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Analyses of multi pion Bose-Einstein correlations for granular sources with coherent pion emission droplets

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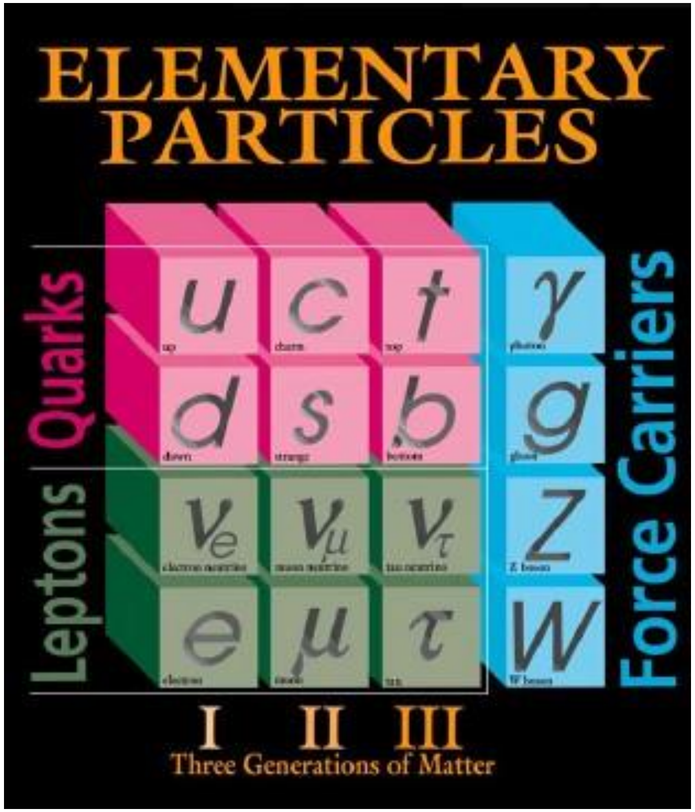
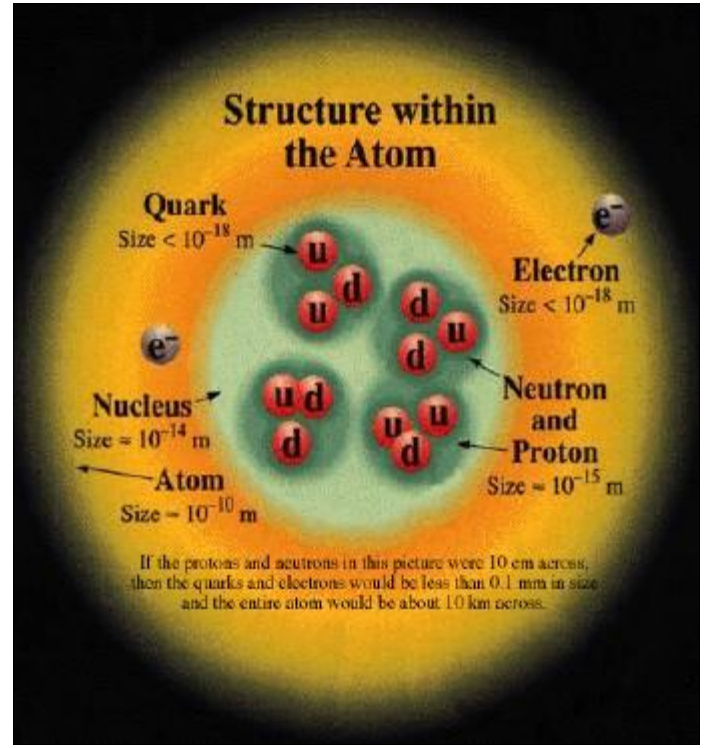
Outline

- Introduction
- Historical Background
- Experimental Results about Bose-Einstein Condensation
- Analyses of multi-pion Bose-Einstein correlations for the granular sources with coherent pion emission droplets
- Conclusion

Introduction

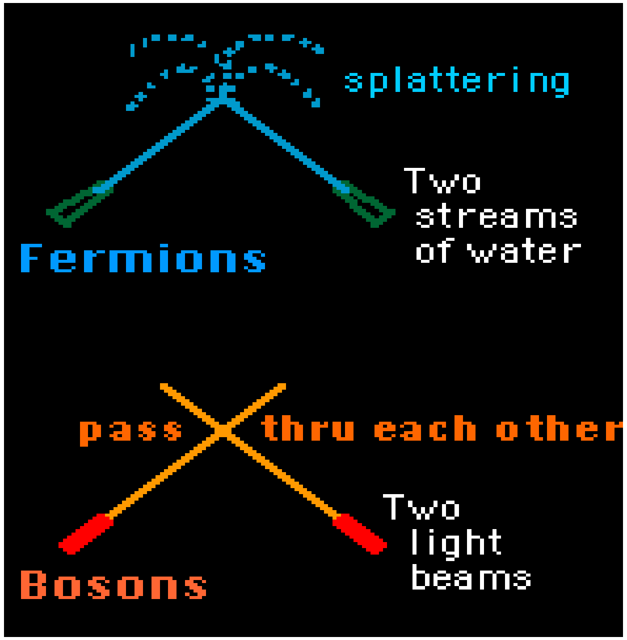




Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$...	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

Quantum Mechanics

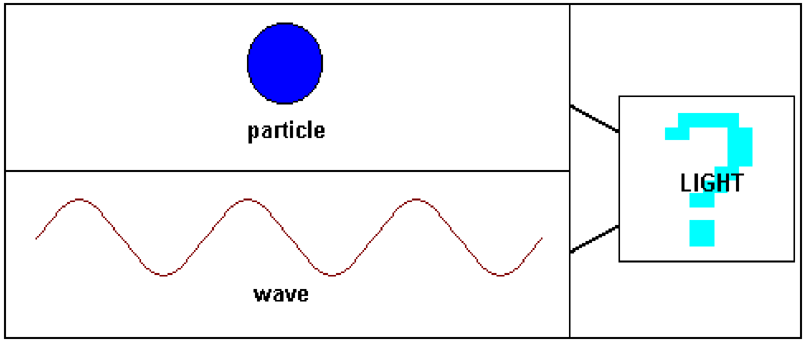
Central concept of quantum mechanics:
all particles present wave-like properties



De Broglie showed that moving particles have an equivalent wavelength λ

$$\lambda \propto \frac{1}{p}$$

So high momentum gives us short wavelengths so we can make out small details



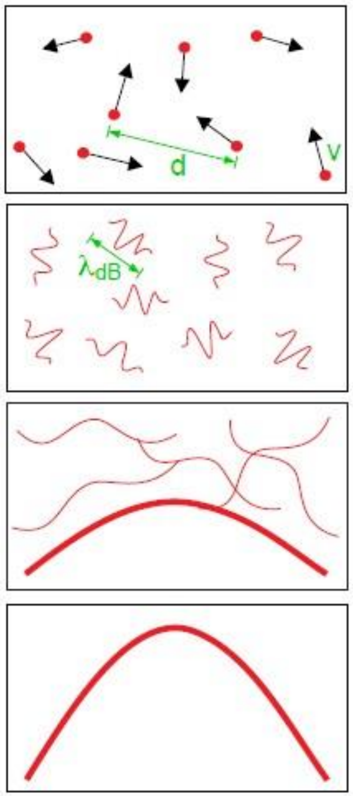
How to imagine the wave-particle duality.

