Probing Multistrange Dibaryons with Momentum Correlations in Heavy Ion Collisions

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Ref: KM, T.Furumoto, A.Ohnishi, PRC91, 024916 ('15). ΛΛ

KM, A.Ohnishi, F.Etminan, T.Hatsuda, PRC94, 031901(R) ('16). pΩ

A. Ohnishi, KM, K.Miyahara, T.Hyodo, NPA954, 294 ('16). ΛΛ, Kbar N

EXHIC Collaboration, Prog. Part. Nucl. Phys.95, 279 ('17). Review

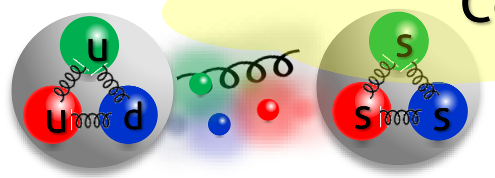
T.Hatsuda, KM, A.Ohnishi, K.Sasaki, NPA967, 856 ('17). pΞ

Baryon-Baryon Interaction

QCD at Low Energy

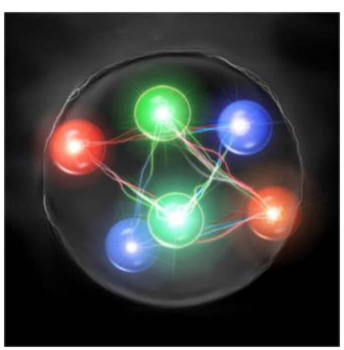
Chiral Symmetry Breaking

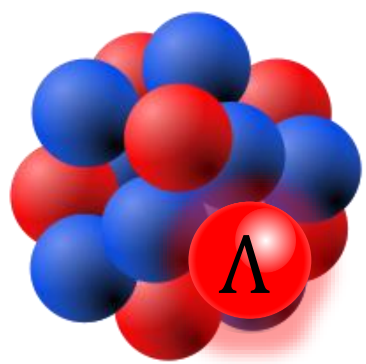
Confinement

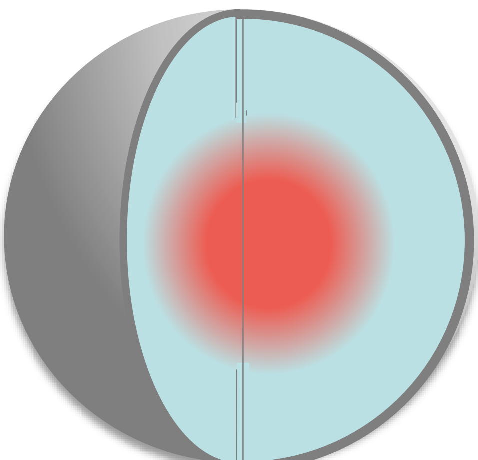


Exotic Hadrons

Neutron Stars



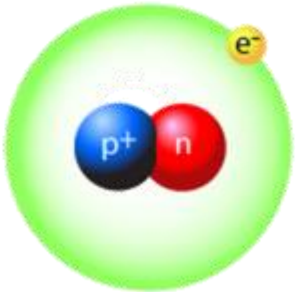




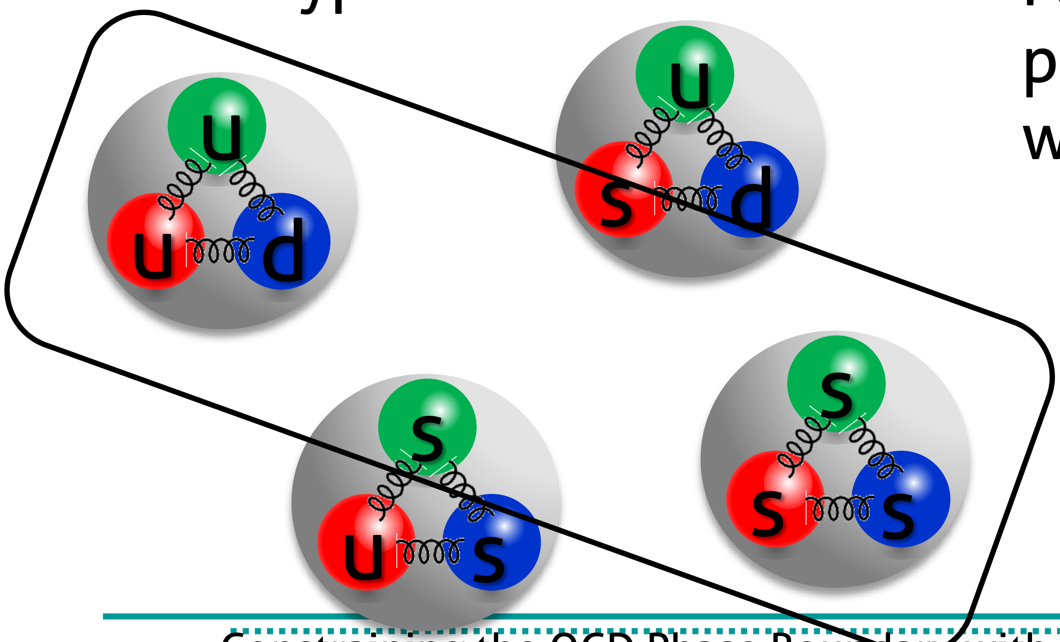
(Hyper)nuclei

Dibaryons

Deutron (Urey et al., 1931)

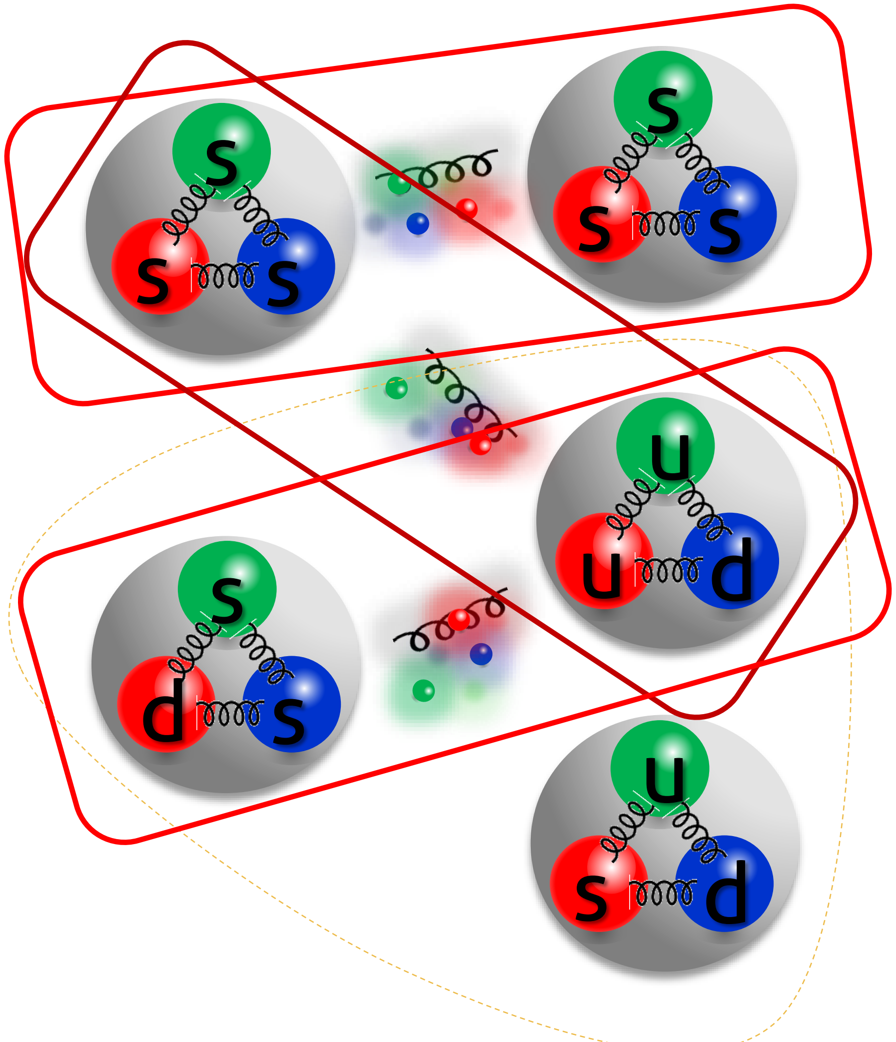


With hyperons? ---------- Flavor SU(3) classification predicts some channels with no Pauli blocking



e.g., NΩ (J=2)

Lattice QCD Studies by HAL QCD Coll.



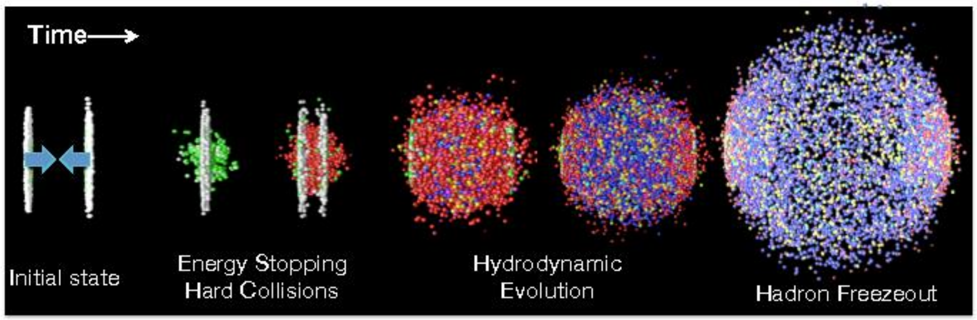
S=-6 : Ω-Ω (J=0)
28-plet in SU(3)

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)

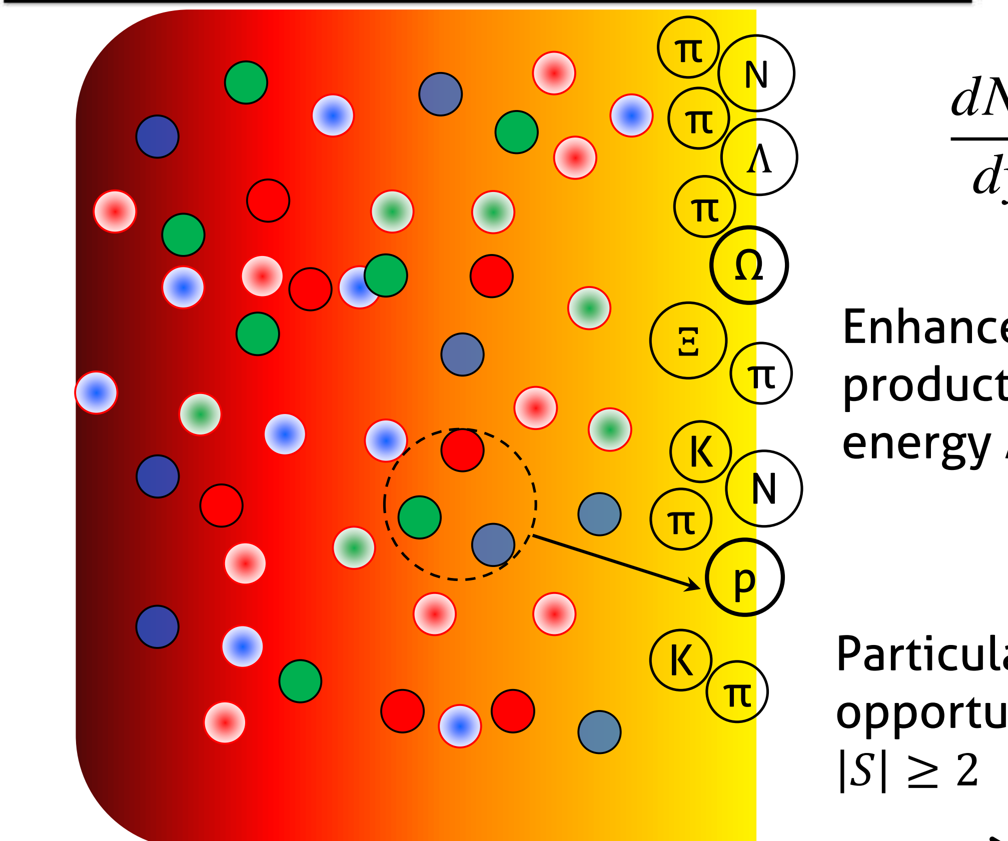
Show strong attraction at almost physical quark masses
Experimental Confirmation – Pair Correlation in HIC

Heavy Ion Collisions as Hyperon Factory



Production of Quark-Gluon Plasma

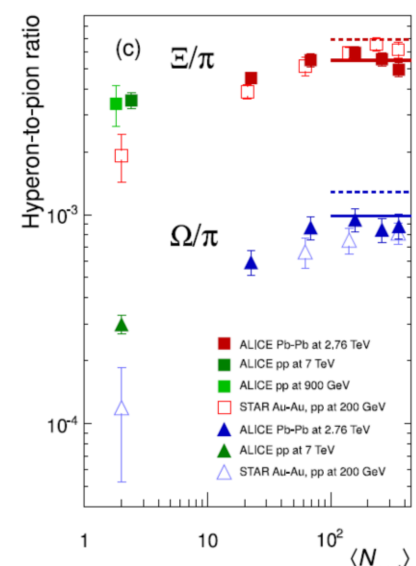
Crossover Transition Into Hadron
Particle Abundance – Thermal Eq.



