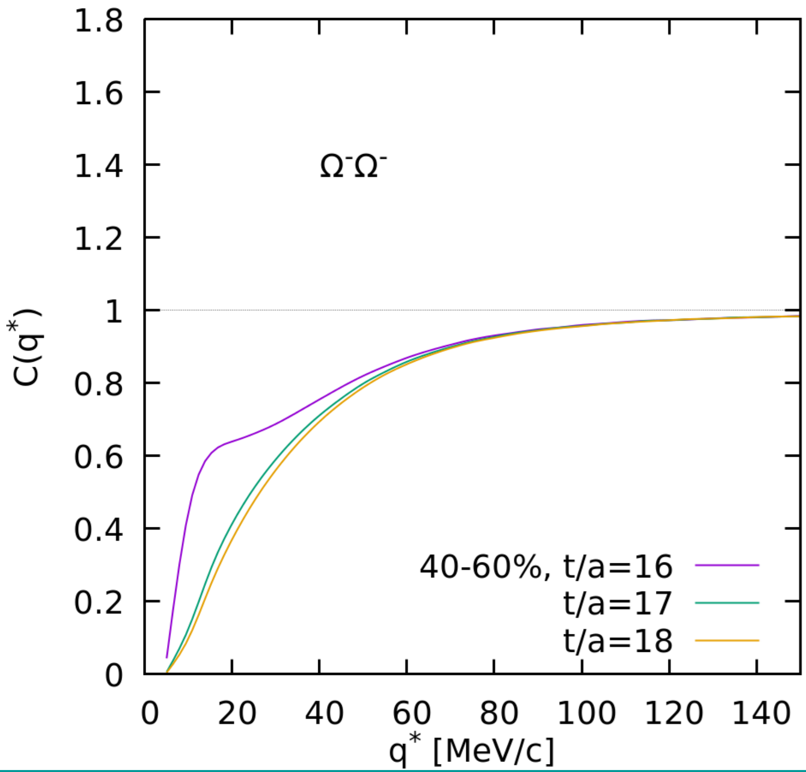
ΩΩ Correlation

Wave function

$$|\varphi^{\text{spin-averaged}}_{\Omega\Omega}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{1}{16}|\varphi(J=0)|^2 + \sum_{J=1}^{3} \frac{2J+1}{16}|\varphi(J)|^2$$