Not only light has a dual nature

Bose-Einstein condensation

1924, Bose-Einstein

1995, Ketterle et al

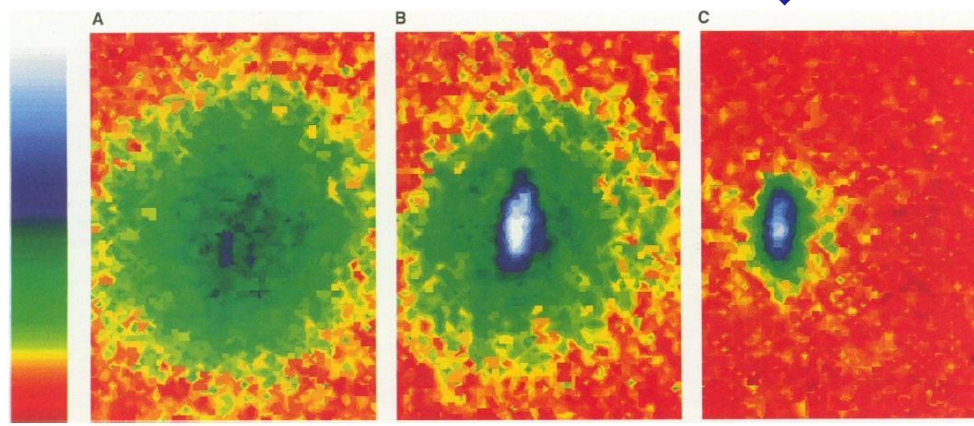


High Temperature T:
thermal velocity v
density d^{-3}
"Billiard balls"

Low Temperature T:
De Broglie wavelength
$\lambda_{dB}=h/mv \propto T^{-1/2}$
"Wave packets"

$T=T_{crit}$: Bose-Einstein Condensation
$\lambda_{dB} \approx d$
"Matter wave overlap"

T=0: Pure Bose condensate
"Giant matter wave"

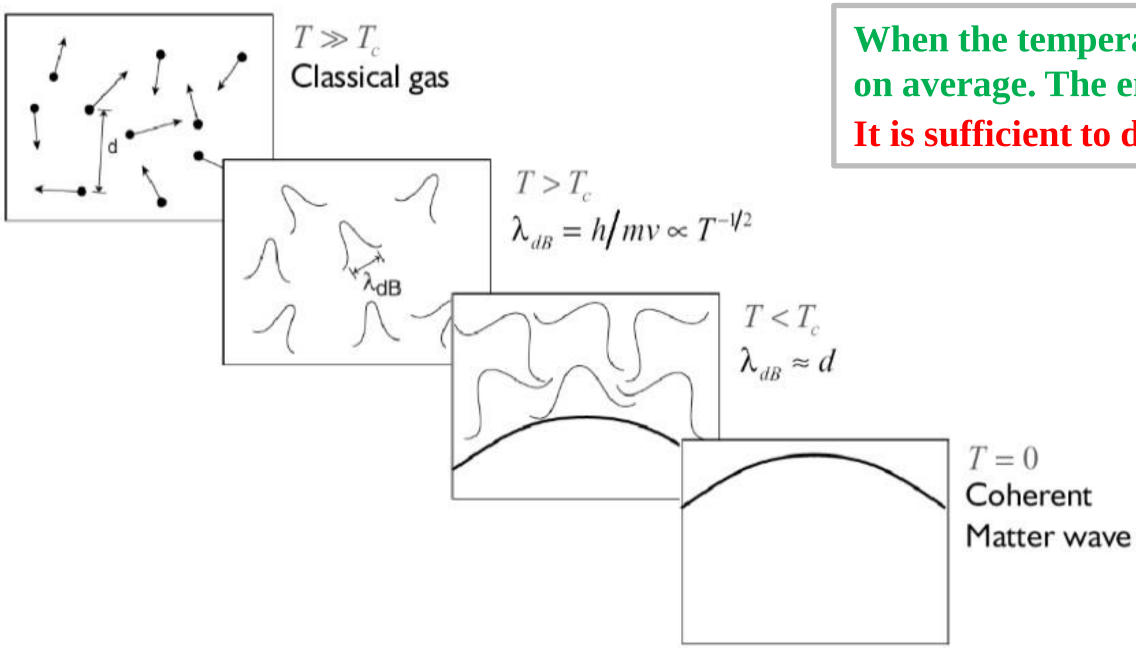


A: Just before the appearance of condensate
B: Just after the appearance of condensate
C: Nearly pure condensate

$\Delta x \Delta p \sim \hbar$

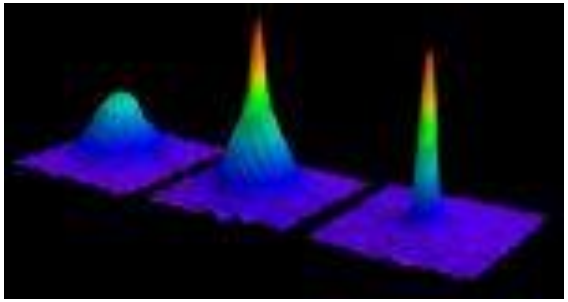
Condensate fraction is elliptical that is an indication of highly non thermal distribution.
This pattern is an image of single, macroscopically occupied quantum wave function

Bose-Einstein condensation



When the temperature is high, the atoms have high energies on average. The energy levels are almost continuous.
It is sufficient to describe the system by classical physics.

When the temperature is very low, a large fraction of atoms suddenly crash into the lowest energy state. This is called Bose-Einstein condensation.



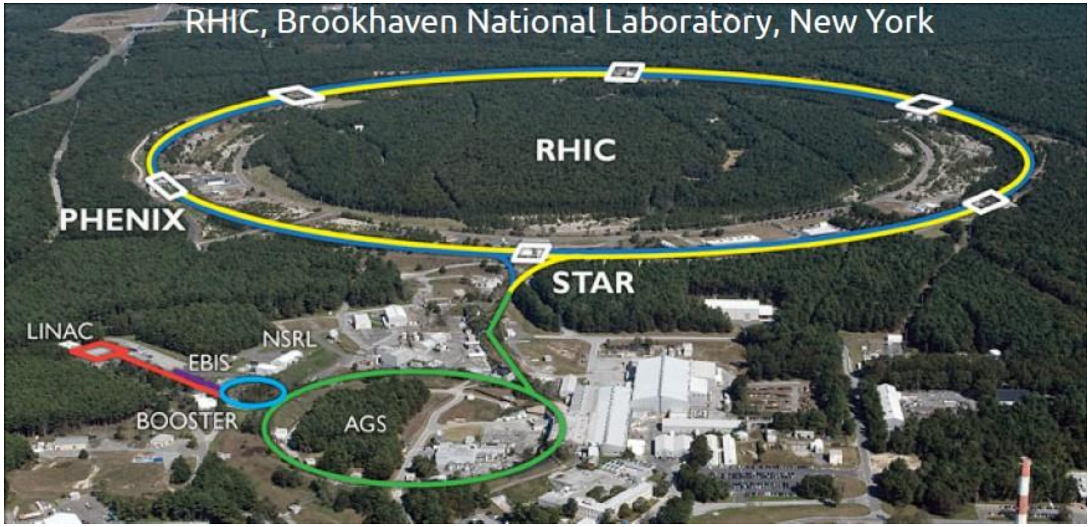
After condensation, the atoms lie exactly on top of each other (a super atom)

What happen at High Energy ?

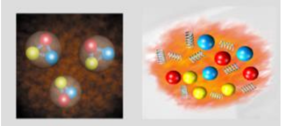
High Energy Heavy-Ion Collisions

Little Bangs

Low energy collisions create no QGP but High energy collisions can



Can we produce particles in lab ?