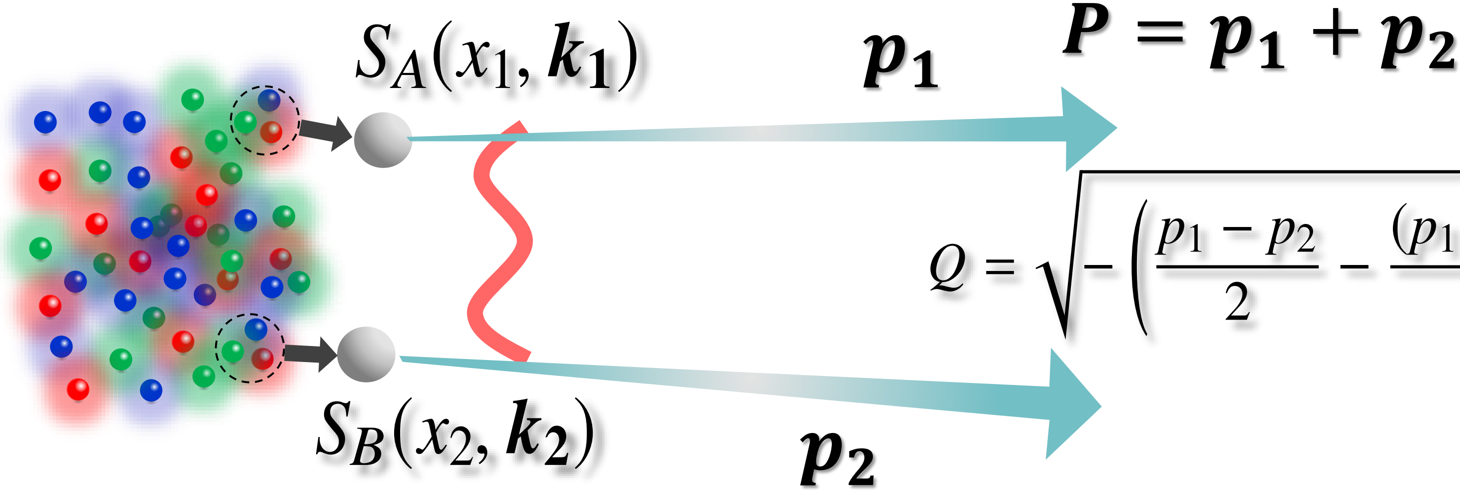
$$\left.\frac{dN_Y}{dy}\right|_{y=0} \simeq \begin{cases} 1-26, & \Lambda\,(S=-1) \\ 0.12-3.3 & \Xi\,(S=-2) \\ 0.015-0.6 & \Omega\,(S=-3) \end{cases}$$

Enhanced strangeness production for high-energy / large systems

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



Two-Particle Correlation



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

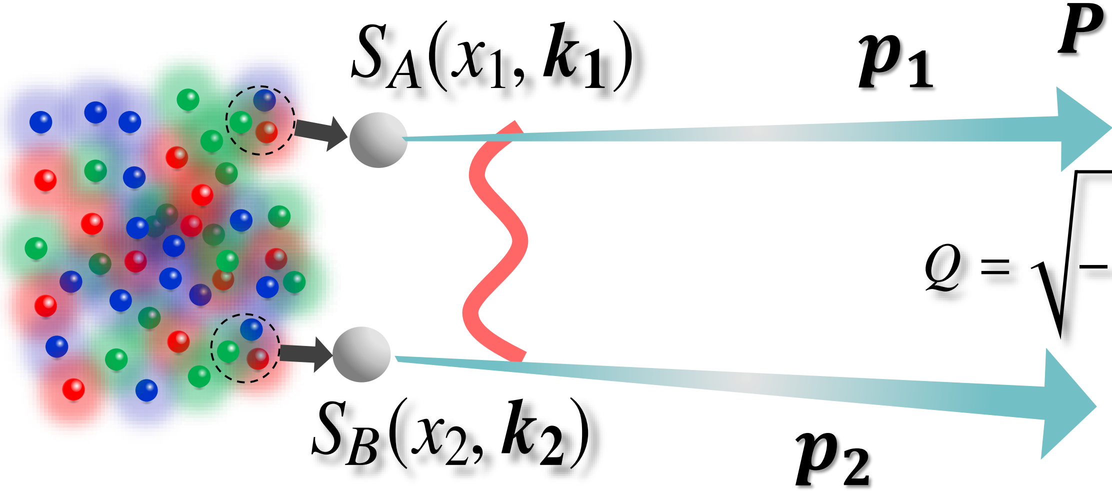
Measuring Pair Correlation
→Constrain Pairwise Interaction

$$C_{AB}(Q) = \frac{N_{AB}^{\text{pair}}(Q)}{N_A N_B(Q)} = \begin{cases} 1 \\ \text{others} \end{cases}$$

No Correlation

Interaction
Interference
etc

Two-Particle Correlation



$$\boldsymbol{P} = \boldsymbol{p_1} + \boldsymbol{p_2}$$

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

Small Q

$$N^{\text{pair}}(Q) \simeq \int_{\Delta \boldsymbol{k}} \int_{x_1} \int_{x_2} S_A(x_1, \boldsymbol{k_1}) S_B(x_2, \boldsymbol{k_2}) |\psi_{AB}^{(-)}(\boldsymbol{r}^*, \boldsymbol{Q}^*)|^2$$

(# 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)

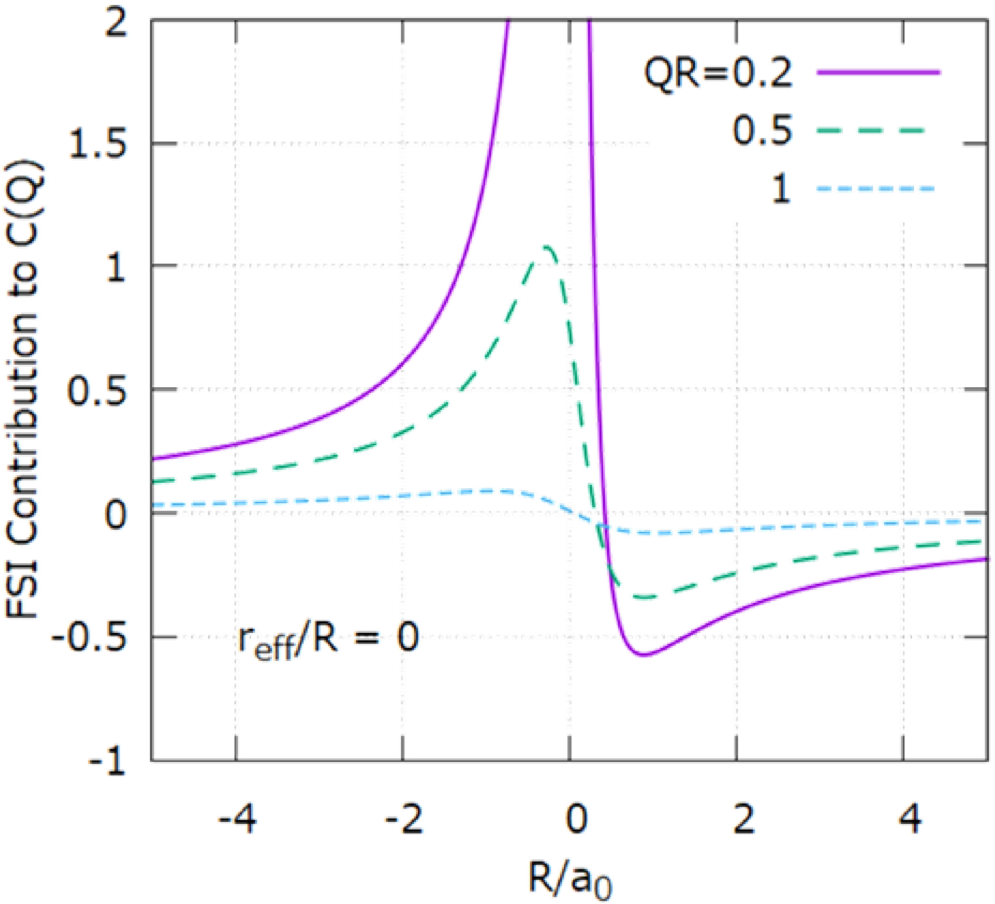
More rigorous formula found in Anchishkin, Heinz, Renk, PRC57 ('98)

Correlation from FSI

Static/Spherical Source

Lednicky+ '82

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



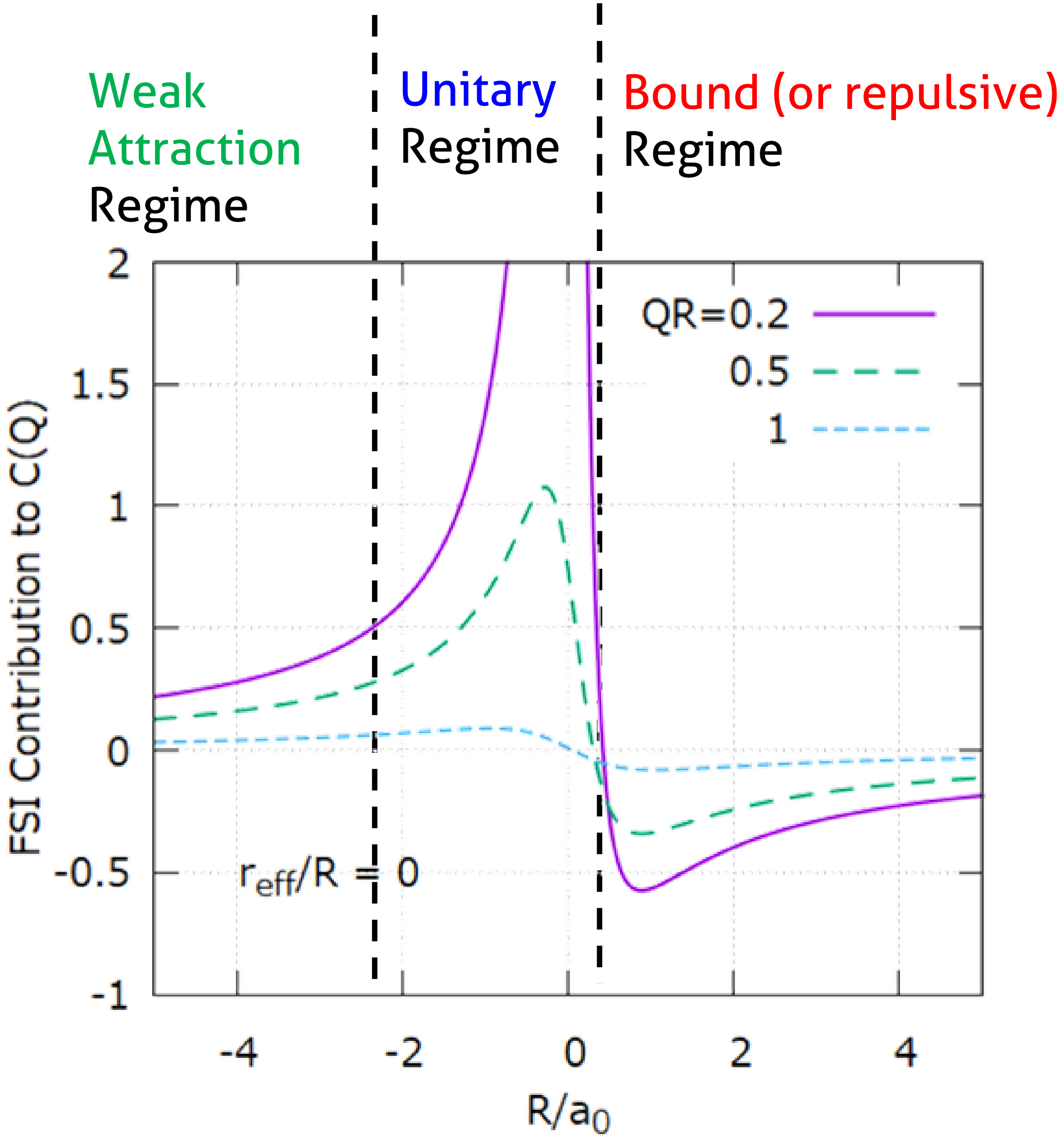
$$S^{\mathrm{rel}}(r) = (\pi R^2)^{3/2} \exp\left(-\frac{r^2}{4R^2}\right)$$

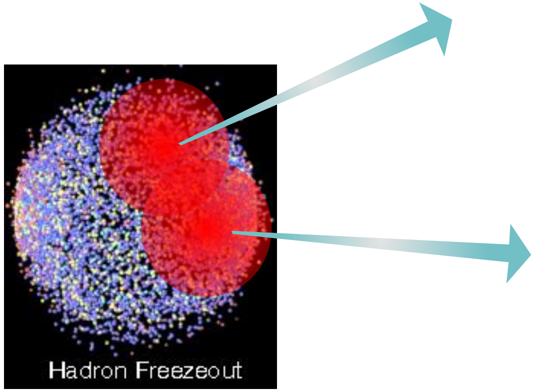
Asymptotic S-wave scattering w.f.

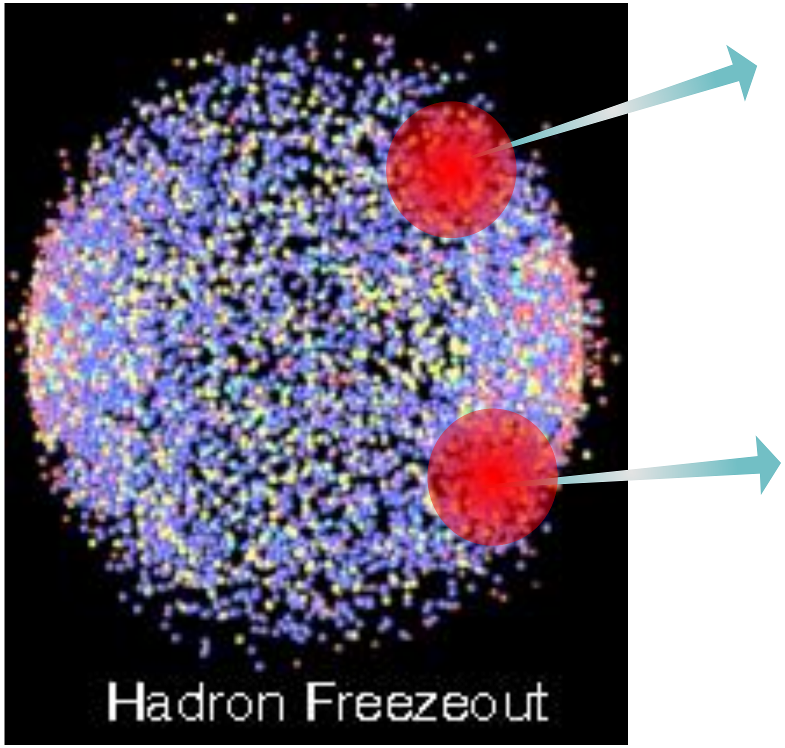
$$\chi_Q(r) = \frac{\sin(Qr + \delta)}{Qr}$$