FSI+Coulomb+symmetrization Coulomb+(a)symmetrization

Correlation function



C(q*) evolves with system size
Coulomb+HBT dominate

Further suppressed by the spin degeneracy factor 1/16

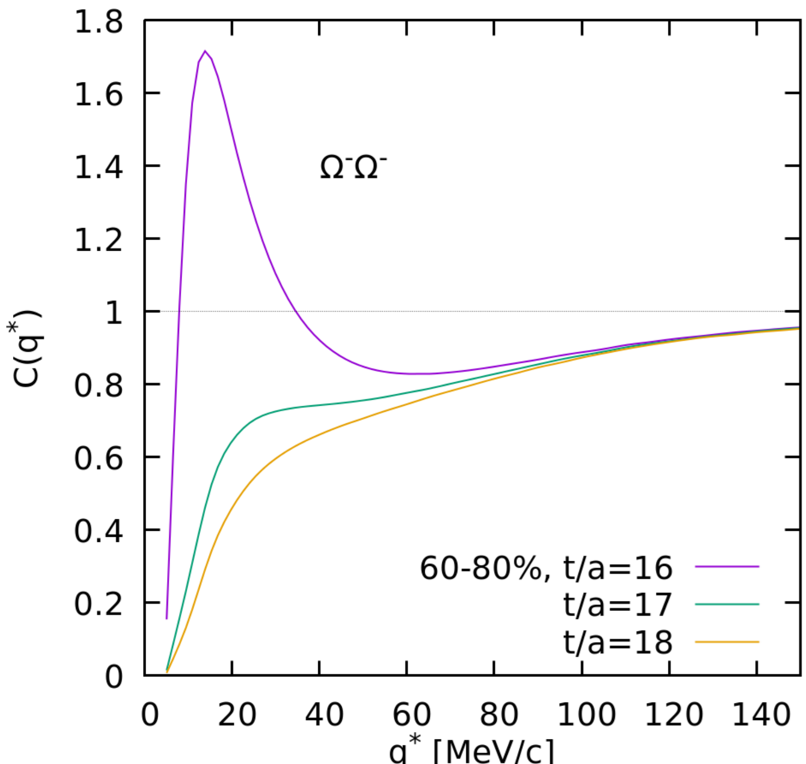
ΩΩ Correlation

Wave function

$$|\varphi_{\Omega\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{1}{16}|\varphi(J=0)|^2 + \sum_{J=1}^{3}\frac{2J+1}{16}|\varphi(J)|^2$$