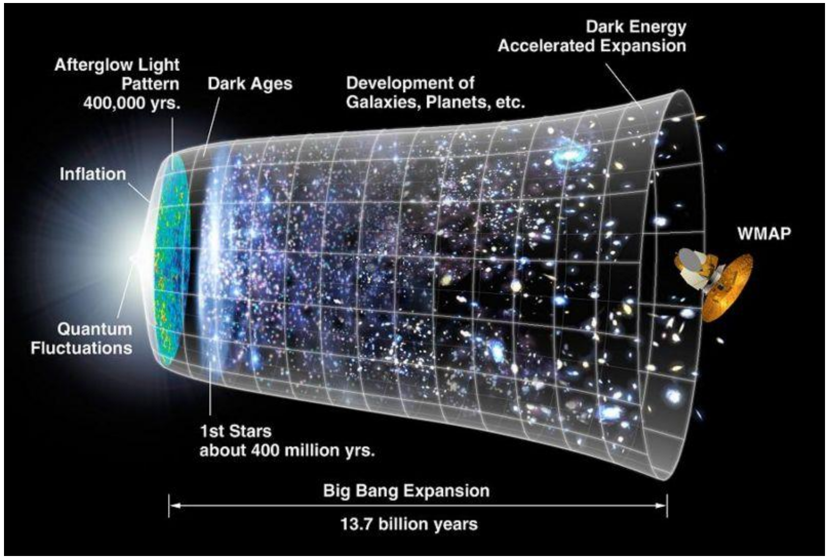
Dynamics: QCD

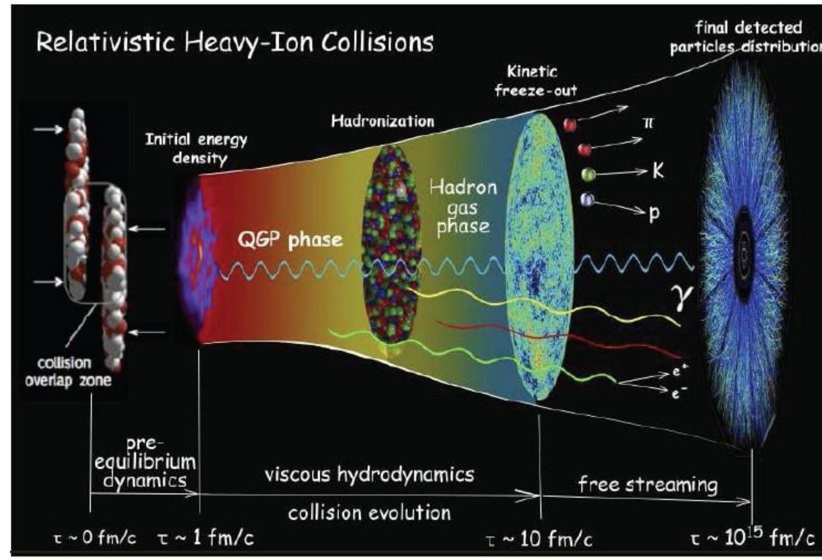
Which Dynamics ?

Various stages of heavy ion collisions

Big Bang

Little Bang



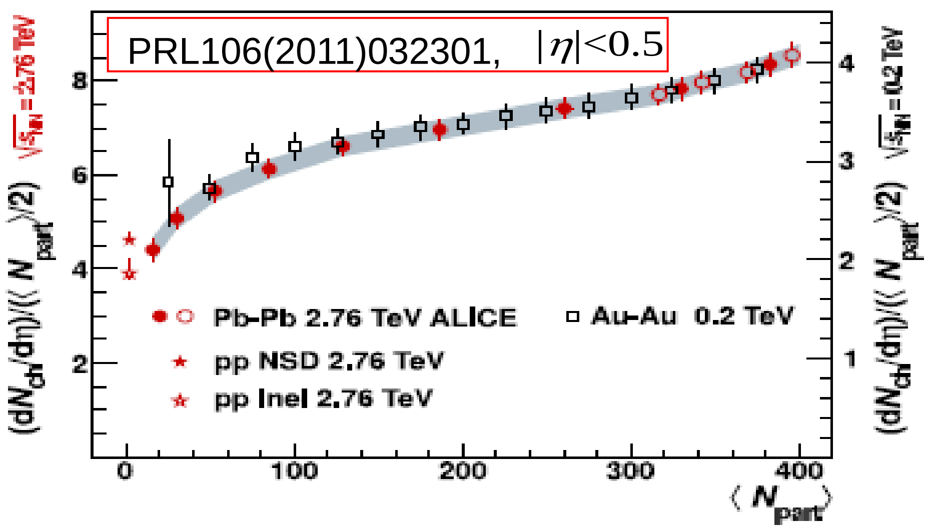


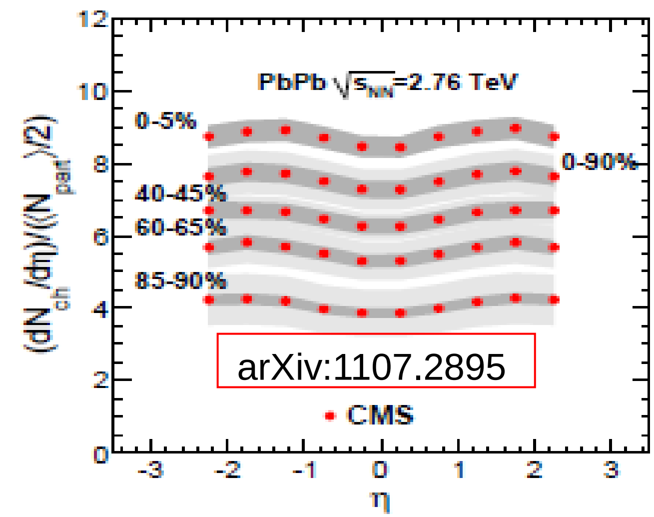
1: Collision of two-nuclei or CGC plates
2: Deposition of kinetic energy and formation of glasma
3: Emission of partons from glasma
4: Thermalization of partons and formation of QGP
5: Hydrodynamic expansion, cooling and dilution
6: Hadronization-kinetic theoretical expansion
7: Chemical freeze-out: Inelastic collisions stop
8: Kinetic freeze-out: Particle scattering stops
9: Detection of particles- Extraction of QGP properties.

HBT

Experimental results

- HBT interferometry is a tool to study the space & time of particle-emitting sources.
- Because HBT correlation occurs only for chaotic sources. So, it can be used to probe the source chaotic degree.
- Pions are the most copiously produced particles in high-energy collisions. In the heavy-ion collisions at the RHIC and LHC, the detected identical pions are about hundreds and thousands.





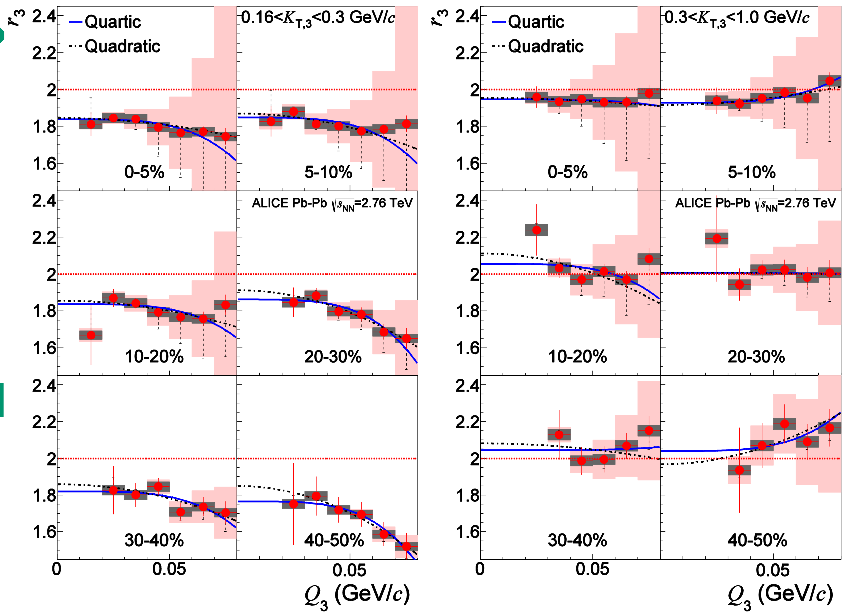
$$0-5\%,\ \langle N_{\rm part}\rangle = 383,\ \ dN_{\rm ch}/d\eta = 1601,\quad N_{\rm ch} \approx 1601\times 4 = 6400$$

The high pion event multiplicity may possibly lead to occurrence of the pion condensate in ultra-relativistic heavy-ion collisions.