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

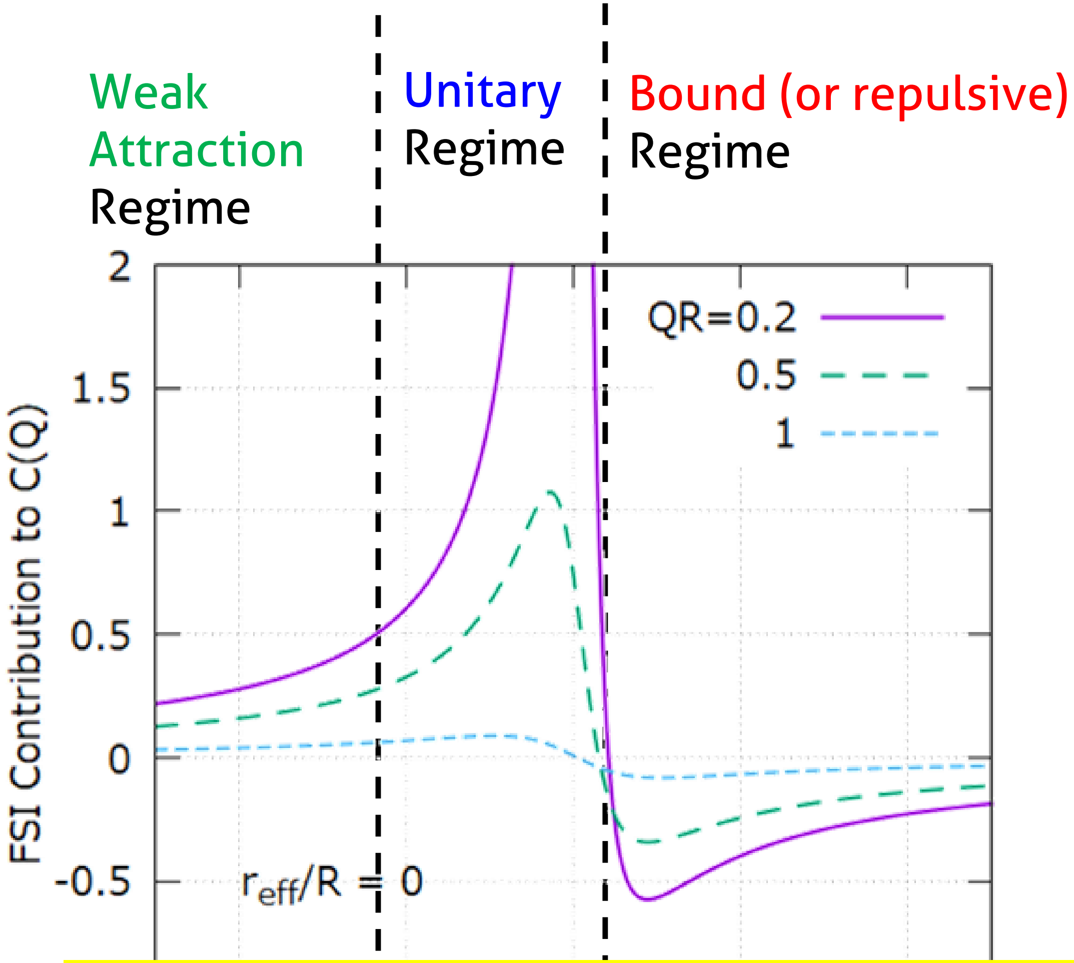
Correlation from FSI

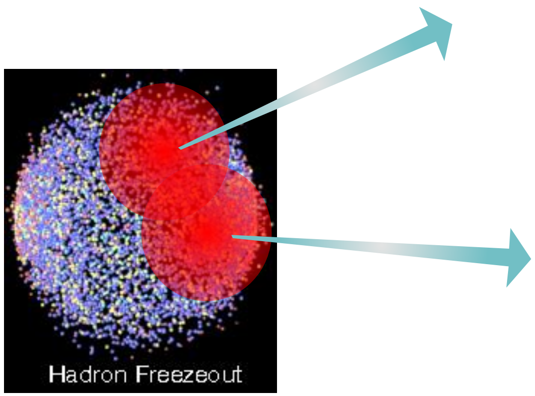


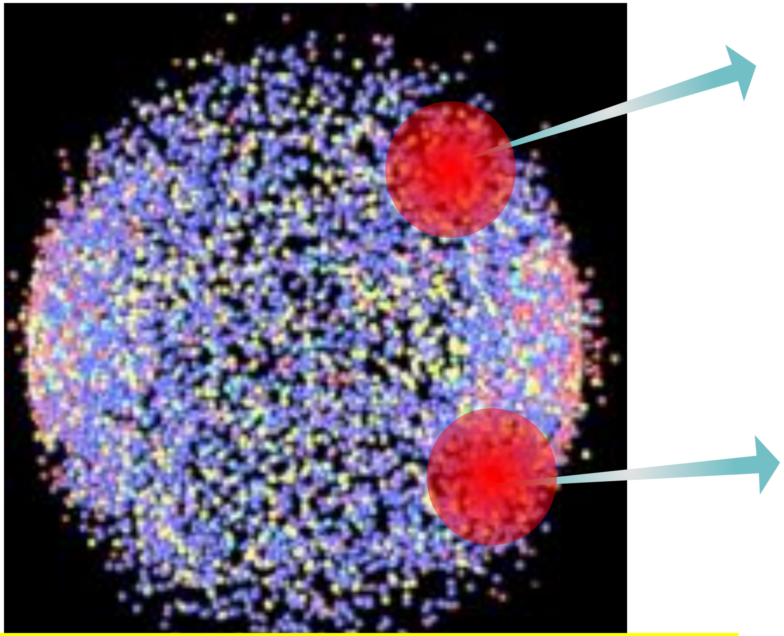




Correlation from FSI



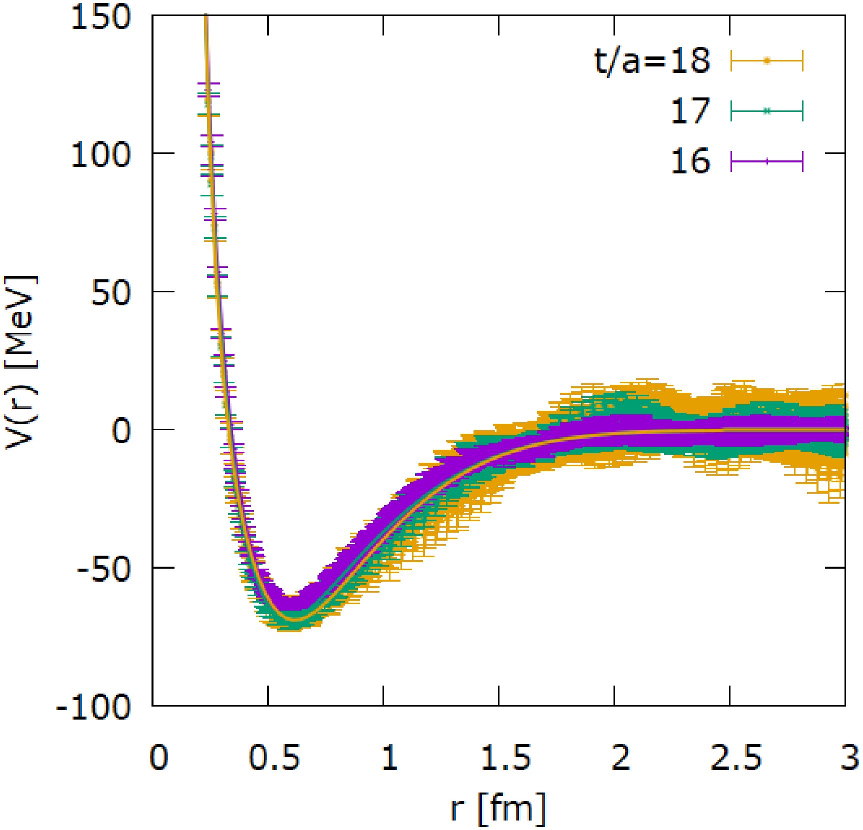




Measuring C(Q) for different system size helps to disentangle the FSI-induced correlation from others

The Most Strange System: ΩΩ (S=-6)

