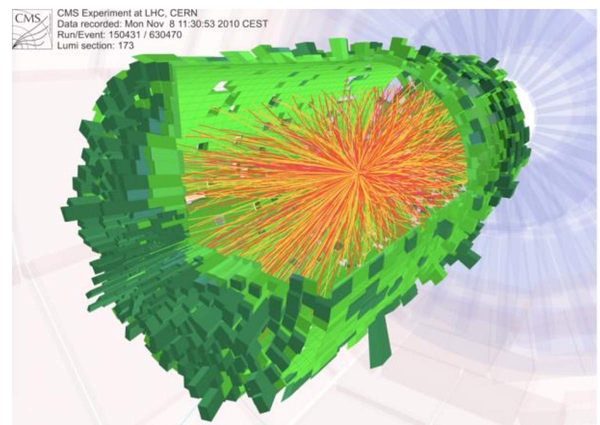
中国物理学会高能物理分会
第十三届全国粒子物理学术会议

Collectivity arising from interference in small and large systems with HBT suppressions

Peng Ru / 茹芃

Institute of Quantum Matter, South China Normal University



PR, G. Bary, Wei-Ning Zhang, PLB 777 (2018) 79-85
PR, W. -N. Zhang, PLB 809 (2020) 135699 & in preparation

2021.08.18
Qingdao

p.ru@m.scnu.edu.cn

Collectivity from coherent and chaotic emissions

Antenna Arrays:
transform spatial anisotropy to
momentum by interference

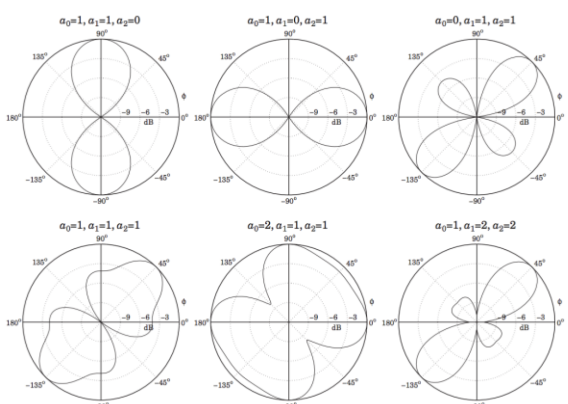
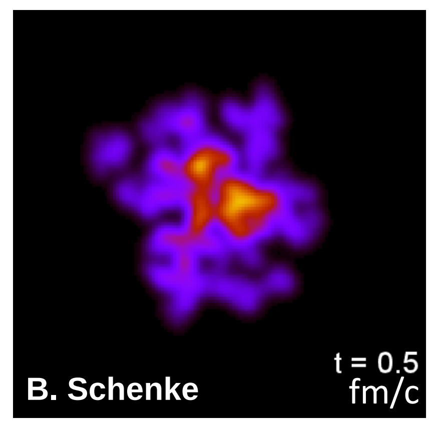


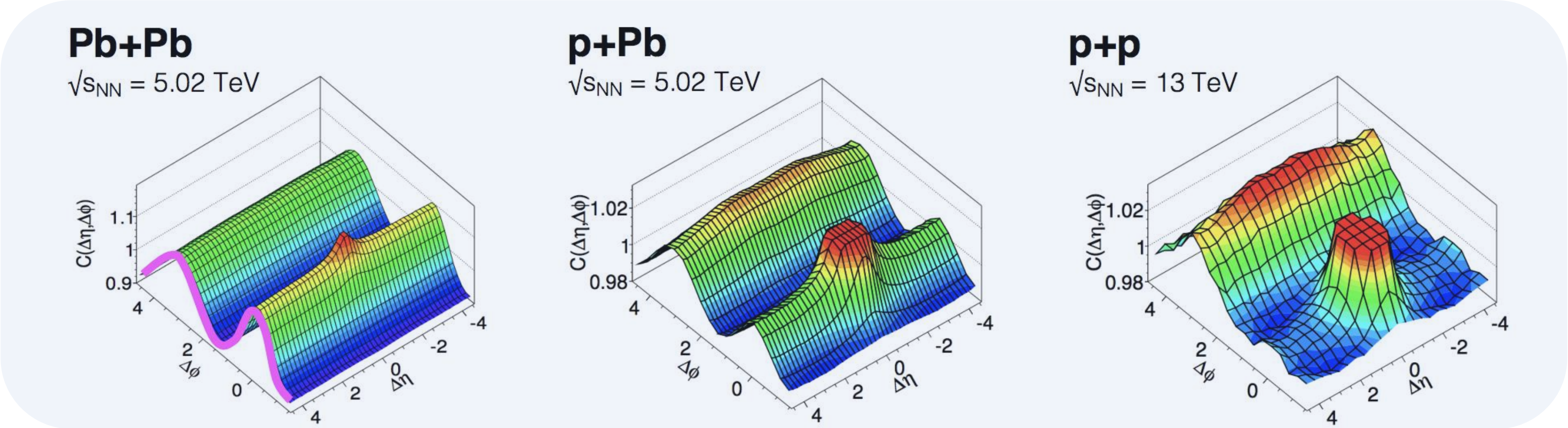
Fig. 22.3.4 Azimuthal gain patterns of two-dimensional array.

Light bulb:
thermal emission
with momentum isotropy



Questions

- Can there be any coherence present from small to large systems of nuclear collisions?
- What if coherent source expand relativistically?
- How to measure the coherent fraction in small and large systems?

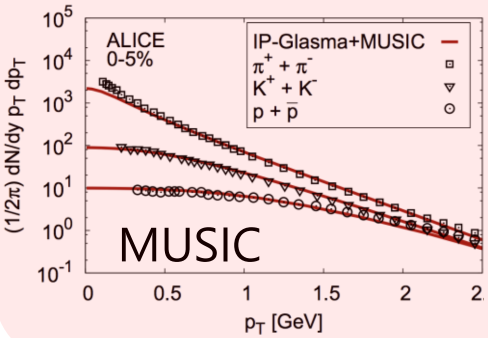


Nagle, et al. ARNPS(2018)

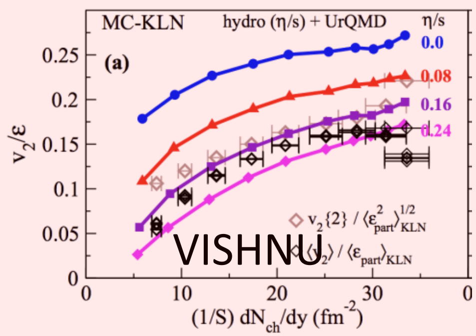
Success of hydrodynamics

Well describe flow observables in large systems

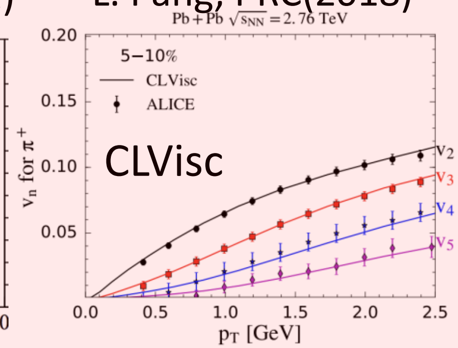
C. Gale, et al, PRL(2013)