FSI+Coulomb+symmetrization Coulomb+(a)symmetrization

Correlation function

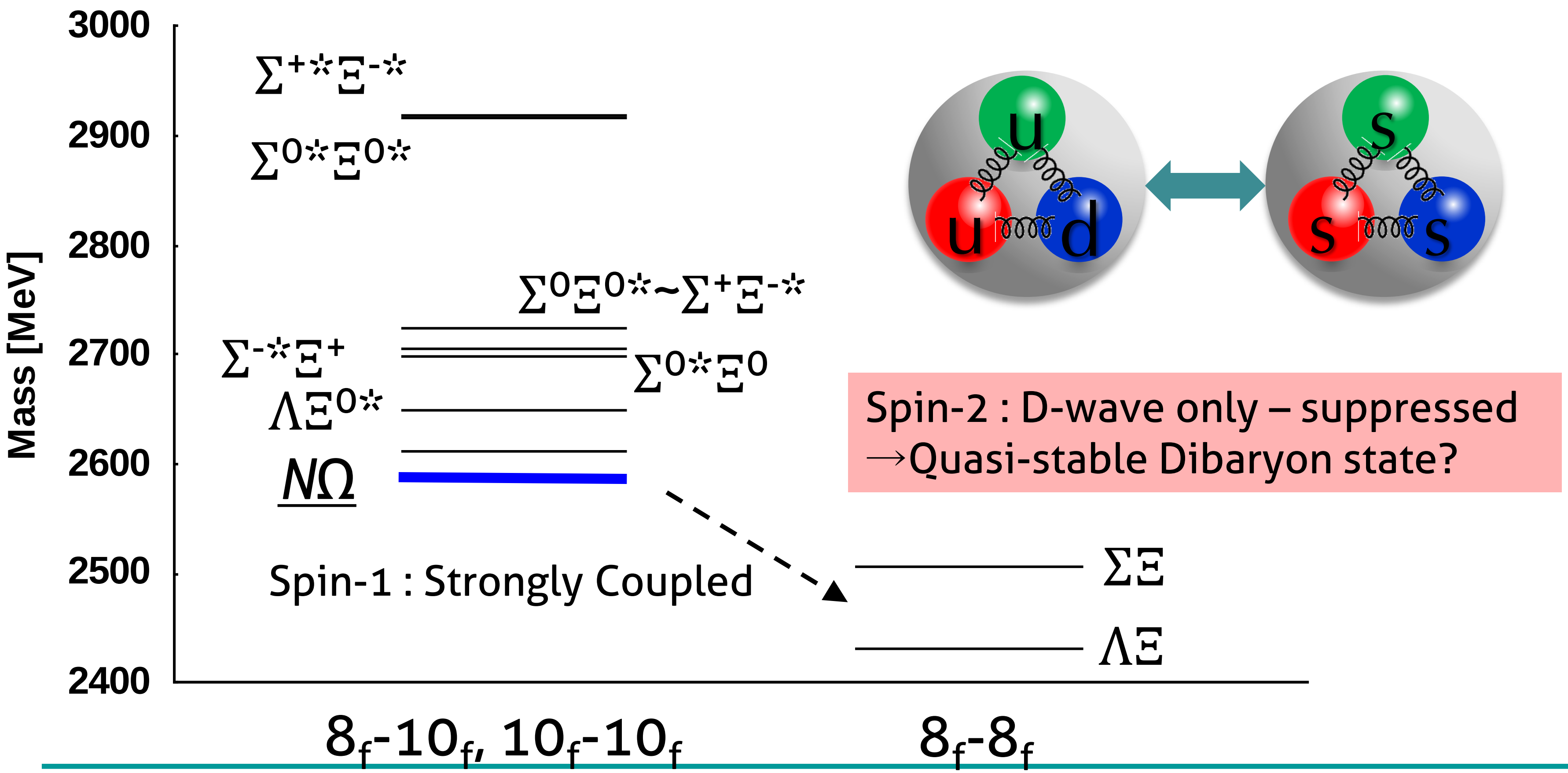


Strong FSI effect for small systems

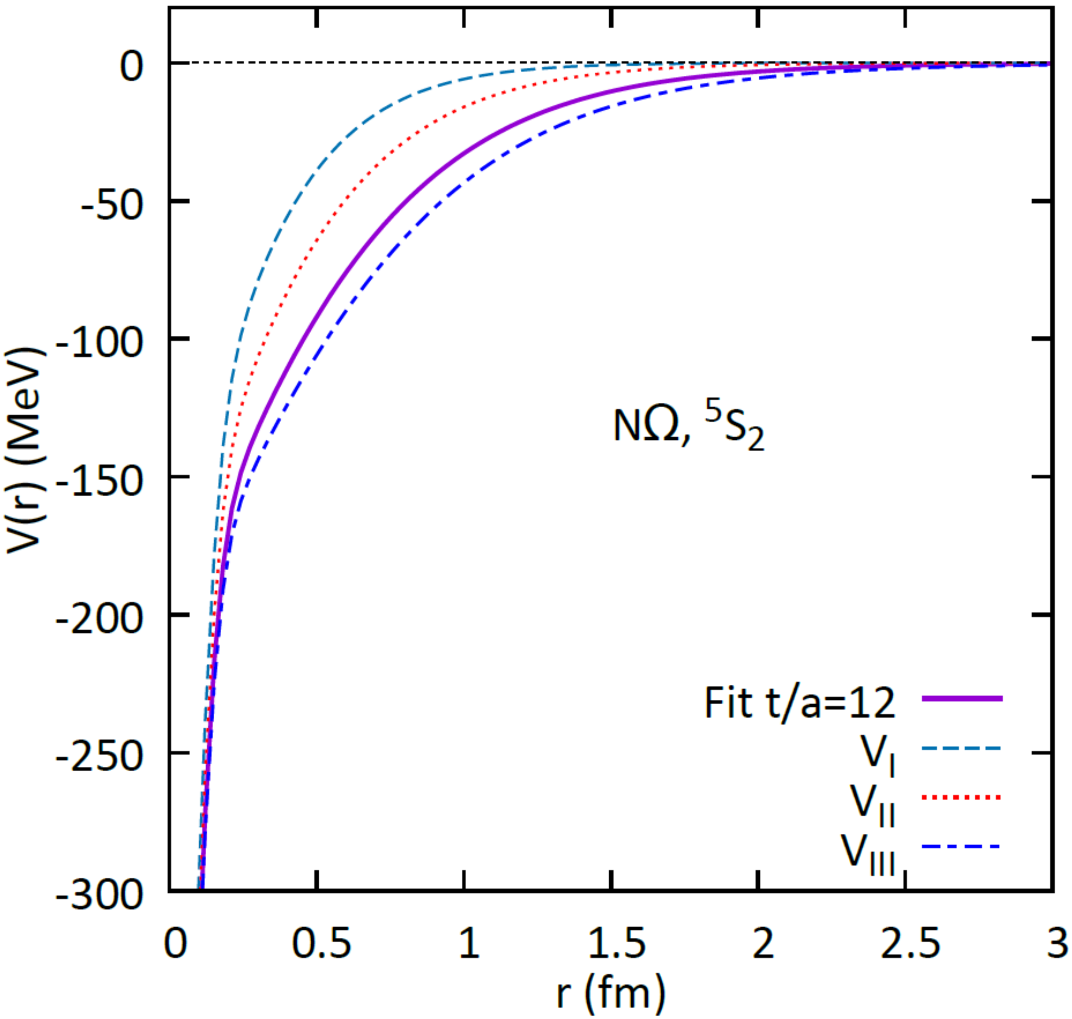
Further suppressed by the spin degeneracy factor 1/16