$^1S_0$ bound state from Lattice QCD



S.Gongyo et al., (HAL QCD), 1709.00654

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 : elements

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

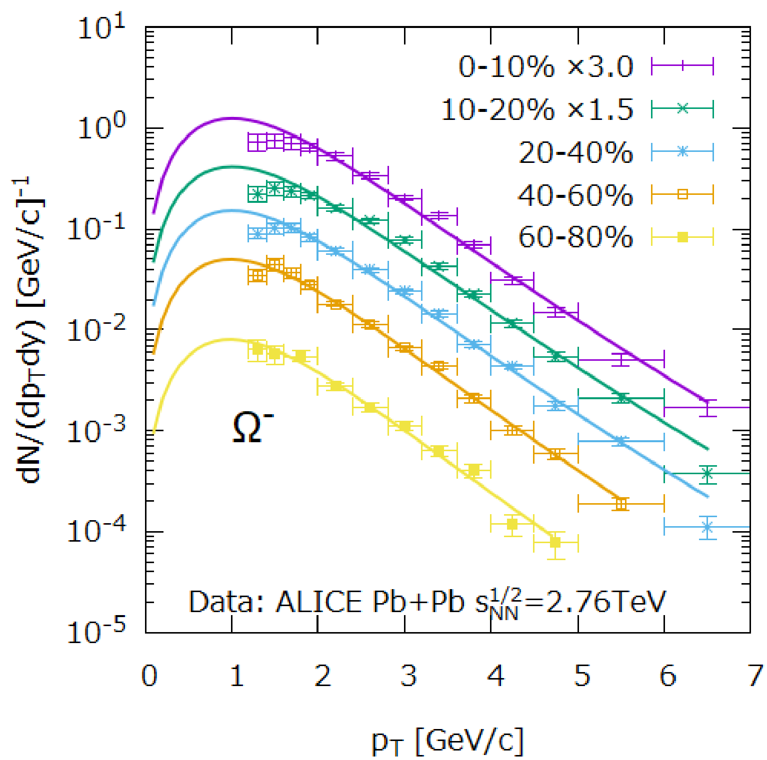
Source function

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

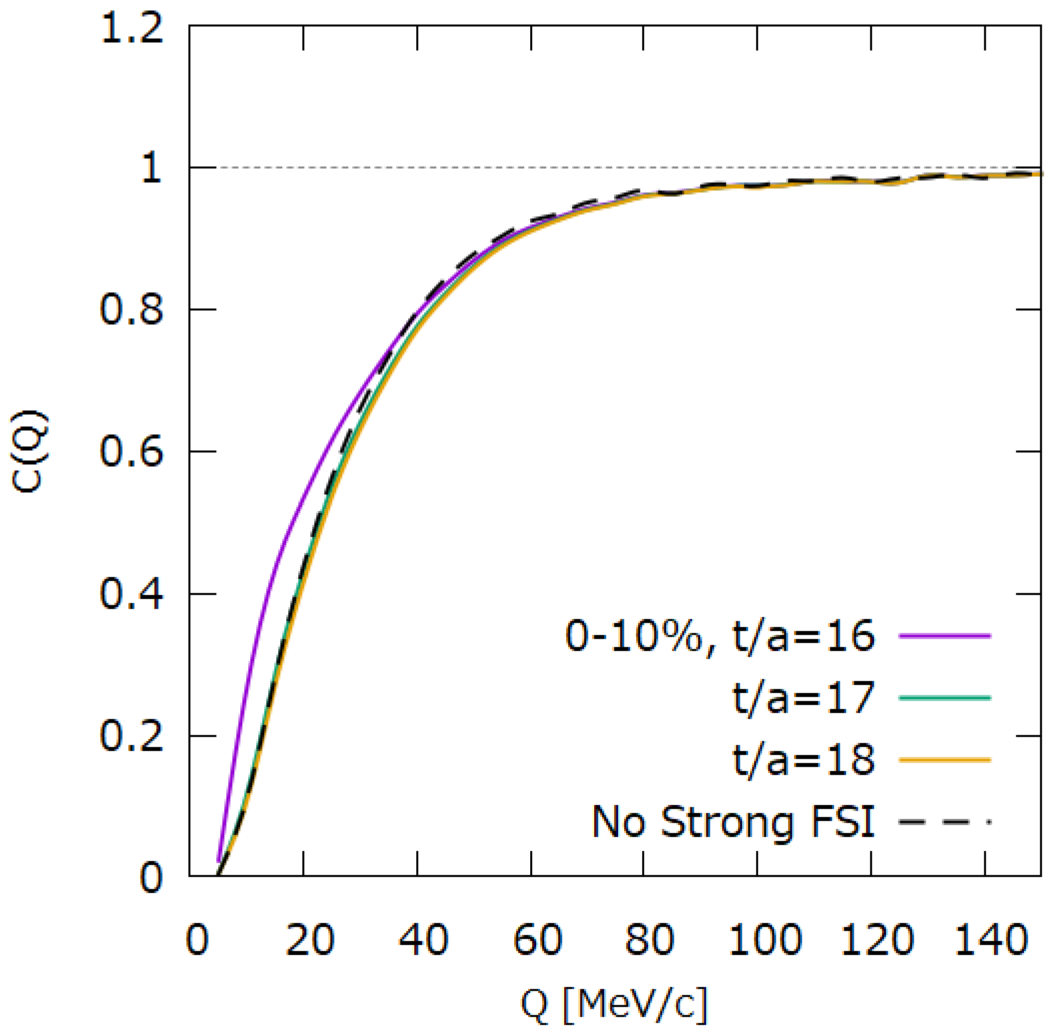
$$y_T = \alpha r / R$$

Boost-invariant, azimuthal symmetric transverse flow

Fit to p_T spectrum with T=164 MeV

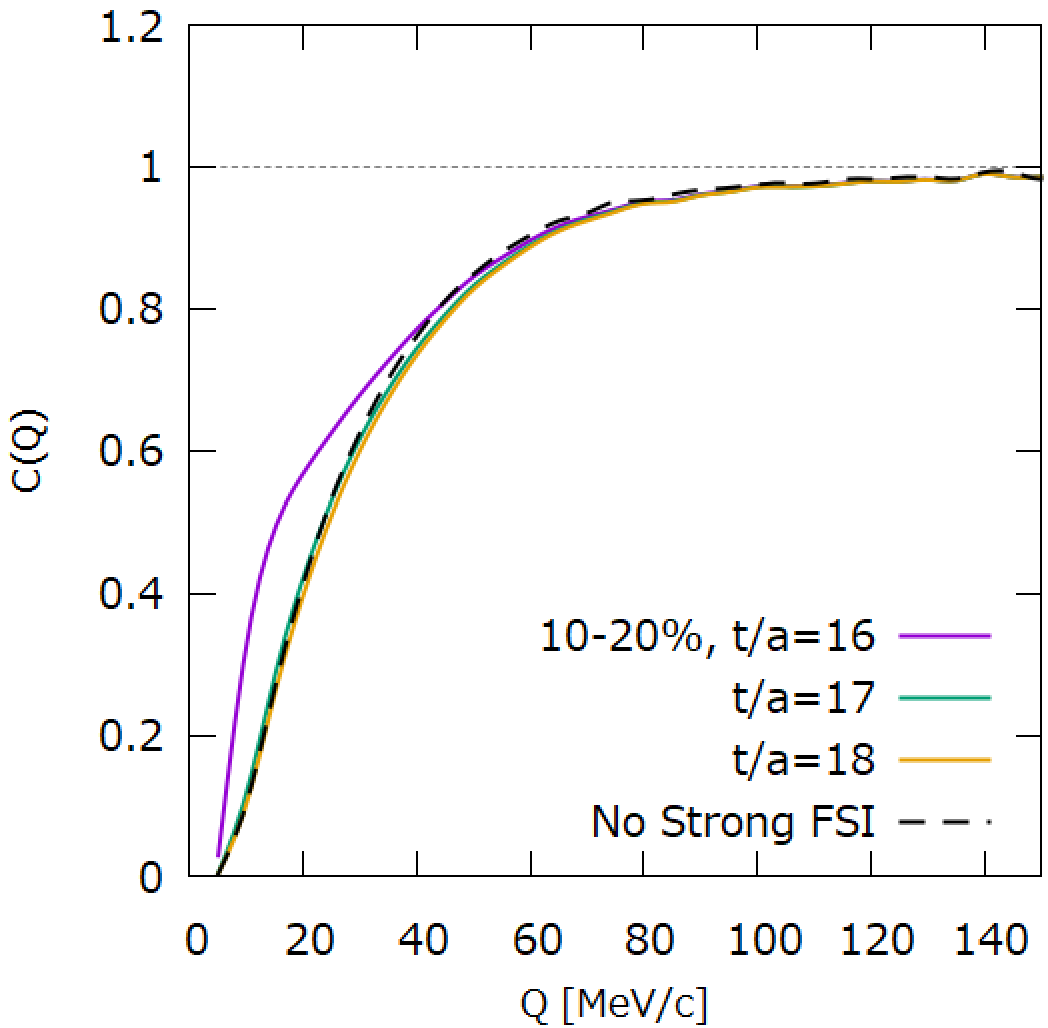


ΩΩ Correlation@LHC



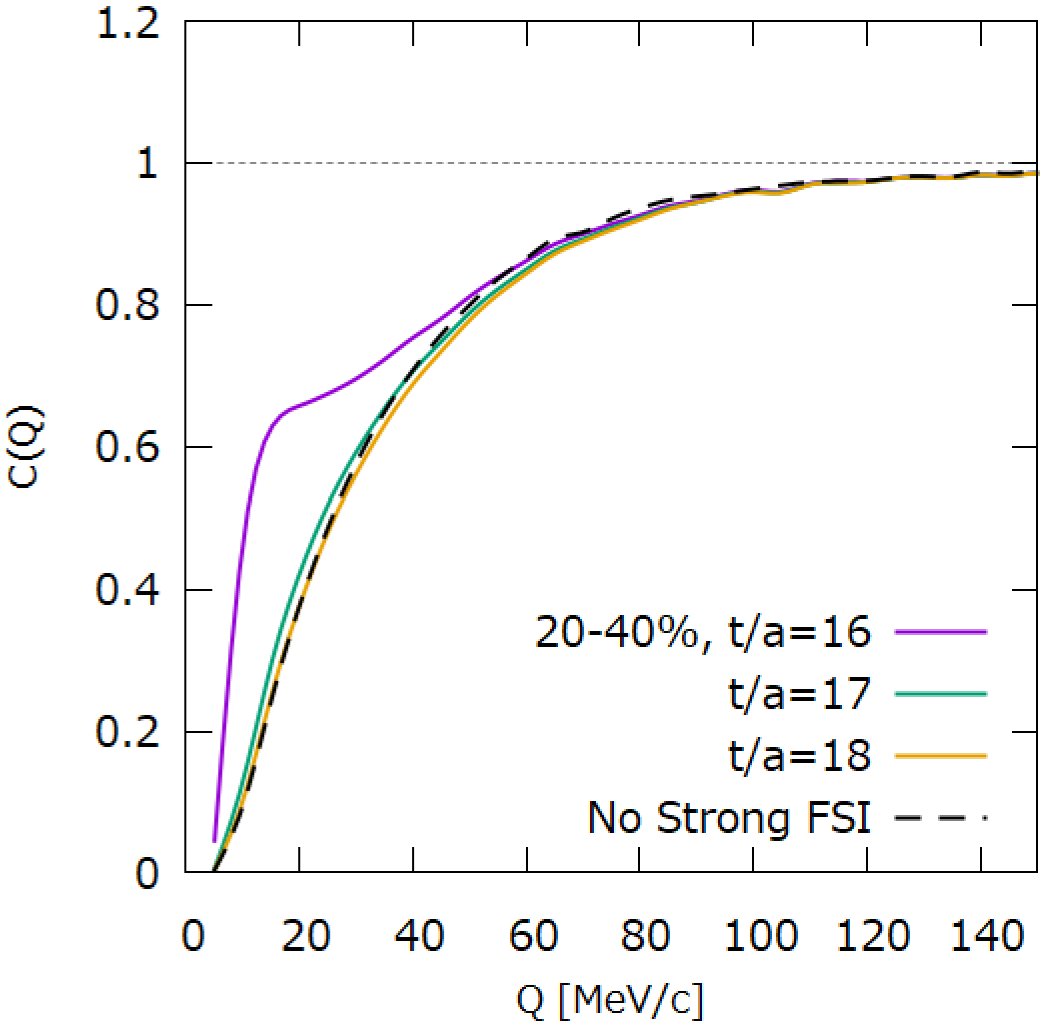
System is too large
Further suppressed by the spin degeneracy factor 1/16

ΩΩ Correlation@LHC



System is too large
Further suppressed by the spin degeneracy factor 1/16

ΩΩ Correlation@LHC



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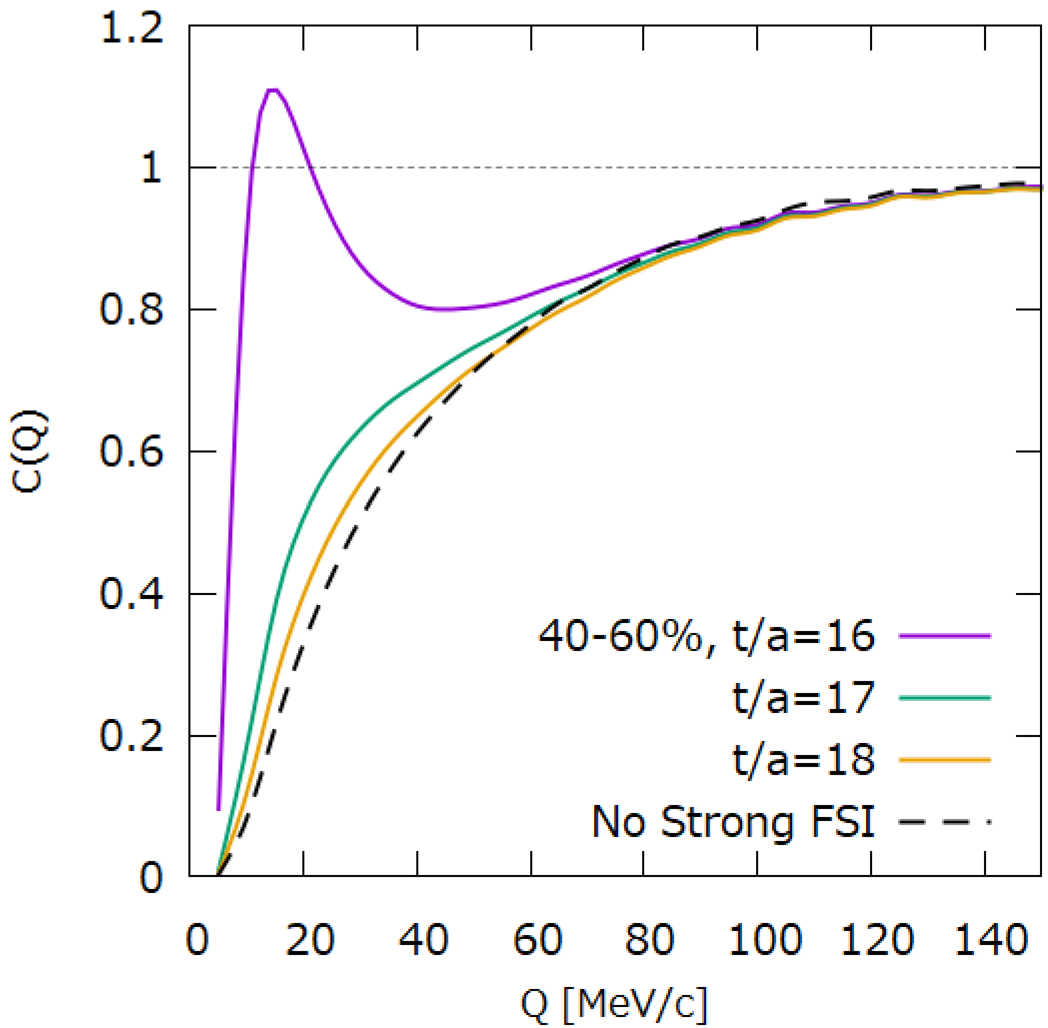
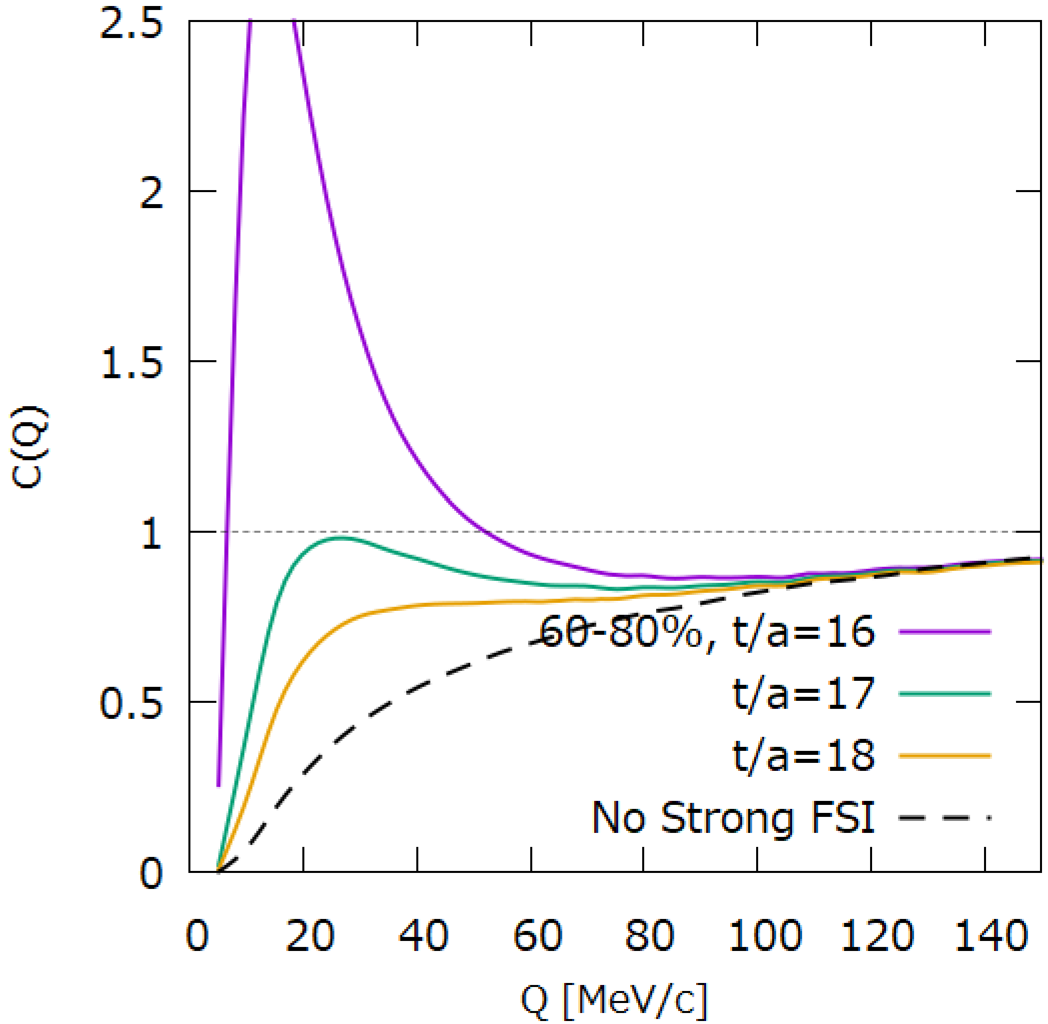
ΩΩ Correlation@LHC



System is too large
Further suppressed by the spin degeneracy factor 1/16

Moderate enhancement from Coulomb+HBT case

ΩΩ Correlation@LHC



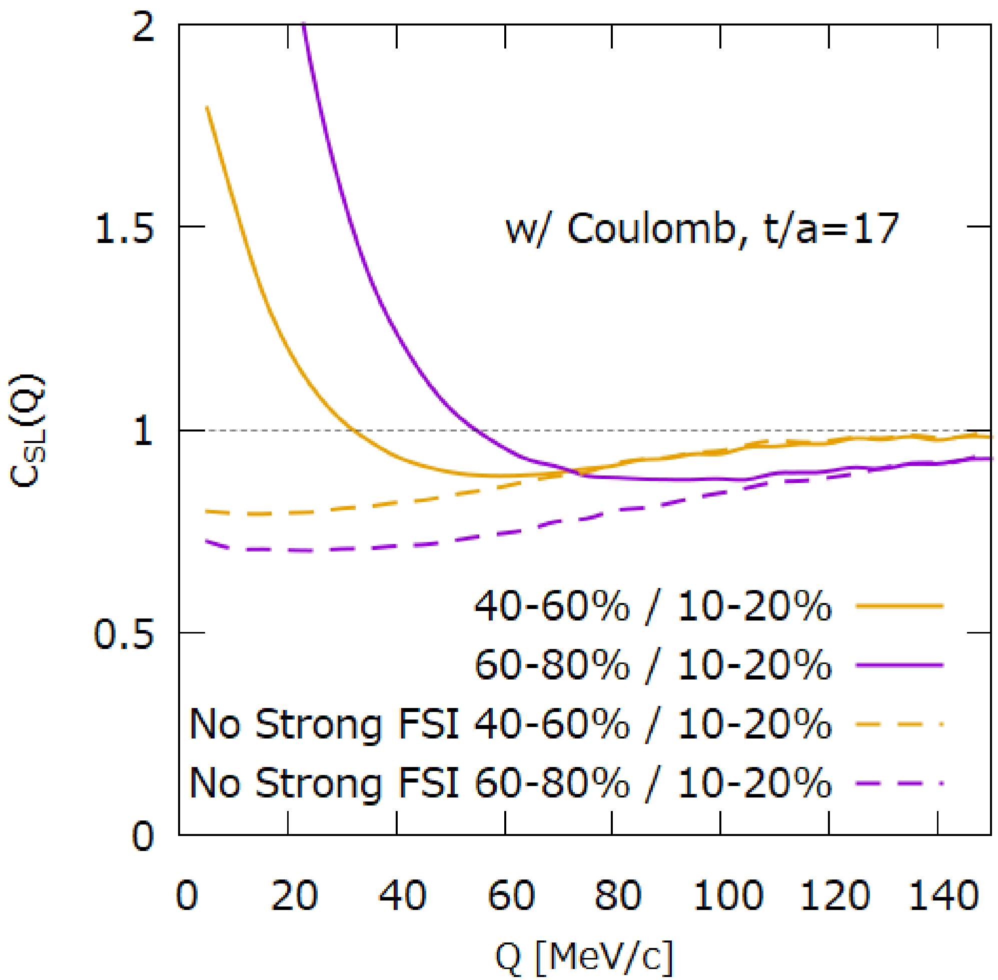
System is too large
Further suppressed by the spin degeneracy factor 1/16

Moderate enhancement from Coulomb+HBT case

Strong enhancement from Coulomb+HBT case

ΩΩ Correlation@LHC

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



Response to system size change

QS (HBT) Correlation suppresses the ratio

Nevertheless FSI dominates at low Q

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

pΩ Correlation

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

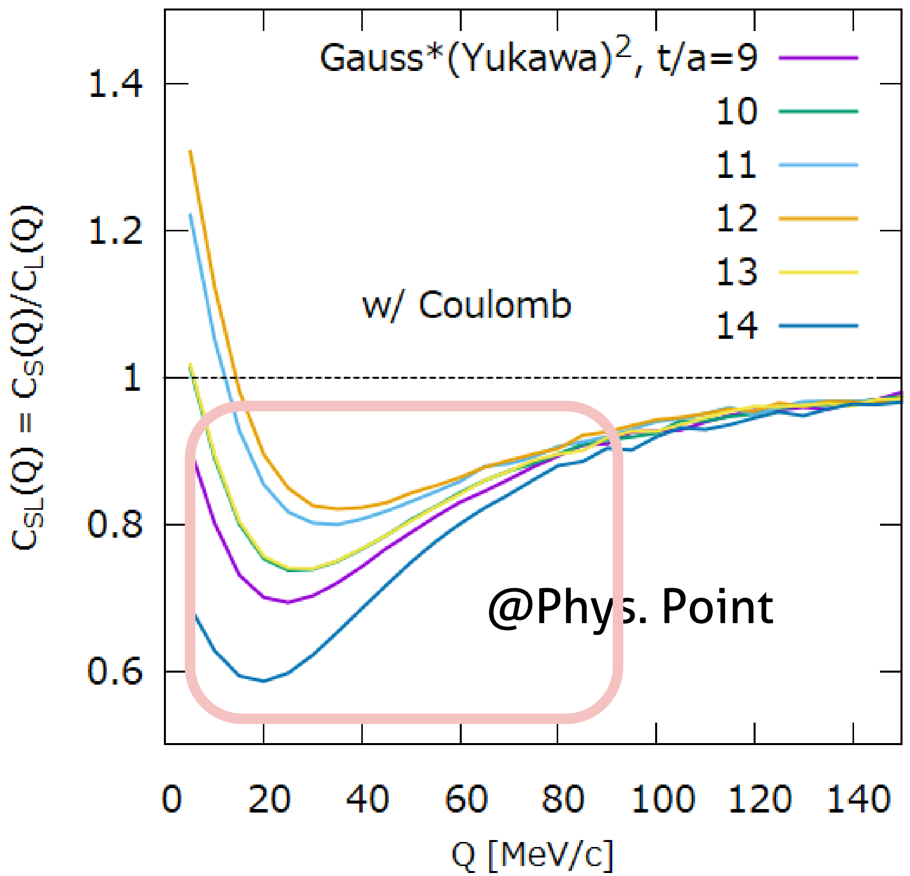
⇓

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)