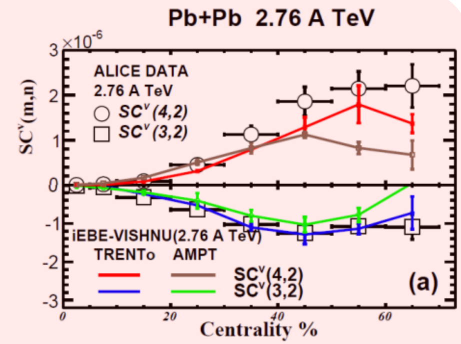


H. Song, et al, PRL(2011)



L. Pang, PRC(2018)

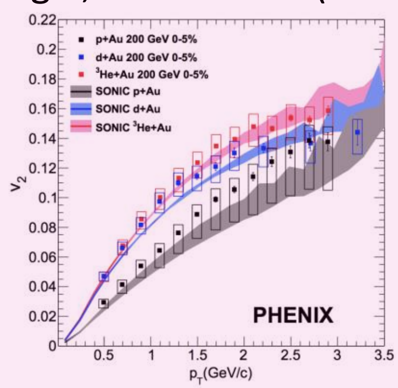




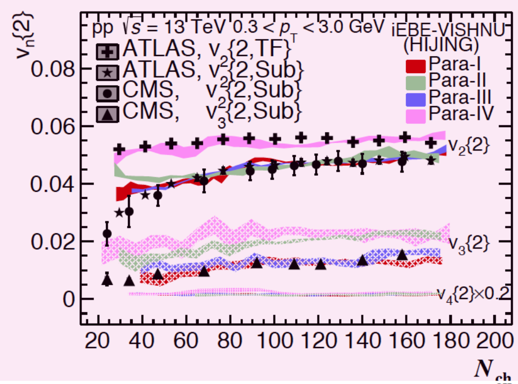
From Wenbin Zhao

Even work in small systems

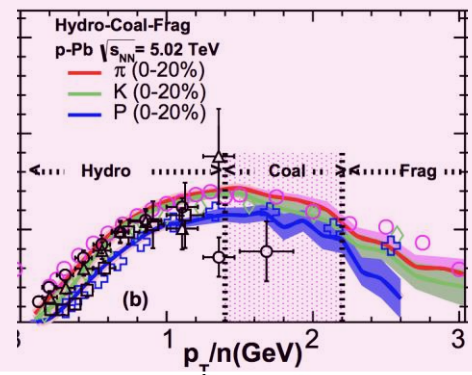
Nagle, et al. ARNPS(2018)



W. Zhao, et al, et al, PLB(2018)



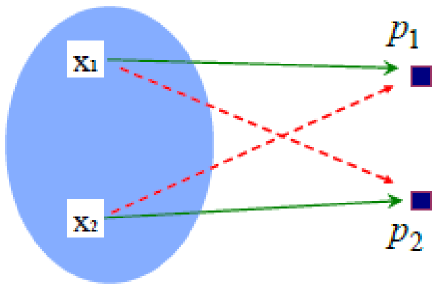
W. Zhao, et al, et al, PRL(2020)



Transport models like AMPT also work well. AMPT also includes only chaotic emissions.

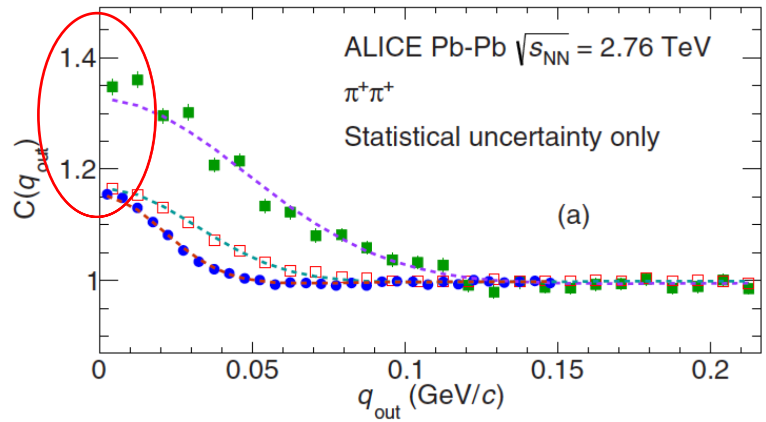
Perspective from HBT correlations

$$C^{(2)}(p_1, p_2) = \frac{\rho^{(2)}(p_1, p_2)}{\rho^{(1)}(p_1)\rho^{(1)}(p_2)}$$

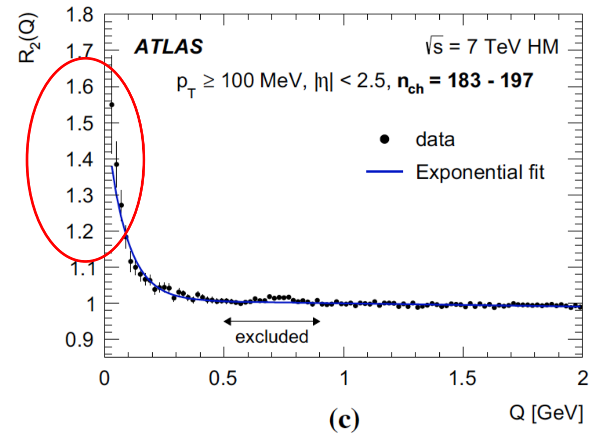


2-pion correlation

AA @ LHC

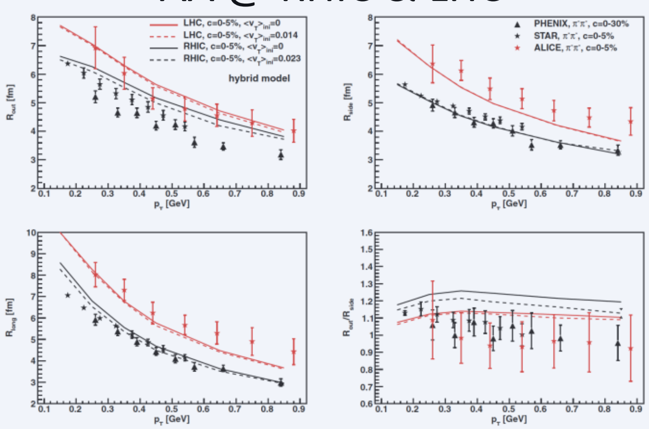


pp @ LHC



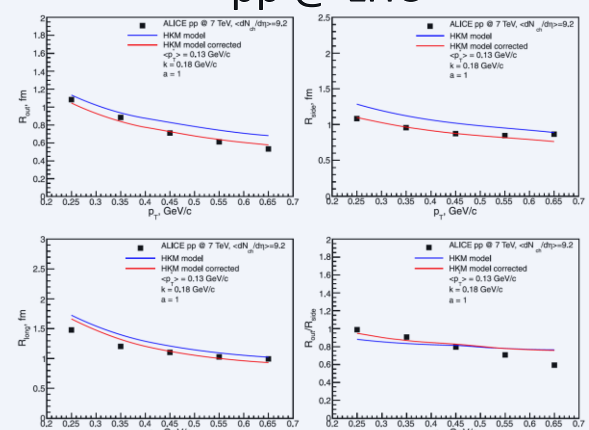
Hydrodynamic model describes HBT radii in small and large systems.

AA @ RHIC & LHC



Karpenko, et al, PRC(2013)

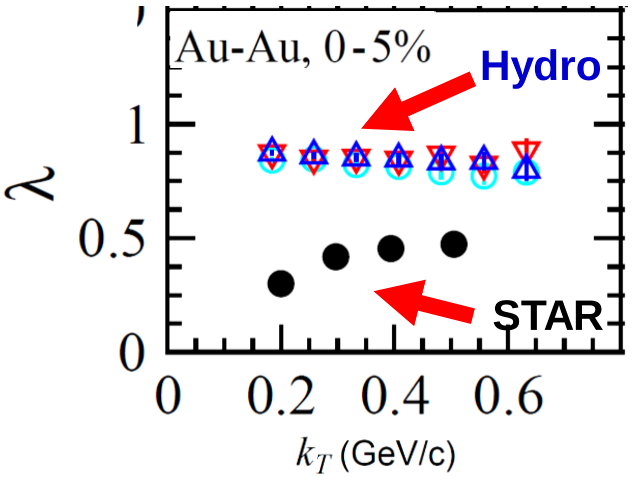
pp @ LHC



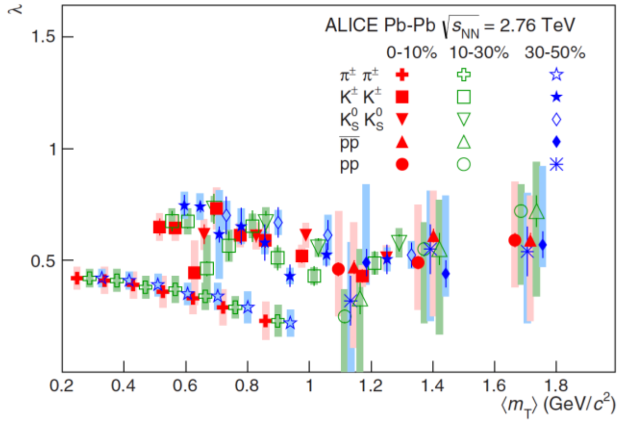
Shapoval, et al, PLB(2013)