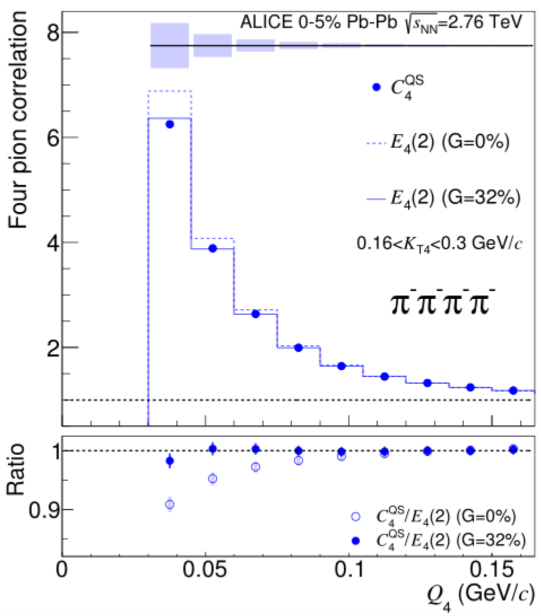
Experimental results

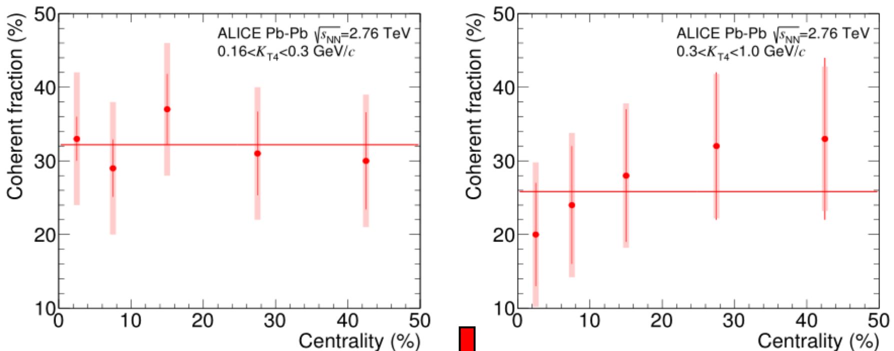
Three-pion HBT measurements for the $\sqrt{s_{NN}}$=2.76 TeV Pb-Pb at the LHC (PRC**89**,2014,024911) indicate that the pion sources are not chaotic completely and with the considerable degree of coherence

r_3 < 2 Partially coherent sources



(PRC**93**,054908,2016)





(a) $0.16 < K_{T4} < 0.3$ GeV/c (b) $0.3 < K_{T4} < 1.0$ GeV/c

20-40 % coherent fraction extracted at ALICE

It is our motivation to study the possible pion Bose-Einstein condensation in ultra-relativistic heavy-ion collisions and investigate the effects of the condensation on pion HBT measurements.

Granular Source Model

Analyses of multi-pion Bose-Einstein correlations for the granular sources with coherent pion emission droplets

J. Phys. G **45**, 065102 (2018), Phys. Lett. B **777**, 89-85 (2018),
J. Phys. G **46**, 115107 (2019), *Chinese Phys. C* **45**, 24106 (2021)

Granular source model

1: The mixed phase must consist of well-separated droplets of plasma
2: At a given temperature, the plasma is much denser than the hadronic gas
3: Needs only small volume to accommodate its share of energy and entropy

Why granularity ?

1: The fluctuating initial density distribution
2: Violent expansion
3: Surface tension
4: Viscosity of the QGP

$$n = \left(\frac{R_G}{d}\right)^3$$

Distributions

1: The mean droplet radius " r_d "
2: The mean separation "d" between the droplets
3: The overall radius " R_G " of the mixed-phase system

R_G: Describes the correlation for small relative momenta

r_d: Describes the correlation for large relative momenta

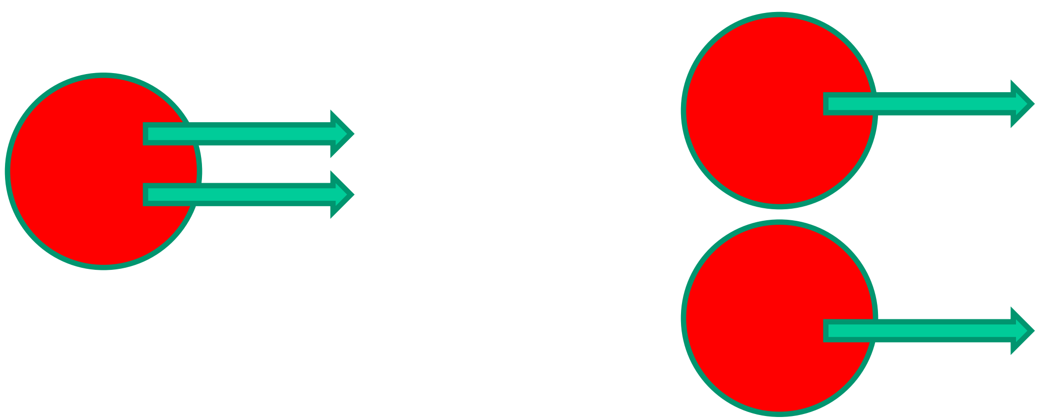
Formula about two-pion correlation

In the case of Two-pion correlations

$$C_2(p_1,p_2) = 1 + \frac{1}{n} exp\left(-q_{12}^2 r_{\mathrm{d}}^2\right) + \left(1 - \frac{1}{n}\right) exp\left[-q_{12}^2\left(r_{\mathrm{d}}^2 + R_{\mathrm{G}}^2\right)\right]$$

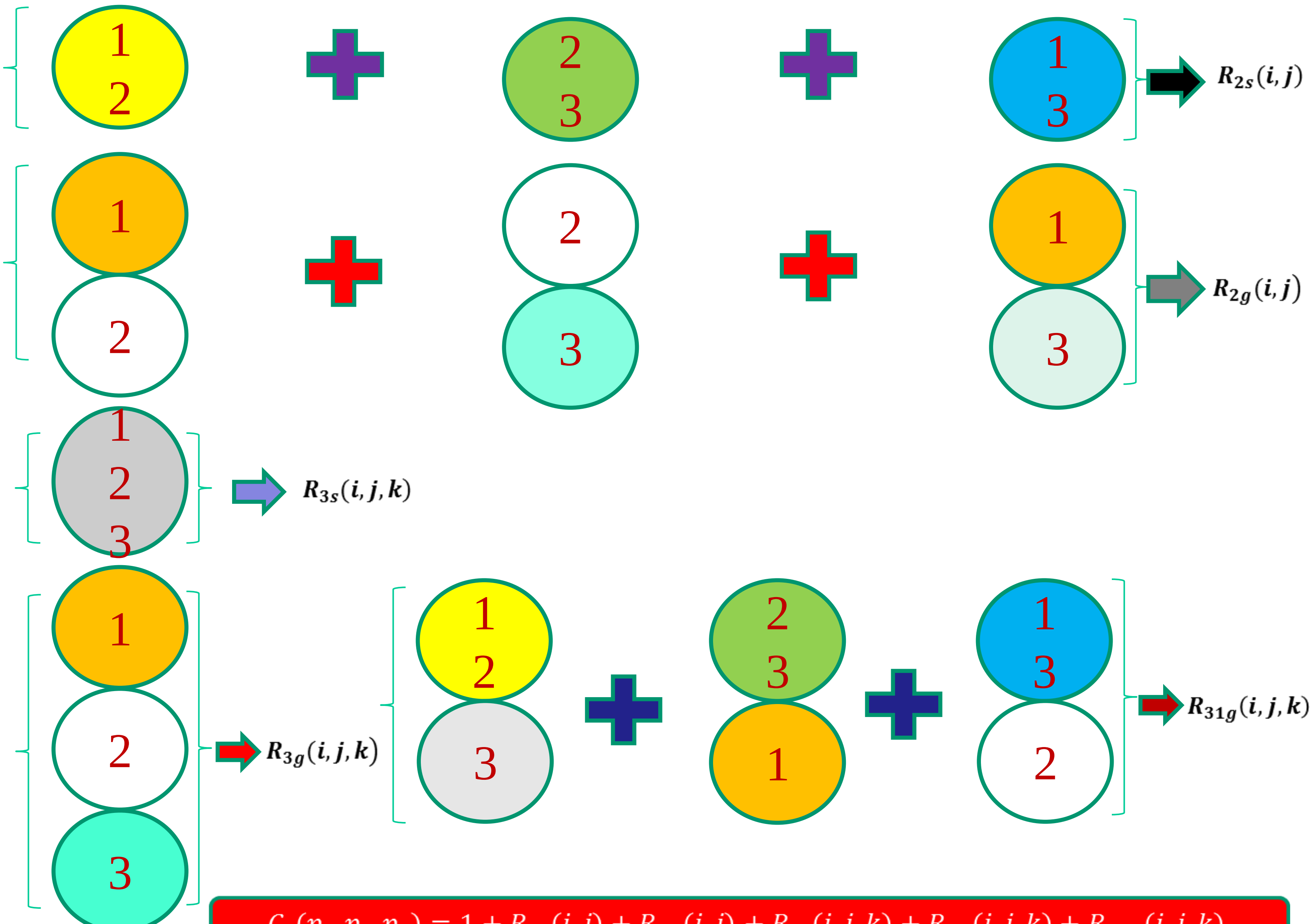
Same droplet

Different droplets



We examine the multi-pion correlation functions for a granular source model of coherent droplets under the assumption that the pions emitted from the same droplet are coherent

