Hadron-Hadron Correlations in Heavy Ion Collisions

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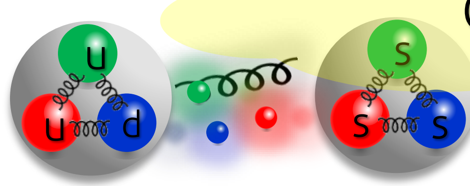
References: PRC94('16) 031901, PPNP95 ('17)279, NPA967('17)856, in prep.

Hadron-Hadron Interaction

QCD at Low Energy

Chiral Symmetry Breaking

Confinement

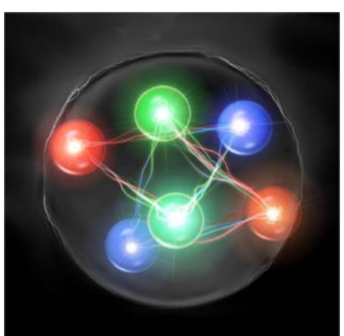


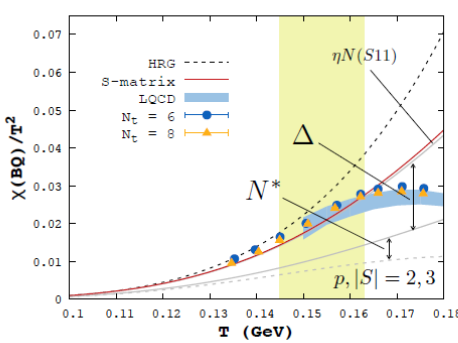
Spectroscopy

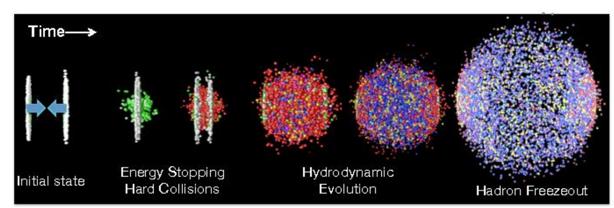
Scattering Experiments

Theory: Lattice QCD
ChEFT
Various Models

Inputs to Many-body hadronic systems

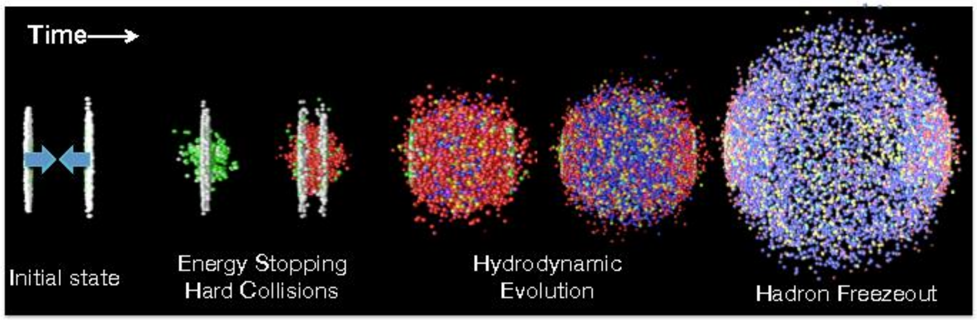






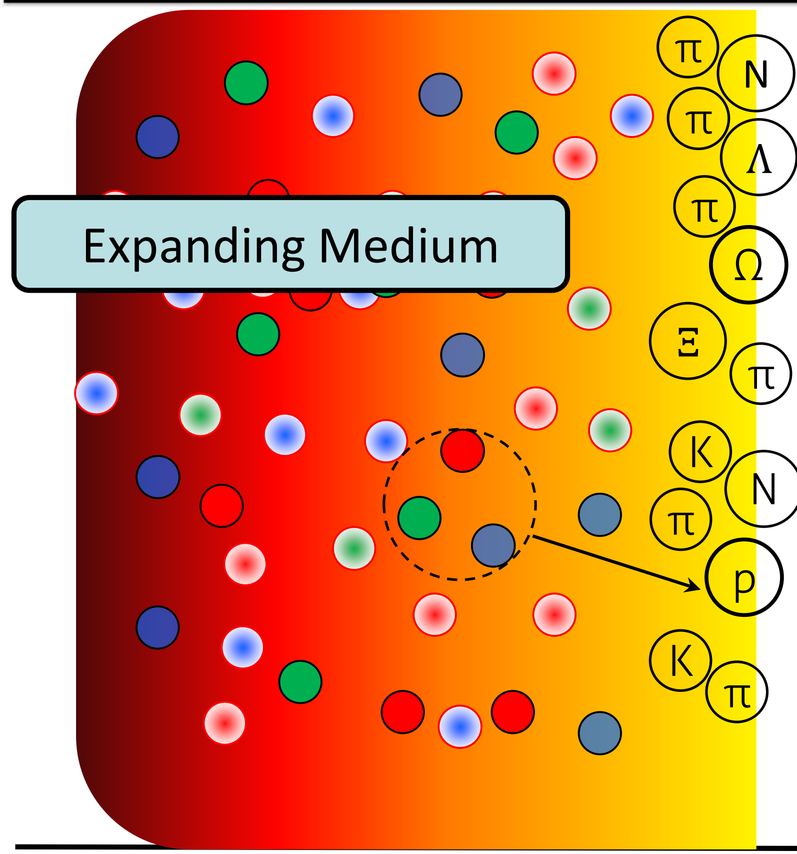
See talk by K. Redlich

Heavy Ion Collisions as Hadron Factory



Production of Quark-Gluon Plasma

Crossover Transition Into Hadron
Particle Abundance – Thermal Eq.

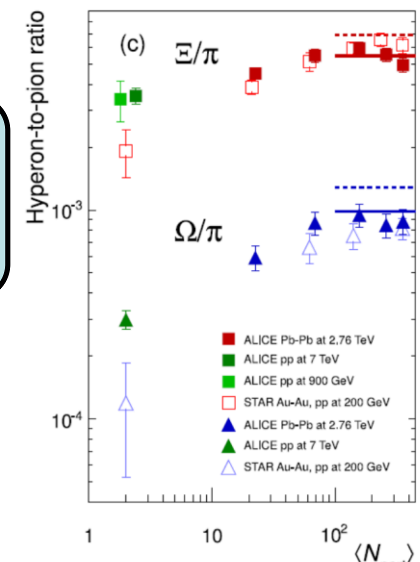


$$\left.\frac{dN_Y}{dy}\right|_{y=0} \simeq \begin{cases} 1-26, & \Lambda\,(S=-1) \\ 0.12-3.3 & \Xi\,(S=-2) \\ 0.015-0.6 & \Omega\,(S=-3) \end{cases}$$

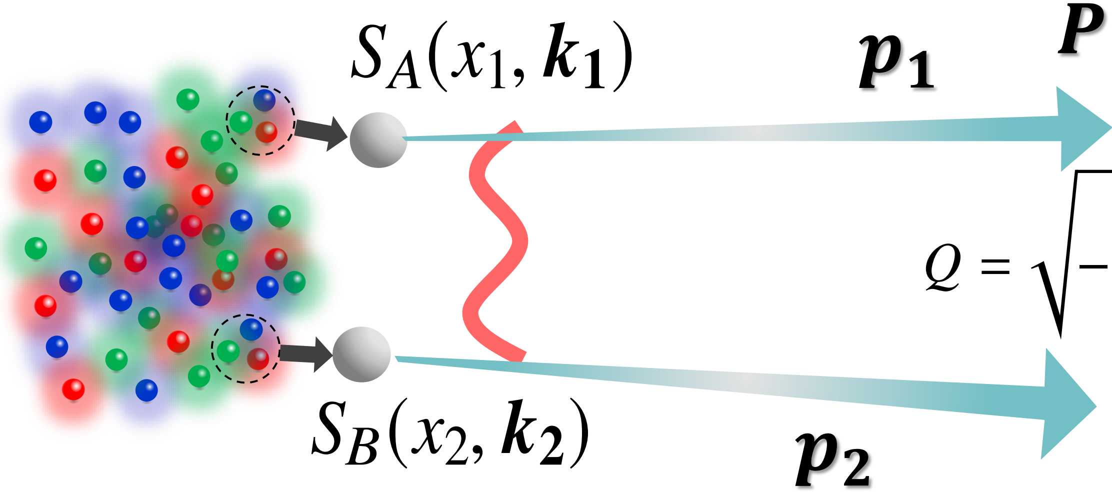
Two-particle FSI

at freeze-out

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



Two-Particle Correlation



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

$$Q = \sqrt{-\left(\frac{p_1 - p_2}{2} - \frac{(p_1 - p_2)\cdot P}{P^2} P\right)^2}$$

Measuring Pair Correlation

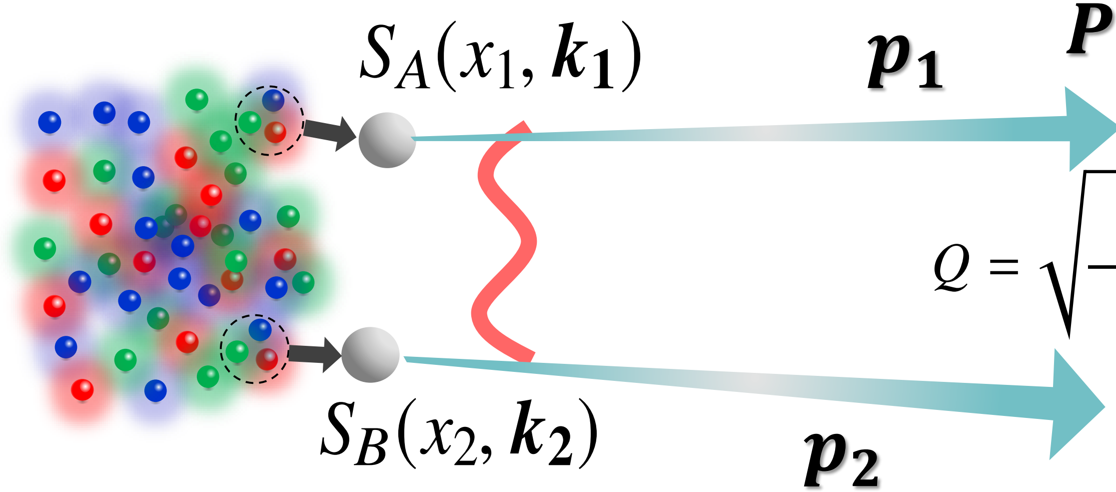
→Constrain Pairwise Interaction

$$C_{AB}(Q) = \frac{N_{AB}^{\mathrm{pair}}(Q)}{N_A N_B(Q)} = \begin{cases} 1 & \text{No Correlation} \\ \text{others} & \text{Interaction, Interference, etc} \end{cases}$$

No Correlation

Interaction
Interference
etc

Two-Particle Momentum Correlation



$$Q = \sqrt{-\left(\frac{p_1 - p_2}{2} - \frac{(p_1 - p_2)\cdot P}{P^2} P\right)^2}$$

Small Q

$$N^{\rm pair}(Q) \simeq \int_{\Delta \boldsymbol{k}} \int_{x_1} \int_{x_2} S_A(x_1, \boldsymbol{k}_1) S_B(x_2, \boldsymbol{k}_2) |\psi_{AB}^{(-)}(\boldsymbol{r}^*, \boldsymbol{Q}^*)|^2$$

(# of pair) = integration of (emission probability x weight factor)

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

Scattering wave function
FSI and (a)symmetrization (for identical pairs)

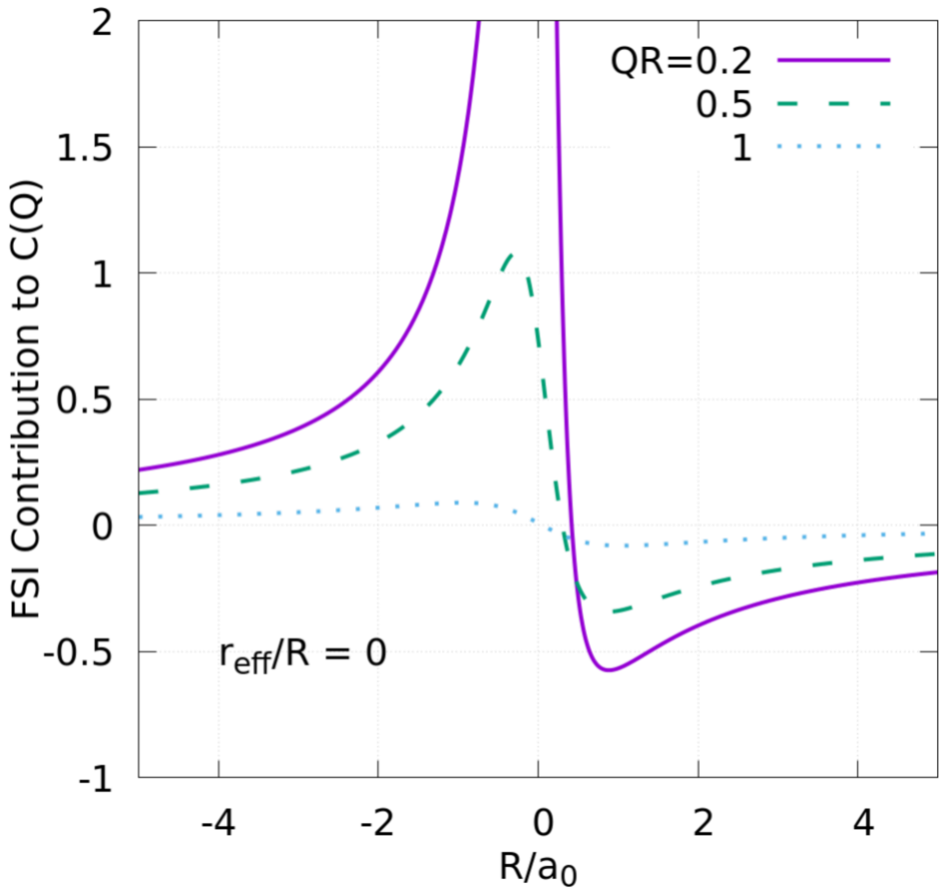
More rigorous formula found in Anchishkin, Heinz, Renk, PRC57 ('98)

Correlation from FSI

Static/Spherical Source

Lednicky+ '82

$$C_{AB}(Q) - 1 = \frac{4\pi}{(2\pi R^2)^3} \int dr r^2 S^{\mathrm{rel}}(r) [|\chi_Q(r)|^2 - |j_0(Qr)|^2]$$



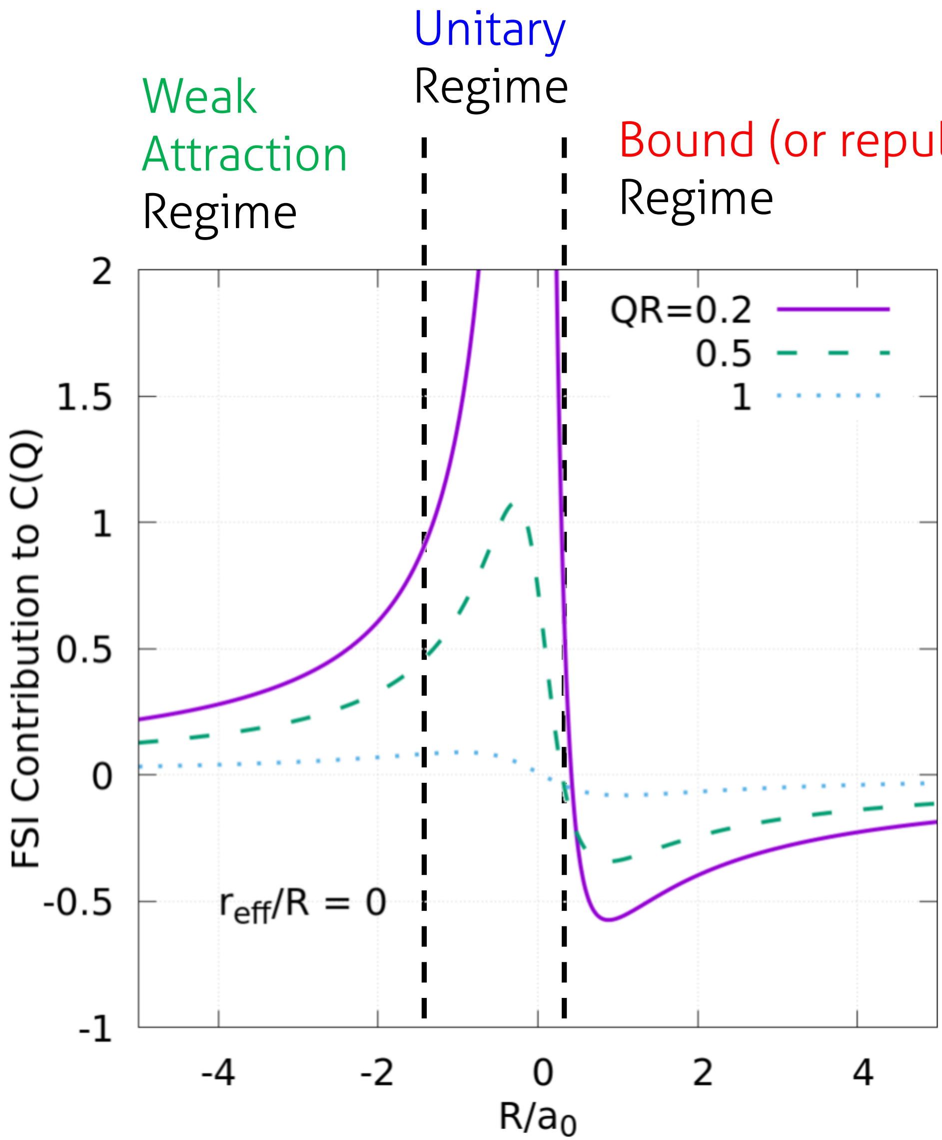
$$S^{\mathrm{rel}}(r) = (\pi R^2)^{3/2} \exp\left(-\frac{r^2}{4R^2}\right)$$

Asymptotic S-wave scattering w.f.