Perspective from HBT correlations

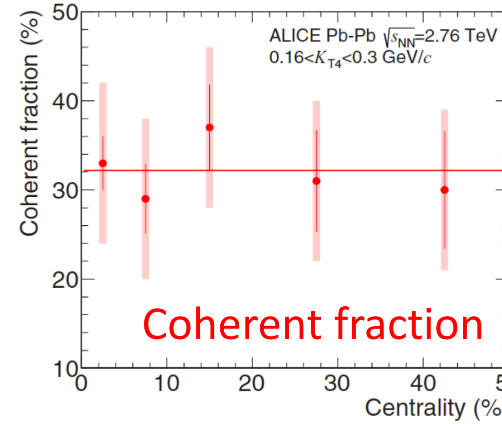
J. Yang, et al, arXiv:1608.04942



ALICE, PRC 92, 054908 (2015)

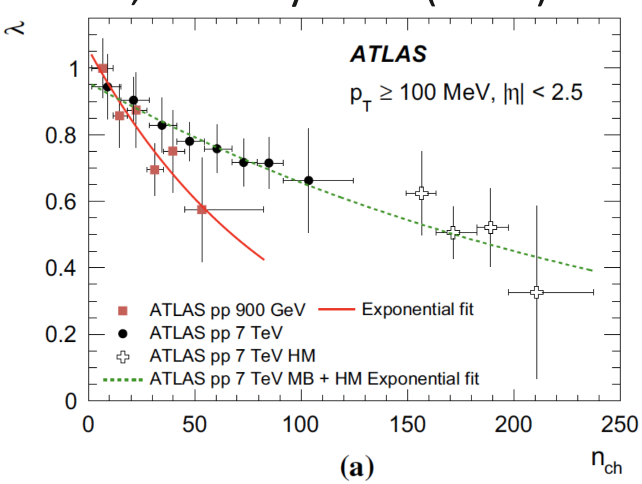


ALICE, PRC 93, 054908 (2016)

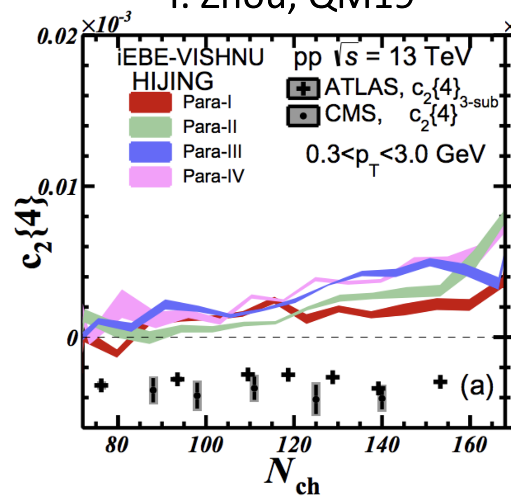


(a) $0.16 < K_{T4} < 0.3$ GeV/c

ATLAS, Eur. Phys. J. C (2015) 75:466



Y. Zhou, QM19



Suppressed HBT strengths indicate possible coherence.

Possible coherence in nuclear collisions

Radiation field of a classical source

$$(\Box + m_\pi^2)\,\phi(x) = \rho(x)$$

$$|\phi_\pi\rangle = e^{-\bar{n}/2}\exp\left(i\int d^3p\,\mathcal{A}(\boldsymbol{p})a^\dagger(\boldsymbol{p})\right)|0\rangle$$

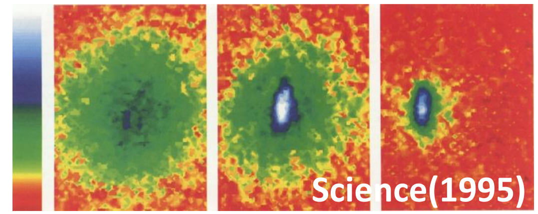
Laser-like emission of particle

M. Gyulassy, et al. PRC(1979)

R. Glauber, NPA(2006) (QM05)

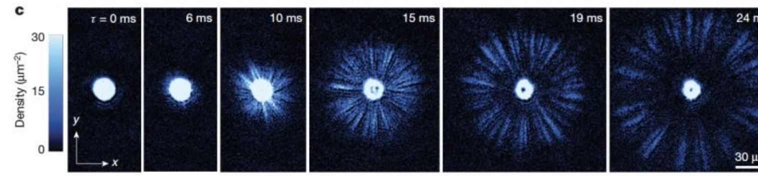
Similarly, Schwinger model of particle production, see, e.g. C.-Y. Wong, Introduction to high-energy HIC

Bose-Einstein Condensate



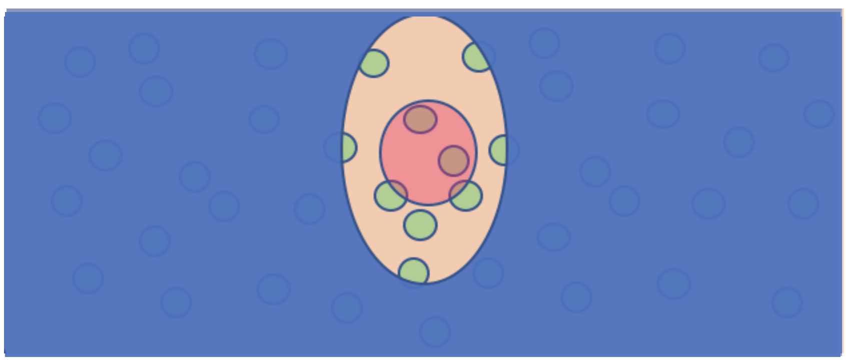
Pion? Gluon? DCC? Overpopulation?......

Symmetry broken in momentum space



Clark, et al., Collective emission of matter-wave jets from driven Bose–Einstein condensates, Nature(2017)

Smaller size, more quantum mechanical

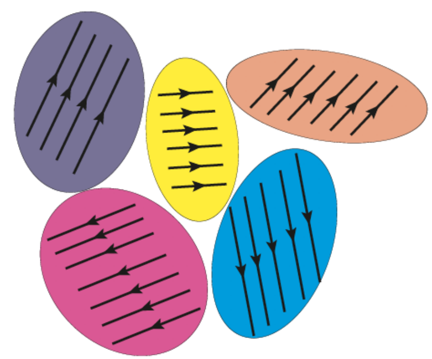


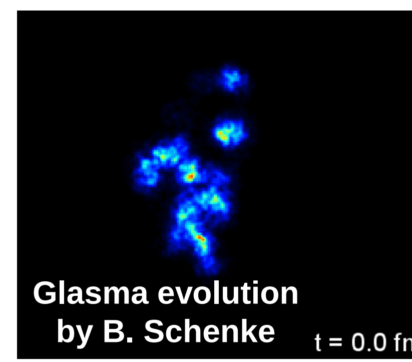
Coherence and v_n from uncertainty principle

Shapoval, et al, PLB(2013) P=500MeV, λ~0.4fm

D. Molnar, F. Wang, C. Greene, 1404.4119

CGC / Glasma





T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP01(2016)061. C. Zhang, C. Marquet, G. Y. Qin, S. Y. Wei and B. W. Xiao, PRL122, 172302 (2019).

Collectivity and effects of source expansion

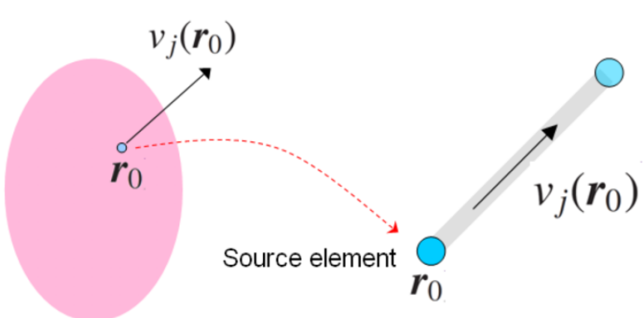
Two types of pion-emitting source

Coherent: classical source radiation

$$E_p P_C(\boldsymbol{p}) = E_p \left| \int d^4x \, e^{ip\cdot x} \, \rho(x) \, A_C(x, \boldsymbol{p}) \right|^2$$

