QGP in small systems?

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Itzhak Tserruya
Outline

- Introduction
- “Collective” observables in small systems
  - Long range correlations
  - Flow: \( v_1, v_2, v_3 \ldots \)
    - mass ordering, quark scaling…
  - HBT radii
- Hard / penetrating probes in small systems
  - Energy loss?
  - HF and J/\( \psi \) \( R_{AB} \)
  - Photons, dileptons?
- Summary
Quark Gluon Plasma formed in AA collisions

- p,d+A:
  - System size too small for quark matter formation
  - Reference for cold nuclear matter effects

- p+p: reference baseline

Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
The possibility that QGP matter is formed in high multiplicity pp events is not a new idea.

Fermilab experiment E735 main goal was just that:

“… to search for evidence of a phase transition of hadronic matter to a deconfined quark-gluon state in ppbar collisions.”

See also:
Friedlander and Weiner, PRL 43, 15 (1979) and PRL 57, 2119 (1986)
Short historic regression

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How do we quantify small vs large

Size of the colliding system:
- $pp < p,d+A << AuAu$ or $PbPb$
- $N_{\text{part}}$
- $N_{\text{coll}}$
- Initial transverse size

Size of the medium formed:
- $dN_{\text{ch}}/d\eta$
- $N_{\text{ch}}$
Small systems: paradigm change?

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- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
  - Long range near-side correlations
Ridge discovered at RHIC

Ridge = Long-range near-side correlations

Au+Au central $\sqrt{s_{NN}}=200$ GeV

- Ridge seen in AA collisions at RHIC, later also at LHC in Pb+Pb collisions
- Not seen in min. bias d+Au collisions
Ridge discovered at RHIC

Ridge = Long-range near-side correlations

Au+Au central $\sqrt{s_{NN}}=200$ GeV

- Ridge seen in AA collisions at RHIC, later also at LHC in Pb+Pb collisions
- Not seen in min. bias d+Au collisions
Ridge in small systems at LHC

- Long-range near-side correlations first seen in high multiplicity p+p collisions and later also in high multiplicity p+Pb collisions at LHC

- Strength of correlation much smaller in p+p than in p+Pb
...and recently also reported by ATLAS

- **p+p √s = 13 TeV – 2015 data**
  - No near-side ridge for low multiplicity events
  - Ridge develops with increasing number of tracks

Both particles with 0.5 < p_T < 5 GeV/c
…and recently also reported by ATLAS

- **p+p √s = 13 TeV – 2015 data**

**Concave shape at low track multiplicity**

**Becomes ~ flat at larger multiplicity**

A clear ridge develops at high track multiplicity

The solid lines show the result of a Fourier fit to the data using harmonics up to fifth order.
Ridge in small systems at RHIC

Two particle correlations measured over a large $|\Delta \eta| > 2.75$ gap

(charged track in central arm and tower hit in forward calorimeter)

- Not present in minimum bias $p+p$ and $d+Au$ collisions
- Long-range near-side correlations in central $d+Au$ collisions in the Au going direction
Shape engineering: $^{3}\text{He+Au}$

Two particle correlations measured over a large $|\Delta \eta| \sim 3.5$ gap

(charged track in central arm and BBC)

- Long-range near-side correlations seen in both Au-going and $^{3}\text{He}$-going directions
Small systems: paradigm change?

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- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
  - Long range near-side correlations
  - Flow
**Flow in small systems: $v_n(p_T)$**

**Origin:** The pressure converts the initial spatial anisotropy (elliptic shape of overlap region) into momentum anisotropy of particle emission.

Quantified by Fourier decomposition of the azimuthal distribution of particles:

$$
\frac{dN}{d\phi dp_T} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos\left[2(\phi - \Psi_{RP})\right]
$$
Flow in small systems: $v_n(p_T)$

- Same qualitative features ($v_n$ shapes and harmonic ordering) as in Pb+Pb
- Similar magnitude within a factor of two
Flow in small systems: multiplicity dependence

$v_2(pPb) < v_2(PbPb)$
Expected

$v_3 < v_2$
$v_3(pPb) \approx v_3(PbPb)$
Similar triangular excentricity in pPb and PbPb
Shape engineering: $d, ^3\text{He}+\text{Au}$

- $v_2$ of $^3\text{He}+\text{Au}$ similar to that of $d+\text{Au}$
- Clear $v_3$ signal in central $^3\text{He}+\text{Au}$ collisions
Flow: Quark scaling