Three-pion correlation function



$$C_3(p_1,p_2,p_3) = 1 + R_{2s}(i,j) + R_{2g}(i,j) + R_{3s}(i,j,k) + R_{3g}(i,j,k) + R_{31g}(i,j,k)$$

Formulas for Granular sources

$$C_3(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3) = 1 + \frac{1}{n}\Big[\mathcal{R}^d(1,2)+\mathcal{R}^d(1,3)+\mathcal{R}^d(2,3)\Big] + \left(1-\frac{1}{n}\right)\Big[\mathcal{R}^G(1,2)+\mathcal{R}^G(1,3)+\mathcal{R}^G(2,3)\Big]$$
$$+\frac{2}{n^2}\Big[\mathcal{R}^d(1,2)\mathcal{R}^d(1,3)\mathcal{R}^d(2,3)\Big]^{\frac{1}{2}} + \frac{2(n-1)}{n^2}\Big[\Big(\mathcal{R}^d(1,3)\mathcal{R}^d(2,3)/\mathcal{R}^d(1,2)\Big)^{\frac{1}{2}}\mathcal{R}^G(1,2)$$
$$+\Big(\mathcal{R}^d(1,2)\mathcal{R}^d(2,3)/\mathcal{R}^d(1,3)\Big)^{\frac{1}{2}}\mathcal{R}^G(1,3) + \Big(\mathcal{R}^d(1,2)\mathcal{R}^d(1,3)/\mathcal{R}^d(2,3)\Big)^{\frac{1}{2}}\mathcal{R}^G(2,3)\Big]$$
$$+\frac{2(n-1)(n-2)}{n^2}\Big[\mathcal{R}^G(1,2)\mathcal{R}^G(1,3)\mathcal{R}^G(2,3)\Big]^{\frac{1}{2}},$$

Cumulant correlation function

$$c_3(Q_3) = 1 + \frac{2(n-1)(n-2)}{n^2} \times \Big[\mathcal{R}^G(1,2)\mathcal{R}^G(1,3)\mathcal{R}^G(2,3)\Big]^{\frac{1}{2}}(Q_3)$$

$$r_3(Q_3) = \frac{[c_3(Q_3)-1][n/(n-1)]^{3/2}}{\sqrt{\mathcal{R}^G(1,2)(Q_3)\mathcal{R}^G(2,3)(Q_3)\mathcal{R}^G(1,3)(Q_3)}}$$

Correlations functions for different droplets

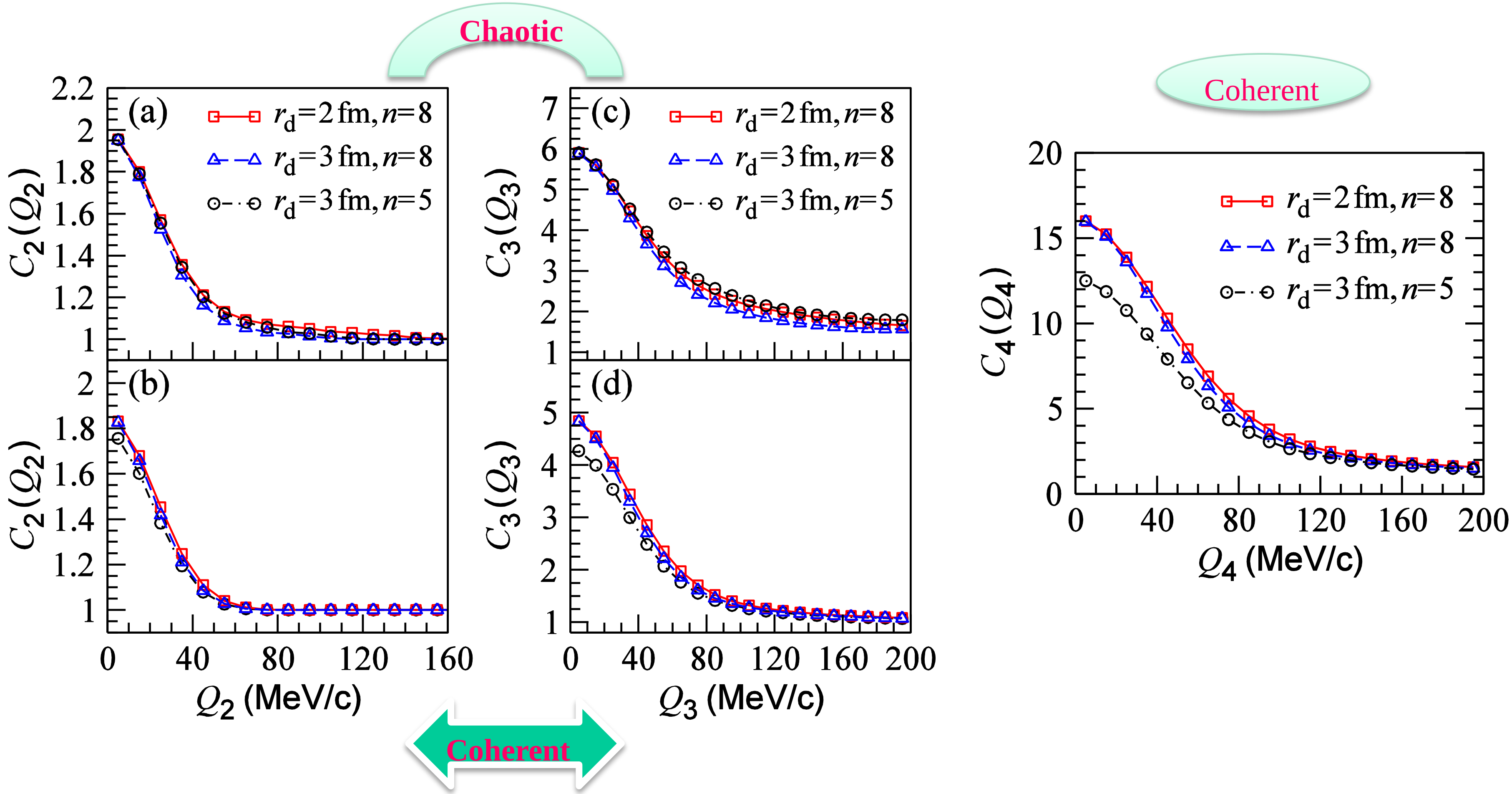
Formulas for Granular sources

$$
\begin{aligned}
C_4(\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3,\mathbf{p}_4) = 1 &+ \frac{(n-1)}{n}\Big[\mathcal{R}^G(1,2)+\mathcal{R}^G(1,3)+\mathcal{R}^G(1,4)+\mathcal{R}^G(2,3)+\mathcal{R}^G(2,4)+\mathcal{R}^G(3,4)\Big] \\
&+ \frac{2(n-1)(n-2)}{n^2}\bigg[\bigg(\mathcal{R}^G(1,2)\mathcal{R}^G(1,3)\mathcal{R}^G(2,3)\bigg)^{\frac{1}{2}} + \bigg(\mathcal{R}^G(1,2)\mathcal{R}^G(1,4)\mathcal{R}^G(2,4)\bigg)^{\frac{1}{2}} \\
&+ \bigg(\mathcal{R}^G(2,3)\mathcal{R}^G(2,4)\mathcal{R}^G(3,4)\bigg)^{\frac{1}{2}} + \bigg(\mathcal{R}^G(1,3)\mathcal{R}^G(1,4)\mathcal{R}^G(3,4)\bigg)^{\frac{1}{2}}\bigg] \\
&+ \frac{(n-1)^2}{n^2}\Big[\mathcal{R}^G(1,2)\mathcal{R}^G(3,4)+\mathcal{R}^G(1,3)\mathcal{R}^G(2,4)+\mathcal{R}^G(2,3)\mathcal{R}^G(1,4)\Big] \\
&+ \frac{2(n-1)(n-2)(n-3)}{n^3}\bigg[\bigg(\mathcal{R}^G(1,2)\mathcal{R}^G(2,3)\mathcal{R}^G(3,4)\mathcal{R}^G(1,4)\bigg)^{\frac{1}{2}} \\
&+ \mathcal{R}^G(1,3)\mathcal{R}^G(2,3)\mathcal{R}^G(2,4)\mathcal{R}^G(1,4)\bigg)^{\frac{1}{2}} + \mathcal{R}^G(1,2)\mathcal{R}^G(2,4)\mathcal{R}^G(3,4)\mathcal{R}^G(1,3)\bigg)^{\frac{1}{2}}\bigg],
\end{aligned}
$$