Chaotic: thermal emission

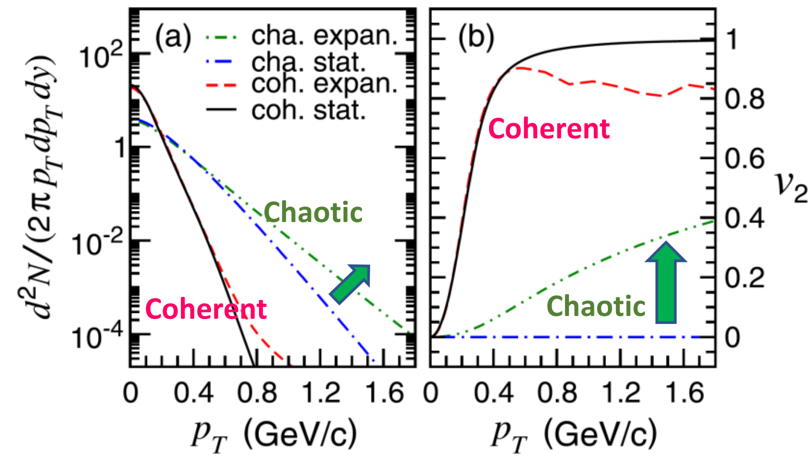
$$E_p P_\chi(\boldsymbol{p}) = E_p \int d^4x \, \rho(x) \, |A_\chi(x, \boldsymbol{p})|^2.$$



$$v_j(\boldsymbol{r}_0) = \mathrm{sign}(r_{0j}) \cdot a_j \left(\frac{|r_{0j}|}{R_{j,max}} \right)^{b_j}$$

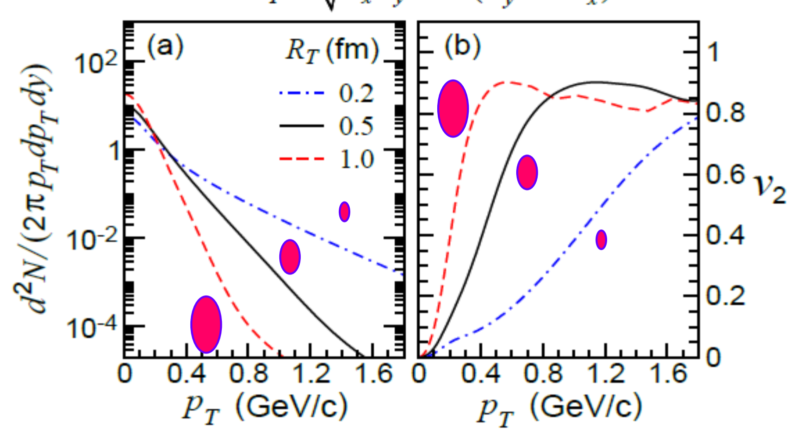
Coherent emission is more sensitive to the geometry of the source at initial time, but not sensitive to the source transverse expansion.

Effects of source transverse expansion



Effects of coherent source size

$R_T = \sqrt{R_x R_y}$ $\quad (R_y = 2R_x)$

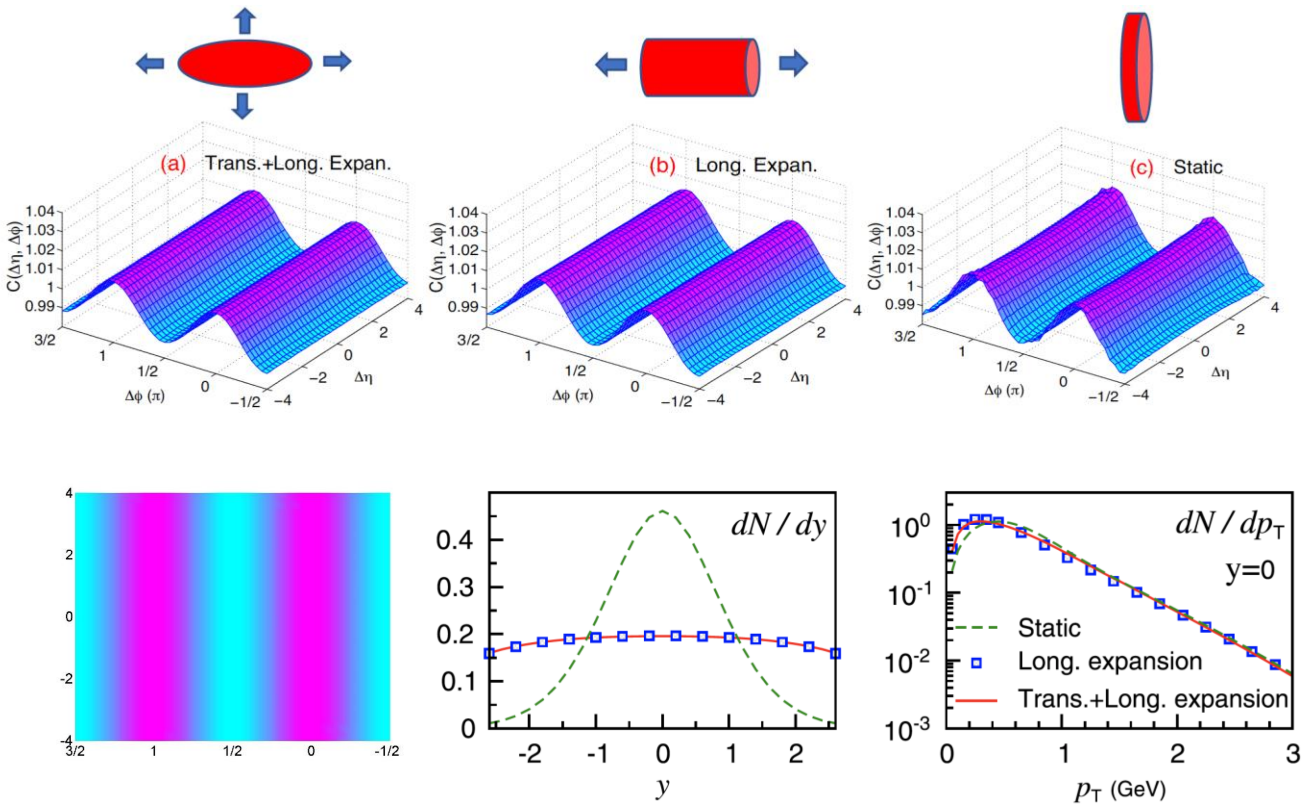


PR, G. Bary, W. -N. Zhang, PLB(2018)

Collectivity and effects of source expansion

Ridge and effects of Bjorken longitudinal expansion

PR, W. -N. Zhang, PLB(2020)



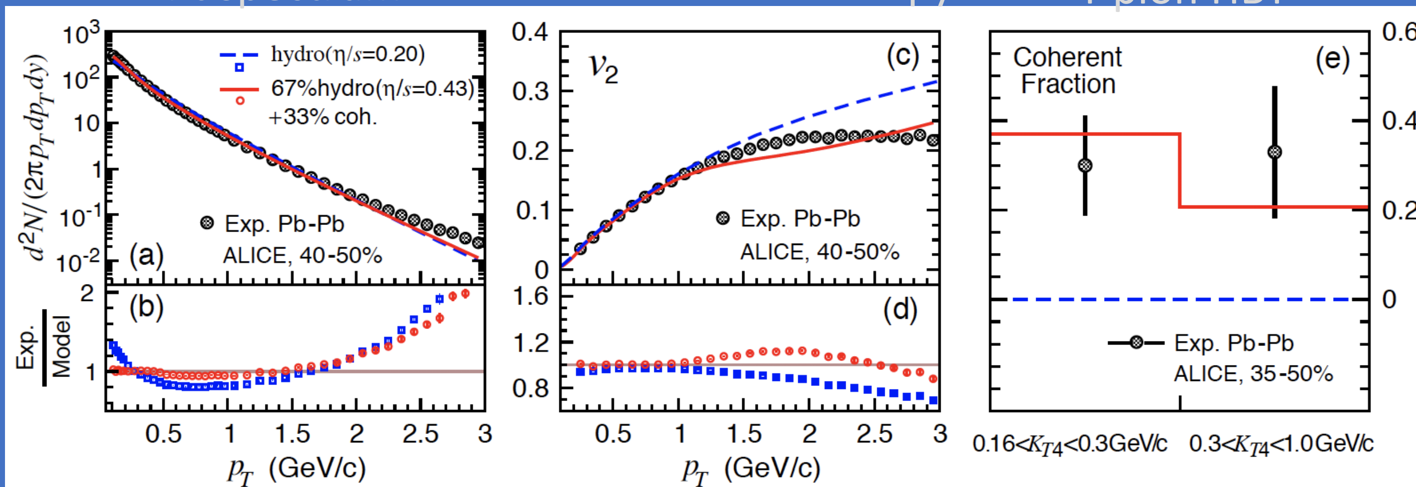
Ridge is related to the interference pattern in momentum space.
Rapidity distribution of coherent emission is sensitive to the longitudinal expansion.