CMS PLB 742, 200 (2015)

Scale with number of valence quarks

\[ p_T \rightarrow KE_T = \sqrt{(m^2 + p_T^2)} - m \]

Flow develops at partonic level in small systems?
Flow: Quark scaling

\[ p_T \rightarrow \sqrt{m^2 + p_T^2} = m + \sqrt{p_T^2} \]

Au+Au \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

**PRL 98, 162301 (2007)**
Collectivity in pPb

CMS arXiv:1502.05382

Flow analysis using the cumulant method in multiparticle azimuthal correlations

\[ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\} \]
Radial flow
STAR pp, dAu, AuAu

BW fit quality comparably good in all three systems
Radial flow

ALICE PLB 728, 25 (2014),

Mass ordering seen down to very low multiplicities

Natural explanation: collective radial expansion of the system
Small systems: paradigm change?

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- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
  - Long range correlations in d,^3^He+Au
  - Flow
  - HBT radii
HBT radii and multiplicity

\[ R_{\text{inv},3}^{E_{\text{w}}} \]

- \( \text{pp } s=7 \text{ TeV} \)
- \( \text{p-Pb } s_{\text{NN}}=5.02 \text{ TeV} \)
- \( \text{Pb-Pb } s_{\text{NN}}=2.76 \text{ TeV} \)

- \( 0.3<K_{T,3}<1.0 \text{ GeV/c} \)
- \( 0.3<k_{T}<1.0 \text{ GeV/c} \)

\[ \kappa_{3}=0.1, \kappa_{4}=0.5 \]

ALICE PLB 739, 139 (2014)
HBT radii and multiplicity

ALICE PLB 739, 139 (2014)

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HBT radii scale with size

PHENIX Au+Au and Cu+Cu: HBT radii scale linearly with initial transverse size

ALICE Pb+Pb: same behavior

\[ \frac{1}{R} = \sqrt{\left(\frac{1}{\sigma_x}\right)^2 + \left(\frac{1}{\sigma_y}\right)^2} \]
...also in small systems

- HBT radii scale linearly with the initial transverse size
- Smooth behavior from small (d+Au, p+Pb) to large (Au+Au, Pb+Pb) systems at RHIC and LHC.
- Imply or consistent with radial expansion in small systems and fsi

arXiv:1404.5291
Many features seen in A+A collisions are seen in p,d+A collisions and even in p+p collisions at high multiplicity:

- Long range correlations
- Flow:
  - $v_n(p_T)$ – similar shape
  - $v_2$ quark scaling
  - multiparticle correlations
  - strong radial flow
- HBT radii scaling with initial transverse size

Smooth evolution from small to large systems.

Small systems exhibit collective behavior consistent with hydro.
and what about hard / e.m. probes?

- If QGP is formed in small systems we should also see all the characteristic features of the medium:
  - high $p_T$ suppression / jet quenching
  - $J/\psi$ suppression
  - Photons and dileptons
Energy loss / quenching?

\[ R_{AA}(p_t) = \frac{d^2 N_{AA} / dp_t d\eta}{N_{coll} d^2 N_{pp} / dp_t d\eta} \]

No evidence of charged particle suppression in d+Au or in p+Pb

Need trigger on much higher multiplicity events

Suppression clearly seen in Au+Au at 40-50% centrality \( \rightarrow dN_{ch}/d\eta \approx 100\)
Smooth evolution of HF $R_{AA}$ from enhancement in small systems to suppression in large systems
Similar \( R_{AA} \) at similar \( N_{part} \) in dAu, CuCu and AuAu systems.

- Similar suppression in Cu+Au (Au-going direction) and Au+Au
- Stronger suppression in Cu+Au (Cu-going direction) – opposite of expected trend if suppression is prop to particle density
Photons and Dileptons

Direct photons

Probably no chance

arXiv:1405.3940

PRC 81, 034911 (2010)

arXiv:1405.4004
Summary

Many features seen in A+A collisions are seen in p,d+A collisions and even in p+p collisions at high multiplicity:

- long range correlations
- Flow:
  - $v_n(p_T)$ – similar shape
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- HBT radii scaling with initial transverse size

Smooth evolution from small to large systems.

Small systems exhibit collective behavior consistent with hydro

No evidence of energy loss or jet quenching in small systems

Heavy flavor and $J/\psi$: smooth evolution from small to large systems.

Need similar systematic approach on hard probes observables in small systems, triggering on very high multiplicity events.