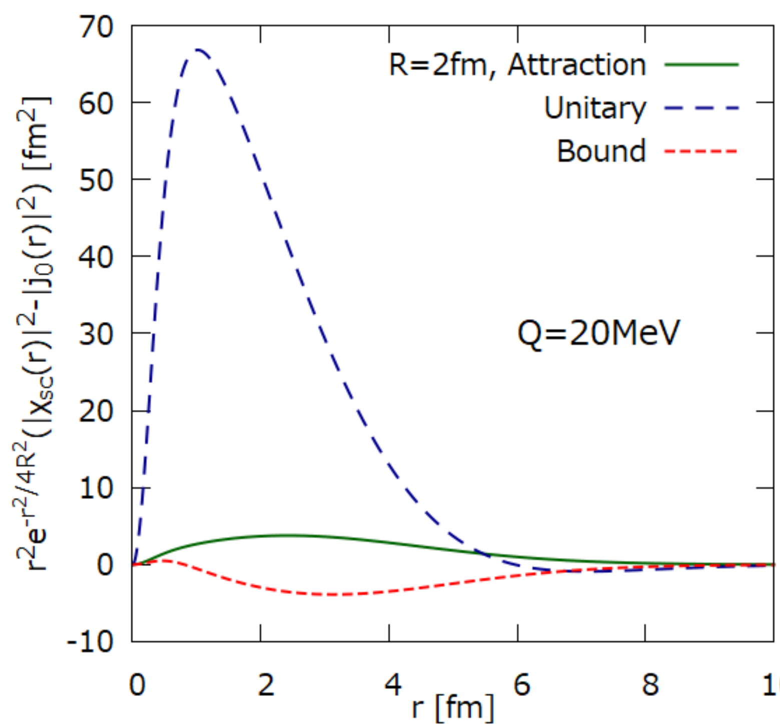
$$\chi_Q(r) = \frac{\sin(Qr + \delta)}{Qr}$$

$$Q \cot \delta = -\frac{1}{a_0} + \frac{1}{2} r_{\mathrm{eff}} Q^2$$

Correlation from FSI



Source func × Wave func diff.

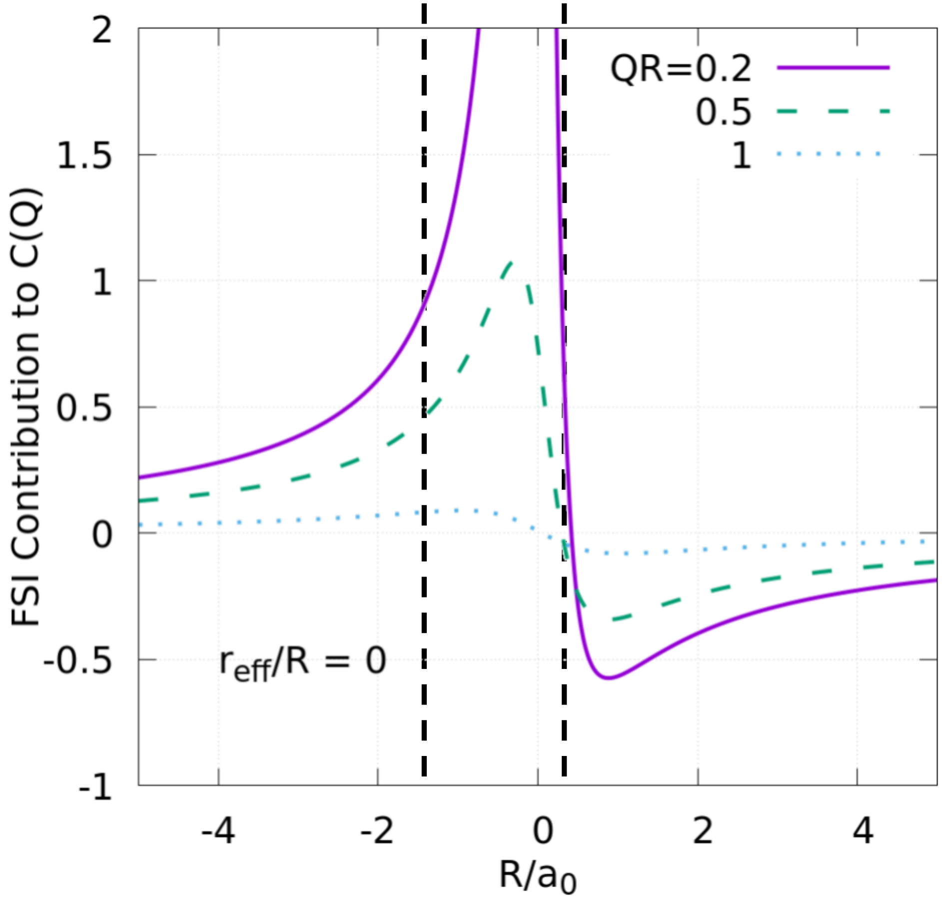


Correlation from FSI

Weak Attraction Regime

Unitary Regime

Bound (or repulsive) Regime



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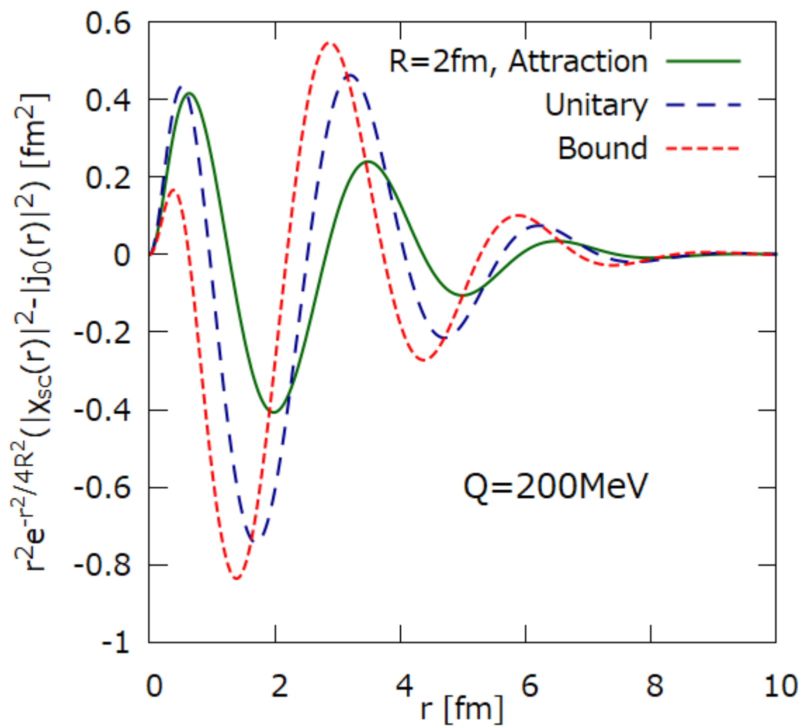
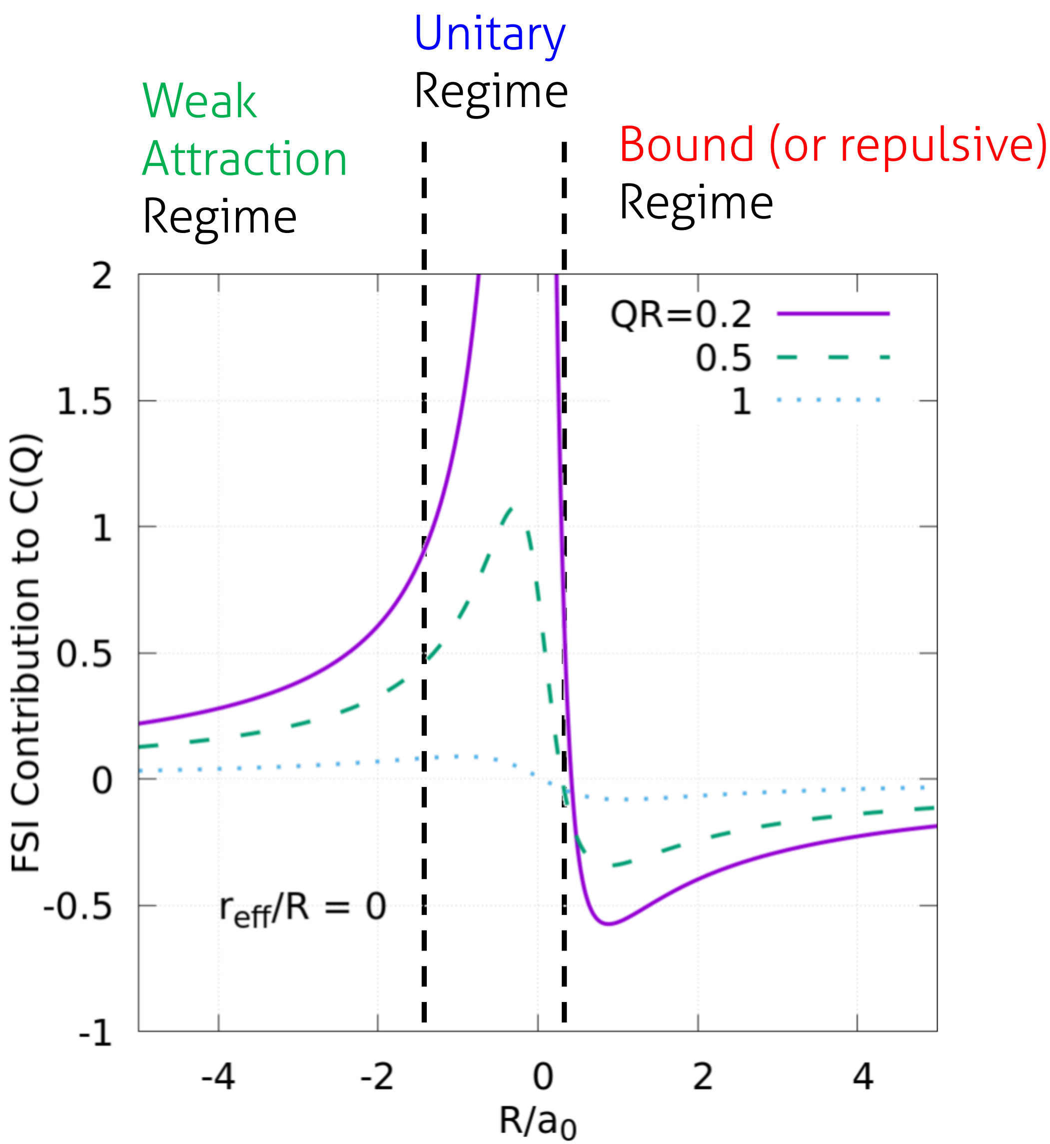
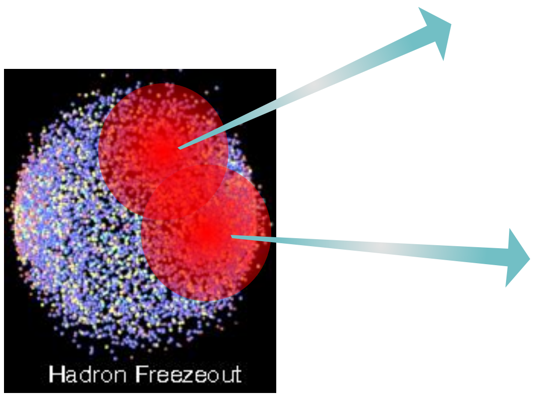
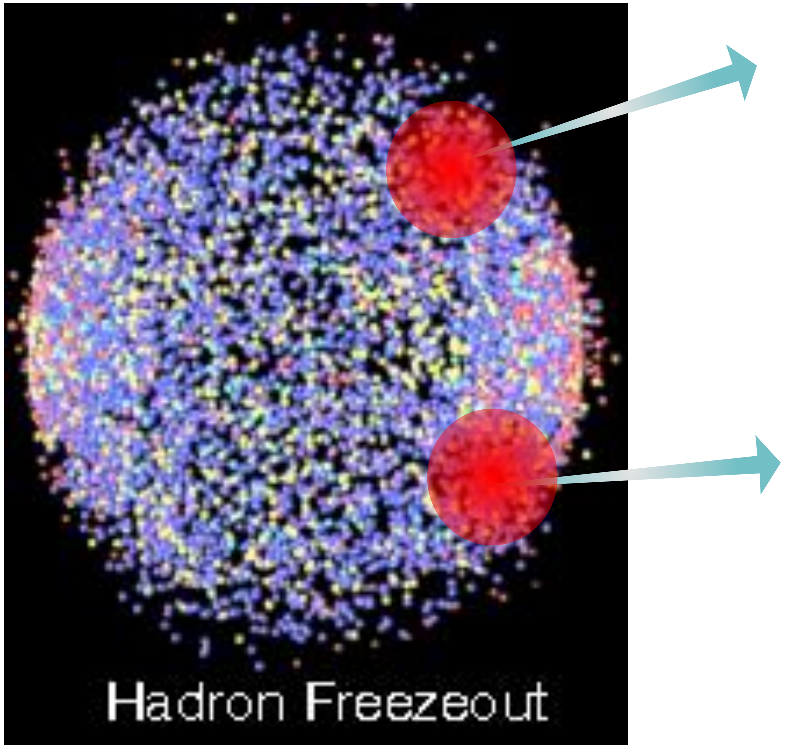