Coherent emission plus hydrodynamic background

Partially coherent pion emission in AA system:

PR, G. Bary, W. -N. Zhang, PLB(2018)

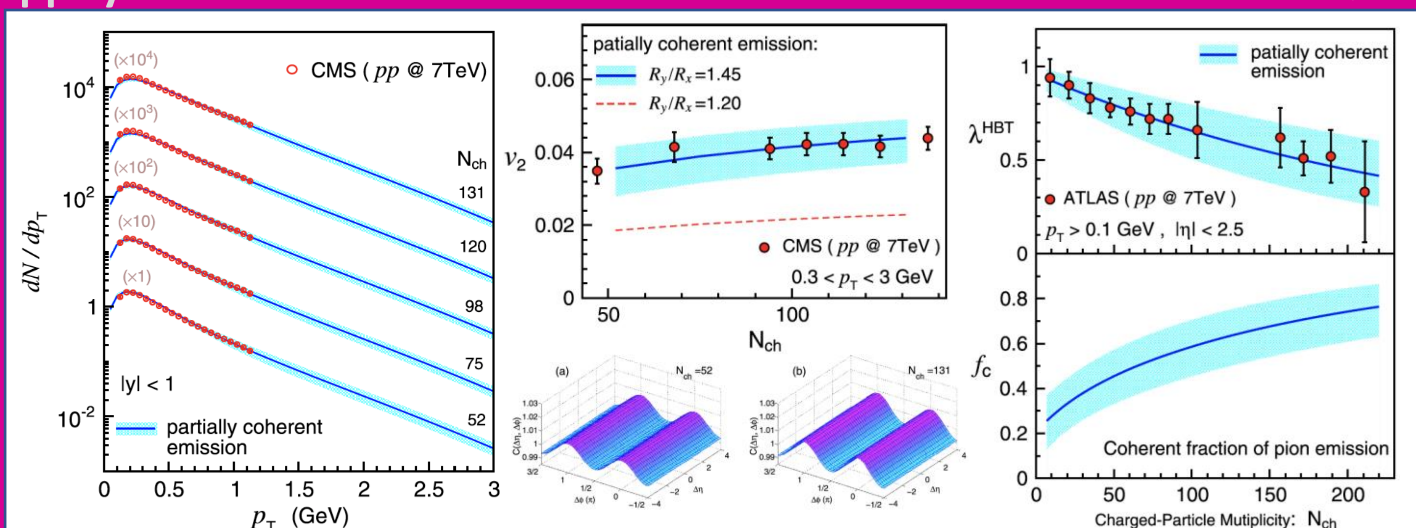
Pt spectrum azimuthal anisotropy 4-pion HBT



Expanding coherent source plus VISH2+1

In pp system:

PR, W. -N. Zhang, PLB(2020)

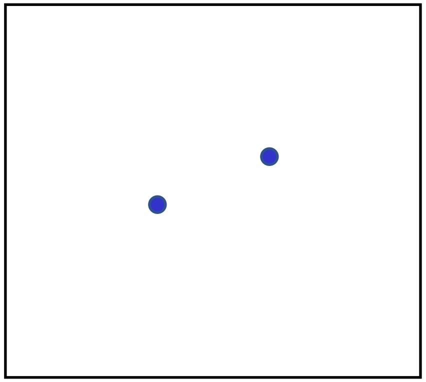


Expanding coherent source plus blast-wave source (hydro like)

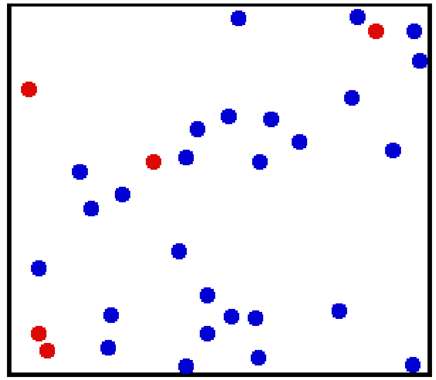
Pt spectra, azimuthal anisotropy, and HBT strength as functions of multiplicity.

Coherence & HBT correlations

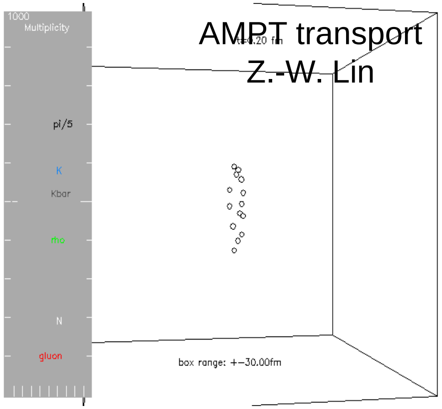
Quantum statistical correlations



2 identical particles
No interaction
Thermal equilibrium



N identical particles
Ideal gas
Thermal equilibrium



Off-equilibrium, relativistic,
Dynamically evolving,
Interactions, coherence

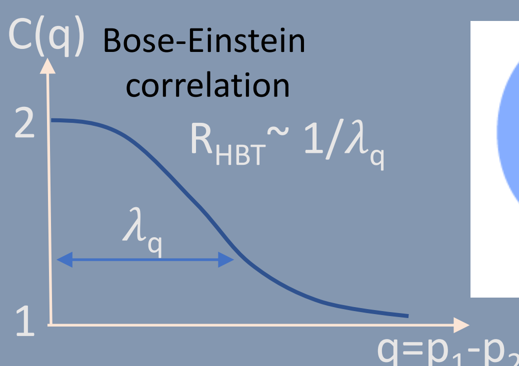
$$\rho^{(1)}(r) = \frac{1}{V} \qquad \rho^{(2)}(r_1, r_2) = \frac{1}{V^2}\left[1 \pm \exp\left(-\frac{2\pi r_{12}^2}{\lambda^2}\right)\right]$$

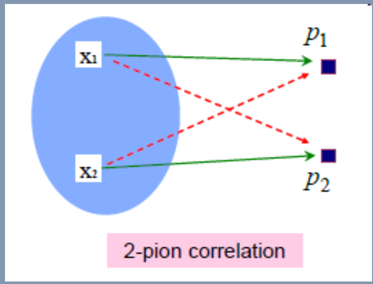
$$C^{(2)}(r_1, r_2) = \frac{\rho^{(2)}(r_1, r_2)}{\rho^{(1)}(r_1)\rho^{(1)}(r_2)} = 1 \pm \exp\left(-\frac{2\pi r_{12}^2}{\lambda^2}\right)$$

(Identical particle)

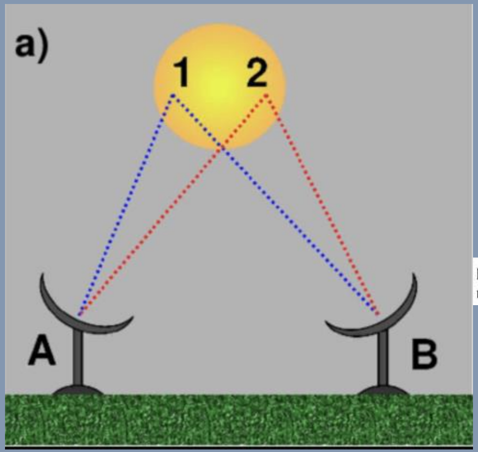
$$\lambda = h/(2\pi m k_B T)^{1/2}$$

Spatial -- Momentum





Coherence & HBT correlations



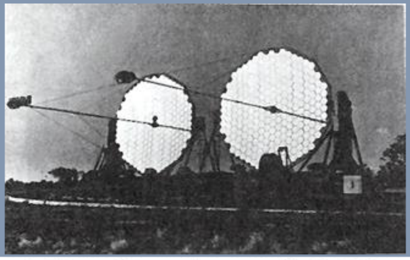
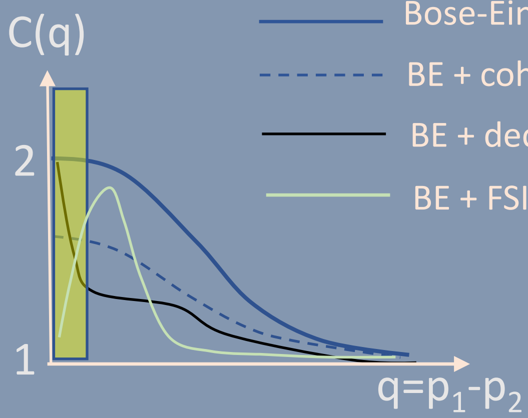
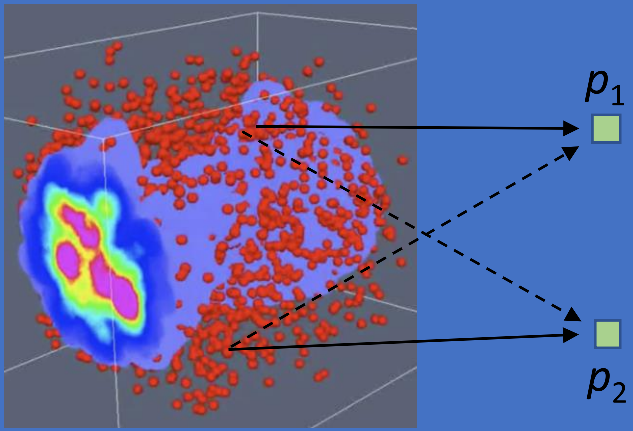