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

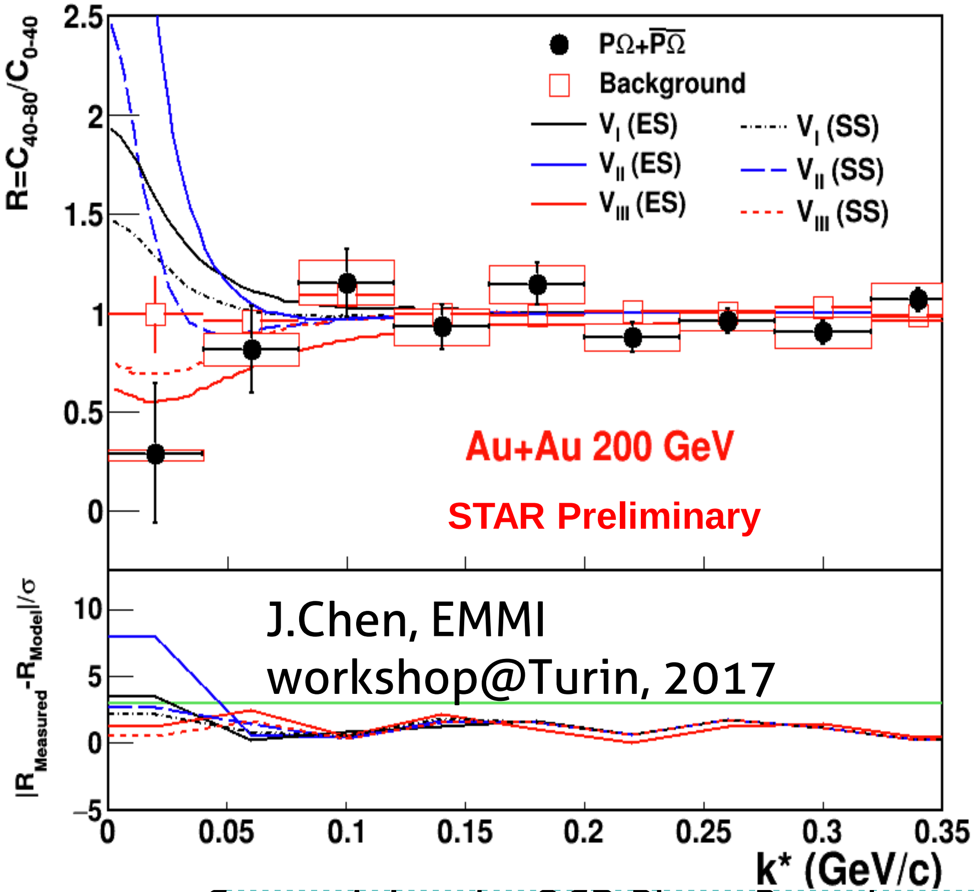
$p\Omega$ Correlation

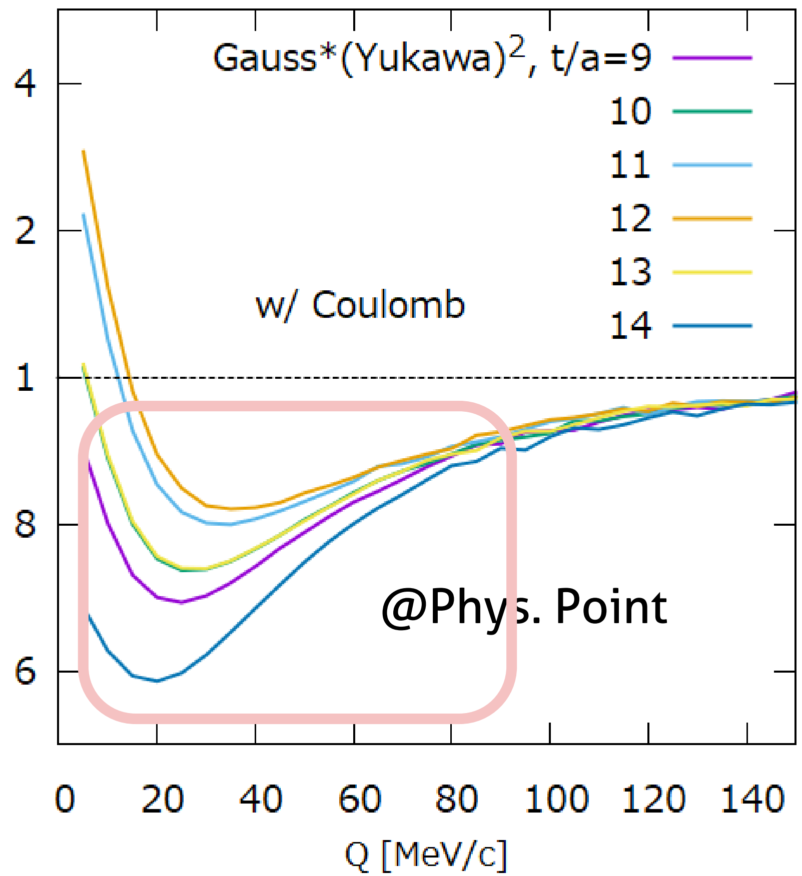
$$|\varphi_{p\Omega}^{\text{spin-averaged}}(\boldsymbol{q}^*, \boldsymbol{r}^*)|^2 = \frac{3}{8}|\varphi(^3S_1)|^2 + \frac{5}{8}|\varphi(^5S_2)|^2$$

⇓

Lattice input: Iritani+ (Preliminary)

Coupled to ΛΞ (2430) and ΣΞ(2507)



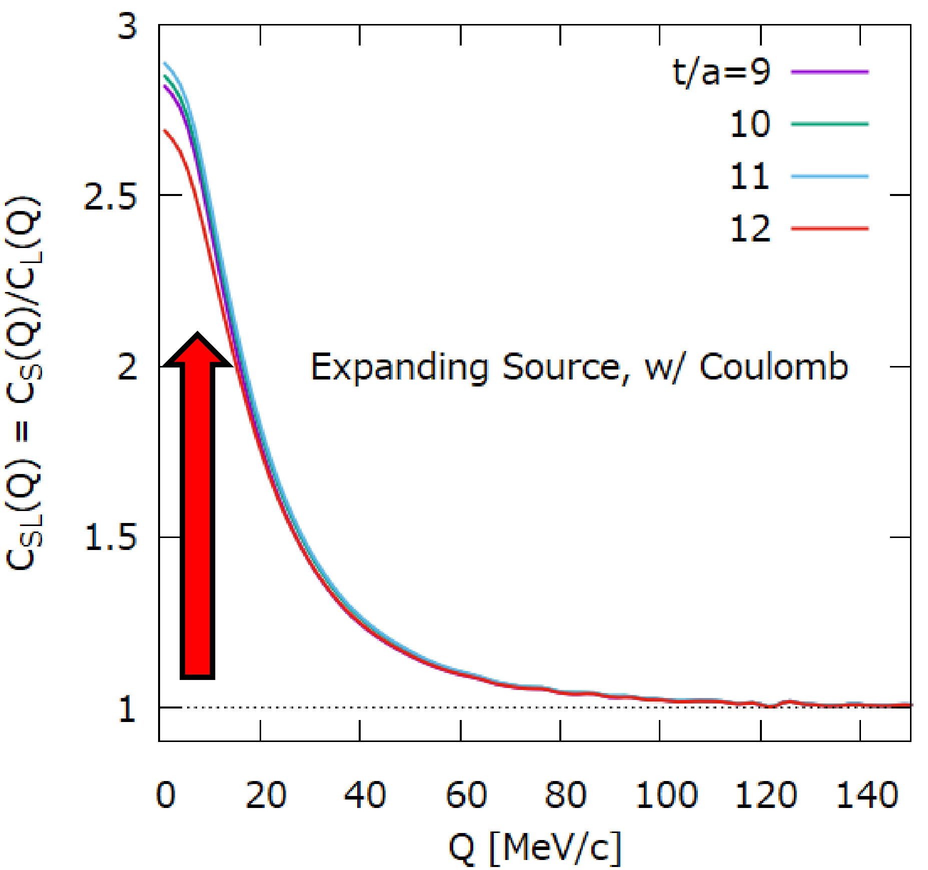


$p\Xi^-$ Correlation

$$|\psi_{p\Xi^-}|^2 = \frac{1}{2}|\psi_{p\Xi^-}^{I=0}|^2 + \frac{1}{2}|\psi_{p\Xi^-}^{I=1}|^2$$
$$= \frac{1}{8}|\psi_{p\Xi^-}^{I=0}({}^1S_0)|^2 + \frac{3}{8}|\psi_{p\Xi^-}^{I=0}({}^3S_1)|^2 + \frac{1}{2}|\psi_{p\Xi^-}^{I=1}|^2$$

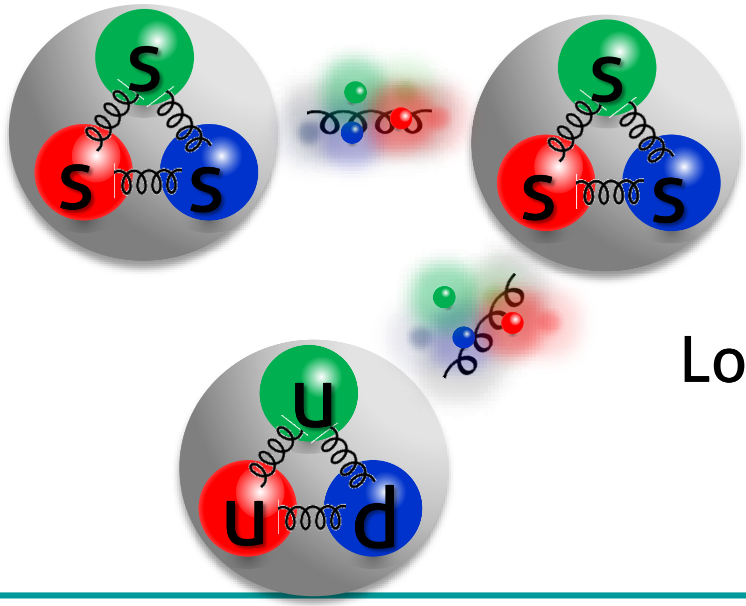
Unitary regime: Notable enhancement by FSI

Lattice input: K.Sasaki+ (Preliminary)



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?

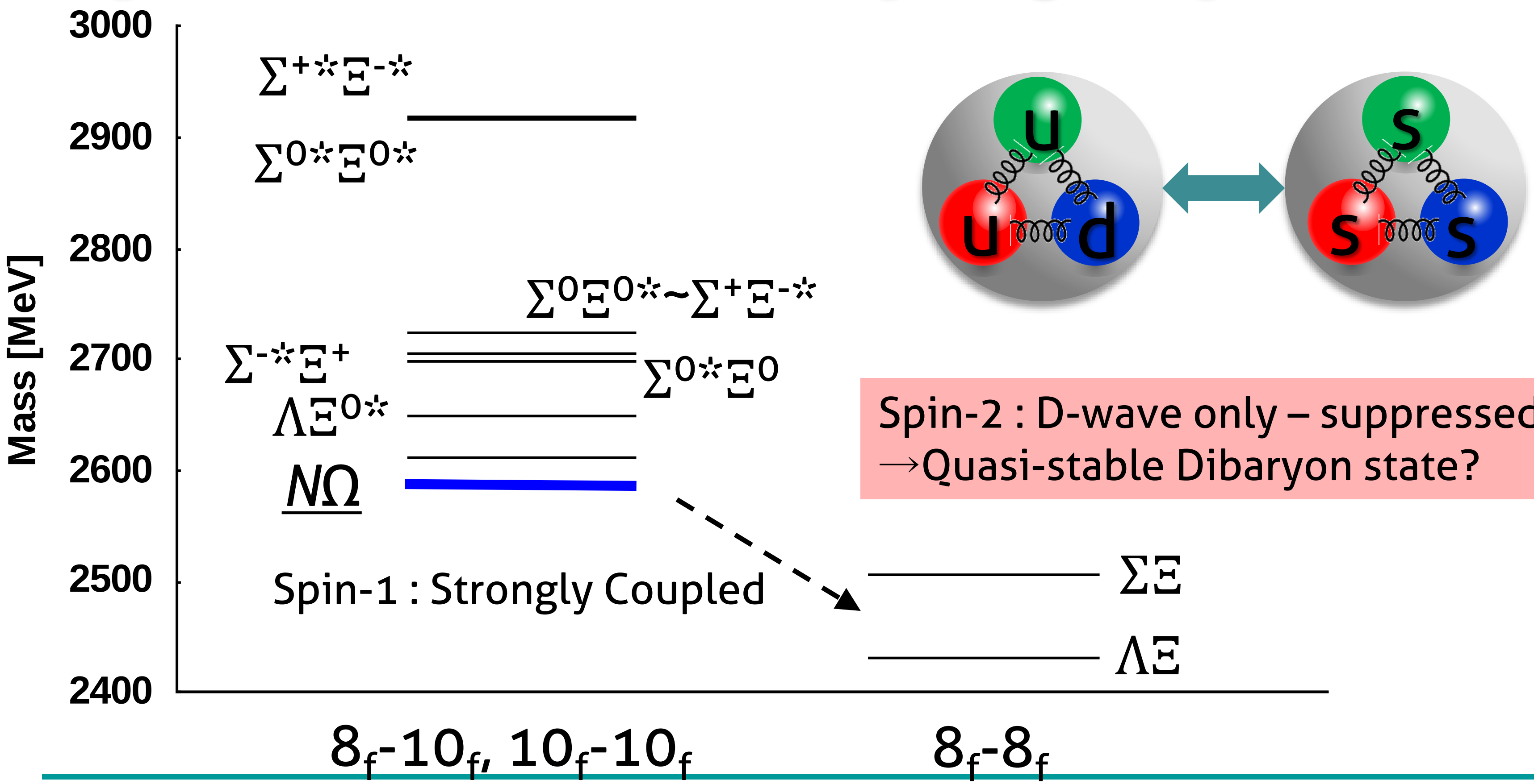
Loosely bound NΩ Dibaryon?

Hint from Correlation!