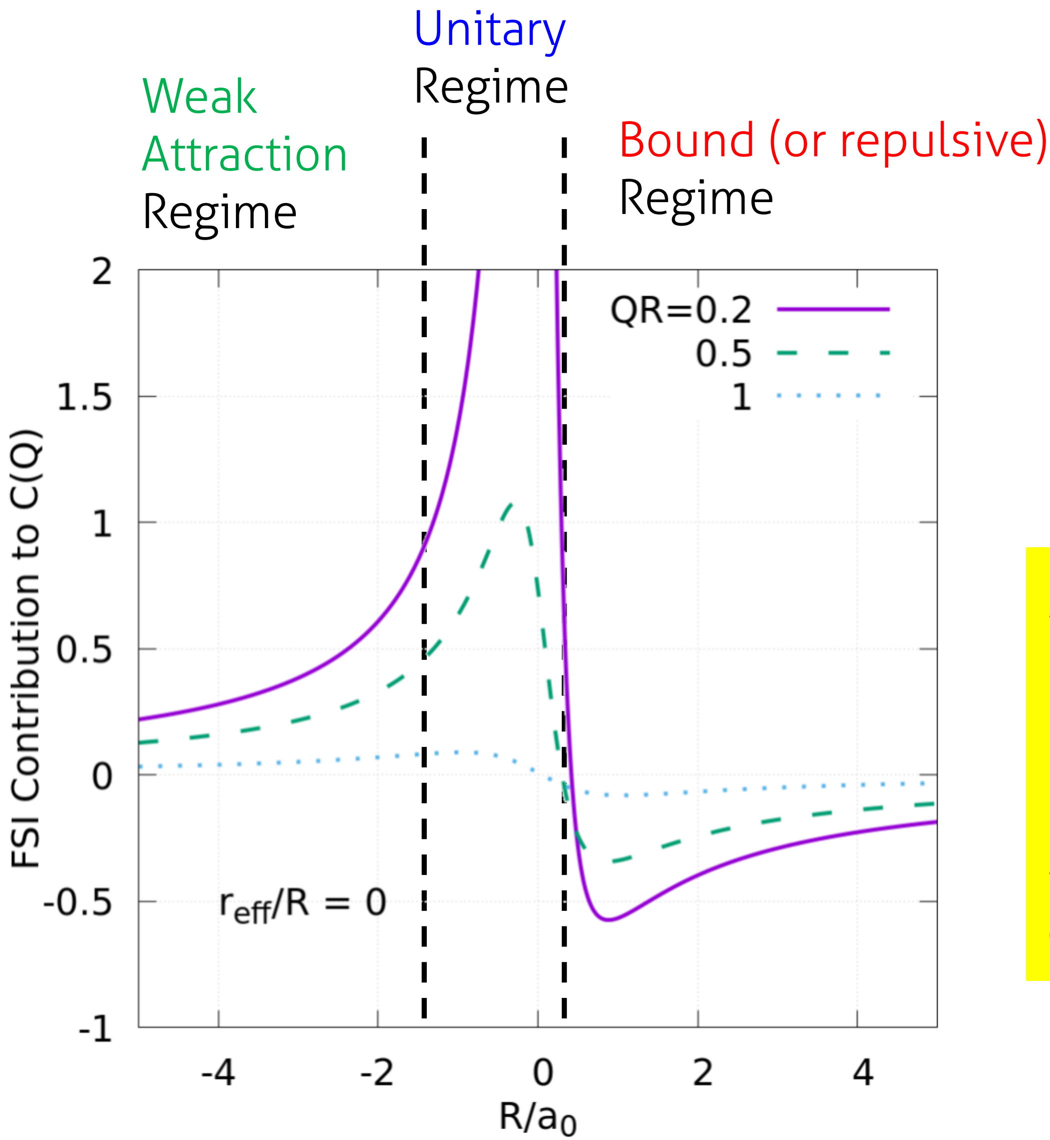
Correlation from FSI

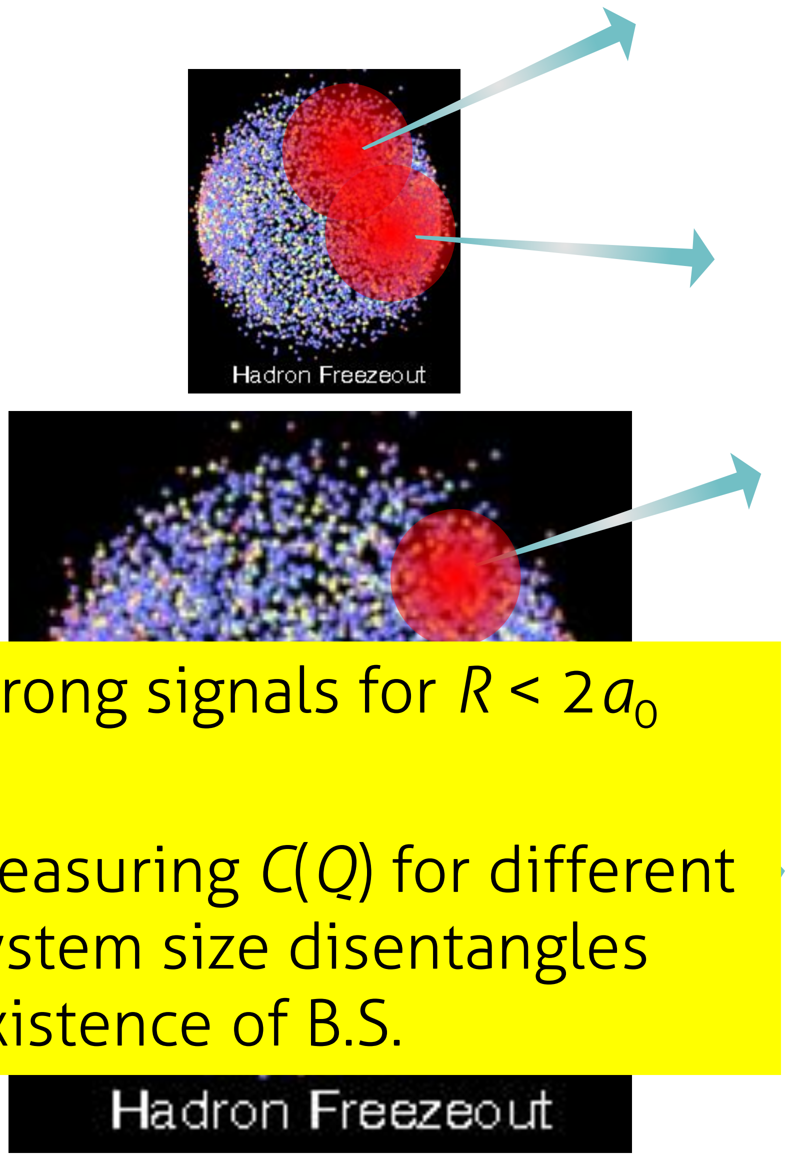






Correlation from FSI



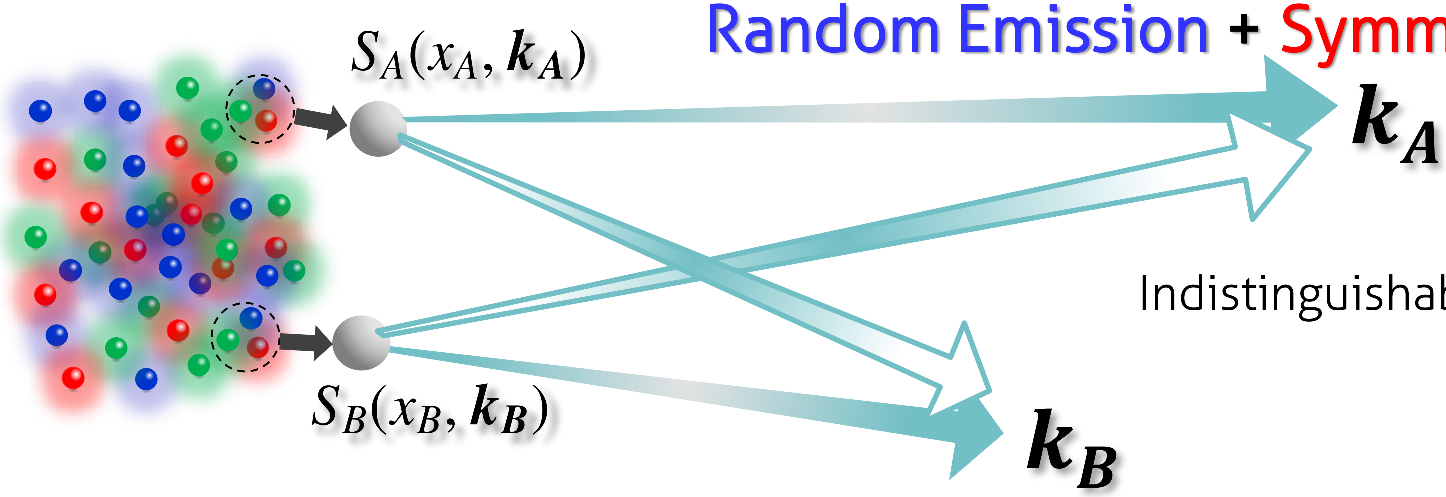


Strong signals for $R < 2a_0$

Measuring $C(Q)$ for different system size disentangles existence of B.S.

Quantum Statistics (HBT/GGLP)

Random Emission + Symmetrization

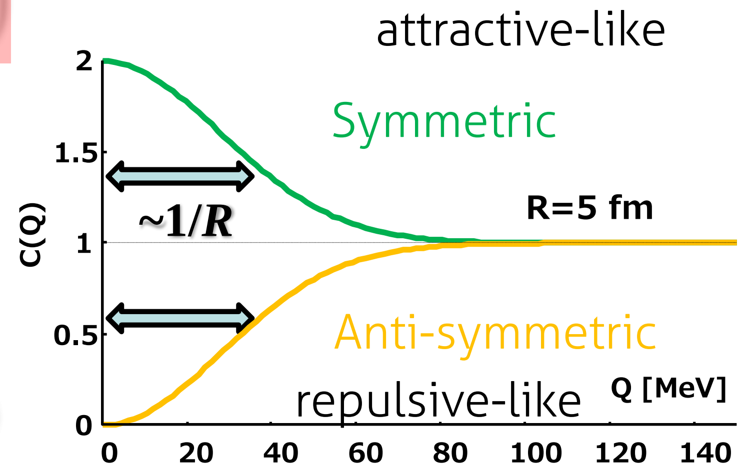


$$\psi_{AB} = \frac{1}{\sqrt{2}}\left(e^{i\boldsymbol{k}_A\cdot\boldsymbol{x}_A}e^{i\boldsymbol{k}_B\cdot\boldsymbol{x}_B} \pm e^{i\boldsymbol{k}_A\cdot\boldsymbol{x}_B}e^{i\boldsymbol{k}_B\cdot\boldsymbol{x}_A}\right)$$

$$= \begin{cases} e^{i\boldsymbol{K}\cdot\boldsymbol{X}}\sqrt{2}\cos(\boldsymbol{Q}\cdot\boldsymbol{r}) \\ e^{i\boldsymbol{K}\cdot\boldsymbol{X}}\sqrt{2}i\sin(\boldsymbol{Q}\cdot\boldsymbol{r}) \end{cases}$$

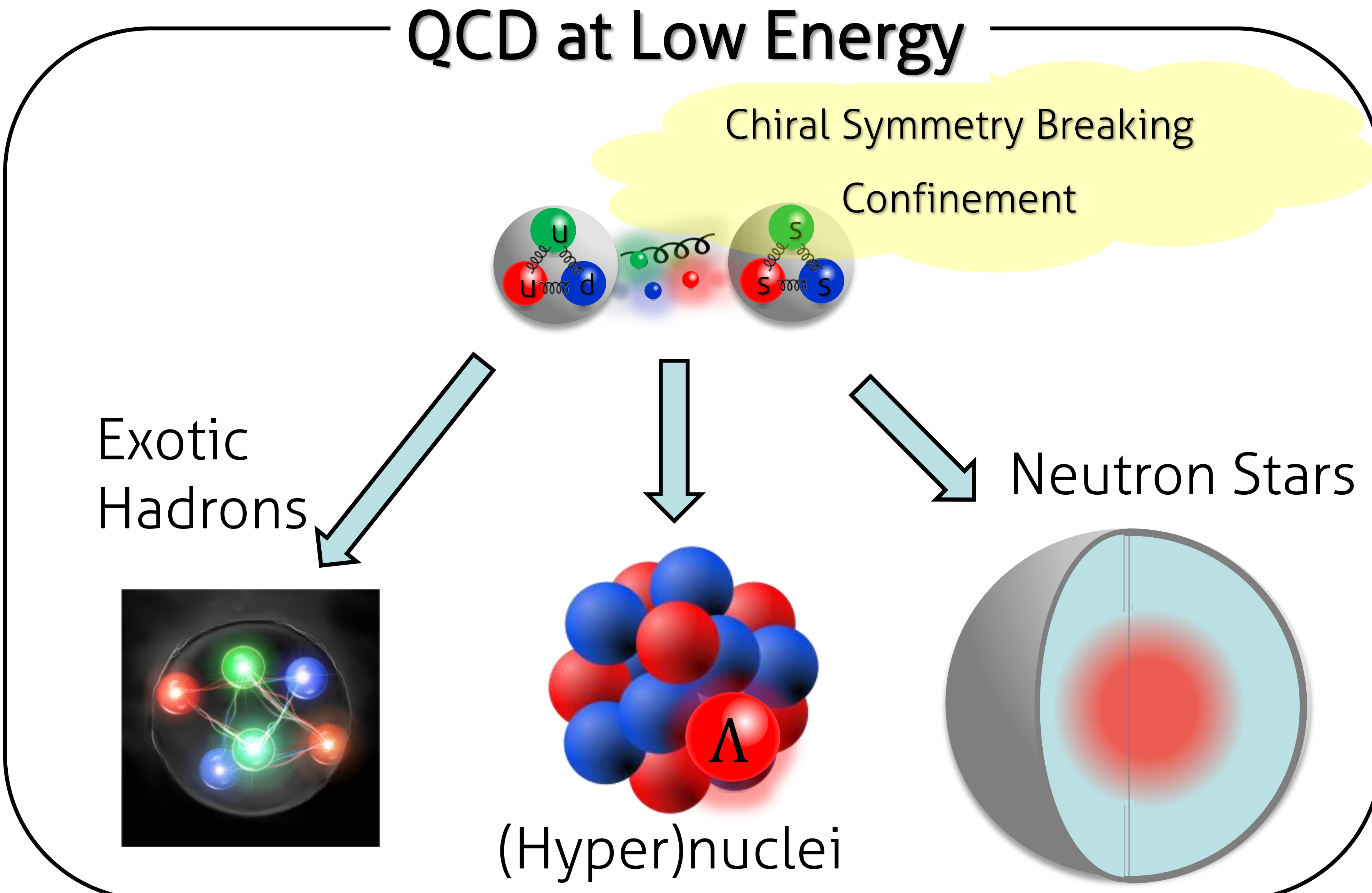
$$C_{id}(\boldsymbol{Q}) = 1 \pm \frac{1}{\mathcal{N}}\int d^3\boldsymbol{r}\cos(2\boldsymbol{Q}\cdot\boldsymbol{r})S^{\mathrm{rel}}_{\boldsymbol{K}}(\boldsymbol{r})$$

Fourier tr. of the emission func.



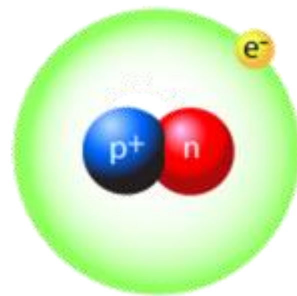
Baryon-Baryon Correlation for Dibaryon Candidates : LHC energies

Baryon-Baryon Interaction

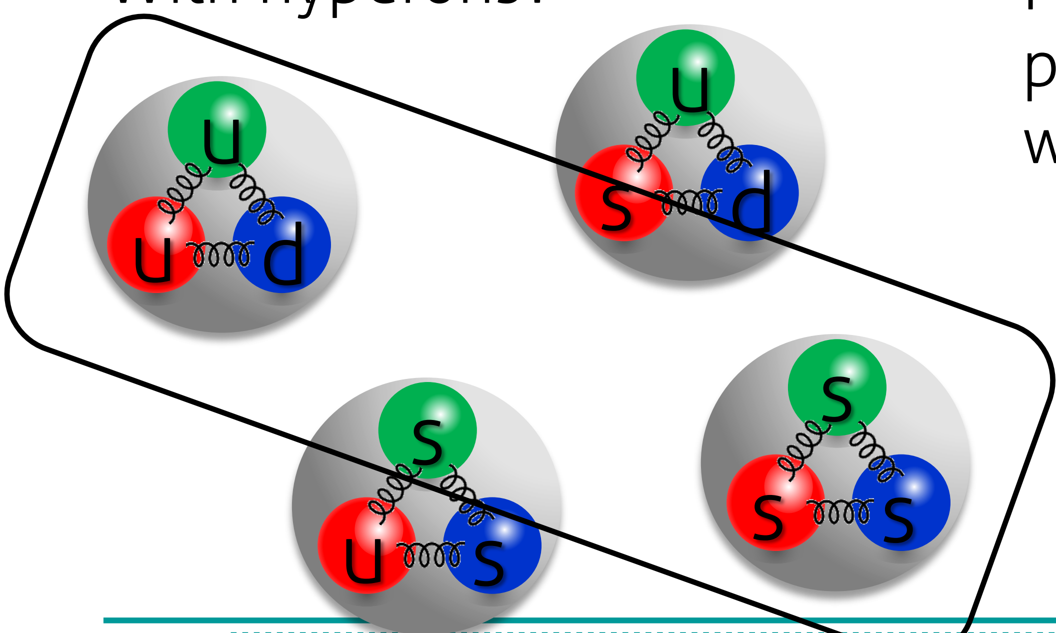


Dibaryons

Deutron (Urey et al., 1931)