S=-3:

$p\Omega$ @almost phys.point

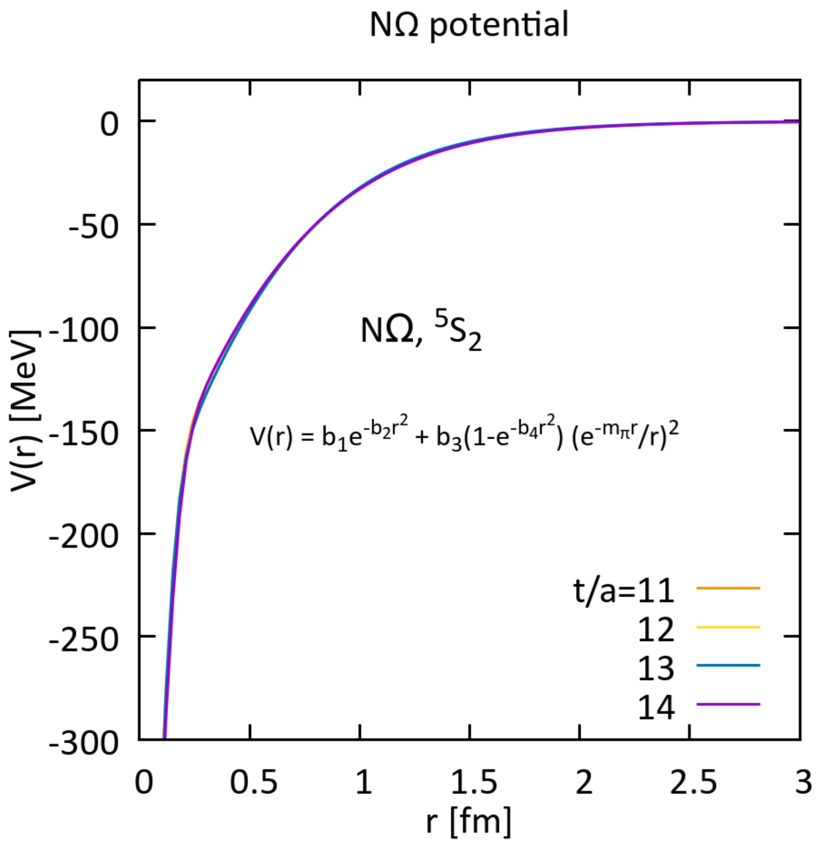


Comparison to Old Potentials



$p\Omega$ Interaction ($^5S_2$)

NΩ potential (fitted to Lattice data) : bound state exists



T.Iritani+ (HAL QCD)

+Coulomb attraction

t/a	a_0 [fm]	r_{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	3.30	1.33	2.24

Bound state regime for Heavy Ion Collisions
Close to unitary for smaller system

Long-range part is assumed to be 2π exchange

$p\Omega$ Correlation

$$|\varphi^{\text{spin-averaged}}_{p\Omega}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{3}{8}|\varphi(^3S_1)|^2 + \frac{5}{8}|\varphi(^5S_2)|^2$$