Backup

S=-3:

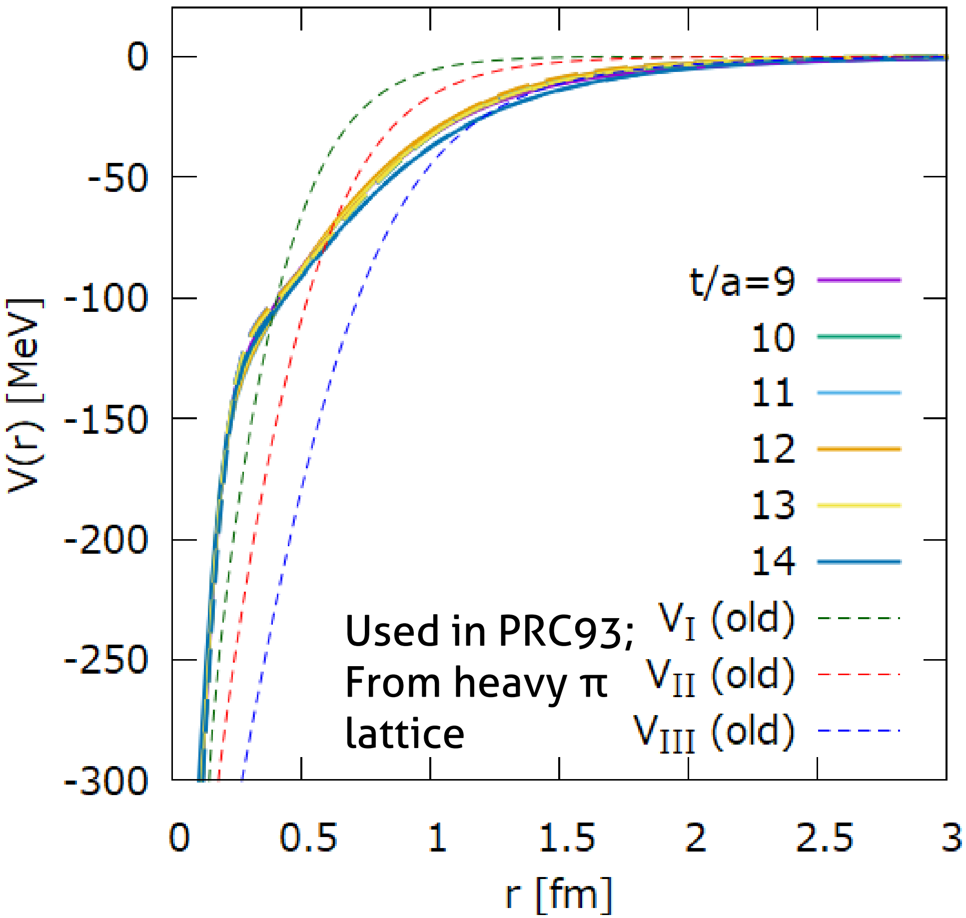
pΩ @almost phys.point



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

*p*Ω Interaction ($^5S_2$)

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



T.Iritani et al. (HAL QCD)

+Coulomb attraction

t/a	a_0 [fm]	r_{eff} [fm]	E_B [MeV]
11	3.77	1.37	1.6
12	3.89	1.38	1.5
13	3.47	1.37	2.0

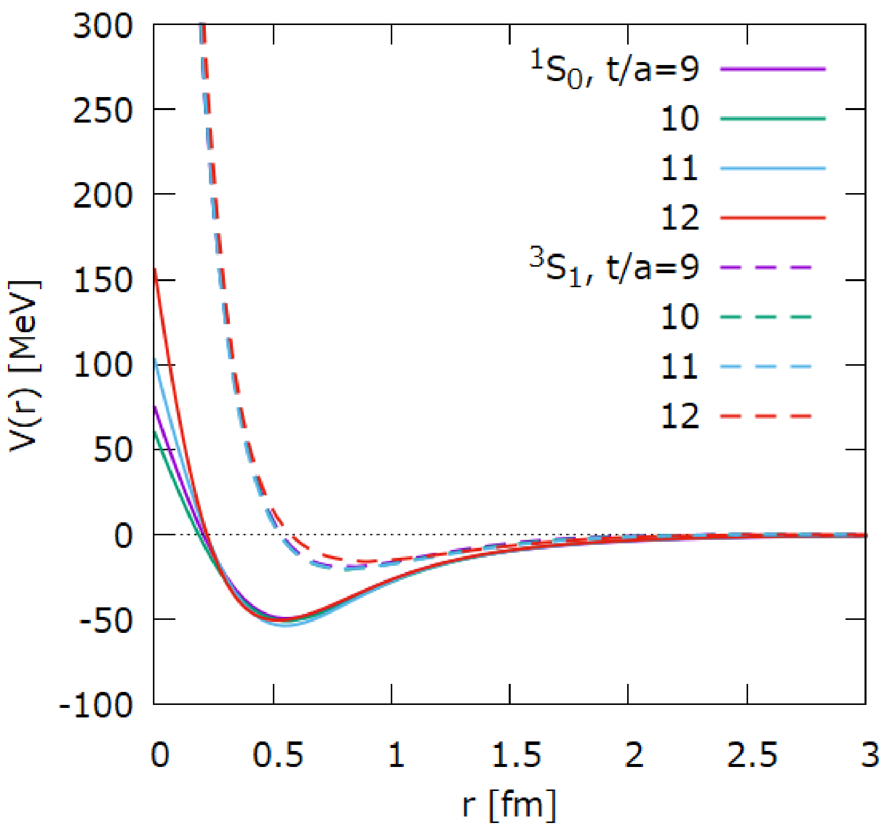
Bound state regime for Heavy Ion Collisions
Close to unitary for smaller system

S=-2:

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

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

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



+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 $\Sigma\Sigma$ incorpolated) dominates

Close to unitary for HIC source

K.Sasaki et al. (HAL QCD)

More on Ω Source Function

Fix τ

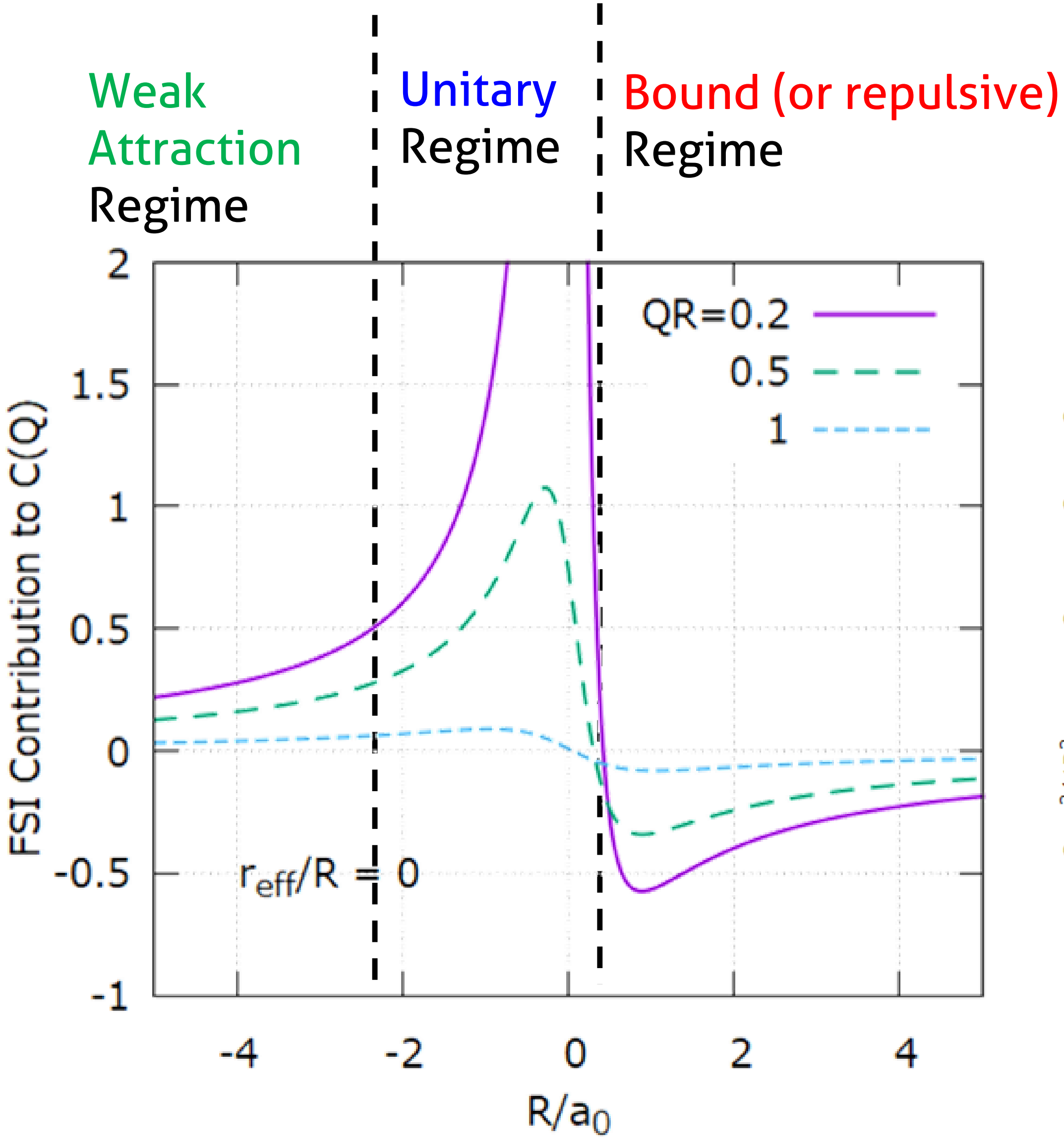
- $\tau \sim R_{long} \sim <N_{ch}>^{1/3}$
- Ω freeze-out from phase boundary due to small cross section

Hybrid model: Zhu et al., PRC'15, Takeuchi et al., PRC'15

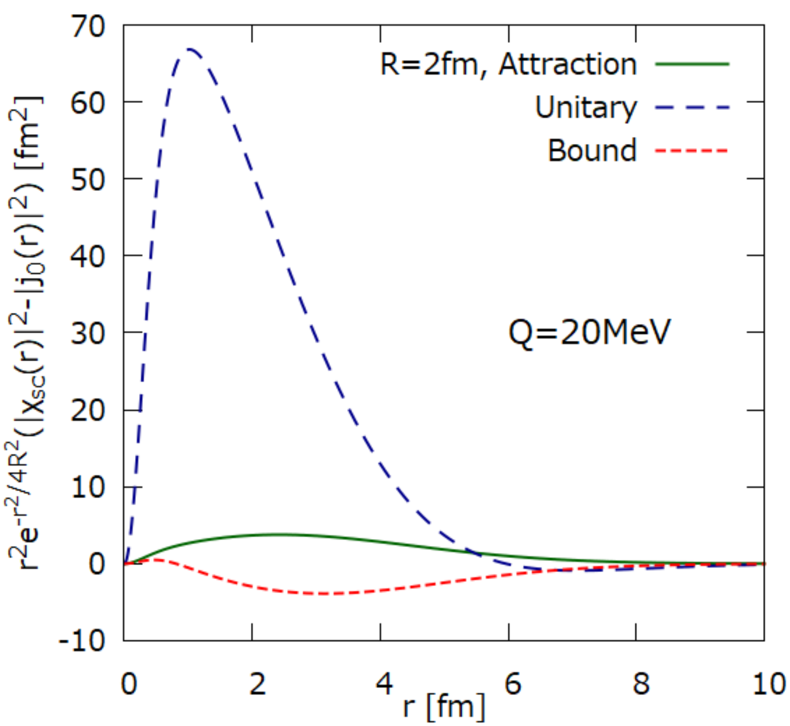
Parameters

Centrality	0-10%	10-20%	20-40%	40-60%	60-80%
τ_0 [fm]	10.0	7.9	6.75	4.89	2.0
R [fm]	5.18	4.74	3.8	2.55	1.6
α	0.38	0.38	0.38	0.38	0.37

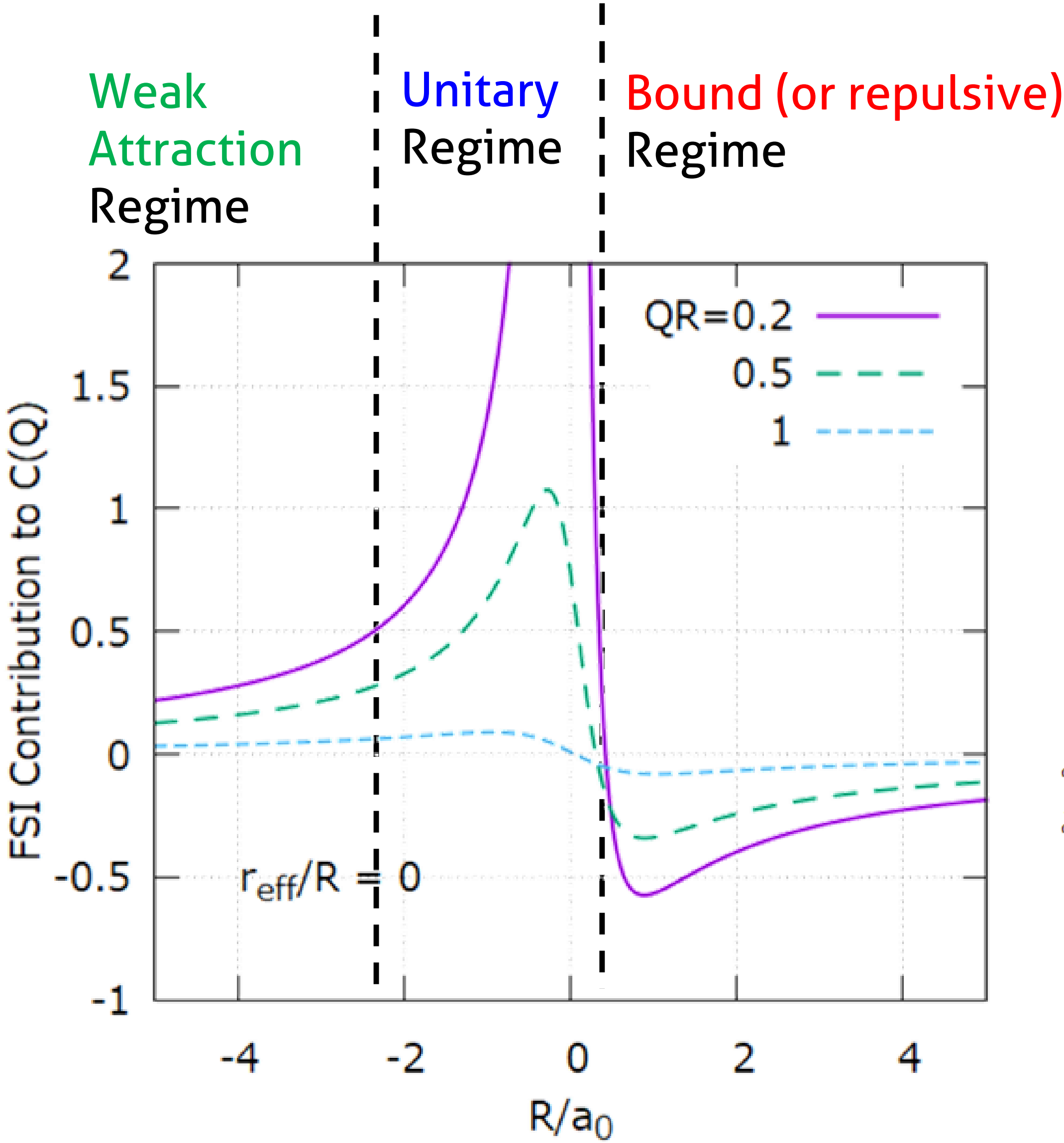
Correlation from FSI



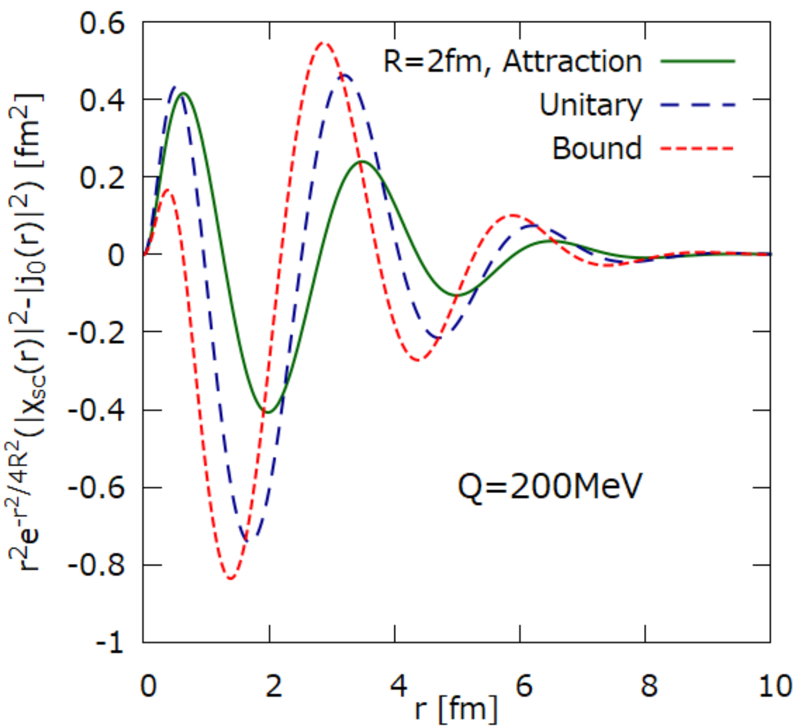
Source func × Wave func diff.