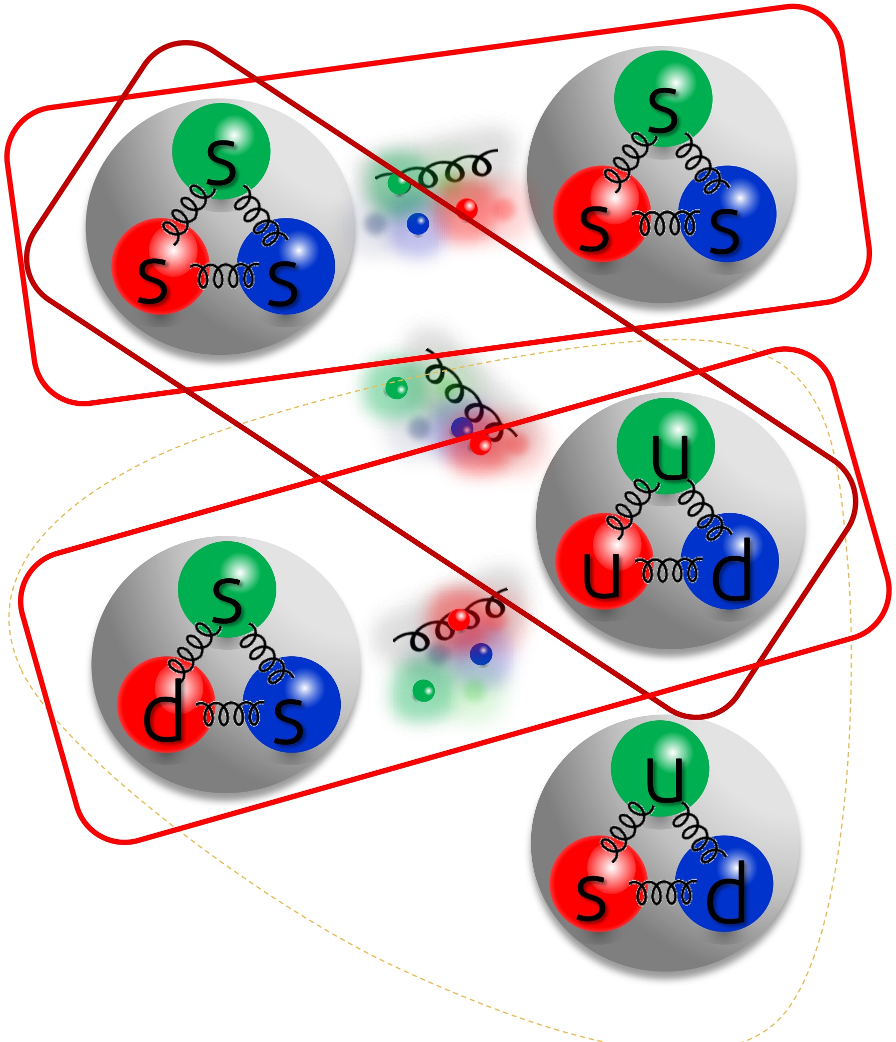
With hyperons? ---------- Flavor SU(3) classification predicts some channels with no Pauli blocking



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

Lattice QCD Studies by HAL QCD Coll.

See talk by T. Hatsuda



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 HIC

Experimental Status

- $p\Lambda$
  - Au+Au 200GeV (STAR), p+Nb 3.2GeV (HADES), p+p 7TeV, 13TeV (ALICE)
- $\Lambda\Lambda$
  - Au+Au 200GeV (STAR), p+p 7TeV, 13TeV (ALICE)
- $p\Xi$
  - p+Pb 5TeV (ALICE)
- $p\Omega$
  - Au+Au 200GeV (STAR) : See next talk by J. Chen

Heavy-Ion Side: Source Functions

- Constraints: reproducing p_T spectra
  - **Fix volume (~$R^{1/3}$) and transverse flow**

relative distance distribution | Momentum dependence

- Detailed shape is not important for the moment
- protons have an additional constraint: HBT radii
- Boost-invariant, Cylindrical sym. Source model

Csörgő+ '95

$$S(x,k) = \frac{d}{(2\pi)^3} m_T \cosh(y-\eta_s) n_f(u\cdot k, T) \exp\left(-\frac{x^2+y^2}{2R^2}\right) \delta(\tau-\tau_0)$$

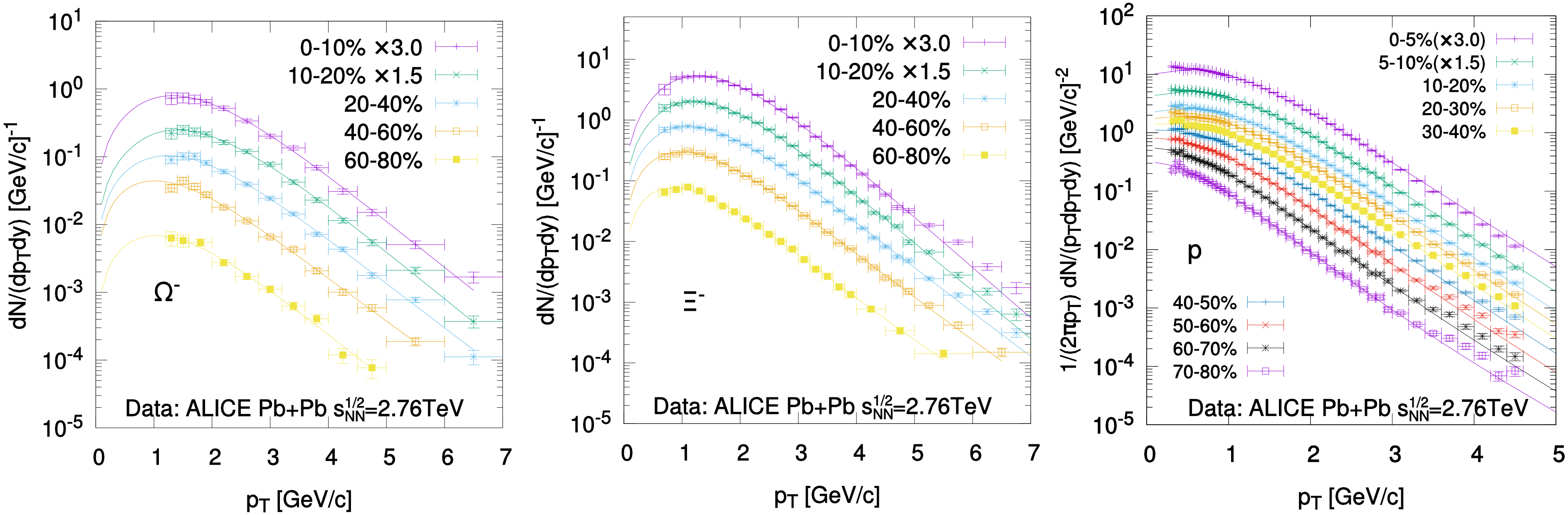
$m \gg T$

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

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

Fitting parameters

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%)

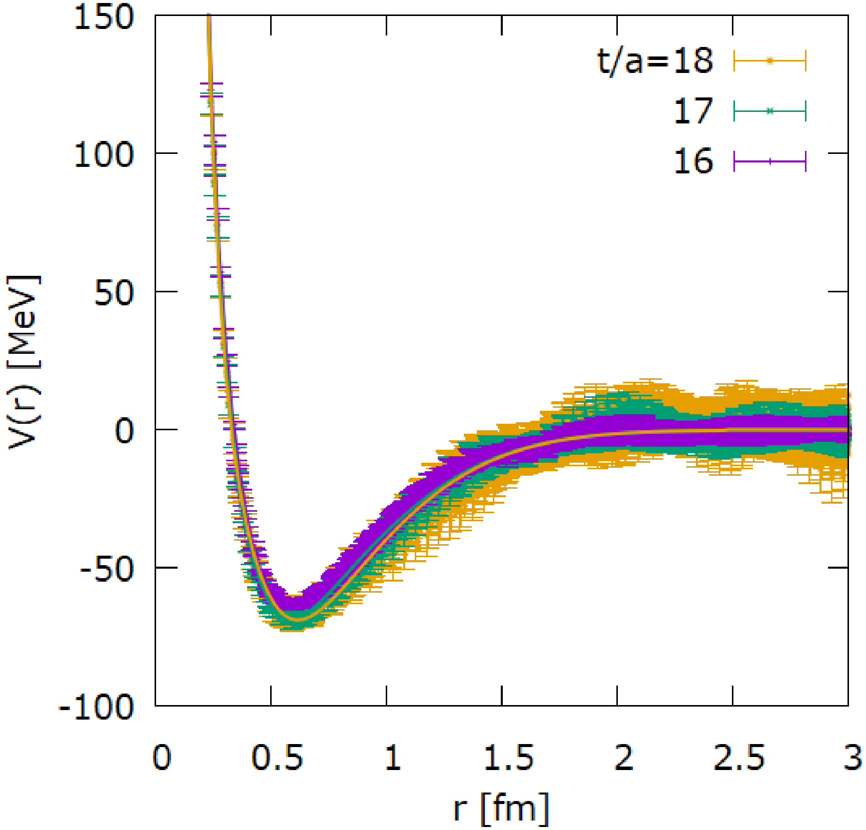
Include m* < 2GeV
V = 110 – 3500 fm^3
(60-80%) (0-10%)

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

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

The Most Strange System: ΩΩ (S=-6)

- $^1S_0$ 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

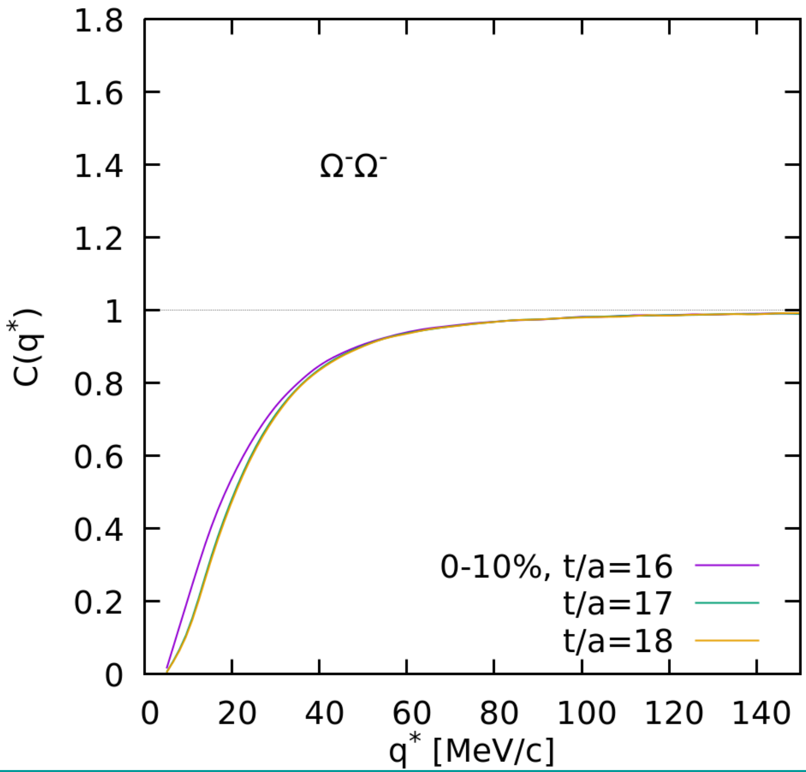
ΩΩ Correlation

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

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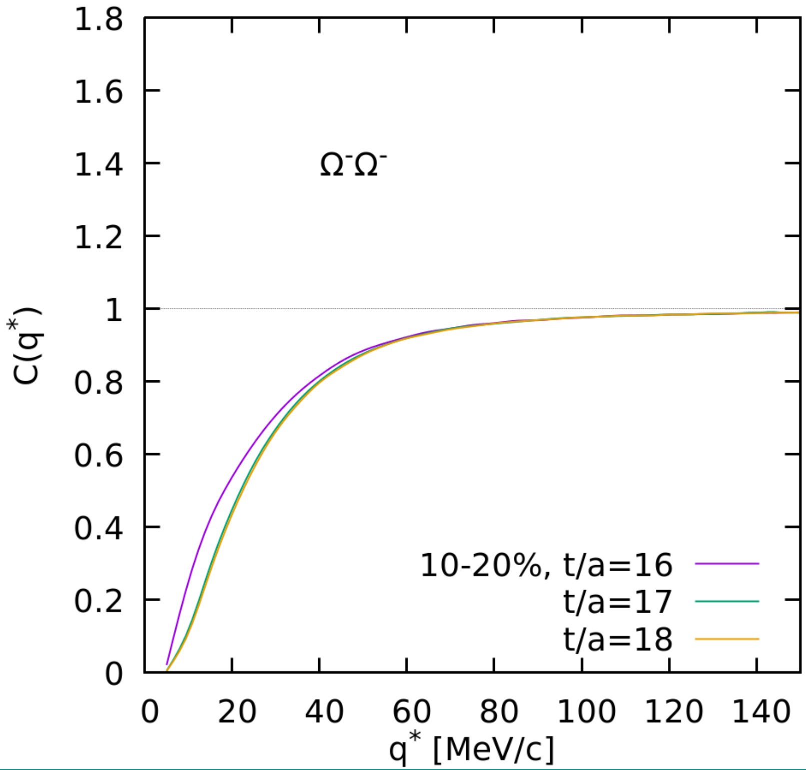

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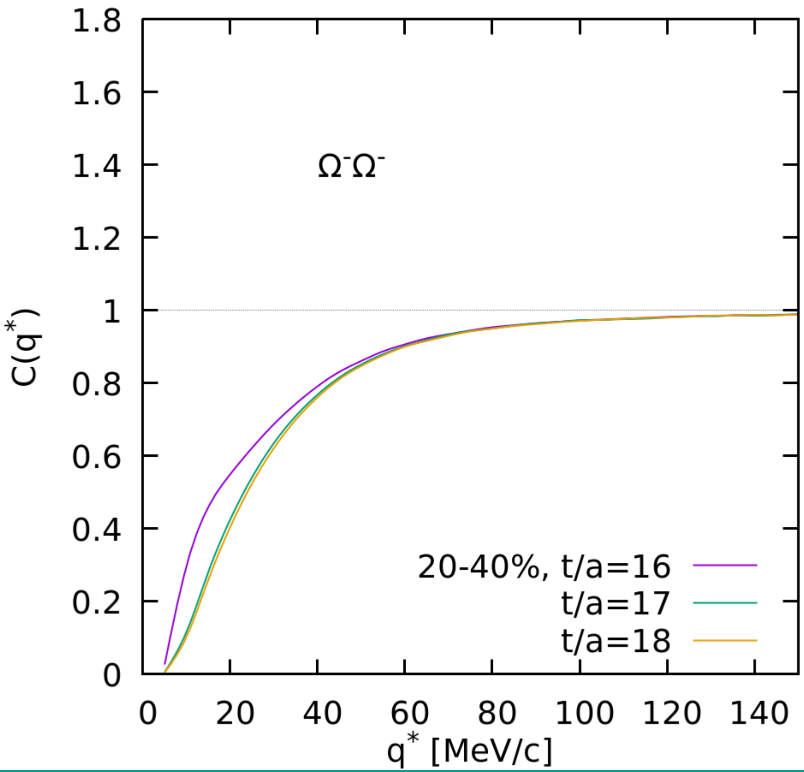
Correlation function



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ΩΩ Correlation

- Wave function

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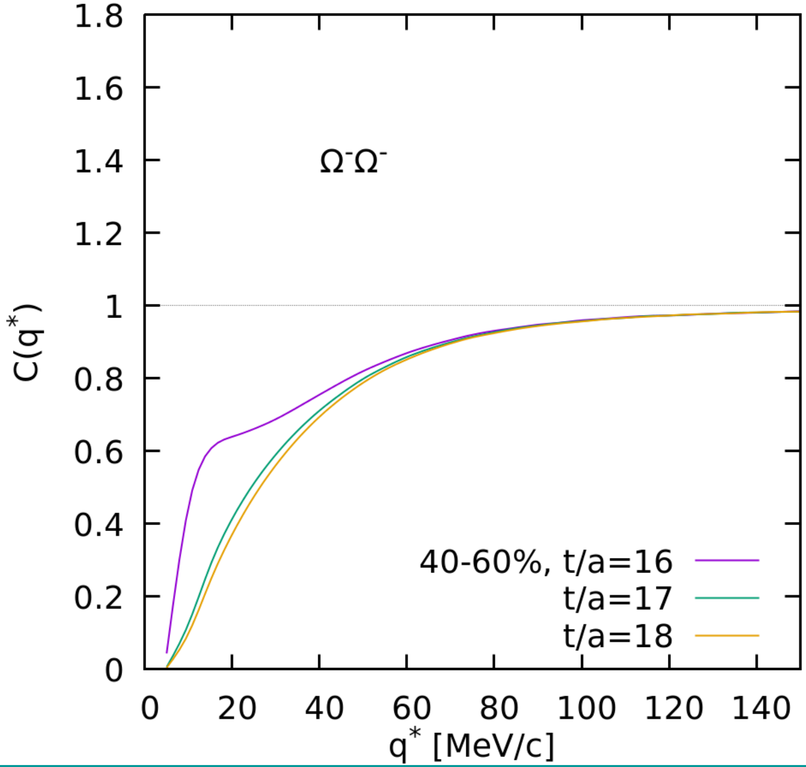
- Correlation function