Normalized correlation function

$$
r_4(Q_4) = \frac{[c_4(Q_4)-1][n/(n-1)]^2}{\sqrt{\mathcal{R}^G(1,2)(Q_4)\mathcal{R}^G(2,3)(Q_4)\mathcal{R}^G(3,4)(Q_4)\mathcal{R}^G(1,4)(Q_4)}}
$$

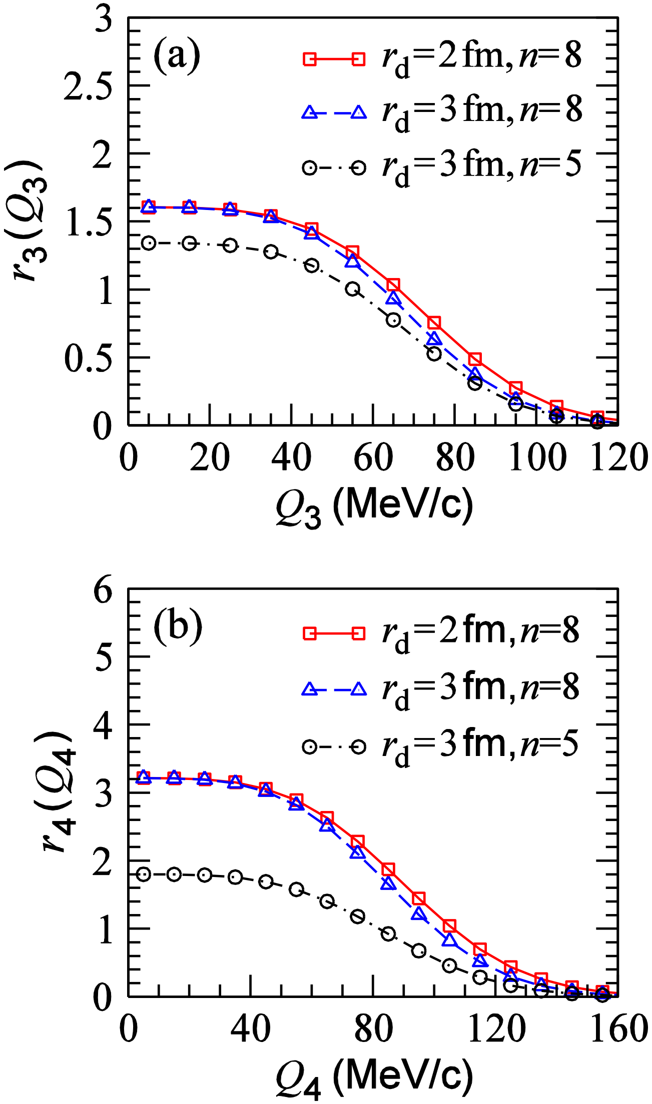
Multi-pion BECS of static granular sources

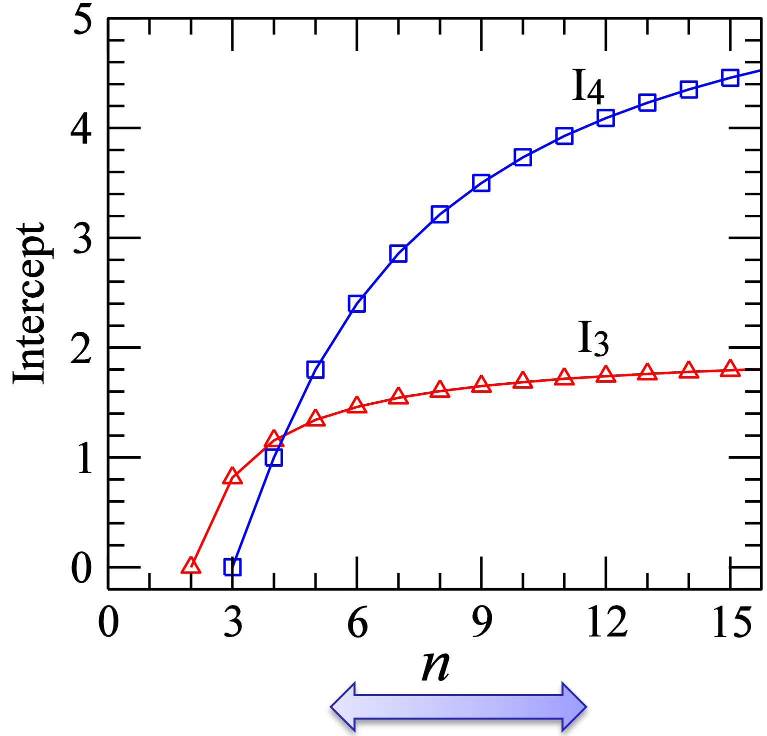


Intercepts of the correlations with coherent pion-emission decrease obviously compared to those with chaotic pion-emission droplets

However, **the widths of the correlation functions change slightly for the granular sources with chaotic and coherent pion-emission droplets**

Normalized correlation functions





Correlation functions have plateaus at low $Q_{3,4}$

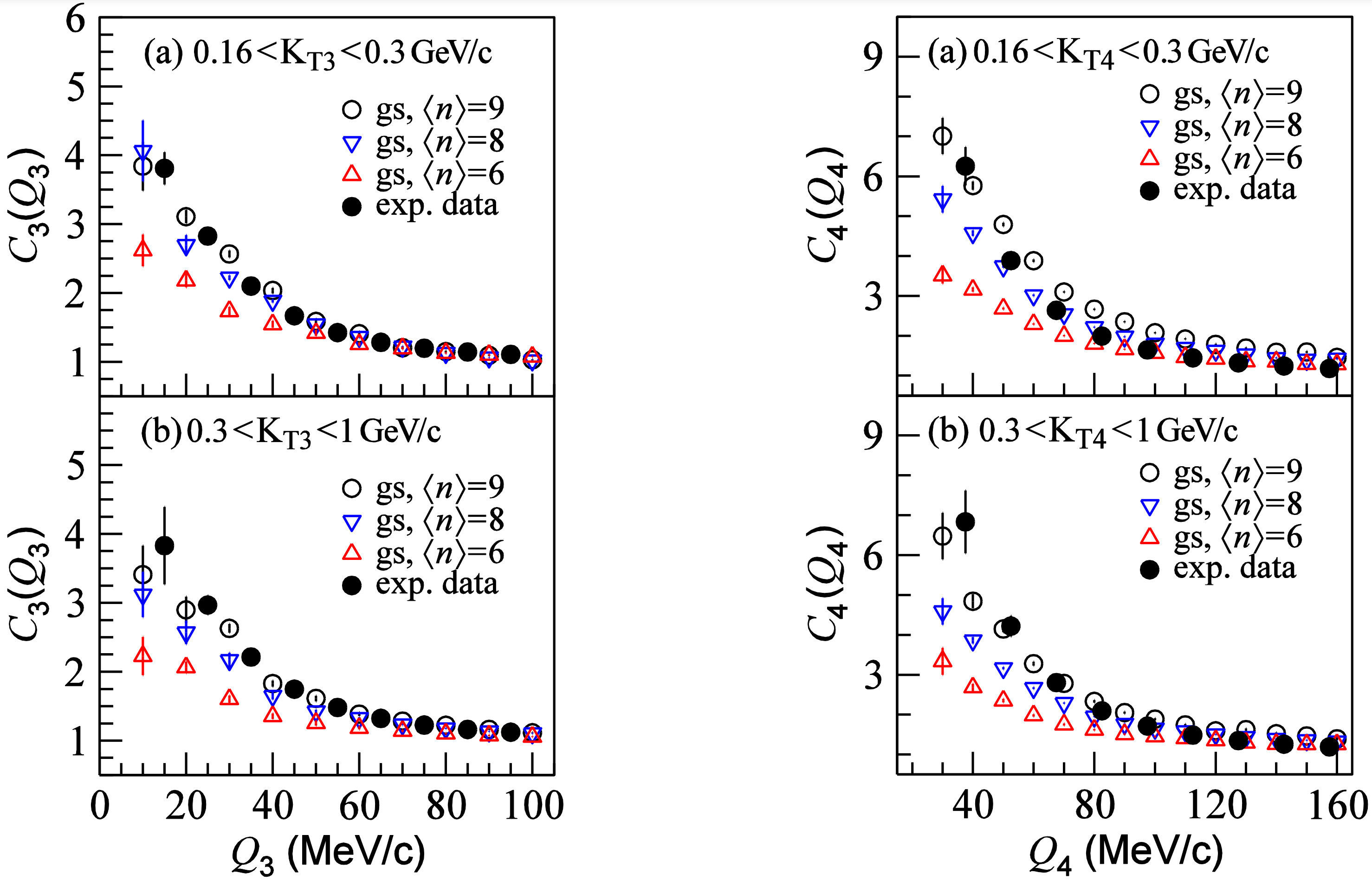
Intercepts of four-pion normalized correlation functions are more sensitive to the droplet number n than three-pion normalized correlation functions when $5 < n < 12$