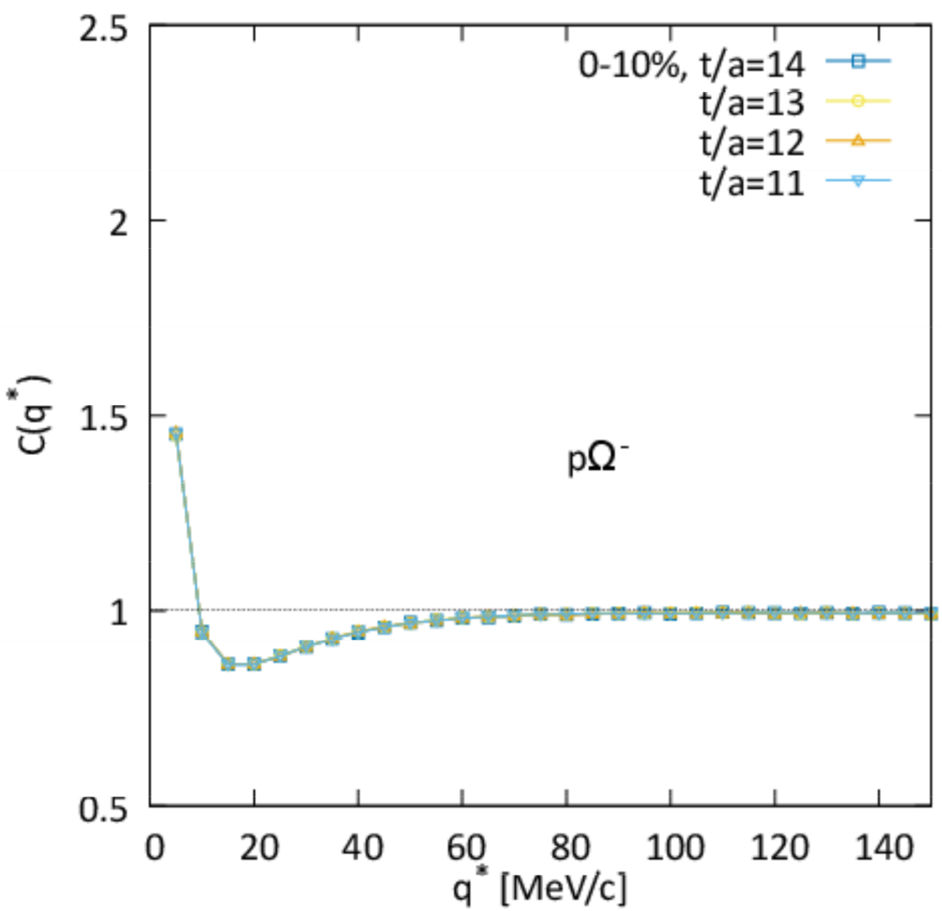
Coupled to ΛΞ (2430) and ΣΞ(2507)

Absorption of S-wave component

$$V_{J=1}(r) = -i\theta(r_0 - r)V_0$$

Large systems in
Bound state regime:
Suppression of $C_{SL}(Q)$
Below unity at low Q