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

Further suppressed by the spin degeneracy factor 1/16

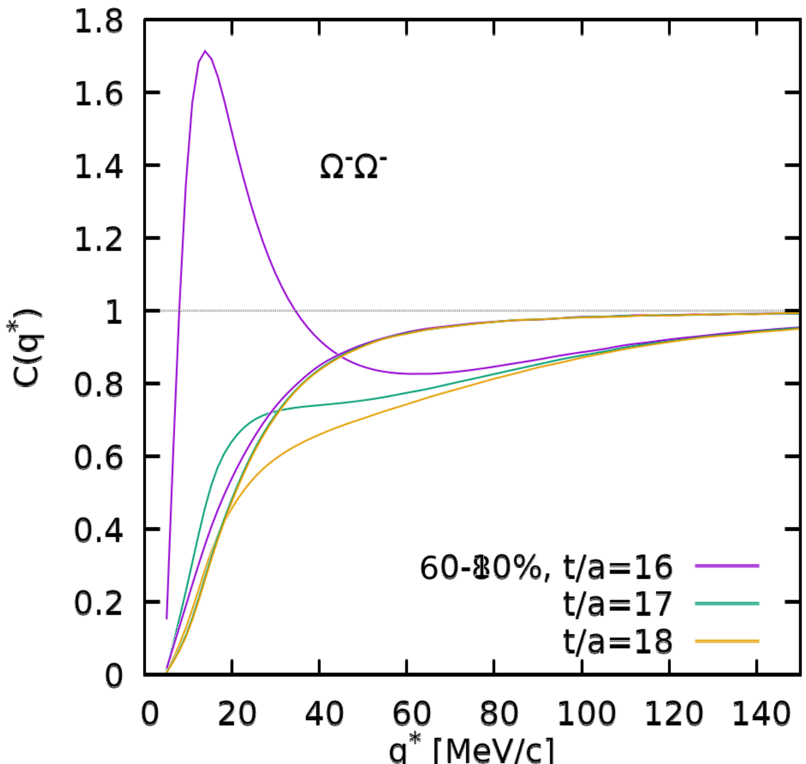
ΩΩ Correlation

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

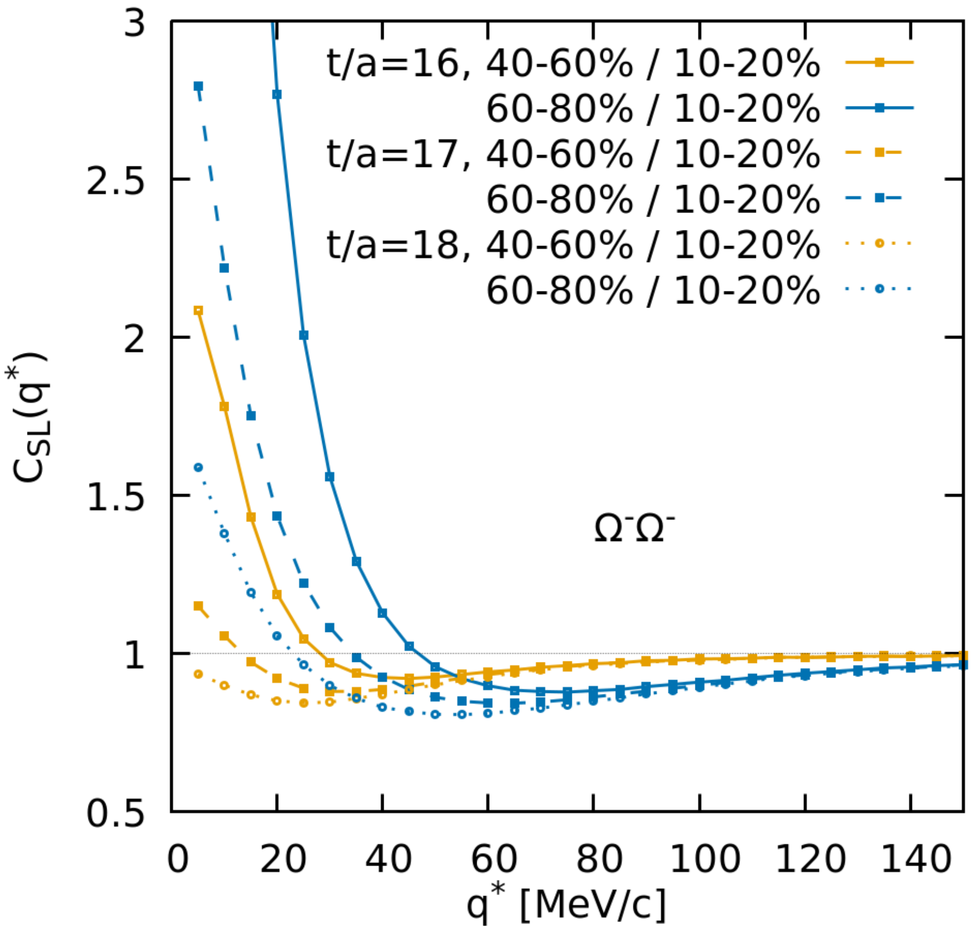


Strong FSI effect for small systems

Further suppressed by the spin degeneracy factor 1/16

ΩΩ Correlation@LHC

The Small-Large Ratio $C_{SL}(Q)$



Response to system size change

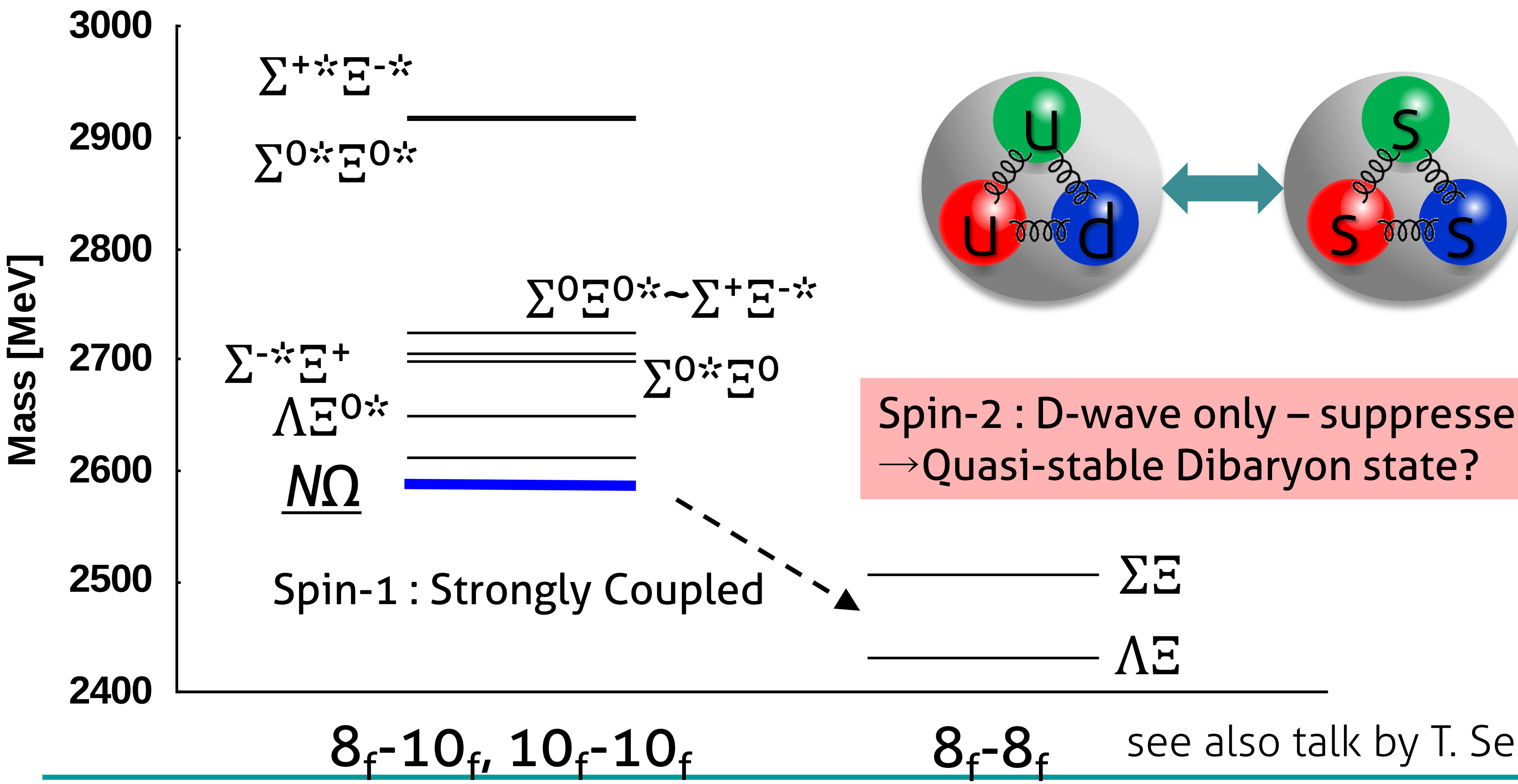
QS (HBT) Correlation suppresses the ratio

FSI dominates $q^* < 40$MeV

Caveat: Statistics (need $N_\Omega \geq 2$ events!)

S=-3:

$p\Omega$ @almost phys.point

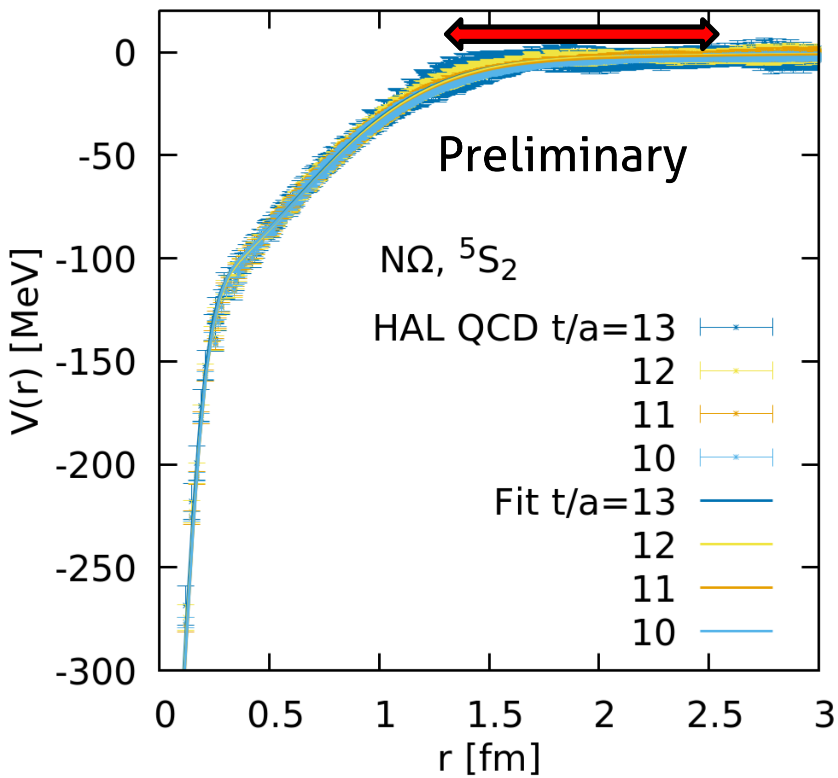


Spin-2 : D-wave only – suppressed
→Quasi-stable Dibaryon state?

see also talk by T. Sekihara

$p\Omega$ 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]
13	4.89	1.24	0.9
12	4.65	1.23	1.0
11	4.30	1.24	1.2
10	4.06	1.26	1.4

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

Caveat : a_0 sensitive to fitting range!
~1fm can be smaller

$p\Omega$ Correlation

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

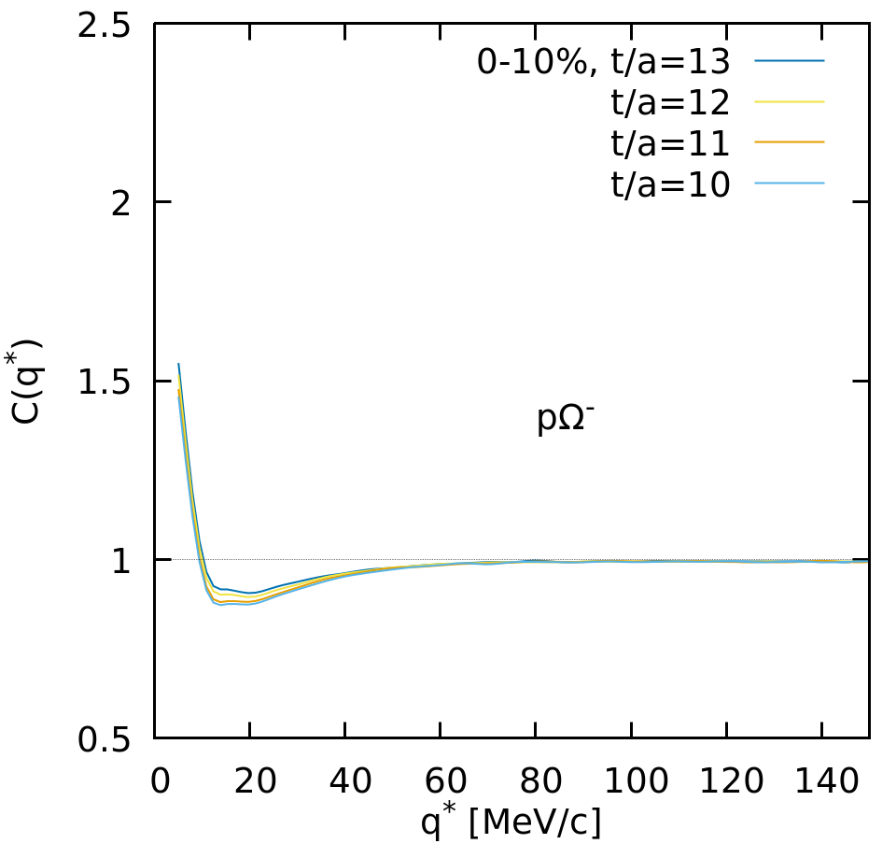
⇓

Coupled to ΛΞ (2430) and ΣΞ(2507)

Absorption of S-wave component

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

Lattice input: Iritani+ (Preliminary)