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

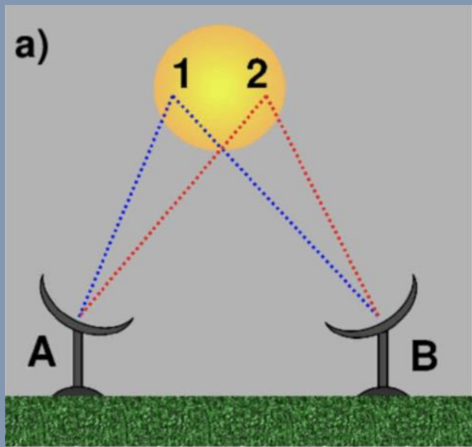
Hanbury Brown, Twiss, **Nature** (London) 177, 27 (1956).

2π-correaltion In heavy-ion collisions





Coherence & HBT correlations



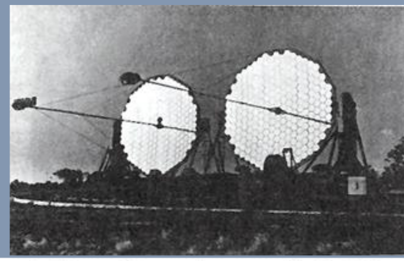
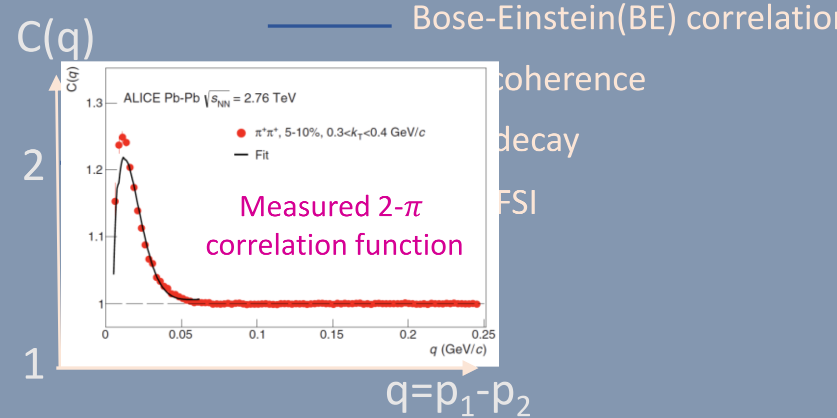
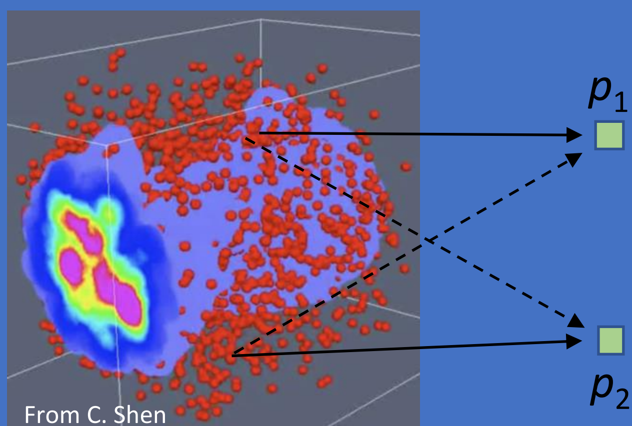


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

Hanbury Brown, Twiss, **Nature** (London) 177, 27 (1956).

2π-correaltion In heavy-ion collisions





Hydro (VISH/MUSIC) + hadron cascade (UrQMD)

\+

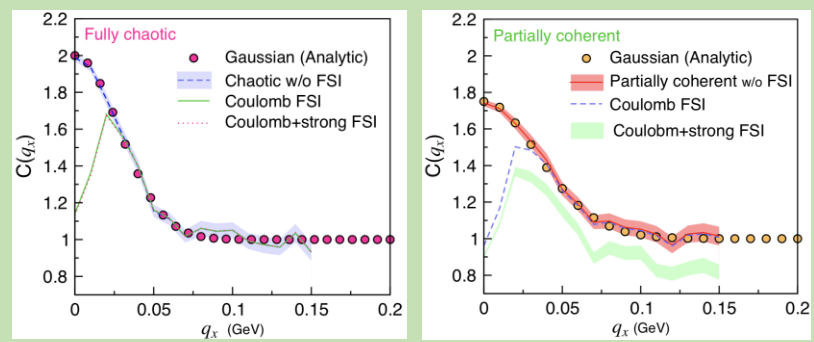
Coherent emission

FSI

HBT Correlation, flow

Not only HBT radii & strength
But also full correlation functions

Preliminary results

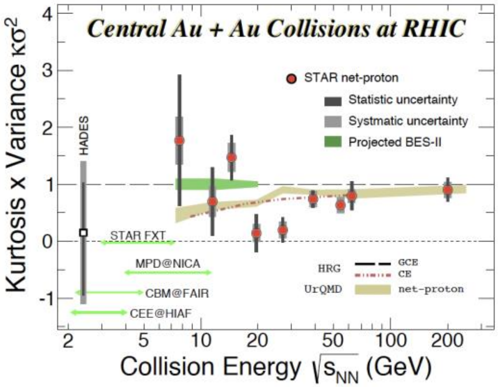


PR, W. -N. Zhang, in preparation

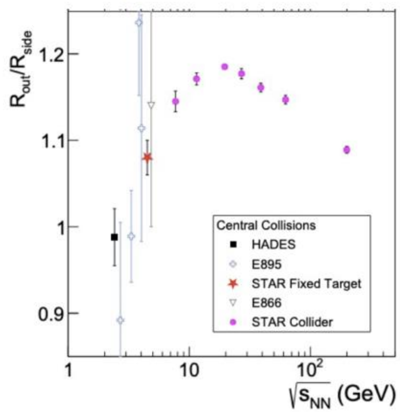
HBT: an old subject in future

Non-monotonic behavior at BES

STAR, Phys. Rev. Lett. 126, 092301 (2021)

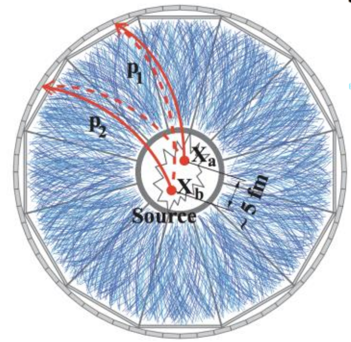


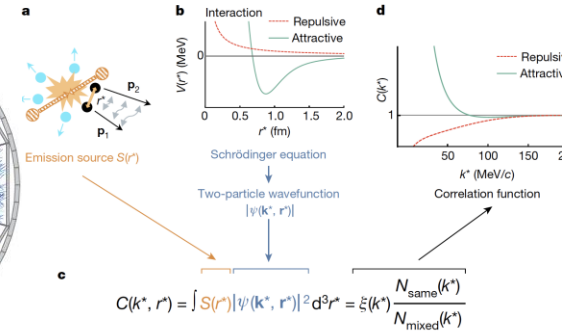
STAR: Phys. Rev. C 103, 034908 (2021)



From talk by X.-F. Luo on QPT2021

Femtoscopy: probe hadron interactions





$$C(k^*, r^*) = \int S(r^*)|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^3r^* = \xi(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

STAR, Nature (2015)

ALICE, Nature (2020)