Correlation from FSI

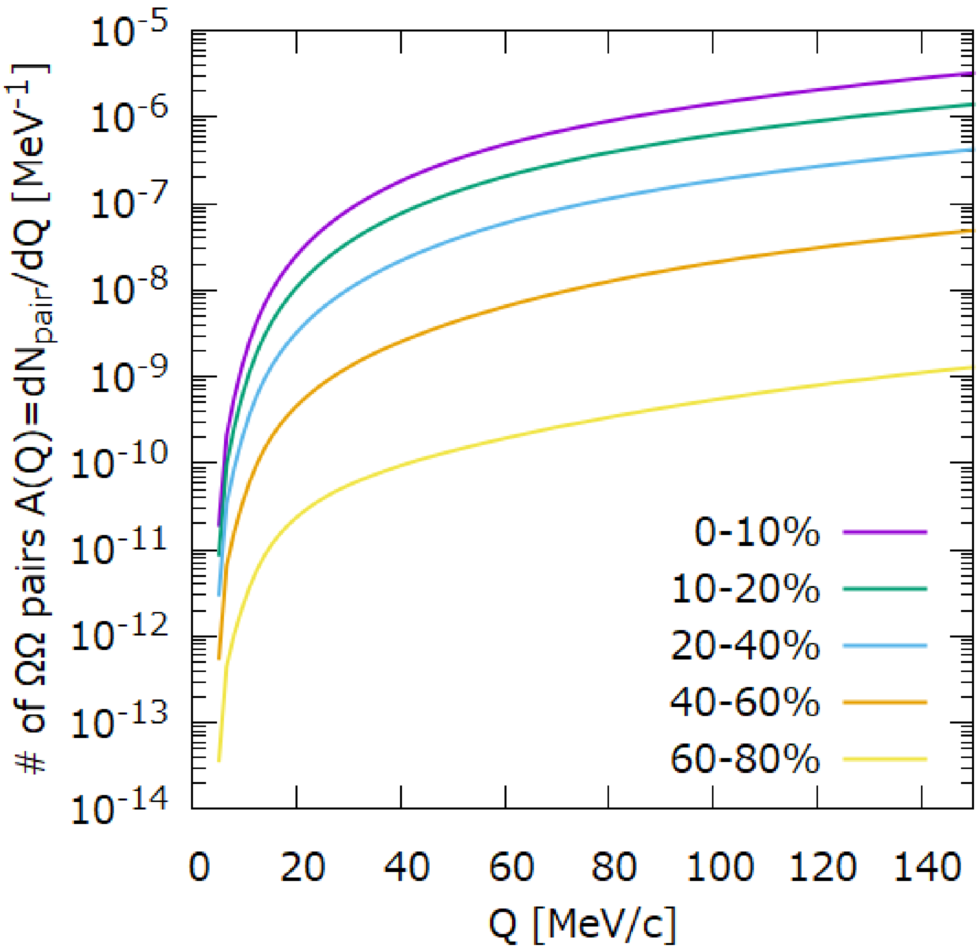


Source func × Wave func diff.



ΩΩ Correlation: Statistics?

of pair A(Q)



To have 100 pairs at low Q:

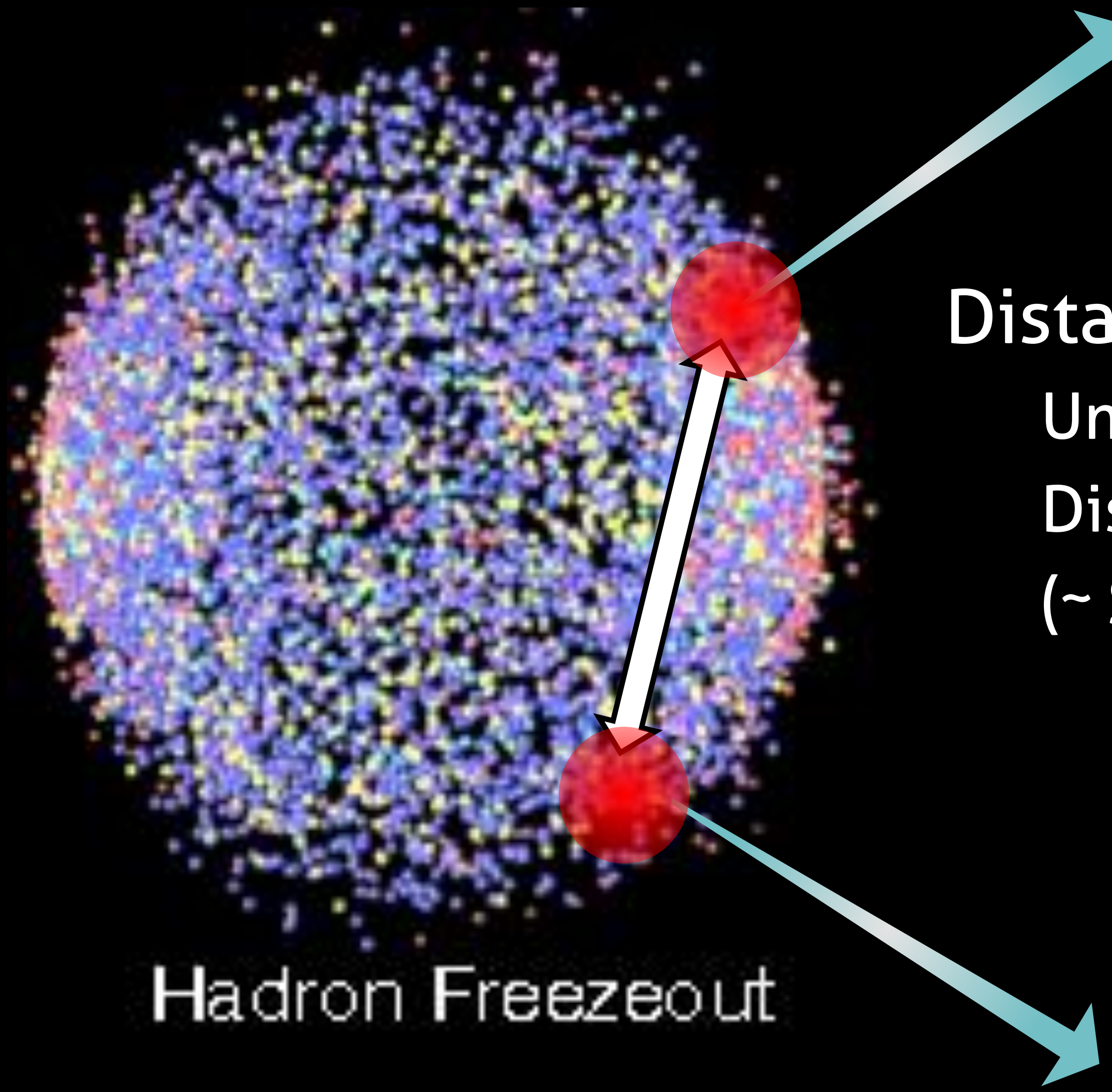
Acceptance×Efficiency : 0.01-0.1

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)

Counting Correlated Pairs



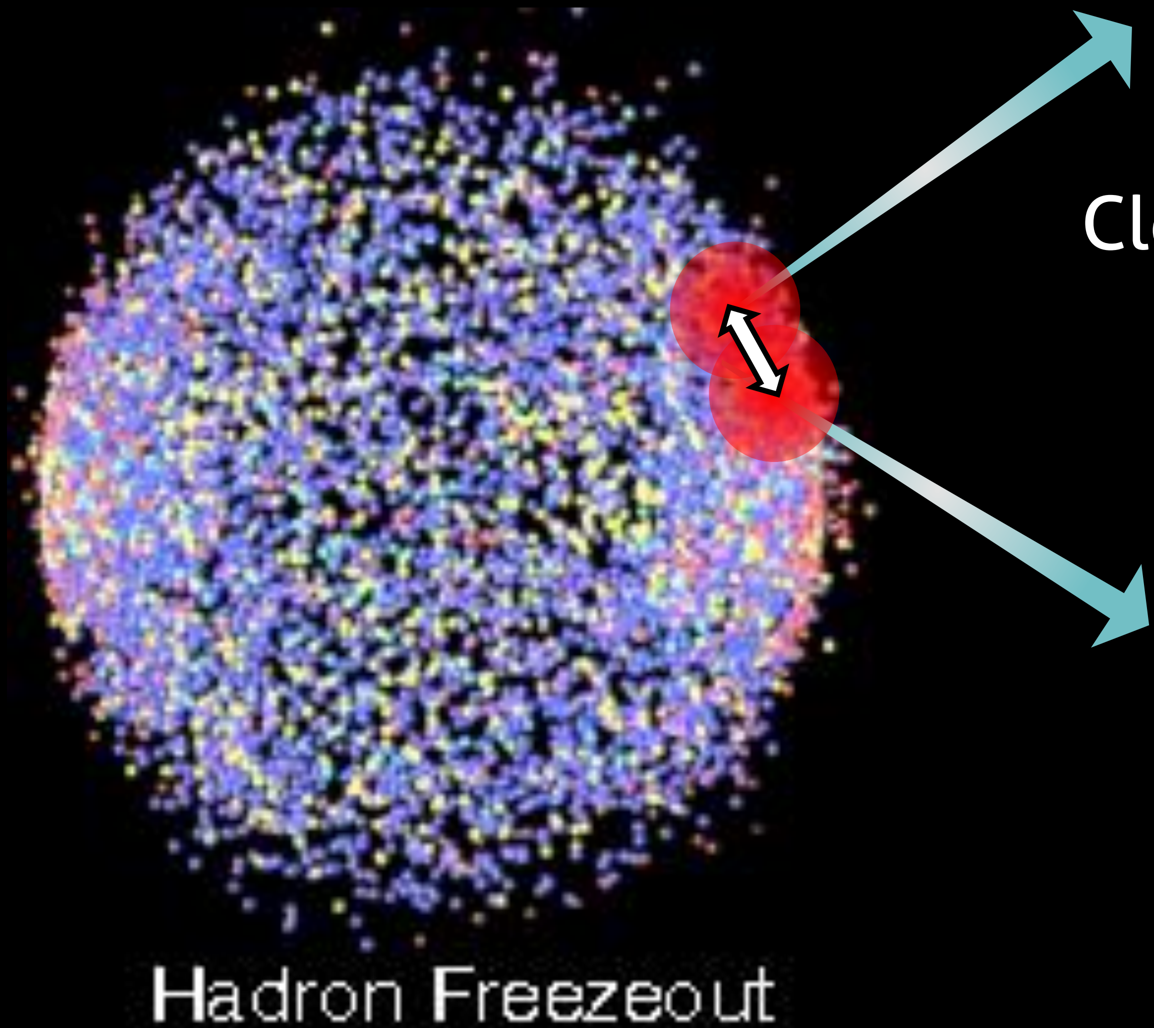
Distant pairs:

Uncorrelated because

Distance < int. range

(~ System size)

Counting Correlated Pairs



Close pairs:

Correlated through FSI

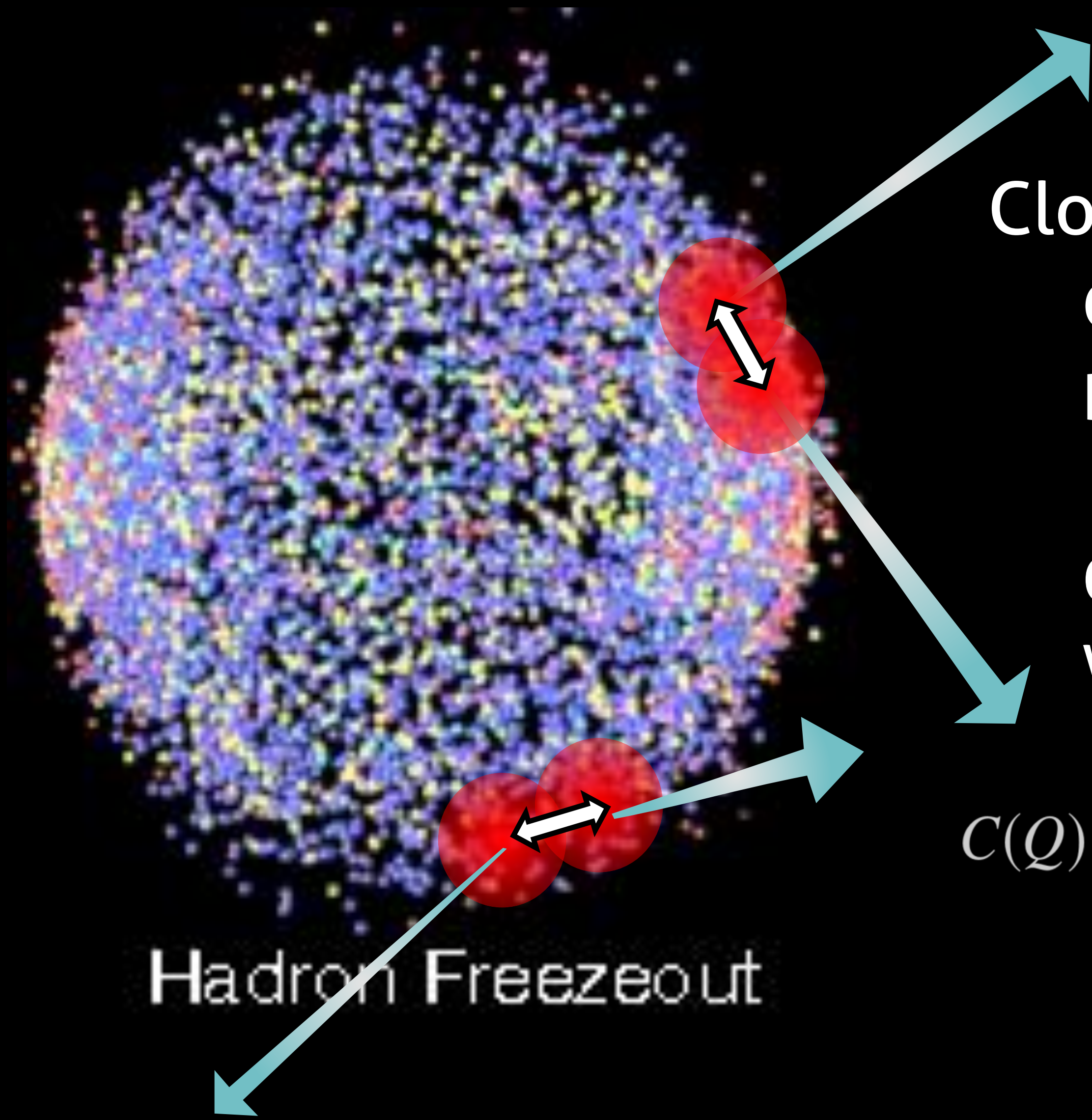
Distance < int. range

FSI : $\psi(Q^*, r^*)$

Input from V(r)