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

$p\Omega$ Correlation

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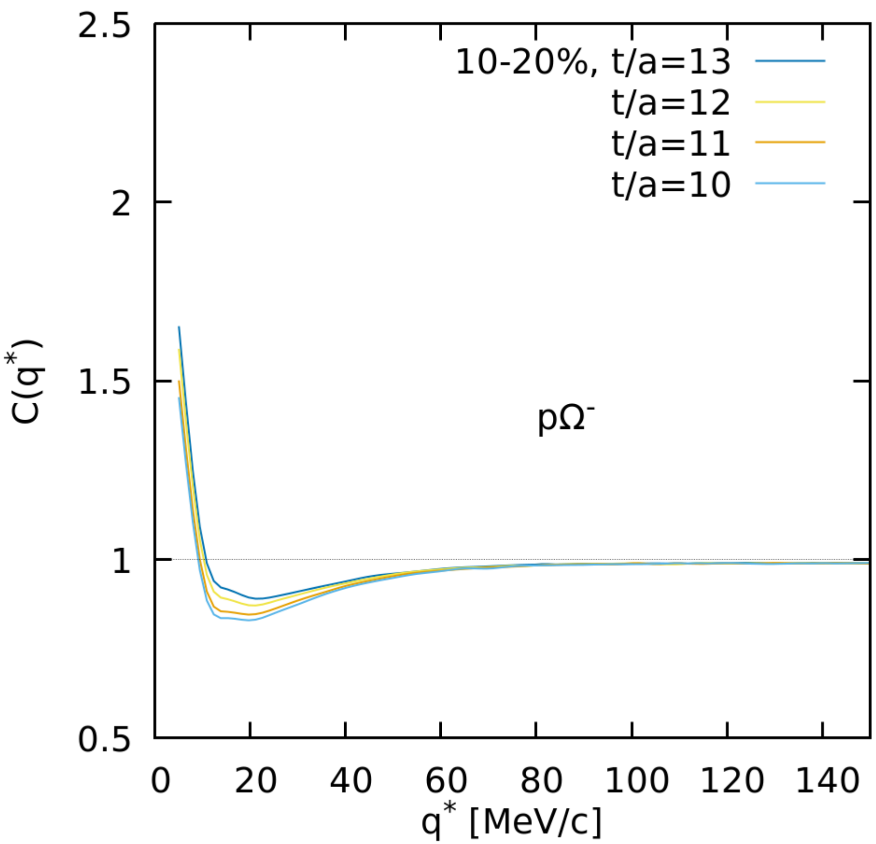

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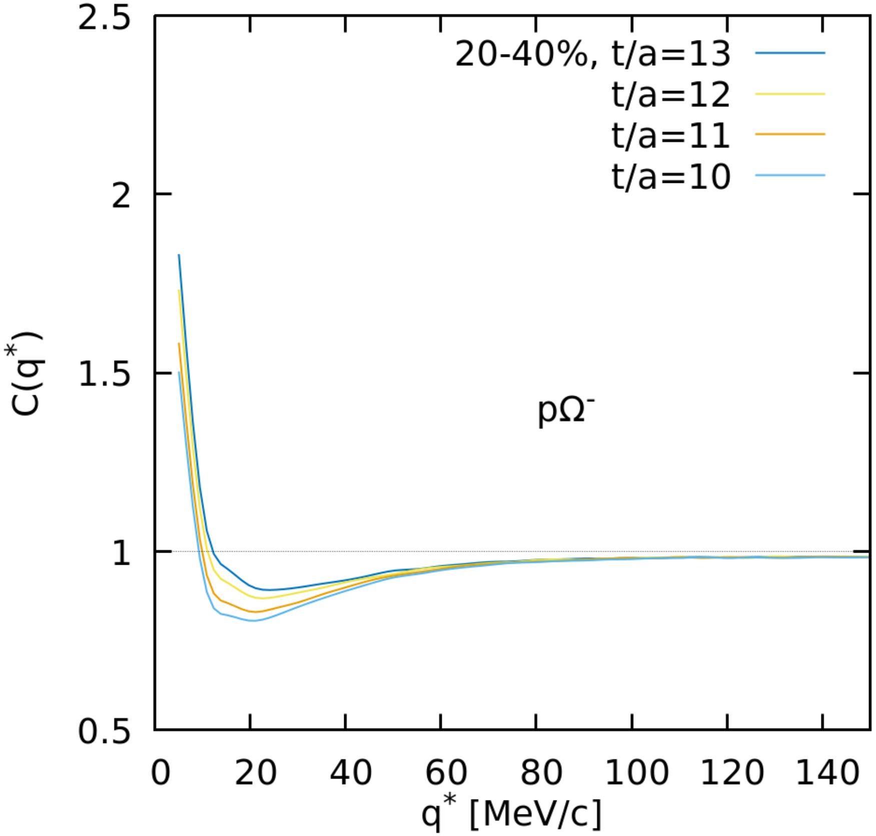

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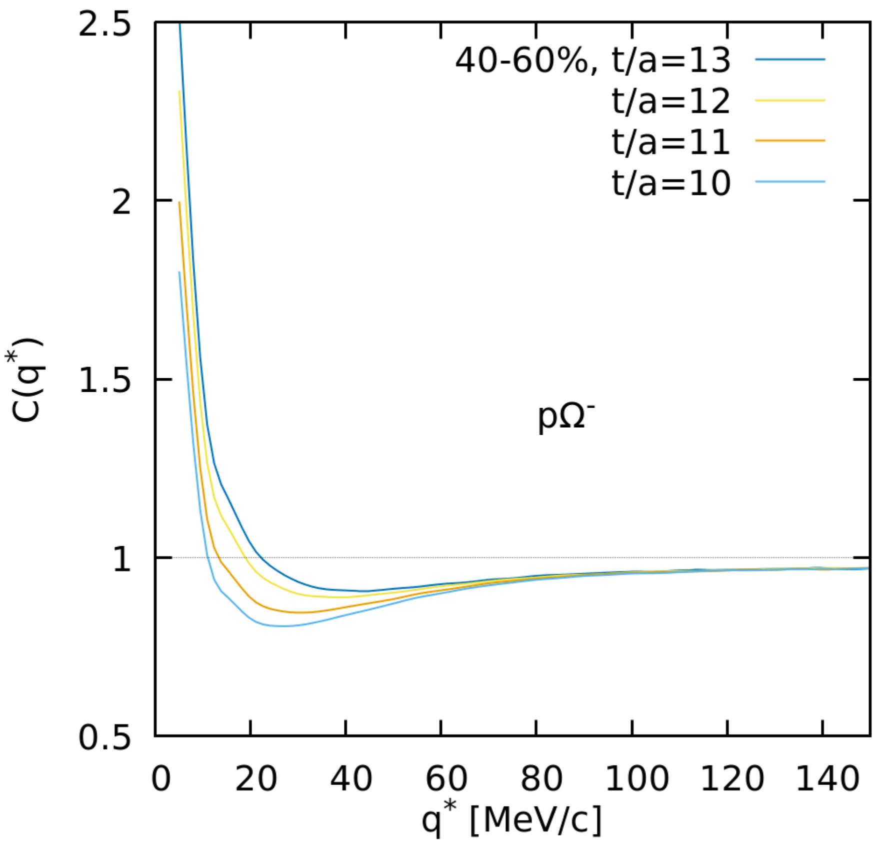

Large systems in
Bound state regime:
Suppression of $C_{SL}(Q)$
Below unity at low Q

Small systems in
Unitary regime

$p\Omega$ Correlation

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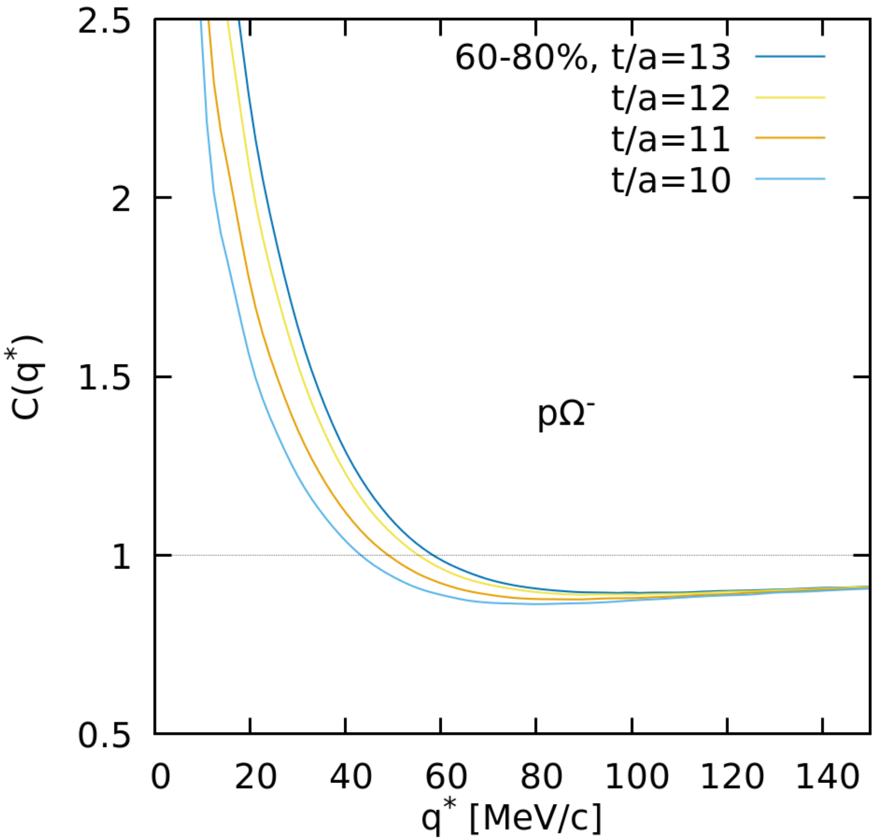
Coupled to ΛΞ (2430) and ΣΞ(2507)

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

Small systems in
Unitary regime



$p\Omega$ Correlation: S-L ratio

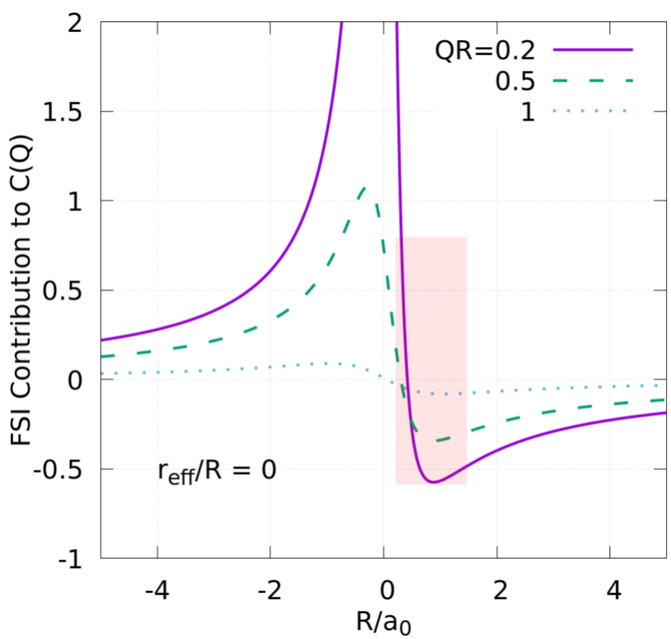
$$|\varphi_{p\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{3}{8}|\varphi(^3S_1)|^2 + \frac{5}{8}|\varphi(^5S_2)|^2$$

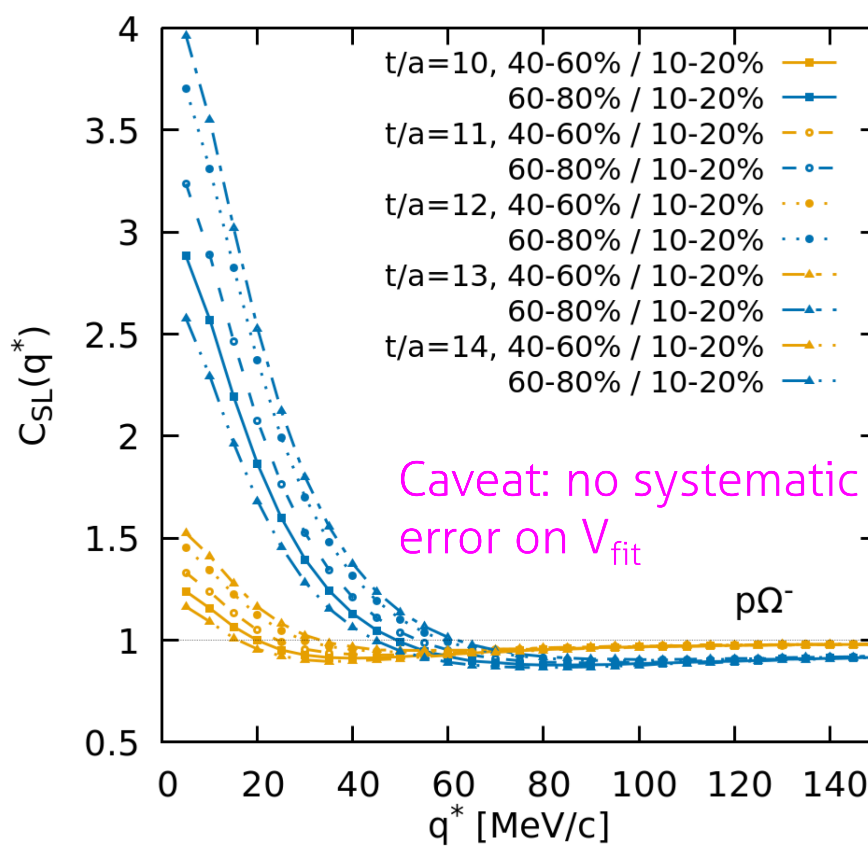
Lattice input: Iritani+ (Preliminary)

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

Absorption of S-wave component

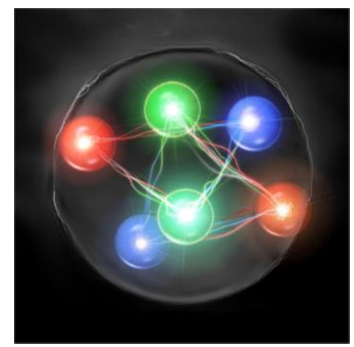
$$V_{J=1}(r) = -i\theta(r_0 - r)V_0$$





S=-2:

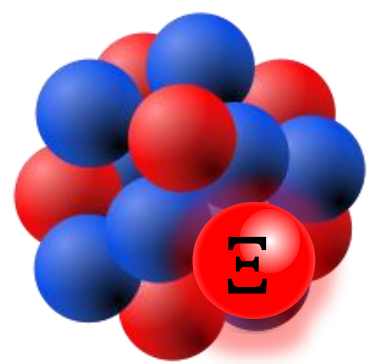
$p\Xi$ @(almost)Phys. Point



I=0 : "H" channel

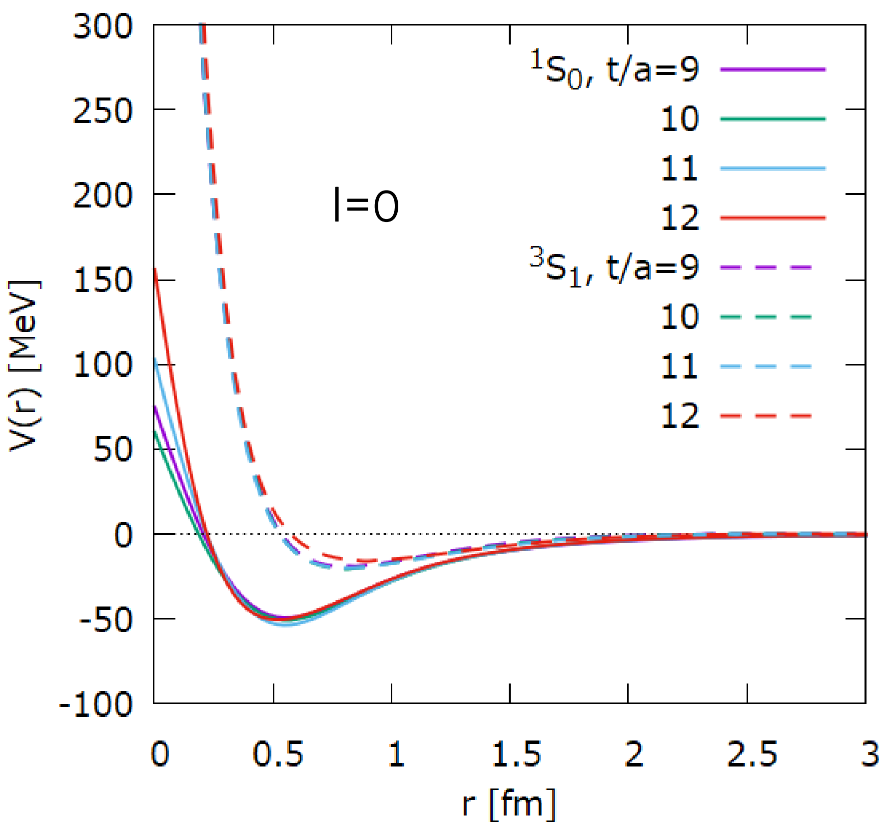
Ξ hypernuclei

Nakazawa+, PTEP2015



$p\Xi$ Interaction (I=0, $^1S_0$, $^3S_1$)

$N\Xi$ potential (fitted to Lattice data)