Model results with experimental data

Pb-Pb @ ALICE

Evolving granular source model

Investigation of the multi-pion BECs for the evolving granular sources in which the droplets expand in viscous hydrodynamics and emit pions coherently and the droplet expansion in whole with anisotropic droplet velocities



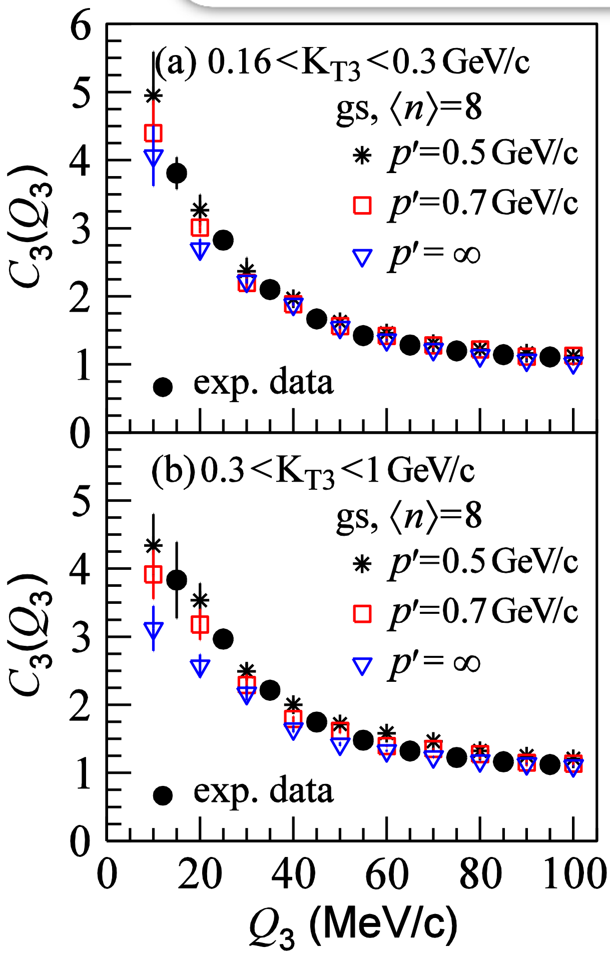
Pions with high momenta are more possibly emitted chaotically from the excited-states

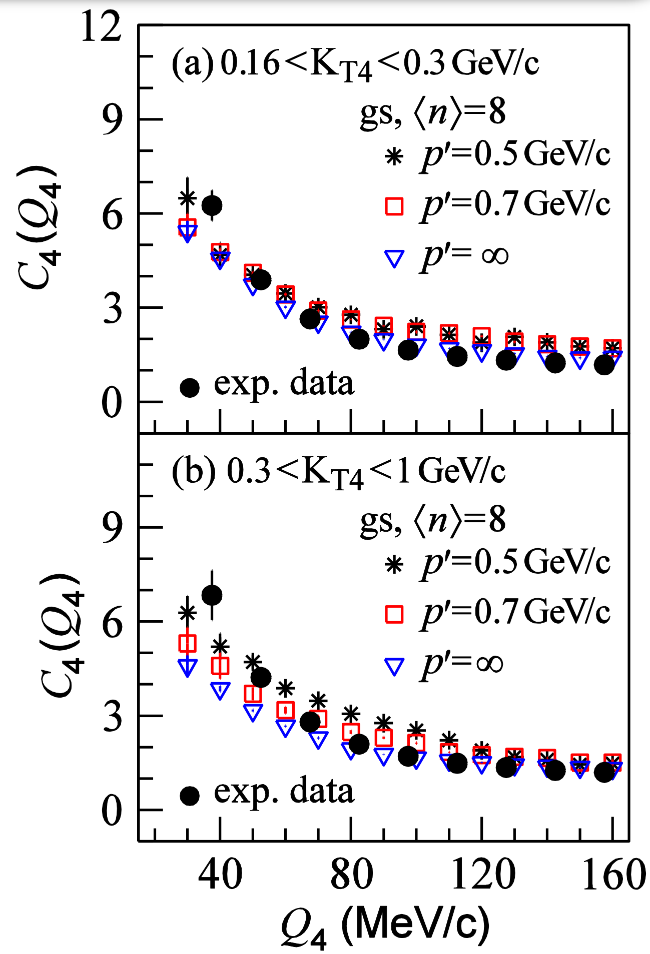
Pb-Pb @ ALICE

We further investigate the multi-pion correlations with partially coherent pion-emission droplets under the assumption that pions emitted from one droplet