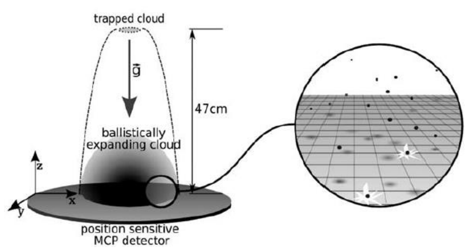
Ultracold atomic system

REPORTS

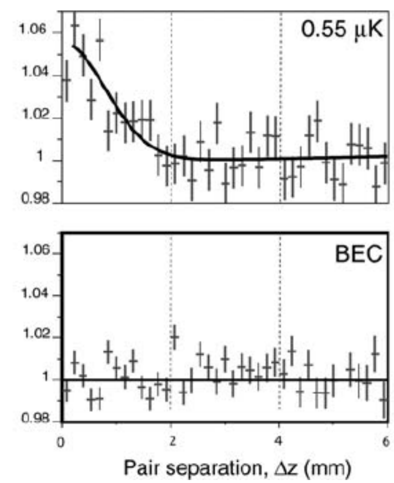
Hanbury Brown Twiss Effect for Ultracold Quantum Gases

M. Schellekens,[1] R. Hoppeler,[1] A. Perrin,[1] J. Viana Gomes,[1,2] D. Boiron,[1] A. Aspect,[1] C. I. Westbrook[1*]

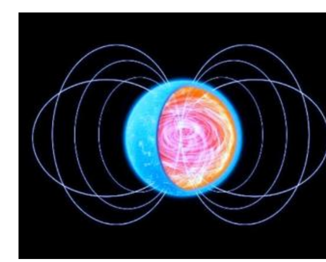
We have studied two-body correlations of atoms in an expanding cloud above and below the Bose-Einstein condensation threshold. The observed correlation function for a thermal cloud shows a bunching behavior, whereas the correlation is flat for a coherent sample. These quantum correlations are the atomic analog of the Hanbury Brown Twiss effect. We observed the effect in three dimensions and studied its dependence on cloud size.



SCIENCE, 310, 648 (2005)



Bose-Einstein condensate inside stars ?

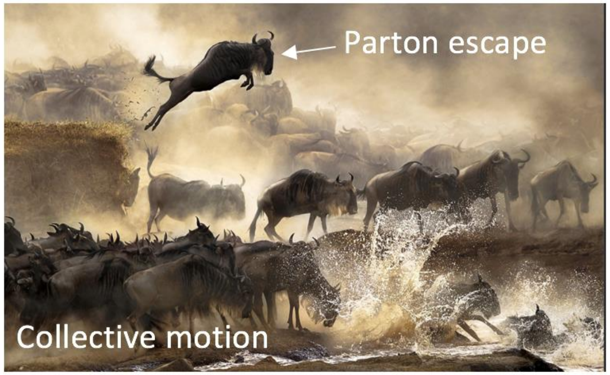


Summary

- Collectivity can arise from interference in coherent emission of particles, where ridge is an interference pattern in momentum space.
- Coherence may play more important roles in smaller systems.
- Azimuthal correlations in coherent emission are insensitive to source expansion. Rapidity distribution is sensitive to Bjorken expansion.
- A joint study of flow and HBT correlation function may help understand coherence and collectivity in small and large nuclear collisions systems.

Coherent

Chaotic



Partially coherent

Thank you for your attentions!

Thank the organizers!

Backup

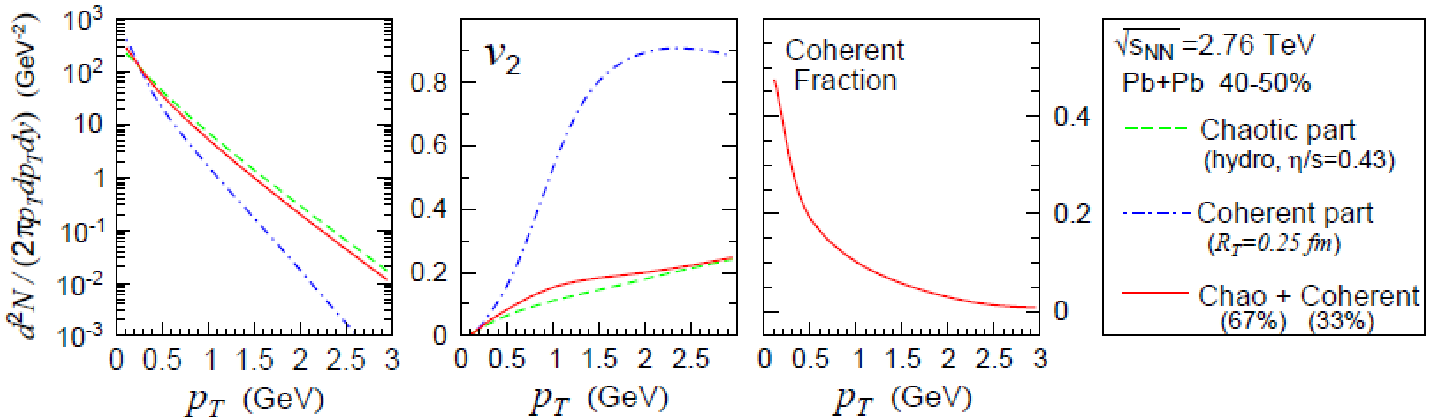


图 6.8 部分相干源模型中的混沌部分和相干部分对结果的贡献。其中，左图为 π 介子的横动量谱，中图为 π 介子的 $v_2(p_T)$。右图为部分相干源 π 介子发射的相干性分数。

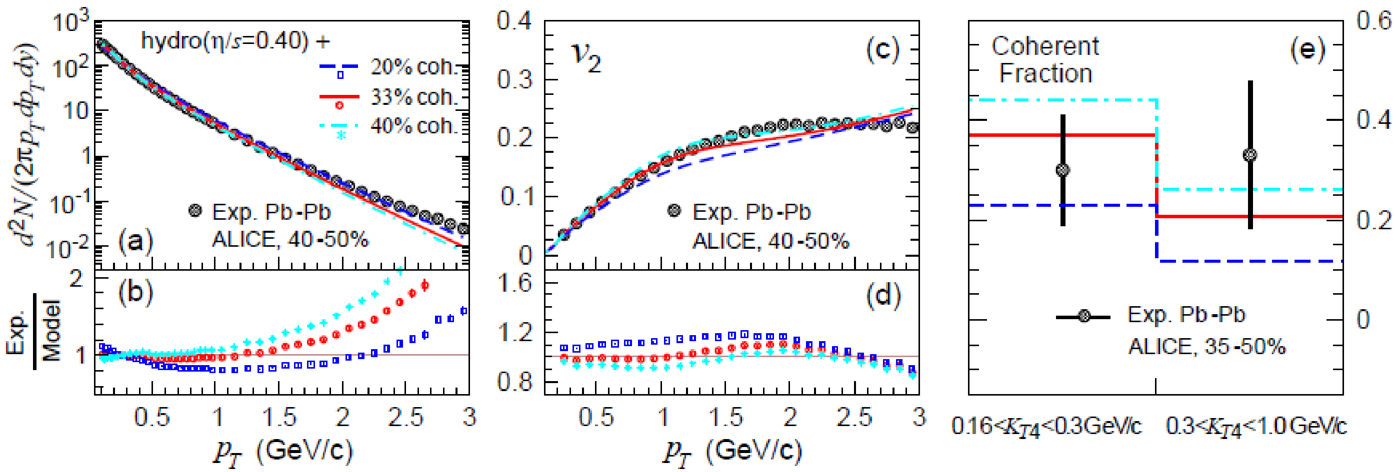
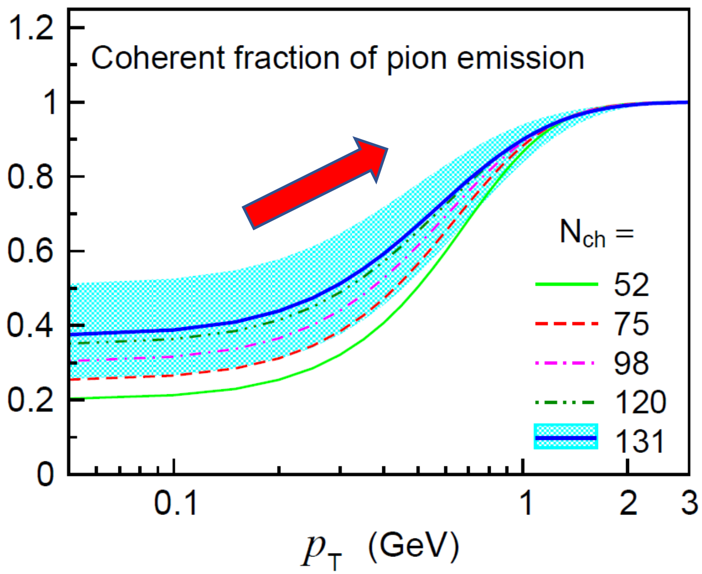
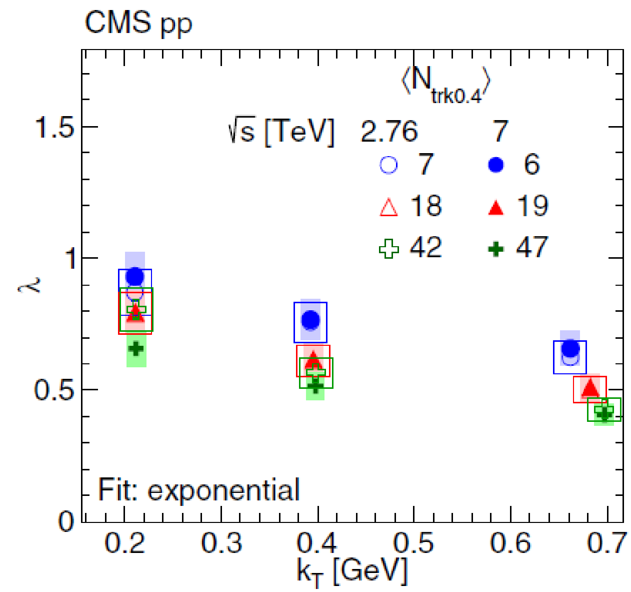
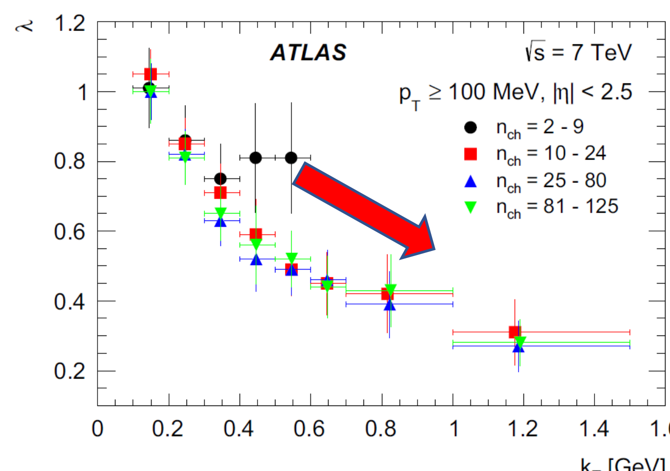