K. Sasaki+ (HAL QCD)

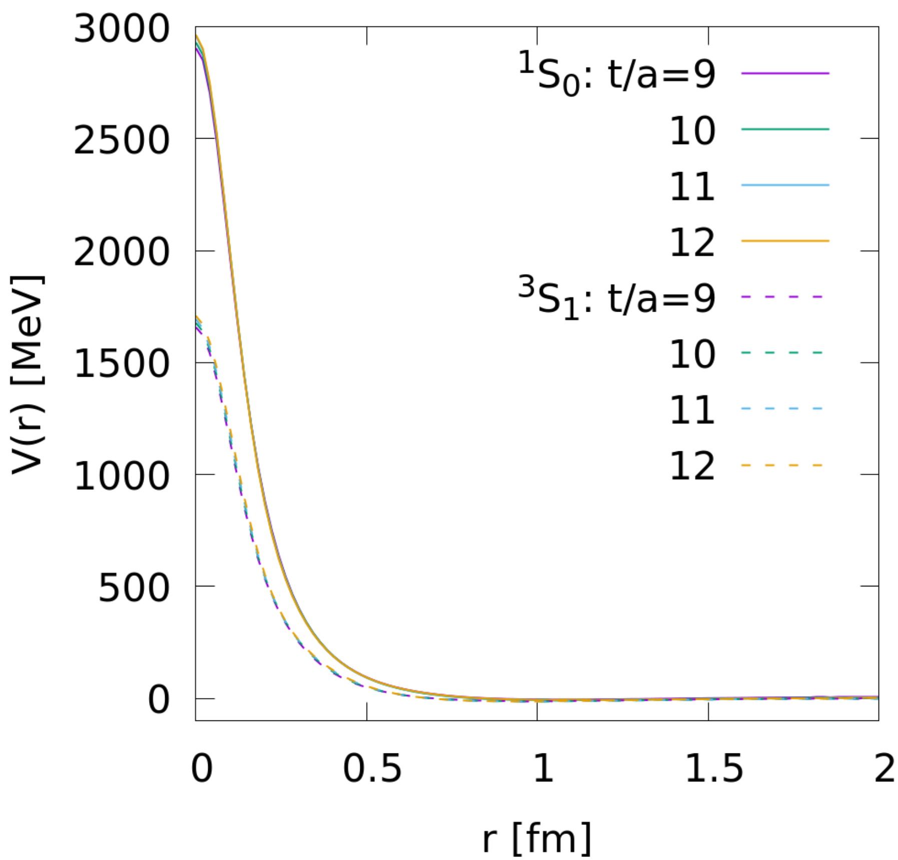
+Coulomb attraction

	Effective $^1S_0$		$^3S_1$	
t/a	a_0 [fm]	r_{eff} [fm]	a_0 [fm]	r_{eff} [fm]
9	-22.66	2.46	-0.60	4.53
10	-19.86	2.30	-0.73	4.17
11	-23.95	2.30	-0.80	4.17
12	-12.39	2.40	-0.61	5.30

$^1S_0$ channel (coupling to ΣΣ incorpolated) dominates
Close to unitary for HIC source

$p\Xi$ Interaction (I=1, $^1S_0$, $^3S_1$)

$N\Xi$ potential (fitted to Lattice data): repulsive



+Coulomb attraction

	$^1S_0$		$^3S_1$	
t/a	a_0 [fm]	r_{eff} [fm]	a_0 [fm]	r_{eff} [fm]
9	3.17	-4.34	0.32	-54.8
10	1.67	-6.42	0.04	-1200
11	0.93	-10.28	-0.145	4.53
12	1.09	-9.26	0.0532	-300.9

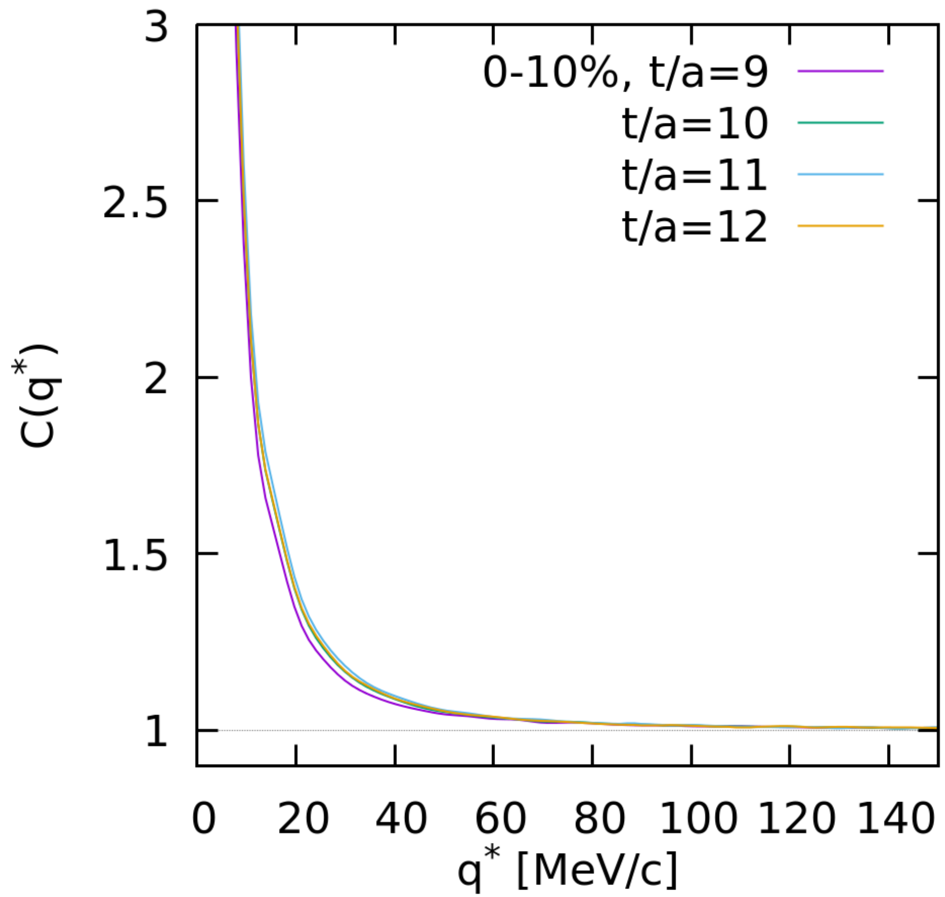
$^1S_0$ channel (coupling to $\Sigma\Sigma$ incorpolated) dominates
Close to unitary for HIC source

K. Sasaki+ (HAL QCD)

$p\Xi^-$ Correlation

$$|\varphi_{p\Xi^-}^{\text{spin-averaged}}|^2 = \sum_{I=0}^{1} \frac{1}{8}|\varphi^I(^1S_0)|^2 + \frac{3}{8}|\varphi^I(^3S_1)|^2$$

Unitary regime:
Notable enhancement by FSI



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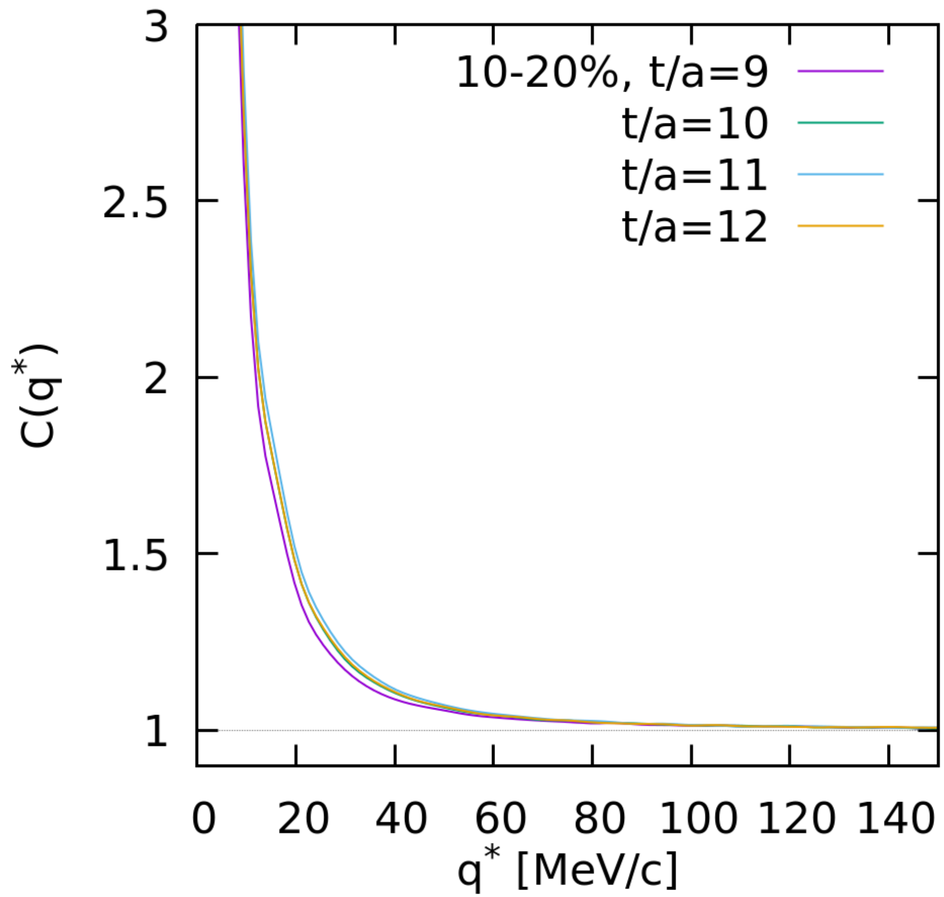

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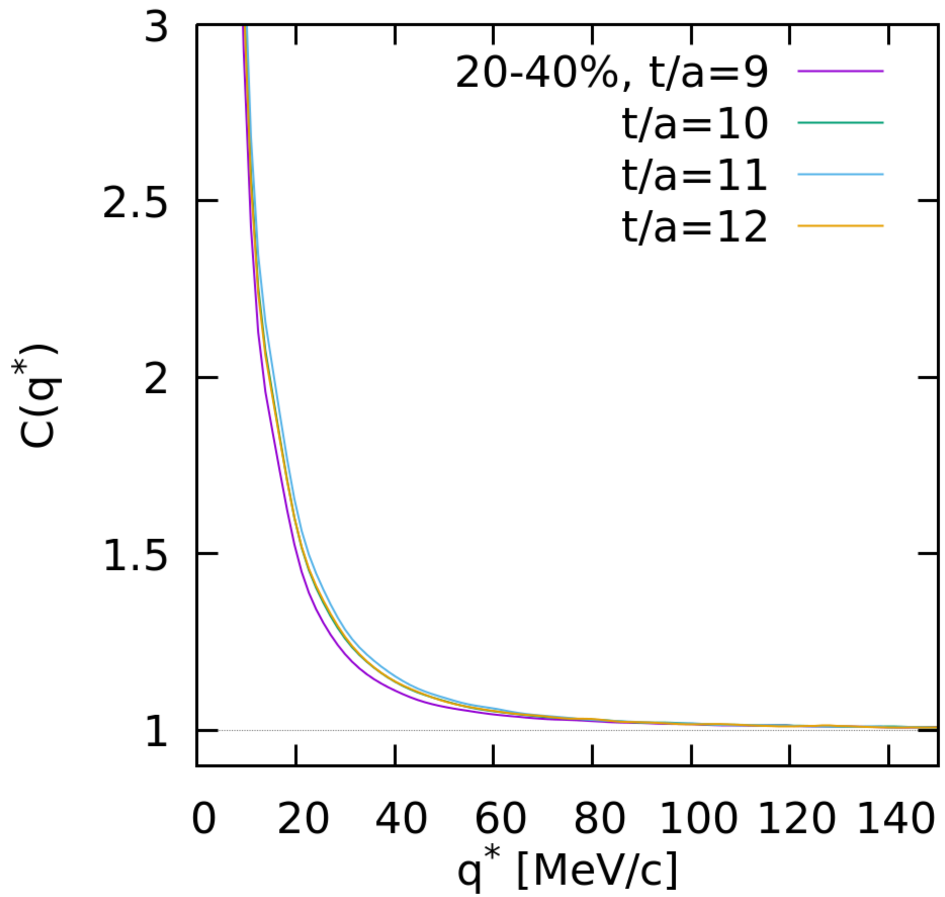

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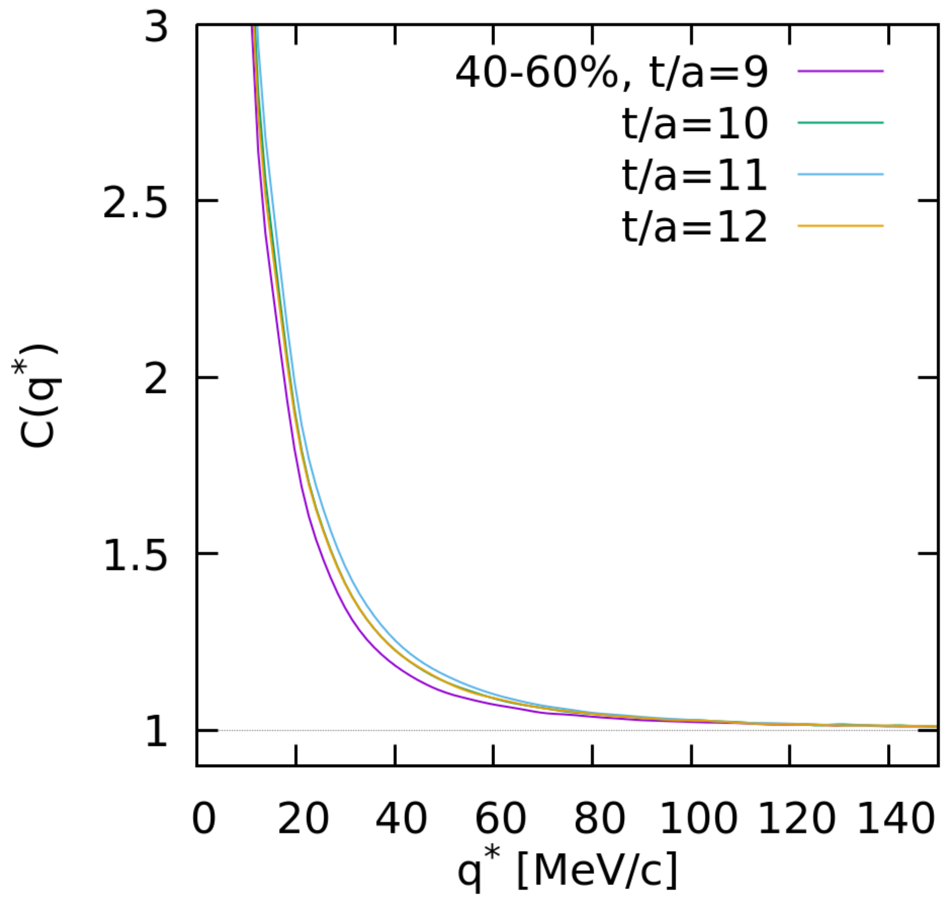

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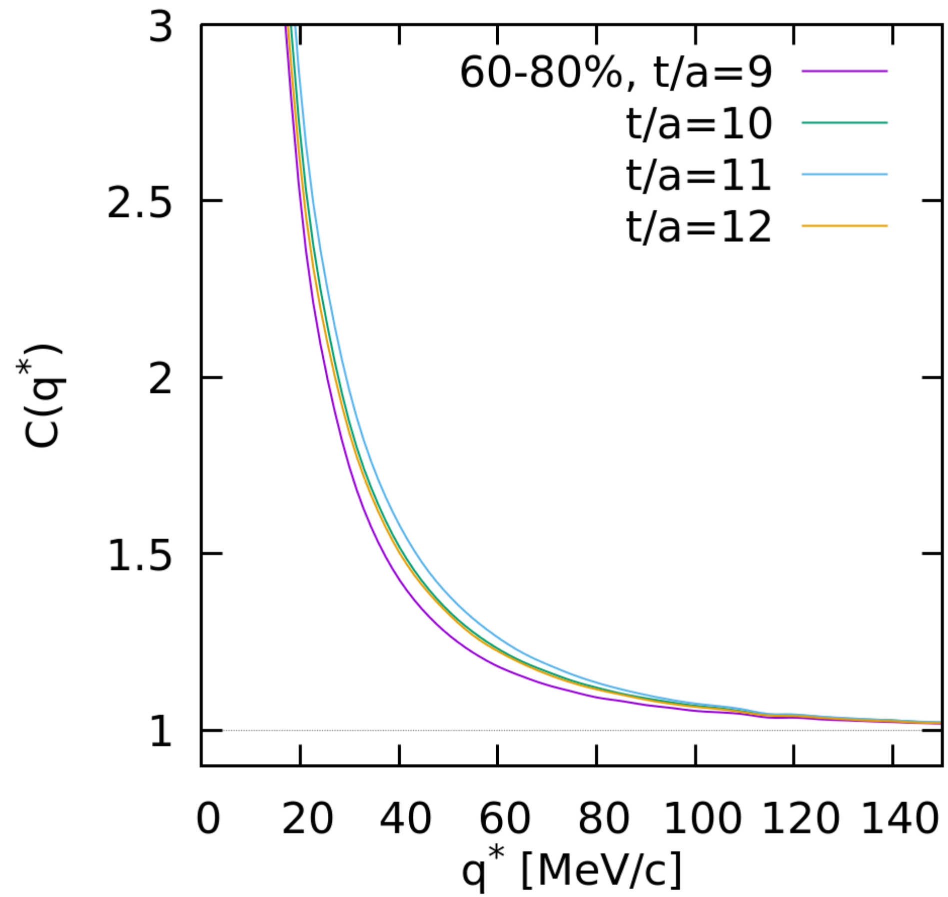