Lattice input: Iritani+



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$$\Downarrow$$

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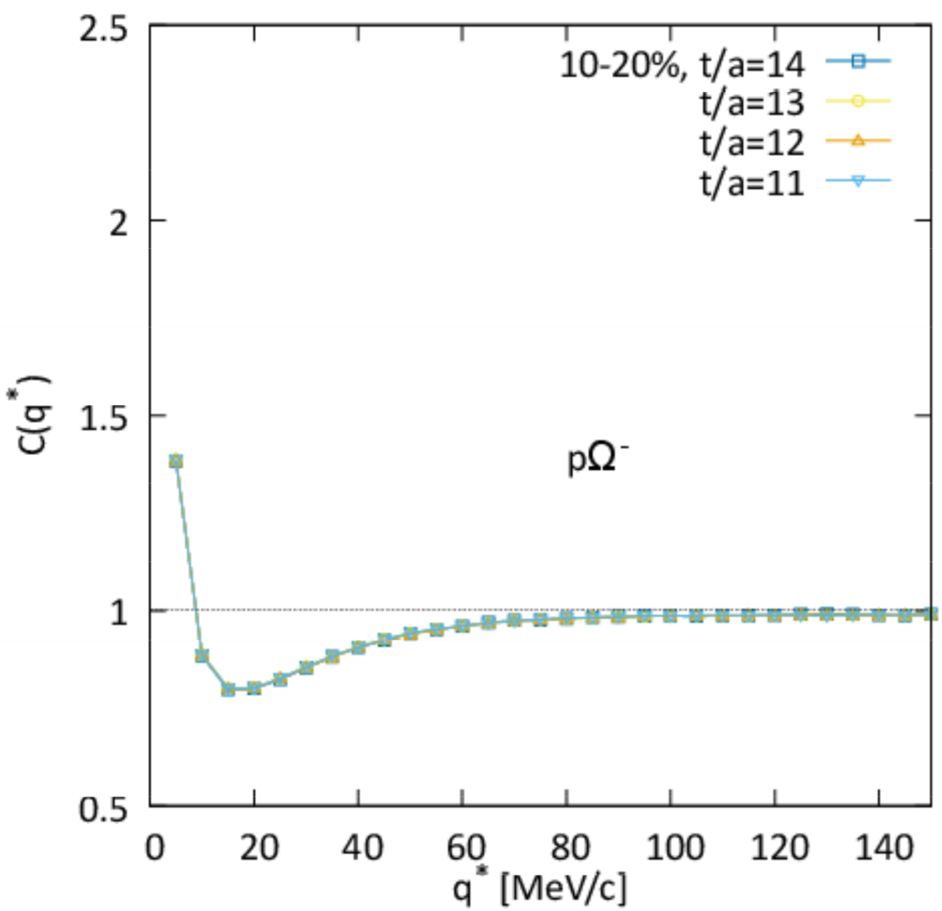

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Bound state regime:
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Below unity at low Q

$p\Omega$ Correlation

$$|\varphi_{p\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{3}{8}|\varphi({}^3S_1)|^2 + \frac{5}{8}|\varphi({}^5S_2)|^2$$

$\Downarrow$

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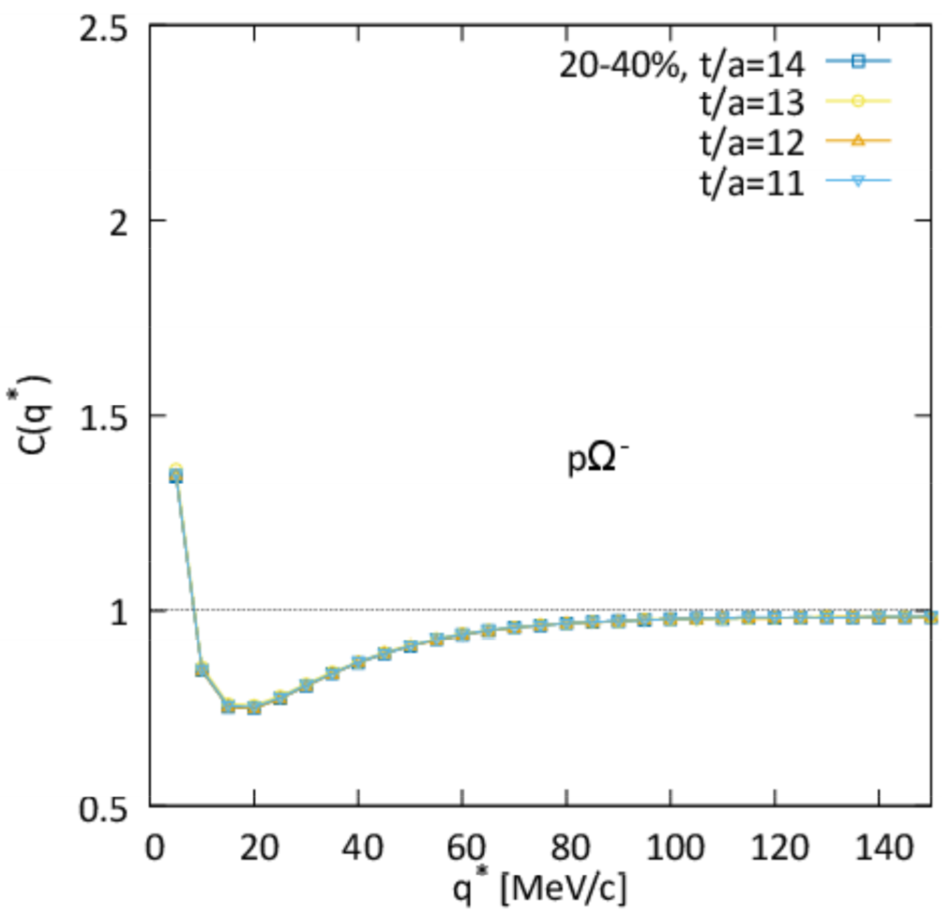