(phenomenological / Lattice)

Counting Correlated Pairs



Close but large Q pairs:

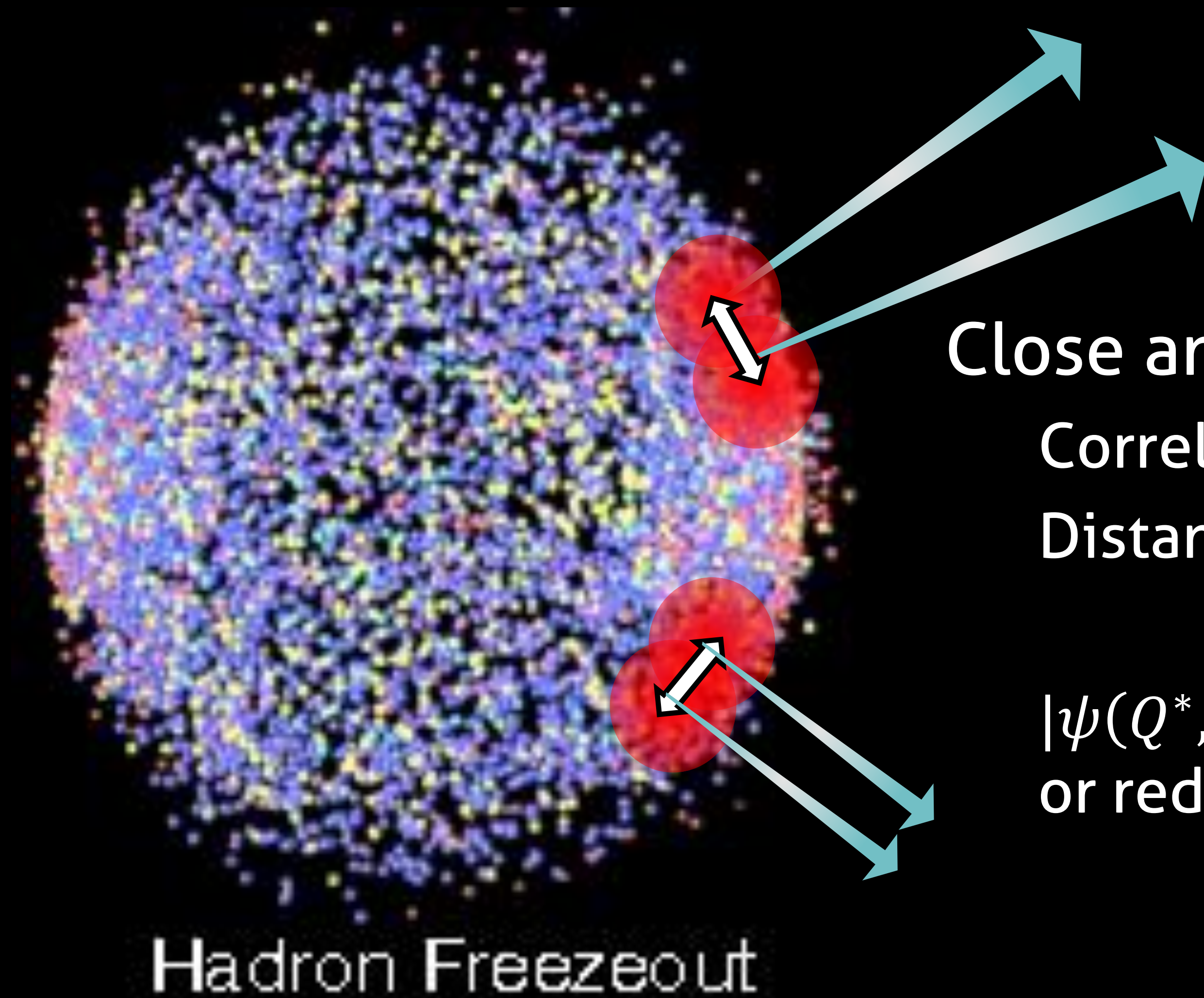
Correlated through FSI

Distance < int. range

Oscillating $|\psi(Q^*, r^*)|^2$ washes out correlation

$$C(Q) \propto \int_r S(r)|\chi_Q(r)|^2 - |j_0(Qr)|^2$$

Counting Correlated Pairs



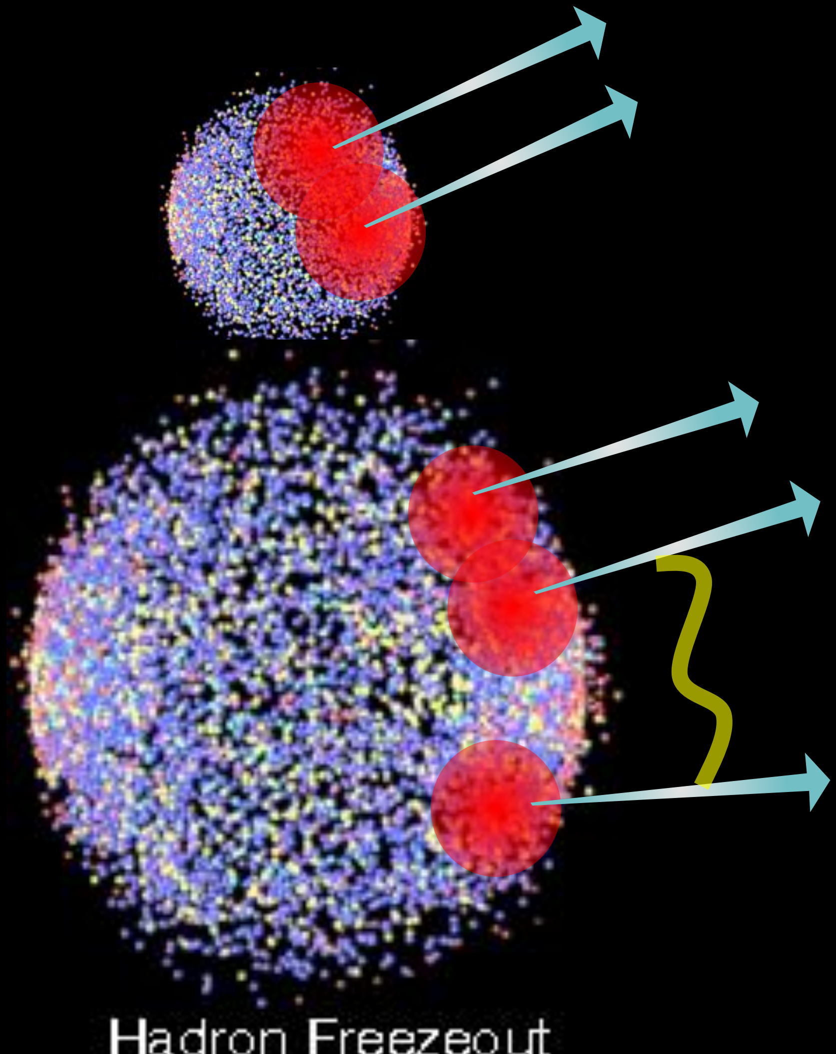
Close and small Q pairs:

Correlated through FSI

Distance < int. range

$|\psi(Q^*, r^*)|^2$ leads enhance or reduction of # of pairs

System Size?



Small System:

Most of observed pairs with small Q correlated

Large System:

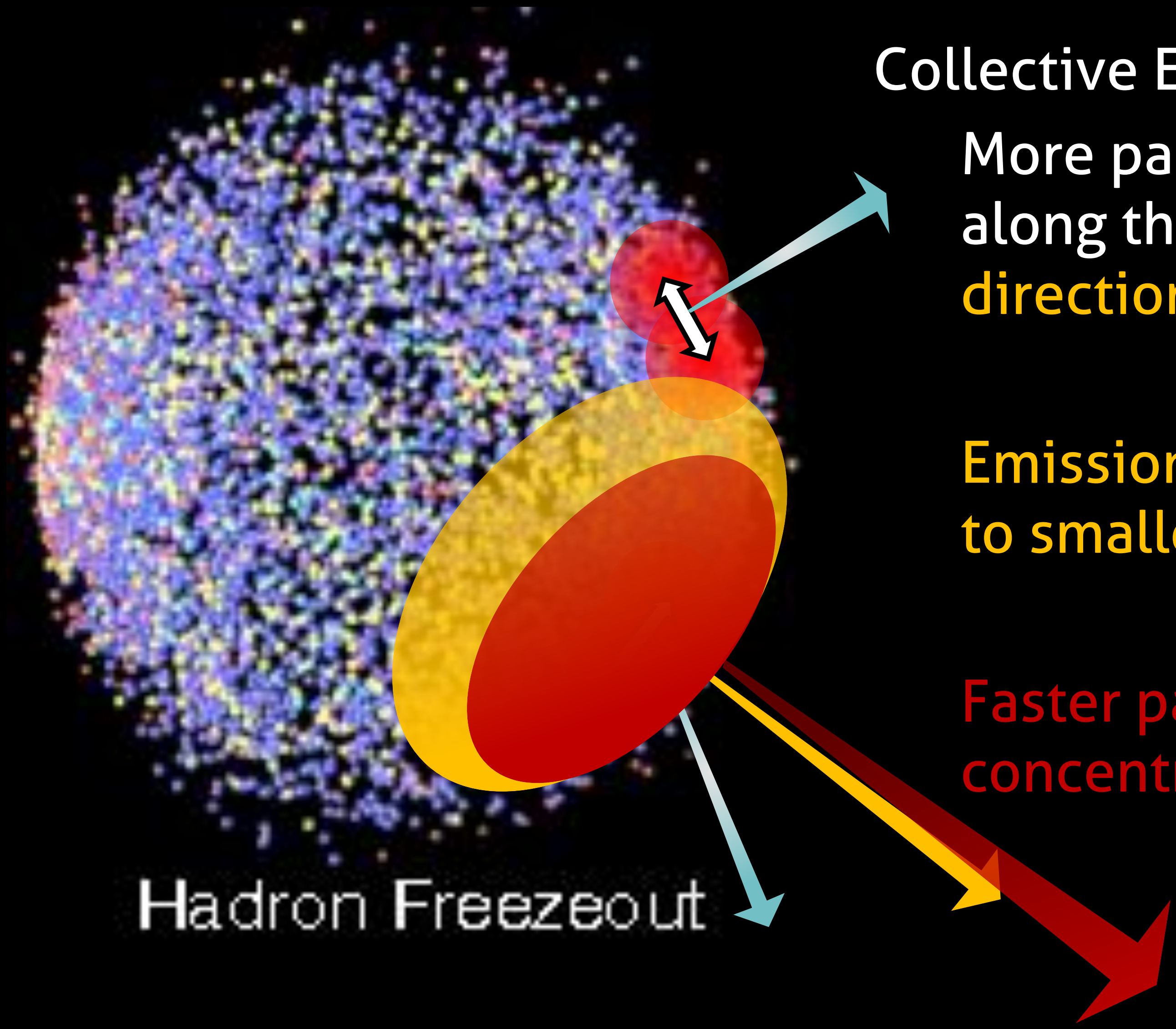
Less pairs coming from close distance

Important Remark:

Coulomb FSI for charged pairs!

Conclusion : measure small Q pairs coming from small region!

Effect of Collectivity



Collective Expansion:

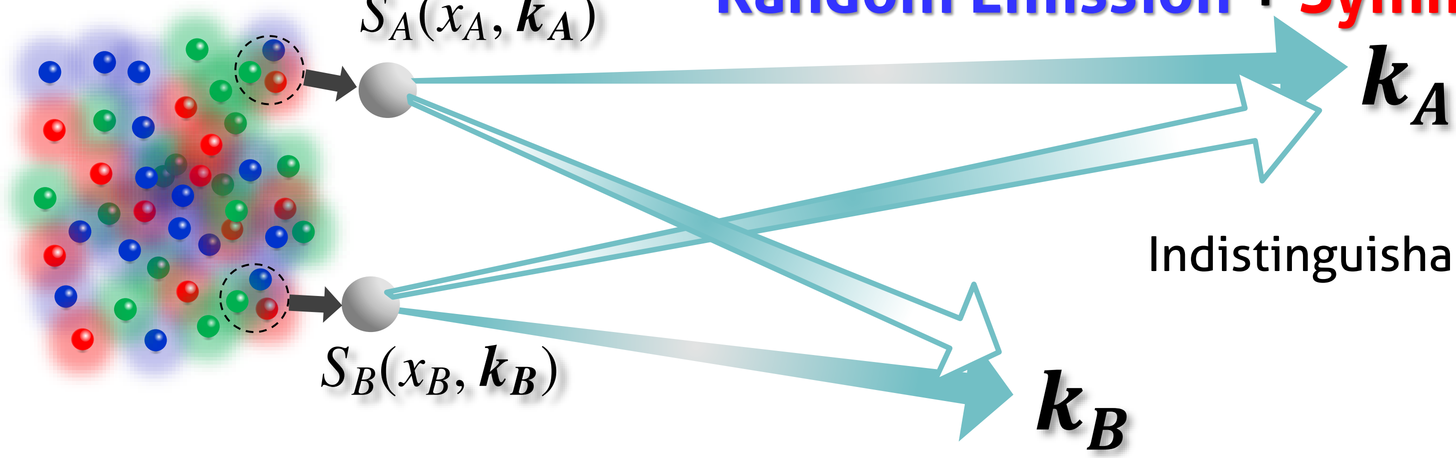
More particles produced along the expanding direction

Emission region deformed to smaller one

Faster pairs more concentrated

Quantum Statistics (HBT/GGLP)

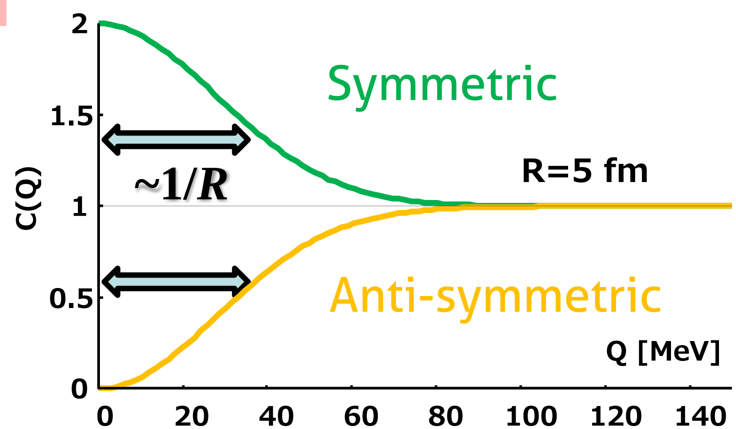
Random Emission + **Symmetrization**



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

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

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



Fourier tr. of the emission func.