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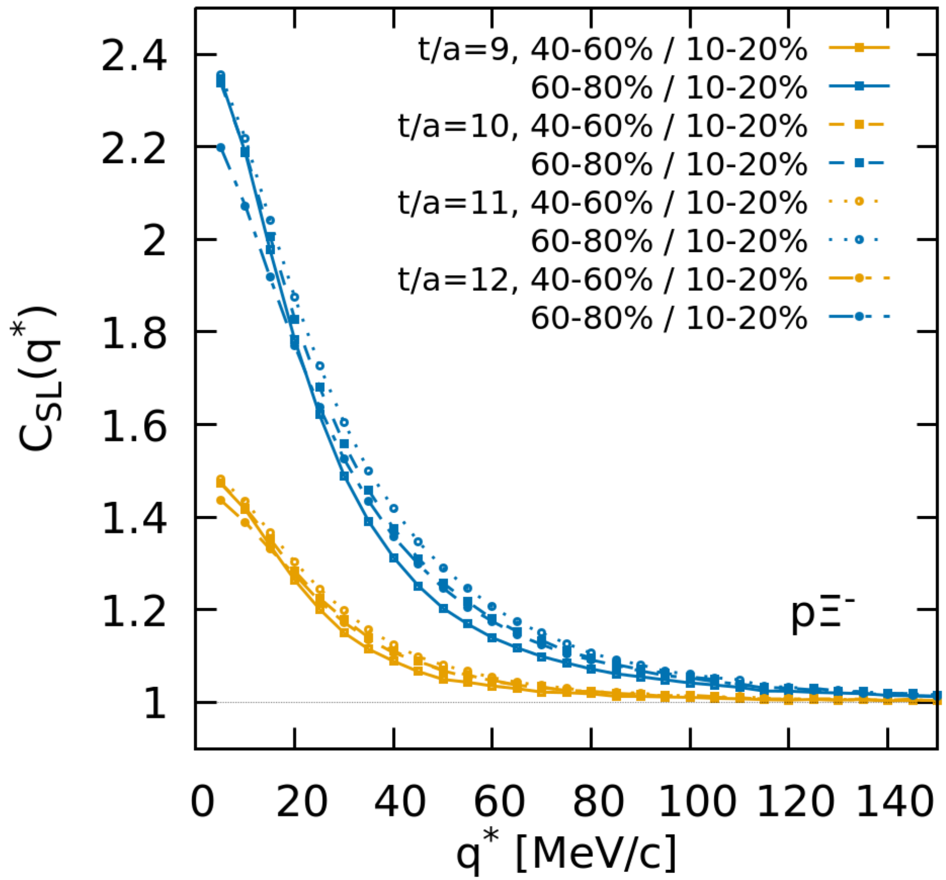


Unitary regime: Notable enhancement by FSI

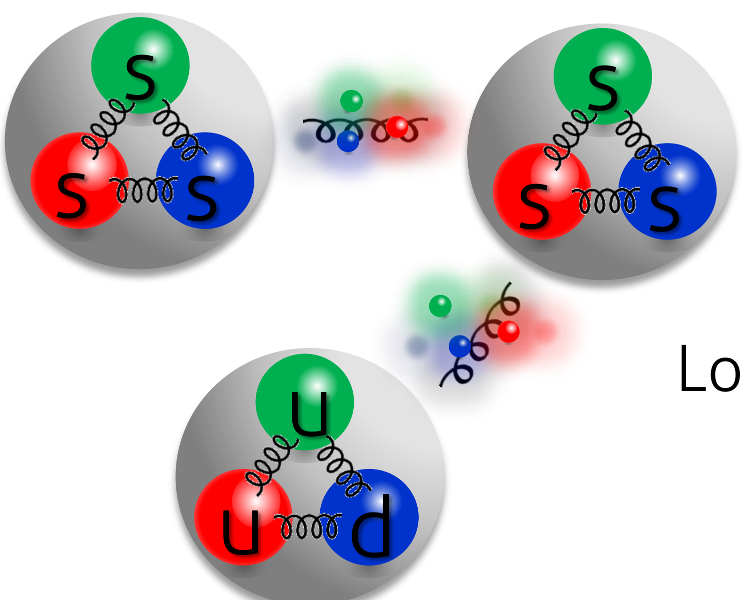
Ratio eliminates Coulomb

Concluding Remarks

- Correlation measurement in HIC can constrain low energy scattering param.
  - FSI contribution is sensitive to system size : Comparing small and large systems via $C_{SL}(Q)$

Concluding Remarks

- Correlation measurement in HIC can constrain low energy scattering param.
  - FSI contribution is sensitive to system size : Comparing small and large systems via $C_{SL}(Q)$
- Indirect search for dibaryon states



Loosely bound ΩΩ Dibaryon?

Loosely bound NΩ Dibaryon?

Hint from Correlation!

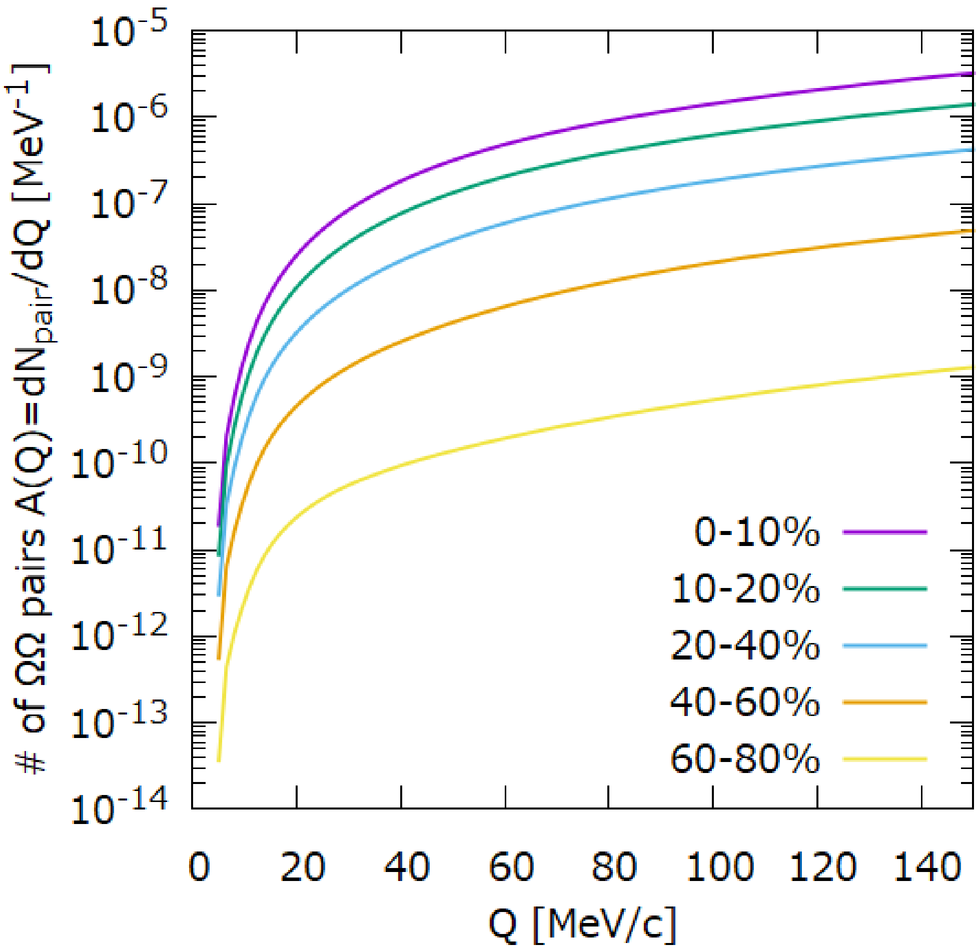
Outlook

- Measurable / Interesting channels
  - Meson-Baryon systems such as Kbar-*N*, ϕ-*N*...
  - Open/Hidden Charm?
  - Higher partial waves (need accuracy=Statistics!)
- Future works
  - Coupled channels
  - Implementation of more sophisticated dynamical models
  - Be aware of production mechanism
    - may induce spurious correlations

Backup

ΩΩ Correlation: Statistics?

of pair A(Q)



To have 100 pairs at low Q:

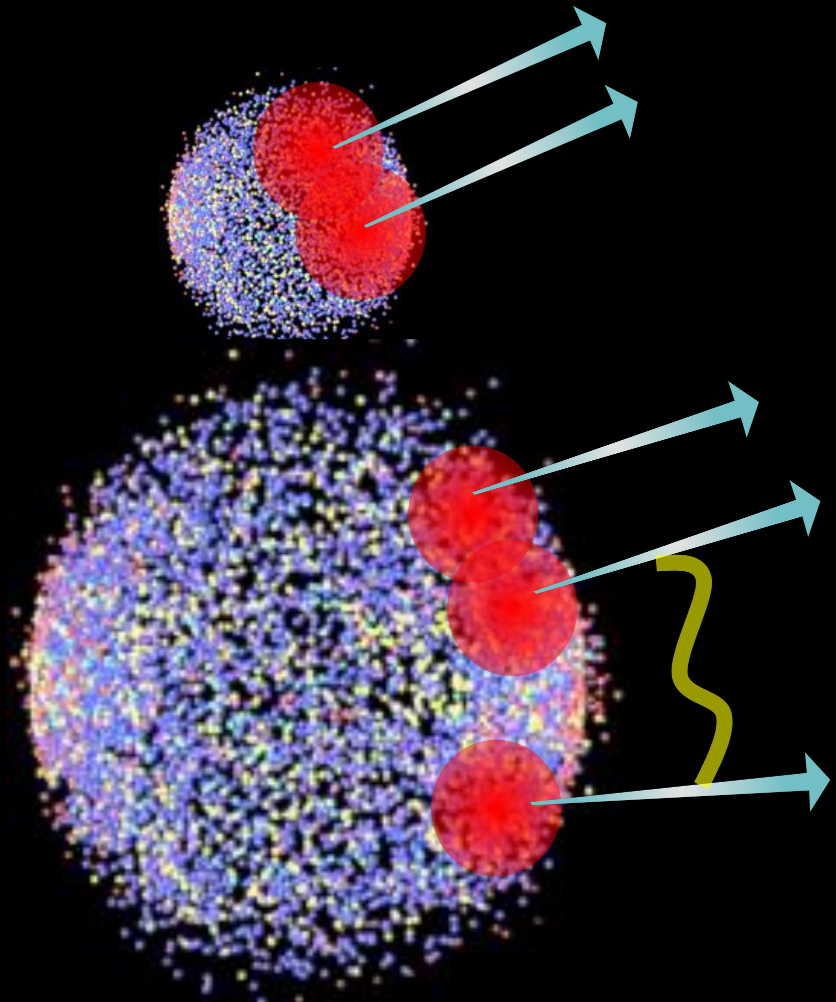
Acceptance×Efficiency : 0.01-0.1

Probability of events with more than 2Ω (assuming Poisson)
0.12 for 0-10%
10^{-4} for 60-80%

10^{11} – 10^{15} events : not realistic at LHC?

Not impossible at Future High-Intensity Facilities?
(e.g., J-PARC: int. rate 10^8 Hz)

System Size?



Small System:

Most of observed pairs with small Q correlated

Large System:

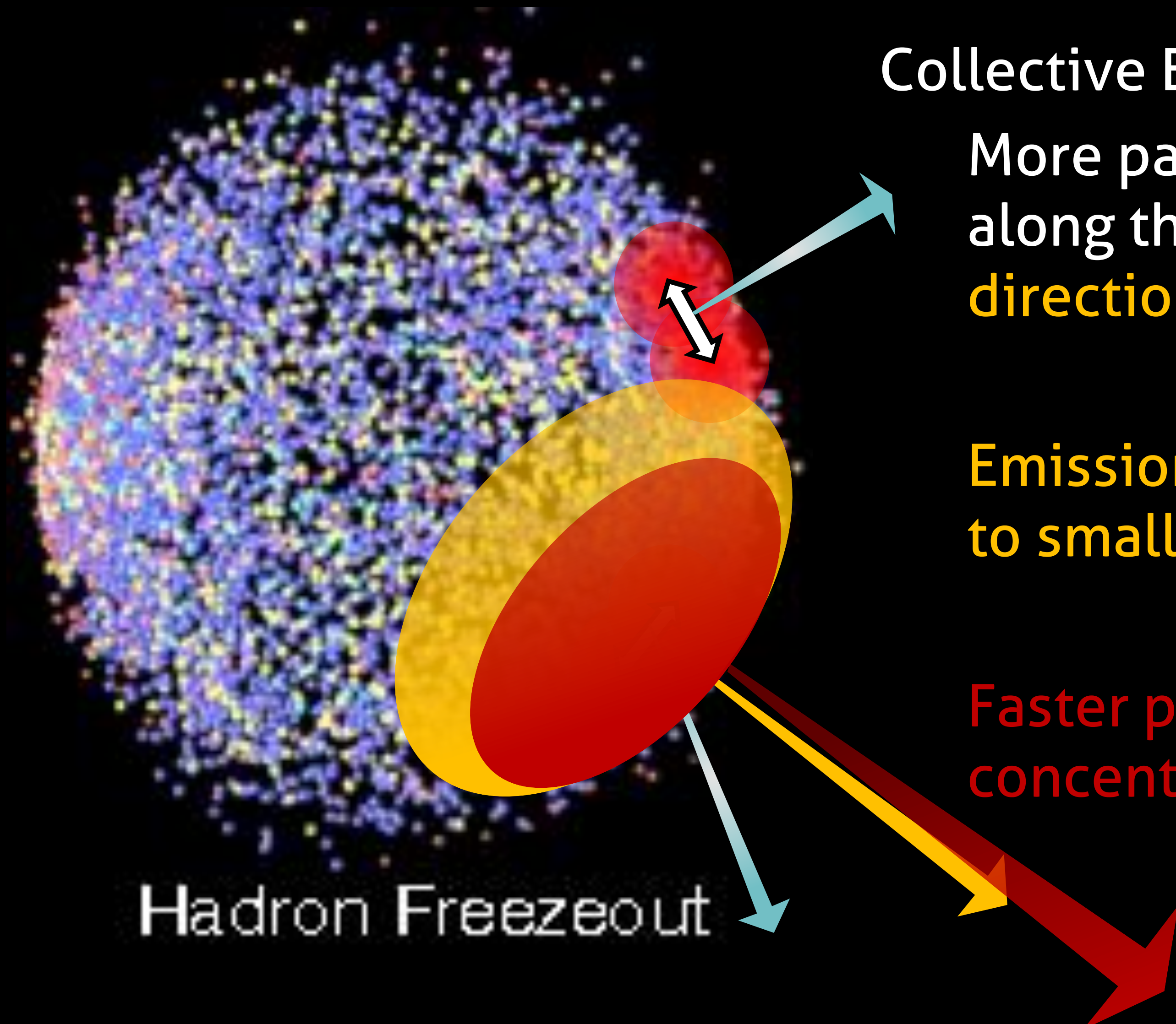
Less pairs coming from close distance

Important Remark:

Coulomb FSI for charged pairs!

Conclusion : measure small Q pairs coming from small region!

Effect of Collectivity



Collective Expansion:

More particles produced along the expanding direction

Emission region deformed to smaller one

Faster pairs more concentrated