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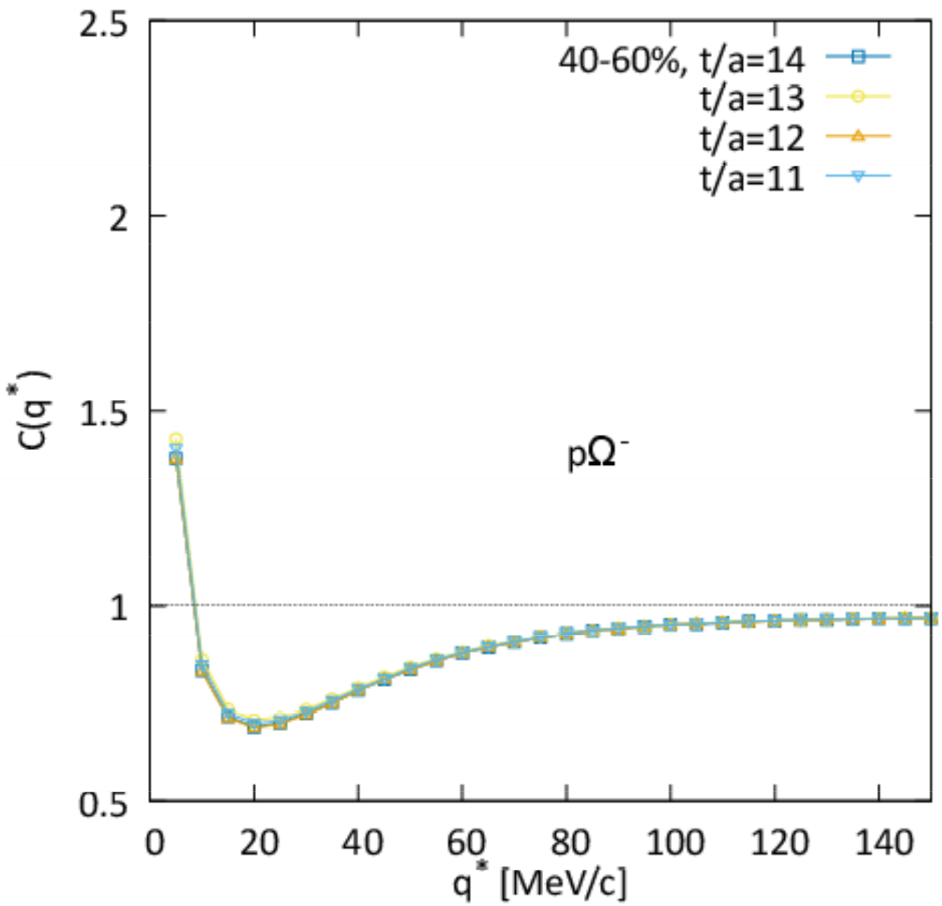