图 6.9 不同相干性分数的部分相干源模型结果与实验数据的对比。其中，左图为 π 介子的横动量谱，中图为 π 介子的 $v_2(p_T)$，右图为 π 介子的相干性分数。图中实验数据与图 6.7 一致。





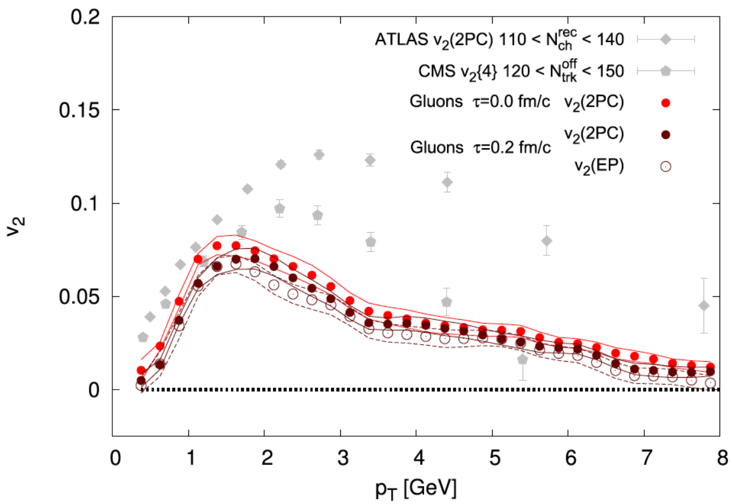


(a)

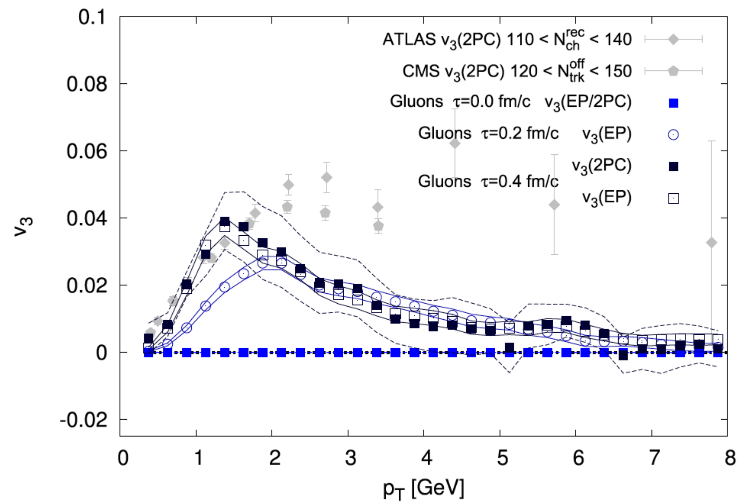
Trends of coherent fraction as a function of pT similar as the experimental measurement.

Azimuthal anisotropies in p + Pb collisions from classical Yang–Mills dynamics

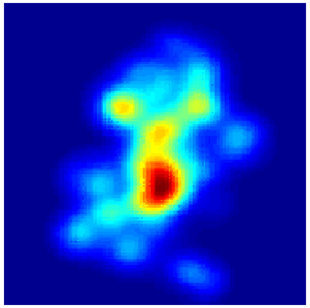
B. Schenke, et al., PLB 747 (2015) 76–82

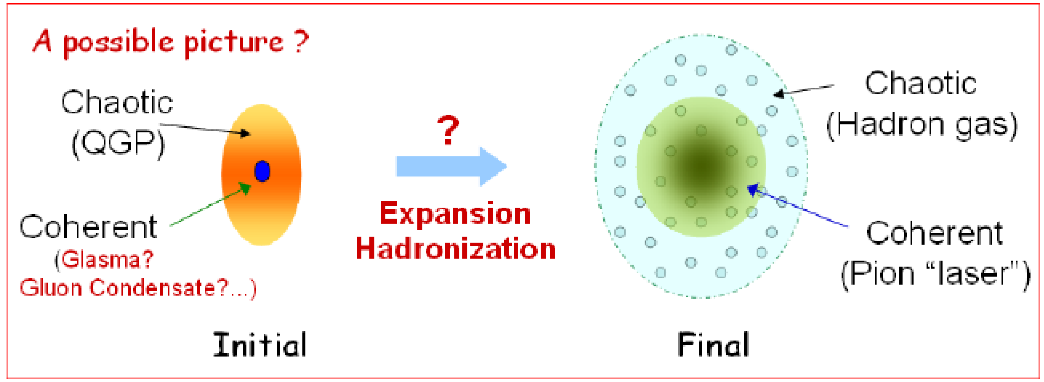


V2>0 at tau=0

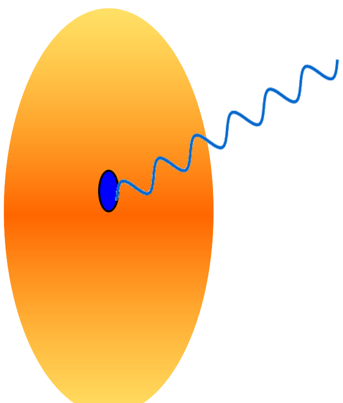


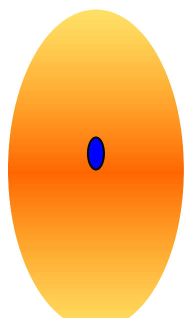
V3=0 at tau=0



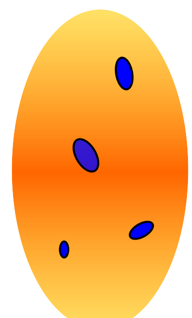


Single- or multi-coherent source ?





Single-source



Multi-source