1: Pions with momenta lower than a fixed value p' are amplitude coherent

2: Pions with momenta higher than p' are chaotic emission

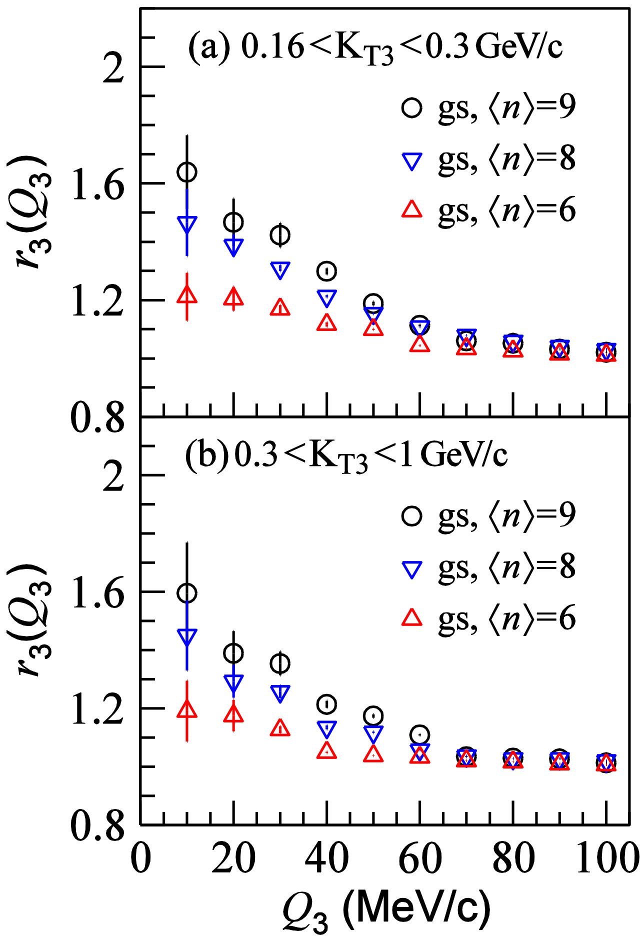


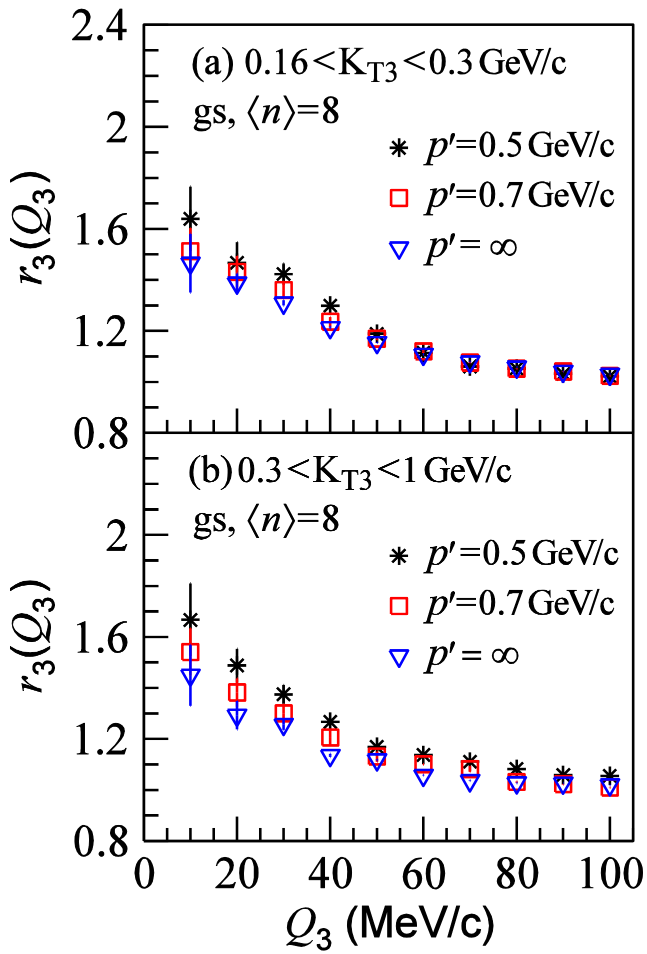


1: coherent pion emission droplets $p' = \infty$
2: The partially coherent pion emission droplets $p' = 0.5$ 0.7 GeV/c

It may needs more considerations to the momentum-dependence of coherent pion-emission from one droplet

Normalized three-pion correlation functions

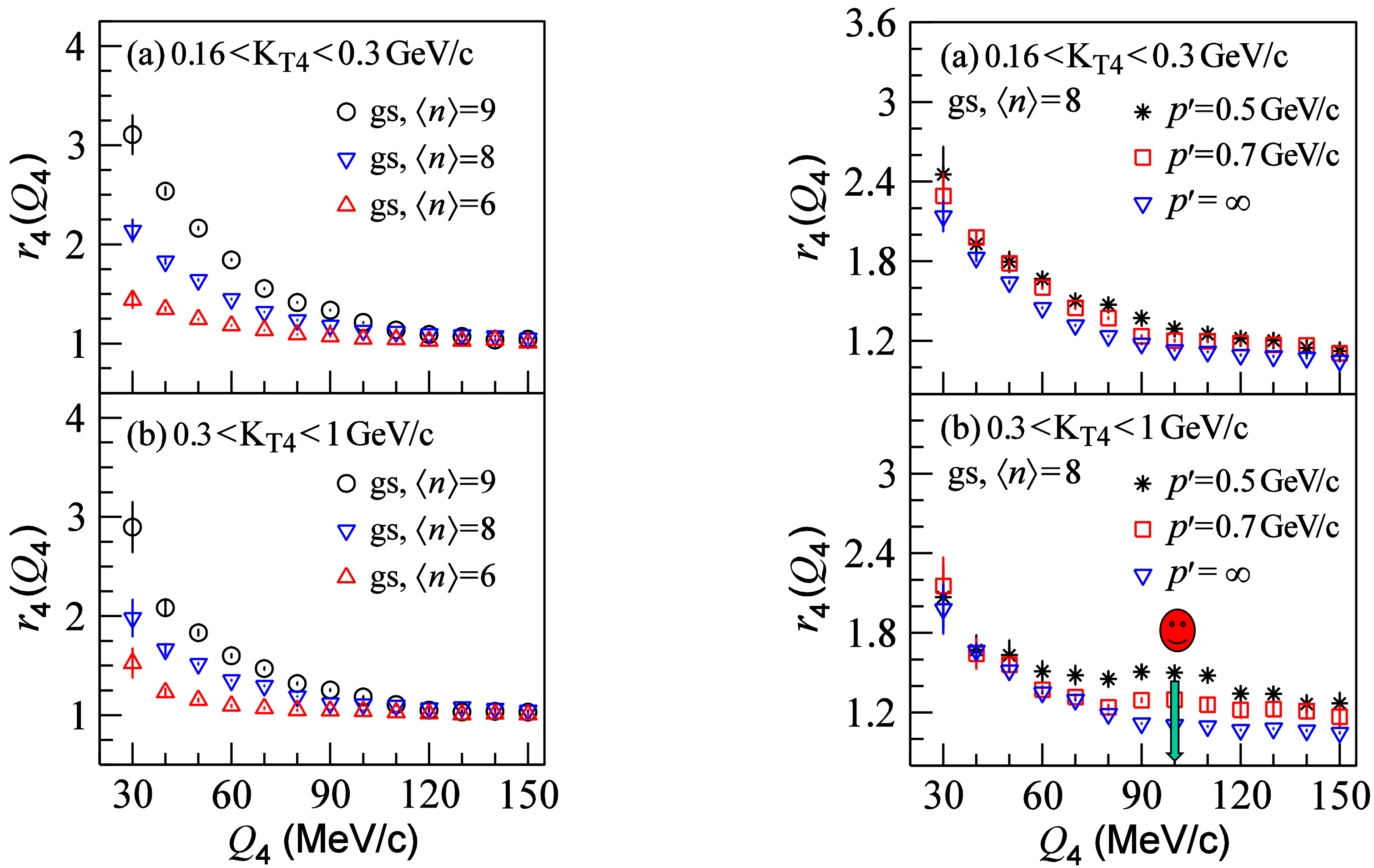




Results indicate that the three-pion cumulant correlation decreasing more rapidly than those two-pion correlations with increasing relative momenta

Intercepts of correlation functions are in approximately in agreement at Q3=0 because the intercepts are mainly determined by droplet number in the granular source

Normalized four-pion correlation function



It is a signal of pion coherent emission caused by identical boson condensation

r4 for smallest p' has a obvious enhancement around $Q4\sim100$ MeV/c due to the momentum dependence of coherence pion emission and the sensitivity of high-order pion correlations to source coherence

Conclusion

- **We investigated the three- and four-pion correlation functions in the granular source model with coherent,chaotic and partially coherent-pion emission droplets**

- It is found that the **intercepts** of the multi-pion correlation functions at **zero relative momentum** are sensitive to the droplet number in the granular source

- **The three and four-pion correlation functions of evolving granular sources are in *basic agreement with recent experiment data* measured by the ALICE Collaboration in central Pb-Pb collisions**

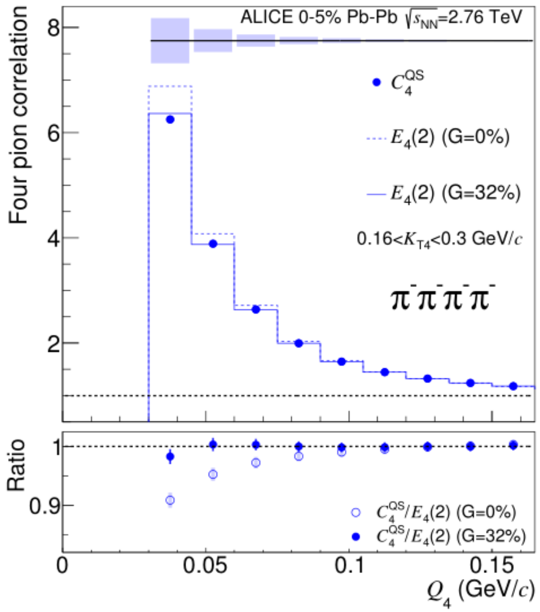
- **Normalized four-pion correlators at the high transverse momentum are more sensitive at large Q4 which is also a signal of coherent pion emission caused by identical boson condensation --------**

↓

Future experimental data

Thanks for your attention!

Backup



(PRC**93**,054908,2016)