Large systems in
Bound state regime:
Suppression of $C_{SL}(Q)$
Below unity at low Q

Small systems in
Unitary regime

$p\Omega$ Correlation

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$$\Downarrow$$

Coupled to $\Lambda\Xi$ (2430) and $\Sigma\Xi$(2507)

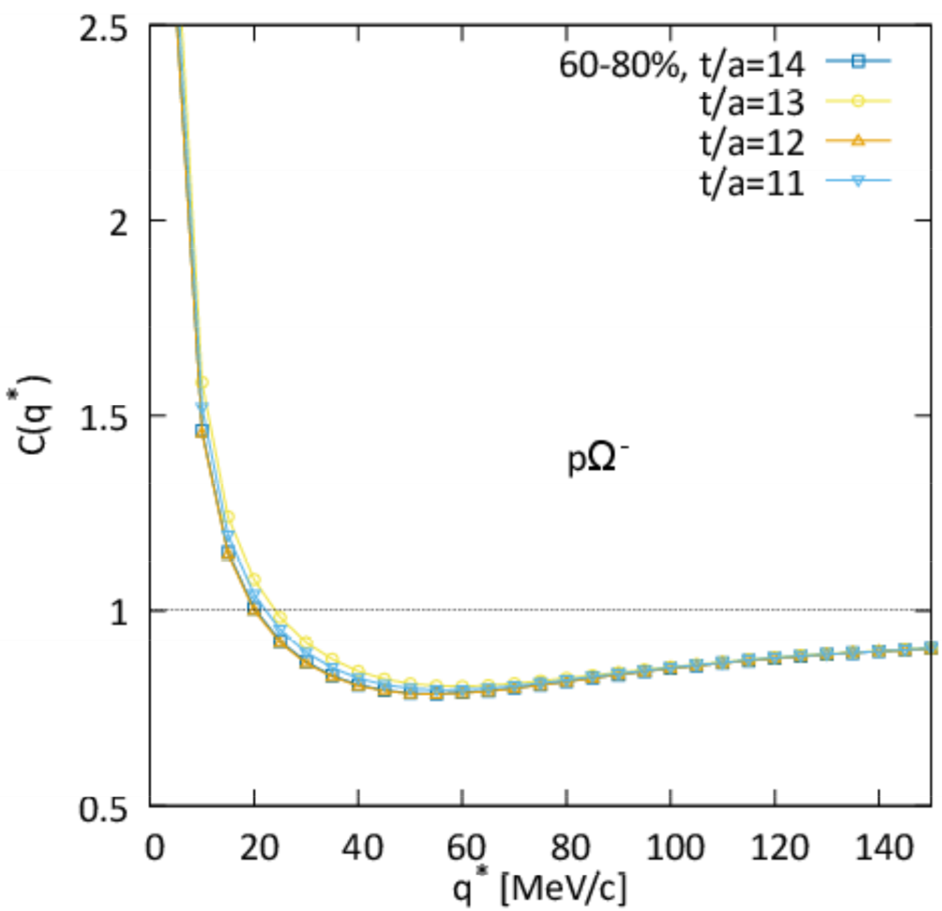
Absorption of S-wave component

$$V_{J=1}(r) = -i\theta(r_0 - r)V_0$$

Large systems in
Bound state regime:
Suppression of $C_{SL}(Q)$
Below unity at low Q

Small systems in
Unitary regime

Lattice input: Iritani+



$p\Omega$ Correlation: S-L ratio

$$|\varphi_{p\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{3}{8}|\varphi(^3S_1)|^2 + \frac{5}{8}|\varphi(^5S_2)|^2$$

Coupled to ΛΞ (2430) and ΣΞ(2507)

Absorption of S-wave component

$$V_{J=1}(r) = -i\theta(r_0 - r)V_0$$